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Reliable Operation of the Brookhaven EBIS for Highly Charged Ion Production for RHIC and NSRL

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Abstract. An Electron Beam Ion Source for the Relativistic Heavy Ion Collider (RHIC EBIS) was commissioned at Brookhaven in September 2010 and since then it routinely supplies ions for RHIC and NASA Space Radiation Laboratory (NSRL) as the main source of highly charged ions from Helium to Uranium. Using three external primary ion sources for 1+ injection into the EBIS and an electrostatic injection beam line, ion species at the EBIS exit can be switched in 0.2 s. A total of 16 different ion species have been produced to date. The length and the capacity of the ion trap have been increased by 20% by extending the trap by two more drift tubes, compared with the original design. The fraction of Au^{32+} in the EBIS Au spectrum is approximately 12% for 70-80% electron beam neutralization and 8 pulses operation in a 5 Hertz train and 4-5 s super cycle. For single pulse per super cycle operation and 25% electron beam neutralization, the EBIS achieves the theoretical Au^{32+} fractional output of 18%. Long term stability has been very good with availability of the beam from RHIC EBIS during 2012 and 2014 RHIC runs approximately 99.8%.

INTRODUCTION

After its commissioning, the EBIS-based injector replaced its predecessor, the Tandem Van de Graaff, which had supplied multiply charged ions for all accelerator applications at RHIC/AGS facility for many years. The new EBIS injector is more compact, can produce a wider variety of ion species, and allows a rapid switching of ion species. The highly charged ions with $M/q \leq 6$ are produced in the ion trap of EBIS and can be extracted as a 10-40μs ion pulse of several mAs peak current, sufficient for 1-4 turn injection into the AGS Booster ring without additional stripping to increase the charge state.

RHIC EBIS utilizes a magnetically immersed electron gun with magnetic compression of the electron beam. With cathode emission current density ~15 A/cm^2 (at electron current 10 A) and a magnetic compression of ~35 the electron beam current density in the center of the superconducting solenoid is ~525 A/cm^2. The design of RHIC EBIS and simulations of the electron gun and electron collector have been published before [1-4]. RHIC EBIS, like its prototype Test EBIS [5-7] has independent solenoidal coils generating axial magnetic fields at the electron gun, trap/ionization region and at the entrance of the electron collector. Four sets of transverse magnetic coils are used to correcting the position of the magnetic axis for improved electron beam propagation. Due to the varying axial magnetic field distribution, the electron beam radius varies along its trajectory and the drift tube structure is designed to accommodate it. Such a magnetic structure is versatile and allows simple control of the electron beam size, current density and position in different regions. The typical axial magnetic field distribution in RHIC EBIS is presented in Fig. 1.

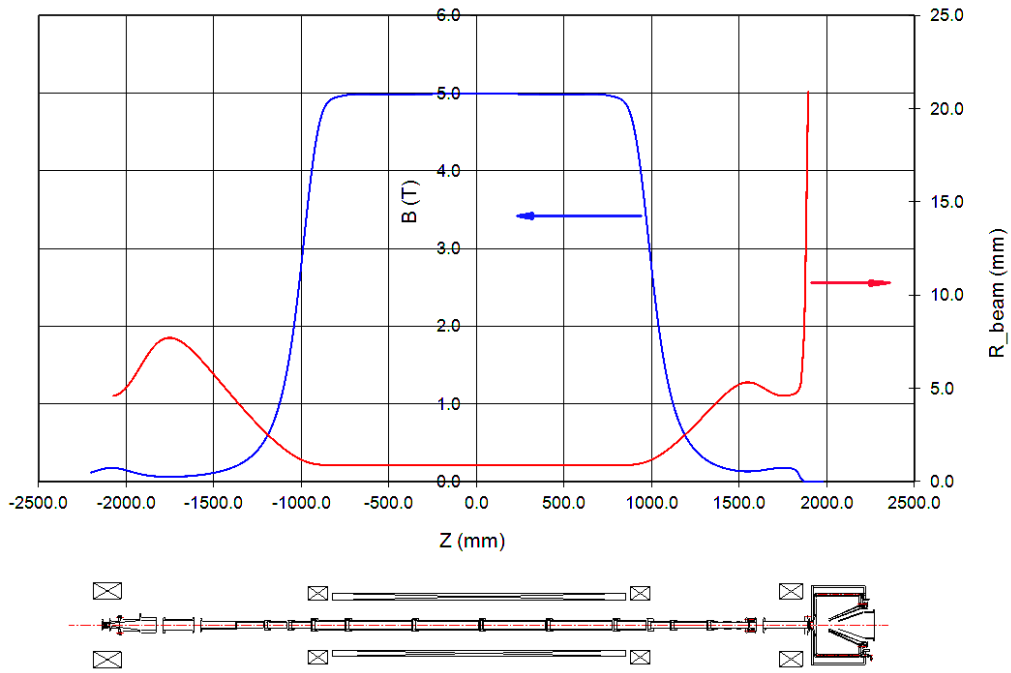


Fig. 1. Axial magnetic field distribution and electron beam envelope in RHIC EBIS.

Typically, the magnetic field on the cathode is 0.14 T, with a similar value at the entrance of the electron collector (center of the collector coil). The maximum magnetic field at the center of our superconducting solenoid is 5.0 T. The drift tube structure is located in the "warm" bore of the superconducting solenoid and the vacuum in the interaction region is provided with conventional methods (turbo pumps, cryogenic pumps, Ti sublimation pumps, NEG strips and vacuum separation). During normal operation with the (pulsed) electron beam running we estimate the pressure of the residual gas in the interaction region to be close to $1 \cdot 10^{-10}$ Torr or better, so that contamination of the extracted ion beam with residual gas ions is less than 5%. One contribution to the gas load in EBIS is neon, the typical buffer gas used in hollow cathode ion sources for external ion injection into the EBIS.

Usually, the RHIC EBIS acts as a charge multiplier, trapping ions from various remote (1+) ion sources and increasing the charge state to the desired value during an easily varied confinement time. The ion injection into EBIS utilizes either "fast" potential injection or a "slow" (over the barrier) ionization injection technique. With "fast" injection the working ions traverse the trap region with only one potential barrier on the gun side, which reflects the incoming ion beam back towards the source. The injected ion velocity is reduced as much as possible within the EBIS trap region to increase the linear charge density (optimize for highest output beam intensity), by adjusting the potential of the drift tubes in the trap region. The injected ions are trapped by raising a second "extraction" potential barrier on the collector end of the EBIS trap region. The "fast" ion injection requires relatively high current of the injected ions, because this current determines the linear current density of the ions traversing the trap region during a round trip time of ~10-400μs. The ion current of heavy and medium mass elements for "fast" injection should be in a range on 10–100μA to get the final neutralization of the multiampere electron beam close to 100%. For the "slow" ion injection method, the working ions traverse the ion trap after entering the EBIS with energy just high enough to surmount the collector end "extraction" barrier. The ions are reflected from the higher gun side barrier and the ions are trapped between the two axial barriers if their charge state increases due to ionization during the round trip. With "slow" ion injection the primary ion current is typically 1-10μA, because the accumulation of ions in a trap can be made as long as necessary, typically 10–40 ms. In general, it is advantageous to reduce the injection time by increasing the current of primary ions when possible, because a lower ratio of injection time to confinement time should result in a narrower charge state distribution of the extracted highly charged ions from the EBIS trap. The choice of the injection method depends on the species and the type of the primary ion source used. A schematic of the EBIS external ion beam lines is presented in Fig. 2.

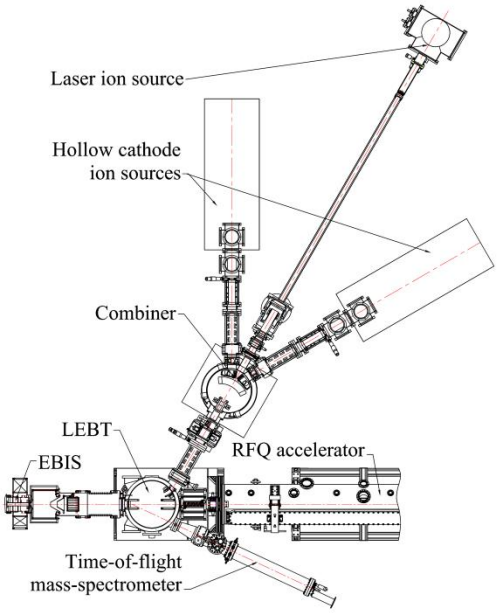


Fig. 2. External ion sources of RHIC EBIS.

The ion beams from the hollow cathode ion sources (HCIS) are directed into a common beam line section with a combiner, using a bipolar electrostatic bender. The beam from the laser ion source (LIS) goes straight into the common line. The beam from the common section, which contains quadrupole lenses, is directed onto the EBIS axis with a combination of spherical bender at the entrance into the LEBT chamber, and a flat bender located at the exit from LEBT. The combined angle of primary beam deflection is 60^0. The primary ion beam is focused with a gridded lens, which is positioned directly after the flat bender and is directed into the electron beam with EBIS internal ion optics. The injection of ions from the external ion sources is usually done at the ground potential of the EBIS platform with ion energy 12 – 14 keV. The ion beam transmission in this electrostatic beam line is not sensitive to the ion charge state or species (q/m). Each of the hollow cathode ion sources (HCIS) is equipped with a Wien filter to select either ions of the cathode material or buffer gas as desired. The HCIS beam lines are also provided with fast mechanical shutters and differential pumping which greatly reduces the migration of buffer gas into the EBIS. The HCIS has provided the bulk of ions for EBIS injection for the first few years of operation. Advantages include ability to provide almost any species of ions including those made from gases (He, N, O, Ne, Ar, Kr, Xe) and the ability to run in the slow injection mode (10-40 ms injection), which is especially important for accumulation of light ions. Recently a laser ion source (LION) for (1+) injection of solid species was commissioned at EBIS. LION now runs routinely, providing ion beams to EBIS for NSRL operation and more recently Au+ to EBIS for RHIC operation. One important advantage of the laser ion source is the absence of a buffer gas, which makes EBIS vacuum better. With ion pulse length of ~200 μs it can be used only in the "fast" ion injection mode, but high ion current ~1mA can provide adequate neutralization of the EBIS electron beam. Work is underway to increase the injection line transport energy to allow more efficient propagation of the relatively short pulsed, high current ion beams of 1+ ions from LION to EBIS, and also to provide rapid switching between several preloaded solid targets for NSRL operation.

To get the energy of extracted highly charged ions of 17 keV/amu required for injection into the RFQ, the EBIS platform potential is provided by a nominal 100kV, 100μs rise-time pulsed high-voltage power supply. The ion beam is formed with EBIS internal ion optics, accelerating tube, gridded lens and the pulsed solenoid lens at the entrance into the RFQ [8]. The low-energy beam line also contains 4 electrostatic deflectors for the transverse beam position correction. The charge state spectra of the extracted ions can be viewed on the detector of both conventional (low resolution) and Mamyrin (energy focusing, high resolution) time-of-flight (TOF) spectrometers.

RHIC EBIS OPERATIONAL PERFORMANCE

RHIC EBIS uses external ion injection as a primary method of ion injection. A flexible control of the electrostatic ion optics allows fast switching between the various ion sources and as well as fast switching between available species within a single hollow cathode ion source plasma (e.g. Ne+ and Au+). The minimum species switching time out of EBIS is limited to 200 ms by control cycle time considerations while the switching time to the AGS Booster ring requires 1 second to allow switching of some slower magnetic devices in the high energy transport line.

RHIC EBIS is used routinely for delivery of highly charged ions to both RHIC (which involves bunch conditioning in the Booster and AGS rings and further stripping), as well as to NSRL (which uses ions accelerated without additional stripping in the Booster). Typically during the RHIC run EBIS supplies ions for both users, and usually these are different species. The RHIC operation requires accumulation in AGS of 8 EBIS ion pulses, which are generated with frequency of 5 Hz as a single train in a super cycle of 4-5 s. In addition, NSRL takes 1 pulse per super cycle. A third species can be added for EBIS beam development purposes. Between fills of the collider, the EBIS can operate in a "standby" mode of 1 pulse per super cycle for the RHIC user to maintain its readiness while reducing ion feedstock consumption and component lifetimes. During such times, NSRL continues to operate normally and independently, according to its 1 pulse per super cycle schedule.

Earlier experiments on Test EBIS demonstrated that it is was possible to increase the intensity of the extracted ion beam by extending the ion trap from the uniform region into that of somewhat lower magnetic field area while maintaining stable EBIS operation [9]. The original RHIC EBIS ion trap included 4 drift tubes in the center of the superconducting solenoid with total length of 1506 mm and the maximum deviation of the magnetic field within this trap was 0.4%. The ion trap has been extended in both directions by including one additional drift tube electrode on each side of the trap. The new ion trap has a length of 1882 mm, which is 20% longer than the original trap. At the edges of the new ion trap the magnetic field is 80% of the maximum value in the center of the superconducting solenoid. The intensity of the beam of highly charged ions from the trap has been increased in the same proportion as the length of the trap. Any decrease in average electron beam current density within the trap can be compensated by adjustment in the ion confinement time, a parameter easily controllable through the control system.

Operation of EBIS for the accelerator facility started in 2011 with ion delivery to NSRL experiments. In 2012 EBIS delivered ions for RHIC, where for the first time it collided U-U, followed by a run of Au-Cu. In the same year it also delivered ions for NSRL. In 2013 most of EBIS operation was dedicated to NSRL. Following an October-November 2013 run for NSRL, EBIS came on for RHIC in January 2014, and operated 24 hours a day, 7 days a week through June. Operation was usually unattended, only monitored along with the rest of accelerator complex from a central RHIC control room. EBIS supplied ions to RHIC for Au-Au and Au-^{3}He collisions and at the same time it delivered 8 different ion species for NSRL. To date 16 beams have been delivered from RHIC EBIS to both users (Table 1):

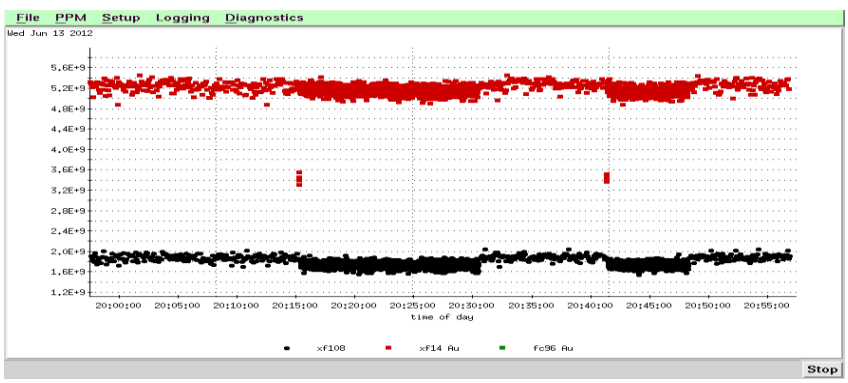
Table 1. Ion beams delivered for RHIC and NSRL.

Element	Charge state(s)	User(s)
^{3}He	2	RHIC & NSRL
^{4}He	1, 2	NSRL
C	5	NSRL
O	7	NSRL
Ne	5	NSRL
Si	11	NSRL
Ar	11	NSRL
Ti	18	NSRL
Fe	20	NSRL
Cu	11	RHIC
Kr	18	NSRL
Xe	27	NSRL
Ta	38	NSRL
Au	32	RHIC & NSRL
Pb	34	AGS
U	39	RHIC

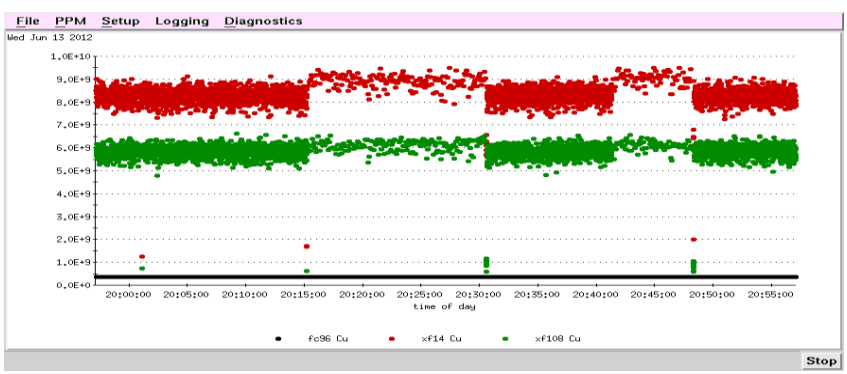
RHIC EBIS operates for both users "simultaneously" (i.e., sequentially within a 4-5s supercycle), with only HEBT component switching limitations (1 second). For each ion species and charge state, archive files are created of optimized electrode potentials, magnet currents, and timing distributions for these. Loading these files nearly always results in the same EBIS performance without any extra tuning. Occasional variations in performance are almost always due to variations in the (1+) external injector source rather than in the EBIS itself, which acts as a charge state multiplier. As a result, EBIS operation is highly reproducibly, even for two or more different users automatically switching between preloaded file archives.

^{3}He ions were a special case, in which ions were produced in EBIS using gas injection into the trap using a pulsed gas valve. The optimum pressure of ^{3}He in EBIS is approximately $2{\cdot}10^{-9}$ Torr with only valves open to turbo pumps (gate valves to cryogenic pumps were closed to avoid their contamination). After He pulsed gas injection is stopped, the vacuum recovers to an acceptable level for Au^{32+} ion production within several minutes. During a 3-week run for ^{3}He-Au collisions we roughly estimate that EBIS consumed approximately 10 atm-cm^3 of ^{3}He gas. If external ion injection of $^3He^{+1}$ ions produced in a plasma source were used instead for ion injection into the EBIS trap, this consumption of ^{3}He gas would be dramatically higher. During this recent ^{3}He-Au RHIC run all EBIS beam switching operations including He gas injection, opening and closing gate valves, Au ion injection, ion extraction, etc., were performed frequently and automatically using scripts run by the main control room operators, and required only rare intervention by EBIS personnel.

The stability of ion beam intensity depends somewhat on the regime of its operation: with 1 pulse per super cycle the stability is higher than with 8 pulses per super cycle. Examples of intensity traces for Au^{32+} and Cu^{11+} run are presented in Fig. 3 a) and b), which show a period with several switches between 8 pulses Au / 1 pulse Cu, and 1 pulse Au / 8 pulses Cu. (From the few missed pulses shown during mode switching, one can see that the current transformer signals are intrinsically noisy).



a)



b)

Fig. 3. Intensity traces for Au^{32+} (a) and Cu^{11+} (b) ion beams for one and eight pulses per super cycle. The top traces are for a current transformer after Linac, the bottom traces are for a current transformer between two dipole magnets just before the Booster injection inflector.

The maximum intensity of the desired charge state in the extracted ion beam is usually achieved at nearly full electron beam neutralization (80-90%), significantly higher than the design neutralization of 50%. A consequence of the high electron beam neutralization is perhaps a broader charge state spectrum than one would obtain with lower neutralization. As a result, at maximum Au^{32+} intensities the measured fraction of Au^{32+} ions in the extracted Au charge state distribution is ~14% instead of theoretical value of 18% (Fig. 4), which we have obtained in tests when limiting the electron beam neutralization to 25%.

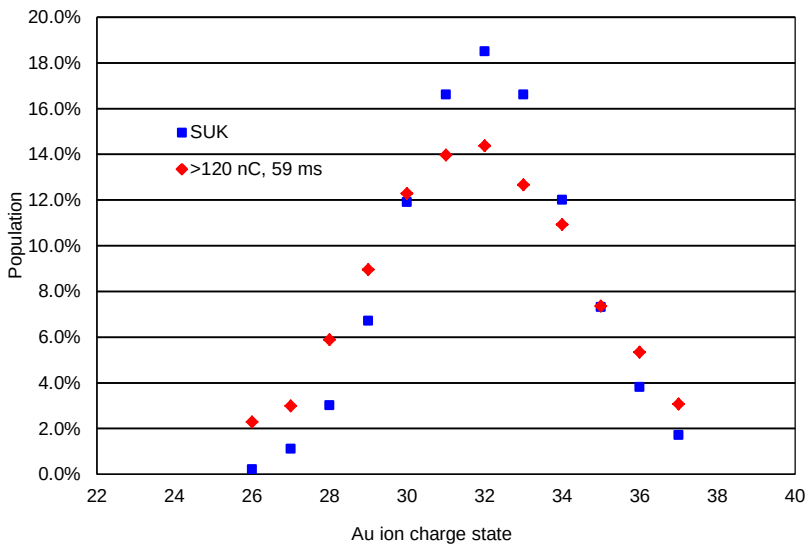


Fig. 4. Experimental (with 80% electron beam neutralization) and calculated with R. Becker's SUK program charge state spectra of Au.

Operation with 8 pulses per super cycle reduces the fraction of Au^{32+} in the Au spectrum to ~12%. This reduction might be attributed to increased neutralization (>90%) of the electron beam space charge in the trap with additional residual gas ions.

Beam intensity from EBIS depends on ion species and charge state. For most ions, we operate with an electron beam current of 7-10A, and with high neutralization of the electron beam space charge we typically get >100 nC of total charge per pulse out of EBIS (6.25e11 charges). The number of ions per pulse for a specific charge state then depends on the % in that charge state. With Au, for example, with 12-14% in 32+, one gets ~ 6.25e11*0.12/32 = 2.3e9 Au^{32+} ions/pulse out of EBIS, in ~20 μs long pulses.

EBIS and the associated RFQ, Linac, and transport lines have proved to be a highly reliable injector system for the facility. The only item inside the EBIS that requires a regular replacement is the cathode of the electron gun. Two replacements have been made after 1.5 years of operation of each cathode. The EBIS superconducting solenoid cryogenic system requires regular refilling of liquid He once every ~25 days. Other than this ~1.5 hour interruption of the beam every few weeks, there is no other routine maintenance required during the long run cycles. (In our case, helium fills can be done during the multi-hour RHIC stores, without any impact on the physics program). Occasional regeneration of cryopumps or flashing of titanium sublimation pumps can also be performed without interruption to the NSRL or RHIC operating schedules.

During 2014 runs for RHIC and NSRL, the only downtime associated with EBIS source was a few hours of time lost associated with power supplies (most commonly collector power supply trips) and some minor problems with equipment protection interlocks. The availability of the beam from EBIS was 99.8%.

ACKNOWLEDGMENTS

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