

NEW RESULTS FROM CRYSTAL COLLIMATION AT RHIC *

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Abstract

In this paper, we discuss new results from the use of the crystal collimator from the 2003 run. The yellow ring of the Relativistic Heavy Ion Collider (RHIC) has a bent crystal collimator. By properly aligning the crystal to the beam halo, particles entering the crystal are deflected away from the beam and intercepted downstream in a copper scraper. The purpose of a bent crystal is to improve the collimation efficiency as compared to a scraper alone. We compare these results to previous data, simulation, and theoretical predictions.

1 INTRODUCTION

A typical collimation system for a collider consists of moveable jaws that are positioned to be the primary machine aperture. Particles with low impact parameters have a finite probability of scattering out of the collimator jaw and forming a secondary halo [1]. This secondary halo can have a significant effect on machine performance [2]. Secondary jaws are used to contain the scattered particles and proper placement of these jaws is necessary for optimal performance.

Finding novel ways to collimate the halo can greatly simplify collimator design. By using bent crystal channeling, a properly aligned crystal will channel the entering particles away from the beam and produce very little halo from scattering. A secondary jaw intercepts the channeled particles with large impact parameters. This secondary jaw can be placed further away from the beam in comparison to a traditional system. This paper discusses our experiences with a bent crystal collimator in the yellow ring of the Relativistic Heavy Ion Collider (RHIC) during the year 2003 run.

2 CRYSTAL CHANNELING

Crystal channeling is a phenomena by which ions entering a properly aligned crystal will follow the crystal planes, even if the crystal is mechanically bent [3]. This makes it possible to give a large angular kick to the channeled ions in a short distance. For proper alignment, the incident particles must be aligned to the crystal planes with an angle less than the critical angle,

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

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where the maximum interplanar potential is given by $U(x_c)$, where x_c is the transverse location where the incident ion enters the electron cloud of the lattice atoms; the momentum and velocity of the ion are p and v respectively. $U(x_c)$ is approximately $Z_{ion}16$ eV for silicon. For RHIC energies, $\theta_c = 37 \mu\text{rad}$ at injection and $11 \mu\text{rad}$ at storage energy. At incident angles greater than θ_c the ion will no longer be channeled but scatters through the crystal as if it were an amorphous solid.

3 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 normal of the input face, and a bend angle $\theta_b = 0.34$ mrad. This crystal is different from the one used during the 2001-2 RHIC run, but is of the same design. There are eight PIN diode loss monitors between the crystal and the scraper (the upstream PIN diodes), and four PIN diodes downstream of the scraper (the downstream PIN diodes) to look for scattered particles from the crystal and scraper respectively. In addition, two scintillators forming a hodoscope aligned to the crystal surface look at particle scattered at large angles. Four ion chamber beam loss monitors are located downstream of the scraper as well [4].

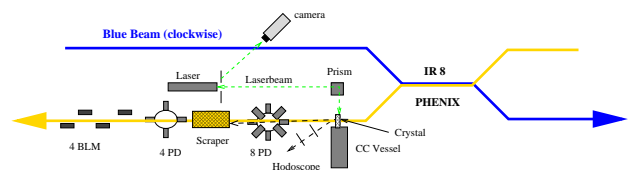


Figure 1: The RHIC Crystal Collimation system

4 THEORY

As previously reported in Ref. [4], the channeling efficiency of the crystal is about one half of the initial expectation [5]. In response, we developed a simple model of the first turn particle distribution on the crystal. We assume an initial distribution of

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

where J is the particle action, ϵ is the unnormalized rms emittance, δ is the momentum deviation, σ_δ is the rms mo-

mentum deviation. This distribution is then transformed into positions and angles, (x, x') by integrating over all momenta to obtain the phase space distribution of all particles at the crystal. Calculating the average angle of all of the particles that will hit the crystal surface, and assuming that the particles have low impact parameters with respect to the rms beam size, or the crystal is far from the beam core one derives

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

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 RHIC, the crystal is at a high β , low dispersion region and Eq. 3 reduces to

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

The expression for the angular spread of the beam that hits the crystal face, σ_θ , is quite lengthy, but it is sufficient to say that σ_θ is strongly proportional to α , β , $D\sigma_\delta$, and the rms impact parameter, and is weakly affected by ϵ , and $x_{crystal}$ [6]. For this RHIC run, $\sigma_\theta = 23\mu\text{rad}$, assuming that particles hit over the entire face of the crystal.

Knowing the angular spread of the particles hitting the crystal, one can estimate the channeling efficiency of a perfectly aligned crystal using Eq. 12 from Ref. [7], and neglecting the small (4%) effect of the bending of the crystal

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

where d_p is the distance between the crystal planes. This formula is only valid as long as $\sigma_\theta > \theta_c$. For this RHIC run $e = 32\%$, and averaging over the data for this run gives an efficiency of $\langle e \rangle = 26\%$.

5 SIMULATION OF 2001 RUN

It was found during the 2001 RHIC run that the beta function at the crystal did not agree with the model [8]. Measurements with the crystal collimator further showed that $-\alpha/\beta$ did not agree with the model and the channeling dip was wider than expected [4]. In fact, it was found that the measured α based on the channeling dip angle versus crystal position is consistent with $\alpha = 1.5\alpha_{model}$ and the measured beta function.

To simulate the action of the crystal in RHIC we used the CATCH (Capture And Transport of CHarged particles in a crystal) code [9]. For computing speed, a 6×6 matrix was used to track the ions around the ring. Particle distributions are gaussian in momentum deviation, δ , and exponential in action, J , with a 15π mm-mrad normalized rms emittance. Only particles that hit the crystal are tracked in the horizontal plane, so as to avoid tracking uninteresting particles in the core. In the vertical plane, the phase ellipse is filled.

Fig. 2 shows simulations of the number of scattered particles versus the crystal angle with the measured and model Twiss parameters and data for the $\beta^* = 1\text{m}$ local PHENIX

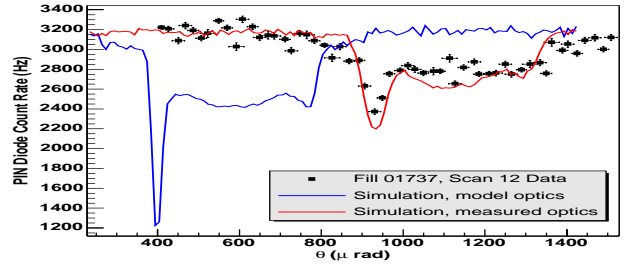


Figure 2: The effects of the modeled (blue) and measured (red) Twiss parameters compared with a typical crystal angular scan. Simulations are shifted $-365 \mu\text{rad}$ to account for survey offsets.

optics during the 2001 run. The large dip is when the crystal planes are aligned with the beam. The effect on the position and width of the dip due to changing α/β is quite clear. The rms width of the large dip is equal to the quadrature sum of σ_θ and θ_c . Efficiency is defined as maximum depth of the large dip divided by the background rate. For the measured optics, $\sigma_\theta = 24 \mu\text{rad}$ and $e = 30\%$, according to the theory. This is in good agreement with the simulation and the data in Fig. 2. For the model optics, $\sigma_\theta = 8.9 \mu\text{rad}$ which is in good agreement with simulation. Formula 5 does not apply in this case because $\sigma_\theta < \theta_c$.

The subsequent structure to the right of the large dip shows channeling of particles that scatter through a fraction of the crystal into a crystal plane and then channel the remaining distance. This is known as volume capture [7]. Fig. 3 shows the effect of multiple turns on the channeling shape. The depth of this subsequent structure is dominated by the number of encounters that particles can have with the crystal. The angular width of the volume capture region and the channeling dip is equal to the bend angle of the crystal.

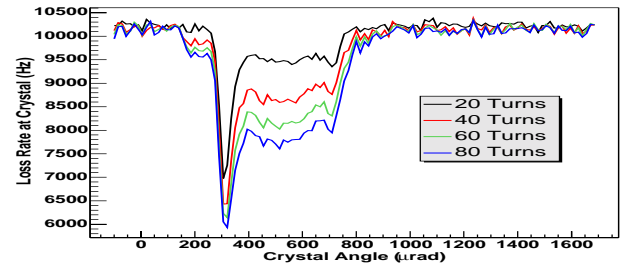


Figure 3: The Effect of multiple turns of the channeling signal.

6 CRYSTAL CHANNELING

Experiments with the crystal collimator have been performed with gold and polarized proton beams in RHIC. The crystal angle was moved 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.

Table 1: Tabulation of Angular Scans

Species	β^* @ IR8	No. of Scans	$\langle \sigma_\theta \rangle$	$\langle e \rangle$
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%

The $\beta^* = 1$ m is at the PHENIX interaction region only, all the other experimental IRs were kept at $\beta^* = 2$ m. The 2003 Run data is taken during deuteron-gold operations.

Fig. 4 shows a typical angular scan from the 2003 RHIC run. All of the data is averaged over 20 μrad , the resolution of the angular readback. The fit is to two gaussians on a sloping background with a sloped line connecting them [4]. For each set of data, approximately 40% of the data can be fit. The remaining data is a combination of data that contains incomplete scans due to technical problems, scans with low signal because the crystal was not close enough to the beam or was shielded by the scraper, scans where the beam has an oscillation due to the AGS Booster cycle, or scans that are well outside of the angular acceptance of the crystal. Of the data that can be fit, the fit function tends to return widths that are wider and efficiencies that are smaller than the data and the simulations show.

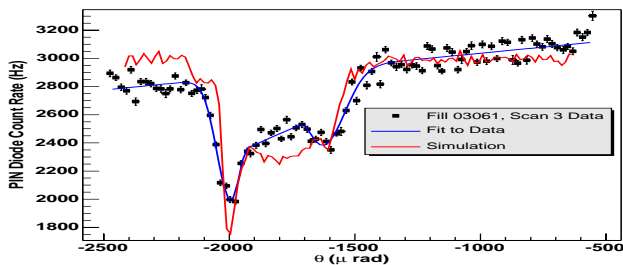


Figure 4: Data from Fill 03061. The simulation is done with the measured machine optics[10].

The values in Table 1 are averages over all of the fits for each RHIC configuration. The average efficiency over all runs is 23%. The average width of the channeling dip over all runs is 68.5 μrad as measured from the upstream PIN diodes. The hodoscope was not used in the averages because in the FY2001-2 run, it was not properly configured, and had a low signal to noise ratio. This was improved for the 2003 run by increasing the gain and improving the relative timing of the phototubes. The $\beta^* = 5$ m and $\beta^* = 2$ m averages have a large variation because of the low number of angular scans taken.

7 CONCLUSIONS AND FUTURE PLANS

We have shown that the channeling efficiency of the crystal, and hence its ability to be an efficient collimator is dominated by the phase ellipse at the collimator entrance. If one were to place a collimator at a location where $\alpha \approx 0$, such as in a quadrupole, the channeling angle would be independent of crystal position, and one may be less sensitive to optical error, since changes in α should be small. Placing the crystal at a large β location has the further advantage that the beam has a very small angular divergence so efficiency is increased. In RHIC, the largest high β location is in the IR triplets. Unfortunately, the β function changes so rapidly outside these quadrupoles, that α quickly becomes large. In places where α does not pass quickly through zero, β is quite small. Unfortunately, because of lattice and space constraints, and the need to improve our collimation efficiency for the upcoming high luminosity run, the crystal collimator will be removed in favor of a conventional two stage collimation system.

Crystal channeling in RHIC could be achieved and is consistent with simulation and theoretical results. Crystal collimation was unsuccessful because of the low efficiency, however, crystal channeling still might be a promising way to collimate beams in future accelerators, provided the position can be chosen appropriately.

8 REFERENCES

- [1] T. Trenkler and J.B. Jeanneret., "The Principles of Two Stage Betatron and Momentum Collimation in Circular Accelerators" CERN Note: SL/95-03 (AP), LHC Note 312;
- [2] R. Abman *et al.* "Requirements for the LHC Collimation System" Proceeding of the 2002 European Particle Accelerator Conference, Paris, France (2002).
- [3] J. Lindhard. *K. Dan. Vidensk. Selsk. Mat.-Fys. Medd.* **34**, No. 14 (1965).
- [4] R. P. Fliller III, *et al.* "Crystal Collimation at RHIC" Proceeding of the 2002 European Particle Accelerator Conference, Paris, France (2002).
- [5] V. M. Biryukov, *et al.*, "Optimization of the Parameters in the RHIC Single Crystal Heavy Ion Collimation" Proceeding of the 1999 Particle Accelerator Conference, New York, New York (1999).
- [6] R. P. Fliller III, Ph. D. thesis, State University of New York at Stony Brook (to be published).
- [7] V. M. Biryukov, Y. A. Chesnokov, and V. I. Kotov. *Crystal Channeling and Its Application at High Energy Accelerators*. Springer-Verlag, Berlin, Heidelberg, 1997.
- [8] T.Satogata, *et al.* "Linear Optics During the RHIC 2001-2 Run", Proceeding of the 2002 European Particle Accelerator Conference, Paris, France (2002).
- [9] V. Biryukov, "Crystal Channeling Simulation - CATCH 1.4 User's Guide", SL/Note 93-74(AP), CERN 1993.
- [10] T.Satogata, *et al.* "Linear Optics Measurement and Correction in the RHIC 2003 Run" These Proceedings; M. Bai *et al.* "Measurement of Betatron Functions and Phase Advances in RHIC with AC Dipoles" These Proceedings.