

# SETUP AND PERFORMANCE OF THE RHIC INJECTOR ACCELERATORS FOR THE 2007 RUN WITH GOLD IONS\*

L. Ahrens, J. Alessi, J. Benjamin, M. Blaskiewicz, J.M. Brennan, K.A. Brown, C. Carlson, W. Fischer, C.J. Gardner<sup>†</sup>, J.W. Glenn, M. Harvey, T. Hayes, Haixin Huang, G. Marr, J. Morris, F. Pilat, T. Roser, F. Severino, K.S. Smith, D. Steski, P. Thieberger, N. Tsoupas, A. Zaltsman, K. Zeno, BNL, Upton, NY 11973, USA

## Abstract

Gold ions for the 2007 run [1] of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) are accelerated in the Tandem, Booster and AGS prior to injection into RHIC. The setup and performance of this chain of accelerators is reviewed with a focus on improvements in the quality of beam delivered to RHIC. In particular, more uniform stripping foils between Booster and AGS, and a new bunch merging scheme in AGS have provided beam bunches with reduced longitudinal emittance for RHIC.

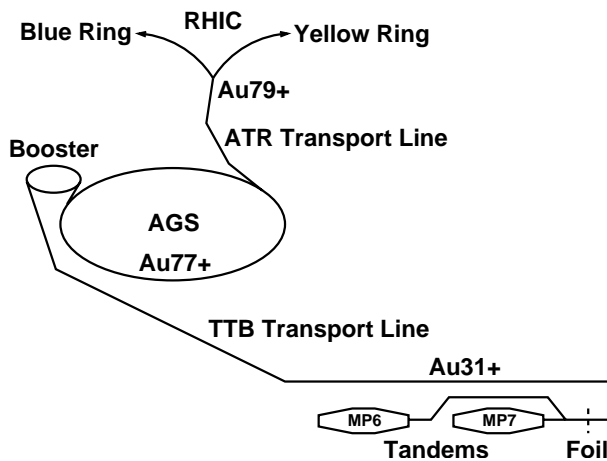


Figure 1: Acceleration of Gold Ions for RHIC.

## TANDEM AND TTB LINE

Acceleration begins in the MP7 Tandem Van de Graaff [2], the first in the series of accelerators shown in **Figure 1**. (MP6, with the indicated bypass line, serves as a spare in the event that MP7 is down for repairs. It also provides ion beams for outside users.) Negative ions ( $\text{Au}^{-1}$ ) from a pulsed sputter source [2] are accelerated from ground potential to +14 MV at the center terminal of the Tandem where they pass through a thin ( $2 \mu\text{g}/\text{cm}^2$  graphite) stripping foil. The ions emerge predominately in charge state +12 and are accelerated back to ground potential. A second stripping to charge state +31 occurs in a  $15 \mu\text{g}/\text{cm}^2$

graphite foil downstream of Tandem as indicated in the Figure. This charge state survives well in the Booster vacuum [3] and allows sufficient energy gain in Booster to efficiently remove all but two electrons before injection into AGS. In the past we have used charge state +32 in order to stay easily within voltage and current constraints on the Booster main magnet power supply. This year we were able to operate within these constraints with charge state +31. The result has been a 20% increase in the number of ions available for Booster injection. This year we also acquired and tested several  $2 \mu\text{g}/\text{cm}^2$  graphite foils formed by laser plasma ablation. These were found to last some three times longer than our standard terminal foils.

The momentum (and charge state) of ions transported down the 840 m Tandem to Booster (TTB) line is selected by the first of the two  $90^\circ$  bends indicated in Figure 1. A pair of slits (one on either side of the beam) located between the two bends serves to define the path that corresponds to the desired momentum. Each slit intercepts a small portion of the beam passing through; this provides electrical feedback to keep the terminal voltage at the value required to give the desired momentum. The field in the bends is monitored by NMR probes but does not require any feedback mechanism to maintain stability. Downstream of the two  $90^\circ$  bends, the TTB line contains two  $24^\circ$  and two  $13^\circ$  bends. (Each pair is depicted as just one bend in the Figure.) Quadrupoles between the bends of each pair are adjusted to make the pair achromatic. Focusing in the line is accomplished with a series of quadrupole doublets.

The nominal momentum and kinetic energy of the  $\text{Au}^{31+}$  ions transported to Booster are 41.6 MeV/c and 0.928 MeV per nucleon respectively ( $\beta = 0.0446$ ). The pulse width from the source ranges from 800 to 900  $\mu\text{s}$ . Intensities of  $5 \times 10^9$  ions per pulse at the end of the TTB line are typical, although intensities twice as high have been achieved. Transport efficiency of the entire line ranges from 80 to 90%. The horizontal and vertical emittances of the  $\text{Au}^{31+}$  beam in the line are of the order of  $1\pi$  mm milliradian (unnormalized). The fractional momentum spread  $\Delta p/p$  has been measured by chopping a short notch out of the unbunched beam in the line, and observing the turn-by-turn spreading of the notch in Booster at injection. This gives  $\Delta p/p = \pm 3.9 \times 10^{-4}$ . Observation of the notch also gives 15.1  $\mu\text{s}$  for the revolution period at injection. The longitudinal emittance of the unbunched beam after accu-

\* Work supported by the US Department of Energy.

<sup>†</sup> cgardner@bnl.gov

mulation in Booster is then 0.022 eV-s per nucleon.

## BOOSTER AND BTA STRIPPING

The 800-900  $\mu\text{s}$  pulse of  $\text{Au}^{31+}$  beam from Tandem is injected at constant magnetic field into the 202 m circumference Booster ring by means of an electrostatic inflector and four programmable injection dipoles. Since the revolution period of the ions in the ring is 15.1  $\mu\text{s}$ , injection occurs over a period of some 53 to 60 turns around the machine. The closed orbit bump produced by the dipoles initially places the orbit near the septum at the exit of the inflector. As beam is injected and begins to circulate, the bump must be collapsed gradually and the incoming beam is deposited into a series of phase space layers surrounding the orbit. The collapse continues until the orbit is so far from the septum that any additional incoming beam will be injected outside the  $185\pi$  (mm milliradians) horizontal acceptance of the machine. This is a delicate process that requires careful tuning to achieve the highest injection efficiency. As reported in [4], we have found that the efficiency is significantly enhanced by the introduction of linear coupling with skew quadrupoles. This allows one to collapse the injection bump more slowly and therefore inject more beam into the machine. The coupling, of course, introduces vertical betatron oscillations which increase the vertical emittance. Careful control of the coupling strength is required to keep the vertical emittance smaller than the  $87\pi$  vertical acceptance of the ring. This is done by programming the uncoupled tune separation. With this setup, injection of 60 turns with 80% efficiency has been achieved.

Capture and acceleration of the injected beam is accomplished with two RF cavities operating at harmonic 6. During capture the Booster magnetic field is held constant and stationary buckets with the RF voltage raised adiabatically from zero are required to keep the longitudinal emittance dilution as small as possible. The two cavities are “counter-phased” so that initially the net voltage seen by the beam is zero. By programming the amount of counterphasing, the net voltage can be raised slowly. Allowing 8 to 10 ms for adiabatic capture keeps emittance dilution at an acceptable level.

After capture, the 6 bunches are accelerated to extraction where the nominal momentum and kinetic energy are 445 MeV/c and 101 MeV per nucleon respectively ( $\beta = 0.4311$ ). Assuming the beam fills the horizontal and vertical acceptances at injection, one expects normalized emittances of at most  $8.3\pi$  and  $3.9\pi$  (mm milliradians) respectively throughout the acceleration cycle. Measurements of bunch width (55 ns), gap volts per turn (30 kV), and  $dB/dt$  (80 G/ms) just before extraction give a longitudinal emittance of 0.046 eV-s per nucleon for the 6 bunches. The bunch half-height is 18 MeV. The emittance at extraction is to be compared with the unbunched measurement of 0.022 eV-s per nucleon at injection. The increase is due to dilution during capture. The combined capture and acceleration efficiency is 70%. This gives an overall Booster

Output/Input efficiency of 56%.

The six bunches are extracted from Booster in a single turn by means of a fast kicker and ejector septum magnet. Measurements of the beam width just downstream of the ejector give 95% horizontal and vertical emittances  $4.2\pi$  and  $2.8\pi$  (mm milliradians) respectively. After extraction, the ions pass through a stripper in the Booster to AGS (BTA) transport line where approximately 60% emerge in charge state  $+77$ . The stripper used this year [5] consists of a  $6.35 \text{ mg/cm}^2$  aluminum foil followed by a  $8.48 \text{ mg/cm}^2$  “glassy” carbon foil mounted just downstream. The thicknesses have been optimized to produce the highest yield of  $\text{Au}^{77+}$ . The high uniformity of the glassy carbon, compared to that of the standard carbon stripper ( $23.1 \text{ mg/cm}^2$  graphite) used in the past, gives a significant reduction in the increase of longitudinal emittance due variable energy loss as the ions traverse the foil. With the standard carbon foil, this increase was approximately a factor of four [6]; with the glassy carbon, the increase is a factor of 1.8. The measured energy spread of the bunches in Booster at extraction is  $\pm 18 \text{ MeV}$  while that of the bunches in AGS at injection is  $\pm 32 \text{ MeV}$ . The measured average energy loss in the foils is 2.5 MeV per nucleon. This is significantly less than the 4 MeV per nucleon observed with the standard carbon stripper.

## AGS

The  $\text{Au}^{77+}$  ions are injected into the AGS by means of a septum magnet and a fast kicker. Four batches of six bunches are injected at constant magnetic field to give a total of 24 bunches on the AGS injection porch. (The AGS circumference is four times that of the Booster, so each batch occupies one fourth of the AGS ring.) The relative timing of the Booster and AGS cycles is shown in **Figure 2**. The bunches are injected into stationary buckets

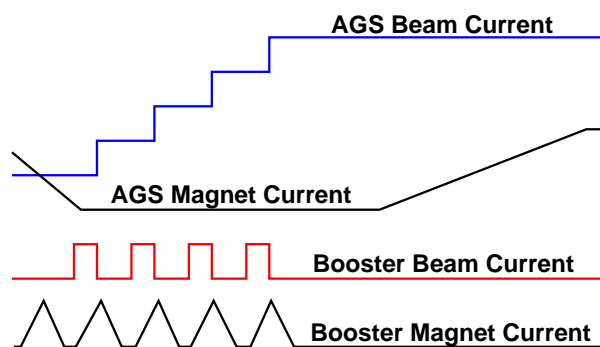


Figure 2: Timing of Booster and AGS cycles. Each Booster cycle is 200 ms long.

at harmonic 24. Because of the reduced energy spread of ions emerging from the BTA stripper used this year, there is more than enough voltage available to match the buckets to the incoming bunches. (This was not possible with the standard carbon foil.) The required voltage was found to be approximately 100 kV per turn. Measurements of

bunch width (55 ns) in the matched buckets give a six-bunch longitudinal emittance of 0.082 eV-s per nucleon. This is a factor of 1.8 greater than the emittance measured at Booster extraction. In addition to emittance growth due to variable energy loss as ions traverse the foil there is a phase mismatch caused by the average energy loss. Since the ions emerge from the foil with a smaller average velocity, the distance between bunch centers is reduced. (The time between bunch centers is unchanged.) This means that the 6 bunches of each batch entering the AGS will occupy slightly less than one fourth of the ring. The effect of the mismatch is to cause some dilution of longitudinal emittance during the merging process discussed below.

In the past, shortly after all four batches from Booster were injected, the harmonic 24 voltage was slowly reduced, adiabatically debunching the beam. Once debunched the beam was adiabatically rebunched into 4 bunches (in order to reach the bunch intensity desired for RHIC) and then accelerated to top energy at harmonic 12 as described in Ref. [6]. Experience with this setup has shown that there can be beam instability and subsequent fast loss due to the small momentum spread of the unbunched beam. To avoid this, a new setup in which the 24 bunches are merged into 4 was developed and implemented this year. The merge is done in two steps. First the 24 bunches are merged into 12 by bringing on harmonic 12 while reducing harmonic 24. Then the 12 bunches are merged into 4 by bringing on harmonics 4 and 8 while reducing harmonic 12. This final merge is done with a single low-frequency cavity [6]. The resulting 4 equally spaced bunches are then accelerated to top energy at harmonic 12. The merging of 6 of the 24 bunches into one is shown in **Figure 3**. Measurements of

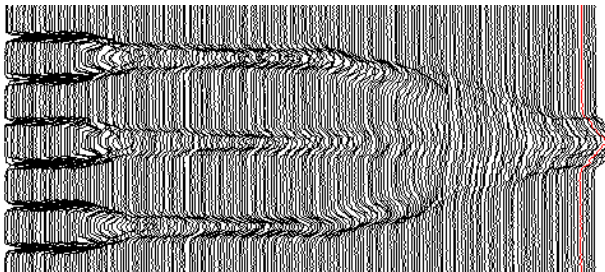


Figure 3: Merging of 6 bunches into 1 in AGS.

bunch width (16 ns) and gap volts per turn (180 kV) just before extraction give a single-bunch longitudinal emittance of 0.23 eV-s per nucleon.

At the intensity desired for RHIC, the extremely tight bunches associated with this small longitudinal emittance require the same fast transition jump system used for high intensity proton operation. Transition ( $\gamma_t = 8.5$ ) for gold ions occurs at more than twice the rigidity as for protons so the available jump in  $\gamma_t$  is somewhat less.

The four bunches are extracted from AGS one at a time by means of a fast kicker and thick ejector septum magnet [6]. Prior to extraction, the AGS RF is synched to the RHIC RF and phase adjusted so that each AGS bunch will

end up centered in the desired bucket on the RHIC injection porch [6]. The nominal momentum and kinetic energy at extraction are 9.75 GeV/c and 8.86 GeV per nucleon ( $\gamma = 10.52$ ). The overall (AGS Output)/(Booster Output) efficiency is 56%. An intensity of  $1.8 \times 10^9$  ions per bunch has been achieved at extraction. (The previous record was  $1.5 \times 10^9$ ). **Figure 4** shows a scatter plot of late intensities in Booster and AGS versus Booster input.

After extraction, the bunches are transported down the AGS to RHIC (ATR) line to RHIC. Final stripping to charge state +79 occurs in a 45 mg/cm<sup>2</sup> tungsten foil in the line. The beam loss in the foil is less than 1%. In the past an aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) flag was used for stripping. This gave a beam loss of 4% due to fragmentation of gold nuclei traversing the flag. Measurements of the normalized horizontal and vertical emittances in the ATR line give  $10\pi$  (mm milliradians) in both planes. The ATR transport efficiency is close to 100%.

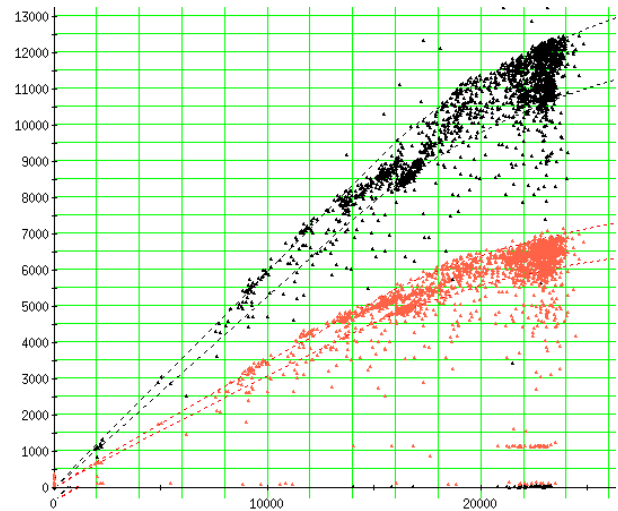


Figure 4: Booster (black) and AGS (red) Late Intensity versus Booster Input. The units are  $1.0 \times 10^6$  ions.

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