MASTER

ION OPTICS ARITHMETIC AND ITS IMPLICATION FOR THE POSITIVE ION CTR PROGRAM

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Abstract

This paper discusses ion extraction optics formulations in which presheath ionization is shown to have a negligible effect on ion optics at optimum perveance; otherwise, the examples shown establish an ionization gradient instability. Infinite slot optics as a function of perveance and potential partitioning is delineated for the TFTR tetrode from 2-D considerations; finite slot optics at optimum perveance is delineated from 3-D considerations. Finally, further 2-D considerations yield an end slot design.

Because of the geometrical constraints imposed upon them, neutral beam generators must produce beams with very low divergence. In a neutral beam system, the component most crucial to the optics is the extraction electrode, where one-hundredth of a centimeter can make the difference between an efficient neutral beam and failure. The following tells part of the story of this one-hundredth of a centimeter, most of which is heretofore unmentioned.

For ion extraction through a collisionless sheath, it is necessary to solve the Poisson-Vlasov equation,

$$\left.\begin{aligned} &\nabla^2\phi = \int f\,dv - e^{-\phi} \qquad (1)\\ &v\cdot\nabla f + \nabla\phi\cdot\nabla_v f = 0 \qquad (2)\end{aligned}\right\} Z > Z_0 ,$$

in the interior of the region, as shown in figure 1.

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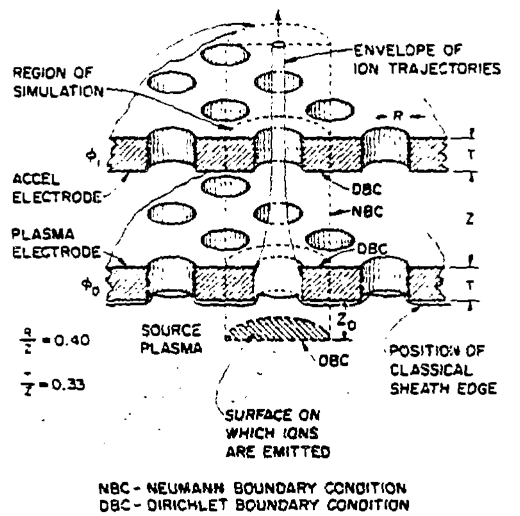

Figure 1. Region in which solution to the Poisson-Vlasov equations is sought.

The boundary constraints are either Neumann,

$$\nabla_\perp\phi = 0\ ,\ \nabla_\perp f = 0\ , \qquad (3)$$

or Dirichlet,

$$\phi = \phi_n\ ,\ f = f_n\ , \qquad (4)$$

where $f_n = 0$ on all Dirichlet boundaries except that of the source plasma, in which case we couple to a collisionless 1-D sheath solution of[1]

$$\frac{\alpha^2}{2}\frac{d^2\phi(Z)}{dZ} = \int_0^Z \frac{g(x)\,dx}{\sqrt{\phi(Z)-\phi(x)}} - e^{-\phi(Z)}\ ,\ Z \le Z_0\ , \qquad (5)$$

where

$$\alpha = \sqrt{2}\,\frac{\lambda_D}{L} = \frac{\nu}{2e}\sqrt{\frac{M}{\pi n_0}}\ ,$$

λ_D is the Debye length, L is the mean free path between ionization, and Z_0 is some arbitrary axial distance from the center of the source plasma in Debye lengths (shown in figure 1). This distance is short enough with respect to the first electrode that the equipotentials are planar, i.e., many Debye lengths from the minimum axial sheath position $Z_s^<$, or

$$Z_s^< - Z_0 >> 1\ . \qquad (6)$$

The distance is not so great, however, that significant ionization takes place between Z_0 and the maximum axial sheath position $Z_s^>$, or

$$Z_s^> - Z_0 << \alpha^{-1}\ . \qquad (7)$$

Solution of equations (1) and (2) is not without difficulty[2-11] because of nonlinearity; however, much progress has been made in this area,[12-19] and there is evidence that the solution obtained is an adequate representation of the facts.[20-39]

Equations (6) and (7) can be simultaneously satisfied for sufficiently dense source plasmas (i.e., where $\alpha < 0.01$). If the source plasma is not so dense ($\alpha > 0.01$) or if the plasma electrode is very thick, then the effects of finite α need to be considered. We will argue that finite-α effects are negligible at optimum perveance if the electrode dimensions are small compared to the Debye length. The argument will proceed in three steps. First, the optimum optics will be shown to be independent of either the electron temperature or the electron distribution function in a particularly sensitive system (Q = 7). Second, given a convergent solution, the optics will be shown to be virtually independent of the ion velocities over a wide range about the mean, such as would occur with strong spatially dependent ionization ($\alpha < 0.01$). Third, a model for ionization will be examined that allows examination

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of finite-α effects. The results of this model show that, at optimum perveance, the optics is unchanged for all situations considered ($\alpha < 1$). However, a previously undisclosed phenomenon appears: a large-ionization-gradient instability, where the sensitivity of the ion optics to plasma density variations is enhanced due to sharp ionization gradients. This phenomenon is unrelated to another ionization instability discussed elsewhere.[40-42]

First, the results of other studies[30-32] indicated that ion optics was a weak function of electron temperature; however, in these studies the potential of the first electrode with respect to the plasma potential ϕ_0 was also varied to keep ϕ_0/kT_e constant (for constant electrode flux). Because of the presence of this other variable, the foregoing results are ambiguous in that they cannot show a similarly weak dependence of the ion optics on the electron distribution function alone. To clear up this ambiguity, we considered the effect on ion optics of varying only the electron temperature or the width of the electron density distribution, while keeping everything else constant.

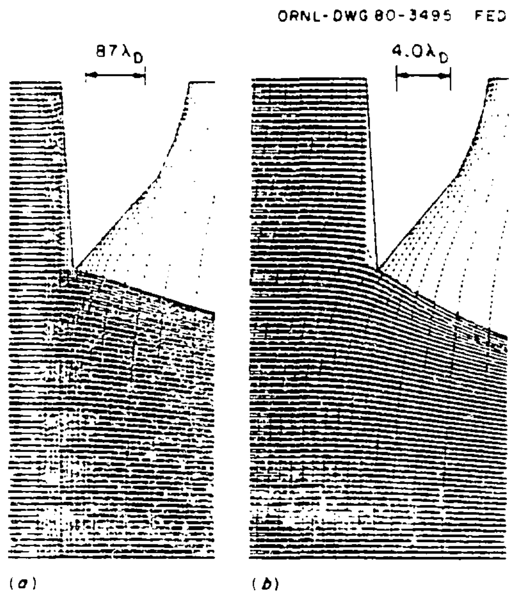

Figure 2. Sheath potentials and ion trajectories for (a) kT_e/e = 2 eV and (b) 128 eV.

Results are shown in figures 2a and 2b for kT_e/e = 2 eV and 128 eV, respectively. The resulting beam divergence is shown in figure 3, which indicates that if the electrode dimension is very large compared to the Debye length, the optics is unaffected by the form of the electron distribution function. This powerful result enables us to choose electron distribution functions that have favorable convergence properties or other computational advantages, instead of the Boltzmann function that is usually used.

Second, one effect of ignoring ionization processes is that a distribution of axial velocities is omitted from consideration. To examine this neglect, a vastly disparate initial ion velocity distribution is considered through a convergent solution of the Poisson-Vlasov equation at a fixed velocity. When velocities of 0.1, 0.3, 3.0, and 10 times this mean velocity are considered, emittance diagrams such as those shown in figures 4a and 4b are

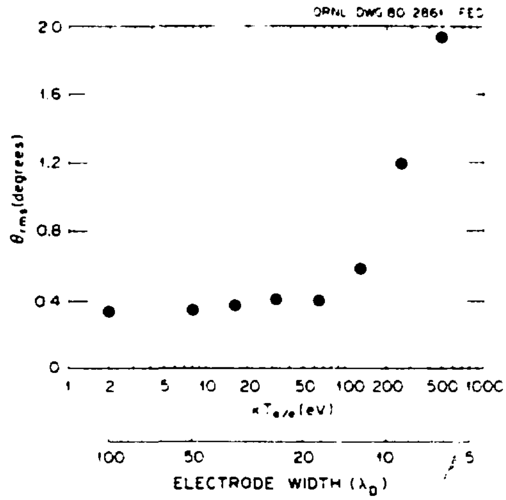

Figure 3. Beam divergence as a function of electron temperature (electrode potential unadjusted).

obtained. We conclude from these diagrams that ions with disparate velocities have little effect on ion optics. This conclusion, in conjunction with evidence that ion optics is independent of either electron temperature[30-32] or electron distribution function, leads to the suggestion that ion optics does not depend on presheath ionization at optimum perveance.

Third, we now consider the following model for ionization. Equations (1) and (2) are replaced by

$$\nabla^2\phi = \left\{\int f\ dv - e^{-\phi}\right\} \times \begin{cases} 1 + \sqrt{2}\alpha Z\ , & \phi < 20 \qquad (8) \\ 1\ , & \phi > 20 \qquad (9) \end{cases}$$

$$v \cdot \nabla f + \nabla\phi \cdot \nabla_v f = 0\ , \qquad (10)$$

where ϕ is in units of kT_e/e and $\sqrt{2}\alpha Z$ assumes constant mean free path. With this model, the newly ionized ions have the same initial velocity as ions that have come to the same position from the center of the plasma. This model also demands that the electron density increase proportionally with the electron source term from the ionization process.

Solutions to these equations show that for finite α the sensitivity of ion optics to plasma density variations is increased. Physically, this can be explained by two facts: (1) for an overdense case the sheath moves into the accel gap; and (2) for a large ionization gradient the density at the

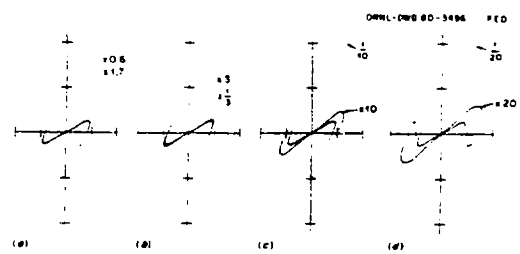

Figure 4. Emittance diagrams for disparate velocities (values are given times the single velocity used for the Poisson-Vlasov equation): (a) × 0.6, × 1.7; (b) × 0.33, × 3; (c) × 0.1, × 10; (d) × 0.05, × 20.

sheath gets even larger, which causes it to protrude further. The reverse argument applies for the underdense case. In any event, the optics at optimum perveance is unchanged, which leads us to conclude that ionization gradients do not affect the optimum ion optics obtainable, at least on systems of interest. Shown in figure 5 is the beam divergence as a function of plasma density for three different configurations, two different geometries, and two different ionization rates. In figure 5a, a triode configuration is shown with straight-bore electrodes in both slot and cylinder geometries. This is similar to the configuration considered in a recent article dedicated to delineating the difference between slots and holes.[33] Slot geometry gives higher minimum beam divergence and higher sensitivity than cylindrical geometry, even for configurations explicitly designed for optimization in slot geometry (the selectivity factor Q is the inverse fractional current density charge for beam divergences that are less than 3/2's of the minimum). Figure 5b shows a notched electrode[34,35] such as those used on PDX injectors, and figure 5c shows a tetrode of the type designed at Lawrence Berkeley Laboratory (LBL).[43] In all cases, finite a enhances the sensitivity of ion optics to plasma density variations.

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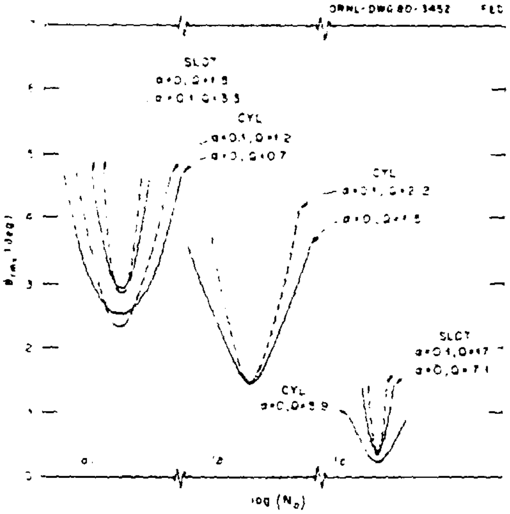

Figure 5. Beam divergence as a function of plasma density for three cases: (a) straight-bore triode, (b) notched triode, and (c) tetrode optimized for slot geometry. Case (a) shows infinite, transverse slot geometries with ionization of ~1, 0; case (b) shows only cylindrical geometry with and without ionization; and case (c) shows slot geometry with and without ionization and cylindrical geometry without ionization.

All this leaves open the question of slot end effects. Figure 6 shows why we concern ourselves with this problem. Figure 7 shows an actual 3-D computation[44-46] at optimum perveance for minimum central transverse beam divergence (this includes the electrodes for the reference TFTR design). In the 3-D calculation for a 5:1 aspect slot, the computed transverse rms angle for all trajectories is 1.1° with an envelope of 3.8°. The longitudinal rms divergence is 1.6° with a 6.1° envelope. The longitudinal 1/e angle is 0.05°. For the middle region of the slot, the transverse rms divergence is 0.73° with an envelope of 2.2°.

Both the examination of the 2-D algorithm[12-19] for the TFTR design using slots and cylinders and the results obtained by varying the transverse dimension or radius of all the electrodes indicate that the ion optics at constant current remains virtually unchanged over a wide range of radii and that the slot end design of figure 8 (patent pending) is preferred for the virtual elimination of extra end effect aberrations.

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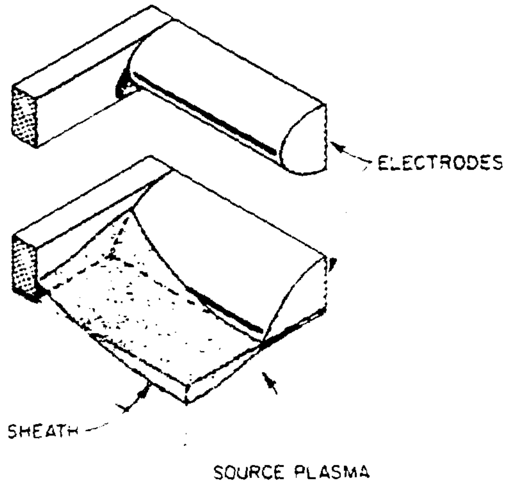

Figure 6. Illustration of slot end.

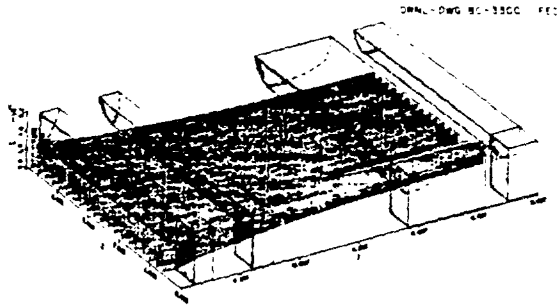

Figure 7. 3-D solution of Poisson-Vlasov equations for slot end.

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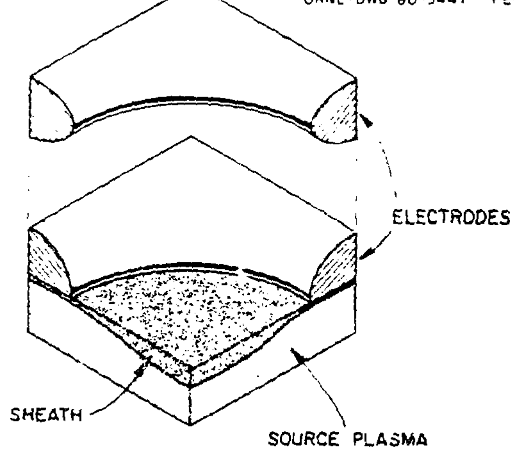

Figure 8. Proposed slot end design.

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