Efficiency Improvement of High-Pressure Microplasma by an Electron Beam

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***Abstract*—Efficiency has been a paramount issue for the past few years in high pressure microplasma devices such as Plasma Display Panels (PDP). In order to achieve a better efficiency, a novel method based upon electron beam emission has been investigated by a two-dimensional (2-D) fluid simulation. The injection of electron beam inside the PDP cell gives rise to substantially large density of excited Xe species (Xe^*), while reducing ionized xenon (Xe^+) and electron densities. This, in turn, enhances the efficiency, luminance, and reduces power consumption. The primary reason for generating more Xe^* species could be attributed to the formation of low electric field region inside the PDP cell, which consequently improves its operational efficiency. The validity of 2-D fluid simulation results is ensured through a qualitative comparison between the one-dimensional fluid and the kinetic results.**

***Index Terms*—Electron beam, fluid simulation, gas discharge, plasma display panel.**

I. Introduction

Efficiency of high pressure microplasma devices, such as Plasma Display Panels (PDP), has been a key issue in widespreading the PDP-technology, which reveals a potentially wide application in the next-generation large, flat screen TV, and other displays [1]–[5]. However, in the present scenario, the efficiency of a PDP-based TV appears to be low compared with CRT-based TV as the latter possesses better luminosity. Efficiency is a physical parameter that cumulatively deals with a variety of physical quantities inside a PDP cell, such as luminosity, power consumption, electron density, and others. Furthermore, improving the efficiency is primarily concerned with the optimization of these parameters, namely increasing luminosity, reducing power consumption, etc. This task has recently attracted a great deal of attention of the PDP researchers. Imperatively, it is thus necessary to optimize various physical parameters so as to achieve a better performance of the PDP cell. It is, therefore, our prime objective in this work to investigate the method, which can lead to a better efficiency from various points of view.

A conventional PDP cell comprises of a mixture of three gases, Xe, Ne, and He. The excited Xe (i.e., Xe^*) species emitting UV photons is better known for its capability of generating the visible light inside the cell, and, hence, ultimately responsible for the luminous efficiency. In the usual PDP cell operation, it has been noticed from the simulation results, that the density of Xe^* species is relatively less than the ionized Xe species (i.e., Xe^+). Consequently, the luminous efficiency is undesirably less. Moreover, the excessive ion density is not desirable as they can cause a variety of physical damages inside the cell by erupting MgO layers, or phosphor region, and further reducing the lifetime. In order to overcome these difficulties, it is further realized that the cell must be operated under low electric field regime. The low electric field regime is prominently regarded as the most favorable regime of PDP operation, and is believed to be more effective in producing a larger population of Xe^* species than that of Xe^+. The low electric field inside the PDP cell can be achieved by a variety of ways. In one of our earlier works, it was successfully demonstrated that a long column positive discharge (effectively low electric field region) can be incited by stretching the overall discharge length with the help of appropriate dielectric tailoring [6], or using a nonuniform secondary electron coefficient [7] inside the PDP cell. The resultant gain in the efficiency was dramatic. We, therefore, concentrate in this paper on the method, which can render a low electric field region inside the PDP cell. In the wake of this objective, we here propose a novel method, using an electron beam in the PDP cell, which is shown to enhance the efficiency by a significant factor. Our simulation results indicate that when an electron beam is injected inside a high pressure PDP cell, the density of Xe^* increases compared with Xe^+ density. As a result, light production capability improves while power consumption reduces, and there is remarkable gain in the efficiency.

In Section II, we describe the comparison between one-dimensional (1-D) kinetic and fluid simulation results with the electron beam present. The prime objective of such studies is to ensure the validity of fluid results when the beam component is present. Section III deals with the proposed two-dimensional (2-D) geometry of the PDP cell for an electron beam injection, as well as the basic equations as modified due to introduction of electron beam. Section IV contains the details of numerical findings. In Section V, we describe the effect of varying electron beam current density. Section VI deals with the discussion.

II. 1-D Kinetic and Fluid Simulations

Our investigation of the efficiency improvement by an electron beam emission, is wholy based upon a 2-D fluid simulation code, which incorporates a drift-diffusion approximation (DDA). More details are discussed in Section III. Such calculation, however, does not deal with the separate momentum equation. It is, therefore, important to understand how the electron beam component is being treated by the fluid code, and whether

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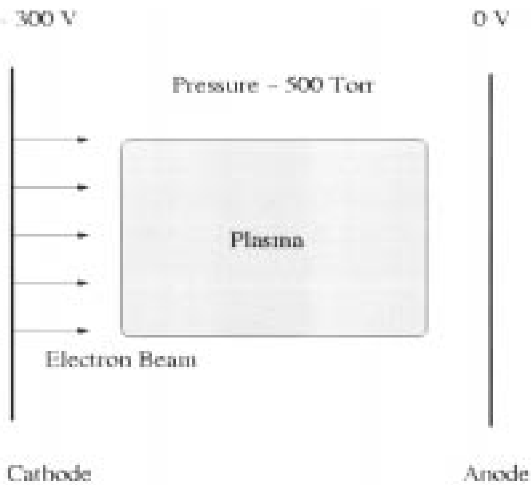

Fig. 1. Schematic of typical 1-D capacitively gas discharge model. Cathode on the left is maintained at -300 V, anode is at 0 V. Electron beam is injected through the cathode. Beam current density and pressure are 10 mA/cm^2 and 500 torr, respectively.

fluid code treating electron beam component provides qualitatively similar results to that of kinetic code. In order to ensure the aforementioned issues, we first carry out simple studies with the help of 1-D kinetic code, and compare its results with 1-D fluid code, for the beam interacting with capacitively discharged plasma. We use XPDP1 and FL2P codes for kinetic and fluid simulations, respectively. The XPDP1 [8] code uses the equations of motion for electrons, ions, and beam. In order to calculate the discharge efficiency, it was modified also to include the motion for excited species. The FL2P code evolves fluid continuity, Poisson, and DDA equations, along with the modification due to beam component described in the next section. The geometry is as shown by the schematic of Fig. 1, and consists of a cathode and an anode plates. Electron beam is injected through cathode side, which is maintained at -300 V. The anode is at 0 V. The gas pressure is 500 torr, while the current density of electron beam is 10 mA/cm^2. Since our major concern here is the efficiency, we, therefore, only compute the discharge efficiency for the sake of comparing the kinetic and fluid results. The discharge efficiency is defined as the ratio of deposited power into excitation of xenon to the total consumed power. Power consumption is calculated by summing the current density of charged particles product the electric field at each position. In fluid simulation, UV photons from excited species $Xe^*(^3P_1)$, $Xe_2^*(O_u^+)$, $Xe_2^*(^1\Sigma_u^+)$, $Xe_2^*(^3\Sigma_u^+)$ are considered, while only 147-nm UV photon from $Xe^*(^3P_1)$ is considered in kinetic simulation. The discharge efficiency is shown in Fig. 2. It is clear from the figure that the efficiency obtained from the fluid code exhibits a qualitatively similar trend as in the kinetic simulation. It is to be noted here that we do not intend to make an exact quantitative comparison between the two results, as fluid and kinetic codes are little different in their basic treatment. However, the qualitative matching of the efficiency-curve in Fig. 2 indicates that fluid code deals equally better with the electron beam component. We next generalize the 1-D case to 2-D case to investigate the effect of electron beam in the PDP cell.

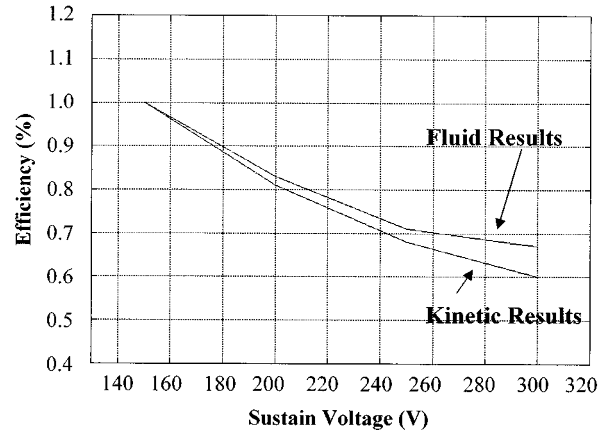

Fig. 2. A comparison of the normalized efficiency trend obtained from 1-D fluid (upper curve) and kinetic (lower curve) codes. The two results show qualitatively similar characteristics and, hence, validate the fluid treatment.

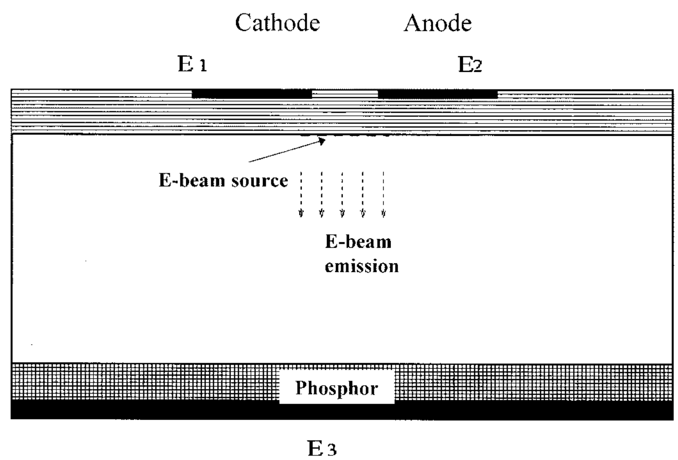

Fig. 3. A typical PDP geometry used in the simulation. Left and right side electrodes appearing on the top are, respectively, anode and cathode, along with a dielectric material. Lower dielectric is covered with the phosphor material. The neutral gas pressures 500 torr, while the gas composition is Ne/Xe $\sim$ 96/4%. The electron beam emission region lies between the cathode and the anode, as indicated by dashed region. Beam current density range is 0.1–10 mA/cm^2.

III. Proposed Geometry and Basic Equations

The PDP geometry [as in Fig. 3], considered in all our 2-D simulations, consists of two electrodes namely, cathode and anode, aligned in the same upper plate [2]. These electrodes are covered by dielectric material. The length and the width of the cell are 1260 and 210 μm, respectively. For our numerical simulation, 48 and 21 meshes are used in each direction. The gap between the two electrodes is 80 μm and the length of each electrodes is 100 μm. The width and dielectric constant of dielectric materials of upper and lower sides are respectively 45 μm, 12, and 40 μm, 10. The applied voltage ranges on top-left, top-right and bottom electrodes are 220–150, 0, 110–75 V, respectively. The electron beam emission region lies between cathode and anode electrodes, as shown in the figure by dashed line region. This is the region wherein localized electric field between the two electrodes is very high and discharges most of the neutral gas. The high magnitude of electric field in the region then could be efficiently utilized by inserting some field-emission material, e.g., carbon nano tube (CNT) which is capable of emitting considerable population of electron species, when the applied localized electric field exceeds a certain threshold. The electron beam produced by this method will, henceforth, be referred to as "CNT E-beam." The other method of electron emission is to inject an electron beam in this region through an external medium. The latter can be called a "Continuous E-beam," as it does not necessarily have to rely upon any local properties (e.g., threshold of electric field).

We have carried out simulations for both the CNT E-beam and Continuous E-beam. The gas pressure inside the cell is 500 torr. The neutral gas composition contains 96% Ne and 4% Xe. We use fluid simulation code FL2P, which has been developed by us [4]. The fluid code uses fluid continuity equations (for electron, ions, and excited species) along with drift-diffusion approximation. These equations are given as follows:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \bar{\mathbf{\Gamma}}_e = R_i - \alpha n_e n_p \tag{1}$$

$$\frac{\partial n_p}{\partial t} + \nabla \cdot \mathbf{\Gamma}_p = R_i - \alpha n_e n_p \tag{2}$$

$$\nabla \cdot (\epsilon \nabla V) = -e(n_p - n_e) \tag{3}$$

$$\mathbf{\Gamma}_e = -D_e \nabla n_e - n_e \mu_e \mathbf{E} \tag{4}$$

$$\mathbf{\Gamma}_p = -D_p \nabla n_p + n_p \mu_p \mathbf{E} \tag{5}$$

where

$n_{p,e}$	density of electron (ion);
$D_{p,e}$	diffusion of electron (ion);
$\mu_{p,e}$	mobility of electron (ion);
ϵ	permittivity;
R_i	ionization rate coefficient;
α	recombination coefficient;
$\mathbf{\Gamma}_e$	electrons;
$\mathbf{\Gamma}_i$	ions fluxes.

These fluxes consist of diffusion and drift terms and are usually referred to as drift-diffusion approximation. Using this approximation, the momentum of the fluid is being updated at each time step. This further allows one to get rid of solving the momentum equation in the fluid framework. The drift-diffusion approximation is also used for beam electrons. Though this approximation is not completely validated, the efficiency obtained by kinetic code and fluid code exhibited similar results in Section II. Further, $\mathbf{E}$ represent the electric field. Notice that the electron flux in (1) is represented by $\bar{\mathbf{\Gamma}}_e$, which represents modified flux due to electron beam emission from the emitter. The modified flux due to CNT depends upon the electric field threshold as follows:

$$\bar{\mathbf{\Gamma}}_e = \begin{cases} \mathbf{\Gamma}_e + \mathbf{\Gamma}_{\text{beam}}, & \text{E} > \text{E}_{\text{threshold}} \\ \mathbf{\Gamma}_e, & \text{otherwise} \end{cases} \tag{6}$$

where $\mathbf{\Gamma}_{\text{beam}} \sim \mathbf{J}_{\text{beam}}/e$, e being electronic charge, depends upon the beam current density $\mathbf{J}_{\text{beam}}$ (mA/cm^2), $\text{E}_{\text{threshold}}$ is the threshold of local electric field above which CNT emits electron beam. However, in the second case when there occurs continuous emission of electron beam, the modified electron flux predominantly stays as

$$\bar{\mathbf{\Gamma}}_e = \mathbf{\Gamma}_e + \mathbf{\Gamma}_{\text{beam}} \tag{7}$$

all the time irrespective of the local properties. Thus, (6) appropriately models CNT E-beam case, while (7) takes care of Continuous E-beam injection case. The injection of electron beam by either methods, modifies the flux function for electron species, which further gets convected by the fluid continuity equation, during the evolution process and makes substantial influence on the discharge characteristics. We have simulated (1)–(5) along with (6) or (7) for various current densities of the electron beam.

IV. Simulation Results

We first discuss the results of Continuous E-beam case. An electron beam of current density range $\text{J}_{\text{beam}} \sim$ 0.1–10 mA/cm^2 is injected into the PDP cell through the specified region, during its sustained operation. The effect of electron beam is to cause a continuous emission of electron population from the region, where it is being inserted. As a result of beam component, appreciable changes in the distribution, and peak values of excited, and ionized Xe densities can be seen. To realize various consequences of the beam dynamics, a comparison with the case of no beam injection (i.e., $\text{J}_{\text{beam}} = 0.0$ mA/cm^2) has been made. At the peak times of ionized Xe densities, the results for the two cases viz $\text{J}_{\text{beam}} \sim 0.0, 10.0$ mA/cm^2 are depicted in Fig. 4. It can be seen from the figure that during the absence of beam component, the peak as well as volume integrated values of ionized Xe species (Xe^+) are apparently larger than that of the excited Xe species $(\text{Xe}^*(^3P_1))$, as shown in Fig. 4(a) and (b). It is also worth noting here that these density distributions are mainly localized near the cathode-anode electrodes region, where the discharge was being initiated in the beginning. Thus, the bulk discharge in the usual PDP cell operation appears to be closer to MgO protective layer than the phosphor dielectric. Such situation in the PDP cell operation is, nevertheless, highly undesirable for the two basic reasons. First, the energetic ions coming out of the bulk plasma, near the MgO protective layer, can cause severe damage to the layer by their continuous bombardment. Second, the resonant excited species $\text{Xe}(^3P_1)$ which is being produced farther from the phosphor layer will not be able to result in the efficient production of visible light due to its optically thick nature when the resonant line is more dominant than the continuum lines. Thus, in order to optimize such situations for achieving the better performance of the cell, it is preferred to have the density distributions as shown in the Fig. 4(c) and (d). This is the case when an electron beam of $\text{J}_{\text{beam}} = 10.0$ mA/cm^2 is being activated in the cell. These results are undoubtly better than the no-beam case for many reasons. The ion density, as shown in Fig. 4(c), is reduced by an order as compared to that in Fig. 4(a). Similarly, the peak, as well as volume averaged Xe ion density, is less than that of Xe excited. In other words, beam electrons produce more excited Xe than Xe ions. Thus, the light production capability increases. If CNT lifetime is longer than the cell lifetime, the lifetime of the cell is also increased. In addition, the excited Xe density distribution has been stretched toward the phosphor layer region. Hence, conversion of excited Xe atoms into visible light obviously becomes more efficient. The

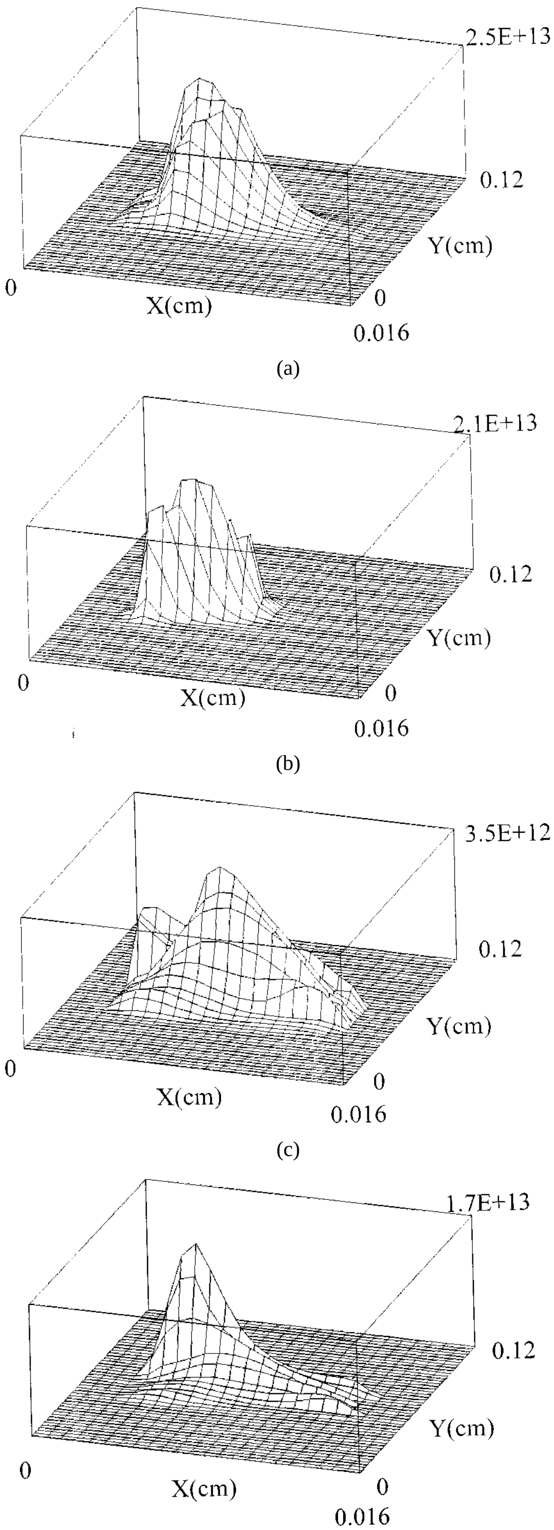

Fig. 4. (a) and (b) show ionized and excited Xe $(Xe^*(3P_1))$ density distribution when the beam is off. Notice that Xe^+ density is larger than Xe^* density. (c) and (d) show ionized and excited Xe density distribution when the beam is on. Xe^* density is larger than Xe^+ density.

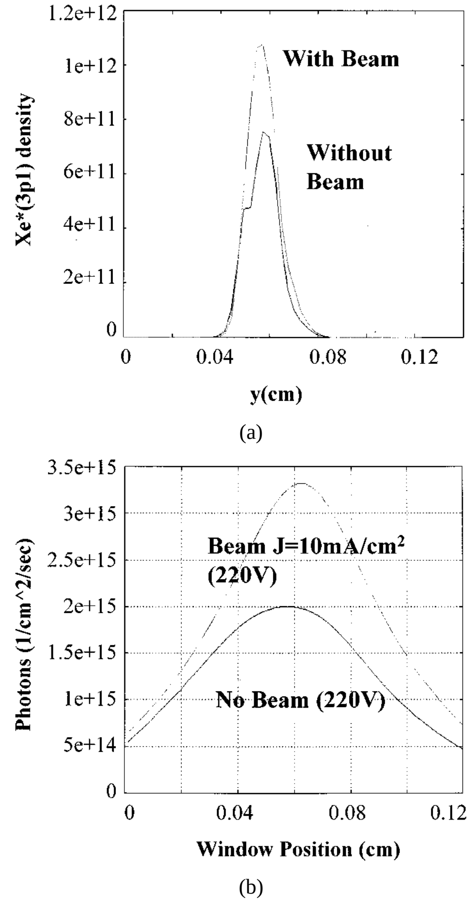

Fig. 5. (a) Xe^* density distribution near the phosphor dielectric. Upper curve stands for the beam case, while the lower curve corresponds to the no-beam case. (b) Light distribution for the beam and no-beam cases, when the sustained voltage is 220 V.

latter can be corroborated with the results of Fig. 5. It is clear from Fig. 5(a) that the excited Xe production near the phosphor layers increases when the beam component is at work in the nearby region. There is more than an order of difference in the peak, as well as volume integrated density distributions between the beam, and no-beam cases. Consequently, the light production efficiency is also improved by a significant factor, when the beam component is present. This can be seen in Fig. 5(b), which displays the light distribution with respect to window position during the PDP cell operation. We have thus seen that the effect of an electron beam in the PDP cell is to enhance the light generation efficiency, as well as to reduce the ion flux, thereby increasing its life time. The efficiency related calculations shall be discussed in Section V. Although, the ion density near the phosphor region also increases due to the presence of beam component, the magnitude is low enough (as compared to the peak density near the MgO region) to cause any more severe damages.

We now present simulation results for the CNT E-beam case. It has already mentioned elsewhere that CNT can emit electrons under the influence of certain threshold electric field. Recent works have quantified the value of CNT threshold as 3 V/μm, which can give rise to electron beam current density up to 10 mA/cm^2 [9], [10]. Though the PDP system is different from their system, we use these values of electric field threshold and current density in the simulation for CNT E-beam case because of the lack of the experimental results in this system. Our simulation results regarding the Xe^* and Xe^+ densities are almost similar to those obtained in the Continuous E-beam case (not shown here). Although the threshold criteria in the latter is a little stringent as well as transient to be met, the characteristic results do not deviate from the Continuous E-beam case. However, there are a few differences in the two cases, which will be highlighted in Section V.

V. Effect of Beam Current Density

We now report on the efficiency, luminance, and power consumption of the PDP cell, and also consider the effect of varying beam current density on these physical properties. As already mentioned earlier, these parameters are important from the point of view of benchmarking the PDP technology. We, therefore, carry out detailed investigations of the effect of CNT E-beam, and Continuous E-beam to optimize these parameters and locate the most favorable operation regime of the PDP cell. Before that, we need to consider the necessity of additional power to generate the electron beam. In our calculation of power consumption, the additional power is not included. For the CNT E-beam case, we assume the electron beam is generated by electric field driven by sustain electrodes, not by additional power source. However, if the additional power source is used for generating the electron beam, our method is effective only when it is much less than the power consumption of the conventional PDP cell.

The results for Continuous E-beam case are presented in Fig. 6. To compare the effect of beam current density on the various parameter, a no-beam case is also displayed along with each profile. It is clear that in the absence of beam component, the efficiency (in terms of lm/W units) is very low as shown in the Fig. 6(a) by the lowest most curve (here $J = 0.0$ mA/cm^2). However, as the beam current density increases, there is dramatic enhancement in the efficiency of the PDP cell. For example, when the beam current density is $J = 0.1$ mA/cm^2, the gain in the efficiency is up to 25% [Fig. 4(a) curve 2], which further increases up to 88% [see Fig. 6(a) curve 3] and 118% [curve 4 in Fig. 6(a)] respectively for 3, 10 mA/cm^2 beam current densities. Thus, it can be realized that the gain in the PDP efficiency is significant, when the electron beam component is present. The efficiency has been computed for various sustain voltages, on which PDP cell operation is possible. Fig. 6(a) further reveals that the efficiency of the cell is better at relatively lower voltage. In short, the efficiency of the PDP cell improves by a significant factor, when an electron beam component is present. In case, the source of electron beam is dependent on a certain threshold of electric field such as CNT, then the CNT E-beam improves the luminous efficiency of the PDP cell up to 46%, as shown in the Fig. 7. The efficiency can be further improved up to 51% when the additional side-dielectrics are present with the phosphor layer on them. However, the improvement due to latter is comparatively smaller than the Continuous E-beam case. The basic difference between the two results shall be illustrated later at the end of this section.

The luminance of PDP cell is another important quantity mainly concerned with the visible light output and is measured in the units of cd/m^2, as depicted in Fig. 6(b), for no-beam and Continuous E-beam cases. Like efficiency, luminance also increases when the beam current density is increased. Thus, it can be seen from Fig. 6(b) that in the absence of beam, the luminance is very low, while it is relatively high for higher

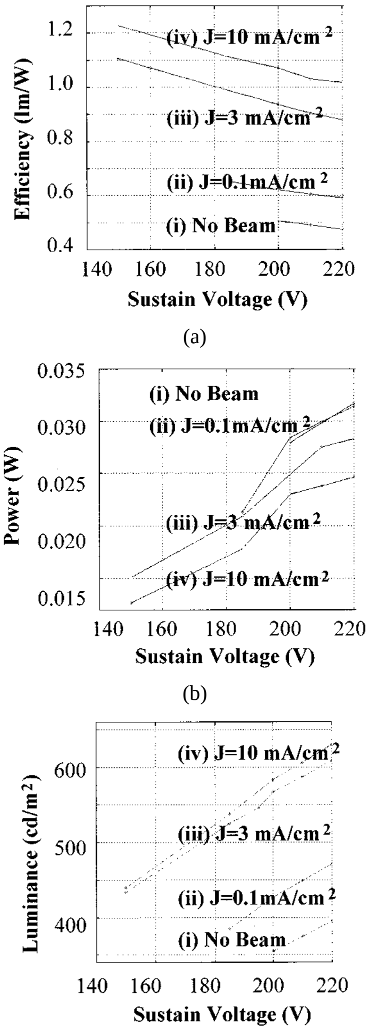

Fig. 6. (a) Luminous efficiency of the PDP cell for various beam current densities at different sustain voltages. On increasing the beam current density, efficiency is also enhanced. (b) Luminance shows similar trends. (c) Power consumption reduces with the larger intensity of the beam current density.

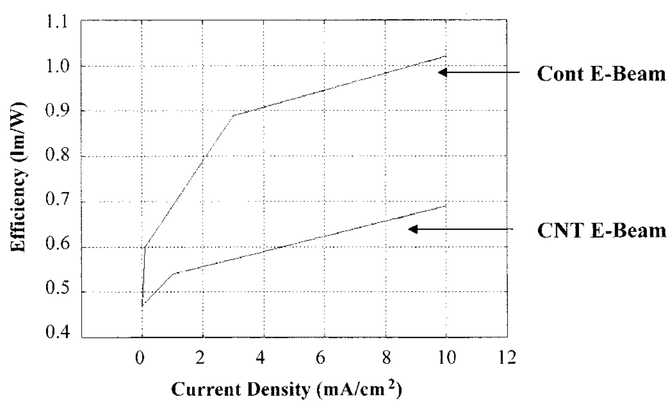

Fig. 7. Luminous efficiency comparison for the CNT E-beam and Continuous E-beam cases, at various beam current densities. The efficiency of the latter is considerably larger than the former.

values of beam current density. However, unlike efficiency, luminance decreases with decreasing the cell sustain voltage, even in the presence of beam component. The luminance for various values of beam current densities is shown in Fig. 6(b)

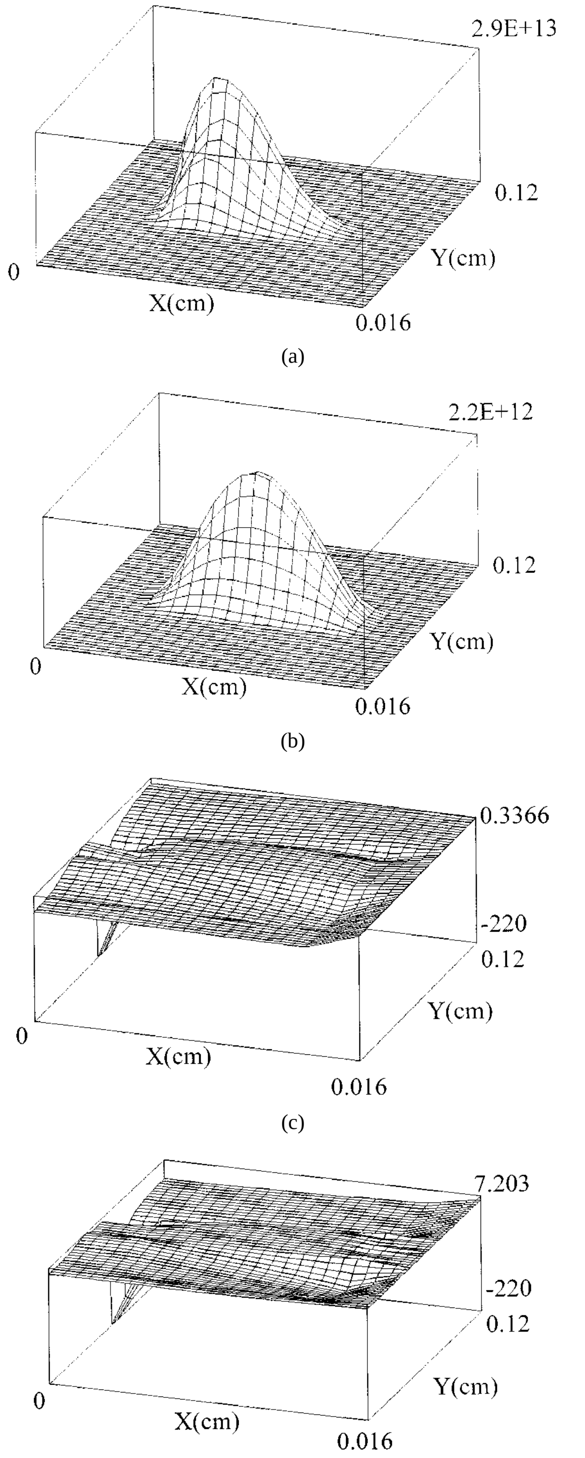

Fig. 8. Electron density distributions for no-beam, and beam cases are shown in (a) and (b), respectively. Similarly, (c) and (d) represent the potential distributions for the no-beam and beam cases respectively.

by curves 1–4, while the power consumption reduces when the intensity of beam current density is high. This is shown in Fig. 6(c) for various values of beam current densities. When beam current density is 0.1 mA/cm^2, there is not much reduction in the power consumption, however it reduces further by 10%, and 21%, respectively for 3, and 10 mA/cm^2 beam current densities. Such reduction in the power consumption, therefore, appreciably contributes to the efficiency enhancement.

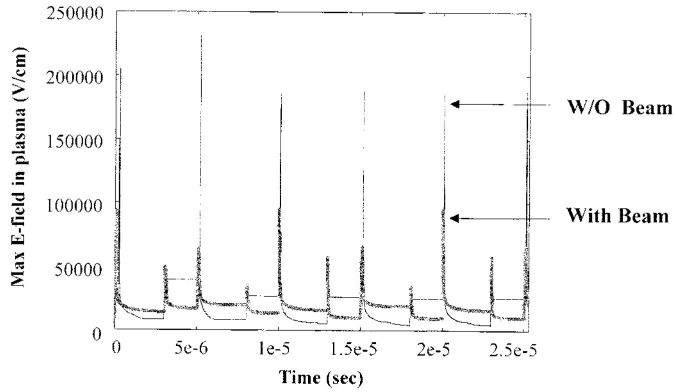

Fig. 9. Space-averaged maximum profile of electric field at different time intervals is shown. Thin lines represent the electric field when beam component is absent. Thick lines correspond to electric field when the beam component is present. The effect of beam is to reduce the electric field in the plasma.

In order to understand the basic mechanism of efficiency improvement due to the beam, it is worthwhile to diagnose the electron density, potential, and maximum electric field (in plasma) profiles at the peak time of Xe ion density, which are displayed in Figs. 8 and 9. The beam component in the plasma apparently widens up the electron density distribution, as shown in the Fig. 8(b), as compared to the density distribution without beam case [see Fig. 8(a)]. Such widened plasma density distribution eventually flattens the potential distribution in space, as seen in the Fig. 8(c) and (d). The flattening of the space potential thereby reduces the electric field in the plasma. Thus, the electric field in the plasma drastically decreases during the peak discharge time. This is clearly shown in Fig. 9. The thin lines represent the space averaged electric field without the beam component, while thick lines correspond to the electric field when the beam component is present. The difference in the two cases is apparently obvious. Such a low electric field is believed to be a cause of considerable excitation of the Xe species, while it reduces the ionized Xe species. Consequently, the light generation ability improves by a significant factor, as shown earlier in the Figs. 4–6. A careful look at Fig. 9 readily indicates that the maximum electric field in plasma stays for a very short period compared to otherwise. Similarly, for the CNT E-beam emission, maximum electric field value exceeding the threshold (i.e., 3 V/μm) is not always met. It means that beam component in the CNT E-beam case exists for a short period, as compared to the continuous beam case. Hence, the CNT E-beam dynamics contributes relatively less to the overall discharge evolution. This is the basic reason why CNT E-beam is less effective in comparison with the Continuous E-beam emission case.

VI. Conclusion

In this paper, we have investigated a method based upon electron beam emission which clearly demonstrates significant enhancement in the efficiency of the PDP cell. The efficiency for the Continuous beam source can increase up to 118% while for the CNT case, it is up to 51%. The basic reason of the efficiency enhancement can be consigned to considerable reduction in the electric field inside the PDP cell. Such low electric field appears to be quite effective in exciting the Xe^* species, and helps reducing Xe^+ species. This method has, therefore, twofold advantages. First, the reduction in ionized species density can prevent the cell from severe damages that are primarily occurred because of energetic ion bombardment on the phosphor/MgO surfaces. Second, significant enhancement of Xe^* species can generate large number of photons, thereby increasing the luminous efficiency. Other improvements such as reduction in the power consumption, and life time improvement can also be expected from our investigations.

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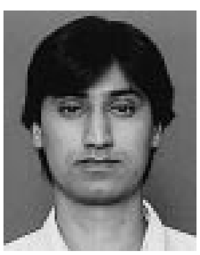

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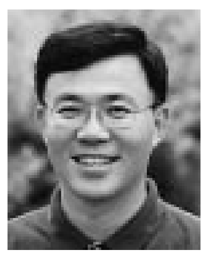

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