Innovative remotely-controlled bending device for thin silicon and germanium crystals

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ABSTRACT: Steering of negatively charged particle beams below 1 GeV has demonstrated to be possible with thin bent silicon and germanium crystals. A newly designed mechanical holder was used for bending crystals, since it allows a remotely-controlled adjustment of crystal bending and compensation of unwanted torsion. Bent crystals were installed and tested at the MAMI Mainz Microtron to achieve steering of 0.855-GeV electrons at different bending radii. We report the description and characterization of the innovative bending device developed at INFN Laboratori Nazionali di Legnaro (LNL).

KEYWORDS: Accelerator Applications; Beam Optics; Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons); Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators)

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1 Introduction

Experimental studies of manipulation with bent crystals via channeling [1] and Volume-Reflection [2] effects received a strong boost in recent years due to technological development which led to the successful demonstration of the LHC 6.5 TeV proton beam deflection [3].

The steering of electrons and negatively-charged particles in general is more challenging due to the shorter dechanneling length compared to their positive counterpart. This fact required the development of thinner crystals [4] to overcome the problem of a shorter dechanneling length and a deeper understanding of scattering processes involved, thus leading to important results in beam steering [5–7], e.m. radiation generation in bent crystals [8, 9] and the observation of quasi-channeling oscillation [10, 11].

In order to exploit channeling phenomena of negative particles high quality bent crystals has to be produced down to few tens of micrometers. The most used materials are Si or Ge, due to the high lattice qualities available, as required also for microelectronics applications. The mechanical bending of such brittle materials [12] is a non-trivial task especially if thin crystal for negative particle application has to be developed. The reason is that in usual bending holders the primary curvature is given during the mechanical clamping procedure causing local stress concentrations that may break the sample during mounting [13].

In the present paper we present an innovative bending scheme to be applied to thin silicon or germanium slabs. Samples are bent only after clamping, in order to minimize local stress. Then the samples are gradually and homogeneously bent without stress concentration, by actuating a single translational degree of freedom. A further degree of freedom to tune the curvature quality is also present and the possibility of manage chemical thinning procedure after clamping and before bending are demonstrated.

2 Bending device

2.1 General features

The basic principle is that of the bow: the crystal slab sides are put under tension by squeezing the sides one toward the other by a translation movement. To avoid stress at the sides, the slab is
clamped on two freely rotating surfaces. During bending the maximum stress is obtained in the middle of slab while it goes to zero close to clamping. In this way low stress concentration occurs at clamping point and the specimen can be used for the application up to curvatures close to the breaking limit.

In this paper we describe the design, the realization and the use of a bending device prototype specifically developed for channeling application, in particular the system has been used to deflect 0.855 GeV electrons by means of planar channeling into (111) Si bent planes at the MAMI microtron of Mainz with an experimental setup based on the one presented in refs. [14, 15]. For this application the quality of the bending is mandatory due to the very limited acceptance angle over which the channeling phenomenon is efficient. Spurious bending (torsion) due to mechanical misalignment are compensated by an additional degree of freedom that takes care of the parallelism between the rotating clamping planes [16]. Both squeezing and torsion degrees of freedoms are remotely controlled by high precision and vacuum compatible piezo motors.

Moreover the bending scheme can be used to obtain very thin bent specimens. Even if the clamping on flat surfaces before the bending is a strong advantage, the specimen can be hardly managed and often break during the clamping procedure if they are below certain thickness (10–15 micron for silicon, 20–30 for the more brittle germanium). In order to overcome this limit too, the clamping is performed with sample over the critical thickness and the specimen are further thinned by chemical procedures before being transferred to the bending device. In summary the procedure is performed in the following steps: i) clamping of the specimen to the rotation axis; ii) eventual further thinning by chemical procedures; iii) transfer to the bender; iv) bending of the specimen. With this method, Si and Ge crystals with a thickness down to 15 µm are bent to a curvature radius down to 3 mm.

2.2 Design description

The design of the bending system is reported in figure 1. The bender is made by different mechanical parts (A to G) including two piezo motors (D: Picomotor actuator 8301-UHV, F: Newport AGLS25). Specimen (H) is clamped to two plugs I1 and I2 that can be transferred into the bender with a translation along axes indicated with black dashed lines. During transfer the plugs are mechanically fixed to a handling holder that avoids the accidental rotation of the plugs and allows to handle also very thin and fragile samples. After complete transfer the handling holder is removed and the plugs are inserted in two couples of holes where they can freely rotate. In order to obtain the sample bending, part A is translated toward part B in order to reduce the distance between the plugs. During translation plugs rotates to minimize the stress of the sample providing a homogenous bow-wise curvature of the specimen. The translation is finely controlled by the linear translation stage F with a step size of about 0.5 µm.

In principle this single translational degree of freedom may be used in order to tune the desired curvature. Practically the obtained curvature could be not satisfactory since of possible imperfection in the parallelism of the two clamped portions of the sample causing an unwanted deformations that may affect the efficiency. An additional remotely controlled degree of freedom is therefore included into the device. It allows to rotate one of the plugs with respect to the other (I1 and I2) to correct parallelism. The plug holder B can rotate with respect to the fixed part E around a cylindrical plug C with a rotation axis parallel to the y direction. The cylindrical plug C is only partially visible
in figure 1 since both B and E parts have cylindrical hollows that act as a guide for the rotation. 
The rotation regulation occurs by a push-pull system: the linear actuator D pushes the plug holder 
B while, on the opposite side (not visible), a spring pulls and keeps stability. Given the fine step 
of about 30 nm and the lever distance of the push pull system (20 mm), the system can in principle 
regulate the parallelism with a resolution lower than 1 µrad.

Such fine tuning is useful for regulating the torsion of the specimen, which is a typical problem 
for channeling application [17]. If the parallelism is not finely tuned, the specimen undergoes a 
screw-like deformation, which has a detrimental effect for the beam alignment with channeling 
planes. As a consequence, only a fraction of the beam would result to be channeled and deflected 
by the device.

In order to obtain a full parallelism between the supporting plugs, a further rotation around 
z-axis should be applied to one of them. To this aim, mechanical part A is machined with a 
symmetric regress that allows to elastically rotate the support of I1 by means of a push pull action 
actuated by two screws calibrated before the sample transfer by a parallel x-ray beam.

The holder is thought to operate with the vertical direction along the x-axis as shown in figure 2. 
In this case the I plugs are avoided to fall by a screw with spherical head centered in the rotation 
axis (G in figure 1). The friction momentum due to the I plugs weight is strongly minimized 
since they have to virtually rotate around a point. During the bending the specimen stress slightly 
push the plugs against their hole walls causing friction. This effect is minimized by using rectified 
stainless-steel plugs and brass hole holder A and B. The suitable hole plugs coupling and the whole 
mechanical accuracy is guaranteed by high precision wire electrical discharge machines used for 
fabrication.

2.3 Sample preparation and bending

Both Si and Ge specimen were produced and bent through the piezo-bender. Silicon samples with 
tens of microns thickness are produced as shown in ref. [4].
Germanium thin plates were produced starting from a 4 inch diameter wafer purchased from Umicore (Olen, Belgium), (211) orientation, EPD lower than 1000/cm$^2$ and thickness ranging from 30 to 70 $\mu$m as claimed by the factory. A dedicated procedure to cut the wafer by chemical etching has been followed in order to avoid breakage. Firstly, a pattern of protecting Cr/Au pads with size $15 \times 13$ mm$^2$ was deposited with RF sputtering on both sides of the wafer through a mechanical mask. Then, the wafer was immersed in an etching bath as described in ref. [18] and the Cr/Au coating was stripped from the surface of the so obtained rectangular plates.

Further wet chemical processing has been applied to thin the plate down to around 15 $\mu$m in thickness by using a low rate etching bath, as described in ref. [19]. The etch rate and the homogeneity in erosion have been characterized by means of HR-XRD, exploiting the Beer-Lambert law [20].

The Germanium plate-like crystal has been anchored using two-side Kapton adhesive tape to the holder plugs and a final thickness characterization by collecting the XRD map reported in figure 3 has been performed.

In figure 2 a bent silicon crystal with a 15 micron thickness is shown. The sample of the photo has a visible primary curvature along the main surface, which is parallel to the (211) planes, with a radius of 2.8 mm. A secondary bending with 10 mm radius due to the quasi-mosaic effect [14, 21] occurs on the inner (−111) planes parallel to x–z plane around the y axis. When the beam coming along the z-axis is aligned with such planes channeling deflection occurs.

2.4 Experimental test

Experiment is performed with the MAMI B line set-up [15]. In order to get the planar channeling condition the sample is rotated around y-axis and the ionization chamber signal is maximized as explained in ref [22]. In order to optimize torsion correction the channeling angle is determined for different positions of the beam along the y direction starting from the center of the sample (y=0).
When no stroke is applied to the torsion correction screw D, the channeling angle condition usually strongly varies with the lateral position (about 900 µrad/mm) due to the fact that I1 and I2 plugs are not parallel, and therefore a screw like elastic deformation is given to the sample. By moving the D screw, I2 plug rotates and torsion is reduced, as one can see in the lower channeling angle variation with lateral position, which reached a final value of 35 µrad/mm after a stroke of 145 µm, as shown in figure 4. This means that a misalignment of 7 µrad is finally present along a beam size with about 0.2 mm root mean square. This value is acceptable, since it is negligible with respect to the channeling critical angle of Si (111), which is about 200 µrad for 855 MeV electrons of MAMI. It is worth to note that the D screw allows for much finer steps (about 30 nm) and in principle much better correction could be reached in case of more critical situations as it occurs at higher beam energies with lower critical angle.

Steering capability of 15 µm long silicon and germanium crystals due to 855 MeV electron interaction with bent (−111) planes has been measured by exploiting the above described bender system and procedure. Data are presented and modeled in details in ref. [14]. The usage of the piezo-actuated mechanical holder allowed to remotely change the crystal curvature modulating the deflection effect as can be noted in figure 5. The typical deflection histograms for several curvatures are presented: zero angle correspond to no electron deflection, many electrons are deflected at negative angle due to volume reflection (VR), while several particles are deflected at positive angle creating the typical channeling peaks. These are due to the particles that follow the bent plane for the whole thickness. Fine alignment of the beam is optimized by maximizing the channeling peak when the sample is rotated around y axis. Particles that undergoes dechanneling due to scattering populate

![Figure 3](image.png)

**Figure 3.** X-ray absorption derived thickness bidimensional map of the Ge plate-like crystal. Color scale is in micrometer units of thickness. Mapping axes are in the same reference of figure 1 and 2.
Figure 4. Channeling angle of (111) plane as a function the lateral position and the D screw stroke. The screw movement allows to effectively correct the torsion, since it allows to stabilize the channeling angle over a linear displacement of the impinging beam along y-axis. A more detailed description is given in the experimental text section.

an exponential tail joining the VR and the channeling peaks. For silicon, the channeling efficiency, i.e. the fraction of particles in channeling peaks over the total number of particles (calculated as explained in [14] and references therein) exceeds 35%, which is a record for negatively charged particles. This was possible due to the realization of a crystal with a thickness of the order of the dechanneling length. On the other hand, for germanium the channeling deflection efficiency is slightly below 10% due to the stronger contribution of multiple scattering for a higher-Z material.

3 Conclusions

In this paper an innovative remotely controlled crystal bender system is presented. The bending device demonstrates many advantages: the clamping of the sample is performed on flat surfaces before impressing the curvature, thus reducing stress concentration and allowing to perform clamping with a reasonable success rate of Si samples down to 15 micron thickness and Ge sample down to about 25 micron. The clamped sample can be further thinned down on-board before bending. This procedure was successfully applied to Ge slab in order to reduce the thickness down to about 15 micron, and could in principle be applied to get even thinner Si sample. After transfer the holder impress a bow-like primary curvature to the sample down to impressive value of 3 mm, by means of one single remotely controlled motor. Curvature may be changed without vacuum breaking. The curvature quality is regulated by a further piezo-motor that can very finely regulate the torsion. Data demonstrating this function are illustrated. Finally, channeling deflection spectra are shown as an example, to complement the data already reported and analyzed in ref. [14].

The present device is also an innovative proof of concept that could be scaled and optimized for different sample thickness to satisfy channeling requirements at different beam energies. Moreover, similar device may be also developed for x-ray beam manipulation applications.
Figure 5. Deflected 0.855 GeV electron beam distribution by channeling in the 15 µm long Si crystal bent through the piezo-holder. $\theta_x$ is the deflection angle in the x–z plane due to interaction with bent (−111) planes. Four different quasi-mosaic curvature radii, $R$, were used: 47.5 mm (blue curve), 27.2 mm (green curve), 20 mm (orange curve) and 13.9 mm (red curve), respectively.

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References

[1] E.N. Tsyganov, Some aspects of the mechanism of a charge particle penetration through a monocrystal, FERMILAB-TM-0682 (1976).

[2] A. Taratin and S. Vorobiev, “Volume reflection” of high-energy charged particles in quasi-channeling states in bent crystals, Phys. Lett. A 119 (1987) 425.

[3] W. Scandale et al., Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC, Phys. Lett. B 758 (2016) 129.

[4] G. Germogli, A. Mazzolari, L. Bandiera, E. Bagli and V. Guidi, Manufacturing and characterization of bent silicon crystals for studies of coherent interactions with negatively charged particles beams, Nucl. Instrum. Meth. B 355 (2015) 81.

[5] A. Mazzolari et al., Steering of a Sub-GeV Electron Beam through Planar Channeling Enhanced by Rechanneling, Phys. Rev. Lett. 112 (2014) 135503.

[6] U. Wienands et al., Observation of Deflection of a Beam of Multi-GeV Electrons by a Thin Crystal, Phys. Rev. Lett. 114 (2015) 074801.

[7] T.N. Wistisen et al., Channeling, volume reflection, and volume capture study of electrons in a bent silicon crystal, Phys. Rev. Accel. Beams 19 (2016) 071001.
[8] L. Bandiera et al., Broad and intense radiation accompanying multiple volume reflection of ultrarelativistic electrons in a bent crystal, Phys. Rev. Lett. 111 (2013) 255502.

[9] L. Bandiera et al., Investigation of the Electromagnetic Radiation Emitted by Sub-GeV Electrons in a Bent Crystal, Phys. Rev. Lett. 115 (2015) 025504.

[10] A.I. Sytov et al., Planar channeling and quasichanneling oscillations in a bent crystal, Eur. Phys. J. C 76 (2016) 77 [arXiv:1505.01831].

[11] T. Wistisen et al., Observation of Quasichanneling Oscillations, Phys. Rev. Lett. 119 (2017) 024801.

[12] F. Serbena and S. Roberts, The brittle-to-ductile transition in germanium, Acta Metall. Mater. 42 (1994) 2505.

[13] H. Neuber, Theory of stress concentration for shear-strained prismatical bodies with arbitrary nonlinear stress-strain law, J. Appl. Mech. 28 (1961) 544.

[14] A.I. Sytov et al., Steering of Sub-GeV electrons by ultrashort Si and Ge bent crystals, Eur. Phys. J. C 77 (2017) 901 [arXiv:1709.01482].

[15] D. Lietti et al., The experimental setup of the Interaction in Crystals for Emission of RADiation collaboration at Mainzer Mikrotron: Design, commissioning and tests, Rev. Sci. Instrum. 86 (2015) 045102.

[16] V. Guidi et al., Manipulation of Negatively Charged Beams via Coherent Effects in Bent Crystals, in proceedings of the 1st International Particle Accelerator Conference (IPAC’10), Kyoto, Japan, 23–28 May 2010.

[17] A. Mazzolari, Manipulation of charged particle beams through coherent interactions with crystals, Ph.D. Thesis, Università degli Studi di Ferrara, Ferrara Italy (2010).

[18] S. Carturan et al., Germanium strips for channeling: Study of the crystal quality after slicing and chemical etching, Mater. Chem. Phys. 132 (2012) 641.

[19] J. Bloem and J.C. van Vessem, Etching Ge with mixtures of HF–H₂O₂–H₂O, J. Electrochem. Soc. 109 (1962) 33.

[20] J. Baltazar-Rodrigues and C. Cusatis, Determination of X-ray photoelectric absorption of Ge and Si avoiding solid-state effects, Nucl. Instrum. Meth. B 179 (2001) 325.

[21] R. Camattari, V. Guidi, V. Bellucci and A. Mazzolari, The ‘quasi-mosaic’ effect in crystals and its applications in modern physics, J. Appl. Crystallogr. 48 (2015) 977.

[22] H. Backe, P. Kunz, W. Lauth and A. Rueda, Planar channeling experiments with electrons at the 855 MeV Mainz Microtron MAMI, Nucl. Instrum. Meth. B 266 (2008) 3835.