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Crystal Collimation at RHIC[1]

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Abstract. Crystal Channeling occurs when an ion enters a crystal with a small angle with respect to the crystal planes, The electrostatic interaction between the incoming ion and the lattice causes the ion to follow the crystal planes. By mechanically bending a crystal, it is possible to use a crystal to deflect ions. One novel use of a bent crystal is to use it to channel beam halo particles into a collimator downstream. By deflecting the halo particles into a collimator with a crystal it may be possible to improve collimation efficiency as compared to a single collimator.

A bent crystal is installed in the yellow ring of the Relativistic Heavy Ion Collider (RHIC). In this paper we discuss our experience with the crystal collimator, and compare our results to previous data, simulation, and theoretical prediction.

INTRODUCTION

The usual collimation system for a collider consists of multiple sets of jaws that are used to remove the beam halo. The primary set of jaws is used to define the primary aperture of the machine. Particles with low impact parameters on these jaws have a finite probability of scattering out of the collimator and form a secondary halo [1]. A secondary set of jaws is used to remove this halo and increase the collimator efficiency.

Because the proper placement of the secondary jaws is crucial to the overall performance of the collimation system, it is advantageous to find a way to relax this constraint. By using bent crystal channeling, it is possible to give a well defined angular kick to the particles that enter the crystal. A secondary collimator can then be used to remove these particles. This process should reduce the amount of secondary halo that is generated and improve collimation efficiency. An added advantage is that the secondary collimator can be placed further away from the beam, while still keeping the impact parameter high enough to reduce the probability of particles scattering out of it. This paper discusses our experiences with a bent crystal collimator in the yellow ring of the Relativistic Heavy Ion Collider (RHIC).

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CRYSTAL CHANNELING

If ions enter a crystal with small angles relative to the crystal planes, the ions are channeled by the interplanar potential, even if the crystal is mechanically bent [2]. This makes it possible to give a large angular kick to the channeled ions within a short distance. In order for the ions to be channeled, the energy of their motion perpendicular to the crystal planes must be smaller than the maximum interplanar potential, $U(x_c)$. x_c is the transverse interplanar location where the incident ion enters the electron cloud of the lattice atoms. $U(x_c)$ is approximately $Z_{ion}16$ eV for silicon, the crystal material. This condition gives the maximum angle for channeling to be

$$\theta_c = \sqrt{\frac{2U(x_c)}{pv}}. \qquad (1)$$

where p and v are the momentum and velocity of the ion respectively. At larger angles, the incoming ions will experience a potential similar to an amorphous solid. For RHIC energies, $\theta_c = 37$ μrad at injection and 11 μrad at storage energy.

LAYOUT

The RHIC crystal collimation system is shown in Fig. 1. It consists of a 5 mm long crystal and a 450 mm long L-shaped copper scraper placed downstream of the PHENIX detector in the yellow (counter-clockwise) ring. The crystal is an O-shaped silicon crystal with the (110) planes placed at a slight angle with respect to the nor-

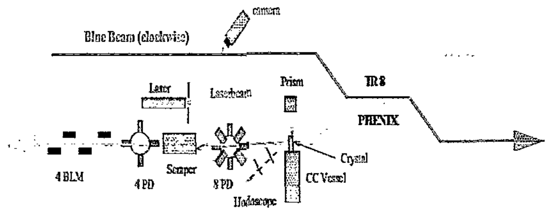

FIGURE 1. The RHIC Crystal Collimation system

mal of the input face. The crystal for the 2001-2 RHIC Run and the 2003 Run are of the same design but different bend angles. The former crystal had a bend angle of $\theta_b = 0.37$ mrad and the latter was bent $\theta_b = 0.34$ mrad, as determined from measurements with the beam. There are eight PIN diode loss monitors between the crystal and the scraper (the upstream PIN diodes) to measure particles scattered from the crystal. Four PIN diodes are placed downstream of the scraper to measure particles scattered from the scraper (the downstream PIN diodes). Two scintillators form a hodoscope aligned to the crystal surface to look for particles scattered at large angles. Four ion chamber loss monitors are also located downstream of the scraper [3].

THEORY

Because the channeling efficiency of the crystal depends on the proper alignment of the crystal to the beam, we have developed a simple model to determine the particle distribution on the crystal face [4]. We assume an initial distribution of

$$f(J,\delta) = \frac{1}{\sqrt{2\pi\sigma_\delta}\varepsilon}\exp\left[-\frac{\delta^2}{2\sigma_\delta{}^2}\right]\exp\left[-\frac{J}{\varepsilon}\right] \qquad (2)$$

where J is the particle action, ε is the unnormalized rms emittance, δ is the momentum deviation, σ_δ is the rms momentum spread. By writing $J = J(x,x',\delta)$ and integrating over all momenta, it is possible to transform $f(J,\delta)$ to $f(x,x')$ and obtain the phase space distribution of all particles that will hit the crystal. One can then calculate the average angle, θ, with which the particles will hit the crystal face. Assuming that particles have low impact parameters with respect to the rms beam size, or that the crystal is far from the beam core, one obtains

$$\theta = x_{crystal}\frac{-\alpha\varepsilon + DD'\sigma_\delta{}^2}{\beta\varepsilon + D^2\sigma_\delta{}^2}. \qquad (3)$$

The crystal edge is at $x_{crystal}$ from the center of the beam, the dispersion and its slope are given by D and D', and α and β are the Twiss parameters at the crystal. For the

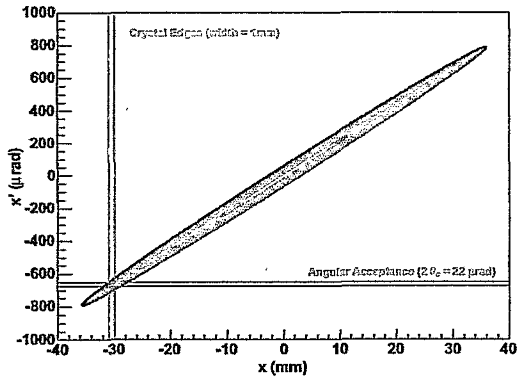

FIGURE 2. The Horizontal Phase Space at the Crystal Collimator. The outermost contour is 10σ. The red and blue lines show the crystal size and angular acceptance.

channeling to occur, the crystal planes must be placed at this angle with respect to the beam direction. For typical RHIC parameters, this expression reduces to

$$\theta \approx x_{crystal}\frac{-\alpha}{\beta} \qquad (4)$$

and is approximately 700 μrad.

One can also calculate the rms angular spread of the beam, σ_θ, that hits the crystal face. In general, it can be shown that σ_θ is strongly proportional to α, β, $D\sigma_\delta$, and the rms impact parameter, and is weakly affected by ε, and $x_{crystal}$ [4]. For the 2003 RHIC parameters, σ_θ is calculated to be 23μrad, assuming that particles hit over the entire face of the crystal. Figure 2 shows the horizontal phase space ellipse of the beam at the location of the crystal collimator for a $\beta^*_{PHENIX} = 2$ m lattice.

By knowing the rms angular spread of the beam that hits the crystal face, using Eq. 2.12 from Ref. [5], one can estimate the channeling efficiency.

$$e \approx \frac{2x_c}{d_p}\frac{\pi}{4}\frac{\theta_c}{\sigma_\theta}. \qquad (5)$$

where d_p is the distance between the crystal planes. This formula is only valid as long as $\sigma_\theta > \theta_c$. For the 2003 RHIC parameters, Eq.5 predicts $e = 32\%$.

SIMULATION

To simulate the effect of the crystal in RHIC, the CATCH (Capture And Transport of CHarged particles in a crystal) code was used [6]. A 6×6 matrix was used to track particles around RHIC so that the effect of multiple turns could be investigated. The particle distribution is chosen identical to that in Eq. 2, using only those particles on horizontal ellipses that will hit the crystal. In the vertical plane the phase space was filled. The design RHIC beam parameters of a 15π mm-mrad normalized rms horizontal and vertical emittance and a 0.0013 rms momentum spread where used.

Figure 3 shows the effect of the crystal on the particles that strike it. The left plot shows the input particle distribution in the horizontal phase space. The edges of the crystal and the angular acceptance are also marked. The right plot shows the output of the simulation. The band of particles around -450 μrad are the channeled particles. Particles near -900 μrad where not channeled.

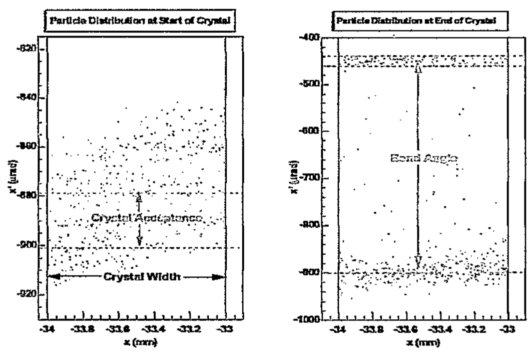

FIGURE 3. Simulation of the effect of Crystal Channeling. The left picture is the input particle distribution into the crystal. The right picture shows the output.

Figure 4 shows a simulation of the number of particles scattered from the crystal vs. the crystal angle for varying number of turns in the simulation. The dip in the scattering rate is due to particles channeling. The large portion of the dip occurs when the crystal is aligned to the beam halo. The remaining structure occurs when particles scatter through a fraction of the crystal into a crystal plane and then channel the remaining distance, this is known as volume capture [5]. The depth is dominated by the number of encounters that particles can have with the crystal, and the width is given by the crystal bend angle.

CRYSTAL CHANNELING

Experiments with the crystal collimator have been performed during the 2001, 2002 and 2003 RHIC runs with fully striped gold and polarized proton beams. The crystal angle was scanned through a range of angles for a variety of different crystal positions, scraper positions, and lattices. Beam losses were recorded by the PIN diodes, hodoscope, and beam loss monitors. Signals from the RHIC experiments were also logged to monitor their background rates. Table 1 lists the available data samples.

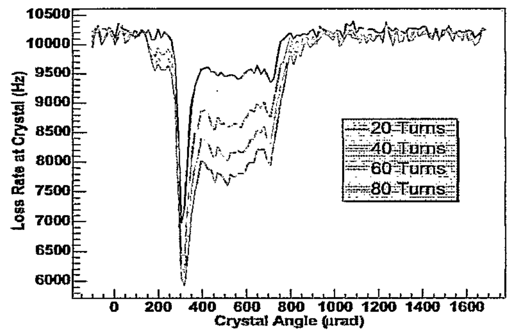

FIGURE 4. The Effect of multiple turns of the channeling signal.

TABLE 1. Tabulation of Angular Scans

Species	β^* @ IR8	No. of Scans	$<\sigma_\theta>$	$<\epsilon>$
Au	5 m	27	45 μrad	20%
Au	2 m	24 (2001 Run)	105 μrad	28%
Au	2 m	20 (2003 Run)	37 μrad	26%
Au	1 m	109	69 μrad	16%
p	3 m	119	70 μrad	26%

Figure 5 shows the scattering rate seen on an upstream PIN diode during a typical scan from the RHIC 2003 run. The data were averaged over 20 μrad, the angular resolution of the crystal positioning system. The function for fitting is empirically determined to be two gaussians on a sloping background, with a sloped line connecting them [7]. The efficiency is defined to be the depth of the narrow dip divided by the background. The fitting function generally returns width dip widths and lower efficiencies than the data and simulations show. The values in Table 1 are averages over all of the fits for each RHIC configuration.

CRYSTAL COLLIMATION

The ultimate measure of the effectiveness of the crystal collimator is its effect on the experimental backgrounds. To measure the collimation performance, the crystal was inserted into the halo and an angular scan was taken. The crystal was then set to the angle which minimized the scattering and thus had the greatest channeling efficiency. Then the copper scraper was moved relative to the crystal until it became the primary aperture. The crystal and scraper where then retracted. The background from the yellow beam was monitored by a detector in the downstream STAR experiment. Figure 6 shows a typical measurement.

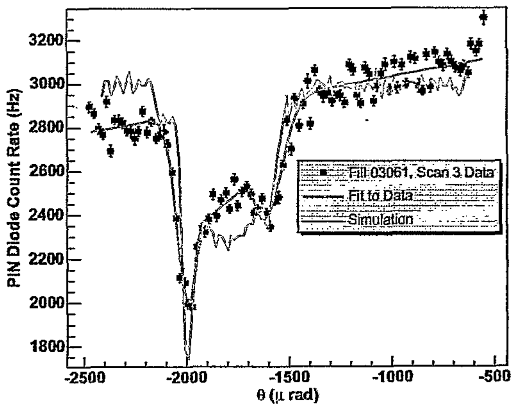

FIGURE 5. Data from Fill 03061. The simulation is done with the measured machine optics[8].

As Fig. 6 shows, the background at the STAR detector is correlated with the crystal angle and the scraper position. At the left side of the figure, the crystal is not channeling. Then it is rotated to the channeling angle, and the background increases at the STAR detector indicating that the channeled beam is not caught by the scraper. With the crystal stationary, the scraper is moved, and the background minimized when the scraper becomes the primary aperture. Near the right edge of Fig.6, the crystal is retracted, and the STAR background is lower than with the crystal in the beam, even when the scraper was the primary aperture. The scraper is finally retracted and the background rises.

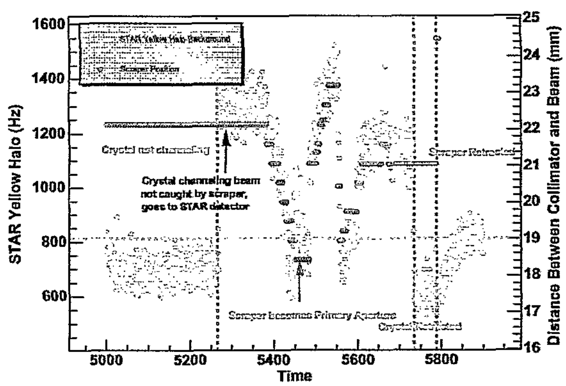

FIGURE 6. The Effect of multiple turns of the channeling signal.

We attribute the poor performance of the crystal to the large tilt of the phase ellipse caused by a large α at the crystal location, as seen in Fig. 2. This increases the angular spread of the beam that hits the crystal, and reduces the amount of beam inside of the crystal acceptance. This increases the amount of particles scattered by the crystal. One can see from Fig. 2 that if the crystal was placed in an area with a small α, the efficiency would be improved, and collimation using a crystal may be more successful.

CONCLUSIONS AND FUTURE PLANS

Crystal channeling was achieved in RHIC, and is consistent with simulations and theoretical predictions. Unfortunately, the current setup could not reduce experimental backgrounds. It is hoped that crystal collimation can be used in the future, provided that the lattice position can be chosen such that the angular spread of particles that will the crystal can be reduced.

All of the available warm spaces in RHIC are at locations where $\alpha \approx 10 \rightarrow 20$. To place a crystal at a cold location would be too expensive and time consuming to be done during the summer shutdown. Therefore, it was decided to abandon the crystal collimator in favor of a traditional two stage collimation system which can be installed in the warm section. The current copper scraper will be moved to the current crystal location to serve as the primary collimator. Two horizontal and one vertical secondary collimators will be placed at various locations downstream of it, in the same warm straight. This will be done in both rings.

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