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BEAM DIFFUSION STUDIES AT RHIC [*]

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Abstract

During the course of a store, particles from the core of the beam continually diffuse out into the halo through a variety of mechanisms. Understanding the rate of this diffusion and how it scales with particle amplitude is important for improving accelerator performance. By using a collimator, it is possible to measure the amplitude growth as function of the particle amplitude. In this paper we present results of diffusion measurements done at the Relativistic Heavy Ion Collider (RHIC) with fully stripped gold ions and protons.

1 INTRODUCTION

Beam halo growth is a topic of great concern for future accelerators. The lifetime of accelerator and detector components can be reduced due to the effects of halo induced radiation. Beam halo can be a large contributor to experimental background. In superconducting machines it is also possible for particles in the halo to induce a magnet quench during beam steering. This can limit the amount of beam that can be injected into the machine. Because of this, understanding the nature of halo growth is necessary to increase the performance of a collider.

Beam halo grows because various processes like intra-beam scattering (IBS) slowly move particles from the core of the beam into the halo[1]. One way to measure this halo growth is using a collimator to measure the diffusion rate of the beam. By measuring the loss rate at a collimator after it moves relative to the beam, it is possible to reconstruct the diffusion coefficient as a function of the action. In this paper we discuss experiments carried out at RHIC to measure the diffusion coefficient with gold and proton beams at $100\ \mathrm{GeV/u}$.

2 THEORY

The theory of how to measure beam diffusion with a collimator is treated in detail in reference [2], and subsequent treatment follows closely. The diffusion equation is

$$\frac{\partial}{\partial t} f(J,t) = \frac{1}{2}\frac{\partial}{\partial J} B(J) \frac{\partial}{\partial J} f(J,t) \tag{1}$$

where $f(J,t)$ is the beam distribution as a function of the particle action J and time, and $B(J)$, given by

$$B(J) = \frac{<\Delta J^2>}{\Delta t} \tag{2}$$

is the diffusion coefficient to be measured. This is related to the average change of the particle action per unit time by

$$\frac{<\Delta J>}{\Delta t} = \frac{1}{2}\frac{\partial}{\partial J} B(J) \tag{3}$$

The usual parameterization of the diffusion is a power law.

$$B(J) = bJ^n \tag{4}$$

where b is the diffusion constant. Near the collimator $B(J)$ can be written,

$$B(J) = b_0 \left(\frac{J}{J_c}\right)^n \tag{5}$$

where J_c is the action of a particle that just touches the collimator, $J_c = x_c/\sqrt{2\beta}$, x_c is the distance between the collimator and the beam, and β is the β function at the collimator, and $b_0 = b{J_c}^n$ is the diffusion coefficient at $J = J_c$.

For $n > 2$ Equation 1 is not solvable analytically. So to continue, one must do simulations or make simplifications. At the collimator action, the left hand side of Equation 1 is just the particle loss rate due to the collimator $\dot{N}(t)$. For actions near the collimator action, $B(J \approx J_c) \approx b_0$. By introducing the variables

$$z = \frac{J_c - J}{J_c} \tag{6}$$

$$R = \frac{b_0}{2{J_c}^2} \tag{7}$$

the fractional change in the collimator action, and the normalized diffusion rate to be determined by a fit, respectively, it is possible to write Equation 1 as

$$\frac{\partial}{\partial t} f(z,t) = R\frac{\partial}{\partial z} f(z,t) \tag{8}$$

Assuming that $f(z,t)$ vanishes at the collimator, and that $f(z,0)$ increases linearly away from the collimator, it is possible to solve Equation 8 and obtain the loss rate at the collimator. The loss rates are

$$\dot{N}^{(1)}(t) = a_0 \left\{1 + \frac{\Delta z}{\sqrt{\pi R(t-t_0)}}\right\} + a_1 \tag{9}$$

$$\dot{N}^{(2)}(t) = a_0 \,\mathrm{erfc}\left(\frac{\Delta z}{\sqrt{\pi R(t-t_0)}}\right) + a_1 \tag{10}$$

where the Equations 9 and 10 are for a collimator that is further inserted into or retracted from the beam respectively. $\Delta z = 2|\Delta x_c|/x_c$ is the absolute change in z due to the change in collimator position Δx_c, a_1 is the count

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rate from background or an activated collimator, measured when the collimator is fully retracted, and a_0 is an arbitrary constant. By fitting one of these solutions to the loss rate after moving the collimator, it is possible to obtain the normalized diffusion coefficient R and then $B(J_c)$. Sampling over many collimator positions, it is possible to reconstruct the diffusion coefficient for the beam halo.

3 EXPERIMENT

The RHIC collimation system has been described in detail in a number of publications [3]. The RHIC collimators are $450\ \mathrm{mm}$ long copper blocks with an inverted L shape residing downstream of the PHENIX detector in both the blue (clockwise) and yellow (counter–clockwise) rings. Downstream of each collimator there are four PIN diodes that are used to monitor the beam losses due to the collimator.

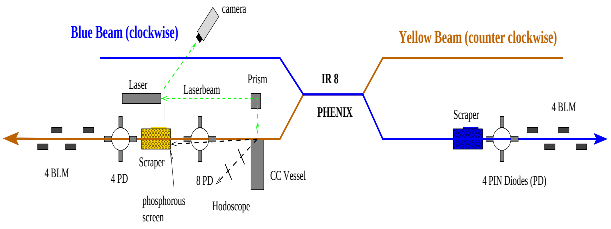

Figure 1: The RHIC collimation system

The collimators were inserted into the beam and rotated to align the face of the collimator to the beam to minimize the secondary halo due to particles scattering from the collimator. Then the collimator was stepped horizontally into and out of the beam varying the collimator position and the stepsize. This way, various actions are sampled, and self-consistancy is checked by using different step sizes and/or directions to measure at the same action.

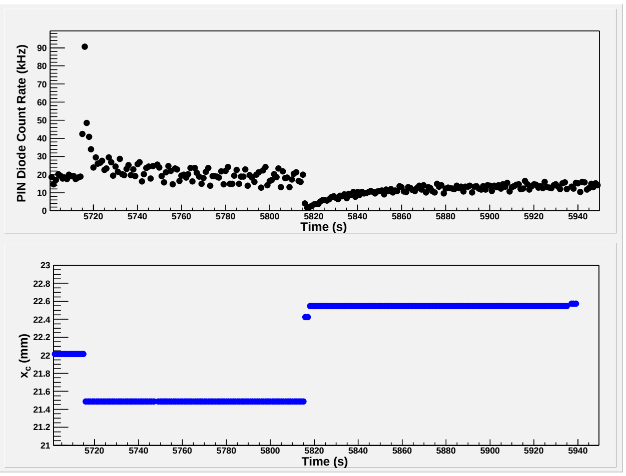

Figure 2: Beam Loss downstream of Collimator due to the Collimator motion during Fill 01413. Error in x_c is $1.6\ \mathrm{mm}$

Figure 2 shows the effect of moving the collimator into and out of the beam as seen from a PIN diode. As the collimator is moved in, it scrapes off all of the halo particles that have large impact parameters within a few turns. This is the large spike in the PIN diode rate. If there was no halo growth, the loss rate would reduce to the rate before the collimator touched the beam as no further particles would intercept the collimator. But, because of diffusion, particles are continually growing in action and hitting the collimator and producing constant losses. As the collimator is moved out, the loss rates decrease because the beam is no longer in contact with the collimator. Because of diffusion, the beam fills up the available phase space and eventually intercepts the collimator again. As in the previous case, an equilibrium state of constant beam loss is reached.

Data were taken parasitically during RHIC physics stores or injection work with both gold and polarized protons. Each data set took approximately one hour to aquire. Table 1 lists the available data samples and relevant accelerator parameters. The data were then separated by collimator position and the data for each PIN diode was fit to Equation 9 or Equation 10 to obtain the normalized diffusion coefficient R. These R's were averaged for each J before reconstructing $B(J)$.

4 RESULTS

The $B(J)$ for store 01413 is shown in Figure 3. The horizontal and vertical error bars are dominated by the uncertainty in the collimator action. This uncertainty is equally due to the uncertainty in the distance between the collimator and the beam and the knowledge of the β function at the collimator [4].

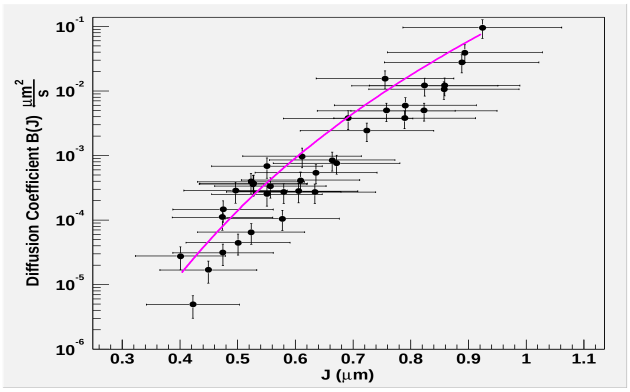

Figure 3: Reconstructed Diffusion Coefficient for Store 01413. Note: the vertical scale is a log scale.

The results of a fit to $B(J) = bJ^n$ are shown in Table 2. Due to logging errors, the data from store 02135 were not available. The data from store 00854 show a puzzling result. The data for the collimator moving away from the beam gives a different b and n then the data for the collimator moving toward the beam. The reason for this is not fully understood. The analysis for stores 01804 and 01808

Table 1: Diffusion Data

Store Number	Species	Ring	β^*	Average Beam Current	Debunched Current	Normalized ϵ_h
00854	Au	yellow	5 m	$< 18 \times 10^9$ ions	$> 9\%$	$38 \pm 3\ \pi\ \mu$m
01413	Au	yellow	2 m	$19.2 \pm 0.2 \times 10^9$ ions	$9.1\% \pm 1.1\%$	$14.6 \pm 0.3\ \pi\ \mu$m
01804	Au	blue	1 m	$< 21 \times 10^9$ ions	–	$13.5 \pm 1.1\ \pi\ \mu$m
01808	Au	blue	1 m	$21.2 \pm 0.7 \times 10^9$ ions	$5.4\% \pm 4.0\%$	$12.5 \pm 0.3\ \pi\ \mu$m
01874(i)	p	yellow	3 m	$5.1 \pm 1.1 \times 10^{11}$ ions	$2.6\% \pm 0.4\%$	–
01924(i)	p	blue	3 m	$8.9 \pm 0.6 \times 10^{11}$ ions	–	–
02135	p	yellow	3 m	–	–	$11.5 \pm 2\ \pi\ \mu$m
02136	p	yellow	3 m	$23.7 \pm 0.5 \times 10^{11}$ ions	$2.4\% \pm 0.1\%$	$8 \pm 1\ \pi\ \mu$m
02175	p	blue	3 m	$9.3 \pm 1.2 \times 10^{11}$ ions	$10.5\% \pm 0.1\%$	$9.2 \pm 0.6\ \pi\ \mu$m

(i) indicates injection energy. β^* is at IR8.

Table 2: Results of Fit to $B(J) = bJ^n$

Store Number	$b\ \mu\mathrm{m}^{2-n}\mathrm{s}^{-1}$	n
01413	0.17 ± 0.09	10.3 ± 1.2
01874(i)	0.045 ± 0.026	8.5 ± 1.5
01924(i)	0.06 ± 0.02	7.0 ± 0.8
02136	7.8 ± 5.5	5.7 ± 0.6
02175	0.0036 ± 0.0005	3.0 ± 0.3

(i) indicates injection energy

is ongoing. Store 01808 had a high debunching rate. The beam current data for store 01804 are incomplete. However, it preceeded store 01808 and very few changes were made between the stores. Therefore, a similar debunching rate is assumed. Debunching will appear as additional transverse diffusion because of dispersion. Unfortunately, our one dimensional model does not account for this.

The large errors in the action dominate the fitting and make it hard to determine $B(J)$ accurately. Nevertheless, it is apparent from Table 2 with the exception of store 02175, that n is consistant across all stores with an average of 7.5 ± 0.5. At this time it is not known what, if anything, was different during store 02175 that would explain the low value of n.

Nevertheless, this is an important result. For the case where beam–gas scattering causes diffusion, n is equal to 1 [2]. We know that IBS [1], magnet nonlinearities in the triplets[5], magnet vibration [6], beam-beam modulation [7], and pressure rises associated with beam intensity [8] are present and contribute to the halo growth rate in RHIC. It is hoped that in the future reducing these effects will translate into a reduction of n.

The values of b at injection with protons are similar. It is not clear what affects its value. With more data, more comparisions at store can be made. Unfortunately because of reasons mentioned above, comparisions between stores 02135 and 02136 and stores 01804 and 1808 are not possible.

5 CONCLUSION

Beam diffusion was measured for gold and polarized protons in RHIC.

During the next run, we plan to investigate beam diffusion further. Plans are underway to measure diffusion early and late in a store to see differences during a store. We also plan to measure diffusion during different stores with similar conditions, this was only done once for each species during the last run, and both attempts were inconclusive. Diffusion measurements on deuterons are also planned.

6 ACKNOWLEDGEMENTS

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