AIP | Applied Physics Letters

Steering of an ultrarelativistic proton beam by a bent germanium crystal

D. De Salvador, E. Bagli, O. Lytovchenko, A. Mazzolari, S. Carturan et al.

Citation: Appl. Phys. Lett. **98**, 234102 (2011); doi: 10.1063/1.3596709
View online: http://dx.doi.org/10.1063/1.3596709
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v98/i23
Published by the American Institute of Physics.

Steering of an ultrarelativistic proton beam by a bent germanium crystal

D. De Salvador,[1,2,a)] E. Bagli,[3] O. Lytovchenko,[1,4] A. Mazzolari,[3] S. Carturan,[1,2] G. Della Mea,[1,4] V. Guidi,[4] M. Bazzan,[1,2] N. Argiolas,[1,2] A. Carnera,[1,2] D. Bolognini,[5] S. Hasan,[5] M. Prest,[5] and E. Vallazza[6]

[1]*INFN Laboratori Nazionali di Legnaro, Viale dell'Università 2, 35020 Legnaro, Italy*
[2]*Dipartimento di Fisica, Universita' di Padova, Via Marzolo 8, 35131 Padova, Italy*
[3]*Dipartimento di Fisica, INFN Sezione di Ferraraand, Universita' di Ferrara, Via Saragat 1, 44100 Ferrara, Italy*
[4]*Dipartimento di Ingegneria dei Materiali e Tecnologie Industriali, Universita' di Trento, Via Mesiano 77, 38050 Trento, Italy*
[5]*Universita' dell'Insubria, via Valleggio 11, 22100 Como, Italy and INFN Sezione di Milano Bicocca, Piazza della Scienza 3, 20126 Milan, Italy*
[6]*INFN Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy*

(Received 12 April 2011; accepted 13 May 2011; published online 10 June 2011)

Curved crystals, thanks to the electrostatic potential generated by the coherent atomic structure, may deflect ultrarelativistic charged particles by means of channeling and volume reflection effects. Most of the experimental knowledge about these phenomena was gathered with Si crystals, though the performance could be improved by using materials with a larger atomic number. In this letter, we investigate planar and axial channeling and volume reflection in a high quality Ge short strip crystal. All the effects are demonstrated to occur in agreement with theoretical expectations, which take into account the stronger confinement potential for an ideal Ge crystal. © *2011 American Institute of Physics*. [doi:10.1063/1.3596709]

The planar channeling effect of ultrarelativistic particles in bent crystals allows to deflect particles, thanks to the interaction with coulomb potential generated by the atoms. If the plane curvature radius is below a critical value (Tsyganov radius),[1] a fraction of the particles is deflected all along the crystal length. The phenomenon is investigated for various applications in circular accelerators for beam steering,[2] extraction, and collimation,[3–5] as well as for splitting and focusing[6] of external beams. Moreover, the curved trajectories of the relativistic particles cause radiation emission and there are proposals to manufacture crystalline undulators with bent crystals.[7,8] The use of bent crystals as primary collimators for halo collimation in hadron colliders has already been proposed[1,9] and recently demonstrated at the Tevatron collider[10] and SPS accelerator at CERN.[11]

Besides planar channeling, other beam deflection strategies based on coherent interaction with bent crystals have been very recently proposed as follows: (i) volume reflection (VR), it occurs when the beam crossing the curved planes becomes tangent to them in the bulk of the material; in this condition the moment of the particles orthogonal to the plane is not large enough to cross the plane and the beam is therefore deflected with an angle typically 1.5 times the planar channeling critical angle[12,13] and (ii) axial channeling that can be used to deflect ultrarelativistic proton beams with a very high efficiency;[14] in this case the most efficient bending mechanism (that occurs above a critical curvature) is the doughnut scattering according to which the particles wander from different axial strings along the path.[15,16]

The above applications and phenomena have been almost completely investigated by using single silicon crystals because of its easy availability, very high quality, and well assessed processing methodologies. 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, VR deflection angle, and doughnut axial scattering critical curvature (about a factor 1.5 for both). The Tsyganov critical curvature and radiation emission efficiency increase by a factor 2 since they depend linearly on the potential and therefore on Z.

Ge is nowadays available in high quality wafers (<1 dislocation/cm^2 as for Si), and the production of thin strips for anticlastic bending with beam entry surface of optimal crystal quality has been very recently accomplished.[17] Moreover, the bending strategy, described in Ref. 18, allows to achieve homogenous curvature that is a key issue to enhance deflection efficiency.

In this letter, an experimental investigation of (111) planar channeling, VR, and axial channeling from a Ge strip with a 400 GeV proton beam is reported. We obtained a sensible improvement of planar channeling efficiency with respect to previous experiments on Ge.[19] Moreover VR and [110] axial channeling tests are in good agreement with theoretical expectations as related to an ideal Ge structure, thereby demonstrating the feasibility of coherent interaction applications with Ge getting advantage from the high Z value.

The ultrarelativistic channeling experiment was performed at the H8 extracted beam line of the SPS accelerator at CERN on a Ge strip with a curvature radius $R = 15$ m. The beam was tracked before and after interaction with the crystal by two Si strip detector telescope system.[20] The crystal was mounted on a two-axes high resolution goniometric manipulator (1 μrad).

Online analysis allows to check and reach the alignment of the beam with the (111) planar direction of the strip by rotating the sample around a vertical axis. In this condition deflection of the particles in the horizontal plane occurs. Fig-

a)Electronic mail: davide.desalvador@unipd.it.

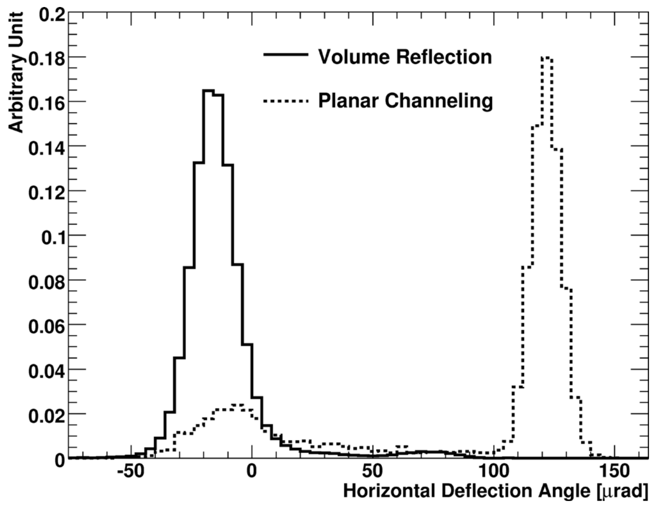

FIG. 1. Deflection angle for the Ge (111) planar channeling condition (dashed line). The continuous line is obtained in VR condition.

ure 1 presents the distribution of particles along horizontal deflection angle (dashed line) for the particles impinging on the crystal in a divergence range of ± 3 μrad in the horizontal direction. The average deflection angle is 122 ± 2 μrad.

In Fig. 2 the efficiency has been plotted as a function of the incoming angle. Given the beam angular distribution of (11.59 ± 0.01) μrad rms, the incoming angle can be changed offline without the need of moving the goniometer. After filtering the particles with incoming angle lying within 2 μrad angular ranges, the efficiencies were computed as the ratio of the number of deflected particles and the total number of particles correcting the data for the long tails as in Ref. 21. The maximum value is $(72.5\pm 1.5)\%$. Continuous lines is a semianalytical simulations obtained by considering the Moliere potential for Ge (111) planar confinement with the crystal bending centripetal term, and supposing that the particles approaching the planes less than a minimum approach distance r_0 are dechanneled by nuclear multiple scattering. The simulation is 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 $r_0=2.5$ $u=0.22$ Å determined by Forster (Refs. 22 and 23) (u is the thermal vibration). This means that less particles than expected—on the basis of the current knowledge on dechanneling—have lost their confinement, thus determining a high value of both critical angle and maximum efficiency. Therefore, the quality of the crystal strip is reasonably very close to the limit of an ideal crystal.

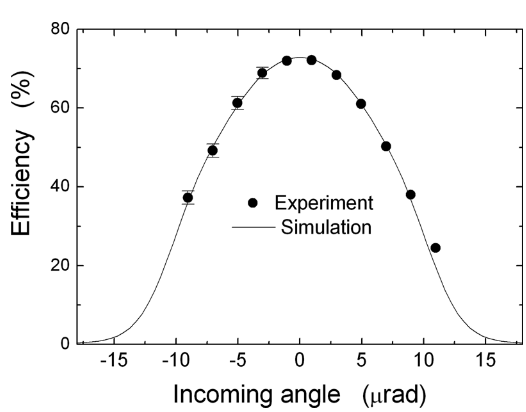

FIG. 2. (111) planar channeling efficiency of the Ge strip as a function of the incoming angle. The black circles are experimental data, the continuous is a simulation.

In previous experiments on a Ge crystal maximum efficiencies of 60% were obtained on a (110) plane for a crystal 50 mm long. Taking into account that (110) confinement is more efficient, it can be inferred that the improvement observed in the present experiment is related to the usage of high quality short crystals, which allows to bent trajectories while hindering dechanneling effects. The critical angle as estimated by the simulation shown in Fig. 2 results to be 11.2 μrad.

A comparison with Si can be performed considering the results of Ref. 24. A Si crystal with a quite similar shape and orientation as our sample was measured with 400 GeV protons, and a 43% efficiency with a curvature of 11.5 m and an incoming beam resolution of 7.84 μrad was reported. If we convolve our experimental data of Fig. 2 in order to get the same resolution, a maximum efficiency of about 53% is obtained. The lower curvature of our Ge strip cannot alone account for the remarkable improvement (51% efficiency is estimated by simulation with R=11.5 m), which is instead mainly ascribed to the larger angular acceptance (i.e., critical angle) of Ge with respect to Si.

Further insight on the Ge strip performances are obtained by the VR experiment that was performed by rotating the goniometric sample holder of a fraction of the bending angle in such a way that the beam becomes tangent to the (111) strip planes in the bulk of the crystal. The deflection angle is shown in Fig. 1 (continuous line).

As can be noted, most of the particles are deflected to a negative angle in the opposite direction of the channeling one. A small fraction of particles is deflected at positive angles thanks to the volume capture, i.e., the capture in channeling at the tangent point of the trajectories.

In order to quantitatively estimate the VR phenomenon, we have fitted the main peaks with a Gaussian curve, determining the average deflection angle θ_{VR} of (15.9 ± 0.3) μrad. The θ_{VR} value can be compared with the theoretical curves proposed by Maisheev and co-workers in Ref. 14 tracing a quite general dependence θ_{VR}/θ_C versus R/R_C, where R_C is the curvature Tsyganov radius. For our sample, being $R_C=2.25$ mm according to Ref. 24 R/R_C results to be about 6.6 and θ_{VR}/θ_C in the range 1.46–1.55 is predicted. Our experimental determination is $\theta_{VR}/\theta_C = 1.42\pm 0.03$ in reasonable agreement with the theory.

We also estimated the VR efficiency according to the procedure defined in Ref. 19, i.e., by calculating the fraction of particles in the histogram with angles from $-\infty$ to $\theta_{VR}+3\sigma_{VR}$, where σ_{VR} is the standard deviation of the VR peak. The obtained value is $95.3\pm 0.4\%$, very close to that determined for (110) Si in Ref. 21 attesting that also Ge can display very high VR efficiencies.

Angular scans around the horizontal axis perpendicular to the beam allow to find the[1–10] axial channeling condition. In Fig. 3 a two-dimensional (2D) histogram of the angular deflection in the vertical and horizontal planes is shown. The plot is obtained by selecting the incoming particles impinging on the strip with a circular condition such as $\sqrt{\theta_{IN,x}^2+\theta_{IN,y}^2}<5$ μrad, where $\theta_{IN,x}$ and $\theta_{IN,y}$ are the incom-

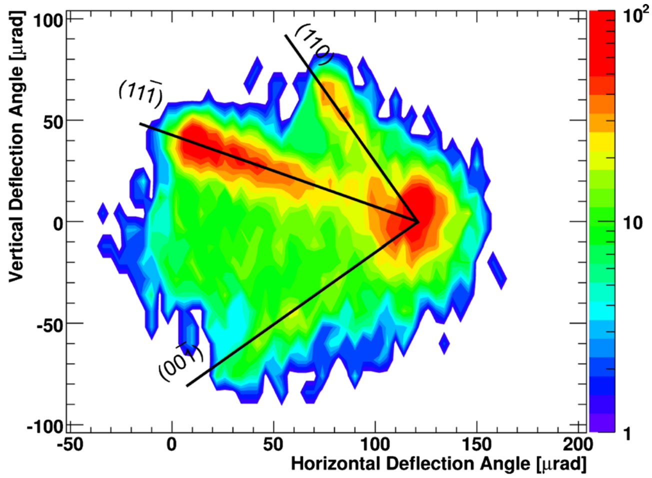

FIG. 3. (Color online) 2D histogram of the vertical vs the horizontal deflection angle with the beam aligned along the [110] axial direction. The black lines identify the skew planes deflection directions.

ing angle in the horizontal and vertical planes, respectively.

The main feature is the particles spot deflected at around $\Delta\theta_x=122$ μrad and $\Delta\theta_y=0$ μrad (where $\Delta\theta_x$ and $\Delta\theta_y$ are the horizontal and vertical deflection, respectively). The angular spread of the particles around this deflection spot is quite wide with an rms. of $\Delta\theta_x$ around the spot of 13 ± 1 μrad (the value is obtained with a Gaussian fit of the $\Delta\theta_x$ deflection histogram considering only particles with $|\Delta\theta_y|<7$ μrad). This spread is 2.3 times larger than the one obtained in (111) planar channeling in agreement with the fact that the critical angle for axial deflection is much larger for axial doughnut scattering regime than for planar channeling.[24] The fact that doughnut scattering is observed is in accordance with the theoretical prediction of a critical radius of 7.5 m for Ge ⟨110⟩ axis,[16] i.e., about half the radius of the strip we are investigating.

Particles deflection occurs also along low index skew planes intersecting the axis indicated with black lines in Fig. 3. In order to estimate the overall deflection we have calculated that $(96\pm1)\%$ of the particles is deflected at an angle $\Delta\theta_x>0$.

In this letter we have studied planar channeling and VR phenomena in a (111) Ge short strip crystal with an ultrarelativistic proton beam. We obtained efficiencies of 72.5% and 95.3% for channeling and VR, respectively, and estimated a critical angle and a VR deflection of 11.2 μrad and 15.9 μrad, respectively. The values are compatible with what expected for high quality short strips Ge samples. The planar channeling efficiency for a nonparallel beam is higher than what reported for a similar Si sample and higher than previous experiments on Ge at similar energies.

Axial channeling was observed in doughnut regime with a ⟨110⟩ axis curvature half than the doughnut critical radius. A fraction of particles as high as 96% is deflected in this condition.

These results open the way for many potential applications of Ge crystals; besides beam conditioning applications, where the advantage is 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 can be exploited.

[1] E. Tsyganov and A. Taratin, Nucl. Instrum. Methods Phys. Res. A **363**, 511 (1995).
[2] A. F. Elishev, N. A. Filatova, V. M. Golovatyuk, I. M. Ivanchenko, R. B. Kadyrov, N. N. Karpenko, V. V. Korenkov, T. S. Nigmanov, V. D. Riabtsov, M. D. Shafranov, B. Sitar, A. E. Senner, B. M. Starchenko, V. A. Sutulin, I. A. Tyapkin, E. N. Tsyganov, D. V. Uralsky, A. S. Vodopianov, A. Forycki, Z. Guzik, J. Wojtkowska, R. Zelazny, I. A. Grishaev, G. D. Kovalenko, B. I. Shramenko, M. D. Bavizhev, N. K. Bulgakov, V. V. Avdeichikov, R. A. Carrigan, Jr., T. E. Toohig, W. M. Gibson, I.-J. Kim, J. Phelps, and C. R. Sun, Phys. Lett. B **88**, 387 (1979).
[3] A. G. Afonin, V. T. Baranov, V. M. Biryukov, M. B. H. Breese, V. N. Chepegin, Y. A. Chesnokov, V. Guidi, Y. M. Ivanov, V. I. Kotov, G. Martinelli, W. Scandale, M. Stefancich, V. I. Terekhov, D. Trbojevic, E. F. Troyanov, and D. Vincenzi, Phys. Rev. Lett. **87**, 094802 (2001).
[4] R. Carrigan, Jr., D. Chen, G. Jackson, N. Mokhov, C. T. Murphy, S. Baker, A. Bogacz, D. Cline, S. Ramachandran, J. Rhoades, J. Rosenzweig, A. Asseev, V. Biryukov, A. Taratin, J. A. Ellison, A. Khanzadeev, T. Prokofieva, V. Samsonov, G. Solodov, B. Newberger, E. Tsyganov, H.-J. Shih, W. Gabella, B. Cox, V. Golovatyuk, and A. McManus, Phys. Rev. ST Accel. Beams **5**, 043501 (2002).
[5] R. P. Fliller III, A. Drees, D. Gassner, L. Hammons,G. McIntyre, S. Peggs, D. Trbojevic, V. Biryukov, Y. Chesnokov, and V. Terekhov, Nucl. Instrum. Methods Phys. Res. B **234**, 47 (2005).
[6] A. S. Denisov *et al.*, Nucl. Instrum. Methods Phys. Res. B **69**, 382 (1992).
[7] V. V. Kaplin, S. V. Plotnikov, and S. A. Vorobiev, Zh. Tekh. Fiz. **50**, 107 (1980).
[8] V. G. Baryshevsky, I. Y. Dubovskaya, and A. O. Grubich, Phys. Lett. A **77**, 61 (1980).
[9] V. M. Biryukov and S. Bellucci, Nucl. Instrum. Methods Phys. Res. B **234**, 23 (2005).
[10] R. Carrigan, A. I. Drozhdin, R. P. Fliller III, N. V. Mokhov, V. D. Shiltsev, and D. A. Still, Proc. SPIE **6634**, 66340I (2007).
[11] W. Scandale, G. Arduini, R. Assmann, C. Bracco, S. Gilardoni, V. Ippolito, E. Laface, R. Losito, A. Masi, E. Metral, V. Previtali, S. Redaelli, M. Silari, L. Tlustos, E. Bagli, S. Baricordi, P. Dalpiaz, V. Guidi, A. Mazzolari, D. Vincenzi, G. D. Mea, A. Lombardi, D. De Salvador, E. Vallazza, D. Bolognini, S. Hasan, D. Lietti, V. Mascagna, A. Mattera, M. Prest, G. Cavoto, L. Ludovici, D. Mirarchi, R. Santacesaria, P. Valente, F. Murtas, A. G. Afonin, Y. A. Chesnokov, V. A. Maisheev, I. A. Yazynin, A. D. Kovalenko, A. M. Taratin, A. S. Denisov, Y. A. Gavrikov, Y. M. Ivanov, L. P. Lapina, L. G. Malyarenko, V. V. Skorobogatov, V. M. Suvorov, S. A. Vavilov, N. Mokhov, D. Still, G. Robert-Demolaize, T. Markiewicz, and M. Oriunno, Phys. Lett. B **692**, 78 (2010).
[12] W. Scandale, D. A. Still, A. Carnera, G. D. Mea, D. De Salvador, R. Milan, A. Vomiero, S. Baricordi, P. Dalpiaz, M. Fiorini, V. Guidi, G. Martinelli, A. Mazzolari, E. Milan, G. Ambrosi, P. Azzarello, R. Battiston, B. Bertucci, W. J. Burger, M. Ionica, P. Zuccon, G. Cavoto, R. Santacesaria, P. Valente, E. Vallazza, A. G. Afonin, V. T. Baranov, Y. A. Chesnokov, V. I. Kotov, V. A. Maisheev, I. A. Yaznin, S. V. Afansiev, A. D. Kovalenko, A. M. Taratin, A. S. Denisov, Y. A. Gavrikov, Y. M. Ivanov, V. G. Ivochkin, S. V. Kosyanenko, A. A. Petrunin, V. V. Skorobogatov, V. M. Suvorov, D. Bolognini, L. Foggetta, S. Hasan, and M. Prest, Phys. Rev. Lett. **98**, 154801 (2007), and references therein.
[13] V. A. Maisheev, Phys. Rev. ST Accel. Beams **10**, 084701 (2007).
[14] W. Scandale *et al.*, Phys. Rev. Lett. **101**, 164810 (2008).
[15] A. M. Taratin and S. A. Vorobiev, Pis'ma Zh. Tekh. Fiz. **4**, 947 (1978).
[16] N. F. Shul'ga and A. A. Greenenko, Phys. Lett. B **353**, 373 (1995).
[17] S. Carturan, Mat. Chem. Phys. (submitted).
[18] V. Guidi, L. Lanzoni, and A. Mazzolari, J. Appl. Phys. **107**, 113534 (2010).
[19] C. Biino *et al.*, Phys. Rev. B **403**, 163 (1997).
[20] L. Celano, D. Creanza, M. De Palma, G. Maggi, L. Fiore, V. Paticchio, G. Raso, G. Selvaggi, L. Silvestris, and P. Tempesta, Nucl. Instrum. Methods Phys. Res. A **381**, 49 (1996).
[21] W. Scandale *et al.*, Phys. Rev. ST Accel. Beams **11**, 063501 (2008).
[22] J. S. Forster, H. Hatton, R. J. Toone, G. Este, S. I. Baker, R. A. Carrigan, Jr., W. M. Gibson, R. L. Wijayawardana, J. A. Ellison, L. Emman-Wori, and B. O. Kolbesen, Nucl. Phys. B **318**, 301 (1989).
[23] W. Scandale, A. Vomiero, S. Baricordi, P. Dalpiaz, M. Fiorini, V. Guidi, A. Mazzolari, R. Milan, G. D. Mea, G. Ambrosi, B. Bertucci, W. J. Burger, P. Zuccon, G. Cavoto, R. Santacesaria, P. Valente, E. Vallazza, A. G. Afonin, Y. A. Chesnokov, V. A. Maisheev, I. A. Yazynin, A. D. Kovalenko, A. M. Taratin, A. S. Denisov, Y. A. Gavrikov, Y. M. Ivanov, L. P. Lapina, L. G. Malyarenko, V. V. Skorobogatov, V. M. Suvorov, S. A. Vavilov, D. Bolognini, S. Hasan, and M. Prest, Phys. Lett. B **680**, 129 (2009).
[24] A. Baurichter *et al.*, Nucl. Instrum. Methods Phys. Res. B **27**, 164 (2000).