A Flat-Cathode Thermionic Injector for the PHERMEX Radiographic Facility

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Abstract.
The PHERMEX (Pulsed High-Energy Radiographic Machine Emitting X-rays) standing-wave linear accelerator is a high- current electron beam generator used for flash-radiography. An improved electron gun has been designed employing a flat-thermionic cathode to replace the existing Pierce-geometry gun. The flat cathode yields increased current with the same applied voltage and cathode area as the Pierce gun. The ISIS code simulations indicate a beam current of 1.5 kA at 600 kV [1] vs. 500 A for the old gun. The new geometry also reduces the probability for high voltage breakdown in the A-K gap. A re-entrant magnet captures the expanding electron beam and a bucking coil nulls cathode-fringe field. A third coil is used to optimize the extraction field profile and reduce the effect of nonlinear space charge on the beam emittance. Time-resolved measurements of beam current and voltage have been made. In addition, a streak camera was used to measure beam emittance and spatial profile. Comparisons of measurements with simulations are presented.

I. INTRODUCTION.

The PHERMEX accelerator at Los Alamos National Laboratory is used for a variety of flash radiographic experiments. The electron injector used a Pierce geometry gun employing a b-type thermionic cathode This injector has remained relatively unchanged, and has performed reliably for over 25 years. To increase the injected current without increasing the probability of high-voltage breakdown, a new gun has been designed with a planar A-K gap. This type of geometry has been used successfully on the REX[2] injector at LANL. The beam is generated on a field-free thermionic cathode, extracted with a system of three solenoidal magnets and transported with an additional three solenoids to the entrance of the accelerator. We report experiments measuring current, voltage and emittance. The experimental data is also modeled with SPEED [3], a 2D static beam-trajectory code.

Work performed under the auspices of the U.S Department of Energy.

0-7803-1203-1/93$03.00 © 1993 IEEE

II. EXPERIMENT.

The electron gun consists of a 5.08-cm-diam thermionic cathode with a 7.5-cm A-K gap spacing. The anode hole diam is 16 cm. High voltage isolation is provided by 2 convoluted Al O_3 ceramic insulators. A schematic of the gun A-K gap and solenoidal extraction magnets is shown in Fig. 1.

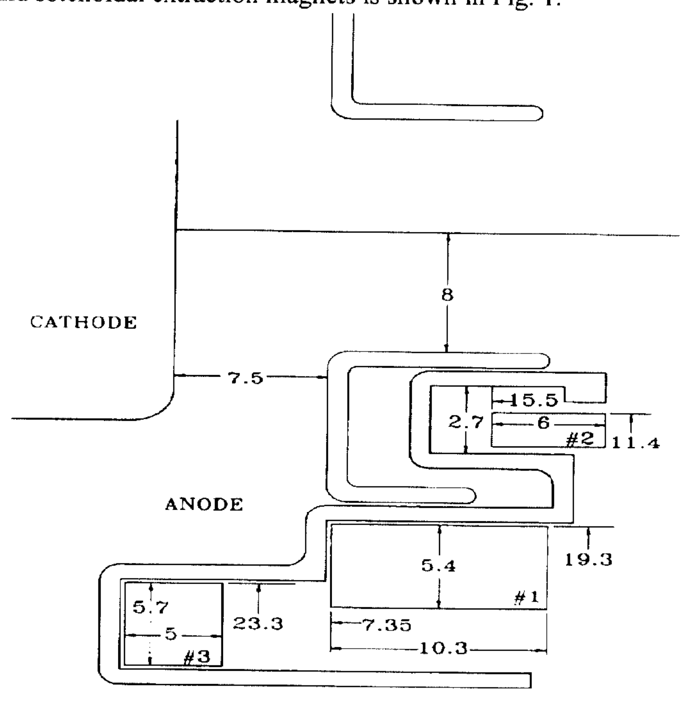

Figure. 1. Schematic of gun A-K gap

The gun mechanical structure and ion plus-cryogenic vacuum pumping system are the same for the existing Pierce gun [4]. Vacuum pressure during operation is approximately 5x 10^{-7} torr and cathode temperature is 1300 C. Both cathode field-forming structure and anode structure are molybdenum while the vacuum vessel is water-cooled stainless steel. The pulse power drive for the gun is a 275 Ω, 11-stage open-air cable Marx bank, which is capable of producing a 500-kV, 200-ns pulse into a matched load. Multiple-stage Marx banks of this type are inherently high impedance and inductance pulsers, and therefore with the capacitance of the A-K gap, form an LRC circuit that exhibits damped ringing.

Voltage was measured with a 945-Ω resistor with an 0.1 Ω divider in parallel with the gun. Extracted current was measured with four-way summed and integrated b-dot sensor-loops. A Tektronix RTD-720 digitizer with a 2-ns sample rate was used to record the data. Typical voltage and current waveforms are shown in Fig. 2.

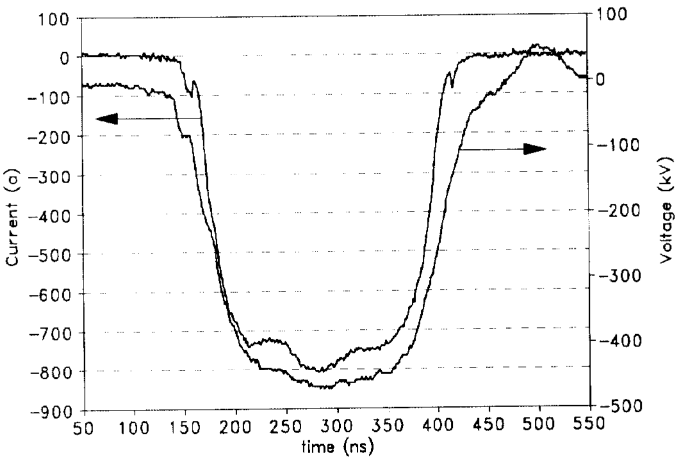

Figure. 2. Plot of current and voltage waveforms

The beam was extracted with a system of three air core solenoidal magnets. The first solenoid is a 19.3-cm-diam coil with 116 turns. The second is 11.4-cm diam. with 26 turns. The third coil is 22.3-cm-diam. with 52 turns. All coils are quadrufiler wound using 0.65-cm square copper wire with water cooling jackets. The third coil was placed with the magnetic pole at the cathode-surface plane, bucking the first extraction magnet. Current on the bucking coil was adjusted to produce a field ull on the cathode. The extraction magnet was placed in a re-entrant anode to capture the expanding electron beam as close to the cathode as mechanically possible. The second coil was also bucking the extraction magnet. It tailors the radial field-profile by flattening $B_z(r)$ which reduces spherical aberration. The beam was then transported with three solenoidal magnets and matched to the entrance of the accelerator. The transport magnets contain six iron homogenizing rings to reduce magnetic field tilt due to random winding errors.

Emittance was measured by intercepting the electron beam with a stainless-steel mask containing 0.4-mm-diam holes spaced 8.0 mm apart. The transmitted beamlets drift 203 mm to a Bicron-422 scintillator and produce light proportional to electron intensity. The light is relayed through a turning mirror and telescope to the streak camera photo-cathode with a Thompson-CSF large format streak camera with a velocity of 4 ns / mm. To measure radial current distribution the emittance mask was replaced by a mask containing a 0.75-mm slit. The streaked images were then captured by an optically coupled, cooled, 1024x1024 pixel back-thinned, 16 bit CCD camera and stored on a 486 PC. Analysis was performed using an IDL computer code[5]. The code displays the streak image and provides rapid analysis for shot-to-shot comparison.

III. RESULTS

A plot of extracted current vs voltage is shown in Fig.3. Initial calculation of gun perveance overestimated the extracted current (20 %). Measurement of the A-K geometry

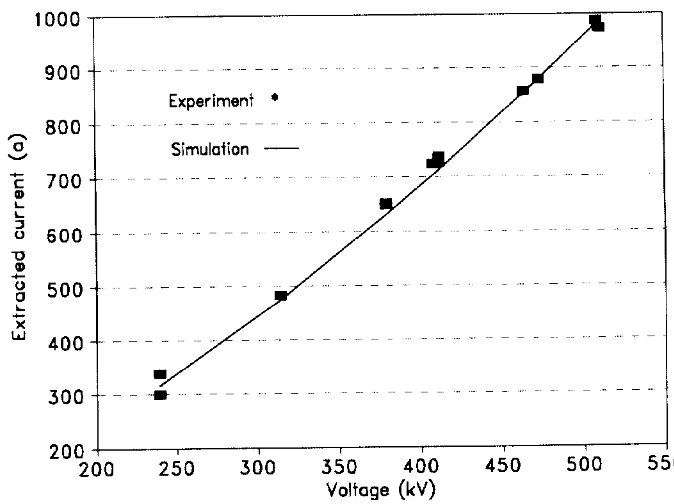

Figure. 3. Extracted current vs. voltage

determined that the cathode was inset 1.5-mm from the field-forming electrode. This reduced the electric field on the outer annulus of the cathode where a substantial fraction of the beam current was generated. Subsequent recalculation with the correct geometry matches the experimental results. A plot of the calculated radial current distribution from the cathode with flush and inset cathodes is shown in Fig. 4. At 400 kV the flush cathode produces 790 A while the recessed was 690 A.

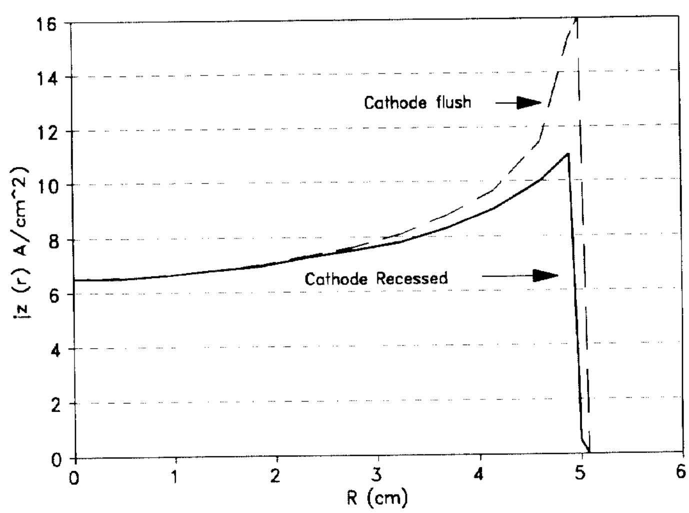

Figure. 4 Current density with flush and inset cathodes

A significant contribution of the electron beam emittance is caused by curvature or "twist " in phase-space. This twist is produced by both nonlinear space-charge and solenoidal over focusing, and is compensated by the introduction of the second solenoid. An emittance plot showing the twist reduction by the second coil is shown in Fig. 5.

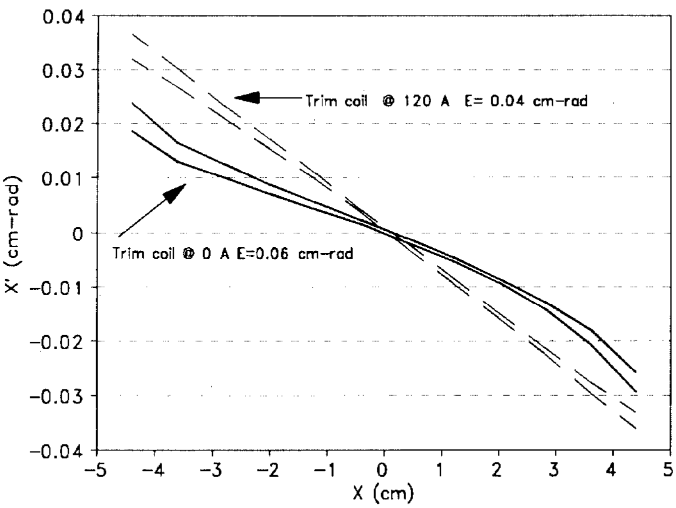

Figure 5. Phase space plots showing improvement in phase-space curvature

The emittance was determined by measuring the parametrically-fit Gaussian distributions of the streaked beamlet widths. From the average positions, the radial velocity of the beamlets can be calculated, while the line widths are related to the transverse beam temperature. The emittance is calculated according to the relation [6]

$$E = 4\, \beta \gamma\, x_{rms}\, x'_{rms}. \quad (1)$$

The center beamlet is used to determine the effective cathode temperature by fitting it to a Gaussian function and correcting (deconvolving) the data for the finite hole size in the mask to yield the angular spread. The spread is then corrected for beam compression by the ratio of cathode to beam diam. at the mask. This angle when normalized to the beam voltage is the angular spread at the cathode surface. The effective cathode temperature is given by

$$T_{eff} = .511 \times 10^6 (\beta \gamma \theta_{rms})^2 = 6.0 \text{ eV}. \quad (2)$$

The corresponding Lapostolle emittance at the cathode is

$$E_L = 2 \times R_{cathode} * \beta\gamma\theta_{rms} = 0.03 \text{ cm-rad}. \quad (3)$$

The radial current distribution is peaked at the outer radius where space-charge depression on the cathode is smallest. As the beam is transported through the remaining three solenoids the beam undergoes charge redistribution and flattens considerably. A plot of the radial current distribution at 225 cm is shown in Fig. 6.

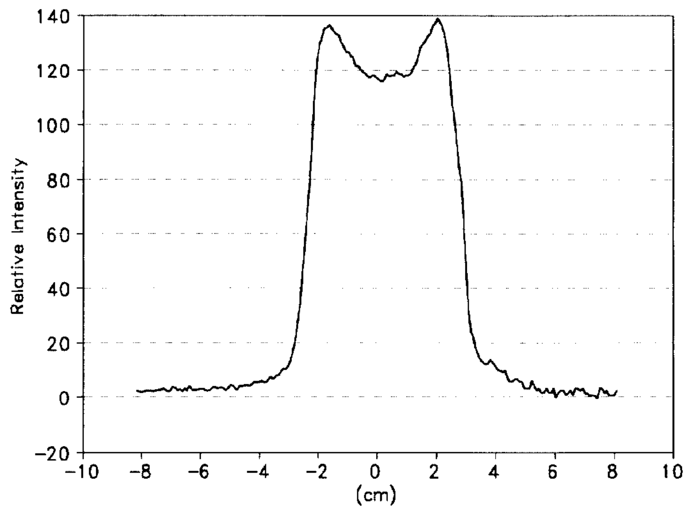

Figure 6. Beam distribution after transport
V= 475 kV, I=860 A

IV. CONCLUSIONS.

The total current the injector produces is slightly lower than predicted. This difference is attributed to the inset of the cathode from the cathode field forming electrode and predicted by SPEED calculation. A new mechanical design will bring the cathode forward and flush. The normalized rms emittance measured with the streak camera was 0.04 cm-rad, which compares favorably with the SPEED calculation of 0.05 cm-rad. The effective cathode temperature is 6.0 eV. The injector voltage of 500 kV nominal produces 950 A. This corresponds to a perveance of 2.7 μP. To produce the necessary current density the cathode must be run at higher than desired temperature, which reduces cathode lifetime and requires the heater filament to be run at correspondingly large input power. A new Spectra-Mat 311 barium ratio cathode with a scandate-dopant will lower cathode operating temperature. Based on the experimental results we expect this new gun may double the output X-ray dose of the PHERMEX accelerator.

V. REFERENCES.

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