A 15 MEV LINEAR ELECTRON ACCELERATOR BASED SOURCE OF TUNABLE MONOCHROMATIC X-RAYS

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Abstract

In an increasing range of research fields there is a strong demand of high-intensity tunable monochromatic X-ray sources. A promising new approach for the production of tunable high-intensity monochromatic beams in the hard X-ray region is the use of electron accelerators of moderate energy (10 MeV range). We developed at the 15 MeV linear electron accelerator of the Ghent University a monochromatic X-ray source with a resolution better than 0.1%, tunable in the energy region between 60 and 700 keV. The original concept is based on the monochromatisation of a broad bremsstrahlung spectrum produced with a high-intensity electron beam, by Bragg-Laue diffraction on a curved single-crystal and focussing through a slit system. The intensity of the monochromatic beams is highly dependent on the quality of the high-power beams delivered by the electron accelerator. The design, construction, performance and some applications of the source are described in detail.

1 INTRODUCTION

X-rays play a key role as an analytical probe in many fields of physics, chemistry, biology and medicine, and as a tool in materials science and technology. The advent of synchrotron radiation facilities has contributed to a rapid growth of research activities in these fields. Undoubtedly, synchrotron radiation facilities have proven to be the brightest sources in the VUV and soft X-ray region. They opened many new windows for experimental studies and created a wealth of possibilities for novel applications. However, the number of synchrotron radiation production facilities is rather limited. The major reason is the fact that very high investment costs in equipment and man-power are required. The beam-time demand at every existing synchrotron radiation facility is largely surpassed by the available beam-time. Therefore it seems appropriate to investigate new production methods which might be used on a smaller 'laboratory' scale.

Production of high-intensity X-ray beams using electron accelerators of moderate energy (10 - 100 MeV) seems to be a promising alternative. Based on earlier theoretical predictions, experimental studies of different accelerator-based production mechanisms were started in recent years at various laboratories all over the world.

The main X-ray production phenomena under investigation are: transition radiation, channeling radiation, parametric X-ray radiation, Smith Purcell radiation, grating transition radiation and diffracted bremsstrahlung. A detailed overview of this research on novel radiation sources using relativistic electrons can be found in [1]. The last two phenomena are studied at our Ghent University 15 MeV linear electron accelerator [2,3]. Extensive theoretical and experimental studies are performed to demonstrate these new radiation production mechanisms and to analyze their major characteristics (intensity, spectrum, angular distribution, polarisation). Compared to synchrotron radiation sources the photon flux intensity obtained using these techniques is relatively low. However there are many experimental situations where this disadvantage is of no relevance or can at least be partly compensated for. Low-energy electron linac based radiation production mechanisms offer some unique features which make them attractive, especially for time-resolved measurements, test purposes or for research and applications on a smaller scale.

In this paper we would like to concentrate on use of diffracted bremsstrahlung for the production of monochromatic X-rays, because it has already lead to a fully operational high-energy X-ray source, tunable in the energy range between 50 and 700 keV. It is the first source of this type. After a short introduction to the basic concept of the source we will discuss the actual set-up for the production of monochromatic X-rays more in detail. We will focus on two basic issues: the high-power bremsstrahlung production and the crystal diffraction. We will end with a short description of some experiments performed at this high-energy source.

2 CONCEPT OF THE SOURCE

The concept of this source consists of a combination of three essential ingredients: an intense bremsstrahlung beam produced with our 15 MeV accelerator, a bent crystal used in the Cauchois geometry and a slit system (see figure 1). Bremsstrahlung provides forward-directed high energy photons with a continuous energy spectrum up to the impinging electron beam energy. The cylindrically bent crystal is hit from its convex side by the bremsstrahlung source. In this configuration, photons incident on the crystal planes under an angle θ, can undergo nth order diffraction if their energy and associated wavelength fulfil the Bragg-Laue condition (d is the lattice spacing of the crystal planes). When diffraction occurs the photons leave the crystal at an angle 2θ with respect to their incident direction. Due to the curved nature of the crystal all the photons fulfilling the Bragg condition for a given energy E, focus on the same point F. The collection of all these points forms the so called Rowland circle, with a radius R which is one half of the bending radius of the crystal. By placing a slit on this Rowland circle it is possible to obtain monochromatic photon beams. In practice the beam will not always be monochromatic, but depending on the crystal the beam can be polychromatic, with a first order peak and its harmonics, due to higher order diffractions.

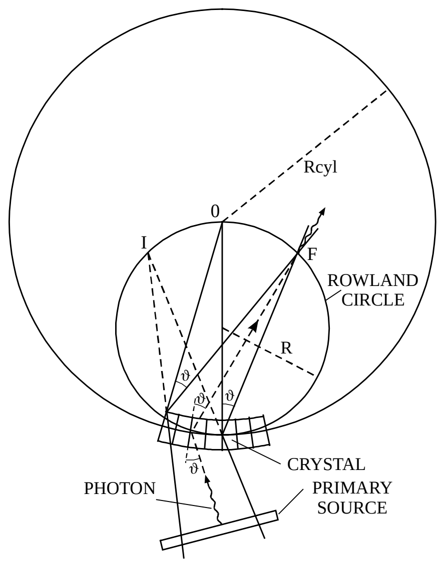

Figure 1: Concept of the monochromatic source.

For energy tuning the source can operated in different modes: either by displacing the slit on the Rowland circle (the Fixed Crystal Movable Target mode) or by turning the crystal in the bremsstrahlung beam (the Rotatable Crystal Fixed Target mode) or by a combination of both (the Rotatable Crystal Movable Target mode).

3 OPTIMISATION OF THE SOURCE

A major part of our work has focused on optimising the monochromatic X-ray intensity throughout the required energy range (50 - 500 keV) and maximising the monochromatic peak-to-background ratio. Crucial in this study are the design of an optimum combination of the bremsstrahlung production and the characteristics of the diffraction crystals. We will discuss these topics now more in detail.

3.1 Bremsstrahlung production

The intense white bremsstrahlung beam is produced with our high-intensity linear electron accelerator facility [2]. The electron beam intensity of the accelerator facility covers a range over 16 orders of magnitude: from an exceptional low current of a few electrons per second (for detector calibration purposes) up to 2 mA average current, while the energy range is continuously variable between 1.75 and 15 MeV. The duty factor is 2% and the maximum average beam power 20 kW. The electron pulse repetition frequency is variable between single shot and 5000 pulses per second, with a pulse length between 1 and 10 µs. The accelerator is capable of delivering beams with a maximum power density up to 140 kW/cm^2 [4].

To create the monochromatic X-ray beams with the highest intensity, the high-power bremsstrahlung radiator has to be of a special design in accordance with these high-power specifications. The bremsstrahlung target has a similar configuration as our ‘classical’ thick radiation-cooled bremsstrahlung targets we developed for high-power white beam X-ray irradiations [5]. They are designed to withstand these extremely high electron beam power densities. Although the white beam design is optimised for maximum electron/photon conversion efficiency and maximum forward photon fluence integrated over the whole energy spectrum, a thick target that completely stops the electron beam is not ideally suited to deliver intense photon beams with an energy in the 100 keV range because of absorption and scattering of the photons in the target. By modifying this design we could increase our monochromatic beam intensity by a factor of 40, without losing the high-power capabilities. We applied Monte Carlo calculations (using the EGS-nrc code [6]) to optimise the target material and thickness in view of a maximum photon production at the required monochromatic energy, associated with a maximum peak-to-background and taking into account thermal constraints imposed by the high-power beams. This lead to the conclusion that a thin radiator composed of a low Z material delivers the highest absolute monochromatic photon intensities in the required energy range. This result is quite surprising as usually a high-Z material is used for efficient transformation of electron power to bremsstrahlung photon beam power. A low-Z radiator however will create a less divergent photon beam, leading to more photons on the effective surface area of the crystal. In figure 2 the bremsstrahlung spectrum on the effective surface area of the crystal is shown for a low-Z and a high-Z material. The variation of the thickness of a low-Z target allows a shift of the maximum towards the required monochromatic energy.

In order to be able to adapt the optimum target quite easy, we use the usual graphite cylinder with a conical hole. At the top graphite targets with variable thickness can be incorporated. Because over the whole energy range the optimum thickness is smaller than the electron range a highly divergent and powerful electron beam, with a wide energy spectrum, will leave the target. Therefore the target is followed by a 90° cleaning magnet dumping the electron beam in a beam stop. Because of the high divergence and the high beam powers involved, special care has to be taken to design of the electron dumping magnet.

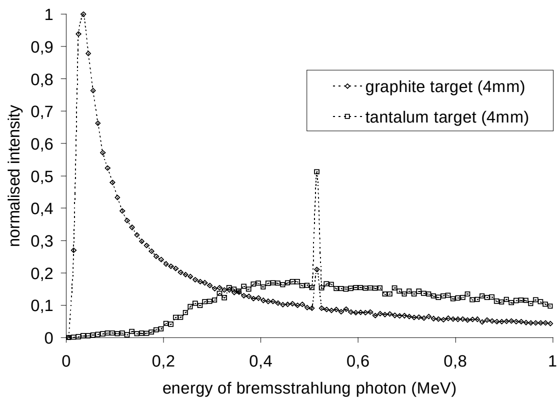

Figure 2: Bremsstrahlung spectrum on the effective crystal surface for a graphite and a tantalum target

3.2 Crystal diffraction

A curved crystal can be precisely positioned and turned in the white photon beam. We use both the Laue and Bragg mode. The experiments, performed up to now, used the 220 plane of symmetrically-cut Si, Ge or Cu crystals, having their reflecting planes perpendicular to the crystal surface. Calculations were performed using the XOP package [7] to find a better optimised crystal set-up. The idea was to use the 311 diffraction plane of an asymmetrically cut Si crystal. This has the advantage that the even harmonics are cancelled out of the diffracted photon beam and that the rocking curve widens resulting in loss of energy resolution and a gain in diffracted photon beam intensity.

Calculations were done as to the degree of asymmetry, the optimal thickness and bending radius of the crystal. Best results were obtained for a Si crystal 85° asymmetrically cut, a bending radius of about 10m and a thickness of 4mm.

Our investigations led to a fully operational tuneable monochromatic X-ray source. Its energy range is between 60 and 700 keV. The bandwith of the peaks is better than 0,1%. The peak-to-background ratio is typically 400/1. The measured intensity of the source is in the order 10^5 photons/sec-cm². Figure 3 shows a typical polychromatic spectrum from a symmetrically-cut Ge crystal. An almost pure monochromatic spectrum is obtained with an asymmetrically-cut Si crystal.

In contrast to synchrotron radiation, the bremsstrahlung beam from an electron linac impinging on a diffraction crystal has a substantial intrinsic divergence. In order to optimise the crystal monochromatisation process further, we are actually developing a model to integrate crystal diffraction theory [8] into the Monte Carlo photon transport code.

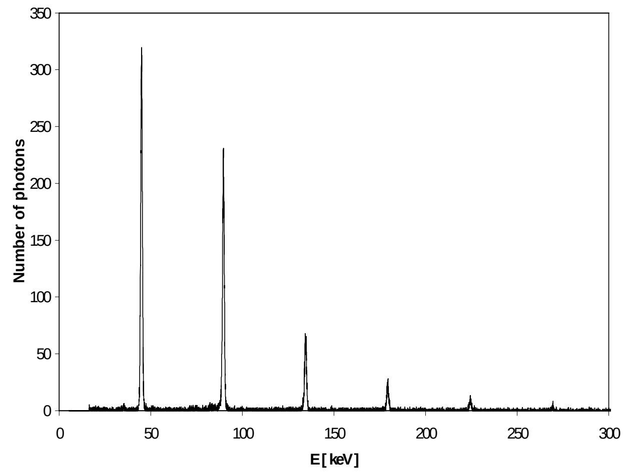

Figure 3: Typical spectrum from a symmetrically-cut crystal

4 APPLICATIONS OF THE SOURCE

Although the intensity of the monochromatic photon source is rather low compared to the high energy beam lines of a third generation synchrotron radiation facility, this monochromatic source allowed first experimental applications requiring high resolution photon beams with very low divergence. We made detailed energy-dependent attenuation measurements around the K-edges of heavy elements with very high resolution by changing the photon energy in 100 steps of 50 eV [9]. The photoelectric effect can be used to perform position-sensitive studies of the distribution of one single element in a sample. The abrupt change in X-ray absorption around the K-edge is used as a fingerprint of an element. Element sensitive tomography can be used for a reconstruction of the three-dimensional distribution of an element, for example uranium in an artificial sample [10].

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