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CHERENKOV LIGHT AS A CURRENT DENSITY DIAGNOSTIC FOR LARGE AREA, REPETITIVELY PULSED ELECTRON BEAMS*

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Summary

Cherenkov light intensity is an ideal electron beam current density diagnostic, giving information about the beam's spatial distribution as a function of time during a pulse. It is free of the fluorescence and saturation often observed in scintillators provided a suitable radiator is chosen. Plate glass has been used for single pulse applications.[1] For repetitively pulsed beams a flowing liquid radiator is used to reduce problems arising from heating and decomposition of the material. Light output is sufficient to study 1 A/cm^2, 250 kV beams with ASA 3000 speed film. Streak photography also appears possible.

Introduction

Ideally the diagnosis of the spatial and temporal behavior of the electron beams used for pumping repetitively pulsed gas lasers requires a large-area, rapid readout detector capable of nanosecond, millimeter resolution. The beam voltages are typically a few hundred kilovolts. The pulse lengths may vary from a few tens of nanoseconds to several microseconds with repetition rates as high as several hundred Hertz. A common feature of these lasers is that the electron beam power is limited by heating of the extraction (anode) foil. The average extracted power may exceed 2000 watt/cm^2. Typically this power must be absorbed by the beam current density diagnostic. One detector with these properties is a flowing liquid Cherenkov radiator. Cherenkov light has been used before to diagnose large area electron beams in a single pulse mode.[1,2,3] In this paper liquid radiators for repetitive service will be considered.

Cherenkov light is emitted whenever a charged particle's speed exceeds the speed of light (c/n) in the medium through which it is passing. It occurs at the time of the particle's passage giving, in the absence of fluorescent noise, an accurate time history of the beam current. To get Cherenkov light from electrons in the range 200 KeV and above, an index of refraction greater than 1.4 is required. This rules out gases for the Cherenkov radiator. Solids are also eliminated since they are unable to withstand the high average power loading. That leaves liquids which can be flowed through the radiator cell for cooling and for removal of the products of electron beam induced decomposition. The Cherenkov light may be photographed open shutter with a high speed camera to measure the time integrated current density at high repetition rates. A single spot on the radiator observed with a photomultiplier tube provides an excellent substitute for a Faraday cup. Finally streak or fast-frame photography yields data on the time evolution of larger areas of the beam during a pulse.

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Description of the Experiment

Table I lists the Cherenkov media that have been studied. They were chosen to give a range of Cherenkov thresholds. All are relatively innocuous, easily available liquids. For large area, high repetition rate systems it is important that the radiation not suffer too much damage as a result of irradiation. Considering that a typical radiator might contain a volume of fluid that is difficult to exchange between pulses, it is desirable that the fluid be relatively undamaged by electron irradiation. Of the materials in Table I only bromoform showed obvious damage after a few 1 microsecond, 10 A/cm^2 pulses. Water, carbon disulfide and carbon tetrachloride appear to be sufficiently stable for use as radiators.

TABLE I
Cherenkov Radiators

Medium	Refractive Index	Cherenkov Threshold
Water	1.34	260 KeV
Carbon Tetrachloride	1.46	190
Bromoform	1.60	144
Carbon Disulfide	1.65	131

Typical electron accelerator voltage and current waveforms are shown in Fig. 1. The voltage risetime is 100 to 200 ns. Depending upon the diode's closure, the voltage typically fell to zero in 1 to 2 μsec. In some cases the voltage was "crowbarred" by a vacuum surface flashover. Current densities used in this work ranged upward from 1A/cm^2.

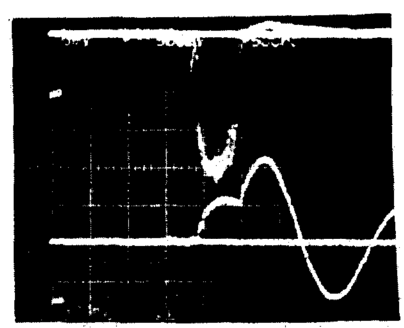

Figure 1. Diode voltage (upper trace, 72 kV/div, 500 sn/div) and accelerator current (lower trace, 10 kA/cm, 500 ns/div)

The diode and Cherenkov cell geometry is illustrated in Fig. 2. The beam was extracted through a 0.0025 cm titanium foil. The distribution of energy for electrons transmitted through the foil peaked 23 KeV below the injection energy with tails upward to the full injection energy and downward virtually to zero.

Cherenkov light was photographed with a Polaroid camera (ASA 3000, f 5.6) located approximately 2 meters from the radiator. For time-dependent measurements a 5 m long optical fiber was attached to the Cherenkov cell. Light was detected with an RCA 7104 phototube.

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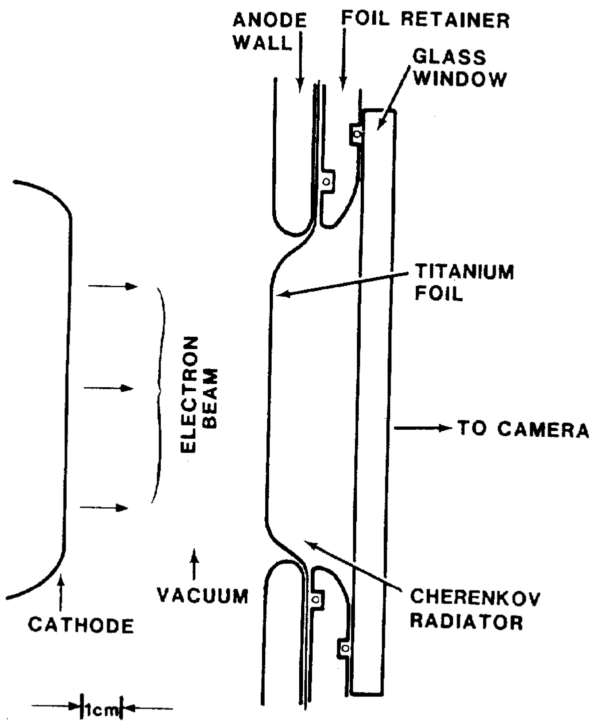


Figure 2. Illustrations of the experimental cell

The current extracted was acceptably consistent from shot to shot, permitting a parameterization of the Cherenkov light to be made when the Cherenkov light and current density were measured in successive experiments.

The peak Cherenkov light signal as a function of peak diode voltage is shown in Fig. 3. The signal falls sharply toward a voltage 19 kV above the Cherenkov threshold of carbon tetrachloride. Onset of Cherenkov emission would have been expected 23 KeV above threshold. Agreement to 4 KeV provides a good check on the voltage calibration. Some signal is observed below the threshold corresponding to the higher voltage electron component passing through the foil or a small non-Cherenkov background. The rise in the signal above the Cherenkov threshold apparently flattens near 250 kV.

Assuming that the Cherenkov signal is proportional to the current density given by Eqn (1), it is reasonable to extract its voltage dependence from a plot like Fig. 4 where the Cherenkov signal less the 5 MV "background" is divided by the current density. The data appear to follow two straight lines broken at 250 KeV. The linear rise from threshold is fortuitous since it gives much better current detection at low voltage than the quadratic dependence that had been expected (see the next section). The break and flattening above 250 kV is thought to result from photomultiplier saturation.

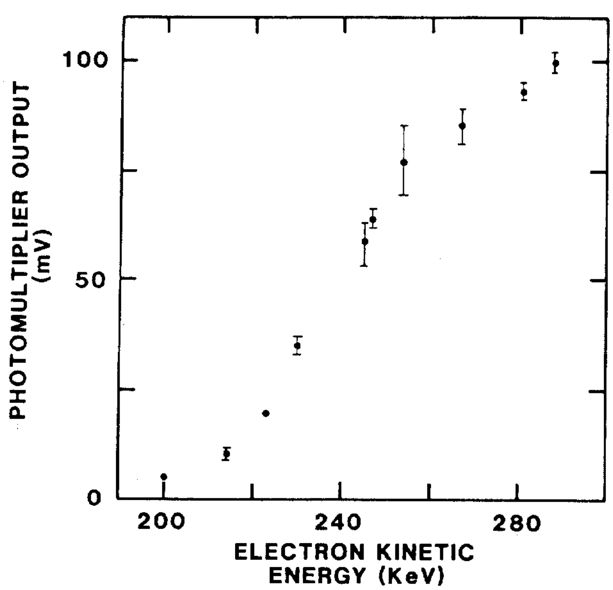


Figure 3. Photomultiplier voltage as a function of the electron accelerator voltage

Data were taken at acceleration voltages between 200 and 300 kV. The peak voltage is assumed to be proportional to the current density extracted opposite the tip of the optical fiber. The constant of proportionality is a function of the diode voltage that incorporates the Cherenkov threshold. The current density was measured by replacing the Cherenkov cell with 0.5 cm^2 Faraday cup assembly. The data presented are represented reasonably well by a current density $j(A/cm^2)$ versus voltage $V(kV)$ of the form

$$j = -2.9 + 0.0195V . \qquad (1)$$

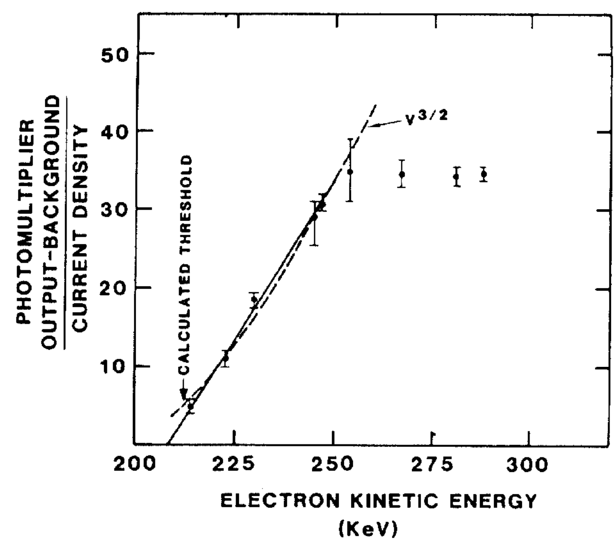
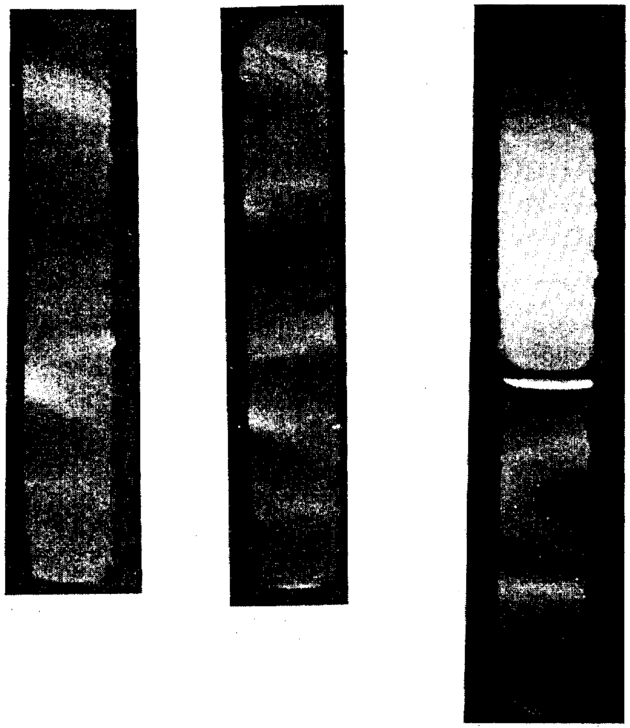


Figure 4. Photomultiplier voltage normalized to the current density as a function of the electron voltage. The solid line is a linear fit to the low voltage data. The dashed line is $(V-198\ kV)^{3/2}$.

Figure 5 contains three photographs of the electron beam pattern from a cathode whose left edge is at the right edge of the radiator cell. Typical mean current density is $1A/cm^2$. The radiator cell is only half filled in Fig. 5c. The Cherenkov light in the upper half of the cell comes from the glass viewing window. Consistent with a 40° rms scatter in the titanium foil, the filamentary beam seen in the liquid has expanded until it is featureless by the time it reaches the glass.



5a 5b 5c

Figure 5. 1 A/cm^2 electron beam pattern

Discussion

The amount of Cherenkov light detected per unit current density depends upon the radiator material, the voltage of the electrons, their direction with respect to the detector, and the properties of the detector. The electrons scatter 40° rms in the foil and up to an additional 40° in the radiator. Thus it is reasonable to model the radiating electrons as having random orientations. Cherenkov light is emitted in a cone with the angle of the light emission with respect to the electrons motion being given (nonrelativistically) by

$$\cos\theta = c/nv = V_{TH}/V \tag{2}$$

(c is the speed of light, n the index of refraction of the radiator, v is the particle speed, V_{TH} is the Cherenkov threshold voltage, and V is the "voltage" of the particle in question defined as its kinetic energy divided by its charge.) The assumption of random angles implies random radiation directions allowing electrons of all speeds to radiate toward the detector with equal probability. The emission intensity per unit path length is

$$\frac{dI}{dx} = K\left(1 - \frac{c^2}{n^2v^2}\right) = K\left(1 - \frac{V_{TH}}{V}\right). \tag{3}$$

Equation 3 assumes that the speed of light in the radiator is constant over the range of frequencies observed. Assuming dE/dt, the energy loss of the electrons is a constant over the energy range of interest, dx is proportional to dV. For any particle radiating toward the detector, only a part of the radiation cone proportional to $(\sin\theta)^{-1} = (1 - V_{TH}/V)^{-1/2}$ is detected. The intensity of the detected light, L, is

$$L \propto \int_{V_o}^{V_{TH}} \left(1 - \frac{V_{TH}}{V}\right) (\sin\theta)^{-1}\, dV \propto (V_o - V_{TH})^{3/2} \tag{4}$$

if the accelerator voltage is near to the Cherenkov threshold. The data are not inconsistent with a "3/2" dependence (see Figure 4) although a linear dependence is preferred. The voltage dependence of the detected Cherenkov light is important when comparisons are made between current densities at different voltages such as the photomultiplier measurements. Time-integrated (open shutter) measurements are fundamentally ambiguous whenever the detector response varies with voltage.

Conclusions

Cherenkov light is a useful diagnostic for measuring the current density as a function of position and time in the high power, repetitively pulsed beams used to pump some gas lasers. The radiator is robust and renewable and the light output is in time with the passage of the particles through the radiator. The lower cutoff on the energy of the particles to be observed may be selected to some extent by proper choice of the radiating fluid. The light output varies with electron voltage particularly near threshold. The physics of the radiation process is relatively simple although the simplest arguments did not lead to the best agreement with the data in this experiment. A Monte Carlo calculation is probably required to predict the output light intensity in any given experiments.

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