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Steering of multi-MeV positron beam by a curved crystal

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We observe positron bending by a crystal lattice, presumably being guided by channeling phenomenon, deflecting the beam by about 10 milliradian over a length of 1 mm of Silicon. This technique may lead to the use of channeling effect for particle beams steering at energies below 1 GeV, for the purpose of producing beams of low emittance with enhanced stability for medical and biological applications.

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The deflection of high-energy charged particle beams in bent crystals is well investigated and successfully applied for extraction of beams at high-energy accelerators, for energies about 10 GeV and higher (see for example Ref. [1]). However, of a big practical interest is the task of bending and extracting 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. Efficiency (Eff) of deflection 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:

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

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

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.

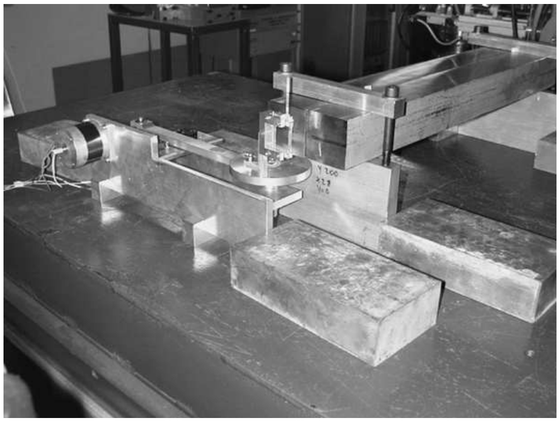

Fig.1. Goniometer for crystal sample rotation (30 microrad step) in front view and steel collimator in back view

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 $\varphi \approx 1\,\mathrm{mrad}$ 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 meters 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.

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 Ref. [3 – 9], which was successfully applied for crystal undulator production. Microscratches on crystal surface allow 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. 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 detector of beam. In Fig.2 the effect of coherent scattering of positron beam was recorded. In this figure at the left the image of a beam measured on distance 0.5 m downstream of the aligned crystal is shown. The result of Monte Carlo simulations considering channeling of particles in crystal and multiple scattering in air in drift space and inside collimator is presented on the right of Figure. 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.

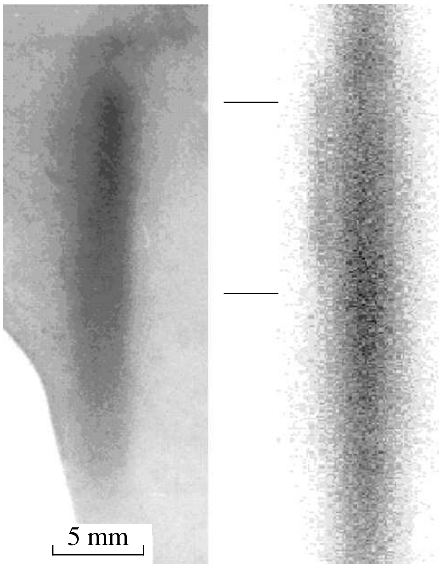

Fig.2. The image of collimated beam scattered on the crystal measured with emulsion layer at 0.5m downstream (at the left) and result of Monte Carlo simulation (at the right)

In Fig.3 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.

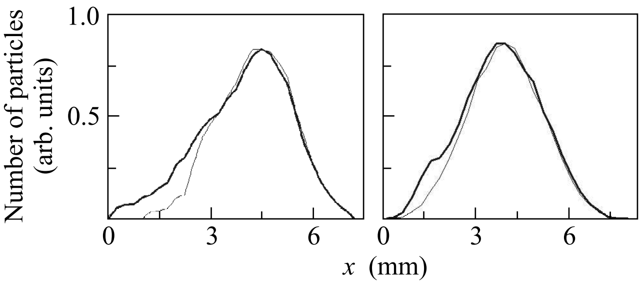

Fig.3. The experimentally measured beam profiles (at the left) and result of simulation (on the right) in 0.5 m downstream of crystal. Thick lines correspond to penetration of beam in bent part of a crystal strip. Thin lines correspond to section, where the crystal was straight.

Another approach for a bend of a short crystal also has been investigated, where the bend angle of 12 mrad is created by means of metal minibracket. The effect of deflection of a positron beam by such crystal is shown in Fig.4a in comparison with results of calculation 4b.

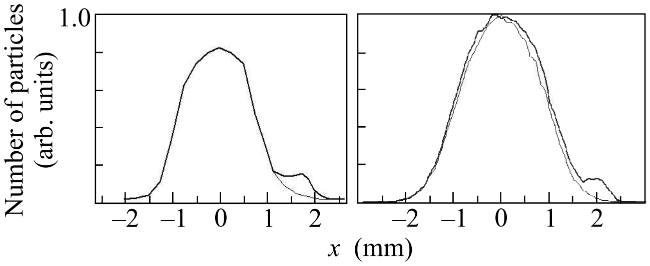

Fig.4. The experimentally measured beam profiles (a) and result of simulation (b) in 0.17 m downstream of 12 mrad bent crystal. Thick lines correspond to penetration of beam in oriented crystal (effect of crystal channeling is seen on the right side of plots). Thin lines correspond to disoriented crystal. In experimental plots 10% level of statistical fluctuations of emulsion analysis data are not shown

Such device allows to extract from particle accelerators low emittance beams in both planes (x, y).

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 (Ref. [10 – 15]).

Let us recall that in Frascati, our activity has been mainly focused on the study of nanostructures [16 – 23]. Our setup for synthesis based upon DC arc plasma, struck between two graphite rods technique yields high quantity of CNTs [24]. We completed a thermal Chemical Vapour Deposition (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.5) for determining optimal conditions for maximum yield of CNTs (in relation to amorphous material, onion-like structures, etc.).

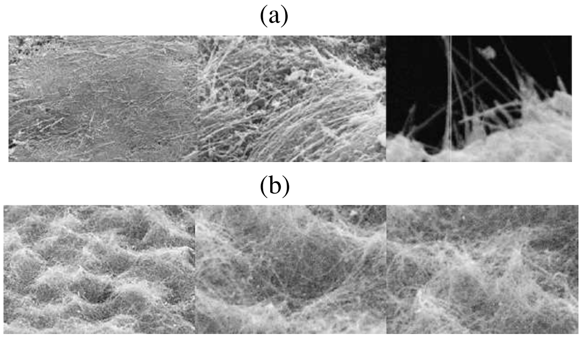

Fig.5. (a) SEM images of CNTs synthesized at INFN-LNF. (b) A carpet of CNTs synthesized at INFN-LNF with an arc-discharge setup

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 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 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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