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Geometric Influence on the Electron Distribution in Gas Discharge Plasma

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Abstract

An analytical model is proposing to investigate the influences of the shape and size of an open and closed cylinder on the electron density distribution. A two-dimensional steady state ionization equation solved analytically by using cylindrical coordinates. The only gain and loss processes consider are the cascade ionization and electron diffusion. The radial behaviour of the diffusion length in both open and closed cylinder for different values of shape and size are calculated and the axial and radial electron density distributions discusses for some values of gas velocity.

Keywords: Laser Produce Plasma; Optical discharge; Plasma

Introduction

The influences of the shape and size of the discharge area on the plasma distribution are subject of many theoretical and experimental studies see for example (Romig [1], Muller [2], Demetrios [3], Al-Hashmiy [4], and Al-Kelly [5]). The electron density distribution associated with the plasma density plays an important role in the overall performance of the discharge. The state of the plasma produced by rf field in cylindrical tube of constant radius has been studied extensively by a number of researchers Mayer[6] Boswell[7], Perry[8], Dender[9], and Charles[10] and is well understood. Little work, however, has done in the study of the plasma state in cylindrical coordinates by using optical frequency and by taking into account the geometrical effect on the plasma distribution and this work has described in a number of publications such as Richard [11], Tarvin [12] and Lieberman [13]. Ionisation equation for length scale was less well understands than the continuity equation. In fact, there is no agreement on what length scale one should choose to represent the plasma density. Most papers dealing with RF discharge used the Debby length to describe the behaviour distribution of the plasma density. Also more than one scale may need because length scales in different co-ordinate direction are no more likely to be proportional to the transport parameter. In optical discharge plasma, one has to deal with verity of parameters, which affect, the density distribution, for example the laser beam configuration, the resonator size and length and other parameters. The shaping of the discharge tube should result in enhanced efficiency, owing to the fact that the optical beams sweep out 100% of the active medium. In the present paper, we will assume that the discharge tube is cylindrical tube with constant radius. The first communication of an observation of breakdown of a gas under the influence of a focussed laser beam, operating in the giant-pulse mode, was first, presented in (1963), by Maker [14]. Meyerand [15] followed this quickly in the same year. Since then many theoretical and experimental work have been done in this respect, and this work can be traced throughout the papers of references Danshchikov [16], Kozlov [17], Lebehot [18], Conrad [19] and Al-Hashmiy [20,21]. The main conclusion reached by these works in both experimental and theoretical aspects may be summarised as follows: There is a definite dependence of the discharge on the geometry of the active region. This implies that the discharge process exhibits threshold behaviour through a balance between the electron production inside the active region and loss of electrons from the diffusion. However, none of these studies seems to give a comprehensive view about such dependence. Al-Hashmiy and Al-kelly find it of great interest to have an idea about this problems when they analysis the diffraction equation, continuity equation and the concept of the continuous optical discharge. The present paper will concern itself with the effect of the shape and size of the discharge tube on the distribution of the plasma density and the gas velocity will include in our analysis.

Formation of the problem

In optical discharge, ionisation causes by the collision of free electrons with the gas atoms. The electrons gain their energies from the laser beam by collision, which changes their ordered oscillatory motion to random motion. Interaction with laser radiation as a rule involves considerably less intense beams and performs under constant pressure conditions. This must strongly affect the parameters of the plasma and consequently the nature of its influence on the interaction. However, an optical discharge in the gas can substantially increase the power flux absorbed by the gas at the centre of the focal spots, while one in the gas transfers the power absorbed from the beam to an area, which is considerably larger than that of the spot. The influence of the container parameter on the efficiency of the localized interaction with the gas is of practical interest. Moreover, various mechanisms contribute to a reduction of the electron density. At low pressure the dominating loss mechanism is the diffusion of the electrons out of the region of high field to a lower field region where ions can no longer gain sufficient energy to make ionising or exciting collisions. At higher pressures other processes such as the recombination of the electrons with ions or the attachment of the electrons to electronegative gas atoms may play an important role. Since space-charge fields cannot exist in plasma over a distribution larger than a Debye length, ambipolar diffusion assumes importance when the Debye length approaches and finally becomes smaller than the container dimension. A steady state discharge occurs when the production of new charge particles in the volume equals their loss to the volume by any of the loss processes mentioned above and the plasma can exist in the form of era-jet plasma of the ionised gases. In order to formulate the problem, we shall make the following assumption:

1) Diffusion controlled discharge will be considered, while the recombination is assumed to take place only outside the container.
2) Any internal drift velocity may occur will be incorporated into an effective diffusion coefficients.
3) We should assume a quasi-neutral discharge in which $N_e \approx N_i$ where N_e and N_i stand for electrons and ions number density.
4) The degree of ionisation N_e/N_i, is small compared to unity so that the conservation equations for the neutral species may be uncoupled from those of the charged particles.
5) We shall neglect the effect of the metastable atoms and other losses on the plasma production.

Now, to determine the equation governing the ionisation process and restricted by the above assumptions, we shall start from the continuity equation of the electrons, which may be written as

$$\frac{\partial N}{\partial t} + \nabla . N\vec{V} = 0 \quad \text{.......(1)}$$

In the above equation, we need to evaluate the quantity *NV*, which represents the current flux of the particles. For the case of ambipolar diffusion controlled decay as we considered, so, there is no electric field present and one can write:

$$N\vec{V} = -\frac{KT}{M\nu_m}\nabla N + N\vec{V} \quad \text{.......(2)}$$

By substituting equation (2) in equation (1) we get:

$$\frac{\partial N}{\partial T} + \nabla .\left(-\frac{KT}{m\nu_m}\nabla N + N\vec{V}\right) = 0 \quad \text{.......(3)}$$

The absence of electric field considered above arises from the assumption that the numbers of electrons in the region equal the number of the ions, in this case the ambipolar diffusion must be considered here. Thus equation (3) is reduced for steady state to:

$$D_a \nabla^2 N - \vec{V}.\nabla N + \alpha_c N = 0 \qquad (4)$$

This equation represents the governing equation for the flowing quasi-neutral steady-state ionisation process including the decay of the plasma by diffusion to the wall and the loss of the plasma due to the drift velocity and, containing the only gain term that is the cascade ionisation.

Result and discussion

For a geometry, which simulate to some extent flow in plasma tunnel, let us consider the geometry as a cylindrical of radius R_0, figure (1), in which there is an axial gas flow velocity U_z. The origin coordinates (r,θ,z) of the focus of the laser beam concentric with the origin of the cylinder. The length of the active area covers 2L of the cylinder. We shall assume that the cascade ionization is constant over the length 2L and zero elsewhere, Roming [1], Al-Hashmiy [4], Shargi [22] i.e.

α_c = constant for all r, $-L \le Z \le L$

= 0 every where

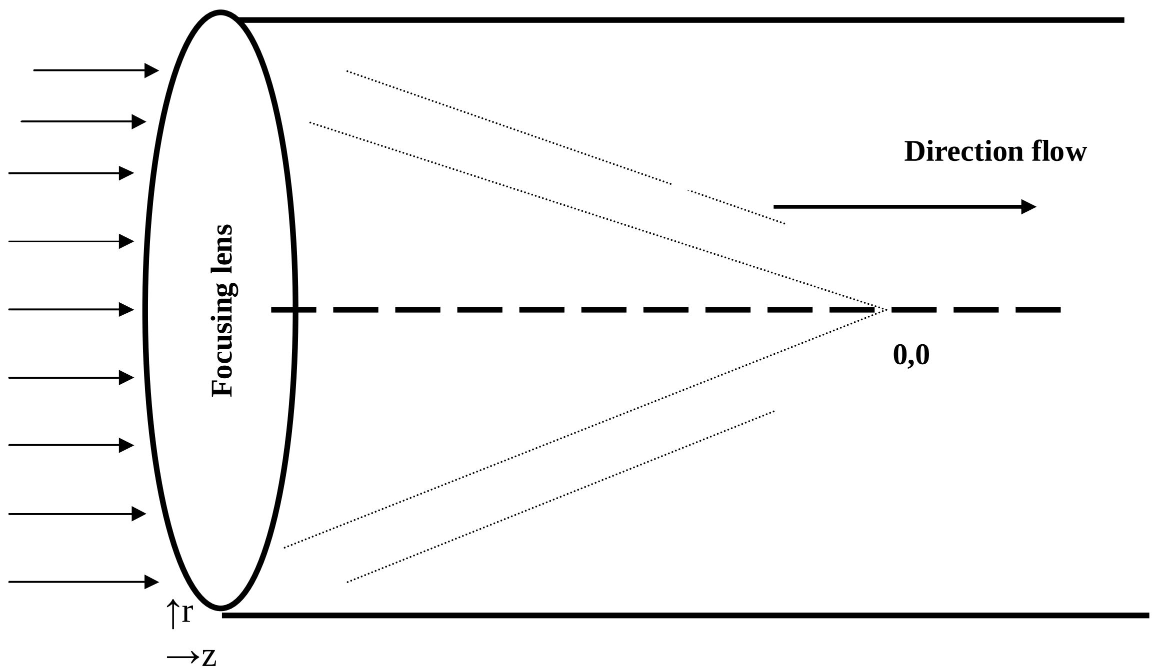


Fig. (1) Flow geometry used.

The boundary conditions are: n(R,Z) = n(R, ±∞) = 0 and n(r,z), ∂n/∂Z are continuous at Z = ±L. In cylindrical coordinates, assuming rotational symmetry equation (4) becomes

$$\frac{1}{L^2}\frac{\partial^2 n}{\partial Z^2} + \frac{1}{R_0^2}\frac{\partial^2 n}{\partial R^2} + \frac{1}{R_0^2}\frac{1}{R}\frac{\partial n}{\partial R} - \frac{U_z}{LD_a}\frac{\partial n}{\partial Z} + \frac{\alpha_c}{D_a} n = 0 \qquad (5)$$

$$where Z = \frac{z}{L}, \ldots R = \frac{r}{R_0}, \ldots n = \frac{N}{N_{max}}$$

Now we shall use the separable of variable techniques to solve this problem, so let as consider the axial and radial distribution of the plasma that may be given as n(R,Z) = n(R)n(Z), then the general solution of the plasma density distribution throughout the active region is

$$n(r,z) = N_{\max} \frac{J_0(2.405R)}{\cos(\mu Z_0)} e^{\beta(Z-Z_0)} \cos(\mu Z) \ldots\ldots(6)$$

Where $Z_0 = \frac{1}{\mu}\tan^{-1}(\frac{\beta}{\mu})$

Where μ, and β are constant related to the coefficient of the axial distribution. The calculations show that the diffusion length in an open cylinder is larger than that of the closed cylinder of the same dimension, figure (2). From this figure, we can say that the difference of the diffusion lengths in the two cylinders occurs only at the region closer to the centre of the discharge region. This means that the magnitude of this difference depends critically on that portion of the open cylinder over which the discharge acts. The difference is more pronounce for small values of active region as we can see in figure (3). As the active discharge length increases, the effect of open ends becomes less pronounced. Figure (4) shows the diffusion length as a function of the container length at different values of the axial flow velocity in an open cylinder but for small value of the non-dimensional quantity L/R. We can see that the diffusion length is increasing toward the ends of the cylinder but decreasing for the larger values of the axial flow velocity. As we expect, there is a strong dependence of the diffusion length on the geometric shape at small L/R. This dependence becomes weaker as the axial flow velocity increasing. This means that at high flow velocity again, the geometric effects are negligible.

The radial behaviour of the diffusion length in both, open and closed cylinder, for small values of the non-dimensional quantity L/R, is show in figure (5). For non-axial flow velocity case, the variation of the diffusion length with the radius of the container is pure straight line in both, open and closed cylinder for small and large of L/R. The diffusion length is being larger for the open cylinder at the portion far from the centre. There is no effect for the axial flow velocity on the radial distribution of the diffusion for both cases, large and small L/R.

The relation between the diffusion length and the diffusion coefficient is show through the figure (6), which illustrates the variation of the diffusion as a function of the diffusion length at a constant ionisation. From the above discussion of the diffusion lengths, it expected that the plasma density distribution for zero axial flow velocity in an open cylinder would approach that of the closed cylinder as the non-dimensional quantity L/R grows large. Figure (7) shows the distribution of the plasma density in both, open and closed cylinder for the value of L/R=2 and constant diffusion. We can see that for the absence of the axial flow velocity, the distribution of the plasma is symmetric about the origin in both, closed and open cylinder. The values of the plasma reached a maximum at the centre of the active discharge and dropped to a minimum at the ends. Because of the small value of the quantity L/R, the distribution of the plasma density in the open cylinder no longer approaches that of the closed cylinder. As this value is increasing, the plasma density distribution of the open cylinder is approximately coinciding with that of the closed cylinder figure (8). The influence of the geometric can be seen clearly in figures (9) and (10) which show, the two dimensional pictures of the plasma density distribution under the effect of the axial flow velocity at small and large values of L/R respectively and for flow velocity of 10000 cm/sec.

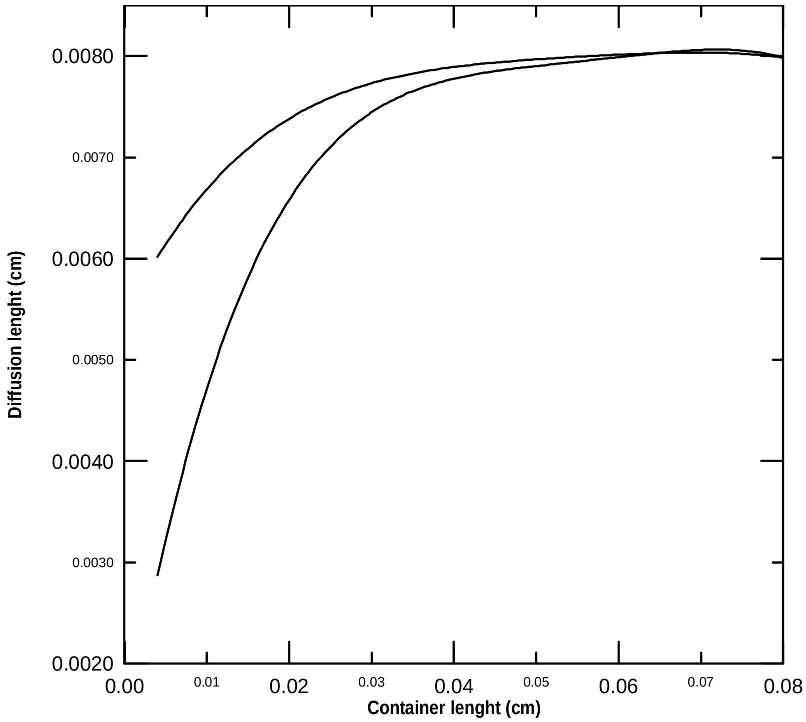


Figure (2) The variation of the diffusion length as a function of the container length at large L/R, upper for an open cylinder and lower for closed cylinder

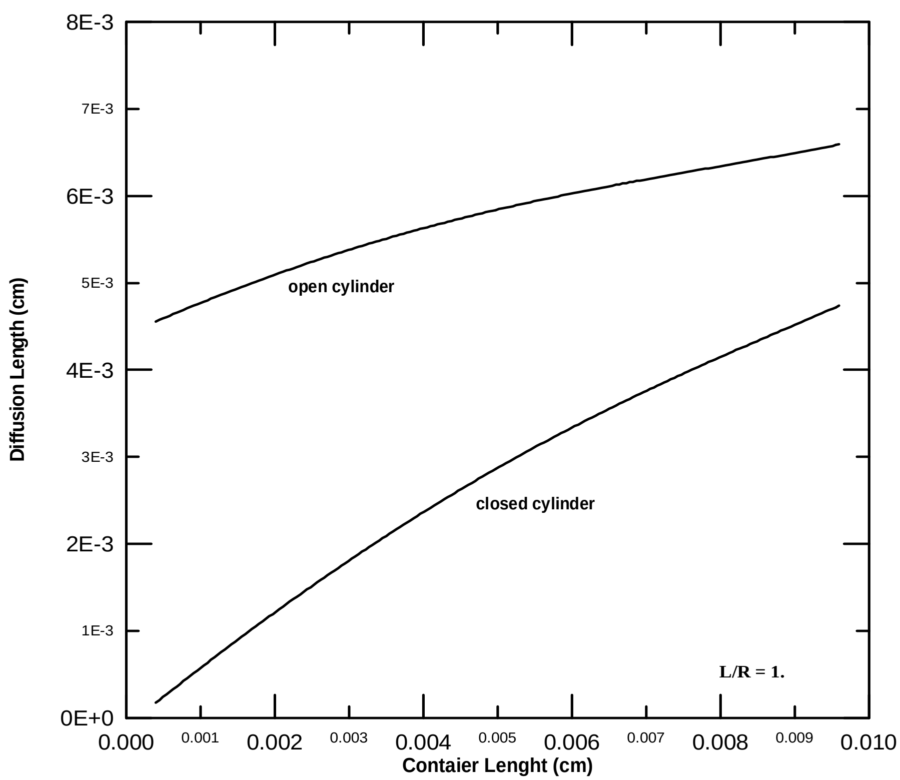


Figure (3) The variation of the diffusion length as a function of the container length at small L/R

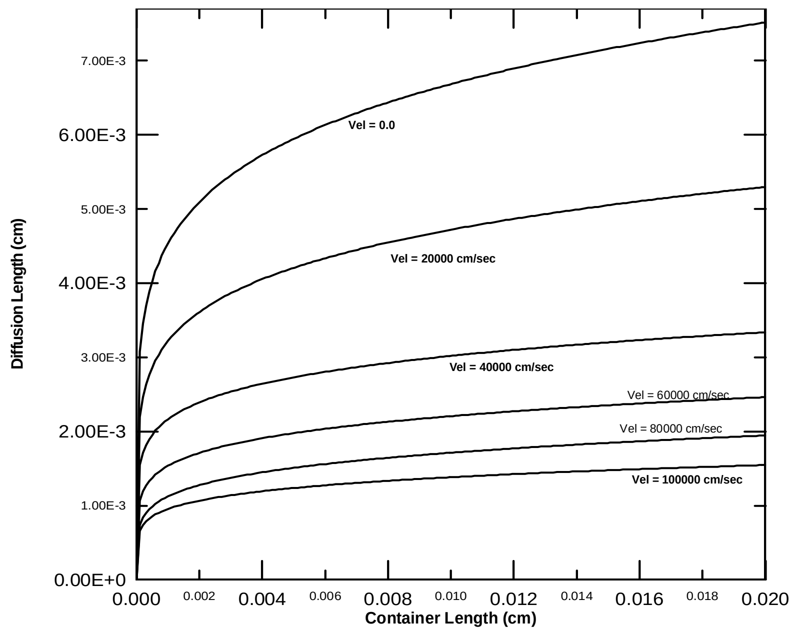


Figure (4) The diffusion length as a function of the container length for different values of the velocity in an open cylinder For small L/R

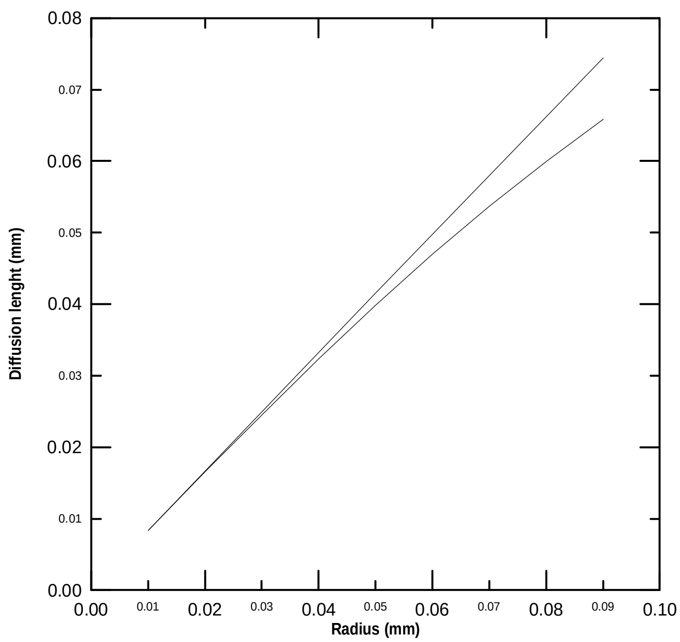


Figure (5) The variation of the diffusion length as a function of the active discharge radius for small L/R

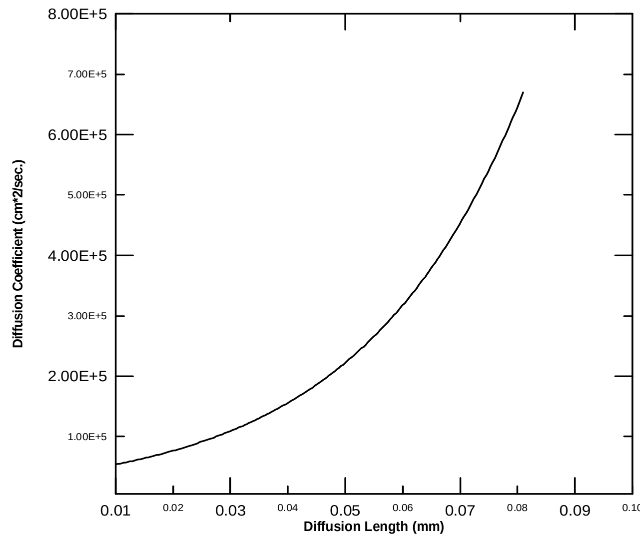


Figure (6) The relation between the diffusion coefficient and the diffusion length at constant ionization

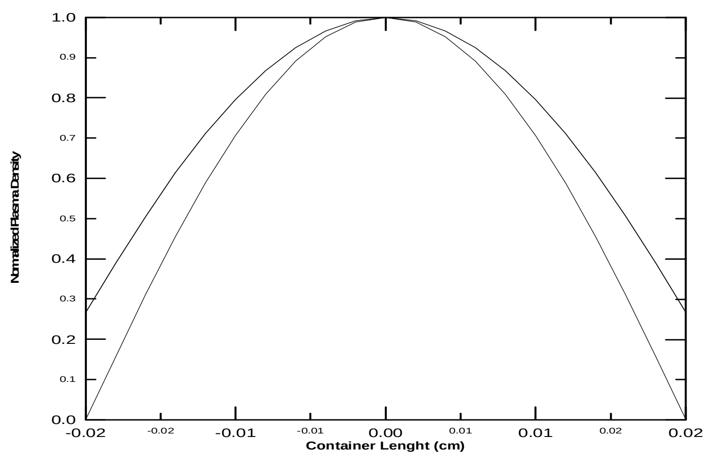


Figure (7) the axial distribution of the plasma density In both closed cylinder (solid line) and open cylinder (dash line) at small L/R

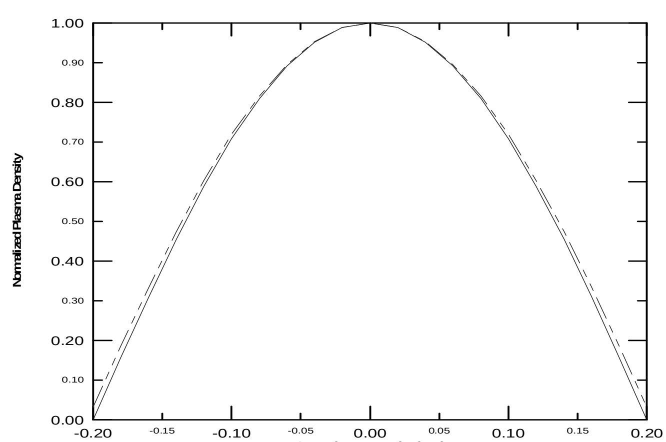


Figure (8) the axial distribution of the plasma density In both closed cylinder (solid line) and open cylinder (dash line) at large L/R

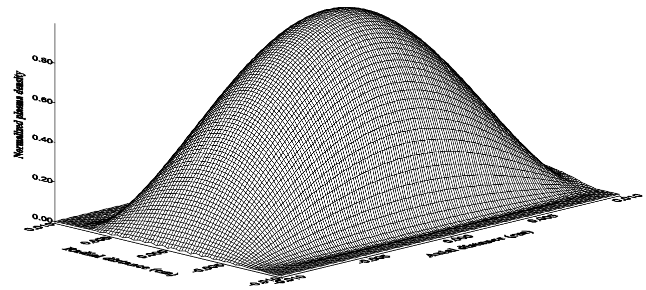
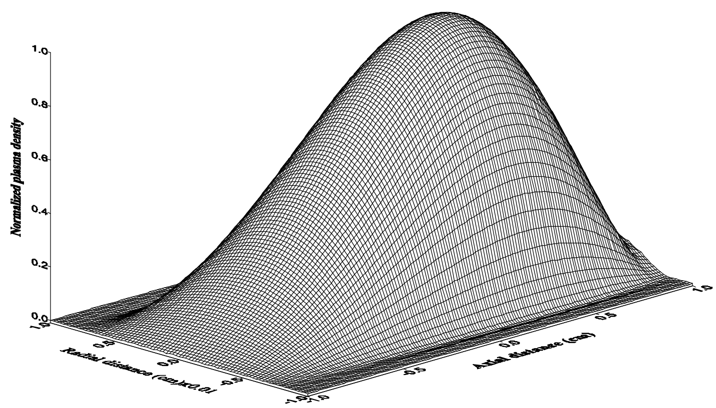


Figure (9) Normalized plasma density distribution for small L/R



Figure(10) Normalized plasma density distribution for large L/R

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التأثير الهندسي لأنبوب التفريغ البلازما على التوزيع الالكتروني

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الخلاصة:

وضع نموذج تحليلي للتحقق من تأثير شكل و حجم أنبوب تفريغ البلازما على التوزيع الإلكتروني داخل الأنبوب في الحالتين عندما تكون الأسطوانة مغلقة أو مفتوحة. تم حل معادلة التأين ذات البعدين في الإحداثيات الاسطوانية. أعُتبر معامل التأين العنقودي هو المؤثر الوحيد في عمليات تكوين البلازما، بينما أعُتبر معامل الانتشار الإلكتروني هو المؤثر الوحيد في عملية فقدان البلازما. لقد تم حساب الخصائص القطرية لطول الانتشار عندما يكون الأنبوب مغلق أو مفتوح لحالات مختلفة من شكل و حجم الأنبوب. لقد تم مناقشة التوزيع القطري والمحوري للتوزيع الالكتروني داخل أنبوب التفريغ لسرع مختلفة للغاز.