RECENT T980 CRYSTAL COLLIMATION STUDIES AT THE TEVATRON EXPLOITING A PIXEL DETECTOR SYSTEM AND A MULTI-STRIP CRYSTAL ARRAY*

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Abstract

With the shutdown of the Tevatron, the T-980 crystal collimation experiment at Fermilab has been successfully completed. Results of dedicated beam studies in May 2011 are described in this paper. For these studies, two multi-strip crystals were installed in the vertical goniometer and an O-shaped crystal installed in a horizontal goniometer. A two-plane CMS pixel detector was also installed in order to enhance the experiment with the capability to image the profile of crystal channeled or multiple volume reflected beam. The experiment successfully imaged channeled beam from a crystal for 980-GeV protons for the first time. This new enhanced hardware yielded impressive results. The performance and characterization of the crystals studied have been very reproducible over time and consistent with simulations.

INTRODUCTION

Efficient collimation systems are necessary for large colliding machines like the Tevatron and the LHC. The Tevatron has employed a 2 stage collimation system since the beginning of Collider Run II starting in 2001 [1]. Since 2005, the T-980 experiment [2-5] has been devoted to studying applications of bent crystal collimation by replacing conventional tungsten scattering targets with short (~5mm) bent crystals to investigate/improve the efficiency of a 1-TeV proton beam collimation. During a 2 week period in May of 2011, a special end-of-run beam study period interrupted the Fermilab Tevatron Collider program. A majority of this period was dedicated to the T-980 experiment. With the shutting down of the Fermilab Tevatron on Sept 30, 2011, the T-980 experiment also comes to an end for studies of crystal collimation. Effects for single or multi-strip crystal explaining channeling (CH), volume reflection (VR) and multiple volume reflection (MVR) can be found in Ref. [6, 7]. Prior to the study period, new hardware was installed into the Fermilab Tevatron tunnel to enhance the ability to detect and image the effects of bent crystals used during this study. A newly built 2-plane pixel telescope consisting of six CMS style pixel sensors was installed [8]. Also, 3 crystals were installed: a 16-strip MS-16 (multi-strip), an 8-strip MS-8 and an O-shaped crystal O-05-09. The study period goals were to characterize the performance of the crystals, and use the pixel detector to image channelled and reflected beams.

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EXPERIMENTAL SETUP

The T-980 setup [2-5] is located in the Fermilab Tevatron tunnel in the E0 straight section (Fig. 1). The experiment utilizes 2 goniometers which are the devices used to change the angle of the bent crystal relative to the beam. The vertical goniometer is capable of producing a total angular range of 16 mrad with a single step of 0.25 μrad while the horizontal goniometer can produce a total range of 8 mrad with a single step of 1 μrad.

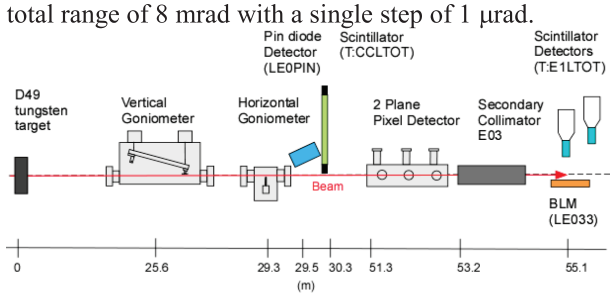

Figure 1: T980 experimental layout. Layout depicts the 2 goniometers, pixel detector, secondary collimator and instrumentation used.

The upstream goniometer contains 2 crystals which are mounted in the vertical orientation. Since both multi-strip crystals are mounted in the vertical goniometer, it means the beam that is multiple volume reflected by the crystal will be displaced vertically above the circulating beam 27.6 m downstream at the secondary collimator E03. The downstream goniometer houses only one O-shaped crystal. This crystal is mounted in the horizontal plane where beam that is channeled from the crystal will be displaced -4.5 mm to the horizontal radial inside of the circulating beam 23.9 m downstream at E03. E03 is a standard 2 plane "L" shaped Tevatron collimator capable of intercepting both horizontal and vertical displaced

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beams from the crystal upstream. Pin diode and scintillator detector systems are used for enhanced beam loss instrumentation. They are used to detect scattering from crystals and are capable of distinguishing loss in time with the bunched beam or the abort gap. The pixel detector is located 1.5 m in front of E03 and has the capability of moving independently in both planes. Typical beam conditions used for these studies consisted of protons and antiprotons that were kept at the end of collider store with beam energy of 980 GeV, a collision low-beta lattice and a proton beam intensity ~ 7×10^{12}. Only protons were used for studies.

IMAGING PIXEL DATA FOR CHANNELED BEAM

The pixel detector must be placed at the appropriate location to intercept the CH beam from the crystal as seen in Figure 2. The horizontal pixel was aligned with the beam edge and then retracted 1 mm from the circulating beam. An internal beam tube picture and diagram of the pixel detector is shown in Figure 3. The pixel detector is made of 3 horizontal and 3 vertical pixel plaquette separated by 60 cm in the beam direction. Each plaquette is 9×17 mm. The pixel data acquisition rate is capable of 1Hz updates. One unique aspect of the pixel detector is that the pixel is installed directly into the vacuum vessel with vacuum pressure at 10^{-9} torr, a first for this type of pixel.

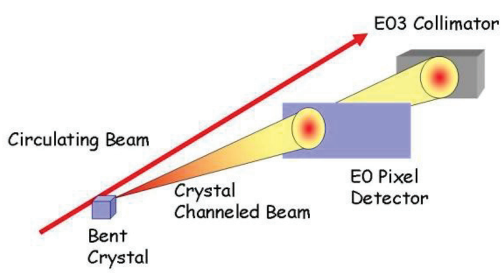

Figure 2: Picture showing the placement of the pixel telescope to intercept and image the CH beam from the bent crystal.

Each pixel is fixed in position on the detector vessel and the vessel can move up, down, inside, outside as well as pitch and yaw. The horizontal crystal used to channel halo onto the pixel detector is a Si (110) O-shaped crystal with a measured bend angle θ_{bend} = 220 μrad and length along the beam of 5 mm. The crystal was placed ~5σ from the beam and the horizontal angle was varied in order to determine the channelling peak for the crystal. The angle of the crystal was then set to the angle of the peak of the channel in this case the CH peak is equal to 0 μrad. The channeled beam at this angular setting is displaced -4.45 mm from the core or circulating beam at the E03 collimator.

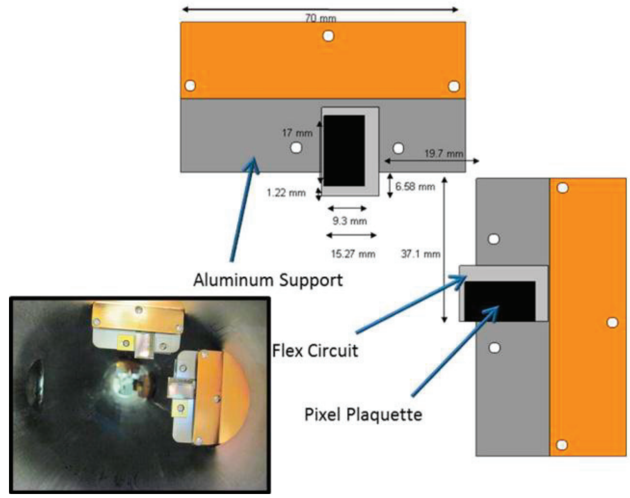

Figure 3: Image inside the vacuum chamber of the pixel detector showing horizontal and vertical pixel plaquettes.

Figure 4 shows an angular scan of the crystal with the CH peak at ~0 μrad. It should be noted that the crystal has very good reproducibility for determining the channelling peak over a couple of years even being installed and removed from the goniometer. The resulting imaged CH beam on the pixel detector can be seen in Figure 5. The bright spot is the CH beam which is displaced from the main beam core by approximately -4.5 mm with dimensions of ~1×3 mm. This is the first occurrence of a crystal channeled proton beam at 980 GeV in collider conditions being imaged on a pixel detector.

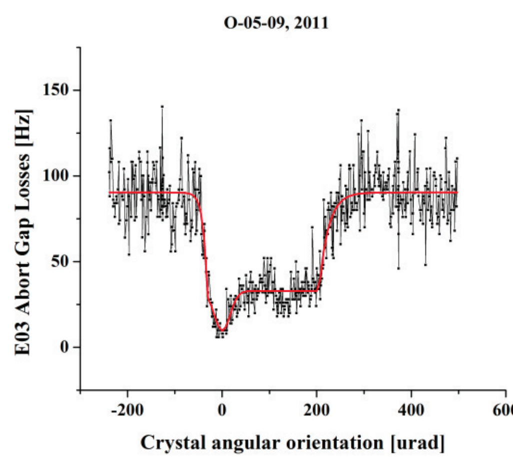

Figure 4: Angular scan of the crystal O-05-09 with channel point ~0 μrad. Red line depicts fitted data. Sections -50 μrad and lower and 250 μrad and higher are amorphous scattering angles. CH region = 0±50 μrad. VR region is 50 to 200 μrad.

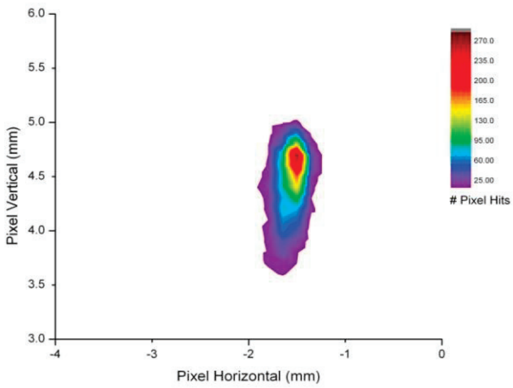

Figure 5: Imaging of the CH beam on the pixels.

PIXEL IMAGING FOR MVR BEAM

In the same way that CH beam was imaged using the O-shaped crystal on the pixel detector, a similar scenario was attempted to image vertical MVR beam from the MS-8 crystal. MS-8 is an 8-strip crystal which has a $\theta_{MVR} = 64\ \mu rad$ total. The resulting MVR beam is displaced 1.7mm vertically above the circulating beam at the pixel detector. This has been a well characterized and reproducible performing crystal [9]. Simulations of the crystal are depicted in Figure 6. The vertical pixel was initially used to profile the MVR beam but due to the large 1.04-mm flex circuit and ~1.3mm of inactive pixels on the leading edge a profile was not possible. There was an additional attempt to use the horizontal pixel since the horizontal edge of the pixel has little flex circuit but was limited to only 3.7 mm of horizontal motion before the beam interacts with the aluminium holder. There is also 1.11 mm of vertical flex circuit and inactive pixel to overcome. Figure 7 is the best partial profile of MVR that could be achieved on the horizontal pixel. There is clear interaction with core halo on the aluminium holder at -10 mm which prohibited any further lowering of the pixel detector into the MVR profile.

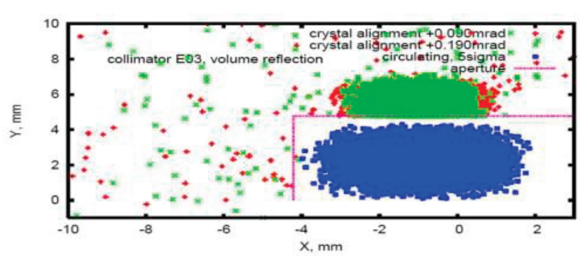

Figure 6: Simulated beam profiles for the MS-8 for MVR beam at the E03 collimator/pixel detector. Blue profile is circulating core and green profile is MVR beam.

MS-16 CRYSTAL

One item worth noting is the attempt to characterize the CH and MVR point by angle scans for the INFN MS-16. There was much interest in demonstrating crystal collimation using a MS crystal in the Tevatron due to the large angular acceptance ~150 μrad with a large MVR angle ~100 μrad over 16 strips.

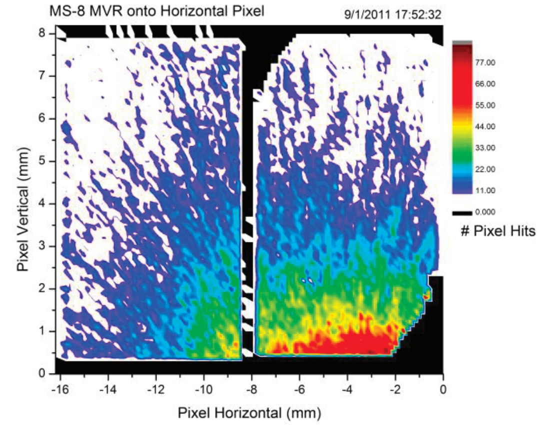

Figure 7: Imaging MVR beam on horizontal pixel.

It was thought that this crystal would have good cleaning performance as well as easier reproducible insertion from collider store to store. There were a number of attempts to find the MVR point and attempt for quantify the collimation efficiency. However, large losses during the motion of changing the angle of the crystal made it difficult to analyse the data. After the study period it was determined that due to the MS-16 length equivalent to 30 mm, the angular motion caused the beam separation distance of the end of the strip array to vary unacceptably.

SUMMARY

Since 2005, T-980 has had a successful history for studying and demonstrating techniques to improve collimation efficiency by the use of bent crystal collimation. The last dedicated beam study period demonstrated improved and impressive techniques for imaging 980-GeV channeled proton beam from a crystal using a pixel detector. A special thanks and congratulations to all collaborators who have dedicated time and effort for T-980.

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