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OPERATION OF THE RHIC INJECTOR CHAIN WITH IONS FROM EBIS*

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Abstract

Since 2012, gold and all other ions for the RHIC injector chain have been provided by an Electron-Beam Ion Source (EBIS). The source is followed by an RFQ, a short Linac, and a 30 m transport line. These components replace the Tandem van de Graaff and associated 840 m transport line. They provide ions at 2 MeV per nucleon (kinetic energy) for injection into the AGS Booster. The setup and performance of Booster and AGS with gold and other ions from the new source are reviewed.

INTRODUCTION

The RHIC injector chain, including both EBIS and Tandem, is shown in Figure 1 . Previous operation of the chain with ions from Tandem is documented in [1]. EBIS and associated components [2, 3] now provide essentially all ion species for both RHIC and the NASA Space Radiation Laboratory (NSRL), and allow both facilities to operate in parallel efficiently. Ions from EBIS are injected into Booster after acceleration by the RFQ and Linac. The EBIS, RFQ, and Linac output kinetic energies are 17 KeV, 300 KeV, and 2 MeV per nucleon, respectively. The nominal velocity of all ions at Booster injection is $c\beta$ where $\beta = 0.06505$. This gives a revolution period in Booster of $10.35\,\mu$s. EBIS delivers a short pulse of 10 to 40 μs, which amounts to 1-4 Booster turns.

The nominal un-normalized 95% transverse emittance of the beam at the end of the EBIS-to-Booster (ETB) transport line is 11π mm milliradians in both planes. This is an order of magnitude larger than the emittance of beams from Tandem, but with injection of EBIS beam occurring over just a few turns, the accumulated gross emittance after injection is somewhat less than that obtained with Tandem beam injected over some 60 turns. Injection proceeds by means of the same electrostatic inflector and four programmable dipoles that are used for Tandem beams. The dipoles move the closed orbit away from the inflector septum as beam is injected. In order to accommodate the larger emittance of the incoming EBIS beam, the gap between the inflector cathode and septum was increased from 17 to 21 mm.

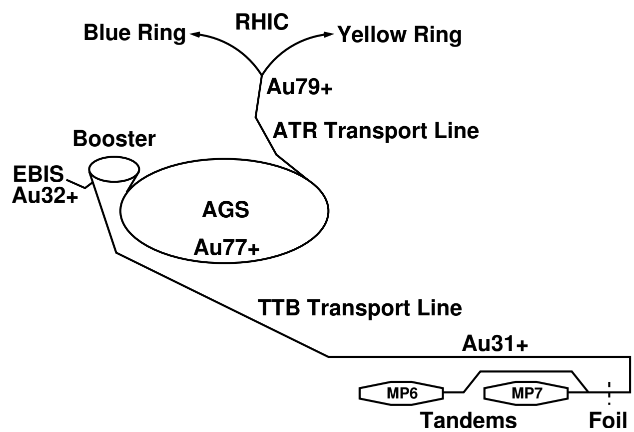

Figure 1: Acceleration of gold ions for RHIC.

The number of gold ions delivered to Booster per EBIS pulse is roughly a factor of four less than that delivered per Tandem pulse. In order to make up for this shortfall, it is necessary to deliver 8 loads of Booster beam to AGS per AGS cycle instead of the usual 4 loads delivered for the setup with Tandem beams. Two bunch merges in Booster and two on the AGS injection porch are also required. One ends up with two bunches at AGS extraction, each of which contains 4 Booster loads. For the setup with Tandem one ends up with 4 bunches, each of which contains 1 Booster load. Thus, although there are half as many bunches at AGS extraction for the EBIS setup, each EBIS-setup bunch contains at least as many ions as each Tandem-setup bunch. The details of the setup with EBIS are given in the next section. Beam intensities and longitudinal emittances are discussed in the subsequent sections.

SETUP WITH IONS FROM EBIS

EBIS provided ions of Cu, Au, and U for Cu-Au and U-U collisions in RHIC during Run 12 [4], and for Au-Au collisions during Run 14 [5]. Helions (3He2+) were also provided for helion-Au collisions during Run 14. We focus here on the setup with gold ions. The setup is essentially

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the same for all other EBIS ions destined for RHIC.

Each Booster cycle, a pulse of Au32+ ions from EBIS some 2 turns long is injected, captured at RF harmonic $h = 4$, and accelerated to an intermediate porch for merging. Here h is fixed by the revolution frequency at injection and the available frequency range of the RF cavities. The Booster cycle time is 200 ms. Longer cycle times produce potentially harmful perturbations of the local power grid and are not allowed. This limits the time available for RF capture and merging to 8 and 20 ms respectively.

The 4 bunches are merged into 2 on the intermediate porch and then the 2 are merged into 1. (For the setup with Au31+ ions from Tandem there are no bunch merges in Booster.) The single bunch is then accelerated, extracted, and transported to the AGS. This is one Booster load. The kinetic energy at AGS injection is 105 MeV per nucleon ($\gamma = 1.113$), somewhat higher than the 98 MeV per nucleon obtained with Au31+ ions from Tandem. In Booster, one pair of RF cavities does the capture and acceleration to the merging porch and a second pair does the 4 to 2 merge. The first pair then does the final 2 to 1 merge and subsequent acceleration. The revolution frequency on the porch is 465 kHz which is high enough for both pairs to operate during the merges.

In the Booster-to-AGS (BTA) transport line the Au32+ ions are stripped to Au77+. The stripper [6] consists of a $6.35\ \mathrm{mg/cm^2}$ aluminum foil followed by a $8.48\ \mathrm{mg/cm^2}$ "glassy" carbon foil mounted just downstream. The thicknesses have been optimized to produce the highest yield of Au77+. The high uniformity of the glassy carbon significantly reduces the increase of longitudinal emittance due to variable energy loss as the ions traverse the foil [1, 6].

Each AGS cycle, 8 Booster loads are delivered to AGS. Having a single bunch in each load removes the constraint on the AGS RF harmonic number imposed by the fixed ratio 4/1 of the AGS and Booster circumferences. Each Booster bunch is small enough to fit into a harmonic 16 bucket on the AGS injection porch. With the available frequency range of the AGS RF cavities, two merges are then possible on the porch. The 8 bunches are injected into 2 groups of 4 adjacent harmonic 16 buckets. In each group the 4 bunches are merged into 2 and then the 2 are merged into 1. This gives 2 final merged bunches and puts 4 Booster loads into each bunch. The first merge is accomplished by reducing the harmonic 16 voltage while increasing the harmonic 8 voltage from zero. Similarly, the second merge is accomplished by reducing the harmonic 8 voltage while increasing the harmonic 4 voltage from zero. The harmonic 8 and 4 voltages are provided by two cavities that have been modified to operate at lower frequency. (For the setup with Au31+ ions from Tandem, 4 loads of 6 bunches are delivered per AGS cycle. The 24 bunches are merged into 12 which are then merged into 4. This gives 4 bunches and puts 1 Booster load into each bunch.)

At the end of the AGS merges, the 2 merged bunches are sitting in harmonic 4 buckets. Each bunch needs to be squeezed into a harmonic 12 bucket for subsequent acceleration. The squeeze is done by again bringing on harmonic 8. If the merged bunch emittance is too large then the combined harmonic 4 and 8 voltages are not sufficient to squeeze the bunch into one harmonic 12 bucket. The result is that some of the bunch leaks into adjacent buckets forming satellite bunches. This of course takes beam away from the main bunches that are ultimately extracted and transported to RHIC.

The Au77+ ions are accelerated to a kinetic energy of 8.865 GeV per nucleon ($\gamma = 10.520$) and the 2 main bunches are extracted and transported to RHIC. A stripper in the AGS-to-RHIC (ATR) transport line strips the remaining two electrons off the ions [6]. The Au79+ ions are injected into waiting RF buckets on the RHIC injection porch.

INTENSITIES

Although a maximum of 1.62e9 Au32+ ions per EBIS pulse has been observed at the end of the ETB transport line, the typical intensity when 8 pulses are being delivered per AGS cycle is 1.2e9 Au32+ ions per EBIS pulse. This is to be compared with the typical 5.0e9 Au31+ ions per pulse from Tandem reported in [1]. Efficiencies as high as 0.95 have been observed for the injection of EBIS ions in Booster. This is significantly higher than the efficiency 0.80 reported for the many-turn injection of Tandem beams. The Booster Output/Input efficiency is typically 0.85 with most of the loss occurring during capture and early acceleration. This gives 1.0e9 Au32+ ions at Booster extraction per EBIS pulse. The 0.85 efficiency is significantly higher than the value 0.56 reported for Tandem beams. The increase is believed to be due to the reduced intensity and the smaller gross emittance of EBIS beam accumulated in Booster at injection. At the lower intensity, there is a reduction in beam loss caused by loss-induced vacuum degradation [7].

Some 65% of the Au32+ ions that pass through the BTA stripper emerge as Au77+ ions for injection into AGS. This number comes from careful measurements of the distribution of ion charge states seen on a multiwire profile monitor downstream of the stripper. Taking the AGS input to be the number of Au77+ ions observed on the injection porch after the 8 transfers from Booster, one would expect the fraction (AGS Input)/(Booster Output) to be close to 0.65. However, the number is typically found to be around 0.56. This is due (in part) to a slow loss that occurs during the 200 ms time intervals between the transfers. This gives 4.46e9 Au77+ ions on the AGS injection porch after 8 transfers from Booster. After the bunch merges one then has 2.23e9 Au77+ ions per bunch.

During Run 12 some 8 to 12% of the gold beam ended up as satellite bunches and there was a significant loss during early acceleration in AGS. The end result was 1.62e9 Au77+ ions per main bunch at AGS extraction. The harmonic 12 capture and acceleration efficiency was then $1.62/2.23 = 0.73$. This was more than adequate for the RHIC physics program.

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The amount of gold beam in satellite bunches was reduced to just 2 to 3% in Run 14. The early acceleration loss was also reduced significantly. The end result was 2.06e9 Au77+ ions per main bunch at AGS extraction. This is a new intensity record and was more than adequate for the RHIC physics program. The harmonic 12 capture and acceleration efficiency was $2.06/2.23 = 0.92$. (For the setup with Tandem beams, the intensity at AGS extraction was 1.57e9 Au77+ ions per bunch as reported in [1]. This typical intensity increased to 1.68e9 in 2008 and intensities as high as 1.8e9 per bunch were observed on occasion.)

During Run 12, the typical intensity of copper (Cu11+) ions at the end of the ETB line was 4.94e9 ions per pulse. This gave 4.06e9 ions at Booster extraction. After 8 transfers to AGS and 2 merges on the injection porch, we ended up with 11.2e9 Cu29+ ions per bunch on the porch and 6.5e9 Cu29+ ions per bunch at AGS extraction. This was again more than adequate for the RHIC physics program. The typical intensity of uranium (U39+) ions at the end of the ETB line was 1.21e9 ions per pulse. This gave 0.59e9 ions at Booster extraction. After 8 transfers to AGS and 2 merges on the injection porch, we ended up with 0.87e9 U90+ ions per bunch on the porch and 0.39e9 U90+ ions per bunch at AGS extraction. This was much lower than expected, due to poor transmission in Booster and AGS and unexpectedly poor stripping efficiency in the BTA stripper. Nevertheless, this was a useful amount of beam for the RHIC physics program.

During Run 14, the typical intensity of helions at the end of the ETB line was 3.15e10 helions per pulse. This gave 2.02e10 helions at Booster extraction. After 8 transfers to AGS and 2 merges on the injection porch, we ended up with 7.58e10 helions per bunch on the porch and 7.28e10 helions per bunch at AGS extraction. This led to a very successful physics program with helion-Au collisions in RHIC, and was an excellent demonstration of the efficiency, flexibility, reliability, and stability of an EBIS source [3].

LONGITUDINAL EMITTANCES

As discussed above, a total of 4 bunch merges (2 in Booster and 2 in AGS) are required to obtain the desired intensity per bunch at AGS extraction. Each of these merges is a 2 to 1 merge in which 2 adjacent bunches are merged into 1. If the 2 to 1 merge is done sufficiently slowly, the gross emittance of the merged bunch will be the sum of the emittances of the initial 2 bunches. In this case we say that the gross emittance has been conserved. If the merge is done too quickly, the merged bunch will be diluted with empty phase space, making its gross emittance larger than that of the slowly merged bunch. In this case we say that there has been emittance growth (even though the area of phase space occupied by beam has not changed). Here we trace the evolution of the gross emittance in Booster and AGS. To save writing we simply use the word emittance to refer to gross emittance.

In Run 14 the measured fractional momentum spread of Au32+ beam from EBIS at Booster injection was $\Delta p/p = \pm 2.2$e-4 as reported in [8]. A similar measurement made in Run 12 gave $\Delta p/p = \pm 3.0$e-4. These small fractional momentum spreads are achieved by careful tuning of debunching cavities in the ETB line. They give longitudinal emittances of 0.018 eV s and 0.024 eV s per nucleon respectively for the unbunched Au32+ beam circulating in Booster at injection. These emittances are comparable to the 0.022 eV s per nucleon measured for unbunched Au31+ beam from Tandem circulating in Booster.

Measurements [8] show that if the 4 captured bunches are accelerated without merging, they end up with a total longitudinal emittance of 0.080 eV s per nucleon at Booster extraction. This amounts to an emittance growth of a factor of 4. Most of this occurs during capture and early acceleration, and is due to the small amount of time (8 ms) allowed for capture. When the 4 bunches are merged into 1, they end up with a total longitudinal emittance of 0.089 eV s per nucleon at Booster extraction, showing that the emittance growth due to merging is relatively small. With the harmonic 16 buckets on the AGS injection porch matched to the incoming bunches, the longitudinal emittance per bunch measured in 2014 was 0.10 eV s per nucleon. This shows that the emittance growth due to the BTA stripper is relatively small. A measurement made in 2012 gave a longitudinal emittance per bunch of 0.14 eV s per nucleon. The reduction from 0.14 to 0.10 is due to the extensive upgrade of the low-level RF system in Booster between 2012 and 2014.

Before the two merges on the AGS injection porch, the total longitudinal emittance for 4 bunches was 0.40 eV s per nucleon. After the two merges the measured longitudinal emittance per merged bunch was 0.428 eV s per nucleon [8], showing that the emittance growth due to the merges is relatively small. A similar measurement (after the merge and before acceleration) made in 2012 gave a longitudinal emittance per merged bunch of 0.56 eV s per nucleon. As already noted, in 2012 some 8 to 12% of the beam ended up as satellite bunches as the merged bunches were squeezed into harmonic 12 buckets. In 2014 this was significantly reduced to just 2 to 3% of the beam [8]. This is most likely a consequence of the smaller merged bunch emittance obtained in 2014.

During acceleration in the harmonic 12 buckets in 2014, the longitudinal emittance per bunch increased from 0.428 eV s to an average of 0.7 eV s per nucleon at AGS extraction. Although larger than the 0.23 eV s per nucleon obtained with Tandem beam, this was not detrimental to the RHIC physics program, thanks to careful control of RF parameters in the collider during capture, acceleration and rebucketing at store. The growth in AGS may have been due to uncompensated ripple in the main magnet current [8].

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