An Intense Large Volume Uniform Source of Bremsstrahlung for Pulsed Gamma Ray Simulation*

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ABSTRACT

The intense radiation fields generated with useful uniformity over large volumes, using the novel compound-lens diode on Hermes III, are characterized. The measurements show that by changing the diode parameters, the peak dose, useful area, and useful volume of irradiation can be varied from ~ 100 krad(Si), ~ 600 cm², and $\sim 20 \times 10^3$ cm³ to 20 krad(Si), ~ 3400 cm², and $\sim 200 \times 10^3$ cm³, in a 19 ± 2 ns radiation pulse. This versatility enables radiation fields to be tailored to a specified exposure requirement, significantly enhancing the capability of Hermes III to test radiation-effects in systems.

INTRODUCTION

Hermes III¹ is a 19-MV, 700-kA, 25-ns accelerator of electrons that is designed to produce an intense burst of bremsstrahlung. This bremsstrahlung is used for the simulation of radiation effects induced by pulsed γ rays. The extended planar-anode (EPA) diode² shown in Figure 1A is used to generate the standard radiation field from Hermes III (Figure 2A and 2B). It is capable of delivering a peak dose of ~ 100 krad(CaF₂) over a useful area of ~ 1000 cm² (area where dose is greater than 50% of the peak dose) in a pulse on the order of 20 ns.³ Because the radial electric field of the incident electron beam at the anode (target) is shorted out, the beam forms a weak pinch at the target and the radiation is focused on-axis (Figure 1A). In previously reported work, we took advantage of this pinch to produce very intense radiation fields (~ 400 krad[CaF₂] over small areas ~ 80 cm²) by introducing a low-pressure gas-cell between an anode window and target.⁴ This pinch can be disadvantageous, however, because it introduces significant non-uniformities in the near field (Figure 2) and thus limits the utility of the EPA diode for generating intense, uniform radiation exposures over large volumes.

By introducing the compound-lens diode⁵ just upstream of the target (Figure 1B), however,

the electron beam can be made to impact the target at normal incidence thus minimizing the pinch and resulting in significantly improved radiation uniformity without loss of radiation fluence.⁶ The beam in this diode is controlled by the electrostatic field between the cathode and tapered anode, and an azimuthal magnetic field generated by the external current (I_E) flowing through the titanium windows of the lens, as illustrated in Figure 1B. By adjusting the shape of the cathode tip, the anode-cathode (AK) gap, and I_E , the radial profile, the radial position, and the angle of incidence of the beam at the target can be varied. In this paper, we characterize the radiation fields measured as a function of these adjustments. We show that intense, uniform radiation fields can be achieved over both small and large volumes near the target. Because of the high degree of control that can be applied to the beam, use of this novel diode enables radiation fields to be specifically tailored for a given exposure requirement.

EXPERIMENTAL ARRANGEMENT

Figure 1B shows the experimental arrangement used for these measurements. The diode configuration is similar to that described in Reference 6, except that the target used is a tantalum graphite laminate, which optimizes the forward radiation fluence (see insert of Figure 1B). Current shunts (IC1, IA1, IA2, IA3) in the diode⁷ and Rogowski coils (I_P , I_R) in the external current source monitored the currents flowing in the diode and through the lens, respectively.

A 48-element array of CaF₂:Mn TLDs (thermoluminescent dosimeters) located at the downstream face of the target monitored the forward dose-area product.^{7,8}

$$DA = \int_0^{5.0\text{ cm}} D(R) 2\pi R dR$$

Here $D(R)$ is the azimuthally averaged dose measured in the TLDs at a given radius R in the $z=0$ plane (see insert at right of Figure 1B).

MASTER

2B

Based on this DA monitor, the peak voltage across the diode was about 1.2 MV less than the nominal value of $(18.7 \pm 0.7) \text{ MV}$, for the measurements discussed here.⁸

An additional 200-element TLD array measured the radiation field to a distance of 110 cm downstream of the target and out to a radius of 33 cm from the beam axis in the horizontal x-z plane. Eight TLDs placed at $z=7 \text{ m}$ and $z=11 \text{ m}$ measured the on-axis dose in the far field.

The TLDs used were the standard ones provided by the Hermes III facility. They consisted of a 0.9-mm thick $\text{CaF}_2\text{:Mn}$ active region surrounded by a 2.3-mm thick aluminum buffer. Over the spatial region explored, the buffer was adequate to yield measured doses comparable in magnitude to equilibrated doses to within about 10%.⁹ Because the effective absorption coefficient in these TLDs is similar to that of Si for the high-energy bremsstrahlung produced on Hermes III, the dose measured in the $\text{CaF}_2\text{:Mn}$ is similar to that which would be measured in Si.¹⁰ Accordingly, no distinction is made between either material and for simplicity the $\text{CaF}_2\text{:Mn}$ material in which the dose is measured is dropped from the dose notation.

To facilitate the comparisons of radiation patterns generated from configurations with differing diode parameters, independent of shot-to-shot variations, we normalize the measured fields such that the corresponding DA equals that measured under nominal conditions, namely $110 \text{ Mrad}(\text{CaF}_2)\text{-cm}^2$. This normalization removes the principal variation in the radiation pattern due to differences in accelerator performance between shots and enables comparisons to be made with that expected under nominal conditions.

Densitometer scans of film taken with an x-ray pinhole camera (PHC) located off-axis in the horizontal plane monitored the radial profile of the electron beam incident at the upstream face ($z=-9.4 \text{ cm}$) of the target and permitted the time-averaged radial position ($R_{-9.4}$) of the peak off-axis dose of the annular beam to be estimated (Figure 3). Examination of the corresponding radial position of the peak off-axis dose (R_0) at $z=0 \text{ cm}$ measured with the 48-element TLD array (see Figure 2A, for example) then permitted the direction of the time-averaged beam incident at the target (Figure 4) to be inferred via:

$$\theta = \tan^{-1} \left(\frac{R_{-9.4} - R_0}{9.4} \right)$$

Lastly, a five-element array of Compton diodes (CDs)¹¹ measured the temporal radiation field over the angular range 0° to 40° at a z of 1.3 m. For these monitors and for the configurations discussed here, the full-width half-maximum and the 10% to 90% rise time of the radiation field were measured to be $19 \pm 2 \text{ ns}$ and $12 \pm 2 \text{ ns}$, respectively.

DIODE OPERATION

As with the EPA diode, the AK gap of the compound-lens diode is adjusted so that the annular electron beam impacts the anode and the subsequent target at the desired radius.² For example, the radius $R_{-9.4}$ of the beam at the target increases from 13 cm to 18 cm as the AK gap is increased from 20 cm to 40 cm (Figure 5) for the diode with a solid cathode tip and no applied external current. As with the EPA diode, the angle of incidence at these radii is correlated with the AK gap, so that over this gap increase the angle decreases from 28° to 17° (Figure 5). This increase in radius and decrease in angle is the result of the beam experiencing more of its repulsive radial self electric field before the field is shorted-out at the anode.

After the beam is injected through the conical anode window, it is rapidly charge and current neutralized by the plasma formed in the 3 torr of N_2 gas contained between the anode window and target. Under these conditions the trajectory of the beam is effectively ballistic.¹² Application of the external current I_E now generates an azimuthal magnetic field the gas region that is used to turn the beam through any desired angle (θ) before it impacts the target (Figure 4), thus changing the correlation between impact position and angle of incidence fixed by the AK gap. For example, for a 30-cm AK gap and solid cathode tip, θ can be varied over the range $+23^\circ$ to -14° by simply increasing I_E from 0 kA to 200 kA (Figure 6A). Over this range, $R_{-9.4}$ increases slightly from 15.6 cm to 17.6 cm (Figure 6B).

Lastly, by changing from an annular to a solid cathode tip, (see cathode shapes illustrated in Figure 1B), electron emission from the tip is altered and the radial profile of the beam at the target (Figure 3) is modified. In general, introducing a solid tip suppresses electron emission from the underside of the annular tip (see dashed electron trajectories in Figure 1A), and the electron density on axis at the target is reduced (see Figure 19 of Reference 13).

Because of the two-component mechanism for controlling the beam (electrostatic from the adjustment of the AK gap and magnetic from the external current), we refer to the diode as the compound lens.

RADIATION FIELDS

Thus, by adjusting the AK gap, I_E , and cathode tip, the position, angle, and radial profile of the beam at the target can be controlled. This section now explores the variation in radiation pattern that can be obtained from these adjustments (Figures 7, 8, and 9). Throughout this section, the patterns measured are contrasted with those measured with the standard EPA diode (Figure 2).

For each configuration measured, two types of figures are presented. In one type (such as shown in Figure 2A), the radial dose profiles measured in x-y planes at $z=0, 10, \dots, 110$ cm (Figure 1B) are presented. In these figures the peak off-axis dose at $z=0$ cm, the radius (R_0) corresponding to this dose, and the average of the $R^{D/2}$ for each measured plane are denoted. Here $R^{D/2}$ corresponds to the radius where the dose has decreased to half the peak dose in the given plane. These radii are linked by dotted curves. In the other type of figure (such as shown in Figure 2B), the on-axis dose (D_c) and the peak off-axis dose (D_R) are plotted, together with $R^{D/2}$, as a function of z . The utility of these two types of figures is illustrated in Figure 2, where the dotted $R^{D/2}$ curve in Figure 2A and dashed $R^{D/2}$ curve in Figure 2B clearly show the radial convergence of the radiation generated from the incident electron beam. This convergence gives rise to the axial focus at $z=15$ cm with a peak dose of 98 krad.

In order to provide a quantitative comparison of the radiation generated among the differing configurations, for a given peak dose, D , in a given x-y plane, we define the useful area of radiation as that area (A) enclosed by the radius $R^{D/2}$ (i.e., that area where the dose is greater than $D/2$ [Figure 10A]). Similarly, for a given peak dose D we define the useful volume (V) of irradiation as that cylindrical volume where the length (L) of the cylinder is such that the on-axis dose at the downstream face of the cylinder equals $D/2$ and the radius of the cylinder corresponds to $R^{D/2}$ on average (Figure 10B). For the compound-lens diode, $R^{D/2}$ is nearly constant (Figures 7-9). Thus, within V the dose is generally greater than $D/4$. The boundaries of the useful volume, corresponding to L and $R^{D/2}$

are shown as the dotted lines in Figures 2B, 7B - 9B for specified peak doses. For the standard EPA diode of Figure 2, for example, the useful area, depth (length), and volume of irradiation for a peak dose of 98 krad is 600 cm^2 , 30 cm, and $1.8 \times 10^4 \text{ cm}^3$, respectively. Or for a peak dose of 50 krad, the useful area, depth, and volume of irradiation are 900 cm^2 , 13 cm, and $1.2 \times 10^4 \text{ cm}^3$ respectively. In this case, the upstream face of the volume of interest begins at a z of 30 cm.

General Characteristics

Just downstream of the target, the radiation profiles (Figure 2 and Figures 7-9) reflect the annular profile of the electron beam incident at the target (Figure 3). With increased distance from the target, the dispersion of the radiation causes the annular structure seen emerging from the target to fill in. Near the beam axis, the radiation pattern results partly from this mechanism, but also partly from the focusing of the annular portion of the electron beam, and partly from the "core" portion of the electron beam that is incident at radii less than 5 cm at the anode. This core does not pass through the magnetic field of the lens.

The enhancement at 15 cm along the beam axis in Figure 2B for instance, provides a clear example of the contribution from the annular portion that is converging at a 30° angle at the EPA anode. On the other hand, the radiation generated from the core electrons is clearly visible in Figure 9C, where the radiation from the annular electrons is directed radially outward, leaving the radiation originating from the core electrons behind.

Variation with I_E

Figures 7 and 8 now illustrate the variation in radiation generated when I_E -- which controls the angle of incidence of the annular beam at the upstream face of the target -- is increased from ~0 kA to 200 kA. Over this range, θ varies from a converging angle of about 23° to a diverging angle of about -14° (Figure 6A). For this change, the radius R_0 of the associated radiation annulus at the downstream face of the target increases from 7.4 cm to 12.2 cm for the geometry of Figure 7 and from 13.0 cm to 22.8 cm for that of Figure 8, where the AK gap is double. The variation is in the direction expected from Figure 6.

This change in the radiation annulus with I_E is also visible downstream of the target. For small I_E , for example, the contraction of the annulus with increased axial distance z is clearly shown in Figures 7A and 8A, reflecting the convergence of the incident electron beam. At the other extreme, when the incident electron beam is directed outward, the annular radiation pattern diverges, as is shown in Figure 8C. A current of ~ 100 kA produces near normal angles of incidence for the configurations discussed here. This current maximizes the on-axis dose in the far field, as is intuitively expected (Figure 11). The pattern associated with this condition is shown in Figures 7B, 8B, and 9A-C. In these examples, the radius of the radiation annulus, when it is discernible, is seen to be nearly independent of depth, thus producing a relatively uniform radiation field.

Variation with AK Gap

Figure 9 illustrates the variation in radiation generated when the AK gap is increased from 20 cm to 40 cm, respectively. Over this range, the radius of the annular electron beam increases by 5 to 6 cm (Figure 5). This increase is reflected in the increase in the radius of the radiation annulus. For example, over this range, R_0 increases from 10.6 cm to 17.0 cm (Figure 9).

Variation with Cathode Tip

For the EPA diode, which operates with a planar anode, the on-axis electrons are reduced and the radius of the annular beam is increased, when the tip type is changed from annular to solid.¹³ For the compound-lens diode, which uses a conical anode, however, little variation is observed. Specifically, comparison of measurements in Figures 7B and 7E (taken with an annular tip) with those of Figures 9A and 9D (taken with a solid tip) or comparison of Figures 8B and 8E with Figures 9C and 9E shows that R_0 and D are nearly identical. However, use of the solid tip does suppress slightly the on-axis radiation near $z=0$ cm (compare Figure 7B with Figure 9A or Figure 8B with Figure 9C), in general agreement with that observed for the EPA diode, reflecting a slight decrease in the core electrons.

DISCUSSION

Table I summarizes the useful A , L , and V , for a given D associated with the configurations discussed. The DV product shown in the last column provides a quantitative figure of merit. The dotted lines in Figure 2 and Figures 7 through 9 provide a visual representation of the size of the useful irradiation volume. For example, by changing the AK from 20 cm to 40 cm and the I_E from 0 kA to 200 kA, D and V can be varied from 103 krad and $19 \times 10^3 \text{ cm}^3$ to 22 krad and $>180 \times 10^3 \text{ cm}^3$, respectively.

Table I. -- Comparison of useful area (A), depth (L), and volume (V) of irradiation as a function of diode configuration (Figure), for a given peak dose D . See Figure 10 for graphical definition of $R^{D/2}$, Z_{up} , and Z_{down} . Shown also is the peak-dose useful-volume product DV . CL refers to the compound-lens diode.

Diode	AK cm	Tip	I_E kA	Figure	D krad	Z_{up} cm	Z_{down} cm	$R^{D/2}$ cm	A cm^2	L cm	V 10^3 cm^3	$D \cdot V$ 10^9 rad cm^3
EPA	53	Annular	--	2B	98	0	30	14 ± 4	600	30	18	1.8
	53	Annular	--	2B	50	30	43	17 ± 5	900	13	12	0.58
CL	20	Annular	0	7D	103	0	33	14 ± 1	600	33	19	2.0
	20	Annular	100	7E	70	0	33	19 ± 1	1100	33	37	2.6
	20	Annular	200	7F	53	0	37	23 ± 1	1600	37	59	3.1
CL	40	Annular	0	8D	51	10	52	20 ± 1	1200	42	50	2.6
	40	Annular	100	8E	33	10	58	30 ± 1	2700	48	130	4.3
	40	Annular	200	8F	22	10	62	>33	>3400	52	>180	>3.9
CL	20	Solid	100	9D	67	0	38	19 ± 3	1200	38	44	2.9
	30	Solid	100	9E	51	0	42	25 ± 2	2000	42	84	4.2
	40	Solid	100	9F	32	10	59	28 ± 1	2500	49	122	3.9

Removal of core electrons

Comparison of Figures 2A and 2B with Figures 7A and 7D illustrates the improvement in uniformity of the radiation field that is achieved with the compound-lens diode at the maximum D available with either diode, namely ~ 100 krad. For both diodes, the useful L, A, and V are similar (Table I). However, over the useful depth in the EPA diode, $R^{D/2}$ and A vary by a factor of 2 and 4, respectively. In contrast, for the compound-lens diode, $R^{D/2}$ and A vary by only $\pm 10\%$ and $\pm 20\%$, respectively. On the other hand, if only half the maximum dose is desired--namely 50 krad--then for the EPA diode the useful volume is limited to $12 \times 10^3 \text{ cm}^3$, where as for the compound-lens diode a V of $84 \times 10^3 \text{ cm}^3$ is available (compare Figures 2A and 2B with Figure 9B and 9E). In this case, V is seven times that of the EPA diode. In general, the DV product is significantly larger than that achievable with the EPA diode.

Moreover, with the compound-lens diode, intense, very-uniform, radiation fields over both small and large areas can be easily generated. Consider, for example, the field measured in the $z=10$ -cm plane for the $AK=30$ -cm diode of Figure 9B. By simply changing I_E from 0 kA to 200 kA, D and A can be varied from 44 krad and 1500 cm^2 to 26 krad and 3500 cm^2 (Figure 12), respectively. Within a subset of these areas, namely 600 cm^2 to 1600 cm^2 centered about the beam axis, D varies by less than $\pm 5\%$ (Table II), respectively.

In general, in order to optimize the exposure options available with the compound-lens diode, systems with radii less than 20 cm or greater than 30 cm should be exposed to the diode with an AK gap of 20 cm or less, or with an AK of 40 cm or more, respectively. Those with radii between 20 cm and 30 cm are well served with the diode operating with a 30-cm AK gap.

Table II: -- Comparison of the useful area A enclosed by $R^{D/2}$, the area A' enclosed by R' where the dose varies by less than $\pm 5\%$, and the associated peak dose D in the $z=10$ -cm x-y plane, as a function of I_E for a compound-lens diode having $AK=30$ cm and solid cathode tip. See Figure 10A for a graphical definition of $R^{D/2}$ and A.

I_E kA	D krad	$R^{D/2}$ cm	A cm^2	R'	A'
0	49	22	1500	14	600
100	36	28	2400	20	1200
200	28	33	3500	23	1600

SUMMARY

The measurements show that use of the compound-lens diode significantly expands the capability of Hermes III to generate intense uniform radiation fields. In specific cases, the useful volume of irradiation is increased by as much as seven times over that which can be achieved with the standard EPA diode. For a fixed AK gap, the peak dose and useful volume of irradiation can be varied by a factor of 2 to 3 by simply adjusting the external current to the lens. This adjustment is made without breaking the accelerator vacuum and thus requires no increase in downtime between successive exposures if a change in exposure condition is required. In conclusion, this new capability allows the study of radiation effects to be extended to larger electronic packages at higher radiation intensities while maintaining good spatial uniformity.

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FIGURE CAPTIONS

1. Schematic of (A) standard EPA and (B) compound-lens diode, showing experimental arrangement. The solid trajectories shown in A and B correspond to the dominant annular portion of the electron beam. The dashed trajectories shown in A correspond to the "core" electrons at the target that originate from the inside edge of the cathode tip.
2. (A) Radial dose profiles and (B) associated axial dose profiles for standard EPA diode, having $AK=53$ cm and annular cathode tip. D_C and D_R correspond to the on-axis and peak off-axis dose at the specified z . $R^{D/2}$ is the radius where the dose equals half the peak dose in the given x-y plane. The dotted lines in D-F correspond to the

- boundaries of the useful irradiated volume (Figure 10) for the indicated peak dose.
3. Radial profile of the electron beam at the upstream face of the target ($z=-9.4$ cm) for the compound-lens diode having $AK=30$ cm, $I_E=100$ kA, and solid cathode tip. The profile is obtained from a densitometer scan of the film along the x-axis. The right-left asymmetry arises from the camera being mounted off axis.
 4. Electron trajectories in magnetic-field region of the compound-lens diode showing trajectories when (a) $I_E \sim 0$ kA, (b) $I_E \sim 100$ kA, and (c) $I_E \sim 200$ kA. Shown graphically are the definitions of $R_{9.4}$, R_0 , and θ .
 5. Radius of the annular electron beam (Figure 3) and angle of incidence of the beam at $R_{9.4}$ on the upstream face of the target as a function of AK gap. The diode used is the compound-lens with $I_E=0$ kA and solid cathode tip. See Figure 5 for graphical definition of $R_{9.4}$ and θ .
 6. (A) θ and (B) $R_{9.4}$ as a function of I_E for compound-lens diode having $AK=30$ cm and solid cathode tip.
 7. Radial dose profiles (A-C) and associated axial dose profiles (D-F) as a function of I_E for compound-lens diode having $AK=20$ cm and annular cathode tip. D_C and D_R correspond to the on-axis and peak off-axis dose at the specified z . $R^{D/2}$ is the radius where the dose equals half the peak dose in the given x-y plane. The dotted lines in D-F correspond to the boundaries of the useful irradiated volume (Figure 10) for the indicated peak dose.
 8. Radial dose profiles (A-C) and associated axial dose profiles (D-F) as a function of I_E for compound-lens diode having $AK=40$ cm and annular cathode tip. D_C and D_R correspond to the on-axis and peak off-axis dose at the specified z . $R^{D/2}$ is the radius where the dose equals half the peak dose in the given x-y plane. The dotted lines in D-F correspond to the boundaries of the useful irradiated volume (Figure 10) for the indicated peak dose.
 9. Radial dose profiles (A-C) and associated axial dose profiles (D-F) as a function of AK gap for compound-lens diode having $I_E=100$ kA and solid cathode tip. D_C and D_R correspond to the on-axis and peak off-axis dose at the specified z . $R^{D/2}$ is the radius where the dose equals half the peak dose in the given x-y plane. The dotted

lines in D-F correspond to the boundaries of the useful irradiated volume (Figure 10) for the indicated peak dose.

10. Graphical definition of useful (A) area A and (B) length L and volume V, for a given peak dose.
11. On-axis dose at $z=7$ m as a function of I_E for the compound-lens diode having $AK=30$ cm and solid cathode tip. For comparison, the standard EPA diode generated a dose of only 79 rad.
12. Radial dose profile at $z=10$ cm as a function of I_E , for the compound-lens diode having $AK=30$ cm and solid cathode tip.

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A. EPA DIODE

B. COMPOUND-LENS DIODE

Fig 1

EPA Diode

AK = 53 cm

Tip = Annular

Fig 2

Fig 3

Fig 4

Fig 5

Fig. 6

Compound-Lens Diode

AK = 20 cm

Tip = Annular

Compound-Lens Diode

AK = 40 cm

Tip = Annular

Fig 3

Compound-Lens Diode $I_E = 100 \text{ kA}$ Tip = Solid

Fig 9

A.

B.

Fig 10

Fig 11

Fig. 12

END

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