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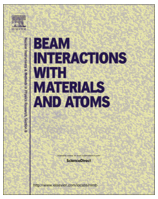

Intense and energetic radiation from crystalline undulators

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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 (Wistisen et al., 2014), the field of specially manufactured crystals, from which specific radiation characteristics can be obtained, has evolved substantially. In the present paper we show how the radiation spectra can be tuned, using electrons and positrons of energies from 100 MeV up to 20 GeV. The latter energy is relevant for possible experiments at the FACET facility at Stanford Linear Accelerator Center (SLAC), whereas 100 MeV has been chosen to show the potentialities connected to using crystalline undulators as radiation targets for Nuclear Waste Transmutation (NWT). Energies in the few hundred MeV range are relevant for the facilities at the MAinzer MIcrotron (MAMI). For the 20 GeV case we show explicitly that quantum corrections to the emission spectrum become very significant, an effect that may be observed in the near future using the FACET beam at SLAC.

1. Introduction

Crystalline undulators are specially manufactured crystals capable of imposing a pre-shaped trajectory onto a channeled, penetrating particle. Since the trajectory is what 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 [2].

By producing a crystalline undulator, the hope is to gain an increased rate of photon emission near a chosen photon energy e.g. at the Giant Dipole Resonance (GDR) of a certain nucleus, compared to the usual channeling radiation. The position of the channeling radiation peak can only be tuned using the beam energy while the crystalline undulator offers tunability, like a conventional undulator, by the period and amplitude of the crystal bending. In addition one can produce a radiation peak at higher photon energies than the usual channeling radiation which means one could reduce the beam energy, and thus the cost of running a potential facility for Nuclear Waste Transmutation (NWT).

Among the many proposed solutions to obtain modified crystalline lattices are acoustic waves, surface indentations (for example by means of laser ablation [3]), mechanical modification [4] and controlled mixing of elements with different lattice constants such as silicon and germanium [5]. We focus here on the latter approach, usually obtained by adding a linearly increasing (small) fraction of Ge to a Si substrate by use of Molecular Beam Epitaxy (MBE) which strains the lattice in the direction of growth. By successively interchanging a linear increase of Ge with a linear decrease (resulting in a sawtooth pattern), and aiming the incoming particle at 45° 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. A comprehensive textbook on the subject of crystalline undulators has recently appeared [6].

For many years it was the dominant attitude that in order for the radiation intensity to exceed that of the ever-present channeling radiation (when the particle is channeled), 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. However, as realized by Kostyuk [7] and the Frankfurt group of Solov'yov and Korol [8], 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).

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, yielding a $2\gamma^2\hbar c/\lambda_u$ dependency of the photon energy on the particle Lorentz factor γ and the period of the crystal λ_u. Thus, as shown by the MAMI experiment [1] and in

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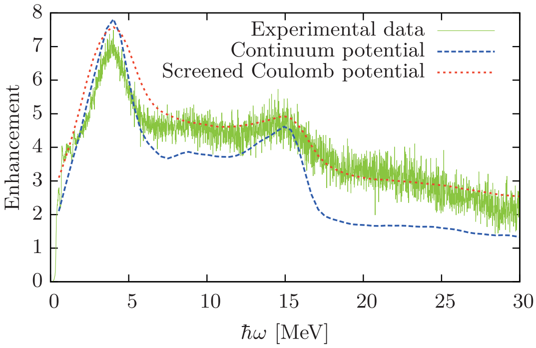

Fig. 1. A comparison of the theoretical and experimental results for 855 MeV electrons penetrating a 10-period crystalline undulator with period 0.4 μm and planar oscillation amplitude 0.12 Å. Adapted from [1].

Fig. 1, 855 MeV electrons may give radiation at about 16 MeV, based on an undulator with period 0.4 μm. In Fig. 1 and below, enhancement is defined as the increase in yield compared to an amorphous target of the same thickness, i.e. compared to the Bethe–Heitler cross section.

At higher energies, though, quantum corrections become important. Evidently, if the emission energy increases as γ^2 and the energy of the impinging particle only as γ, for some value of the Lorentz factor, $\gamma_t = \lambda_u mc^2/4\pi\hbar c$, such a calculation would yield a radiative loss equal to the full energy of the particle. For a period of $\lambda_u = 0.4$ μm, $\gamma_t = 82 \cdot 10^3$, corresponding to an energy of 42 GeV. Long before this, and so also at 20 GeV, quantum corrections become significant as shown in Fig. 2.

As shown in Fig. 3, the monochromaticity of the undulator peak increases with increasing number of periods. Moreover, the undulator peak arising at about 16 MeV eventually attains a very sharp upper edge, akin to the peaks observed in coherent bremsstrahlung or the channeling radiation peak observed with positrons of 6.7 GeV, around the so-called γ-magic [9]. Even with $N = 32$ periods the full crystal length, 13 μm, is still significantly shorter than the dechanneling length, about 42 μm [10]. It is therefore permissible as a first approximation to neglect dechanneling, as has been done here.

Likewise, as shown in Fig. 4, increasing the planar oscillation amplitude has the effect that the channeling radiation becomes less pronounced, while the undulator peak becomes stronger. Already at a planar oscillation amplitude as small as 0.05 Å the spectrum becomes markedly different from the straight crystal case.

With the observation from Figs. 3 and 4, that SASP undulators offer an opportunity to get intense and energetic radiation in the region of the Giant Dipole Resonance (GDR) of most nuclei, the question of its applicability for Nuclear Waste Transmutation (NWT) immediately arises.

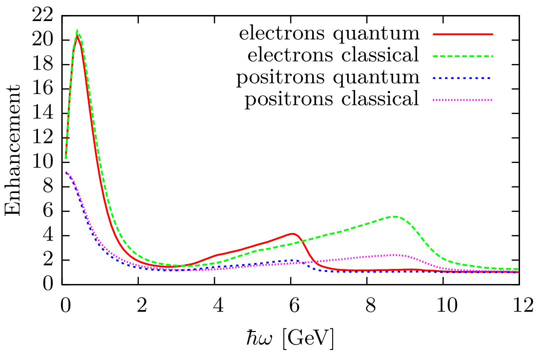

Fig. 2. Calculated emission spectra for 20 GeV electrons and positrons passing a 10-period crystalline undulator, with period 0.4 μm. The amplitude of the bending of the crystalline planes is 0.13 Å.

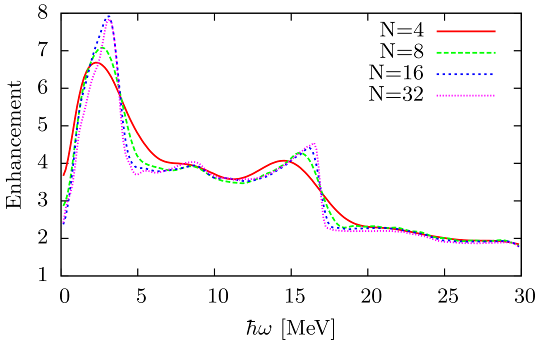

Fig. 3. Calculated emission spectra for 855 MeV electrons passing a crystalline undulator, with *N* periods of 0.4 μm, as indicated. The amplitude of the bending of the crystalline planes is 0.13 Å.

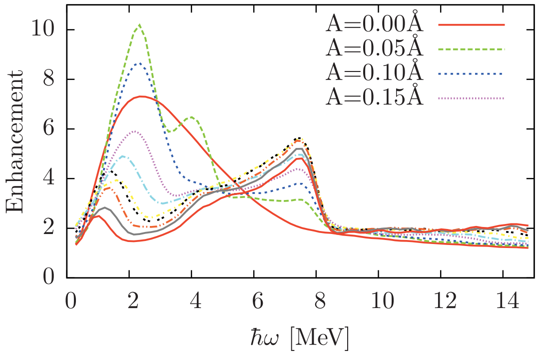

Fig. 4. Calculated emission spectra for 600 MeV electrons passing a crystalline undulator, with 10 periods of 0.4 μm, and planar oscillation amplitudes varying from 0 to 0.45 Å in steps of 0.05 Å, as indicated. Adapted from [1].

2. Nuclear Waste Transmutation

One of the serious drawbacks of nuclear power as it is presently in use, is the substantial production of long-lived waste products. A typical 1 GW power plant has an annual production of about 6 kg of Iodine-129, with a half-life of 15.6 million years. However, as an example, interacting with the GDR in I-129 using photon excitation, the nucleus may be transmuted into I-128 which has a half-life of only 23 min. The technique of NWT does not hold the promise to completely remove the problem of long-lived waste products, nevertheless, the nuclear waste problem may be significantly alleviated. NWT has been discussed previously in the crystal undulator literature, see e.g. [4], but none seem so far to have even sketched a possible scenario where energy consumption, target robustness, etc. are taken into consideration. The following is a first step towards remedying this sitation.

With present-day technology it is possible to produce a 100 MeV, 100 mA CW linac. Since the energy consumption of such a machine is huge, some 40 MW given an efficiency of 25%, one has to employ techniques such as energy recovery [11] to keep the wall-plug power acceptable. Likewise, supposing all the electrons from such a 100 mA linac emit a 10 MeV photon, the power in the photon beam is 1 MW.

Energy recovery efficiencies as high as 75% have been reported for the JLAB FEL [12] and although the technology remains to be proven, there are proposals for energy recovery linacs with average currents of 100 mA and energies as high as 5–10 GeV [13,15]. Presently, CEBAF is upgrading to 12 GeV beam energy, although with a significantly smaller current.