SETUP AND PERFORMANCE OF THE RHIC INJECTOR ACCELERATORS FOR THE 2005 RUN WITH COPPER IONS*

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Abstract

Copper ions for the 2005 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 these accelerators with copper are reviewed in this paper.

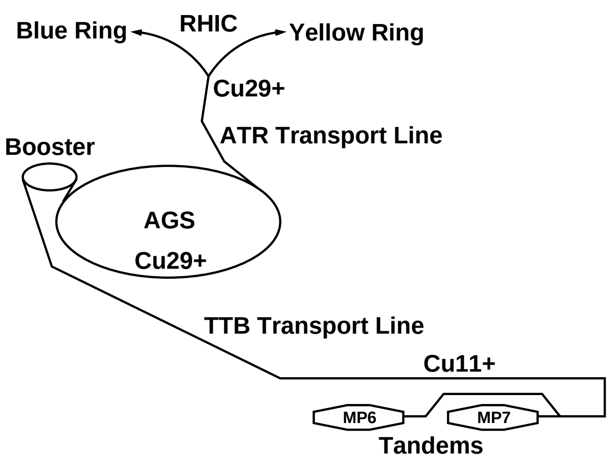

Figure 1: Acceleration of copper ions for RHIC.

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 when MP7 is in service.) Negative ions (Cu^{-1}) from a pulsed sputter source [2] are accelerated from ground potential to $+13$ MV at the center terminal of the Tandem where they pass through a thin ($4\ \mu\mathrm{g/cm}^2$ carbon) stripping foil. The ions emerge predominately in charge state $+11$ and are accelerated back to ground potential. Copper ions in this charge state survive well in Booster so no further stripping is required after Tandem. 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° 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 Cu^{11+} ions transported to Booster are 68.1 MeV/c and 2.49 MeV per nucleon respectively ($\beta = 0.0730$). The nominal pulse width from the source is $900\ \mu$s. Currents of 30–45 μA at the end of the TTB line are typical, although currents as high as $90\ \mu$A have been achieved. Transport efficiency of the entire line ranges from 85 to 95%. The horizontal and vertical emittances of the Cu^{11+} beam in the line are of the order of 1π 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 $\Delta p/p = \pm 2.5 \times 10^{-4}$. Observation of the notch also gives $9.22\ \mu$s for the revolution period at injection. The longitudinal emittance of the unbunched beam after accumulation in Booster is then 0.022 eV-s per nucleon.

BOOSTER

Injection

The $900\ \mu$s pulse of Cu^{11+} 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 $9.22\ \mu$s, injection occurs over a period of some 98 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 sep-

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tum that any additional incoming beam will be injected outside the 185π (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 [3], 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 typical

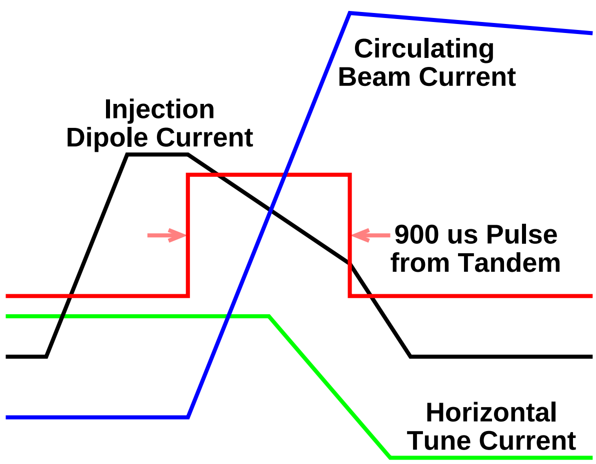

Figure 2: Typical timing at Booster injection.

timing of the Tandem beam pulse, the injection dipole current, the Booster circulating beam current, and the horizontal 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 decreasing the horizontal 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 98 turns with 63% efficiency has been achieved.

Capture and Acceleration

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 "counterphased" 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 ($\beta = 0.4319$). Assuming the beam fills the horizontal and vertical acceptances at injection, one expects normalized emittances of at most 13.5π and 6.4π (mm milliradians) respectively throughout the acceleration cycle. Measurements of bunch width, synchrotron frequency, and dB/dt just before extraction give a single-bunch longitudinal emittance of $0.027/6$ eV-s per nucleon. (The total emittance of the six bunches is 0.027 eV-s per nucleon.) This is consistent with the unbunched measurement of 0.022 eV-s per nucleon at injection. Loss of particles with large $\Delta p/p$ during acceleration results in some reduction of the longitudinal emittance. The combined capture and acceleration efficiency is 71%. This gives an overall Booster Output/Input efficiency of 45%. (The efficiency did not depend strongly on the input intensity.)

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 $14\ \mathrm{mg/cm^2}$ carbon foil in the Booster to AGS (BTA) transport line and emerge fully stripped with charge $+29$. The stripping efficiency is close to 99%. The energy loss in the foil is approximately 1.2 MeV per nucleon. This is significantly less the the 4 MeV per nucleon observed for gold ions [4]. One expects a corresponding reduction in the energy straggling in the foil. Measurements of the normalized emittances in the BTA line upstream of the stripping foil give 5.0 to 8.0π (mm milliradians) in the horizontal plane and 2.2 to 4.2π in the vertical.

AGS

Injection, Capture and Acceleration

The Cu^{29+} ions are injected into the AGS by means of a septum magnet and a fast kicker. As with the gold setup [4], four batches of six bunches of 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 buckets at harmonic 24. With the RF voltage adjusted to match the buckets to the incoming bunches, measurements of bunch width and synchrotron frequency on the injection porch give a single-bunch longitudinal emittance of $0.072/6$ eV-s per nucleon. This is a factor of 2.7 greater than the emittance measured at Booster extraction. The increase is due to the increase in energy spread upon traversal of the BTA foil. There is also a slight phase mismatch caused by the energy loss in the foil. Since the ions emerge from the foil with a smaller velocity, the distance between bunches is reduced. (The time between bunches is unchanged.) This means that the 6 bunches of each batch entering the AGS will occupy slightly less than one fourth

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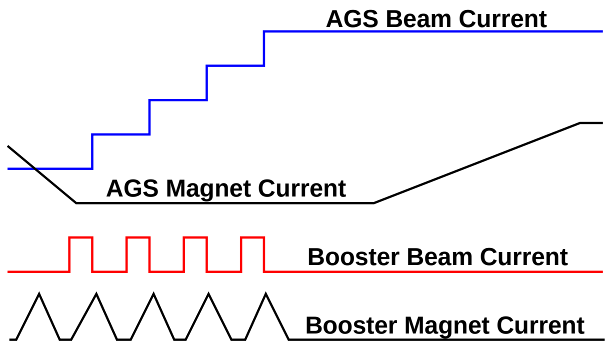

Figure 3: Timing of Booster and AGS cycles. Each Booster cycle is 200 ms long.

of the ring. For gold ions this mismatch is quite pronounced and produces significant filamentation of the longitudinal emittance. For copper ions the mismatch is barely perceptible and does not produce significant dilution.

Although keeping emittance dilution as small as possible dictates matching the buckets on the injection porch to the incoming bunches, we found that the peak bunch current maintained under these conditions is large enough to produce a substantial slow loss. The total voltage required for matching is 220 kV. To get optimum beam survival on the porch it was necessary to reduce the voltage to just 20 kV. The resulting filamentation in the mismatched harmonic 24 buckets produced a single-bunch longitudinal emittance of $0.169/6$ eV-s per nucleon.

Shortly after all four batches from Booster have been injected, the harmonic 24 voltage is slowly reduced, adiabatically debunching the beam. This is done so that the 24 bunches can be rebunched into four in order to meet the desired intensity of 5 to 7×10^9 ions per bunch for RHIC. (Here we found that we could not bring the voltage all the way to zero without producing an instability and subsequent fast loss. This would be expected above transition but not necessarily below.) Once debunched the beam is adiabatically rebunched at harmonic 4 using a single low-frequency RF cavity. The other AGS cavities operate at harmonic 24 for the initial bunch-to-bucket injection and then at harmonic 12 for acceleration to full energy. Through a series of RF gymnastics described in Ref. [4] the four bunches end up in every third of 12 stationary buckets on the injection porch and are then accelerated to full energy. The final single-bunch longitudinal emittance is 0.4 eV-s per nucleon, which is acceptable for RHIC operation. (We found that the same final emittance was obtained even if the RF buckets were matched to the incoming bunches on the injection porch. This could have been due to less than perfect rebunching of the beam.) 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 copper ions occurs at more than twice the rigidity as for protons so the available jump in γ_t is somewhat less.

The nominal momentum and kinetic energy at extraction are 11.2 GeV/c and 10.3 GeV per nucleon ($\gamma = 12.075$). The overall (AGS Output)/(Booster Output) efficiency is 78% with roughly two thirds of the 22% loss occurring on the injection porch after each transfer and the rest occurring during rebunching and early acceleration. These losses are intensity dependent, becoming less at lower intensities. An intensity of 9×10^9 ions per bunch has been achieved at extraction.

Extraction and ATR Transport

The four bunches are extracted from AGS one at a time using the Fast Extracted Beam (FEB) system [5, 6]. 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 extraction of the copper beam at a rate of 15 Hz each AGS cycle. After extraction, the bunches are transported down the AGS to RHIC (ATR) line to RHIC [7]. Synchronization of the transfer of bunches between AGS and RHIC is described in [8]. Measurements of the normalized horizontal and vertical emittances in the ATR line give 14π and 13π (mm milliradians) respectively. The overall (RHIC Input)/(AGS Output) efficiency is close to 100%.

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