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Recent Measurements of Coherent Transition Radiation

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An extended series of experiments has been used to investigate transition radiation in the x-ray spectral region. The x-rays were generated at the Lawrence Livermore National Laboratory electron-positron linear accelerator by 54 MeV electrons traversing multiple thin-foil targets. The measured angular and spectral distributions have shown excellent agreement with calculated predictions based on a simplified theoretical description of transition radiation. Recently, energy-resolved measurements of x-ray generation by targets consisting of multiple closely-spaced foils has clearly demonstrated the longitudinal coherence of transition radiation. This behavior might lead to a variety of applications such as tuneable narrow-band x-ray sources, measurement of x-ray dielectric constants, or particle beam diagnostics. These issues will be discussed and recent results will be presented.

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The study of interactions with photons in the x-ray spectral region has been the focus recently of numerous active research programs. This effort has been encouraged by the advent of new, intense photon sources and by a wide variety of possible applications in fields such as biology, medicine, and industry. For example, x-ray sources such as synchrotron facilities and x-ray lasers are in the process of being applied to techniques such as high resolution medical imaging, x-ray microscopy, and microlithography. The widest and most economical application of these developments will require ever brighter and more efficient photon sources.

In extended series of experiments at the LLNL electron-positron linear accelerator we have studied the feasibility of applying transition radiation in the x-ray spectral region to the issues mentioned above.^{1,2} Transition radiation is generated when an energetic charged particle crosses the boundary between two different dielectric media.³ Figure 1 shows the schematic design of a transition x-ray source. When the thin-foil target is irradiated by relativistic electrons, transition radiation appears as a narrow, forward-directed beam of x-rays.

Our experiments have included extensive measurements of the x-ray spectral and angular distributions for a wide variety of experimental conditions. In most cases, the measured distributions have shown excellent agreement with predictions based on a simplified theoretical description of transition radiation. The results have shown high photon-production efficiencies and have demonstrated the spatial coherence properties of these sources. The data further suggests that it might be feasible to develop transition x-ray sources for a variety of practical applications.

When considering the merits of different x-ray sources, one simple unit of comparison is production efficiency in terms of photons generated per

incident electron. In this case, transition radiation sources driven by 100-MeV electrons can generate more than 10^{-5} photons per 0.1% bandwidth in the soft x-ray spectral region.⁴ This efficiency is many decades greater than those achieved by conventional electron-driven bremsstrahlung or line excitation sources and is at least comparable to the efficiencies of synchrotron sources driven by electrons with energies in the GeV range.⁵

Figure 2 presents a more specific comparison of these sources in units of peak photon brightness. The unit "brightness" is conventional and familiar to workers in this field, but it can paint an unduly gloomy picture of transition radiation. Before concluding that Fig. 2 shows that transition photon sources cannot compete with synchrotron radiation, the reader should note that for many applications (such as microlithography) it may be the spectral flux or total photon emission rate that is important. In this case, when the emission distributions have been integrated over angle of emission and electron beam cross section, we find that the peak transition photon emission rate can be comparable to currently-available synchrotron sources. Although transition photons are radiated into broader "cones," typical divergence half-angles of 3-10 mr are sufficiently narrow to allow efficient optical transport of the beam by conventional methods. In addition to electron beam energy and current, transition radiation sources may have other significant advantages (such as modest vacuum requirements). Thus, for some applications, a careful comparison of overall system performance might find that transition radiation can serve as an advantageous x-ray source.

The most interesting result of our work is the clear demonstration that transition photons are longitudinally coherent with respect to the multiple surfaces in a target. Figure 3 shows measured and calculated angular distributions of 1 keV photons generated in 1-m thick beryllium foils irradiated by

25 MeV electrons. A discussion of this experiment has been published elsewhere.² For our present purposes, note that the measured distribution corresponds clearly to the case where photons generated are coherent with respect to the two surfaces of single foils. The "incoherent" calculation, which simply adds photon intensities generated at the foil surfaces, clearly does not match the measurement. The interference behavior in Fig. 3 is strong, in spite of the fact that the foil thickness ($\sim 1 \mu\text{m}$) is much greater than the photon wavelength ($\sim 15 \text{ \AA}$). This behavior has been demonstrated before with spectral measurements, and it can be used to design transition photon sources that radiate into a desired broad spectral range.⁶ The new feature of our measurements is to use high-resolution absolute measurement of angular distributions to study x-ray emission distributions.

Demonstration of intra-foil coherence was followed by attempts to study inter-foil coherence in multiple-foil targets. The unusual feature of this experiment is that interference phenomena can be demonstrated clearly in systems where foil separations are many decades greater than the wavelengths of interest. This behavior results from Lorentz contraction of the target spacing for the incident electrons, followed by Doppler shifting of photons radiated in forward directions.⁷ In the present case the foil separations of about $100 \mu\text{m}$ are relativistically contracted to wavelengths of about $100 \text{ \AA}$. Early measurements of this behavior were successful with 2-foil targets, but 4-foil targets gave results that did not match perfectly our expectations.⁷ Inaccurate foil-to-foil spacing throughout the multiple-foil target was suspected to be the cause of this difficulty.

Using targets consisting of either two, or four, $1800\text{-\AA}$ thick boron-nitride membranes suspended from silicon wafer frames over 7-mm square clear apertures, we have repeated the measurements. Figure 4 shows preliminary

results for the measured and calculated angular distributions of 2- and 4-foil targets with 100- μm foil separation. While there are discrepancies between the measured and calculated distributions in Fig. 4, there is clear evidence of interference enhancement of emissions by all membranes in the 4-foil target. This process cannot be extended indefinitely, because x-ray absorption and elastic scattering of the electrons will put an upper limit on the number of foils that can be expected to radiate coherently.

As an example of the kind of source that might be developed, Fig. 5 shows a calculated contour plot of photon energy vs. angle of emission for a target consisting of six 5000- $\text{\AA}$ thick boron-nitride membranes separated by 50 μm and irradiated by 100-MeV electrons. The peak intensities of the contours are about 0.1 photons/elec-ster-eV and span a photon energy range from about 0.4 to 1.0 keV. The contours show "Fabry-Perot" type rings, and if circular collimators are used to select the angle of emission, then photon energies can be chosen with a precision of about 10%. Thus, a source following this design could be used as an efficient, weakly monochromatized x-ray generator in the 0.4- to 1.0-keV energy range. By changing the design parameters, targets can be designed to access different portions of the 0.1- to 3.0-keV soft x-ray range.

In conclusion, this paper has presented a brief description of the types of x-ray sources that can be designed with transition radiation. The longitudinally-coherent nature of the emissions allows tuneable pre-selection of the photon energies delivered by these sources. The preliminary results of our experiments suggest that construction of these sources is now feasible. We also have preliminary results suggesting that a number of foil materials will be able to survive incident electron beam currents high enough to produce useful x-ray emission intensities.

Tuneable x-ray sources are only one direction of application for transition radiation. Because of its high intensity and spatially-coherent nature, transition radiation also can be applied to other problems, such as electron beam diagnostics and relativistic particle detection and identification.^{8,9,10} Because of its unique relationship to the dielectric constant, transition radiation can serve as a complementary source of data on the dielectric properties of materials in the x-ray spectral region.^{11,12} In some cases the emission distributions also can be used to study the micro-structural nature of solid materials.¹³ More exciting possibilities relate to the application of these sources to the development of short-wavelength free-electron lasers.¹⁴ The basic physics of these processes have been developed and verified over a long period of time. Current rapid developments in accelerator technology, modern materials fabrication techniques, and x-ray technology may lead to numerous useful applications of these ideas.

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FIGURE CAPTIONS

- Figure 1. This schematic demonstrates the basic operation of a transition radiation source: forward-directed rays are generated when a relativistic electron beam is incident on a target consisting of one or more thin foils.
- Figure 2. This plot shows the approximate spectral brightness of x-ray emissions available from transition radiation, relative to existing (solid curves) and proposed (dashed curves) synchrotron sources.
- Figure 3. Measured and calculated single-foil transition photon angular distributions. The "coherent" sum obtains intensities after adding amplitudes from the foil surfaces, while the "incoherent" form simply adds intensities from the surfaces.
- Figure 4. Comparison of calculated (solid and dashed curves) and measured (squares and circles) angular distributions for 2-foil and 4-foil targets, respectively. The distributions integrate over photon energies from 50 to 200 eV.
- Figure 5. Calculated contour plot of emissions from 6-foil target. The "Fabry-Perot"-type fringes result from coherent contributions by each of the foils. Note the intense emissions below the boron K-edge near 190 eV.

Transition Radiation

FIGURE 1

Figure 2

Fig 3

FIGURE 4

FIG 5