SOFT X-RAY PRODUCTION BY MEANS OF AN ELECTRON BEAM

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Abstract

The possibility to use the ELSA electron linac as a driver for an X-ray transition radiation source is considered. Soft X-ray pulses as short as 10 to 20 ps, in the energy range 0.5 to 2 keV can be produced by means of this process. Numerical computations to design multifoil targets as well as multilayers of two materials of different permittivities are presented. Spectral peak brightness curves are derived and a test experiment is described.

1 INTRODUCTION

The interest for intense X-ray sources has considerably increased in the last few years. Until now, only synchrotron radiation sources have been widely used. The main advantage of these sources is to reach a high continuous photon flux owing to the electron beam recirculation in the storage ring. Another advantage of using synchrotron-radiation sources is the high degree of collimation of the photon beam emitted close to the electron-orbit plane. However, in many experiments (plasma physics, fluorescence measurement, etc…), the continuous aspect of the source is useless and only the single-pulse mode of operation is of interest. Consequently, one can consider the use of X-ray sources driven by electron linacs of moderate energy. An important advantage of these machines is the short-pulse mode of operation (pulses of the order of picoseconds are frequently available) that allows temporal investigation of the physical properties of matter. Many physical processes of X-ray production have been investigated, involving the interaction of relativistic electrons with amorphous media or crystals [1]. Channeling radiation, coherent bremsstrahlung and parametric X radiation can be generated from single crystals, and transition radiation can be produced from a foil stack of amorphous materials.

The transition radiation process has been widely studied and used in our laboratory since many years for beam diagnostics, in the visible domain, on the ELSA electron linac [2]. Taking advantage of this experience we have considered the possibility of installing a soft X-ray source on the ELSA linac. A possible application of this source concerns the exploration of atomic processes involved in plasma physics.

We present here two types of X-ray producing targets: the foil stack and the multi-layer arrangement. The first part of this paper is devoted to theoretical consideration in order to derive expressions allowing to predict the intensity radiated with each type of source. Then, the ELSA electron linac is presented and performances of the proposed X-ray sources are discussed. An experimental set-up with a foil-stack target is also described and preliminary results are commented.

2 THEORETICAL ASPECT

Transition radiation (TR) is intensively used as a source of visible light for beam diagnostics on many electron accelerators for, at least, two decades [3]. Radiation is emitted when a charged particle crosses the interface separating two media of different permittivities, and most of this radiation is emitted in a cone with an apex angle proportional to the inverse of the particle Lorentz factor. In the soft X-ray domain, the radiation is emitted only in the forward direction. In this short wavelength region, the permittivity ε can be approximated by the Drude-model formula for a free-electron gas; this gives, for $\omega \gg \omega_p$:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

where ω_p is the plasma pulsation and ω is the radiation pulsation. With this approximation, the spectral density of photons emitted per unit solid angle by a relativistic electron crossing the interface between two media with ω_{1p} and ω_{2p} plasma pulsations, can be written as follows :

$$\frac{d^2I}{d\Omega.d\omega} = \frac{e^2}{\pi^2 c}\sin^2\theta\left[\frac{1}{\gamma^{-2}+\theta^2+\dfrac{\omega_{1p}^2}{\omega^2}} - \frac{1}{\gamma^{-2}+\theta^2+\dfrac{\omega_{2p}^2}{\omega^2}}\right]^2$$

where e is the electron charge, c the light velocity, γ the incident-particle Lorentz factor and θ the direction of the emitted radiation with respect to the normal to the interface. This equation shows that the radiated intensity is maximum for a vacuum-to-medium transition, whereas for a medium-to-medium transition, the yield is considerably reduced because of the close values of plasma frequencies even in the case of materials with very different Z.

If we consider a stack of M foils with permittivity ε_1 sandwiched between M foils with permittivity ε_2, the intensity radiated by the stack can be expressed, for weak X-ray absorption and M sufficiently high, as:

$$\frac{d^2I_t}{d\Omega.d\omega} = \frac{d^2I}{d\Omega.d\omega}\Phi_2^2\frac{\sin^2\left(\dfrac{\Phi_2}{2}\right)}{\left(\dfrac{\Phi_2}{2}\right)^2}\frac{\sin^2\left(\dfrac{MX}{2}\right)}{\sin^2\left(\dfrac{X}{2}\right)}$$

In this expression, Φ_2 is the phase difference between photons produced at the front and the back of a foil with permittivity ε_2 and $X = \Phi_1 + \Phi_2$ is the sum of phase differences of two successive foils. This expression is formally analogous to the one giving the intensity diffracted by a grating in classical optics, and it shows that if the phase differences are correctly matched, i.e., if:

$$\Phi_2 = (2m+1)\pi \Rightarrow \sin^2\left(\frac{\Phi_2}{2}\right) = 1$$

and simultaneously:

$$X = \Phi_1 + \Phi_2 = 2p\pi \Rightarrow \frac{\sin^2\left(\frac{MX}{2}\right)}{\sin^2\left(\frac{X}{2}\right)} = M^2$$

m and $p \neq 0$ being integer numbers, then the radiated intensity is increased and we obtain:

$$\frac{d^2 I_t}{d\Omega . d\omega} = 4M^2 \frac{d^2 I}{d\Omega . d\omega}$$

which shows that the intensity is proportional to the square of the number of foil pairs in the stack.

3 SIMULATION RESULTS

The detailed features of the TR angular and spectral distributions can be derived from the above settled formulas. We can then design a photon source having the required properties for a dedicated experiment. The characteristics of the target, which may be a foil stack or a multi-layer arrangement, can be optimized to produce either the maximum spectral brightness per bunch or the minimum angular spread of X-rays in a given wavelength range. For the purpose of our future works, the design of an X-ray source should satisfy a good compromise between high spectral brightness and small emission cone.

3.1 Foil stack

The foil stack consists of a mechanical assembly of thin foils tight between rings and separated by vacuum. In the simulations, only Mylar, Al and Be foils have been considered, because they are easy to handle and X-ray absorption is reduced for these low-Z materials. Calculations indicated that, to enhance radiation production and to minimize absorption and Coulomb scattering within the target assembly, the thickness of the foils and, above all, their spacing must be very small.

Simulation results for a Mylar-foil stack are displayed in Fig. 1, showing the spectral brightness per bunch as a function of X-ray energy. Calculations were performed for a target assembly of 10 Mylar foils, 1.5 µm thick, with 10 µm spacing, and for an ELSA electron-beam energy of 18 MeV and a charge per bunch of 5 nC. These data, labelled ELSA in Fig. 1, are compared with estimated synchrotron-radiation yields from the ESRF 6-GeV electron beam through a 22.36-m radius bending magnet (labelled ESRF) and from the Super-ACO 800-MeV electron beam through a 1.80-m radius bending magnet (labelled Super-ACO).

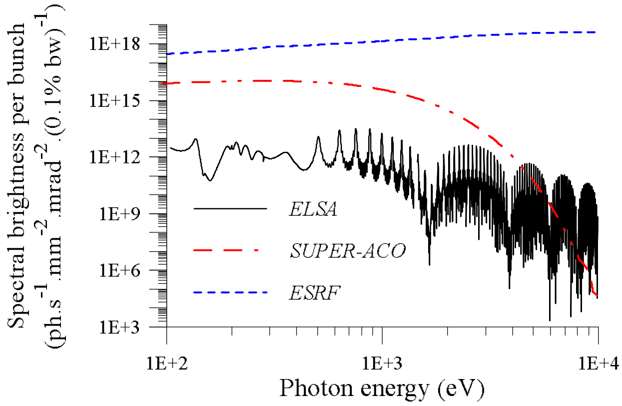

Figure 1: Comparison of bunch spectral brightnesses of the ELSA, ESRF and Super-ACO X-ray sources.

The ELSA X-ray-source capabilities are shown to be comparable, in the keV energy range, to synchrotron-radiation sources driven by medium-energy electron storage rings.

3.2 Multi-layer target

The above described target assembly would be difficult to machine. To avoid difficulties encountered with the very small foil spacing, we have considered the possibility of making a multi-layer target.

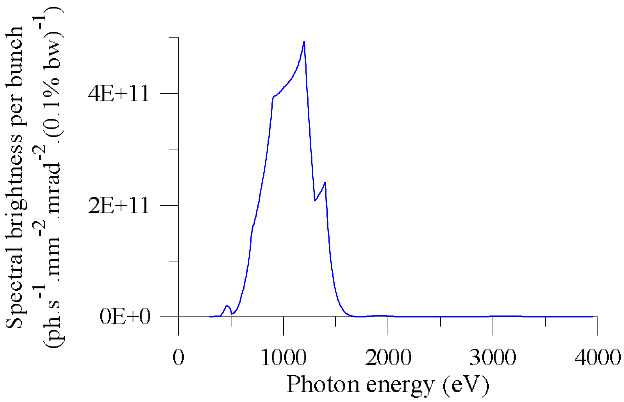

Figure 2: Bunch spectral brightness of a C-Al multi-layer target with a 18-MeV, 5-nC/bunch electron beam.

The multi-layer arrangement is made by evaporating or depositing on a substrate a first layer of given material and thickness, and, over it, another one with different characteristics, then by repeating M times the operation. Many materials can be evaporated under vacuum or deposited in µm-size layers. Simulations were performed for an electron beam of 18 MeV energy and 5 nC/bunch charge on a target made of 5 successive C-Al transitions. Bunch spectral brightness was optimized by varying the C and Al-layer thicknesses. Best results were obtained with thicknesses of 0.50 µm for C and 0.54 µm for Al;

they are displayed in Fig. 2. Calculations were also done for a Al-Au multi-layer target, indicating a slight enhancement of the radiation yield.

5 EXPERIMENTAL SET-UP

The foil-stack target can be used even with a very large foil spacing. Radiation production is, however, reduced since interferences between foils vanish. Such a target has been designed, built and installed on the ELSA linac. It consists of a stack of five 0.5-µm-thick Mylar foils with 3.5 mm spacing. The radiation yield expected with this arrangement is displayed in Fig. 3.

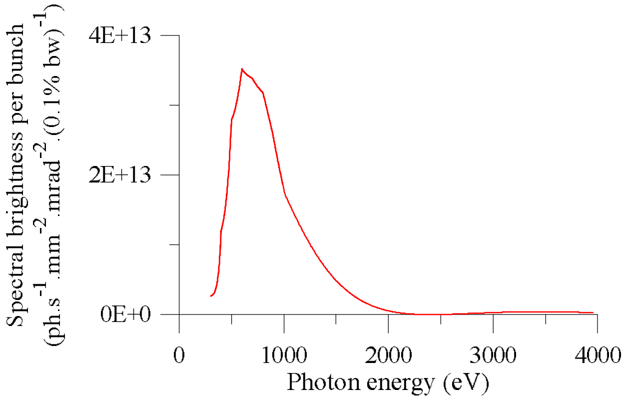

Figure 3: Bunch spectral brightness of the Mylar-foil stack installed on the ELSA accelerator.

The foil stack is located near the end of the accelerator beam line. This accelerator, originally designed for free-electron laser (FEL) experiments, has been described in detail elsewhere [4]; only characteristic features are recalled here. The linac is composed of a laser-driven photoinjector cavity followed by three accelerating cavities. It delivers a pulsed electron beam of 18-20 MeV maximum energy. The temporal structure consists of macropulses of 20 to 150 µs duration, at a maximum repetition rate of 10 Hz. The macropulse consists of 20-ps long micropulses at a repetition rate of 14.4 MHz. The extracted charge is routinely 1 to 5 nC/ micropulse. The beam is deflected in the optical FEL line by a 180° bending-magnet system. At the end of this beam line, the beam is deflected and trapped in a 150° bending magnet followed by a Faraday cup used as a current monitor.

The X-ray transition radiation (XTR) experimental set-up, schematically described in Fig. 4, is located inside the FEL optical line. The foil stack is centered on the object point of the 150° magnetic spectrometer. The foils are inclined at 45° with respect to the electron-beam axis, in the horizontal plane. X-ray detection and electron-beam monitoring are made as follows:

- the first foil of the stack is aluminized in order to produce backward optical transition radiation for beam observation and tuning on the target,

-X-rays produced in the stack impinge on a NE 102 A plastic scintillator where short-wavelength radiation is converted into visible light. The scintillator front end is aluminized to suppress, in the measured spectra, the background visible and UV light from forward transition radiation. Observation of the converted light is made with a vidicon camera located off the beam axis and heavily shielded with lead to avoid X-ray noise. Image acquisition is made by a frame grabber.

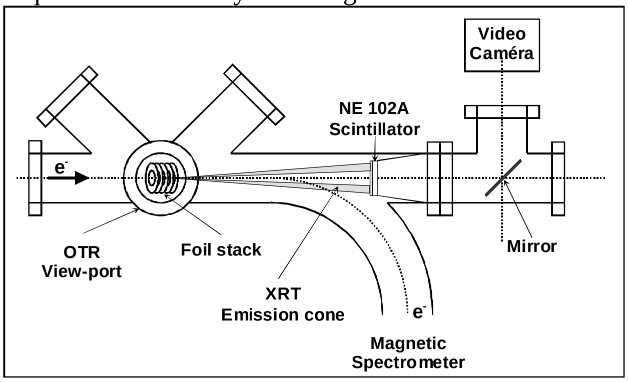

Figure 4: Layout of the X-ray experimental set-up.

Preliminary tests of the experimental set-up have been performed by observing the characteristic O-ring pattern of the X-ray angular distribution. The O-ring image was highly shifted on the TV screen because the electron-beam trajectory was bent by an important magnetic fringe field in the vicinity of the foil stack. Modifications of the set-up must, thus, be done.

7 CONCLUSION

The foil stack has been shielded against the fringe field by putting Armco iron plates between the stack and the spectrometer entrance. Measurements indicate an important field reduction in front of the plates.

Experiments are planned and will be performed soon in which the X-ray angular distribution will be again observed and spectral distribution will be measured with appropriate detectors.

8 ACKNOWLEDGMENTS

The authors wish to thank all the ELSA staff, especially S. Seguin for building the foil-stack targets.

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