ISSN 0021-3640, JETP Letters, 2006, Vol. 83, No. 3, pp. 95–97. © Pleiades Publishing, Inc., 2006.

Steering a Multi-MeV Positron Beam with a Curved Crystal¶

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Received December 15, 2005

We observe positron bending by a crystal lattice, presumably being guided by a 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 the channeling effect for steering particle beams at energies below 1 GeV, for the purpose of producing beams of low emittance with enhanced stability for medical and biological applications.

PACS numbers: 07.85.–m, 41.60.–m, 61.85.+p

DOI: 10.1134/S0021364006030039

The deflection of high-energy charged particle beams in bent crystals has been well investigated and successfully applied for extraction of beams at high-energy accelerators, for energies of about 10 GeV and higher (see, for example, [1]). However, of much 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 energies 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 beams of such energy connected to the small size of the bent crystal samples. The efficiency (Eff) of deflection of particles is determined by the ratio of the critical channeling angle θ to beam divergence φ and decreases exponentially with the crystal length L:

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

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

We first obtained the experimental conditions necessary for channeling investigation in the BTF area of LNF. An experimental arrangement was 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 the background situation there, and a hodoscope detector to monitor particle profiles in the horizontal and vertical planes.

We make use of a special iron collimator in order to get a low emittance positron beam. A horizontal emittance of the beam of $\varepsilon \approx 1$ mm $\times$ 1 mrad and $\varphi \approx 1$ mrad were achieved. The image of the collimated positron beam 0.5 m downstream from the collimator was registered with a high-resolution photoemulsion detector. The effect of beam collimation was also observed by a scintillation hodoscope detector placed at the end of vacuum system, 4 meters behind the collimator. Thus, 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 a high curva-

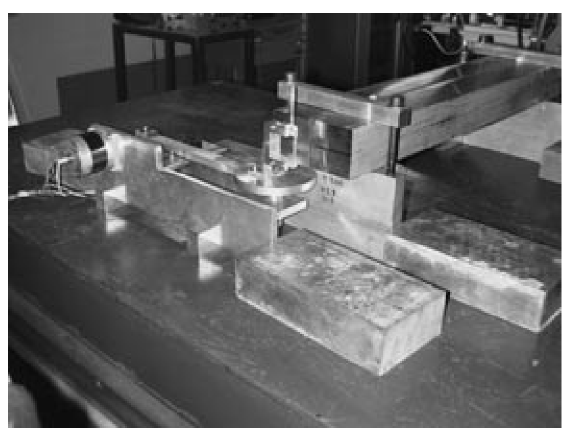

Fig. 1. Goniometer for crystal sample rotation (30-microrad step) in front view and steel collimator in back view.

¶ The text was submitted by the authors in English.

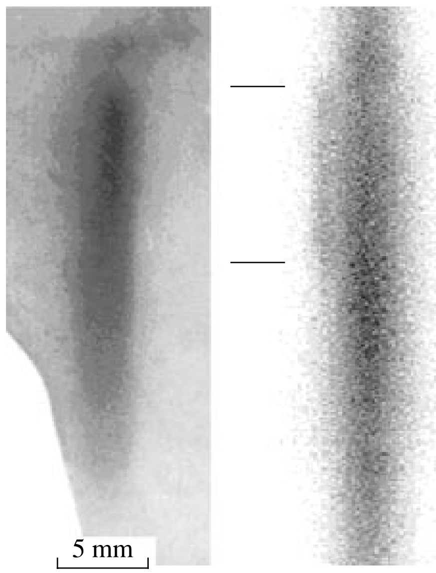

Fig. 2. The image of a collimated beam scattered on the crystal measured with emulsion layer 0.5 m downstream (on the left) and result of Monte Carlo simulation (on the right).

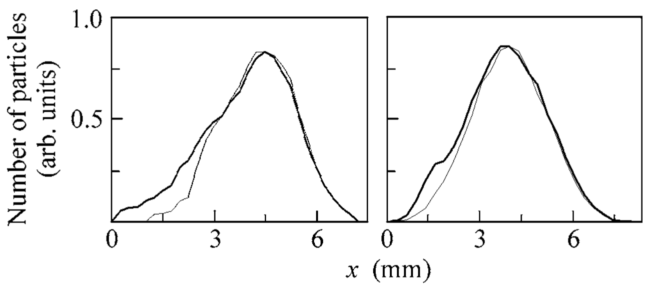

Fig. 3. The experimentally measured beam profiles (on the left) and result of simulation (on the right) 0.5 m downstream of the crystal. Thick lines correspond to penetration of the beam in the bent part of a crystal strip. Thin lines correspond to sections where the crystal was straight.

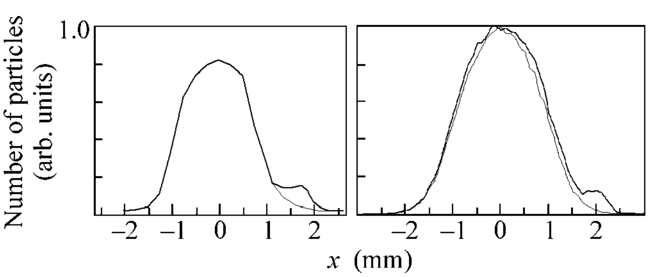

Fig. 4. The experimentally measured beam profiles (a) and results of simulation (b) 0.17 m downstream of the 12 mrad bent crystal. Thick lines correspond to the penetration of the beam in the oriented crystal (the effect of crystal channeling is seen on the right side of the plots). Thin lines correspond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

ture. This technique is based on the method described in [3–9], which was successfully applied for crystal undulator production. Microscratches on a crystal surface allow a high curvature of crystal bend to be reached: up to 10 mrad over a length of 0.5 mm. These parameters of crystal deformation were optically measured with a laser system. Under these conditions, a pure separation of a channeled 500-MeV beam with an efficiency of a 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 the positron beam was recorded. At the left of this figure, the image of a beam measured 0.5 m downstream from the aligned crystal is shown. The results of Monte Carlo simulations considering channeling of particles in the crystal and multiple scattering in air in the drift space and inside the collimator are presented at the right of the figure. The region between the two markers in the top part of the figure designates the position of the bent section of the crystal. In the position below the markers, the crystal was straight. This part of the crystal strip was used only as a holder and could not strongly deflect particles of the beam. 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. 3, the one-dimensional beam profiles corresponding to bent and straight sections of crystal strip are compared. A good agreement of the experimental data (the left picture) with the results of simulation (the right picture) is observed.

Another approach for a bend of a short crystal has also been investigated, where a bend angle of 12 mrad is created by means of a metal minibracket. The effect of deflection of a positron beam by such a crystal is shown in Fig. 4a in comparison with the results of calculation 4b. Such a device allows low-emittance beams to be extracted from particle accelerators in both planes (x, y).

A further approach to be undertaken in the 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 [10–15].

Let us recall that our activity in Frascati 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 yields a high quantity of CNTs [24]. We constructed a thermal chemical vapor 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 and thermal gradients. The samples are studied with electron microscopy (Fig. 5) to determine the opti-

(a)

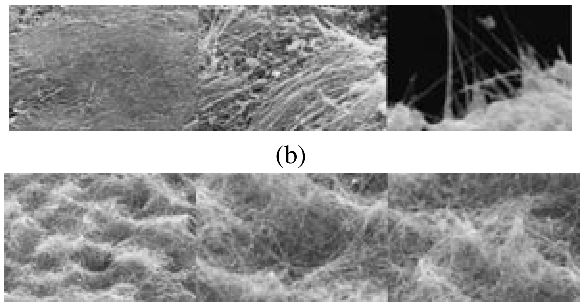

Fig. 5. (a) SEM images of CNTs synthesized at INFN-LNF. (b) A carpet of CNTs synthesized at INFN-LNF with an arc-discharge setup.

mal conditions for maximum yield of CNTs (in relation to amorphous material, onionlike structures, etc.).

Concerning the characterization of INFN-LNF CNTs, a morphological analysis of our samples by SEM, TEM, and AFM yields the 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 of 1.3 nm and a length of several microns. They exist in bundles 20–40 nm in transverse size. MWCNTs have a wide range of diameters (20–60 nm). A newly commissioned chamber of synthesis at LNF based on the CVD technique promises to deliver in the near future samples of aligned carbon nanotubes. This will then provide the basis to proceed to the realization of nanostructured particle deflectors.

This work is supported by TARI, contract number RH3-CT-004-506078.

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