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Radiation emission phenomena in bent silicon crystals: Theoretical and experimental studies with 120 GeV/c positrons

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ABSTRACT

The radiation emission phenomena in bent silicon crystals have been thoroughly investigated at the CERN SPS-H4 beamline. The incoming and outgoing trajectories of charged particles impinging on a silicon strip crystal have been reconstructed by high precision silicon microstrip detectors. A spectrometer method has been exploited to measure the radiation emission spectra both in volume reflection and in channeling. The theoretical method used to evaluate the photon spectra is presented and compared with the experimental results.

1. Introduction

Bent crystals are devices developed to deflect relativistic charged particles, producing the same effect of a huge magnetic field, thanks to the coherent interaction of particles with the ordered crystalline structure.

Since the first idea (proposed by Stark in 1912 [1]) that certain directions in a crystal could be more transparent to the passage of charged particles and its theoretical explanation by Lindhard in 1964 [2], the phenomena that occur inside a crystal with respect to the ones in amorphous materials have been thoroughly investigated [3,4]. In 1976 Tsyganov proposed to bend a crystal and to use it to deflect particles [5]; his pioneering idea was experimentally confirmed in 1979 [6] at JINR.

The physical principle at the basis of a bent crystal is that an atomic plane behaves as a continuous charge distribution with respect to a charged particle travelling almost aligned with the plane. In this way, two neighbouring planes can confine the particle trajectory between themselves, in the so called *channeling* condition [3]. In a bent crystal, channeling is not the only phenomenon able to deflect charged particles: when the particle trajectories become parallel with the channel inside the crystal "volume", an angular shift on the opposite direction with respect to the channeling side occurs: this effect is called *volume reflection* [7].

As described in [8], volume reflection offers excellent performances in terms of angular acceptance and efficiency at the expense of the deflection angle while larger and adjustable deflection angles can be obtained in the channeling orientation. Moreover, channeling performs a slight deviation of the particle trajectory all along the crystal length, while reflection is a point-like event located in a small region of the crystal.

The deflection properties of a bent crystal have been thoroughly investigated both from the theoretical [5,7,9] and experimental [6,8,10–12] point of view. By contrast, the radiation emitted by light leptons in the channeling or in the volume reflection condition is still under study and some features need to be explained [13].

This article presents the results obtained in the test performed at the CERN SPS-H4 beamline with 120 GeV/c positrons. An introduction to the radiation emission phenomena in bent crystals is presented in Section 2 together with the theoretical calculation;

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Section 3 is devoted to the experimental setup description while the results are summarized and compared with the calculations in Section 4.

2. Radiation emission phenomena in bent crystals

2.1. The state of the art

Since 1950 many experimental and theoretical studies have been dedicated to the investigation of photon emission by relativistic electrons and positrons crossing straight single crystals (see [14] and the literature therein). These studies have demonstrated the strong difference of the electromagnetic processes inside crystals with respect to the ones in amorphous media; nevertheless this phenomenon, together with its possible advantages, is still under investigation.

As mentioned in the previous section, channeling and volume reflection phenomena are really different from the deflection point of view. But when radiation emission is taken into account, their description becomes similar: in both cases the microscopic interaction with the interplanar potential plays the main role producing an oscillation in the transversal direction with respect to the motion. In channeling, the particle transversal energy is smaller than the potential barrier and the particle performs a quasi harmonic oscillation (Fig. 1 left). In volume reflection, the transversal energy exceeds the potential barrier so that the particle crosses the crystalline planes in an almost regular sequence (Fig. 1 right). These effects are responsible of the enhancement in the radiation emitted by channeled and volume reflected particles.

2.2. The theoretical calculations: a physical model

A considerable number of theoretical [15] and experimental [16] studies have been dedicated to the radiation emission investigation in straight crystals in the energy range from several hundreds of MeV to some tens of GeV. The spectrum of the emitted radiation depends on the contribution of the different oscillation harmonics and changes when increasing the energy of the incoming particles. Nevertheless, in the 100 GeV region, no literature can be found both from the theoretical and experimental point of view.

2.2.1. Channeling radiation in bent single crystals

As far as the channeling radiation emission in straight crystals is concerned, the calculation of the spectrum has been investigated in [19–21]. The single photon spectrum calculation is based on the Baier, Katkov and Strakhovenko method [17] for the radiation of high energy particles in quasiperiodic motion. Even if this method is not directly applicable to the experimental conditions of this article, taking into account the large enough bending radius of the used crystal, it can be demonstrated that the channeling radiation (in the 100 GeV region) is practically the same of a straight crystal.

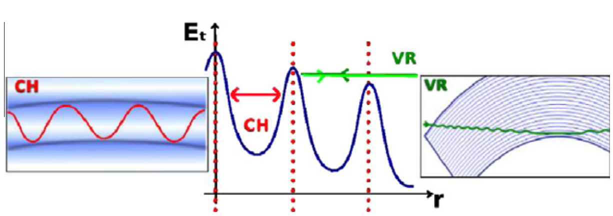

Fig. 1. Trajectories of a channeled (left) and a volume reflected (right) particle inside a bent crystal. Also the quasi harmonic interplanar potential is shown (center).

When the crystal is bent, the oscillations are superimposed on the circular motion so that the radiation intensity at a given time t is determined by the local characteristics of the particle motion at that time, that can be described by the trajectory curvature radius R_T. In other words, the differential intensity $\frac{dI}{dE_\gamma}$ depends on R_T: the larger R_T, the smaller $\frac{dI}{dE_\gamma}$ [18].

In a straight crystal the mean radius of curvature (i.e. the average over all the possible channeled particle trajectories) for a 120 GeV positron is $R_T = 0.6$ m. Defining R as the crystal bending radius, if $R \gg R_T$ the local curvature of the particle trajectory is approximately the same as in the straight crystal case. In other words, the intensity of the emitted radiation is practically the same in the two cases (bent and straight crystal).

The influence of bending on the emitted radiation can be thus investigated comparing the radiation intensity of a positron moving along a circular trajectory and the one of a channeled particle in a straight single crystal (in the (1 1 0) silicon plane). Since a bending radius of 5 m produces an intensity per unit length of 1.182 GeV/cm and the energy loss in a straight crystal is about 80 GeV/cm [18], the contribution given by the crystal curvature can be neglected [20,21].

Another aspect that should be taken into account is the multi-photon emission probability for a single positron; the method presented in [18] allows to estimate the single photon emission probability for a positron crossing a crystal length ds. When a positron crosses a macroscopic crystal (i.e. 2 mm long) the probability of multi-photon emission is not negligible. To introduce this effect, a Montecarlo simulation has been performed; particles are generated with a random alignment with an equiprobable distribution. Using this variable the transversal energy and thus the oscillation amplitude have been computed, so that the particle is tracked along the crystal associating an emission probability to every step of the trajectory. Only photons in the energy interval 50 MeV$< E_\gamma <$ 50 GeV have been considered; also the dechanneling process due to the scattering with the lattice nuclei has been included in the calculation [22]. The distribution obtained for the photon multiplicity is shown in Fig. 2: the average number of emitted photons per positron is around 4.

2.2.2. Photon emission in the volume reflection condition

As for the channeling radiation phenomenon, also the description of the volume reflection radiation emission starts from its straight crystal counterpart, the coherent bremsstrahlung [9]. A volume reflected particle crosses in sequence the different

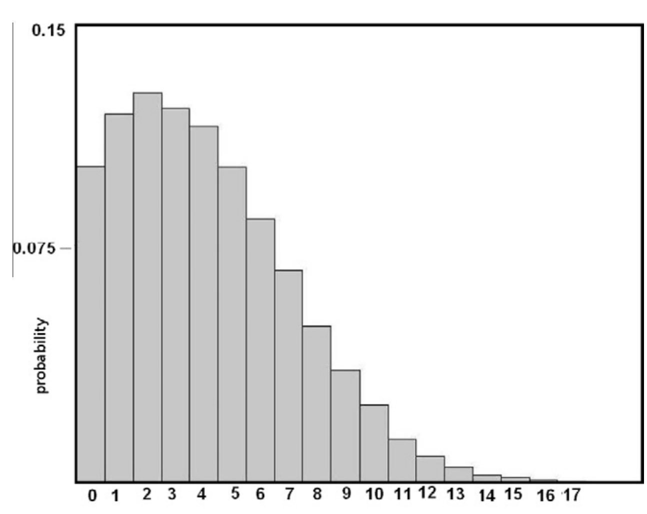

Fig. 2. Probability distribution of the multi-photon emission in channeling.