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FUNCTIONAL MODELING FOR THE ANALYSIS OF HIGH DENSITY PLASMA EXPERIMENTATION

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***Abstract-* One major challenge of plasma experimentation is to evaluate different engineering designs and provide systematic mapping to plasma simulation. Due to the complexityinvolved, and costs to establish a realistic and practical plasma experiment, it is important to study different setups and configurations of plasma experiments. However, this requires proper and systematic modeling to be able to evaluate the alternative setups. This paper proposes a framework for functional modeling of plasma experimentation, which will support the analysis and evaluation of plasma experimentation, along with the required measurements, controls, and simulation practices. It is applied to the prototype experimental setup used by HOPE Innovations, where simulation results are correlated to the physical models in view of the proposed functional modeling framework proposed in this paper**.

Keywords: *Functional Modeling, Intersecting Plasma Beams, Dense Plasma, Pinch, Plasma Simulation, Plasma Instability Tracking*

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INTRODUCTION

Over the past one and a half years, the University of Ontario Institute of Technology (UOIT) has been involved in research of plasma science and development of scientific equipment for studies of plasma in collaboration with HOPE Innovations. A feasibility study conducted at UOIT on current plasma technologies and a configuration proposed by HOPE, led to a joint effortbetween UOIT and HOPE to further investigate properties of plasma. Methods for plasma simulation, radiation detection, control systems, and cooling were evaluated and chosen in preparation for future experiments at UOIT.An existing experiment involves the use of two opposing plasma torches connected to the electrodes of a test circuit. The analysis and understanding of the experiment was performed to validate the settings and their potential in the research area of dense plasmas. The procedure to install the experiment was founded on the principle of design for safety and identification of specific risks. The long-term plan of implementing the fault prevention strategies in the high density plasma research is to make safety procedures and strategies for controlling runaway reactions and instabilities. The work presented here describes what has been accomplished at UOIT in regard to the plasma research.

Thermonuclear fusion is a global engineering challenge that can lead to a clean, sustainable, and inexpensive energy supply [1]. The fusion advantage is the abundance of fuel available [2]. Using primarily deuterium and lithium (for tritium breeding [3]), the energy generated with available resources may be able to supply humanity's needs for hundreds of years [4]. As with nuclear fission, thermonuclear fusion does not produce any sort of greenhouse gas. However, in an accident situation, a fusion reactor is potentially much safer than current fission reactors [5]. It is possible to stop the reaction simply by shutting off the fuel source. In a well-designed fusion reactor, the unstable plasmas quickly dissipate and do not affect the surrounding systems [6]. Also, when comparing a possible fusion reactor to a fission reactor, there are relatively fewer radioactive waste products [7]. This means that the decommissioning phase of a fusion reactor would be much shorter than that for a fission reactor and more of the materials could be recycled [8]. Despite this favourable outlook for fusion reactors, the process of achieving fusion is nested with difficult problems of containing extremely high temperature reactions, maintaining high purity of fuels, and preventing plasma instabilities that run the reactions to null [9]. The research performed at UOIT is aimed at functional modeling in order to perform accurate analysis of high density plasmas in experimental settings.

In this paper, a functional model is carried out for the plasma experimentation at UOIT. Section 2 lists the hazards and risks associated with the plasma research and propose the necessary safety procedures to prevent any potential accidents. An overview of the common diagnostic tools used for monitoring plasma properties in experiments is given in Section 3. Section 4 describes the experimental setup of HOPE's exploratory experiments conducted at STERN Laboratories, in Hamilton, Ontario. A functional model of thee electrical and thermal components of HOPE experiment is carried out in Section 5. Data analyses and experimental results of HOPE experiment are discussed in Section 6. A discussion and summary of major findings are presented in Section7.

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Fusion Risks and Hazards

Table 1. Faults, impacts, and prevention strategies in dense plasma research.

#	Fault	Impact	Prevention
1	Temperature too high	Could damage containment or melting or excess fusion reactions	Emergency cooling system on standby and Several temperature measuring devices
2	Voltage too high	Plasma source/head-piece damage	• Temperature gage in closed feedback • Material used for head-piece has to withstand high temperature • Cooling system for head-piece in standby
3	Over pressure in Containment	Rupture of containment	• Containment made to withstand very high temperature • Pressure gauge • Pressure reliefvalves
4	Impurities/ particulate in containment	Disturbance/ Unwanted reactions	Vacuum and purging system
5	Plasma overload	Uncontrollable/runaway fusion	Provide limited fuel and stabilize the plasma via confinement
6	Corrosion in plasma source	Malfunction of head-piece elements	Regular change of the head-piece elements
7	Fuelling line malfunction	No fuel	Regular maintenance of machine and a standby back-up machine
8	Electric bolt mis-fire	Low temperatures	Focussing and confinement mechanism
9	Fuel pellet* wrong size	Fusion not occurring as planned	Policy to check fuel in accordance to standards
10	Power Outage	Malfunction of control device or possible shutdown	Backup system /power for emergency systems
11	Fuel proportions incorrect	Fusion not occurring as planned	Policy to check proportions
12	Leakage of coolant	Loss of cooling accident	Gauge to check coolant level and a sealed coolant system
13	Leakage of fuel	Loss of fuel	Measured at regular intervals, regular checking for leakages, and a sealed confinement unit
14	Leakage of catalyst	Slowdown of fusion and loss of catalyst	Gauge to determine the catalyst level and a sealed confinement system
15	Temperature too low	Loss of fusion reaction	Temperature measuring devices and sensors to indicate temperature, as well as insulation to prevent excessive heat losses
16	Malfunction of controls	Loss of control	Regular system inspection and more than two of three logic for system robustness
17	Damage done to plasma source	Loss of fusion and unwanted results	Regular inspection and protective layer surrounding the source element to protect it from external harms

*Note: No radioactive sources with activity higher than from a conventional fire detector are used throughout the research.

Many scenarios had to be considered before any experimental work, in order to prevent the possible occurrence of faults. Table 1, below, lists some of the most common issues possible in dense plasma (DP) research. In order to apply precautions, the safety systems have to be redundant, independent and applied to multiple layers.

The long-term fault prevention strategy in dense plasma research is to make safety procedures and strategies for controlling runaway reactions and instabilities. Furthermore, by mapping out a range of possible faults, their causes, and prevention strategies it is possible to apply the safety precautions to the DP systems of varying scale. Based on anticipatory risks, it is possible to size a particular system that employs dense plasma and meet the minimum safety requirements while attaining the intended requirements.

Currently, some of the most prominent safety requirements for safe research in the DP area are as follows:

- Have the means to mitigate the negative impacts of DP occurrence (such as stray neutrons and x-rays) by employing protective shielding
- The equipment must handle the high pressure and high temperature environment
- Multiple safety systems are implemented to prevent malfunctions
- The system must contain failsafe safety devices
- Independent power supplies for safety systems must be present and maintained at regular intervals
- Means for controlling DP occurrence must be present
- Means and procedures for containment must be present
- Impurities must not lead to safety breaches
- The DP testing rig must have limiters for the fuel injection
- Power outage shall not result in an unsafe operation
- Means to prevent and detect leakages must be present
- Control devices are well calibrated, reliable, and robust in the case of a safety breach
- Shutdown systems are fully functioning and upon deactivation of the active components of the test rig, the safety systems of the rig remain in an alert state.

The implementation of these safety rules is foundational when designing any DP systems.

Review of DP Monitoring

Fusion reactions and dense plasma phenomena in general, create an enormous amount of heat, which needs to be monitored and controlled [10]. Good diagnostics are crucial for fusion control and DP research due to the variety of information that may be extracted and used for reaching the goal of DP or fusion research. The most used diagnostics methodologies include the magnetic, microwave, and the spectroscopic diagnostics.

Although, the use of magnetic diagnostic varies depending on the type of dense plasma reactor, there are essential requirements pertaining to plasma [11]. Magnetic diagnostics measure the basic equilibrium parameters such as current, the position of plasma, its shape, and any magnetic fluctuations during operation [12]. This diagnostic operates in the electromagnetic spectrum ranging from 100 Hz to a few MHz [13].

The microwave diagnostics are placed in three categories. The first is reflectometry, which measures the phase shift of an injected resonance wave with respect to the plasma, and, consequentially, helps to determine the position of plasma. The other method is electron cyclotron emission, which is used to measure the temperature of the electron radial profile. The amount of energy released due to black body radiation is proportional to this temperature. Lastly, interferometry is used to measure the difference between the wave sent through the plasma and a wave that is sent through a vacuum. This diagnostic provides an average plasma density along the path of the injected wave. These diagnostics are applicable in the range from 1 GHz to 3 THz [13].

Within the electromagnetic wavelength range of 10 nm to 10 μm, it is possible to investigate the Bremsstrahlung spectrum as well as radiation from the minute impurities that may be present in the plasma, hence, the use of spectrometry in DP research is essential. It is possible to determine the electron temperature, plasma rotation, the Doppler shift, as well as the plasma density using the spectrometry [13]. Also, in combination with the laser induced fluorescence and Fourier Transform Spectroscopy it is possible to selectively analyze the minute properties of plasma on a quantum level [14].

Radiation is a major source of energy loss in plasma, therefore it can be used as a diagnostic to measure the acceleration of plasma particles and their interactions with electric and magnetic fields [15]. However, the integration of the detectors into the DP experimental setup faces the challenge of the intense heat of the plasma, which may damage the detectors. The detector window must be placed a safe distance away from the plasma channel to prevent damage to the detector. Due to the hypothesized high rate of collisions occurring within DP and the ensuing flux of electromagnetic radiation, detecting the radiation is not significantly affected by the distance from the plasma.
Based on the knowledge of the existing measuring devices the relevant formulations for the plasma simulation were chosen in order to yield practical outcomes.

Experimental Setup

The experimental setting for the dense plasma study was created by keeping in mind the interrelationships of plasma phenomena conditions. A functional model in Figure 1 is a representation of a potential experiment. The heating source raises the plasma temperature to the desired level. The temperature sensor is used to check the temperature of the focus point and a controller will be necessary to control the reaction due to high temperatures and any potential emissions. The Y terms in Figure 1 represent the changes in temperature, coulomb forces, mass flow rate, inter particle distance (cross-section), and the plasma density.

In the existing experiment, a pair of opposing plasma torches generate plasma. The cathodes of the torches are connected to a power supply, and when in operation, the cathode discharges electrons to the anode in the form of an arc, thereby forming plasma. After analyzing the plasma generators, the main parameters pertaining to the production of the plasma jet are:

- Gas pressure created within the generator
- Temperature
- Potential (Volts)
- Current (Amperes)

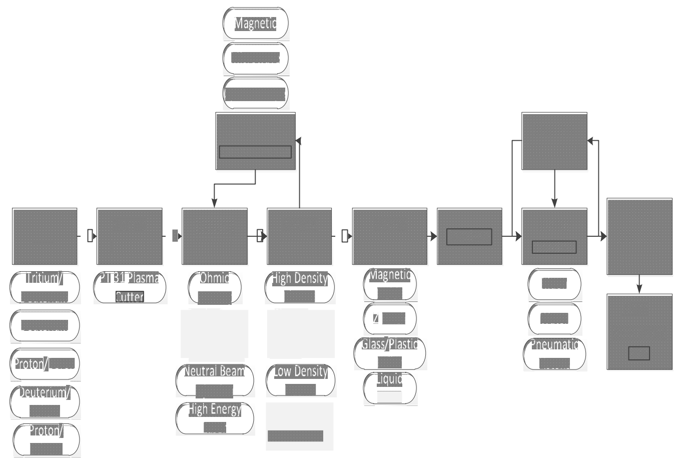


Figure 1. Experimental setting functional model.

The nozzles of the plasma generators as well as the leads of these generators are insulated near the gap space between the nozzles. The block diagram for the experiment is shown in Figure 2.

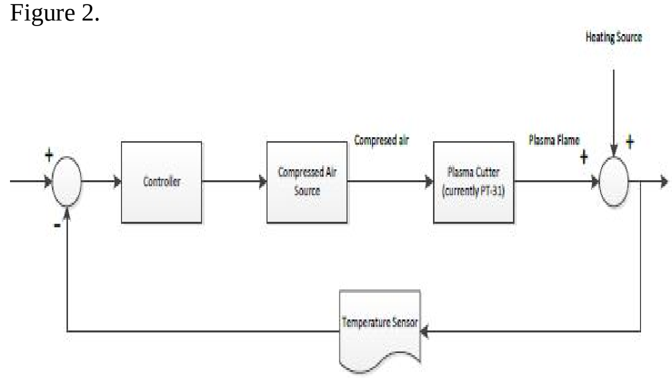


Figure 2. Basic block diagram for the process control.

Experiments conducted at STERN Laboratories by HOPE Innovations in 2012were meant to investigate the behaviour of an electric current passed through the plasma created by the described setup. Figure 3, below, depicts the setup of the experiment and shows the jets produced by the two plasma torches in the area between the electrodes. The temperature measurement of the space between the plasma torches was of prime interest due to its importance for control system design.

Figure 3. HOPE experiment setup [16].

Multi-Physics and Functional Modeling of Fusion/Plasma Experiment

The back-ground to the multi-physics modelling of DP physics stems from fluid dynamics, heat transfer, electrodynamics, and circuit analysis. The map, shown in Figure 4, demonstrates the different branches of plasma phenomena [17]. The methodology of the research involved the creation of physics simulation software that is based on the formulations relevant to each specific branch of plasma phenomena. The focus of the formula-based simulation is to compute and to evaluate the theoretical behavior of plasmas with collisional dynamics. By developing the dynamic representations of the plasma under different one-dimensional conditions it is intended to proceed to two and three dimensional models without compromising the realism of the simulation.

The systematic approach to modelling the physical phenomena of the DP interactions, conducted at Energy Safety and Control Lab (ESCL), was based on a combination of fundamental physics functions. The process of accounting for the said physics function involved the use of Simulink as the sandbox tool. The outline of the resulting model pertaining to the experiment conducted by HOPE is shown as a representation in terms of the electrical components inFigure 5, and the associated thermal components inFigure 6.

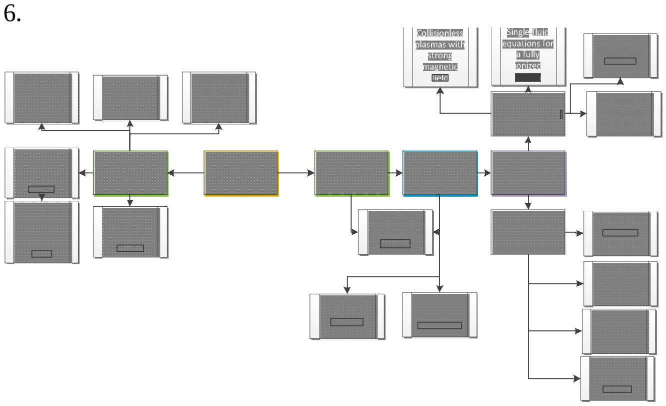


Figure 4. Plasma phenomena physics map [17].

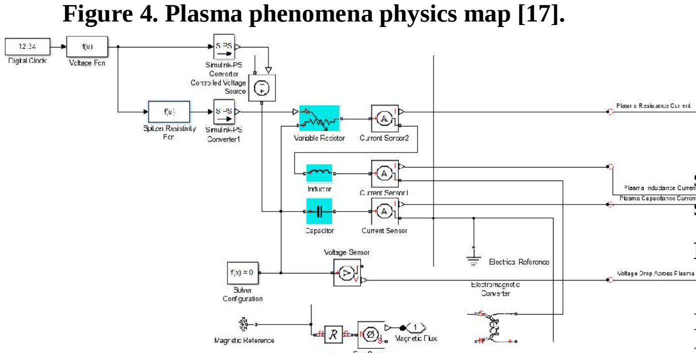


Figure 5.Functional modelling of the electrical components of plasma in HOPE experiment.

The cyan components of the Figures 5 and 6 are the functional representations of the plasma beam occurring between the two plasma jets.

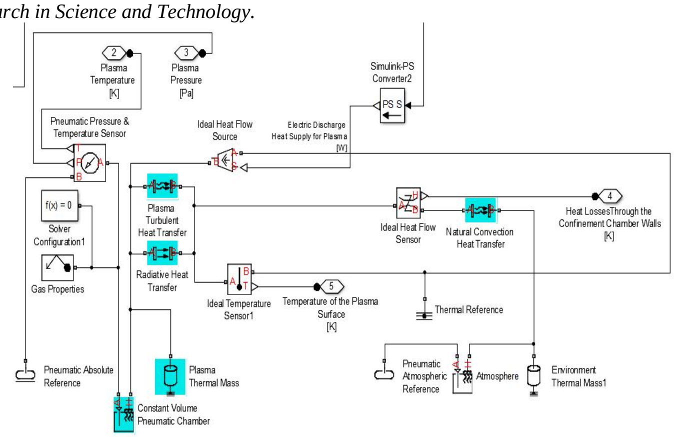


Figure 6.Functional modelling of the thermal components of plasma in HOPE experiment.

Figure 7 shows the analytical representation of the beam of plasma in the form of a slender cylindrical volume exposed to conditions of the room where the experiments have been performed. Circuit analysis has been carried out for the plasma discharge. The plasma discharge circuit in HOPE experiment can be simplified to a series RLC circuit as shown in Figure 7. The RLC circuit consists of two capacitor banks gated by an SCR switch. The initial ionization and the current ramp-up is provided by the fast bank, whereas the plasma current plateau is maintained by the slow bank. The fast and slow capacitor banks are independently charged to voltages denoted by V_f and V_s, respectively. The capacitance of the fast and slow banks is given by $C_f$and C_s, respectively.

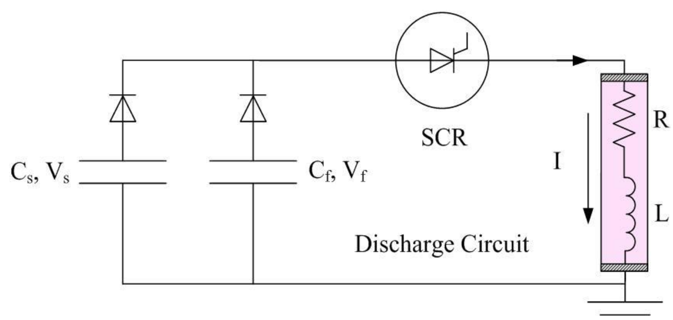


Figure 7.The equivalent circuit representation of the plasma discharge.

The design parameters of the HOPE experiment are showcased in Table 2, these parameters will be used as the system variables for the simulation.

Data Analysis of HOPE Experiment

The data from STERN Laboratories are presented in Figures 8, 9, and 10. Figure 8 depicts the voltage as a function of time, Figure 9 shows a relationship between the negative electrode temperature and the voltage, and Figure 10 shows the plasma current as a function of voltage drop across a 19 centimeter gap. The data shown in the figures below was gathered at a sampling rate of 10 Hz, the reason for this sampling rate is the limitation by the data acquisition equipment provided by STERN Laboratories at the time of experimentation.

Table 2. Design Parameters of the Case Studies

Design Parameters of the Chamber	HOPE Experiment
Electromagnetic Properties	
Maximum DCVoltage [V]	800 [16]
Operational Frequency [Hz]	DC[16]
Maximum Current [A]	20,000 [16]
Plasma Resistance at Breakdown [Ohm]	0.001
Plasma Capacitance [pF]	1.38×10^{-16} [16]
Plasma Inductance at Breakdown [uH]	1×10^{-3}
Plasma Relative Permeability	1
Cross-Sectional Area of Stable Plasma Beam [m^2]	1.257×10^{-5} [16]
Length of Plasma Section [m]	0.19 [16]
Equivalent Number of Turns for the current carrier	2 [16]
Gas/Thermal Properties	
Specific heat at constant pressure Cp [J/(kg*K)]	1007 [18]
Specific heat at constant volume Cv [J/(kg*K)]	719.3 [18]
Dynamic viscosity [s*Pa]	1.983×10^{-5} [18]
Initial Pressure [kPa]	620.5
Initial Temperature [K]	293.15
Stable Plasma Beam Occupied Volume [m^3]	2.388×10^{-6}
Plasma Beam Mass [kg]	7.53982×10^{-6}
Radiation Coefficient [$W/(m^2*K^4)$]	5.103×10^{-8} [18]
Plasma Beam Enclosing Surface Area [m^2]	2.388×10^{-3}
Convective Heat Transfer Coefficient [$W/(m^2*K)$]	91.1 [18]

The process of accounting for all the presented factors in the simulation model is intended to result in an accurate representation of the actual results.

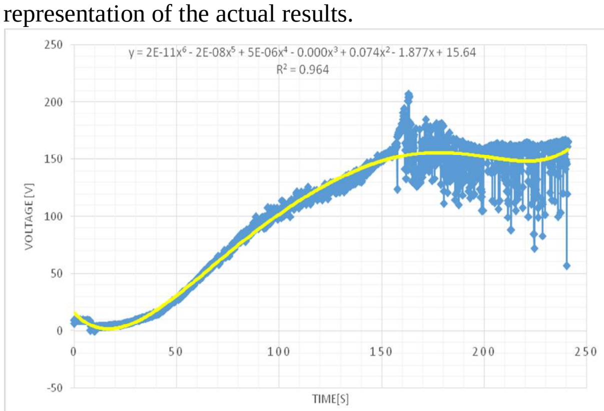


Figure 8. Voltage as a function of time relationship for HOPE Experiment.

The function for the discharge voltage is set to be the input parameter for the simulation model in the Simulink.
The multiple fitting curves shown in Figure 10 are the current functions of voltage are made to match the data within the range of the standard deviation. The solid green curve is a Lorentzian fit represented by the function:

$$I_{plas} = -77.7694 + 2*83{,}621.6407/\pi*81.8554/(4*(V_{plas}-78.5090)^2+81.8554^2)$$

Here, I_{plas} is the current in the plasma generation circuit, likewise, the V_{plas} is the discharge voltage.

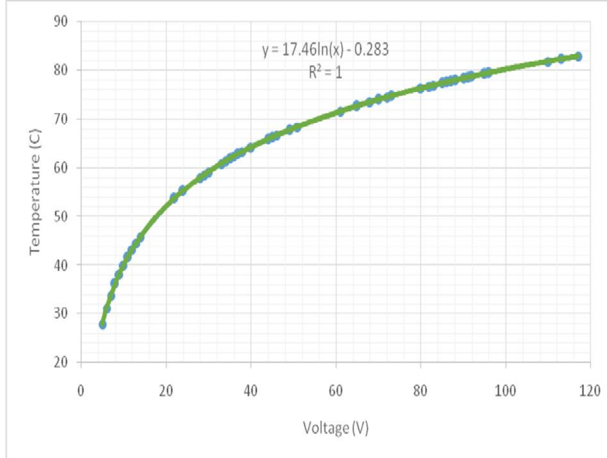
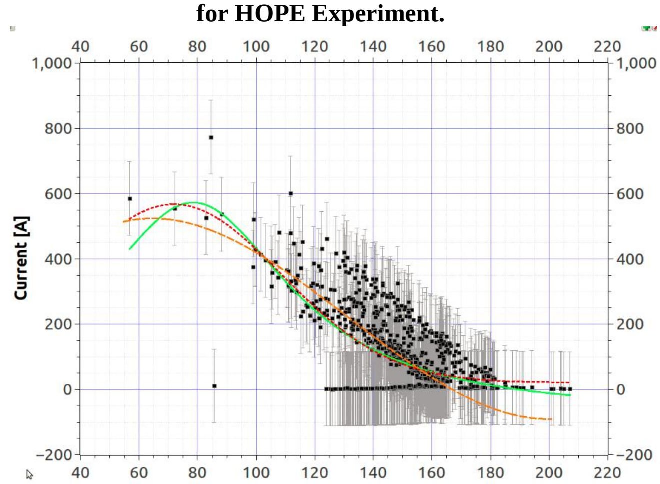


Figure 9. Voltage vs. electrode temperature relationship for HOPE Experiment.



Voltage [V]

Figure 10. Voltage vs. current relationship in the plasma test circuit.

The dotted red curve is a Gaussian fit for the relationship and its corresponding function is

$$I_{plas} = 20.6405 + 50{,}297.4741*sqrt(2/\pi)/73.4289*exp(-2*((V_{plas}-71.9451)/73.4289)^2)$$

Finally, the dashed orange curve is the polynomial fit of the 3rd order on the segment between 50 and 200 V, the associated function of this fit is

$$I_{plas} = -32.965 + 19.332*V_{plas} - 0.1981*V_{plas}^2 + 0.0005*V_{plas}^3$$

It is evident from Figure 10 that there is a non-linear relationship between the current and the voltage in the discharge circuit. It was observed that some instances of current interruptions have occurred, and plasma beam from one of the torches would extinguish partially. The resulting irregularities as seen in the figures are the result of such interruptions, aside from the small sampling rates.

The implications of Figure 10 are that as the supply voltage increases, the plasma resistivity increases exponentially due to the increasing inter-molecular interactions of the composing ions. The voltage drop is believed to be caused by the protective circuitry in the power supply, which is designed to prevent short-circuiting. It seems that the arcing between the electrodes somehow triggers the protective circuitry, as this arcing (high current) is seen as a short circuit, causing a drop in voltage. This function is implemented in the Simulink representation of the experiment along with the parameters identified in Table 2.

CONCLUSION

The first objective of the current work was to review different fusion literature and develop a foundation for plasma studies. The knowledge and information gained was applied in the project implementation and further planning of the possible plasma experiments.

Secondly, the analysis and understanding of the plasma experiment at STERN was performed to see the existing experimental settings and their potential in the research area of dense plasmas. In the long run, these experiments will be supported by fundamental modeling techniques that help establish a better understanding of the dense plasma behaviour.

Finally, it is recommended to establish a laboratory setting at UOIT to further investigate plasma phenomena and test control. The procedure to install the facility will be founded on principles of safety by identifying different risks associated with conducting experiments.

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