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CRYSTALS APPLICATION IN THE TOTEM EXPERIMENT TO INCREASE THE ACCEPTANCE OF A ROMAN POT*

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Abstract

Bent crystal may enhance the physics reach of a near-beam physics detector in the CERN-LHC, by increasing the acceptance of scattered protons in low transverse momentum reactions. As an example we present simulations demonstrating the increase of the Roman Pot acceptance in the TOTEM apparatus. Starting from the MadX v6.5 collision optics, a crystal is placed at different longitudinal and transversal positions: for each scheme a gaussian beam of protons with different kinematic variables is created and tracked along the optical line with crystal. The number of protons with transversal coordinates greater than $10\,\sigma + 0.5$ mm, that is inside the Roman Pot, is compared with the total number of protons. The possible gain in acceptance is around $15 - 20\%$.

INTRODUCTION

The TOTal Elastic and diffractive cross section Measurement (TOTEM) collaboration at the LHC aims at measuring the total elastic scattering over a large range of 4-momentum transfer and single diffractive scattering cross section in proton-proton collisions from 10 to 14 TeV center of mass energies [1]. As shown in [2] the nominal acceptance of the Roman Pot at 220 m from the IP is close to zero in the region where $-10^{-2} < \frac{\Delta P}{P} < -10^{-4}$ that is for particles with momentum $6930\ \mathrm{GeV/c} < \mathrm{P} < 6999.3\ \mathrm{GeV/c}$. In such a region the dispersion is not enough to deflect particles with a loss of momentum smaller than 1% in the Roman Pot with respect to the nominal momentum; the scenario can change by introducing a bent crystal between the IP and the Roman Pot. The crystal used in the simulation is assumed to provide an horizontal deflection of $10\ \mu\mathrm{rad}$ through five consecutive volume reflections at $7\ \mathrm{TeV/c}$.

LAYOUT

Nominal layout

The nominal layout of TOTEM (from the IP of CMS to the Roman Pot at 220 m) is shown in Fig. 1.

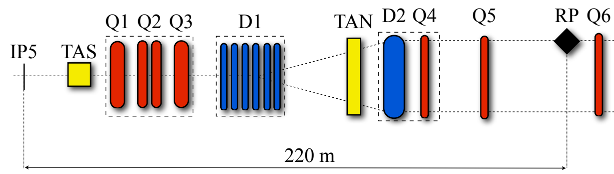

Figure 1: Nominal TOTEM layout.

The optics, shown in Fig. 2, is the official v6.5 optics of MadX in collision, that is with $\beta^* = 0.55$ m and a full crossing angle of $285\ \mu\mathrm{rad}$. Other possible optics for TOTEM are with $\beta^* = 90$ m and $\beta^* = 1540$ m; the choice of the optics with $\beta^* = 0.55$ m is to compare the results of this paper with [2].

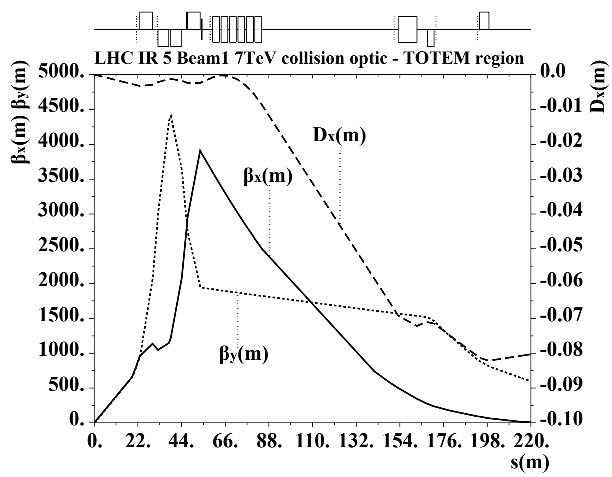

Figure 2: Nominal optics from the IP of CMS to the Roman Pot at 220 m.

In this region the horizontal dispersion is not zero due to the bump used to create the crossing angle of $285\ \mu\mathrm{rad}$. Because of the dispersion, the particles with a momentum lower than $6930\ \mathrm{GeV/c}$ can be deviated into the Roman Pot placed at 220 m from the IP. The horizontal distance between the Roman Pot and the closed orbit is $10\,\sigma + 0.5$ mm (1.21 mm).

Layout with crystal

The crystal is placed at 100 m from IP, after D1 (see Fig. 3), with an horizontal distance from the beam of 6 σ (i.e. 5.8 mm with $\beta = 1913$ m). In this layout it is possible to intercept the scattered protons with an amplitude of 6 σ and modify the p_x component by the momentum of about

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10 μrad of angle with the action of the crystal. A particle with an energy close to 7 TeV, that receives the kick from the crystal, can benefit from a lever arm of 120 m and a phase advance of 12°. For particles with a non negligible energy loss, the scenario is more complex because the phase advance changes with energy and the dispersion starts to play a role in the trajectory of such particles: a full tracking is mandatory to understand the acceptance with the crystal.

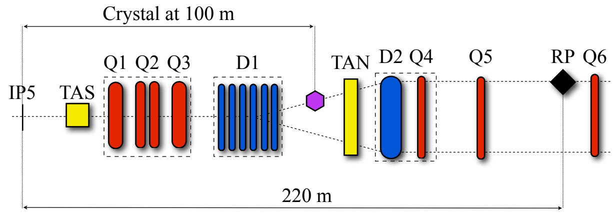

Figure 3: TOTEM layout with crystal.

CRYSTAL BEHAVIOR

The interaction of a high energy charged particle with the ordered atomic structure of a crystal presents peculiar aspects which can be exploited to steer a high energy particle beam.

If the particle trajectory is aligned to the crystalline planes, the atoms of the plane can be described by a continuous charge distribution with planar symmetry. The electric field produced by this distribution creates a sequence of potential barriers that, for positive particles, are located in the interplanar region. When the particle transversal energy (with respect to the crystal planes) is smaller than the maximum value of the interplanar potential, the particle is trapped in the channel formed by the surrounding atomic planes.

The condition on the transverse energy can be expressed as: $|\theta| < \theta_L$, where θ is the angle between the particle trajectory and the crystal plane, $\theta_L = \sqrt{\frac{2E_c}{pv}}$, E_c is the maximum value of the interplanar potential (for (*110*) silicon is about 16 eV, giving $\theta_L \simeq 10\mu$rad at 400 GeV/c) and p and v are, respectively, the particle momentum and the particle velocity. If the crystal is bent (through a mechanical device) a channeled particle is forced to follow the crystal curvature emerging from the crystal with a different angle.

Fig. 4 shows the scheme of a bent crystal and the possible paths of a particle.

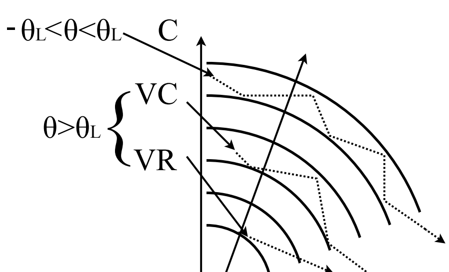

Figure 4: Scheme of a bent crystal.

When $-\theta_L < \theta < \theta_L$ the particle is channeled (C), receiving a kick $\theta_C = l/R$ (where l is the crystal length and R the curvature). When $\theta > \theta_L$ the particle crosses the crystal as an amorphous media reducing the misalignment with the crystal planes and reaching (if $\theta < \theta_C$) a tangency point in the crystal volume. Here, if the particle lost part of its transverse energy because of previous scattering, it will be captured (VC) in the channel, otherwise, if the transverse energy is enough, it undergoes an elastic scattering with the potential barrier which results in a reflection (VR) of the proton trajectory with an angle $\theta_{VR} \sim 1.5\,\theta_L$. In the region of $\theta < -\theta_L$ the crystal is an amorphous media and does not change significantly the angle of the particle.

Fig. 5 shows the crystal behaviour as measured by the H8RD22 collaboration [3] with a 400 GeV/c proton beam.

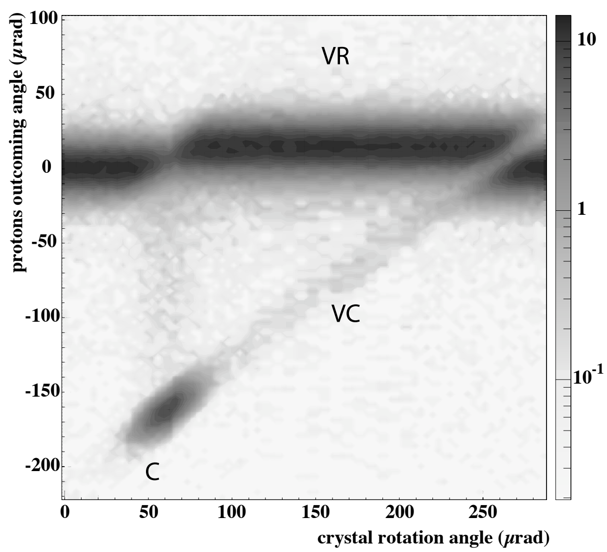

Figure 5: The crystal behaviour in H8RD22 [3].

In this experiment the crystal was aligned with an offset of -50 μrad with respect to the reference orbit of the particles. The particle angular distribution after the crystal is plotted as a function of the crystal rotation angle θ: for $\theta <$ 30 μrad the crystal is misaligned and produces only multiple scattering. For 30 μrad $< \theta <$ 90 μrad, the crystal is aligned and the channeling peak ($\theta_C \sim 160$ μrad) appears. It's interesting to note that, for a crystal of $\theta_L = 10$ μrad, and an alignment offset of -50 μrad, the channeling region should be between 40 μrad and 60 μrad, but in the Fig. 5 is between 30 μrad and 90 μrad. This smearing effect is produced by the beam divergence and the imperfections of the crystal. For 90 μrad $< \theta <$ 250 μrad the tangency point between the particle trajectory and the crystal planes is in the crystal volume. The diagonal line is filled with volume captured particles when the beam core is shifted of $\theta_{VR} \sim 14$ μrad.

Volume reflection is an interesting phenomena as it has a high efficiency and a large angular acceptance; the crystal presented in Fig. 5 shows an angular acceptance greater than 150 μrad and an efficiency of about 98%. A deflection angle greater than θ_{VR} can be obtained by means of subsequent reflections in a series of aligned crystals since the total angle is given by the single reflections sum [4].

ACCEPTANCE

To evaluate the acceptance of the Roman Pot versus $\mathrm{Log}(-\xi)$ (with $\xi = \frac{\Delta P}{P}$) the software DPMJET [5] is used as Monte Carlo particles events generator. The inputs of DPMJET are pairs of protons distributed as the LHC nominal beam with normalized emittance of $3.75 \times 10^{-6}\ \mathrm{m \cdot rad}$, $\beta^* = 0.55\ \mathrm{m}$, full crossing angle of $285\ \mu\mathrm{rad}$ and a momentum of $7\ \mathrm{TeV/c}$.

Only protons with $4786\ \mathrm{GeV/c} < \mathrm{P} < 7000\ \mathrm{GeV/c}$ are considered. MadX is used to track particles in dipoles and quadrupoles, while the crystal behaviour is implemented by CRYM, which is an emulation routine based on the experimental data (collected at $400\ \mathrm{GeV/c}$). The volume reflection's angle is rescaled with the inverse of the energy square root , in this way five volume reflections at $7\ \mathrm{TeV/c}$ produce a total deflection angle of $\sim 10\ \mu\mathrm{rad}$.

The acceptance of the Roman Pot without crystal (in nominal conditions) is shown in Fig. 6.

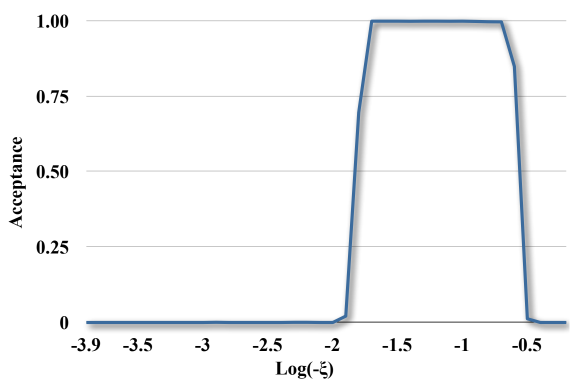

Figure 6: Nominal acceptance of Roman Pot. Acceptance vs. $\log_{10}$ of energy spread.

The particles with $\xi < -10^{-2}$ (that is with an energy loss < 70 GeV) are not capable to deflect enough to be detected by the Roman Pot, and the acceptance for this particles is close to zero. With the crystal the situation is shown in Fig. 7

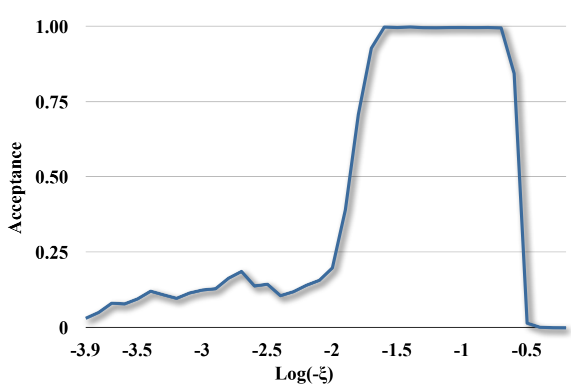

Figure 7: Acceptance with crystal.

It is easy to see that the action of the crystal changes the behavior of elastic protons and increases the acceptance in the region of small ξ. The acceptance for such protons changes from zero to $10 - 20\%$ depending on the energy loss of particles.

This result can also be improved with an optimization of the crystal's position, for example if the crystal is moved to $5\ \sigma$ the acceptance for elastic protons can increase up to 40%. The problem of this distance is that some protons at $5\ \sigma$ are not produced by an elastic collision but they come from the tails beam diffusion. A different tracking, multi turns or with a diffusion simulator, is mandatory to understand how much noise is produced by diffusion with respect to the scattered protons.

$6\ \sigma$ is the simplest choice to avoid the problem of diffusion because the primary collimators of LHC are at $6\ \sigma$ and clean the beam from undesired protons (i.e. the presence of primary protons after $6\ \sigma$ is considered negligible); nevertheless a more detailed simulation can show a better position for the crystal with a higher increase in acceptance.

CONCLUSION AND REMARKS

This study shows that a crystal could be used to increase the acceptance of a TOTEM Roman Pot in particular in the region of elastic scattered protons. The increase of acceptance corresponds to an increase in the precision of the characterization of the total elastic and diffractive cross section of protons.

As a general remark it is important to consider that the crystal was experimentally characterized at $400\ \mathrm{GeV/c}$ [6] and the behavior at $7\ \mathrm{TeV/c}$ is just extrapolated in a conservative simplification with respect to the volume reflection angle. A true experimental characterization of the crystal at $7\ \mathrm{TeV/c}$ could show a deflection angle for the multiple volume reflection greater than $10\ \mu\mathrm{rad}$ with a consequent increase in the acceptance.

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