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Characteristics of transition radiation in the x-ray spectral region

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Abstract

Measurements of soft x-ray production by transition radiation have been performed in a series of experiments at the Lawrence Livermore National Laboratory. The results have shown that transition radiation is an intense and predictable source of photons in the soft x-ray energy range. This paper will give a brief review of the general properties of the x-ray distributions generated by these sources.

Introduction

Transition radiation is generated when an energetic charged particle crosses the boundary between two different dielectric media (see Figure 1). For relativistic particles most of the radiation is emitted into a narrow cone in the forward direction. The intensity distribution has a minimum in the direction of the particle velocity, and has a maximum at an angle given roughly by $1/\gamma$ radians, where γ is the relativistic energy parameter (for electrons, $\gamma = E(\text{MeV})/0.511$). The radiation spectrum extends from the microwave well into the x-ray spectral regions. With the current high level of interest in x-ray sources and applications, transition radiation can be used to complement other conventional x-ray generation techniques. Although its intensities will probably never equal the emissions from high-power synchrotron sources, transition radiation has advantages such as high photon production efficiencies with moderate electron energies. For electrons with energies from 10 to 100 MeV, transition radiation can be an efficient source of photons with energies from 0.1 to 30 keV. The integrated emissions in this range can be one to three decades greater than the corresponding Bremsstrahlung emissions.

Figure 1. Schematic diagram of transition radiation mechanism.

At a vacuum-dielectric interface, transition radiation is generated as a particle penetrates a characteristic distance into the dielectric. This characteristic distance, the "formation length," z , (see Figure 2), represents the minimum thickness of dielectric required for efficient photon generation. Transition radiation intensities are roughly proportional to the square of the formation length. Since it is associated with the medium boundary, additional transition photon emission is negligible as the particle penetrates to depths greater than z . For relativistic velocities, the photon emission is nearly identical when the charged particle is crossing a vacuum interface into, or out of, a dielectric medium.

Figure 2. Schematic definition of formation length.

Thus, for efficient transition radiation source design, the system parameters must be chosen such that L is small compared to the characteristic absorption length for the photon energy of interest. For the electron and photon energies mentioned above, the formation length varies roughly from 0.01 to 5 microns, depending on the material chosen. Since the corresponding absorption lengths vary from 0.1 to hundreds of microns, a system can usually be identified that will function as an efficient source.

These considerations lead to some basic characteristics of transition radiation source design. The sources tend to consist of thin foils of a given material. And since a foil has two surfaces, each foil acts as two roughly equal sources. These two sources will be spatially coherent with respect to each other in the direction of the particle velocity, and they will interfere with each other in a manner similar to a double-slit photon interference experiment. This interference behavior can be used to enhance the spatial and spectral distributions of the transition photon emissions by careful choice of the foil thickness.

Depending on the relative sizes of the formation and absorption lengths for the desired photon energy, sources often can be constructed as multiple-foil targets (see Figure 3). This approach increases the integrated photon generation efficiency; but when the total thickness of the foils equals the photon absorption length, further increases in the number of foils give only small improvements in efficiency. Sources based on this design give emission distributions with forms that are similar to the single-foil distributions.

The single-foil spatial coherence mentioned above can extend throughout all of the foils of a multiple-foil target. With proper spacing, this extended coherence can result in sharply enhanced spatial and spectral emission intensities for particular photon energies. The relativistic nature of the emission process means that targets with characteristic foil spacings on the order of microns can coherently generate photons with wavelengths on the order of angstroms. Thus, contemporary advances in the engineering of microscopic structures can be used to design targets that coherently generate soft x-ray photons. This technique has the advantage of better spectral and spatial definition of the emissions. Careful application of this technique may lead to the development of tuneable, narrow-band x-ray sources.

The design principles outlined above are the result of a series of experiments performed with the LLNL electron-positron accelerator. The results of the experiments have been discussed in several publications.¹⁻³ One of the features of the results is that the measured emissions have been accurately predicted by calculations of the expected emissions. The theory of transition radiation was correctly predicted more than forty years ago, and has been a topic of continued study since that time.³⁻⁸ Application of transition radiation has been hampered by the complicated, multiparameter nature of the theories, making it difficult to understand how transition radiation might apply to a given situation. This difficulty can now be avoided with relatively simple computer calculations of transition radiation emission distributions. Although the equations are difficult to interpret, they can be written in forms that are easy to program and use for prediction of expected emissions.^{1,2}

The remainder of this paper will present a variety of calculations intended to demonstrate various characteristics of transition radiation sources. The calculations are

not directed toward any particular application; but are intended to illustrate some of the basic principles of source design and to give an intuitive feeling for the emission distributions that can be expected. The specific equations used for the calculations will not be presented; for a more thorough discussion of the theory, the reader is referred to any of a number of appropriate references.¹⁻³

The formation length

The formation length, z , is the distance in a material over which transition radiation is emitted (see Figure 2). z can be thought of as the distance in the material required for the energetic charged particle to experience a phase shift relative to a photon propagating along with it. This relative phase shift occurs because of the slight difference in velocities between the two particles and can result in some of the electron kinetic energy being converted to emitted photons. In this respect, the emission process is analogous to the operation of a microwave travelling-wave amplifier.

z is a function of the particle energy, the photon angle of emission, and the material dielectric constant, which is itself a function of the photon energy. Because of complicated multiple parameter dependencies, z is difficult to characterize in general. One consistent dependence is that, for a given photon energy, z tends to increase with particle energy. Figure 4 shows the dependence of z on electron energy for three different materials, with 3 keV photons and an angle of emission of $1/\gamma$ radians. The calculations in Figure 4 have assumed an approximate form for the dielectric constant, $\epsilon(\omega)$, of the material (given by the Drude free-electron theory as $\epsilon(\omega) = 1 - \omega_p^2/\omega^2$, where ω is the photon angular frequency and ω_p is the plasma frequency of the material given by $\omega_p = \sqrt{4\pi n e^2/m}$). Here, n is the electron density, e is the electronic charge, and m is the electron mass.)

Transition radiation

Figure 3. Multiple-foil transition radiation x-ray source.

Figure 4. Formation length vs electron energy.

The plots in Figure 4. show that λ is on the order of microns for the electron energies of interest, that λ increases with particle energy, and that λ decreases with increasing electron density of the material.

Single-foil emissions

The transition radiation generated by a single foil exposed to relativistic electrons can be written in the simplest form as:

$$dN/d\omega = (4\pi/\omega) (N) (1/\omega)$$

where N is the number of photons, and α is the fine structure constant ($\alpha = 1/137$). This formula is roughly correct for all frequencies ω less than γ times the plasma frequency of the material, ω_p . For frequencies greater than $\gamma\omega_p$, the emissions decline rapidly with increasing frequency.

For a more detailed description of the emissions, Figures 5a and 5b show the angular and spectral distributions, respectively of x rays generated by a single 1-micron thick beryllium foil exposed to 50 MeV electrons. The angular distribution is for 1 keV photons, and the spectrum is calculated for an angle of emission of $1/\gamma$ (9.4 mrad). Figure 5 shows that the angular distribution peaks at an angle near $1/\gamma$ and that the spectrum peaks near 1 keV.

Figure 5a. Angular distribution.

Figure 5b. X-ray spectrum.

Figure 5. Transition radiation x-ray distributions.

Multiple-foil emissions

The 1-micron thick beryllium foil can be used as the basis of a high-intensity source of x rays with energies between 1 and 2 keV. This is an interesting case to consider because of its possible application to x ray microlithography. Figure 6 shows the angle-integrated spectrum of x rays generated by targets consisting of 30, 60, and 120 foils exposed to 100 MeV electrons. The foils are spaced far enough apart (3 mm) that coherent interference between the individual foils is not important. The results are expressed in terms of joules of x-rays per coulomb of incident charge. The calculations include the effects of x-ray absorption in the foils. The plots show that increases in emission with increasing number of foils results mainly in a "hardening" of the photon spectrum. This happens because the "softer" x rays generated in the front of the target are unable to penetrate the additional foils before being emitted from the target. But, the "harder" photons, with their longer absorption lengths can penetrate the entire target and are seen in the final emissions.

The foil thickness also can be used as a design parameter. Figure 7 shows the angle-integrated emissions from a target consisting of 60 foils with thicknesses of 0.5, 1, and 2 microns exposed to 100 MeV electrons. Here, the effects are more complicated, because increasing the foil thickness increases the x-ray absorption; and it also changes the photon energies that enjoy the enhancement associated with coherent interference between the two surfaces of each foil.

Figure 6. Angle-integrated x-ray spectrum vs number of foils.

Figure 7. Angle-integrated spectrum vs foil thickness.

Figure 8 shows the angular distribution of photons emitted with energies between 1 and 2 keV from a target consisting of 60 beryllium foils with the same thicknesses as above exposed to 100 MeV electrons. Again, the distributions peak at an angle near $1/\gamma$. For a realistic source, the incident electron beam could have an emittance large enough that the sharp emission minimum in the direction of the electron velocity would be "washed out" to give a roughly uniform distribution out to angles of about 10 mrad .

Multiple-foil coherence

Our most recent results have measured soft x-ray emissions from sources in which the foil-to-foil spacing was close enough that interference effects between foils were clearly observed in the measured distributions.^{3,4} Again, for two-foil targets, we have succeeded in predicting the measured emissions with calculations. Multiple-foil targets of this type are interesting because they might ultimately lead to the development of narrow-band, tuneable x-ray sources. In this case, x-ray energies would vary in a prescribed fashion with angle of emission. At any given angle, the photon energy, E , would have a definition $\Delta E/E$ of about $1/N$, where N is the number of foils in the target.

Figure 8. Angular Distribution of x rays from 1 to 2 keV.

Figure 9 shows a 3d contour plot of the calculated photon energy vs angle of emission for a target consisting of twelve 0.36-micron thick polypropylene foils exposed to 54 MeV electrons. The distribution is dominated by one emission band that could be used as a tuneable source from roughly 140 eV to 229 eV photons by varying the accepted angle of emission from 10 to 8 mrad, respectively. Although it is not obvious in this plot, the photons would have about 8% energy definition at any point in this range. Unfortunately, in the laboratory, we have not succeeded in demonstrating well-defined interference in targets with more than two foils. We believe that this limitation reflects the precision of our current target fabrication techniques, and we are working to find better ways to build these sources.

Figure 9. Contour plot of x-ray energy vs angle of emission.

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