Crystal devices for beam steering in the IHEP accelerator

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Abstract. Different crystal devices are described, which provide an extraction and splitting of beams for a long period of time at the U-70 accelerator of IHEP. The modes of channeling and volume reflections in the bent crystals are used for these tasks. In regular accelerator runs crystals produce the particle beams in a wide range of intensity, from 10^6 up to 10^{12} particles in a cycle. Novel crystal techniques suitable for charged particle beams deflection and focus as well as photon generation are presented also.

1. Introduction

Ideas of use the particle channeling in bent crystals for steer the beams have been checked up and advanced in many experiments (see [1, 2, 3] and references herein). This method has found the widest practical application in U-70 accelerator of IHEP, where crystals are used in regular runs for beam extraction and forming. The questions of crystal channeling physics were described in [4, 5]. Here we concentrate on aspects of different bent crystal devices peculiarities.

2. Various options of beam deflection by bent crystals

Today, about 10 locations on the IHEP 70-GeV main ring of the accelerator facility are equipped by crystal extraction systems, serving mostly for routine applications rather than for research and allowing a simultaneous run of several particle physics experiments, thus significantly enriching the IHEP physics program (see figure 1).

In a figure 2 few developed crystal devices for beam steering are presented:

1 – The first long bent crystal for beam splitting in U-70 beam lines (1987) [6].
2 – The working model of the bent crystal for beam extraction in beam lines N2 and N4 [7].
3 – A thin crystal of a strip-type for a highly-efficient crystal extraction of a beam in beam line N8 [8, 9].
4 – The device for beam collimation, based on multiple reflection on a chain of the bent crystals [10, 11].
5 – The device for focusing of particle trajectories in ultrahigh energy region [12].

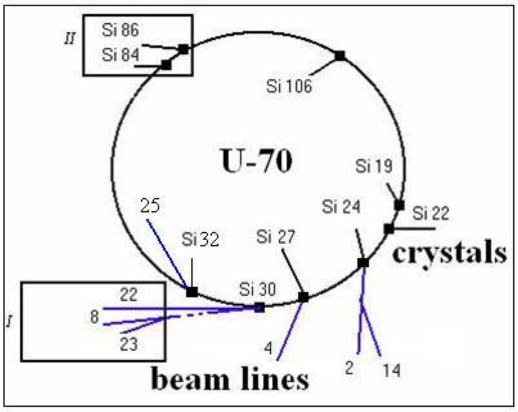

Figure 1. Crystal location at U-70 ring.

Figure 2. The arrangement of crystals at the stand.

On figures 3÷6 principles of work and the characteristic of these devices are briefly described.

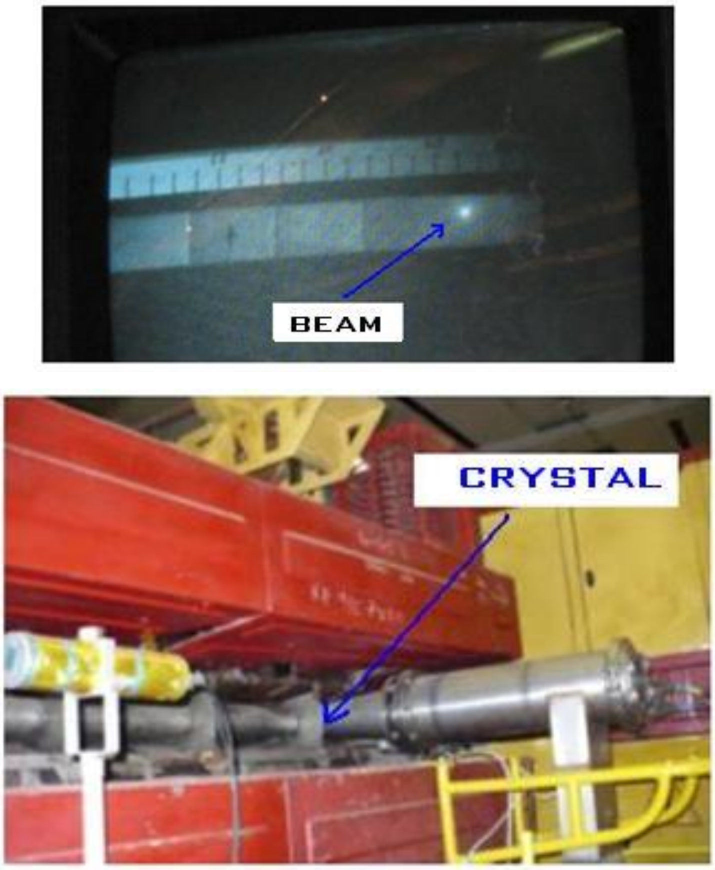

Figure 3. The extraction of a beam from U-70 ring by crystals 1 and 2 in a direction of beam lines N2 and N4.

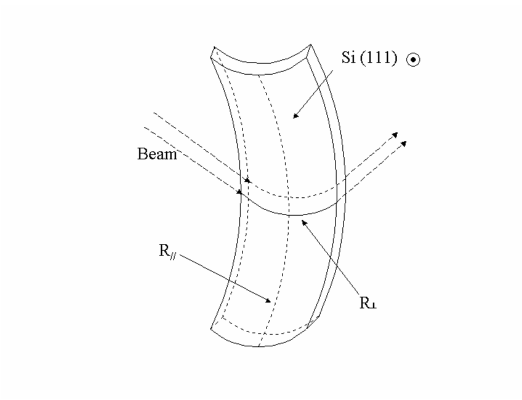

Figure 4. The Principle of a bend of a strip-type crystal (the device 3).

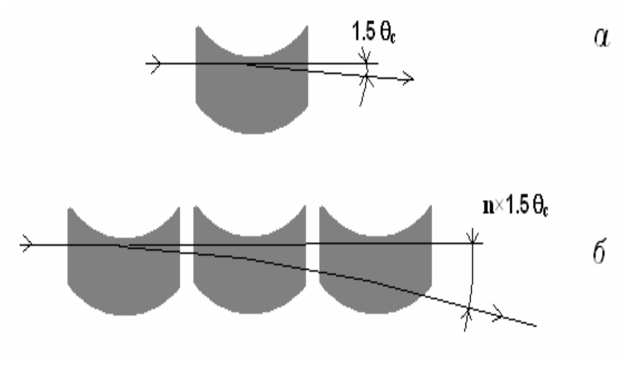

Figure 5. Amplification of deflection angle by multiple reflection of the particles on a chain of the bent crystals (the device 4).

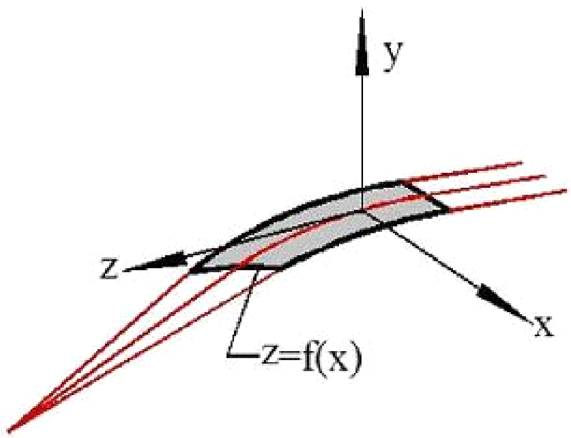

Figure 6. The principle of beam focusing by the device 5.

Employing the devices 1 and 2, the first extracted charged particle beams were obtained with a moderate intensity of up to 10^7 particles per pulse at extraction efficiencies of $10^{-4}\div10^{-3}$. In 1989, at the IHEP U-70 accelerator, a proton beam with energies of 50 and 70 GeV was extracted into one of the existing beam lines. To direct the extracted beam into this beam line, it was necessary to bent a (111) silicon crystal 65×15×0.6 mm in size to a large angle, about 90 mrad. As can see on figure 2, the crystals 1 and 2 were bend by metallic holders in longitudinal direction [7]. The moderate extraction efficiency in experiments with long crystals was caused by the fact that particles are captured into the channeling regime mostly during the first passage through the crystal.

It was predicted [13] that efficiency of crystal channeling extraction can be boosted to much higher values by multiple particle encounters with a shorter crystal (about 1mm in length) installed in a circulating beam (see figure 7). To clarify this mechanism a new experiment was started at IHEP at the end of 1997, with intention to test very short crystals and achieve very high efficiencies of extraction [8, 9]. Radical increase of extraction efficiency up to 85% was achieved with the help of the device 3, figure 2 known as “strip crystal”. This method of bending is based on the anisotropic properties of crystal lattices. From the theory of elasticity, it is known that bending a crystal plate in a longitudinal direction gives rise to deformations that assume a saddle- or barrel-like shape, depending on the particular anisotropic properties and orientation of the crystal (e.g., see [4, p. 85]). In silicon crystals, the largest lateral deformations are produced for the (111) orientation and take on a saddle-like shape (see figure 4). In this case, bending the crystal in height through an angle of 100 *mrad* ensures beam deflection through an angle of ~1 mrad in a transverse direction, which is sufficient for the beam extraction. This principle of crystal bend appeared fruitful for creation of multi-crystals (device 4, figure 2) and focusing crystals (device 5, figure 2). This design was modified at further in precision experiments with short crystals in CERN.

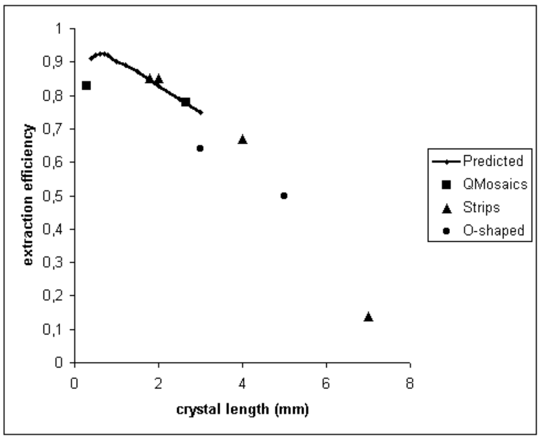

Figure 7. Extraction efficiency dependence versus crystal length.

After the success [9] research collaboration in CERN with participation of IHEP experts starts study of high energy particle beam bending by short crystals. The main goal of these researches will consist in study of crystal collimation of the LHC beam for increasing of its luminosity [14]. The big attention is given research of beam bending with the help of reflection in short crystals [15, 16]. Volume reflection is caused by interaction of incident particle with potential of the bent atomic lattice and occurs on small length in the vicinity of a tangent to the bent atomic plane, leading to deflection of a particle aside, opposite to a bend (figure 8). The probability of reflection is very high and comes nearer to unit at the energies bigger 100 GeV. The phenomenon of reflection occurs in wide area of angles and is more effective, than usual channeling. Therefore, there are real prospects to use of reflection for extraction and collimation of beams from U-70 accelerator [10, 11].

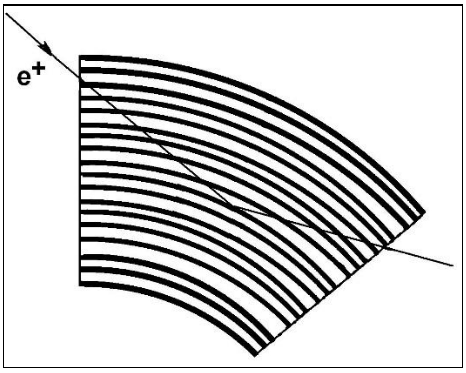

Figure 8. Scheme of volume reflection**.**

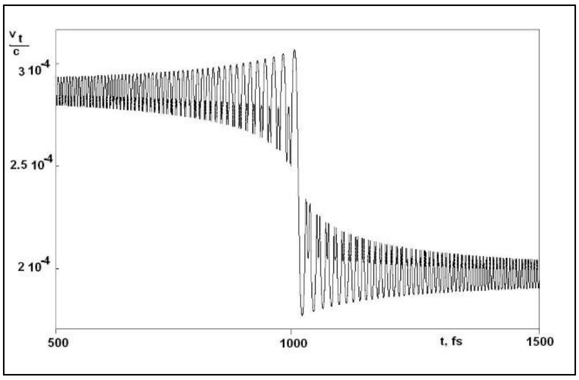

Figure 9. Behavior of velocity near reflection point.

3. New sources of radiation based on short bent crystals

In 2008 in [17] we have paid attention for the first time, that the short bent crystals are a new source of intensive radiation of photons at passage through them of charged particles in mode of reflection. At volume reflection particles cross a row of bent crystallographic planes (figure 8) and the behavior of its transversal velocity has aperiodic oscillation character (figure 9). On the basis of consideration of this motion in [17] the new type of intensive coherent radiation for electrons and positrons was predicted for these conditions. Due to high value of a Lorentz factor γ this radiation is more significant for light leptons than for other particles. The first experiment on detection of this radiation has been carried out in IHEP with 10 GeV positrons [18]. Positrons were directed on 0.65 mm silicon crystal bent at 0.5 mrad angle.

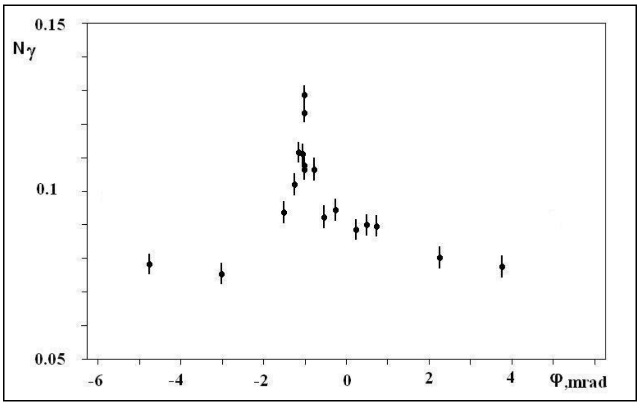

Figure 10. Orientation curve of photon yield.

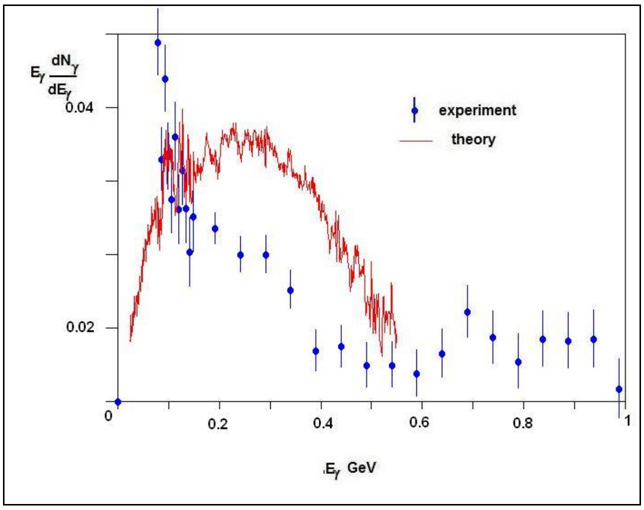

Figure 11. Differential energy losses.

Initially the orientation dependence of radiation intensity was found. Figure 10 illustrates the result of these measurements. One can see that the orientation curve has a clear maximum. Figure 11 illustrates the measured radiation energy losses $E_\gamma dN_\gamma / dE_\gamma$ of positrons in single crystal. For comparison, one can point that value of energy losses for amorphous silicon (or disoriented crystal) is 0.007 and it is practically independent of gamma-quantum energy. Thus presented here experimental results show on valuable radiation process of 10 GeV positron beam at volume reflection in bent single crystals. The more detailed researches of volume reflection radiation were carried out in CERN with 180 GeV positrons [19]. Even more impressing data are received recently with application of crystals of axial orientation in [20]. The main positive feature of volume reflection radiation is independence (within the limits of whole crystal bend) of radiation intensity from an incident angle of a particle. Such type of radiation can be applied at accelerators for production of intensive gamma-quantum beams and positron sources. In [21] the opportunity of bent crystal radiators application was proposed for beam cleaning systems in the ILC.

In the near future, we plan to show enhancement of radiation intensity from applications of chain of bent crystals (the device 4 on figure 2). It is expected that intensity of radiation will be proportional to amount the short bent crystals in a chain while in straight crystals intensity of radiation slows down the growth with length of a crystal [22, p.321].

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