TEMPORAL EVOLUTION OF BEAM EMITTANCE AND CATHODE PLASMA UNIFORMITY FROM A FIELD EMISSION DIODE

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Abstract — *The temporal evolution of the beam emittance from a multi-electrode field emission electron gun (1.3 MV, 0.5 kA, 30 ns) has been measured with nanosecond time resolution, using a novel Čerenkov-electrooptic diagnostic. In addition, we report experimental studies of the cathode plasma uniformity from a field emission diode (250 kV, 2 kA, 100 ns) The observations from both systems show that diodes provided with velvet-backed cathodes behave differently, and are superior to, the more conventional graphite cathodes.*

1. Introduction

Intense relativistic electron beams find application in many diverse areas including x-ray production [1], excimer laser pumping [2], material response studies [3], generation of coherent electromagnetic radiation [4], and inertial confinement fusion [5]. The generation of such beams entails use of electron guns equipped with field emission (explosive emission) cathodes which are capable of providing current densities ranging from hundreds to thousands of amperes per square centimeter of surface area.

In many applications [4,5] high beam quality as exemplified by a low beam emittance ϵ_n, and a high beam brightness B_n, is of paramount importance. In this paper, we report what we believe is the first detailed study of the temporal evolution of these quantities. Measurements, obtained using a novel Čerenkov-electrooptic shutter, show that guns provided with velvet-backed [6] cathodes behave differently, and are superior to the more conventional graphite cathodes. Such time resolved measurements may help towards our understanding of the complex cathode phenomena studied by many workers during the past two decades, and ably summarized by Hinshelwood [7].

In addition, we report experimental studies of the cathode plasma uniformity in a field emission diode, for two different cathode materials. These results confirm the superiority of velvet-backed cathodes : better uniformity of the cathode plasma, yielding a lower beam emittance and a higher beam brightness than the more conventional graphite cathodes.

2. Time-resolved emittance measurements

The overall experimental setup is shown in Fig.1. A Physics International Pulserad 110A electron accelerator is used to energize a five stage multi-electrode field emission gun [8]. The resulting paraxial electron beam (1.3 MV,0.5 kA,30 ns), of radius $r_b \simeq 2.5$ cm, impinges on a 1 mm thick tantalum disc. A small pinhole aperture 0.5 mm in diameter allows a low current ($\simeq 0.2$ A) beamlet to propagate in a 35 cm field free region before it strikes a 3 mm thick Plexiglas plate used as a Čerenkov radiator. The Čerenkov radiation is then sampled by an electrooptic crystal gated for a few hundred picoseconds and recorded on regular 35 mm film after amplification by a pulsed microchannel image intensifier [9].

The emittance is determined by observing the photographed spot sizes, which is directly proportional to the beamlet microscopic spread angle $\delta\theta$ (see Fig.1), at a given time in the voltage pulse. Different photographs, taken at different times, then allow one to observe the temporal evolution of the beam emittance. A variable delay allows the sampling of the Čerenkov light at different times in the voltage pulse. The relative timing of the optical gate in the electron beam pulse is recorded on each shot by a dual beam oscilloscope. The temporal accuracy of these measurements is approximately 1 ns. Neutral density light attenuators placed in front of the electrooptic shutter are used to supply a known linear intensity scale for the optical system and to insure that the film emulsion operates in the "gray zone". The optical gate used for the experiments described here is 1.8 ns wide. The insert to Fig.1 illustrates the photographed spot sizes at four consecutive times during the voltage pulse, for the graphite and velvet cathodes, respectively. We note that whereas the spot sizes for the velvet cathode remain virtually unchanged with time, those for graphite decrease substantially as time increases.

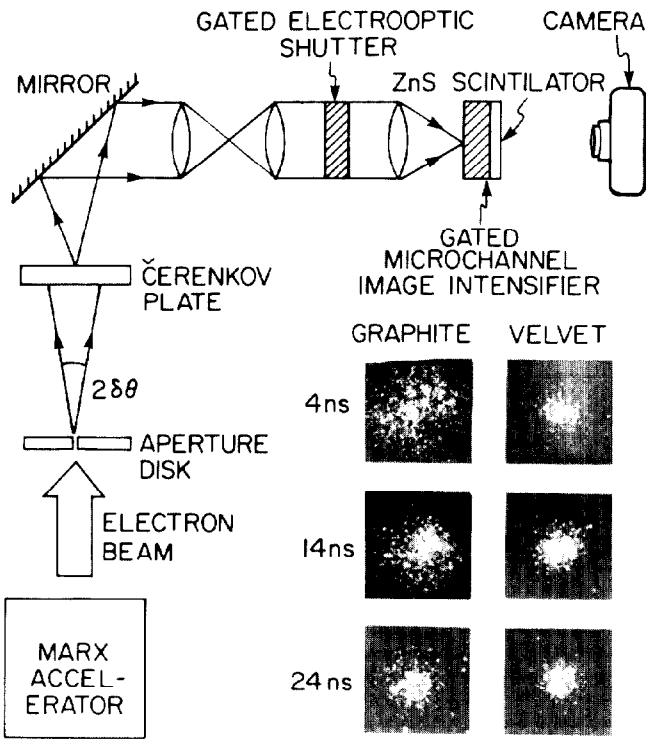

Fig.1. *Overall experimental setup. Insert : photographs of beamlet sizes at different times during the voltage pulse.*

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The unnormalized beam emmitance ϵ is given by $\epsilon \simeq r_b(v_\perp/v_\parallel) \simeq r_b\delta\theta$, where $v_\perp$ and $v_\parallel$ are the transverse and axial electron velocities, respectively ; and r_b is the effective beam radius. Both $\delta\theta$ and r_b are functions of time t during the voltage pulse, although the variations of r_b are relatively small (for velvet r_b lies in the range 2.6-2.8 cm, for graphite in the range 2.1-2.5 cm). Thus ϵ can be obtained directly from a knowledge of the electron beam radius r_b and the measured beamlet spread angle $\delta\theta$. For a more accurate description of the emittance calculation, we report the reader to references [8] and [10].

Figure 2 illustrates the temporal behavior of the beamlet microscopic spread angle $\delta\theta$ as a function of time for a reactor graphite cathode and a velvet-backed cathode. Except for the change of emitting materials, the experimental conditions for graphite and velvet are the same. The cathode plate consists of a large (5 cm radius) spin-formed aluminum disk with a cylindrical hole in the middle which allows the insertion of a 1 cm radius plug of emitting material. The remainder of the cathode surface is covered with a hard aluminum oxide (anodized) coating to minimize undesired emission [8]. An electric field $E = 210$ kV/cm is applied between the cathode and the first (extraction) anode (anode-cathode gap $d = 1.55$ cm). Four additional electrodes then accelerate the beam to its final energy. At the gun exit, the electron beam radius has expanded to ~ 2.5 cm. Henceforth we shall discuss the quantity $\gamma\beta\delta\theta$ rather than $\delta\theta$ itself. The reason is that, barring emittance growth and large changes of r_b within the gun and transport line, $\gamma\beta\delta\theta$ is an invariant ; this is consistent with the notion that the normalized emittance is conserved during the acceleration process.

Figure 2 shows that graphite and velvet behave in markedly different ways. In the case of the velvet-backed cathode it is readily calculated from the current-voltage characteristics that space-charge limited (Child-Langmuir) flow is attained rapidly, in less than ~ 5 ns, at which time $\gamma\beta\delta\theta \simeq 20$ mrad. Substracting $[\gamma\beta\delta\theta]_{\rm mesh}$, leaves $\gamma\beta\delta\theta$ of ~ 14 mrad believed to be caused at the cathode. Here, $[\gamma\beta\delta\theta]_{\rm mesh} \simeq 6$ mrad is an irreducible normalized spread angle that results from the lensing effect [11] at the extraction and final anodes which consist of transmitting tungsten meshes.

Thermal effects are found to be too small to explain the observed emittance. We speculate that surface roughness of the plasma-coated cathode may well be an important contributor. Surface roughness, recently studied theoretically by Lau [12] primarily in regard to thermionic cathodes, causes field lines to diverge from the protusions, thereby giving electrons a component of velocity parallel to the cathode plane. Applying Lau's calculations to field emission cathodes shows that for protusions of height h (and width $\lesssim h$)

$$\gamma\beta\delta\theta \simeq 0.1(Jh^2)^{1/3} \quad \text{(rad)}, \tag{1}$$

where J is the space-charge limited current density in the anode-cathode gap. Taking $h = 30\,\mu$m which is typical [7] of surface roughness, and using the measured current density $J = 3 \times 10^6$ A/m^2, yields $\gamma\beta\delta\theta \simeq 14$ mrad, in agreement with observations. It is also noteworthy that on the basis of equation (1), the beam brightness scales with current density as $B_n \sim J^{1/3}$ which is in rough conformity with earlier time-integrated brightness measurements [13].

The picture is quite different in the case of the graphite cathode. The turn-on time is quite long, and the current takes some 20 ns to reach its maximum value. The observed length of turn-on time is in good agreement with earlier observations [14] which show that this time is a strong function of the applied electric field and cathode material. Calculations made from the voltage-current characteristics also indicate that space-charge limited flow is not attained at any time during the voltage pulse. From Fig.2 we see that unlike the case of velvet, $\delta\theta$ is now a strong function of time and $\gamma\beta\delta\theta$ varies between ~ 33 mrad at early times and ~ 16 mrad at late times. Substracting the contribution to $\gamma\beta\delta\theta$ associated with lensing (see above), leaves a range of $\gamma\beta\delta\theta$ from ~ 27 mrad at early times to ~ 10 mrad at late times attributable to cathode related effects.

The poor performance of graphite is believed to be the result of patchy, incomplete [7,15] turn-on of the cathode at the relatively low applied electric field of 210 kV/cm. This conforms with earlier time-integrated measurements [8,13] which show that electric fields in excess of ~ 400 kV/cm are needed for complete turn-on of graphite cathodes. Several experiments have shown that the overall beam evolves from microscopic emission sites [16,17] located on the cathode. Electrons stream from these sites in the form of secondary conical beamlets [15] whose number density N has been estimated [7] to be $\sim 10^2 - 10^4$ cm^{-2}.

A portion of the net $\gamma\beta\delta\theta$ that needs to be accounted for (10–27 mrad) in graphite is believed to be due to space-charge repulsion within the individual beamlets. Calculating the transverse motion of an electron in the combined radial self-electric field and the azimuthal self-magnetic field, one finds that

$$\gamma\beta\delta\theta \simeq \alpha\sqrt{I_b/I_A} \quad \text{(rad)}. \tag{2}$$

Here $I_b = J/N$ is the beamlet current and $I_A = (4\pi\epsilon_0 m_0 c^3/e)\gamma\beta = 17\gamma\beta$ (kA) is the Alfven current ; $\alpha \simeq 2\sqrt{\ln(a/a_0)}$ is a dimensionless constant with a_0 and a as the initial and final beamlet radii. Over the cathode-anode gap distance, the beamlet radii increase by $\sim 30\,\%$, with the result that $\alpha \simeq 1$. Taking $I_b \simeq 1$ A yields $\gamma\beta\delta\theta \simeq 4$ mrad. Surface roughness may well account for the remaining spread in $\delta\theta$.

The observed decrease of $\gamma\beta\delta\theta$ with time by a factor of ~ 3 is not fully understood. One may conjecture [7] interactions between beamlets. However, calculations show that purely quasi-electrostatic forces between beamlets have no effect on the spread angle $\delta\theta$. An alternate form of interaction [18] comes about as a result of the fact that the space-charge field of an existing beamlet shields the neighboring cathode surface from the applied field. This reduces the likelihood of further beamlet formation via the explosive field-emission process. Details as to how this may affect $\delta\theta$ are not clear.

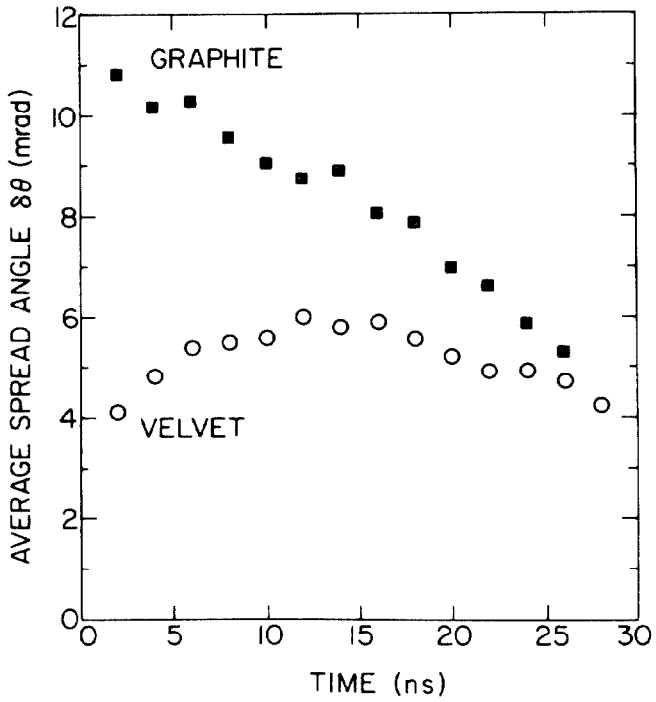

Fig.2. *Averaged beamlet spread angle $\delta\theta$ as a function of time.*

3. Cathode plasma uniformity

Emission uniformity measurements carried out on the Science Research Laboratory Cathode Test Stand indicate that the turn-on characteristics of velvet cathodes are dramatically different from those of graphite cathodes. In these measurements a high voltage pulse of 80 ns duration was applied to a diode with a variable anode-cathode gap consisting of a planar foil and a 20 cm diameter cathode. The cathode surface was shaped into a Chang profile in order to insure electric field uniformity and reduce edge emission. The anode comprised a range thick (4 mil) Al foil with a thin coating of P11 phosphor on the reverse side. The phosphor was excited by beam electrons as they stopped in the foil and was photographed with an open shutter camera to provide a time integrated record of beam uniformity at the anode.

Figure 3 shows the beam image on the phosphor screen for a graphite cathode at two values of voltage and anode-cathode gap. This figure clearly illustrates the "spotty" nature of the electron emission from the graphite cathode and the strong dependence of uniformity on diode parameters. Emission uniformity from a velvet covered cathode is shown in Fig.4. In this case there is evidence of electron emission over the whole surface and the scale size for current density variations is much smaller than for the graphite cathode. This behavior is evident over a wide range of diode parameters for the velvet cathode. Experiments are underway to determine the dependence of uniformity on diode voltage, current and gap ; to measure the temporal evolution of cathode emission uniformity during the diode pulse and to investigate the correlation between beam uniformity and beam emittance.

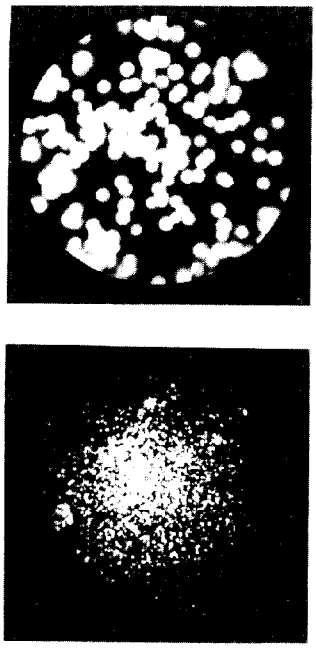

Fig.3. *Beam image for a graphite cathode with* $E = 168$ *kV/cm,* $d = 1.52$ *cm (top) and* $E = 182$ *kV/cm,* $d = 0.76$ *cm (bottom).*

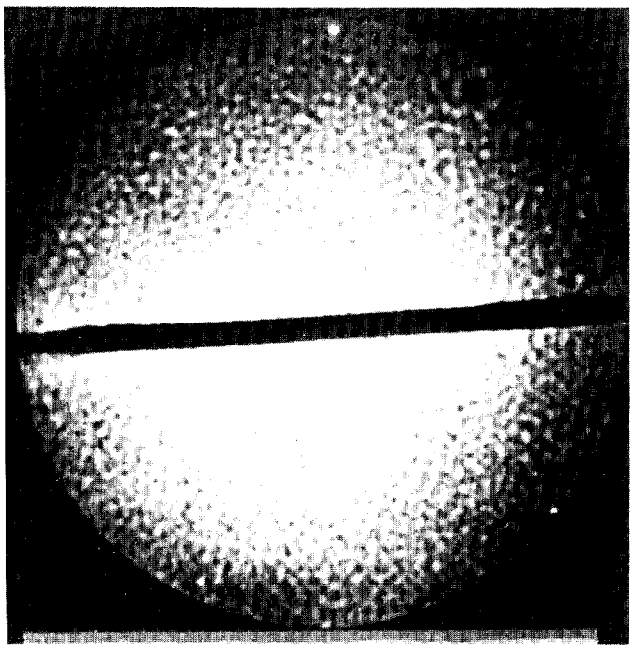

Fig.4. *Beam image for a velvet cathode with* $E = 131$ *kV/cm and* $d = 0.56$ *cm. The black stripe is the shadow of a 6 mm wide lead strip on the beam side of the anode foil used for scaling purposes.*

Acknowledgements

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