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ELECTRODE SHAPING FOR ION AND ELECTRON EXTRACTORS*

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Summary

A technique has been developed that defines the shapes of electrodes needed to produce a good-quality cylindrically symmetric beam of ions or electrons. This work was motivated by the need to optimize electrode shapes for a high-brightness, low-energy, deuteron injector. Our experience had indicated that correct shaping of electrodes becomes increasingly important as beam perveance increases. This provided the motivation for developing a computer program that could specify electrodes producing optimum or improved beam quality. Several techniques have been developed and evaluated. The procedure described here has been very successful in meeting our design goals.

Background

Nearly 2 years ago a technique[1] was described by the authors that is useful for a wide class of extractor designs. Unfortunately, because of the ill conditioning of a problem with Cauchy boundary conditions in conjunction with an elliptic differential equation (such as the Laplace equation), the method reverts to multivalued ambiguities for many high-perveance cases of interest. The method mentioned briefly at the end of Ref. 1--that of converting the differential equation into one of hyperbolic form--eliminated the ambiguity problem when used to design extractors without an exit-lens correction. Frequently, this technique provided either electrode shapes that were inconvenient to fabricate or that created problems at the plasma/ion beam interface when modeled by the SNOW[2] code. All attempts to incorporate some form of exit-lens correction invariably led to potential distributions that would be impractical to implement.

In principle, if a self-consistent solution of the Poisson equation for a good-quality extracted particle beam is determined, the resulting distribution of potential along the beam edge can be used to match a Laplace solution in the region external to the beam that will support the charge flow.

One finds, in attempting this procedure, that there exists a very large number of approximate solutions in the exterior region that will support the desired charge flow pattern to sufficient accuracy. The remaining design challenge then is that of selecting from this subset some electrode shapes (equipotential surfaces) that are physically realizable and desirable.

The procedure adopted more recently represents an attempt to completely avoid the limitations of working with an elliptic differential equation and to use an optimizing procedure to "improve" an existing or initial electrode design. The optimizing procedure used is one developed many years ago by Klaus Halbach.[3]

General Technique

The operator must first make a "guess" for the electrode shapes, symbolized by the m solid dots on Fig. 1. He selects which section of the electrodes will be allowed to vary in position (depicted by the ml points marked with an x). Finally, he specifies the points at which the potential is to be matched.

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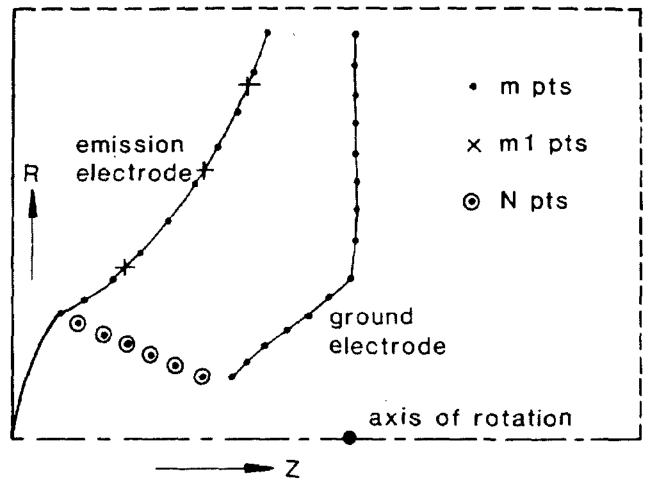

Fig. 1. Geometry used in optimizer calculation.

The program starts with the initial guess for electrode shapes, fits a smooth curve through these (m + ml) points by a least-squares fitting procedure, and then determines how well the resulting polynomial expansion fits the specified N points (usually along the beam boundary). Finally, the optimizer will make small adjustments to the location of the ml areas of the electrodes in an attempt to improve the fit at the specified N points.

This general technique has several advantages:

- If the initial choice of electrode shapes was "good," the convergence is very fast.
- It allows the designer to have significant control over the approximate final electrode shapes. For example, the operator can limit the optimizing to a single section of one electrode, allow optimization of the entire electrode, or search for optimum shapes for all electrodes.
- Weighting of all coordinates and regions along the beam edge is completely arbitrary and can be adjusted according to the operator/designer's intuition.
- The procedure is very fast. Because all matrix operations are done in machine language, a user-friendly interactive program on the Apple-II microcomputer can provide a complete electrode design in a few hours. A quick plot of equipotential surfaces (electrodes) can be evoked at any point so the operator can verify or redirect the design.
- This technique fits polynomial expansions to any desired beam shape and potential distribution. Unfortunately, the only well-known simple form for the beam edge is that of a straight edge with a resulting potential variation only along a spherical radius.[1] In practice, this straight edge is severely perturbed by the exit-lens effect. To obtain an acceptable solution for a high-perveance case, the program must make correction for the exit-lens perturbation. A very simple technique is used to account for the perturbing effect of the exit lens. An improvement

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in this technique would probably lead to a substantially better electrode design.

- This technique can be used equally well for cylindrical, polar, and rectangular slit geometry. Some program rewrites are now under way to extend this procedure to other coordinate systems.

As with other techniques known to the authors, this optimizer must be used with some degree of care. For example, the number of ml points that are allowed to vary must be only a fraction of the number of N points at which the potential is to match. The relative number of points needed seems to be about 1 to 5 or 7. Also, it is possible for the optimizer to "find" a local minimum, which may be rather far removed from the potential fit that one would hope to reach eventually.

None of these cautions should significantly limit the usefulness of this program. If the designer has in mind the general shapes of the electrodes that he would like to use for a charged particle extractor, then a couple of passes through this program will almost invariably provide a higher quality beam than he had initially.

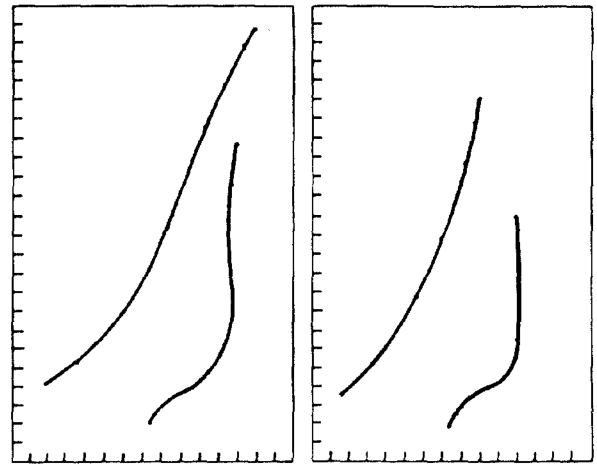
Specific Example

In December 1980, the method reported earlier by the authors was used to design electrodes for the Fusion Materials Irradiation Test (FMIT) prototype injector. The electrodes were fabricated and used for 2 years because they provided a beam quality and extractor operation that were substantially improved over previous geometries. There was some noticeable halo on the beam, and it was suspected that at least a fraction of the observed beam emittance was due to aberrations at the ground electrode. New designs with the previous method and parameter searches with the SNOW code failed to yield an improved design.

The present method was developed and tried on this electrode geometry. Very quickly it became obvious that small changes in the electrode shape could produce an improved fit of potential along the beam edge. For convenience, we elected to maintain the same shape for the ground electrode and to allow changes only in the emission electrode. A new electrode shape was generated, the SNOW code verified its performance, and a numerically controlled milling machine cut the new electrode. The change in the electrode's shape is shown in Figs. 2 and 3.

Differences Between Old and New Extractor Geometry

- There is significantly less ion current in the beam halo. This effect was predicted by the SNOW code and verified in operation. In the earlier design, the angle between the beam edge and the emission electrode was too small, resulting in some outer rays being overfocused and eventually becoming highly divergent. This same effect apparently was responsible for unacceptably large emittance growth in the earlier design.
- The new geometry is much more tolerant to changes in beam perveance. In the previous design, the extracted current and extractor voltage had to be tracked very precisely or some portion of the beam would impinge on one of the ground electrodes and initiate a breakdown. Apparently the newer design keeps the accelerated beam smaller and farther from the ground electrode so that the extractor voltage may be varied substantially without significant changes in extracted current.



Original Profile Improved Profile

Fig. 2. Electrode profiles as output from programs. Beam center line is at bottom axis. Radius is plotted vertically. Index marks are spaced 0.100 in.

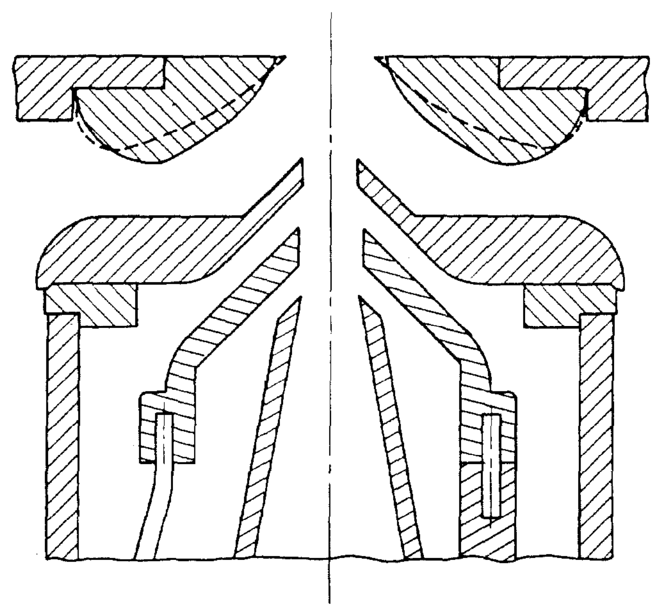


Fig. 3. Geometry of electrodes in FMIT injector. (Dotted lines show profile of new optimized electrode.) Ion source plasma is above top electrode. Second electrode from bottom is normally biased ∿-2 kV to suppress electrons.

- The accelerated beam, several centimeters downstream of the ground electrode, is less divergent than the beam from the previous geometry. A smaller beam at this point implies less beam impingement on several transport elements and reduced aberrations from the dipole magnet.
- The SNOW simulation indicated a reduction by a factor of 2.5 to 3.0 in the emittance of the extracted ion beam. Measured emittance of the actual extracted beam was reduced by a factor slightly greater than 2.0. The point of measurement is downstream of the dipole species analyzing magnet, known to introduce a nonnegligible aberration.

- With the previous electrode a maximum of less than 90 mA of H_2^+ ions could be delivered to the RFQ input point. Using the optimized electrode, more than 110 mA of H_2^+ can be delivered to the RFQ input under the same conditions of 250-mA total extracted ions.

Acknowledgments

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