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Using a deformed crystal for bending a sub-GeV positron beam

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Abstract

We analyze the scattering of 480 MeV positrons in bent crystal lattices carried out at the Beam Test Facility of the INFN – Laboratori Nazionali di Frascati. We observe experimentally that some particles follow the bending of the crystal lattice, presumably being guided by channeling phenomenon, and are deflected through the angles of about 10 mrad over length of 1 mm of silicon. This technique may lead to the use of channeling effect for steering of particle beams at the energies under 1 GeV, aimed at the production of ultrastable beams of low emittance for medical and biological applications.

We study channeling of fast charged particles in deformed crystals. The phenomenon of deflection of charged particle beam in a bent crystal is well investigated and successfully applied for extraction of beams at high-energy accelerators, at energies of about 10 GeV and higher (see for example [1]). However, of a big practical interest is the task of bending and extraction of charged particles with energies below 1 GeV, for example, aimed at the production of ultrastable beams of low emittance for medical and biological applications.

We investigate the deflection of a positron beam with energy of 400–700 MeV, available in BTF of INFN – Laboratori Nazionali di Frascati (LNF) [2], by means of bent silicon crystals. There exists a serious experimental problem in steering of beams of such energy connected to the small size of bent crystal samples. The channeling efficiency of particles is determined by the ratio of the critical channeling angle θ to beam divergence φ and it decreases exponentially with the crystal length L:

$$\mathrm{Eff} \sim (\theta/\varphi) \times \exp(-L/L_\mathrm{d}),$$

where characteristic parameter L_d, called dechanneling length, is relatively small for low energy. In our case for $E = 500$ MeV, $\theta = 0.24$ mrad and $L_\mathrm{d} = 0.4$ mm.

We firstly obtained the experimental conditions necessary for channeling investigation in BTF area of LNF. An experimental arrangement was been set up (see Fig. 1), which included: a collimator specially made for this experiment, a goniometer with channeling samples to be irradiated and tested, electronics to control the goniometer remotely, a vacuum pipe with a pump in order to reduce scattering on the way from the sample to detector and thus improve background situation there, and hodoscope detector to monitor particle profiles in horizontal and vertical planes.

We make use of a special iron collimator, in order to get a low emittance positron beam. The horizontal emittance of the beam $\varepsilon \approx 1\ \mathrm{mm} \times 1\ \mathrm{mrad}$ and $\varphi \approx 1$ mrad were achieved. The image of the collimated positron beam in 0.5 m downstream of collimator was registered with high resolution photoemulsion detector. The effect of beam collimation was also observed by a scintillation hodoscope detector, placed at the end of vacuum system in 4 m behind the collimator. So, in our case the ratio $(\theta/\varphi) \approx 0.2$ was achieved, which is appropriate for observation of the effect of particle deflection.

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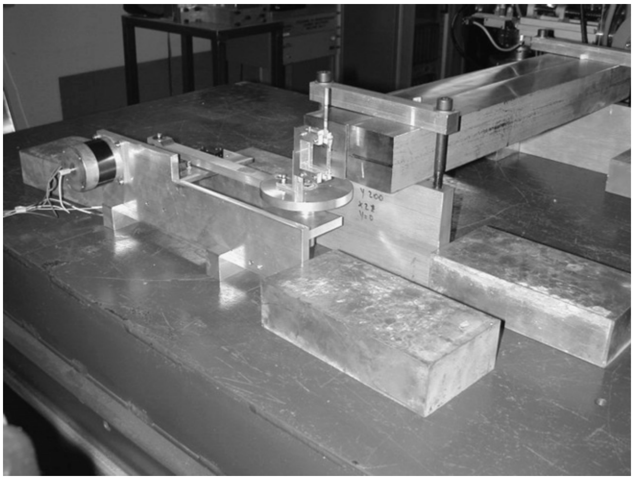

Fig. 1. Goniometer for crystal sample rotation (30 μrad step) in front view and steel collimator in back view.

A new recently invented technique of crystal bending was applied to produce samples with high curvature. This technique is based on the method described in [3–9], which was successfully applied for crystal undulator production. Microscratches on crystal surface allow us to reach high curvature of crystal bend: up to 10 mrad over 0.5 mm length. These parameters of crystal deformation were optically measured with laser system (Fig. 2). In these conditions, a pure separation of channeled 500 MeV beam with the efficiency of few tens of percent is possible.

At the first experimental stage we used nuclear emulsion layers as a beam detector. In Fig. 3, the effect of coherent scattering of the positron beam was recorded. In this figure, to the left, the image of a beam measured at a distance of 0.5 m downstream of the aligned crystal is shown. The result of Monte Carlo simulations, based on the model described in [10], considering channeling of particles in crystal and multiple scattering in air in drift space and inside collimator is presented on the right of the figure.

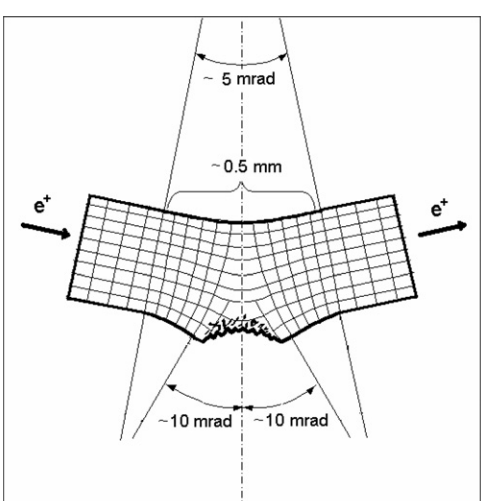

Fig. 2. Scheme of the crystal deformation due to a mechanical scratch.

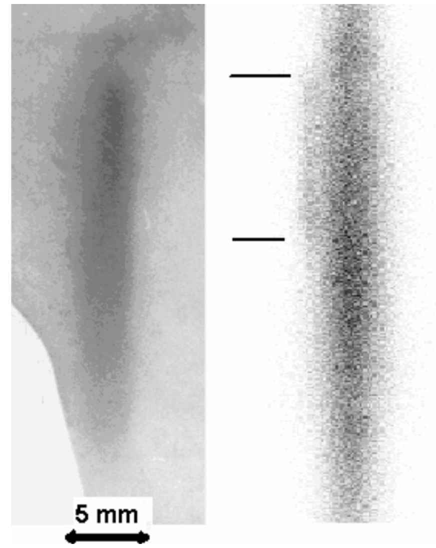

Fig. 3. The image of collimated beam scattered on the crystal measured with emulsion layer at 0.5 m downstream (at the left) and result of Monte Carlo simulation (at the right).

The region between two markers in the top part of figure designates position of bent section of the crystal. In the position below markers the crystal was straight. This part of the crystal strip was used only as the holder and could not deflect particles of the beam strongly. In both experimental and theoretical pictures the tail of the particles deflected to the left in the field of between markers is visible.

In Fig. 4, the one-dimensional beam profiles corresponding to bent and straight sections of crystal strip are compared. The good agreement of experimental data (the left picture) with results of simulation (the right picture) is observed.

Another approach for the bending of a short crystal has been also investigated, where the bending angle of 12 mrad is obtained by means of a metal minibracket (Fig. 5).

The effect of deflection of a positron beam by such crystal is shown in Fig. 6(a) in comparison with results of calculation Fig. 6(b). Such device allows to extract from particle accelerators low emittance beams in both planes (x, y).

In the next accelerator runs applications of crystal deflectors with even higher bending and reconstruction of particle tracks with the help of four layers of the straw tube detectors is foreseen. A further approach to be undertaken in future will assume that oriented arrays of nanotubes will trap and channel part of the incident beam. By giving to nanotubes a controlled bending of a few milliradian, we could deflect the channeled particles out of the incident beam. The creation of such nanodeflectors is in progress [11–16].

Let us recall that in Frascati, our activity has been mainly focused on the study of nanostructures [17–24]. Our setup for synthesis based upon DC arc plasma, struck between two graphite rods technique yields high quantity

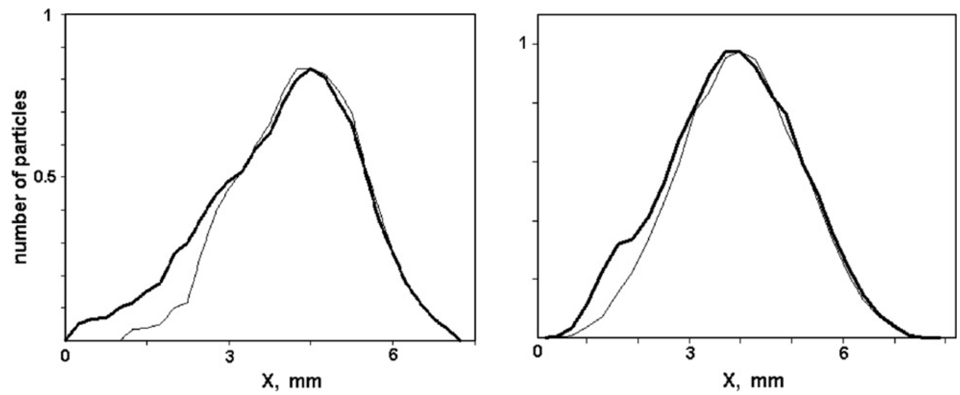

Fig. 4. The experimentally measured beam profiles (at the left) and result of simulation (on the right) in 0.5 m downstream of crystal. Thick lines correspond to penetration of beam in bent part of a crystal strip. Thin lines correspond to section, where the crystal was straight.

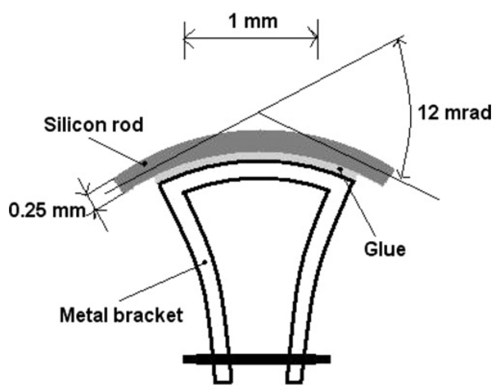

Fig. 5. Another-type of bent crystal. A bending angle of 12 mrad is obtained, owing to the pressure of a metallic microbracket.

of CNTs [25]. We completed a thermal CVD chamber, for patterned substrate and large area deposition. SWCNTs and MWCNTs are obtained in our laboratories under varying synthesis conditions, using different parameters e.g. the plasma current, thermal gradients. The samples are studied with electron microscopy (Fig. 7) for determining optimal conditions for maximum yield of CNTs (in relation to amorphous material, onion-like structures, etc.).

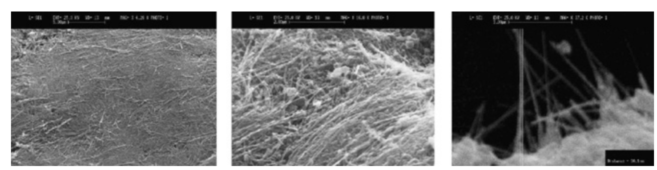

Fig. 7a. SEM images of CNTs synthesized at INFN – LNF.

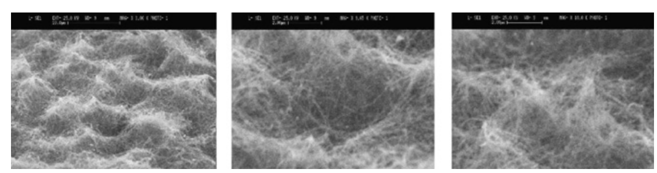

Fig. 7b. A carpet of CNTs synthesized at INFN – LNF with an arc-discharge setup.

Concerning the characterization of INFN – LNF CNTs, a morphological analysis of our samples by SEM, TEM and AFM yields ratio and dimensions of the CNTs. SEM images show that the ratio of NTs is very high (more than 70%). SWCNTs have an average diameter 1.3 nm and a length of several microns. They exist in bundles of

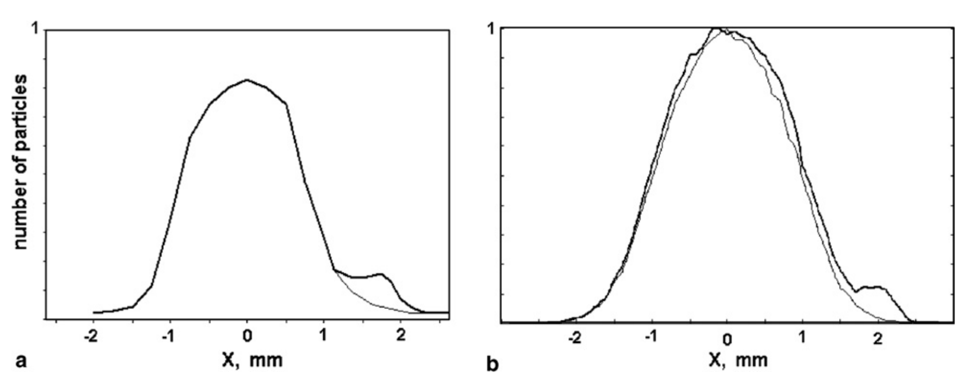

Fig. 6. The experimentally measured beam profiles (a) and result of simulation (b) in 0.17 m downstream of 12 mrad bent crystal. Thick lines correspond to penetration of beam in oriented crystal (effect of crystal channeling is seen on the right side of plots). Thin lines correspond to disoriented crystal. In experimental plots 10% level of statistical fluctuations of emulsion analysis data are not shown.

20–40 nm transverse size. MWCNTs have a wide range of diameter (20–60 nm). A newly commissioned chamber of synthesis at LNF based on the chemical vapour deposition (CVD) technique yields the promise to deliver in the near future samples of aligned carbon nanotubes. This will then provide the basics, in order to able to proceed to the realization of nanostructured particle deflectors.

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