ENHANCING THE BRIGHTNESS OF HIGH CURRENT ELECTRON GUNS*

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ABSTRACT

Concepts such as the two-beam accelerator offer the possibility of translating pulsed power technology into a form useful to the design of high luminosity accelerators for high-energy physics applications. Realization of the promise of these concepts will require the design of electron guns which are optimized with respect to beam brightness at current levels of approximately 1 kA. Because high luminosity implies accelerator operation at high repetition rates, the high-current beam source must be designed so that the beam does not intercept the electrodes. In our investigations of electron gun configurations, we have found that the brightness of a given source is set by practical design choices such as peak voltage, cathode type, gun electrode geometry, and focusing field topology. To investigate the sensitivity of beam brightness to these factors in a manner suitable for modelling transient phenomena at the beam head, we have developed a Darwin approximation particle code, DPC. The main component in our experimental program is a readily modi ied electron gun that allows us to test many candidate cathode materials, types, and electrode geometries at field stresses up to 1 MW/cm. We have also developed several diagnostics suitable for measuring the brightness of intense, low-emittance beams.

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I. Introduction

The search for means of accelerating electron beams to extremely high energies (>1 TeV) in distances less than 10 km has emphasized means of generating microwave radiation at very high-peak power. The simultaneous requirement that the beams have high luminosity implies that these radiation sources operate at high-average power. The free-electron-laser amplifier (FEL) shows particular promise to be able to meet these power requirements.

As described in ref. 1, increasing the brightness of the high-current electron beam used in FEL amplifiers can markedly increase the amplifier gain and energy conversion efficiency. To exploit this potential, the Beam Research Program at LLNL has embarked upon a dedicated campaign to explore the limits of designing and operating bright, high-current electron beam sources at repetition rates consistent with high-luminosity accelerators (>100 Hz). The "brightness campaign" has proceeded along several fronts: injector design using state-of-the-art computer codes[2], development of a test stand, HBTS[3], suitable for evaluating numerous injector configurations and choices of cathode materials, and development of diagnostics capable of measuring the brightness of kiloampere electron beams at high-current density.

For the purpose of comparing the calculated and/or measured brightness of a given injector design with the beam specifications used in the FEL design code, FRED[4], we define the normalized brightness, J_n, as π^2 times the current density in transverse phase space; i.e.,

$$J_n = \frac{\pi^2}{(\beta\gamma)^2} \frac{dI}{dV_{(4)}} \qquad (1)$$

where β, γ are the usual relativistic factors and where $dV_{(4)}$ is an elemental volume of transverse phase space. If the beams fills an ellipsoidal 4-volume uniformly, then J_n can be expressed in terms of the total beam current, I, and the edge emittance, E_n;

$$dV_{(4)} = \frac{\pi^2 E_n^2}{2} \qquad (2)$$

from whence we have

$$J_n = \frac{2I}{E_n^2} \tag{3}$$

Experimentally, it is often easier to measure the rms value of the emittance. For the case just considered,

$$E_n = 3E_{rms} \tag{4}$$

or

$$J_n = \frac{2I}{9E_{rms}} \tag{5}$$

II. Tools

A. Diagnostics

In carrying out its brightness campaign, our group has employed three types of diagnostics to measure beam emittance. These devices are a standard "pepper pot" emittance box, a scanning field-free collimator, and an ELF emittance selector[5].

The emittance box consists of a range thick slab of carbon with a set of orthogonal, thin, rectangular slits. The many beamlets formed when the electron beam impinges on the slab expand as they traverse a field-free drift space terminated by a fast phosphor. The size of the beamlets at the phosphor determines the rms angle of the electron motion. The overall size of the beam image determines the rms beam radius. The beam brightness is then given by eq.(5).

The emittance selector originally developed for the Electron Laser Facility (ELF) is a long, cylindrical collimator surrounded by solenoids. If the collimator is more than one cyclotron wavelength long, the acceptance of this transport element can be calculated analytically;

$$dV_{(4)} = \frac{\pi^2 K^2 a^4}{6} \qquad (6)$$

where

$$K = B\ (kG)/1.7\ \beta\gamma \qquad (7)$$

Here a is the collimator radius and B is the solenoidal field strength.

The final diagnostic illustrated in Fig. 1 is a field-free collimator[6] developed for use with the High Brightness Test Stand (HBTS). The collimator is formed by circular apertures in two range-thick plates. Focusing and steering coils allow us to measure the brightness distribution within the beam. In the absence of space charge effects[7], the current which passes through the second aperture is a direct measure of the beam brightness,

$$J_n = \frac{IL^2}{(\beta\gamma)^2 a^4} \qquad (8)$$

where L is the separation between the two plates. For this device to measure the emittance of the beam rather than the net convergence or divergence of the beam, the size of the beam incident on the front plate must be large enough that the thermal angles of electrons in the beam are much larger than the rate of change of the beam radius.

B. Experimental Facilities

To expedite our experimental program, we employed three different injectors and a diode test stand in our investigations. The injectors of the Advanced Test Accelerator (ATA) and the Experimental Test Accelerator were used for studying the improvements possible in medium field stress (100-300 kV/cm) configurations operating at low repetition rates (1 Hz). Our original measurements[8] with plasma cathodes operating in low stress environments were also carried out with these injectors.

For studying high-field-stress configurations and for investigating the repetion rate limitations of various designs, we constructed a dedicated facility, HBTS. The HBTS is designed to accomodate electron sources ranging from small field emission sources requiring up to 1 MV/cm extraction fields to medium area (< 100 cm^2) thermionic cathodes. Typically the anode voltage ranged from 1.0 to 1.5MV in these studies to extract up to 2kA, 50ns current pulses. The stand allows evaluation of not only the intrinsic brightness of the cathode but also the source ruggedness, usefulness for high-average power operation and lifetime. The power drives for the HBTS are MAG-1 magnetic modulators capable of more than 100 Hz continuous operation. The HBTS is housed in a radiation shielding pool designed to provide more than 10^5 attenuation. A 15 hp pump combined with a $4x10^4$ l storage tank provides for removal of the shielding in less than 15 min. The two halves of the injector are independently mounted on tracks to facilitate access to the electrodes.

Finally, a special diode stand permitted measurements of the characteristics of the flashboard plasma cathode.

C. Design Codes

Our design efforts were guided by several analytical models of injector operation. The mainstay of the design effort, however, has been a state-of-the-art computer code, DPC. DPC is a particle-in-cell code which employs the Darwin approximation to Maxwell's equations to follow the beam generation from emission at the cathode through acceleration to full energy. The Darwin approximation is the magnetostatic limit of Maxwell's equations that retains the first order relativistic correction to the particle Lagrangian. In this approximation, inductive effects are modelled without creating non-physical radiation. Consequently, we are able to model transient effects in the injector which are beyond the scope of the more typical steady-state codes such as EGUN and EBQ. Presently DPC has the capability of modelling external magnetic fields, finite electrode voltage rise-times, and "staircase" shaping of the electrodes for geometric effects.

III. Cathode Types

Our survey of cathode types has been limited to sources which can deliver up to 5kA of beam at >10 Hz with emissivity >5A/cm^2. The categories we have considered - though not necessarily tested - are listed in Table 1. The emissivity listed for BaO cathodes is typical of long-duration operation; at vacuums of 10^{-9} Torr up to 100 A/cm^2 can be generated in short pulses.

A. Flashboards

Flashboard cathodes in gridded injector configurations have been used for several years as the beam sources in both the ETA and ATA. In both cases, the measured brightness was approximately 3000 A/cm^2-rad^2, well below the maximum expected value[8] for these cathodes. Moreover, the measurements reported in ref. 8, revealed the presence of a fast component in the plasma which produced the effects of a high-plasma temperature. This and other characteristics suggested in our first measurements on the ATA were confirmed in measurements on a diode test stand. The plasma density as measured with Langmuir probes was about $10^9 cm^{-3}$ nearly the same as the extracted beam density. The presence of a plasma component with velocity >10 cm/µs was confirmed. The final difficulty with these sources is diplayed in fig. 2; the emission from the cathodes as evidenced by emitted light is grossly non-uniform. In fig. 2 the number in the photographs is the time after the flashboard igniter pulse in nanoseconds.

These investigations lead to our abandoning flashboard cathodes from further consideration; they also suggested approaches for improving beam brightness.

B. Field Emission Cathodes

Many of the short-comings of ATA and ETA injector operations with the flashboard seemed connected with the interaction of the extraction grid with the marginally dense plasma produced from the flashboard. Our first approach was to switch to a field emission cathode deployed in a medium field stress configuration (Fig. 3). Other investigators[9] had found that ordinary velvet produced a dense plasma under moderate stress conditions. Tests on the ATA have showed that by properly cancelling the B_z field at the cathode surface we are able to produce 10 kA beams with a brightness of 44000 A/cm^2-rad^2. Observation of the cathode surface after more than 10^4 pulses shows the cathode material to appear carbonized. Measurements of the conductivity of the cathode show, however, that the cathode remains a dielectric. In the configuration of Fig. 3, the beam contains a very bright central core. By filtering the beam with an emittance selector downstream of the cathode, we find that more than 3 kA of the ATA beam has a brightness exceeding $4x10^5$ A/cm^2-rad^2. Although this beam filtering approach is not consistent with high repetition rate operation, it suffices to provide a bright enough, high-current beam for optical FEL amplifier experiments on the ATA.

This type of velvet cathode has been installed on the ETA for use in the ELF experiments. The performance of the ETA injector averaged over the duration of the pulse is compared with that of the ATA injector in Fig. 4. The discrepancy in performance can be attributed to the fact that the ETA voltage pulse is gaussian in shape in contrast with the ATA pulse which has a nearly 50 ns flat-top. That neither follow a $V^{3/2}$ behavior is a consequence of the impossibility of compensating space charge forces with electrostatic focusing in a simple diode. Nonetheless, the amount of current which passed through the emittance selector was more than doubled. Moreover, the rf noise carried on the beam was reduced by more than three orders of magnitude. Also, as predicted in ref. 1, the increase in beam current and beam radius lead to a doubling of the small signal gain in the system[10].

A more complete investigation of the performance of cold, field emission cathodes was carried out in the HBTS. The general approach adopted in these studies assumed that non-uniformities in the electric field would produce an irreducible rms thermal angle of electrons in the beam. Then,

$$J_n \propto \frac{I}{\langle\theta\rangle^2 a^2} \qquad (9)$$

or

$$J_n \propto \frac{V^{3/2}}{d^2 \langle\theta\rangle^2} \propto \frac{E_0^{\,2}}{V^{1/2}} \qquad (10)$$

where E_0 is the maximum tolerable field stress and d the cathode to anode spacing. This heuristic approach argues for field stress approaching 1MV/cm in small injectors operating at the lowest possible voltages.

To keep the thermal angle to a minimum, we employed configurations with mutliple intermediate electrodes. These electrodes were arranged so as to create a Pierce column; i.e., the accelerating potential was constrained at multiple positions to satisfy the Pierce condition that the electrons feel no radial force. In such an arrangement, electrostatic forces balance the space charge forces to provide focusing for the beam. Our most successful realization of the Pierce correction was the pentode design of Fig. 5.

The small, high-stress designs are very susceptible to arcing in the presence of electron bombardment of the electrodes. Consequently, successful configurations were a fortiori consistent with operation at high repetition rate.

Several varieties of field emitters were tested in the stand: tungsten needles, ceramic-metallic matrix, polymer-metallic matrix, grooved poco graphite, reactor-grade graphite, carbon brush, and porous dielectrics - feltand velvet. The best performance was delivered by the velvet, which yielded a 2 kA beam at a brightness of $2x10^5$.

These cathode materials were also tested for their suitability for repetition-rated operation. In no case was operation above 50 Hz possible for extended periods. At rates above 50 Hz, emission soon became grossly non-uniform and finally ceased; after waiting several minutes, the cathodes again performed satisfactorily at low rates. The observed behavior is consistent with the hypothesis that the beam is extracted from a dense plasma generated in desorbed gas by local arcing along the cathode surface. At high repetition rates, the gas reservoir is exhausted faster than it can be replenished in the vacuum environment (10^{-6} Torr). The superior characteristics of the velvet are probably related to its having the largest surface area and, hence, the largest gas reservoir.

For our most recent set of studies, the HBTS was modified to allow operation of thermionic cathodes which require vacuums better than 10^{-7} Torr for extended operation. Rather than the planar cathodes used in the field emission studies, we have used a concave dispenser cathode (produced for SLAC klystrons) which produces a converging beam. Guided by detailed calculations with the DPC injector-design code, we have produced triode designs such as that in Fig. 6 with brightnesses approaching 10^6 for currents of 1 kA. These designs are far from optimized as the cathode size and shape were determined by ready availability from the vendor not by design considerations. For example, higher currents can be obtained by scaling the cathode size from 3.5" to 5.0".

We have tested these dispenser cathodes in HBTS at repetition rates exceeding 900 Hz without discernible degradation in their performance. With the cathodes operating at nearly 1300^0 C, lifetimes of 40 hours are typical. Better vacuum conditions may improve this performance.

Tests of BaO cathodes in high vacuum conditions did show emissivities in excess of 50 A/cm^2. The brightness of the beam produced from these cathodes was lower than that from similar dispenser sources. The culprit in degrading performance seems to be the relatively rough surface of the oxide when it is applied by standard techniques.

IV. Conclusions

Fig. 7 illustrates our progress in the design of multi-kiloampere injectors during the past year. The performance of these injectors easily exceeds that needed for FEL amplifiers of microwave radiation. Indeed, it is now sufficiently good to allow high gain, high extraction experiments in the near IR. As the observed brightnesses are at least an order-of-magnitude less than the intrinsic cathode brightness as tabulated in Table 1, we expect further improvements in injector performance during the next year.

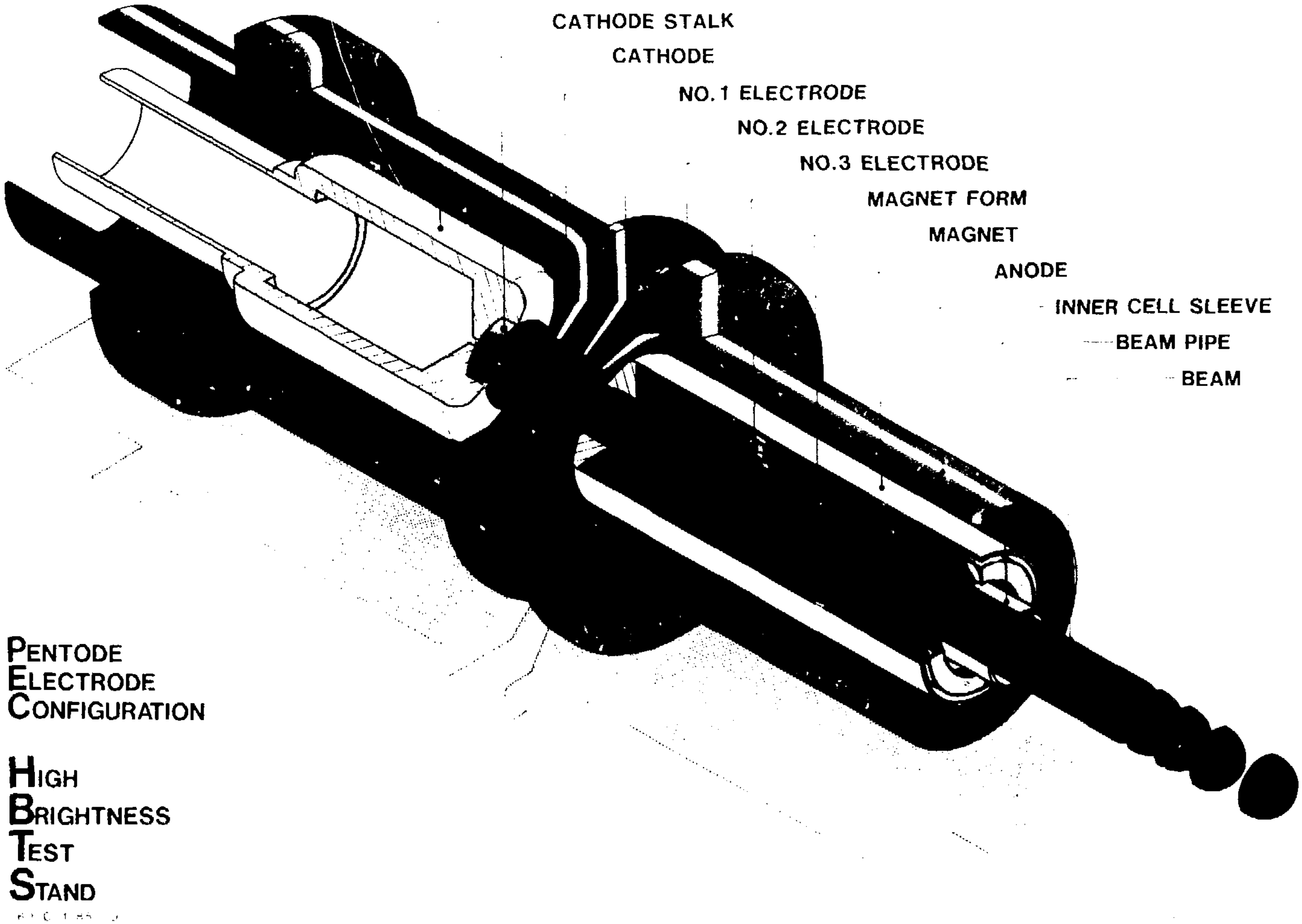
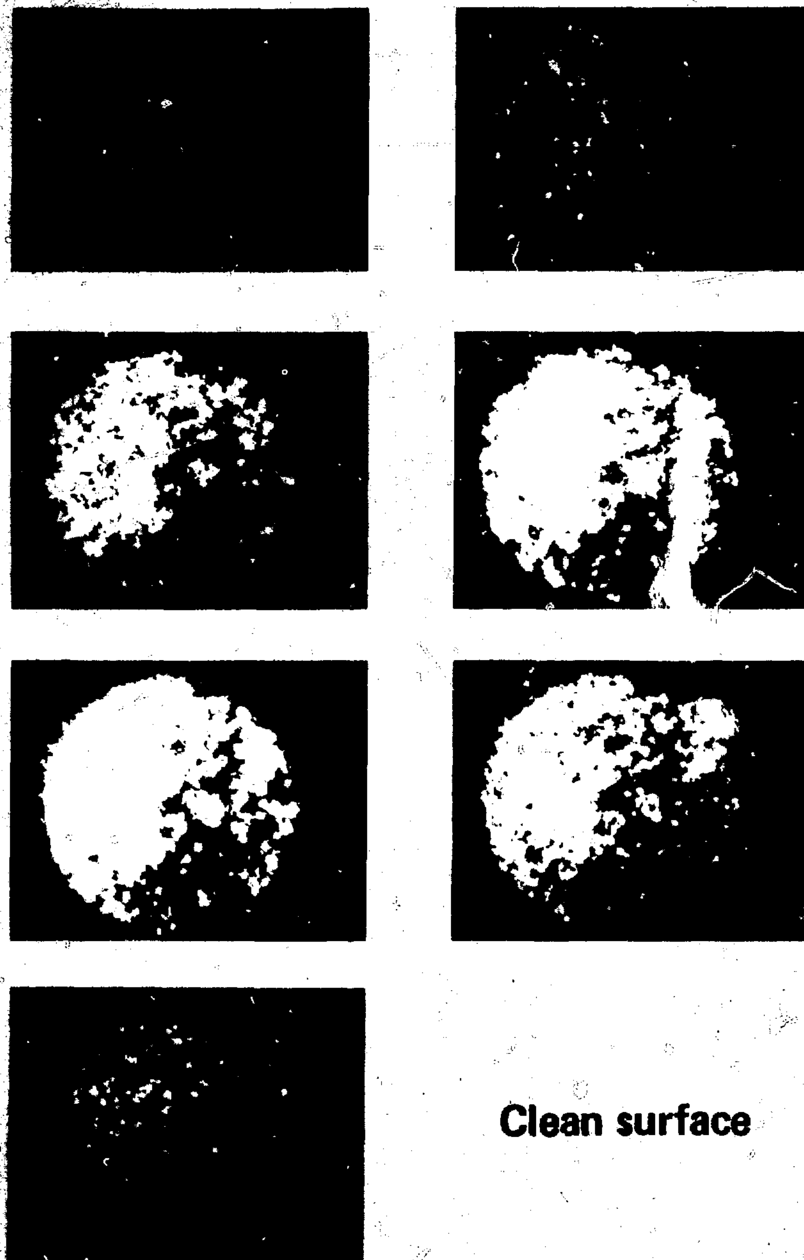

CATHODE STALK
CATHODE
NO. 1 ELECTRODE
NO.2 ELECTRODE
NO.3 ELECTRODE
MAGNET FORM
MAGNET
ANODE
INNER CELL SLEEVE
BEAM PIPE
BEAM
PENTODE
ELECTRODE
CONFIGURATION
HIGH
BRIGHTNESS
TEST
STAND

Figure 1

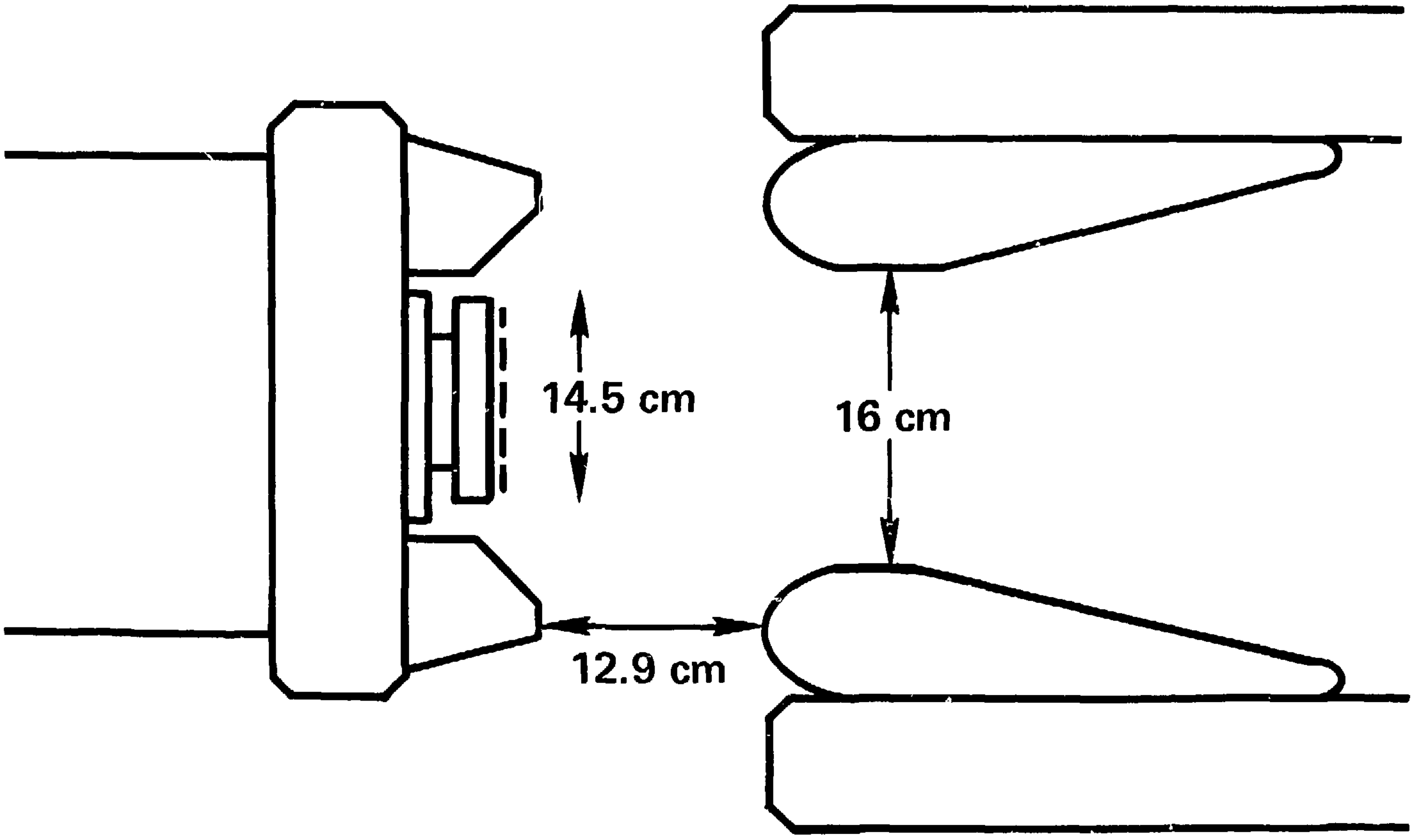
Flashboard turnon



Clean surface

Figure 2

Electrode geometry for ATA experiments



50 K-1085-1

Figure 3

Comparison of velvet cathode performance in ATA and ETA

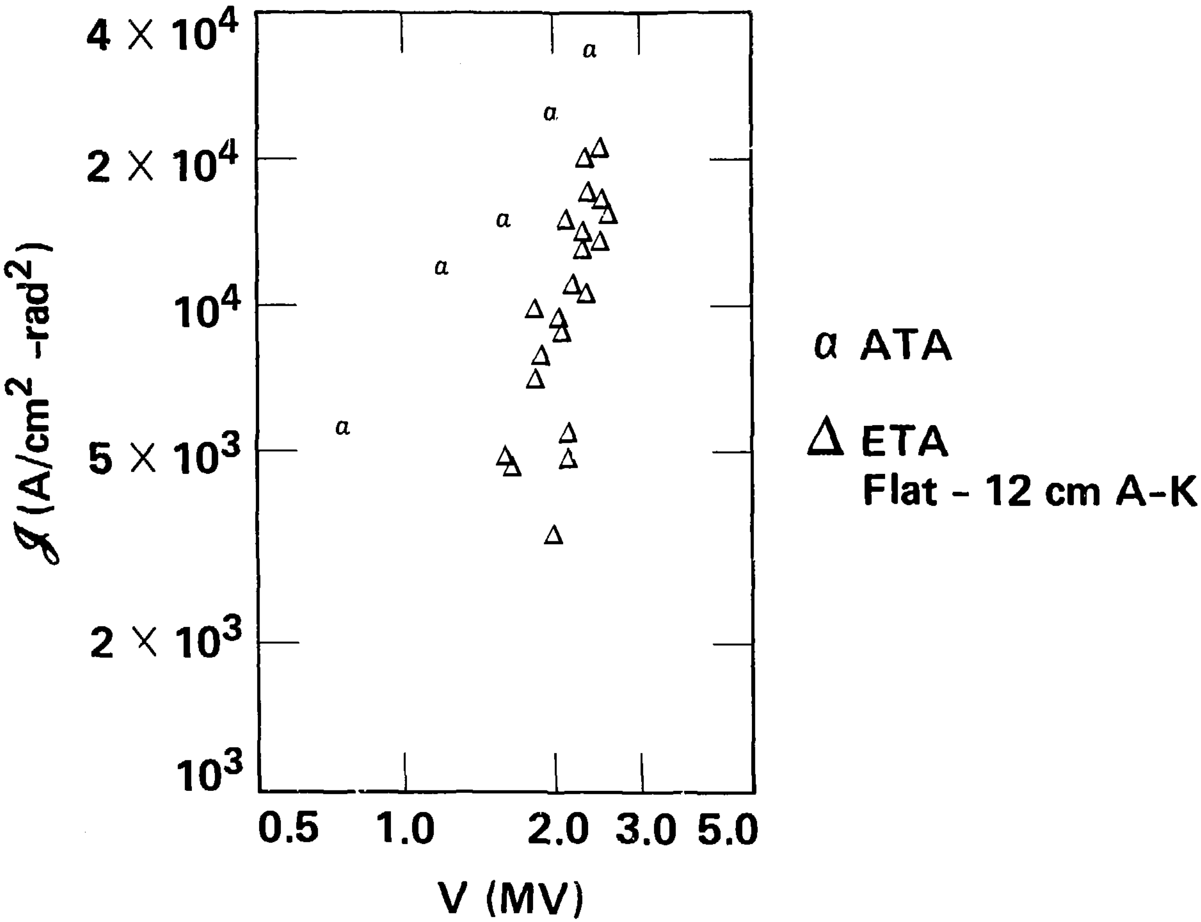


Figure 4

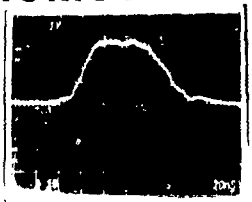
HBTS

High Brightness Test Stand

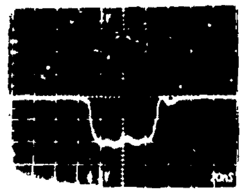
accelerator output waveforms

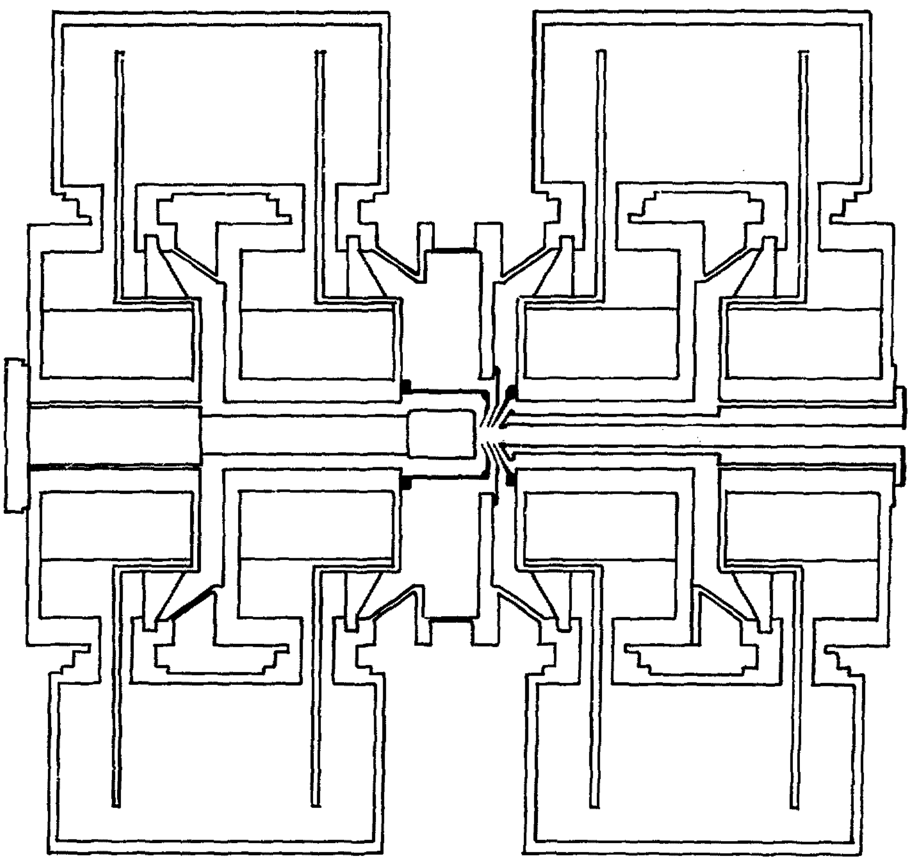
all pulses 20ns/div.

.5Mev/div.



1ka/div.



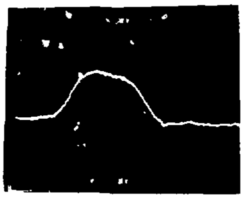


80-C-01/85-82

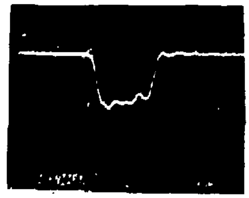
Figure 5

HBTS

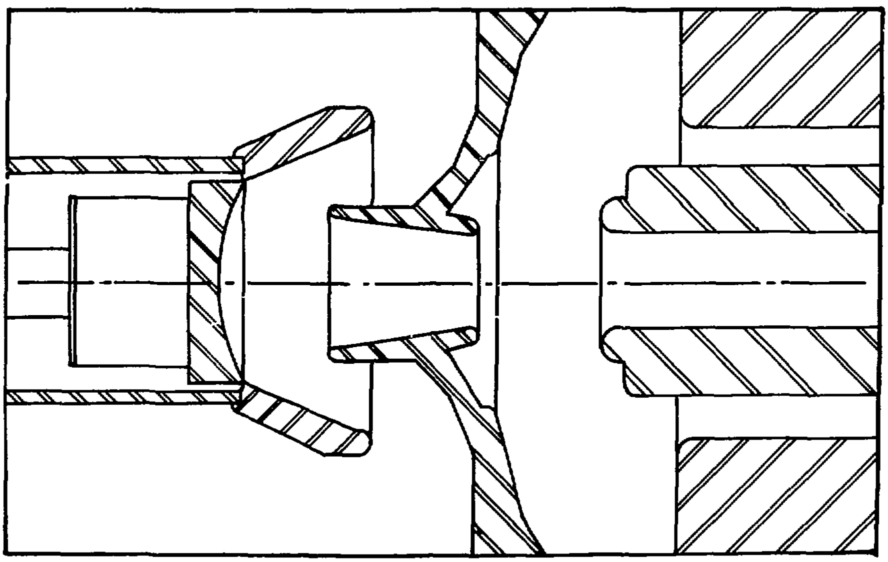
HIGH BRIGHTNESS TEST STAND



INJECTOR VOLTAGE
.5 MEV/d, 20 ns/d



OUTPUT CURRENT
500 AMPS/d, 20 ns/d



PRELIMINARY RESULTS:

3.5" DIA. DISPENSOR CATHODE

60-C-06/85-119

Figure 6

Progress in building high brightness beams during past year

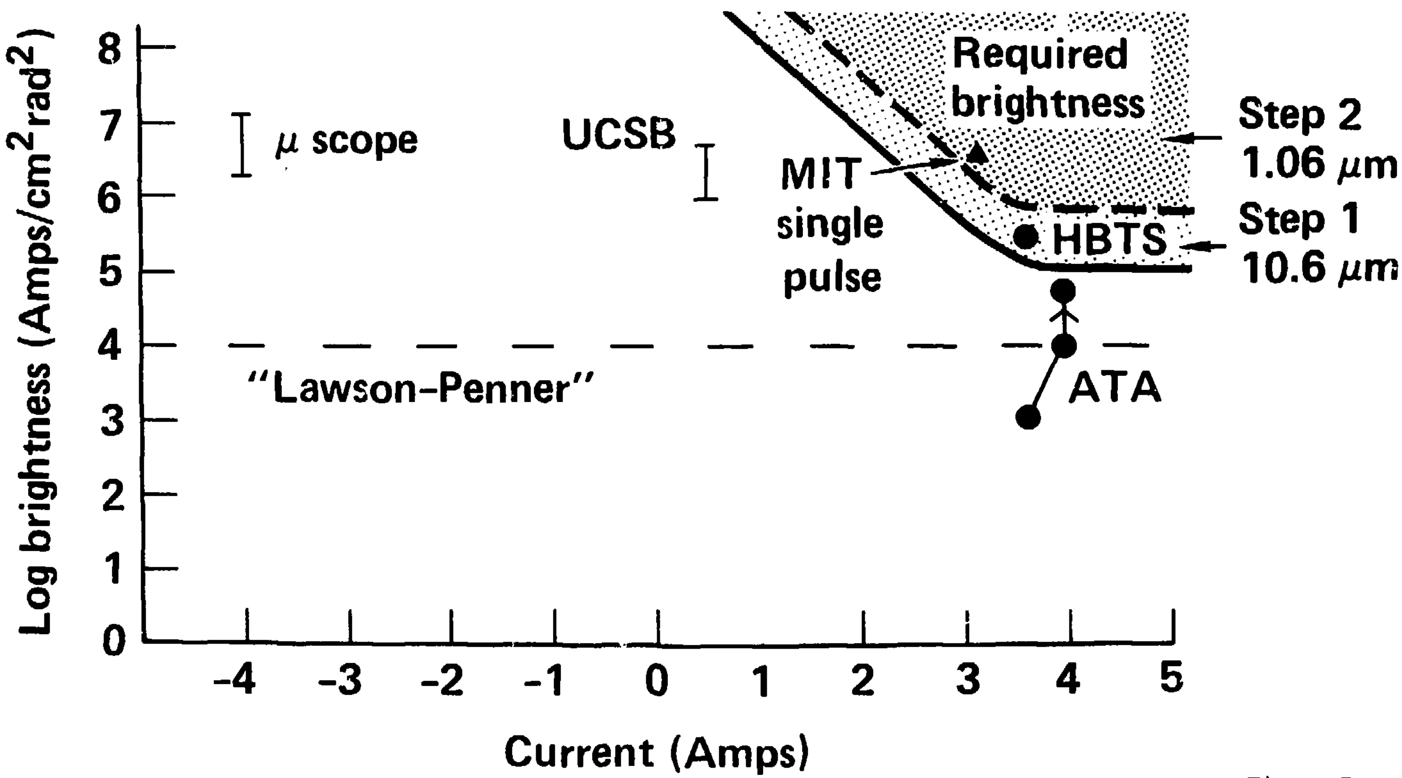


Figure 7

Cathode type		T_{eff} (eV)	J (A/cm^2)	B (A/rad^2 - cm^2)	Area (cm^2)	Vacuum (Torr)	Lifetime (hr)	Comments
Thermionic	BaO	~ 0.1	~ 5	$\lesssim 10^7$	~ 1000	10^{-7}	$< 10^3$	Moderately susceptible to poisoning
	LaB_6	~ 0.2	$\lesssim 30$	$< 3 \times 10^7$	~ 200	10^{-7}	$< 10^3$	High temperature
Dispenser	Random porosity	~ 0.2	< 30	$< 3 \times 10^7$	~ 200	$< 5 \times 10^{-7}$	10^3	Uniformity depends on porosity
	Controlled porosity	~ 0.2	$\lesssim 40$	$\lesssim 5 \times 10^7$	~ 200			Uniform, rugged
Laser heated		$\gtrsim 0.2$	$\sim 10^3$	$\sim 3 \times 10^8$	~ 5	10^{-8}	10^3	Easily poisoned, not mature
Photo-emissive		< 0.1	—	—	—	$\sim 10^{-11}$	$\sim 10^3$	
Field emission	Controlled	1	600	2×10^8	~ 10	10^{-6}	$> 10^3$	Experimental, rugged
	Uncontrolled	1	100-1000	3×10^7	~ 5 - 50			Rugged
Flashboard		~ 70	~ 30	$\sim 10^5$	~ 200	10^{-6}	$> 10^4$	Multi-component beam

Table 1

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