UA9: Crystal Collimation Experiment at CERN

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The main UA9 scope is to study experimentally and theoretically fundamental properties of interactions for relativistic channeled particles (protons and ions) in crystals that aim in the crystal-assisted collimation of the CERN SPS ring beams. After a set of successful experiments on the beam collimation by various schemes of crystal bent systems the project is suggested to be continued in order to investigate the crystal technique feasibility for the LHC beams collimation (a "LUA9" project).

For 2012 the LNF team activity was dedicated to the experiments on the GEM & Medipix detectors optimization and to theoretical studies on simulation of inelastic scattering of relativistic protons and heavy ions in aligned bent crystals. Additional activity was performed to continue our research on relativistic electron/positron beams channeling in various straight crystals, from thin to thick ones. The particle loss in the volume of a bent crystal when relativistic ions pass through the bent crystal under channeling and quasichanneling conditions is simulated. Multiple passage of projectiles through an idealized crystal collimator is considered. The crystal orientation dependence for a particle loss function is obtained.

1 Introduction

As in previous years the project aims in preparation, installation and managing GEM & Medipix detectors to be used at CERN as well as in computer simulations of relativistic proton & ion beams deflection by bent crystal potentials taking into account all the processes of beam scattering in a crystal. Within the project we have established a new testing facility at X-Lab Frascati to characterize the crystals. This facility deals with various X-ray techniques like diffraction and stress analysis, including also a possibility for elemental mapping. Within theoretical part of the collaboration research we have developed several codes dedicated to computer simulations of relativistic beams (electrons, positrons, protons, ions) passage through aligned to the beam straight and bent crystals.

During 2012 we have developed new "Mathematica" codes to study relativistic electrons diffusion/scattering in aligned straight crystals based on both Fokker-Planck equations and multiple scattering simulations. By means of these codes we have analyzed in details the features of axial and planar electron channeling in the crystals of various thicknesses. A special code for simulating relativistic proton/ion beam crystal collimation has been upgraded that allows the peculiarities of inelastic scattering at proton/ion channeling in bent crystals to be taken into account.

One of the important aims of present projects based on the bent crystal technology is to collimate the beam of relativistic protons or ions. However, when the crystal is used to deflect the beam, one has to consider the problem of beam particles interactions in a crystal characterized by energy loss. The important origins of the loss are inelastic nuclear interactions (i.e. close collisions of beam nuclei with crystal nuclei) and electromagnetic dissociation (i.e. the nucleus decay at crystal electric field influence). Using earlier developed computing code successfully applied for protons, we have analyzed the probability of a particle loss in dependence on crystal orientation for the case of relativistic Pb ions moving into bent crystals.

2 Activity in 2012

2.1 Theory and simulations

Let us follow some basic principles of a simple method for the idealized experiment. Namely, let a non-divergent beam of the intensity I enter the experimental setup. Main unit of this setup is a bent crystal, which scatters αI ($\alpha \leq 1$) particles at different directions. Projectiles penetrate into the crystal at small incident glancing angle θ_0 to bent planes, so they can move through the crystal under channeling or quasichanneling conditions. Another element of the setup is the absorber, which stops the particles deflected at the angles exceeding the cutting angle θ_b. Non-caught particles pass to the 'focusing system' restoring the beam profile. Obviously, simulation of real collimator systems should include the change in a beam profile. Nevertheless, dedicated equipment of the focusing system is omitted here to avoid the technical details and, moreover, to clarify the nature of the particle loss with respect to the crystal orientation defined by the angle θ_0. Behind the focusing system non-divergent beam is again delivered to the setup entrance. So, the model permits describing particle's multiple passage through the crystal. Obviously, if the number Z of lost particles due to the interactions into the crystal volume is much less than that of the initial beam, $Z << I$, the angular distributions of scattered particles remain the same at every turn of a beam.

To estimate the intensity of particle loss at single particles passage through the setup, the average probability of interactions P (API) between a beam particle and nuclei of a crystal can be introduced. In amorphous solid API can be defined by the expression $P = \sigma N z$, while $P << 1$. Here z is the particle path length in a solid, σ is the particle loss cross-section due to the particle interaction with one atom, N is the nuclear density. In aligned crystal, for both channeling and quasichanneling conditions, the nuclear density N strongly depends on the distance from crystallographic planes due to the nuclei thermal oscillations near the equilibrium position located on a plane. Then, for aligned crystal API can be rewritten as follows $P = \sigma \left\langle N \right\rangle_{tr} z$, where $\left\langle N \right\rangle_{tr}$is the averaged nuclear density over the projectile path. In simulations we used the Gaussian distribution for the displacement of nuclei from the plane.

The beam divergence in recent experiments on beam collimation is very small (for example, experimental horizontal beam emittance was 0.011 μm_rad). So, for estimation let now consider a non-divergent beam hitting a bent crystal at the incident angle θ_0. The particle trajectory in the crystal is defined by its initial position in a channel. It is important to underline that the width of a channel is about a few Angstroms, whereas the characteristic transverse beam size is about a few tens of μm. Hence, to perform simulations for a beam, the projectile has to be characterized by random initial distance that results in equal probability for a particle to move over any possible trajectory (of course, taking into account a weight factor due to space distribution of particles in a beam). If the beam contains a large number of particles, in simulations we deal with the variety of defined trajectories in a crystal. Therefore, one can evaluate a lot of trajectories with equidistant initial points. Then calculating the averaged nuclear density $\left\langle N \right\rangle_{tr}$ over each trajectory, we have to define the averaged nuclear density $N(\theta_0)$ at the crystal orientation angle θ_0. This approach allows getting the API value in a crystal volume without each trajectory examination $P = \sigma N(\theta_0) z$ for one arbitrary projectile, where z is the crystal thickness. As above said, the expression is valid while $P << 1$.

To obtain the density $N(\theta_0)$ the evaluation of 100-1000 trajectories is enough, whereas the beam can contain about 10^8-10^{10} particles. That makes suggested approach effectively applied without the necessity to consider the trajectories for all beam particles.

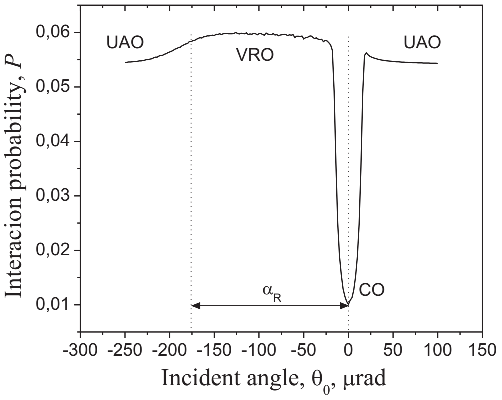

Figure 1: The API dependence P versus the incident angle θ_0.

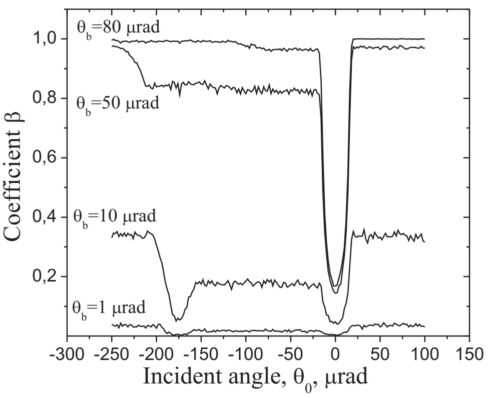

Figure 2: The coefficient β as a function of the incident angle θ_0 at different cutting angles θ_b. Each cutting angle corresponds to different relative position of the absorber in respect with the crystal.

The results of simulations revealed are presented in Fig. 1. The beam of Pb ions with the momentum 9840 GeV/c passed a Si crystal bent along (110) planes over the angle $\phi_R = 167$ μrad was considered. The crystal thickness $z = 2$ mm and the interaction cross-section $\sigma = 5.414 \cdot 10^{-24}\text{cm}^2$ were chosen to be in agreement with other results. One can see in the figure three areas corresponding to different crystal orientations with respect to the beam direction: CO corresponds to the "channeling orientation", VRO – the "volume reflection orientation", UAO – the "unaligned orientation" (no coherent interactions). These areas reflect distinct characteristics of the projectiles motion. In the CO regime most of the particles cross the crystal being channeled. These particles remain in a central area of the planar channels characterized by the minimal nuclear density. Hence, one can see a sharp deep at CO. At both UAO and VRO most of the projectiles are quasichanneled. They cross bent planes where the local density of crystal nuclei is maximal; API for both orientations becomes many times larger than at the CO orientation. At VRO the volume reflection effect takes place for quasichanneled projectiles: particle moving initially to the center of crystal curvature changes its direction. Near the "reflection point", where the direction has been changed, the projectile moves along bent plane with extremely high nuclear density. Finally, at the VRO conditions API is revealed to be higher than at UAO.

When the bent crystal is used as a collimator in real experiments with ion beams, the beam particles can pass through experimental setup many times. To investigate the multiple passage of particles through the bent crystal, a theoretical model earlier proposed introduces the coefficient β , which characterizes the fraction of particles crossing the crystal and successfully passing to the ring focusing system. This coefficient can be evaluated from the angular distribution of projectiles behind the crystal. The dependencies $\beta(\theta_0)$ at different cutting angles θ_b for the considered parameters are presented in Fig. 2. All curves in the figure demonstrate a deep for the CO area. Indeed, channeled projectiles are deflected by a bent crystal at large angles θ close to the crystal bent angle α_R. Hence, all channeled particles hit the absorber and, thus, leave the beam ($|\theta| > \theta_b$).

At small cutting angle $\theta_b = 1$ μrad some projectiles scattered by a crystal passes to the focusing system revealing a slight variation at the orientation angle θ_0; therefore, the corresponding coefficient β changes slightly. On the contrary, at largest cutting angle $\theta_b = 80$ μrad almost all projectiles pass to the focusing system except those for CO. Therefore, one can see $\beta \approx 1$ except the sharp decrease at CO. For intermediate angles the coefficient β

demonstrate quite different behavior in the transition area from VRO to UAO. Namely, for the case $\theta_b = 10$ μrad one can see the β parameter suppression for large incident angles ($\sim$175 μrad) whereas for the case $\theta_b = 50$ μrad it disappears. This feature is related to the scattered beam splitting at corresponding orientation angles. One part of the projectiles moves under the volume reflection condition while other projectiles are deflected mainly due to multiple scattering. Therefore, the first particles are deflected jointly at large angles whereas the deflection angles of second particles are distributed close to the initial beam direction. Hence the beam is split. The observer watching the projectiles at the entrance of focusing system scans both produced beams at $\theta_b = 50$ μrad, i.e. he observes the smooth transition from VRO to UAO (the splitting is absent at both areas). But at condition $\theta_b = 10$ μrad the observer registers only one beam (the second is cut off by absorber). As a result, the number of particles passing to the focusing system decreases with respect to VRO as well as to UAO.

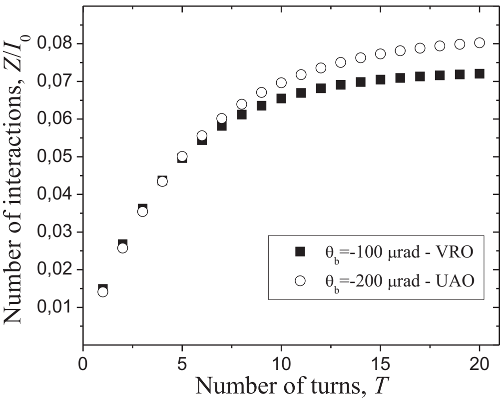

Figure 3: The number of loss Z divided to the initial number of nuclei I_0 as a function of the turns number T at $\alpha = 0.25$, $\theta_b = 10$ μrad.

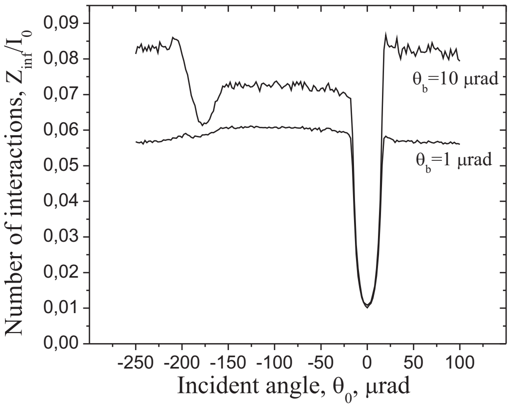

Figure 4: The number of loss for the saturation state $Z_{\inf}$ with respect to the initial number of nuclei I_0 in dependence on the incident angle θ_0 at different cutting angles θ_b.

Successfully, total number Z of the projectile loss in a crystal volume over T turns under the condition $\beta < 1$ (i.e. when the absorber catches particles) is defined by the expression $Z = \frac{1-(1-\alpha+\alpha\beta)^T}{1-\beta} P I_0,$ Z tends to saturate with the increase of the number of turns approaching the following limit $Z_{\inf} = \frac{P}{1-\beta} I_0$, where I_0 is the initial number of particles in a beam. Fig. 3 presents the evolution of this saturation effect. As seen, the number of interactions is initially larger at VRO with respect to the UAO case that is in agreement with the results of Fig. 1. However, the situation becomes inverted starting from the 5-th turn. Indeed, at UAO the ions are deflected at small angles close to initial beam direction whereas at VRO the ions can be deflected at large angle from this direction. Therefore, at UAO selected ion has a chance to make more turns before being deflected by the angle $|\theta| > \theta_b$(when it will be caught by the absorber, i.e. this ion leaves the beam definitively) in comparison with the number of turns at VRO. Due to the fact that probability of interaction grows with the increase of the number of turns, multiple passage at VRO is characterized by reduced interaction probability with respect to UAO. This conclusion is also proved by Fig.4, where the dependences of projectile loss in saturation regime are shown for two different cutting angles θ_b. At small cutting angle $\theta_b = 1$ μrad particle passes through the crystal one time only being deflected into the absorber. As seen, the curve at $\theta_b = 1$ μrad is almost the same as the API dependence of Fig. 2. Hence, the projectile loss under the VRO conditions is more than that for the UAO conditions. On the contrary, at moderate cutting angle $\theta_b = 10$ μrad the reflected particle is deflected to the absorber, whereas non-reflected quasichanneled particle can pass several times through the crystal. Finally, the loss at UAO becomes more than at VRO.

As regards the curves in Fig. 4, the deep in the CO area is due to the deflection of channeled ions at large angles (Fig. 2) combined with the API decrease (Fig. 1). The left deep at $\theta_b = 10$ μrad is related to the splitting of angular distribution in this area as described above.

It is remarkable that the cross-section for ions considered in this work is 10 times larger than that for protons. It brings us to the conclusion that at large cutting angles the ratio Z_{inf}/I_0 should approach 1 at both UAO and VRO, and the deep remains only at CO.

Obviously, when bent crystal is used to deflect the beam, the orientation optimized for beam channeling is preferable to reduce the number of particle loss in the crystal volume. However, in this case a precise crystal orientation is required because of the fact that small deviations from the optimal value $\theta_0 = 0$ lead to essential increase in the loss intensity. The total loss can exceed 5%.

3 Conclusions

We have applied earlier developed theory that describes inelastic nuclear interactions at proton multiple passage through bent crystals, to the crystal collimation studies for ions. Originally, the approach is valid for small particle loss with respect to total intensity hitting the crystal entrance for each system passage ($P << 1$). In this case the loss of projectiles does not essentially influence the angular distribution of scattered ions. As seen in Fig. 1, for relativistic ions considered here we are practically in the limit of proposed theory applicability.

Nevertheless, we have to underline that for heavy ions beam the particle loss cross-section may exceed the one for Pb nuclei. In this case the influence of projectile loss on angular distributions should be included in the model. For example, reflected ions undergo a strong loss. Hence, in angular distributions the intensity of reflected ions may be noticeably changed in comparison with the case when the ion loss is not taken into account. On the contrary, channeled ions almost do not interact with the nuclei of a crystal that results in the negligible change in angular distribution even at very large cross-sections. Therefore, the method to study the angular distributions of scattered ions versus the particle loss should be developed in future.