Theoretical Study of Discharge Confinement in an Electron-Beam-Controlled Laser Discharge Cavity

B. N. Srivastava*
Avco Everett Research Laboratory, Inc., Everett, Massachusetts

Electron-beam-controlled pulsed lasers utilize bladed shields in the laser cavity to prevent transverse spreading of the electron beam in order to achieve high electrical efficiency. These shields also tend to cause electric field nonuniformity and stress concentration in the laser cavity resulting in the degradation of the overall performance of the cavity. This paper describes the results of theoretical studies aimed at understanding these effects in relation to the bladed shield design. Numerical solutions are developed which account for the effects of finite electron beam, finite electrode length, arbitrary electrode shape, and specific size and shape of the bladed shield. Results are presented to demonstrate the effects of various parameters of the blade design on the laser cavity performance.

Nomenclature

d = blade spacing
E = electric field magnitude
N = gas number density
S = electron-beam source term
t = blade thickness
ϕ = electric potential

I. Introduction

DISCHARGE confinement in an electron-beam-controlled laser discharge cavity is an important technical consideration for achieving high electrical efficiency of laser discharges. For efficient discharge operation it is necessary to confine the discharge zone of the laser cavity to the active laser volume, from which the laser power is extracted. This is generally accomplished by employing some means of controlling the transverse spreading of the electron beam in the laser cavity. One of the approaches is to employ a well-designed n-bladed shield in the laser cavity which is intended to prevent such transverse spreading of the electron beam.[1] However, insertion of shields also tends to cause two other effects which are detrimental to the overall laser performance. One of these effects is the creation of electric field nonuniformity in the laser cavity due to the particular shape and size of the blades. This effect leads to energy deposition nonuniformities and, hence, poor optical quality of the laser output beam. The second effect occurs through highly localized stresses on the surface of these blades that can result in the onset of arcing in the laser cavity, and subsequent collapse of the discharge pumping process for the laser. An understanding of these effects in relation to the blade design of the n-bladed shield is, therefore, an important factor in determining the overall performance of the laser cavity.

The problem as just outlined is quite complex in nature, due to the simultaneous presence of several complex phenomena such as electron-beam scattering and energy loss through the foil and gas medium, discharge effects on the electron beam, effect of self-induced magnetic field (due to the discharge current) on the electron beam, and interaction of the electron beam with the n-bladed shield and anode. There have been several efforts in the past[2-9] to address the basic issues of ionization source uniformity, discharge field and energy deposition uniformity in the active volume of the laser cavity, which relate to improving the overall efficiency and performance of such devices. A good description of these approaches appears in Refs. 1 and 7. Most of these past efforts, however, are confined to studying these issues by ignoring the presence of the bladed shield. The general objective in these studies has been to obtain realistic estimates of controlling design considerations for the overall cavity by excluding complex local (near the blade) effects. Such local effects, however, become important when the problem of efficient discharge confinement is considered. This problem relates more to the evolution of design considerations for the n-bladed shield in order to minimize local effects detrimental to the overall performance of the laser cavity. A limited effort toward achieving this goal was reported in Ref. 1, where a self-consistent numerical solution of the laser discharge problem including the effects of finite electron beam, finite electrode length, arbitrary electrode shape, and n-bladed shield was used to demonstrate the influence of some parameters of the blade design on the overall cavity performance. The present paper deals with further studies in this area relating to the effect of various other parameters of the blade design on the overall cavity performance and is an extension of the previous paper.[1] Specific studies relate to the overall performance of the cavity relative to the choice of blade material, such as insulator or conductor (or a combination thereof), and the choice of number and shape of the blades in an n-bladed shield design.

The present paper is divided into several parts. Section II deals with the problem definition, the modeling description, and the numerical techniques. Section III deals with the comparison of the numerical predictions with previous experiments. Section IV deals with the discharge confinement issues such as the effect of blade material (e.g., conductor vs insulator or a combination thereof), number of blades, nose shape of the blades, and the shape of the electrodes on the electric field distribution in the laser cavity. The last section outlines the conclusions relevant to the discharge confinement in a laser cavity.

II. The Problem and Its Analysis

Figure 1 shows the schematic of the laser discharge cavity with an n-bladed shield placed downstream of the flow. The dotted line in this figure shows the active cavity volume. It is this region within which discharge and energy deposition uniformity is desired. Notice that the protruding blade acts as an obstruction in the path of the electron beam outside the active volume achieving the desired confinement. However,

Received July 6, 1981; revision received Jan. 17, 1983.

*Principal Research Scientist. Member AIAA.

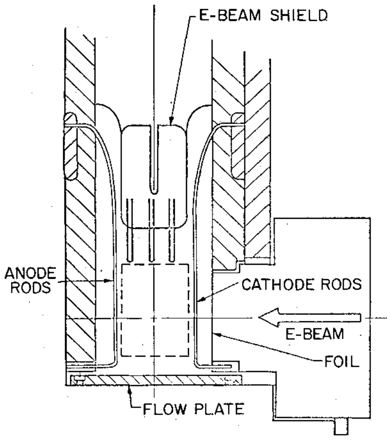

Fig. 1 Schematic of discharge cavity with three-bladed e-beam shield.

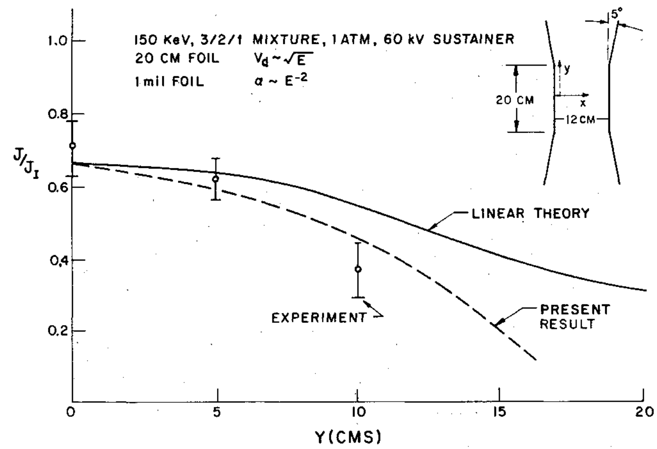

Fig. 2 Predicted and experimental variation of current density (case 1).

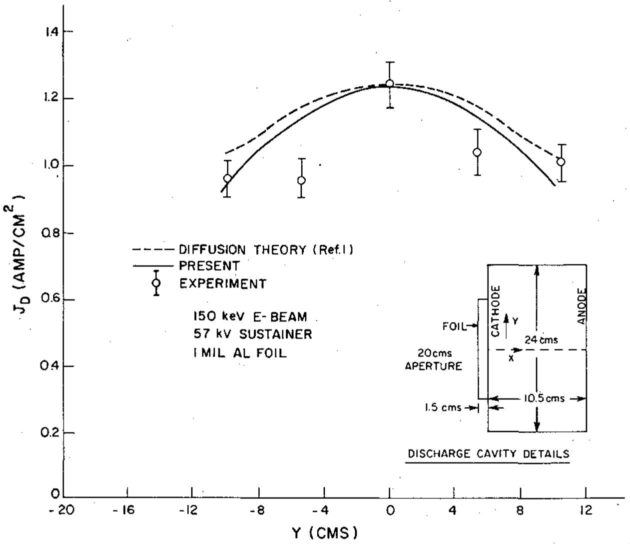

Fig. 3 Predicted and experimental variation of current density (case 2).

this protrusion also tends to create perturbations in the field/energy deposition in the active cavity zone which must be minimized in order to achieve an optimum cavity performance. This can be done by studying the effect on the field distribution in the cavity of the various parameters of the blade design, such as number of blades in a given discharge length, thickness of the blades, its nose shape, and the nature of the blade material (e.g., insulator or conductor or a combination of insulator and conductor material). Besides these, the shape of the electrode (see Fig. 1) and the manner in which it is terminated downstream of the blades is an important consideration in the design. The former influences the stress distribution near the blades (and also in the cavity), while the latter governs the stress enhancement at the triple point [a point where electrode, its terminating surface (generally an insulating material), and laser gas meet]. A theoretical study of these effects on the overall design of the n-bladed shield forms the core of the problem analyzed here.

The cavity discharge can be modeled as a nonuniform, nonlinear, two-dimensional resistor between the anode and the cathode. Mathematically, this is given as

$$\nabla \cdot \sigma(\nabla \phi) = 0 \tag{1}$$

where $E = -\nabla\phi$ and $\sigma = c(E/N)^m\sqrt{s}$. c and m are constants (see Ref. 1). N is the gas number density, s the electron-beam source term, and σ the gas conductivity. A mathematical solution of Eq. (1) with appropriate boundary conditions is desired. This is done first by obtaining the electron-beam source distribution s in the cavity using a Monte-Carlo code, and then solving Eq. (1) using a finite element technique (for a given electrode geometry and boundary conditions). Details of the analysis are discussed in Ref. 1.

The boundary conditions used for the solution of these problems can be obtained from the current conservation equation as discussed in Refs. 1-10. Basically, this amounts to applying $\partial\phi/\partial n \simeq 0$, where n is taken normal to a nonconducting wall and also specifying a potential ϕ on the electrode surface. The former is applicable outside the Debye length near a nonconducting wall.[10] However, since the Debye length is very small for such problems, its effect on the overall field distribution is neglected.

III. Comparison Between Theory and Experiment

A comparison between the theory as just described (and also in Ref. 1) and experiments is necessary to establish the validity of the theoretical predictions. Two different comparisons demonstrate that the present theoretical approach yields results that are in reasonably good agreement with experimental measurements. Figure 2 shows one of these results where the variation of the normalized discharge current density[2] is shown as a function of distance along the anode. The discharge geometry and other details of this problem are shown as an insert in this figure. Notice that the linear theory[2] fails to predict the proper fall off of the discharge current density while the present predictions are in reasonably good agreement with the data. This implies that the "stream tube" approach[2] has limited application in discharges where rapid variation in current is encountered, basically due to the failure of its small perturbation assumption. A second comparison between the theory and experiment is shown in Fig. 3. The geometry and the discharge conditions for this experiment[6] are shown in this figure. For comparison purposes the results obtained by the diffusion theory[6] are also shown. Notice that the diffusion theory and the Monte-Carlo calculations give similar results with a maximum difference of nearly 10%. However, two of the experimental points are off from both the calculations. As discussed in Ref. 6, this is the result of prefoil electron-beam distortion due to magnetic field effects which are not modeled in the current effort. A point of further comment here relates to the use of the diffusion theory[6] for simulating the source function in laser discharges. Several comparative calculations between the present approach and the diffusion theory suggests (see Ref. 1) that the diffusion theory does not provide the correct trend of two-dimensional ionization source variation in the laser cavity, especially when backscattering from the anode material is important. Care must be exercised, therefore, to use this theory in its appropriate limit as discussed in the original development of the theory.[9]

IV. Results and Discussion

The study of the discharge confinement issues of this paper is divided into several categories in an effort to determine the impact of various parameters of the n-bladed shield design. One of these categories is an n-bladed insulator electron-beam shield, whose characteristics and design considerations are discussed first. Others follow after this discussion.

Bladed Insulator Shield Studies

The analysis reported previously[1] has shown that when an insulator e-beam shield is introduced in a discharge region, the stress distribution near the shield is governed more from perturbations caused by the insulator's shape, thickness, etc. rather than nonlinearity of the discharge and nonuniformity in the e-beam source. A basic conclusion due to this study (see Ref. 1) was that a design based on linear analysis would be sufficient to provide useful information on discharge characteristics of the cavity. The results that follow were obtained using this approach. It was also shown that the peak stress for these blades occurs near the nose region. It is this stress concentration zone that may become critical in initiating arcing in the laser cavity. A redistribution of this peak stress, therefore, is necessary to avoid/delay the initiation of arcing in the laser cavity. This can be done through an appropriate choice of the design parameters of the blades such as number, thickness, and nose shape of blades.

Figure 4 shows the effect of the number of blades for a given discharge dimension. Notice that as the number of blades is increased (keeping the same thickness of each of the blades and distributing them equispaced), the stress enhancement at the nose of the blade (E_m/E_0) decreases rapidly initially and then more slowly later. In the limiting case of a very large number of blades the stress enhancement will be very small, however, flow consideration will limit the number of such blades. It is obvious from this figure that beyond about 3-4 blades the decrease in stress enhancement is so slow that any additional gain is marginal. Note also, that the number of blades, in practice, should be viewed in terms of a thickness ratio t/d, where t is the blade thickness and d the blade spacing. It is clear that increasing t/d will result in a reduction of the stress enhancement. This means that from a stress viewpoint, a large number of thin blades can be made no more efficient than a few thicker blades. From a design standpoint, therefore, an important parameter to optimize is t/d which should be determined from a structural (mounting, flutter, and strength), flow (pressure loss, flow disturbance such as wakes, boundary layers, etc.), and electrical (peak stress enhancement and stress distribution) viewpoint. A proper tradeoff within these requirements would be needed to determine its optimum value.

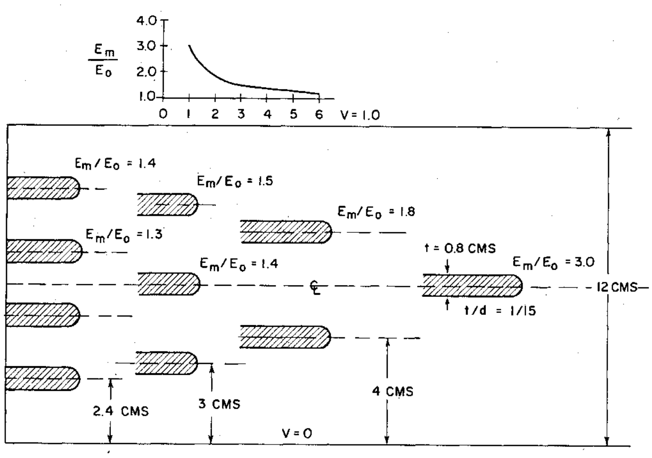

Fig. 4 Calculations demonstrating the effect on the maximum stress of the number of insulator blades for an n-bladed e-beam shield in a laser cavity.

Further studies related to the nose shape of these blades suggest that the nose shape of the blades play a very important role in determining the magnitude of the stress enhancement. In general, it was found that for lower t/d values the nose shape was important because the peak stresses were higher. For higher t/d values (for thick blades) the nose shape did not play a very prominent role. However, a circular nose shape is recommended for all t/d values.

Yet another important aspect to evaluate is the effect of the electrode shape on the stress enhancement of the insulator blades and field perturbations in the laser cavity. Since an abrupt and rapid turning of the electrode causes severe stress perturbations, it is customary to turn the electrodes smoothly into the terminal point (commonly known as triple point). This, however, is necessary only when a bladed insulator shield is not present. In order to understand this better, consider the results shown in Fig. 5. This figure shows the potential and field lines for half of the laser cavity for three different electrode shape configurations and an identical three-bladed insulator shield. In Fig. 5a the electrode was taken parallel to the blade, in Fig. 5b the shape of the electrode was gradually changed, while in Fig. 5c an abrupt termination followed by an insulator was modeled. It is clear from the equipotential lines that the stresses at the triple point (where electrode terminates) for all three cases is nearly nonexistent (very small). This is because the insulator blade tends to shield (redistribution of stresses) everything behind it. This implies that a careful contouring of the electrode shape is not necessary as long as the contoured part lies behind the insulator blades. Figure 6 shows the influence of the electrode shape on the stress distribution at the blade nearest to the electrode. The plot shows the variation of the electric field (E_0 represents field value without any blade and straight electrode) near the blade surface as one moves along the surface from left to right on the top surface and then from right to left at the bottom surface. The station locations on the surface are used from numerical calculations for convenience. Note that,

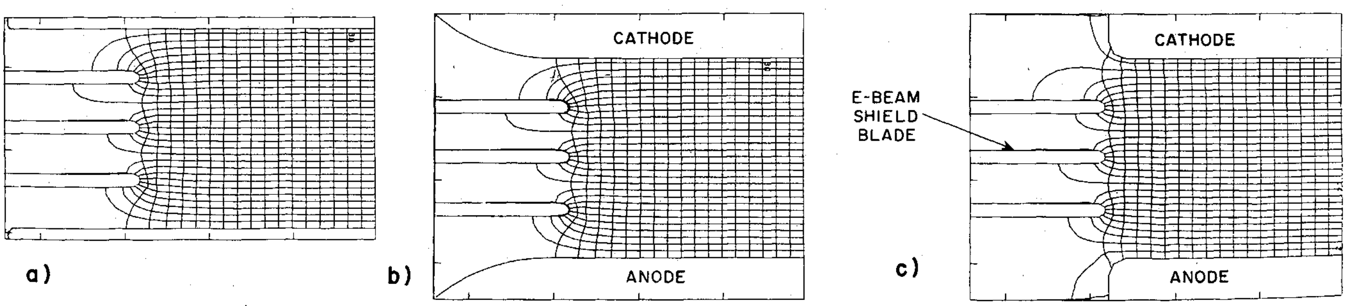

Fig. 5 Equipotential and field lines for a three-bladed insulator e-beam shield with various electrode shapes: a) straight electrode, b) gradually rolled electrode, and c) sharply rolled electrode.

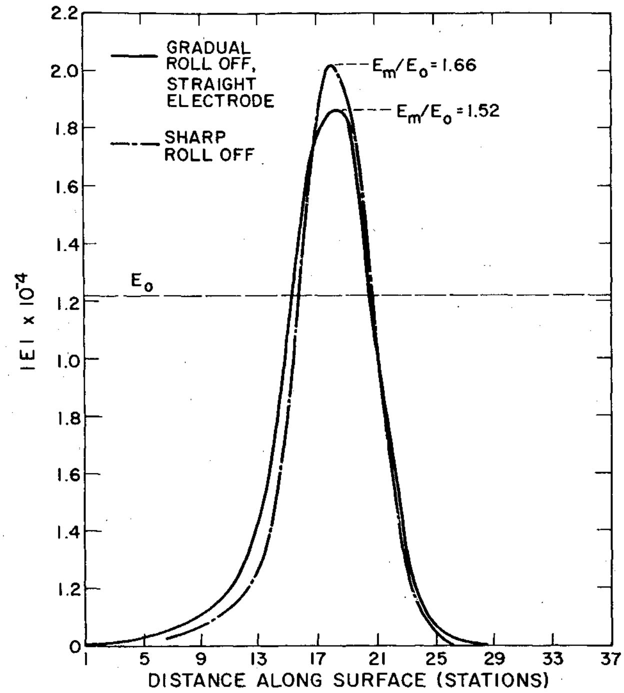

Fig. 6 Stress distribution near the first blade for the three cases shown in Fig. 5.

for a severe case of Fig. 5c, the stress enhancement as shown in Fig. 6 is very small. These results clearly indicate that for insulator e-beam shields the electrode shape does not play any significant role provided the shaped part of the electrode lies in the shadow zone of the shield.

The basic question that remains unanswered, as yet, is whether any alternate means of further reducing the stress enhancement on such blades can be identified. It is this motivation that led us to study whether a conductor or a combination of conductor and insulator can be used more effectively to achieve a more efficient discharge confinement. These efforts are described next.

Bladed Conductor Shield Studies

Our results and analysis indicate that floating conductor blades can not be successfully used a shield material due to several difficulties outlined in this section. For the purpose of demonstrating the basic concepts, it will be sufficient to consider a single blade situation. Figure 7 shows the results where equipotential lines are plotted for various cases. Figure 7a shows the insulator blade and Fig. 7b shows the conductor blade. For both of these calculations, it was assumed that the discharge is linear and the e-beam source term is uniform. A comparison of these two cases suggests that for a linear and uniform discharge the stress enhancement (demonstrated by bunching of equipotential lines) at the nose of the insulator blade is relieved when a floating conductor is used. Figure 8 further illustrates this, where stress distribution near the surface of the two blades (as shown in Figs. 7a and 7b) is plotted. Notice that the conductor blade acquires a potential which results in a net decrease in the peak stress as compared to the insulator blade. The maximum stress for the conductor blade occurs at the shoulders. The reduction in peak stress for the conductor blade, however, is artificial since source nonuniformity plays a very significant role in determining the stress distribution around such a blade. It has been demonstrated before that for insulator blades, the nature of source variation in the shadow region does not perturb the stresses around such blades due to the shielding effect of the blades. However, such shielding effect is not present (as seen in Figs. 7a and 7b) for conductor blades since the blades themselves

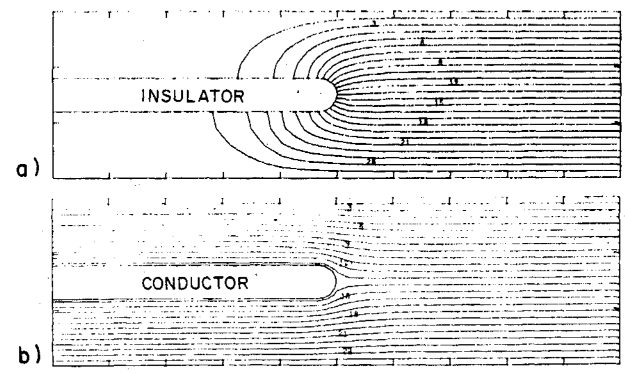

Fig. 7 Equipotential lines for a single blade in a uniform, linear discharge for a) insulator blade and b) conductor blade.

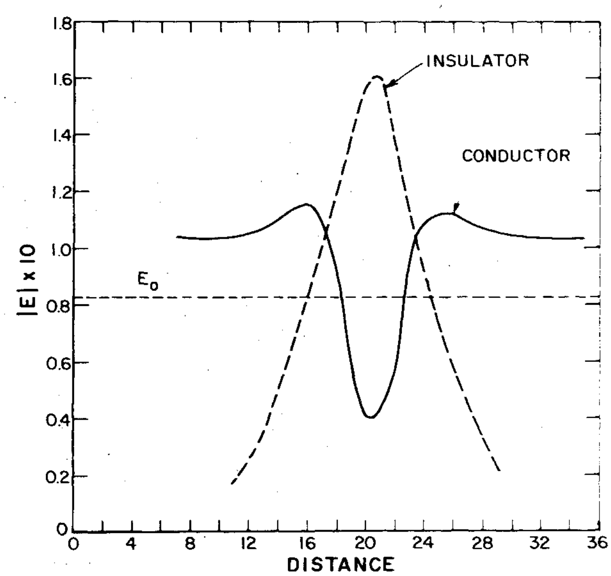

Fig. 8 Stress distributions near the blade for the two cases shown in Fig. 7.

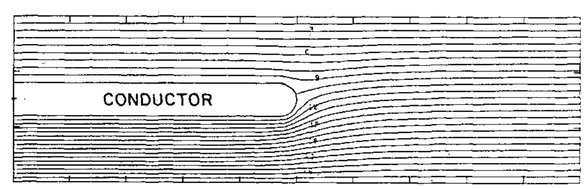

Fig. 9 Equipotential lines for a single conductor blade in a nonuniform discharge with ionization source fall off in the shadow zone.

acquire a potential. This, in turn, results in the presence of significant stresses between the conductor blades. Depending on the nature of the e-beam source variation in the shadow region, the stresses around the conductor blade will change drastically. This is demonstrated in Fig. 9, where the shadow region was assumed to have an exponential drop in the source function (see Ref. 1). Notice that the stresses build up in the shadow region and the stress concentration becomes more severe at the bottom shoulder. Besides this, there are several other difficulties associated with conductor blades. For example, the triple point (not shown in the preceding calculation) is no longer shielded, the mountings of these blades must be designed carefully, and the electrode shape will play an important role even if it is behind the conductor blade. It is quite evident, therefore, that the conductor blade as a shield is undesirable for laser applications unless other ways to overcome the problems just mentioned are found.

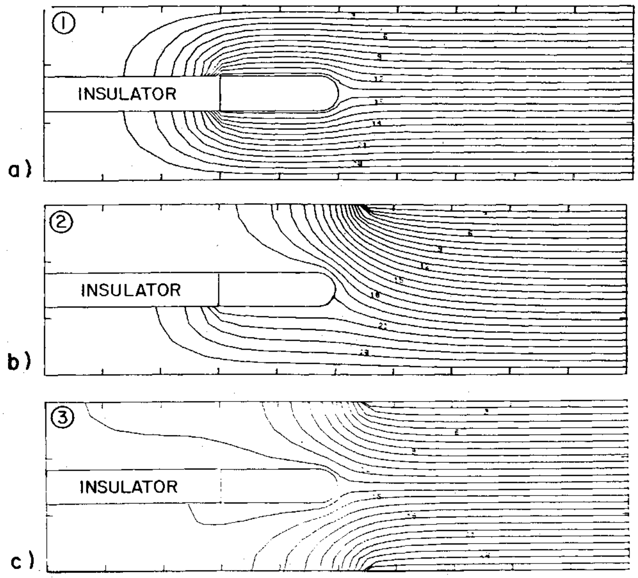

Fig. 10 Equipotential lines for a single blade in a uniform, linear discharge for a combination of rear insulator and front conductor with a) both electrodes straight, b) top electrode short, c) both electrodes short.

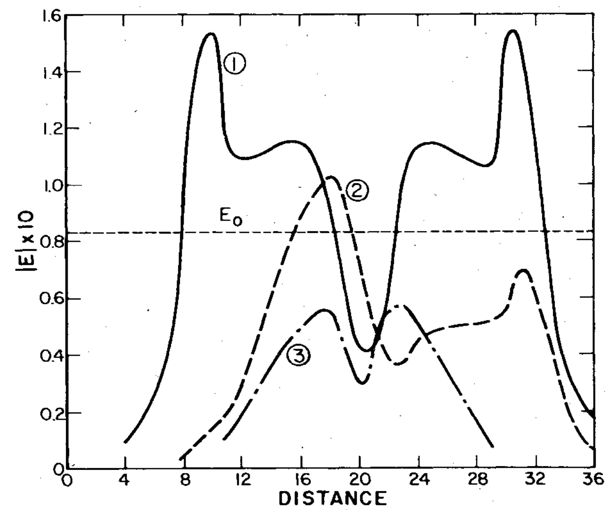

Fig. 11 Stress distribution around the blade for the three cases shown in Fig. 10.

Bladed Conductor and Insulator Shield Studies

A possible way to overcome some of the problems associated with the conductor blades is to use a blade consisting of a rear insulator and front conductor. This arrangement is shown in Fig. 10a where equipotential lines are shown. The difficulty associated with this arrangement is obvious from Fig. 10a. At the insulator and conductor juncture point the stresses build up resulting in severe stress enhancement shown by bunching of equipotential lines. This calculation, however, is also for a uniform source. For a nonuniform source the problem of further stress buildup at the bottom blade shoulder still exists. This study suggests that use of insulator rear can solve some of the difficulties (such as shielding triple point, blade mounting, electrode shape), creates at least one new difficulty at the junction point, and can not overcome the problem associated with shadow zone of the conductor shield. The bulk of the remaining problems can be overcome by using a short electrode that is slightly displaced away from the edge of the shield. Two such arrangements are shown in Figs. 10b and 10c. In Fig. 10b the top electrode has been shortened. Making this electrode short pulls away the equipotential lines to the triple point (where electrode has terminated) resulting in relieving stresses at the insulator/conductor junction point. In Fig. 10c equipotential lines are shown for the case where both electrodes are shortened. For this case, it is quite clear that the stresses all around the blade are significantly lower than the blades shown in Figs. 10a and 10b. A quantitative comparison of the stress distribution around the three different configurations is shown in Fig. 11. It is quite clear that the arrangement shown in Fig. 10c is quite attractive in so far as the stress considerations on the blade itself are concerned. This, however, does not solve the problem of avoiding stress enhancement at the triple point. In fact, this arrangement has merely shifted the location of critical stress concentration from the blade to the triple point in the cavity. The electrode shape and the triple point will play a dominant role for such a design. In fact, the same effect can be achieved by using insulator blades with short electrodes; therefore, this design does not offer any new alternative to get more efficient discharge confinement.

V. Conclusions

This paper deals with discharge confinement for laser applications. Bladed shield concept of discharge confinement, which is commonly used in CO_2 laser cavities, has been theoretically studied. The overall electrical performance of the laser cavity in relation to several parameters of the blade design such as the number of blades, blade spacing, nose shape, blade material, and electrode shape has been discussed. These results are obtained by using a self-consistent numerical solution of the laser discharge problem. The validity of the numerical calculations are established by comparing the results of the prediction with previous experiments. These calculations suggest that an n-bladed insulator (as against conductor or conductor/insulator combination) shield with appropriately optimized design parameters is most desirable for laser applications.

Acknowledgments

This research was supported by the Army MIRADCOM and Air Force Weapons Laboratory (AFWL) under Contract DAAK40-75-C-1272.

References

[1] Srivastava, B. N., Theophanis, G., Limpaecher, R., and Comly, J. C., "Flow and Discharge Characteristics of Electron-Beam Controlled Pulsed Lasers," AIAA Paper 80-1433, 1980; also, *AIAA Journal*, Vol. 19, July 1981, pp. 885-892.

[2] Jacob, J. H., Reilly, J. P., and Pugh, E. R., "Electron-Beam Spreading and Its Effect on Sustainer Current and Field Distribution in CO_2 Lasers," *Journal of Applied Physics*, Vol. 45, June 1974, p. 2609.

[3] Smith, R. C., "Computed Secondary-Electron and Electric Field Distributions in an Electron-Beam Controlled Gas-Discharge Laser," *Applied Physics Letters*, Vol. 21, Oct. 1972, p. 352.

[4] Smith, R. C., "Use of Electron Backscattering for Smoothing the Discharge in Electron-Beam-Controlled Lasers; Computations," *Applied Physics Letters*, Vol. 25, Sept. 1974, p. 292.

[5] Boyer, K., Henderson, D. B., and Morse, R. L., "Spatial Distribution of Ionization in Electron-Beam-Controlled Discharge Lasers," *Journal of Applied Physics*, Vol. 44, Dec. 1973, p. 5510.

[6] Theophanis, G., Jacob, J. H., and Sackett, S., "Discharge Spatial Nonuniformity in E-Beam Sustainer CO_2 Lasers," *Journal of Applied Physics*, Vol. 46, May 1975, pp. 2329-2331.

[7] Dutov, A. I., Mianev, S. V., and Nikolaev, V. B., "Optimization of the Electron Beam Parameters and Choice of the Foil in Electro-Beam-Controller Lasers," *Soviet Journal of Quantum Electronics*, Vol. 9, Aug. 1979, pp. 995-1000.

[8] Cason, C, Perkins, J. F., Werkheiser, A. H., and Duderstadt, J., "E-Beam Spreading and Resulting Field Variations in CO_2 Laser Plasmas," *AIAA Journal*, Vol. 15, Aug. 1977, pp. 1079-1083.

[9] Bethe, H. A. and Jacob, J. H., "Diffusion of Fast Electrons in the Presence of an Electric Field," *Physical Review A*, Vol. 16, Nov. 1977, pp. 1952-1963.

[10] Parazolli, C. G., "Electron-Beam-Stabilized Discharge in a Flowing Medium; Numerical Calculations," *AIAA Journal*, Vol. 16, 1978, pp. 592-599.