Potential Enhancement of Warm X-ray Dose from a Reflexing Bremsstrahlung Diode*

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Abstract

The potential for generating intense bursts of warm x rays (20 to 60 keV) using electron reflexing diodes on pulsed-power accelerators is evaluated with the TIGER Monte Carlo code, showing that hundreds of kilojoules of warm x rays can be generated under idealized conditions. The calculations are compared with data from Gamble-II experiments and applied to two suggested Jupiter (60-MA, 5-MV, 100-ns) diode configurations. If the simultaneous irradiation from the high-energy tail of the bremsstrahlung which accompanies the warm x rays is a concern, then the reflexing technique is shown to be limited to the irradiation of targets thinner than $\sim 400 \mu\text{m}$ for low-Z targets like aluminum and thinner than $\sim 5 \mu\text{m}$ for high-Z targets like gold.

I. INTRODUCTION

The generation of intense bursts of warm x rays are of interest for the study of in-depth nuclear radiation effects [1]. Plasma radiation from a conventional z-pinch provides an excellent source of low-energy x rays [2]. These x rays are generated by thermal processes when a radially imploding plasma stagnates on the z axis, and the kinetic energy is converted into internal heat and thermal radiation. Owing to the onset of the Rayleigh-Taylor instability for high-velocity implosions, however, the yields of conventional z-pinchs are limited to x-ray energies below $\sim 5 \text{ keV}$ [3]. On the other hand, pulsed-power bremsstrahlung generators with MeV endpoint energies are capable of generating higher-energy x rays with relatively high efficiencies [4]. Unfortunately, when used with standard thick tantalum converters, x rays below $\sim 200 \text{ keV}$ are significantly absorbed in the converter. The use of the electron reflexing technique where the electron is forced to make many passes back and forth through a thin tantalum converter as shown in Fig. 1 avoids this problem [5,6]. Because the converter is thin, the low-energy x rays escape before being reabsorbed, as shown in Fig. 2 when the spectrum from the thin $2.5\text{-}\mu\text{m}$ converter is compared with that generated from the thicker $125\text{-}\mu\text{m}$ converter. Because the electron makes multiple passes through the converter, the total x-ray yield remains high.

Figure 1. Schematic of reflexing geometry simulated by TIGER showing the electron converter and x-ray target. Electrons reflex through the tantalum converter until they are completely absorbed.

Figure 2. Comparison of simulated 4π x-ray spectra from a thin ($2.5 \mu\text{m}$) and thick ($125 \mu\text{m}$) Ta reflexing converter for a 1-MeV electron source.

The use of macroscopic electric and magnetic fields for reflexing electrons in various geometries has been studied extensively in the past [5-12]. Diode fields, other externally applied fields, and electron-beam self fields were considered in these investigations with one of two objectives. In one, these techniques were studied as a means of enhancing the power depo-

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sition from electron beam sources used in electron beam inertial confinement fusion. In the other, they were considered, as in the present work, as methods for improving the efficiency for extracting radiation, especially the low-energy component of radiation, from electron-to-bremsstrahlung converters. In the latter case, they consistently predicted improved efficiency. However, there has been little experimental verification of these "advanced converter" predictions and virtually no application of these methods in operational x-ray or gamma-ray facilities.

In this paper, we examine the potential and limitations of this technique for producing warm x rays over the range 20 to 60 keV, using the 1-dimensional TIGER code of the ITS series [13,14], modified to specularly reflect electrons at the surfaces of the converter, to simulate the radiation from the configuration of Fig. 1. The 20-60 keV x-ray range was identified in Ref. 1 as an important range for nuclear radiation effects studies. Presently, no laboratory source exists in this range with sufficient energy yield to be of interest. These simulations illustrate, however, the potential for generating high yields of such warm x rays from a Jupiter-class (60-MA, 5-MV, 100-ns) accelerator. ITS is a series of coupled electron/photon Monte Carlo transport codes that has been extensively verified over the region covered by these calculations [15].

Results were obtained using monoenergetic electron beams of 5- and 1-MeV energy. These simulations are applied to two diode configurations [16] suggested for the Jupiter accelerator that generate ~ 40 kJ of x rays between 20 and 60 keV. One configuration (Fig. 3A) is a single reflexing diode operating at 5 MV (Config. A), and the other configuration (Figs. 3B and 3C) consists of five (Fig. 3C) such reflexing diodes connected in series, but now with each diode operating at 1 MV (Config. B). Both diode configurations are simulated by the idealized model depicted in Fig. 1, using either 5- or 1-MeV electrons normally incident on the tantalum converter and are discussed in Section IV. The electrons interact in the metal and are forced to pass back and forth until the electron loses its initial energy. The continuum and K-shell radiation are attenuated in the converter and absorbed in the target.

This model is discussed in Section II. Section III summarizes the results of the model calculations for 5- and 1-MV electrons. Section IV then applies these model results to the two Jupiter configurations A and B, and discusses the practical limitations of this reflexing technique in the context of experiments. Section V provides a brief conclusion.

II. MODEL

All simulations were carried out with modifications of the one-dimensional TIGER code of Version 3.0 [14] of the Integrated TIGER Series (ITS) of coupled electron/photon Monte Carlo transport codes [13]. ITS is a system of physically sophisticated, highly flexible, and user-friendly codes for simulating the production and transport of the electron/photon cascade from 1.0 GeV down to 1.0 keV with or without the presence of macroscopic electric and magnetic fields. The one-dimensional TIGER code was employed rather than the multidimensional

Figure 3A. Coaxial pinch-reflex triode for Jupiter.

Figure 3B. Planar pinch-reflex triode for Jupiter series diode.

Figure 3C. Two-stage series configuration of planar pinch-reflex triodes. A five-stage version would reduce the voltage on each diode from 5 MV to 1 MV.

codes because these exploratory studies were performed at a time when hardware configurations were highly speculative. Similarly, although diode electrical fields are assumed to be the cause of reflexing, ITS member codes with the capability for simulating the effects of these fields were not used because their time and spatial dependence were unknown.

Two types of simulations were performed: radiation *production* and radiation *deposition*. Source electrons were injected into various converters, and escaping radiation was scored. This radiation was then used as the source in subsequent calculations of the energy deposition in various targets.

A. Simulation of Radiation Production

The radiation source was obtained by assuming that electrons would reflex through tantalum foils until they thermalize. This is, of course, an upper bound to the radiation production in any realistic geometry. In any realistic configuration some electrons might stochastically scatter into regions of phase space corresponding to "holes" in the diode field through which they could escape from the foil. Others could diffuse laterally along the surface of the foil until they encounter some form of support structure. These losses are ignored in the present work owing to the variability of such processes.

The primary modification to the TIGER code for simulating the radiation production was that of localized specular reflection at the surface of the converter foils. This approximation was made instead of explicitly simulating transport in the macroscopic diode fields because (a) the form of those fields remains highly speculative and (b) lateral motion is suppressed in one-dimensional modeling. Each time an electron reached one of the escape surfaces of the foil, it was specularly reflected at the point where it reached that surface. The equality of the angles of incidence and reflection is only rigorously correct for a constant diode electric field.

Simulations were carried out at 5.0 and 1.0 MeV. Both electron and photon cutoff energies were 20.0 and 10.0 keV, respectively. Source electrons were normally incident. Converter thicknesses ranged from 2 to 880 μm at 5.0 MeV and from 2.5 to 130 μm at 1.0 MeV. In order to ensure an adequate random walk in the thinnest converter foils, the electron random walk segments were reduced by as much as a factor of 0.075. The only biasing was the standard scaling of bremsstrahlung production that is routinely employed for electron sources at these energies and electron trapping at energies below 65.0 keV. The latter means that at energies below 65.0 keV, electron histories were terminated with local charge and energy deposition when they could no longer escape from the foil. Trapping at higher energies would have precluded electron impact ionization of the K shell and the subsequent production of line radiation.

As electrons were thus forced to thermalize in the foil, the escaping radiation was accounted for. The total radiation as well as its spectrum was obtained, and line radiation (annihilation radiation and K-shell fluorescence) was obtained separately from continuum radiation. The radiation was obtained in units of photon number for subsequent radiation deposition simulations and in kilojoules per coulomb.

Reflexing distributions were also obtained to provide a better understanding of the model. This distribution consisted of the number of source electrons as a function of the number of specular reflections of *primary electrons only* plus the initial entry of the source electron. The average and RMS deviation for the distributions were also calculated. One would expect the loss mechanisms in realistic configurations to suppress the high-entry-number tail of this distribution, leading to reduction in radiation production. However, one might also expect that by the time lateral diffusion takes its toll on reflexing, electron energies may already be degraded to the point that radiation production is no longer significant.

B. Simulation of Radiation Deposition

The differential photon number spectra from the radiation source calculations were then employed as sources for calculating radiation dose in various one-dimensional targets. Here again, because the ultimate exposure geometry is unknown, absolute normalization was not possible. We used the total escape spectra from the source calculations to irradiate one side of a target foil and sampled the angle of incidence from a cosine-law angular distribution with respect to the normal to the foil. This calculational method is equivalent to exposure of one side of the target foil to a uniform isotropic radiation field. Finally, except where specified otherwise, it should be remembered that the 5.0 and 1.0 MeV sources do not include the radiation below 20.0 and 10.0 keV, respectively.

In order to understand the Z (atomic number) dependence of the absorbed dose with x-ray energy, target foils were either aluminum or gold. Foil thicknesses ranged from two microns to three millimeters. Because some of the target foils were highly transparent to the radiation, some variance reduction procedures were employed. Photons were forced to interact at higher than their natural probability. Electrons were also fully trapped, meaning that, regardless of their energy, their histories were terminated with local charge and energy deposition when they could no longer escape from the foil.

The primary output of the radiation deposition simulations was not the total energy deposition, but rather the "sensitivity function." The sensitivity function is defined as the fraction of the total dose due to source photons below a certain energy as a function of that energy. This function gives the relative sensitivity of target dose to spectral energy and shows what portion of the dose is due to line radiation.

III. MODEL RESULTS

The increase of the 4π total x-ray energy production and the rapid increase in the 20- to 60-keV x-ray continuum, as a function of decreased tantalum converter thickness, is shown in Figs. 4A and 4B, for 5- and 1-MeV incident beam electrons, respectively. Also shown in Figs. 4A and 4B is the variation in K-shell radiation yield with converter thickness. For example, with a 110- μm thick converter and 5.0-MeV electrons (Config. A), the simulations (Fig. 4A) show that 160 kJ of 20- to 60-keV continuum radiation plus K-shell x rays are produced, corresponding to a warm x-ray conversion efficiency of 0.54% for a 30-MJ Jupiter accelerator. For this ideal configuration, TIGER predicts that the incident beam electrons make on average 12.5 entries into the converter with an RMS variation of 4.2 entries (Figs. 5 and 6A). Shown also in Figs. 5 and 6A for comparison are the calculated entry distribution for a 25- μm converter and the associated average/RMS of the entry distribution as a function of converter thickness for 1-MeV electrons, respectively.

Even if electrons were to leave the converter region after only half the mean number of idealized entries, the simulations show that still ~ 50% of the dose is generated (Fig. 7) in a typical target, illustrating the robustness of the technique. More-

Figure 4. 4π total, 20-60 keV continuum, and tantalum K-shell radiation as a function of converter thickness, for (A) 5-MeV and (B) 1-MeV electrons.

Figure 5. Distribution of the number of primary electron passes through the converter for 5-MeV electrons (110- μ m thick converter) and 1-MeV electrons (25- μ m thick converter).

over, the simulations (Fig. 4A) show that warm x-ray yields twice the above idealized yields are possible if converters as thin as a few μ m are employed. In this case, the primary electrons would make hundreds of entries into the converter (Fig. 6A). The practical considerations associated with this large number of entries are discussed in Section IV.

Figure 6. Average and RMS variation of the number of primary electron entries into the converter as a function of converter thickness, for (A) 5-MeV and (B) 1-MeV incident electrons.

Figure 7. Relative energy deposition in various targets as a function of the maximum number of primary electron passes in the converter for 5-MeV electrons, with a 110- μ m thick converter.

Although our simulations indicate that high yields of warm x rays are possible, these diodes also generate x rays up to the endpoint energy of the incident beam electrons (Fig. 2). These x rays interact in any target being irradiated by the warm x rays. They have the potential to dominate the response generated by the warm x rays. In this respect, a 1-MeV electron source is

superior to a 5-MeV electron source as a larger fraction of warm x rays are generated by the former. Moreover, Fig. 8 illustrates the almost linear increase in warm x-ray yield with incident electron energy for electron energies of 0.5 to 5 MeV. So, aside from the complications of current loss associated with the series diode technique (Fig. 3C), a set of five 1-MV diodes (Fig. 3B) operated in series generates almost the same warm x-ray yield as a single 5-MV diode (Fig. 3A) under the assumption that the same current flows through all five diodes. In the remainder of this section then, only the characteristics of the radiation generated from a set of 1-MV diodes is evaluated. Assuming that five diodes is a reasonable limit to use with the series technique, the calculations discussed thus put a reasonable upper limit on the potential of the reflexing technique for generating useful warm x-ray fields.

Figure 8. X-ray energy yields as a function of incident electron energy for a 2- μm thick tantalum target.

For a 1-MeV source, Figs. 9A and 9B show the fraction of the dose absorbed (y axis) in various targets by photons up to a given x-ray energy (x axis) for selected tantalum converter thicknesses and target thicknesses for aluminum and gold targets. The discontinuity near 60 keV shown in Fig. 9 is due to the absorption of the K-shell line radiation. These sensitivity functions show that the warm x-ray deposition becomes more dominant, and therefore, the reflexing technique becomes more applicable for warm x-ray deposition studies, as the converter becomes thinner, the target becomes thinner, and the atomic number of the target becomes smaller. These trends are expected, because (1) for thinner converters, a larger fraction of the warm x rays escape, (2) the thinner the target, the lower the probability that the high-energy x rays will interact in the target, and (3) the higher the Z of the target, the more the photoelectric absorption dominates Compton scattering at higher x-ray energy.

As an example, if we assume that 80% of the absorbed dose in the target is required to be from the warm x-ray band of interest to provide the conditions necessary for a meaningful nuclear-radiation effects test, then Table I shows the upper end of the x-ray band for which this criterion would hold for the simulation of Fig. 9 (the lower limit being fixed at 10 keV) for two converter thicknesses, 25 μm and 2.5 μm . For example, using a

Figure 9. Sensitivity functions for several converter and target thicknesses for (A) aluminum and (B) gold targets.

tantalum converter of thickness 25 μm (which is routinely used on pulsed-power facilities) or thinner, a 1-MeV source could provide a useful simulation of the effects from 20- to 60-keV x rays in aluminum targets of thickness $\sim 25 \mu\text{m}$ or thinner. On the other hand, for a high-Z target like gold, only irradiations of targets of a few μm thickness would be meaningful.

For the thinner $\sim 2\text{-}\mu\text{m}$ thick tantalum converter (the thinnest converter considered practical for use with a reflexing source), Figs. 10A and 10B show the sensitivity function for aluminum and gold targets, respectively. The associated x-ray energy X where 50%, 80%, and 90% of the dose deposition in the target comes from x rays whose energy is less than X is given in Figs. 11A and 11B for these aluminum and gold targets, respectively. Again taking the criterion that 80% of the dose deposition comes from warm x rays (i.e., those up to 60 keV), then from Figs. 11A and 11B, we see that the thinner reflexing converter can provide an excellent high-yield warm x-ray source (Fig. 8) for irradiation of aluminum targets up to 400- μm thickness and for gold targets up to 5- μm thickness. The use of the ten-times thinner converter with the larger number of electron passes (Fig. 6B), thus increases the range of useful target thicknesses also by about an order-of-magnitude.

Table I

X-ray energy X in keV corresponding to upper-end of the warm x-ray band criterion discussed in text (where 80% of the absorbed dose arises from x rays between 10 keV and X), for a 1-MeV electron source as a function of converter thickness, target thickness, and target atomic number.

Target thickness	2 μm	25 μm	3000 μm
<u>Aluminum Target</u>			
Conv. thickness			
2.5 μm	19	29	
25 μm		56	290
<u>Gold target</u>			
Conv. thickness			
2.5 μm	37	95	
25 μm		103

Figure 10. Sensitivity functions for a thin (2.54 μm) tantalum converter and target thicknesses varying from 2 to 3000 μm for (A) aluminum and (B) gold targets.

IV. PRACTICAL APPLICATIONS AND LIMITATIONS ON PULSED POWER GENERATORS

The calculated bremsstrahlung radiation presented above assumes ideal reflexing, that is, electrons pass through the con-

Figure 11. Maximum photon energy for a specified percentage of the dose from warm x rays as a function of target thickness for (A) aluminum targets and (B) gold targets, corresponding to Figs. 10A and 10B, respectively.

verter until they lose all their energy. Several factors make it difficult to achieve this in practical applications on pulsed-power generators. This section describes these limitations, based on experimental experience, and possible ways to optimize reflexing for warm x-ray production from a Jupiter-class generator.

A. Gamble II reflexing experiment and practical considerations

One experiment [12] designed to measure the increase in warm x-ray production associated with reflexing was performed on the Gamble II generator. This experiment used a ~ 1 -MeV electron beam on tantalum targets of various thicknesses, from 13 μm to 360 μm . The experiment was performed using a positive high-voltage center conductor, and a cylindrical, electron-emitting cathode (the outer conductor) at ground potential (like the top half of Fig. 3A). Electrons that passed through the tantalum converter entered a large vacuum space inside the center conductor where a virtual cathode could form. Subsequent electrons could be repelled back through the converter by the space-charge field of the virtual cathode. The reflexing could be prevented using a thick carbon block behind the converter. Comparing radiation measurements with and without the carbon block indicated a significant increase in radiation, by a factor of three or more, when reflexing was allowed through thin converters. The radiation spectrum, inferred from a depth-dose stack of thin thermoluminescent dosimeters, indicated that electrons made, on average, 6 passes through a 13 μm thick tantalum converter, and 9 passes through a 100 μm thick titanium converter. This number of passes is about a factor of two smaller than optimal for the tantalum converter thickness, indicating that some electrons are collected at anode locations other than the converter, as discussed in Section II. This limitation may be eliminated using a different reflexing configuration, as described below. The front-surface dose from thin, reflexing converters was about a factor of five greater than for a standard tantalum converter thickness (100 μm) in the conventional negative polarity configuration.

These experimental results can be compared with the above calculations. In Fig. 4B, the calculated photon-energy production for an ideal, reflexing tantalum converter with 13- μm thickness is about 55 kJ/C. The Gamble-II reflexing experiment resulted in about 30 kJ/C with the limited reflexing obtained with the virtual cathode configuration (equivalent to 6 passes through the converter). The spectrum determined from the Gamble-II measurements is intermediate between the spectra shown in Fig. 2, as expected for the 13- μm converter thickness in the experiment. These experiments illustrate the enhancement in warm x-ray production predicted by the above calculations; however, the reflexing efficiency must be improved (by about a factor of two for the 13- μm converter, or more with thinner converters) on a Jupiter-class machine to obtain the radiation output predicted in Fig. 4B.

The radiation calculations above account only for attenuation in the converter. Practical bremsstrahlung configurations also have a beam stop and a debris-stopping vacuum window. These elements attenuate the x rays that escape the converter, especially in the low-energy range of interest. It is imperative to minimize these attenuations to maximize the radiation output for warm x-ray testing. One approach to accomplish this is to operate the generator in positive polarity. This means that the vacuum window is at the same potential as the cathode, and the

converter is at a positive high voltage. In principal, no beam stop is required in positive polarity because electrons have zero energy at the cathode. In negative polarity, the beam stop must be thick enough to stop electrons that pass through the converter, significantly attenuating warm x rays. The debris window is required to maintain the integrity of the vacuum chamber after the converter is vaporized. This window thickness scales roughly as the square root of the converter mass from simple momentum considerations. The thin converters used in reflexing diodes allow correspondingly thin debris windows.

Reflexing converters can be copious sources of ion currents and electrode plasmas that short out the diode gap. The ion current effectively subtracts from the electron current, reducing the radiation yield. This effect has been observed in experiments where, on the 100-ns timescale, ion currents can become up to 50% of the total current. The deleterious effect of ion currents must be circumvented to optimize the radiation yield. Surface treatments, such as cleaning, heating, or coating, could reduce or delay the onset of the ion current. High-density electrode plasmas from both the cathode and anode can move across the gap at speeds of 2 to 10 cm/ μs , eventually shorting out the gap and limiting the energy deposited in the converter. A fast pulse, perhaps < 50 ns, may be sufficient to extract the radiation before ion emission starts and before electrode plasmas short out the diode.

The ultimate limit on reflexing converters is the number of entries electrons make in the converter. This number determines the optimum converter thickness, the thickness of the debris window, and the resulting radiation output. Space-charge effects in the diode gap limit the number of passes. The presence of ion space charge allows greater electron space charge, but at the cost of ion current losses as described above. The limited number of passes in the Gamble-II experiment was probably related to these space-charge effects and the fickle nature of the virtual cathode. The ultimate limit on the number of passes electrons can make in these configurations is a complicated problem that requires more research, but there is no evidence that this number will be too small to be of practical interest.

B. Conceptual Jupiter reflexing diode designs

A conceptual drawing of a reflex diode [16] for Jupiter is shown in Fig. 3A. The modules of the generator would be connected to drive two opposing cathodes, with a single, positive polarity converter. This diode operates at 5 MV and 60 MA (30 MA from each cathode), so it could be used for testing where a high-energy bremsstrahlung background were tolerable. The dimensions are calculated using simple critical-current arguments [17] and a minimum practical gap size of 3 mm. If the beam pinches to 1/3 of the initial radius, the effective radiating area would be ~ 1000 cm². Assuming 50% energy loss to ion currents and an 0.54% conversion efficiency from the 30-MJ electrical energy to radiation in the 20- to 60-keV range (see Section III), the radiation output would be 40 kJ of 20- to 60-keV photons in the forward direction. Close to the source, this would result in a fluence of about 10 cal/cm² over 1000 cm².

For applications where the high-energy bremsstrahlung generated by a 5-MeV beam is unacceptable, for example, as determined from the sensitivity functions in Figs. 9 and 10, a series diode could be used to lower the endpoint energy. For example, a five-stage series diode would reduce the voltage on a single diode to 1 MV. A conceptual drawing of an individual diode is shown in Fig. 3B. This diode is a planar, linear pinch-reflex triode, driven at 1 MV and 2 MA. A two-stage version of this diode is shown in Fig. 3C, where post-hole convolutes are used to connect the diodes in series. The convolutes introduce another potential current loss if vacuum-flowing electrons are not retrapped by the undermatched load impedance. It is estimated that 32 of these series diodes could be packed into a 105-cm by 135-cm rectangle, irradiating a 15,000 cm² area. The estimated fluence of 20- to 60-keV x rays for this configuration is 0.7 cal/cm², and would be proportionally greater if the converters could be packed into a smaller area.

V. CONCLUSION

These simulations show the capability of generating hundreds of kilojoules of warm x rays using the reflexing technique on a Jupiter-class accelerator under idealized conditions. For applications where the high-energy bremsstrahlung (which simultaneously accompanies the desired low-energy radiation) is of concern, the simulations also show that the technique is then limited to the irradiation of targets with thicknesses less than ~ 400 μ m and ~ 5 μ m for low- and high-Z targets like aluminum and gold, respectively. The enhanced emission of warm x rays from electrons reflexing through a thin converter as calculated here has been demonstrated experimentally on Gamble II, lending support to the calculations. In addition to the several practical concerns, such as suppressing ion currents, the ultimate limit on reflexing converters is the number of entries the electrons make in the converter. From the existing data there is no evidence that this number will be too small to be of practical interest. In conclusion, the application of the reflexing technique to a Jupiter-class generator is a challenging task with many potential pitfalls, but it remains one of the few ways to generate significant warm x rays for effects testing applications.

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