3-D CALCULATIONS FOR A 4 kA, 3.5 MV, 2.5 MICROSECOND INJECTOR*

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Abstract

The DARHT-2 machine under construction at Los Alamos National Laboratory requires a long-pulse (2.5 μsec) 2–4 kA, 3.5 MV, low-emittance electron beam source. The injector is being designed at LBNL and consists of a large-area thermionic cathode mounted atop a vertical column. The 90° bend between the horizontally emitted beam and the column produces dipole and higher-pole fields which must be corrected. In addition, the fast rise of the current flowing into the vacuum tank excites RF modes which cause transverse oscillations of the beam centroid. We have modeled these effects with the 3-D electromagnetic code LSP. The code has models for pulsed power transmission-lines attached to boundaries, space-charge-limited emission and transport of charged particles, externally applied magnetic fields, and frequency-dependent absorption of RF. We calculate the transverse displacement of the beam as a function of time during the current pulse, and the positioning and thickness of ferrite absorber needed to damp the RF modes. The numerical results are compared to analytic calculations.

1 INTRODUCTION

The DARHT radiographic facility at LANL requires two linear induction accelerators at right angles to each other. The second accelerator is currently being designed and will provide a long-pulse (2 μsec flat-top) high current (2–4 kA) beam. This paper describes calculations carried out for the beam injector, shown in Fig. 1. The thermionic emitter is mounted on top of a vertical high-voltage conductor and insulator column inside a large vacuum vessel. This arrangement simplifies the problem of supporting the weight of the long insulator column. The diode is driven directly by a Marx bank which sits underneath the vacuum vessel. In order to produce a linear potential drop across the insulator column, resistors are wound helically around the insulator column, connecting the cathode dome on top to ground at the bottom. The beam is extracted at right angles to the high-voltage feed, and this results in both quasi-static and RF transverse forces on the beam. To calculate these effects, we have used the parallelized 3-D electromagnetic particle-in-cell code LSP[1].

2 QUASI-STATIC PERTURBATIONS

The largest perturbation to the beam is due to the transverse magnetic field produced in the AK gap by the current flowing in the vertical high-voltage conductor and the return currents flowing in the outer wall. The force is analogous to the hoop-stress in an electron-beam ring, and deflects the beam upward in Fig. 1. If we neglect wall currents, the Biot-Savart law applied to the net current I_{net} (high-voltage conductor current less the resistor current) gives

$$B_\perp \approx \frac{\mu_0 I_{net}}{4\pi R_{AK}} \quad (1)$$

in the AK gap, where R_{AK} is the radius of the AK gap. For $I_{net} = 4$ kA, $R_{AK} = 1.35$ m, this gives about 3 gauss. The resulting deflection of the beam is given roughly by $\frac{1}{2}(eB_\perp/\gamma m_e c)d^2$, (where d is the AK gap length and γ is the average relativistic factor in the gap) which is of order a few mm at the anode. In order to include the effect of wall-currents, and obtain time-dependent effects, we carried out a calculation through the approximately 500 ns rise-time of the voltage pulse using LSP. In this calculation, the Marx

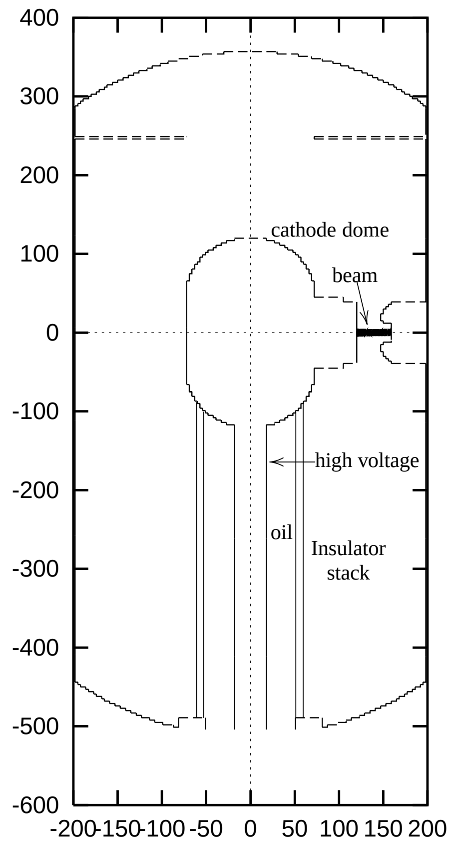

Figure 1: Injector geometry used in 3D simulations. Dimensions in cm.

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bank is approximated using a simple $745\,\Omega$ transmission-line (matched to the nominal $875\,\Omega$ diode impedance in parallel with a $5\,\mathrm{k}\Omega$ resistor) connected to the coaxial conductors at the bottom of Fig. 1. The numerical grid dimension is about 3 cm and the timestep is the Courant-condition value. The $5\,\mathrm{k}\Omega$ resistor is represented by a cylindrical shell of finite conductivity. The current and voltage at the inlet (the bottom of Fig. 1) and the beam current and AK voltage are shown in Fig. 2. The difference between the steady-

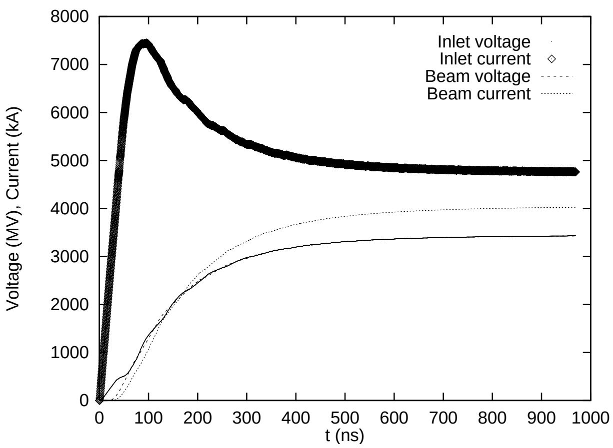

Figure 2: Inlet and AK current and voltage vs. time

state inlet current and the beam current flows in the $5\,\mathrm{k}\Omega$ resistor on the inside of the insulator stack. The effect of the asymmetry of the wall return currents on the azimuthal magnetic field is shown in Fig. 3, where we see that there

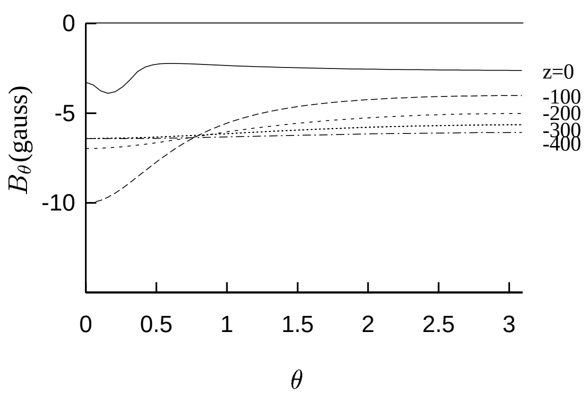

Figure 3: Azimuthal variation of B_θ at different z positions, at a radius of 134 cm. AK gap is at $\theta = 0$.

is a strong azimuthal asymmetry at the elevation of the AK gap.

The transverse magnetic field in the AK gap and the beam deflection 30 cm from the cathode (the AK gap is about 30 cm) are plotted in Fig. 4. In this simulation, no external focusing fields are applied. In practice, the anode contains solenoidal magnets to capture the high-current beam. To compensate for the transverse magnetic field in the AK gap, static dipole coils wound on the solenoidal

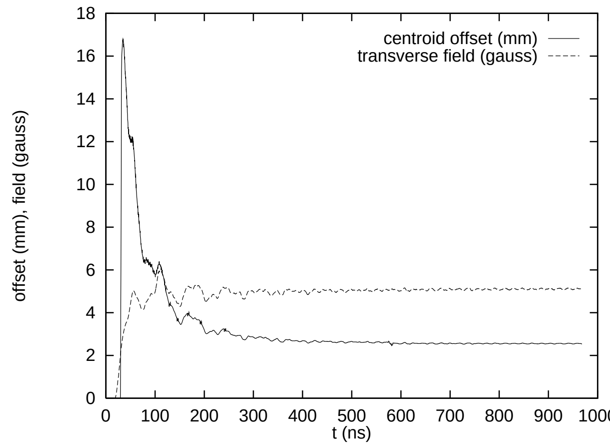

Figure 4: Transverse magnet field 14 cm from the cathode and beam deflection 30 cm from the cathode.

magnets will be used to steer the beam back on axis. If the deflecting field were proportional to the beam current, as would be the case if the system had a matched impedance from the Marx to the AK gap, then the correction fields would need to vary with the beam current to keep the beam-head on axis. However because of the large capacitance of the vacuum vessel (about 320 pF), the risetime of the current flowing into the vacuum vessel is much shorter than the risetime of the beam current (see Fig. 2). It turns out that the deflecting field in the AK gap is almost constant during the rise of the beam current, as shown in Fig. 4. As a result, static correction fields provides much better steering for the beam-head than one might expect.

On the cylindrical stalk to which the emitter is attached, the difference between the current flowing in the top and bottom halves is about 740 A for a 4 kA beam current. This asymmetry is consistent with a simplified calculation of the dipole current on the surface of a conducting cylinder immersed in a transverse magnetic field. The dipole current is given by $I_d = (1/\mu_0)\int_0^\pi B_\theta dl = 4B_0 a/\mu_0$ where B_0 is the transverse magnetic field as $r \to \infty$, and a is the radius of the stalk. Inserting the values for the stalk in Fig. 1, i.e., $a = 0.4\,\mathrm{m}$, $B_0 \approx 3 \times 10^{-4}\,\mathrm{T}$ (3 gauss), we get $I_d \approx 380\,\mathrm{A}$. This is in reasonable agreement with the simulation value ($740/2 = 370\,\mathrm{A}$). On the emitting disk of the cathode, the current density is determined by the normal electric field stress, which is symmetric about the center of the cathode to a high degree. Thus the asymmetric currents flowing in the cathode stalk rearrange themselves on the emitting face to produce an (almost) symmetric beam. There may be some higher-pole magnetic fields associated with this process, but we have not yet attempted to extract them from the simulation.

3 RF PERTURBATIONS

The LSP calculations reveal that, in addition to a quasi-static deflection, the beam centroid undergoes smallamplitude transverse oscillations. The beam displacement 40 cm from the cathode surface is shown on a magnified scale in Fig. 5. The frequency spectrum shows peaks at 38,

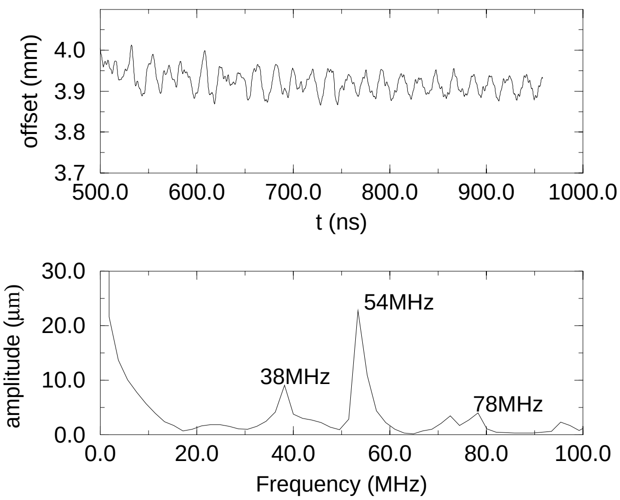

Figure 5: Beam transverse displacement vs. time plotted on a magnified scale, and its Fourier transform.

54 and 78 MHz. By externally driving the injector cavity at each of these frequencies to establish the mode-patterns, we find that they are predominantly TE_{11}-like modes. The dispersion-relation for TE_{11} modes in a cylindrical cavity of length L, radius b with a center conductor of radius a is

$$J_1'(a\gamma)Y_1'(b\gamma) - Y_1'(a\gamma)J_1'(b\gamma) = 0 \qquad (2)$$

where $\gamma = \sqrt{\omega^2/c^2 - k_z^2}$ and $k_z = (2n-1)\pi/L, n = 1, 2, \ldots$, is the axial wavenumber. For $a = 0.5$ m (the radius of the 5 kΩ resistor), $b = 2$ m, $L = 8$ m, the lowest frequency is about 44 MHz. In the actual geometry, this is lowered to 38 MHz (see Fig. 5), probably by the AK gap structure. The frequencies in Fig. 5 are in rough agreement with eigenmode calculations using the MAFIA code and a LANL finite-element code[2].

Since the amplitude of the transverse oscillations is about the same magnitude as the design specification for beam alignment (100 μm), schemes for damping the RF modes have being modeled numerically. In one scheme, we placed a ring of ferrite material 50 cm high and 3 cm thick around the inside wall of the vacuum vessel near the bottom, where the magnetic field of the TE_{11} modes have a maximum. The effect was modeled using the dispersive-material model in LSP, with the the real and imaginary permeability values for "ETA-II ferrite" in the region of 50 MHz ($\mu_r \approx 50$, $\mu_i \approx 100$) as given in Ref. [3]. The numerical results show a strong damping of the RF-driven centroid oscillations to below 20 μm, as shown in Fig. 6. In the simulation, the thickness of the ferrite ring cannot be made smaller than the radial cell-size (3 cm). Thinner ferrite may have a larger damping effect, however. From the expression for the reflection coefficient of a normally-

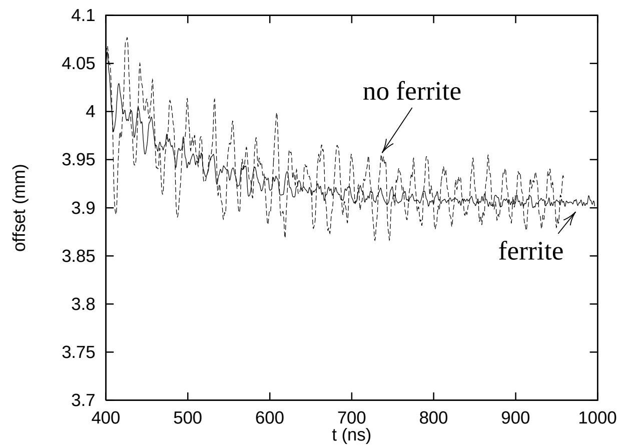

Figure 6: Comparison of beam centroid motion with and without ferrite-ring damper.

incident wave[3], we find that the optimal thickness for frequencies in the range 40–70 MHz is on the order of 1 cm. The enhanced absorption is due to reflection of the incident wave from the conducting surface behind the ferrite. We have verified this result in coaxial geometry using LSP.

4 CONCLUSIONS

The asymmetric design of the DARHT-2 injector produces both quasi-static and RF transverse displacements of the beam centroid. We have modeled these effects with the 3-D electromagnetic particle-in-cell code LSP. For a 4 kA beam current, the quasi-static transverse magnetic field is on the order of 3 gauss and produces a beam deflection of several millimeters at the anode. The effect will be corrected using static magnetic dipoles. The RF oscillations are produced by TE_{11}-like modes of the injector vessel excited by the current rise. Using ferrite damping, the oscillation amplitude can be reduced to $< 20\,\mu$m. The DARHT-2 injector will initially be operated at 2 kA, which further reduces the amplitudes by about a factor of 2.

5 ACKNOWLEDGMENTS

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6 REFERENCES

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