INTRODUCTION

When particles impinge on lattice planes with an incidence angle lower than the channelling critical angle, the internal electrostatic potential of the crystal confines the particles trajectories between the planes. The channelling confinement persists also in bent crystal provided that the lattice curvature radius is higher than the Tsyganov critical radius [1], this cause the bending of the particles trajectories along the crystal curvature.

The channelling effect of ultra-relativistic particles in bent crystals has been investigated for various applications such as in circular accelerators for beam steering [2], extraction, and collimation [3–5], as well as for splitting and focusing [6] of external beams. The use of bent crystals as primary collimators for halo collimation in hadron colliders has already been proposed [1,7,8] and recently demonstrated at the Tevatron collider at Fermilab [9] and SPS accelerator at CERN [10].

The above applications have been almost completely investigated by using silicon crystals because of its easy availability, very high quality and the well assessed processing knowledge; these advantages are due to the large usage of Si in microelectronics technology. The only drawback of Si is the relatively low atomic number that limits the confinement potential.

Ge can be an interesting alternative to Si: the atomic number is almost double and the crystallographic structure is the same. This would result in a larger critical angle, a larger volume reflection deflection angle (about a factor 1.5 for both). Ge is nowadays available in high quality wafers (less than 1 dislocation per cm² as for Si) and it has been very recently investigated to produce high quality thin strips for anticlastic bending [11]. Thin strips allows to produce homogenous bending by means of anticlastic two point bender [12] that is strategic to maximize deflection efficiency.

In this work, an experimental investigation of (111) planar channelling from a Ge strip with 2 different curvature radii exploiting a 400 GeV proton beam is detailed.

The good agreement between the experimental results and the theoretical expectations as related to an ideal Ge structure is highlighted, thereby demonstrating the feasibility of channelling applications with Ge.

RESULTS

The Ge strips production is extensively described in ref. [11]. A single strip was tested with two different curvature radii of the (111) plane: 10 and 15 m.

The ultrarelativistic channelling experiment was performed at the H8 extracted beam line of the SPS accelerator at CERN. A 400 GeV beam was used.

The beam was tracked by a Si strip detector telescope system. The crystal was mounted on a high resolution goniometric manipulator (1 μrad). After the interaction with the crystal, the beam was tracked by the downstream part of the silicon telescope.

On line analysis allows to check and reach the alignment of the beam with the (111) planar direction, in this condition deflection of the particles occurs. Figure 1 presents the distribution of particles the along horizontal deflection angle in the case of the crystal with a 10 m radius (dashed line) and with a 15 m (continuous line) one for the particles impinging on the crystal itself in a spatial range of ± 0.15 mm in the horizontal and ± 0.5 mm in the vertical direction and in a divergence range of ± 3 μrad in the horizontal and of ± 6 μrad in the vertical one.

The average deflection angles are computed with a gaussian fit and result to be (122 ± 2) μrad and (185 ± 2) μrad for the 15 m and 10 m planes curvatures respectively.

The efficiency has been calculated as a function of the incoming angle. Given the beam angular distribution of (11.59 ± 0.01) μrad r.m.s., the incoming angle can be changed offline without the need of moving the goniometer. After filtering the particles with an incoming angle in a 2 μrad intervals, the efficiencies were computed as the ratio of the number of deflected particles and the total number of particles. Figure 2 presents the efficiency as a function of the incoming angle for the two curvature radii.

The maximum values are (71 ± 1) % for R = 10 m and (72.5 ± 1.5) % for R = 15 m. All the experimental points for the R = 10 m case are smaller according to the fact that in this case the curvature induced dechannelling is larger.

Continuous lines are semi-analytical simulations obtained by considering the Moliere potential for Ge (111) planar confinement with the crystal bending centripetal term, and supposing the fast nuclear dechannelling of particles approaching the planes less than a minimum
approach distance $r_0$. The simulation are convoluted with the experimental incoming angle resolution in order to properly compare the data. $r_0$ determines both the critical angle and the maximum efficiency of the simulation. A good fit of the data for both the curvature is obtained with $r_0 = 0.18$ Å smaller than what expected on the basis of the empirical rule $r_0 = 2.5\mu = 0.22$ Å determined by Forster [13] ($\mu$ is the thermal vibration). This means that less particles than expected loss their confinement and both critical angle and maximum efficiency are very high. Therefore the quality of the crystal strip is reasonably very close to the limit of an ideal crystal.

![Deflection angle for the Ge (111) planar channelling condition. The dashed line is relative to a curvature radius of 10m; the continuous line is obtained with a 15 m curvature radius.](image)

Fig. 1. Deflection angle for the Ge (111) planar channelling condition. The dashed line is relative to a curvature radius of 10m; the continuous line is obtained with a 15 m curvature radius.

The critical angles estimated by simulation in Fig. 2 result to be 11.2 and 10.9 $\mu$rad for the larger and smaller curvature radii respectively.

A Si crystal with a quite similar shape and orientation as our sample was measured with 400 GeV protons in Ref. [14] where a 43% efficiency with a curvature of 11.5 m and an incoming beam resolution of 7.84 $\mu$rad. If we convolve our experimental data for the $R = 10$ m radius in order to get the same resolution, a maximum efficiency of about 51% is obtained. The larger angular acceptance (i.e. critical angle) of Ge with respect to Si accounts for the improvement.

As a conclusion, we have studied planar channeling in a (111) Ge short strip crystal with an ultra-relativistic proton beam. We obtained an efficiency larger than 70% and estimated a critical angle of about 11 $\mu$rad. Both values are demonstrated to be comparable with what expected on the basis of the confining potential for an ideal Ge bent crystal. Even if a direct comparison with a Si crystal is not available, the obtained results demonstrate that the strip works as expected for an ideal Ge crystal structure and has in principle all the advantages of the increased potential confinement due to the higher $Z$.

![Efficiency as a function of the incoming angle.](image)

Fig. 2. (111) planar channelling efficiency of the Ge strip as a function of the incoming angle. The black squares refer to a curvature radius of 15 m while the white dots to one of 10 m. The two continuous lines represent the simulation result (the higher for the 15 m curvature radius).

These results open the way for many potential applications of Ge crystals: besides beam conditioning applications, where the advantage should be an increase of 1.5 in the acceptance angle, we think that the next steps will be in the field of radiation emission application where twice the curvature and the emission efficiency with respect to Si could be exploited.