THE RHIC INJECTOR ACCELERATOR CONFIGURATIONS, AND PERFORMANCE FOR THE RHIC 2003 Au-d PHYSICS RUN*

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Abstract

The RHIC 2003 Physics Run [1] required collisions between gold ions and deuterons. The injector necessarily had to deliver adequate quality (transverse and longitudinal emittance) and quantity of both species. For gold this was a continuing evolution from past work [2]. For deuterons it was new territory. For the filling of the RHIC the injector not only had to deliver quality beams but also had to switch between these species quickly. This paper details the collider requirements and our success in meeting these. Some details of the configurations employed are given.

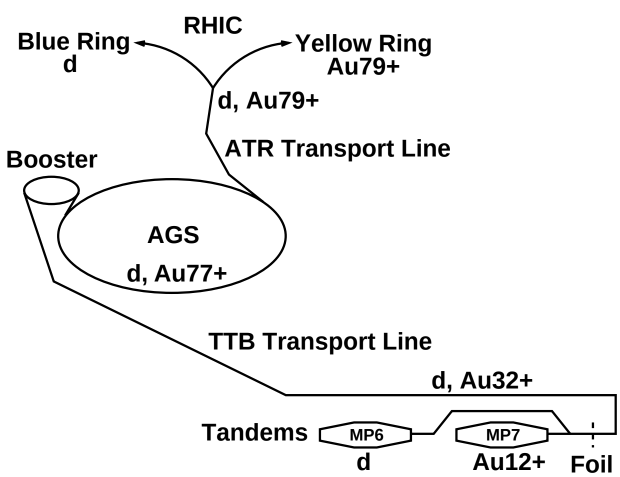

Figure 1: Acceleration of Deuterons and Gold for RHIC.

INTRODUCTION

The RHIC injector complex, shown schematically in Figure 1, comprises two Tandem Van de Graaffs (MP6 and MP7) [3], the Tandem-to-Booster (TTB) transfer line, the Booster synchrotron, the Booster-to-AGS (BTA) transfer line, the AGS synchrotron, and the AGS-to-RHIC (ATR) transfer line. This paper will describe how these pieces were configured for the 2003 RHIC Au-d physics run. The performance goals for the run were defined during the winter of 2002 in order for the RHIC experiments to optimize their configurations. For the gold beam, goal specification was a simple extension from the past several RHIC runs. For deuterons, expectations again derived largely from experience with gold and protons but necessarily required assumptions about this new beam species coming from the Tandem. The goals worked out required that the injector complex provide gold bunches of 1×10^9 ions, deuteron bunches of 8×10^{10} ions, transverse emittances of about 15π mm mradians in both planes and for both beams, and longitudinal emittances consistent with allowing rebucketing into the RHIC 200 MHz RF system [4] at store.

GOLD ACCELERATION

The goals for gold were to be back where we had ended the previous run. The essential acceleration strategy did not change from that of the 2001 Au run [2]. Historically the intensity, and particularly the efficiency for the multiturn injection and early acceleration in the Booster, improves slowly over the months of the run. To the extent that this improvement is a result of the Booster beam tube surfaces being slowly "scrubbed" clean by gold beam particles that end up outside the machine acceptance at injection and during RF capture, such improvement could suffer from time spent learning to optimize the deuteron acceleration. In addition for this run there would not be a "back-up" Tandem set up for gold; the second Tandem (MP6) would be for deuterons. The possibility of switching to the other Tandem to e.g. replenish the essential and short-lived stripping foils in the terminal would be more costly to the run. Foil consumption rates were an issue. These concerns were qualitatively correct, but managed to stay off the run "critical path".

The gold acceleration strategy [2] involves accelerating on RF harmonic $h = 6$ in the Booster, boxcar transferring four Booster loads into an AGS whose RF runs at $h = 24$, debunching this beam at the AGS injection energy and rebunching into four bunches (in an $h = 12$ RF structure) and accelerating to RHIC injection energy. Transfer into RHIC through the ATR line is done one bunch at a time. The longitudinal emittance demands from RHIC constrain this dance. In particular an additional merge to double the intensity per bunch but also the longitudinal emittance is ruled out. As in the past, achieving the 1×10^9 gold ions per bunch RHIC goal was possible but difficult, and not routine. One evolution during this run relevant here involved the stripping foil between Booster and AGS which

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takes Au^{32+} to Au^{77+}. The standard 23 mg/cm^2 carbon foil was replaced for two weeks of the run by a 23 mg/cm^2 fused silica foil. The silica foil, because of its better uniformity produced a beam with a longitudinal emittance less than half that obtained from the carbon foil. The average energy loss from both foil passages were by design very comparable; the percentage of the beam ending in the $77+$ charge state was empirically found to be about 10% lower for the Silica. This intensity cost was too much for this run when the intensity crunch came, but the result opens up serious planning for an additional merge in the future.

DEUTERON PRODUCTION AND ACCELERATION

Production and acceleration of deuterons generated many new challenges, and the beam performance provided feedback to correct the flaws in our initial assumptions. The setup evolved rapidly throughout the run. The intensity design was based on having a 100 μA deuteron beam available coming into the Booster. The multiturn injection process was expected (from gold experience) to allow at most 45 turns to be accumulated, and with 50% overall efficiency explains the intensity goal. First the radiation issues associated with accelerating this proton and its loosely bound neutron in the relatively lightly shielded Tandem and TTB lines had to be dealt with. The "Access Control" system for the Tandem and beam line was upgraded. Shielding was added where necessary. A fail-safe system to limit beam intensity was installed. Because the potential amount of prompt radiation from scraping the beam increases rapidly with beam kinetic energy, a maximum (intensity) $\times$ (kinetic energy) constraint follows from this.

Several other factors come in to determining the optimal energy for the TTB transfer, and indeed two solutions were worked through. The first began with deuterons from Tandem at a kinetic energy of 6 MeV per nucleon. These were transported to Booster, injected, adiabatically captured at RF harmonic $h = 6$, and accelerated to the maximum frequency of the RF system as is done in the canonical gold setup. However, the magnetic rigidity of the deuteron beam at the top frequency is only 3.7 Tm compared to 9.2 Tm for gold (Au^{32+}) which means that the current required in the Booster extraction septum magnet is less than half that required for gold. Since the power supply does not regulate well at this reduced current, one is forced to operate at a higher current with beam extracted on the rising portion of the half-sine wave output of the supply. This makes the trajectory of the extracted beam sensitive to timing jitter of the power supply pulse. (The pulse was not RF locked.)

The jitter problem was eventually resolved, but in the mean time another scheme was worked out. The RF system has enough range to capture and accelerate the 6 MeV per nucleon deuterons on harmonic $h = 3$ which allows for acceleration to a much higher magnetic rigidity (7.3 Tm). Although this eliminates the problem of operating the extraction power supply at low current, another problem arises at AGS injection. Here the injection kicker magnet has two modes of operation, a "long pulse" mode and a "short pulse" mode, which deliver pulse widths of 1400 and 500 ns respectively. For the $h = 6$ setup, the required pulse width of the kicker is 1350 ns which is just accommodated by the long pulse mode. However, for the $h = 3$ setup, the required pulse width is reduced to 640 ns which is too short for the long pulse mode and too long for the short pulse mode. If one uses the long pulse, three transfers of three bunches to AGS are possible. Debunching these and rebunching into four bunches as per the canonical gold setup gives a single bunch intensity equal to three fourths of one Booster fill. On the other hand if the short pulse is used, only two of the three bunches in each Booster fill can be transferred to AGS, but six transfers are possible. This gives a total of 12 bunches which, after debunching and rebunching into four, gives a single bunch intensity equal to one Booster fill. This is the scheme that was adopted for the first part of the run.

The next step in the evolution of the deuteron setup required increasing the kinetic energy of deuterons from Tandem to 8.7 MeV per nucleon. This allowed for capture in Booster at even lower harmonic $h = 2$ and helped the Tandem transmission efficiency (which was marginal at the lower kinetic energy). The captured beam could be accelerated to top energy at $h = 2$, but well before this, the revolution frequency of the beam is high enough (some 800 kHz) for a merge of two bunches into one using the available proton RF system. After the merge, acceleration continues to top energy at $h = 1$ with the proton RF system. Due to the very low RF voltages required, the merge is a delicate process that required some time and new gear to perfect. Figure 2 shows a turn-by-turn "mountain range" of the process. (Time moves up in the figure.)

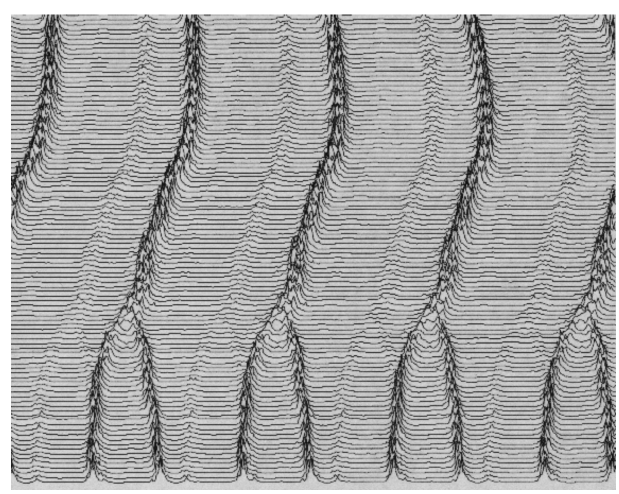

Figure 2: Merging of Two Bunches into One in Booster.

Having just one bunch in Booster effectively eliminated the constraint imposed by the pulse width of the AGS injection kicker and opened up the possibility of transferring up to eight Booster fills per AGS cycle. Initially the control system could deal with only enough Booster cycles for seven transfers but eventually controls modifications allowed for eight. The eight bunches were debunched and rebunched into four (in an $h = 8$ RF structure) on the AGS injection porch giving a single bunch intensity equal to two Booster fills. This scheme was used for the remainder of the run and easily met the initial goal of 8×10^8 deuterons per RHIC bunch.

Getting sufficient numbers of negative ions of deuterium (D^-) from the source that feeds the Tandem (MP6) also proved to be a challenge. Both the Au^- and D^- ions were generated using a PSX-120 cesium sputter ion source [5] operating in a pulsed mode. Initially TiD_2 powder was used in the D^- source but this produced a large amount of O^- ions which created significant space charge forces and lowered the transmission efficiency. Eventually the powder was replaced by a solid TiD_2 cathode which minimized the production of other negative ions. With pulsed currents as high as 496 μA at the source output, currents as high as 188 μA were seen at the Tandem output with 144 μA transported to the end of the TTB line.

MODE SWITCHING

The blue RHIC ring is filled with 56 deuteron bunches and then the yellow RHIC ring with 56 gold bunches. Doing this as quickly as possible is required. Besides the time lost the beam emittances somewhat deteriorate while circulating at RHIC injection energy. Most of the injector accelerator controls have built-in the capability to follow one of four different sets of commands–there are four ”Users” predefined. Changing from one User to another is fast relative to the 5 second AGS cycle. This now familiar business is referred to as “pulse-to-pulse modulation”, PPM. For the change from deuterons to gold several major systems that are not PPM must also be switched. All of the three transfer lines ended up having different rigidities for the two species. Many of the magnets in these lines are inherently slow to change. The TTB magnets with large bends and small fields have to be very carefully controlled. Further there are mechanical systems–foils to insert or remove, and kicker systems that need pulse-forming networks adjusted–which must be allowed to switch. All of this process, which is referred to as a ”mode switch” was orchestrated using a software program to do the ”sequencing”. The execution followed similar programs used at RHIC for example for quench recovery. The actual application to Au-d mode switching was the responsibility of the Operations group. A goal for this switching of 5 minutes was met gradually but easily once confidence in all of the steps was established.

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