SLAC-PUB-2631
October 1980
(A)

NUMERICAL DESIGN OF ELECTRON GUNS AND SPACE CHARGE LIMITED TRANSPORT SYSTEMS*

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ABSTRACT

This paper describes the capabilities and limitations of computer programs used to design electron guns and similarly space-charge limited transport systems. Examples of computer generated plots from several different types of gun problems are included.

Presented

at the

Conference on Charged Particle Optics
Giessen, West Germany

September 8-12, 1980

*Work supported by the Department of Energy under Contract DE-AC03-76SF00515.

As in so many other fields of physical design, the large, high-speed digital computer has become the tool in the design of electron guns and other electron and ion-optical systems. The electrolytic tanks, rubber membranes and resistive paper techniques have mostly been replaced by computer programs which are more general, less dependent on careful laboratory technique (e.g., the "chemistry" involved in using an electrolytic tank), and, perhaps most important, directly account for the effects of self fields and external magnetic fields.

This paper will not include a review of the history and the numerical methods involved in such programs. For this material, the reader is referred to review articles such as that by Weber.(1) Nor will we attempt to give instructions for the use of a specific program, such as the SLAC program(2) from which most of the illustrations are derived. Rather this will be a sort of "travelogue" of gun problems illustrating a few of the techniques and limitations of such design procedures.

To set the stage, we first should note some of the limitations:

1) Two-dimensional calculations of electric fields; either cylindrical or rectangular symmetry. In cylindrical coordinates, a cylindrically symmetric beam is propagated along the axis. In rectangular coordinates, both the electrodes and the beam extend infinitely far in the directions normal to the "plane of the paper" on which the problem is shown. In both symmetries,

the nominal direction of propagation of the beam lies in the "plane of the paper" but transverse motion is allowed. Thus, for example, the spiral motion of a beam in an axial magnetic field can be simulated.

2) Time independence: these are dc calculations after the beam has reached "steady state." A common characteristic of such programs is that if steady state cannot be achieved, for example, if an attempt is made to propagate a beam beyond the space-charge limit, then the programs will not converge to a satisfactory steady solution. Under such conditions, one is not justified in claiming any physical reality for the results.

3) Idealized computer models: the nature of modeling programs is to ignore various real complications. Such things as tolerances out of cylindrical symmetry, stray electrons or ions, partially poisoned cathodes, etc., may play large parts in any real device but are usually ignored in models. Other aspects of models; finite elements, numbers of trajectories, iteration stops, etc., may also affect the accuracy of the results. One should not expect a computer code to yield exactly correct predictions of operating parameters. One should expect that the effects of varying input parameters, particularly for small perturbations, should be reliable. Of course, some predictions are better than others; for example, the SLAC program typically predicts gun perveance correctly to within a few percent but has a somewhat harder time in predicting beam diameter.

In operation, the class of programs we are considering all begin with the user drawing the cross section view of the device to be studied. Data describing the boundaries are then placed in the appropriate format for the program to solve the La Place equation, i.e., the solution to the static electric field without space charge. Initial conditions for the charged particle beam are determined next and the beam trajectories are followed. It is at this point that there are two distinct classes of programs:

1) Programs, such as the SLAC program, in which space charge is deposited at the nodes of the mesh for the solution of the Poisson equation. In an iterative process, subsequent cycles of ray tracing and solving the Poisson equation are used to achieve a steady state result.

2) Programs, such as EBQ by Art Paul,(3) in which the electromagnetic forces of the trajectories, working on each other, are calculated simultaneously with the transport through the charge-free space.

The first class of program is the more general since it is not restricted by conditions which require an entire beam to march along "in step." Thus for example, such progress can be used to design a depressed collector. The second class of program is more suited to the transport of high intensity relativistic beams. This class bears a distinct resemblance to the "particle pushing" codes in which a statistical assembly of particles are followed through a transport system. There are many problems, including most of those used here for examples, which can be solved equally well by either method.

There are other differences between programs which, although sometimes major, nevertheless can be classed as details. For example, the SLAC program uses a square mesh and accounts for the displacement of boundaries from mesh lines by calculating adjusted coefficients for the difference equations. Other programs use deformable meshes so that boundaries always lie on mesh nodes. An extreme case of deformable mesh is the triangular mesh used by Halbach for Wolf[4] and for the magnetic and RF field programs, Poisson[5] and Superfish.[6] An example of a triangular mesh field used to solve a gun problem is shown in Fig. 1 from the program written by True.[7] The principal advantage of the triangular mesh, as illustrated in Fig. 1, is that a higher density mesh can be used near the cathode and in other critical areas, while limiting the total number of mesh nodes. It is this author's personal opinion that newer, large computers have made this more of an aesthetic advantage than an important real difference in electron optics problems. The triangular mesh approach is essential for magnet programs in which saturation effects in the iron are to be calculated. However, the complications involved in setting up the mesh and in the coding of the ray tracing routines offset this advantage for electron optics programs. Debates on this position are suitable topics for after-dinner discussions at such conferences as this one.

We turn now to the travelogue, a survey of results from the SLAC program chosen to illustrate specific capabilities and limitations. In Fig. 2, the example is of a run for a SLAC klystron gun. The plot has been drawn with different vertical and horizontal scales, resulting in a distorted look to the spherical cathode. This makes it difficult to tell by the picture whether the hollow beam effect is due to nonuniform cathode loading or to some other deficiency. As in all the following plots, the electrons go from left to right and the equipotential lines lead up from the axis.

The gun in Fig. 3 is a very high brightness (low emittance) gun intended for injection into an accelerating column as shown in Fig. 4. This pair of figures illustrate the continuation of a problem into a subsequent stage. The division line between the two segments is chosen for ease in determining appropriate boundary conditions; in this case it is in a region of nearly zero axial electric field so that a radial Neumann boundary defines the interface between the two parts.

Most high-current electron guns are essentially an adaptation of the geometry shown in Fig. 5, consisting of a pipe of radius R_T with an end cap at Z_T. The cathode of radius R_K has a focus electrode extending to R_F and a bulge extending to Z_F. If a spherical rather than a flat cathode is chosen, then the beam will tend to converge to a smaller waist before space charge forces push it apart. The curves shown in Fig. 5 illustrate that for small Z_T, the perveance behaves as predicted for a diode, i.e., $K \propto Z_T^{-2}$ while for larger Z_T, the perveance approaches a constant depending more on R_T than on Z_T.

In an extreme limit calling for low current and high voltage, the illustration in Fig. 6 shows the roles of the pipe and the inserted cylinder reversed for the cathode and anode, respectively. Because of the very small radius of the beam, a reliable calculation demands higher resolution. The portion of the gun between the cathode and the anode has been expanded in Fig. 7 by using the potentials calcualted from the run of Fig. 6 to determine the upper boundary.

Magnetic fields play an important role in many electron devices. Fig. 8 shows a gyrotron gun in which the magnetic field (the axial field is plotted as the extra "trajectory" increasing from left to right) first causes the beam to spiral rather than to strike the first anode. As the field increases, the spirals grow smaller and faster.

Another magnetic field problem is shown in the gun for the Fermilab electron cooling system illustrated in Fig. 9. The "mod-anode" controls the gun current and sets up the possibility of adjusting the location of the accelerating gap between the mod-anode and the grounded pipe to compensate for the defocusing at the anode opening. In this way it is possible to completely eliminate the ripple in the transported beam, thus reducing the transverse energy in the electrons to under one electron volt. To make the "location" of this gap adjustable, three electrodes and four gaps have been used so that different voltages can be imposed, effectively changing the points at which acceleration and/or deceleration occurs.

As with most programs, the SLAC program requires a fixed conductor to define the cathode and the nearby starting surface in order to make the calculations for Child's law space charge limited emission. For problems involving emission from a plasma, the user is faced with the problem of defining this profile consistent with plasma and extraction conditions. A workable, if not rigorous, solution appears to be to assume that, since the plasma sheath cannot support electric fields in any direction except normal to the sheath, that emission must be uniform over the sheath. By iterating to find a surface for which uniform emission results, one finds one of a set of viable solutions. Plasma conditions of pressure, temperature, etc., can in principle be found that are consistent with such a solution. In Fig. 10, a solution of a plasma extractor is shown in which the starting surface was automatically iterated to find a surface of uniform emission. In this approach, by John Orthel,[8] the SLAC program is treated as a subroutine of a fitting program to find an acceptable plasma sheath profile.

In Fig. 11, an example in rectangular coordinates is presented to illustrate the next development of the SLAC program. In this variation, space charge is deposited by an ensemble of particles going away from the plane of the figure. The electrodes at top and to the right are parts of a quadrupole;

only one quadrant is being calculated. The distorted equipotential lines show the presence of space charge. The short dashes are the trajectories on the outside of an ellipse, defining the envelope of the beam, being focussed (pushing inward) in one coordinate and defocussed (going outward) in the other. In this way this program effectively bridges the gap between ray-tracing and particle-pushing programs, as described earlier. Beams do not need symmetry and the electric fields can be described with analytic expressions for the end effects, thus allowing fully three-dimensional electrostatic and/or magnetic fields to be defined.

FIGURE CAPTIONS

1. An example of a relaxed triangular mesh is shown in contrast to the usual square mesh. In a square mesh, difference equations are adjusted for the position of the boundary; in a stretched mesh the nodes are moved to the boundary.

2. Typical output of the SLAC program: electron trajectories go from left to right, equipotential lines run up from the axis. Note different horizontal and vertical scales.

3. Gun designed for injection into the accelerating structure of Fig. 4.

4. Trajectories from Fig. 3 are continued in this example of dividing a problem into two parts.

5. The family of curves gives the perveance as a function of the several variables defined in the gun drawing on the left.

6. A gun designed for a high brightness x-ray source has a beam cross section too small to resolve safely with this much density.

7. The gun in Fig. 6 is expanded using the potential distribution along the top as determined from the run that generated Fig. 6.

8. The gyrotron gun is a novel example of the effects of the magnetic field; the axial magnetic field strength is plotted superimposed on the gun drawing.

9. Modified klystron gun used for the electron-cooling experiment at Fermilab. Note the focusing lenses behind the mod-anode which are adjusted to minimize transverse energy in the beam.

10. An ion gun with the plasma sheath profile determined by iterating the emitting surface to obtain uniform emission.

11. Variation of the conventional mode of operation of the SLAC program in

which the beam propagates normal to the plane of the picture. The electrodes are in rectangular coordinates and the short trajectory lines result from the focusing/defocussing action of the electric quadrupole.

REFERENCES

1. C. Weber, Chapter 1.2, Focusing of Charged Particles, edited by A. Septier, Academic Press, New York, 1967.
2. W. B. Herrmannsfeldt, SLAC-226, Stanford Linear Accelerator Center, Stanford, CA., November 1979.
3. A. C. Paul; see A. C. Paul and V. K. Neil, IEEE Transactions on Nuclear Science, NS-26, No. 3, June 1979.
4. K. Halbach, LBL 4444, Lawrence Berkeley Laboratory, Berkeley, CA., 1975.
5. K. Halbach and R. F. Holsinger, private communication, documentation for the IBM version of this program is available from R. E. Early, SLAC, Stanford CA., 94305.
6. K. Halbach and R. F. Holsinger, Particle Accelerators, Vol. 7, pg 213, 1976.
7. R. True, IEDM Technical Digest, pp 257-260, December 1975.
8. J. Orthel, LIFE/DE-TN-pp4, TRW Defense and Space Systems Group, Redondo Beach, CA., May 1980.

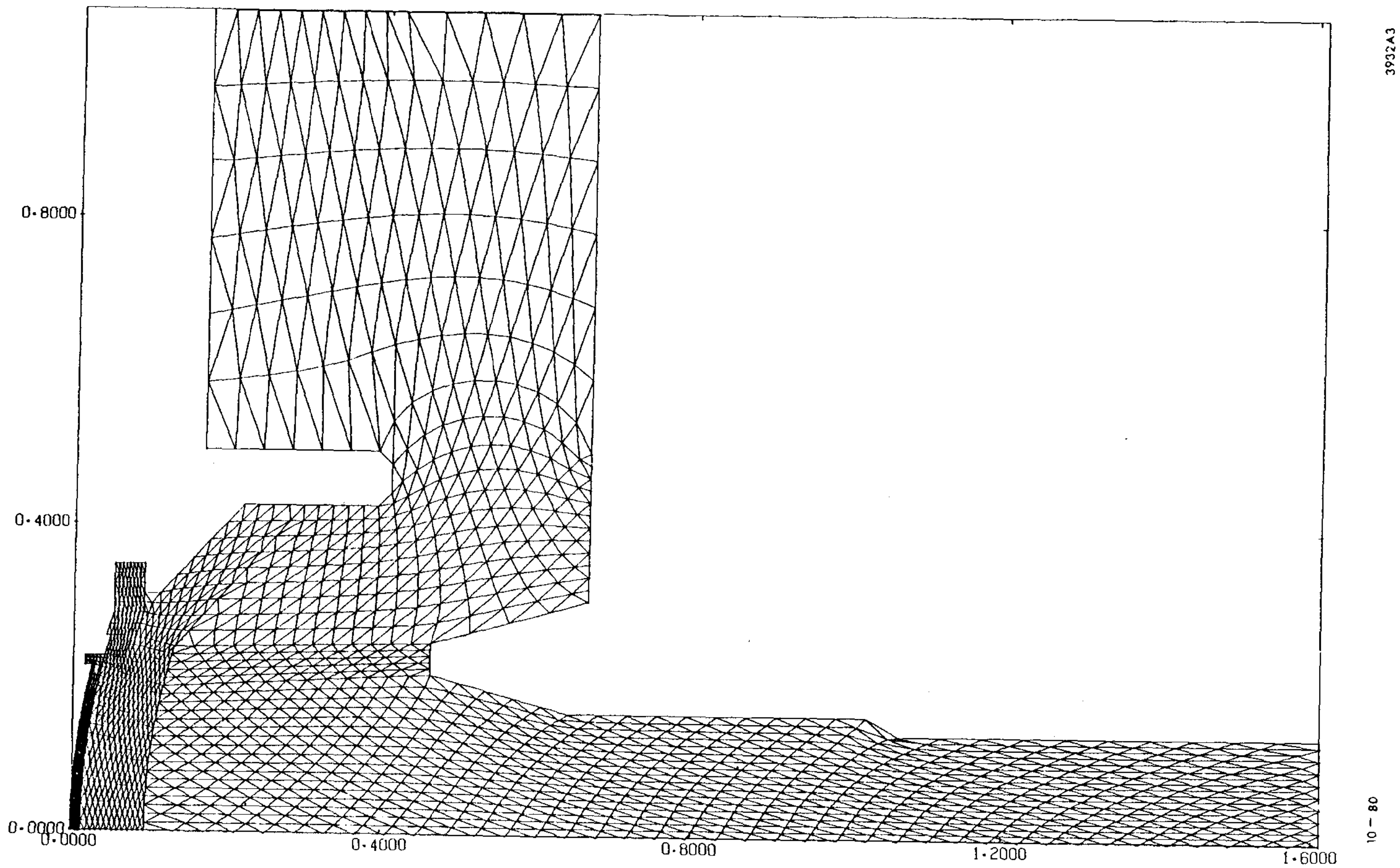
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Fig. 1

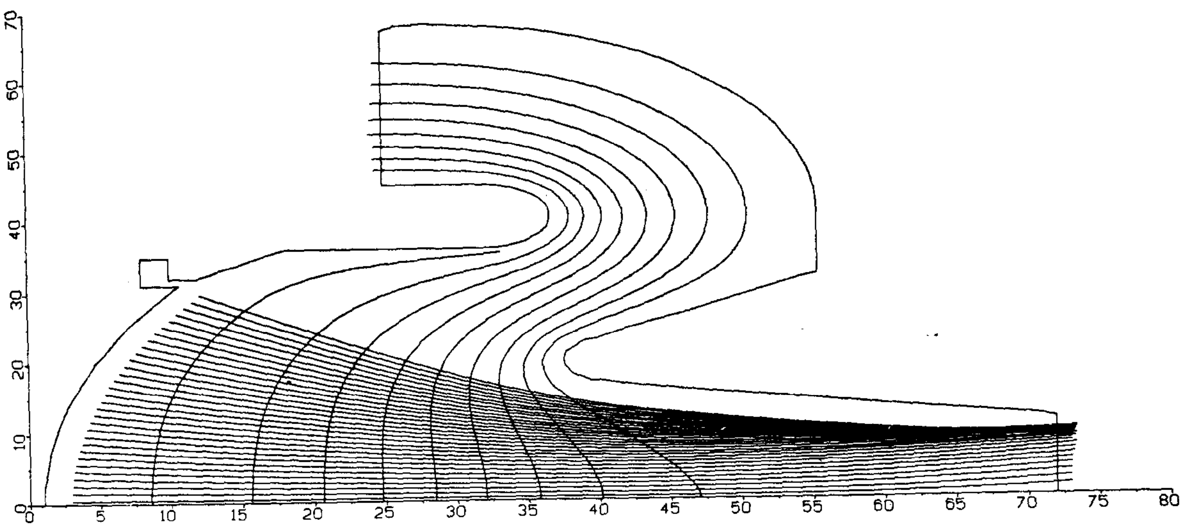

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Fig. 2

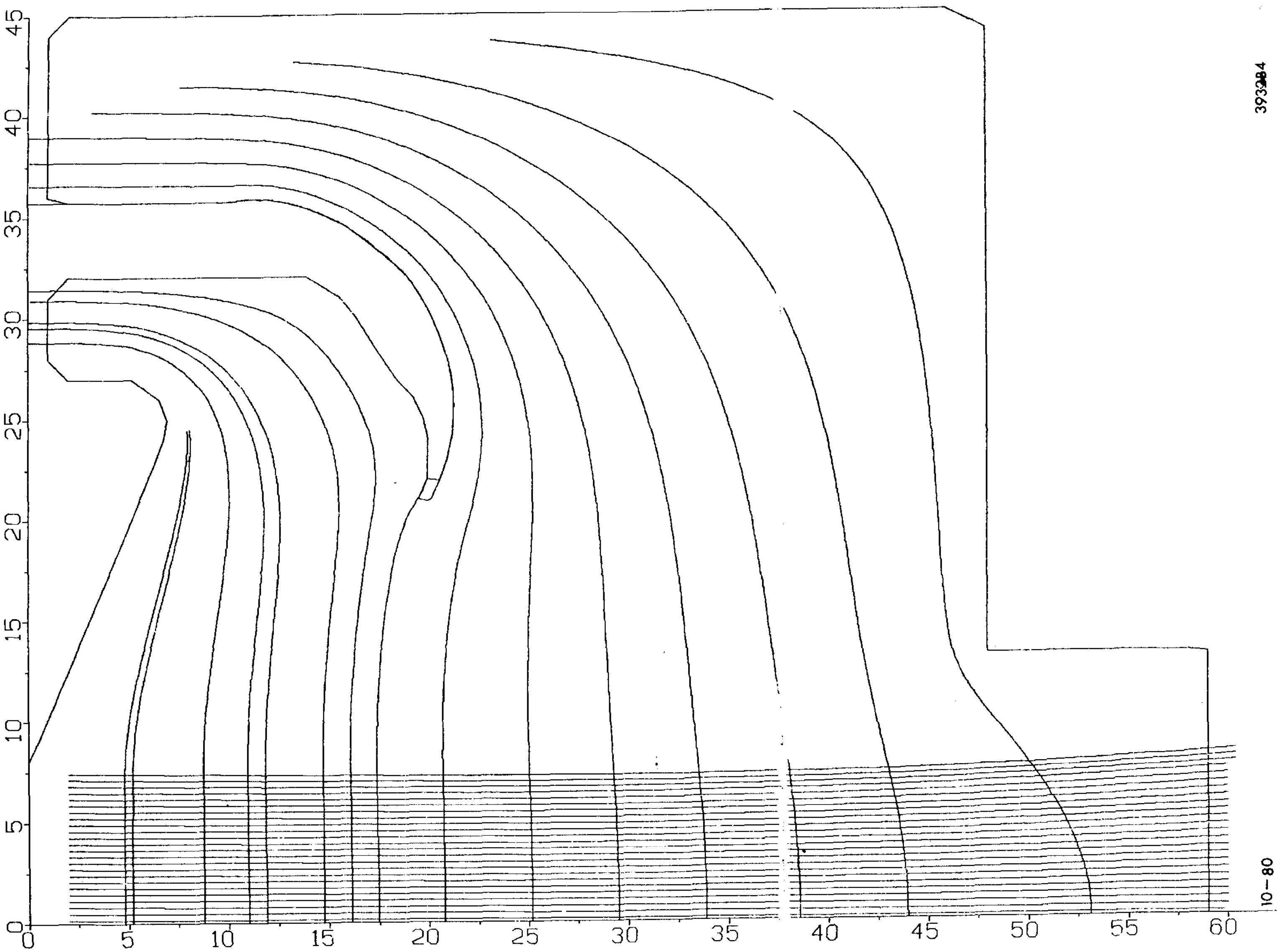
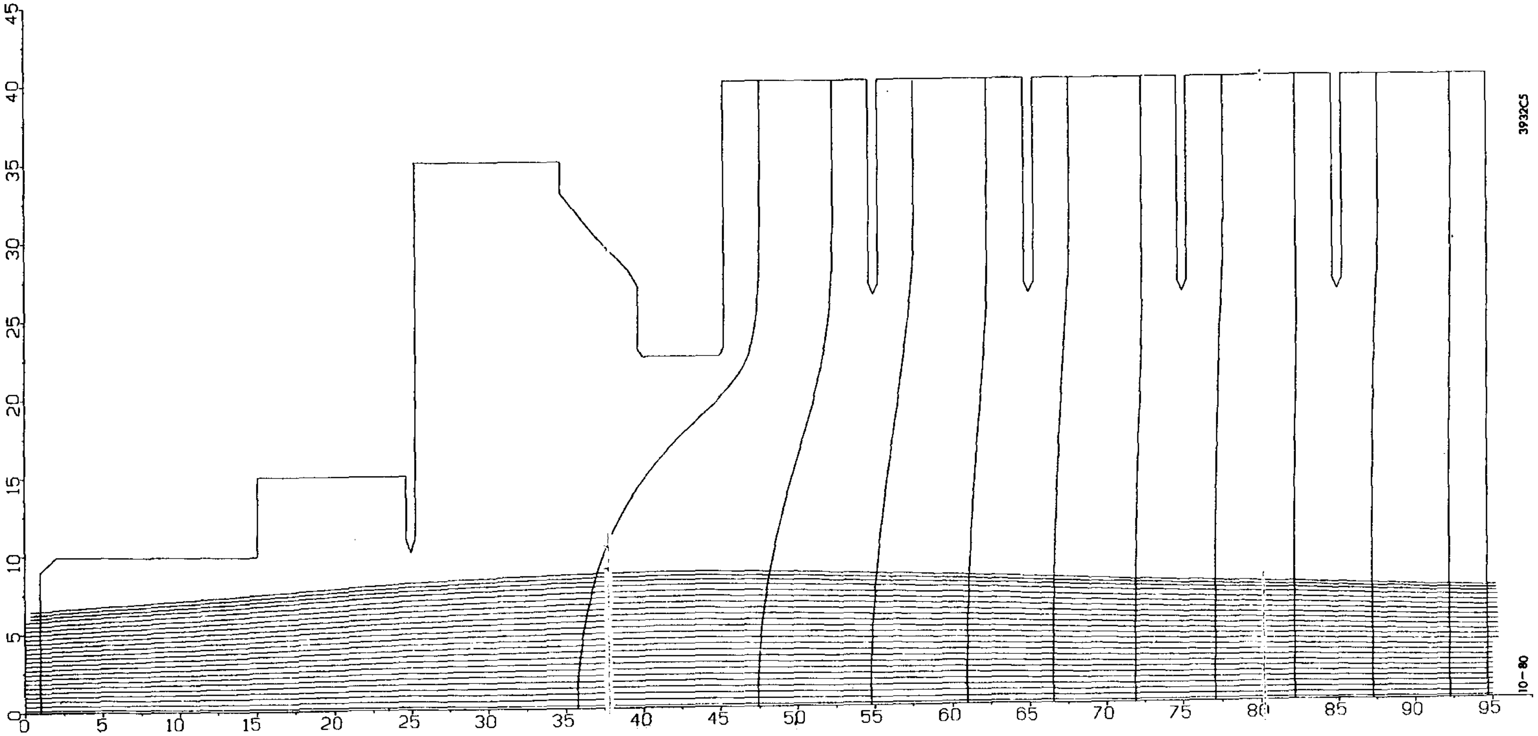


Fig. 3



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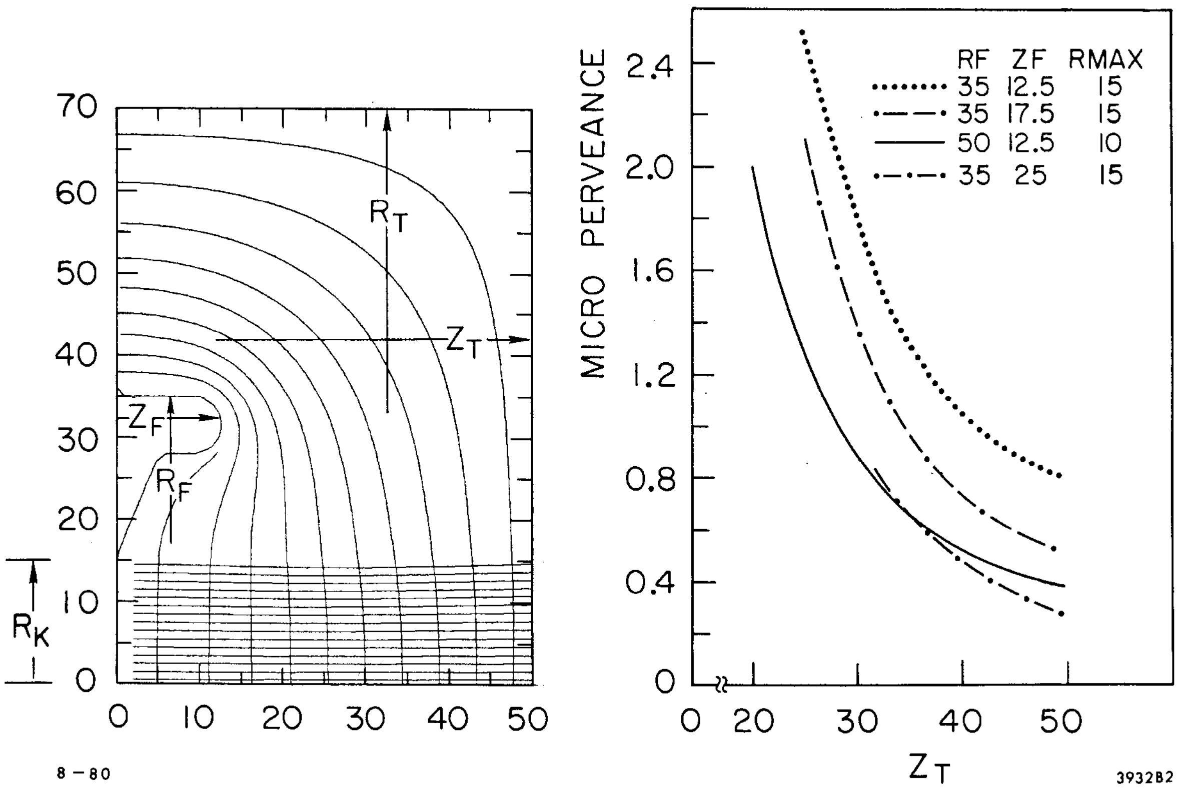

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3932B2

Fig. 5

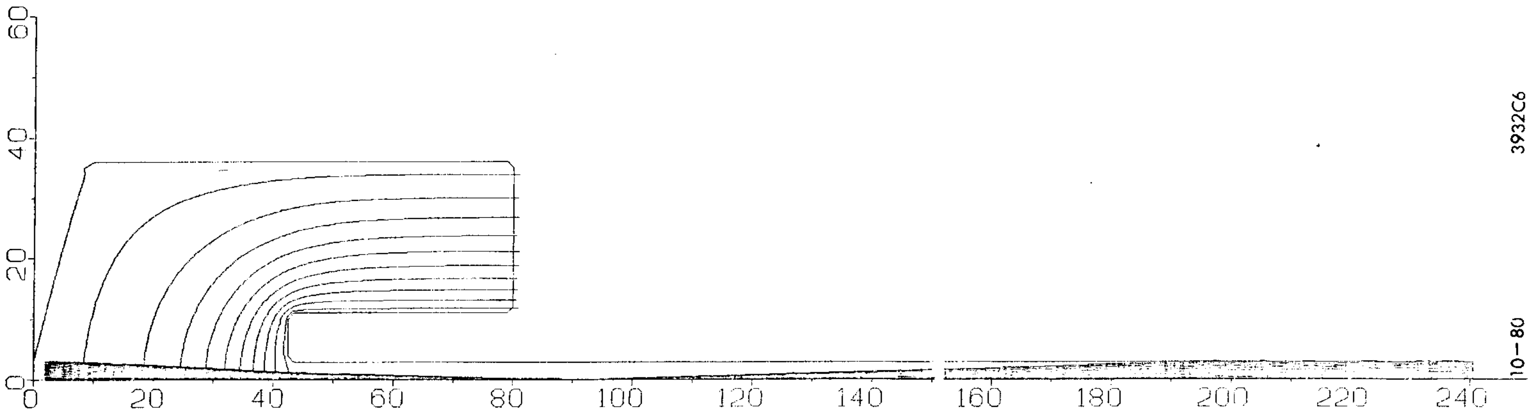
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Fig. 6

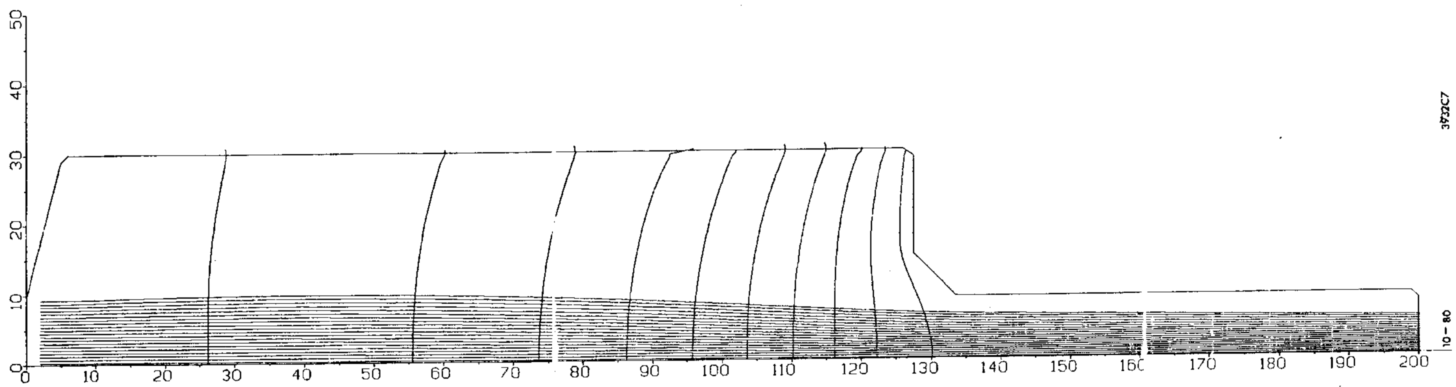

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Fig. 7

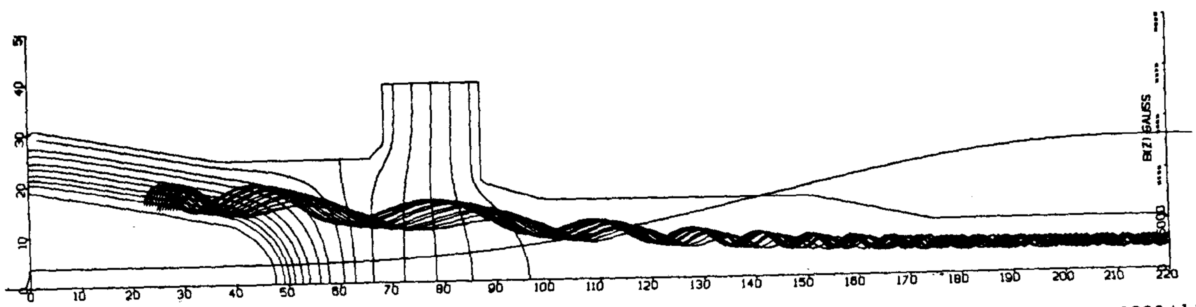

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Fig. 8

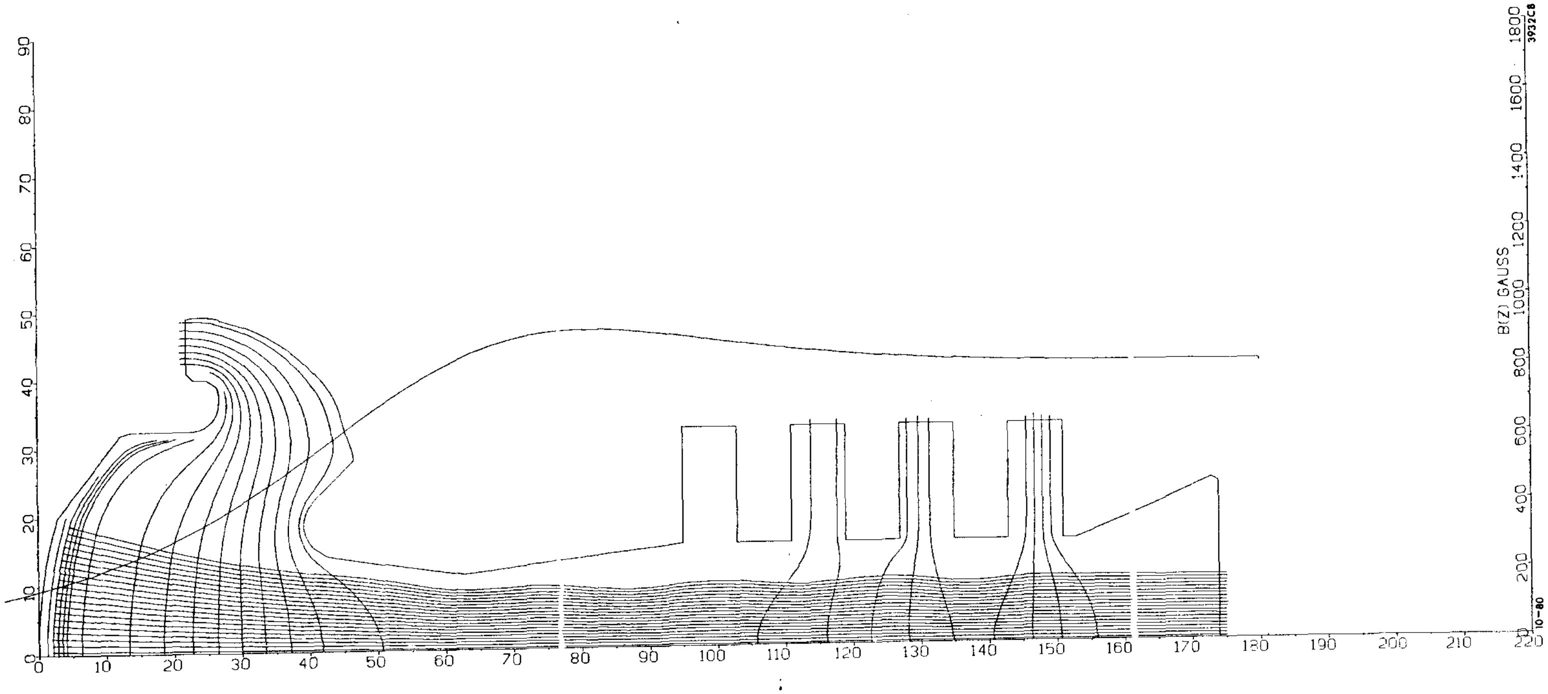
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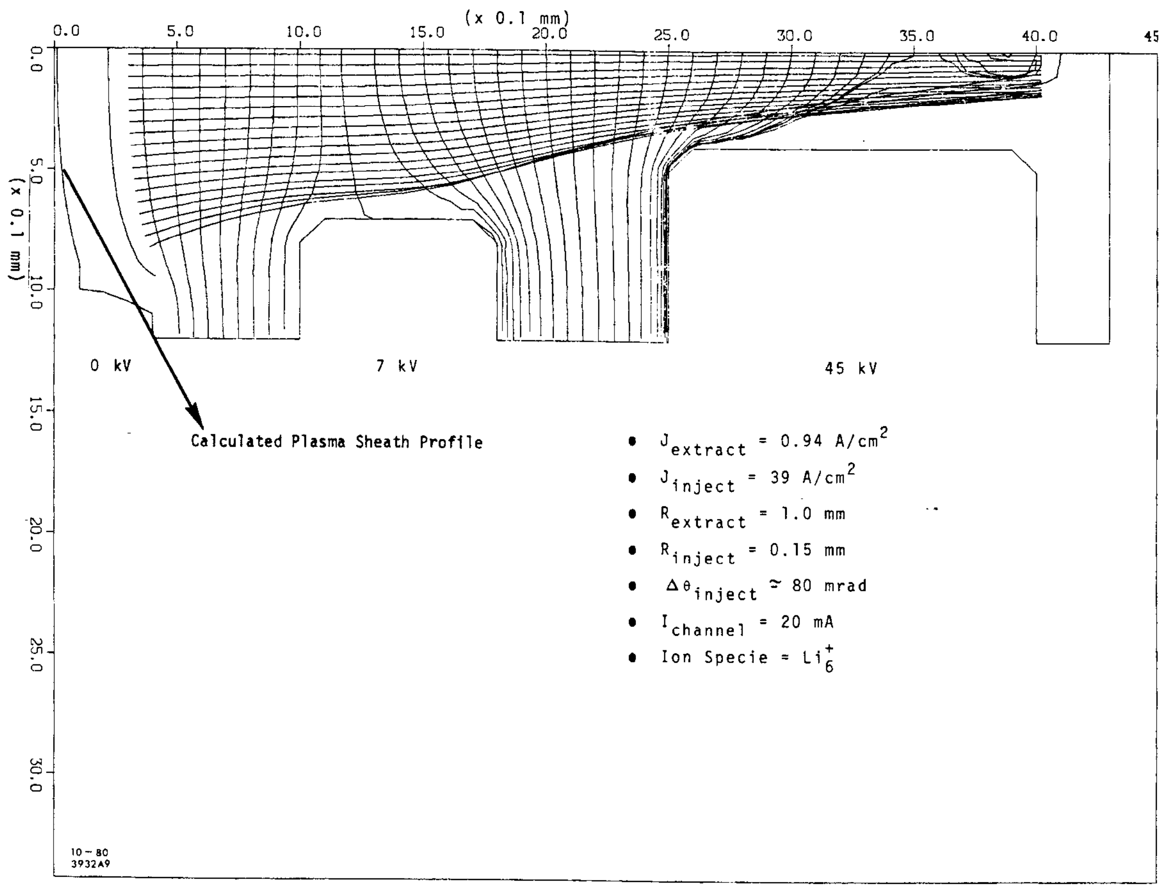
Fig. 9



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5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45
(x 0.1 mm)
0 kV
7 kV
45 kV
Calculated Plasma Sheath Profile
• $J_{extract}$ = 0.94 A/cm²
• J_{inject} = 39 A/cm²
• $R_{extract}$ = 1.0 mm
• R_{inject} = 0.15 mm
• $\Delta\theta_{inject} \simeq$ 80 mrad
• $I_{channel}$ = 20 mA
• Ion Specie = Li_6^+
10 – 80
3932A9

Fig. 10

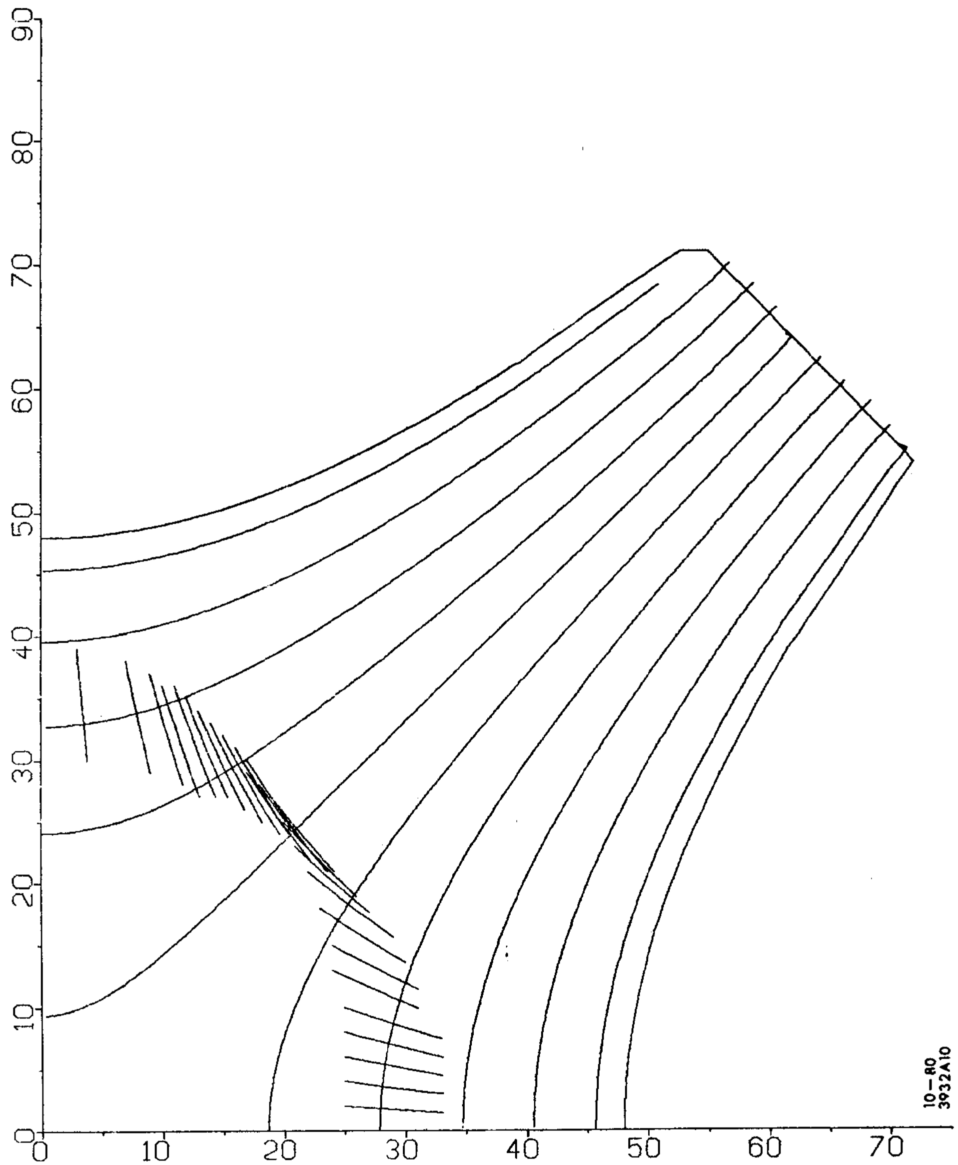

Fig. 11