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Coherent Multiple-Foil X-Ray Transition Radiation

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ABSTRACT

Intense x-ray transition radiation can be generated when relativistic electrons pass through a multiple-foil target. When the foil spacing is periodic, the transition radiation can be spatially coherent with respect to the target period. The spatial coherence can be evident in the spectra and angular distributions of transition radiation from such targets. A series of experiments has measured coherent transition radiation distributions from multiple-foil targets (up to six foils) with spacings of 50 μm and 100 μm . The electron energy was about 75 MeV and the photon energies were about 200 eV. Agreement between calculation and experimental data is excellent. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract number W-7405-ENG-48.

INTRODUCTION

The passage of an energetic electron across a dielectric interface produces transition radiation (TR).¹ For relativistic energies, the angular distribution of TR from a single interface is a narrow forward-directed cone with an on-axis minimum and a maximum near the angle $1/\gamma$, where γ is the particle total energy divided by its rest mass. Single-interface TR has a broadband energy spectrum that is nearly independent of the angle of emission.^{2,3} TR also is spatially coherent because the phases of individual photons are spatially correlated with the intersection of an electron trajectory and the dielectric interface.

The spatial coherence can lead to strong interference effects in TR emission distributions. For example, a target that presents a periodic sequence of dielectric interfaces to the incident electrons can produce TR angular distributions that display multiple maxima and minima.^{2,3,4} The associated TR spectra can show well defined dispersion of photon energy versus angle of emission. There is a long history of excellent agreement between measurements and predictions of such interference effects for photon energies from the microwave to the x-ray spectral regions.^{4,5,6,7,8,9,10,11,12}

TR has been studied for its potential application as an intense tuneable, collimated x-ray source for applications such as microlithography or medical imaging.¹³ Coherent enhancement of the emission distributions is desirable for such applications. Here, the enhancement takes the form of peak intensities that scale with the N^2 , where N is of the number of interfaces in the target, and of bandwidths that scale with $1/N$. Theoretical studies suggest that it is possible to design TR x-ray sources whose emission distributions (in terms of intensity, collimation, and spectrum) are specifically matched to any of a variety of industrial applications.

THEORY

TR first was discussed as a theoretical possibility by Ginzburg and Frank.¹ Since that time, a wide variety of theoretical and experimental research has studied various aspects of TR. Theoretical work has included description of spatially coherent emission distributions from multiple-foil radiators.^{2,3} The comparison of theory with experimental data has been supported by the development of accurate simplified forms for theoretical expressions that describe TR.

One simple description of the TR emitted into a solid angle element $d\Omega$ and bandwidth $d\omega$ at a frequency ω from a multiple-foil target can be written in the form⁴:

$$\frac{d^2N}{d\omega d\Omega} = F_0 \cdot F_1 \cdot F_M, \quad (1)$$

where F_0 describes production of TR at a single dielectric interface in the target, F_1 accounts for the coherent summation of TR from the two interfaces of a single foil in the target, and F_M provides for the coherent summation of TR from M multiple foils (note that $N = 2M$).

F_0 can be written as:

$$F_0 = \left(\frac{\alpha \omega \sin^2 \theta}{16\pi^2 c^2} \right) (Z_0 - Z_1)^2. \quad (2)$$

The function F_0 is a simplified version of the original formulation of TR from a single interface.¹ Here, α is $1/137$, θ is the angle of photon emission, c is the speed of light in vacuum, and Z is a critical parameter called the "formation length".^{14,15} Z_0 and Z_1 are the formation lengths in vacuum and the foil material, respectively. The formation length is a measure of the difference between the electron speed and the phase velocity of a photon. The formation lengths represent the path lengths that are required in order to accumulate a significant shift of relative phase (shift $\approx \pi$ radians) between an electron and a co-propagating photon in each region, and it they can be written as:

$$Z_i = \frac{2\beta c/\omega}{\left(1 - \beta \sqrt{\epsilon_i(\omega) - \sin^2 \theta}\right)}, \quad (3)$$

where ϵ_i is the appropriate dielectric constant.

Proper description of $\epsilon_1(\omega)$ is required in order for Eq. (2) to be accurate. In the x-ray spectral region, there are two general types of behavior for $\epsilon_1(\omega)$. For most frequencies and materials, $\epsilon_1(\omega)$ is less than one. In this case, useful descriptions of TR have been obtained simply by using the dielectric constant of a free-electron gas having an electron density that matches the material of interest:

$$\epsilon_1 \approx 1 - \frac{\omega_1^2}{\omega^2}, \quad (4)$$

where ω_1 is the plasma frequency of an electron gas with density N_e that matches the material of interest: $\omega_1 \equiv (4\pi N_e e^2 / m_e)^{1/2}$, where m_e is the rest mass of an electron. Since ω_1 are typically tens of eV and x-ray ω are hundreds or thousands of eV, ϵ_1 typically are slightly less than one. This approach has been used successfully to compare measurements of broadband x-ray TR with theoretical predictions. However, when there is interest in narrow spectral bands, or when the x-ray frequencies of interest are near atomic resonances, the free-electron description probably will be inadequate. In this second case, it becomes necessary to use specific descriptions of $\epsilon_1(\omega)$. In the discussions below, such descriptions will take the form of choosing appropriate effective plasma frequencies ω_1 .

Coherent summation of field amplitudes from the two surfaces of a single foil leads to the form:

$$F_1 = 1 + \exp(-\sigma_1) - 2 \exp\left(-\frac{\sigma_1}{2}\right) \cos\left(\frac{2l_1}{Z_1 \cdot \cos \theta}\right). \quad (5)$$

This particular form accounts for x-ray attenuation through the thickness of a single foil, and assumes that the foils are normal to the electron trajectories. Here, $\sigma_1 = \mu_1 l_1 / \cos \theta$, μ_1 is the x-ray absorption coefficient of the foil material, and l_1 is the foil thickness.

Similarly, the summation over multiple foils can be written:

$$F_M = \frac{1 + \exp(-M\sigma_1) - 2 \exp(-\frac{1}{2}M\sigma_1) \cos(2MX)}{1 + \exp(-\sigma_1) - 2 \exp(-\frac{1}{2}\sigma_1) \cos(2X)}, \quad (6)$$

where $X = l_0/Z_0 + l_1/Z_1$ and $l_0 + l_1$ is the foil-spacing period.

EXPERIMENT

The purpose of the present work is to demonstrate that coherent TR radiators can be designed and used as a tuneable x-ray sources. In spite of numerous experimental demonstrations of the basic phenomenon, full demonstration of an intense tuneable TR x-ray source has been hampered by a variety of experimental problems that range from target design and construction to overall experimental resolution or electron-beam quality. The present experiment uses multiple-foil targets with foil-spacing periods of either 50 or 100 μm , a well defined 75-MeV electron beam and energy-resolved measurements of TR angular distributions to demonstrate coherent generation of x rays with energies from about 100 to 200 eV. Analysis of the data show that the emissions can be described by simple theories, but that parameters such as foil spacing, thickness, and energy-dependent dielectric constant must be chosen carefully.

The individual foils were either 1800 Å- or 5000 Å-thick free-standing boron nitride (B_5N) membranes 8 mm square. The membranes were supported by 2-mm wide square frames of silicon having nominal thicknesses of either 50 or 100 μm . The membranes were formed by etching square areas of silicon from wafers that had been coated with the desired thicknesses of B_5N .

Multiple-foil targets were formed by stacking the desired number of membranes. The frame (i.e., the initial wafer) thickness produced a corresponding periodic spacing for the membranes. The support frames helped to position the membranes, and spring compression eliminated the need for glue or other materials between the frames. When the resulting structures were viewed with filtered visible light, Fabrey-Perot fringes were apparent. The fringes indicated that the membranes were parallel to within a few μm . Targets with one,

two, four, and six membranes were used for the experiment. These numbers of foils were expected to produce emission distributions that could be studied with good resolution by the experiment. Greater numbers of membranes probably would have resulted in emission-distribution details too fine to be resolved.

The experiment used a well-defined electron (e^-) beam and an energy-resolved scanning proportional counter (PC) to measure the emission distributions, as shown in Fig. 1. A combination of analyzing magnets and collimators produced a 75-MeV e^- beam at the target with, approximately, a 1-mm diameter 1-milliradian (mrad) divergence, and energy uncertainty less than 75 keV. After passing through the foils, a magnet deflected the electron beam into a shielded beam dump that included a beam-current

Figure 1 Schematic diagram of experimental arrangement.

monitor. Remote-controlled scans of the PC (with a 1-mm square aperture) across the initial e^- -beam line of sight, two meters downstream from the target, measured the TR angular distributions. A multilayer reflector (with a period of XX Å) used in a reflection-monochromator geometry (see Fig. 1) selected the x-ray energies, with a resolution of about 6 %, that were incident on the PC.

The PC measured both angular distributions and coarse energy spectra at specific angles of emission. Angular distribution data consisted of 256 points representing an angular span of about 35 mrad. Each data point corresponded to the same total beam charge through the target, as measured by the beam-current monitor. When the angular distributions were recorded directly by the PC over broad spectral bands, the data were convenient for comparison with theoretical predictions of absolute intensity.

Measurements of absolute intensity rely on among other factors, knowing the e^- -beam current accurately. We believe that there was a systematic error in our beam-current monitor, in that low-level activation of the detector scintillator led to erroneously high indications of beam current. This, in turn, leads to misleading measurements of low absolute radiation production efficiency. The system was vulnerable to this problem because of the extremely low beam currents that were used (≈ 1 picoamp), in order to avoid count pile-up problems in the PC. Because of this problem, it is unlikely that the absolute measurements are better than a factor of two.

Generally, background contributions to the data were small - less than 10% of the peak amplitude. Unless specifically indicated otherwise, data presented below is "raw", with no smoothing, corrections for background or other procedures having been applied.

RESULTS

Figure 2 shows the angular distributions measured for targets consisting of 1, 2, and 4 foils of 5000-Å thick B₅N with spatial period of 50 μm. For these measurements, the PC integrated all photons from 95 to 260 eV. The figure also shows a theoretical calculation of the emission distribution expected for the six-foil target. The single- and two-foil target data have had bremsstrahlung-type backgrounds subtracted.

The single-foil data shows the normal behavior associated with TR: an on-axis minimum and a peak at an angle of $1/\gamma$ (≈ 6 mrad). The 2-foil target data show two clear maxima in the angular distribution. The 4-foil distribution shows enhanced interference maxima and minima. Finally, the theoretical calculation shows intensity maxima and minima at angles that match the data very nicely. As mentioned above, the discrepancy in absolute intensity between the calculated and measured intensity probably is due to a systematic error in the e-beam current measurement.

Similar data was recorded for a 6-foil target, but the results were nearly identical to the 4-foil data. This is roughly consistent with corresponding calculations that predicted about a 25% increase of emission for the 6-foil target. The reason that the emission saturates with the number of foils is that the total target

Figure 2 Broadband multiple-foil angular distributions.

Figure 3 Boron nitride (B₅N) absorption length model.

thickness becomes equivalent to several x-ray absorption lengths. When this is the case, emissions from the first few foils are absorbed before they emerge from the exit side of the target. Figure 3 shows the model of x-ray absorption length that was used as part of the calculations of predicted emissions. Over the 75 to 187-eV energy range, the model assumes that the absorption length varies as $\omega^{2.3259}$. Comparison with measured absorption lengths is very good.¹⁶

The angular distributions from these targets also were studied in an energy-resolved mode. Figure 4 compares data recorded from a 4-foil target (5000 Å B₅N x 50 μm) with the multilayer monochromator adjusted to detect 117-eV and 165-eV photons. The reflectivity was about 10%, and the bandwidth $\Delta\omega/\omega$ of the overall system was about 6 %, or 8 eV.

Figure 5 compares the data with two predictions of the distribution for 117-eV photon emission the 4-foil target. One prediction uses the nominal target parameters of a 50-μm spacing and 25-eV ω_p , and the other uses a 70-μm spacing and a 21 eV for ω_p . Clearly, the distribution based on the nominal target parameters shows radical departures from the measured distribution. The distribution based on the 70-μm/21-eV parameters shows excellent qualitative agreement with the measured distribution. The choice of 21 eV rather than 20 eV produces noticeably improved agreement for this photon energy.

Figure 4 Energy-resolved angular distributions, 4 foils B₅N

Figure 5 Comparisons of calculations with data, 117 eV.

Figure 6 compares the data with two predictions of the distribution for 165-eV photons from the same target. Again, one prediction uses the nominal target parameters, while the other prediction uses 70- μm spacing and an ω_p of 19 eV. While the difference is not so dramatic as in Fig. 5, the nominal parameters clearly is a poor model of the emission distribution. Here, 19 eV is the ω_p that leads to a good model of the emission distribution, provided that the same 70- μm foil spacing is used.

Figure 6 Comparisons of calculations with data, 165 eV.

DISCUSSION

Figure 4 compares the measured emission distributions from 1-, 2-, and 4-foil targets of 5000- $\text{\AA}$ thick B_5N membranes with nominal foil spacing period of 50 μm . The calculation shown in Fig. 4 of emission from the 4-foil target is a straightforward application of Eqs. (1)-(6). However, some parameters have been adjusted in order to improve the agreement between the calculated and measured distributions. The calculation uses a foil spacing period of 70 μm , rather than the nominal 50 μm , and has used a constant ω_p of 20 eV, rather than the 25 eV that would be calculated from the 1.6 g/cm^3 density of the B_5N . The foil spacing has substantial uncertainty because when the original silicon wafers were manufactured, quality control was more concerned with maintaining parallel surfaces than with achieving a specific thickness. The foil thickness was left at 5000 $\text{\AA}$, as this was determined by ellipsometry for the refractive index, optical interferometry for thickness, and by Rutherford backscattering for total atom content.

With these adjustments, the agreement of general features between the measured and calculated distribution in Fig. 4 is quite good, except that the measured intensity appears to be less than predicted. The intensity discrepancy is greater for the first peak (at ≈ 8 mrad), but the peaks at larger angles seem to show better agreement. However, similar discrepancies are noticed when the data are compared with similar calculations for the 1-foil and 2-foil targets. As mentioned above, this discrepancy probably is due to systematic errors in the beam-current measurement.

The energy-resolved measurements make possible more detailed comparisons between the data and theory. Figures 5 and 6 show comparisons of data and calculations for the 4-foil target and 117-eV and 165-eV photon energies. These comparisons show that not only does the nominal 25-eV ω_p give poor results with the calculations, but the calculations require different ω_p for the different photon energies. For 117-eV photons, the best fit is obtained with $\omega_p = 21$ eV; and with 165-eV photons, the best fit requires $\omega_p = 19$ eV. That the ω_p are smaller than the nominal value of 25 eV implies that the effective electron density contributing to the x-ray dielectric constant is less than would be calculated from the 1.6 g/cm^3 density of B_5N .

The adjustments to ω_p may seem haphazard, but they actually are fairly tightly restricted. The chosen parameters were developed by comparing results from a number of different targets and photon energy ranges. The theoretical models used specific physical dimensions for any given target, while the dielectric constants for different targets were the same for identical photon energy ranges. This is a reasonable approach, since the foil thickness must remain the same for subsequent measurements (damage to or ablation of the target material was not observed). Similarly, except for possible electrostatic forces between individual foils, the foil separation probably is invariant for a given target. Beyond these considerations, there are numerous aspects such as variations in density, stoichiometry, density, or thickness of the B_5N that are too detailed to study with the present data. Thus, the present approach to analysis of the data is not unique or complete. Although the results are not conclusive, our approach has proven useful for interpreting the experimental results.

Figure 7 shows a contour plot of the calculated spectral-

Figure 7 Spectral-angular distribution of 4-foil 5000-Å x 50-μm B_5N target.

angular distribution produced by the 4-foil target. Each level of black contour represents an intensity of roughly 0.1 photons/electron-steradian-eV (each gray scale represents about 0.02 in these units). The effect of x-ray absorption within the target is evident as a dramatic drop in emission intensity as photon energies increase above the boron absorption edge at 187 eV. Here, the calculation assumes a constant ω_p of 20 eV. Thus, line plots from the specific energies will not match exactly the calculated curves in Fig. (5) and (6). The calculated angular distribution in Fig. 2 represents an integration over energy of the contour plot.

The contour plot shows how this target can be used as a tuneable x-ray source. Collimators that select a specific range of angles of angles of emission will select the corresponding portion of the emission distribution. For example, if a collimator passes the angles from 3 to 10 mrad, then the source will be a rather intense broadband soft x-ray source for 100 to 180 eV. However, for angles of emission from 15 to 20 mrad, the photon energy varies rapidly with angle. If a 1-mrad wide collimator selects emissions at 17 mrad, for example, then the emission spectrum will be centered at about 170 eV, with a FWHM of about 30 eV.

Together, the data and calculations show that tuneable TR x-ray sources can be designed and operated. The data above is for a source that is not very efficient, because x-ray absorption in the relatively thick foils prevents the use of a large number of foils. Figure 8 shows a contour plot of the emission distribution from a similar target: 50- μm spacing, but with ten 1800- $\text{\AA}$ thick foils. Again, the contour levels represent 0.1 photons/electron-steradian-eV. The peak intensities are roughly the same as for the 4-foil target in Fig. 7, but the

Figure8 Calculated Spectral-angular distribution of 10-foil 5000- $\text{\AA}$ x 50- μm B₅N target.

distribution is much narrower. Here, the first-order "mode" (from about 11 to 16 mrad has bandwidths similar to Fig. 7, but intensities that are about 25% higher. However, the the second-order mode (from 18 to 25 mrad, produces bandwidths of about 10 eV for a 1-mrad angular selection width with peak intensity that is about 60% of Fig. 7. Data recorded with a 5-foil target of this type has demonstrated emissions with these kinds of characteristics.

CONCLUSION

The data and calculations presented above demonstrate that multiple-foil TR sources can exhibit strong interference behavior which can be described by a simple theoretical prescription. Comparison of data and calculations have led to adjustments in both the x-ray dielectric constant and the foil spacing in the target. With these adjustments, the agreement between experiment and theory is very good.

The data and calculations above demonstrate that multiple-foil targets can generate coherent TR in the x-ray spectral region. The nature of the coherent emission distributions allows these targets to function as tuneable x-ray sources. Analysis of the data found that accurate models of the emission distribution required dielectric constants that were different from those given by the free-electron gas model. Furthermore, details of the emission distributions were very sensitive to changes in the physical dimentions of the target. With 75-MeV electrons, the present targets were restricted to efficient operation in the soft x-ray spectral region. With higher electron energies similar targets would generate coherent output with higher x-ray energies. Together, these results domonstrate the feasibility of tuneable TR x-ray sources, but they demdonstrate also the need to design such sources carefully.

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