HIGH-CURRENT BEAM TRANSPORT IN ELECTROSTATIC ACCELERATOR TUBES †

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ABSTRACT

The UCSB Free Electron Laser (FEL) has successfully demonstrated the use of a commercial 6 megavolt electrostatic accelerator as a high current beam source in a recirculating configuration[1]. The accelerator, manufactured by National Electrostatics Corp. (NEC), Middleton WI, uses two standard high gradient accelerator tubes. Suppression of ion multiplication was accomplished by NEC with apertures and a shaped electrostatic field. The field shaping has fortuitously provided a periodically reversing radial field component with sufficient focussing strength to transport electron beams of up to 3 Amps current. Present two-stage FEL work requires a 20 Amp beam and proposed very high voltage FEL designs require currents as high as 100 Amps. A plan to permit transport of such high current beams by the addition of solenoidal focussing elements is described.

INTRODUCTION

The UCSB FEL uses a 6 MV electrostatic accelerator with negative terminal potential as its electron beam source. Two standard high gradient accelerator tubes of 3.6 meter length are used - one for acceleration and one for deceleration. The tubes are made from .2 meter modules (Fig 1) which employ 2.5 cm aperture disks and a shaped electric field gradient for suppression of ion multiplication. This field shaping (Fig 2) results in a periodically reversing radial field component with sufficient net focussing to provide electron beam transport for currents as high as 3 Amps (Fig 5). Use of these tubes at 20 Amperes for present two-stage FEL work, and up to 100 Amperes for future FELs using 25 MV electrostatic accelerators, requires additional confinement against space charge forces. Physical constraints preclude the use of anything but focussing solenoids located in place of the ion loading apertures at 1 MV intervals where power is available. Solenoids are not particularly desirable for two reasons. First, the focussing strength

$$\frac{1}{f} = \frac{1}{4}\left(\frac{q}{\beta c \gamma m_0}\right)^2 \int_{-\infty}^{+\infty} B_z^2 dz$$

has an inverse gamma squared dependence becoming quite feeble at high energies. For example, a 500 Gauss solenoid with a focal length of 2.4 meters at 1 MeV would have a focal length of almost 45 meters at 6 Mev. Second, solenoids tend to introduce beam abberations, particularly spherical aberration, where focussing strength increases with distance off-axis. The generation and acceleration of an electron beam with near thermally limited emittance was demonstrated by the UCSB FEL project[2] and is a particularly important characteristic for two-stage FEL work[3]. Any serious emittance degradation would be unacceptable. These concerns motivated an analysis of the beam transport properties of the standard NEC accelerator tubes used in conjunction with solenoids.

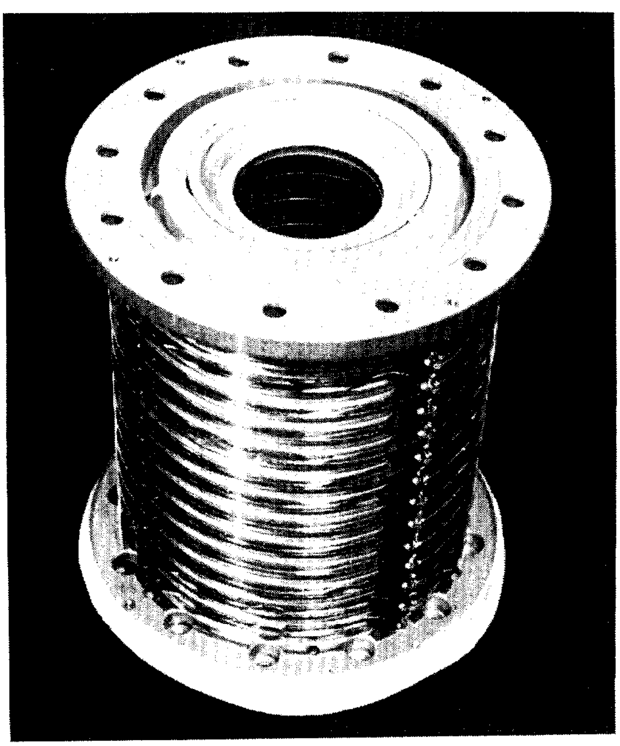

FIG. 1 333 KV section of NEC high-gradient accelerator tube

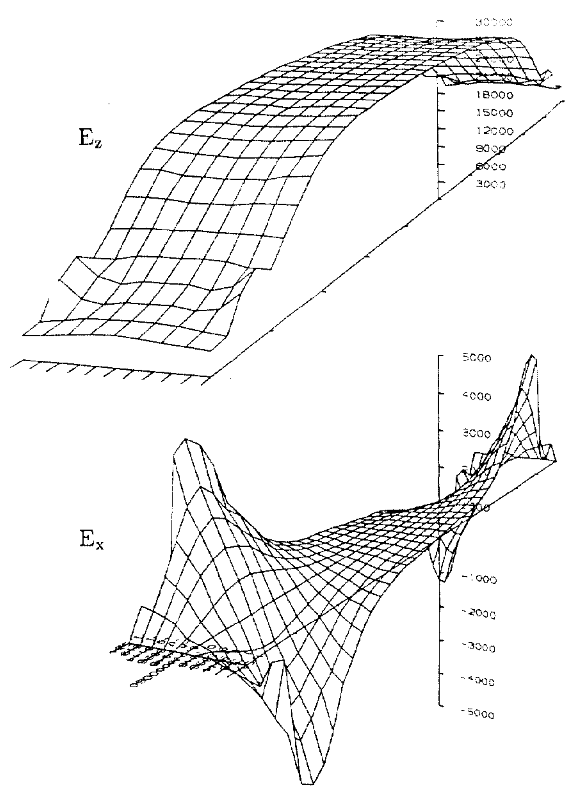

Fig. 2 Longitudinal and transverse electrostatic fields of 333 KV accelerator tube section

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SOLENOIDS

Originally it was thought that a solenoidal peak field on axis B_{z0} of 1.5 kilo-Gauss would be required at 20 amps beam current. Physical size and power dissipation constraints, however, precluded incorporation of a sufficient number of ampere-turns within the available space so a novel solution using electromagnetically-modulated permanent magnets was developed. Fig. 3 is a photograph of the prototype. Fig. 4 shows measured longitudinal and transverse fields. Neodymium-Iron-Boron material is used and peak longitudinal field on axis is variable from 0 to 2.0 kilo-Gauss. Operation as a pure electromagnetic solenoid is accomplished by replacing the magnets with steel blocks.

ANALYSIS

A trajectory analysis is performed by numerical integration of the relativistic equations of motion in a rotating cylindrical frame.

$$r_i'' = \frac{q}{\gamma m_0 \beta^2 c^2}\left[\beta c r_{i0}\theta_{i0}' B_{zi} + E_{racc} + \sum_{j\leq i}\frac{I_j(1-\beta^2)}{2\pi r_j \epsilon_0 \beta c}\right] + r_i {\theta_i'}^2 + \frac{\epsilon^2 r_i}{r_b^4}$$

$$\theta_i'' = \frac{q}{\gamma m_0 \beta c r_i}(B_{ri} - r_i' B_{zi}) - \frac{2\theta_i' r_i'}{r_i}$$

The beam is represented by a number of concentric cylinders of current permitting calculation of space charge force in the presence of uneven current distribution. The effect of emittance is included as an inverse radius cubed term as in the K-V envelope equation. The electrostatic fields are calculated numerically by finite difference approximation to the Laplace equation in cylindrical symmetry. The solenoid magnetic fields are calculated by fitting measured data to a self consistent model using a 3rd order polynomial dependence in r and an exponential dependence in z.

$$B_r = 2B_{z0}z(r + \frac{ar^3}{3})e^{-bz^2}$$
$$B_z = B_{z0}(1 + ar^2)e^{-bz^2}$$

This model is accurate for the relatively thin electromagnet design with a=4262.0 and b=7496.0. Measured data with interpolation is used directly with the more complicated fields of the permanent magnet solenoids.

Figs. 6 and 7 show trajectory plots for the 6 MV accelerator tube with a 20 Amp beam and for the first 6 MV of a 25 MV tube with a 100 Amp beam. Emittance degradation from spherical aberration varies with the fourth power of angle through which the beam envelope is changed and inversely with the square of focal length for a given envelope radius, while space charge spreading force varies inversely with envelope radius, suggesting the use of the largest possible beam radius. Solenoid currents were, therefore, chosen to produce a large radius collimated beam as quickly as possible. Parameters of the 20 Amp UCSB gun were used in Fig. 6 while a .5 MeV injector beam is assumed for the 25 MV tube of Fig. 7. It is apparent that as long as the solenoids are used with just sufficient strength for beam confinement, serious emittance degradation does not occur. The crowding of outer current cylinders characteristic of the spherical aberration of the first solenoid of the 25 MV tube is apparent but as the beam grows back to it original radius and propagates further, the current distribution becomes uniform again. The same effect is seen in plots of phase-space where the spherical aberation produces a strongly curved distribution that is seen to straighten out as gamma increases. This is the same as conservation of normalized emittance even though the transverse momentum spread remains correlated.

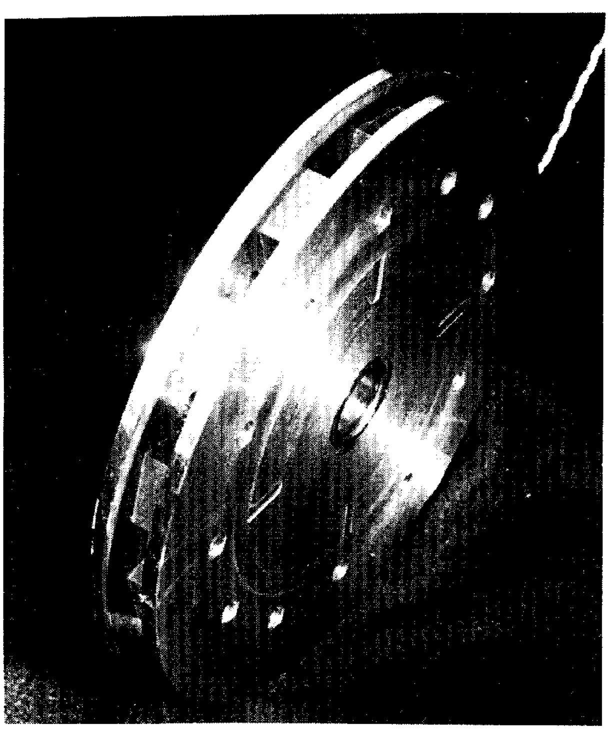

Fig. 3 Modulated permanent magnet focussing solenoid designed for insertion between accelerator tube sections

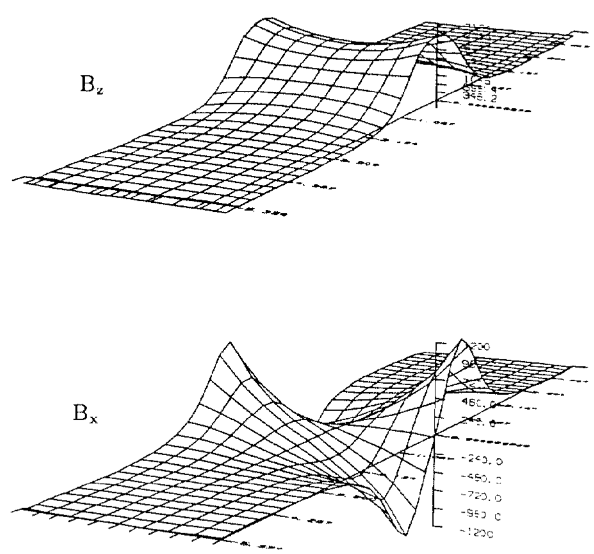

Fig. 4 Measured longitudinal and transverse magnetic fields of focussing solenoid. Peak B_{z0} on axis is 2 KG.

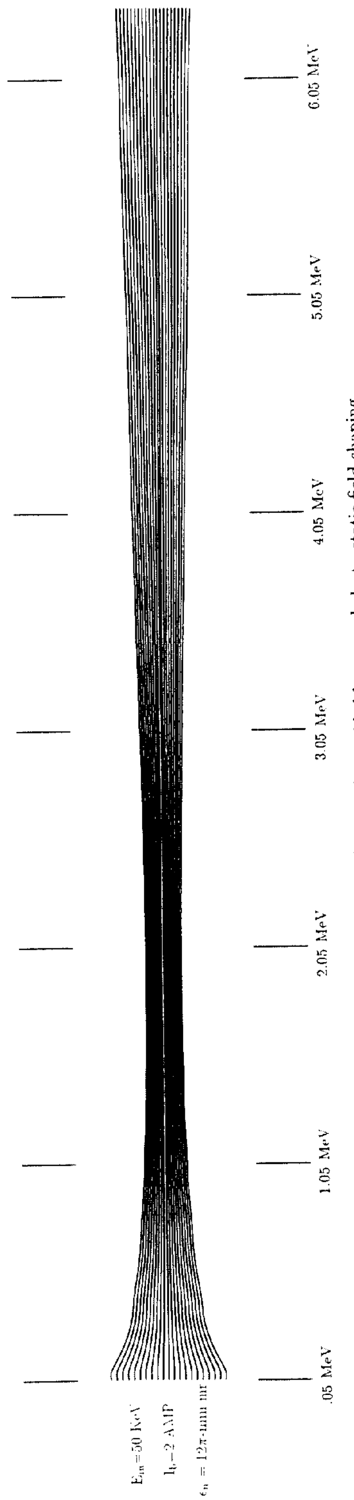

Fig. 5 2 Amp beam in unmodified 6 MV accelerator tube. Beam confinement is provided by normal electrostatic field shaping.

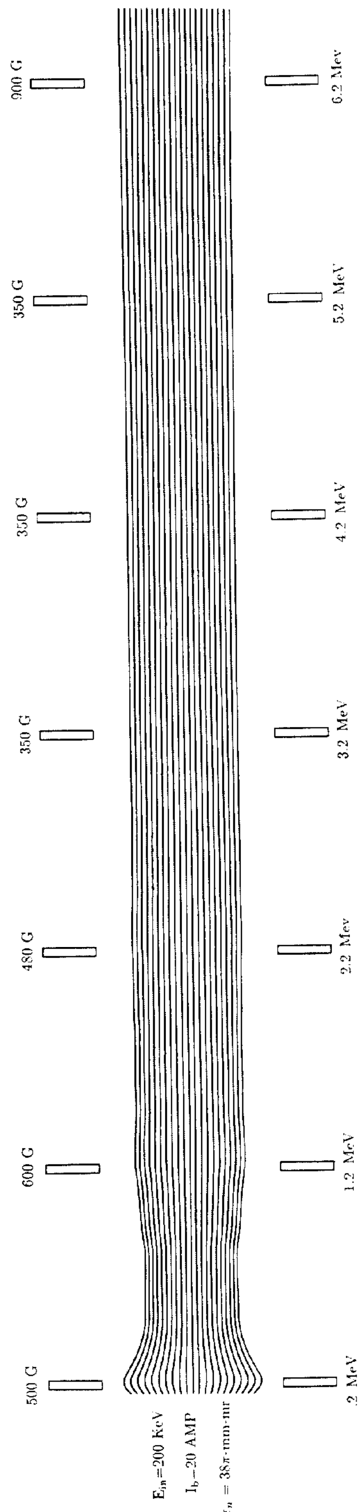

Fig. 6 20 Amp beam in modified 6 MV tube. Focussing solenoids have been added at 1 MV intervals.

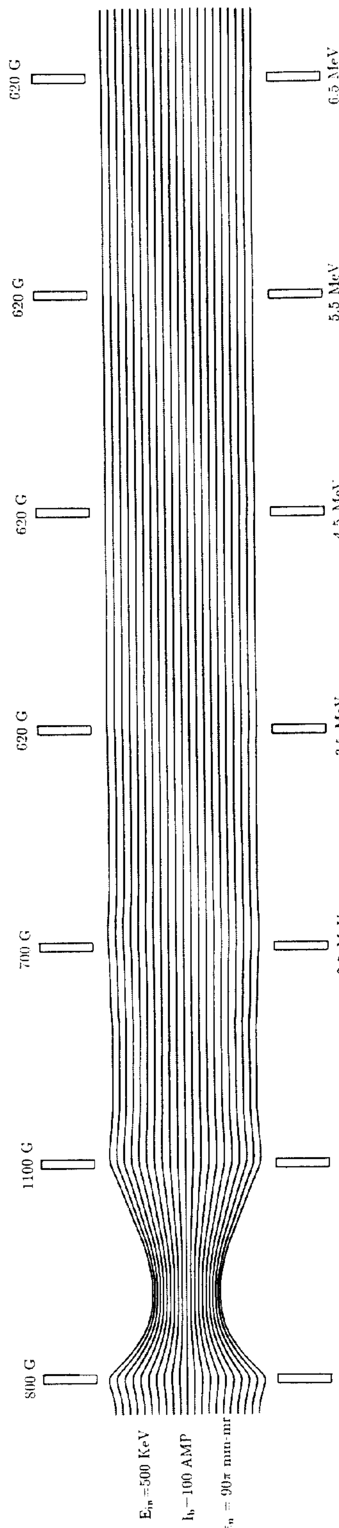

Fig. 7 100 Amp beam in first part of a 25 MV tube. The beam is injected at .5 MV from a gun/preaccelerator. solenoid strengths are chosen to quickly produce a large radius collimated beam thus minimizing emittance degradation.

CONCLUSION

Trajectory calculations indicate that standard NEC high gradient accelerator tubes in combination with focussing solenoids at 1 MV intervals are suitable for use with electron beam currents as high as 100 Amps with minimal emittance degradation, thus satisfying the requirements for present two-stage FEL work at 20 Amps and permitting up to 25 MV Electrostatic accelerator driven FELs for the future.

REFERENCES

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