

COMMISSIONING OF THE EBIS-BASED HEAVY ION PREINJECTOR AT BROOKHAVEN*

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Abstract

The status is presented of the commissioning of a new heavy ion preinjector at Brookhaven National Laboratory. This preinjector uses an Electron Beam Ion Source (EBIS), and an RFQ and IH Linac, both operating at 100.625 MHz, to produce 2 MeV/u ions of any species for use, after further acceleration, at the Relativistic Heavy Ion Collider (RHIC) and the NASA Space Radiation Laboratory (NSRL). Among the increased capabilities provided by this preinjector are the ability to produce ions of any species, and the ability to switch between multiple species in 1 second, to simultaneously meet the needs of both science programs. For initial setup, helium beam from EBIS was injected and circulated in the Booster synchrotron. Following this, accelerated Au³²⁺ and Fe²⁰⁺ beams were transported to the Booster injection point, fulfilling DOE requirements for project completion.

available from the Tandem Van de Graaff preinjectors, such as noble gas ions for NASA, and uranium ions for RHIC. The RFQ and linac which are used for acceleration are a simpler and more modern technology than the Tandems. Also, by producing the desired high charge states directly in the EBIS, two stripping stages are eliminated. Finally, since the new preinjector is located close to the injection point of the Booster synchrotron, one eliminates the need for the 860 m long transport line between the Tandem and Booster. While the EBIS-based preinjector will meet all the needs of RHIC and NSRL, the Tandem Van de Graaffs will continue to operate for the active outside user program. Parameters for the preinjector are given in Table 1. The preinjector is shown schematically in Fig. 1.

INTRODUCTION

A new EBIS-based, high charge state heavy ion preinjector is being commissioned at Brookhaven National Laboratory (BNL). The preinjector will provide increased flexibility to handle the simultaneous needs of the RHIC and NASA programs, since it will allow one to switch rapidly between ion species injected into the accelerator chain. It will also provide ions not presently

Table 1: Preinjector Parameters

Ions	He – U
Q / m	≥ 1/6
Current	> 1.5 emA
Pulse length	10–40μs (for few-turn injection)
Rep rate	5 Hz
EBIS output energy	17 keV/u
RFQ output energy	300 keV/u
Linac output energy	2 MeV/u
Time to switch species	1 second

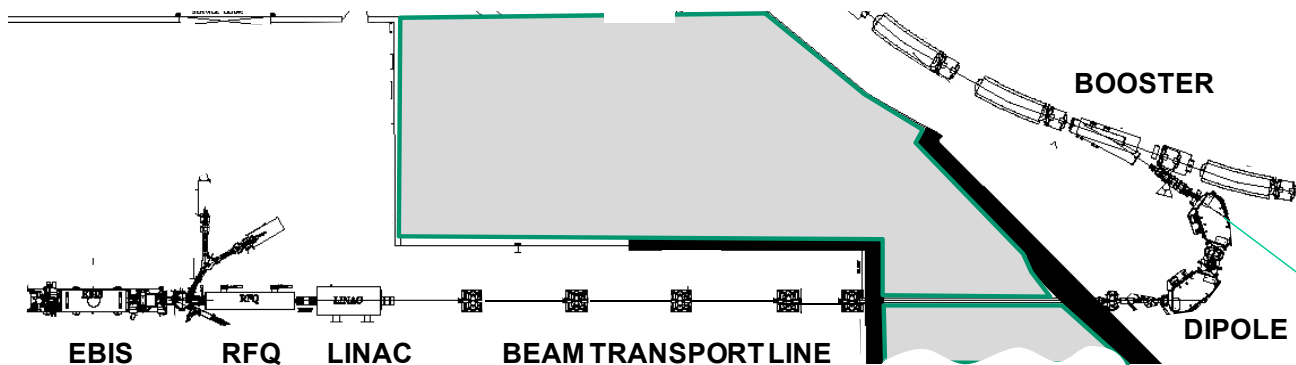


Figure 1: Layout of the EBIS Preinjector.

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EBIS

An EBIS produces high charge state heavy ions through stepwise ionization by an electron beam while the ions are held in a trap region. Once the desired charge state is reached, the ions are released from the trap and extracted at high voltage. The electron beam is produced at one end of the source, is compressed before entering the trap region by a strong magnetic field, makes a single pass through the trap region, and then is decelerated and stopped in the electron collector at the other end. Radial trapping of ions is via the space charge of the electron beam. The ions are trapped axially by electrostatic potentials applied to electrodes at both ends of the trap. Primary ions are injected into the trap either by feeding gas, or typically in our case, by injecting singly charged ions of the desired species into the trap from an external ion source.

The total charge of ions extracted per pulse is typically 60-85% of the number of electrons in the trap, so the extracted ion output per pulse is proportional to the trap length and the electron current. The ion charge state increases with increasing confinement time, so one can select the desired charge state. To first order, the total output current per pulse is independent of ion species or charge state. The BNL EBIS is shown schematically in Fig. 2.

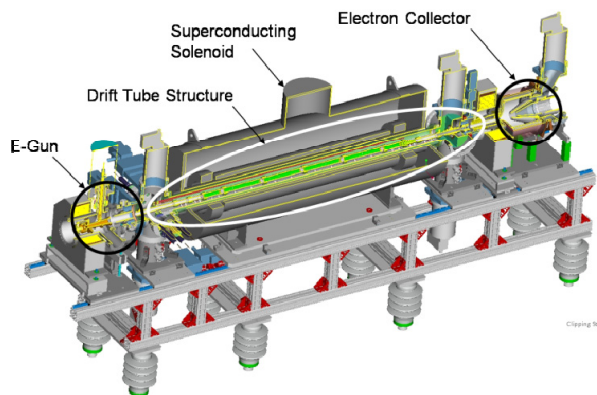


Figure 2: Schematic of the BNL EBIS.

Design Features of the BNL EBIS

Details of the EBIS design can be found in [1, 2]. The 10A electron gun uses a 9.2 mm diameter IrCe cathode [3]. The 5T EBIS superconducting solenoid has a length of 2m, and an 8" warm bore. The magnet [4] has a liquid helium cryostat, with a cryocooled intermediate thermal shield. Operating in persistent mode, it is filled with ~200 l of liquid helium every 30 days.

The trap region contained within the solenoid bore is 1.5 m long, and has 6 electrodes of 42 mm diameter aperture forming the trap. There are an additional 8 electrodes between the electron gun and collector held at potentials of ~10-20 kV to allow low loss propagation of the electron beam. In addition, there are 4 sets of horizontal and 4 sets of vertical magnetic steering coils

between the gun and collector for fine adjustment of the electron beam steering.

The electron collector is a water-cooled BeCu structure, designed to cool up to 300 kW, (20A, 15 kV electron beam). The maximum heat load on the inner surface is ~350 W/cm². The electron beam is typically operated in pulsed mode to reduce the total power to the collector.

The EBIS source and all associated EBIS power supplies sit on an isolated platform. The platform is at ground potential during ion injection and charge breeding, and pulses to ≤100 kV only during ion extraction, to provide ions at 17 keV/amu for any species at $Q/m \geq 1/6$.

Table 2 gives source parameters and Fig. 3 shows a photo of the EBIS.

Table 2: EBIS Source Parameters

Species	He to U
Output (single charge state)	$\geq 1.1 \times 10^{11}$ charges
Ion output (Au ³²⁺)	3.4×10^9 particles/pulse
Q/m	$\geq 1/6$, depending on ion
Pulse width	10 - 40 μ S
Max rep rate	5 Hz
Beam current (single charge state)	1.7-0.42 mA
Output energy	17 keV/amu
Species switching time	1 second
Electron beam current	10 A
Trap length	1.5 m
Trap magnetic field	5 T

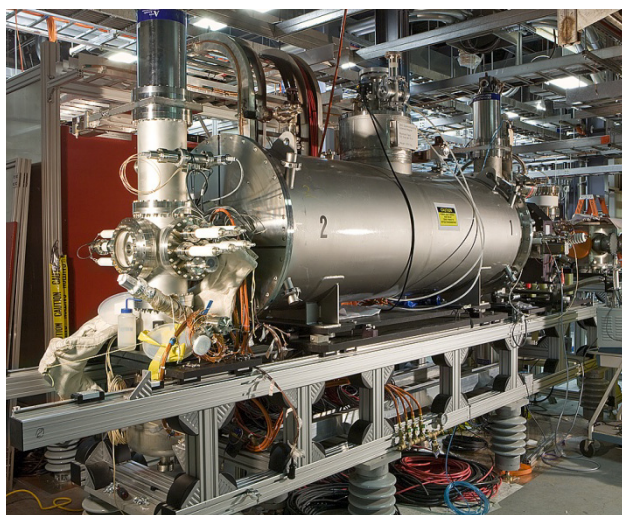


Figure 3: Photo of the EBIS.

Ions can be injected into EBIS from one of two external beamlines, with the capability of switching between these two injectors on a pulse-to-pulse basis at 5 Hz. While any type source can be installed on either beamline, presently one beamline has a Hollow Cathode Ion Source (HCIS) and the other a Metal Vapor Vacuum Arc source

(MeVVA). A Wien filter in the HCIS beamline allows mass separation so one can inject either the working gas of the source, or the solid target material. Other than this Wien filter, both injection lines have all electrostatic elements – quadrupole quadruplets for transverse matching, and both spherical and flat deflectors for fast switching of ions from either beamline into the EBIS trap.

EBIS Performance

First ions from the EBIS were produced in February, 2010. Initial operation was with helium gas feed, and ion output was exactly as expected. The ion yield vs. electron beam current showed twice the output, compared to the BNL Test EBIS [5], since this EBIS has twice the trap length of the Test EBIS. The measured electron beam perveance of $P=2.2 \times 10^{-6} \text{ A/V}^{1.5}$ was in agreement with the calculated value. The electron beam has been operated at up to 8A for few ms pulses, and later (for Fe^{20+} ion production), operation was at 5A, 160 ms electron beam pulses.

The superconducting solenoid has been operating in persistent mode at 5T for approximately 6 months continuously.

EBIS has generated beams of He^{1+} and He^{2+} ions with gas injection, Au ions with external injection from a HCIS, and Fe ions from both the HCIS and a MeVVA source. With helium gas injection the maximum extracted ion charge was $Q_{\text{ion}}=82 \text{ nC}$ for electron current of $I_{\text{el}}=6.2 \text{ A}$ with energy $E_{\text{el}}=26.3 \text{ keV}$, which constitutes approximately 85.6% of the electron charge in the volume of the ion trap. The peak extracted current for helium 1+ or 2+ was $\sim 5 \text{ mA}$. For Au and Fe ions, peak extracted currents were also in the milliampere range, but since the high resolution time-of-flight diagnostic has not yet been completed, we cannot quote exact currents for specific charge states of these beams.

As mentioned previously, in order to reach the required 17 keV/u for ion injection into the RFQ, the EBIS and all its power supplies are pulsed up to high voltage just prior to ion extraction. The platform operates successfully at 100 kV, exceeding the voltage required for any ions.

LEBT & RFQ

Following the high voltage acceleration from EBIS, beam matching into the RFQ is primarily via a gridded electrostatic lens, a drift space with electrostatic deflectors, and a magnetic solenoid right before the RFQ entrance. The LEBT is $\sim 1.2\text{m}$ in total length, with a 10 cm diameter open bore. The gridded lens is used because, depending on species, one needs either a focusing or defocusing lens at this location. The magnetic solenoid is pulsed, with $B \sim 0.9\text{T}$ peak on axis, and a length of 25 cm.

Prior to installation of the RFQ, a slit-collector emittance unit was installed at near the RFQ entrance point, and a normalized, rms emittance of $0.09 \pi \text{ mm-mrad}$ was measured for He^{1+} .

The RFQ is a 4-rod structure designed and built by IAP, Frankfurt [6]. It operates at a frequency of 100.625 MHz,

and accelerates beams with m/Q up to 6.25 from 17 keV/u to 300 keV/u. The RFQ length is 3.1 m, and the peak power required for the heaviest ions is $\sim 100 \text{ kW}$. Operation is at a repetition rate of 5 Hz, with 1 ms wide pulses. It is powered by a 350 kW amp from Continental Electronics [7]. This amplifier combines power from two 175 kW units, each using a TH535 tetrode, so the RFQ can also be powered from only a single 175 kW unit.

Prior to installation on the EBIS preinjector, the RFQ was tested on the Test EBIS, where beams of Cu^{10+} , He^{2+} , He^{+} and Ne^{5+} were used. The beam energy was confirmed to be 300 keV/u and was varied within $\pm 2.5 \text{ keV/u}$ depending on the vane voltage. The momentum spread was measured as $\pm 2\%$ based on the beam size after a magnetic bend.

On the RHIC EBIS, RFQ transmission for helium beams is in excess of 80%. Since there is no mass or charge state selection between the EBIS and RFQ, one cannot directly measure transmission for other beams.

More details on RFQ performance can be found in [8].

MEBT & LINAC

In the medium energy beam transport (MEBT), matching between the RFQ and linac is done via four pulsed magnetic quadrupoles and one rebuncher cavity. A photo of this section is shown in Fig. 4.

The quadrupoles operate in pulsed mode, so are made with laminated yokes. The magnet length is 70 mm, and the beampipe through the quads has a bore of 32 mm diameter. At the full operating current of 677 A, one gets 70 T/m at the center of the magnet. The coils are water cooled. The pulsed power supply drives 15 ms of rise time and 10 ms of flattop current with up to a 5 Hz repetition rate.

The rebuncher cavity was made by IAP, Frankfurt, and is a spiral, 4-gap structure. Maximum operating power is on the order of 1 kW.

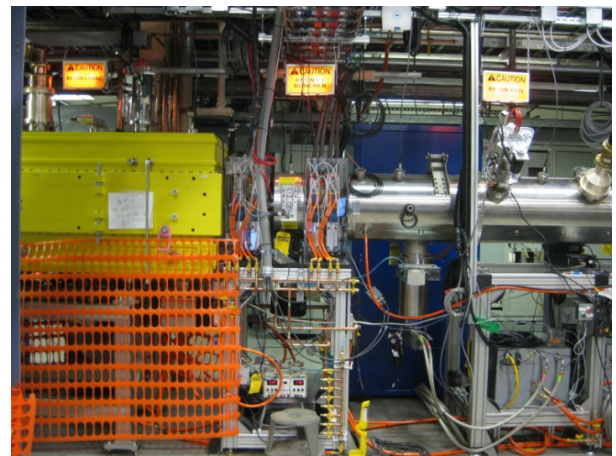


Figure 4: Photo (right to left) of the RFQ, MEBT, and linac.

Prior to installation of the linac, a slit-collector emittance diagnostic was installed near the linac entrance point. The measured normalized rms emittance was 0.13

π mm mrad for He^{1+} , and 0.19π mm mrad for Au ions, which included several charge states around $31+$.

The linac is a 100.625 MHz IH structure, designed and built by IAP, Frankfurt. It has a length of 2.46 m, and accelerates the beams with $m/Q \leq 6.25$ from 300 keV/u to 2 MeV/u. It is designed for a peak current up to 10 mA, and has 27 gaps and 1 internal pulsed quadrupole triplet. It is powered by a 375 kW amplifier identical to that used for the RFQ, and requires a maximum power of ~ 200 kW. As with the RFQ, the linac operates at up to 5 Hz, with 1 ms rf pulses.

The linac was delivered to BNL in April, 2010. Upon arrival at BNL, it was discovered that there was a shorted coil on one of the internal quadrupoles. Fortunately, the short was ultimately repaired without having to remove the quadrupole, and the linac was ready for beam testing in June. RF conditioning took only a few days. Transmission through the linac exceeds 80%. Further details can be found in [9].

HEBT

The High Energy Beam Transport (HEBT) line from the IH linac to Booster injection includes is a ~ 17 meter section before a shield wall, drift through the ~ 8 meter thick shield wall, and then inside the Booster tunnel a ~ 12 meter transport, including two dipoles, to inject beam into the Booster at the same location as beam coming from the Tandems. The two identical dipoles [10] each have a bend angle of 72.5 degrees, a 13.5 cm gap, 1.3 meter bend radius, and 1T maximum field. The dipoles are laminated to meet the required 1 second field change time for different ion species.

The transport line has a quadrupole triplet directly after the linac, followed by 7 quadrupoles, two bunchers, three horizontal steerers and four vertical steerers. Ion species are not separated until the dipole, so initial tuning of the preinjector on a particular charge state can be hard, but once tuned, settings are very reproducible.

Diagnostics in the HEBT line include three Faraday cups, three current transformers, three profile monitors, two phase probes, and a pepperpot emittance measurement unit. A photo of the linac and HEBT is shown in Fig. 5

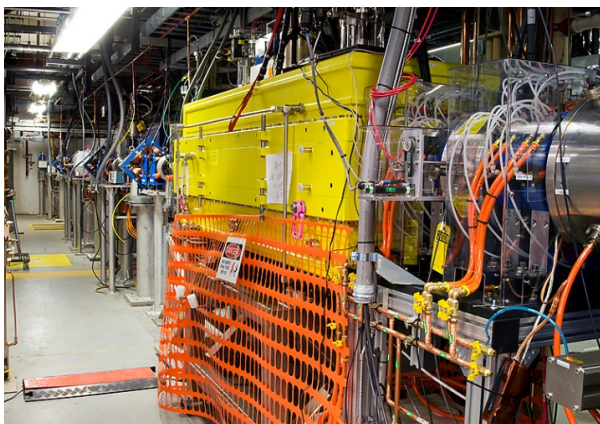


Figure 5: Looking down the HEBT line.

FINAL COMMISSIONING

As mentioned above, the RFQ was initially operated with beam from the Test EBIS, where He, Cu, and Ne beams were accelerated and the RFQ output energy and energy spread were verified. The emittance of a helium beam from the RHIC EBIS was next measured, where helium was used to avoid confusion over charge states. The RFQ and MEBT beamline were then installed, and emittances of He^{1+} and Au^{32+} measured as given above.

The linac was delivered in April, 2010, but the repair of the shorted quad was not completed until mid-June. Eight days later, on June 19, we had first accelerated beam through the linac. Five days after that, helium beam had been transported around the bend (momentum analysis), verifying the proper energy for the linac. One week later (6/30-7/2) we had He^{1+} beam from EBIS circulating in the Booster synchrotron for the first time. From a measurement of the debunching of a short ($< 10 \mu\text{s}$) beam pulse vs. turns in the Booster, the momentum spread in the Booster for He^{+1} beam was found to be $2x 10^{-4} \pm 1.0 x 10^{-4}$, exceeding our requirements. Following this, the Booster was shut down for summer maintenance.

Commissioning of beams required for official completion of the project (CD-4) then began, with the measurement point being after the first of the two 73 degree dipoles before the Booster injection point. One could first transport beam from the RFQ around the bend, with the linac and all buncher cavities off. Then beam with the RFQ plus first buncher on could be transported, and the buncher phase set such that the beam energy was not changed. The linac was then turned on and adjusted, and finally the debuncher cavity after the linac used to minimize the beam energy spread. Once this momentum-analyzed beam was established, the EBIS output could be optimized for the desired charge state.

Requirements for CD-4 were approximately 10% of the design intensity, so operation during this phase was typically at ~ 5 A electron beam current. A Au^{32+} beam current of $3.8 x 10^8$ ions/pulse was achieved at the middle of bend, followed by an Fe^{20+} current of $4.75 x 10^8$ ions/pulse. Both beams exceeded the CD-4 requirements. Table 3 shows beam parameters for helium, gold, and iron.

The last requirement for project completion was a demonstration of switching between species. The preinjector was operated with alternating Au^{32+} and Fe^{20+} beam pulses around the bend, at a 0.5 Hz repetition rate. For this successful switching, the following were changing on a pulse-to-pulse basis: 1) ion injection into the EBIS trap was alternating between Fe^{1+} from LEVA and Au^{1+} from the HCIS; 2) EBIS confinement time was switching between 65 ms for Au^{32+} and 130 ms for Fe^{20+} ; 3) platform high voltage was switching between 92 kV (Au) and 32 kV (Fe); 4) power to all RF systems was alternating by factor of 4.8; 5) the current to the large dipoles was switching between 2270A (Au) and 1030 A (Fe). In addition, all other transport line elements were switching values pulse-to-pulse (ion injection line quads

and deflectors, LEPT solenoid & deflectors, MEBT quads, linac quads, and HEPT quads & steerers).

Table 3: Parameters for helium, gold and iron ions demonstrated for CD-4.

Parameter	He ⁺¹	Au ⁺³²	Fe ⁺²⁰
q/m	0.25	0.162	0.357
Platform Voltage (kV)	68	104	47.6
RFQ Power (kW)	40	95	20
Linac Power (kW)	75	180	37
Dipole Current (A)	1415	2270	1030
Pulse Length (μ s)	20	20	36
Rep. Rate (Hz)	1	1	1
Intensity (10^8) ions/pulse	1250	3.7	4.75
Energy (MeV/u)	2	2	2
Transmission,	75	90*	60*
RFQ input to middle of bend (*=inferred, due to multiple charge states)			

TRANSITION TO OPERATIONS

Following this successful demonstration of CD-4 requirements, we now have a plan to ramp up the intensity to the full design values during the coming RHIC run cycle. Helium and neon beams from EBIS will be used for experiments at the NASA facility in November, 2010. Increased intensities for Au, U, Fe, etc. will then come about through a combination of the following: 1) doing a full bake of EBIS (EBIS has yet to be baked, so there is a significant impurity content in the beam), 2) transmission improvements, 3) routine operation at 10A electron beam, and 4) increase of injected 1+ ion intensity.

EBIS beams can be developed even while RHIC and NSRL are taking beams from the Tandem, since pulses from both preinjectors can be interleaved within one accelerator "supercycle". Once the required intensity is achieved from EBIS for any species, EBIS will be used rather than Tandem. EBIS is expected to provide uranium ions for a short run of uranium for RHIC in the spring.

SUMMARY

All systems making up the new EBIS preinjector are operating, and performing as expected. There has been

good agreement between measurements and simulations for the EBIS, RFQ, linac, and transport lines. The EBIS has operated continuously for multi-day shifts. The superconducting solenoid has been at full field for many months. He¹⁺, Au³²⁺ and Fe²⁰⁺ beams were transported to Booster, and helium was circulated in Booster. Alternating pulses of Au³²⁺ and Fe²⁰⁺ every 2 seconds has been demonstrated. All CD-4 requirements (for official project completion) have been achieved. The full design parameters are met routinely for platform voltage, rf powers, magnet currents, etc., except for full electron current and source repetition rate (pushing these parameters was delayed until after completion of CD-4 requirements). The next phase is now ramp-up of the intensity, but no new hardware is required for this.

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