The Plasma Characterization of Argon and Helium Gases in Inertial Electrostatic Confinement Fusion Plasma Device

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Abstract

One of the numerous methods that could be used in order to confine hot fusion plasma is the Inertial Electrostatic Confinement (IEC) fusion. IEC plasma device was studied experimentally with Argon and Helium gases at different pressures. IEC will be supplied with an electric field to heat ions to suitable conditions for nuclear fusion. IEC fusion plasma device must be required to control plasma shape, color, and parameters easily. The inner electrode (cathode) and the outer electrode (the anode) were established with specific characteristics and features. Using Paschen's Curve, it is concluded that, the breakdown voltage (V_b) depends on the product of the working gas pressure (P) and the gap distance between two electrodes (d). The minimum breakdown voltages$(V_b)_{min}$are 97.82volts at$Pd = 0.5\, torr.cm$ and 74.72volts at $Pd = 2\, torr.cm$for the Argon and Helium gases respectively i.e. the minimum breakdown voltages $(V_b)_{min}$for Argon gas is higher than minimum breakdown voltages for Helium gas. The Townsend Second Ionization Coefficient dependson the type of gas, the material of cathode, and reduced electric field (E/P).The visible light intensity of Argon glow plasma was found to be greater than Helium glow plasma.

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1. Introduction

The devices of inertial electrostatic confinement work by using the electrostatic field to confinement the particle of plasma. In this device, the ions are recycled through the cathode grid, trapped, and remain within the system until they collide with the neutrals and the background ions, and the wires of the cathode grid. Consequently, the concentration of secondary electrons increases nearby the center region.P. Farnsworth proposed the theoretical concept of IECF for the first time and later R. Hirsch studied an experimental IECF concept [**1**]. One type of the fusion power devices is the Inertial Electrostatic Confinement (IEC) which uses electric field in order to confine the plasma rather than using magnetic fields which is a more common method that is available in the Magnetic Fusion Energy (MFE) designs. The plasma processing or the process of hot plasma confinement for fusion is a hard and rather difficult process due to the inability to use a material confinement vessel because of the hot plasma [**2**]. IEC fusion offers many potential advantages, including simplified support structures and the ability to create non-Maxwellian plasmas that can be used with a variety of fusion fuels. The IEC device is characterized by its simple construction and also has an important trait which is providing a relatively high fusion rate in a small volume. The IEC is a unique approach to fusion in that electrically driven units offer a number of near-term “spin-off” applications. In order to generate fusion plasma for research and industrial applications, inertial electrostatic confinement provides a relatively simple and cost-effective method [**3**].

The idea of building a machine capable of achieving stable nuclear fusion and producing clean energy has been around for decades. A result of the strongly repulsive electrostatic forces between protons, the ions accelerate to reach their maximum speed, at which the attractive nuclear force that binds protons and neutrons to each other is generated in the nucleus and overcomes the repulsive electrostatic force, which causes the protons to approach each other and they can fuse, then the energy released [**4**].The fusion of inertial electrostatic confinement (IEC) provides an alternative method for magnetic confinement instead; the devices are used as compact neutron generators for medical isotope production, neutron imaging, and security applications [5].

The aim of this research is to examine the characteristics of two gases: Aragon and Helium gases, after fusion process using Inertial Electrostatic Confinement fusion plasma device and investigate experimentally some of the electrical parameters for both gases. Part of this work devoted to study the effect on the fusion plasma caused by the changes in voltage, current, and pressure. Moreover, the unique plasma characteristics for the color and shape of both gases were recorded during glow discharge using camera monitor. Also, to have a comprehensive overview of the characteristics of Aragon and Helium during fusion, the breakdown voltage is an important factor to be recorded.

2.Materials and Methods

Inertial Electrostatic Confinement (IEC) Plasma is generated between two concentric electrodes at high voltage and low pressure, and then the formation of glow discharge takes place. Relatively homogeneous electric field is produced by the electrodes which consist of stainless-steel wire structures. Inertial Electrostatic Confinement fusor consists of two electrodes, generally in spherical symmetry.First electrode is called cathode (inner grid) and other electrode is the anode (outer grid).Cathode is connected to negative high voltage and is located inside the anode which is connected to the ground. IEC include two pairs of spherical electrodes which are located inside discharge chamber made of Pyrex glass which its diameter and height are 0.10 m and 0.30 m respectively, which ismounted between two bases, the two electrodes are isolated from each other by an insulator such as Perspex, the gap between to electrodes is 0.01 m.

Difference pumping is used inside vacuum chamber to achieve a pressure of ~10^{-2}Torr. A stainless-steel wire of diameter 0.001 m represented the IEC cathode grid. High voltage insulation is supplied by ceramic feed through system that is reached into the center of the chamber and connected to the cathode grid. The diameter of inner electrode is 0.028 m. The outer electrode was constructed from stainless steel wire with diameter is 0.002m, as inner electrode was created from stainless steel with diameter wire 1mm. **Fig.1** shows the experimental device of the IEC plasma in the laboratory.To adjust the gas mass flow rate, the injection process of

Helium and Argon gas will be done through the mass flow controlled into quartz tube. The typical operating pressure is $8x10^{-2}$ – 1.0 Torr for Helium and Argon gases.

At the beginning, there are will be a water vapor, grease, surface contaminants and additional impurities inside the vessel if the vacuum vessel was opened recently. For chamber preparing measurements, it takes about 20-30 minutes for surface cleaning and the impurities are pumped outside of the system.The vacuum chamberof glass tube is washed by gas after clearing by the rotary pump, to prevent vapor from back streaming.The IEC device is straddling on a laboratory table.

When the device is connected to an electric field, positive ions move towards to cathode grid and collide in the center, and then they can fuse with enough energy to make a fusion case [**2**]. When connecting the inner grid to negative voltage, a glow discharge starts. Electrons move towards to the positive charged (outer grid) when the gas pressure is low in the vessel[**6**].

When the acceleration of ionshappens in the direction of the inner cathode, causing them tocollide with each other in the center, the high temperature plasma is generated by the transformation of their kinetic energy into thermal energy.

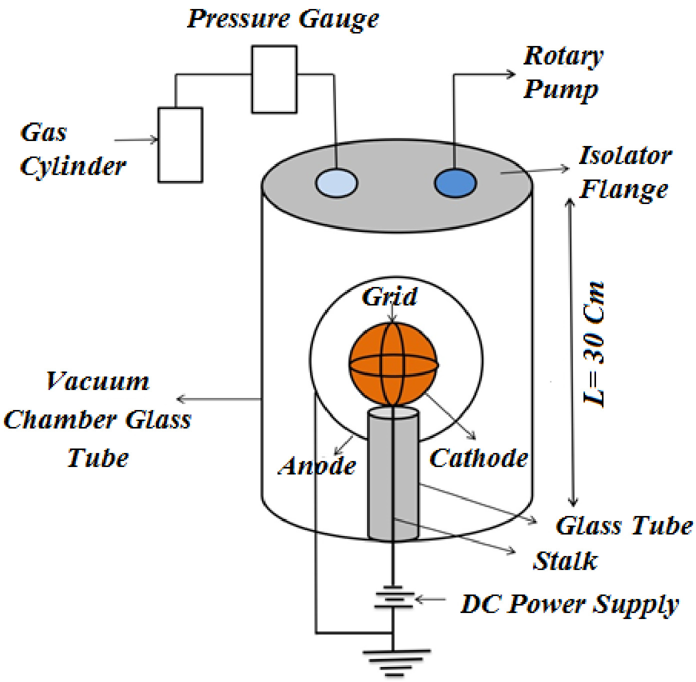

Fig.1: IEC Experimental Setup

2.1 Breakdown Voltage and Paschen's Law

Break down voltage is a significant factor for a device of gas discharge. The increase in the cathode voltage causes the initiation of the plasma discharge till breakdown occurs. There are three main steps for the performance of Paschen's curve: first when breakdown voltage has high values, and at lower value, it tends to dropped sharply, then again it rises to high breakdown voltage. Paschen's rule (**Fig.2**) indicates that, the breakdown voltage (V_b) depends on the product of $(P)$and(d), where $(P)$the working gas pressure and $(d)$is the electrodes distance [**7**].

$$\mathbf{V_b}=\frac{\mathbf{B(Pd)}}{\mathbf{C+ln\ (Pd)}} \qquad \textbf{(1)}$$

$$;\boldsymbol{C} = \ \mathbf{ln}\,\boldsymbol{A} - \ \mathbf{ln}\left[\mathbf{ln}\left(\mathbf{1}+\frac{\mathbf{1}}{\boldsymbol{\gamma}}\right)\right] \qquad \textbf{(2)}$$

; where B, C are constants

The Townsend Second Ionization Coefficient (γ) dependson the type of gas, the cathode material and reduced electric field (E/P) [**8**]. WhereV_b, d andPare the breakdown voltage (volts), the gap distance (cm), and the gas pressure (torr or mbar) respectively.

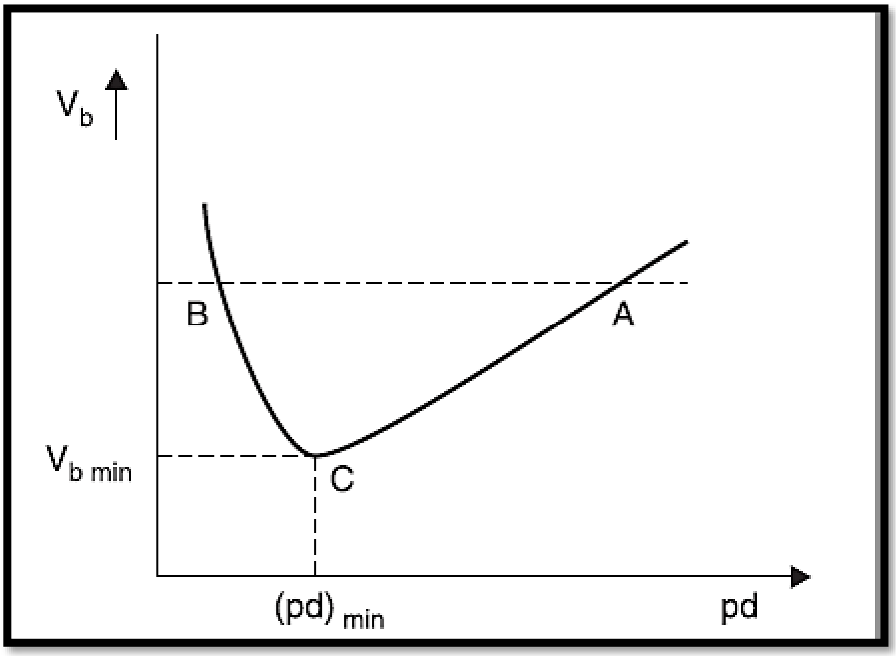

Fig.2: Paschen’s law curve [9]

In Paschen's curve, the minimum breakdown voltage may be explained as: Electrons passing the gap, create reiterated collisions with gas molecules more than at$(Pd)_{min}$, but the energy acquired between collisions is lower, for values of $Pd > (Pd)_{min}$. Consequently, to keep the desired ionization more voltage must be applied. Electron can pass the gap without creating a collision or even making fewer numbers of collisions only to obtain it$Pd < (Pd)_{min}$, when breakdown occurs more voltage must be applied to maintain the required ionization [**9**].

2.2 Townsend's Coefficients

Paschen's law illustrates the gas breakdown phenomena.Townsend's First Ionization Coefficient (TFIC) α is defined as the number of electrons produced by an electron per unit path length in the field direction. As the electric field condenses, the Townsend Ionization Coefficient becomes high enough to convert non self - maintained current into self-maintained current, and then electric breakdown occurs. The Townsend First Ionization Coefficient(α) depends on the gas pressure, type of gas and the reduce electric field (E/P) [**10**] is expressed as:

$$\boldsymbol{\alpha = PA\left[\frac{B}{E/P}\right]} \qquad \textbf{(3)}$$

; where*A* and *B* are constants, (P)is the pressure of gas, and finally (E) is the electric field [**11**].Due to the electric field, the emission of electrons from the negative electrode is accelerated by positive ions. In addition to first ionization coefficient (α), there is another important parameter in the Townsend system is the effective secondary electron emission coefficient, or Townsend's Secondary Ionization Coefficient (TSIC) i.e. the rate of γ electrons per incident ion [**12**]. Secondary ionization coefficient (γ)depends on the material of electrode, on the nature of the filling gas used and adds to on the ratio E/P [**7**]. It is related to Townsend's First Ionization Coefficient (α) by the following equation:

$$\boldsymbol{\gamma = \frac{1}{\exp\left(\frac{\alpha}{P}Pd\right)-1}} \qquad \textbf{(4)}$$

3. Results and Discussion

Argon and Helium gas supplied in the system until pressure started to rise using the needle valve. The gas flow system is using gas cylinder and flow meter to measure the flow rate. The camera monitor and current signalwere monitored for predicted plasma indicators. When plasma was seen visually and through increasing grid current, pressure was steady with the needle valve. Classifications were recorded for plasma properties including and color. Stable collections of current, voltage, and pressure were recorded. It is easy to determine the effects on the plasma due to the change in voltage, pressure and current.Helium gas the orange color glow is caused by electrons emitted from inner grid which called cathode.With increasing voltage, the plasma light is focused in center and on all sides of the vacuum chamber. Glow discharge of Helium gas is shown in **Fig.3**. Argon gas the blue color glow is caused by electrons emitted from inner grid. With increasing voltage concentrated the light of the plasma in the center and on one side from the vacuum chamber. Glow discharge of Argon gas is shown in **Fig.4**.Further increase in voltage caused the plasma concentered in brightness in the center.A Rogowiski coil which can be located upon returning to the ground measuresthe current flowing through air.

Fig.3: Helium gas's glow discharge **Fig.4: Argon gas's glow discharge**

The discharge current increases by increasing the discharge voltage. **Figs. 5&6** illustrate the correlation between discharge current (mA), and the discharge voltage (kV), for both Argon and Helium gases.

The current increases gradually at higher voltages, when electrons are pull out from the surface of cathode per unit area.

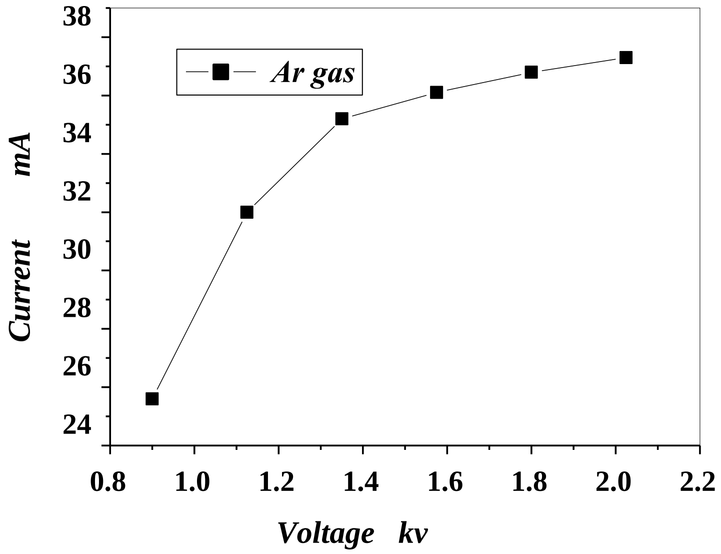

Fig.5: The correlationbetween discharge Current (*mA*)and discharge voltage (*kV*)for Argongas

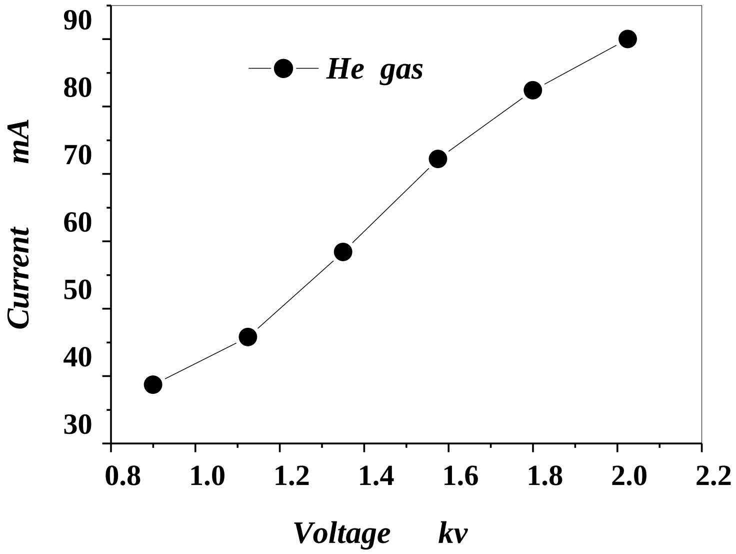

Fig.6: The correlationbetween dischargecurrent (*mA*) and dischargevoltage (*kV*) for Helium gas

The electron mean free path became large at low pressure,afterwards,electrons acquire a large amount of energy from the supplied electric field which cause to produceadditional excitations and ionizations caused by their inelastic collisions with other plasma particles, the intensity of visible light will be raised as a result, during emission transmission andthe ions recombination with the electrons. **Fig.7** shows the intensity of visible light released from Argon and Helium glow plasmas at different pressure.

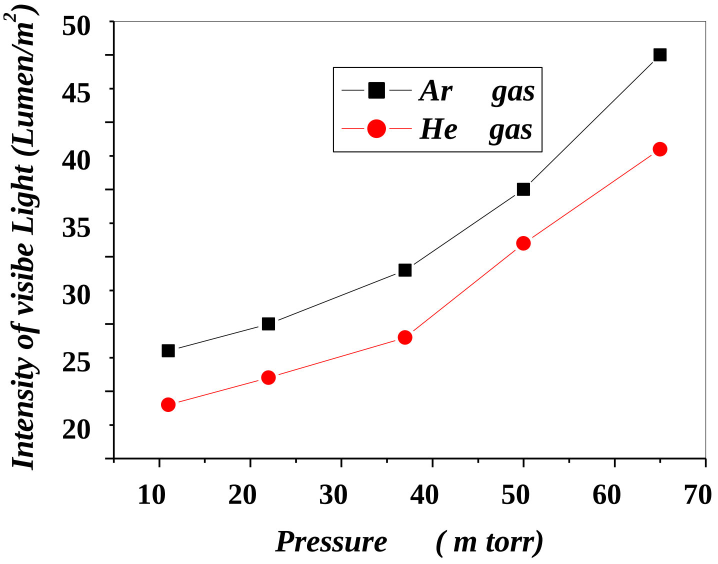

Fig.7: The comparisonof the correlation of visible light intensity and pressurebetween Argon and Helium glow plasma

The intensity of visible light tends to increase with the increase in pressure for the two previously mentionedgases. Intensity of visible light is measured using a lux meter is called light-meter [Model LX-101A].

Table 1presents the breakdown voltage and Pd measurementvalues for Helium and Argon gases.

Table1: Break down voltage for Helium andArgon gases at different pressures

Gas	**Pd** (***Torr.cm***)	**(*Volt*)$V_{\text{break down}}$**
Helium	1.00	154.54
	1.50	82.25
	2.00	74.72
	2.50	74.82
	3.00	77.86
	4.00	85.00
	4.50	88.95
	5.00	93.40
Argon	0.30	131.70
	0.50	97.82
	0.80	103.59
	1.00	111.80
	1.50	134.32
	2.00	156.52
	2.50	178.14
	3.00	200.00
	4.00	240.00
	4.50	260.00
	5.00	280.37

From **Fig.8**, it is observed that the minimum breakdown voltage value $(V_{\text{br}})_{min}$ for Helium gas is 74.72 Volt at the intermediate value of $(\text{Pd})_{min}$ value is 2 Torr.cm.While the minimum breakdown voltage value $(V_{\text{br}})_{min}$ for Argon gas is 97.82 Volt at the intermediate value of $(\text{Pd})_{min}$ value is 0.5 Torr.cm.

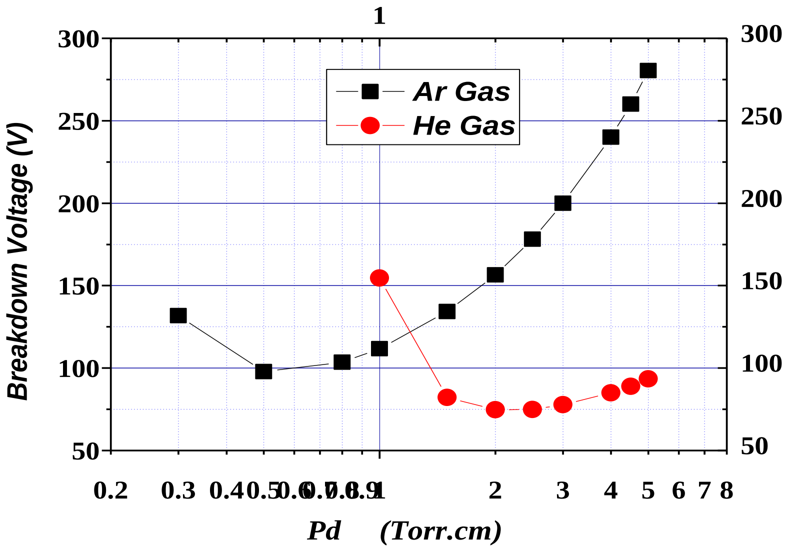

Fig.8: Breakdown voltage comparison for Helium and Argon gases

It is clear that, $(V_{br})_{min}$value for Argon gas is higher than $(V_{br})_{min}$ value for Helium gas (**Fig.8**). A longer mean free path of electron was noticed at low gas pressure, however, less collision probability than that when the gas pressure is high was noticed, therefore, there were few collisions. Accordingly, more energy is needed in order for electrons to ionize the neutral atoms.

The measurement values of Townsend First Ionization Coefficient (α) and the reduce electric field (E/P) for both two gasses are recorded in **Table 2**.

Table2: The Townsend First Ionization Coefficient (α) and the reduce electric field (E/P) for both two gases.

Gas	**E/P (*V/cm*)**	**(TFIC)α**
Helium	400	2.75536
	444	2.77884
	500	2.80278
	666	2.85069
	800	2.87517
	1000	2.89971
	2000	2.94943
	1333	2.99235
Argon	400	7.65000
	666	9.16000
	800	9.58000
	1000	10.0200
	1333	10.4800
	2000	10.9600
	2500	11.1600

The dependence of Townsend First Ionization Coefficient (α) on the reduce electric field (E/P) for both two gasses is shown in and **Fig.9**.

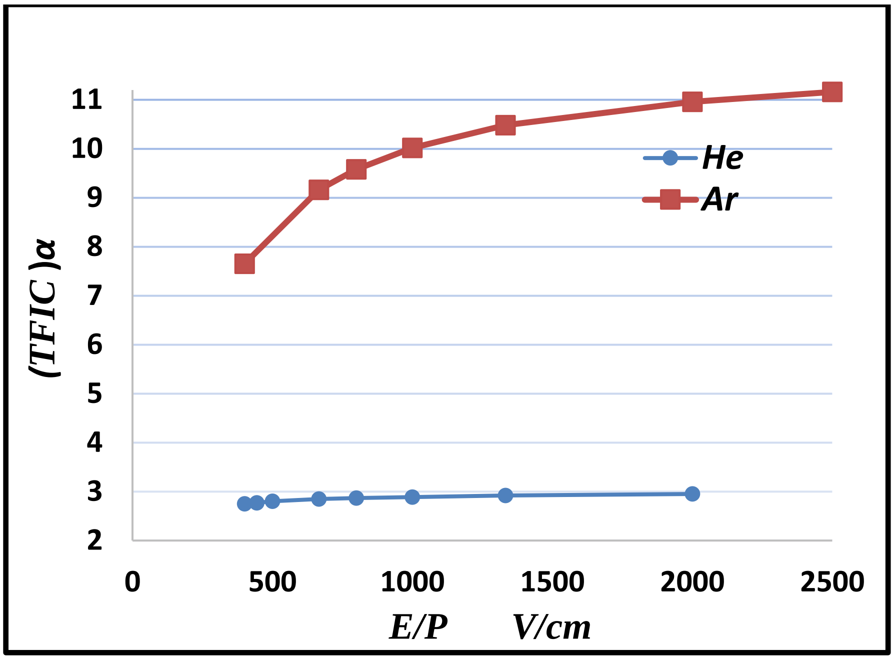

Fig.9: Townsend First Ionization Coefficient(α)forHelium and Argongases

It is clear that from **Fig.9**, the Townsend First Ionization Coefficient of Argon gas is higher than the Townsend First Ionization Coefficient of Helium gas.

The measurement values of the Townsend Second Ionization Coefficient (γ) and the Townsend First Ionization Coefficient for two gasses represented in **Table 3**.

The relation between the Townsend Second Ionization Coefficient (γ) and the Townsend First Ionization Coefficient $(\alpha)$for the Helium in comparison to that for the Aragon is represented in **Fig.10**.

It is noticed that from **Fig.10,** the Townsend Second Ionization Coefficient (γ) is inversely proportional to the Townsend First Ionization Coefficient$(\alpha)$for both Helium and Argon gases. Also, the Townsend Second Ionization Coefficient of Helium gas $(\gamma)_{He}$is lower than the Townsend Second Ionization Coefficientof Argon gas$(\gamma)_{Ar}$.

Table3: The Townsend Second Ionization Coefficient (γ) and the Townsend First Ionization Coefficient for two gases.

Gas	α/ P	(TSIC) $\gamma \times 10^{-4}$
Helium	2.99235	29.1
	2.89971	30.9
	2.87517	32.2
	2.85069	33.5
	2.80287	37.1
	2.77884	39.74
	2.75536	41
Argon	11.4700	32.4
	11.1600	37.8
	10.9600	41.8
	10.4800	53.2
	10.0200	67.1

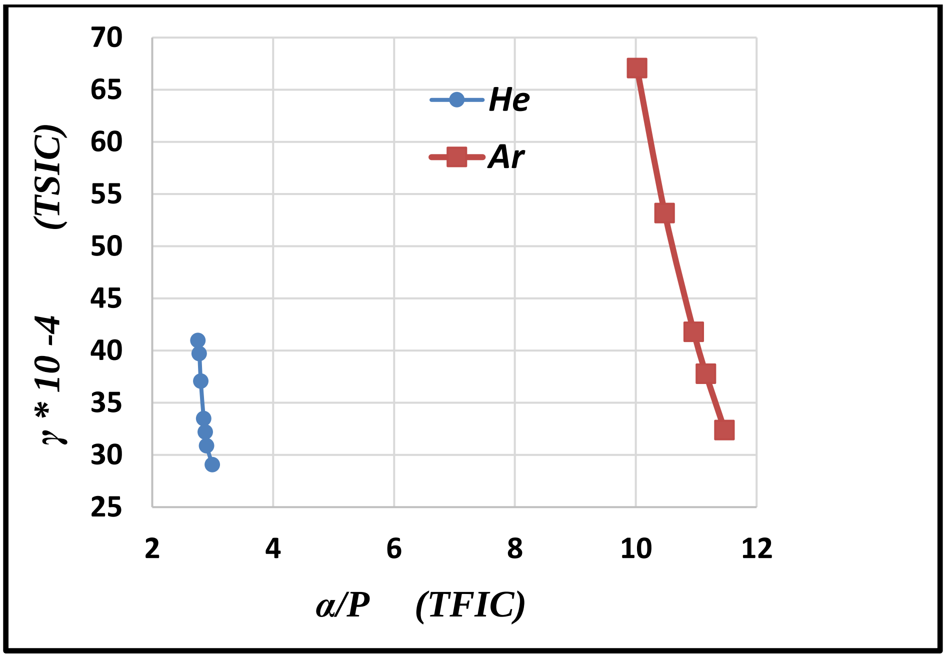

Fig.10: The Correlation between the Townsend Second Ionization Coefficient (γ) for Helium and Argon gases

4. Conclusion

This paper shows someelectrical parameters of the Inertial Electrostatic Confinement fusion plasma device using Argon and Helium gases. By analyzing the data from the experiment using the (IEC) plasma device, it concluded the discharge current increases by increasing the discharge voltage.The visible light intensity of Argon glow plasma was found greater than that of Helium glow plasma. Both of the First and Second Townsend Ionization Coefficientsare functions of the energy gain of charged particles between collisions and pressure. Also,to maintain the discharge, high and low pressures require a high voltage.The minimum breakdown voltages are: 97.82volts at $Pd = 0.5\ \text{torr.cm}$ and 74.72volts at $Pd = 2\ \text{torr.cm}$ for the Argon and the Helium gases respectively.It can be concluded that, the minimum breakdown voltages$(\mathrm{V_{br}})_{\min}$for Argon gas is higher than thatfor Helium gas.

References

[1] D. Bhattacharjee, N. Buzarbaruah and S.R. Mohanty, "Kinetic characteristics of ions in an inertial electrostatic confinement device", (2020), arXiv:2002.05941v2 [physics. plasma-ph]

[2] G. H. Miley, S. Krupakar Murali, Inertial Electrostatic Confinement (IEC) Fusion, Fundamentals and Applications, (2014) Springer New York Heidelberg Dordrecht London

[3] J. Rasmussen, T. Jensen, S.B. Korshdm, N.E. Kihm, F.K. ohms, M. Gockenbch, B.S. Schmidt and E. Goss, "Characterization of fusion plasmas in the cylindrical DTU inertial electrostatic confinement device", (2020), AIP Physics of Plasmas, 27, 083515

[4] M. C. C. Messmer, "Towards advanced operation modes of magnetic and electrostatic confined fusion machines", (2019), Eindhoven University of Technology, ISBN: 978-90-386-4812-5

[5] R.B. Reid, Ph.D. Thesis, An Experimental Study of Gridded and Virtual Cathode Inertial Electrostatic Confinement Fusion Systems", (2019), University of Sydney

[6] D.R. Boris, E. Alderson, G. Becerra, D.C. Donovan. "Deuterium Anions in Inertial Electrostatic Confinement Device", (2009), Physical Review E, vol. 80, 036408

[7] M.K. Khalaf, Ph.D. Thesis, "Investigation of the Interaction of Glow Discharge Plasma with Metal Surfaces", (2010), University of Baghdad, Baghdad

[8] G.A. Guilot, Ph. J. Faly, and H. Brunet, "Experimental Study of the Effective Secondary Emission Coefficient for Rare Gases and Copper Electrodes", (1998), Journal of Applied Physics, 83, 5917.

[9] M.S. Naidu, V. Kamaraju, "High Voltage engineering", (2009), Tata McGraw Hill Publications, 4th Edition.

[10] T. Aoyama, "Generalized gas gain formula for proportional counters”, (1985), Nucl. Instrum and Meth, A234, 125-131.

[11] Y.P. Raizer, "Gas Discharge Physics", (1991), Verlag, New York.

[12] N.J. Braithwaite, "Introduction to gas discharges", (2000), Plasma Sources Science and Technology, 9 517–527, IOP science**.**

ملخص البحث

توصيف بلازماغازى الأرجون والهيليوم في جهاز الحصرالاندماجى الكهروستاتيكي

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جهاز الحصر الاندماجى الكهروستاتيكى (IEC) هو احد الاجهزه المستخدمه فى حصر البلازما الساخنه والذى يتم مده بمجال كهربى بدلا من استخدام المجال المغناطيسى المتبع عادة فى هذا المجال.يتكون هذا الجهاز من قطبين أحدهما كروي الشكل وهو الأنود والأخر اسطواني الشكل وهو الكاثود وهما مصنوعين من الصلب الغير قابل للصدأ . يوجد وعاء زجاجي بقطر 0.10 m وارتفاع 0.30 m مصنوع من البيركس لتحمل الضغط ودرجة الحرارة ويحوي الأنود والكاثود بداخله. يصل ضغط الهواء داخل وعاء التفريغ إلي $\mathrm{torr.cm}10^{-2}$ باستخدام طلمبة تفريغ. يوجد عدة فتحات للتفريغ ولدخول الغازات والتشخيص من خلال فلانشة علوية لوعاء التفريغ. يعمل جهاز الحصر الكهروستاتيكي بنظام التفريغ الوهاجي. تم تصوير وتوصيف بلازما الأرجون والهيلوم وفحص مابين الجهد والتيار لكل من الغازين وكذلك العلاقة بين شدة الضوء المرئي وضغط الغاز في حالتى كل من غازى الأرجون والهيليوم. اسفرت نتائج التجربه عن ان كلما زاد تفريغ الجهد زاد تيار التفريغ وان شدة الضوء المرئى لوهج غاز الارجون اقل من شدة الضوء المرئى لوهج غاز الهيليوم،ويتطلب جهدا عاليا للوصول الى مرحلة التفريغ سواء للضغط المنخفض او الضغط العالى ووجدايضا ان قيمة انهيارالجهدلغاز الهيليوم يساوى 74.72 فولت وهو اقل من قيمة انهيارالجهد لغاز الارجون والذى يساوى 97.82 فولت.