Fermi National Accelerator Laboratory

FERMILAB-Conf-97/331

Gun and Optics Calculations for the Fermilab Recirculation Experiment

Thomas Kroc

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

October 1997

Presented at the *Medium Energy Electron Cooling Workshop*,
Novosibirsk, Russia, February 26-28, 1997

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

Gun and Optics Calculations for the Fermilab Recirculation Experiment

Thomas Kroc, FNAL, Batavia, USA

Abstract

Fermilab is investigating electron cooling to recycle 8 Gev antiprotons recovered from the Tevatron. To do so, it is developing an experiment to recirculate 2 Mev electrons generated by a Pelletron at National Electrostatics Corporation. This paper reports on the optics calculations done in support of that work. We have used the computer codes EGN2[1] and MacTrace[2] to represent the gun area and acceleration columns respectively. In addition to the results of our simulations, we discuss some of the problems encountered in interfacing the two codes.

Introduction

Fermilab is in the process of conducting an electron beam recirculation experiment at National Electrostatics Corporation in Middleton Wisconsin. The voltage source is a Pelletron (a Van DeGraaff with a proprietary charge transfer mechanism) with accelerating and decelerating tubes (Figure 1 bottom) standing off 2MV. The present source is a Pierce type electron gun (Figure 1 top). The electron beam is accelerated to 2 MeV, passes through a couple of solenoids, an achromatic bend, two more solenoids, and then back up the decelerating column to a collector. The goal is to do this at high current with minimal losses, at least less than the current the Pelletron can supply. Another gun has been purchased from BINP in Novosibirsk (Figure 1 middle). The Fermilab gun is expected to be able to produce about 200 milliamps while the Novosibirsk gun was designed to produce 500 mA.

The studies described in this paper are intended to provide understanding of the optics of this system and to provide guidance for setting the optical elements. Two simulation codes are used, EGN2 and MacTrace to simulate the gun and beamline areas respectively. The results are used to predict the settings of optics elements in the beamline (Figure 2). The beamline is symmetrical about the quad and so most of the MacTrace simulations stop half way through the quad. The currents simulated here do not produce appreciable asymmetry due to space charge. To ensure the achromaticity of the bend we require that the dispersion and its derivative be zero at that point. The thin lens at the top of the column is required to match between the EGN2 information and the MacTrace code and will be described in more detail later. Solenoids S1, S2, and S3 are then used to control the beam properties to guide it through the beamline.

EGN2 Features

"EGN2 is an enhanced version of the program developed at the Stanford Linear Accelerator Center for the design of electron guns for accelerators, microwave tubes, and other electron/ion devices. EGN2 calculates the trajectories of charged particles in electrostatic and magnetostatic fields. Particles can

[1] EGN2 is an electron and ion optics design program by G.A. and W.B. Herrmannsfeldt

[2] MacTrace is produced by G.H. Gillespie Associates, Inc.

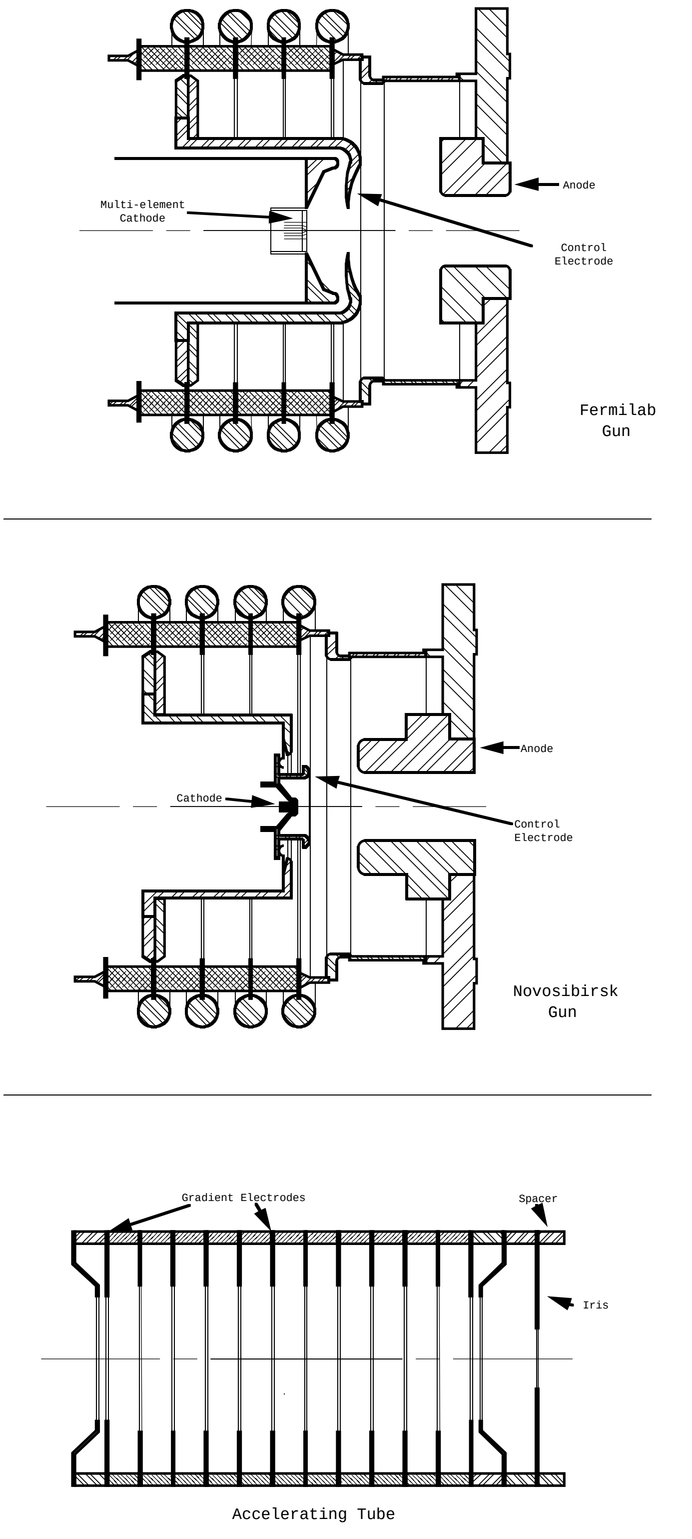

Figure 1: Guns and accelerating tube. Top: Original gun, Middle: New Gun from BINP, Bottom: one of 14 - 7 accelerating, 7 decelerating - tubes.

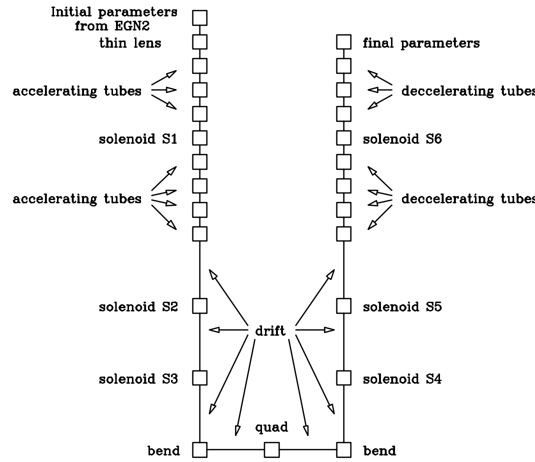

Figure 2: Recirculation beamline at NEC

be initialized using space charge limited emission (Child's Law), temperature limited emission, or user specified data. Electric fields are calculated from arbitrary shaped boundaries, with any number of applied voltages, and suitable boundaries of symmetry. [1]"

EGN2 was used to simulate the gun area of the experiment. The trajectories of the rays generated are traced to the center of the first accelerating tube. Here Twiss parameters are computed and given to Trace. Some aspects of the EGN2 simulation need to be further investigated.

1) Do the results depend on the location of the transfer of information between the two programs? If we do this at the center of the first accelerating tube or the center of the last tube, do we get the same answer?

2) The center of the accelerating tubes was chosen as the transfer point because the equipotentials are perpendicular to the beam axis. Therefore, all the trajectories stop at the same z position and at the same energy. Does space charge affect this assumption significantly?

MacTrace Features

"TRACE 3-D is an interactive beam-dynamics program that calculates the envelopes of a bunched beam, including linear space charge forces, through a user defined transport system. TRACE 3-D provides an immediate graphics display of the envelopes and the phase space ellipses and allows nine types of beam-matching options. [2]"

"MacTrace is a graphical user interface which has been integrated to run with the accelerator beam dynamics code TRACE 3-D. The interface is based on the Shell for Particle Accelerator Related Codes (SPARC) software technology written for the Macintosh operating system in the C programming language. [3]"

Trace transports beam envelope parameters through matrix elements whereas EGN2 propagates rays through field potentials. Therefore the output of EGN2 must be transformed to the parameters Trace needs. This is done by computing the rms values for r, r', which are used to compute the emittance, alpha, and beta.

MacTrace presently assumes that the beam is bunched. Since we are simulating a DC beam, we increase the beam current by 1.333 to get the proper effect of space charge. This factor of 4/3 is an empirical value determined by the developers of MacTrace.

Our standard practice is to use EGN to generate 200 particles and transport them to the center of the first accelerating tube. Accelerating tubes are not part of the original Trace program. MacTrace has the capability of using accelerating tubes however it assumes the beam is entering from a no field region and passes through the fringe of the field when entering the tube.

To counteract the defocusing of the entrance fringe we have to modify the lattice slightly. This is done by placing a thin lens, a matrix element with no longitudinal thickness, at the entrance to the first accelerating tube. The strength of the lens depends on the energy of the electrons. We have determined this relationship (Figure 3) so we can conduct the transfer at any point in the column. While the strength of this lens is set to negate the defocusing of the tube, thus preserving the slope of the ray, it does introduce a slight transverse displacement of the ray's position.

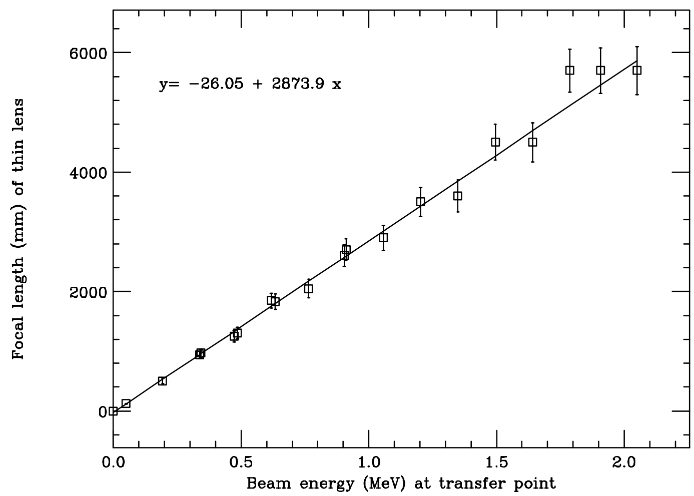

Figure 3: Strength of thin lens

Tests

One test has been performed to verify the continuity of the transfer of the beam from EGN to Trace. This was done by transporting the beam to the halfway point of each of the seven accelerating tubes. At this longitudinal point, the equipotential lines are almost vertical (they are vertical in the absence of space charge) so the beam ellipse parameters can be calculated without worrying about z effects. The beam is then put into Trace at each of these seven points and transported by Trace to a common point. The beam parameters at this point are then compared for differences. Most of the comparisons yielded small differences. However, when the transfer was done in the middle of the fifth tube, the beam as described by EGN2 was not converging as it was in the others. We assume that this is an error in the EGN2 calculations for this one instance possibly due to the large mesh space (1.6 million mesh points) but investigation continues.

Results - Fermilab Gun

The requirement that the beam be dispersionless through the 180 degree bend requires that there be a waist in the beam envelope at the center of the quad. The focusing characteristics of the 90 degree bends then require that there be an image of this waist on the other side of the bend magnet approximately 50 cm towards the solenoid at the bottom of the accelerating column. Therefore, the electron gun and the focusing elements of the column must be able to produce this waist.

For the Fermilab gun, this is possible at very low currents, below 10 mA, and at high currents, above 100 mA. In the intermediate range however, the beam from the gun is converging towards a waist between S1 and S2. Because of the very small transverse dimension of the beam at these elements there is very little focusing power. The beam essentially drifts until it reaches S3. Even here it does not have enough transverse dimension to produce the necessary focus before the bend magnet.

Therefore, it seems we will not be able to use the present gun to get above 10 mA. The analysis for this statement was done based on a 2MV column with an anode voltage of 50 kV and a control electrode voltage of 10 kV. Recent operational experience has shown that we cannot operate at these values reliably. At an accelerating voltage of 1.5 MV, anode voltage of 35Kv and control voltage of 8 kV, the current limit appears to be 1 mA. Therefore, our present plans are to switch to the Novosibirsk gun once we have achieved about 1 mA.

Another caveat is that presently, the simulations use a cathode emitting surface that represents the center dot and the first ring. Actual running nominally uses only the center dot. However, some of the surrounding rings are heated as the center ring will not emit when the surrounding rings are cold. What this does to the emission distribution is not known.

Results - BINP Gun

The Novosibirsk gun has a single cathode element with radius of 3.5 mm. The current emitted is controlled by a control electrode collar which can be set at a negative potential. This collar generates a zero voltage equipotential that penetrates the cathode surface and varies the surface area that is exposed to a positive gradient and therefore can emit.

The simulations with the Novosibirsk gun look very good. Figures 4, 5, and 6 show the EGN2 results for three examples. The plot follows the trajectories to the center of the first accelerating column. The equipotential lines shown are placed at regular z intervals not regular voltage increments. At turn-on (≈ -1800 V on the control electrode) the beam pinches down and crosses over before diverging to the exit of the gun. At medium currents (90 mA, -1000 V), the beam narrows then expands, again diverging at the exit. High currents (>300 mA, 0V) have the beam expanding immediately off the cathode. The trajectories level off as they leave the gun.

Figures 7, 8, and 9 show the MacTrace results. The fifteenth element in 7 is an inactive thin lens. It was placed there as a target for properly focusing the trajectories through the bend. The currents listed in the MacTrace output are higher than the actual values by 1.33. This is done to compensate for the DC nature of our beams. In all cases the beam is large and either parallel or diverging at S3 and S2. This leaves much tuning range to get the necessary focus before the bend.

Figure 10 shows the relationship between the control voltage electrode and the emitted current. These results are lower than results obtained from simulations conducted at BINP. When the trajectories are started in EGN2, they are started 2 mesh points out from the actual cathode surface to overcome the space charge at the surface. In the results presented here the cathode is only 8 mesh units tall, giving the starting volume, the Langmuir diode, an aspect ratio of 4 to 1. This is probably too small, reduces the emission capability of the cathode and will be investigated.

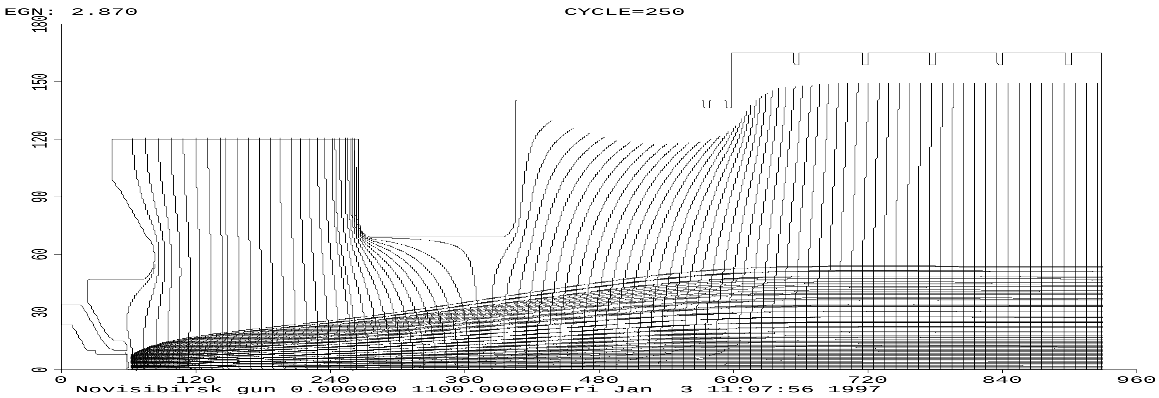

Figure 4: EGN2 results for control voltage of 0 volts. (375 mA)

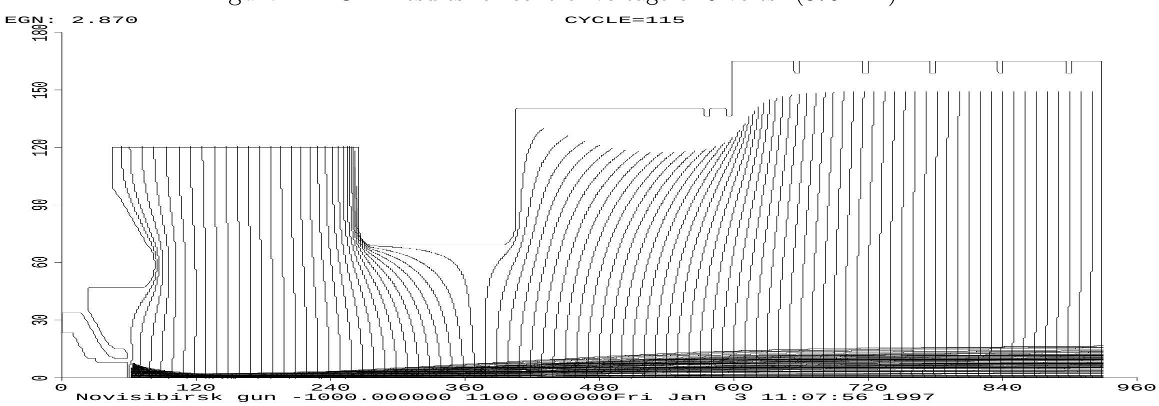

Figure 5: EGN2 results for control voltage of -1000 volts. (77 mA)

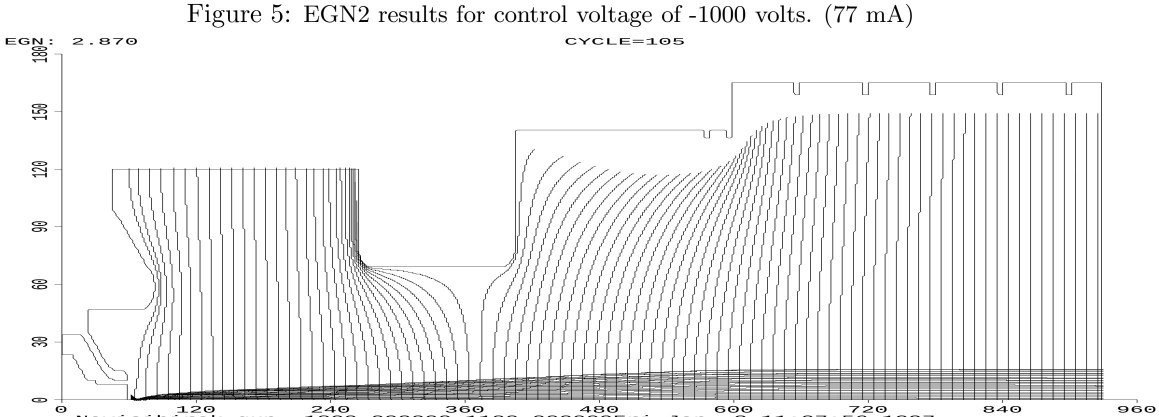

Figure 6: EGN2 results for control voltage of -1800 volts. (.2 mA)

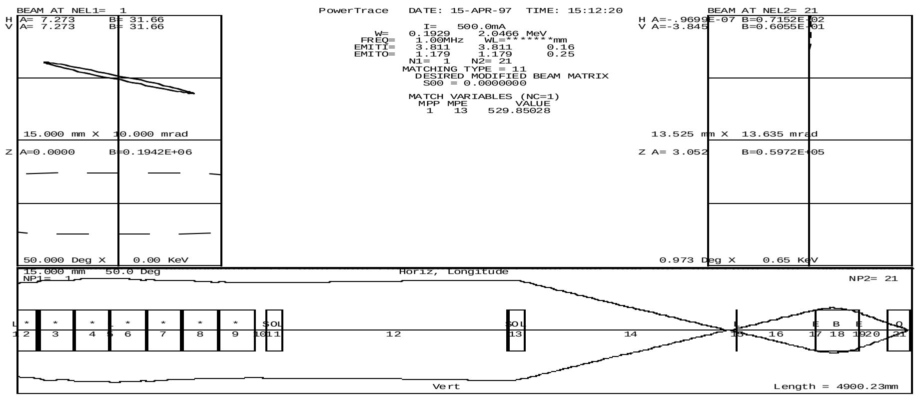

Figure 7: MacTrace results for control voltage of 0 volts.

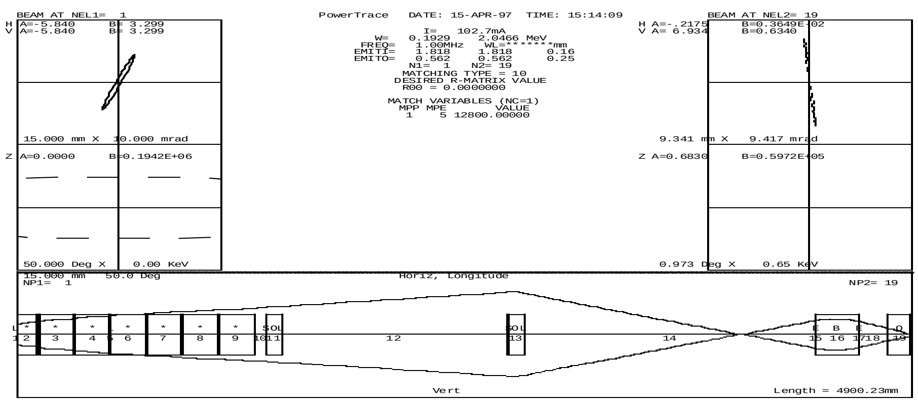

Figure 8: MacTrace results for control voltage of -1000 volts.

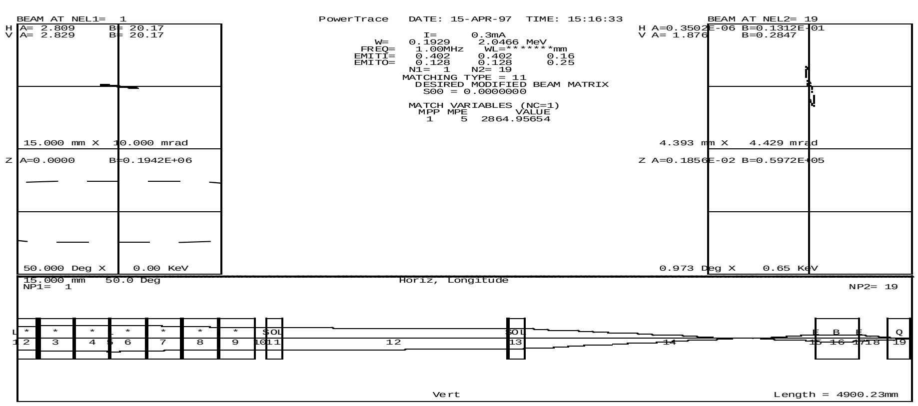

Figure 9: MacTrace results for control voltage of -1800 volts.

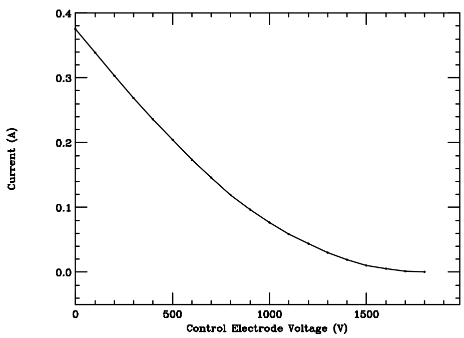

Figure 10: Current emitted by Novosibirsk gun as a function of voltage on the control electrode.(EGN2 results)

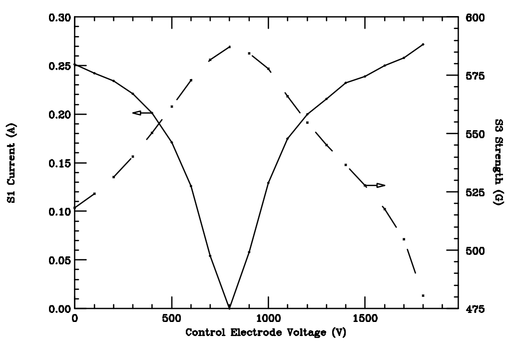

Figure 11: Tuning curves for S1 and S3 for Novosibirsk gun as a function of voltage on the control electrode.

Figure 11 shows the tuning for S1 and S3 to match through the bend. Note that the abscissa is voltage on the control electrode so tuning up from 0 current involves moving from high control voltage to 0. The curve is well behaved with no discontinuities. S2 is set at a constant value of 108 Gauss.

Conclusions

Simulations of expected performance of the present electron gun used in Fermilab's recirculation experiment do not suggest good running conditions. The achromatic conditions necessary can not be maintained at moderate currents. Simulations of a new electron gun built by BINP promise smooth operation over the full current range. This paper has also reported on a number of techniques that are useful to using EGN2 and MacTrace together.

Acknowledgments

Fermilab is operated by the Universities Research Association, Inc. under contract No. DE-AC02-76H03000 with the U.S. Department of Energy.

References

[1] W. B. Herrmannsfeldt, " Egun - An Electron Optics and Gun Design Program", SLAC-Report-331, (Stanford, Oct. 1988).

[2] K.R. Crandall (revised by D. P. Rusthoi), "Trace 3-D Documentation", 2nd ed., LA-UR-90-4146, (Los Alamos, 1990).

[3] G. H. Gillespie Associates, Inc., "MacTrace User Manual", (Del Mar, CA, 1992).