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Analysis of Gas Breakdown and Electrostatic Simulation Characteristics of a Spherical Inertial Electrostatic Confinement Fusion Chamber (SIEC-K)

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ABSTRACT

In this study, a spherical inertial electrostatic fusion (SIEC-K) chamber is designed, built and operated to analyze electrostatic characteristics and gas breakdown conditions. The fusion chamber consists of two spherical electrodes; where the anode is the outer chamber of the chamber made out of two aluminum hemispheres and the cathode is a combination of stainless-steel wires forming a cage like structure aligned within the center. Design considerations and processes are introduced as the execution of this technology sustains the fundamental grounds to understanding gas breakdown. The conditions for gas breakdown are that under a low pressure environment where a certain potential difference is created between two electrodes, a deep potential well will be formed within the cathode region. The gas filled in the chamber will be ionized and the nucleus of the atoms will be accelerated towards the negative potential well, creating gas breakdown. Considering that this study will not focus on nuclear fusion reactions, the main fuel source is chosen to be air and it is also very convenient to operate with. Electrostatic simulation was made to estimate the plasma region inside of the SIEC-K chamber and check if the proposed design is in accordance with the literature, which is to validate the formation of the potential well within the structure of the cathode. The pressure-voltage values within the range of hardware limitations (1-6 kV) for gas breakdown values are recorded and qualitatively compared to their corresponding values for linear Paschen's gas breakdown voltage law. The main motivation behind this study is to uncover the basis of plasma characteristics of the SIEC-K Reactor for future studies.

Keywords: Gas breakdown, Spherical inertial electrostatic fusion chamber (SIEC-K), Spherical electrode geometry, Electrostatic simulation, Low pressure air

1. Introduction

Small scaled fusion device technologies promise many applications ranging from portable neutron sources to medical isotope production Fig.1 [1]. The potential of this technology has created a source of motivation for many studies which in consequence created countless approaches to building a fusion reactor. The scope of this study is limited to Inertial Electrostatic Confinement fusion reactors, best known as Farnsworth-Hirsch fusor, the design specifications of which was established in 1967 [2]. Within the scope of IEC fusion reactor technology, a unique operational design is created after electrostatic simulations and then, the gas breakdown pressure-voltage values are extracted from the reactor setup. Due to limitations in funding and the safety

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considerations of the researcher, nuclear operations of the designed reactor will be the subject of future studies after necessary resources and safety precautions are allocated accordingly. System elements of an IEC fusion reactor is given in Fig.2.

Under a low-pressure environment, which indirectly controls the flow of the fuel, IEC devices generate an electrical potential difference when a negative voltage of few kilovolts is generated at the inner grid [3]. Positive ions fall within this negative voltage area, creating a potential well.

Gas breakdown threshold value depends on the nature of the potential well formed, and is directly related to the voltage value and cathode geometry [4].

Theory of potential well in the IEC fusion reactors are formulated by two fundamental principles; ion injected or electron injected structures [5]. The nature of the structure depends on the polarity of the spherical electrodes, in other terms, determined by the type of particle to be accelerated towards the center of the reactor geometry. For gas breakdown applications, the particle of interest is the nuclei of the chosen fuel, therefore, the

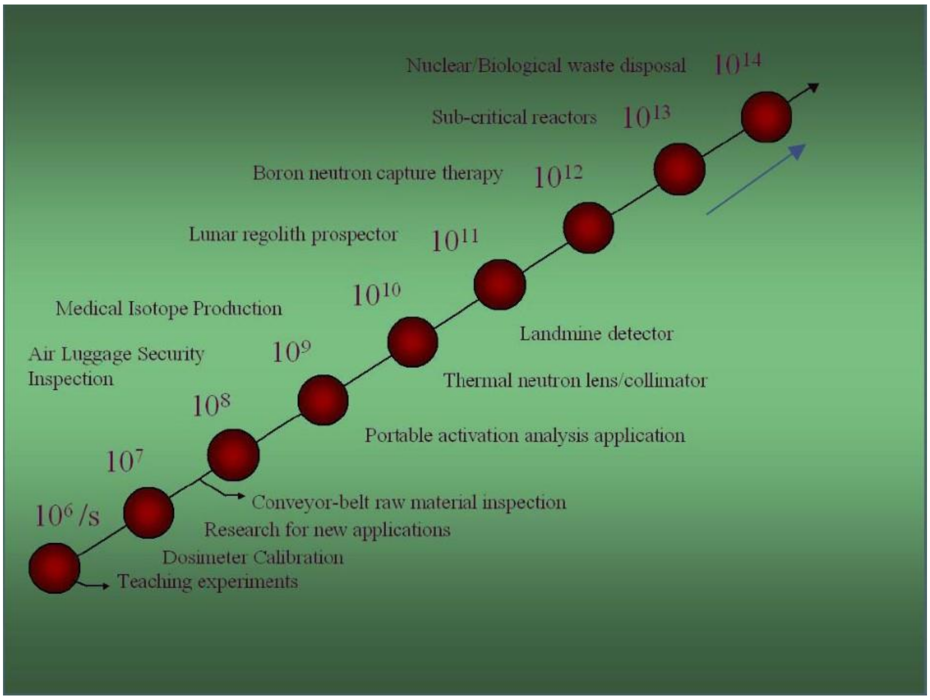

Fig.1 *Possible applications of an IEC device [1]*

If the ion density is large enough, a visible plasma is created and the conditions for gas break down are satisfied.

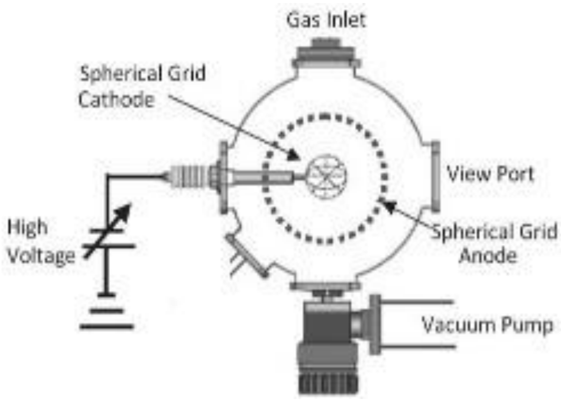

Fig.2 *System elements of an IEC fusion reactor [7]*

injection polarity is set to ion injection and the polarity of the reactor electrodes are chosen accordingly.

The fundamental components of an IEC fusion reactor are the inner and outer electrodes, vacuum chamber, roughing pump, power supply and the fuel delivery system [6]. For experimental purposes, the designed system also includes an analysis system, which is fitted to measure the voltage-pressure values.

2. Material and Methods

2.1 2D Electrostatic Simulation

The generation of electrostatic potential well necessary for ion confinement depends on well structure [9]. 2D electrostatic simulation is required to estimate the region of the deep potential well, which will also project the region of the reactor where the plasma is expected to be observed. For this purpose, QuickField simulation software is utilized [10]. The input parameters of for the electrostatic simulation is given in Table 1, which is elaborated in the design methodology and experimental setup section.

Table 1: Electrostatic simulation parameters

Parameters	**Anode**	**Cathode**
Diameter (cm)	25.5	5
Potential (V)	0	6000
Electric Permittivity (F/m)	8.8542×10^{-12}	8.8542×10^{-12}

2.2 Paschen's Law

Paschen's law is an electrostatic approach to analyze the level of ionization required within a system of two parallel electrodes, which depends on the type of gas, the distance between electrodes and the pressure within the system [8][11]. Equation (1) yields a voltage V_b, which is the gas breakdown voltage value. Considering that the experimental setup will have fixed values for the distance between electrodes, V_b will depend on the pressure of the system, which also determines the amount of fuel.

$$V_b = \frac{Bpd}{ln(pd) + k}$$
$$k = ln\left[A/ln(1 + \frac{1}{\gamma})\right] \qquad (1)$$

Furthermore, the type of gas is set to air, the parameter and resulting values of which are given in Table 2 and Fig.3.

Table 2: Paschen's Law constant values for air [12]

Coefficient	**Value**
Secondary ionization, γ	0.01
Saturation ionization, A *(cm^{-1} $Torr^{-1}$)*	15
Excitation, B *(cm^{-1} $Torr^{-1}$)*	365

Table 3: Paschen's Law constant values for air [12]

Design Part Number	**α (°)**	**β (°)**	**Length (cm)**	**Flange**	**Function**
(i)	0	0	9	KF40	HV Feedthrough
(ii)	0	50	3.4	DN50CF	Viewport
(iii)	315	45	3.2	KF25	Vacuum Gauge Inlet
(iv)	45	40	3.2	KF25	Fuel Inlet
(v)	0	180	5.3	DN16CF	Vacuum Pump Inlet

2.3 Design Methodology and Experimental Setup

IEC device and the experimental setup for achieving gas breakdown consists of four main systems; chamber, vacuum, power and fuel. Experiment setup is given in Fig.4 and Fig.5.

2.3.1 Chamber System

IEC device has a spherical geometry, consisting of five interfaces: the fuel input, vacuum pump gauge, high voltage cathode feed through, digital manometer probe input and a viewing window. Each element is positioned to the chamber design accordingly, given in Table 3. The outer chamber is also utilized as the anode. Chamber design and production steps are given through Figs. 6-10.

2.3.2 Vacuum System

A roughing pump capable of reaching 10^{-2}-10^{-3} millibars of pressure is used to conduct gas breakdown studies [13]. Considering the fact that the main fuel is used air within the scope of this study, there is no need to

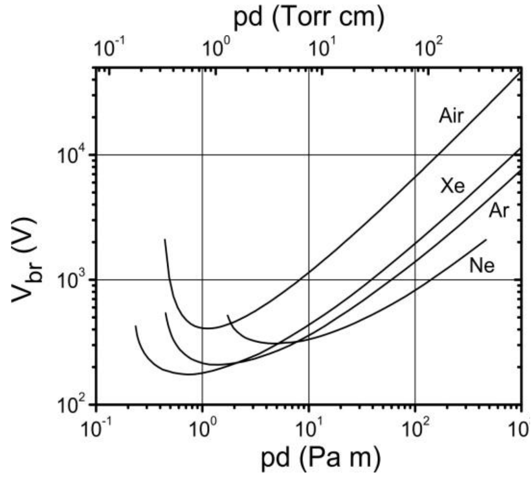

Fig.3 *Paschen's curve for air [11]*

completely evacuate the air inside of the chamber as it is not considered to be a contaminant. For possible future studies involving fusion reactions, the gas inside of the reactor chamber must be strictly controlled and a vacuum system capable of reaching deep vacuum must be considered.

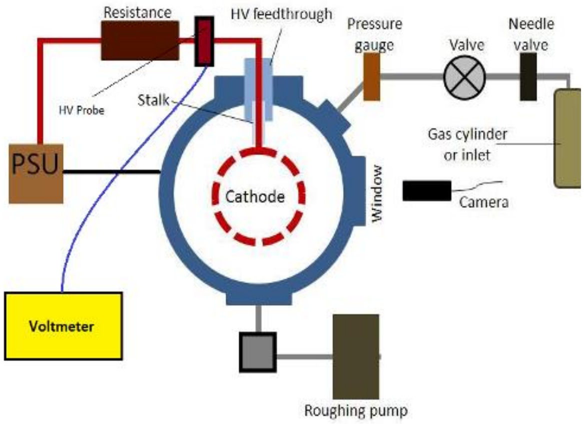

Fig.4 *IEC Device Experimental Setup [4]*

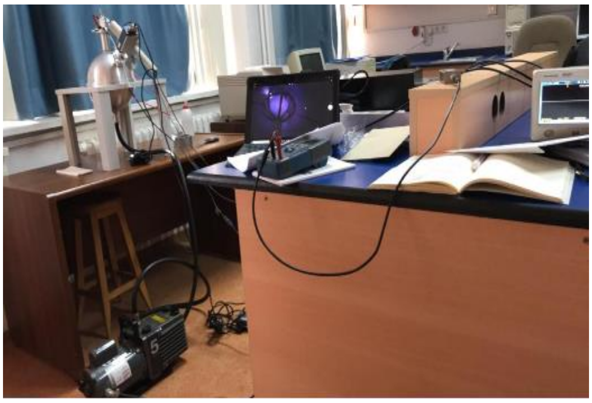

Fig.5 *The experimental setup for gas breakdown analysis of SIEC-K.*

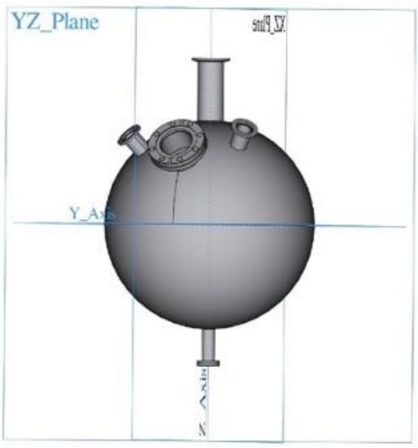

Fig.6 *Axial view of the reactor chamber*

Fig.7 *Aluminum blocks before being processed into two hemispheres of the chamber system*

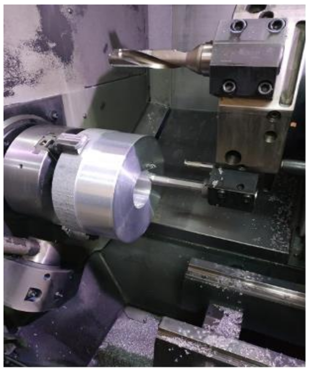

Fig.8 *CNC processing of the aluminum blocks*

Fig.9 *Post-CNC manufacturing, basic spherical geometry reached*

Fig.10 *Completed chamber system with attached parts*

2.3.3 Power System

The power delivery is composed of a DC power source rated at delivering a maximum of 6000 volts, connected to the cathode through a 55 kΩ resistor in series to limit the current. For this study, the state of the plasma should be glow-discharge, which is directly linked to the current given to the system, seen in Fig.11. Furthermore, a VARIAC, a HV probe and HV feed through are essential to the operation and measurement of voltage values of the system. The cathode-anode diameter ratio is chosen to be around 20%, similar to successful operations dictated in literature [4].

2.3.4 Fuel System

As aforementioned, main source of fuel is determined to be air for the scope of this study. For delivering the fuel to the reactor chamber in a controlled manner, a needle valve is attached directly to the chamber where the input is left open to be exposed to the atmosphere.

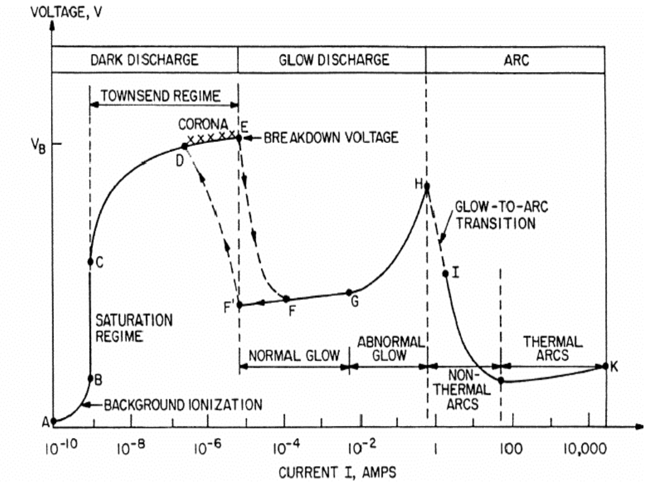

Fig.11 *Plasma phases [14]*

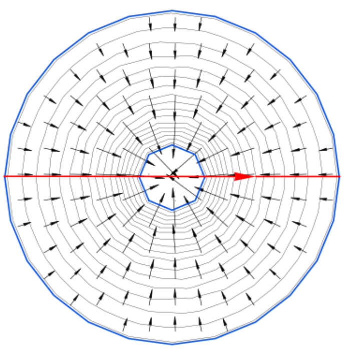

Fig.12 *Ion displacement vectors (in black) and contour (in red) where the potential values inside the reactor depending on distance is simulated upon [13]*

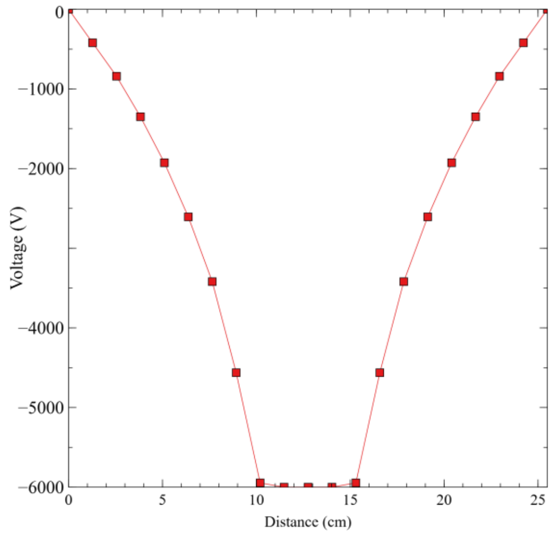

Fig.13 *Distance versus potential graph from simulation [13]*

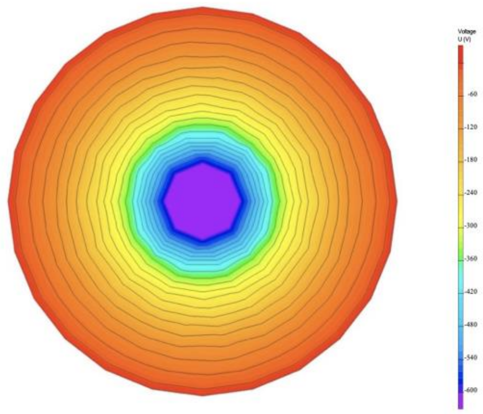

Fig.14 *Electrostatic simulation visualization of the reactor model [13]*

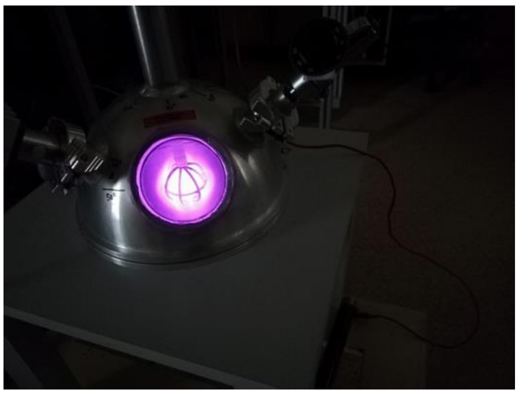

Fig.15 *Gas breakdown through view port of SIEC-K*

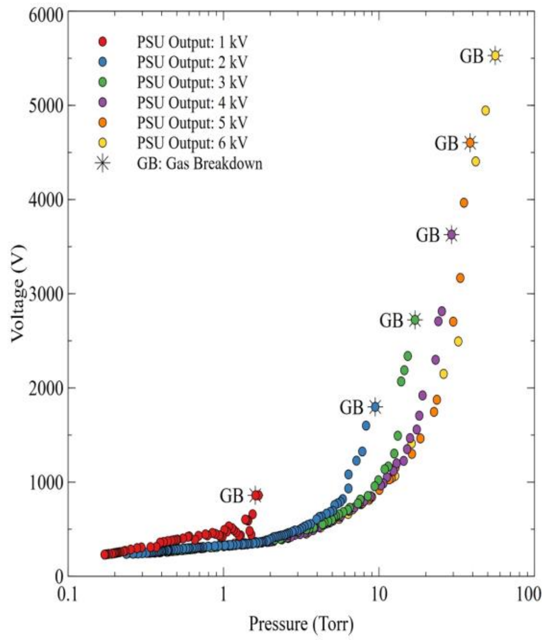

Fig.16 *Pressure-Voltage values for PSU outputs*

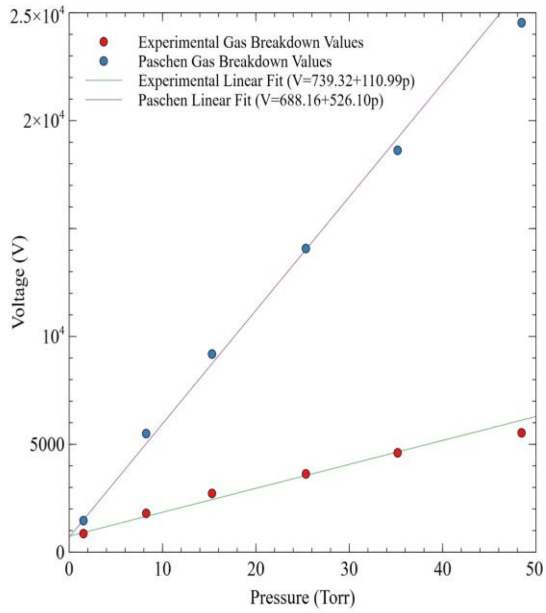

Fig.17 *Experimental and Paschen's gas breakdown values in linear fit*

3. Results and Discussion

3.1 Electrostatic Simulation Results

The 2D electrostatic simulation results clearly validate the formation of a potential well within the center of the reactor (inside the cathode) as indicated in Fig.13 and Fig.14. The chosen parameters for the chamber design of SIEC-K chamber are confirmed and gas breakdown is expected to be at the center of the reactor, where the ion displacement vectors direct to, seen in Fig.12.

3.2 Experimental Results

A clear visual representation of gas breakdown can easily be observed from the view port of the chamber, given in Fig.15. Furthermore, the voltage value seems to drop drastically at the instance of gas breakdown, which also confirms the formation of plasma without visual aid. Several gas breakdown voltage-pressure values set by the limitations of the power supply unit are given in Fig.16 [13].

With the impediment of the used hardware, only a small range of the pressure-voltage values are observed, given in Fig.3. Within the range of 1-6 kV, the extracted gas breakdown values can be assumed to show a linear relationship, seen in Fig.17. Under this assumption, spherical compared to linear geometry appears to be more favorable as it requires a smaller amount of potential difference to reach gas breakdown under the same pressure. If a linear relation is to be extracted within the given voltage range for the experimental gas breakdown values, it will yield $V_b = 110.99p + 739.32$. Although this expression produces somewhat reliable values within 1-6 kV potential range, for values outside, an expression cannot be established.

4. Conclusion

In this study, a spherical IEC device was designed after validating key elements such as the formation of the potential well to trap positive ions by electrostatic simulation, built bearing in mind the experimental goal of achieving gas breakdown and the breakdown results obtained from the experimental setup were qualitatively compared to Paschen's law. Spherical electrode geometry resulted in lower voltage values when we compared to those calculated from the Pashen's law for linear geometry at the same pressure values. A linear relation between breakdown voltage and pressure data was estimated for SIEC-K chamber between 1-6kV potential range when air was used as a fuel. One must mention that this relation cannot produce reliable results outside of the boundaries set by the limitations of the used hardware. As established by the simulation findings, the plasma was observable in the deep potential well, which is the spherical cathode region. This paper is a result of exploring the initial experimental operations regarding gas breakdown voltage-pressure values for IEC devices by utilizing the hardware at one's disposal to its limits. In the future, insights gained from this operation can be used to expand the gas breakdown studies using better hardware to explore a wider spectrum of the breakdown voltage-pressure relation for the spherical electrode scenario.

Conflict of Interest

The authors have no conflict of interest.

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References

[1] K. M. Subramanian, Diagnostic study of steady state advanced fuel (deuterium-deuterium and deuterium-tritium) fusion in an IEC device. The University of Wisconsin-Madison, 2004.

[2] M. Smith, "Confining plasma in a spherically-convergent electrostatic potential well: the Farnsworth-Hirsch fusor," 2005.

[3] G. M. El-Aragi, "Building Inertial Electrostatic Confinement Fusion Device Aimed for a Small Neutron Source," High Energy Physics, vol. 4, no. 6, pp. 88–92, 2017.

[4] S. H. M. van Limpt, "Characterization of fusor jets," 2013.

https://research.tue.nl/en/studentTheses/characterization-of-fusor-jets

https://pure.tue.nl/ws/portalfiles/portal/67737681/851859-1.pdf

[5] G. H. Miley and S. K. Murali, "Inertial electrostatic confinement (IEC) fusion," Fundamentals and Applications, 2014.

[6] G. M. Elaragi, "Operation of Inertial Electrostatic Confinement Fusion (IECF) Device Using Different Gases," Journal of Fusion Energy, vol. 37, no. 1, pp. 37–44, 2018.

[7] E. C. G. Hermans, "The design and optimization of an inertial electrostatic confinement fusion device-Eindhoven University of Technology research portal," feb 2013.

[8] P. Mathew, J. George, T.S. Mathews, and P. J. Kurian, "Experimental verification of modified Paschen's law in DC glow discharge argon plasma," AIP Advances, vol. 9, no. 2, p. 025215, 2019.

[9] M. Ghasemi, M. Habibi, and R. Amrollahi, "Prediction of potential well structure formed in spherical inertial electrostatic confinement fusion devices with various parameters," Journal of Plasma Physics, vol. 79, no. 3, p. 295, 2013.

[10] QuickField Simulation Program, https://quickfield.com/allnews/qf64.htm, "Student Edition 6.4," Svendborg, Denmark, 2020.

[11] E. Wagenaars, "Plasma Breakdown of Low-Pressure Gas Discharges," p. 177, 2006. https://pure.tue.nl/ws/portalfiles/portal/2206211/200612099.pdf

https://research.tue.nl/en/publications/plasma-breakdown-of-low-pressure-gas-discharge,available: 10.6100/IR614696

[12] A. A. Martins and M. J. Pinheiro, "On the propulsive force developed by asymmetric capacitors in a vacuum," in Physics Procedia, vol. 20. Elsevier B.V., jan 2011, pp. 112–119. [Online]. Available: 10.1016/j.phpro.2011.08.010

[13] A. Fettahoglu, "How does pressure effect the plasma breakdown voltage of air as a fuel source in the designed IEC fusion reactor?" Ankara, March 2019. [Online]. Available: http://tedprints.tedankara.k12.tr/939/

[14] E. B. Sozer, "Gaseous Discharges and Their Applications as High Power Plasma Switches," Auburn University, May 2008.