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ABSTRACT

Several techniques using small radius collimating pipes with and without axial magnetic fields to measure the brightness of an extracted 1 - 2 kA, 1 - 1.5 MeV electron beam will be described. The output beam of the High Brightness Test Stand as measured by one of these techniques is in excess of 2×10^5 amp/cm^2/steradian.

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INTRODUCTION

Electron beams of very high brightness are required for free electron laser applications. A special High Brightness Test Stand (HBTS) has been constructed to study different cathode materials and electrode configurations in an attempt to develop a high brightness injector for the Advanced Test Accelerator (ATA) at the Lawrence Livermore National Laboratory.

DEFINITIONS

The definition of the normalized brightness J_n, used in this paper is given in Eq. (1) and is equivalent to π^2 multiplied by the density in four dimensional transverse trace space:

$$J_n = \frac{\pi^2}{(\beta\gamma)^2} \frac{d^4I}{dV_4} \quad . \tag{1}$$

Here dV_4 is the differential volume element in the four-dimensional transverse trace space (x,x',y,y') [1] where a prime denotes differentiation with respect to z, the coordinate along the beams' direction of propagation, and d^4I is the element of current enclosed in that element of four volume. $\beta\gamma = \sqrt{\gamma^2 - 1}$ where γ is the usual Lorentz factor.

For example, if the distribution in trace space is ellipsoidal with a boundary satisfying the equation $1 - (x^2 + y^2)/b^2 - (x'^2 + y'^2)/v^2 = 0$, then it is easily shown that $V_4 = \pi^2E^2/2$ where E the edge emittance is = bv. If the trace space density is uniform then the normalized beam brightness in our definition is $J_n = 2I/E_n^2$ where I is the total beam current and $E_n = \beta\gamma E$, the normalized edge emittance.

EXPERIMENTAL DESCRIPTION

A schematic of the HBTS [2] is shown in Fig. 1. The typical anode voltage for the test stand varies from 1.0 to 1.5 MV and the extracted beam current ranges from a few hundred amperes up to over 1 kA in a 50 nsec pulse at a repetition rate of approximately 1 Hertz.

For the measurements described here the gun was configured as a pentode [3] as shown in Fig. 2. The cathode consisted of ordinary velvet cloth which produced electrons via field emission. Only electrostatic focusing was employed in the anode-cathode gap although solenoidal focusing was used downstream of the anode.

Two widely separated small diameter apertures were used to diagnose the brightness of the extracted beam. Wall current monitors were positioned to measure the beam current exiting the gun as well as the current surviving downstream of each of the two apertures. A diagram of the arrangement is shown in Fig. 3.

MEASUREMENT THEORY

An explanation of the brightness measuring method follows. Consider a magnetic field free pipe of radius R_p and length L. If the beam entering

It is desirable that the typical thermal angle of the beam be larger than that of the beam envelope so that the collimating system measures brightness and not the effects of beam convergence or divergence. Thus, we want $E/R_b >> R'$.

Now the maximum angle passed by the collimator is $2R_p/L$ and this angle must be smaller than the typical thermal angle in the beam so that the system will collimate in x' - y' space. Thus, $2R_p/L < E/R_b$. Note that if R_b becomes too large the pipe will collimate only in x - y space and hence will simply measure current density. Thus, the radius of the incident beam must satisfy the relation

$$R_p < R_b < \frac{EL}{2R_p} \tag{6}$$

and

$$R' << E/R_b \quad . \tag{7}$$

These relations may be written in terms of beam brightness and current through use of the approximate relation $J_n = 2I/E_n^2$ to give

$$R_p < R_b < \sqrt{(1/2J_n)}\ \frac{L}{\beta\gamma R_p} \tag{8}$$

and

$$R' << \sqrt{(2I/J_n)}/(\beta\gamma R_b) \quad . \tag{9}$$

In practice, a gated television camera views the entrance aperture to judge spot size while the wall current monitor downstream of the first aperture allows a qualitative check on the size of the beam. A short steering magnet is placed upstream of both apertures to compensate for any positioning or alignment errors of the system and to permit sampling of different portions of the beam (in x - y space) at the entrance to the first aperture.

The collimating system used in the HBTS consisted of plates with 3/16 in. diameter holes placed 15 inches apart. The anode voltage was nominally 1.25 MV and the gun had an output current of nearly 1.2 kA. The waveforms of the incident beam current and voltage and the currents through both apertures are shown in Fig. 4. The current transmitted through the second aperture was 5 amperes yielding a normalized brightness of 2 x 10^5 amp/cm^2/steradian.

MAGNETIC COLLIMATOR

Another type of collimator employing a pipe emersed in a uniform solenoidal field may also be used to determine brightness. [5] In this system the particle orbits are assumed to be pure cyclotron orbits and the allowed volume [4] in trace space is $V_c = \pi^2 k_c{}^2 R_p{}^4/6$. The current passed by this system will yield the brightness as

$$J_n = \frac{6I}{k_o{}^2 R_p{}^4} \quad , \tag{10}$$

where $k_o = eB/mc^2$. Note that with this type of collimator the calculated brightness is independent of the beam energy.

As with the field free collimator this system must also satisfy certain conditions in order to produce a valid measurement. The space charge requirement is the same as that given in Eq. (5). The condition on the angle of the beam envelope given by Eqs. (7) and (9) is also valid for the magnetic collimator. The maximum angle accepted by the magnetic collimator is $k_c R_p$ so that Eq. (6) becomes

$$R_p < R_b < \frac{E}{k_c R_p} \quad . \tag{11}$$

Another requirement for the magnetic collimator is that it be at least one cyclotron wavelength long so that all particle orbits may be fully "filtered." The magnetic collimator has been used on the Experimental Test Accelerator but has not yet been used on the HBTS.

CONCLUSIONS

In summary, two brightness measuring diagnostics have been described along with the required beam conditions necessary to insure their proper operation. The field free collimator was used to diagnose a normalized beam brightness of 2×10^5 on the HBTS.

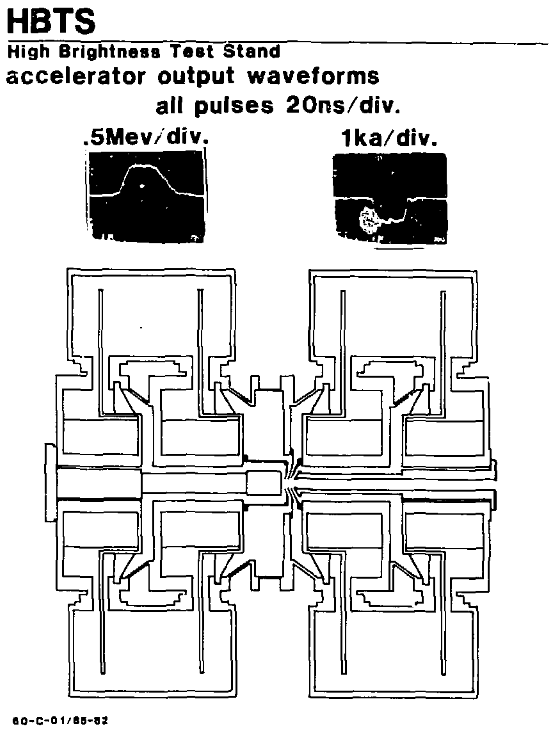

Fig. 1. Schematic of the High Brightness Test Stand showing the four induction accelerator modules that supply the power to four electrodes of the pentode structure. The gun is electrostatically focused and uses a field emission cathode (velvet cloth).

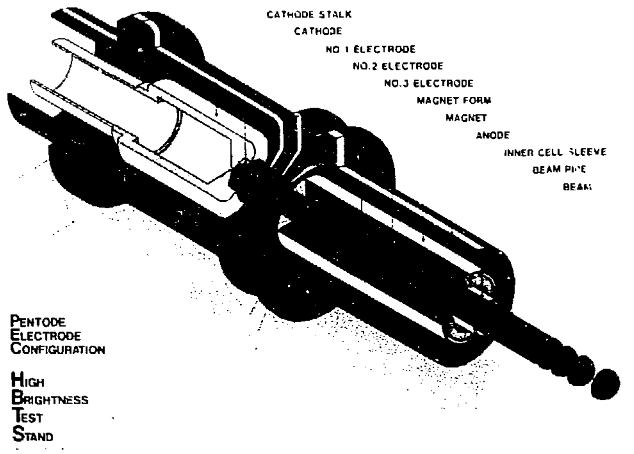

Fig. 2. Diagram of the pentode gun structure showing the cathode stalk, three intermediate electrodes and the anode. The voltage differences between all electrodes are equal in this configuration. Also shown is a solenoid used to focus the beam downstream of the anode hole.

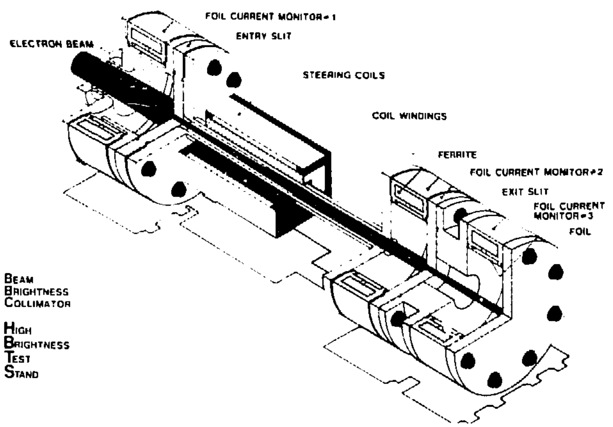

Fig. 3. Schematic of the field free collimator showing the two apertures with three wall current monitors which measure incident beam currents on the first and second apertures and current which emerges from the second aperture. Also shown is the inter-aperture steering coil. An additional steering coil, not shown, is upstream of the first aperture.

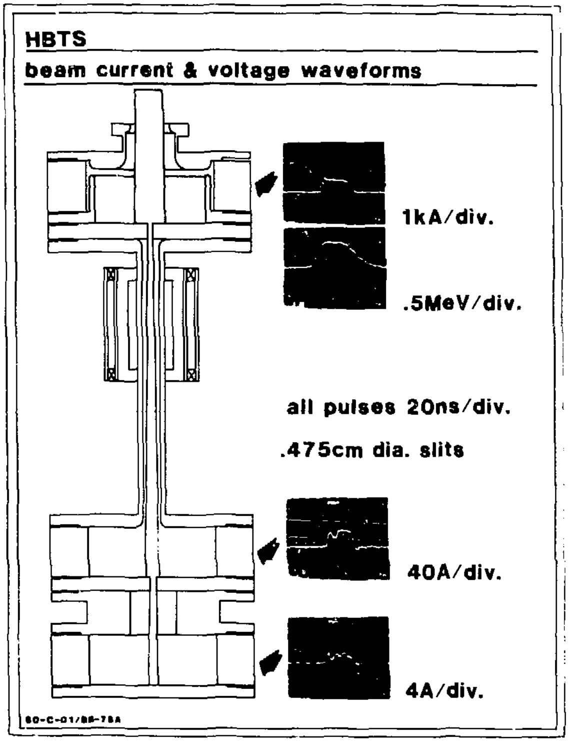

Fig. 4. Another schematic of the field free collimator system showing waveforms of the incident current and voltage as well as the current just upstream and downstream of the second aperture for the measurement described in the text.

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