University of Ontario Institute of Technology

DESIGN, ANALYSIS AND VALIDATION OF ELECTRODE-LESS PLASMA GENERATOR

by

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in

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Faculty of Faculty of Engineering and Applied Science

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Tiefe Brunnen muss man graben wenn man klares Wasser will.
Acknowledgements

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Abstract

The current work investigates a method for generating plasmas without damaging electrodes. The primary objective is the creation of an electrode-less potential region (virtual cathode) through the use of electron emission and active feed of radio frequency (RF) signal. The reason for pursuing this was to make plasma devices that are compact, efficient, resilient, and low maintenance. The foundational scientific theory, model, and the simulation were applied in Elmer multi-physics software and validated by experiments. The experiments were conducted with electrode based plasma generator, ionization setup, and RF assisted configuration, and compared with respect to their operational parameters. It has been determined that it is possible to create a plasma generator with a virtual cathode that receives substantial electromagnetic energy from RF and competes with a direct arc discharge method in performance, and longevity, albeit requiring a more refined control.
# Contents

1 Introduction .................................................................................................................. 3
  1.1 Motivation .................................................................................................................. 3
  1.2 Thesis Objectives ...................................................................................................... 3
  1.3 Plasma State Overview ............................................................................................. 4
  1.4 Innovation and Contributions .................................................................................. 6
  1.5 Thesis Structure ........................................................................................................ 6

2 Literature Review ......................................................................................................... 8
  2.1 Plasma State Definition and Measurement ................................................................. 8
  2.2 Plasma Generation ..................................................................................................... 11
  2.3 Plasma Applications ................................................................................................. 15

3 Methodology Framework ............................................................................................ 17

4 Proposed System Design ............................................................................................ 20
  4.1 Preliminary Concepts ............................................................................................... 20
  4.2 Concept Components .............................................................................................. 22
  4.3 Analysis of Plasma Generation Properties ................................................................. 26
    4.3.1 Ionization .......................................................................................................... 27
    4.3.2 RF Coupling and Confinement ......................................................................... 43
    4.3.3 Plasma as a Fluid ............................................................................................. 51
    4.3.4 Circuit for Plasma Power and Control ............................................................... 61

5 Plasma Generator Experiment ....................................................................................... 71
  5.1 Experiment Setting .................................................................................................... 71
    5.1.1 Safety .............................................................................................................. 72
    5.1.2 Power Supplies ............................................................................................... 74
    5.1.3 Data Acquisition Methodology ...................................................................... 75
  5.2 Experiment Results and Analysis ............................................................................. 77
    5.2.1 Pressure error due to leakages ........................................................................ 77
8 Conclusion and Future Work

8.1 Conclusion ........................................... 129
8.2 Recommendations for Industrial Application .......... 130
8.3 Future Work ........................................... 131
## List of Figures

3.1 Methodology framework. .................................................. 18
4.1 Functional Representation of the Virtual Electrode Plasma Generator 21
4.2 Concept 1 of Plasma Generator with Core-Less Induction Coupling . 21
4.3 Concept 2 of Plasma Generator with Cored Induction Coupling . . . 22
4.4 The Components of Conceptual Plasma Generators . . . . . . . . . . . 23
4.5 The physical components of conceptual plasma generator. . . . . . . . 26
4.6 Emitted Current vs. High Field Potential for Tungsten Metal . . . . 32
4.7 The minimum sparking potential $V_{b,\text{min}}$, as a function of the secondary
electron emission coefficient, $\gamma_{SE}$, for several gases . . . . . . . . 35
4.8 A schematic of a cylindrical plasma with electrical conductivity $\sigma$,
radius $a$, and skin depth $\delta$, coupled to the RF coil of radius $r_c$ . . . . . . . 49
4.9 A schematic of the concept plasma generator with an electron emitter,
coupled to the RF coil, and subjected to the flow of a neutral gas. . . 52
4.10 Schematic Diagram of Virtual Electrode Plasma Generator Components 61
4.11 Circuit Schematic of Single Stage High Field Multiplier . . . . . . . . 66
4.12 RF Coupling Circuit Schematic . . . . . . . . . . . . . . . . . . . . . 68
5.1 Schematic layout for plasma generator experiment in vacuum . . . . . 71
5.2 Physical layout for plasma generator experiment in vacuum . . . . . . 72
5.3 Plasma generator configuration in the vacuum chamber . . . . . . . . 72
5.4 Circuit diagram of the Colpitts oscillator used in the experiment . . . 74
5.5 Circuit Diagram of Triple Langmuir Probe . . . . . . . . . . . . . . . 76
5.6 Pressure loss due to leakages at -28Hg. . . . . . . . . . . . . . . . . . . 78
5.7 Pressure change due to gas flow into the chamber . . . . . . . . . . . 79
5.8 Plasma Generator Experiment Layout . . . . . . . . . . . . . . . . . . 80
5.9 Measured Plasma Current in Arc. . . . . . . . . . . . . . . . . . . . . . 81
5.10 Comparison of the potential readings for indicated configurations. . . 82
5.11 Comparison of the current readings for indicated configurations. . . 83
6.1 Modelling meshes used in Elmer for CFD analysis, resolutions from left to right: 0.25mm, 0.1mm, and 0.05mm.

6.2 Flow profile cross-cut section of the velocity layers for a 0.25mm resolution mesh.

6.3 Flow profile cross-cut section of the velocity layers for a 0.1mm resolution mesh.

6.4 Flow profile cross-cut section of the velocity layers for a 0.05mm resolution mesh.

6.5 Temperature profile cross-section for a 0.25mm resolution mesh.

6.6 Temperature profile cross-section for a 0.1mm resolution mesh.

6.7 Temperature profile cross-section for a 0.05mm resolution mesh.

6.8 Adjusted Colpitts RF circuit.

6.9 Voltage and current on the coupling LC side of Colpitts circuit.

6.10 Voltage multiplier concept for the electron emission.

6.11 Voltage multiplier potentials and current for a 10 stage configuration.

6.12 RF inverter for the plasma confinement.

7.1 Direct Discharge Plasma Generation Mode.

7.2 Single Emitter Plasma Generation Mode.

7.3 RF Assisted Single Emitter Plasma Generation Mode.

7.4 7MHz dominant RF Spectrum in the Colpitts circuit.

7.5 Temperature profile, Kelvin, for direct discharge plasma configuration with computed conductance.

7.6 Concentration profile for direct discharge plasma configuration with computed conductance.

7.7 Current profile, Amperes per meter, for direct discharge plasma configuration with computed conductance.

7.8 Joule heating profile, Watts per meter, for direct discharge plasma configuration with computed conductance.

7.9 Magnetic strength profile, milli-Telsa, for direct discharge plasma configuration with computed conductance.

7.10 Temperature profile, Kelvin, for direct discharge plasma configuration with experimentally derived conductance.

7.11 Concentration ratio profile for direct discharge plasma configuration with experimentally derived conductance.

7.12 Current profile, Amperes per meter, for direct discharge plasma configuration with experimentally derived conductance.
7.13 Joule heating profile, Watts per meter, for direct discharge plasma configuration with experimentally derived conductance. ............... 118

7.14 Magnetic strength profile, milli-Telsa, for direct discharge plasma configuration with experimentally derived conductance. ............... 118

7.15 Temperature profile, Kelvin, for single emitter plasma configuration. . 119

7.16 Concentration ratio profile for single emitter plasma configuration. . 119

7.17 Current profile, Amperes per meter, for single emitter plasma configuration. ................................................................. 120

7.18 Joule heating profile, Watts per meter, for single emitter plasma configuration. ................................................................. 120

7.19 Temperature profile, Kelvin, for MHz RF assisted configuration. . . 121

7.20 Concentration ratio profile for MHz RF assisted configuration. . . . 121

7.21 Current profile, Amperes per meter, for RF assisted configuration. . 122

7.22 Joule heating profile, Watts per meter, for RF assisted configuration. 122

7.23 Magnetic strength profile, milli-Telsa, for RF assisted configuration. . 123

7.24 Magnetic flux profile, mT per m2, for MHz RF assisted configuration. 123

8.1 Plasma Discharge at -29Hg, at -28Hg plasma turns into a streamer, conductivity of which is measured. ......................... 139
List of Tables

1.1 Benefits and Drawbacks of the primary methods for plasma generation [51] .......................................................... 5
1.2 Benefits and Drawbacks of the primary methods for plasma generation [51] .......................................................... 5

4.1 Phenomenological constants A and C for first ionizations .............. 34
4.2 Stoletov constants of selected gases ........................................ 36
4.3 Atomic diameters of selected gases .......................................... 46
4.4 The rarefaction of flow based on Knudsen number ...................... 51

5.1 The statistical data for the voltage measurements from the triple Langmuir probe in the four modes of plasma generation .............. 84
5.2 The statistical data for the current measurements from the triple Langmuir probe in the four modes of plasma generation .............. 84
5.3 The test statistics for the voltage measurements from the triple Langmuir between the plasma generation modes ...................... 85
5.4 The test statistics for the current measurements from the triple Langmuir between the plasma generation modes ...................... 85
5.5 The plasma properties in the four modes of generation ................ 85

6.1 The expected current density readings and the Joule heating parameters for the computed and the experimentally derived plasma conductivities ........................................ 95
6.2 The expected parameters for the single emitter configuration ......... 96

7.1 The minimums and the maximums of plasma properties in the four modes of generation, as a result of triple Langmuir probe use .... 109
7.2 The temperature comparison between the computed, experimentally derived, and the simulation values .............................. 124
7.3 The concentration comparison between the computed, experimentally derived, and the simulation values .............................. 125
7.4 The hypothetical thermal energy required in perfect conditions to reach
the temperatures found by computing, experiment, and simulation . 126
## Nomenclature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Interpretation</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Rydberg constant</td>
<td>$10^967758 \text{cycles/m}$</td>
</tr>
<tr>
<td>c</td>
<td>speed of light</td>
<td>$2.998 \times 10^8 \text{m/s}$</td>
</tr>
<tr>
<td>h</td>
<td>Planck constant</td>
<td>$6.624 \times 10^{-34} \text{J} \times \text{s}$</td>
</tr>
<tr>
<td>Z</td>
<td>atomic number</td>
<td>$\text{[]}$</td>
</tr>
<tr>
<td>$A'$</td>
<td>constant</td>
<td>$1.2 \times 10^6 \text{[A/(m \times K)^2]}$</td>
</tr>
<tr>
<td>$k_B$</td>
<td>Boltzmann constant</td>
<td>$8.617332478 \times 10^{-5} \text{[eV/K]}$</td>
</tr>
<tr>
<td>$k_B$</td>
<td>Boltzmann constant</td>
<td>$1.3806 \times 10^{-23} \text{[J/K]}$</td>
</tr>
<tr>
<td>E</td>
<td>electric potential at the surface</td>
<td>$\text{[V/m]}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>surface work function</td>
<td>$\text{[V]}$</td>
</tr>
<tr>
<td>$f(y)$</td>
<td>a dimensionless elliptic function</td>
<td>$\approx 1 - 14 \times 10^{-10} \times \left( \frac{E}{\varphi} \right)$</td>
</tr>
<tr>
<td>$r_{\text{emitter}}$</td>
<td>radius of the emitting element</td>
<td>$\text{[m]}$</td>
</tr>
<tr>
<td>$d_{\text{anode}}$</td>
<td>distance to the receiving anode</td>
<td>$\text{[m]}$</td>
</tr>
<tr>
<td>$V_{b,\text{min}}$</td>
<td>minimum sparking potential</td>
<td>$\text{[V]}$</td>
</tr>
<tr>
<td>$\gamma_{SE}$</td>
<td>secondary electron emission coefficient</td>
<td>$\text{[n}_{e^-}/n_i$</td>
</tr>
<tr>
<td>$\mu_i$</td>
<td>ion mobility</td>
<td>$\text{[m}^2/(\text{V} \times \text{s})]\text{]}$</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>permittivity of free space</td>
<td>$8.8542 \times 10^{-12} \text{[F/m]}\text{or}[\text{C}^2 \times \text{m}/\text{J}]$</td>
</tr>
<tr>
<td>$I_{\text{emission}}$</td>
<td>emission current</td>
<td>$\text{[A]}$</td>
</tr>
<tr>
<td>$v_{i,d}$</td>
<td>ion drift velocity</td>
<td>$\text{[m/s]}$</td>
</tr>
<tr>
<td>$m_i$</td>
<td>ion mass</td>
<td>$\text{[kg]}$</td>
</tr>
<tr>
<td>$m_g$</td>
<td>ambient gas molecule mass</td>
<td>$\text{[kg]}$</td>
</tr>
<tr>
<td>$\rho_{\text{Air}}$</td>
<td>air density</td>
<td>$\text{[kg/m}^3\text{]}$</td>
</tr>
<tr>
<td>$A_{\text{release}}$</td>
<td>area of neutral particles passing</td>
<td>$\text{[m}^2\text{]}$</td>
</tr>
<tr>
<td>$N_i$</td>
<td>number density of ionized particles</td>
<td>$\text{[prtcls]}$</td>
</tr>
<tr>
<td>$N_n$</td>
<td>number density of neutral particles</td>
<td>$\text{[prtcls]}$</td>
</tr>
<tr>
<td>$T_{\text{ion}}$</td>
<td>ion thermal equilibrium temperature</td>
<td>$\text{[K]}$</td>
</tr>
<tr>
<td>U</td>
<td>ionization energy</td>
<td>$\text{[eV]}$</td>
</tr>
<tr>
<td>$P_i(\text{absorbed})$</td>
<td>power absorbed by ionization</td>
<td>$\text{[W]}$</td>
</tr>
<tr>
<td>$P_E$</td>
<td>coupling circuitry electrical power</td>
<td>$\text{[W]}$</td>
</tr>
<tr>
<td>$N_0$</td>
<td>molecule number density in space</td>
<td>$\text{[prtcls]}$</td>
</tr>
<tr>
<td>$m$</td>
<td>mass of the particles in a volume</td>
<td>$\text{[kg]}$</td>
</tr>
<tr>
<td>$v$</td>
<td>speed of the particles</td>
<td>$\text{[m/s]}$</td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>incident EM radiation frequency</td>
<td>$\text{[Hz]}$</td>
</tr>
<tr>
<td>B</td>
<td>incident magnetic field</td>
<td>$\text{[T]}$</td>
</tr>
<tr>
<td>Variable</td>
<td>Interpretation</td>
<td>Unit</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>permeability of free space</td>
<td>$4 \pi 10^{-7}[T * m/A]$</td>
</tr>
<tr>
<td>$N$</td>
<td>number of coil turns</td>
<td>$[\text{turns}]$</td>
</tr>
<tr>
<td>$l$</td>
<td>length of the coil</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$I_{c_{oil}}$</td>
<td>current in the coil</td>
<td>$[A]$</td>
</tr>
<tr>
<td>$A_{p_{rob}}$</td>
<td>area of plasma contact with the probe</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$t_{sw}$</td>
<td>time that a switching signal is active</td>
<td>$[s]$</td>
</tr>
<tr>
<td>$\tau_{cyc}$</td>
<td>total period of the cycle</td>
<td>$[s]$</td>
</tr>
<tr>
<td>$P_c$</td>
<td>chamber pressure</td>
<td>$[Pa]$</td>
</tr>
<tr>
<td>$V_c$</td>
<td>volume of the chamber</td>
<td>$3.785 \times 10^{-3}[m^3]$</td>
</tr>
<tr>
<td>$R_{air}$</td>
<td>gas constant of air</td>
<td>$8.31446[m^3 * Pa/(K * mol)]$</td>
</tr>
<tr>
<td>$T_{air}$</td>
<td>ambient air temperature</td>
<td>$297.15[K]$</td>
</tr>
<tr>
<td>$C_{Av}$</td>
<td>a Avogadro’s constant</td>
<td>$6.02214 \times 10^{23}[\text{particles/mol}]$</td>
</tr>
<tr>
<td>$C$</td>
<td>a</td>
<td>$b$</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Motivation

There are problems in existing plasma generation devices due to their short life-span and ionization inefficiencies. Some of the existing dense plasma generators operate at temperatures in the range of 5000 Kelvin, which causes the metal electrodes to degrade at the rate dependant on the operating pressures. Most of the high density plasma generators used in waste gasification can only last 5 years before they are changed [51]. It would be beneficial to find plasma generation method that can utilize an electrode-less configuration and last beyond the material limitations. However, without an electrode the amount of ions generated decreases significantly and the proposed alternative in this thesis is the use of a virtual electrode discharge to make the plasma generation more durable and efficient. The virtual electrode can be created by forming a region of alternating magnetic field that will lead to the creation of associated electric field which will be able to trap the electrons in space. The intention this thesis is to design, test, and compare a virtual electrode plasma generator concept with the the most used direct arc discharge method. The design has to be efficient and to provide a wide range of plasma densities without damaging the generator itself. The methods for plasma generation will be investigated in order to attain a robust, long-lasting, and reliable design.

1.2 Thesis Objectives

The main goal of the current work to pursue a method of hybridization in order to achieve overall improvement in plasma generator efficiency and performance. The plasma generator design will be based on the scientific foundations and models and will be tested by experiments and simulations. The model of plasma simulation will
be implemented in Elmer for the purposes of validating the theoretical work, as well as for calibration based on information attained from the experiments. The results of the experiment and simulation will be compared to gain an insight into the validity of the simulation which is used in design of plasma devices. Hence, the key objectives of the thesis are:

1. To investigate plasma generation mechanisms, related physics, associated equation models, operation capabilities, applications, and design features.

2. To design a virtual-electrode device and compare it to existing plasma generation devices in accordance with their respective features.

3. To create a functioning prototype of experimental design to validate the proposed plasma generation technique, and to compare it with simulation results.

4. To examine the proposed plasma generation technique by simulation of composing sub-systems.

1.3 Plasma State Overview

Plasma is the most dominant state of visible matter in the universe, and it can be simply classified as a hot ionized gas. This gas responds to electric and magnetic fields thereby making it available to be manipulated by their use. The industrial interest for plasma use developed fairly recently due to scientific strides and a growing diversity of extensible and innovative technologies. There is a wide range of applications that have had some benefit from either treatment by, or the direct use of plasma with a a small list of plasma technologies such as: chemical analysis, material processing, satellite propulsion, communications, radar, lighting, welding, cutting, waste-to-energy conversion, neutron generators, and the fusion reactors. The plasma generation depends on application and currently there are six primary methods for producing and sustaining plasma: Direct Arc Discharge, Direct Induction Coil Coupling, Ferrous Core Induction Coupling, Capacitive Coupling, Wave-guide Coupling, and Laser Coupling. These are evaluated in terms of benefits in tables 1.1, 1.2 and 1.3. Each method can be applied in very specific niches and their individual features make them quite rigid in terms of transferable applications due to the nature of gases, pressures required for operation, and the coupling circuits. Also, the individual techniques of plasma generation yield unfavourable results in terms of efficiency and performance that could be alleviated through hybridization.
Table 1.1: Benefits and Drawbacks of the primary methods for plasma generation

<table>
<thead>
<tr>
<th>Plasma Gen.</th>
<th>Arc Discharge</th>
<th>Coil Induction</th>
<th>Ferrous Induction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>-Fast</td>
<td>-High temp. plasmas</td>
<td>-High temp. plasma</td>
</tr>
<tr>
<td></td>
<td>-High Power [MW]</td>
<td>-Freq. 100s of MHz</td>
<td>-Freq. 100s of KHz</td>
</tr>
<tr>
<td></td>
<td>-Low part count</td>
<td>-Long life span</td>
<td>-Strong coupling</td>
</tr>
<tr>
<td></td>
<td>-High plasma density</td>
<td>-Low maintenance</td>
<td>-Low interference</td>
</tr>
<tr>
<td></td>
<td>-60% ionization eff.</td>
<td>-Low maintenance</td>
<td>-Low maintenance</td>
</tr>
<tr>
<td>Drawbacks</td>
<td>-Electrode destruction</td>
<td>-Need low pressures</td>
<td>-Need low pressures</td>
</tr>
<tr>
<td></td>
<td>-Plasma contamination</td>
<td>-Signal interference</td>
<td>-Low plasma densities</td>
</tr>
<tr>
<td></td>
<td>-Destructive operation</td>
<td>-Low plasma densities</td>
<td>-Slow start</td>
</tr>
<tr>
<td></td>
<td>-Requires maintenance</td>
<td>-Slow start</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Signal interference</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2: Benefits and Drawbacks of the primary methods for plasma generation

<table>
<thead>
<tr>
<th>Plasma Gen.</th>
<th>Capacitive Coupling</th>
<th>Waveguide</th>
<th>Laser Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>-Fast</td>
<td>-Fast</td>
<td>-Fast</td>
</tr>
<tr>
<td></td>
<td>-Low part count</td>
<td>-High power</td>
<td>-High power</td>
</tr>
<tr>
<td></td>
<td>-Quality ionization</td>
<td>-High density plasma</td>
<td>-Long life-span</td>
</tr>
<tr>
<td>Drawbacks</td>
<td>-Need low pressure</td>
<td>-Microwave gen. in-eff.</td>
<td>-Plasma gen. limited</td>
</tr>
<tr>
<td></td>
<td>-Creates interference</td>
<td>-Powerful interferences</td>
<td>-Expensive</td>
</tr>
<tr>
<td></td>
<td>-Needs Steady Cond.</td>
<td>-Bulky and complex</td>
<td>-Need good optics</td>
</tr>
<tr>
<td></td>
<td>-Meticulous to Design</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1.4 Innovation and Contributions

The primary expected innovations of a virtual electrode plasma generator are the low-maintenance and endurance to wear. The process of attaining a hybridized design can serve as a convenient guideline for researchers and investigators who aim to industrialize plasma. The contributions expected include:

- A design that can compete with direct discharge plasma generation device through longevity, reliability, and resiliency to plasma conditions in varying harsh environments.
- The verification of the tools for achieving the hybridized design by comparing the simulation results with the experimental data.
- Development of a plasma generator with ability to shield itself against the thermal effects.

1.5 Thesis Structure

The following breakdown is an overview of the thesis structure:

Chapter 2 contains literature review on the definition of plasma state, plasma generation technologies, and their applications.

Chapter 3 presents the methodology framework of approach to the design of the concept plasma generator.

Chapter 4 proposes a system design as well as reviews plasma properties and governing equations.

Chapter 5 presents an experimental design to create a physical prototype and use it to collect data for a practical understanding of the plasma generation process, and to use it for tuning the analytical models.

Chapter 6 showcases the computational models associated with the plasma generator experiment.

Chapter 7 compares and analyse the results from the experiment and from the computational models.
Chapter 8 is the summary and conclusion of the thesis. The contributions will be evaluated in terms of the ability to meet the primary objectives. The recommendations for the industrial applications and the directions for future work will be highlighted.
Chapter 2

Literature Review

2.1 Plasma State Definition and Measurement

The theory of plasma behaviour has been developing over the course of history in the form of electrical and fluid theory, and during the 20th century it has been identified as a special branch of science. Given that the plasma is very common in the universe, it is best to begin with the description of its properties and how they can be observed.

Plasma is a highly agitated form of gas where the process of ionization creates a suspension of ions, electrons, and neutral particles in a volume of space. This agitated gas can be formed as the result of the strong gravitational force (most evident in stars, black-holes, pulsars, and other similar stellar objects), nuclear forces, and the electromagnetic forces. Due to the suspension of ionized particles the plasma is able to undergo chemical reactions with the surrounding materials, interact with electrical and magnetic fields. To understand plasma properties it is necessary to take into account the thermodynamics, the electrodynamics, and the fluid behaviour. From the perspective of thermodynamics, the creation of plasma is a phase change of a gas to an energetically stable state where the supplied energy achieves a state of equilibrium [1]. The collisions with high-energy particles and atomic recombinations lead to increasing ionization at elevated temperatures [2]. It is possible to express the quantum mechanical behaviour of plasma at various temperatures by the use of Saha equation:

$$\frac{N_i}{N_n} = 2.405 \cdot 10^{21} \cdot \frac{T^{3/2}}{N_i} \cdot e^{-U/(k_B\cdot T)}$$

(2.1)

Where, \(N_i\) is the density of ionized atoms (on the RHS and in the denominator of the equation, it indicates the action of recombination), \(N_n\) is the density of neutral atoms, \(T\) is the fixed temperature of plasma in thermal equilibrium, \(U\) is the ionization energy, and \(k_B\) is the Boltzmann constant \(1.3806 \times 10^{-23}[J/K]\). The ionization
energy $U$, for various particles differ based on the electron affinity of the elemental atoms involved [2]. At the high ion densities the equilibrium degree of ionization decreases, thus the sustainment of plasma at low pressures is much easier. Furthermore, the probability of having particles in the plasma attain specific speeds based on the plasma temperature can be found by the use of Maxwell-Boltzmann distribution [1]. For the steady-state quasi-neutral plasmas the equation for the Maxwell-Boltzmann distribution is as follows:

$$f(v_i) = N_i \cdot \left(\frac{m_i}{2 \cdot \pi \cdot k_B \cdot T}\right)^{3/2} \cdot e^{(-m_i \cdot v_i^2)/(2 \cdot k_B \cdot T)} \quad (2.2)$$

Where, $m_i$ is the mass of the ionized particles occupying the volume of space, and $v_i$ is the speed of the ions. At the equilibrium state it is possible to observe few particles that have velocities above the overall temperature of plasma. This phenomenon is attributed to the Coulomb collisions within plasma, where ions and electrons interact with the electric and magnetic fields rather than direct collisions between the particles [1]. The Coulomb interactions decrease as the temperature and the volume of plasma increase, which correspond to decreases in energy, free energy, pressure, and entropy [3]. As a result, the heat capacity of plasmas increase, because there is a tendency of ions to attract the oppositely charged ions, thereby shielding the Coulomb field of each ion and weakening its potential [3]. The increase in heat capacity and the decrease of entropy is an indicator of the ordered thermodynamic structure. As a result, there is a need for additional energy for the destruction of thermodynamic order, making plasma capable of self regulation at the different energy levels, or temperatures. This equilibrium structure is electrodynamic due to the behaviour of charges in motion that create self-sustaining magnetic fields [4]. The interaction of plasma with electric and magnetic fields as well as the electromagnetic radiation is the key to creating plasma and coupling it to external systems, in order to change its behaviour according to the demands of any particular design. The electric and magnetic fields may change the charge interactions in plasma which would affect the fluid-dynamics of plasma. Also, the compressibility and diffusivity of plasmas play a major role in heating plasma via shock-waves, mixing, and turbulent flows. The turbulence that occurs within the high energy plasmas, particularly intended for fusion, has the tendency to self-sustainment in form of protrusions and laminations that lead away from the occurrence of quantum tunnelling. Hence, the study of fluid-dynamic behaviour of plasmas bears an important value to investigating the dynamic equilibrium states. An approach to studying the magneto-hydrodynamics (MHD) strives to encompass the fluid-dynamic and electrodynamic aspects of plasma.
One particular useful aspect of this approach is the non-dimensionality of the fluid-dynamic structures, which plays an important role in modelling and predicting plasma flows [5]. The behaviour of plasma can be described by the principles commonly encountered in thermodynamics, electrodynamics, and fluid mechanics. Though these factors also play a significant role in magneto-hydrodynamics in metal-forges and the electrochemical processes, the key differences are in the compressibility of plasma, its diffusivity, and the high energy density, despite the low material density.

The key defining plasma properties include the temperature, degree of ionization, electromagnetic emission and absorption, as well as spatio-temporal changes in magnetic and electric fields. The measurement of plasma temperature is linked to particle speeds and can serve well as a handle on other properties. The most notable and historic tool in measuring plasma temperature is the Langmuir probe. Such probe is capable of measuring a electron-ion density, electron temperature, plasma potential, floating potential and electron energy distribution in the plasma body. However, the primary disadvantage of such probe is melting at plasma energies higher than 15 eV [6]. The Langmuir probe operates on the principle of ion repulsion to a distance away from the probe based on the surface charge concentration, an effect known as Debye shielding [1]. Despite their ability to measure properties at point locations, the Langmuir probes create considerable physical interference by being submerged into plasma. On other hand, it is possible to measure the bulk temperature of plasma using the bolometers. A bolometer is an instrument that is used to evaluate the power of electromagnetic radiation (EMR) by a simple use of the Wheatstone bridge and a light sensitive resistor on one of the bridge arms. The EMR detected by the sensor can be read off from the voltage and current of the circuit and provide the information on the power and the temperature of plasma [7]. Although the bolometers allow only to estimate the overall temperature of plasma, they have an advantage of non-interference. In fact, besides the Langmuir probes, most of the plasma diagnostic tools operate without the direct contact in order to get "clean" readings and avoid the impurities and noise. Based on the Saha equation (2.1) it would be possible to derive the degree of ionization of the plasma based on the plasma temperature alone. However, besides the utilization of data from either the Langmuir probe or the bolometer (or both), the use of lasers is the most desirable way to determine the electron density as well as the temperature precisely and at very specific points of interest [8]. The scattering of the high power laser radiation creates a spectral broadening due to the Doppler effect [8]. This broadening allows for a measurement of temperature from the amplitude of the scattered laser light [8]. Using the line radiation, in a frequency range between 10 nm to 10 m, it is possible to measure the continuum Bremsstrahlung spectrum,
the amount of impurities that may be present, and the electron temperature. Most of the existing laser analytical tools have the Thompson scattering as the key tool for measuring plasma temperatures and ionizations, there are also creative approaches that take advantage of the improved sensing technologies [9] as well as advances in processing algorithms [10]. Plasma can act as a frequency filter to certain radio and microwave signals which is particularly useful in determining the precise position of plasmas of specific ionization energies and densities. There are three primary types of microwave diagnostics: reflectometry, electron cyclotron emission, and interferometry [11]. The reflectometry measures the phase shift of a plasma synchronous wave (having the same frequency as electron frequency in plasma) that is infused into the plasma and reflected from its position. The electron cyclotron emission is used to measure the temperature of the electron radial profile of plasma that is proportionally linked to the amount of energy released. Lastly, the interferometry is used to measure the difference between the wave sent through the plasma and a wave that is sent through the vacuum, and it provides an average plasma density along the path of the wave sent into plasma. The diagnostic techniques encompassing the RF and microwave cover the electromagnetic range between 1 GHz to 3 THz, roughly covering most of the resonant frequencies of plasmas [11]. It is worthwhile mentioning the techniques associated with the plasma spatio-temporal changes in electric and magnetic fields (EMF). The EMF diagnostics measure the current, position, shape of the plasma, as well as any magnetic fluctuations that may take place in plasma. These properties may be caused from turbulence within the plasma and can provide an in-depth perspective on its fluid behaviour [12]. The EMF diagnostic technique covers the EM frequency range between 100 Hz to a few MHz and has the advantage of sensor design simplicity; the Rogowski as well as regular coils and simple metal plates can provide a good picture of plasma MHD behaviour even when the visual inspection is not possible. Though EMF diagnostics may not present exact positioning of the individually moving particles in the plasma body its main disadvantage is the weak coupling to the plasma, which slightly alters the plasma behaviour. Nonetheless, the most non-intrusive methods of plasma analysis are optical devices that can observe plasmas at distance, and given the simplicity of EMF diagnostics they present effective means to analyse plasmas via the weak coupling methods.

2.2 Plasma Generation

There are six recognized techniques of coupling energy supply to plasma: (1) direct arc discharge, (2) capacitive, (3) inductive, (4) waveguide, and (5) laser coupling [2].
The plasma power density is determined by the specific application requiring plasma, and the coupling process cannot be considered independently of the reactor design, volume of plasma, and the geometrical configuration. Each of the above plasma coupling methodologies encompass different applications and processes requiring particular power densities. The direct arc discharge is the best studied plasma generation and coupling methodology because it is also the easiest and the quickest way to generate plasma [13][14]. Though, it is an advantage to generate plasma quickly by the arc discharge in a wide range of pressure conditions, the costs of material destruction in the process, the material abrasion, the particle contamination, and a maximum efficiency of roughly 65%. The key principle of the direct coupling operation is rooted in the electron emission from the cathode to anode, which are subjected to the electrical potentials. The consequential emissions and ionizations are dependant upon the particular geometry, configuration, and the materials used in the coupling device, though they are not limited to direct coupling only. The capacitive coupling of plasma is similar to the direct coupling in terms of the need for the electrodes, however, the capacitive method has the electrodes covered with a layer of insulating film that serves for distributing the charge and preventing the sputtering and evaporation. The agitation of the plasma bearing medium is done via the high frequency alternating current (in the range of 30MHz and up), that leads to the stripping of the electrons from host atoms in the work gas [15]. Though the effects of electrode destruction are alleviated in the capacitive coupling, this method is only effective under the low pressure conditions, preferably vacuum. Furthermore, the design of the capacitive coupling device is highly constricted by the chamber configuration, the electrode geometry, and the associated connectors, which all contribute to the parasitic effects that drive the overall efficiency far below that of the direct coupling [15]. The other method of using the high frequency plasma ionization is the inductive coupling, which has more flexible options for creating and sustaining plasmas. The inductive coupling method is quite similar to the operation of a transformer where the energy is coupled via the primary windings to the secondary winding, role played by the plasma. The flexibility of inductive coupling design is evident in the use of the cored, core-less, flat spiral, and helical configurations, chosen in accordance to a particular application and can operate in the range of frequencies (20 to 400 kHz for the cored, higher than 400 kHz for core-less and flat-spirals, and 1 to 50 MHz for the helicon)[15]. The induction coupling using the ferrous cores is primarily used in the ohmic plasma heating (also known as Joule heating) inside the experimental fusion reactors [16]. Although, certain processing techniques may implement the cored designs the core-less method gives a broader frequency range. The core-less direct induction has
two key configurations: a solenoidal and a flat spiral coil [17]. The performance of the induction coupling is not as good as the direct coupling, though it is much better than the capacitive coupling, since most of parasitic effects can be reduced. The operating pressures of induction coupling are in the range of medium to low vacuum. Also, the isolation of the inductive coils offers a much better control over the purity of plasma. The coupling to plasma is much better established in inductive coupling rather than in the capacitive coupling due to the use of magnetic fields rather than the electric fields. However, the inductive coupling requires the warm up time to produce steady plasma, there are RF interference artefacts, and the number of parts may exceed the capacitive coupling, leading to stray losses in the plasma generator circuit [17]. The generation of plasma equivalently nearly as good as the direct coupling method is the waveguide coupling. The fast creation of plasma at different pressures, including atmospheric, and without the immediate destruction of electrodes make the waveguide coupling a favourable option. Unfortunately, the technological growth has not yet reached a level to make the waveguide coupling quite as efficient, or as simple as the direct coupling. The high power micro-wave generators typically have peak instantaneous efficiencies of 40 to 50%, and only 10% efficiencies at the continuous operation [18]. Certainly, the developments in the area of microwave devices may spearhead the development in the plasma generators in future, at the current time though, they are fairly bulky and complex. The wavegudes require a focusing antenna that can receive the microwaves and collect them into a plasma discharge [19]. Typically such an antenna is made out of a conducting metal, such as tungsten, to withstand the effects of material vaporization similar to the direct coupling. As such, the waveguide coupling configurations may encounter similar negatives as the direct coupling [19]. If the waveguide coupling deals with the electromagnetic radiation in the microwave range (GHz) the laser plasma coupling deals mostly with the visible radiation, with the exception of few cases where the x-rays and VUV radiation is utilized [20]. As in case of the microwave coupling, however, the laser coupling is also quite bulky and not very efficient to compete with the direct coupling on its own. The most extreme exemplification of laser plasma coupling is evident in the inertial confinement fusion [16]. The uniqueness of laser coupling however lies in the matter that it is possible to use chemical reactions to create intense photonic cascades capable of stripping off the electrons from host atoms [21]. The focusing of the intense cohesive laser beams will agitate the steady state of the gas by stripping of the electrons and ionizing the medium. It is possible to calibrate chemical reactions to produce a significant lasing yield and to argue that the process is technically 100% efficient, as all of the initial material’s energy is used for producing the synchronous radiation [21]. Nonetheless,
in terms of re-usability, the laser coupling via the chemical lasers heavily relies on the available fuel, which needs to be processed an prepared for the use, thereby lowering the overall usefulness of the chemical lasers. The conventional, electronically powered, lasers have the peak efficiencies of about 30% at best, and it is the case of the gas powered lasers (such as $CO_2$ lasers), which on their own rely on either direct or capacitive plasma coupling methods. The efficiencies for the solid state lasers are much lower (1 to 5 %), and their use in the plasma creation is only limited to lab spaces devoted to investigation of high energy physics. As in case of the microwave devices, the development of the laser technologies may eventually play a crucial role in improving the performance of the plasma devices. In fact, the hybrid virtual electrode plasma generation options may hold the future for the laser and plasma engineering developments, if the maintenance and replacement of process crucial parts will be reduced.

The ongoing development of the high power plasma generators is primarily lacking due to the material limitations as well as the design constraints of the existing technologies. The challenges faced in creating the dense plasma generators opens up a broad range of opportunities for shielding devices and improving the materials for withstanding the extreme heats. It is quite clear that the three coupling methodologies that do not utilize the electrodes are the inductive, the waveguide, and the laser coupling techniques. The virtual electrode configurations share similar qualities that make them challenging in terms of improving efficiency and performance. Particularly, the challenges of maintaining the constant and uniform ionized species include the prevention of the material abrasions, sustainment of the continuous plasma heating while alleviating the losses in the coupling circuitry, and reduction of the energetic particle diffusion away from the plasma focus areas. It makes sense that a body of plasma not confined by any vessel will go directly to equilibrium with environment and have some of the energetic particles diffuse away [22]. The uniform and constant ionization is not possible to achieve due to the particle velocity distributions, as is apparent by equation (2.2), although it is possible to implement the confinement techniques to keep plasmas at a focused region. The use of the magnetic coils and cages is common for confining plasmas to a certain degree [16]. Furthermore, even when plasmas are confined in a focused region, their extreme heat presents danger to the materials immediately surrounding it, either due to the effects of high power electromagnetic radiation, convection currents, or combination of both (depending primarily on the pressure conditions of plasma)[23]. The virtual electrode option presents a lower risk of contamination by unwanted abrasion species of the confinement vessel walls, and may lead to reducing the maintenance and extending the life-cycle of the generator.
With the development of the improved switching technologies and advances of the control algorithms at the current time, it may just be possible to generate steady streams of plasma and control their interactions with the confining walls [24]. When the plasma is released into the focus region it is most preferable to keep it in this region in order to reduce the supply energy at a high loss [25]; this is quite similar to maintaining the constant and uniform species ionization. If these challenges of the virtual electrode plasma generators are overcome then it would be possible to leverage them above the performance of the direct coupling technologies.

2.3 Plasma Applications

The radiant matter, or the cathode rays, that was observed within the ”aurora tubes” captured the imaginations and the curiosity of the scientists at the turn to the 20th century [4]. As a result of investigative inquiry, the tools for chemical and particle analysis that implemented plasma phenomena have become quite popular. The present day advantage of the plasma analysis tools is their capability to work with minuscule samples, be highly accurate, and quick in reaching concrete results in both the analytical chemistry and the particle physics [26]. The investigations into plasma phenomena were also gaining momentum due to the growing need for cheap and efficient lighting, as the access to electricity was becoming more available. A notable researcher was Nikola Tesla, who, in 1899, has conducted a variety of high frequency, high energy experiments that have dealt with the wireless transmission of electrical signals as well as lighting [27]. The present day utilitarian use of plasma in fluorescent lighting has origins from the times of Francis Hauksbee, although, the modern use of plasma also can be found in lasers, displays, as well as the emerging hologram projectors. Incidentally, during Tesla’s field work there are claims that he was able to detect an intercontinental signal from Marconi, which was both a radio communications milestone, and an accidental discovery of plasma belt surrounding Earth, known today as the Van Allen radiation belt [28]. The discovery of the long-range communications by the use of the RF-reflective properties of the stratosphere has brought in the new age of dynamic communications and radar technologies. One stark example of the present day radar innovation is the compact and adjustable plasma antenna. The plasma antennas can work in a broad-band range, have adjustable radar detection characteristics, and are easily tunable to meet a multitude of UHF needs [29][30]. The scientist who has recognized the behaviour of ionised gas carried by the electromagnetic fields resembling the blood plasma, where the blood cells are carried by a vascular flow, Irving Langmuir specifically, was also the one
who was first to implement the atomic hydrogen welding [31]. The modern industrial processes rely largely on the variety of different plasma welders and cutters for quick and precise manufacturing. The application of plasma phenomena in plasma stream cutters, laser cutters, and plasma arc welders is the modern approach for just in time manufacturing, and it is continuously improving to be more energy efficient, faster, and precise. Furthermore, since plasma is a unique property of matter that can perform a variety of chemical processing tasks, and it is a high temperature phenomena, it has also been applied in the field of rubbish and oil gasification for waste-to-energy conversion [32]. The gasification of heavy fuels and rubbish into the synthetic gas may become an environmentally benign option for dealing with a possible energy crisis. The non-recyclable plastics, hazardous chemicals, and heavy fuels are subjected to a noble gas atmosphere and high current plasma arcs to be effectively converted to synthetic-gas and biodegradable ashes [33]. The generation stations using this principle exist in few locations around the world; the current material limitations make this option for energy conversion fairly expensive to maintain. To a lesser extreme, and the more common industrial use of plasma, besides welding and cutting, is the micro-chip manufacturing. The manufacturing of semiconductor based technologies has vastly improved due to the plasma etching process and has lead to a significant miniaturization of integrated technologies. By using the calibrated plasma etchers it is possible not only to etch the materials but also deposit a multitude of elements for design specific purposes of the integrated circuits [34]. From the applications point of view, the conglomeration of success stories in plasma research is evident in the man-made satellites where the multitude of plasma technologies converge not only for the safe delivery and return, but also for the actual propulsion. Unlike the conventional means of propulsion, where the combustion products propel the work-load, the plasma propulsion relies on the electrostatic repulsion of charged particles. Despite the low exhaust velocities, the plasma thrusters can accelerate the work-loads, theoretically, to the universal speed limit, given enough time and a clear path are provided [35]. The highlight of these technological developments is the shear magnitude of applications that resulted from the involved research efforts made only a century earlier, and the growth of such developments is still on the rise.
Chapter 3
Methodology Framework

An in-depth presentation of the plasma generation techniques and their individual descriptions was made by Ernest [44]. With the exception of the laser coupled systems, Ernest made an extensive analysis of the key plasma generation techniques ((1) direct arc discharge, (2) capacitive, (3) inductive, (4) waveguide). In his work it is made evident that by far the plasma generator that is capable of producing high temperatures with a high conversion efficiency is the direct arc discharge. As discussed in the plasma generation section of the literature review chapter, the ionization efficiencies of roughly 60% are achievable with the direct arc discharge. Although, the waveguide coupling method could possibly act as a contender, due to the inefficiencies of the micro-wave generators, however, it falls far behind as possible competitive option. Therefore, a comparative study of the hybrid option will be made with respect to the direct arc discharge plasma generator based on the following key features: efficiency, ionization temperature range, contaminants present during operation, cost, and the number of parts.

In order to achieve these features the methodology followed in the present thesis encompasses creating a concept design of a hybrid plasma generator device and evaluating its properties based on governing equations. The framework of the methodology is shown in Figure 3.1. The first step in designing the plasma generator is the creation of a possible system design by considering preliminary ideas, breaking them down into key components, and then associating the properties and governing equations for the most relevant aspects of the design. Thereafter, a prototype experiment is conducted to gather the data for evaluation of conventional plasma generation method and the prototype design for the virtual cathode concept. The experiment is conducted with the governing equations as foundations although it is also done to tune and validate the aspects of computational simulations. Based on the governing equations and the experiment it would then be possible to use the modelling software to tune the
simulation model for realistic representation of a physical prototype. By comparing the results of the simulation to the experiment it will then be possible to derive the lessons for implementing in a design of a hybrid plasma generator.

The end-goals of successfully completing the robust hybrid virtual electrode plasma generator for the efficient industrial processes will include the miniaturization of plasma actuators and analytical devices, the dynamic monitoring and control of the plasma phenomena, functional modelling of plasma phenomena for comprehensive and computationally quick results, and the advanced circuit design of plasma integrated components.

To alleviate the hazards and to maintain the equipment integrity the safety system will need to take care of the possible risks of plasma generation. Certain risks can only be alleviated by considering the specific design features, while other risks can be prevented by placing warning systems. The identified risks and the possible alleviation techniques are as follows: 1. Hot areas need to be cooled and be ventilated to prevent hot-spots, proper labelling; 2. HV area in case it is non-isolatable then it needs to be shielded and labelled; 3. Magnetic field interference proper shielding from outside is the best option; 4. View-port dislodging/cracking, possible leakage area, explosion/implosion hazard can only be prevented by employment of quality seals and flanges; 5. Chamber strain is alleviated by the means of structural confinement; 6. Charge accumulation and X-ray areas need to have shielding and labelling; 7. Plasma gas puff instabilities, irregular generation, mismatched timing of plasma discharge/gas

Figure 3.1: Methodology framework.
release can prevent only by the proper selection of quality components and good control systems; 8. Laser beam input area (plasma laser coupling) has to be labelled and handled with care like the rest of the devices associated with the generator. The control for plasma regulation is going to be adaptive to the immediate changes occurring within the plasma for preventing the destruction of the nearest components.

There are some estimated innovations that can be the outcome of the virtual electrode plasma generators. The control of plasma instabilities can encompass the hybrid systems of pulsed laser, electro-magnetic coupling, and directed ion-beams guided by the use of advanced back-stepping algorithms. The miniaturization of the vacuum-sustaining technologies is expected to be embodied by implementation of the 3D printing technologies for creating chamber components and the MEMS for the alleviation of leaks and contaminants. The plasma boundary interaction modelling can use a hybrid modelling of MHD plasma with mesh adaptation, Large Eddy Simulation approach to the instability tracking, and the Direct Monte-Carlo algorithm at the locations of plasma’s high-energy interaction points. The low-cost plasma diagnostics can be created using off-the-shelf sensors and the advanced algorithms for the pattern recognition. Also it is expected to achieve a cohesive integration of systems, which will be carried out by the implementation of the intelligent agent controllers capable of communicating between the interconnected parts of the plasma generator. These innovations will likely to push the performance of the designs under consideration to higher domains.
Chapter 4

Proposed System Design

4.1 Preliminary Concepts

In the current section the particular focus will be the generation of the initial designs. The virtual electrode concepts will focus on hybridization of ionization technologies. The goal of creating the plasma generator is to avoid any use of the physical electrodes and aim to replace them with virtual cathodes instead. Also, the goal is to achieve the efficiency in plasma generation at worst higher than the efficiency of the direct coupling techniques and at best as close to 100% as possible by the current technologies. The functional representation of the virtual electrode plasma generator is presented in Figure 4.1.

The two preliminary concept ideas for the virtual electrode plasma generator are based on the hybridization of the three plasma coupling methods: induction, microwave, and laser. These preliminary concepts are presented in Figures 4.2 and 4.3. The main features of these designs will be the use of either a UV boosted ionization technique or a high field emitter, which will localize an ionization region (create a virtual cathode) and will receive energy through main induction coils. The shape and temperature of plasma will be regulated through the plasma retention coils, the feed rate of fuel, and the configuration of the plasma nozzles. The main difference between the two concepts is the configuration of the coupling mechanism which will optimize the performance of the generator without damaging the structure and material near the plasma generation region. In Figure 4.2 the main induction coils are directly coupled with plasma and a permanent magnet is acting as a discharge distribution mechanism, for alleviating the hotspots on the surface of tungsten electrodes. In the case of the concept presented in Figure 4.3 main induction coils are used in tandem with the ferrite core.

The components of these conceptual designs of virtual electrode plasma generator
will determine the effectiveness of the final design. The option to employ the UV laser diodes or high-field emitters are intended for encouraging the initial ionization regime and the creation of a region that can serve as a virtual cathode and accept
energy from the induction coils. The main induction coupling coils as well as the associated cores will be used for pumping power into the ionized region and creating a region of high magnetic density. The choice of coil configurations will play a major role in the decision making for the creation of a robust design. The plasma retention coils are intended for keeping plasma localized and for bleeding excess into the region of activity without damaging the immediate structure of the generator. The intake manifold will be accepting the fuel or gas into the region of ionization and will regulate the rate of fuel input. The nozzle component of the plasma generator will be directing the plasma stream/beam away from the generation components and create favourable microwave conditions for focusing the plasma in the region of its required activity. The tungsten discharge elements could be used for initial agitation.

4.2 Concept Components

The mechanical and electrical components are summarized in Figure 4.4. The goal in the case of both concepts is to alleviate the excessive use of the electrodes and use a small ionized region as a virtual cathode capable of efficiently accepting the energy from the induction coils.

The merits of having an virtual electrode plasma generator that is capable of competing with the electrode-based direct discharge coupling devices include the longer life-span, lower maintenance, flexibility of creating a range of plasmas, no contaminations.
tion, possibility of better control as well as efficiency. The disadvantages are primarily
the complexity of such devices, the associated costs of making the virtual electrode
plasma generators, and the higher level of EM radiation as a result of coupling ei-
ther via waveguide or inductive means. The two concepts of the plasma generators
presented in the previous section are largely based off the current ideas for virtual
electrode coupling. The hybridization of these concepts is expected to boost the
overall performance of the virtual electrode generator above the performance of the
electrode-based plasma generators. The purpose of the current work is to develop
a plasma generator that, despite the high density and high temperature plasma, is
shielded against the destructive effects of plasma generation, thereby extending the
life-cycle of the generator. In the current section the decision making process re-
garding the possible concept for implementation in modelling and analysis will be
conducted to narrow the options and focus the efforts for achieving a detailed design
for the system analysis and simulation in the following chapter.

It has become apparent in the literature review that the inductive coupling to plasma is quite flexible in terms of coil configurations. The use of the cored, core-less, flat spiral, and helical configurations, are chosen in accordance to a particular application and can operate in the range of frequencies; 20 to 400 kHz for the cored, higher than 400 kHz for core-less and flat-spirals, and 1 to 50 MHz for the helicon configurations. If a small region of plasma is initiated via the ionization it is worthwhile considering what is the resonant frequency of this virtual cathode region. According to the works on the plasma physics, the plasma frequency of the arc discharges is in the range between 5.6 and 1122 THz, whereas the plasmas subjected to agitation by the virtual electrode means has the frequency ranging between 170 MHZ and the 564 GHz [1]. The temperature ranges for such plasmas, however, lie in the range between $10^3$ and $10^6$ Kelvins. The metals such as stainless steel or tungsten could be used to shield against such temperatures if additional cooling systems and shielding potentials are applied. Also, the magnetic confinement of the plasma within the generator body could prevent some of the potential damage that may occur as a result of high temperature. The use of the ceramics in the design of chamber is a possible option, although the ceramics have the disadvantage of hot spot formation; the metals have the limited ability to shield against hot spot formation as a result of the eddy currents forming on their surface and shielding against plasma. In the concept design the use of multiple materials is necessary in the associated conductive and isolation components and the use of tungsten for electron emitters, copper for coupling coils, and ceramics for insulation layers is required. Based on the preliminary concepts it has identified that the potential virtual electrode plasma generator would consist of nine primary components:

1. Gas Supply Source: The gas supply has to provide a controlled amount of substance to sustain plasma without extinguishing it, and at the same time keep the generator chamber walls cool.

2. Inlet Manifold: A gas distribution manifold that has to evenly distribute the flow into the plasma generation region, has to be controlled to divert the flows for optimal performance of the generator.

3. Ionizing Configuration: A tungsten discharge element enacts the process of ionization and shifts the focus of ionization region depending on the requirements for plasma.

4. Primary Induction Coupling Coil: A coil that feeds a powerful RF signal into
the plasma region to generate high temperatures. The capacitive coupling needs to be suppressed, to avoid the interference signals, using a Faraday shield near the inductive coils.

5. Plasma Magnetic Confinement Coils: The electro-magnets (magnetic bucket) confine the plasma, enhance the uniformity, and increase the plasma density in the plasma generation region.

6. Nozzle Configuration: The nozzle will release the plasma into the environment and act as a wave-guide to focus the plasma in region of key activity.

7. Plasma Diagnostics: The probes will gather information regarding the state of plasma.

8. Power Supply and Distribution: A standard RF system for maintaining a discharge consists of a generator, typically combined with an impedance matching network, and the reactor with the electrodes (a virtual electrode in the case of the current thesis). The power amplification can be achieved by compressing electrical signal energy into tight pulse packets, which can be an effective way to improve the plasma coupling without raising the operating costs [17]. The generator type would have to be licensed in terms of the frequency band for commercial use. A matching network has to match the impedance of the generator with the impedance of the plasma. By implementing the matching network the power transfer from the generator to the discharge is at peak efficiency and the reflected RF power is minimized [17].

9. Process Controller: Controls the virtual electrode plasma generator by attaining the data from the diagnostic probes and processing it through an algorithm for providing the feedback to the power supply and the actuators within the plasma generator.

Among the aspects pertaining to the components of the virtual electrode plasma generator the technical features will also be considered, particularly the following: costs, reliability, size, coupling of energy, signal conditioning of energy, efficiency, spatial distribution of plasma parameters (homogeneity), positioning of plasma, controlling of boundary conditions, throughput, and safety. These technical features will be over-viewed in topological manner in the next chapter.
4.3 Analysis of Plasma Generation Properties

The equation models for ionization will be devoted to the gas supply source, and will focus on the plasma initiation and sustainment. The coupling and confinement will present the theory on the electromagnetic coupling. The fluid equations will focus on the flow and its coupling with electric and magnetic fields. Lastly, the circuit design for power distribution will be based on the principles of power electronics.

This section focuses on the properties and the equation models of the plasma generator components. Consider the Figure 4.1 that presents an concept plasma generator and the associated physical components. First, it should become evident that the plasma generator’s function is to convert the incoming gaseous flow into plasma. The focus region has some ions that drift in the flow and act as small conductors. Once the creation of an ionization region is initiated the over-riding conducting properties can be used to act as a receiving circuit, in a way similar to a resonant circuit. By feeding a resonance frequency corresponding to the oscillation of the ionized region it would then be possible to supply large amounts of focused electromagnetic energy in a form of oscillating magnetic field and reinforce plasma generation.

In the Figure 4.5 there are indicated components marked from a) to e) corresponding to: a) Inlet, b) Step, c) Nozzle, d) Outlet, and e) Exhaust. These components are associated with the flow of the gas from the source and to the output. In each portion there will be flows that may be laminar, although the turbulent flows will dominate.
due to the high temperatures and associated convection of the plasma. The effects of flow characteristics on the focus zone of plasma production are important because they will determine the rates of diffusion and mixing of the ionized particles, thereby determining the optimal resonant frequency fed by the primary coupling coil. The energy supplied by the flow, the ion supply, the resonant feed, and the confinement fields are the factors contributing to the generation of plasma. The range of energy dissipative processes that would decrease the overall performance of the plasma generator include the turbulent dissipation, diffusion, heat losses via the convection and radiation, and the shocks, audible as noise at Standard Atmospheric Temperature and Pressure (SATP).

4.3.1 Ionization

The ionization process is primarily concerned with displacement of the electrons from the host atoms. The ionization properties of various gases and the corresponding data are very well researched due to their value in the multiple manufacturing and chemical industries. In the interest of plasma generation it is best to avoid hazardous gases and focus on the gases that can be safely utilized. Specifically, the gases such as air, argon, and helium are considered due to their relatively safe operation. The approximate energy required to remove a single electron from the Nitrogen atom is 14.54 [eV] (78% of Air), it is 13.61 [eV] for the Oxygen atom (21% of Air), for the Argon atom the ionization energy required to remove an electron is roughly 15.76 [eV], and for the Helium it is about 24.58 [eV][4]. Furthermore, with every additional electron removed, more energy is required to remove the remaining electrons in the host atoms; this is due to the electrons closer proximity to the atom’s core. The energy required to move an electron from an orbit, \( n_1 \), to another orbit, \( n_2 \), corresponding to a higher energy level is:

\[
\Delta W = R \cdot c \cdot h \cdot Z^2 \cdot \left( \frac{1}{(n_1)^2} - \frac{1}{(n_2)^2} \right) \text{[joules]} \tag{4.1}
\]

Where \( R \) is the Rydberg constant (10,967,758 cycles/m), \( c \) is the speed of light (2.998·10^8 [m/s]), \( h \) is the Planck’s constant (6.624·10^{-34} joule-seconds [J·s]), and \( Z \) is the atomic number. For ionization to occur, the electron would have to be removed from an atom at a ground/lowest energy state. Using the above formula it is possible to verify the first ionization potentials for the gases presented above, considering that electron becomes free of the coulomb force confining it to the nucleus, when \( n_2 = \infty \).

The process of electron removal, ionization, has to do with the supply of sufficient
amounts of energy, and can be achieved by any of the following three mechanisms: Photo-ionization, Kinetic, and Potential.

Photo-ionization occurs by the transfer of energy in the form electromagnetic radiation to the neutral atoms. The effective cross-section of a gas molecule for intercepting the photon is peaked, when the energy content of the photon is just slightly greater than the ionization potential of the molecule.

\[ E_{\text{photon}} = h \cdot f = \frac{h \cdot c}{\lambda} > E_{\text{ionization}} \] (4.2)

If the first ionization energy of Helium is taken to be the goal of hypothetical plasma initiation, then the energy of slightly more than 24.58 [eV] is necessary [1]. If the energy of 25 [eV] (or roughly \(3 \cdot 10^{-18} [J]\)) is supplied to a Helium atom, or any of the above gases, they are going to be ionized due to the loss of the outermost electron in the atom. The associated wavelength that is required to achieve this ionization can be found by a simple re-arrangement of equation (4.2) to yield 49.6 [nm], and the corresponding temperature that would be required to keep the gas in the steady-state plasma would be 290,000 [K]. Understandably, such short light wavelength and a high temperatures are not quite easy to achieve with current day technology, and it is not the intention to pursue this theme presently. However, besides the use of the deep UV spectrum for ionization there is another way to create a plasma discharge using laser light. Such method proceeds by focusing an immensely powerful beam of laser light at a point; the heating by radiation causes a rapid and explosive expansion that creates plasma as a result of kinetic collisions of expanding shock-waves, regardless of the type of radiation [45]. Most of the experiments conducted in this regime employ IR laser wavelengths. Although, in order to create such conditions the laser beam power intensity has to be on the order of \(10^9 - 10^{10} [W/cm^2]\) [45]. Furthermore, such intensities need to be concentrated in a time-frame of nano-seconds, or even femto-seconds, to yield any sufficiently noticeable plasma discharge in a gas. Unfortunately this method is lacking efficiency-wise; the conversion efficiency of electricity into plasma is only 2% [45]. Therefore, any premises of using lasers for gas ionization need to be dropped at this point due to the un-availability of efficient laser systems.

The methods of Kinetic and Potential ionization are evidently the most optimal and sufficiently employable in the virtual cathode plasma generator. The tungsten metal is chosen as initiating ionization source, due to its ability to withstand high temperatures, up to 3695 Kelvin before melting. Hence, the initiation of electron emission needs to be addressed first before dwelling further on the processes of ionization. The electron emission occurs when sufficient kinetic excitation energy is transferred to some of the conduction band electrons present near the emission surface. This
transfer allows the electrons to overcome a natural potential energy barrier, or the surface work function, and be expelled from the metal [4]. The electron emission can be identified by one or more of the following methods of energy transfer to the electrons [4]:

- **Photoelectric emission**: An electron is emitted due to an incident electromagnetic radiation with energy content $h \cdot f$, that may be slightly higher than the surface work function.

- **Emission due to ion bombardment**: occurs when a positive ion interacts with the metal surface either via the kinetic, potential, or both methods. This process is quite inefficient, though it is primarily found in the gas discharge tubes.

- **Thermionic emission**: takes place at the heated surfaces ($1500 \text{–} 2700[K]$) that can supply the energetic thermal vibrations to the lattice bonds of the emitter of the conduction band electrons.

- **High field emission**: also known as auto- or cold-cathode emission, takes precedence when a high potential electric field ($> 10^9[\text{volts/meter}]$) in the immediate vicinity of the emitter surface can reduce the effective surface barrier and permit relatively low energy electrons to tunnel through.

- **Secondary emission**: in this case the required energy is obtained from the kinetic energy of incident primary electrons. This process is a common as an after-effect of the thermionic and high-field emissions, especially in the cases where the supply potential is alternating.

- **Emission due to metastable atoms**: this process happens as a result of surface interaction with the elements that posses metastable levels of atomic excitation. The atoms in metastable state must either gain additional energy to reach an ordinary excitation level from which radiation of energy is permitted, or it must exchange this energy by the transfer to the free electrons at the surface.

The electron emissions due to photoelectric effect, ion bombardment, and metastable atoms are not considered further for the reason of their inefficiencies as the electron emitters, and possible ionization sources. The process of secondary emission occurs depending on the field near the emitter and is entwined with the processes of thermionic and high-field emissions. Hence, the thermionic and high field emission processes will be considered as candidates for ionizing the work gases. The metal
of choice for the electron emission is chosen to be Tungsten due to its structural resilience and relatively low evaporation; tungsten begins to evaporate roughly around 1100 Kelvin at a rate of $10^{-30}[g/(cm^2 \cdot s)]$ [46]. The maximum heating temperature of Tungsten emitter is expected to be 1000 Kelvin to prevent the effects of metal evaporation, this precaution is taken to avoid the possibility of a reduced life-span of plasma generator.

The thermionic process relies on the vibration of the metal lattices at elevated temperatures [11]. The expression for finding the current produced by the thermionic emission is expressed by Richardson-Dushman equation:

$$J = A' \cdot T^2 \cdot \exp\left(-\frac{\text{work-function}}{k_B \cdot T}\right)$$  (4.3)

Where, $U_m$ is the work function of the metal, and the constants are $A' = 1.2 \cdot 10^6[A/(m \cdot K)^2]$, and the Boltzmann constant expressed in terms of electron-Volts is $k_B = 8.61798 \cdot 10^5[eV/K]$.

If the temperature of $U_m = 1000[K]$ is reached by the tungsten electron emitter with the corresponding work-function of 4.5 [eV] then the expression yields the following:

$$J = A' \cdot 1000^2 \cdot \exp\left(-\frac{4.5}{k_B \cdot 1000}\right) = 7.225118 \cdot 10^{-41}[A/m^2]$$

Given that the radius of the tungsten rod tip is 1.2[mm], standard welding electrode, then the emitted electron current at the tip would roughly be $7.225118 \cdot 10^{-41}[A/m^2] \cdot 0.0012[m]^2 \cdot \pi = 3.2686 \cdot 10^{-46}[A]$, or $3.2686/10^{-46}[C/s] = 2.043 \cdot 10^{-27}[e^-/s]$.

In this case not even a single electron is capable of escaping from the surface of the conductor, and there is no electrical potential applied to the emitter. Furthermore, in the case of the concept plasma generator the inlet and the outlet boundaries for the gas would ensure that temperature would drop as a result of convective cooling, as a result of the flow passing over the emitter. Therefore, the thermionic emission process would not be sufficient to be used in the concept because at the temperatures higher than 1100 Kelvin the electrode begins to erode away due to evaporation, and at the lower temperatures there is simply not sufficient energetic electrons that would be able to ionize the working gas. Based on these results, it is apparent that the process of high field emission and the secondary emission are the only alternatives left that present an opportunity for efficiently producing ionized species.

The high field emission or cold-cathode emission may occur between the metal lattice and the working gas due to the electric potential in the immediate vicinity of
the emitter. The zone near the emitter surface may have a potential that is only a fraction of a volt, and this could be sufficient to reduce the effective work function for an excited electron to be accelerated from the surface of the emitter and to the nearest gas molecule. The process of cold-cathode emission operates in the field strengths above $10^9[V/m]$ and depends on small fraction of electrons to tunnel through the barrier at the surface [4]. It is possible to compute the energy needed to liberate an electron in the outermost surface of the emitter in accordance with the material’s surface work-function. In case of tungsten emitter, for instance, without taking into account the potential created due to the quantum surface barrier, the computed energy required to eject an electron is $4.5[eV] \cdot 1.60 \cdot 10^{-19}[J/eV] = 7.2 \cdot 10^{-19}[J]$. However, this value is not wholly representative of the actual high-field emission process. In 1928, Fowler and Nordheim have used the theory of quantum mechanics to derive an expression for the emitted current density caused by the high-field emission [47]. The following is the derived equation for 0[K]:

$$J = 1.54 \cdot 10^{-6} \cdot \frac{E^2}{\phi} \cdot 10^{-6.83+10^9\phi^{3/2}} f(y)/E[A/m^2] \quad (4.4)$$

Where the electric potential at the surface is $E [V/m]$, the surface work function is $\phi$ in $[V]$ (4.5[V] for Tungsten). The factor $f(y)$ is a dimensionless elliptic function introduced by Nordheim to account for the image force effect at the surface of the emitter. The approximation for this function is $f(y) \approx 1 - 14 \cdot 10^{-10} \cdot (\frac{E}{\phi})$ [4]. Considering that the intended emitter has to operate at temperatures below 1000 [K], to prevent the cases of contamination of plasma with metal gas, the equation (4.5) holds fairly well according to Dolan and Dyke [48]. In their work, Dolan and Dyke computationally investigate the effect of the temperature on the field emission process and they find that above 1000 [K] noticeable changes to the emission begin to take place, and below this range it is relatively safe to operate with Fowler and Nordheim equation for electron emission current density. Therefore, based on these sources, Fowler and Nordheim equation (4.5) can be used to find the electron emission density. The plot for the emitted current density versus the high-field potential in a range between $2 \cdot 10^9 < E < 4 \cdot 10^9[V/m]$ is presented in the Figure 4.2.

To get the gauge on the readings for the electron emission, according to the computations for the electric current to be $1.1063[A/m^2]$ a potential of $3.8 \cdot 10^9[V/m]$ has to be applied at the tungsten emitter. If the emitter is a standard welding rod with a radius of 1.2[mm] then the potential at the emitter can be expressed by the following equation [51]:

$$31$$
Figure 4.6: Emitted Current vs. High Field Potential

\[ E_s = \frac{V_{b,\text{min}}}{r_{\text{emitter}} \cdot (1 - (r_{\text{emitter}}/d_{\text{anode}}))} [V/m] \approx \frac{V_{b,\text{min}}}{r_{\text{emitter}}} [V/m] \quad (4.5) \]

Where, \( r_{\text{emitter}} \) is the radius of the emitting element, and \( d_{\text{anode}} \) is the distance to the receiving anode, which in the current case is assumed to be infinite given the case of the unipolar discharge configuration. Hence, the potential would have to be \( 4.56 \cdot 10^6 [V] \). The expected current at the conditions indicated above would be close \( 5 \cdot 10^{-6} [A] \) or \( 5 \cdot 10^{-6} [C/s] = 3.125 \cdot 10^{13} [e^-/s] \). This result is far more favourable than the thermionic emission process, although it does appear to be quite energy intensive. By comparison to a case where the surface barrier is not taken into account, the hypothetical energy needed to remove the same amount of electrons would fall around \( 7.2 \cdot 10^{-19} [J] \cdot 3.125 \cdot 10^{13} [e^-/s] = 2.25 \cdot 10^{-5} [W] \), on other hand, when the surface barrier is included, the hypothetical energy needed to remove the electrons is \( 5 \cdot 10^{-6} [A] \cdot 4.56 \cdot 10^6 [V] = 22.8 [W] \). The difference of roughly six orders of magnitude is a significant indicator of the electron retention due to the surface barrier effect. However, the notion that such large potentials are necessary to initiate electron emission do not quite fit well with experimental observations of the static discharge machines and the corona discharge effects at standard atmospheric conditions [49].
for this effect is due to the Townsend discharge breakdown and the avalanche of the electrons that follow as a result of secondary emissions, which lowers the overall emission barrier. Unfortunately, the complete array of events that play a role in the electron avalanche process are complex and could hardly be accounted for the cases that are not purely theoretical, such as the Fowler-Nordheim equation; a partial reason for this is that such avalanches occur due to the effects of cosmic rays and subatomic fluctuations, which are currently non-controllable. However, significant experimental data exists to assist with estimation of the potentials and the released energy when dealing with the room temperature discharges [50]. Particularly, the corona and brush discharges that occur when the potential near an emitter is in the range of, or above, 500[kV/m] at standard atmospheric temperatures and pressures (SATP), the corresponding energies associated with these discharges are between 1 and 4 [mJ]. These discharges are a common trait to the step up transformers, commonly known as Tesla coils or Van de Graaf generators. The brush discharges have initial charge accumulation that starts at 3[µC/m²], and with 7.4[µC/m²] on a negatively charged emitter, they also present an ignition hazard in flammable environments [50]. Thus, the electron emission can be expressed based on the particular breakdown potential of the surrounding gas and its pressure. In dry air, at atmospheric pressure, the break down potential is roughly 300[kV/m]. The breakdown potential makes sense when dealing with the cathode-anode discharge system. In the case of the plasma generator under consideration, however, a single electron emitter is used to initiate the ionization process (a unipolar discharge configuration[44]), due to the lack of degrading inter-electrode attachment effects; these effects are present in anode-cathode systems, which lead to the formation of the hot spots on the metal surfaces and lead to plasma contamination by metal evaporation. Therefore, in order to deal with tangible descriptions of ionization process in gases, the following equation for the minimum breakdown potential needs to be considered [51]:

\[
V_{b,\text{min}} = e^1 \cdot \frac{C}{A} \cdot \ln(1 + 1/\gamma_{SE}) = 2.718 \cdot \frac{C}{A} \cdot \ln(1 + 1/\gamma_{SE})
\] (4.6)

Where, \(V_{b,\text{min}}\) is the minimum sparking potential, \(C\) and \(A\) are constants, as indicated in the table 4.1[51], and \(\gamma_{SE}\) is the secondary emission coefficient. Note, the range of validity for values in table 4.1 is \(C/2 \leq E/p \leq 3 \cdot C\) [51].

The secondary electron emission coefficient \(\gamma_{SE}\) is defined as the number of electrons emitted, \(n_e\), over the number of incident ions that fall into the emitter, \(n_i\) [51].
Table 4.1: Phenomenological constants A and C for first ionizations

<table>
<thead>
<tr>
<th>Gas</th>
<th>A (ion − pairs)/(m · Torr)</th>
<th>C V/(m · Torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>1200</td>
<td>20000</td>
</tr>
<tr>
<td>Air</td>
<td>1220</td>
<td>36500</td>
</tr>
<tr>
<td>CO₂</td>
<td>2000</td>
<td>46600</td>
</tr>
<tr>
<td>H₂</td>
<td>1060</td>
<td>35000</td>
</tr>
<tr>
<td>He</td>
<td>182</td>
<td>5000</td>
</tr>
<tr>
<td>H₂O</td>
<td>1290</td>
<td>35000</td>
</tr>
<tr>
<td>N₂</td>
<td>1060</td>
<td>34200</td>
</tr>
</tbody>
</table>

\[ \gamma_{SE} = \frac{n_e}{n_i} \] (4.7)

At the initial conditions, prior to discharge, there is practically no electrons emitted as a result incident ions because there is a lack of such in the surrounding gas, hence, \( \gamma_{SE} = 0 \) initially. Understandably, the initiation potential would have to be infinite if the formula is used on its own. However, the experiments conducted in the area of sparking potential have provided data that the potential does not have to be as extremely high to initiate the electron emission, made particularly evident by Figure 4.3 [51]. In this figure it should be noted that as the number of electrons emitted as a result of ion interaction increases, the minimum sparking potential decreases thereby lowering the surface barrier work energy.

Also, the initiating electric field can be assumed to be close to the Corona initiating potential, and the following empirical expression found by Cobine [52] works sufficiently well for a wide range of pressure conditions:

\[ E_{corona} = \frac{1.8 \cdot 10^5}{\sqrt{r_{emitter}}} [V/m] \] (4.8)

Provided the case of the tungsten emitter is still applicable, the corresponding initiating potential for corona discharge is \( 5.2 \cdot 10^6[V/m] \), which corresponds to the field at the tip of the tungsten emitter, mentioned previously, to be \( 6.24 \cdot 10^3[V] \), which is far better rather then the case without secondary emission, as found by Nordheim-Fowler equation. Nonetheless, the effective ionization potential would have to be higher in order to continuously ionize the surrounding gas without the loss of energy to the inelastic collisions. Given the operation range for the ionization of gases is dependant upon the gas nature and the pressure, having the notion of the potential...
Figure 4.7: The minimum sparking potential $V_{b,\text{min}}$, as a function of the secondary electron emission coefficient, $\gamma_{SE}$, for several gases [51].

can provide only so much as to indicate that the electrical breakdown has occurred. Without having an idea of the current emitted into the flow of gas, the nature of ionization for further plasma generation is not entirely understood. The pressure for maximum current has been investigated by Stoletov [51] and the outcome of his investigations was be expressed in the table 4.1 for $C_{opt}$, which stands for the optimal electric potential over the operating pressure. The $\alpha[\text{ion} \text{- pairs/m}]$ is Townsend’s first ionization coefficient that indicates the average number of ionizing collisions made by an electron as it traverses one meter along the electric field [51]. The point $A_{opt}$ indicates the optimal number of ion-electron pairs generated per meter at a particular pressure, and $\eta_{min}$ is the approximate minimal cost in [eV] for the generation of the gaseous ion-electron pairs based on the combined effect of the gas work function and the metal surface work-function. The point of generating ion-electron pairs at the minimum energy expense is known as the Stoletov point, and the expanded table for Stoletov constants in optimal conditions is presented in Table 4.2 [51].

Therefore, using the empirical values provided in table 4.2 it is possible estimate what would be the required potential for initiating ionization at a particular pressure. The approximation is relatively safe by the use of these values, and would provide the averages for the potential and the current that is produced as a results of the electron
Table 4.2: Stoletov constants of selected gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>((E/p)<em>{opt} = C</em>{opt} )</th>
<th>((\alpha/p)<em>{opt} = A</em>{opt} )</th>
<th>(\eta_{min} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>20000</td>
<td>443</td>
<td>45</td>
</tr>
<tr>
<td>Air</td>
<td>36500</td>
<td>449</td>
<td>81</td>
</tr>
<tr>
<td>CO₂</td>
<td>46600</td>
<td>736</td>
<td>63</td>
</tr>
<tr>
<td>H₂</td>
<td>35000</td>
<td>390</td>
<td>90</td>
</tr>
<tr>
<td>He</td>
<td>5000</td>
<td>67</td>
<td>75</td>
</tr>
<tr>
<td>H₂O</td>
<td>35000</td>
<td>475</td>
<td>61</td>
</tr>
<tr>
<td>N₂</td>
<td>34200</td>
<td>390</td>
<td>88</td>
</tr>
</tbody>
</table>

emission. The deviation from these averages can occur either as a result of the secondary electron emissions, which can yield higher currents at lower potentials, or the attachment processes, where the host gas takes the free electrons out of circulation by recombination [51].

The Stoletov’s constants approach is much more conservative, almost by an order of magnitude compared to Cobine’s equation[51]. The expression for Townsend’s first ionization coefficient, \(\alpha\), in terms of the mean free path for ionization, \(\lambda_i\), and kinetic theory parameters, is:

\[
\alpha \approx \frac{1}{\lambda_i} = A_{opt} \cdot p \cdot \exp(-A_{opt} \cdot p \cdot x_i) \tag{4.9}
\]

At the distance \(x_i\), an electron can gain enough energy from the electric field \(E_{b,min}\) to ionize the host gas with an effective ionization potential \(V_{eff} > V_{b,min}\). The effective ionization potential is greater than the minimal breakdown ionization potential, due to the losses by the electron by the elastic and inelastic (excitation) collisions, as well as ionization. Understandably, near the surface of the emitter \(x_i = 0\), hence \(\alpha = A_{opt} \cdot p\).

Depending on how quickly the electron discharge takes place it is possible to estimate the current produced by the use of this computed value. However, in the case of the unipolar discharge configuration at the tip of the cylindrical emitter, the following expression yields better results[51]:

\[
I_{emission} = -6 \cdot \pi \cdot r_{emitter} \cdot \mu_i \cdot \varepsilon_0 \cdot (E_{unipolar})^2[A] \tag{4.10}
\]

Where \(\mu_i\) is ion mobility, \(\varepsilon_0\) is the permittivity of free space with a constant value of \(8.8542 \cdot 10^{-12}[F/m]\). Ion mobility is the ratio of the ion drift velocity, \(v_{i,d}[m/s]\),
over the electric potential $E \text{[m/s]}$. The absolute values for ion mobility in gas are not easy to obtain for multiple reasons [44]. First, the average ion must be able to make a sufficient number of collisions in crossing the drift space in the experimental measuring equipment. This is not possible when the dimensions for the drift space are on the same order of magnitude as the mean free path of the ion. Due to this, low pressures and vacuum conditions are usually out of question. Second, the number of collisions per second per unit volume is very high and can easily be anywhere between one and three orders of magnitude of the impurity concentration. This implies that a noticeable number of ions collide with foreign molecules each second, and thereby alter the measured value of the mobility. Lastly, many gases that form multi-charged molecules or molecular clusters cannot maintain themselves very long because of splitting and charge transfer caused by collision, also known as Kallman-Rosen effect [44]. On other hand, using the ion drift velocity is an option that may alleviate the necessity of dealing with the ion mobility. The expression for ion mobility in terms of the ion drift velocity and the average velocity was presented by Compton [44] in the following expression:

$$\mu_i = \frac{v_d}{E} = \frac{8}{3 \cdot \pi} \cdot \frac{q}{m_i} \cdot \frac{\lambda_i}{v_a} \cdot \left(\frac{m_i + m_g}{m_g}\right)^{1/2}$$  \hspace{1cm} (4.11)

Where, $q$ is elementary charge ($1.602 \cdot 10^{-19}[C]$), $m_i$ is the mass of the ion and $m_g$ is the mass of the ambient gas molecules. In the case where the ions and ambient gas molecules are of the same element, then $m_i \approx m_g$. In this case, equation 4.12 can be simplified into:

$$\mu_i = \frac{8 \cdot \sqrt{2}}{3 \cdot \pi} \cdot \frac{q}{m_i} \cdot \frac{\lambda_i}{v_a}$$  \hspace{1cm} (4.12)

Using this expression in equation 4.11, it would be possible to approximate the emission current using the average velocity of the ionized particles. The average velocities of the ionized particles can be found either via an experiment or an approximation by the use of the flow velocity. If the pressure change between the inlet and outlet is $\Delta P$ then finding the average velocity is a matter of solving the Bernoulli equation for the outlet velocity [60]:

$$p_1 + \gamma \cdot z_1 + \frac{v_1^2}{2} = p_2 + \gamma \cdot z_2 + \frac{v_2^2}{2}$$  \hspace{1cm} (4.13)

Given that the height effect is negligible, terms $z_1$ and $z_2$ are removed, also, the velocity $v_1$ is assumed to be 0 because the source is a uniform and much more stationary in respect to $v_2$ at the outlet port. The flow is assumed to be steady
and viscous effects are not considered. Therefore, the rearrangement of the equation (4.14) for \( v_2 \) yields:

\[
v_2 = v_n = \sqrt{2 \cdot (p_1 - p_2)}
\]

(4.14)

Therefore, in order to find the current from a unipolar electron emitter the short-form equation is:

\[
I_{\text{emission}} = -16 \cdot \sqrt{2} \cdot r_{\text{emitter}} \cdot \left( \frac{q}{m_i} \cdot \frac{\lambda_i}{\sqrt{2 \cdot (p_1 - p_2)}} \right) \cdot \varepsilon_0 \cdot (E_{\text{unipolar}})^2[A]
\]

(4.15)

Assuming that the process of ionization near the electrode is relatively quasi-neutral and the potential distribution is focused near the electrode tip, then it is possible to consider that the charge density of ions and electrons is approximately equal. Therefore, taking the average charge of the ion pairs to be equivalent to the elementary charge, \( q = 1.602 \cdot 10^{-19}[C/\text{ion – pair}] \), it is possible to derive the charge density near the emitter surface using \( A_{\text{opt}} \) from table 4.2.

Knowing the number of ion-electron pairs it is then possible to find the average temperature of the ionized gas near the emitter. However, in order to do this it is necessary to find how many particles pass near the emitter. To derive the density of neutral atoms flowing past the emitter it is possible to use the mass flow rate equation in the following fashion:

\[
N_n = \frac{\rho_{\text{Air}} \cdot v_n \cdot A_{\text{release}}}{m_{\text{Air}}} - N_i = \frac{\rho_{\text{Air}} \cdot \sqrt{2 \cdot (P_1 - P_2) \cdot A_{\text{release}}}}{m_{\text{Air}}} - N_i
\]

(4.16)

Where, \( \rho_{\text{Air}} \) is the density of air, assume here it is at a temperature of 393.15 [K] and is 1.204[kg/m³]), and \( A_{\text{release}} \) is the area through which the neutral particles pass.

By finding the ion density and the density of the neutral molecules it is possible to derive the ion temperature using the Saha equation [1]:

\[
\frac{N_i}{N_n} = 2.405 \cdot 10^{21} \cdot \frac{T_{\text{ion}}^{3/2} \cdot e^{-U/(k_B T_{\text{ion}})}}{N_i} \cdot e^{-U/(k_B T_{\text{ion}})}
\]

(4.17)

Where, \( N_i \) is the density of ionized atoms (on the RHS and in the denominator of the equation, it indicates the action of recombination), \( N_n \) is the density of neutral atoms, \( T_{\text{ion}} \) is the fixed temperature of ions in thermal equilibrium, \( U \) is the ionization energy, and \( k_B \) is the Boltzmann constant 1.3806 \cdot 10^{-23}[J/K]. The ionization energy \( U \), for various particles differ based on the electron affinity of the elemental atoms.
involved, for air it is roughly equivalent to the ionization energy of Nitrogen ($\approx 15 [eV]$ or $2.403 \cdot 10^{-18} [J]$). The solution for the $T_{ion}$ can be easily obtained using a Computer Assisted Algebra System (CAAS) if the following re-arrangement is made:

$$1 = \frac{2.405 \cdot 10^{21} \cdot T_{ion}^{3/2} \cdot e^{-U/(k_B T_{ion})}}{N_i^2 / N_n}$$

(4.18)

Though the temperatures found this way may appear high, indicating the possibility of the emitter melting, this will not happen due to the convection effects near the emitter as well as the energy loses associated with the ionization (especially when fluid flows are present). The ionization process depends entirely on the in-elastic collisions between the electrons and the host gas. However, the collisions between the neutral gas and electrons do not always lead to ionization; the kinetic energy of the electron must exceed the ionization energy of the molecule and it it has to make an inelastic collision with the gas molecule [44]. The fraction of energy that an electron loses to a gas molecule upon making an elastic collision is expressed by:

$$f_E = \frac{2.66}{4} \cdot \left(1 - \frac{v_{neutral}^2}{v_{e}^2}\right)$$

(4.19)

Where the electron velocity can be found by the following equation for an electron moving through a field [53]:

$$v_e = \sqrt{\frac{2 \cdot e^- \cdot E_{unipolar}}{m_e^-}}$$

(4.20)

Should the average electron posses a noticeable emission velocity, then the potential distribution assumes a form of virtual cathode, where the electric field is zero. All electrons that within this region can be assumed to have been emitted by a virtual cathode located at this point [4]. The remainder of the energy is primarily used up in the in-elastic collisions, recombination, and radiation. However, the emission velocity is high for the electron therefore the indication of virtual cathode formation is present. In this respect, it is worthwhile to consider the speed distribution of ionized species in plasma. If the electrons released from the cold cathode posses velocities much greater than the thermal velocities of the neutral molecules then the gas molecules may be considered as being at rest relative to the electrons [4]. In order to find the maximum velocity of the singly charged particle subjected to field $E_{unipolar}$ it is possible to assume that initial velocity is zero [4] and then the maximum speed at which the charged ion particle moves in this field can be found by:
\[ v_i = \sqrt{\frac{2 \cdot q \cdot E_{\text{unipolar}}}{m_i}} \]  

(4.21)

However, this expression does not take into account the interaction of the particle with the surrounding gas and may provide a misleading representation of the plasma. On other hand, the root mean square ion velocity derived from the Maxwell-Boltzmann distribution is based on the mean ion temperature and provides a much better approximation of the maximum speed of the ionized particle in plasma [1]:

\[ v_{\text{rms-ion}} = \sqrt{\frac{3 \cdot k_B \cdot T_{\text{ion}}}{m_{\text{ion}}}} \]  

(4.22)

Assuming the electron temperature is equivalent to the ion temperature at the quasi-neutral condition, it is likewise possible to express the electron RMS velocity as follows:

\[ v_{\text{rms-e}} = \sqrt{\frac{3 \cdot k_B \cdot T_{\text{e}}}{m_{\text{e}}}} \]  

(4.23)

The differences in speeds due to the electric field and the thermal effects are additional key indicators to the formation of a virtual cathode region [4]. In this region, the ionised species are able to be created and removed in the flow, thereby forming a potential well that allows plasma to receive external energy, such as the Radio-Frequency (RF) energy. Comparing these velocities with the inflow velocity showcases a stark exemplification of the mobility of ions compared to the non-ionized gas. The concentration of charge carriers near the emitter has a pronounced effect on the potential distribution throughout any gaseous or vacuum electron device, and the ratio of the speeds between the ionized and non-ionized particles is another indicator for the virtual cathode formation [4]. However, at the high ion densities the equilibrium degree of ionization decreases and, thus, the sustainment of plasma at low pressures is much easier. The probability of having particles in the plasma attain specific speeds based on the plasma temperature can be found by the use of Maxwell-Boltzmann distribution [1]. For the steady-state quasi-neutral plasmas the equation for the Maxwell-Boltzmann distribution is as follows:

\[ f(v) = N_0 \cdot \left( \frac{m}{2 \cdot \pi \cdot k_B \cdot T} \right)^{3/2} \cdot e^{(-m \cdot v^2)/(2 \cdot k_B \cdot T)} \]  

(4.24)

Where, \( N_0 \) is number density of molecules in a specific space, \( m \) is the mass of the particles occupying the volume of space, and \( v \) is the speed of the particles.
The ion (4.25) and the electron frequencies (4.26) could be expressed based on the assumption that the number of ions and electrons is approximately the same [11].

\[ f_{\text{ion}} = \frac{1}{2} \cdot \pi \cdot \sqrt{\frac{N_i \cdot q^2}{M_i \cdot \varepsilon_0}} \]  \hspace{1cm} (4.25)

\[ f_{e^-} = \frac{1}{2} \cdot \pi \cdot \sqrt{\frac{N_e \cdot q^2}{m_{e^-} \cdot \varepsilon_0}} \]  \hspace{1cm} (4.26)

The particular feature of these frequencies is in the interest of the resonant frequencies that can be supplied by an external circuit in order to supply the energy to the plasma either to improve the process of ionization or to sustain the plasma in equilibrium. Based on these frequencies it is possible to find the corresponding wavelengths and an indication of the plasma virtual electrode locations at a distance away from the emitter. If these frequencies are emitted in a manner of an electromagnetic (EM) source then it is possible to assume that their speed of propagation is equivalent to the speed of light, and based on the antenna theory [54], it is possible to find the location of the highest particle concentrations at a quarter of the EM wavelength, or the virtual electrode locations using a simple expressions:

\[ \lambda_{\text{ion}} = \frac{3 \cdot 10^8 \text{[m/s]}}{f_{\text{ion}}} \]  \hspace{1cm} (4.27)

\[ d_{\text{ion}} = \lambda_{\text{ion}}/4 \]  \hspace{1cm} (4.28)

\[ \lambda_{e^-} = \frac{3 \cdot 10^8 \text{[m/s]}}{f_{e^-}} \]  \hspace{1cm} (4.29)

\[ d_{e^-} = \lambda_{e^-}/4 \]  \hspace{1cm} (4.30)

It is worthwhile to consider that the emitter has been intrinsically assumed to be the primary emitter of the electrons. However, due to the high speeds of the emitted electrons there is a region right near the surface of the emitter where a negative virtual electrode is present indicated by (4.30). Furthermore, the location of the ion region as found by (4.28) roughly corresponds to the breakdown distance in air if actual electrode was present at that location and with a respective potential [51]. To gain a perspective on the positioning of the virtual cathodes with respect to the location of the plasma near a perfectly conducting body it is necessary to compute the Debye Length [1]:

41
\[
\lambda_D = \sqrt{\frac{\epsilon_0 \cdot k_B \cdot T_e}{N_i \cdot q_e^2}}
\]  

(4.31)

The plasma location near the emitter is sufficiently close to potentially cause the emitter evaporation, especially if there is no acting field or gas flow over the emitter. However, based on the locations of the negative and the positive virtual electrodes the chance of damaging the actual emitter would be reduced, because the plasma will tend to reside in these regions rather than near the immediate vicinity of the emitter[1][51].

Provided with above information it is interesting to find the efficiency of the ionization process:

\[
\eta = \frac{P_i(\text{absorbed})}{P_E}
\]  

(4.32)

Where, \(P_i(\text{absorbed})\) is the power absorbed in producing ionized species at rate specific to the plasma generator, and \(P_E\) is the electrical power used by the coupling circuitry. The electrical coupling circuitry may vary in nature depending on whether the direct arcing, direct induction, ferrous core induction, capacitive, wave-guide, laser, or a combination of the above methods is chosen.

To increase the efficiency of the unipolar emitter configuration it is possible to reduce the diameter of the emitter, in order to increase the ionizing potential. Also, if the emission is limited by the power supply then it would be possible to increase the number of emitters up to the point of current limitation; that is, in a single emitter there is a limitation due to its singular operation, on other hand, if multiple emitters are present in an array, then the emission efficiency will increase to the point of available current provided by the supply. Furthermore, by having multiple emitters with smaller emission diameters there is a substantial advantage due to the creation of a uniform and focused virtual cathode region, which can also act as an antenna for receiving RF energy. Reece Roth [51] mentions the use of the high-field emission electrodes and proposes the methods of decreasing the electrode diameters to micro-meter scales to achieve optimal electron emission. He also mentions that a small power consumption can be achieved with this configuration while operating at SATP conditions and the life-span is significantly better than in the direct-discharge configuration on its own. Nonetheless, the primary disadvantages for unipolar emitter configuration include the sputter erosion and the need for a pulsed power supply to avoid detrimental effects of electric breakdown. The sputtering can be reduced by implementing an array of emitters, and the use of the pulsed power supply can be made optimal using the current day switching circuits.
4.3.2 RF Coupling and Confinement

The ionized gas molecules and electrons become a focused in a region of space as a result of unipolar electron emission. This region can be agitated by an external oscillating magnetic field. Gradually, the particles trapped in the region become so energetic that the resulting collisions propagate the plasma creation and confinement. A coil that feeds a powerful RF signal into the plasma region is able to generate high enough temperatures to continue sustaining the ionized state.

Unlike the metals that maintain their electrical integrity even in molten condition, plasma does not behave the same due to its fluidity and compressibility. If the metals can respond to the impulse signal from the induction circuit, plasma needs to be stirred to form a kind of vortex that responds to its resonant frequency. The goal for radio frequency (RF) heating of plasma is to stir the gas in such a manner that it will maintain its ionized state. In the previous section it was found what parameters play key roles in initiating the ionization process, and in current section coupling to plasma by RF will be presented. It is possible to heat plasma by three modes of RF coupling: an oscillating magnetic field (inductive coupling), an oscillating electric field (capacitive coupling), or both (quasi-optical or microwave coupling)[51]. The primary mode of RF coupling and confinement that will be implemented in the plasma generator for this thesis is the oscillating magnetic field. The frequency of field oscillation, the electron plasma frequency, and the electron collision frequency in the plasma are key to RF coupling and are determined by the electrical conductivity, the energy transfer frequency of the plasma, as well as the plasma skin depth. These aspects as well as the energy efficiency of RF power transfer from the oscillating magnetic field will be presented.

\[
f_{e^{-}} = \frac{1}{2 \cdot \pi} \sqrt{\frac{N_e \cdot q^2}{m_{e^{-}} \cdot \varepsilon_0}} = 8.97766 \cdot \sqrt{N_e} [Hz]
\]  

The frequency of plasma electrons, expressed by a short form equation (4.26), establishes the capability of an electromagnetic (EM) wave to interact with plasma. When the incident EM radiation frequency, \(\nu_0\), is below plasma electron frequency, the low inertia of the electrons allows them to respond to the electric field in the incident electromagnetic wave and absorb its energy [51]. The absorbed EM energy in plasma would be able to heat it through collisions, or be re-radiated in the form of a reflected electromagnetic wave from the surface of the plasma. On other hand, if the incident EM radiation frequency is higher than \(f_{e^{-}}\), then the high electron inertia does not allow plasma to respond fully to the incident EM wave [51]; the
EM radiation will simply propagate through the plasma as if it were a quasi-optical dielectric medium without significantly interacting with the electrons.

The critical number density separates the particle interaction regime from the collective interaction regime [51] and can be found for the incident EM radiation frequency by inverting equation (4.33):

$$N_{\text{crit}} = 1.2407 \cdot 10^{-2} \cdot \nu_0^2[e^-/m^3]$$

(4.34)

The incident EM wave with frequency $\nu_0[Hz]$ will interact with a plasma collectively if the value computed by (4.34) is below plasma electron density, and it will weakly interact with the individual electrons if the number density is above plasma electron density. In other words, if plasma electron density is above the value computed by (4.34), then the EM radiation will interact with plasma; if plasma electron density is less than the value computed by (4.34), then the EM radiation will propagate through the plasma without significant interaction. Based on the critical number it is possible to derive how many electrons will be engaged by the incident EM wave with frequency $\nu_0[Hz]$, as long as this critical number is less than, or equal to the plasma electron density. If the critical number density matches the electron density then most of the EM radiation will be absorbed by the plasma, if it is more than the plasma electron density it will primarily pass through, if it is slightly less, then it will be absorbed at the surface layer, and the lower the critical number gets the more EM radiation will be reflected from the surface.

On one hand plasma can interact with oscillating magnetic fields based on how close their oscillation frequency matches the plasma resonance frequency. On other hand, depending on the strength of this field, plasma can also engage in the gyro-resonance frequency heating, where the electromagnetic radiation could be strongly absorbed by plasma if the gyro-frequency matches the plasma frequency [51]. Hence, the mode of RF coupling to plasma can be regulated by both the frequency of the field oscillation and its strength. To heat the plasma at electron gyro-resonance frequency, the incident radiation must be:

$$\nu_{ce-} = \frac{\omega_{ce}}{2 \cdot \pi} = \frac{q \cdot B}{2 \cdot \pi \cdot m_e} = 2.7992 \cdot 10^{10} \cdot B[Hz]$$

(4.35)

Where B is the incident magnetic field in Tesla [B]. If this field is generated by a solenoid coil then the magnetic field at the core of such solenoid [53] can be computed as follows:

$$B = \mu_0 \cdot N_{\text{coil}}/l_{\text{coil}} \cdot I$$

(4.36)
Where $\mu_0$ is the permeability of free space $4 \cdot \pi \cdot 10^{-7}[T \cdot m/A]$, $N_{\text{coil}}$ is the number of coil turns, $l_{\text{coil}}$ is the length of the coil in [m], and $I_1$ is the current moving through the coil in amperes, [A].

In order to have a strong interaction of the incident EM radiation the gyro-frequency generated by the field should be greater than the electron plasma frequency [51]:

$$\omega_{ce} = \frac{q \cdot B}{m_e} \geq \omega_{pe} = \sqrt{\frac{N_e \cdot q^2}{m_e \cdot \varepsilon_0}}$$  \hspace{1cm} (4.37)

By squaring the equation (4.37) a relationship for the electron number density of a plasma subject to electron gyro-resonant heating, as a function of the magnetic induction of the magnetized plasma is found to be:

$$n_e \leq \frac{\varepsilon_0 \cdot B^2}{m_e} = 9.72 \cdot 10^{18} \cdot B^2[e^-/m^3]$$  \hspace{1cm} (4.38)

Equation (4.38) showcases two potential operating regimes for plasma RF coupling: the collective interaction or quasi-optical regime, where the electron gyro-frequency is greater than the electron plasma frequency, and the particle interaction or ‘overdense’ regime, for which the electron plasma frequency is greater than the electron gyro-frequency [51]. In the case of the collective interaction, the incident EM radiation at the electron gyro-frequency interacts with the plasma as a collective whole; that is, the electromagnetic radiation can penetrate throughout the bulk of the plasma and interact with the electrons at their gyro-frequency. In the case of particle interaction regime the incident EM radiation interacts strongly with the individual particles at the surface of the plasma without penetrating into the core of the plasma. To ensure efficient heating of plasma it is most preferred to operate in the collective interaction regime as it is able to heat the interior of the magnetized plasma.

Although it is critical to cover the necessary frequencies for the magnetic field oscillation to couple with plasma, the energy delivered to the plasma also depends on the three inter-related factors: the conductivity of plasma, the energy transfer frequency, and the plasma skin depth. Therefore, explanation of these factors are necessary in order to have a good grasp on RF coupling to plasma.

The average collision frequency [11] of ionized particles and electrons can be found by the following two expressions:

$$\nu_{ci} = \frac{v_{\text{ion\_rms}}}{\lambda_i} [Hz]$$  \hspace{1cm} (4.39)
\[ \nu_{ce} = \frac{v_{ce,m}}{\lambda_{e,mfp}} \text{[Hz]} \quad (4.40) \]

The mean free path for the ionized species, \( \lambda_i \), can be found using the Stoletov constants, presented in table 4.2. On other hand, the mean free path for electrons, \( \lambda_{e,mfp} \), can be found using the following expression which uses the expression for the electron collision frequency [4]:

\[ \lambda_{e,mfp} = \frac{4 \cdot k_B \cdot T_e}{\pi \cdot d_{ion}^2 \cdot P[m]} \quad (4.41) \]

Where \( d_{ion} \) is the approximate atomic diameter of the ionized gas, some selected gases are presented in the table 4.3 [4], below.

**Table 4.3: Atomic diameters of selected gases**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Atomic - Diameter nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>0.142</td>
</tr>
<tr>
<td>H</td>
<td>0.106</td>
</tr>
<tr>
<td>He</td>
<td>0.062</td>
</tr>
<tr>
<td>O</td>
<td>0.096</td>
</tr>
<tr>
<td>N</td>
<td>0.112</td>
</tr>
<tr>
<td>Air</td>
<td>( \approx 0.11 )</td>
</tr>
</tbody>
</table>

The electrical conductivity of an un-magnetized Lorentzian plasma, in Siemens per meter [S/m], is expressed as a function of the electron density and the collision frequency in equation (4.40)[51]. The un-magnetized Lorentzian plasma, in the current case, is a plasma not subjected to a steady magnetic field that is perpendicular to the plasma’s electric field [51].

\[ \sigma_0 = \frac{q_e^2 \cdot N_e}{m_e \cdot \nu_{ce}} \text{[S/m]} \quad (4.42) \]

Based on equation (4.37), the electrical conductivity equation (4.42) may be also written in terms of the plasma electron frequency in the following manner:

\[ \sigma_0 = \frac{\varepsilon_0}{m_e \cdot \nu_{ce}} \cdot \omega_{pe}^2 \text{[S/m]} \quad (4.43) \]

Equation (4.43) contains an element representing the fundamental frequency for energy transfer into un-magnetized Lorentzian plasma. The fundamental frequency
for energy transfer indicates the frequency of electrostatic energy density transferred
to unit of plasma volume by an external power supply, and it is a function of electron
number density, electron kinetic temperature, the type of gas, the plasma electron
and gyro-frequencies, as well as the neutral background pressure [51]. The expression
for the energy transfer frequency of an un-magnetized plasma is:

\[
\nu_{*0} = \frac{2 \cdot \omega_{pe}^2}{\nu_{ce}}
\]

(4.44)

Thus, the electrical conductivity of un-magnetized plasma in terms of the energy
transfer frequency can be expressed as:

\[
\sigma_0 = \frac{\varepsilon_0}{2} \cdot \nu_{*0}[S/m]
\]

(4.45)

If the collective plasma effects of shielding against an externally imposed electric
field are ignored [51], then the total power absorbed per unit volume of plasma from
the applied electric field can be computed to be:

\[
u_{E-unipolar} = \frac{E_{unipolar}^2 \cdot N_{e^-} \cdot q^2}{\nu_{ce} \cdot m_{e^-}} \cdot \nu_{*0}[W/m^3]
\]

(4.46)

This computation fits well with the observations for the streamers produced by
the high-voltage transformers [51]. Furthermore, the streamer like behaviour high-
lights three important aspects for the plasma generation via the unipolar method.
First, the decrease in the emitter diameter would benefit for the decrease of material
costs. Second the creation of small diameter unipolar emitter array would generate
a more uniform plasma distribution with multiple streamers and lead to an over-all
improvement in efficient plasma generation compared to a single emitter. Lastly, the
streamer may have a very high temperature on its own, however due to its small size
and instantaneous existence it can hardly act as a significant source of ions. Therefore,
the design conclusions that can be derived are: an efficient plasma generator device
can implement an array of micro-meter electron emitters for plasma initiation and
use a tandem configuration with the RF coupling to boost the overall performance
and efficiency.

Provided that the plasma conductivity is known it is necessary to also find the
skin depth of plasma because the combination of these two factors can lead to the
derivation of plasma resistivity. Based on plasma resistivity and the energy supplied
via the oscillating magnetic field into plasma it is possible to use the expression for
Ohmic heating to find the efficiency of the coupling method for plasma sustainment
and confinement.
When plasma is exposed to RF radiation below the electron plasma frequency, the interaction of the RF energy with the plasma occurs in a surface interaction layer where the RF energy is either absorbed, reflected, or scattered. This surface interaction layer is called the skin depth and its distance is equivalent to an EM wave propagating into this medium during one period of the electron plasma frequency [51]. The skin depth for the interaction of EM radiation with plasma is proportional to the square root of the electron collision frequency, and inversely proportional to the square root of the electron number density and the driving frequency and represented in the following equation form:

$$\delta_{\text{skin}} = \sqrt{\frac{2 \cdot m_e}{q^2 \cdot \mu_0}} \cdot \sqrt{\frac{\nu_0}{N_e \cdot \omega_{pe}}} = 7.516 \cdot 10^6 \cdot \sqrt{\frac{\nu_0}{N_e \cdot \omega_{pe}}}[m] \quad (4.47)$$

The plasma skin depth would be a fairly large and therefore irrelevant for a single streamer with diameter equivalent to the one presented in example 4N and the plasma conductivity could be assigned straight away. On other hand, if multiple such streamers are present, then the effect of the skin depth would be much more pronounced due to the increase in the thickness of the plasma region and a uniform distribution of charges in this region. Therefore, there are multiple aspects that still need to be covered to link the RF coupling and confinement such as the power supplied by the oscillating magnetic field, the current induced via the RF coupling, and the ohmic heating of the plasma region.

The magnetic energy density stored per unit volume in the steady state magnetic field inductor is a function of the magnetic field and the permeability of the material [53], which is taken to be the permeability of free space in the equation below:

$$u_{B_{\text{rms}}} = \frac{B^2}{2 \cdot \mu_0}[J/m^3] \quad (4.48)$$

Therefore, the peak energy stored per unit volume would be $u_{B_{\text{rms}}} \cdot V_{\text{influence}}$, where $V_{\text{influence}}$ is the volume of influence of the magnetic field, or $V_{\text{influence}} = \pi \cdot r^2_c \cdot l_{\text{coil}}[m^3]$, and $l_{\text{coil}}[m]$ is the length of the coil enclosing such volume. The RMS power of the incident oscillating magnetic field with a frequency of $\nu_0$, provided that the field is oscillating in a uniform sinusoidal fashion, is:

$$P_{B_{\text{rms}}} = \frac{u_{B_{\text{rms}}} \cdot \nu_0 \cdot V_{\text{influence}}}{\sqrt{2}}[W] \quad (4.49)$$

Knowing how much EM energy is delivered to the plasma via the oscillating magnetic field allows understand how much of this energy is utilized by plasma for sustainment. Assuming that the confinement chamber is hollow cylinder radius $r_w$, the
plasma body is approximated by a cylinder of radius $a$, and it receives inductively coupled RF power from a coil of radius $r_c$, as showcased in Figure 4.8. Also, the plasma has an electrical conductivity $\sigma$ and a skin depth of thickness $\delta$. The advantage of this geometry is that the plasma would focus in the region of the most dense magnetic field, or the core of the coil, rather than near the confining walls, thereby alleviating the risk of destroying the generator body and components thermally [51]. Based on this geometry several observations can be made: plasma behaves as a relatively uniform conducting body (depending on the skin depth) that can be approximated as a single winding [44], plasma would act as a receiving circuit under the influence of the RF coupling, and plasma does not stay in the same place because it is a compressible fluid. As a result of these observations it is then possible to infer that the current produced within the plasma can be closely approximated by the following equality $I_1 \cdot N_1 = I_2 \cdot N_2 = I_2$, where $I_1$ is the current in the coil $N_1$ is the number of windings of the coil, and $I_2$ is the current induced in the plasma. Since plasma is behaving as a receiving circuit of the RF concoction, then the energy received from the incident EM wave by the plasma, at the skin depth and through the induced current (a process known as Ohmic heating), can be correlated to the RMS energy stored in the magnetic field, which would indicate the efficiency of the coupling process. The efficiency won’t be able to reach 100% because plasma does not stay in the same place as a result of its fluid behaviour, which would have the
additional possible losses. However, the fluid description of plasma will become most relevant in the next section and meanwhile it is assumed that plasma is generated at uniform and steady rate that allows for un-interrupted reception of RF energy. Therefore, the energy delivered into the plasma by the RF coil configuration is in the form of ohmic heating, and this heating energy can be simply computed based on the resistivity of plasma at the volume of the EM penetration layer. The RMS ohmic heating power absorbed by a stream of plasma of length $l_{\text{plas}}$ in such a configuration is then expressed as:

$$P_{\Omega_{\text{rms}}} = (N_1 \cdot I_1)^2 \cdot \left( \frac{2 \cdot \pi \cdot (a - \delta/2)}{\sigma \cdot l_{\text{plas}} \cdot \delta} \right) / \sqrt{2}[W] \quad (4.50)$$

The Ohmic heating power is directly supplying energy into plasma, thereby altering its characteristics to a narrow range of that corresponds to the frequencies provided by the coupling circuit. Therefore, provided the RF coupling is established efficiently with the plasma it is possible to drive the frequency to control the plasma temperature by varying the coupling frequency of the generator circuit. The ratio of the ohmic heating energy and the energy delivered by the EM wave would yield the efficiency of RF coupling:

$$\eta_{RF} = \frac{P_{\Omega_{\text{rms}}}}{P_{B_{\text{rms}}}} \quad (4.51)$$

The fundamental energy transfer frequency acts as a the effective resonance frequency for the body of plasma and the conductivity of the plasma is based on the incident EM wave. The method that may boost the performance of the plasma generator would be with the use of the RF coupling by the means the plasma volume and the supply of the resonance frequency that would match to the energy transfer frequency. Although, it is not the only method.

The aspects of the losses encountered at the generating circuit are an additional area of interest where the possible improvements can be made. In fact, the most disadvantages associated with RF coupling are the result of the coupling circuit structure. Approximately 10% of the input AC power is lost in AC to DC conversion, 40% is lost in the oscillator and tank circuit, and 10% to 30% of the input power is lost in the coil-plasma coupling process (which is typically a result of the need for a dynamic matching circuit)[51]. In most RF powered plasma application, only 20% or 40% of the input power is available for sustaining plasma state, as would roughly correspond to the geometrical derivations expressed by equation (4.51).

The equations derived in the present section are particularly critical for sustaining plasma in a region of the strongest magnetic field. In the next section, the aspects
of fluid mechanics are going to be covered to account for the additional effects of the energy losses associated with the flow of the neutral gas and the plasma. Based on these derivations the picture for the magneto-hydrodynamic approach to the plasma generator design would be sufficient to proceed with the circuit theory for the plasma generator and to dwell deeper on the matters of improving the circuit topology.

4.3.3 Plasma as a Fluid

Plasma is a hot, ionized gas that acts based on the principles of fluid behaviour, despite its ability to respond to the electric and magnetic fields. In order to classify a particular plasma flow regime it is critical to consult with the Knudsen number which indicates the measure of the flow rarefaction [55]. The Knudsen number is defined as follows:

\[
Kn = \frac{\lambda_i}{L} = \frac{k_B \cdot T}{\sqrt{2} \cdot \pi \cdot d_{ion}^2 \cdot P \cdot L}
\]  

(4.52)

Where \( L \), the characteristic or equivalent length, which is taken to correspond to the diameter of the confining chamber of the plasma generator, \( 2 \cdot r_w \), where the action of plasma generation is dominant [56]. The flow regimes based on the Knudsen number are presented in table 4.4 [55].

<table>
<thead>
<tr>
<th>Flow Regime</th>
<th>Knudsen number range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum Regime</td>
<td>(&lt; 0.001)</td>
</tr>
<tr>
<td>Slip Flow</td>
<td>(0.001 - 0.1)</td>
</tr>
<tr>
<td>Transition Flow</td>
<td>(0.1 - 10)</td>
</tr>
<tr>
<td>Free Molecular</td>
<td>(&gt; 10)</td>
</tr>
</tbody>
</table>

Based on the previous two chapters it is safe to assume that the flow mode to be in the continuum regime as the mean free path for the ions is on the micro-meter scale whereas the diameter of the confining chamber would be on the scale of the several milli-meters. Based on this assumption, the utilization of the continuum description of the plasma flow using the Navier-Stokes equations becomes possible and plausible. Hence, the key aspects that are most critical to describing the plasma flow behaviour in the plasma generator configuration will focus on the magneto-hydrodynamic (MHD) description of plasma via the Reynolds numbers, the Navier-Stokes equations, and the heat equations.
Figure 4.9, below, presents a schematic of the concept plasma generator with an electron emitter, coupled to the RF coil, and subjected to the flow of a neutral gas. The advantage of this configuration is that the plasma generation region is confined to the center of the cylinder, where the magnetic flux is highest, and the neutral gas flow envelops plasma in a manner that it does not thermally interact with the confinement walls. The gas supply has to provide a controlled amount of substance to sustain plasma without extinguishing it, and at the same time the flow has to keep the generator chamber walls cool. Furthermore, the plasma region produced by the dual action of the unipolar emitter and the RF coupling has advantage of reinforcing the secondary emission effect on every cycle where the magnetic field leads the electrons to hit the emitter surface. However, the unipolar emitter in the final prototype design is not going to be singular, instead an array of emitters will be implemented to boost the performance and efficiency of the final plasma generator design.

Figure 4.9: A schematic of the concept plasma generator with an electron emitter, coupled to the RF coil, and subjected to the flow of a neutral gas.

The equations thus far and the ones to follow, provide only a representation of the real situation without the full spectrum of all the possible factors, which are many to account for in a single thesis. It is possible to get an idea of the plasma generator operation and compute values that would be close to the measurements in an experiment. However, a well made experiment will always over-ride the theoretical computations and will test their validity. Therefore, the experiment in chapter 5 will
help to secure the perception of the theory and allow for tuning of the a computer model. Meanwhile, the aspects essential for fluid description of plasma will be presented to the extent most relevant for the current plasma generator without the level of depth and diversity of more capable works[37][57].

Magneto-hydrodynamics (MHD) is a modelling methodology of the dynamic and conductive fluids that are capable interacting with electromagnetic fields. In their core, the governing equations of MHD are composed of the Newtons laws of motion and the laws of electrodynamics. It is quite common to describe the foundations of MHD as a union of Navier-Stokes Equations and the Maxwells Equations [37]. Originally MHD theory was found useful in dealing with the liquid metal flows and forging via the electro-magnetic induction. With the growth of research in the plasma physics area, the MHD theory became useful modelling tool. In the case of Kinetic modelling of plasmas the behaviour of ionized particles is considered on the atomic scale and the collisional effects are of the primary interest, this type of modelling is most relevant in the area of fusion research. MHD modelling of plasma on other hand takes into account the bulk properties of compressible plasma and uses computational approximations for the flow modes that are either laminar or turbulent.

Many situations involving electrically-conducting gas flows require detailed description that involves Boltzmann equation to describe the plasma physics. In general, MHD focuses on the mutual interaction of fluid flows and electromagnetic fields. The fluid has to be electrically conducting and non-magnetic, which is particular to liquid metals, hot ionized gases (plasmas) and strong electrolytes. The fluid would interact with the magnetic field but in itself it is magnetically neutral. The fluid behaviour of plasma is unlike the conventional fluid due to the Coulomb interactions of the flowing ionized particles, which result in electric currents that lead to generation of the magnetic fields. Furthermore, the ion flow of plasma forms vorticity and plasma ”ropes”, which have an advection-diffusion behaviour similar to the behaviour of the miniature fire whirls [57]. The whole conglomeration of the Fluid mechanics, heat transfer, and the electro-magnetics are the foundations of plasma modelling, which can be fairly well represented by MHD modelling.

The joint effect of a magnetic field and a velocity field happens due to the Faradays, Amperes, and Lorentzs laws [37]. The process of MHD can be conveyed as three simultaneous processes:

1. According to the Faradays law the electromotive force (e.m.f.) is created due to the relative movement of the conducting fluid and the magnetic field. The electrical current will occur with a density of \( \delta \cdot (u \times B) \), where \( \sigma \) is the electrical
conductivity of the medium, $u$ is the velocity vector of the fluid, and $B$ is the magnetic field.

2. From Amperes law then, the induced currents ($J$) will create their own magnetic fields that adds to the original magnetic field and acts in opposite direction, thereby dragging the magnetic field lines along.

3. Finally, by Lorentz’s law the combined magnetic field and the induced currents, $J$, will result in the volume force $J \times B$. Such volume force inhibits the movement of both the fluid and the magnetic field.

The degree of fluid velocities’ influence on the magnetic field is related to the product of (i) the typical velocity of the motion, (ii) fluid conductivity, and (iii) the characteristic length scale, $l_{flow}$, of the motion. The characteristic length scale is as important as the fluid velocity and conductivity albeit being the more elusive component of MHD. This becomes evident when considering that a small current density applied in a small area yields a small magnetic field, but when the area is increased, even with the same current density, the magnetic field will increase respectively. Therefore, the characteristic length scale for plasma would be the length of plasma streamer where the influence of the flow is critical to the behaviour of plasma.

The product $\sigma_u = \sigma \cdot u \cdot l_{flow}$, determines the ratio of the induced magnetic field to the applied field. If the product is near zero then the applied magnetic field is unaffected. On the other hand, when this product is close to infinity (behave associated with ideal conductors) the ratios of magnetic fields is equal to a unity, or in MHD terms, the magnetic field is locked to the liquid. The locking effect of the magnetic field and the fluid is quite strong in astrophysics, important in geophysics, meagre in metallurgical MHD and practically non-existent in electrolytes.

Some of the key parameters in electrodynamics and MHD are as follows: permeability of free space $\mu_0$, electrical conductivity $\sigma$, density of the conducting medium $\rho_s$, and characteristic length scale $l_{plas}$. The magnetic Reynolds number is a dimensionless measure of the medium conductivity, and it is expressed as:

$$Re_m = \mu_0 \cdot \sigma \cdot v_{RMS} \cdot l_{plas} \quad (4.53)$$

Comparing to the flow Reynolds number:

$$Re = \frac{\rho \cdot v_{RMS} \cdot l_{flow}}{\mu_f} = \frac{v_{RMS} \cdot l_{flow}}{\nu} \quad (4.54)$$
Where, $\rho [kg/m^3]$ is the fluid density, $\nu [m^2/s]$ is the kinematic viscosity, and $\mu_f [N \cdot s/m^2]$ is the dynamic viscosity. Note that the key meaning of the Reynolds number is it is a ratio of (nonlinear) inertia forces to the (linear) viscous force. The inertial forces are responsible for the flow instability, while the viscous forces convert the kinetic energy into thermal energy [37]. The distinct feature of the flow Reynolds number use is the ability to classify a particular mode of flows into either a laminar ($Re < 2300$), transient ($2300 < Re < 4000$), or turbulent ($Re > 4000$). In case of the laminar flow the velocity distribution in the fluid is uniform and has a distinct layering, or laminations, of the fluid velocities. The turbulent flow does not have the uniformity of the laminar flow and can be described simply as chaotic and unevenly varying both temporally and spatially. The transient flow switches between the laminar and the turbulent flow modes due to the varying inertia forces within the flow.

Some additional parameters that need to be highlighted in relation to the magnetic Reynolds number include Alfven velocity and magnetic damping time. The Alfven velocity expression is:

$$v_{Alf} = \frac{B}{\sqrt{4 \cdot \pi \cdot N_i \cdot m_i}} \quad (4.55)$$

The Magnetic damping time is:

$$\tau_B = \frac{\rho_*}{\sigma \cdot B^2} \quad (4.56)$$

When the magnetic Reynolds number is low, the flow velocity has little effect on the acting magnetic field, since the induced magnetic field is low. The flow is dissipative and the kinetic energy is converted to heat via the Ohmic heating at a rate comparable with the magnetic damping time. For the large magnetic Reynolds number the magnetic field is locked onto the medium stronger. The effect is that the magnetic flux passing through the material is conserved when the fluid moves, and any disturbances occurring within the fluid behave quite elastically (since, the magnetic field provides restoring force for the vibration). The elastic behaviour produces the Alfven waves that have a frequency of roughly $v_{Alf}/l_{flow}$.

The fast magnetic damping time is an indicator that the magnetic coupling with the plasma is strong, which is confirmed by the high magnetic Reynolds number. The low Alfven velocity and the corresponding low Alfven frequency are indicators of plasma “rigidity” in the magnetic field; that is, although the magnetic field will tend to lock in position that corresponds to the plasma flow the plasma will tend to oscillate in the most dense magnetic flux region at the frequency corresponding to the Alfven frequency, and the lower this frequency is the plasma is more rigidly confined.
to the magnetic field.

The key MHD equations are coupled to the Navier-Stokes equation. In the case of the plasma generator at hand, the aspects of describing the plasma behaviour through the sections on ionization and RF coupling deal with a very specific case. Hence, the principles presented thus far make it convenient to implement the fluid description of plasma via the Navier-Stokes equations, because plasma acts as the virtual cathode region positioned in the flow to be a source of heat and ions. This virtual cathode region is only coupled with the electron emitter and the RF field, hence the behaviour of plasma in that region is the only focus for the means of generating plasma and affecting the flow of gas. The Navier-Stokes equations describing this flow are derived from the basic principles of conservation of mass, momentum and energy and are expressed as continuity and momentum equations. The description of plasma fluid can be assumed to act as a Newtonian if the continuum regime, computed via the Knudsen number, is satisfied [37]. The Navier-Stokes equations for a plasma fluid are expressed in terms of the continuity (conservation of mass), motion (conservation of momentum), and shear stress [56]. Below, the equations for Navier-Stokes equations in terms of the Vector form are presented.

**Vector Form of Navier-Stokes Equation**

Continuity (conservation of mass):

\[
\frac{\delta \rho_f}{\delta t} + \nabla \cdot (\rho_f \cdot \mathbf{v}) = 0 \quad (4.57)
\]

Motion (conservation of momentum):

\[
\rho_f \cdot \frac{\delta \mathbf{v}}{\delta t} = -\nabla P - \nabla \cdot \tau_f + \rho_f \cdot \mathbf{F} \quad (4.58)
\]

Shear stress:

\[
\tau_f = -\mu_f \cdot (\nabla \mathbf{v} + \nabla \mathbf{v}^{Transpose} - \frac{2}{3} \cdot \nabla \mathbf{v}) \quad (4.59)
\]

In Figure 4.9, there is an indication of the boundary layer in the flow near the insulating wall of the plasma generator and near the surface of the electron emitter. This boundary layer is a region of retardation of fluid due to the viscous effect from the solid surface, the velocity at the surface is taken to be as zero (no-slip condition), and the succeeding layers away from the solid surface have increasing velocities. Commonly, the boundary layer thickness is defined as a distance normal to the surface at which the ratio of local velocity to free-stream velocity is a fraction close to unity, approximately 0.99. For analytical cases this approximation is not entirely reliable.
however, there are only handful of cases where the exact computation of the boundary layer thickness can be computed exactly, and most of them deal with laminar flows over flat plates. For more complex examples the numerical methods and the finite element tools are used to model the flows at the solid wall boundaries. The works describing the behaviour of the fluid flow due to boundary layers provide the foundations for the numerical models [60][61][61], although they agree that the use of computing tools for the complex designs is a reliable and a quicker approach, especially with the present day computational tools.

The coupling to electric and magnetic fields is expressed through $\mathbf{F}$ [58]. In electrokinetics the fluid may have charges that are coupled to external electric fields and lead to an external force that is:

$$ F_{\text{unipolar}} = -\rho_{e^-} \cdot \nabla \phi $$  \hspace{1cm} (4.60)

Where, $\rho_{e^-}$ is the electron charge density per volume and $\phi = E_{\text{unipolar}} \cdot r_{\text{emitter}}$ is the external electric field. The charge density may be a variable, depending on how quick the ions are generated and removed, although in steady state it can be approximated to be constant. Also, if the fluid has ionized species it will also couple with the magnetic field [58]. The magnetic field induced force term for the flow momentum equations is defined as:

$$ F_{\text{Magnetic}} = -\mathbf{J} \times \mathbf{B} $$ \hspace{1cm} (4.61)

Where, the current density $\mathbf{J}$ induced in the virtual cathode plasma region by the effective electric and magnetic fields (as per sections on Ionization and RF coupling), it is defined as:

$$ \mathbf{J} = \sigma \cdot (\mathbf{E}_{\text{eff}} + \mathbf{v} \times \mathbf{B}_{\text{eff}}) $$ \hspace{1cm} (4.62)

The diffusion-advection-convection effect in flow is the transport of scalar quantity of ionized species by diffusion, advection, and convection. The difference in the nomenclature usually indicates that an advected quantity does not have an effect on the velocity field of the total fluid flow, and a convected quantity has [58]. Diffusion-advection-convection effect is derived from the principle of mass conservation of each species in the fluid mixture and may have sources or sinks either at the boundary conditions (electron emitter) or within the body (virtual cathode). Hence, multiple advection-diffusion equations may be coupled together to analyse plasma interaction in mixtures and convective flows at different temperatures. If the velocity field is zero, then the advection-diffusion equation reduces to the diffusion equation, which
The diffusion-advection-convection effect may, in general, be expressed in terms of relative or absolute mass or molar concentrations. When the transported quantity is carried by an incompressible fluid, the relative mass concentration, \( c_i = C_i / \rho \) for the ionized species, is used (\( C_i \) is the absolute mass concentration in [kg/m\(^3\)], and \( \rho \) is the total density of the mixture) [58]. The approximation is valid for dilute multi-species flows that can be used for plasma modelling (0 ≤ \( c_i \) ≤ 1). The diffusion-advection-convection effect for a compressible fluid in equation form is:

\[
\frac{dC_i}{dt} + (\nabla \cdot \mathbf{v}) \cdot C_i + (\mathbf{v} \cdot \nabla) \cdot C_i = \nabla \cdot (D_i \nabla C_i) + S_i \tag{4.63}
\]

Where, \( \mathbf{v} \) is the advection velocity, \( D_i \) the diffusion coefficient and \( S_i \) is a source, sink or a reaction term. The velocity of the advecting fluid, \( \mathbf{v} \) is calculated by the Navier-Stokes equations above. All quantities can also be functions of temperature that is given or solved by the heat equation. Several diffusion-advection-convection equations for different ionized species may be coupled and solved for the same velocity field.

Due to the plasma generation via the RF coupling it is possible to include temperature and magnetic field diffusion, or Bohm diffusion. This introduces a \( D_{Bohm} \) term instead of \( D_i \) on the right hand side of equation (4.71):

\[
\nabla \cdot (\rho \cdot (D_{Bohm} \cdot T_{ion}) \cdot \nabla T_{ion}) \tag{4.64}
\]

Where, \( D_{Bohm} \) is the magnetic field and thermal diffusion coefficient for ionized species. The coefficient \( D_{Bohm} \) is expressed in [m\(^2\)/s] regardless of the concentration and is computed according to the following [59]:

\[
D_{Bohm} = \frac{k_B \cdot T_{ion}}{16 \cdot (q) \cdot (B)} = 5.386 \cdot 10^{-6} \cdot T_{ion} / B [m^2/s] \tag{4.65}
\]

The heat equation for the plasma flow results from the requirement of energy conservation. The Fouriers law is used to model the heat conduction through the plasma fluid with the combination of the diffusion-advection-convection equations to account for the dynamic behaviour [58]. The linearity of the equation may be ruined by temperature dependent thermal conductivity, or by heat radiation so for the sake of simplifying the modelling process these effects are assumed to be constant, which is realistic for the applications requiring a steady supply of plasma. For compressible fluids, the heat equation is written as:
\[ \rho \cdot c_v + \left( \frac{\delta T}{\delta t} + \mathbf{v} \cdot \nabla T \right) - \nabla \cdot (k_B \cdot \nabla T) = -P \cdot \nabla \cdot \mathbf{v} + 2 \cdot \mu \cdot \tilde{\varepsilon}_f + \rho \cdot H \quad (4.66) \]

Where, \( c_v \) is the heat capacity at constant volume, \( \tilde{\varepsilon}_f \) is the linearised strain rate tensor, and \( H \) is the auxiliary heat source, such as the resistive Ohmic heating mode. The term \( 2 \cdot \mu \cdot \tilde{\varepsilon}_{fluid} \) is the frictional viscous heating term, which is comparatively smaller than the possible auxiliary heat sources. The density can be calculated from the perfect gas law:

\[ \rho_f = \frac{P}{R_f \cdot T} \quad (4.67) \]

Where \( R_f \) is a gas constant expressed by:

\[ R_f = \frac{\gamma - 1}{\gamma} \cdot c_p = \frac{c_p}{c_v} \cdot c_p = c_p \cdot c_v \quad (4.68) \]

The key auxiliary heating source in plasma is the Ohmic heating mode which is computed for the heat equation via:

\[ H_{\Omega} = \frac{1}{\sigma} \cdot J^2 \quad (4.69) \]

If the flow of plasma is laminar, then the effects of plasma generation take on the convective terms and at the high enough temperatures can lead to thermal destruction of the generator body. Hence, most of the time the turbulent mode of operation for the plasma generation is engaged due to the high speeds at which plasma can move and the necessity to cool the solid surfaces of the plasma generator. Assuming, the turbulent flow is homogeneous (uniform, and the intensity of turbulence fluctuations, \( k \), is low) and stationary (the convection and the diffusion terms are negligible compared to the turbulent fluctuations). If the turbulent flow is analysed along a horizontal axis then the following equations describe its approximate behaviour:

\[ \frac{\delta k}{\delta t} + \tilde{U}_j \cdot \frac{\delta k}{\delta x_j} = u'_i u'_j \cdot \frac{\delta U'_i}{\delta x_j} - \frac{\delta}{\delta x_j} \left\{ u'_j \cdot \left( \frac{k}{2} + \frac{p'}{\rho} \right) - \nu \cdot \frac{\delta k}{\delta x_j} \right\} - \nu \cdot \left( \frac{\delta u'_i}{\delta x_j} + \frac{\delta u'_j}{\delta x_i} \right) \quad (4.70) \]

The rate of change for intensity of the turbulence fluctuations \( k \), that describes the unsteady flows is:

\[ \frac{\delta k}{\delta t} \]

The convection term is:

\[ \tilde{U}_j \cdot \frac{\delta k}{\delta x_j} \]
The turbulence production term for k is:

\[ \overline{u_i u_j} \cdot \frac{\delta \bar{U}_i'}{\delta x_j} \]

The turbulence diffusion term is:

\[ -\frac{\delta}{\delta x_j} \cdot \left\{ u'_i \left( \frac{k}{2} + \frac{p'}{\rho} \right) - \nu \cdot \frac{\delta k}{\delta x_j} \right\} \]

The turbulence dissipation term is:

\[ -\nu \cdot \left( \frac{\delta u'_i}{\delta x_j} + \frac{\delta u'_j}{\delta x_i} \right) \]

The outcome of having a homogeneous and stationary turbulence flow (when the rate of turbulence generation is balanced by the rate of turbulence dissipation) results in the following form:

\[ \overline{u_i u_j} \cdot \frac{\delta \bar{U}_i'}{\delta x_j} = \nu \cdot \left( \frac{\delta u'_i}{\delta x_j} + \frac{\delta u'_j}{\delta x_i} \right) \]

Working with the original k-equation provided, and recognizing the key similarities the outcome equation takes the following form:

\[ 0 = \overline{u_i u_j} \cdot \frac{\delta \bar{U}_i'}{\delta x_j} - \frac{\delta}{\delta x_j} \cdot \left\{ \frac{k}{2} \cdot \bar{U}_j + 0 - \nu \cdot \overline{u'_i \left( \frac{\delta u'_i}{\delta x_j} + \frac{\delta u'_j}{\delta x_i} \right)} \right\} - \varepsilon \]

Note, since the turbulence is homogeneous the term \( \frac{\delta}{\delta x_j} \cdot \left\{ \frac{k}{2} \cdot \bar{U}_j \right\} \) reduces to zero, thereby leading to the following:

\[ \overline{u_i u_j} \cdot \frac{\delta \bar{U}_i'}{\delta x_j} = \frac{\delta}{\delta x_j} \cdot \left\{ \nu \cdot u'_i \left( \frac{\delta u'_i}{\delta x_j} + \frac{\delta u'_j}{\delta x_i} \right) \right\} - \varepsilon \]

The \( \varepsilon \) term is the rate of dissipation and \( u'_i \left( \frac{\delta u'_i}{\delta x_j} + \frac{\delta u'_j}{\delta x_i} \right) \) is the turbulence dissipation term. If the rate of dissipation is comparable to the dissipation term, then the left hand side of the equation simply becomes \( \nu \cdot \left( \frac{\delta u'_i}{\delta x_j} + \frac{\delta u'_j}{\delta x_i} \right) \).

Despite this reductive form of the turbulent flow under the simplified conditions, it is not quite easy to compute it along with the equations for the plasma behaviour, keeping in mind that the above only takes into account the flow without any MHD terms. Hence, although the methodology taken in modelling the plasma behaviour implements the theoretical foundations presented, solving the Navier-Stokes equations with the MHD coupling terms even for the steady state flows would become an intensive mathematical challenge of solving complex partial differential equations. In order to avoid this cumbersome path the method of applying finite element methods...
for computing the fluid-dynamic changes at very-fine meshes will be implemented through Elmer FEM as it can closely produce a solution via the use of a Large Eddy Simulation (LES) technique, which has the capacity to compete with the direct numerical simulation (DNS), provided it is done correctly. The development of the DNS has the potential to model the turbulent flows with significant detail. DNS is the numerical technique that provides the most accurate turbulent flow data because it takes into account the system of Navier-Stokes partial differential equations describing a model and solves them without any approximations (unlike the case of equation (4.78) where the turbulence fluctuations term k is just an approximation). The LES technique makes approximations, unlike the DNS method, though these approximations are based on the rigorous data sampling of actual flows. By and large, the LES method takes into account the physical phenomena and implements the ODEs with approximations based on the measurement of eddies in the experiment, thereby making the equation value models work together with the real-world data. The LES method lies somewhere between the RANS, $k-\omega$, $k-\varepsilon$, and the DNS methods, in terms of the computational accuracy and time[60]. If there is an option to choose the more time-efficient option, for a particular model, between the DNS and LES, LES will have be the better choice, because the accuracy of the computations will be comparatively close to DNS, and unlike the RANS, $k-\omega$, and $k-\varepsilon$ it is grounded in real data rather than strict approximations [57].

4.3.4 Circuit for Plasma Power and Control

![Figure 4.10: Schematic Diagram of Virtual Electrode Plasma Generator Components](image-url)
The electric energy is supplied to ionize a gas via a high field emission and the resulting plasma is supported by the Ohmic heating process, sustained by the RF coupling circuit. Certainly, covering these processes can provide a perspective on nature of plasma, although not covering the circuits behind them would be loss of an essential piece of plasma generation. Plasma’s characteristics are altered and tuned to a narrow range of frequencies provided by the coupling circuits, which are key to creating plasma in the first place. Therefore, in current section the essential components of the plasma generator will be presented, and the analysis of the key elements to generate plasma efficiently will be highlighted.

Figure 4.10 presents a schematic diagram of the virtual electrode plasma generator device. The gas flow control and supply is responsible for providing the work gas to be converted into plasma at a rate required to treat a particular element in the work space. The cooling component assures that the plasma generator case does not disintegrate, and prolongs the operational lifetime of the device, depending on the size of the device the cooling can be achieved either via the forced gas convection or by liquid cooling. As far as the primary electronic components for plasma generation, they are going to be the primary focus in this section. There are three primary circuits in the virtual plasma generator: power control, high field generator, and RF coupling circuit. These components are working together to generate plasma, although their assessment on individual basis will provide an insight into overall performance of the device. The data sampling for the properties of plasma will also be presented in respect to the generator efficiency, plasma temperature, and plasma flow.

The power for the plasma generator is typically obtained from either an alternating current (AC) supply, from the power grid, or via the conversion from the a direct current (DC) supply, by the use of the rapid switching techniques. The current needs to be converted into a structured signal that can then be used in either boosting the potential at the high field emitter, to enable the escape of electrons, or for raising a high frequency current at the RF coupling coil, for a more dense magnetic field in the solenoid core. The area of electrical conversion is known as power electronics. The key components in the modern power electronics are the semiconducting (or solid-state) switches, that either use doped silicon compound or metal oxides. These switches are critical due to their ability to be low power, high frequency, and capable of providing robust control options. Based on the characteristics of the semiconducting switches the power converters are correspondingly structured. There are basic electronic components that can be used in power electronics: the traditional switches, the resistors, the capacitors, the magnetics, and the semiconducting devices. However, in the case of the power electronics design it is preferable to avoid the resistors and the linear...
mode semiconducting devices to avoid power losses. The role of the switched-mode semiconducting devices is essential for the development of efficient power devices. The power diodes can be used in the uncontrolled switches for turning the electronic devices on and off. In the standard rectifiers the use of the power diodes is gradually being replaced by the IGBTs (Insulated Gate Bipolar Transistors) due to the fact that diodes have a low efficiency (about 68%)[63]. However, the process of change is slow because the power diodes are very robust (safety factor of 99%). Also, IGBTs are not very reliable due to the difficulties of cooling them down. The unidirectional capability components include the SCRs (Silicon Controlled Rectifiers), GTOs (Gate Turn Off Thyristors), BJT (Bipolar Junction Transitors), MOSFETs (Metal Oxide Semiconducting Field Effect Transistors), SiCFETs (Silicon Carbide Semiconducting Field Effect Transistors), and IGBTs [63]. BJT, MOSFET, SiCFET, and IGBTs also meet the continuous gate signal requirement and, like the Power Transistors, can meet controlled "on" and "off" characteristics. The SCRs and the GTOs are also able to meet the pulse gate requirements, although, unlike the regular rectifiers, their safety factor is low. The electrical converters usually include the standard voltage regulators (AC to AC), DC choppers (DC to DC), controlled rectifiers (AC to DC), and the inverters (DC to AC)[63]. The primary scope of the converter technology is the compactness, durability, high-power handling, and high efficiency. The voltage regulators are able to convert the incoming fixed AC voltage into the outgoing variable AC voltage, usually via the use of TRIACs [63]. The DC choppers change the constant input DC voltage into variable DC voltage by the variation of the duty cycle. Where the duty, $D_{cyc}$, cycle is the ratio of the time that a switching signal is active to the $t_{sw}$, over the total period of the cycle $\tau_{cyc}$:

$$D_{cyc} = \frac{t_{sw}}{\tau_{cyc}}$$

The boost converters are the sub-category of the DC to DC converters that raise the DC voltage output from the input. The buck converters, on other hand, step down the input voltages. A buck-boost converter is capable of converting the DC voltage inputs to lower or to higher levels depending on the settings made by the user, but they are not as efficient as the Boost or buck converters on their own [63]. The controlled rectifiers convert the AC voltage into DC voltage and can be either single phase or triple phase. The use of diodes is preferred due to their robustness and fixation of DC voltage, but the use of the thyristors is also possible to vary the DC output via the variation of the thyristor firing angle [63]. The inverters convert the DC voltage to the AC voltage by producing a sinusoidal signal of controllable magnitude and
frequency via the pulse width modulation (PWM) at the semiconducting circuitry [63]. Typically, the output filter (depending on operation it may be either a low pass or a high pass filter) is needed to smooth the irregularities, like harmonics, that may be encountered due to the high frequency switching at the devices presented above [63]. The PWM is the most common go-to method for regulating the switching frequencies of a power electronics device [63], whereas the ZVS and ZCS are more commonly found in the self-regulating oscillator circuits of the resonant converters. The PWM is a regulated switching via a programmable integrated circuit or a clock chip that produces switching pulses that are maintained at a particular pulse-width via the modulation by a secondary regulator, such as an oscillator crystal [63]. The implementation of either ZVC or the ZCS means that the operational frequencies are higher than those for the PWM converters, making the self-regulation of the converter circuit dependant on the intrinsic properties of the device rather than hard control by the means of PWM. Despite a favourable outlook of the resonant converters in terms of switching performance, they are not without disadvantages. First of all, the analysis of the resonant converters can get fairly complex depending on the circuit topology [63]. Second, it is possible to tune the performance of the resonant converters to a specific operating point, but the ranges of the input voltage and the load power variations become narrow [63]. Third, when used with either light loads or no loads at all, the resonant converters have a low efficiency due to large currents that can potentially circulate through the tank elements [63]. Fourth, the range of switching frequencies for resonant converters can be large due to the control that relies on the variation of the switching frequency [63]. Lastly, the resonant converters operate with the quasi-sinusoidal waveforms instead of the rectangular waveforms alone, and the corresponding high peak values in such mode of operation results in higher conduction loads that hinders the switching losses [63]. The operation of the power switches comes with a cost of thermal losses. The harmonics, switching losses, and the transient interference can also compromise the performance of the electronic switches. To alleviate the losses and to improve the performance of the electronic switches it is favourable to improve the drive, and snubber circuits. The cause of the switching losses is that the electronic switch cannot rapidly transition its states. The resonant converters alleviate the switch losses by natural oscillation to switch the states when either the current or the voltage is zero. The gate drivers are partitioned into the low-side drivers and the high-side drivers [63]. The low-side drivers are intended to have the control over the gate voltage and current of the switching devices, since a mere input signal is from low-voltage digital logic devices is not always adequate to turn on the electronic switch [63]. To be operational the
low-side drivers have to be connected to the circuit ground. During the switching the on/off-state gate currents are practically non-existent. However, it is the parasitic input capacitance that must be charged to turn the electronic switch on, and must be discharged to turn it off. Hence the switching frequencies are found by the time it takes to transfer a charge to/from the gate [63]. On other hand, the high-side drivers are not connected to the circuit ground and remain floating. Hence, the gate-to-source voltage must be sufficiently high to turn on the electronic switch. In fact, for the applications like buck converters the gate voltage must be higher than the supply voltage because the voltage at the source terminal of the electronic switch, like a MOSFET, is the same as the supply voltage. For the high-side drivers it is critical to electrically isolate the electronic switches and the control circuitry, since the high voltage levels yield a higher risk of breakdown at the junction of the switch [63]. The methods of optical or magnetic coupling are most common for the electrical isolation from the oscillator circuits and the power handling semiconductors, and serve as a protection layer against possible harmful distortions.

The high field emitter circuit is necessary for ionizing the neutral gas species. Typically, the circuit for producing a high field at the emitter can either be a step up transformer, or a controlled rectifier (Boost converter). A step up transformer is an efficient and robust option for generating high potential electric fields, although the conventional iron-composite core transformers can be quite bulky and heavy. It is possible to use an air core transformer to step up the potential to produce the ionized species, this device is commonly known as a the Tesla coil, and it operates based on the impulse driving a resonance in the inductance-capacitance circuit that leads to a spill-over of electrons into a gas. The Tesla coil is lighter than a iron-composite transformers although it typically has to be quite large to reach high potentials necessary for initiating ionization. On other hand, a robust and compact option in Boost converters is a voltage doubler or multiplier, which uses semiconducting devices and capacitors to produce high potentials at a point. Unlike the transformer based voltage multipliers, the solid state voltage doublers produce high potential direct discharges [63]. It is possible to effectively combine the air core transformers and the boost converters to produce quite efficient high field generators. Combining such circuit with an array of point electron emitters would yield a device that could efficiently and effectively produce ionized species for plasma generation. In Figure 4.9, the switching regulator and the multiplier circuit serve as the high-field generator components. The idea pursued for the virtual cathode plasma generator aims to reduce the power wasted by the circuitry and to efficiently produce a high potential at the emitter array. Hence, a simulation circuit in PSIM was made for a device that could be implemented.
in the final version of the preliminary design. This circuit is shown in the Figure 4.10, and it consists of a transformer, a switching regulator circuit, and a multiplier circuit. The transformer boosts the grid potential and decreases the current supplied into the circuit as well as prevents any of the harmonics generated in the multiplier circuit to be alleviated at the input. The switching regulator maintains a high speed switching frequency at the multiplier circuit to alleviate the heating of the semiconductors and the potential generated at the emitter array ($V_{emitter}$). Finally, the multiplier circuit boosts the potential to a level sufficient for causing ionization. Depending on the frequency at the control oscillator ($Control\_Freq$), the multiplier circuit is able to dynamically adjust the potential generated at the emitter side, thereby regulating the rate of gas ionization and the electron emission from the emitter array. Typically the optimal frequency at the control oscillator is about the double of the input source frequency [63], which will become quite apparent in the analytical results chapter.

The RF generation circuit is an inverter that operates at a high frequency and creates dense oscillating magnetic field, due to high currents, that support the ionized state of plasma and confines it to a limited region of space, also known as the virtual cathode, produced as a result of electron emission. A conventional RF system for sustaining a discharge consists of a generator, usually combined with an impedance matching network (a control component), and the reactor with the electrodes, or a virtual electrode [63]. The power amplification can be achieved by compressing energy...
into tight pulse packets, which are effective method for improving plasma coupling without raising the operating costs [44]. The power delivered by the RF is circuit is wireless, hence, the resonant transformer bank could be used on short distances. Their operation is reminiscent to that of a transformer, where the primary coil uses the magnetic properties of the medium to transfer the electromagnetic energy to the secondary coil. Depending on the winding count on the primary and secondary coils, the received power can be either be stepped up or down in current or voltage. Although, in the RF plasma coupling it is primarily used for stepping up the current in the body of plasma, as was made apparent by the section on RF coupling and confinement. Naturally, the alternating current has to be in a safe range for operation to prevent the electromagnetic radiation from harming people. The frequency range of operation for the wireless power transfer devices is typically between 22 and 100 kHz, and the currents transmitted can be anywhere between 200 to 400 Amperes [63]. The limit on the EM radiation has to be lower than $5[\mu T]$[63]. Unlike the direct coupling by wires where the transfer efficiency is nearly 100 %, the wireless power transfer reached an efficiency of 90% thus far, though it is expected to go higher [63]. The reason is that there is a leakage to the environment with a changing magnetic reluctance, unlike a standard core transformer, where the magnetic properties are confined to the hysteresis loop. In the case of the RF coupled plasma generator, an effective coupling to plasma reduces the harmful EM emissions by converting the supply power into heat via the ohmic heating. Hence, achieving efficient power transfer into plasma via RF heating is important not only in order to avoid losses, but also to reduce the harmful effect of EM radiation. The inductances (L[H]) and capacitances (C[F]) in a switching network of the RF generator, lead to a sinusoidal variation in the voltage and current waveforms over the course of a single or multiple sub-intervals of each switching period [63]. The coupling to the plasma via the feed coil requires that theses inductances and capacitances result in an adjustable configuration that allows for the maximum energy transfer into the plasma; in other words they have to make a matching network. The sinusoidal waveforms have a large amplitude when the switching frequency, the resonant frequency of the LC network, and the plasma frequency closely match, thereby reducing the harmonics at the output. The LC combinations are referred to as the resonant tank networks and are usually categorized in four variations: series LC tank network, parallel LC tank network, LCC tank network, and a LLC tank network. A variation of the conventional resonant converter with a combination of PWM circuit is known as a quasi-resonant converter. Due to the resonant operation of the resonant converters their primary advantages is the reduced switching loss and the reduced electro-magnetic interference (EMI), particularly in
case of Zero Voltage Switching (ZVS). The switching losses are reduced using either the zero-current (ZC) or the zero-voltage (ZV) soft switching techniques, whereby the on-off transitions on the semiconducting switches happens at the zero point transition of the tank voltage or current waveforms. The power input to maintain the high field discharge is increased as the frequency of RF coupling circuit is reduced until about 10[kHz], the minimum discharge diameter becomes more than 1[m], and a power input of about 1[MW] would be required from RF circuit [44] to maintain the plasma. Normal RF operating frequencies are about 6[MHz] hence the sloshing of a high current would inevitably lead to the heat generation in the induction coil [44]. Low-power induction coupled torch (ICT) coils, such as those used for spectroscopy or laboratory applications (<30 kW), can be cooled by compressed air (<10[kW]) or by water (<30[kW]); however, higher powers for industrial applications require water-cooled ceramic tubes or axially segmented metal tubes which minimize eddy currents [44]. The overall efficiency of power generation using the RF coupling circuits at high frequencies (>100 kHz) is less than 50%. However, effective combination of the high field ionization circuit and RF coupling in a single package, with consideration of the physical structuring of the device, could lead to the production of an efficient plasma generator. A PSIM model circuit made for a potential device that could be in the final version of the preliminary design is shown in the Figure 4.11. There are seven key components in the RF coupling circuit: the step-down transformer, the rectifier stage, the rectifier switching regulator, DC filter, Inverter Bridge, Inverter Switching Regulator, and the Resistive Coil RF coupler, which also contains the matching circuit configuration inside of it.

The purpose of the step-down transformer is to decrease the potential to the work-
ing range of the thyristors in the rectifier stage, as well as provide a suitable current for the inverter. The rectifier stage uses the thyristors to regulate the rectification process so that the output DC is not interfering with the input, thereby avoiding any losses due to the source interference. The total harmonic distortion is significantly reduced when the thyristors are activated at controlled interval, therefore, the use of the rectifier switching regulator (controlled oscillator) is critical to maintaining a steady DC output from the thyristors. Furthermore, the combined use of the thyristors in the rectifier stage and the use of the switching regulator allow for the control of the current passing through the rectifier thereby controlling the heating of the thyristors below their critical operation range. The DC filter is intended to reduce the high frequency noise from the rectifier stage and acts as a low pass filter, that makes the ripple current smooth before it enters into the inverter. The inverter bridge is made of the field effect transistors (FETs) that fire in a sequence that matches most closely to the energy transfer frequency (as per equation (4.44)). The bridge has to handle fairly high currents so the preferred semiconducting switches for this operation are based on the Silicon Carbide technology due to their robustness, longevity, and high frequency operating range[63]. The low gate capacitance of the SiCFETs makes them preferable because the resonant switching frequency can be closely tuned to the energy transfer frequency of the plasma [44]. Although the inverter bridge would be able to oscillate at the preferred frequency range, the control of its operation is done via the inverter switching regulator, which consists of the variable oscillator controlled by an external micro-controller that supplies a PWM signal. The PWM signal regulates the variable frequency oscillator in the mega-Hertz range thereby tuning in to the energy transfer frequency of the plasma. The coupling to the plasma itself, is done via the resistive coil, which contains matching circuit configuration as part of the coupler design. The resistive magnetic coil, also known as the Bitter coil [65], is able to focus dense magnetic fields in the core of the magnet due to its ”pancake” coils. The design of this coil would be most suitable in the high current, low voltage application as is the case with the RF coupling configuration. The impedance of plasma will be matched if no reflection occurs from it, or is minimized. If the reflected wave is out-of-phase with the transmitted wave, the voltages of the transmitted and reflected waves add, or subtract, and can damage the power supply or cause instrumentation errors if it is not correctly matched to the source or instrument [44]. The geometry of the bitter coil allows to regulate the positioning of the plasma thereby making the geometry of the coil act as a tuning surface for the plasma, intrinsically acting as a matching network [44]. Also, the frequency sensor picks up the current variations in the coil due to mismatch between the phases and adjusts the frequency feed respectfully to
minimize the EM reflections back into the coupling coil.

The frequency generated by a series connected LC circuit is expressed as

$$f_{LC} = \frac{1}{2 \pi \sqrt{L \cdot C}} [Hz]$$

(4.72)

The power delivered by the supply to a plasma is determined by the dynamic state of the plasma. Plasma is affected by factors such as voltage, current, gas pressure, impurities and working gases, making it impossible to analyse the behaviour of the power supply and the plasma independently. The design requirements of a supply start with the requirements of the plasma, principally power and power density at the operating pressure, gas. The key plasma parameter is the voltage drop across the plasma and power required, and hence current and impedance to give the required power and power density, working back to matching the supply to the plasma. [44]
Chapter 5

Plasma Generator Experiment

5.1 Experiment Setting

The intention of this chapter is to create a small scale plasma generator configuration to be used for concept testing and model verification. The physical prototype will be created and tested in order to validate, test, and tune the simulation models. The experiment is composed of three key subsections: safety procedures, and power supply, and data acquisition methodology.

In the experiment, it is assumed that the air is dry and its molar mass is roughly 28.9645 [g/mol] at SATP [68]. It is also assumed that the plasma behaves closely to an ideal gas, since the conditions are near vacuum and the collisional effects are far below the levels required for fusion. The continuity of fluid behaviour in the experiment is assumed to be valid. Lastly, the pressures of plasma are expected not to exceed the SATP conditions, hence the convection of fluids is possible [60]. These assumptions will be carried over to the simulations available in the next chapter.

Figure 5.1: Schematic layout for plasma generator experiment in vacuum
5.1.1 Safety

Figure 5.1 presents a schematic of the plasma generator experiment and Figure 5.2 presents the actual physical layout of the experiment. The most notable experiment risks in this configuration include the use of high voltage, high current electrical equipment, and the vacuum conditions. The risk components needed to be handled in the experiment include a 9[kV] transformer, the RF circuit combined with the DC Power Supply, and one gallon vacuum chamber.

Figure 5.3 presents the plasma generating end of the experiment. This nozzle
and probe configuration has to be pre-assembled into vacuum chamber lid prior to the conduction of any experiments. Respectively, there is a safety procedure for working with this configuration. A person responsible for assembling this working end is required to use the utmost care during handling. The use of insulating surgery gloves are highly advised to prevent the contamination of the components by any alien contaminants such as dust and dirt. In case the device is deemed to have been contaminated, it is advised to use cotton damped with a 99% propanol solution and clean any of the surfaces under suspicion. Also, the assembly is fragile, the pink ceramic nozzle is linked with a glass tube, this glass tube has the RF coil wrapped around it and can crack if force is applied onto it. In order to avoid cracking and breaking the assembly the device needs to be handled with care. Lastly, the plasma generator assembly with lid of the vacuum chamber needs to evaporate any of the propanol remnants before being mounted onto the steel vacuum chamber.

The primary control mechanisms of the plasma generation process in the experiment include: the activation of the HV transformer, RF Circuit Power Supply, and the control of the gas inflow via the insulated inlet valve. The awareness of these control components and their careful utilization are essential to keeping the experimenters and the experiment safe. Therefore, familiarization with the use of these control components is necessary prior to conducting any experiments.

The 9[kV] transformer is used to provide a source of high electric field and current for direct discharge configuration, as well as for the single electrode electron emission. This transformer is a substitution for a high-field multiplier circuit (such as the one showcased in Figure 4.10). The transformer operates in a single stage step-up manner and it is controlled by an on/off switch. The safety procedure for working with the high voltage sources is as follows: when the experiment is ready, turn on the transformer switch in order to gather the data, and upon completion of the task shut the switch off. The safety procedure for working with the vacuum chamber when the lid with the plasma generator assembly is mounted is similarly simple: when the experiment is set, activate the vacuum pump until favourable conditions are met, then slowly turn on the insulated inlet valve to bleed air into the plasma generator. Furthermore, the operation of the experiment requires that at any time during the experiment there are two people participating: one responsible for the safe operation of the equipment, and the other responsible for gathering the data and assisting the safety manager if necessary. The "buddy-system" is the most preferable operational procedure for conducting the experiment with high potential and the vacuum equipment.
5.1.2 Power Supplies

The power supplies available for the experiment include the high-voltage (HV) transformer, the power supply for the RF circuit, and the oscillator, that is actually generating the RF signal and couples electric source with the plasma. The HV transformer is fairly rudimentary device that is used in the case for driving a direct discharge plasma generation mode as well as the single emitter mode. The power supply for the RF coupling circuit supplies a steady 20[V] DC at the maximum current level of 2[A]. This standard supply also provides power for the triple Langmuir probe that is responsible for gathering property information about plasma (discussion on the data acquisition is available in the respective subsection). Therefore, it is of the primary interest to consider the oscillator circuit for the RF coupling which only operates during the single emitter mode.

The circuit diagram of the RF oscillator is shown in Figure 5.4. The layout of this circuit is based on the principles of the Colpitts and Gouriet-Clapp type oscillators [66]. However, unlike the typical Gouriet-Clapp oscillator, the oscillator under consideration has a balanced resistor configuration that is only slightly skewed towards the ground (the difference between the 0.982[kOhm] and 0.984[kOhm] resistors). This minute difference is significant enough to cause a response on the MOSFET capacitance to lead to the switching frequencies in a controllable range between 7 and 11[MHz]. Also, another key difference of the circuit presented is that it is driven
by the resonant switching of the inductance-capacitance bridge formed by the input inductances and the MOSFET capacitance. The combined effect of slight resistive imbalance and the unique LC formation make this circuit quite formidable in terms of coupling the RF energy to plasma.

In the case of the GourietClapp oscillator, the tank inductor found in the Colpits configuration is replaced by the series combination of an inductor and a variable capacitor, that is enacted by the plasma [64]. Hence, the frequency stability is improved because the reactance of this circuit varies more rapidly with frequency than that of a single inductor. Although, the possibility to improve the oscillator stability by connecting a capacitor in series to either one or each inductor, the drawback would be the dampening of the resonant frequency that would be more closely matched to the plasma frequency [66].

5.1.3 Data Acquisition Methodology

The process measurement and data acquisition allows to evaluate the critical plasma variables. In the experiment presented, there are four primary variables that can assist in determining the properties of plasma: vacuum pressure, power used in generator, and the combination of current and potential readings from the triple Langmuir probe.

The pressure inside the vacuum chamber is measured using the pressure gauge, seen in Figures 5.1 and 5.2, and as far the practical experiments allow, this measurement proved to be quite sufficient to indicate the gas flow rate into the plasma generator.

The power use of the plasma generator is found by taking the readings of the potential and current supplied by the device as set by the power supply, in the case of the of the transformer it is rated to provide alternating current at 9[kV] and 0.03[A], or a power of 270[W], the power provided for the RF generator, on other hand, is supplied at 20[V] and 1[A], or 20 [W]. The voltage and current of a plasma often fluctuate, hence, the RMS values are most commonly used, because they relate to useful power from the plasma [44]. If the measurements are taken at the generator side, in term of the power used from the grid, it is possible to use digital means. However, if the readings are taken directly at the plasma, the conventional digital meters may not be reliable due to the high-frequency behaviour of the plasma. Hence the measurement of power used by the device is measured from the grid side, and compared to the power used by the coupling coil. If the voltage and current are stable, the analogue or digital instruments calibrated for DC, average, or RMS waveforms can be used [44].
On other hand, the triple Langmuir probe is slightly more detailed and involved in terms of the plasma diagnostics, as it helps to determine the electron temperature, $T_{e-}$, the current density, $J_{\text{plas}}$, and the electron density, $N_{e-}$. The circuit detail of the triple Langmuir probe is presented in Figure 5.5.

There are two variables that are measured directly using this probe: the potential [V] across a positive lead and a neutral lead (V in the Figure 5.5), and the current conducted [A] by the plasma between the positive and the negative leads (A in the Figure 5.5). The potential supplied by a steady potential source is set to 10[V] and it has shown to be sufficiently reliable to yield a maximum error of 15% in similar experiments [56][69].

In order to find the electron temperature, $T_{e-} [eV]$, the current density, $J_{\text{plas}} [A/m^2]$, and the electron density, $N_{e-} [\text{particles}]$ the formulas derived via an experiment are as follows [69]:

$$T_{e-} = \frac{V}{ln(2)} [eV] \quad (5.1)$$

$$J_{\text{plas}} = \frac{A}{Prob_A} \cdot \frac{1}{10^{-V/T_{e-}} - 1} [A/m^2] \quad (5.2)$$

Where, $Prob_A [m^2]$ is the area of plasma contact with the probe, in the experiment it was found to be 0.0002005$[m^2]$, by using the Vernier calliper and measuring an area of probe’s thermal discolouration at the end of experiments.

$$N_{e-} = \frac{|J_{\text{plas}}| \cdot 10^{(1/2)}}{q_e \cdot \sqrt{q_e \cdot T_{e-}/m_i}} [\text{particles}] \quad (5.3)$$
The voltage and current may vary from cycle to cycle in the plasma generating processes where plasma can move and be affected by the supply gas flow. When the plasma voltage and current fluctuate with time the only true measurement of these quantities can be made using an oscilloscope [44]. Hence, there are some errors encountered in the triple Langmuir probe. When the Langmuir probe is inserted into plasma, its electrically conducting surface superimposes an equipotential in the plasma region thereby forming a space charge and flow of current between the probe leads. A space charge preserves charge equilibrium in the plasma. The electrons have a much higher velocity than the ions and they strike the probe more and form a negative space charge due to the few slow-moving positive ions in the region [69]. The problem of disrupting the plasma is overcome partially by the Langmuir probe via application of a bias voltage to the probe and nullifying the current flow from the plasma, so that a floating potential $V$ is produced equal to the local potential in the undisturbed plasma [69]. Also, by making the probe diameter very much less than the principal dimensions of the plasma and the probe face, leads to minimization of the effect on the local electric field in the plasma. In the experiment the chamber pressure is maintained at 7.2[kPa], and the use of the triple Langmuir probe provides fair results that can be used for verifying computational simulations [56][69].

5.2 Experiment Results and Analysis

By following through with the experimental procedures presented, the current section will showcase, analyse and compared the results of the experiment.

5.2.1 Pressure error due to leakages

The data gathered in the process of pressure loss due to leakage is visualized in Figure 5.6.

The mean rate of pressure loss is computed to be 101.35[Pa/s], with standard deviation of 13.3[Pa/s]. Respectively, using the mean rate of pressure loss, the initial pressure of -28[inHg] (or 7180.8[Pa]), and the volume of the chamber, 1[Gal](or $3.785 \cdot 10^{-3}[m^3]$) it is possible to find the mass flow rate as a result of the leak. Assuming that air is an ideal gas it is possible to use the following equation in order to find the number of moles in the chamber at a particular pressure:

$$mol_{\text{Air}} = \frac{P_c \cdot V_c}{R_{\text{air}} \cdot T_{\text{air}}}[mol]$$  \hspace{1cm} (5.4)

Where, $P_c$ is the chamber pressure (a variable), $V_c$ is the volume of the chamber
(3.785 \cdot 10^{-3}[m^3]), R_{air} is the gas constant of air \((8.31446[m^3 \cdot Pa/(K \cdot mol)])\), and T_{air} is the ambient air temperature which was measured to be 297.15[K] at the time of experiment [68]. The average molar mass of air at the ambient temperature indicated is 28.9645 \cdot 10^{-3}[kg/mol], hence, it is possible to find the mass flow rate as a result of the average pressure leakage rate or:

\[
\dot{m} = \frac{dP_c}{dt} \cdot \frac{V_c}{R_{air} \cdot T_{air}} \cdot 28.9645 \cdot 10^{-3}[kg/mol] = 4.4373 \cdot 10^{-8} \cdot \frac{dP_c}{dt}[kg/s] \tag{5.5}
\]

Using the equation (5.5) it is then possible to be confident that the most probable leak mass flow rate is 4.4373 \cdot 10^{-5} \cdot (101.35)[kg/s] = 4.497 \cdot 10^{-6}[kg/s]. Using this value as an error that will need to be subtracted from the flow rate going into the plasma generator will help in creating an accurate representation of the model in computational simulation.

### 5.2.2 Gas flow rate into the chamber

Figure 5.7 showcases a side by side comparison of the data gathered for the pressure leak (Red: Error), and for the flow as a result of inlet valve activation (Green: Flow).

As in case of finding the mass flow rate as a result of pressure loss, the equation (5.5) can be used to find the mass flow rate for the flow inlet.
The mean pressure change as a result of flow is computed to be 470.588[Pa/s], with standard deviation of 26.5[Pa/s]. Using the mean pressure change in equation (5.5) yields $4.4373 \cdot 10^{-8} \cdot (470.588)[kg/s] = 2.088 \cdot 10^{-5}[kg/s]$. This computation includes the error as a result of the pressure leakage, hence the best approximation for the most likely mass flow rate is $2.088 \cdot 10^{-5}[kg/s] - 4.497 \cdot 10^{-6}[kg/s] = 1.638 \cdot 10^{-5}[kg/s]$. The assumption that air is an ideal gas holds, and it is possible to use the molar mass of air along with the Avogadro’s constant ($C_{Av} = 6.02214 \cdot 10^{23}[particles/mol]$ [68]), to find the rate of particle inflow into the chamber in the conditions of flow and a steady pressure of 7180.8[Pa] maintained within the chamber. Such rate without the error due to the pressure leakage is computed to be $2.47177 \cdot 10^{20}[particles/s]$; that is, the value provided is the number of particles passing through the plasma generator section.

Provided that the mass flow rate is now known it is possible to use the dimensions of the plasma generator inlet nozzle to find the flow rate into the plasma generator section. The inlet dimensions are presented in Figure 5.8, and allow to determine...
the area of the gas inflow into the generator region (green arrow indicates the inlet region).

\[ A_{in} = \pi \cdot (R_{outer}^2 - R_{inner}^2) = \pi \cdot (0.004^2 - 0.0031^2) \text{[m}^2\text{]} = 2.01 \cdot 10^{-5} \text{[m}^2\text{]} \]

Using this information along with the assumption that the density of the gas stays relatively the same at the pressure of 7180.8[Pa], as a result of constant removal of the gas by the pump and the re-supply through the flow inlet (the density of air is then approximately \( \rho_{air} = 0.0841839[\text{kg/m}^3] \)). The velocity of the gas entering the nozzle is then found using the following expression:

\[ v_{flow} = \frac{\dot{m}}{\rho_{air} \cdot A_{in}} \] (5.6)

By plugging in the according values into equation (5.6) the velocity of the flow entering into the plasma generator is computed to be most likely 9.701[m/s]; this value is the flow into the generator that already excludes the error due to the pressure loss as a result of leaks. Therefore, by the use of the experiment and relatively straight forward computations one of the essential variables in the generator has been secured.

5.2.3 Plasma Conductivity

The conductivity of plasma is one of the key aspects necessary for creating the plasma simulation in Elmer, hence and experiment has been conducted to find it. The current readings for an arc discharge of plasma between two electrodes at 9[kV] and at a separating distance of 0.0125[m] have been collected and are presented in Figure 5.9.

Although, the rating of the transformer is set to provide 0.3[A] of RMS current, it is evident from the data that the mean current provided into the plasma is only
0.152[A] RMS, with the standard deviation of 0.085[A]. In this case, the computation of the RMS resistance of plasma in the provided vacuum conditions is simply:

$$R_{\text{plas}} = \frac{(V_{\text{transformer}}) / \sqrt{2}}{I_{\text{plas}}}[\Omega] = \frac{9000 / \sqrt{2}}{0.152[A]}[\Omega] = 4.16 \cdot 10^4[\Omega]$$  \hspace{1cm} (5.7)

The respective conductivity needed by Elmer for performing simulations is computed as follows [58]:

$$C_{\text{plas}} = \frac{l_{\text{electrodes}}}{R_{\text{plas}}}[m/\Omega] = \frac{0.0125}{4.16 \cdot 10^4}[m/\Omega] = 3.005 \cdot 10^{-7}[m/\Omega]$$  \hspace{1cm} (5.8)

Knowing the conductivity of the plasma through the experiment helps particularly to observe the effects of Ohmic heating in plasma during the simulation, hence this variable will become useful in the next chapter.
5.2.4 Data for the direct discharge, single emitter, and RF assisted single emitter configurations

In this section the properties of four different plasma generation technologies are going to be investigated. First, the results of the experiments are going to be compared using the hypothesis testing to find if the data gathered is actually different in each case. Then the plasma properties such as the electron temperature, $T_e$, the current density, $J_{\text{plas}}$, and the electron density, $N_e$, will be found as per procedures in section 5.1.3.

![Figure 5.10: Comparison of the potential readings for indicated configurations.](image)

The number of sample points for all experiments exceed 30 so the samples can be assumed to be normally distributed. Therefore a test statistic of the following form can be used.
\[
 z = \frac{x_2 - x_1}{\sqrt{\left(\frac{s_2^2}{n_2}\right) + \left(\frac{s_1^2}{n_1}\right)}}
\]  
(5.9)

Where, \( x_1 \) and \( x_2 \) are the mean values for the two different samples, \( s_1 \) and \( s_2 \) are the sample deviations for those samples, and \( n_1 \) and \( n_2 \) are the number of sample point in each of the sample population. For the confidence of 99.9\% (0.1\% level of significance) the value of \( z \) is 3.275 \( (z_{0.0005} = 3.275) \), and for the confidence of 99\% (1\% level of significance), \( z_{0.005} = 2.575 \). Hence, the sample points are going to be compared with respect to one another on the 99\% confidence interval, if 99.9\% confidence interval indicates that there is no difference between the samples.

Figure 5.11: Comparison of the current readings for indicated configurations.

Figures 5.11 and 5.12 show the respective samples for the voltages and currents measured by the triple Langmuir probe in the different plasma generation modes. These modes are distinguished by the indication arrows: Red (Direct Discharge),
Yellow (Single Emitter(SE)), Green (11[MHz] assisted SE), and Blue (7[MHz] assisted SE). The sample point data are presented for the means, the standard deviations, and the number of sample points for the four different plasma generation modes in tables 5.1 and 5.2.

Table 5.1: The statistical data for the voltage measurements from the triple Langmuir probe in the four modes of plasma generation

<table>
<thead>
<tr>
<th>Plasma Generation Mode</th>
<th>$\bar{x}[V]$</th>
<th>$s$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Discharge</td>
<td>0.02970</td>
<td>0.00441</td>
<td>52</td>
</tr>
<tr>
<td>Single Emitter</td>
<td>0.08566</td>
<td>0.02224</td>
<td>35</td>
</tr>
<tr>
<td>11[MHz] assisted SE</td>
<td>0.10072</td>
<td>0.00093</td>
<td>36</td>
</tr>
<tr>
<td>7[MHz] assisted SE</td>
<td>0.21102</td>
<td>0.00943</td>
<td>46</td>
</tr>
</tbody>
</table>

Table 5.2: The statistical data for the current measurements from the triple Langmuir probe in the four modes of plasma generation

<table>
<thead>
<tr>
<th>Plasma Generation Mode</th>
<th>$\bar{x}[A]$</th>
<th>$s$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Discharge</td>
<td>0.33721</td>
<td>0.17778</td>
<td>36</td>
</tr>
<tr>
<td>Single Emitter</td>
<td>0.60076</td>
<td>0.20575</td>
<td>35</td>
</tr>
<tr>
<td>11[MHz] assisted SE</td>
<td>0.84941</td>
<td>0.02001</td>
<td>36</td>
</tr>
<tr>
<td>7[MHz] assisted SE</td>
<td>2.39819</td>
<td>0.04398</td>
<td>44</td>
</tr>
</tbody>
</table>

Based on the data available in these tables it is then possible to conduct the hypotheses tests with respect to whether or not the modes are different; that is, the null hypothesis assumes that the differences are non-existent ($\bar{x}_2 - \bar{x}_1 = 0$) and the test hypothesis assumes that the differences exist ($\bar{x}_1 - \bar{x}_2 \neq 0$). The outcomes of these test statistics in terms of $z$ are presented for the voltages and the currents in tables 5.3 and 5.4 respectively, on a side by side comparison between each individual mode of plasma generation.

Evidently, all the modes of plasma generation are different from each other with a 99.9% confidence. Knowing this it is then possible to move forward with determining the key plasma properties without doubting that the results would somehow overlap. The electron temperature, $T_{e-}$, the current density, $J_{\text{plas}}$, and the electron density, $N_{e-}$, for the four different modes of plasma generation are presented in table 5.5, based on the mean values from the experiment and formulas (5.1), (5.2), and (5.3).
Table 5.3: The test statistics for the voltage measurements from the triple Langmuir between the plasma generation modes

<table>
<thead>
<tr>
<th>Plasma Generation Modes</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD vs. SE</td>
<td>14.693</td>
</tr>
<tr>
<td>SE vs. 11[MHz]</td>
<td>4.003</td>
</tr>
<tr>
<td>11[MHz] vs. 7[MHz]</td>
<td>78.843</td>
</tr>
</tbody>
</table>

Table 5.4: The test statistics for the current measurements from the triple Langmuir between the plasma generation modes

<table>
<thead>
<tr>
<th>Plasma Generation Modes</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD vs. SE</td>
<td>5.768</td>
</tr>
<tr>
<td>SE vs. 11[MHz]</td>
<td>7.117</td>
</tr>
<tr>
<td>11[MHz] vs. 7[MHz]</td>
<td>208.681</td>
</tr>
</tbody>
</table>

Table 5.5: The plasma properties in the four modes of generation

<table>
<thead>
<tr>
<th>Plasma Generation Mode</th>
<th>$T_e$ [eV]</th>
<th>$J_{\text{plas}} [A/m^2]$</th>
<th>$N_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Discharge</td>
<td>0.04285</td>
<td>2109.4</td>
<td>1.093 $\cdot 10^{20}$</td>
</tr>
<tr>
<td>Single Emitter</td>
<td>0.12358</td>
<td>3758.1</td>
<td>1.147 $\cdot 10^{20}$</td>
</tr>
<tr>
<td>11[MHz] assisted SE</td>
<td>0.14531</td>
<td>5313.5</td>
<td>1.496 $\cdot 10^{20}$</td>
</tr>
<tr>
<td>7[MHz] assisted SE</td>
<td>0.30444</td>
<td>15002</td>
<td>2.917 $\cdot 10^{20}$</td>
</tr>
</tbody>
</table>

Evidently, the plasma generation processes differ significantly. There is an apparent distinction between the direct discharge mode and the modes involving the single emitter configuration. However, the most notable feature is the performance of the plasma generator with RF assistance does indeed generate higher electron temperature, current density, and boosts the electron density.

Based on the limitations of the triple Langmuir probe and the visual observations, the interest of focus is how these details can assist in pinning down the process behind the plasma generation mode via the RF assisted single emitter configuration. It is known that an approximate distance between the emitter and the center of the triple Langmuir probe is 26.5[mm]. Via the visual observations a cylindrical shape approximation could be applied to the plasma body, with the radius closely matching the radius of the glass tube insulator ($R_{\text{glass} - \text{in}} = 0.002[m]$). Using these dimensions,
the plasma property values in table 5.5, and some of the equations from section 4.1, the next two chapters are going to pursue the answer as to why the 7[MHz] signal is able to sustain better plasma conditions than the 11[MHz] signal.
Chapter 6

Simulation and Modelling

This chapter is composed of six sections where in the simulation and modelling approach is presented first, and thereafter the sections deal with case studies for the plasma generation. Section 6.2 present the simulation of fluid behaviour without any plasma. Section 6.3 deals with plasma modelling for the direct discharge configuration. Section 6.4 provides an approach to a single emitter configuration and section 6.5 elaborates further on the means of RF assisted device. Lastly, section 6.6 presents models for the electrical circuits involved in the plasma generation process.

The theoretical models of the plasma generators, and the experiments conducted in the previous chapter come together to be used in a virtual environment provided by Elmer FEM. The theory and the experiment will be put to use to tune the virtual model for the use in creating a plasma generator design that can be used in a range of industrial and academic applications. The multi-physics simulation models will include the fluid behaviour, the direct discharge, the single emitter, and the RF assisted single emitter plasma generation modes. Also, the electrical system modelling by the use of PSIM will be conducted.

6.1 Simulation and Modelling Approach

The modelling of the plasma generation process is done via the use of Elmer FEM and PSIM. Plasma behaviour is modelled in Elmer FEM, and the power circuit for the plasma generator is simulated using PSIM. The use of PSIM for the simulation is relatively straightforward as long as the foundations of the power circuit modelling are understood; the components can be arranged in specific manner to gain an intuitive insight on the signal behaviour in the circuit. On other hand, the use of Elmer FEM is quite involved as it requires understanding of the plasma physics and the property interactions of between the plasma and the multi-physics boundaries. First of all, the
finite element method (FEM) discretization is based on a piecewise representation of the solution in terms of the basis functions. The computational domain of the body of interest is divided up into smaller, finite element, domains and the solution in each element is constructed from the basis functions. The equations to be solved are obtained by restating the conservation equation in a weak form: the field variables are written in terms of the basis functions, the equation is multiplied by relevant test functions, and then integrated over an element [67]. Since the FEM solution is in terms of specific basis functions, a great deal more is known about the solution than for the Finite Volume Method (FVM). This can be questionable, as the choice of basis functions is critical, and the boundary conditions may be more difficult to formulate. A system of equations is obtained (usually for nodal values) that must be solved to obtain a solution [67].

The comparison of the FEM to FVM is difficult due to the many variations of these methods. A finite volume method (FVM) discretization is based upon an integral form of the partial differential equations (PDEs) to be solved (e.g. conservation of mass, momentum, or energy) [67]. The PDE is written in a form that can be solved for a finite volume unit (or cell). The computational domain of the body of interest is discretized into finite volumes and then for every volume the governing equations are solved. The resulting system of equations usually involves fluxes of the conserved variable, and thus the calculation of fluxes is very important in FVM. The FVM does not require the use of structured grids, and the effort to convert a particular mesh into a structured numerical grid is completely avoided. The resulting approximate solution is a discrete, and the variables are typically placed at cell centres of the volumes rather than at the nodal points, as in FEM [67]. The values of the field variables at non-storage locations (e.g. vertices) are obtained using interpolation [67].

In order to model the plasma gas supply source it is necessary to consider the compressibility of gases entering the plasma chamber, the boundary layers that would occur near the chamber walls, and the ionization energies of the gases, and the behaviour under turbulent conditions. The gas supply has to provide a controlled amount of substance to sustain plasma without extinguishing it, and, at the same time, it has to keep the generator chamber walls cool. The thermodynamics and fluid dynamics play a large role due to the flow modes that may occur, in case the plasma generator creates supersonic flows. As for any other element of the plasma generator, it is essential to account for variables involved in the design that will be optimized based on a non-dimensional model. In the cases of the gas supply source and the inlet manifold the primary design concerns are about the thermodynamics and fluid dynamics of the chamber rather than the effects of the plasma. The use of Elmer is suitable
for tackling these concerns without involving complex multi-physics models though it will also be crucial to consider the effects of heat transfer and possible back-flows that pose a danger of affecting the plasma generator structurally as well as impeding the flow and de-stabilizing the plasma generation regime. In order to direct a plasma stream away from the generation region it is necessary to implement a nozzle that will release the plasma into the environment and act as a wave-guide to focus the plasma in the area of key activity. The modelling of the plasma exiting the generation and confinement region will be based on the methods outlined in the previous subsections, though the particular focus on fluid behaviour will determine the effectiveness of the acting nozzle. Furthermore, it will be necessary to keep in mind how to keep the nozzle cool, to avoid excessive explosive shocks.

The plasma initiation region is created via the high-field electron emission. The process of ionization occurs due to the stripping of electrons from the atoms of working gas, thereby creating a focused region of charged particles, which acts as a virtual cathode capable of receiving electro-magnetic energy. This region can be shifted depending on the requirements for plasma generation and confinement. The modelling methodology of the ionizing configuration is intrinsically complex and deals with matters bordering quantum mechanics. It is possible to model the interaction with working gases and plasma by the use of the FEM. The primary induction coupling coil deals with the coupling of electrical energy to plasma and feeding a powerful RF signal into the focus area of gas ionized region. The coupling of the induction coil to the plasma region is intended to produce high temperatures of the plasma region. By and large, the efficiency of the plasma generator device will primarily depend on the combined performance of the high-field emitter and coupling induction coil configuration. The RF magnetic confinement coils will act as the electro-magnets behaving in magnetic bucket manner, which are expected to enhance the uniformity of plasma distribution, as well as increase the plasma density in the plasma generation region. Though, the main focus is on the confinement of the plasma in a location that will not cause the damage to other component of the plasma generator. This component is similar in terms to the primary coupling, however the collisional effects and the particle retention will be of the main interest.
6.2 Fluid Simulation

The first model performed in Elmer FEM is a fluid simulation of the work gas (Air) entering into the vacuum chamber. As has been found in the experiment section, 5.3.2, the speed of the gas entering into the chamber is 9.701[m/s]. The model has only an inlet, an outlet, and the boundaries which act as non-slip surfaces. Since, the flow velocity at the non-slip surfaces is zero there is a formation of a boundary layer, which affects the heat dynamics in the plasma generation process, as does the actual flow. In order to see the effects of the flow and the heat transfer in a configuration where no plasma is generated, a computational fluid dynamics (CFD) model is set with boundary conditions (no-slip flow) and initial conditions (inlets and outlets) and tested on the three different meshes that have the following surface resolutions in the zones of interest (the electrode and the glass confinement): 0.25[mm], 0.1[mm], and 0.05[mm] (Solver Input Files (SIFs) for Elmer can be provided upon a request). The reasons for choosing these resolutions of the meshes have to do with the boundary layer thickness. By running the CFD simulations with of these meshes it will be necessary to compare the results and profiles so that the future simulations could be run, preferably, with a mesh that is small enough to yield good results, and big enough to be handled by a desktop computer.

The side by side comparison of the meshes is shown in Figure 6.1. The results for the flow and temperature profiles in the cross-cut sections for the three different types of meshes are presented in the figures below.

By observing the computational results of a CFD simulation performed by Elmer FEM it is possible to conclude if the choice of mesh resolution is 0.1[mm] then it should be sufficient for modelling the flows encountered in the experiment. Also, the results for the temperature profiles in a cross section are presented in Figures 6.5 for
Figure 6.2: Flow profile cross-cut section of the velocity layers for a 0.25mm resolution mesh.

Figure 6.3: Flow profile cross-cut section of the velocity layers for a 0.1mm resolution mesh.

Figure 6.4: Flow profile cross-cut section of the velocity layers for a 0.05mm resolution mesh.

the 0.25[mm] resolution mesh, 6.6 for the 0.1[mm], and Figure 6.6 for the 0.05[mm] mesh. These temperature profiles make it quite evident that the effect of convective cooling occurs when the flow passes over the electrode configuration. Provided that now the flow and thermal effects are found for the gas entering the plasma chamber it
is now possible to proceed into the simulation stage for the plasma generation modes in Elmer FEM.
6.3 Direct Discharge Modelling

The modelling of the direct discharge plasma generation uses the data gathered in the experiment, sections 5.3.3 and 5.3.4, and applies them to the multi-physics computations performed by Elmer FEM. Firstly, it has been found that an approximate plasma conductivity for a direct discharge configuration is $3.005 \times 10^{-7}[m/Ω]$, and the associated current is $0.152[A]$. Also, the limits of the electron temperature, $T_{e-}$, the current density, $J_{plas}$, and the electron density, $N_{e-}$, are known for the experiment. By calibrating the simulation parameters it is expected that the computational results would be somewhere within these limits. For the sake of modelling with available computing power, it was assumed that the plasma is quasi-neutral, and that the resistive modelling of plasma is applicable.

However, there was one key inconsistency encountered during the simulation tuning of Elmer, and it was the conductivity of plasma. The value obtained by the experiment was deemed different from the conductivity in Elmer, $C_{plas}$, computed by dividing the emission current by the potential applied, or:

$$\sigma_{plas} = \frac{0.152[A]}{9000[V]} = 1.689 \times 10^{-5}[S]$$

When this value is used there is a reasonable response in Elmer that is sufficiently consistent with the experimental results. If the experimental conductivity value is to be used then it needs to be computed as:

$$\sigma_{plasExp} = \frac{1}{R_{plas}} = \frac{1}{4.16 \times 10^4[Ω]} = 2.404 \times 10^{-5}[S]$$

In the simulation of the direct discharge plasma generator it is essential to consider both of these cases in order to validate the simulation with respect to the experimental data. Hence, the process of deriving simulation critical variables, and the corresponding simulation results will be presented in this section.

First, some of the necessary simulation variables that need to be highlighted include the current in the generator ($I = 0.152[A]$), the potential ($V = 9000[V]$), the reference pressure ($P_{ref} = 7180.8[Pa] = 53.8604[Torr]$), and the RMS mass transfer coefficient between the electrons and ions ($(m_{e-}/m_i)/(\sqrt{2}) = 1.36094 \times 10^{-5}$). Based on the current and the potential it is possible to attain an approximate ion-electron generation rate, using the data from table 4.2 ($\eta_{opt-Air} = 81[eV/ion - e^- pair]$) and the following relation [51]:

$$\dot{N}_{i-e^-} = \frac{I \cdot V}{\eta_{opt-Air} \cdot q} = \frac{0.152 \cdot 9000}{81 \cdot 1.602 \cdot 10^{-19}}[i - e^-/s] = 1.054 \cdot 10^{20}[i - e^-/s]$$
In ElmerFEM, the concentration at the boundary is expressed as a ratio to the number of available neutral particles. In the current case, the rate of neutral particles entering the chamber corresponds to the flow rate found in section 5.3.2, or \(2.47177 \cdot 10^{20}\) [ptcls/s]. The ratio of these rates yields a value that is interpreted by Elmer for computing the ion behaviours in the plasma, \(C_i = 1.054 \cdot 10^{20}[i - e^-/s]/2.47177 \cdot 10^{20}[ptcls/s] = 0.426415[i - e^-/ptcl]\). The concentration flux is the other parameter necessary to compute the plasma behaviour, it is approximated at the emitter to roughly correspond the number of ions passing through the area confined by the glass (ceramic) chamber \((\text{Flux} - \text{Area} = \pi \cdot 0.0022[^2m] = 1.2566 \cdot 10^{-5}[^2m])\). The equation for concentration flux states:

\[
\frac{\dot{M}_i}{\text{Flux} - \text{Area}} = \frac{\dot{N}_{i-e^-} \cdot m_i}{\text{Flux} - \text{Area}}
\]

For the direct discharge mode, the concentration flux is 0.3971\([kg/m^2]\). Furthermore, other verification parameters that need to be included are the expected plasma temperature based on the ion concentration, as well as the current density reading range and the expected Joule heating parameter for ElmerFEM based on the computed and the experimental conductivities. The expected plasma temperature can be estimated using the relation (4.18) and CAAS, and it is found to be 23365[K] or 2.014[eV]. Evidently, this temperature far exceeds the temperature obtained via the experiment. However, this value showcases an upper limit to the ideal plasma state, provided that the species have indeed ionized fully in correspondence to relation (4.18). The discrepancy between this ideal value and the experiment only indicates that in the direct discharge configuration the ionization process was not efficient enough to reach the ideal state. Regardless, the discussion of the simulation results and how they compare to the experiment will be dowelled on in the next chapter. The computation of the expected current density reading range and the expected Joule heating parameter are based on the ElmerFEM models manual [58]:

\[
\overrightarrow{J_{\text{Elmer}}} = \frac{I}{\text{Arc - Length}}
\]

\[
h_{\Omega} = \frac{\overrightarrow{J_{\text{Elmer}}} \cdot \overrightarrow{J_{\text{Elmer}}}}{\sigma_{\text{plas}}}
\]

Respectively then, for the computed and the experimental plasma conductivities the expected current density reading range and the expected Joule heating parameter are computed and presented in table below.
Table 6.1: The expected current density readings and the Joule heating parameters for the computed and the experimentally derived plasma conductivities

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Computed</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity [S]</td>
<td>$1.689 \cdot 10^{-5}$</td>
<td>$2.404 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>Current Density [A/m]</td>
<td>12.16</td>
<td>12.16</td>
</tr>
<tr>
<td>Maximum Joule Heating [W/m]</td>
<td>$8.755 \cdot 10^{6}$</td>
<td>$6.151 \cdot 10^{6}$</td>
</tr>
</tbody>
</table>

Using the properties derived in Table 6.1 it is then possible to evaluate the legitimacy of the ElmerFEM simulation and verify how reasonable the simulation is with respect to the experiment. All things considered, the Joule heating parameter would have to roughly correspond to $9000[V] \cdot 0.152[A]/0.0125[m] = 109440[W/m]$. However, the specific mode of computation done by ElmerFEM necessitates that the maximum possible value be actually computed as $8.755 \cdot 10^{6}[W/m]$. Hence, it becomes evident by the experimental data that the actual heating efficiency is approximately $\eta_\Omega = (6.151 \cdot 10^{6})/(8.755 \cdot 10^{6}) = 70.257\%$. Although, the plasma conductivity is made available by the experiment for the direct discharge configuration, the attainment of this parameter for the single emitter condition is made significantly easier by approximating the conductivity based on the potential available at the emitter and the emission current.

The outcomes of the plasma simulation results for the direct discharge configuration as well as the results for other modes of plasma generation are all made available in the Appendix.

6.4 Single Emitter Modelling

As in case of the direct discharge model similar assumptions apply in the single emitter configuration. The electron emission rate (current) can be found using equation (4.15), the Stoletov constants from table 4.2, and the velocity near the emitter.

6.4.1 Single Emitter Current

If the tungsten cathode has a radius of $r_{Emitter} = 0.0012[m]$ and it is subjected to the potential of $V_{unipolar} = 9000[V]$, then $E_{unipolar} = 2.598 \cdot 10^{6}[V/m]$. The pressure in the chamber is still $7180.8[Pa] = 53.8604[Torr]$ and is assumed to be unchanging. The working gas is Air, moving with a velocity of roughly $v_a =$
19.9\,[m/s] \text{ near the zone of emission (as per fluid simulations), with the average ion mass of } m_{i,\text{Air}} \approx 4.733 \cdot 10^{-26}[kg], \text{ and the mean free path attained from table 4.2 is } \lambda_i \approx 1/(449 \cdot 53.8604)[m/ion \text{ pair}] = 4.135 \cdot 10^{-5}[m/ion \text{ pair}]. \text{ Using equation (4.15):}

\[
I_{\text{emission}} = -16 \cdot \sqrt{2} \cdot r_{\text{emitter}} \cdot \left( \frac{q}{m_i} \cdot \frac{\lambda_i}{v_a} \right) \cdot \varepsilon_0 \cdot (E_{\text{unipolar}})^2[A]
\]

The current produced under such conditions will then be \( I_{\text{emission}} = 0.1141[A]. \) Based on the potential and the current, the power associated with the plasma sustenance is \( 0.1141[A] \cdot 9000[V] = 1027.233[W]. \) This power for sustaining electron emission allows to find the approximate number of electron-ion pairs generated per second based on the value provided for the minimum ionization cost in table 4.2

\[
\dot{N}_{\text{ion-e}} = (1027.233[W])/(81[eV/ion \text{ e-pair}] \cdot (1.602 \cdot 10^{-19}[J/eV])) = 7.9163 \cdot 10^{19}[\text{ion-e/s}].
\]

As in the case of the direct discharge modelling it is necessary to get bearings on the expected properties of plasma for validating the Elmer model. Hence, table 6.2 lists the parameters for the ion-neutral concentration ratio, the ion concentration flux, plasma conductivity, current density, and the Joule Heating. Ion flux at emitter is computed for the area of \( 4.5239 \cdot 10^{-6}[m^2], \) and the ion flux at exhaust area of \( 0.001257[m^2], \) which correspond to the dimensions of the computer model respectively.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion-Neutral Concentration Ratio ,[ions/neutrals]</td>
<td>0.3203</td>
</tr>
<tr>
<td>Ion Flux at Emitter ,[kg/m^2]</td>
<td>0.2986</td>
</tr>
<tr>
<td>Ion Flux at Exhaust ,[kg/m^2]</td>
<td>0.00298</td>
</tr>
<tr>
<td>Conductivity ,[S]</td>
<td>1.2682 \cdot 10^{-5}</td>
</tr>
<tr>
<td>Current Density ,[A/m]</td>
<td>6.917</td>
</tr>
<tr>
<td>Joule Heating ,[W/m]</td>
<td>3.773 \cdot 10^6</td>
</tr>
</tbody>
</table>

Knowing the rate of ion production and the rate of neutral flow, \( 2.47177 \cdot 10^{20}[\text{ptcls/s}], \) it is then possible to find the approximate the plasma temperature using relation (4.18) and CAAS, which yields \( 21659[K] \) or \( 1.867[eV]. \) Knowing this, it is then possible to find the RMS speeds of the ions and electrons using expressions (4.22) and (4.23).
6.4.2 Ion and Electron RMS speeds

The ion RMS speed is found to be:

\[ v_i = \sqrt{\frac{(3 \cdot k_B \cdot 21659[K])}{(4.733 \cdot 10^{-26}[kg/ptcl])}} = 4353.57[m/s] \]

The RMS speed of electrons is:

\[ v_e^- = \sqrt{\frac{3 \cdot k_B \cdot 21659[K]}{9.1094 \cdot 10^{-31}[kg/e^-]}} = 992359.14[m/s] \]

The concentration of ions and electrons in the plasma are used to find the resonance frequencies using expressions (4.25) and (4.26) respectively, as well as the electron and ion collision frequencies using (4.40). It will also be necessary to find the emission wavelengths (as per equations (4.27) to (4.30)), the conductivity of plasma (4.42), energy transfer frequency for un-magnetized plasma (4.44), and the total power absorbed per unit volume of plasma (4.46).

6.4.3 Ion and Electron Resonance Frequencies

Ion resonance frequency:

\[ f_{ion} = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{(7.9163 \cdot 10^{19}[ptcls]) \cdot (1.602 \cdot 10^{-19}[C])^2}{(4.733 \cdot 10^{-26}[kg/ptcl]) \cdot (8.8542 \cdot 10^{-12}[F/m])}} = 350.43[MHz] \]

Electron resonance frequency:

\[ f_e^- = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{(7.9163 \cdot 10^{19}[e^-]) \cdot (1.602 \cdot 10^{-19}[C])^2}{(9.1094 \cdot 10^{-31}[kg]) \cdot (8.8542 \cdot 10^{-12}[F/m])}} = 79.877[GHz] \]
6.4.4 Electron MFP

Assuming that Air is the working gas, that electron temperature is \(21659[K]\) and the operating pressure is \(7180.8[Pa]\) then the mean free path for the electron can be found as

\[
\lambda_{e_{\text{mfp}}} = \frac{4 \cdot 1.3806 \cdot 10^{-23}[J/K] \cdot 21659[K]}{\pi \cdot (0.11 \cdot 10^{-9}[m])^2 \cdot 7180.8[Pa]} = 0.004382[m/e^-]
\]

6.4.5 Ion and Electron Collision Frequencies

Provided the RMS velocity of the ions is assumed to be \(4353.57[m/s]\) and the ion mean free path is \(4.135 \cdot 10^{-5}[m/ion]\) then the average collision frequency is

\[
\nu_{ci} = \frac{4353.57[m/s]}{4.135 \cdot 10^{-5}[m/ion]} = 105.286[MHz]
\]

The RMS velocity of the electrons is assumed to be \(992359.14[m/s]\) and the mean free path is \(0.004382[m/e^-]\) then the average collision frequency is

\[
\nu_{ce^-} = \frac{992359.14[m/s]}{0.004382[m/e^-]} = 226.463[MHz]
\]

6.4.6 Plasma Emission Wavelengths

Taking the case from before and using it to find the electron and ion wavelengths, as well as the ion and electron concentration region distances from the emitter:

\[
\lambda_{\text{ion}} = (3 \cdot 10^8[m/s])/(350.43 \cdot 10^6[Hz]) = 0.8561[m]
\]

\[
d_{\text{ion}} = \lambda_{\text{ion}}/4 = 0.214[m]
\]

\[
\lambda_{e^-} = (3 \cdot 10^8[m/s])/(79.877 \cdot 10^9[Hz]) = 0.003756[m]
\]

\[
d_{e^-} = \lambda_{e^-}/4 = 0.000939[m]
\]
6.4.7 Plasma Conductivity

The conductivity of plasma based on electron availability is:

\[
\sigma_0 = \frac{q^2 \cdot N_e^-}{m_e \cdot \nu_{ce}^-}[S/m] = \frac{q^2 \cdot 7.9163 \cdot 10^{19}}{m_e \cdot 2.26463 \cdot 10^8}[S/m] = 9848.258[S/m]
\]

On other hand, the conductivity of plasma based on ion availability is:

\[
\sigma_0 = \frac{q^2 \cdot N_i^+}{m_i \cdot \nu_{ci}^+}[S/m] = \frac{q^2 \cdot 7.9163 \cdot 10^{19}}{m_i \cdot 1.05286 \cdot 10^8}[S/m] = 0.4077[S/m]
\]

6.4.8 Energy Transfer Frequency for Un-magnetized Plasma

The energy transfer frequency for electron component of the plasma is:

\[
\nu_{0e^-} = \frac{2 \cdot \omega_{pe}^2}{\nu_{ce}^-} = \frac{2 \cdot (79.877 \cdot 10^8[Hz])^2}{2.26463 \cdot 10^8[Hz]} = 56.348[THz]
\]

The energy transfer frequency for ion component of the plasma is:

\[
\nu_{0i^+} = \frac{2 \cdot \omega_{pi}^2}{\nu_i} = \frac{2 \cdot (3.5043 \cdot 10^8[Hz])^2}{1.05286 \cdot 10^8[Hz]} = 2.333[GHz]
\]

6.4.9 Total Power Absorbed per Plasma Unit Volume

If the collective plasma effects of shielding against an externally imposed electric field are ignored [51], then the total power absorbed per unit electron filled volume of plasma from the applied electric field can be computed to be:

\[
u_{0e^-} = \frac{E_{anipolar}^2 \cdot N_e^- \cdot q^2}{\nu_{ce}^- \cdot m_e^-} \cdot \nu_{0e^-}[W/m^3]
\]

\[
u_{0e^-} = \frac{(2.5980762 \cdot 10^5)^2 \cdot (7.9163 \cdot 10^{19}) \cdot q^2}{(2.26463 \cdot 10^8) \cdot m_e^-} \cdot (5.6348 \cdot 10^{13})[W/m^3] = 3.746 \cdot 10^{28}[W/m^3]
\]

For an ion filled unit volume the computed value of total power absorbed is:

\[
u_{0i^+} = \frac{E_{anipolar}^2 \cdot N_i^+ \cdot q^2}{\nu_{ci}^- \cdot m_i^-} \cdot \nu_{0i^+}[W/m^3]
\]
Based on these calculations it becomes evident that the contribution of total power absorbed by the ions with respect to the electrons is practically unnoticeable. Hence, the value $3.7458 \cdot 10^{28} [W/m^3]$ is used to find the volume of influence provided the maximum power fed into the region of plasma is computed as $P_E = V \cdot I = 9000[V] \cdot 0.114137[A] = 1027.233[W]$. Therefore, the volume of influence by the emission process is found to be $V_{influence} = 2.742 \cdot 10^{-26}[m^3]$, this will be useful when dealing with the RF assisted mode for the single emitter configuration.

Lastly, the emission efficiency can be computed using expression (4.32).

### 6.4.10 Emission Efficiency

The expected power absorbed due to ionization:

$$P_{absorbed} = T_i \cdot q \cdot \dot{N}_i$$

$$P_{absorbed} = 1.867[eV] \cdot 1.602/(10^{19})[J/eV] \cdot 7.9163 \cdot 10^{19}[i-e^- pairs/s] = 23.677[W]$$

$$\eta = \frac{P_i(\text{absorbed})}{P_E} = \frac{23.677}{1027.233[W]} = 2.3\%$$

Hence, with all the above data it would then be possible to tune the plasma simulation in Elmer for single emitter configuration, as well as get a start on the RF assisted mode. Also, the indication that for the particular configuration of the emitter geometry provides an opportunity in a design of miniature emitter array that would boost the performance of the single emitter configuration.

### 6.5 RF Assisted Single Emitter Modelling

Based on the findings for the single emitter configuration it is possible to progress into the RF coupling and confinement analysis. The properties found in the previous
section can help in seeing the effects of the electromagnetic waves interaction with plasma. The use of expressions for the incident magnetic field strength (4.36), the magnetic field energy density in a steady state (4.48), and the plasma electron gyro-resonance frequency (4.35) will help to narrow the search for the available plasma frequencies.

6.5.1 Plasma electron gyro-resonance frequency

The incident magnetic field strength at maximum amplitude, with the 8 turn coil of length 0.021[m], and an input current of 1[A]:

\[
B = \mu_0 \cdot \frac{N_{\text{coil}}}{l_{\text{coil}}} \cdot I = 4 \cdot \pi \cdot 10^{-7}[T \cdot m/A] \cdot 8/0.021[m] \cdot 1[A] = 0.00479[T]
\]

The magnetic field energy density in steady state is:

\[
U_{B_{\text{RMS}}} = \frac{B^2}{2 \cdot \mu_0} = 0.0913[J/m^3]
\]

Then the plasma electron gyro-resonance frequency is:

\[
\nu_{c-e} = 2.7992 \cdot 10^{10} \cdot B[Hz] = 13.4003[MHz]
\]

It is worthwhile noting that the gyro-resonance frequency seems to closely correspond to the second harmonic of a 7[MHz] RF signal. Considering that the signal in the experiment was showcasing harmonic behaviour and was slightly varying around the 7[MHz] signal, it is likely that the main culprit of the results attained in the experiment is the fact that the RF frequency of the second harmonic was closely matching with the plasm gyro-resonance frequency. Hence, it is worthwhile to take the plasma gyro-resonance frequency into account in the following computations.

Since, the dimensions of the plasma are known based on experiments, then the additional properties such as the critical number density (4.34), and the skin depth of plasma (4.47), will be able to help in finding the power provided by the incident oscillating magnetic field (4.49), and the RMS ohmic heating power (4.50).
### 6.5.2 Plasma Skin Depth and Critical Number Density

The critical number density can be found for the incident EM radiation frequency by:

\[ N_{\text{crit}} = 1.2407 \cdot 10^{-2} \cdot \nu_0^2 \left[ e^-/m^3 \right] \]

The plasma skin depth is found by the following expression:

\[ \delta_{\text{skin}} = 7.516 \cdot 10^6 \cdot \sqrt{\frac{\nu_0}{N_e \cdot \omega_{pe}}} \left[ m \right] \]

The plasma skin depths and the critical number densities for 7[MHz], 11[MHz], and 13.4[MHz], are presented below.

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>N_{\text{crit}} [ptcls/m^3]</th>
<th>Skin Depth [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>6.0794 \cdot 10^{11}</td>
<td>7.9079</td>
</tr>
<tr>
<td>11</td>
<td>1.5012 \cdot 10^{12}</td>
<td>9.9131</td>
</tr>
<tr>
<td>13.4</td>
<td>2.2278 \cdot 10^{12}</td>
<td>10.9413</td>
</tr>
</tbody>
</table>

The electron density created as a result of the single emitter operation far exceeds the critical number densities computed. This means that the frequencies indicated, will strongly interact with the collective body of plasma.

### 6.5.3 Incident oscillating magnetic field power and RMS ohmic heating

The magnetic power provided by the incident oscillating magnetic field is:

\[ P_{B\text{rms}} = \frac{u_{B\text{rms}} \cdot \nu_0 \cdot V_{\text{influence}}}{\sqrt{2}} \left[ W \right] \]

The RMS heating power provided by the incident oscillating magnetic field is:

\[ P_{\Omega\text{rms}} = (N_1 \cdot I_1)^2 \cdot \left( \frac{2 \cdot \pi \cdot (a - \delta/2)}{\sigma \cdot l_{\text{plas}} \cdot \delta} \right) / \sqrt{2} \left[ W \right] \]

The incident magnetic power and the RMS heating power for 7[MHz], 11[MHz], and 13.4[MHz] is presented below, considering that the length of influence by the magnetic field is roughly equivalent to the length of the magnetic coil (0.021[m]).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1.239 \cdot 10^{-20}</td>
<td>0.6874</td>
</tr>
<tr>
<td>11</td>
<td>1.947 \cdot 10^{-20}</td>
<td>0.6874</td>
</tr>
<tr>
<td>13.4</td>
<td>2.372 \cdot 10^{-20}</td>
<td>0.6874</td>
</tr>
</tbody>
</table>
The RMS heating power is roughly the same for all the RF frequencies (the differences are quite small on a comparison), however, the incident magnetic field power is substantially different which leads further confirm the effect of the plasma gyro-resonance frequency on the matter of boosting the plasma generator performance. Furthermore, based on the fact that due to the RF source there is an induced magnetic field in the volume of plasma, then based on the number of induction coils it is possible to roughly derive the number of the newly ionized species in the plasma as well as the temperature of such plasma.

### 6.5.4 RF assisted generation current, ion density, and plasma temperature

The induced RMS current in plasma can be found by:

\[ I_{RMS} = \frac{N_1 \cdot I_1}{\sqrt{2}} [A] = 5.657[A] \]

This implies that the number of actively participating electrons that are induced in the plasma changes from \(7.9163 \cdot 10^{19}[e^{-}/s]\) (under quasi-neutral assumption), to \(7.9163 \cdot 10^{19}[e^{-}/s] + 5.657 \cdot 6.24 \cdot 10^{18}[e^{-}/s] = 1.1446268 \cdot 10^{20}[e^{-}/s]\). Therefore, using CAAS and equation (4.18) yields a temperature of 24485[K] or 2.11[eV].

It is evident that the RMS heating power remains the same for the two cases of RF assisted plasma. On other hand the matter of performance based on the effects from the harmonics may provide an answer for the generator improved performance. In fact, just the second harmonic of the RF circuit would approximately be 14[Mhz] which closely matches the plasma electron gyro-resonance frequency of 13.4[Mhz]. This observation combined with the fact that there are multiple harmonics of this frequency provided by the Colpitts circuit, may be a strong indication that plasma heating by the combined effect of the magnetic field and the corresponding gyro-resonance oscillation is the method for improving the plasma generator performance.
6.6 Electrical System Modelling

6.6.1 Model of the RF oscillator in PSIM

The circuit presented in Figure 5.4 is simulated using PSIM. The simulation are conducted in PSIM due to the use of power electronics components necessary for creation of plasma. This circuit was actually built for the experiment as the primary RF supply circuit and it was able to produce the frequencies of 7[MHz] and 11[MHz] with the current in the coil peaking at 1[A] and a potential of 20[V]. Using this original circuit, there is an apparent discrepancy between the experiment and the simulation: the circuit on its own showcases a current peaking at 3.295[A] and oscillating at a frequency of 14.76[KHz](period=\(6.775 \cdot 10^{-5}[s]\)), and a relatively steady potential of 20[V]. Unfortunately, in PSIM neither the variation of the frequency regulating resistance \(R_{req}\), nor the implementation of a frequency switching regulator does not lead to achieving the desired frequencies of 7 and 11[MHz]. After reconsideration of the physical circuit and additional measurements from the circuit elements it becomes clear that each coil winding has a more prominent effect on the circuit than the circuit as a whole. Therefore, the circuit in Figure 5.4 has been modified accordingly to match the reality of the experiment and a modified circuit is showcased in Figure 6.8.

The frequency in the model circuit corresponds to 7.33[MHz] and the associated
inductance $L_{rf}$ is 0.19[nH]. On other hand, the 11[MHz] configuration has the associated inductance of 0.018[nH]. The changes that correspond to the change in the inductance have to do with the winding distances and the inductances of 0.1[nH] on either side of the SiCFET. Also, based on observation that the actual circuit generates harmonics there could be additional parasitic capacitance created by the breadboard on which the circuit has been built. The PSIM outputs for 7[MHz] configuration is presented in Figure 6.7 for a steady state operation.

![Figure 6.9: Voltage and current on the coupling LC side of Colpitts circuit.](image)

From these figures it is evident that there is no indication of harmonics of 7[MHz]. Also, the peak current is not sinusoidal and is pulsed, which is the most likely scenario based on the RC link that initiates the pulse mode in the circuit. Furthermore, the although the this circuit has shown that the improvement of plasma generation is possible by the means of achieving the gyro-resonance, due to its limitations in terms of the low resilience of the components, and the bulkiness of the transformer, a better circuit would be preferable in an efficient plasma generation.
6.6.2 Model of the prototype voltage multiplier and RF generator

By consulting with the equations, the experiment, and the simulation models there are multiple design features that have to be considered for an efficient plasma generator device. First, the implementation of an emitter array made of multiple microscopic metal rods would make it easier to release electrons and allow them to engage in ionization. Second, by regulating the potential at the emitter array it would be possible to control the number of electrons that will be involved in the ionization and would correspond to a specific mode of flow necessary for a specific plasma application. Third, an effective method to confine and ionize the plasma is by implementing a regulated magnetic field and oscillate it at the plasma gyro-resonance frequency associated with this field. Lastly, the regulation of flow is directly correlated with the ionization of the plasma, hence, the effects of flow change need to be accounted for in the control of the plasma generator electrical parameters.

The implementation of these design features can result in a plasma generator that will out-perform the direct-discharge configuration. The circuit design of such plasma generator is composed of the voltage multiplier circuit and the RF inverter, presented in Figures 6.10 and 6.12, respectively.

![Figure 6.10: Voltage multiplier concept for the electron emission.](image)

The voltage multiplier is composed of several stages of rectifiers that are able to focus electrons at the emitter end of the generator and upon reaching a critical value be released into the gas in order to ionize it. For the configuration composed of ten multiplication stages the output potentials are presented in Figure 6.11.
The definitive feature of the voltage multiplier outputs presented is that the leading sinusoidal frequency fed into the IGBTs is 120[Hz]. At lower or higher frequencies than this, the potential drops significantly. If the regular rectifying diodes are used, then the performance would drop even further. Although, the conventional silicon based diodes have a significant safety advantage, with the development of the Silicon Carbide technology the IGBTs will have a superior advantage due to their improved tolerance to the heat and high frequency switching. Furthermore, by regulating the leading frequency it will be possible to generate a range of different temperature plasmas and adjust the generator to a variety of needs.

The RF inverter configuration is intended to provide an oscillating magnetic field in a core of a resistive magnet. The resistive magnet is capable of confining a focused and dense magnetic field and oscillate it at the plasma gyro-resonance frequency. Hence, the inverter switching regulator has a current sensor that adjusts the switching frequency based on equations (4.36) and (4.35). Also, it is duly noted that feeding the same frequency as the resonance frequency of the RF coupling is dangerous to the
Figure 6.12: RF inverter for the plasma confinement.

inverter bridge and can cause the breakdown in the gate. Therefore, the resonance frequency can be varied to alleviate the effects of the high current breaking the circuit and to prolong the work life-span of the circuit. Also, the amount of current passing through the resistive magnet is directly proportional to the resistance of the coils and it is necessary to implement insulation from plasma and cooling method to ensure that the heat does not affect the performance of the electro-magnetic coil. The matching network in the coupling coil can be played by an isolated conductor tube. This thin conductor tube can be made of copper and isolated from plasma circuitry by being encased in a ceramic structure. The length of the tube is dependant on the quarter-wave-length that corresponds to the preferred temperature of the plasma, and the associated frequency. By implementing such a configuration it would be possible to have tunable plasma and use it for anything ranging from the ion infusion into the living cells and to the plasma gasification.

The simulation of this circuit for a case when the regulating frequency is 7 [MHz] is shown in Figure 6.8. The efficiency of such circuit approximately 83.7% at 7 [MHz], and 81.8% at 14 [MHz]. Some harmonics are to be expected based on the nature of inductance of the resistive coil, and the could be taken as an advantage to produce plasma efficiently at a frequency that has a harmonic frequency corresponding to the plasma gyro-resonance frequency.
Chapter 7

Results and Analysis

7.1 Experimental Results

It is worthwhile to consider what does the obtained data mean with respect to the limitations of the triple Langmuir probe. As mentioned in section 5.1.3, the maximum error in the case of the triple Langmuir probe can reach 15% of the measured value. Therefore, considering table 5.5, there is a need to re-evaluate the found value in terms of the maximums and minimums, table 7.1 is the exemplification of that.

Table 7.1: The minimums and the maximums of plasma properties in the four modes of generation, as a result of triple Langmuir probe use

<table>
<thead>
<tr>
<th>Plasma Generation Mode</th>
<th>( T_e ) [eV]</th>
<th>( J_{\text{plas}} ) [A/m²]</th>
<th>( N_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Discharge Min.</td>
<td>0.03642</td>
<td>1793</td>
<td>0.929 \cdot 10^{20}</td>
</tr>
<tr>
<td>Direct Discharge Max.</td>
<td>0.04928</td>
<td>2425.8</td>
<td>1.257 \cdot 10^{20}</td>
</tr>
<tr>
<td>Single Emitter Min.</td>
<td>0.10504</td>
<td>3194.4</td>
<td>0.975 \cdot 10^{20}</td>
</tr>
<tr>
<td>Single Emitter Max.</td>
<td>0.14212</td>
<td>4321.8</td>
<td>1.319 \cdot 10^{20}</td>
</tr>
<tr>
<td>11[MHz] assisted SE Min.</td>
<td>0.12351</td>
<td>4516.5</td>
<td>1.272 \cdot 10^{20}</td>
</tr>
<tr>
<td>11[MHz] assisted SE Max.</td>
<td>0.16711</td>
<td>6110.5</td>
<td>1.720 \cdot 10^{20}</td>
</tr>
<tr>
<td>7[MHz] assisted SE Min.</td>
<td>0.25877</td>
<td>12751.7</td>
<td>2.479 \cdot 10^{20}</td>
</tr>
<tr>
<td>7[MHz] assisted SE Max.</td>
<td>0.35011</td>
<td>17252.3</td>
<td>3.355 \cdot 10^{20}</td>
</tr>
</tbody>
</table>

Based on the minimums and the maximums an several observations can be made. The direct discharge is not quite getting to the level of producing the same electron temperature and plasma current as other modes, though the electron density might overlap for the cases of single emitter, and 11[MHz] RF assisted configurations. The reasons for the possible overlaps in the electron density include [56]:

1. Secondary emission as a result of AC discharge; more electrons are generated
as a result of alternating electric fields.

2. Spread of the electron flow onto the Langmuir probe; the electrons disperse and create a differentiating flow of ions.

3. Splattering effect from the walls; the electrons bombarding the back wall reflect back at the Langmuir probe due to the proximity of the wall and the secondary emission effects.

4. General flow effects; flow simply reflects back at the Langmuir probe due to the proximity of the wall.

Similar explanations could be attributed in the cases where other properties overlap as well. However, an evident distinction in the experiment is the 7[MHz] RF assisted single emitter configuration, which is still the best confirming case that outperforms the direct-discharge configuration. Therefore, it is still possible to have a 99.9% confidence that the 7[MHz] RF assisted single emitter configuration differs from other modes of plasma generation. Provided that the measurement using the triple Langmuir probe do not yield the exact values, it is useful nonetheless to have a range of values at minimal and maximal errors. The reason is that the use of the simulation model may not yield the exact solutions either, so having a range of approximate results certainly helps in tuning of the simulation model to attain reliable results for engineering design. Furthermore, although the equipment setting that was used for the experimentation is not of the level of a high budget lab, it does the job it was set out to do. As far as the experimental results are concerned (as made evident in the tables above), the experimental setting has done a good job in achieving its intended purpose.

The most intriguing part to investigating the plasma generation, now that experiments have been done, is the search for the answer to the following question: why is the 7[MHz] signal is able to sustain better plasma conditions than the 11[MHz] signal? Visually, it is not easy to see the differences between the different modes of plasma generation modes without some sensing equipment. Although, the behaviour of the plasma is worthy of noting by observing pictures provided in Figures 7.1, 7.2, and 7.3. The quality of the pictures is not the best, and nonetheless they provide insight onto the modes of plasma generation. For instance, in case of the direct discharge configuration (the picture shown is one of the earlier ones where the piece of anode is simply a wire), shows arcing between the electrodes.

Also, the readings for 7 and 11[MHz] are normalized from the oscilloscope samples. However, the harmonics that are picked up by the oscilloscope would mean that there
is a range of frequencies that are fed into plasma. It seems that the frequency with most amplitude is the one picked as the dominant one. By considering a spectrum of harmonic frequencies for the 7[MHz] configuration in Figure 7.4, it is possible to count roughly 37 harmonics. The presence of the harmonics might explain the exceptional
response from the plasma and will be considered further in chapters 6 and 7.

Figure 7.4: 7MHz dominant RF Spectrum in the Colpitts circuit.

The arcing in the direct discharge configuration (seen in Figure 7.1) showcases the confinement of the plasma to a region that is strongly coupled with electric field. Therefore, when plasma is created in direct discharge the effect necessary from the plasma for a particular use is limited to a very close proximity near the generator. The visual differences in plasma generation between a single emitter and the RF assisted single emitter are primarily the deviation of the plasma stream for the single emitter, and the wrapping of the plasma around the RF coil. The deviation of the plasma from a straight path for a single emitter configuration is due to the effect imposed by the potential produced at the triple Langmuir probe, it is noteworthy to know that the distance between the plasma generator and the triple Langmuir probe is 15[mm] in Figure 7.2, although for the experiments conducted the distance was 10[mm]. In the case of the RF assited single emitter configuration the effect of plasma wrapping around the coil occurs as a result of the oscillating magnetic field, this effect is best to be avoided for the prototype design of a novel plasma generator as it encourages
losses. The means to avoid plasma wrapping could include insulation of the RF coil, and the confinement of plasma in a ceramic tube that has an isolated conducting surface on the plasma generating side that is tuned to reflect resonant frequencies coming onto it (this would allow for self regulation of plasma without excessive losses via EM radiation).

7.2 Simulation Results

The figures below are representative of the results for the direct discharge (with conductances computed and derived by an experiment), single emitter, and RF assisted configurations. The results computed via the simulations include the properties of plasma such as temperature, the ion-to-neutrals concentration ratio, current, joule heating, and the magnetic strength.

7.2.1 Direct Discharge Simulation Results

Results for Configuration with Computed Conductance.

![Temperature profile, Kelvin.](image)

Figure 7.5: Temperature profile, Kelvin.
Figure 7.6: Concentration profile.

Figure 7.7: Current profile, Amperes per meter.
Figure 7.8: Joule heating profile, Watts per meter.

Figure 7.9: Magnetic strength profile, milli-Tesa.
Results for Configuration with Experimentally Derived Conductance.

Figure 7.10: Temperature profile, Kelvin.

It is worth noting that the differences between the results obtained by the use of computed and the experimentally derived conductances are fairly close to each other. The area of interest is near the outlet of the generator and in all cases it is relatively uniform. Nonetheless, there are zones where the results obtained by running the cases with the experimentally derived conductance yield higher results, due to a higher conductance. These results can serve a convenient purposes for "roughing-in" to the results when the exact conductance of the material is not known and an approximate handle value is necessary to proceed with the design. Although, the result obtained based on the experimentally derived conductance are more representative of the natural process it is interesting to consider the approximate values as they present a critical perspective on the design capabilities.
Figure 7.11: Concentration ratio profile.

Figure 7.12: Current profile, Amperes per meter.
Figure 7.13: Joule heating profile, Watts per meter.

Figure 7.14: Magnetic strength profile milli-Tesla.
7.2.2 Single Emitter Simulation Results

Figure 7.15: Temperature profile, Kelvin.

Figure 7.16: Concentration ratio profile.
7.2.3 RF Assisted Single Emitter Simulation Results

The performance of the RF assisted generator improves compared to the single emitter configuration, although the transient behaviour of the simulation leads to some stark
Figure 7.19: Temperature profile, Kelvin.

Figure 7.20: Concentration ratio profile.

differences in the results, specifically in the case of the concentration profile, where the variation in the concentration are quiet extreme in a very short frame of time.
Figure 7.21: Current profile, Amperes per meter.

Figure 7.22: Joule heating profile, Watts per meter.
Figure 7.23: Magnetic strength profile, milli-Tesla.

Figure 7.24: Magnetic flux profile, mT per m², for MHz RF assisted configuration.
7.3 Comparison and Analysis of Experimental and Simulation Results

Based on the experimental findings and the computational models it is possible to draw some conclusions to the matters of using ElmerFEM and PSIM for simulations of the plasma generator. Furthermore, based on the findings relevant to the design of the plasma generator it is possible to implement them in the computer models and produce a working concept that is able to closely match the results of an experiment. However, several pitfalls of using equations prior to setting of an experimental model need to be addressed as it may become evident that there are several discrepancies between what has been computed, and what has been found via an experiment and simulations. Particularly, the most notable discrepancies need to be addressed include the difference in the temperatures and concentration for the plasma found by the formulas and the experiment, and the exceptional performance of the plasma generator at the RF feed frequency of 7[MHz].

Table 7.2: The temperature comparison between the computed, experimentally derived, and the simulation values

<table>
<thead>
<tr>
<th>Plasma Generation Mode</th>
<th>$T_e$ [eV]</th>
<th>$T_e$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Discharge Computed</td>
<td>2.014</td>
<td>23365</td>
</tr>
<tr>
<td>Direct Discharge Experiment</td>
<td>0.03642 − 0.04928</td>
<td>422.5 − 571.7</td>
</tr>
<tr>
<td>Direct Discharge Simulation</td>
<td>0.02931 − 0.04327</td>
<td>340 − 502</td>
</tr>
<tr>
<td>Single Emitter Computed</td>
<td>1.867</td>
<td>21659</td>
</tr>
<tr>
<td>Single Emitter Experiment Range</td>
<td>0.10504 − 0.14212</td>
<td>1218.464 − 1648.592</td>
</tr>
<tr>
<td>Single Emitter Simulation</td>
<td>0.0271 − 0.0335</td>
<td>315 − 389</td>
</tr>
<tr>
<td>13.4[MHz] assisted SE Computed</td>
<td>2.11</td>
<td>24485</td>
</tr>
<tr>
<td>13.4[MHz] assisted SE Experiment Range</td>
<td>0.2588 − 0.3501</td>
<td>3001.7 − 4061.3</td>
</tr>
<tr>
<td>13.4[MHz] assisted SE Simulation</td>
<td>0.0294 − 0.0337</td>
<td>341 − 391</td>
</tr>
</tbody>
</table>

In section 5.3.5 the remarks regarding the possible causes for variations in temperature, current density, and electron density were mentioned as possible causes for im-perfect measurement. However, by conducting the simulations in Elmer, it becomes quite apparent that the discrepancies arising as a result of excessive electron emission may have indeed caused the results obtained from the Langmuir probe to be overly optimistic. It is worthwhile to compare the results for the temperatures, and ion densities (under the quasi-neutral assumption) between the computations,
experiment, and Elmer simulation, as is showcased in tables 7.1 and 7.2. Case for 11[MHz] is removed due to its close overlap with the single emitter case, and instead of the 7[MHz] case the gyro-resonance case is presented as it appears be the legitimate choice for the plasma heating that was observed in the experiment.

Table 7.3: The concentration comparison between the computed, experimentally derived, and the simulation values

<table>
<thead>
<tr>
<th>Plasma Generation Mode</th>
<th>(N_e \cdot 10^{20})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Discharge</td>
<td></td>
</tr>
<tr>
<td>Computed</td>
<td>1.054</td>
</tr>
<tr>
<td>Experiment Range</td>
<td>0.929 – 1.257</td>
</tr>
<tr>
<td>Simulation</td>
<td>1.3</td>
</tr>
<tr>
<td>Single Emitter</td>
<td></td>
</tr>
<tr>
<td>Computed</td>
<td>0.7916</td>
</tr>
<tr>
<td>Experiment Range</td>
<td>0.975 – 1.319</td>
</tr>
<tr>
<td>Simulation</td>
<td>0.951</td>
</tr>
<tr>
<td>13.4[MHz] assisted SE</td>
<td></td>
</tr>
<tr>
<td>Computed</td>
<td>1.1446</td>
</tr>
<tr>
<td>Experiment Range</td>
<td>2.479 – 3.355</td>
</tr>
<tr>
<td>Simulation</td>
<td>1.483</td>
</tr>
</tbody>
</table>

The source of error for the experiment appears to be the electrons that do not go through the full process of ionization with the neutral gas as they do not posses sufficient energy to interact with it. Also, the difference in the temperatures for the plasma found by the computations, the experiment, and the simulation is rooted in the convection effects as well as the incomplete ionization of the neutral particles. If plasma was confined in a vessel, where there is no external flow of neutral particles, it would not display the behaviour observed in the experiment and the simulation and would match more closely with the computed values. It has been observed via the simulations that the flow remains relatively unchanged over the course of different plasma generation modes. This is not surprising as the flow entering into the vacuum chamber at a high rate would posses such a low energy level that additional energy would be required to significantly ionize it. In fact, as seen in the simulation results for the flow and the temperature on their own (section 6.1), the temperature of the flow roughly drops to 292[K], this implies that the flow itself loses approximately 0.0988[W] of thermal energy in form of radiation to the walls of the chamber. This energy due to convective cooling can be simply found by:

\[
\dot{Q} = \dot{m} \cdot C_p \cdot (T_{out} - T_{in})[W]
\]  

(7.1)

Where, the mass flow rate has been found to be \(\dot{m} = 1.638 \cdot 10^{-5}[kg/s]\) experi-
mentally, the specific heat at a constant pressure is $C_p = 1005\, [J/(kg \cdot K)]$, and the temperatures at the outlet and the inlet are $T_{out}$ and $T_{in}$, respectively. Based on this equation and the temperatures found computationally, experimentally, and by simulation it is possible to appreciate the amount of thermal energy that would have to be added in each case and compare it to the power utilized by the generator circuit.

Table 7.4: The hypothetical thermal energy required in perfect conditions to reach the temperatures found by computing, experiment, and simulation

<table>
<thead>
<tr>
<th>Plasma Generation Mode</th>
<th>$Q[W]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Discharge Computed</td>
<td>379.73</td>
</tr>
<tr>
<td>Direct Discharge Experiment</td>
<td>2.05 – 4.51</td>
</tr>
<tr>
<td>Direct Discharge Simulation</td>
<td>0.69 – 3.35</td>
</tr>
<tr>
<td>Single Emitter Computed</td>
<td>351.64</td>
</tr>
<tr>
<td>Single Emitter Experiment</td>
<td>15.15 – 22.23</td>
</tr>
<tr>
<td>Single Emitter Simulation</td>
<td>0.28 – 1.50</td>
</tr>
<tr>
<td>13.4[MHz] assisted SE Computed</td>
<td>398.16</td>
</tr>
<tr>
<td>13.4[MHz] assisted SE Experiment</td>
<td>44.51 – 61.95</td>
</tr>
<tr>
<td>13.4[MHz] assisted SE Simulation</td>
<td>0.71 – 1.53</td>
</tr>
</tbody>
</table>

Based on the heating energies several aspects become apparent by considering how much energy is supplied and utilized by the ionization process. In case of the direct discharge approximately 820.8[W] to 961.11[W] out of 1368[W] supplied are involved in the ionization process. In the case of Single Emitter configuration roughly 23.677[W] out of 1027.233[W] are used by ionization process. Lastly, in case of the RF assisted configuration approximately 24.364[W] out of 1047.233[W] supplied are used for the ionization process. Therefore, not all of the ionization energy is used in the heating process of the gas, it is doubly evident that the effect of convection in the experiment and the simulation cause the offset in the plasma temperature, and the effects of low-power electrons cause discrepancies in the experimental readings picked up by the Langmuir probe.

Despite the sources of error however, the case for the RF assisted single emitter configuration still showcases a possibility to be successfully implemented as a competing technology to the direct discharge devices. The experimental observation of improved performance at 13.4[MHz](gyro-resonance frequency) as well as the results obtained from simulation point to a better design option that utilizes an electron source and confines them to a magnetic field that can induce sufficient currents and lead to effective plasma generation. It is evident from both the experiment and the
simulation that plasma is acting as an active component and alters the behaviour of the coupling circuitry. Also, it is evident from observations that it is necessary to have better isolation between the emitter circuit and the RF coil. The experiment had plasma coming in contact with the coil which down-graded the quality of plasma at the Triple Langmuir Probe. In the concept, it would be best to have an insulated conductive sheath facing the plasma and acting as a wave-guide conduit. This will provide the stability and can be tuned to a particular gyro-resonance frequency and have a very specific operating temperature. It cannot be emphasized enough that the emitter component has to have an array of hollow emitters that can provide electrons to the gas. This setting will allow for good control over the emitter temperature, provide neutral gas straight into the ionization zone, assure the longevity of operation, and reduce the maintenance times. It has been observed that the best means for heating plasma without the use of high frequency RF sources would be via the gyro-resonance frequency. Hence, the use of a good electromagnetic coil that is able to handle high currents and frequencies is preferable, and in the case of the concept design the resistive magnet would be the optimal option. Lastly, in the circuit it would be best to use the high frequency switching high current Silicon Carbide FETs and IGBTs, and a variable and controlled oscillator (to tune to specific frequency that corresponds to the gyro-resonance frequency). Case in point, the prototype design is the conglomeration of all the analytical models created based on the design features outlined in section 6.5.2.

The method for generating plasmas without the damage to physical electrodes is the focus. The reason for pursuing research of plasma generation is to make plasma devices that are compact, efficient, resilient, and low maintenance. The aspects of plasma state definition, generation, and applications serve as the base for highlighting the importance of the plasma generation technologies and provide the direction for an in depth engineering design and analysis of plasma generation options. The advantages of taking an engineering approach to the plasma generator design will have the benefit of scaling in size without the loss of performance, and the potential to suit a multitude of industrial applications. The use foundational scientific theory, model, and the simulation of the device, are performed in Elmer multi-physics software as well as tested by an experiment. The fundamental design idea of the electrode-less plasma generator is the creation of a virtual cathode through the use of electron emission and active pumping of RF energy. The comparison of the model and experiment is also conducted with respect to an electrode based plasma generator, with respect to the efficiency, operational life-span, ionization temperature, creation of possible contaminants, and cost. Using this approach, it has been determined that it is in-
deed possible to create a plasma generator with a virtual cathode that is capable of receiving substantial amounts of electromagnetic energy compatible with a direct arc discharge method, albeit requiring a more involved process of control.
Chapter 8

Conclusion and Future Work

8.1 Conclusion

First and foremost, a comprehensive study of plasma generation mechanism, related physics, associated equation models, and most relevant parameters has been established. A detailed analysis and comparative study of plasma generation technologies, their operation capabilities, applications, and design features was performed to comprehend the benefits and dis-advantages of each technology. Based on these comprehensive studies and analyses a design for a possible plasma generation device has been made, and was compared to existing plasma generation devices, in accordance with their comparative features. Such design was then examined by the simulations of the composing sub-systems and components on an individual as well as integrated basis. Lastly, a functioning prototype of experimental design was created to validate and test the proposed plasma generation technique, and to compare with simulation results. Therefore, the goals set out in the beginning have been achieved.

It was intended to pursue the hybridized, virtual electrode plasma generator that will be low-maintenance, endure wear, and will have an elegant design, not limited to a small niche of applications. What has been achieved in the process was the derivation of a design that can compete with direct discharge plasma generation device by being more lasting, resilient to plasma conditions in varying environments, and capable for adjusting in multitude of applications. Also, the tools for achieving such a design have been verified to work sufficiently well by comparing the simulation results with the experimental data. Therefore, by the use of engineering foundations it is possible to develop a plasma generator with an ability to shield itself against the thermal effects of plasma. The model of plasma simulation was implemented in Elmer and validated and calibrated in relation to a small-scale experiment. The results of the experiment were be compared to the simulation results and were found to match sufficiently well.
for Elmer to be used as a tool for designing plasma devices.

8.2 Recommendations for Industrial Application

Since, the proposed plasma generator device has a virtual electrode configuration and relies on the production of electrons for an ionization process assisted with RF, a variety of opportunities open up for application of such a device. First, it will become a lot easier to operate such a device and to maintain it. The tungsten emitters can act sufficiently well in the emitter array and last for extended periods of time since their purpose will be primarily the supply of electrons into the high power RF field, which will maintain and support the plasma generation process continuously. This will allow extended application in treatment, production, and refining purification of high purity materials, silica, refractory materials, as well as ultra-fine and spherical fine powders. By sizing the generator and calibrating the number of multiplier stages as well as the dimensions of the RF coupling coil it will be possible to employ such device in high temperature thermal treatment processes like heat treatment of metals and plasma sintering of wide range of metals and ceramics. The processes of surface treatment and coating will also benefit from the proposed plasma generator device as it will widen the range for pure results in oxidation, nitriding, plasma flame spraying, and surface coating of powder materials. The chemical engineering sector will also benefit in respect to broadening the capabilities for the chemical vapour deposition (CVD) at pressures that do not have to be at the vacuum conditions, and the processes of chemical synthesis and processing will have a significant advantage in control of the plasma generation processes ranging from drug creation and to the waste to energy production. Also, the manufacturing and material processing would expand in the fields of plasma vapour deposition, etching, and cutting. Lastly, a wide range of experimental applications will benefit from the virtual cathode plasma generation technology by employing it in furnaces, high intensity light sources, spectroscopic analysis, isotope separation, ion source, and as a high power density plasma source.

The intent was to make a lasting change in the industrial processing field by presenting a device that is simple to handle and robust in the harsh environments. It is expected that the hybridized design presented will serve as a convenient guideline for researchers and investigators who aim to industrialize plasma. In the long run, it is expected that the current thesis can act as a guiding milestone in the development of the plasma technologies for the future plasma engineers and scientists.
8.3 Future Work

For the academic work it would be interesting to implement a larger scale experiment and compare it with the performance of the standard plasma cutters that operate by the use of arc discharge. It would also benefit the concept to be tested in hash environments where contamination has to be avoided and the presence of the dust and particles that need to be treated is constantly bombarding the device, this would help to test the robustness and resilience of the device. It would be also interesting to implement a tunable passageway for the plasma generator and a better isolation methodology of the RF feed coil. Simulation-wise it would also be interesting to see the performance of the plasma generator device with a microwave passageway implemented and analyze the regions of highest plasma activity in such a configuration. Furthermore, it is possible to utilize the Monte-Carlo algorithm in Elmer, although, in order to attain this feature in Elmer it is necessary to customize a code able to handle the interaction of ionized particles. The Direct Monte-Carlo algorithm may be implemented at the high-energy locations of plasmas interaction points and for instability tracking. Fortunately, Elmer has the capacity to be altered and modified at the source code as well as have the ability to enact the custom made modelling toolboxes, and should be looked into further to increase the practical range of Elmer application in the engineering design of plasma devices. By following through with Elmer and by validating other modes of plasma in this program it would be possible also use it in design of plasma microwave tubes, fusion energy devices, particle accelerators, and design of plasma diagnostic devices. The industrial applications that can be derived from such research would then benefit the fields medicine (cleaning and sanitization), communications (via the microwave technologies), lighting and laser devices, entertainment [70], and space propulsion.
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134


Appendix

Experimental Procedures

In this section the procedures for performing the experiment to gain insight for the possible chamber leakages, the gas inflow into the plasma generator, and the conductivity of plasma. These experimental procedures will help to secure the foundational knowledge about plasma. Also, the experimental procedures for finding the electron temperature, $T_{e^-}$, the current density, $J_{plas}$, and the electron density, $N_{e^-}$, will be presented with respect to four different configurations: direct discharge, single emitter, and RF assisted single emitter with feed frequencies of 7[MHz] and 11[MHz]. By using these procedures it will become evident which methods are producing the most plasma, and will help to build functional representations of the plasma generator in the computer simulations.

Finding pressure error due to leakages

1. Turn the vacuum pump on.
2. Evacuate the chamber to -28[in Hg], and turn off the pump.
3. Close the pump valve and turned on the timer simultaneously.
4. Check and note the gauge readings and time at regular intervals.
5. Compute the average rate of gas diffusion into the chamber without the pump operation.

Finding gas flow rate into the chamber

1. Turn pump on evacuate the chamber to -28[in Hg].
2. Turn off the pump.
3. Open the gas inlet valve
4. Close the pump valve and turn on the timer simultaneously.

5. Check and note the gauge readings and time at regular intervals.

6. Compute the average rate of gas inflow and subtract the error value into the chamber without the pump operation.

**Measuring plasma conductivity**

1. Make sure the high voltage (9[kV]) leads of the transformer are connected to the anode and cathode.

2. Connect the oscilloscope in the RMS current measuring mode between the transformer supply and one of the emitter leads.

3. Turn pump on and evacuate the chamber to -28[in Hg].

4. Turn off the pump.

5. Turn on the transformer for plasma generation.

6. Write down the oscilloscope readings for the current entering into the chamber.

7. Turn off the transformer.

8. Shut off the inlet valve.


10. Knowing the potential and the distance between the electrodes (0.0125[m]) compute the conductivity of plasma.

**Collecting data for the direct discharge configuration**

1. Make sure the high voltage leads of the transformer are connected to the anode and cathode.

2. Activate the langmuir probe (connected to the power supply at +10V).

3. Turn on the oscilloscope to measure the RMS potential and current.

4. Turn the pump on, and evacuate the chamber to -28[in Hg].

5. Open inlet valve (Keep the pump operating and do not shut off the pump valve).
6. Turn on the transformer for plasma generation.

7. Write down the oscilloscope readings.

8. Turn off the transformer.

9. Turn off the pump.

10. Shut off the inlet valve.

11. Purge chamber.

**Collecting data for the single emitter configuration**

1. Make sure that one of transformer high voltage leads is connected to a single electrode only and the other electrode is removed from the vicinity of the emitter.

2. Activate the langmuir probe (connected to the power supply at +10V).

3. Turn on the oscilloscope to measure the RMS potential and current.

4. Turn the pump on, and evacuate the chamber to -28[in Hg].

5. Open inlet valve (Keep the pump operating and do not shut off the pump valve).

6. Turn on the transformer for plasma generation.
7. Write down the oscilloscope readings.

8. Turn off the transformer.

9. Turn off the pump.

10. Shut off the inlet valve.

11. Purge chamber.

**Collecting data for the RF assisted single emitter configuration**

1. Make sure that one of transformer high voltage leads is connected to a single electrode only and the other electrode is removed from the vicinity of the emitter.

2. Make sure the RF coil is connected to the oscillator circuit.

3. Activate the langmuir probe (connected to the power supply at +10V).

4. Turn on the oscilloscope to measure the RMS potential and current.

5. Turn the pump on, and evacuate the chamber to -28[in Hg].

6. Open inlet valve (Keep the pump operating and do not shut off the pump valve).

7. Turn on the transformer for plasma generation.

8. Turn on the power supply for the RF oscillator circuit (The adjustment of the gate capacitance can be manipulated to obtain either 7[MHz] or 11[MHz]).

9. Write down the oscilloscope readings.

10. Turn off the transformer.

11. Turn off the power supply for the RF oscillator circuit.

12. Turn off the pump.

13. Shut off the inlet valve.

Additional Literature Read


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