Novel X-ray sources Produced by Electron Beams

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Abstract

High-intensity X-ray beams are routinely used in a wide variety of applications in atomic and solid state physics, medicine, biology and materials science. New developments achieved in the design and construction of strong radiation sources such as synchrotron radiation laboratories and X-ray lasers have contributed to the rapid growth of activities in this field. Due to the considerable investments in man-power and funds needed to build and operate such facilities it seems appropriate to look for alternative methods which might be used in some cases and could be achieved on a smaller scale. Production of high-intensity X-ray beams using electron accelerators of moderate energy has been studied during the past few years at several laboratories. A description of the main techniques used to produce intense radiation from optical wavelengths to MeV energies is given, with special emphasis on transition radiation, channeling radiation and coherent bremsstrahlung. The main characteristics of the X-ray beams, i.e. intensity, spectrum and angular distribution, are discussed and compared to other radiation sources. The advantages and limitations of the different techniques in view of possible applications are given.

1. INTRODUCTION

In many fields of solid state physics and atomic physics X–rays with wavelengths of the order of the interatomic distances are a valuable tool for research and applications and there is a rapidly growing demand for strong radiation sources. Undoubtedly, synchrotron radiation (SR) has proven to be one of the brightest sources in the VUV and soft-X-ray energy domain and special insertion devices have been installed at SR laboratories to optimize the spectral flux according to the needs requested for the different experiments. New developments in the free–electron-laser (FEL) technique will complement these radiation sources at longer wavelengths.

Compared to synchrotron radiation, the photon flux intensity obtained using other techniques at electron accelerators of moderate energy is relatively low. Although the photon flux per electron is much higher for these other types of radiation, in a synchrotron or storage ring the recirculation of the electrons gives a much larger average current and, therefore, the photon flux per second is drastically enhanced. A second advantage of SR over accelerator-based radiation is the rather strong collimation and the high degree of polarization of SR emitted close to the plane of the electron orbit.

There are, however, several situations where these disadvantages of accelerator-based radiation can at least partly be compensated for. Accelerators of 50-200 MeV are relatively inexpensive and readily available at a number of laboratories. Without any modification they could be used to produce intense radiation from infrared (IR) to X-rays of several 100 keV using suitable radiators according to the techniques described below. In order to have a measure for the usefulness of these techniques, the intensities will be compared to SR from bending magnets at BESSY and ESRF and from a 5 T wavelength shifter at ESRF as an example for a SR source in the hard-X-ray energy domain.

All of these techniques have been studied theoretically in great detail and for most of them extensive experimental work has been performed in order to characterize the radiation. It would be beyond the scope of this paper to give a concise list of publications. The reference list given here may serve as a convenient introduction into the different fields and be helpful in finding further references to recent experimental work.

2. TRANSITION RADIATION

Transition radiation (TR) is emitted when a charged particle crosses the boundary between two media of different electrical or magnetical properties [1]. TR can be described conveniently in dipole approximation in the rest frame of the electron.Therefore, the angular distribution of the emitted radiation is strongly peaked forward in the laboratory, with a typical opening angle of $2/\gamma$, γ being the electron energy in units of the electron rest mass. Contrary to SR, which is isotropic in the plane of the electron orbit, TR is axially symmetric with an intensity maximum at an angle $1/\gamma$ to the beam axis and very small intensity on the axis. The intensity of TR rises with increasing electron energy.

The spectral distribution shows a threshold effect which is used to discriminate between ultrarelativistic charged particles of different mass in TR-detectors [2]. At optical wavelengths TR has been used successfully as a monitor to determine the energy and emittance of electron beams in an accelerator [3,4].

TR from a stack of foils of appropriate thickness can be used as a practical radiation source in the soft-X-ray energy domain. Fig.1 shows the calculated brightness of a TR source proposed for X-ray lithography [5], consisting of 25 Be foils of 2.1 μm thickness, for a beam energy of 245 MeV and 100 μA beam current.

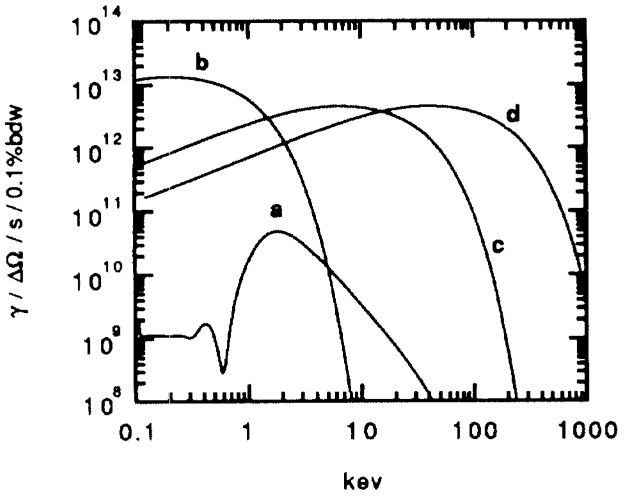

Figure 1. Brightness of a) TR using a 245 MeV beam and a stack of Be foils. b) SR at BESSY. c) SR at ESRF. d) SR from a 5T wavelength shifter at ESRF. Opening angles: 2/γ.

For comparison, in Fig.1 is also shown the brightness of SR produced at the bending magnets of BESSY and ESRF, and assuming a 5T wavelength shifter at ESRF. The horizontal and vertical collimation was assumed to be ±2/γ, which corresponds to an exposure area of about 2x2 cm^2 at practical distances. Although the brightness of TR is considerably smaller than the brightness of SR in the 1-2 keV range, in several experiments on X-ray lithography it has been demonstrated that sufficient power densities are obtained to expose wafers in a reasonable time. Exposure times as short as 180 sec have been achieved [5].

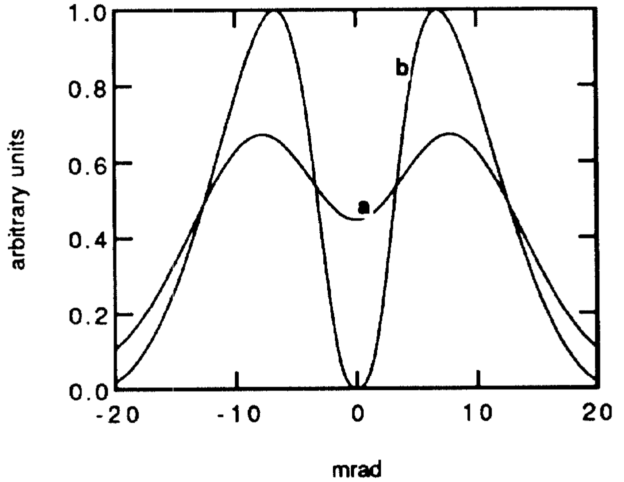

Figure 2. Angular distribution of TR emitted by a 100 MeV electron beam. a) beam divergence of 10 mrad. b) no beam divergence.

The characteristic angular distribution of TR is of some disadvantage in the exposure of the wafers. The homogeneity of the exposure could be improved by sweeping the electron beam across the foil [5]. An alternative method would be to defocus the electron beam to an angular divergence of the order 1/γ compromising between homogeneity and some loss in resolution. Fig.2 demonstrates the difference in the radiation pattern when a collimated beam and a beam with an angular divergence of 2/γ (FWHM) are used.

The total power emitted by TR is concentrated in a narrow energy band of about 1-2 keV, depending on the photon attenuation in the radiators. This results in a much reduced heating load as compared to the use of SR, when measuring without windows at long wavelengths. Using materials with suitable absorption edges in the 1-10 keV energy range an additional narrowing of the spectra is obtained [6]. Fig.3 shows TR spectra calculated for a 100 MeV electron beam and stacks of Be and Al foils, respectively.

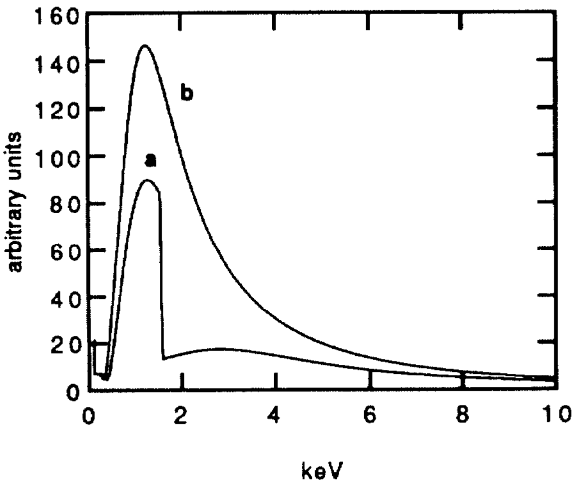

Figure 3. TR spectra produced using a 100 MeV electron beam. a) stack of 11 foils of 0.8 μm Al. b) stack of 25 foils of 2.1 μm Be.

Of great advantage would be the excellent time resolution obtained when the micro-bunch structure associated with the GHz rf modulation in a LINAC is used. At the Geel linear accelerator, in a typical 'short burst' operation mode electron pulses of 10 ns length are accelerated at a peak current of 12 A (i.e. 120 nC per pulse) and at a repetition rate of 800 Hz. In each of these pulses there are 30 micro-bunches of typically 10 ps length. Due to the filling time of about 1 μs of the cavities the energy of the electrons in the different micro-bunches is not constant. This is used in a specially designed magnetic structure to compress the 10 ns pulse length to less than 1 ns (FWHM). The same magnetic device could be used to isolate the individual micro-bunches. In Fig.4 the flux of TR produced by one of these micro-bunches is compared to the flux produced by one single bunch at the SR sources of Fig.1 assuming $2x10^{11}$ electrons per bunch. Although a significant amount of TR is produced per electron bunch, the rather low repetition rate of only 1 kHz for a LINAC as compared to MHz for a synchrotron or storage ring will be a severe limitation for many applications.

The total energy in the TR spectrum integrated up to 10 keV amounts to about 250 J/C which corresponds to a peak power of 100 kW radiated by each micro-bunch of 4 nC and 10 ps duration. Reduction of the peak current would further improve this time resolution.

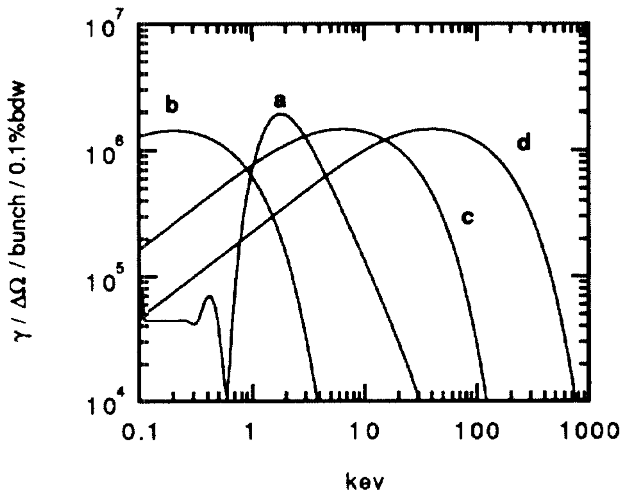

Figure 4. a) TR produced by one LINAC micro-bunch of 4 nC. b)-d) SR produced by one electron bunch of $2x10^{11}$ electrons for SR sources as given in Fig.1 .

3. CHANNELING RADIATION

When single crystals are used as radiators large enhancements in the observed yield can be obtained due to interference effects. If the electrons enter the crystal at small angles relative to a crystal axis or plane they can be guided along that axis or plane, performing an oscillatory motion [7]. This motion leads to the emission of electromagnetic radiation, as in an undulator [8-10]. The spectrum of channeling radiation (CR) can be calculated from radiative transitions between bound levels in the crystal potential determining the transverse motion. Typical transition energies are of the order of several 10 eV in the rest frame of the electron. After Lorentz transformation into the laboratory frame, the energy of the emitted radiation is of the order of 10-100 keV for electrons of 10-100 MeV [11-13]. Fig.5 shows a recent measurement performed with a 5.9 MeV electron beam and a diamond crystal [14]. The photon lines corresponding to different transitions are clearly visible.

The photon energy ω scales with the electron energy approximately according to $\omega \sim \omega_0 \gamma^{\alpha}$ with exponents α of the order of 1.5- 3 , depending on the crystal potential and the levels involved [11,14]. The intensity strongly increases with energy. Calculations [15] show that with a 130 MeV electron beam of 20 μA, between 10^{10} and 10^{12} photons per second and per 10% bandwidth can be expected between 1 keV and 1 MeV.

The maximum intensity of CR is observed in the forward direction, which makes this type of radiation convenient to use in connection with monochromators. The radiation is elliptically polarized with the degree of polarization depending on the motion of the electron inside the crystal, i.e. axial or planar channeling.

Using positrons for production of CR reduces the bandwidth of the spectrum because the positrons oscillate in an almost harmonic potential and the transverse energy levels are nearly equidistant, but the intensity of CR produced by electrons is much larger.

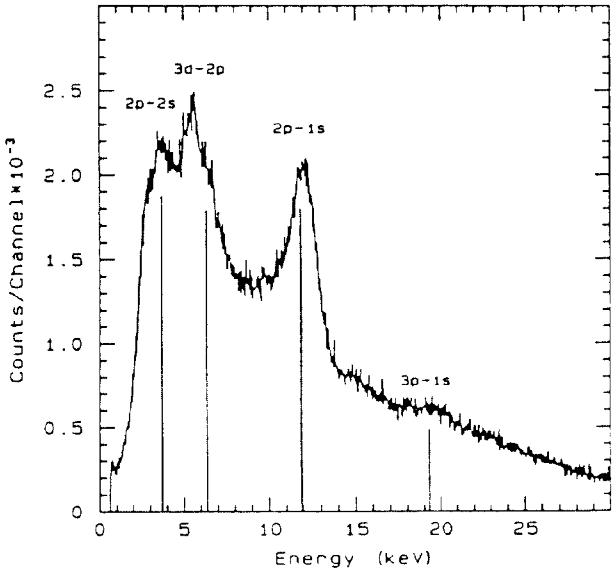

Figure 5. Channeling radiation spectrum obtained from 5.9 MeV electrons channeled along the [110] axis of diamond [14]. Contributions due to bremsstrahlung have been subtracted (20% at 12 keV).

4. COHERENT BREMSSTRAHLUNG

The conditions under which CR can be observed are determined essentially by the Lindhard characteristic angle [7], which is of the order of a few mrad for electrons of 100 MeV. At incident angles larger than the Lindhard angle the transverse momentum becomes too large and the electron is no longer guided along the axis or plane. Therefore, mainly bremsstrahlung from collisions with the atoms of the crystal will be observed. Under certain kinematical conditions the bremsstrahlung contributions from the individual atoms along a row in the crystal can interfere and a strong enhancement of the intensity is observed [16-18].

The coherent bremsstrahlung (CB) spectrum shows discontinuities at characteristic energies dependent on the electron energy and on the incident angle of the electron with respect to a crystal axis. Fig.6 shows the CB spectrum calcuated for a 200 MeV electron beam moving close to a [111] axis in a diamond crystal of 25 μm thickness. Contributions from normal (i.e. incoherent) bremsstrahlung have been subtracted (10% at the first peak). The brightness of SR emitted from bending magnets and from a 5 T wavelength shifter at ESRF is shown for comparison.

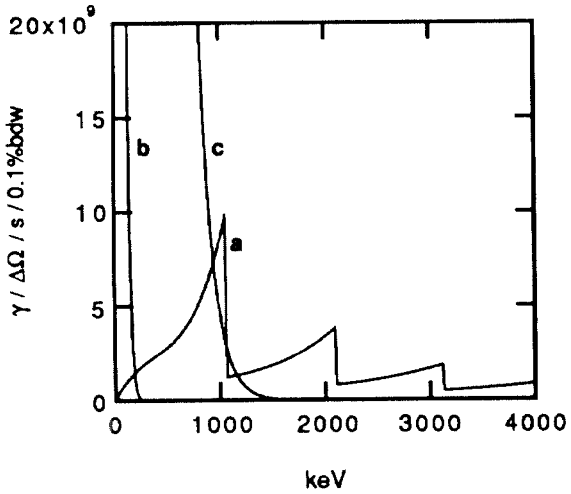

Figure 6. Brightness of hard X-ray spectra in the MeV energy domain. a) Coherent bremsstrahlung for 200 MeV electrons moving close to a [111] axis in a diamond crystal of 25 μm thickness (background due to incoherent bremsstrahlung subtracted : 10% at the first peak).
b) SR from a bending magnet at ESRF. c) SR from a 5 T wavelength shifter at ESRF.

As can be seen from Fig.6, coherent bremsstrahlung is a radiation source of very high brightness at energies of several 100 keV and in the MeV energy domain. CB could be used in photon scattering experiments, i.e. in Compton scattering for the determination of electron momentum distributions in solids [19].

The position of the peaks in the spectrum can be easily changed by tilting the crystal. The intensity, however, decreases rapidly with increasing incident angle. For practical reasons, optimum conditions for CB are found at photon energies of the order of several percent of the electron energy.

At the peak maxima the CB is strongly polarized. Collimation of the photon flux reduces the amount of CB in the low-energy tails of the individual peaks, thus further reducing the bandwidth of the individual lines.

5. PARAMETRIC X-RAYS

Parametric X-rays (PX) are produced by relativistic charged particles travelling in single crystals. Unlike CB and CR, PX are observed at large angles relative to the beam axis. The effect can be considered as the diffraction of the virtual photons associated with the relativistic charged particle by the crystallographic planes (see [20-22] and references given therein).

The observed spectrum shows prominent peaks at energies defined by the Bragg angles relative to the crystallographic planes. These angles do not depend on the particle energy. Therefore, the position of the peaks in the spectrum can be changed tilting the crystal or changing the angle of observation [21].

Typical PX energies are of the order of several keV, thus complementing TR and CR. The intensity increases slowly with the electron energy. Electron beams of 200-400 MeV seem to be most advantageous [22]. As for CB, collimation of the photon beam offers the possibility to reduce the bandwith of the observed radiation and to take advantage of the high degree of polarization.

6. SMITH-PURCELL EFFECT

At long wavelengths in the infrared energy domain new developments in FEL construction show promising results and a number of user facilities are coming into operation [23]. Infrared FEL radiation is produced at accelerators of typically 10-100 MeV using suitable undulators. These complex and expensive instruments as well as the severe demands for low emittance beams make the use of a conventional accelerator as a FEL source a difficult task. The Smith-Purcell effect could be a method to produce IR radiation of high intensity with less stringent demands on the beam quality and using simple optical gratings.

In the Smith-Purcell effect, radiation is produced by fast charged particles moving close and parallel to the surface of an electrically conducting grating. It can be considered as the diffraction of the virtual photons associated with the relativistic charged particle by the grating. The wavelength depends on the angle of observation, the periodic length of the grating, and the velocity of the particle [24,25].

To our knowledge, all the experiments and calculations published until now have been performed for electron energies of the order of 10-100 keV. It seems that at relativistic energies a considerable increase in intensity can be expected. Detailed calculations are currently being carried out in order to investigate the potential use of this effect as a source for intense IR radiation and to make quantitative comparisons with other radiation sources.

Table 1. Spectral ranges of typical application for accelerator-based radiation using electron beams of 20-200 MeV

radiation	energy range	bandwidth	energy tuning	polarization
Smith-Purcell Effect	infrared	10 - 50% depending on collimation	changing the angle of observation	
Transition Radiation	0.5 - 20 keV	50% depending on absorption properties	energy mainly determined by radiator	
Parametric X-rays	10 - 50 keV	10 - 50% depending on collimation	tilting the crystal and changing the angle of observation	linear polarization
Channeling Radiation	10 - 1000 keV	10 - 20% in the individual lines	changing the energy of the electron	elliptical polarization
Coh. Bremsstrahlung	0.1 - 10 MeV	10 - 50% depending on collimation	tilting the crystal	linear polarization at peak maxima

7. CONCLUSIONS

Electron accelerators of moderate energy can be used as intense radiation sources in a broad spectral range without need for costly modifications. Different types of radiation can be chosen according to the spectral range of interest, by simply exchanging the radiators in use. In Table 1 the spectral range and main properties of these radiations are summarized.

Although less intense than specialized facilities like FEL or SR sources, accelerator-based radiation offers some features which make it attractive for test purposes and for research and applications on a smaller scale:

- tunability from IR to MeV energies
- high natural collimation with opening angles of a few mrad depending on the electron energy
- partially polarized
- excellent time resolution with high power in a single pulse
- simple installation on available facilities

Beam currents of the order of 100 μA at 20-200 MeV are best suited for these applications. In many cases the low duty-factor of a LINAC beam is of disadvantage, in particular in measurements characterizing the radiation. In such cases a c.w. beam from a microtron or stretcher ring would be favourable whereas the good time resolution achieved in a LINAC would be of advantage in time-resolved measurements. A beam emittance better than 10^{-1} π·mm·mrad is advisable.

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