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Radiation collimation in a thick crystalline undulator*

Tobias Nyholm Wistisen[1], Ulrik Ingerslev Uggerhøj[1,a], John Lundsgaard Hansen[1], Werner Lauth[2], and Pascal Klag[2]

[1] Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, 8000 Aarhus C., Denmark
[2] Institut für Kernphysik Universität Mainz, J.-J.-Becher-Weg 45, 55099 Mainz, Germany

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Abstract. With the recent experimental confirmation of the existence of energetic radiation from a Small Amplitude, Small Period (SASP) crystalline undulator [T.N. Wistisen, K.K. Andersen, S. Yilmaz, R. Mikkelsen, J. Lundsgaard Hansen, U.I. Uggerhøj, W. Lauth, H. Backe, Phys. Rev. Lett. **112**, 254801 (2014)], the field of specially manufactured crystals, from which specific radiation characteristics can be obtained, has evolved substantially. In this paper we confirm the existence of the crystalline undulator radiation, using electrons of energies of 855 GeV from the MAinzer MIcrotron (MAMI) in a crystal that is approximately 10 times thicker than the previous one. Furthermore, we have measured a significant increase in enhancement, in good agreement with calculations, of the undulator peak by collimation to angles smaller than the natural opening angle of the radiation emission process, $1/\gamma$.

1 Introduction

Crystalline undulators are specially manufactured crystals capable of imposing pre-shaped oscillations onto the trajectory of a channeled, penetrating particle. Since the trajectory determines the radiation characteristics for relativistic particles, specific photon spectra can be obtained by carefully selecting a combination of incoming particle charge and energy, and oscillation amplitude and period of the crystalline lattice. An introduction to the passage of high energy particles through crystals can be found in [1], and a comprehensive textbook on the subject of crystalline undulators has recently appeared [2].

For many years it was the dominant attitude that in order for the radiation intensity to exceed that of the channeling radiation produced by the channeling oscillations of the particles, the amplitude of the imposed oscillation had to be significantly larger than the planar distance and thus the period had to be much longer than the channeling oscillation wavelength for the particle to stay channeled in the so-called Large Amplitude, Long Period (LALP) regime. However, as realized by Kostyuk [3] and the Frankfurt group of Solov'yov and Korol [4], even with Small Amplitudes and Short Period, the so-called SASP-regime, the penetrating particle radiates intensely, and at even higher energies (for fixed energy of the incoming particle). The SASP regime is expected to be less coherent, though, than the LALP regime.

In essence, the radiation frequency, and thus its energy, can be found using length contraction of the crystal period as observed by the penetrating particle, and a relativistic Doppler shift back into the laboratory frame. This yields a $2\gamma^2 hc/\lambda_u$ dependency of the photon energy on the particle Lorentz factor γ and the period of the crystal undulations, λ_u. Thus, 855 MeV electrons gives radiation at barely 15.8 MeV, based on an undulator with period 0.44 μm. Enhancement here is defined as the increase in radiation yield as compared to the yield for an amorphous target of the same thickness, i.e. compared to the Bethe-Heitler cross section.

2 Crystal and experiment

Among the many proposed solutions to obtain modified crystalline lattices are acoustic waves [5], surface indentations (for example by means of laser ablation [6]), mechanical modification [7] and controlled mixing of elements with different lattice constants such as silicon and germanium, $Si_{1-x}Ge_x$ crystals [8]. The crystal fabricated in this paper was based on the latter approach, and was produced by adding a linearly increasing fraction $0.5\% < x < 1.5\%$ of Ge to a Si substrate by use of Molecular Beam Epitaxy (MBE). This strains the lattice and by successively interchanging a linear increase of Ge with a linear decrease (resulting in a sawtooth pattern), and aiming the incoming particle at 45 degrees to the direction of growth, two superimposed sinusoidal-like oscillations – one for the channeling motion and one for the undulator motion – of the particle is obtained. The crystal used in the present study was grown with 120 periods, and a total thickness of $L_0 = L/\sqrt{2} = 37$ μm thus giving $\lambda_u = 0.44$ μm along (110). This wavelength is slightly above that used in our previous investigation [9], $\lambda_u = 0.41$ μm, where the crystal

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[a] e-mail: ulrik@phys.au.dk

was $L_0 = 3\ \mu$m in thickness and with 10 periods. In both cases, the expected oscillation amplitude of the plane is $a_u \simeq 0.12$ Å.

Naively judging from these numbers, one should expect an undulator radiation peak that is slightly lower in energy in the present experiment compared to the previous one. Furthermore, with the substantial increase in thickness, processes that are coherent over long distances, or that are not disrupted as with e.g. dechanneling, would be expected to gain from the thicker crystal. According to calculations the total dechanneling length in the present case is expected to be about 33 μm ([10], Tab. 1), i.e. comparable to the thickness of the crystal employed.

At 855 MeV, the natural opening angle of the radiation emission process is $1/\gamma \simeq 0.6$ mrad. In the experiment the full width of the collimator corresponds to $\theta_w = 0.49$ mrad, half of which, $\theta_w = 0.24$ mrad, should be compared to $1/\gamma$. So the collimation is approximately to an angle $\theta_c \simeq 1/2\gamma$. Calculations have been performed for 855 MeV electrons in $L = 12\ \mu$m along the SASP (110) direction, with $\lambda_u = 400$ nm, and for various amplitudes ([10], Fig. 6). They show that for $a_u \simeq 0.12$ Å the peak of the undulator radiation is of height $dE/d(\hbar\omega)(\times 10^3) \simeq 0.12$ for the case of collimation to $\theta_{\max} = 0.21$ mrad, and height $dE/d(\hbar\omega)(\times 10^3) \simeq 0.48$ for the case of collimation to $\theta_{\max} = 4$ mrad. As the former case corresponds quite closely to our collimator setting, and the latter must be close to no collimation, we may use these numbers for estimations of the effect of collimation. As was the case in [9], where the effect of collimation reduced the overall intensity by a factor of 5.5, we should here expect an increase of radiation arising from the collimation of $\approx 6.77 \times 12/0.48 \simeq 1.7$. The factor of 6.77, based on integrations of ([9], Eq. (7)), used here is slightly higher due to the more narrow collimation used in the calculation.

The experiment was performed at the MAinzer MIcrotron (MAMI), using 855 MeV electrons. A schematical drawing of the setup is shown in Figure 1.

The setup is in essence identical to the one used in [9], and we refer to that paper for more details. The significant part here is the movable collimator of inner diameter 4 mm, made from Densimet, a tungsten-based alloy.

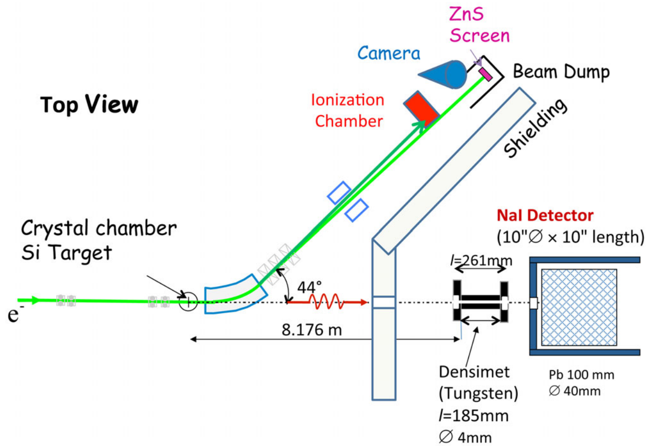

Fig. 1. A schematical drawing of the setup used for the present measurement. The electron beam enters from the left, passes the crystal and is subsequently bent away by a magnet. The emitted radiation may travel through the collimator – which can be moved in and out – and is detected by a NaI detector.

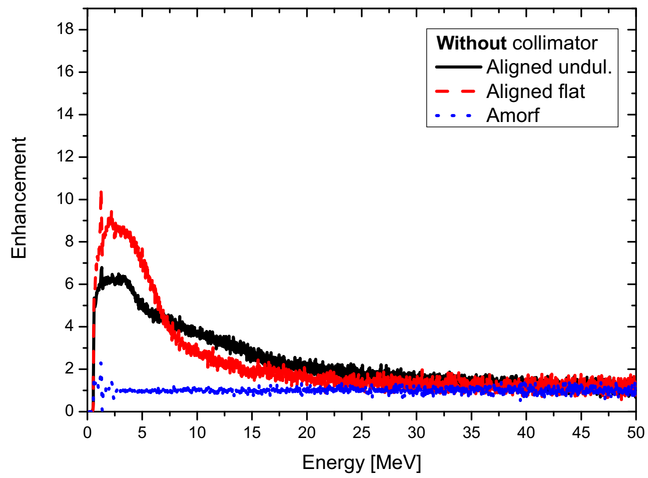

Fig. 2. Radiation spectra enhancements for the measurement performed without collimation. The full-drawn black line shows the measured values for the undulator crystal in the aligned case, the dashed red line shows the measured values for the flat crystal in the aligned case, and the blue dotted line shows the case of an amorphous, but otherwise identical, material.

3 Results and discussion

In Figure 2 we show the results obtained in the measurement of radiation without the use of the collimator. Although there is an excess for the undulator crystal compared to the flat crystal, in the region near the expected undulator peak, $\hbar\omega_u \simeq 16$ MeV, the excess is broad. Furthermore, the channeling radiation emission, giving rise to the peak at low energies, up to 7–8 MeV, is suppressed for the undulator.

In Figure 3, on the other hand, we show the results obtained in the measurement of radiation *with* the use of the collimator.

In this case, the undulator radiation peak becomes significantly sharper. The channeling radiation peak for the undulator crystal also narrows and increases in enhancement. Also for the flat crystal, the enhancement of the channeling radiation increases markedly – as expected from the mentioned theory – by the collimation. There is no clear sign of second harmonics near 32 MeV, in agreement with expectations based on calculations which state that amplitudes in excess of 0.2 Å are required to observe second harmonics.

In Figure 4 is shown the ratio between aligned undulator spectra for the collimated and uncollimated measurements. As the above discussion showed, the theoretically expected increase in radiation enhancement through collimation is up to about a factor 1.7, in nice agreement with the factor 1.6 that is observed.

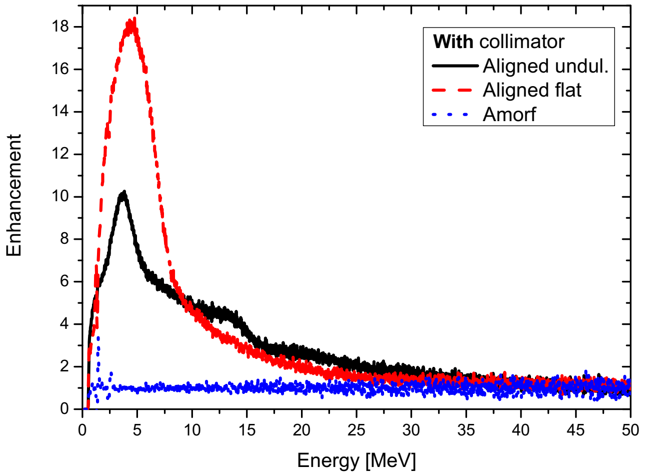

Fig. 3. Radiation spectra enhancements for the measurement performed with collimation to an angle $\theta_c = 0.25$ mrad. Lines and scales as in Figure 2.

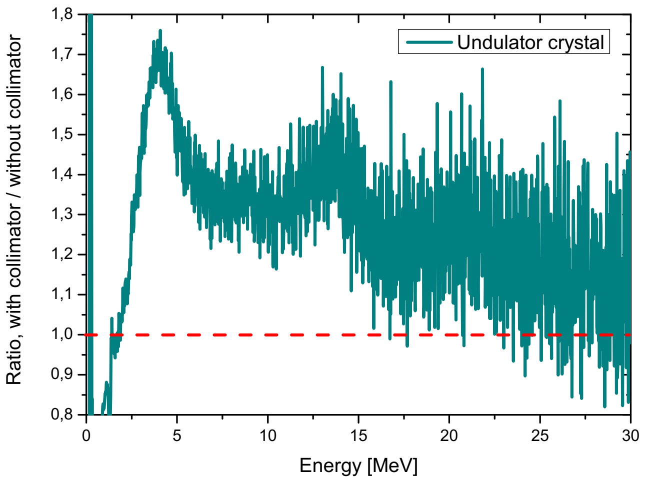

Fig. 4. The ratio between enhancements measured for the aligned undulator crystal in the collimated case, Figure 3 black line, and the uncollimated case, Figure 2 black line.

Finally, in Figure 5 is shown our previous data set, obtained for a $L = 3$ μm aligned undulator crystal with $\lambda_u = 0.41$ mm, and the present data set, the $L = 37$ μm aligned undulator crystal with $\lambda_u = 0.44$ mm, both collimated to the same angle.

As expected from the differences in wavelength of the two undulators, the present data set shows an undulator peak at slightly lower energies. Furthermore, the enhancement of the channeling radiation has increased significantly going to the thicker crystal, while the enhancement of the undulator peak has decreased slightly. Coherence in the SASP regime is comparatively low. For radiation of $\hbar\omega = 2$ MeV from a 855 MeV electron, the formation length is given as $l_{\rm f} = 2\gamma^2 c/\omega = 0.55$ μm. The channeling motion wavelength, on the other hand, is approximately $l_c \simeq d_p/\theta_L = 0.67$ μm, where θ_L is the Lindhard critical angle for channeling and $d_p = 1.92$ Å the planar spacing, i.e. l_c is somewhat longer than the undulator wavelength.

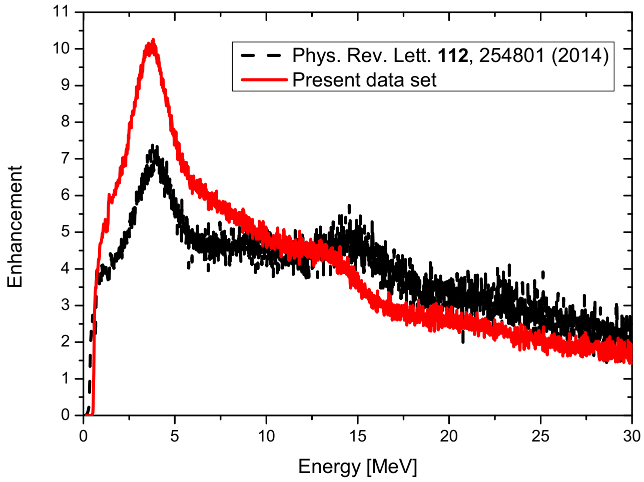

Fig. 5. The enhancement measured for the $L_0 = 37$ μm aligned undulator crystal in the collimated case, Figure 3 black line, here shown as the full-drawn red line, and the enhancement measured previously for a $L_0 = 3$ μm aligned undulator crystal in the collimated case, shown as a dashed black line.

The $L_0 = 3$ μm crystal is thus barely thick enough to generate a substantial amount of channeling radiation, while that thickness seems sufficient for the generation of the radiation of the SASP undulator type, which anyway has low coherence. On the other hand, issues related to the accuracy of fabrication for the comparison of the two undulators cannot be excluded to be also affecting the spectra.

4 Conclusion

Previous studies [9] established the existence of the crystalline undulator radiation. With the present study, we confirm this for an undulating crystal that is approximately 10 times thicker. We have furthermore demonstrated the effect of collimation to angles smaller than the natural opening angle of the radiation, $1/\gamma$. Our findings are in good agreement with calculations [10]. As shown in those calculations, in order to optimize the undulator peak for a $\lambda_u = 400$ μm crystalline undulator, an amplitude around $a_u = 0.4$ Å would be desirable. Using the approximate relation for the Ge content necessary to achieve a certain amplitude, $x \simeq 170 a_u/\lambda_u$, this translates into $x \simeq 1.7\%$ for $\lambda_u = 400$ nm. With this germanium content, the maximum epitaxial layer thickness for the graded composition strained layer is more than 100 μm [11], so there should not be problems related to relaxation in growing such a device. Future investigations will address these issues.

Author contribution statement

T.N.W. participated in the measurement and performed the data analysis, U.I.U. suggested the experiment and was the main writer of the paper, J.L.H. produced the crystal, W.L. led the experiment and P.K. participated in the measurement.

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