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Future aspects of X-ray emission from crystal undulators at channeling of positrons

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Summary. — In connection with ideas to produce undulator-like radiation in the hundreds of keV up to the MeV region by means of positron and electron channeling, there is renewed interest to study various channeling phenomena also experimentally. With electrons experiments have been performed at the Mainz Microtron MAMI to explore channeling-radiation emission by a 4-period epitaxially grown strained layer $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ undulator with a period length of $\lambda_u = 9.9\,\mu\mathrm{m}$. Unfortunately, high-quality positron beams of sufficient intensity are not easily accessible. The only serious candidate in Europe seems to be the Beam Test Facility (BTF) at INFN/LNF, Frascati, Italy. Some requirements to extent BTF in a facility which is also well suited for positron channeling-radiation experiments will be outlined.

PACS `41.60.-m` – Radiation by moving charges.
PACS `61.85.+p` – Channeling phenomena (blocking, energy loss, etc.).
PACS `87.56.bd` – Accelerators.

1. – Introduction

Undulator-like radiation in the hundreds of keV up to the MeV region can be produced by means of positron channeling as discussed in a number of papers, see *e.g.* [1-4]. However, one obstacle for the success of radiation production by this means lies in the

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fact that the fabrication of suitable crystalline undulators is an experimental challenge. Our approach to realize them is based on the method of epitaxially growing graded composition $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ strained layer superlattices [5]. In a preceding paper of this issue [6] promising experiments with such an undulator crystal have been described employing 270 MeV and 855 MeV electrons from the Mainz Microtron MAMI. The results encouraged us to propose experimental investigations with 500 MeV positron beam of good emittance as well to be developed at the Beam Test Facility BTF of INFN/LNF Frascati, Italy. In the following some basic considerations of such an experiment are outlined.

2. – Advantages of positrons

It has been shown in ref. [6] that an undulator crystal has been prepared at MBE Aarhus which exhibits some of the expected features in experiments with electrons. However, the absence of the expected photon distribution in combination with the suppression of the channeling radiation for K parameters in the order of 0.4 for the experiment at 855 MeV raises the question whether electrons are as well suited as positrons to produce undulator radiation [7, 8]. To discuss this question we refer to fig. 1(a) where the sum of the centrifugal potential $U_c(x,z') = pvk_u^2 A\cos(k_u x)\cdot z'$ at maximum and the crystal potential $U(z')$ are depicted, for details see ref. [6]. The coordinate x coincides with the beam direction, z' with the normal of the (110) planes in which the electrons channel. For the situation shown, the barrier height is reduced from $U_m = 22.6\,\mathrm{eV}$ to about 12.6 eV, *i.e.* by nearly a factor of two. This fact already enhances the dechanneling probability considerably. But even worse, a still channeled electron resides rather close to an atomic plane, indicated by the arrow in fig. 1(a). Here it experiences a much stronger transverse energy increase than a weakly bound electron in a flat crystal at $E_\perp/U_m \approx 1$. As a consequence, a dramatically enhanced dechanneling probability is expected. In other words, deeply bound electrons experience a rather strong transverse energy heating and rapidly boil off from the potential pocket at the curved parts of the undulator.

A completely different scenario is observed for positrons. Of course, the barrier reduction is similar as for electrons with the difference that the potential shown in fig. 1(a) must be reflected at the horizontal z'/d_p axis, see fig. 1(b). Also in this case positrons are lost due to the reduction of the barrier height. In addition, the local potential minimum shifts to 0.3 d_p and the oscillating positrons come at one of their turning points rather

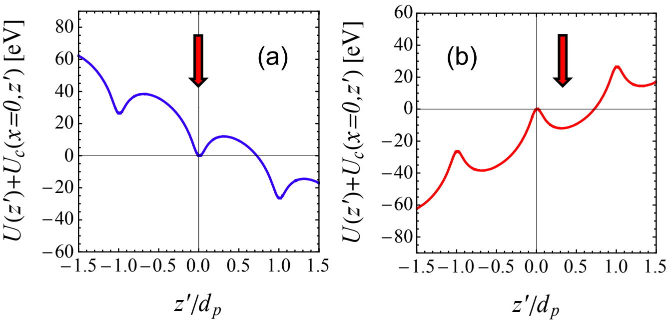

Fig. 1. – Sum of the maximum centrifugal potential $U_c(x=0,z') = E_e \cdot A \cdot k_u^2 \cdot d_p \cdot (z'/d_p)$ and crystal potential $U(z')$ at $pv \simeq E_e = 855\,\mathrm{MeV}$ for the (110) plane; $A = 4.0\,\text{Å}$, $\lambda_U = 9.9\,\mu\mathrm{m}$, and $d_p = 1.92\,\text{Å}$, the distance between (110) planes, for electrons (a), and for positrons (b).

close to the thermally vibrating atoms comprising the atomic planes. This effect as well as the rather small barrier width close to the local maximum must be taken into account in a more detailed investigation. Nevertheless, at least part of the bound positrons experience a more than two orders of magnitude reduced transverse energy heating as electrons. This fact can be concluded from fig. 2 of ref. [9]. Therefore, the dechanneling length as obtained for planar crystals is expected to be maintained also in the undulator crystal for a certain fraction of channeled positrons.

3. – Experiment proposal at the DAΦNE Beam Test Facility BTF

In the following we discuss a possible experiment with positrons at BTF at INFN/LNF Frascati, Italy. Positrons which are normally released for the DAΦNE damping ring from the end of a high-intensity LINAC can also be diverted into a 100 m^2 BTF hall. According to refs. [10, 11], a positron beam with an energy of 500 MeV, an emittance of 5–10 mm mrad and up to 10^{10} positrons per pulse can be provided at a repetition rate of up to 49 Hz. The beam emittance can be reduced on the expense of the beam intensity by means of slit systems.

For the calculations it has been assumed that a positron beam can be prepared in the BTF hall, *e.g.* by collimation accepting much smaller pulse intensities than 10^{10} positrons, with beam emittances $\varepsilon_h = \varepsilon_v = 0.1\,\mathrm{mm\,mrad}$ in the horizontal and vertical directions, respectively. At beam spot sizes with standard deviations $\sigma_h = \sigma_v = 1.5\,\mathrm{mm}$ the angular spreads are $\sigma'_h = \sigma'_v = 0.067\,\mathrm{mrad}$ which are, according to eq. (A.2) of ref. [6], small in comparison with the critical angle $\psi_{\mathrm{crit}} = 0.30\,\mathrm{mrad}$. It is also worthwhile to compare these numbers with the rms values for multiple scattering through small angles in amorphous matter which amounts for a 40 μm thick silicon layer to $\theta_0 = 0.39\,\mathrm{mrad}$ [12]. This angle is somewhat larger than the critical angle ψ_{crit}. However, due to the reduced interaction of the positron moving in the channel with crystal lattice atoms in comparison with amorphous matter, no problems because of this fact are expected.

4. – The undulator radiation spectrum

For the undulator described in ref. [6], fig. 1, and a positron beam energy of 500 MeV the undulator parameter is $K = 0.246$, and the undulator radiation which peaks at 233 keV would have a width of 52 keV. If line broadening effects as quoted in the caption to fig. 2(a) are taken into account properly, the line broadens to a width of 70.5 keV. In fig. 2(b) a calculation on the basis of the classical undulator theory [13] is presented in which line broadening effects due to dechanneling, coherence loss by phase fluctuations, and a damping of the amplitude have been omitted. However, in contrast to fig. 2(a), the angular spread of the beam, the beam spot size, and the finite detector aperture have been taken into account. The peak shifts to 210 keV and the line broadens from 53 keV for a point-like source and a point-like detector to 72.4 keV. This broadening is about the same as that for fig. 2(a). If all line broadening effects are taken into account, a proper quadratic subtraction and summation results in a total line width of 87 keV which is small enough for the envisaged experiment. Notice that a finite number of periods is invoked in both distributions of fig. 2 and must not be taken into account twice.

5. – Radiation background

Two radiation background components will be discussed in the following. One is the unavoidable bremsstrahlung background from the undulator target itself, the other is the

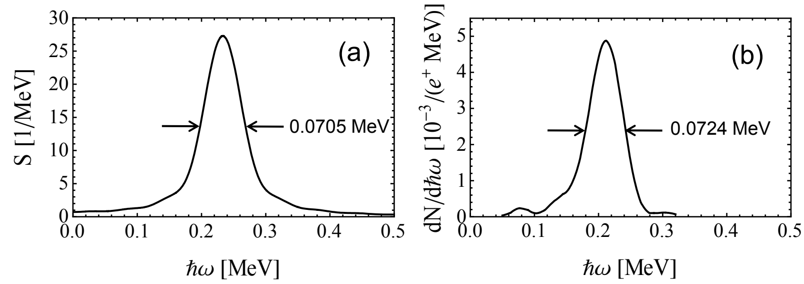

Fig. 2. – (a) Calculated radiation spectrum from a 4-period undulator with a period length of 9.9 μm and amplitude of 4.0 Å at a positron beam energy of 500 MeV. Assumed were a dechanneling length $\ell_{\text{dech}} = 126\,\mu$m, a coherence length due to phase fluctuations caused by multiple scattering $\ell_{\text{phase}} = 106\,\mu$m, and a relaxation of the undulation amplitude in crystal undulator $\ell_{\text{relax}} = 40\,\mu$m. (b) Expected spectral distribution as calculated on the basis of the classical undulator theory [13]. Beam spot size and divergence at the target position: $\sigma_h = \sigma_v = 1.5$ mm, $\sigma'_h = \sigma'_v = 0.067$ mrad; beam emittance: $\varepsilon_h = \varepsilon_v = 0.1$ mm mrad; distance target to detector: 6 m, diameter of aperture in front of detector: 4 mm.

background produced in the beam transport system and the beam dump.

For the former background component the bremsstrahlung contribution has been calculated under the same conditions as for the spectrum shown in fig. 2(b). The result is that a peak-to-background ratio of about 20 can be expected. However, this number will be somehow reduced due to the fact that not all positrons channel. Assuming that the fraction of channeled positrons is 20%, the peak-to-background ratio reduces to 4 which still is a sufficient large number for the proposed experiment.

For the latter background component it has been assumed that the positron beam is deflected with a dipole magnet, which has been positioned directly behind the undulator target, by 12.5° horizontally. Detector and beam dump are situated at a distance of 6 m from the target. Simulation calculations have been performed with the computer code GEANT4. Figure 3 shows that the bremsstrahlung background can be reduced by a large factor if the experiment is performed under vacuum conditions. The remaining count rate mainly originates from bremsstrahlung production in the target itself. The background from gamma rays and neutron production in the beam dump turns out to be negligibly small.

6. – Count rate estimate

The integrated count rate seen by a $2'' \times 2''$ NaI detector at 6 m distance from the 39.6 μm thick silicon target, without any aperture in front of the detector, amounts to $3.64 \cdot 10^{-3}$/positron, see fig. 3 (inset). Production of channeling radiation may increase this number by a factor of 2. With an aperture of 4 mm diameter at 6 m distance in front of the detector the count rate will be reduced by a factor of about 7. To avoid pileup, the detector should not count more than 0.2 events in a single pulse, meaning that the number of positrons at the target must not exceed 200/pulse. Since the preparation of the beam emittance of $\varepsilon_h = \varepsilon_v = 0.1$ mm mrad, causes a reduction of the beam intensity by a factor of about 10^3–10^4, a beam intensity of $2 \cdot 10^5$–$2 \cdot 10^6$/pulse is needed which can easily be provided. At 50 Hz repetition rate of the LINAC the intensity in front of the

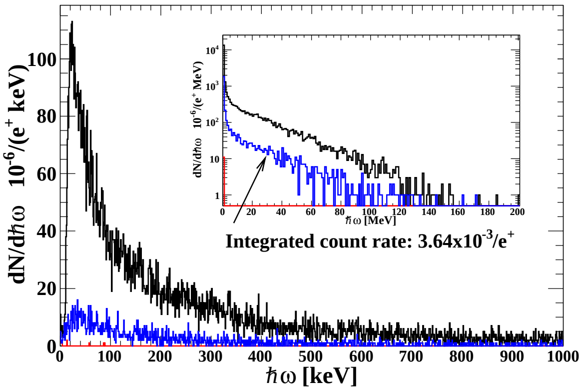

Fig. 3. – (Colour on-line) Results of GEANT4 simulations. Silicon target thickness 39.6 μm, distance target to a $2'' \times 2''$ NaI detector 6 m, deflection angle of the positron beam 12.5°. The upper black histogram corresponds to an experiment in air, the lower ones to experiments under vacuum conditions under different assumptions: dedicated beam dump (blue), without radiator (red). The inset shows the spectra up to a photon energy of 200 MeV in a semi-logarithmic representation.

slit and aperture system must be in the order of 10^7–10^8 positrons/s. With an integrated count rate of about $3.5 \cdot 10^{-4}$/positron for the undulator radiation peak, as estimated from fig. 2(b), and an assumed channeling probability of 0.2, a total number of about $1.5 \cdot 10^8$ positrons on target would be sufficient to collect 10^4 events in the undulator peak. With 200 positrons/pulse and a LINAC repetition rate of 49 Hz this statistics is collected in $1.5 \cdot 10^4$ s or about 4 hours beam on target.

7. – Detectors

For the observation of the undulator radiation peak at 210 keV, a NaI detector seems to be appropriate. Its energy resolution of about 8%, corresponding to about 17 keV, is sufficient. At such a resolution a broadening of the expected peak with a width of 87 keV can be neglected. The time resolution should be as good as possible, *i.e.*, of the order of 1 ns, in order to suppress background which is expected to originate from the slit and collimator system in which more than 99.9% of the positrons must be discarded. The suppression can hopefully be maintained by means of the time-of-flight differences between undulator-target events and the background events. In addition, a good detector shielding is required.

8. – Discussion

It has been shown that the Beam Test Facility BTF, despite the low repetition rate of the LINAC of 50 Hz, is well suited for undulator-radiation experiments at channeling of positrons. However, a number of modifications must be performed. The main ones are 1) removal of the conversion target, 2) replacement of the 500 μm thick beryllium foil, which separates the ultrahigh-vacuum system of DAΦNE and the LINAC from the high-vacuum system of BTF, by a thinner foil to avoid deterioration of the beam emittance, 3) transportation of the positron beam under high vacuum to avoid bremsstrahlung background from air, 4) construction and installation of a goniometer vacuum chamber, and 5) installation of several in-vacuum beam monitor detectors.

It should be mentioned that a similar facility was in operation about 25 years ago at the Lawrence Livermore National Laboratory Electron-Positron Linear Accelerator, USA [14].

9. – Conclusions

As shown in ref. [6], undulator-like radiation has been observed employing an epitaxially grown $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ 4-period $\lambda_U = 9.9\,\mu\mathrm{m}$ undulator and an electron beam with energies of 270 MeV and 855 MeV. A corresponding experiment with positrons can presently not be performed because a suitable machine in Europe is missing. Nevertheless, detailed experimental studies also with high-quality positron beams are absolutely imperative to judge wether radiation production in the hard-X-ray region by means of crystal undulators is a viable concept, or not. It has been shown in this paper that the Beam Test Facility BTF at INFN Frascati, Italy, would be a good candidate if a number of modifications are performed.

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