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Theoretical Computation of Electron Density in Laser-Induced Carbon Plasma using Anisimov Model

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Abstract

In this work, electron number density was calculated using Matlab program code and the writing algorithm of the program. Electron density was calculated using the Anisimov model in a vacuum environment. The effect of spatial coordinates on the electron density was investigated in this study. It was found that the Z axis distance direction affects the electron number density (n_e). There are many processes such as excitation, ionization, and recombination within the plasma that may affect the density of electrons. The results show that as Z axis distance increases electron number density decreases because of the recombination of electrons and ions at large distances from the target and the loss of thermal energy of the electrons at high distances with the progress of time and at a certain coordinate. The target is carbon (graphite). The results were selected in four dimensions where three of them belong to the spatial coordinates x, y, z and the fourth dimension is the electron density (n_e).

Article Info.

Keywords:
Laser induced plasma, electron number density, plasma plume, Anisimov model, electron-ion recombination.

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1. Introduction

With the development of laser technology, it was possible to get laser-induced plasma [1]. Gases are insulating and transparent to the laser beam at normal intensities, which quickly turns to high-conductive, self-lighting and hot plasma when exposed to radiation from a strong-intensity laser [2-4]. In plasma production by laser, high-intensity laser pulses interact with the target, leading to plasma formation within nanoseconds due to high plasma propagation [5-8]. The nature and dynamics of laser plasma generated depend on several variables, including the laser wavelength, the laser spot size, the laser pulse width, and the pressure of the surrounding gas [8-10]. During the ablation process, laser bombards the target material. Plasma is produced through heat conduction, melting and evaporation of the target material [9]. There are many applications for Laser-Induced Plasma (LIP) in many important areas, including the deposition of thin films, etching, drilling, surface processing optoelectronics devices and the sensors industry [10-12]. The analysis and measure of the electron density n_e and electron temperature T_e in LIP are difficult tasks because the plasma generated is transit with time and space; practically, several ways have been used to measure them like shadowgraphy, interferometry, intensified charged-coupled device (ICCD) camera, optical emission spectroscopy (OES), Langmuir probe and Faraday cup [13-16]. Theoretically, several models have been used to find the plasma parameters (T_e and n_e) in the case of vacuum and background argon gas [17-20]. In the case of vacuum, the Anisimov model was used in this study to calculate the plasma variables. While Sedov-Taylor model, Friewald-Axford model, and Shock wave model were used in the case of background gas models [20-24]. Anisimov model was used in this theoretical research to compute the density of electrons in the plasma for the carbon element produced by Nd:YAG laser of fundamental wavelength 1064 nm, frequency 6 Hz, a pulse width of 10 ns. Programming was done using the well-known Matlab program according to a mathematical algorithm.

The aim of this work is to theoretically find the electron number density n_e using the Anisimov model with Matlab code for the carbon target laser induced-plasma.

2. Anisimov Model

Fig. 1 shows a typical laser spot irradiated on the target.

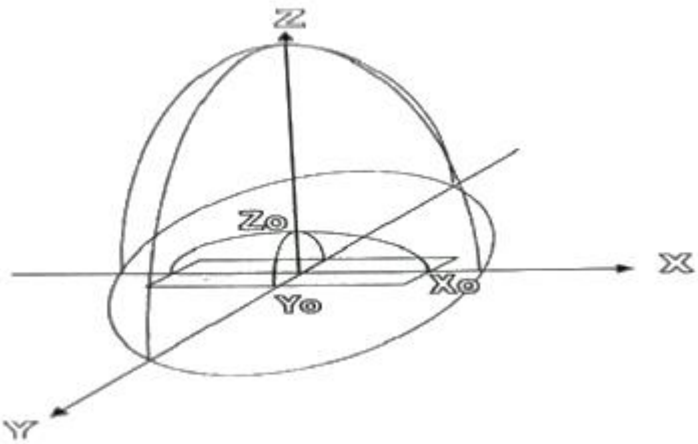

Figure 1: Scheme of the ellipsoid assumed for the vacuum plasma expansion. Grey rectangle represents the laser spot [1].

The laser beam of 10ns pulse duration produces a vapor cloud near the target surface at z=0. The vapor cloud spreads in vacuum until it reaches a distance $z=z_s$ when $t = t_s$, as in Fig. 1, which approximately equals to value of z_s/c_s, where c_s is the speed of sound. The direction of the laser beam is 45^0 with the normal on the target surface. The initial time to form a vapor cloud was supposed to be much shorter than its spread time. The spread extension of vapor is qualified by the equations of gas dynamics [18]:

$$\frac{\partial \rho}{\partial t} + div(\rho v) = 0$$
$$\frac{\partial v}{\partial t} + (v\nabla) + \frac{1}{\rho}\nabla p = 0 \qquad (1)$$
$$\frac{\partial S}{\partial t} + v\nabla S = 0$$

where: ρ, p, v and S are the density, pressure, velocity and entropy of the gas, respectively.

In Anisimov model, it is supposed that the flow parameters are fixed on ellipsoidal surfaces, and the density and pressure profiles are as stated below. Anisimov found a relationship between density, pressure as well as the entropy of the plasma plume as follows [18]:

$$\rho(x, y, z, t) = \frac{M}{I_1(\gamma)XYZ}\left[1 - \frac{x^2}{X^2} - \frac{y^2}{Y^2} - \frac{z^2}{Z^2}\right]^{\alpha} \qquad (2)$$

$$P(x, y, z, t) = \frac{E}{I_2(\gamma)XYZ}\left[\frac{X_0 Y_0 Z_0}{XYZ}\right]^{\gamma-1}\left[1 - \frac{x^2}{X^2} - \frac{y^2}{Y^2} - \frac{z^2}{Z^2}\right]^{\alpha+1} \qquad (3)$$

where: $M = \int\rho\,(r, t)\,dV$ is the mass of the plasma plume, $E = (\gamma - 1)^{-1}\int p(r, 0)dV$ is the initial energy of the vapor cloud, $\gamma = C_p/C_v$ is the ratio of the plasma specific heats, and x, y, and z are the spatial dimensions of the plasma plume.
The constants I_1 and I_2 are equal to [18]:

$$I_1(\gamma) = \frac{\pi^{\frac{3}{2}}\Gamma\,(\alpha+1)}{2\Gamma\left(\alpha+\frac{5}{2}\right)} \quad (4)$$

$$I_2(\gamma) = \frac{\pi^{\frac{3}{2}}\,\Gamma\,(\alpha+2)}{2\Gamma(\gamma-1)\,\Gamma(\alpha+\frac{7}{2})} \quad (5)$$

where: Γ(z) is the Gamma function.

Equations (2) and (3) depend on two spatial variables, X_0 and Y_0, which belong to the form of the laser spot, in addition to Z_0, a third variable related to the vertical dimension of the surface of the target material. This variable depends on the physical properties of the plasma through γ [18].

3. The Description of the Matlab Program

Matlab is a programming system used for advanced applications in science and engineering. This program can be used to solve many mathematical problems more easily than other programs such as C and FORTRAN languages. Matlab has powerful features that connect many individual programs into one structure. For example, a program can be written to calculate the masses of the stars in Milky Way galaxy, and write a second program to calculate the orbits of each star, then combine both programs in one major (and third) program. This can be made using the “functions” feature. In the theoretical part of the plasma generated by laser, the famous mathematical Matlab program was used in programming and computing the theoretical equations for n_e from Anisimov model in vacuum. The algorithm of the program is shown in Fig. 2.

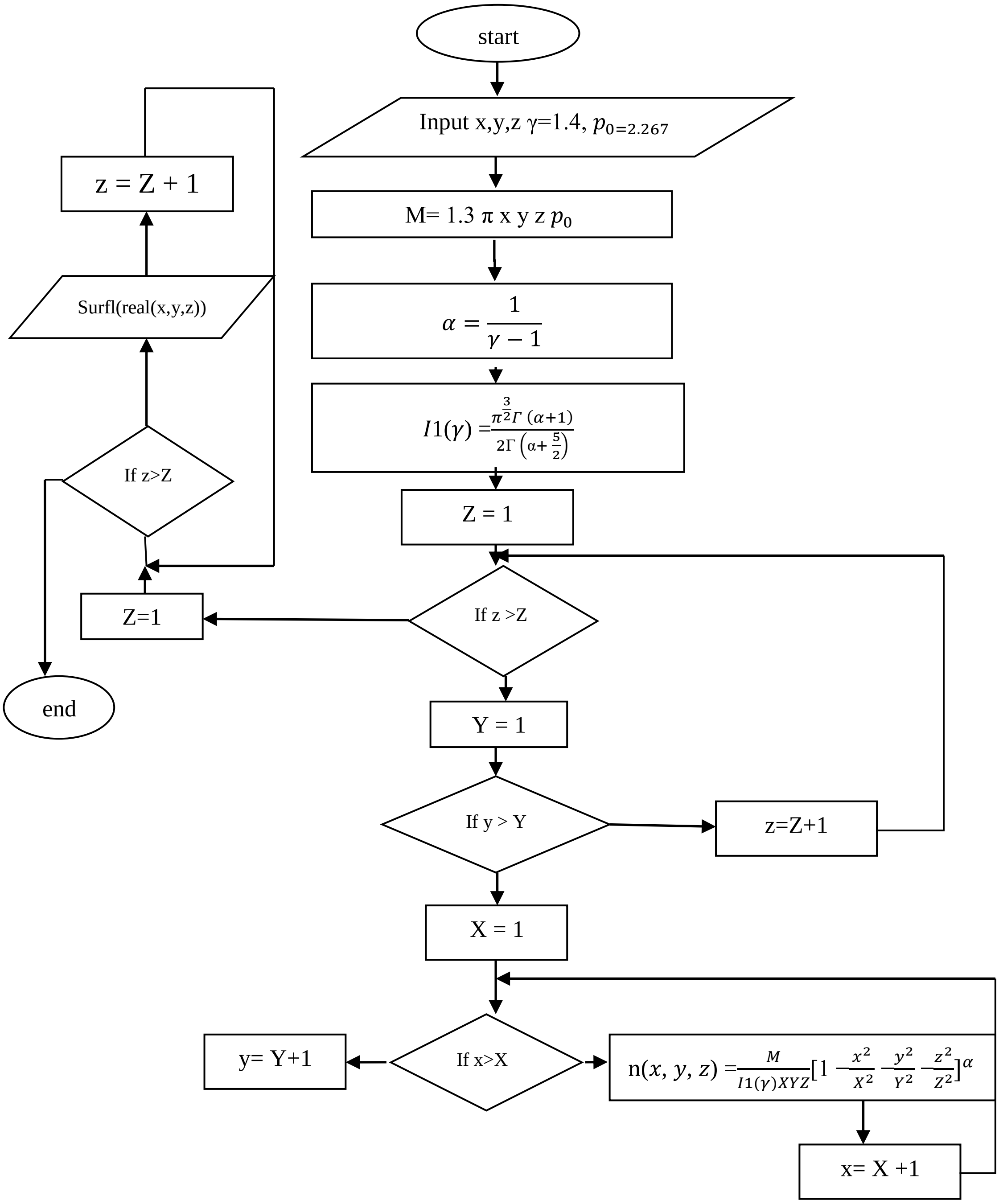

Figure 2: The algorithm of the Anisimov model Matlab program.

4. Results and Discussion

Figs. 3 - 10 represent the electron density as a function of x, y and z to the field of plasma, i.e., a spatial profile of the density of electrons. It was found that the lateral change of electrons was smaller with the vertical change because according to the laser-induced plasma theories, the spread of plasma particles is at right angle on the target surface to be θ_s 90^0, i.e., the plasma particles distribution is with spread at 90^0 on the target surface.

The flow of plasma particles decreases when the angle θ is less than 90^0. All electrons and ions can be large and maximum in the forward direction on the target surface, θ_s $=90^0$, and thus the density of electrons can be large in the vertical direction on the surface, i.e., in the direction of Z. The spatial attribution of electron density follows the geometry of the plasma and the temperature of plasma components according to the equation $n_j(\text{r}) = \bar{n}_j \exp\left(\frac{-U_{ij\,(r)}}{KT}\right)$ [24], where: $\bar{n}_j$ is the average density of particles with charge q_j in plasma. There are many processes that take place within plasma which possible to affect the density of electrons, for example (excitation, ionization, recombination, charge transfer, attachment, dissociation photo – dissociation). When increasing Z, perhaps the most important of these processes that affect the electron density of these operations above are recombination divided into five secondary operations:

Ion - electron $A^+ + \bar{e} \rightarrow A + h\nu$

$\qquad\qquad\qquad\qquad \rightarrow A^* + h\nu$-

Where it is reconfigured neutral atom of the operation of electrons with positive ion and releasing of energy in form of a photon, and this is the main reason for the decrease in the density of electrons at high distance Z.

Ion – ion (radiative) $A+ + B^- \rightarrow AB + h\nu$

Ion – ion (neutralizing) $A+ + B^- \rightarrow A^* + B^*$

$\qquad\qquad\qquad\qquad \rightarrow A^* + B$

Ion – ion (ternary) $A^* + B^- + X \rightarrow AB + X$

Molecular Ion – electron (dissociative) $AB^+ + e^- \rightarrow A + B^*$

When increasing Z to large distance the first operation recombination (Ion–electron) plays an important role in decreasing the number of free electrons, i.e., increase in the density of electrons, in addition to the other reason for the loss of thermal energy of the electrons. In other sense decreasing in distance away from the carbon (Graphite) target with proceed of time and at a certain point, the electron density will vanish i.e. plasma ends, all connected ions and electrons Fig. 2 – 9 are three dimensions X,Y,Z coordinate and the fourth is an intensity of color that represent the density of electrons. The findings agree with Hussain et al. [25]. T_e indirectly affects n_e. The plasma is formed because of the high temperature of the electron, and the ionization of the atoms of the target is due to the high intensity of the laser beam.

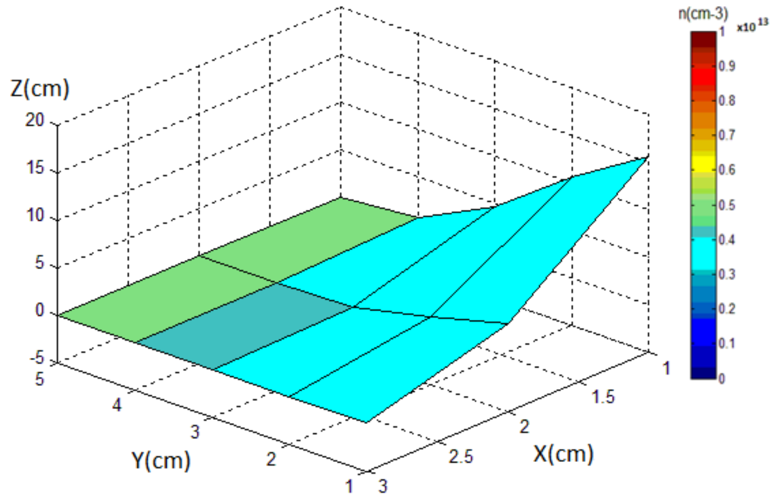

Figure 3: The spatial profile of electron number density of carbon laser induced plasma at z=1cm.

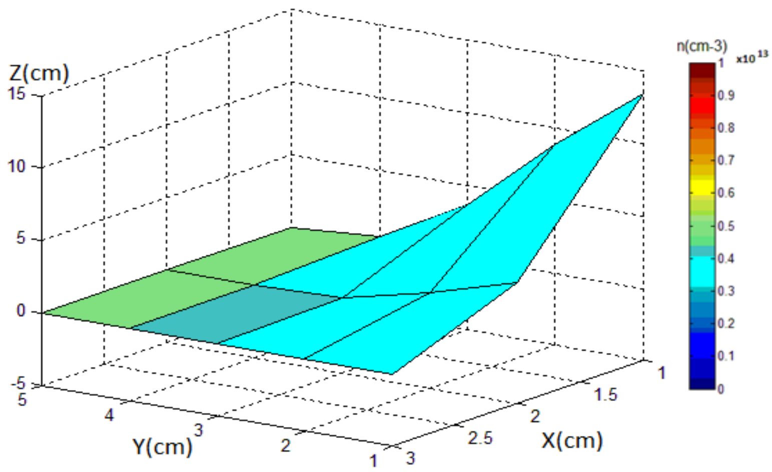

Figure 4: The spatial profile of electron number density of carbon laser induced plasma at z=2cm.

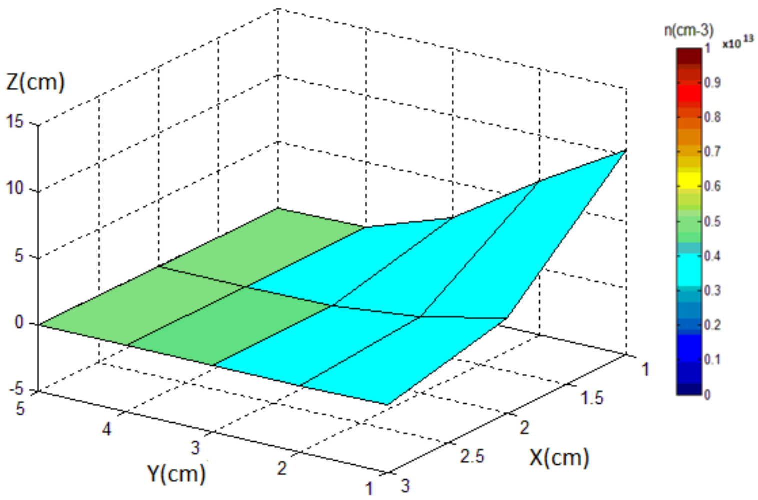

Figure 5: The spatial profile of electron number density of carbon laser induced plasma at z=3cm.

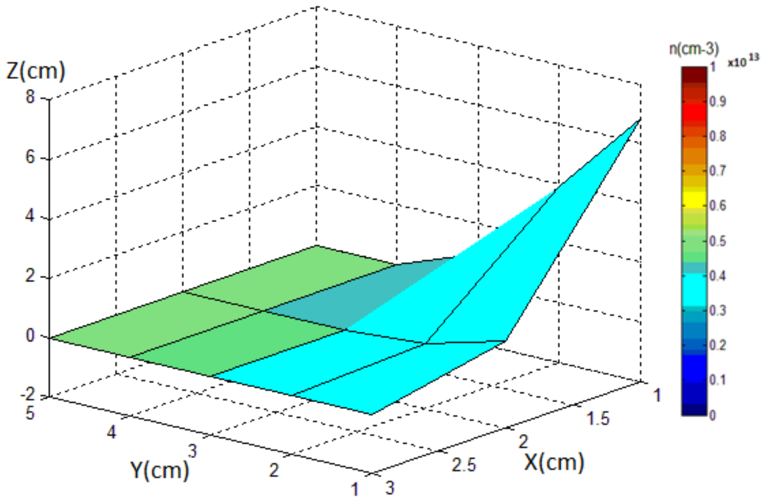

***Figure 6:** The spatial profile of electron number density of carbon laser induced plasma at z=4cm.*

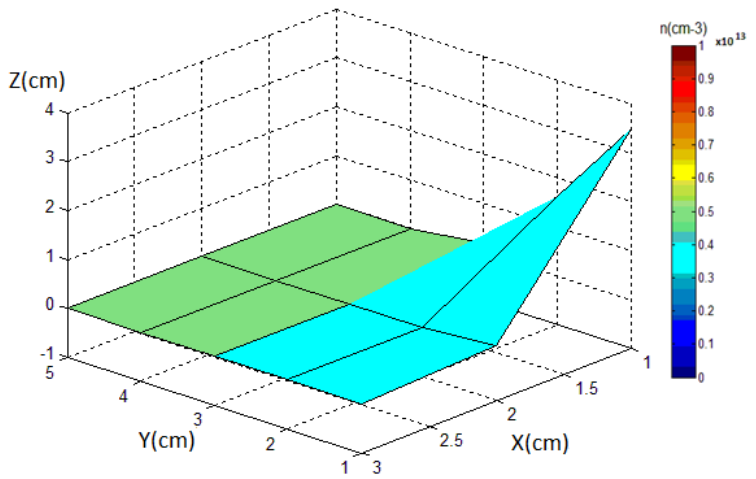

***Figure 7:** The spatial profile of electron number density of carbon laser induced plasma at z=5cm.*

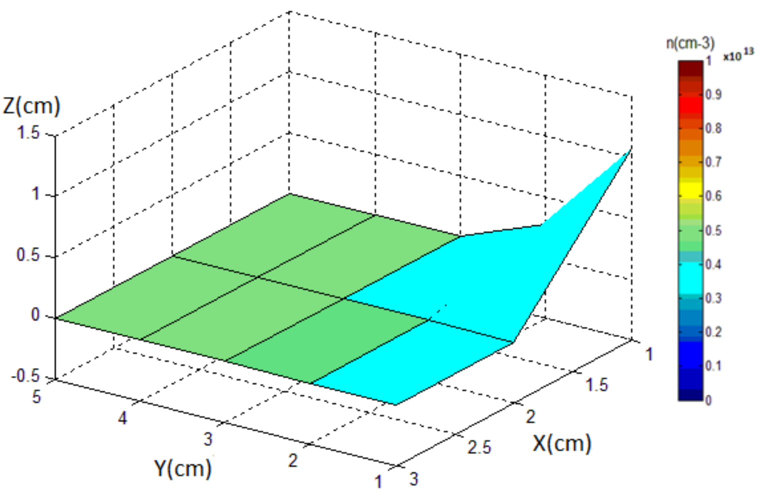

***Figure 8:** The spatial profile of electron number density of carbon laser induced plasma at z=6cm.*

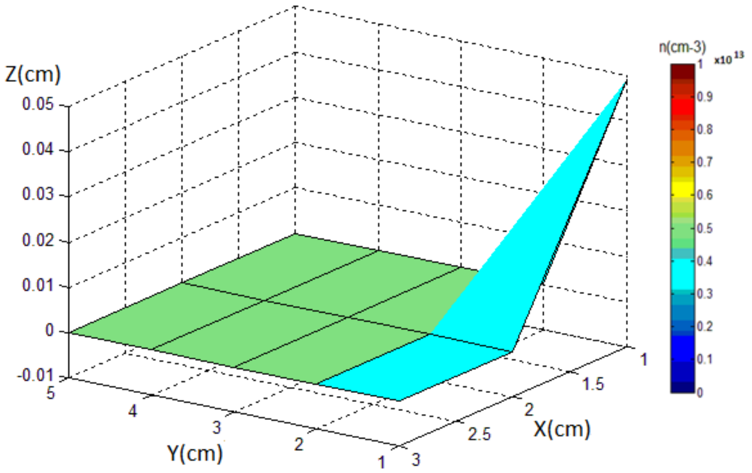

Figure 9: The spatial profile of electron number density of carbon laser induced plasma at z=7cm.

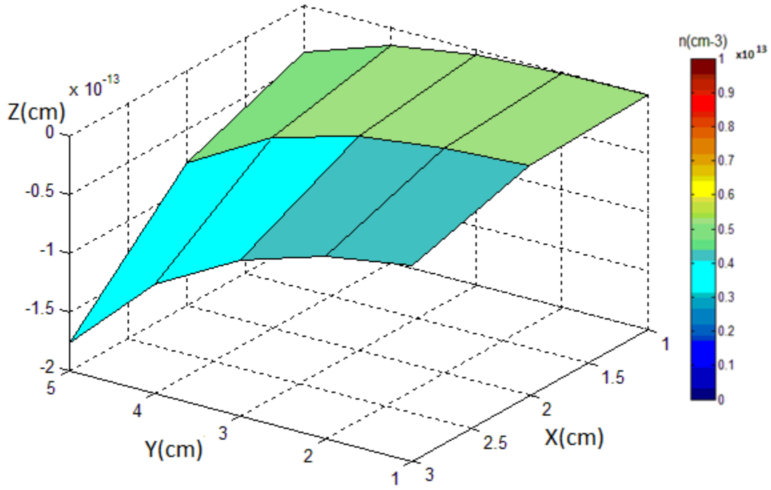

Figure 10: The spatial profile of electron number density of carbon laser induced plasma at z=8cm.

5. Conclusions

MATLAB is a mathematical program that has proven its effectiveness in calculating the plasma properties accounted for in this study. Plasma output parameters are based on the application of theoretical Anisimov model variables such as the spatial profile of plasma plume position, plasma parameters I_1, I_2, mass flow, and the value of the (n_e). Fixing the axes X and Y and changing the value of the Z axis leads to a change in n_e; it decreases with increasing the distance from the target surface. Collision between plasma particles significantly impacts the value of n_e (electron density) at long distances from the target surface.

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Conflict of interest

Author declares that they have no conflict of interest.

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الحساب النظري لكثافة الإلكترون في بلازما الكربون المستحثة بالليزر باستخدام نموذج انيسيموف

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الخلاصة

في هذا العمل تم حساب كثافة الإلكترونات العددية باستخدام كود برنامج ماتلاب مع خوارزمية الكتابة للبرنامج ، وتم حساب كثافة الإلكترونات باستخدام نموذج انيسيموف في بيئة الفراغ. تم التحقيق في تأثير الإحداثيات المكانية في هذه الدراسة. لقد وجد أن اتجاه مسافة المحور Z يؤثرعلى كثافة الإلكترونات n_e. هناك العديد من العمليات التي تحدث داخل البلازما والتي من الممكن أن تؤثر على كثافة الإلكترونات على سبيل المثال (الإثارة ، التأين ، إعادة التركيب ، نقل الشحنة ، التعلق ، صورة التفكك - التفكك). كلما زادت المسافة Z تنخفض كثافة الإلكترونات. هذا بسبب إعادة اتحاد الإلكترون والأيونات على مسافات كبيرة من الهدف وفقدان الطاقة الحرارية للإلكترونات بمعنى آخر يتناقص في مسافة عالية مع تقدم الوقت وعند نقطة معينة . الهدف هو الكربون (الجرافيت). تم اختيار أربعة أبعاد حيث تنتمي ثلاثة منها إلى الإحداثيات المكانية x و y و z والبعد الرابع هو كثافة الإلكترونات n_e.