

PERFORMANCE OF THE NEW EBIS PREINJECTOR*

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Abstract

The construction and initial commissioning phase of a new heavy ion preinjector was completed at Brookhaven in September, 2010, and the preinjector is now operational. This preinjector, using an EBIS source to produce high charge state heavy ions, provided helium and neon ion beams for use at the NASA Space Radiation Laboratory in the Fall of 2010, and gold and uranium beams are being commissioned during the 2011 run cycle for use in RHIC. The EBIS operates with an electron beam current of up to 10 A, to produce mA level currents in 10-40 μ s beam pulses. The source is followed by an RFQ and IH linac to accelerate ions with $q/m > 0.16$ to an energy of 2 MeV/amu, for injection into the Booster synchrotron. The performance of the preinjector is presented, including initial operational experience for the NASA and RHIC programs.

2.5 m long IH Linac. Both operate at 100 MHz, and both structures were designed and built by IAP, Frankfurt. There is a ~ 17 m long transport line before the beam passes through a ~ 8 m thick shield wall, and into the Booster synchrotron tunnel. The beam then goes through two 73 degree dipoles, before being injected into the Booster at the same point as heavy ions from the Tandem Van de Graaffs.

The project received CD4 approval (DOE Project Completion) in September of 2010. In November of 2010, helium and neon ion beams were accelerated in the Booster and delivered to the NSRL facility for experimental use. In February 2011, gold beam was accelerated in the Booster, and in March, iron beam was accelerated and delivered to NSRL from EBIS for experiments. During this run cycle, EBIS will continue to deliver beams to NSRL (He^{1+} , Ne^{5+} , Ar^{10+} , Fe^{20+} , O^{7+} , and Ti^{18+}). In addition, Au^{32+} and U^{40+} beams will be commissioned for RHIC.

INTRODUCTION

A new EBIS-based heavy ion preinjector is now operational, and has begun to supply beams to the NASA Space Radiation Laboratory (NSRL). Some ions for RHIC will be provided during this spring running period. Once at full intensity, the EBIS preinjector will replace the existing Tandem Van de Graaff accelerators for all heavy ions for RHIC and NSRL, but they will continue to operate for an active outside user program. High level parameters for the preinjector are given in Table 1, and the layout of the preinjector is shown in Fig. 1.

Heavy ions of any species are produced in the desired charge state in a state-of-the-art EBIS source, designed to operate at an electron current of up to 10A. The ions are then accelerated by a 3.2m long RFQ, followed by a

Table 1: Preinjector Parameters

| | |
|------------------------|----------------------------------|
| Ions | He – U |
| Q / m | $\geq 1/6$ |
| Current | > 1.5 emA |
| Pulse length | 10–40ms (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 |

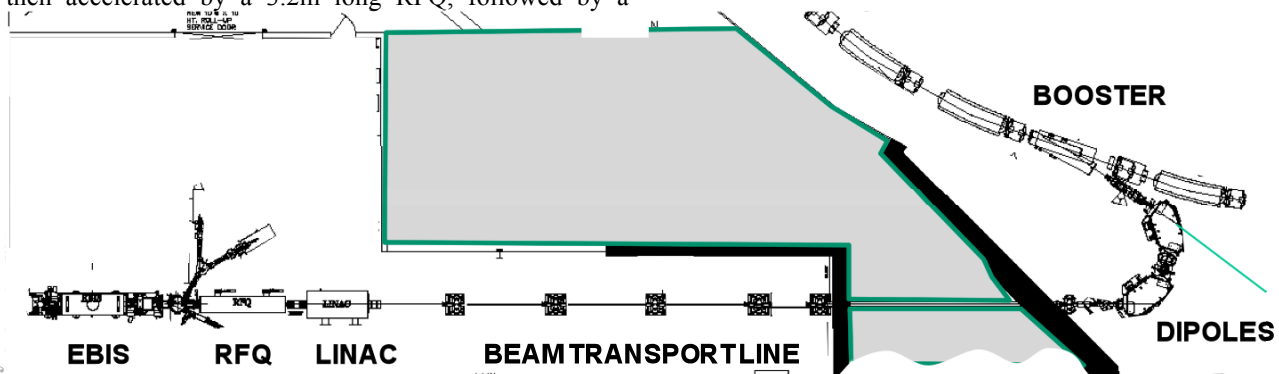


Figure 1: Schematic of the EBIS-based heavy ion preinjector

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EBIS PERFORMANCE

The BNL EBIS has a 5T superconducting solenoid which compresses an electron beam of up to 10A into a 1.5 m long trap region. Ions of the desired species are injected, held in the trap, and stepwise ionized by the electron beam. When the desired charge state is reached, they are released from the trap in a short pulse. Just prior to this extraction of ions from the trap, the EBIS platform is pulsed up to ≤ 100 kV, depending on Q/m, to get the proper RFQ input energy. While designed for operation with an electron beam current of 10A, we have so far only pushed the electron current to 8A, and have typically operated at ~ 5 A electron current since the focus of our effort has primarily been in the transport and acceleration of the ions. A photo of the source is shown in Fig. 2.

The ion output from the EBIS consistently exceeds our design value of 50% of the trap capacity. Therefore, the current out of EBIS with a 5A electron beam is 2-3 mA in 20 μ s pulses, and proportionally higher when the pulse is shorter. This current includes the normal distribution of charge states of the desired species, plus $<10\%$ coming from background ions.

While helium and neon have been produced by gas injection into EBIS, Au and Fe (and all future ions) are produced by injection of singly charged ions into the trap from an external hollow cathode ion source [1]. This source has proved to be very stable, with long lifetime. The EBIS is designed to operate at a 5 Hz repetition rate, and by changing the species injected into the trap, the output beam can be switched on a pulse-to-pulse basis.

The EBIS superconducting solenoid operates in persistent mode, and it has remained at full field for ~ 1 year, with the exception of a few weeks when it was ramped down to perform a bakeout of the EBIS. The pressure in the EBIS trap region is in the mid- 10^{-11} Torr. Operation of the EBIS has been very stable, and operating parameters are very reproducible. More details on the source performance are given in [2].



Figure 2: The EBIS source, with the 2m long superconducting solenoid producing a 1.5 m trap region.

ACCELERATION AND TRANSPORT

Beam from the EBIS is focused by several electrostatic lenses, and finally a magnetic solenoid lens, to get the proper matching into the following RFQ. There is

incomplete separation of species or charge states from EBIS until the dipoles bending the beam into Booster, so all measurements upstream of the first bend are generally including multiple charge states. Prior to installation of the RFQ, an emittance measurement for a pure He^{1+} beam from EBIS at the RFQ entrance point gave a value of 0.09π mm mrad (normalized, rms).

The RFQ is a 4-rod structure operating at 100.625 MHz. The maximum power required is <100 kW, and the duty factor is ≤ 5 Hz, 1 ms. Transmission for helium ions is $>90\%$, and we estimate that transmission for Au^{32+} and Fe^{20+} is $\geq 80\%$. Further details on the RFQ performance can be found in [3].

Following the RFQ, there is a short MEFT line containing four pulsed quadrupoles and one rebunching cavity. Prior to installation of the linac, emittances were measured for He^{1+} and Au (containing multiple charge states peaked at 32+). The rms, normalized emittances were 0.13 and 0.19π mm mrad, respectively.

The linac is an interdigital-H structure, 2.5 m long, with one internal quadrupole triplet. The maximum power required is ~ 200 kW for $q/m = 0.16$. We estimate that the linac transmission is $>80\%$ for all beams run to date. Details on the linac can be found in [4]. Figure 3 shows a photo of the acceleration and transport line.

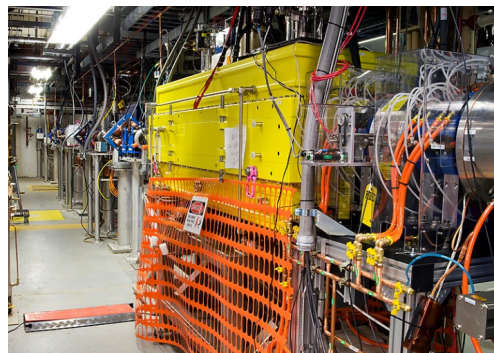


Figure 3: High energy end of the RFQ is seen on the right, linac (yellow) in the center, and the high energy transport on the left.

The efficiency of transport of the charge state of interest the ~ 30 m from the linac exit to the middle of the bend (the first location where we have a single charge state), is estimated to be 100%. Table 2 shows maximum intensities in the single charge state measured to date after the first 73 degree bend to Booster. Also shown in the Table is the number of charges this represents.

Table 2: Intensities Measured after the 73° Dipole

| | Ions per pulse | Charges per pulse |
|--------|--------------------|----------------------|
| He 1+ | 67×10^9 | 6.7×10^{10} |
| Ne 5+ | 5.5×10^9 | 2.7×10^{10} |
| Fe 20+ | 1.7×10^9 | 3.4×10^{10} |
| Au 32+ | 0.92×10^9 | 2.9×10^{10} |

All beams are performing more or less as expected. The Au^{32+} intensity represents 72% of our design value for a 5A electron beam. When properly tuned, the current

at Booster input is very stable, with pulse-to-pulse fluctuations of <1%.

The preinjector has been operated with alternating Au³²⁺ and Fe²⁰⁺ beam pulses around the bend, at a 0.5 Hz repetition rate. Ion injection into the EBIS trap was alternating between Fe¹⁺ from LEVA and Au¹⁺ from the HCIS, while the EBIS confinement time was switching between 65 ms for Au³²⁺ and 130 ms for Fe²⁰⁺. Also switching pulse-to-pulse were platform high voltage, power to all RF systems, the current to the large dipoles, and all transport line elements. This rapid switching of species will be a frequent mode of operation when RHIC and NSRL are both taking beams from EBIS.

INJECTION AND ACCELERATION IN BOOSTER

The 10-40 μ s pulse of ions from EBIS is injected at constant magnetic field into the 202 m circumference Booster ring by means of an electrostatic inflector and four programmable injection dipoles. These devices have been in use for many years for the injection of ions from Tandem as described in [5]. The inflector brings the incoming beam to the edge of the Booster acceptance and the dipoles produce a closed orbit bump that initially places the closed orbit near the septum at the inflector exit. During injection the orbit bump must be collapsed at a rate that keeps the injected beam from hitting the septum while continuing to allow beam to be injected into the machine acceptance. Since the revolution period of the ions in the ring is 10.4 μ s, injection occurs over a period of 1 to 4 turns around the machine. Assuming a nominal transverse emittance of 11π mm-mrad (95%, unnormalized), modelling of the injection process shows that in principle 4 turns can be injected into the machine acceptance with 100% efficiency.

He¹⁺, Ne⁵⁺, and Fe²⁰⁺ ions from EBIS have been injected and accelerated to kinetic energies of 500, 500, and 1000 MeV per nucleon, respectively, in Booster and have been extracted and transported to NSRL for irradiation of biological samples. Au³²⁺ ions from EBIS have been injected and accelerated to a kinetic energy of 100 MeV per nucleon, which is the energy required for efficient stripping to Au⁷⁷⁺ in the Booster-to-AGS transport line [5]. The number of ions per pulse observed just upstream of Booster (input), at injection and extraction, and the number delivered to NSRL, are summarized in Table 3.

The RF capture and acceleration efficiency for Fe²⁰⁺ is thought to be low because an RF de-bunching and re-bunching maneuver, required for acceleration of Fe²⁰⁺ to energies above 500 MeV per nucleon, extends the time spent at low energy where the loss rate is high.

Table 3: EBIS Ions in Booster and at NSRL

| Ion | Input | Injection | Extraction | NSRL |
|--------|-------|-----------|------------|-------|
| He 1+ | 33e9 | 23e9 | 12e9 | 8e9 |
| Ne 5+ | | | 14e8 | 9e8 |
| Fe 20+ | 12e8 | 6.5e8 | 2.6e8 | 1.4e8 |
| Au 32+ | 5.7e8 | 2.8e8 | 1.7e8 | |

Figure 4 shows traces associated with the injection, acceleration, and resonant extraction of helium ions at 500 MeV per nucleon. Here the red, yellow, and blue traces are the Booster main magnet current, the circulating beam current and the RF gap voltage respectively.

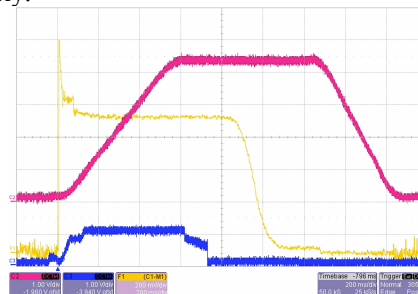


Figure 4: Acceleration and extraction of He¹⁺, showing Booster main magnet current (red), circulating beam current (yellow) and rf gap voltage (blue).

SUMMARY

All systems making up the new EBIS preinjector are operating as expected. The source has now operated for ~2000 hours, and while it has run continuously for periods of several days, this has not been typical since it is not yet ready for unattended operation, and the entire preinjector takes only ~40 minutes to start or shutdown. To date, the time spent optimizing beams in Booster has been very short, so further improvements in efficiencies are expected. He, Ne, and Fe beams from the preinjector have been used by the NSRL facility, while O, Ti, Ar, Au, and U beams are still planned for this spring's NSRL/RHIC run cycle.

REFERENCES

- [1] B. Visentin *et al.*, Phys. Scr., T 71 (1997) 204.
- [2] E. Beebe, *et al.*, "Experimental Study of the RHIC EBIS Performance", these proceedings.
- [3] M. Okamura, *et al.*, "Beam Commissioning Results for the RFQ and MEBT of the EBIS Based Preinjector for RHIC", Proc. Linac 2010.
- [4] D. Raparia, *et al.*, "Commissioning of the IH Linac and High Energy Beam Transport of the EBIS Based Preinjector for RHIC", Proc. Linac 2010.
- [5] C. Gardner, *et al.*, "Setup and Performance of the RHIC Injector Accelerators for the 2007 Run with Gold Ions", PAC'07, p. 1862.