STATUS AND RECENT PERFORMANCE OF THE ACCELERATORS THAT SERVE AS GOLD INJECTOR FOR RHIC*

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Abstract

The recent successful commissioning and operation [1] of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) requires the injection of gold ions of specified energy and intensity with longitudinal and transverse emittances small enough to meet the luminosity requirements of the collider. Ion beams with the desired characteristics are provided by a series of three accelerators, the Tandem, Booster and AGS. The current status and recent perfomance of these accelerators are reviewed in this paper.

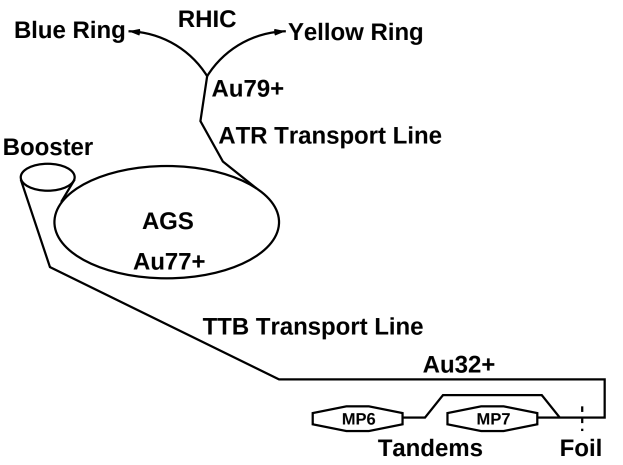

Figure 1: Acceleration of Gold Ions for RHIC.

1 TANDEM

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 when MP7 is in service.) Negative ions (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 $\mu\mathrm{g/cm}^2$ carbon) stripping foil. The ions emerge predominately in charge states $+10, 11, 12$ and are accelerated back to ground potential. A second stripping to charge state $+32$ occurs in a 15 $\mu\mathrm{g/cm}^2$ carbon foil downstream of Tandem as indicated in the Figure. This second stripping is necessary for adequate beam survival in Booster; the lower charge states do not survive well at Booster injection [3]. The momentum (and charge state) of ions transported down the 840 m TTB (Tandem To Booster) line is selected by the first of the two 90° 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° bends, the TTB line contains two 24° and two 13° 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 Au^{32+} ions transported to Booster are 41.5 MeV/c and 0.925 MeV per nucleon respectively. Typical pulse widths from the source are 500–700 μs. Currents of 20–30 μA at the end of the TTB line are typical, although currents as high as 80 μA have been achieved. Transport efficiency of the entire line ranges from 85 to 95%. The horizontal and vertical emittances of the Au^{32+} beam in the line are of the order of 1π mm milliradian (unnormalized). The fractional momentum spread is estimated to be $\pm 2.5 \times 10^{-4}$.

2 BOOSTER

2.1 Injection

The 500–700 μs pulse of Au^{32+} beam from Tandem is injected into the 202 m Booster ring by means of an electrostatic inflector and four programmable injection kickers. Since the revolution period of the ions in the ring is 15.1 μs, injection occurs over a period of some 33 to 46 turns around the machine. The closed orbit bump produced by the kickers 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 185π (mm milliradians) hori-

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zontal 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 87π vertical acceptance of the ring. This is done by programming the uncoupled tune separation. (The current in the tune quadrupoles can be varied much more quickly than the current in the skew quadrupoles.) Figure 2 shows the

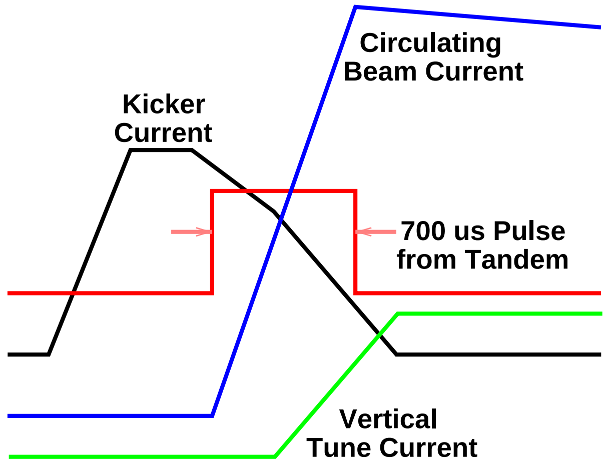

Figure 2: Typical Timing at Booster Injection.

typical timing of the Tandem beam pulse, the injection kicker current, the Booster circulating beam current, and the vertical tune quad current. Not shown is the current in the skew quadrupoles; this is held constant during injection and is then slowly reduced to zero. We have found that increasing the vertical tune over the last half of the Tandem beam pulse is an effective way to reduce the strength of the coupling. With this setup, injection of 35 turns with up to 85% efficiency has been achieved.

2.2 Capture and Acceleration

Capture and acceleration of the injected beam is accomplished with two RF cavities operating at harmonic 6. During injection and capture, the Booster magnetic field is held constant. Capture requires stationary RF buckets with the RF voltage raised adiabatically from zero. This is accomplished by "counterphasing" the two RF cavities 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. We have found that extending the time allowed for adiabatic capture on the Booster injection porch from the 1–3 ms used in the past to approximately 6 ms improves beam survival. This is contrary to the expectation that spending more time at low energy produces more beam loss. Here the cross sections for electron capture interactions between gold and residual gas or ions in the vacuum chamber are relatively large [5]. Clearly, if too much time is spent at low energy, these interactions will produce significant loss. On the other hand, if too little time is spent on capture, there can be substantial capture loss. The loss itself will generate more residual gas or ions in the vacuum chamber thereby increasing the rate of loss due to electron capture interactions. One therefore expects some sort of optimum setup in which the benefits of reducing capture loss outweigh the cost of spending more time at low energy. This is evidently what we have found with the 6 ms capture setup. Along with the higher intensity, this strategy gives a smaller longitudinal emittance.

After capture, the 6 bunches are accelerated to extraction where the momentum and kinetic energy are nominally 446 MeV/c and 101 MeV per nucleon. Assuming the beam fills the horizontal and vertical acceptances at injection, one expects normalized emittances of 8.2π and 3.9π (mm milliradians) respectively throughout the acceleration cycle. The longitudinal emittance of a single bunch at extraction has been measured and found to be $0.045/6$ eV-s per nucleon. The combined capture and acceleration efficiency is about 80%.

2.3 Extraction and BTA Transport

The six bunches are extracted in a single turn by means of a fast kicker and a septum magnet. After extraction, the ions pass through a foil in the BTA (Booster To AGS) transport line and emerge with charge $+77$. The stripping efficiencies and energy loss have been calculated and measured by Roser [6] for various foils (Carbon, Aluminum, Copper) with ion momenta ranging from 330 to 760 MeV/c per nucleon. A 22 $\mathrm{mg/cm^2}$ carbon foil gives the optimum efficiency of approximately 60% for stripping the 446 MeV/c Au^{32+} ions to Au^{77+}. The energy loss is approximately 4 MeV per nucleon.

3 AGS

3.1 Injection, Capture and Acceleration

The Au^{77+} ions are injected into the AGS by means of a septum magnet and a fast kicker. Under the present setup for RHIC operation, four batches of six bunches of gold ions are injected at constant magnetic field. (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 3. The bunches are injected into stationary RF buckets at harmonic 24. Because of the large increase in energy spread upon traversal of the BTA foil, there is not enough RF voltage to match the buckets to the incoming bunches. Debunching measurements on the injection porch give an energy spread of 80 MeV which would require 840 KV per turn for matching. The maximum available is 320 KV. In addition to this shape mismatch there is a phase mismatch caused by the energy loss in the foil. Since the ions emerge from the foil with a smaller velocity, the spacing between bunches is reduced. This means that the 6 bunches of each batch entering the AGS will occupy slightly less than $1/4$ of the ring. The result is that the incoming bunches cannot be centered exactly in the waiting RF buckets. These two mismatch effects cause the bunches to filament in the RF buckets. The longitudinal emittance growth from the energy straggling in the foil is a factor of 4. The growth due to filamentation is an additional 50% with the shape mismatch about twice the effect of the phase mismatch.

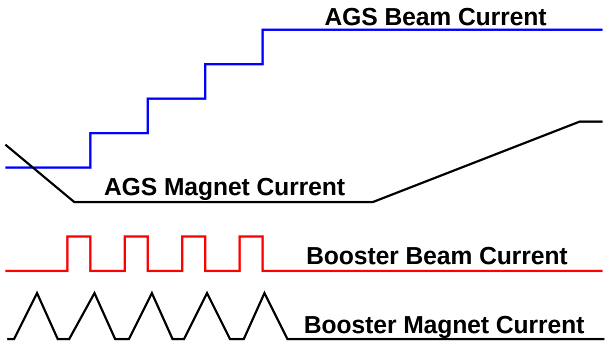

Figure 3: Timing of Booster and AGS cycles. Each Booster cycle is 200 ms long.

Shortly after the four batches have been injected, the RF voltage is slowly reduced to zero, adiabatically debunching the beam. This is done so that the 24 bunches can be rebunched into 4 bunches in order to meet the design intensity of 10^9 ions per bunch for RHIC. Once debunched the beam is adiabatically rebunched at harmonic 4 using a single low-frequency RF cavity. (This is the KEK magnetic alloy loaded cavity used for barrier bucket experiments [7].) The other AGS cavities operate at harmonic 24 for the initial capture and then at harmonic 12 for acceleration to full energy. Once the beam has been bunched at harmonic 4, the amplitude of this harmonic is slowly decreased to zero and at the same time harmonic 8 is brought on (in the low-frequency cavity) with every other harmonic 8 bucket centered on a harmonic 4 bucket. As the harmonic 8 and 4 amplitudes are respectively increased and decreased adiabatically, the bunch widths are reduced and the four bunches are captured into every other harmonic 8 bucket. This makes it possible for each bunch to fit inside a harmonic 12 bucket when these are brought on. Finally, bringing on harmonic 12, one ends up with beam captured in every third of 12 stationary buckets on the injection porch. The four bunches are then accelerated to extraction at harmonic 12. The final single-bunch longitudinal emittance is 0.3 eV-s per nucleon.

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

The nominal momentum and kinetic energy at extraction are 9.75 GeV/c and 8.86 GeV per nucleon ($\gamma = 10.520$). The normalized transverse emittances have been determined from IPM measurements throughout the acceleration cycle; they are approximately 7π (mm milliradians) in both planes, well within the maximum of 10π allowed for RHIC. Intensity of 0.9×10^9 ions per bunch has been achieved with overall efficiency from AGS injection through extraction of 95%.

3.2 Extraction and ATR Transport

The four bunches are extracted one at a time using the Fast Extracted Beam (FEB) system [8, 9]. This system consists of a fast kicker and a thick ejector septum magnet with local extraction orbit bumps. It is capable of performing single bunch multiple extraction of the gold beam at a rate of 30 Hz each AGS cycle. After extraction, the bunches are transported down the ATR (AGS To RHIC) line to RHIC [10]. Final stripping to charge state +79 occurs in a flag in the ATR line and has negligible effect on the beam parameters. Synchronization of the transfer of bunches between AGS and RHIC is described in [11].

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