BEAM OPTICS IN THE FXR 1.5 MeV, 4 kA INJECTOR*

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Abstract

The 20 MeV, 4 kA linear induction accelerator (FXR), currently under construction at LLNL, will use a cold cathode injector. The foil cathode consists of a 0.03 mm tantalum ribbon wound in a spiral with successive turns spaced 0.8 mm apart. The emitted current will be 15-20 kA but will be reduced to 4 kA by collimating immediately beyond the anode. This will minimize the beam emittance and maintain a good impedance match with the low impedance driving source. Computer simulation was used extensively to optimize the configuration of the beam forming electrodes, the emitter geometry, and the overall focusing and beam transport system in the injector region. This paper will discuss the approach used and the problems encountered in the design of the diode geometry and of the overall beam optics. Preliminary experimental results will be presented and will be compared with the computer model predictions.

Introduction

FXR is a linear-induction accelerator being built at Lawrence Livermore National Laboratory (LLNL). It will accelerate a 4 kA electron beam to an energy of 20 MeV. The accelerator consists of a 1.5 MeV injector, plus 48 accelerator modules, each of which produces a 350-400 kV, 90 ns pulse. The overall injector design is given in a companion paper[1]. This paper will describe the electron injector only, and in particular, the design of the anode and cathode and the design of the beam transport system. Initial experimental results show an injector beam current of 3.4 kA having an emittance of 60-70 mr-cm.

The Injector

The injector has been designed to emit approximately 18 kA from the cathode, mainly to improve impedance matching. Immediately after passing through the anode, the beam is collimated and the central 4 kA of the beam is transported through the injector into the accelerator proper. By collimating, the outer edges of the beam are stopped and only the cooler, central portion of the beam is transported.

Earlier work had indicated that a cold emitter could serve as an electron source for FXR.[2] Although a cold emitter is not as well understood as a thermionic emitter and is prone to nonuniform emission, it costs less, is simpler, and is not susceptible to poisoning, as are thermionic emitters.

The Diode

Some basic considerations in the diode design were:

1) The electric field at the emitting surface had to be high enough to cause fast "turn-on" for uniform emission over the entire surface.
2) The electric field at the non-emitting electrode surfaces had to be low enough to render electron emission from these surfaces negligible.
3) Beam pinching beyond the anode mesh could not occur.
4) Feasible fabrication methods, materials, and mechanical tolerances had to be established.

Because of the first and second considerations, we chose an anode-cathode (A-K) spacing such that the average field was 400 kV/cm at the cathode. Since an estimated macroscopic field enhancement of 5 to 6 times is obtained on the emitting surface, an electric field of 2-2.4 MV/cm exists there. The "turn-on" time for this material at these field strengths is estimated to be 5 - 10 ns[3].

The Cathode Assembly. The cathode assembly consists of a focus electrode and an electron emitter. The purpose of the focus electrode is to aid in focusing the beam and to minimize the electric field enhancement at the edge of the emitter. The focus electrode is stainless steel, which has been electro-polished to remove surface irregularities and buffed to a mirror finish. Initial testing has shown no problem of emission from the focus electrode. The focus electrode with the emitter in place is shown in Figure 1. The emitter consists of a tantalum foil strip, 0.03 mm X 10 mm wide, laid on its edge in a spiral over a convex stainless steel form. This form is coated with a 0.08 mm thick layer of copper. Each successive tantalum layer is separated by 0.8 mm with three strips of 0.25 mm X 6 mm wide stainless steel foil strip. The emitter is furnace-brazed using this copper coating as the base brazing material.

If we assume a Child-Langmuir space-charge limited behavior, then the radius of the emitting surface is related to the other diode parameters by:

$$R_{cath} = \left(\frac{I \times d_{A-K}}{7.3\text{x}10^{-6} V^{3/2}} \right)^{1/2}$$

Allowing for a beam current of 18 kA, an A-K spacing 3.75 cm, and a diode voltage of 1.5 MV, the cathode radius was fixed at 4.4 cm. In the vicinity of the anode mesh, the radially-outward space-charged fields of the beam are shorted out by the mesh, leaving only the radially-inward magnetic self-fields. To compensate for this, the emitting surface was made convex which provides the electrons with an initially outward-directed momentum. This outward momentum maximizes the beam radius and minimizes the angle of convergence at the cathode, two desirable characteristics a planar emitter could not supply. A secondary effect is that the electric fields are greatest near the axis, causing the central portion of the cathode to turn on first.

The Anode Assembly. The anode is planar and consists of a grid. This anode grid is made of a 0.033 mm thick, 16 lines/cm, tungsten mesh. The mesh has a transmission of 80%. The tungsten mesh was a photo-etched grid (not a weave) forcing us to design mounting rims to minimize wrinkles. Directly

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behind this grid is a low-conductance-water (LCW) cooled, aluminum-to-stainless steel, roll-bonded collimator. The collimator is water-cooled to dissipate the 400 watts generated in stopping part of the beam. We chose aluminum for the collimator because back-scattered and side-scattered electrons are thereby kept to a minimum. Scattered electrons would cause an increase in beam emittance. The stainless steel backing served as the cooling channel, thus eliminating electrolysis problems which would develop in a LCW system of combined aluminum, copper, and stainless steel plumbing.

The anode stem has an inner liner. This liner is tapered to aid in beam transport by minimizing the space-charge potential depression . The inner liner was perforated for vacuum pumpout.

To arrive at the final diode design, the computer code EBQ[4] was used. This is a relativistic beam transport code which takes into account the self-forces on the beam. EBQ was also used to predict the beam behavior up to 15 cm beyond the anode mesh. To predict the beam behavior beyond 15 cm, we used the TRANSPORT[5] code.

The diode configuration is shown in Figure 2. This figure shows the electron trajectories, the equipotential surfaces set up by the anode and cathode, and the electron beam itself. The focus electrode design and emitter design ensure uniform current emission over the entire emitting surface. This is shown in Figure 2 where a uniform spacing between the emitting surface and the first equipotential line illustrates a constant electric field across the emitter surface.

The Transition Region

The 76 cm long transition section, the axial magnetic field profile and the calculated beam envelope are shown in Figure 3a, b. The transition section was designed to allow some axial coil adjustment and for access to the anode and cathode electrodes. The electrical continuity through the mechanical joints is maintained by a silver-plated expansion band and soft tin solder. Both the anode and cathode surfaces are visible through viewports.

Test Results

Initial testing of the injector has begun. An overlay of the total emitted current and the diode voltage is shown in Figure 4a. Notice there is a 10-20 ns time delay between the voltage rise and current rise which corresponds to an emitter "turn-on" delay of 10-15 ns which is reasonable for the predicted electric field at the emitter. A 10 shot overlay for the transmitted current is shown in Figure 4b. From these figures we see a peak emitted current of 15.1 kA and a peak transmitted current of 3.1 kA for a diode voltage of 1.5 MV. Also notice in Figure 4a that the current ramps up with time. If this is a result solely of plasma closure, the resulting plasma velocity is between 5 and 8 cm/μs.

The total emitted and transmitted currents are measured on resistive monitors located on the anode stem support structure. Summing the voltage of the six capacitor monitors yields the diode voltage. Table 1 shows the peak emitted beam current for peak diode voltages ranging from 1.0 MV to 1.5 MV. Note that the perveance remains essentially constant for all voltages, indicating space-charge limited behavior.

Table 1

Voltage (MeV)	1.05	1.26	1.46	1.56
Current (kA)	7.54	10.10	12.40	13.70
Perveance ($I/V^{2/3}$)	7.01	7.14	7.03	7.03

Preliminary measurements on beam emittance have been obtained by letting the beam strike a 1 mm thick perforated brass plate. The beamlets passing through impinge upon an aluminum-backed phosphor screen. A picture is taken of the fluorescing phosphor. One such picture is shown in Figure 5. The negative of the picture is scanned with a microdensitometer to determine beamlet sizes. Preliminary measurements show that the beam has an emittance of 60-70 mr-cm.

Future Work

Testing will continue to further optomize beam emission and transport. This will include modifying the injector magnetic fields as well as experimenting with a graphite emitter and an aluminum foil anode.

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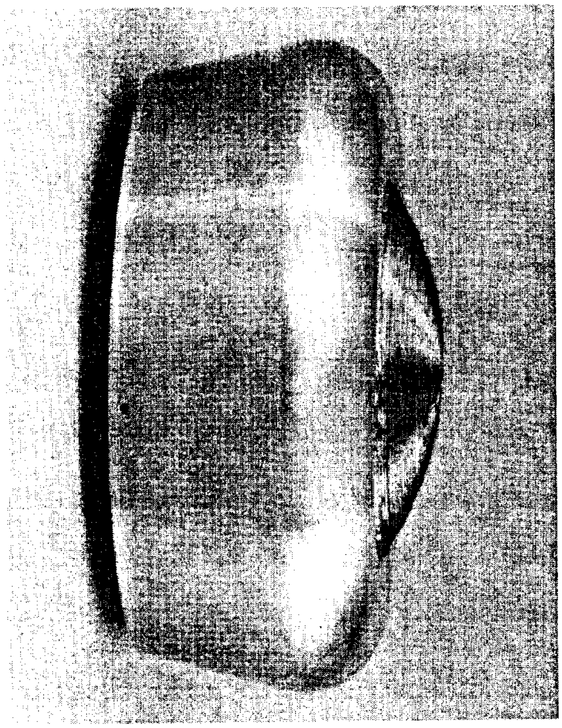

Fig. 1. Cathode focus electrode with tantalum spiral emitter

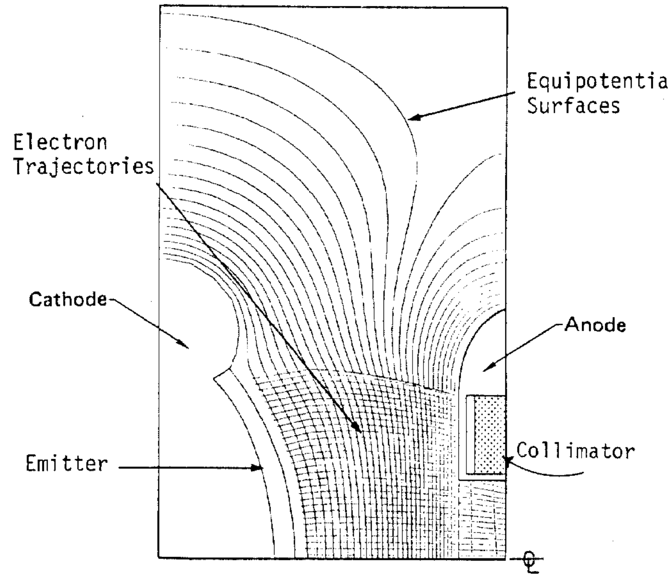

Fig. 2. Diode configuration showing the electron trajectories. The emitter radius of curvature is 9.6 cm.

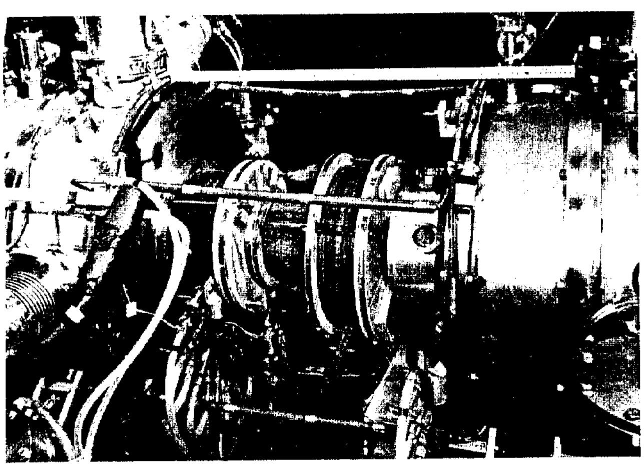

Fig. 3a. Transition Section

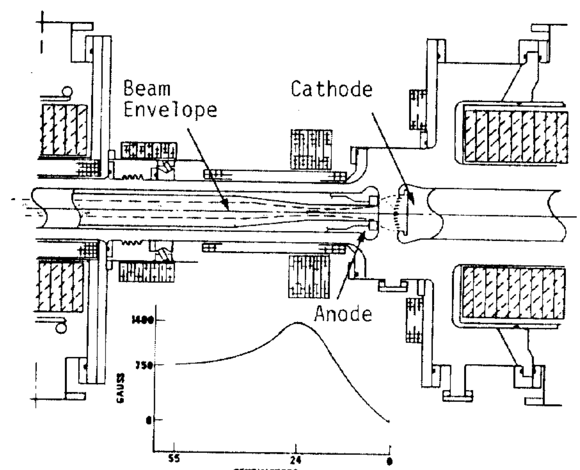

Fig. 3b. Transition Section

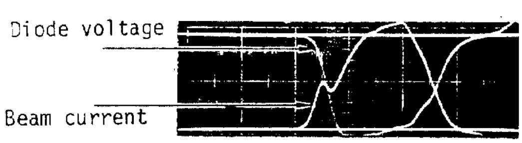

Fig. 4a. Beam current (15.1 kA peak) and diode voltage (1.5 MeV) 50 ns/div

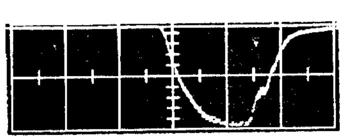

Fig. 4b. Transmitted current 3.1 kA peak 50 ns/div

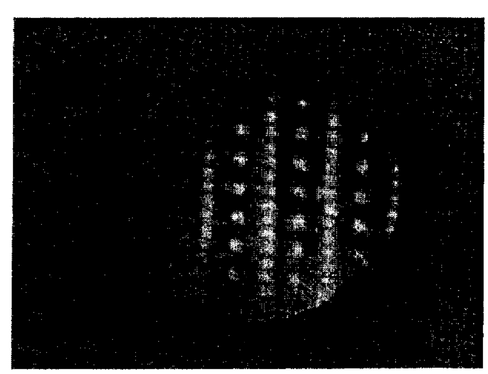

Fig. 5. Beam emittance picture