# A STUDY OF RHIC CRYSTAL COLLIMATION

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*Abstract*

The Relativistic Heavy Ion Collider (RHIC) will experience increasing longitudinal and transverse heavy ion emittances, mostly due to intra-beam scattering (IBS). The experiments in RHIC are expected to not only have reduced luminosities due to IBS but also background caused by beam halo. Primary betatron collimators will be used to remove the large amplitude particles. The efficiency of the primary collimator in RHIC strongly depends on the alignment of the jaws which needs to be within about ten micro-radians for the optimum conditions. As proposed by V. Biryukov [1] bent crystals could be used to improve the efficiency of an existing collimation system by installing them upstream of the collimator jaws. Bent crystals have been successfully used in SPS, Protvino and Fermilab for extraction of the beam particles channeled through them. This study examines possible improvements of the primary collimator system for heavy ions at RHIC by use of bent crystals. Bent crystals will reduce the collimator jaws alignment requirement and will increase collimator efficiency thereby reducing detector background. [1]

## 1 INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) has two large angle acceptance detectors PHENIX and STAR placed at the interaction regions (IR-'s) where the heavy ion beams (like fully striped gold $^{+79}Au^{197}$ ions) from the two parallel rings will be focussed to $\beta^{\star} = 1 - 2m$. The intra-beam scattering of the heavy ions like gold $^{+79}Au^{197}$ ions is expected to be a dominant cause of emittance growth with a fast loss of luminosity. The transverse and longitudinal emittances are expected to double in size between one to two hours due to intra-beam scattering which may lead to transverse beam loss. Particle amplitudes also grow due to other effects like beam gas interaction, beam diffusion due to the nonlinear beam dynamics etc. This results in beam loss at limiting apertures at the triplet magnets close to the large detectors which in turn creates hadronic showers leading to larger than desirable backgrounds in detectors. To reduce this background it is necessary to scrape the unwanted beam. The primary betatron collimator has to be able to remove particles with large amplitudes. The RHIC collimator studies previously reported [2], had shown that a combination of the primary with the secondary collimators reduced the background around the large detectors. The studies have shown that losses of the out-scattered ions from the primary collimators were, as expected, localized at the high beta focusing quadrupoles. The amplitude growth of the the gold $^{+79}Au^{197}$ and proton ion beams was estimated by a diffusion process based on measurements at the SPS-CERN [3]. The energy and phase distributions of the out-scattered ions from the primary collimators were obtained by using the "ELSHIM" Van Ginneken code [5], which simulated transport of the 100 GeV gold $^{+79}Au^{197}$ ion beam through the primary collimator jaws. The previous study [2] had shown that for the best collimation of the gold ions the alignment of the primary collimators' jaws has to be within about 10 $\mu$rad. This is a report where a simulation of the bent crystal deflection for the RHIC beam collimation of the heavy ion beam is described.

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### 1.1 Bent Single Crystal Deflection

The protons and heavy ion (like fully stripped lead $^{208}Pb^{82+}$ ions) bent single crystal extraction has been demonstrated and continually used at many laboratories like (SPS, Fermilab, IHEP, etc.) and previously reported in many articles [6], [7] etc. The high energy relativistic particles are channeled within the bent crystal planes and bent away from the center of the beam.

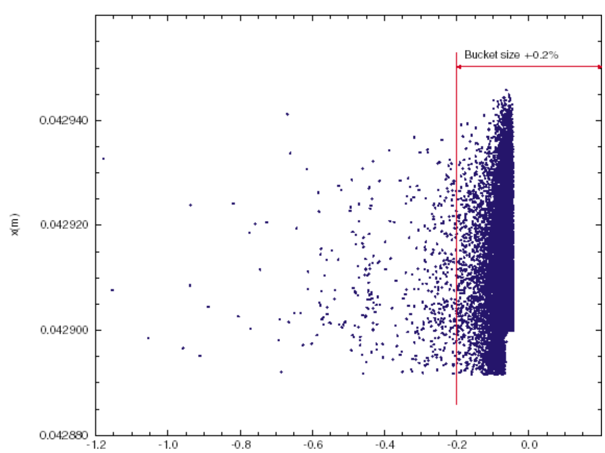


Figure 1: Distribution in *x* vs. dp/p phase space at the crystal end.

The theoretical predictions and experimental results of the crystal extraction and deflection are very well understood. The crystal extraction efficiency is defined as the number of ions extracted by the crystal with respect to the number of lost particles due to the crystal. The theoretical predictions of the crystal extraction F are obtained by tracking the particles through the potential of the bent crystal lattice taking into account the multiple and catastrophic scattering, nuclear and electronic collisions with the crystal discontinuities, surface effects and dislocations [7]. The heavy ions (like $^{+79}Au^{197}$) interact with the crystal matter differently than protons due to their large mass and high charge state. The critical angle $\psi_c$, one of the most important parameters for the channeling acceptance [4] scales with the mass and charge as $\psi_c \sim \sqrt{\frac{Z}{p}}$.

## 2 BENT CRYSTAL COLLIMATION SIMULATION IN RHIC

The crystal collimation is clearly a multi turn process. The multi turn efficiency for the TEVATRON is estimated well above 90% at the peak according to our simulation. In this report, instead of a proper simulation of the multi turn deflection a simulation a single pass of the diffused gold ions is performed. The initial horizontal and vertical phase space distributions of 19528 gold $^{+79}Au^{197}$ ions in front of the crystal were obtained by selecting ions which had their amplitudes grown above $5\sigma_x$ horizontally by diffusion process. The diffusion was described by the published experimental and theoretical results from the SPS (CERN) [3]. All particles in the initial horizontal phase space distribution have the horizontal distance larger than $x \geq$0.04290 m which represents $5\sigma_x$ of beam with the 40 $\pi$ $mmmrad$ emittance. The betatron functions at this position of the crystal are $\beta_x$=1223 m, $\beta_y$=366 m,$D_x$=-1 m. Before the gold ions were transported through the 1 mrad bent silicon single crystal, with the Si(110) aligned to the beam, a value for the crystal length was selected to be *l*=1 cm long along the beam direction. This length provides large enough deflection efficiency and is still practical for the experimental use. The gold $^{+79}Au^{197}$ ions, with an input energy of $\gamma$=108.4, are transported through the lattice of the bent silicon crystal by the Monte Carlo program "CATCH" [9]. The total number of the gold ions which passed the crystal was 18296. The number of particles which interacted with the crystal nuclei was 5%. The simulation of the bent crystal collimation is continued by using the ions obtained from the output at the crystal edge. Four coordinates of each ion (x, x', y, y', dp/p) were used as an input into the tracking program TEAPOT [8]. All measured systematic as well as the random multipole errors in the magnetic field for each magnet were introduced into the lattice as well as the measured magnet misalignment errors. The bent single crystal is placed in the lattice at the position downstream of the high focusing quadrupoles at the IR where the PHENIX detector is located. The tracking was performed at the top energy of 100 GeV/nucleon for gold for 256 turns. The rms values for misalignment of the arc quadrupoles were $\Delta$x,y=0.5 mm $\Delta\theta$=0.5 mrad, while from the measurements of the triplet quadrupoles the roll and misalignment errors for the rms values were $\Delta\theta$=0.5 mrad and $\Delta$x,y=0.5 mm. During tracking the RF voltage was included and the longitudinal motion of the surviving particles could be monitored. Particles which survived, with momentum offsets within the bucket size limit, executed synchrotron oscillations. Fig. 1 shows phase space of the gold ions at the end of the crystal, where on the x-coordinate is shown as dp/p dependent. There are large number of particles with momenta larger than the bucket size. If these particles are not removed by the primary collimators they will be lost due to their large momentum offsets. The crystal length. together with its bending angle, can be further reduced to affect the momentum loss distribution which will be addressed in our future simulations.

### 2.1 Transverse Phase Space Distribution at the Crystal End

The position of the primary collimator is 7.68 m downstream of the single crystal. Each tracking run was performed with a different position of the primary collimator selected to a distance from center of the beam, starting with a position completely away from the beam. Fig. 2 represents gold ion distributions in the horizontal phase space at the downstream edge of the crystal. A particle distribution in the vertical phase space is not shown has very similar features as the input distribution.

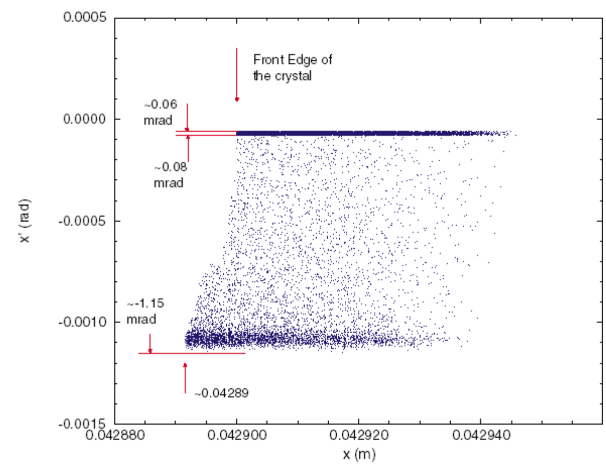


Figure 2: Gold ions distribution in the horizontal phase space at the end of the crystal.

There are several important features to point out:

-The channeled particles are contained in the upper part of the *x* and *x'* plot with a slope of $x'_{ch}$ ~0.073 mrad. The slope of the gold ions, used for the input into the bent crystal as presented is within the range of -1.080 mrad< $x'_{input}$ <-1.058 mrad. A difference between the average slopes of $x'_{ch} - x'_{input}$ $\simeq$1 mrad, shows that the channeled particles are bent for $\simeq$1 mrad.

-Particles from the initial distribution with values of x$\simeq$0.04289 m and with the slope of *x'*$\geq$-1.15 mrad are not channeled. The slope of the horizontal amplitude *x'* 1.15 mrad reaches negative values larger than the end within the initial distribution (-1.108 mrad).

-Particles with the slope of the horizontal amplitude between the channeled ones and the edge clearly interacted with the crystal lattice. When the primary collimator was completely away from the beam, the particles from the crystal are lost mostly at the first quadrupole downstream of it and some of the particles are unfortunately lost at the high focusing quadrupoles around the IR's where the $\beta^{\star}$=1 m. The gold ion distribution in the horizontal phase space, at the 7.68 m downstream of the crystal at the position of the primary collimator, is presented in fig. 3. Particles

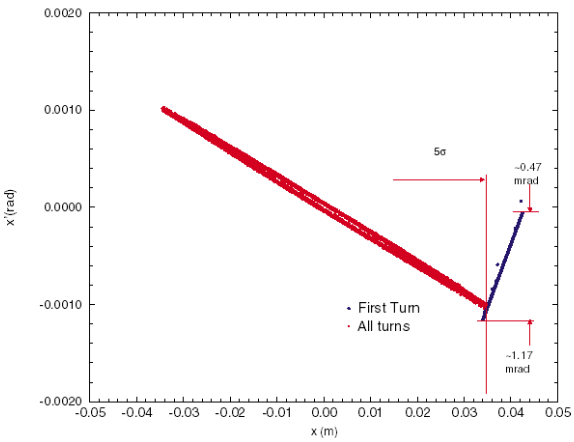


Figure 3: Gold ion distribution in the horizontal phase space at the primary collimator.

which reached the primary collimator in the first pass are presented within a very narrow region between values of the slope of the horizontal amplitude -1.17 mrad$<x'<$-0.47 mrad. Particles within th ellipse survived many turns and

Table 1: Ring Losses for Standard and Crystal Collimation

| Location | S. Open | Sec.6$\sigma$ | Pr.Open | Pr.@5$\sigma$ |
|---|---|---|---|---|
| Sec. Col. | 0.0 % | 62.3 % | – | – |
| Q2 @ 8 | 42.4 % | 17.0 % | 0.7 | 0.0 % |
| Q3 @ 8 | 8.2 % | 3.30 % | 1.9 | 0.0 % |
| Q3 @ 6 | 14.3 % | 0.30 % | 14.6 | 0.5 % |
| Pr. Coll. | 12.1 % | 5.10 % | 0.0 | 99.4 % |
| Crystal | — | — | 2.7 % | 0.00% |

reach every turn the primary collimator again. If all the particles are channeled than the primary collimator could be set up at the distance close to 0.042 m. It is clear that not all the particles are channeled (as shown in Fig. 2) and that some of them will be lost around the ring even when the primary collimator is set to a horizontal distance of $5\sigma_x$ of the beam. This is due to the particles which come from the crystal with the slopes larger than 1.08 mrad from the crystal edge.

## 3 A COMPARISON OF THE CRYSTAL COLLIMATION WITH THE PREVIOUS RESULTS

The large amplitude particles are mostly likely to get lost at the most limited apertures in the two RHIC accelerator rings which are located at the high focusing triplet magnets. The background of the two large detectors will be enhanced by the showers generated by these lost particles. Table 1 represents the losses around the RHIC rings from the particles scattered of the standard primary and secondary collimators and at the second part of it shows the losses from the particles deflected by the crystal. Two extreme cases are presented when the primary collimator downstream of the crystal is wide open and when it is set to $5\sigma_x$, the same horizontal distance as a front edge of the crystal.

## 4 CONCLUSIONS

We presented a simulation study where the bent single crystals are used in the RHIC collimation system. The preliminary results are very encouraging. The 100 GeV/nucleon gold ions were transported through the bent single crystal Si(110) and the gold ions from the crystal were tracked through the RHIC storage lattice. A comparison to the previous results with a standard two stage collimator system shows lower losses around the ring from the outscattered particles. This would possibly reduced background at the two large detectors due to smaller losses at the high focusing limited apperture quadrupoles located around the detectors. The study of the crystal collimation in RHIC will be continued by the multiturn crystal deflection simulation and with a shorter length and smaller bending angle single crystal. We expect improvement in the momentum distribution of the ions passed through the crystal and a reduction of lost particles around the ring.

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