DOSE-VOLTAGE DEPENDENCE FOR HELIA/HERMES III BREMSSTRAHLUNG DIODES

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Abstract

The relation $\dot{D} \propto IV^{2.65}$ is widely used to estimate the on-axis radiation dose rate, $\dot{D}$, downstream of an optimized bremsstrahlung target as a function of diode voltage, V, for flash x-ray sources. This relation is valid only for pencil beams. For diodes having beams with finite spatial and angular extent, the power 2.65 is reduced. This reduction is evaluated via the MAGIC and CYLTRAN codes for diodes operating on the projected 20 MV HERMES III and existing 3 MV HELIA accelerators. For HERMES III, a power of 2.2 is obtained for near-field exposures using a fixed converter optimized at 20 MV. For HELIA, a power of 1.8 is obtained when the change in electron flow with voltage is also taken into account. This voltage dependence, together with the measured voltage and current waveforms on HELIA is used to calculate the expected temporal shape of the radiation pulse. The shape is consistent with that measured using a PIN diode.

Introduction

High-power, pulsed, electron-beam diodes are widely used to produce intense bursts of x-rays via bremsstrahlung conversion in the anode. Forster and colleagues [1] have shown that for small beam radii the on-axis radiation dose rate, $\dot{D}$, measured 1 m downstream of the anode can be expressed by a relation of the form:

$$\dot{D} \propto IV^{\alpha} \quad , \tag{1}$$

where V is the voltage applied across the anode-cathode gap, I is the diode current, and α equals 2.8 over a wide range of anode-converter materials. Martin [2] has reevaluated this relation and finds that α equals 2.65 for optimized bremsstrahlung converters. These authors point out that not only is this relation useful for predicting the forward radiation output but that the relation can be inverted to extract the diode voltage from a measure of both I and $\dot{D}$.

Equation 1, however, is valid only for pencil beams. For diodes generating beams with finite spatial and angular extent, the power 2.65 is reduced. In this paper, we calculate the reduction for a proposed diode for the 20 MV, 800 kA HERMES III accelerator [3] that is capable of providing a uniform irradiation over a 500 cm^2 area close to the converter. This accelerator is being constructed to provide an intense source of γ-rays over a large area for the simulation of nuclear effects. The calculations show the magnitude of the variation in α that can be expected from finite sources. Knowledge of α for the near-field exposures together with Eq. 1 and the estimated V and I pulse shapes enables the temporal behavior of the near-field radiation pulse from HERMES III to be estimated. This calculation is demonstrated for the HELIA accelerator [4] operating at 3 MV and 150 kA. This accelerator is the pulsed-power test bed for HERMES III. Before these calculations are presented, however, we discuss why α is reduced for finite-area sources and show that our calculations reproduce the empirical relation of Martin.

The spatial and angular distribution of the electrons incident on the anode converter was calculated at four discrete voltages (5, 10, 15, and 20 MV) using the electromagnetic particle-in-cell code MAGIC [5] to model diode performance. These distributions were used as input to the CYLTRAN Monte Carlo transport code [6] for prediction of the radiation dose profiles in CaF_2 thermoluminescent dosimeters using the next-event-estimator method [7,8]. The resulting doses were then fit to Eq. 1 to extract α.

α for Pencil Beam Source

The efficiency for producing bremsstrahlung radiation in the forward direction increases super linearly as the energy of the incident electron at the converter is increased [7] because the radiation becomes more and more concentrated in the forward direction. Figure 1 illustrates the relative reduction in the angular width of the resulting radiation pattern over the range 5 MeV to 20 MeV from a converter optimized [7] at 20 MeV. This converter is composed of 4.81 gm/cm^2 of Ta, followed by 5.24 gm/cm^2 of graphite, and 0.832 gm/cm^2 of kevlar.

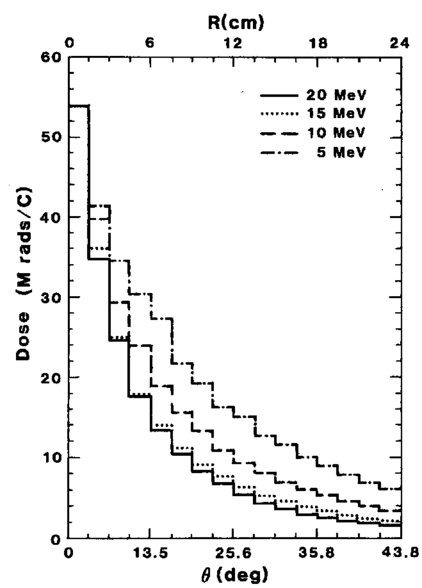

Fig. 1. Comparison of radial or angular dose profiles in a plane 25 cm downstream of a pencil beam incident on the 20 MeV optimized converter for 5, 10, 15, and 20 MeV incident electrons. All curves have been normalized to the peak value of the 20 MeV histogram.

Because the width of the radiation narrows with increasing energy, the non-forward radiation fluence does not increase as rapidly with energy or, equivalently, with diode voltage as does the forward radiation fluence. Accordingly, the power dependence, α, of Eq. 1 decreases with increasing angle, θ, of the radiation relative to the incident electron. For the optimized 20 MeV converter, the decrease we calculate is plotted in Fig. 2 for pencil beams. In the forward direction, α equals 2.89; it is reduced to 1.88 at 43°. Plotted also in Fig. 2 is α calculated when the converter is optimized at each incident electron energy. In this case, α is reduced from that obtained

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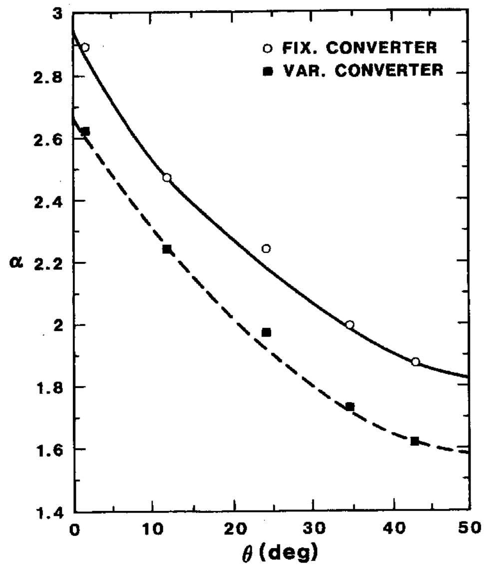

Fig. 2. Calculated values of α vs. θ, the angle of the radiation with respect to the direction of the incident electrons, for a pencil beam. The o data points correspond to α calculated using the fixed 20 MeV optimized converter. The ■ data points correspond to α calculated using the variable converter optimized at each incident electron energy.

using the fixed 20 MeV optimized converter. This reduction is easy to understand, because at each electron energy below 20 MeV, the converter is now optimized and thus produces more radiation at the lower energy than for the 20 MeV optimized converter. In the forward direction, our calculated power of 2.62 for this variable converter is in excellent agreement with the 2.65 emperically determined by Martin.

α for HERMES III Source

For finite-size electron-beam sources, the radiation on-axis in the near field is no longer due to just radiation generated at zero angle. Instead, the radiation is a composite of that produced at many angles relative to incident electron. Based on the above discussion, which shows that α decreases with increasing angle, we therefore expect α to be reduced for finite-size sources. As an example of the magnitude of the reduction in α expected from a finite-size source, we have calculated α expected from a typical source projected for HERMES III. The source uses an indented-anode diode [9] to produce a beam at the converter that provides a relatively uniform radiation pattern. The beam used in the CYLTRAN calculations is derived from a MAGIC simulation of the electron flow in the diode and is shown in Fig. 3.

On axis, near the source, our calculations show that α is reduced from 2.89 (Fig. 2) for a pencil beam to about 2.2 for the HERMES III beam. Figure 4 shows the variation in α as the position along the axis is increased from the near field to the far field. The variation in α as a function of radial distance r from the beam axis at Z = 10, 25, and 40 cm is shown in Fig. 5. The increase in α with increasing Z shown in Fig. 4 is expected, because at large distances from the converter, the fluence is more forward directed.

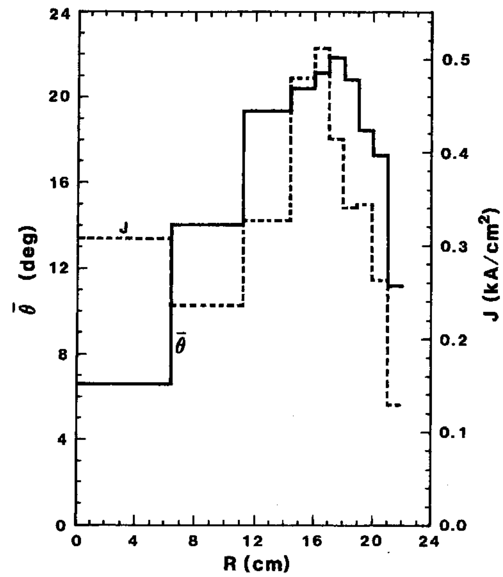

Fig. 3. Angular and radial current density distribution of the incident electron beam at the converter used for the finite-size source in the HERMES III simulations.

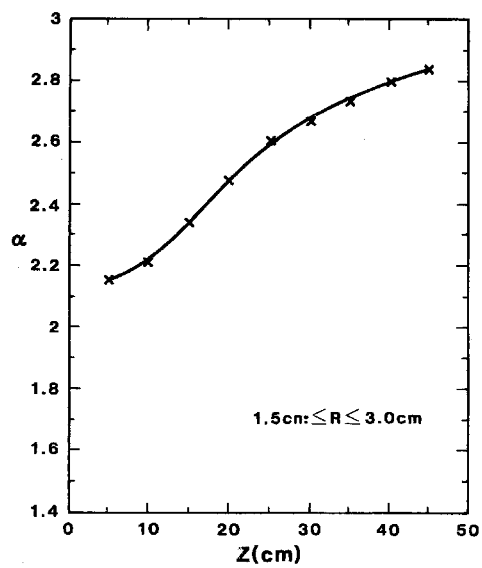

Fig. 4. Variation in α for on-axis exposures as a function of axial distance Z downstream from the 20 MeV optimized converter corresponding to the finite-size source of Fig. 3.

α for HELIA Source

We checked our calculational technique by evaluating α for a planar-anode diode source on HELIA [10]. Specifically, we used the calculated α together with Eq. 1 and the measured V and I waveforms for a given shot on HELIA to predict the relative $\dot{D}$ waveform as measured in a Si PIN diode located 2.5 m downstream of the 5 cm thick graphite anode-converter. The PIN diode was estimated to have a temporal resolution of less than 3 ns [11]. The radial extent of the beam at the anode converter was about 12 cm and had a pinch angle that varied from 8° at 0.5 MV to about 30° at 3 MV. Using the MAGIC code, we took account of both the changing radial and angular

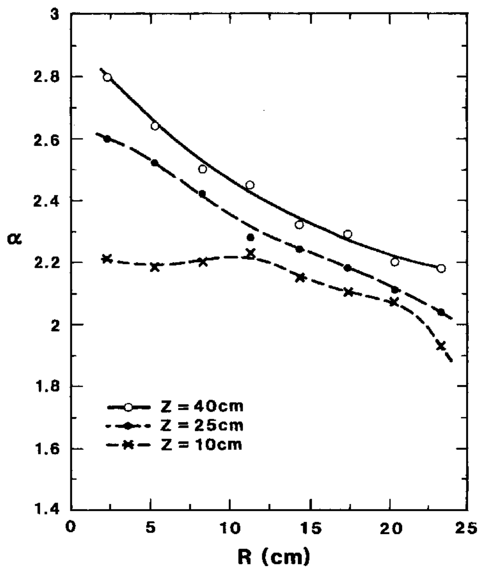

Fig. 5. Variation in α as a function of radial distance r from the beam axis at Z = 10, 25, and 40 cm for the 20 MeV optimized converter corresponding to the finite-size source of Fig. 3.

electron distribution at the converter. As before, we used these MAGIC distributions as input to CYLTRAN. In CYLTRAN, the exact geometry and detector materials were used. The calculations showed that the increased pinch angle of the beam at the converter with increased voltage reduced the effective α at the position of the PIN diode to 1.8.

Using this value for α, we expect that the relative variation in the radiation pulse, $\dot{D}$, should follow $IV^{1.8}$. This behavior is in excellent agreement with that measured (Fig. 6). Because of the delay between the turn-on of the current with respect to the voltage, the comparison is not very sensitive to the exact power of V. This lack of sensitivity follows from the observation that the bulk of the variation in the leading edge of the voltage wave shape occurs when little current is flowing. Additionally, the trailing edge of the voltage pulse fell precipitously due to self-breaking switches in the pulse-forming lines [4]. Consequently, the time over which the voltage was changing was small, and the effect of varying α on the predicted radiation output was masked by experimental resolution. We find, in fact, that IV--the power pulse--gives an equally valid description of the relative shape of the radiation pulse. This insensitivity to α for our experimental conditions helps to explain why other experiments with similar conditions have often found an unexpectedly good correlation between the shape of the power pulse and the radiation pulse.

Summary

The relation $\dot{D} \propto IV^{\alpha}$, which is used to evaluate the on-axis rate downstream of optimized converters has been evaluated for a finite-size source operating on the projected HERMES III accelerator. The calculations show that α varies by 36% over the near field for a fixed converter optimized at 20 MeV and illustrates the variation possible from a finite-size source (Figs. 4 and 5). For exposures near the converter, an α of about 2.2 is obtained.

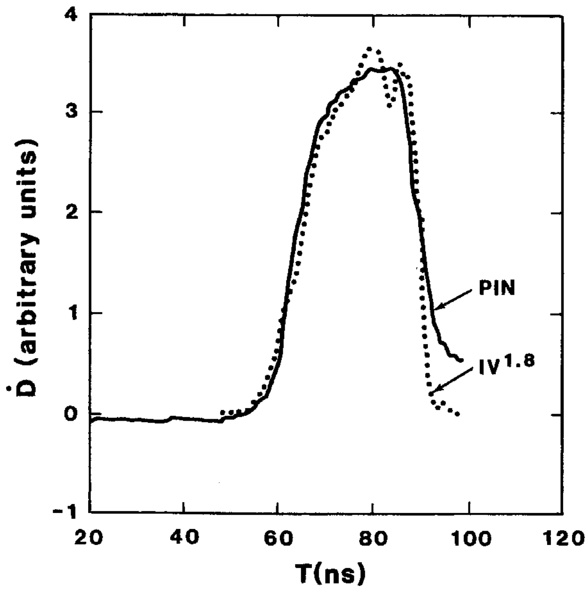

Fig. 6 Comparison of radiation pulse measured in the PIN diode relative to that calculated using $\dot{D} \propto IV^{1.8}$.

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