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CRYSTAL COLLIMATION STUDIES AT THE TEVATRON (T-980)*†

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Abstract

Bent-crystal channeling is a technique with a potential to increase beam-halo collimation efficiency in high-energy colliders. First measurements at the Tevatron in 2005 have shown that using a thin silicon crystal to deflect the 1-TeV proton beam halo onto a secondary collimator improves the system performance by reducing the machine impedance, beam losses in the collider detectors and irradiation of the superconducting magnets, all in agreement with simulations. Recent results, obtained with an improved goniometer and enhanced beam diagnostics, are reported here for dedicated beam studies and first full collider stores along with simulation results and plans for substantial enhancement of the T-980 experimental setup.

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INTRODUCTION

Beam collimation is mandatory at any collider and high-power accelerator. A common approach is a two-stage collimation system in which a primary collimator is used to increase the betatron oscillation amplitudes of the halo particles, thereby increasing their impact parameters on secondary collimators. A bent crystal can coherently direct channeled halo particles deeper into a nearby secondary absorber. This results in a reduction of out-scattering from the system, thereby reducing beam losses in critical locations and radiation loads to the downstream superconducting magnets. The first suggestion to use a bent crystal for beam halo collimation was made for the SSC [1]. Studies investigating crystal collimation were conducted at IHEP and RHIC [2, 3]. These were followed by studies at the Fermilab Tevatron [4], which have ultimately become the T-980 experiment [5]. T-980 is the first crystal collimation experiment in realistic conditions of a TeV hadron collider. Recent experience with the T-980 beam studies including the first crystal collimation runs for the full collider stores is described in this paper. In addition data analysis, supporting simulations, the problems that are revealed and upgrade plans for two-plane collimation using alternating crystals of two different types are discussed as well.

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EXPERIMENTAL SETUP

Fig. 1 shows a schematic of the T-980 experimental layout which is similar to that used in previous tests [4]. During normal Tevatron operations, a 5-mm tungsten target scatters beam-halo into a 1.5-m long stainless steel secondary collimator E03, 50 m downstream of the target. For the bent crystal experiments, a goniometer containing a 5-mm thick O-shaped bent crystal is installed 23.7 m upstream of E03. Scintillation counter telescopes detect secondary particles from protons interacting with the target and E03 collimator. An ionization chamber (beam loss monitor LE033) also detects secondaries scattered from E03. A PIN diode telescope detects secondaries scattered from the bent crystal. Under the above configuration, channeled beam is signaled by a reduction of the rate in the PIN telescope with attendant increases in the rates of the LE033 and E1 counters. Studies of the E11 flying wires 33-m downstream of the crystal have shown that their sensitivity is several orders of magnitude below that needed to measure the channeled beam.

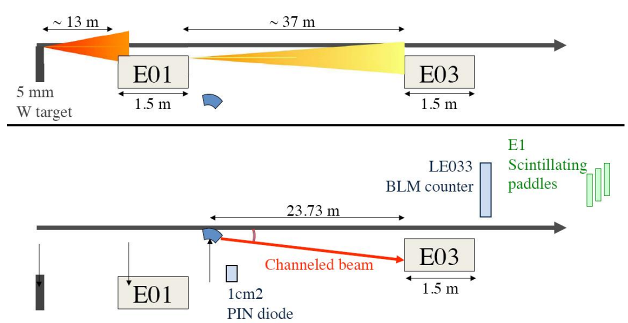

Figure 1: Layout of the Tevatron E0 region with tungsten target (top) and crystal (bottom).

The 2005 studies have demonstrated improved collimation efficiency with the crystal, in particular a factor of two reduction of beam losses in the CDF experiment (in agreement with simulations). Several problems with the crystal goniometer mechanics were revealed. In 2008, the T-980 hardware was substantially improved. The goniometer was modified – by replacing several key components - to fix the angular motion, vibration and dragging arm problems. Angular positioning of the crystal is now done in 1.36μrad steps, with angular resolution of 2.1 μrad. The re-characterized O-shaped crystal with a bending angle of 410 μrad was re-installed.

END-OF-STORE STUDIES

Two types of studies were performed at the end of Tevatron stores to measure and optimize performance of the bent crystal system, angular scans of the crystal and scans of the E03 collimator, both after positioning the crystal at 6σ as the leading edge of the collimation system. The enhanced beam diagnostics system made it possible to distinguish the effects of the bunched beam and beam in the abort gap.

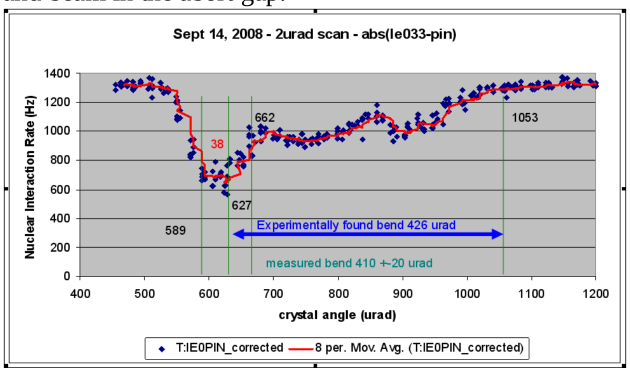

Figure 2: Results of crystal angular scan.

Angular Scan

Angular scans (setting the crystal in the channeling configuration) are performed by measuring losses at E03 while the orientation of the crystal is changed (Fig. 2). The E03 collimator distance from the beam is set to be slightly larger than that of the crystal. In principle, one expects to see a loss peak on the E03 collimator when the halo particles are aligned with the crystalline planes at the entrance face of the crystal. The angular acceptance for channeling is predicted to be $1.5\theta_c \approx 10$ μrad, where $\theta_c = 6.7$ μrad is the critical angle.

Collimator Scan

To measure the deflection of the channeled beam - once the crystal angle is set to the channeling peak - the E03 collimator is slowly scanned, starting from a completely retracted position and moving toward the beam edge. There are three distinct regions (Fig. 3):

1. A region of negligible losses, where the collimator does not intercept any beam.
2. A steep increase in the losses, where the collimator intercepts the channeled beam.
3. A region where the losses increase slowly: the collimator is additionally intercepting dechanneled and amorphous scattered particles.

When the collimator finally touches the beam envelope, the losses rise abruptly and the PIN diode signal decreases to zero: the collimator becomes the primary scatterer masking the crystal. The expected displacement of the channeled beam (middle of Region 2) with respect to the beam envelope is 9.7 mm, while the measured distance is only about 7 mm.

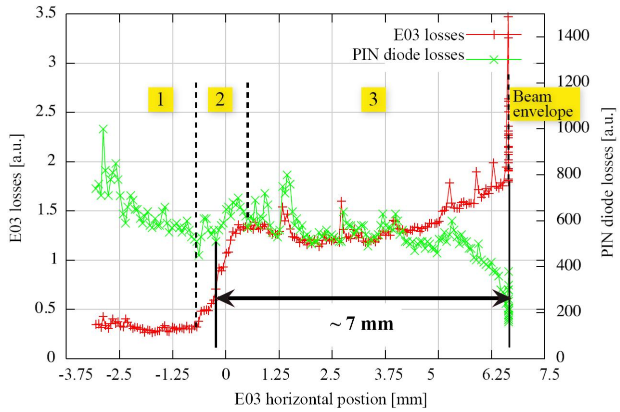

Figure 3: Collimator scan with crystal at channeling.

Miscut Angle

The miscut angle of the crystal – as measured during the characterization process – is quite large, $\theta_m = 1.6$mrad. Using a purely geometrical analysis, it was demonstrated that for the crystal angular scan over the bending angle region of 410 μrad, there is always an impact parameter region where the particles are channeled with a reduced angle. This would explain both the extended channeling region observed in the angular scans and the reduced channeling kicks measured with the collimator scans. To verify this hypothesis additional collimator scans were made for a variety of crystal angles. The displacements of the beam from the beam core at the E03 collimator for these angles were recorded. A summary plot is shown in Fig. 4, where the red line is the expected angle in accordance with the miscut hypothesis. The agreement between the data and the expectation is fairly good for the kicks larger than 100 μrad. For the remaining orientations, the measured kicks do not follow the linear trend, as if the partial channeling was covered by a different effect. The observed kick could be explained by multiple volume reflections or volume capture.

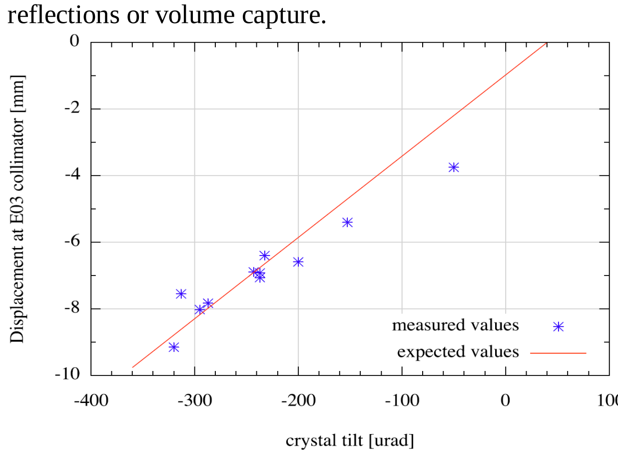

Figure 4: Displacement of channeled beam from beam core at E03 *vs.* crystal angle.

To justify this analysis and better understand the process of beam-crystal interactions, detailed Monte-Carlo simulations with the CRYAPR and STRUCT codes were performed. It is interesting that the red line of Fig. 4 is quantitatively reproduced in these calculations – at the rate of 2.2 mm per 100 μrad – being attributed to the volume capture effect. The simulations revealed that for the Tevatron conditions any θ_m>100 μrad would affect the expected distributions if θ_m>0. With a negative orientation, the results are not very sensitive to the value of θ_m inducing clear effects of channeling as shown in Fig. 5 for θ_m = -1.6 mrad. In this case, the partially channeled protons – those with a small impact parameter passing a thin crystal corner – create a first peak in a 2-mm innermost layer of E03 starting at its edge at -4 mm. Increased beam loss localization on E03 and a corresponding reduction of beam loss in the rest of the machine are clearly seen. For positive miscut angles – as assumed for the crystal used in the current studies – the channeling efficiency (and as a result, collimation efficiency) is substantially lower.

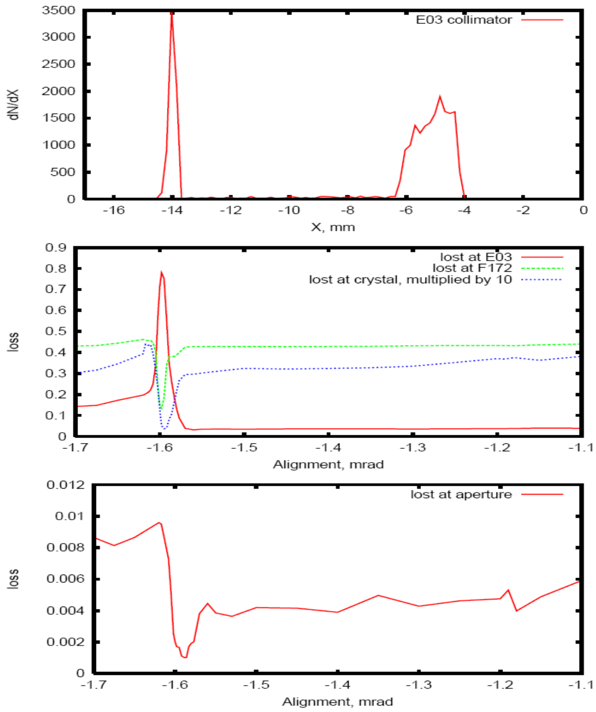

Figure 5: Channeled and partially channeled peaks at E03 (top), fractional beam loss on E03 and F172 collimators and crystal (middle), and fractional beam loss in the rest of the Tevatron (bottom), for miscut angle θ_m= -1.6 mrad.

CRYSTAL CHANNELING DURING FULL COLLIDER STORE

Crystal collimation has been used during four full Tevatron collider stores with the first conducted on March 17-18, 2009. A successful automatic insertion test of crystal has been achieved. A reduction of ring losses was reproducibly observed along with local loss effects on the E03 collimator due to crystal channeling. No adverse effects were found during these tests. A problem was revealed during the first store with crystal angle drift wandering approximately 90 μrad due to heating from a nearby bus but was fixed with angular feedback software. A more quantitative analysis of these topics will be conducted in the fall of 2009. Inserting the crystal during collider stores has provided valuable experience for future practice with improved crystals to demonstrate improved halo cleaning performance.

STATUS AND PLANS

In the recent crystal collimation tests at the Tevatron channeling has been observed once more. The angle scan results are reproducible. There is evidence that channeling improves beam loss localization. Simulations show that the miscut angle should be small and its orientation should be negative. The collimator positions need to be tuned for crystal collimation. The practical aspects of crystal collimation are more delicate than those in a conventional two-stage collimation system.

At the same time, there are a few effects in the recent data which are not fully understood. The width of the channeling peak is wider and its depth is less compared to the 2005 measurements, which results in a lower channeling efficiency. According to simulations, this can be attributed to the wrong sign of the miscut angle. The important phenomenon is that at the end-of-store, predominantly the beam in the abort gap is channeled while there is an indication that at the beginning of store the bunched beam is primarily affected by the system.

In the summer 2009 the O-shaped crystal will be replaced with a new one with a much smaller miscut angle and a negative orientation. In addition, a second (vertical) goniometer with two alternating crystals will be installed: an O-shaped crystal (to exploit channeling) and a multi-strip array (to exploit volume reflection). Improved beam diagnostics will be installed. In the fall of 2009, beam studies are planned to start for two-plane beam cleaning aimed at observing convincing reproducible loss reduction in the superconducting ring and the CDF/D0 detectors. It is worthwhile noting that a complementary experiment is almost ready to go at CERN SPS [6].

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