Generation and Diagnosis of Terawatt/Centimeter^2 Electron Beams*

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Relativistic electron-beam current densities as high as 2.7 MA/cm^2 and power fluxes of 1.87 TW/cm^2 have been generated and diagnosed on a pulsed electron-beam accelerator. The beam was field emitted from a 2-mm-diam glass cathode toward a transmission anode. Current densities were inferred by passing the beam through apertures as small as 1 mm and measuring the transmitted current with a Faraday cup.

There has recently been considerable interest in the use of intensely focused electron production. Morrow *et al.* have implied generation of relativistic electron beams in excess of 10^7 A/cm^2 based on target damage,[1,2] although they made no direct measurement of current density. Kerns, Rogers, and Clark[3] and McCann, Rogers, and Payton[4] have used these beams to generate neutron bursts of 5×10^7 neutrons. Neutron yields exceeding 10^{10}/burst were reported by Freeman *et al.*[5] Condit and Pellinen have made voltage and current studies of such electron beams. Their preliminary current density studies using x-ray photography implied lower limits on time-average current densities of 1.66×10^5 A/cm^2.[6]

All of the experiments use a glass-rod cathode that has a gap of several millimeters between it and an anode. A voltage pulse is applied to the cathode from a coaxial pulse-forming network typically charged to 1.5 MV or higher. The rod appears to break down or track along the surface, generating a highly conductive plasma from which electrons are emitted into the gap and accelerated through the gap potential difference.[6,7] Large magnetic fields induced by the beam current tend to focus the beam quite sharply. The beam has sufficient intensity to vaporize easily any known material.

In an effort to determine exactly how sharply the beam is focused, we have used an apertured Faraday cup to measure instantaneous current densities as high as 2.71 MA/cm and power fluxes as high as 1.87 TW/cm^2. Apertures were drilled in tantalum disks, which, though vaporized, maintained their integrity on the time scales of interest. This was suspected from image-converter photographs and ensured experimentally by directing the beam into undrilled disks and measuring zero transmitted current. Also, when damage patterns indicated the beam missed the aperture, which happened as much as two shots out of three for the smallest apertures, little or no current was recorded with the Faraday cup.

The experimental configuration, shown in Fig. 1, consisted of a 2-mm-diam glass cathode emitting toward a planar anode located 2.25 mm away. Current density is inferred by placing the totally absorbing 0.405-mm-thick tantalum disk with aperatures of various sizes behind the anode foil and then measuring the current with a Faraday cup.[8,9] The cup has a second foil about $\frac{1}{2}$ mm

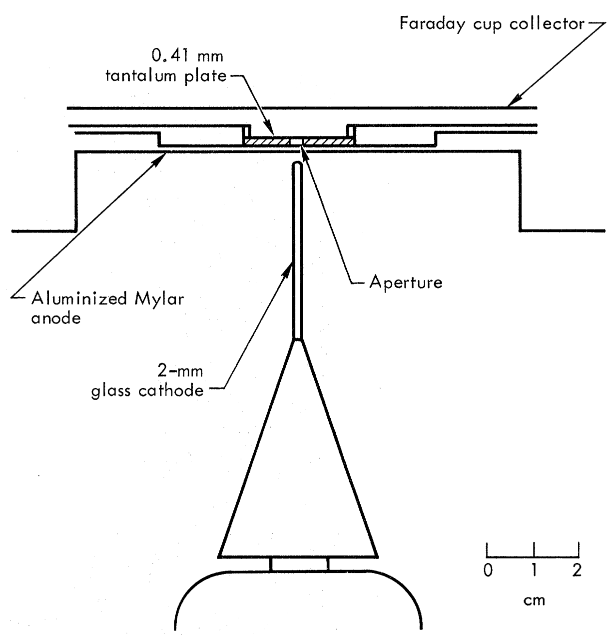
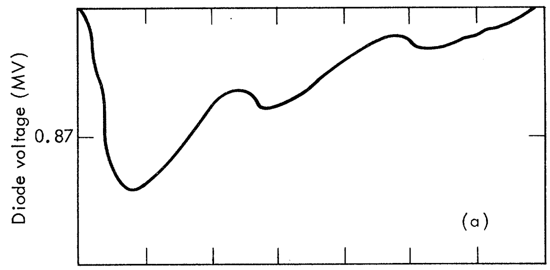


FIG. 1. Experimental configuration of diode and apertured Faraday-cup collector.



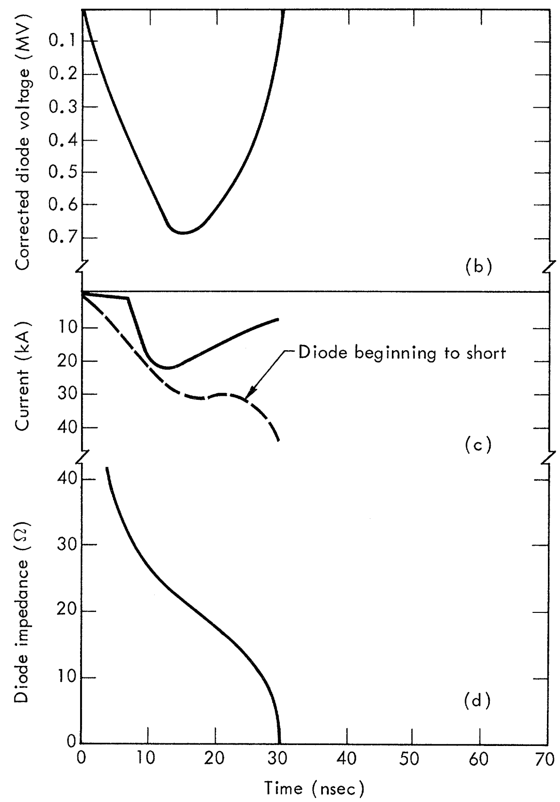


FIG. 2. Beam diagnostic wave forms from pulse 22 710; 1-mm aperture on Faraday cup. (a) Diode voltage; (b) diode voltage corrected for induced voltage $(V - K\,di/dt)$; (c) superposition of diode and apertured Faraday-cup current wave form (solid line, F_c current; dashed line, diode current); and (d) diode impedance $[(V - K\,di/dt)/I_{\rm diode}]$.

from the collecting surface to stop secondaries and low-energy electrons. The beam is transported approximately 6 mm in a space-charge-neutralized drift space to the foil-covered collector of the Faraday cup. For large apertures, the current measurement was independent of drift-space pressure in the range 20–200 μm of air. Current neutralization along the beam was not occurring. A number of pulses made with $1\frac{1}{2}$-, 2-, and 3-mm-diam apertures indicated that more than 75% of the beam passed into the cup at peak diode voltage.

Two successful pulses in six attempts were made into a 1.0-mm-diam (0.785×10^{-2} cm^2) aperture; peak current densities in excess of 2.5 MA/cm^2 were recorded. Diagnostic wave forms

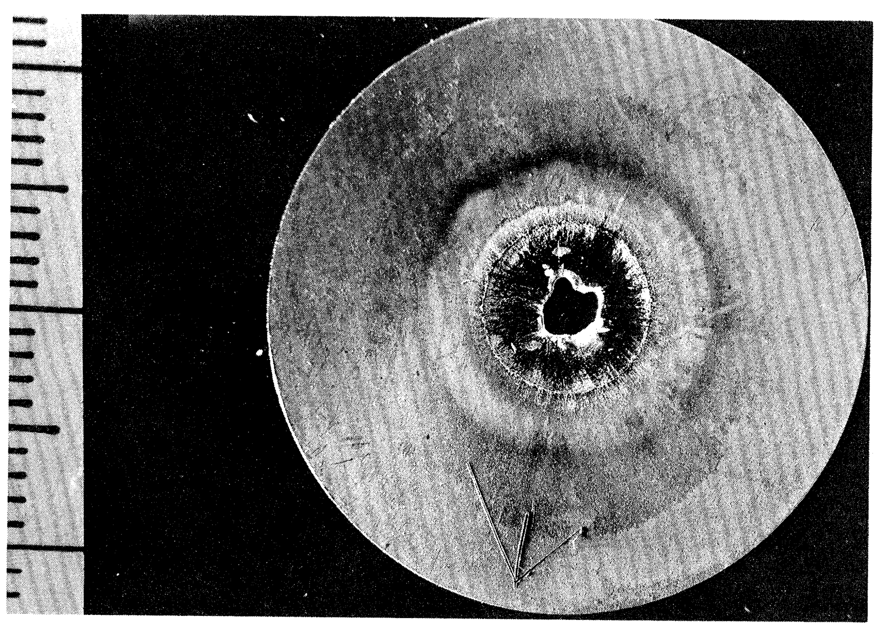


FIG. 3. Aperture after pulse 22 710; minor divisions are millimeters.

from the higher of the two pulses are shown in Fig. 2. In Fig. 2(b) the diode voltage has been corrected for induced voltage.[10] The peak voltage was 0.69 MV, which coincided with the peak indicated Faraday-cup current. The diode space was shorted by debris or plasma at $t = t_0 + 30$ nsec.

Figure 2(c) shows an overlay of the diode and Faraday-cup currents. The Faraday-cup trace indicates that only a very small fraction of the diode current entered the aperture before $t = t_0 + 7$ nsec, when the beam focused sharply and more than 90% of the entire beam passed through the aperture. At $t = t_0 + 14$ nsec the Faraday-cup surface apparently became conductive and probably was reading a current less than the total incident beam current.[11] The peak current positively diagnosed was 2.71 MA/cm^2, and the peak power flux was 1.87 TW/cm^2. The rate of rise of power on the target was 9×10^{20} W/cm^2 sec. Figure 3 shows the aperture after the shot and indicates that the area where the tantalum was vaporized away had a radius of approximately 1 mm. The tantalum was lightly damaged to a radius of 3.5 mm. This probably occurred in the first 7 nsec of the beam pulse, before the beam self-pinched into the aperture. The current after 7 nsec was always considerably in excess of the minimum current[12] for a diode self-pinch, and one would not expect subsequent defocusing.

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[11]An alternative explanation is that the 1-mm-diam aperture was being partially closed by the edges of the aperture blowing inward. Image-converter camera photographs have shown luminescent material expanding from targets struck by this beam at velocities of 1 to 4×10^6 cm/sec. This is large enough to provide significant area reduction in 5 to 10 nsec.

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Linear Contribution to Spatial Dispersion in the Spin-Wave Spectrum of Ferromagnets

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The implications of magnetic symmetry on the spin-wave spectrum of ferromagnets are examined. Contrary to the usual result, the spin-wave dispersion relation is found to contain a term linear in the wave vector for a definite set of magnetic symmetries. This linear dispersion is shown to be a consequence of antisymmetric exchange.

One of the most widely accepted results of spin-wave theory in ferromagnets[1-3] is the quadratic dispersion law

$$\omega = a + ck^2. \tag{1}$$

Here, ω is the angular frequency of a spin wave and k is its wave number. Although the constants a and c depend upon the exact form of the magnetic anisotropy, the exchange energy, external magnetic fields, sample shape, and the direction of propagation of the spin wave, the quadratic dependence on k remains unaltered. The purpose of this paper is to show that the above quadratic dispersion law is a consequence of assumptions regarding the magnetic symmetry of the medium and/or the symmetry of the exchange coupling. The apparent generality of Eq. (1) can lead to the incorrect conclusion that this quadratic dispersion law is fundamental to the nature of magnetic excitations in ferromagnetic media. The approach used here is largely phenomenological and is based upon the classical continuum model of a ferromagnet as discussed in Ref. 3. However, a microscopic example of a relevant system is also discussed.

The energy density of a ferromagnet can be

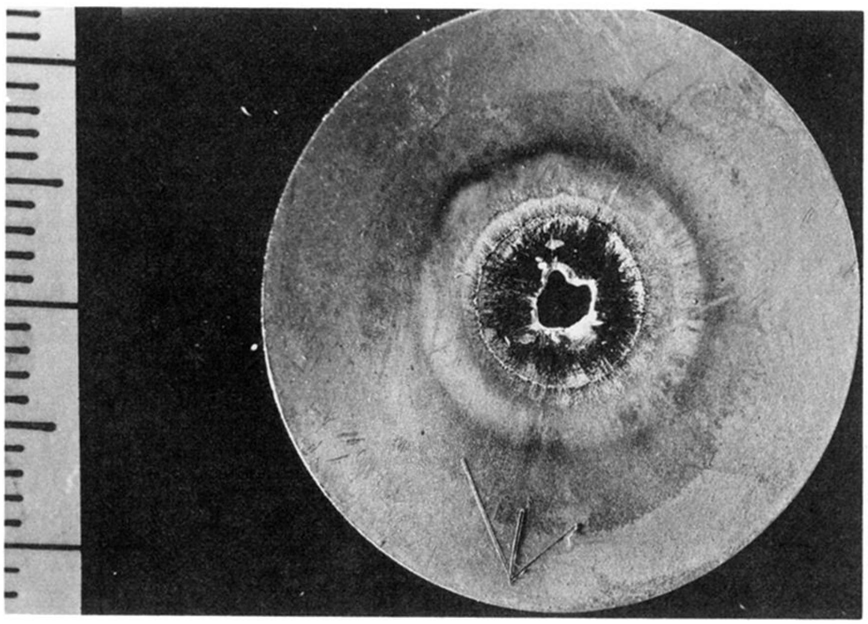

FIG. 3. Aperture after pulse 22 710; minor divisions are millimeters.