FERMILAB-CONF-06-309-AD

# Channeling collimation studies at the Fermilab Tevatron

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## ABSTRACT

Bent crystal channeling has promising advantages for accelerator beam collimation at high energy hadron facilities such as the LHC. This significance has been amplified by several surprising developments including multi-pass channeling and the observation of enhanced deflections over the entire arc of a bent crystal. The second effect has been observed both at RHIC and recently at the Tevatron. Results are reported showing channeling collimation of the circulating proton beam halo at the Tevatron. Parenthetically, this study is the highest energy proton channeling experiment ever carried out. The study is continuing.

Keywords: Channeling, collimation, accelerator, Tevatron

## 1. THE CHALLENGE OF COLLIDER COLLIMATION

During the design of the Superconducting Super Collider (SSC) it was recognized that collimating the intense proton beams required for high luminosity posed daunting challenges. A halo develops around any circulating beam due to many effects such as beam-gas and beam-beam interactions. Superconducting magnets can be quenched or destroyed if they scrape even a tiny portion of the beam. Collider detector devices such as silicon strip detectors are even more sensitive.

In so-called single stage conventional collimation the beam halo is scraped by a collimator moved into the halo. Typically the collimator is a 1.5 m long block of steel or other medium or high-Z material. A certain fraction of the halo will survive, either by traversing the length of the collimator or by scattering out of the collimator block. Suppressing the out-scattered particles can be quite difficult. A more sophisticated way to handle the out-scattered particles is to go to a *two-stage collimation* system[1]. A thin primary target is used to scatter the beam out by increasing the amplitude of the betatron oscillations of the halo particles and thereby increasing the impact parameters on to secondary collimators during the next turns without influencing the unscattered beam.

At the SSC, Mokhov and his colleagues[2] proposed an innovative solution to the collimation problem. In their arrangement an aligned, bent single crystal is used to deflect the beam out into a collimator much as a magnetic septum would. However, using the crystal results in a much higher deflection per unit length with little effective septum width. Since the SSC design there have been several developments that have made crystal collimation even more promising. One was a fuller understanding of so-called crystal multi-pass extraction first observed at CERN[3]. The other was the development of several approaches at the Institute for High Energy Physics (IHEP) and the Petersburg Nuclear Physics Institute (PNPI) for producing very short crystal bending lengths characteristically using anticlastic crystal deformations[4]. In view of the promise for both extraction and collimation the SSC sponsored a research program on crystal extraction at the Tevatron. That experiment, E853[5], showed that extraction was possible in the context of a superconducting accelerator.

Several years ago a study of crystal collimation was carried out at the superconducting Relativistic Heavy Ion Collimator (RHIC) at Brookhaven[6]. Because of limitations of useful space in the accelerator lattice the crystal was

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[†] Fermilab is operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy.

mounted at an unfavorable location where the angular divergence was high. While the experiment did see channeling behavior, it increased the background rate at one of the major detectors rather than decreasing it. Because of the unfortunate crystal location this result was not unexpected. What the study did see was an extremely interesting effect, oriented crystal behavior over the whole arc of the crystal bend. This unusual behavior was largely ignored because of the absence of collimation. The result observed at RHIC is now widely attributed to *volume reflection*[7]. This whole-arc effect is potentially important in two ways. It could simplify crystal alignment since the arc of the bend is typically an order of magnitude larger than the channeling critical angle. Beyond that it might even be possible to use the whole-arc effect directly for collimation.

Meanwhile at the start of Run II at the Tevatron, the initial beam halo and the associated backgrounds at the collider detectors were disconcertingly high, in part because of the rising luminosity and difficulties with beam quality. The Run II halo problem was solved over the Tevatron 2004 shutdown by instituting the so-called double scrape collimation system and improving the vacuum and alignment. The initial Tevatron beam halo challenge along with awareness of the impending collimation requirements at LHC reawakened interest in the possibility of crystal collimation at the Tevatron[8]. The RHIC goniometer with the associated PNPI "O-shaped" crystal were brought to the Fermilab and installed in the Tevatron in 2004. The bent crystal was put into operation in the fall of 2005.

## 2. STUDY APPARATUS

The approach employed for the Tevatron crystal collimation study has been to install the crystal in the E0 straight section, one of the locations of the sets of conventional collimators in the Tevatron. In the two stage conventional collimation system used at E0 the halo first interacts with a tungsten target at D49 that extends 5 mm along the beam direction. The scattered halo particles with large amplitudes are then shaved off by a 1.5 m long steel collimator located at E03H. The bent crystal and goniometer were installed 8 m downstream of E0 in the proton beam. The front face of the E03H collimator was 23.8 m downstream of the crystal. At E0 the proton helical orbit is on the inside of the accelerator central orbit. Figure 1 is a schematic of the location. The four conventional magnets at E0 provide a dogleg for beam manipulations in the horizontal plane. They were off for these measurements.

The crystal was mounted in a high vacuum goniometer. It rotated around a vertical axis with a pivot point about 8 cm from the beam and deflected the halo in the horizontal direction. The crystal orientation could be monitored with a laser system. The device moved in and out of the accelerator beam pipe in the horizontal plane. The crystal was a so-called "O" crystal of silicon with the bend in a (110) plane. It had a miscut angle of 465 μrad arranged so that there was not a possibility of partial deflections for particles near the crystal face. The "O" geometry pioneered at PNPI[9] produces a bend in the small leg of the "O" by compressing the long leg (see Figure 2). The length of the crystal along the beam was 5 mm. The long leg of the "O" was 45 mm. The bending angle was approximately 440 μrad. The crystal deflected the beam toward the inside of the ring.

The principal detector used for this investigation was an ion chamber beam loss monitor (LE033) behind the E03 collimator (labeled E03H in Figure 1). The LE033 signal was generated by scraped or channeled halo showering in the E03 collimator. The signal was reduced significantly when the collimator was withdrawn. For example the collimator out/collimator in ratio when the crystal was aligned for channeling was < 0.01. A standard PIN diode[10] (LE0PIN) was also available about 25 cm downstream of the crystal. It was at an angle of about 45 degrees to the beam so that it was detecting mostly low energy secondaries from interactions in the crystal. Removing the crystal from the beam halo caused the LE0PIN signal to disappear. Detectors like C:LOSTP at the CDF collider detector were used to monitor proton losses for different collimation arrangements at E0.

## 3. CHANNELING DEFLECTION

When the E03 collimator is outside the crystal radial position, halo particles can strike the collimator for one of several reasons. The projected multiple scattering angle for the 5 mm long crystal is 3 μrad so that the beam halo would be displaced on average 80 μm at the collimator or much less than the characteristic relative displacement between the crystal and collimator. Multiple scattering in the crystal is small compared to the beam halo angular distribution so that scattered particles may typically make several passes by the crystal and then pass through it again. This is the origin of the multipass effect. Particles can also undergo an elastic or inelastic nuclear interaction in the crystal. Assuming an average transverse momentum of 300 MeV/c in the interaction this might result in a deflection of 300 μrad. The deflection at the front of the E03 collimator would be O(7 mm). Most of the signal in LE033 is due to these nuclear interactions. When the crystal is aligned two things happen. The channeled particles will be deflected across the collimator face by an angle of 440 μrad and raise the count rate. On the other hand channeled particles undergo substantially fewer nuclear interactions thereby diminishing the rate. (This diminution of nuclear interactions was demonstrated some years ago[11].) Calculations show that the net effect is to decrease the LE033 rate.

Since the crystal is 5 mm long, the interaction probability per pass is only 1.6%. Thus when the 1.5 m collimator is moved in closer to the beam than the crystal the count rate in LE033 should be sixty times higher.

The crystal was aligned in the halo by varying the crystal angle in steps of several μrad. Typically the crystal angle was scanned over 2000 μrad in forty-five minutes. Several points were taken for each angular setting. At any angle there were statistical fluctuations due to slight beam motions in the Tevatron at a minute by minute level. Figure 3 shows the LE033 yield behind collimator E03 in arbitrary units as a function of the crystal angle for a typical scan. The crystal angle scale has been set to 0 μrad for the situation where the upstream end of the crystal is aligned. Characteristically the crystal was at 5.5 $\sigma_b$ from the beam while the collimator was at 6 $\sigma_b$ ($\sigma_b$, the horizontal spread of the beam, was 0.45 mm).

A channeling dip is present at 0 μrad with a width of 22 ± 4 μrad (rms). The width of the channeling dip is a convolution of the beam divergence, the channeling critical angle, and multipass channeling effects. The width of this distribution can be compared to the 32 μrad width (rms) observed in the E853 crystal extraction experiment at the Tevatron for a collider mode beam angular divergence at the crystal of 18 μrad. It is difficult to do a deconvolution of the crystal angular scan to get the critical angle. However, the distribution is consistent with the beam divergence and the 5 μrad channeling critical angle at 980 GeV. At the bottom of the dip the LE033 signal is 22% of the signal at a random angular setting. This depth is a measure of the channeling efficiency and gives a channeling efficiency of $\eta_c = 78 \pm 12\%$ including the effects of multiple passes.

A shoulder extends 460 ± 20 μrad to the right of the channeling dip. A similar feature was observed for the first time at RHIC. This shoulder width is close to the expected magnitude of the crystal bend. The shoulder is a coherent crystal effect acting over the whole arc of the crystal bend. This might be, for instance, due to volume reflection[12]. A typical volume reflection away from the convex side of the crystal is on the order of the critical angle. It is a coherent process so over several passes through the crystal it can grow to a deflection several times the critical angle. Like channeling it will diminish nuclear interactions and thereby decrease the LE033 rate. The whole-arc efficiency, $\eta_r$, was 52 ± 12%.

The larger dots and associated curve show the results of Biryukov's CATCH simulation[13] for the conditions in the Tevatron. Note that there are no free parameters in this simulation except average counting rate.

The angular distribution of particles interacting with or channeling in the crystal can be measured by plotting the LE033 count rate as the E03 collimator is withdrawn further from the beam. Note that the LE033 signal is an integral of the flux as a function of radial position along the front face of the collimator. This distribution is plotted in Figure 4 for several different goniometer settings. More negative values are for larger retractions. The 0 μrad case (circles) is for the aligned crystal. The 225 μrad distribution (triangles) is for a goniometer setting on the whole-arc shoulder. The 688 μrad (x) is beyond the arc of the bend. The distribution with the crystal out is also shown (squares). For the crystal-out case one sees just the beam halo distribution.

For the aligned case the yield drops rather slowly at first possibly suggesting dechanneling. At -7 mm it drops quickly. These are the channeled particles that make it around the bend. Beyond the channeling peak the LE033 rate is small and essentially the same for both the channeled and shoulder cases.

The crystal gives a substantial deflection. However, the deflection implies an angle of O(300) μrad rather than 440 μrad. Checks have been carried out to show this reduced deflection angle is not due to aperture restrictions in the E0 straight section or around the accelerator ring. Likewise it is probably not due to a relaxed crystal bend since the whole-arc shoulder signature matches the expected bend angle. This shortfall in the deflection is a puzzle but may be due in part to not fully understanding the correct zero position at the collimator for the equivalent source at the crystal. Since the unshadowed halo flux should be sixty times the interaction flux from the crystal it is necessary to go up by an equivalent amount on the rise in the LE033 signal that occurs when the E033 collimator moves out of the crystal shadow. The most optimistic fit to a Gaussian error function indicates that the peak for the forward beam in the aligned case would be at +0.6 mm relative to the zero in the figure. Data from the 225 μrad crystal orientations gives a distribution centered at +0.85 mm. Taking this as the most optimistic case of the undeflected beam direction from the crystal gives a deflection of 330 μrad. The scale at the top of Figure 5 gives the equivalent deflection angle in μrad.

In Figure 5 the plots have been smoothed to get a better appreciation of the measurements. After subtraction of a flat background beyond the channeling peak, the aligned case for 0 μrad (circles) was fitted with a Gaussian error function (the integral of a Gaussian) centered at 7 mm with a $\sigma = 0.3$ mm (13 μrad). The channeling peak is the solid black Gaussian. The shallower region was fitted with an exponential. The fits are shown as dot-dash lines. The shallower region is due in part to bending dechanneling but probably also contains a background contribution. The black solid curve at the bottom is the derivative of the “dechanneling tail” integral distribution. It is shallow and contains 30-40% of the deflected beam. Normal dechanneling for the 5 mm long crystal should be about 1%. Bent crystal dechanneling could be somewhat larger. There should also be a contribution due to surface dechanneling and possibly from a miscut and beam contributions that are outside the critical angle when the crystal is aligned.

The 225 μrad curve (labeled 343) was also fitted with an error function. The fit distribution (solid triangle, dotted line) is centered at 0.85 mm and has a $\sigma = 3$ mm equivalent to a projected angle of 126 μrad or an angular production cone of 180 μrad. This is in the range of the 300 μrad rms suggested earlier. As expected from Figure 4 the count rates for the whole-arc case is higher at $x = 0$ than the aligned case. The derivative of the 225 μrad distribution is shown as a dashed line.

## 4. COLLIMATION RESULTS

The central purpose of the Tevatron investigation has been to demonstrate and study effective crystal collimation to reduce halo at the Collider detectors. Both of the large detectors at Fermilab have halo monitors to monitor these losses continuously. During the crystal collimation studies, the CDF LOSTP halo monitor was recorded for most of the runs. Figures 6 and 7 show a comparison of crystal collimation with the crystal aligned for channeling collimation and for the case for conventional collimation with a thin tungsten target at D49. For the crystal case LOSTP goes down to a rate about half the rate with the conventional D49 W target. In the crystal case, Figure 6, LE033 (solid circles) follows the behavior seen in Figure 4 while the D49 case behaves like an unaligned crystal (Figure 7).

To reiterate, when using the crystal the secondary collimator E03 achieved almost a factor of 2 better reduction of CDF losses a half a ring or three kilometers downstream!

The existing crystal collimation test system collimates only in the horizontal plane. A comprehensive system would also collimate in y and in dispersion. These results are multiplicative so the halo could be reduced by up to a factor of eight. The original modeling indicated an order of magnitude reduction might be achieved. Thus, the present incomplete and rudimentary system appears to be well on the way to fulfilling the potential of crystal collimation.

## 5. PLANS FOR THE FUTURE

During 2006 a new optimized crystal is being installed at the Tevatron. It is 3 mm long with a 150 μrad bend. The crystal has been prepared at the Institute of High Energy Physics at Serpukhov and characterized by IHEP and Ferrara.

Future studies will focus on studying collimation in detail. It is important to obtain information that can direct and illuminate plans and possibilities for crystal collimation at the 7 TeV LHC. One place where this can be investigated is by looking at the interplay of accelerator beam dynamics and crystal collimation. In addition, studies will be undertaken to investigate the whole-arc region.

At this time the whole-arc shoulder remains something of a puzzle. Simulations indicate that the relative size of the channeling peak and shoulder are related to crystal distance from the beam. This needs to be studied further from the standpoints of both measurements and simulations. Other collimator and machine variables might be used to tune the number of multiple passes through the crystal and see how this affects the channeling/whole-arc shoulder ratio. Finally, it would be helpful to determine whether the first deflection for beam interactions that give rise to the whole-arc effect are in the direction of the bend or away from it. If the deflection is in the direction opposite to the bend the process is most likely volume reflection. Studying this might require a fast kicker and dedicated accelerator time.

An intriguing question not related directly to collimation is whether negative particle channeling can be observed for short crystals and very high energy. The crystal now at E0 could be put in the antiproton beam. Some orbit gymnastics would be necessary so special accelerator time would be required. In the far future, such information might be relevant for collimation in a muon collider.

## ACKNOWLEDGEMENTS

V. Biryukov has carried out the modeling studies for this test. Y. Ivanov has contributed insights into the whole-arc bend results. Ivanov, Y. Chesnokov and V. Guidi produced and characterized the crystal. G. Annala, T. Johnson, R. Reilly, D. Plant, S. McCormick, and J. Featherstone helped in the installation of the crystal and the goniometer.

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# FIGURES

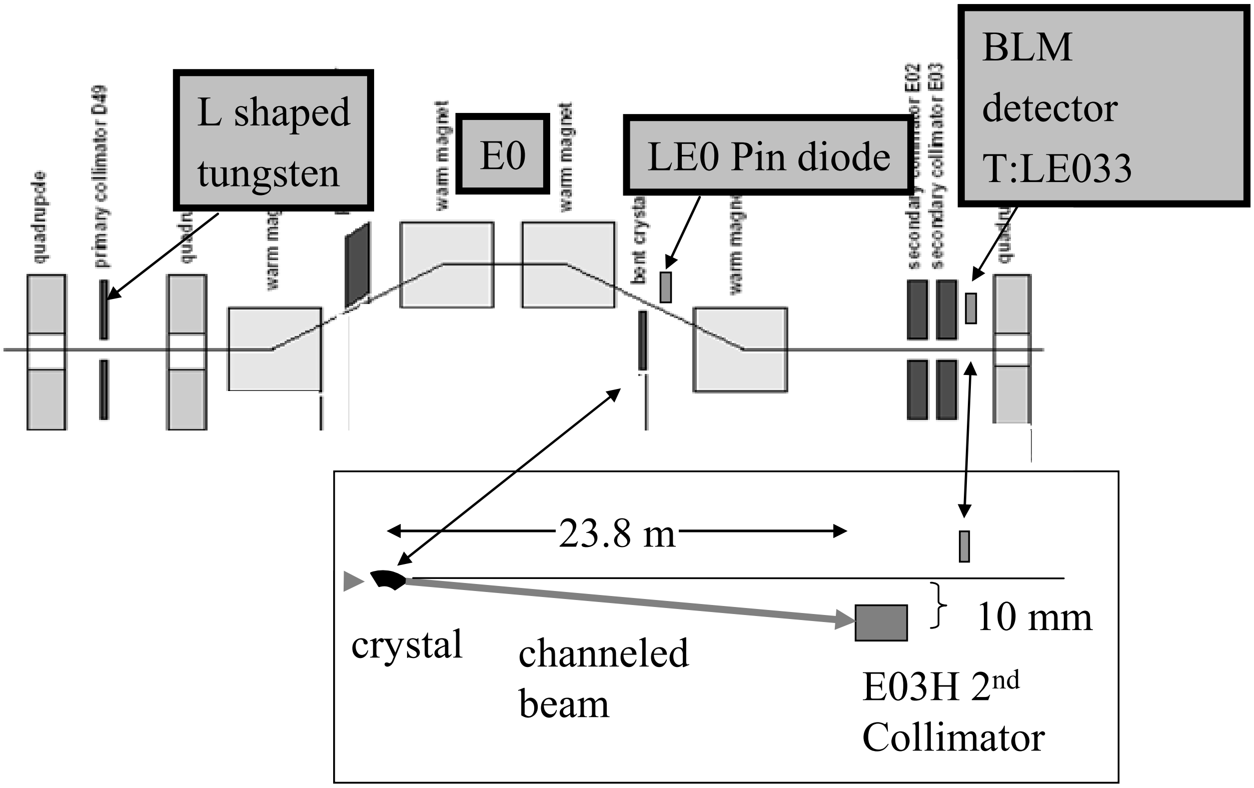

Figure 1: Schematic of E0, the straight section used for the crystal collimation test. The inset shows the dimensions.

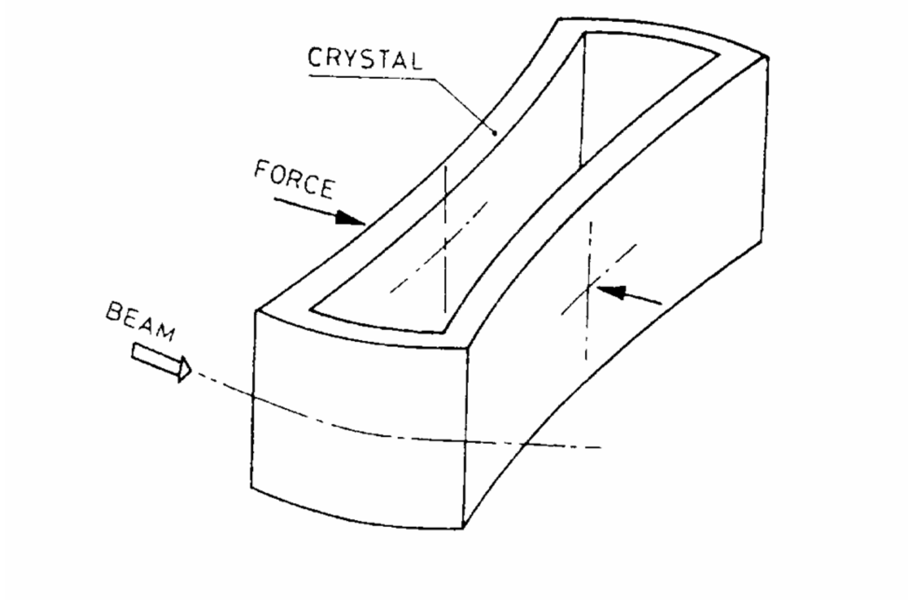

Figure 2: PNPI “O” geometry crystal used at RHIC and Fermilab. The length along the beam is 5 mm. In the Fermilab case the beam comes in from the right.

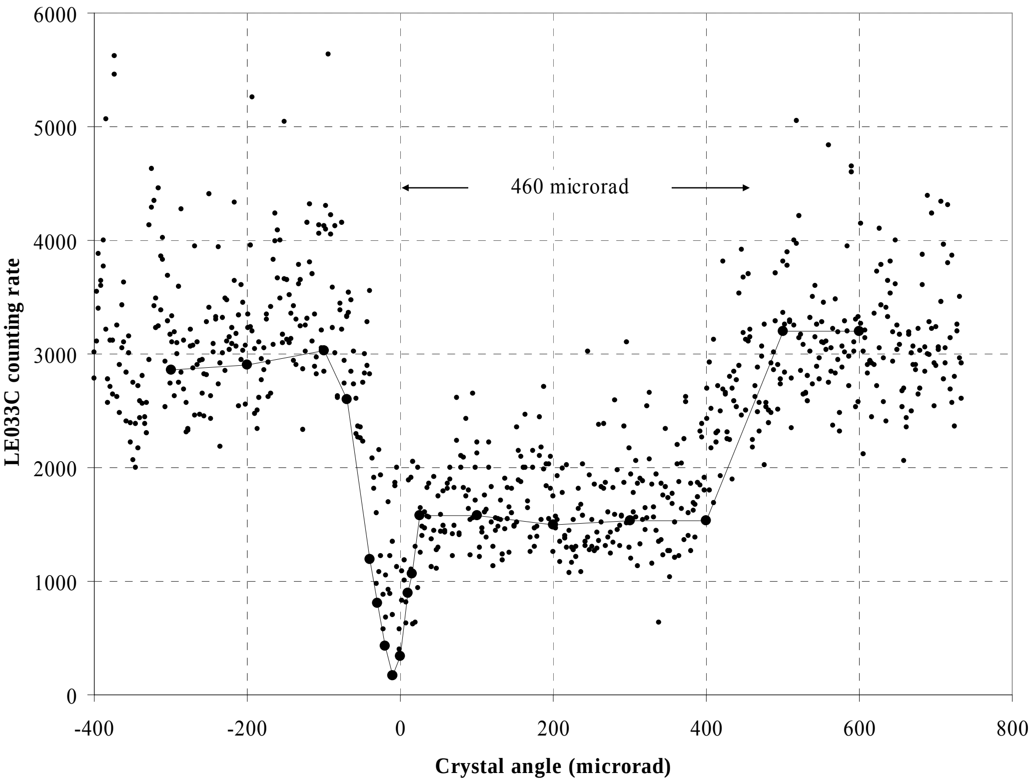

Figure 3: Crystal angle scan. The CATCH results are shown as larger circles.

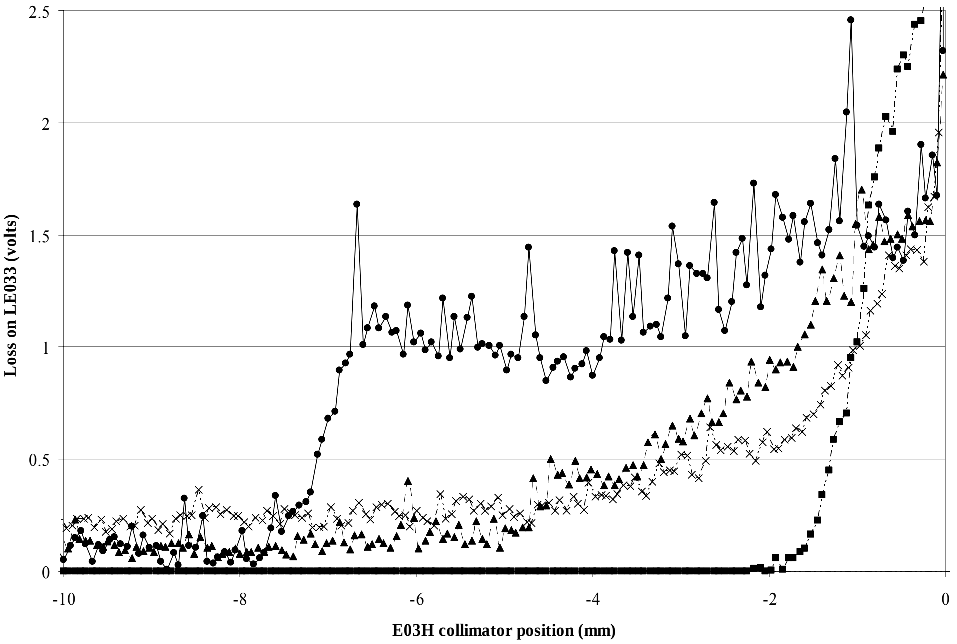

Figure 4: Yield vs E03H collimator displacement for several crystal angles. The collimator is further out of the beam for larger negative values. Solid circles are aligned, triangles – 225 μrad on the shoulder, x – 688 μrad beyond the shoulder, and squares are for the crystal out case.

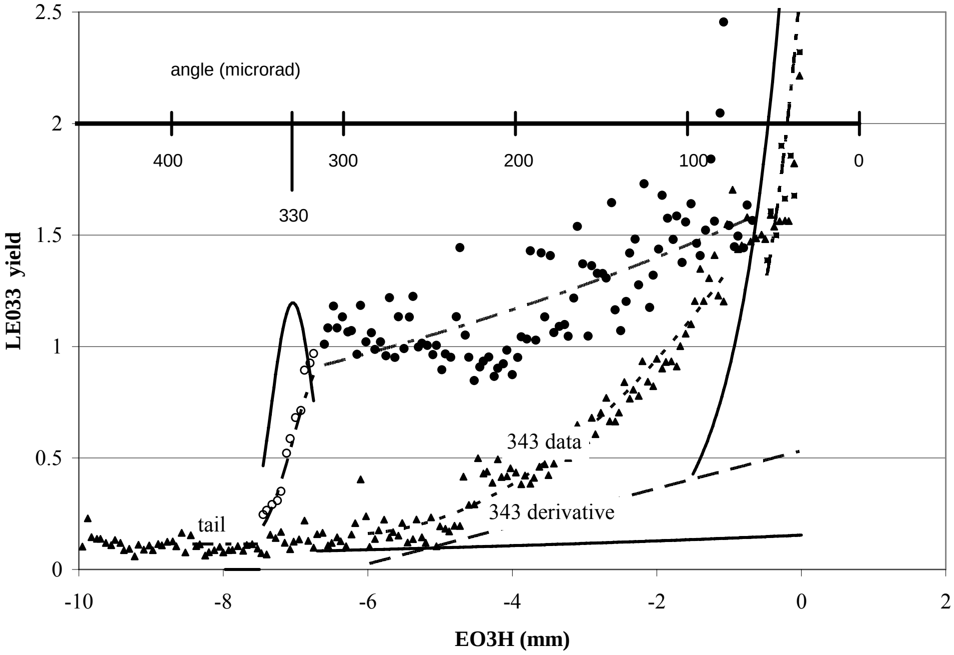

Figure 5: Fitted curves for the aligned case (black circles, dash-dot lines) and on the shoulder (filled triangles, dotted lines). Solid curves are the derivatives for the aligned case. The scale at the top of the figure gives the equivalent deflection angle in μrad. Triangles and dotted curve are for the 225 μrad (labeled 343) while the dashed curve is the derivative.

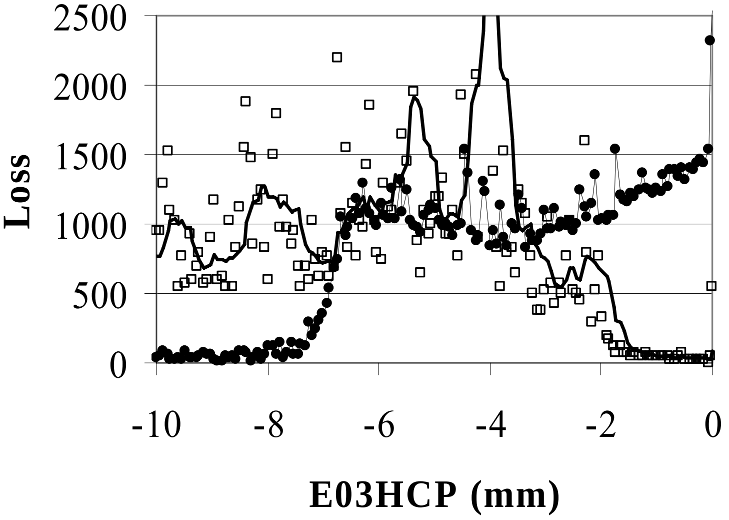

Figure 6: E03H collimator effect on halo at CDF using the bent crystal. Squares are C:LOSTP at CDF and solid circles are LE033. The C:LOSTP curve is a smoothed average over 8 points. There is significantly more halo reduction than for the amorphous case shown in Figure 7.

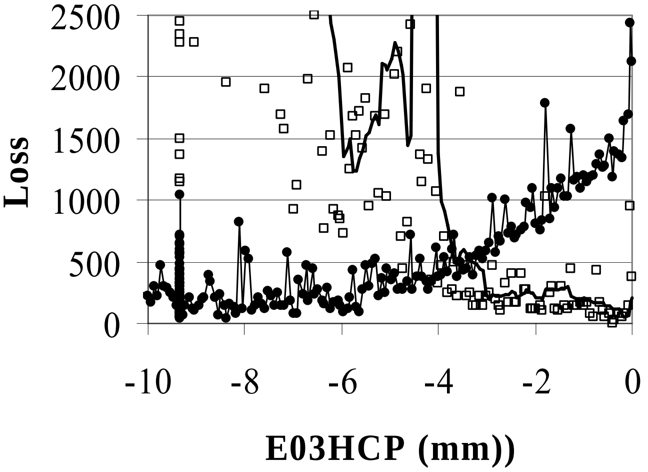

Figure 7: E03H collimator effect on halo at CDF for D49 amorphous target. Squares are C:LOSTP at CDF and solid circles are LE033. The C:LOSTP curve is a smoothed average over 8 points. There is significantly less halo reduction than for the crystal case.