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A HIGH-PERFORMANCE ELECTRON BEAM ION SOURCE*

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Abstract

At Brookhaven National Laboratory, a high current Electron Beam Ion Source (EBIS) has been developed as part of a new preinjector that is under construction to replace the Tandem Van de Graaffs as the heavy ion preinjector for the RHIC and NASA experimental programs. This preinjector will produce milliampere-level currents of essentially any ion species, with $q/A \geq 1/6$, in short pulses, for injection into the Booster synchrotron. In order to produce the required intensities, this EBIS uses a 10A electron gun, and an electron collector designed to handle 300 kW of pulsed electron beam power. The EBIS trap region is 1.5 m long, inside a 5T, 2m long, 8" bore superconducting solenoid. The source is designed to switch ion species on a pulse-to-pulse basis, at a 5 Hz repetition rate. Singly-charged ions of the appropriate species, produced external to the EBIS, are injected into the trap and confined until the desired charge state is reached via stepwise ionization by the electron beam. Ions are then extracted and matched into an RFQ, followed by a short IH Linac, for acceleration to 2 MeV/A, prior to injection into the Booster synchrotron. An overview of the preinjector is presented, along with experimental results from the prototype EBIS, where all essential requirements have already been demonstrated. Design features and status of construction of the final high intensity EBIS is also be presented.

INTRODUCTION

A new heavy ion preinjector is presently under construction at Brookhaven. This preinjector will replace two existing Tandem Van de Graaff accelerators and an 800 m transport line, as the heavy ion preinjector for both the Relativistic Heavy Ion Collider (RHIC) and NASA Space Radiation Laboratory (NSRL). The front end of the preinjector is shown in Figure 1. Following the IH linac, there is a 37 m long beam transport line matching the beam into a Booster synchrotron. A key component of this preinjector is a high-performance EBIS source, which is based on the successful performance of the prototype BNL Test EBIS. Other key elements of this preinjector include an RFQ and IH linac.

The preinjector is designed to deliver milliampere currents of any ion species in ~10 μs pulses, to allow single-turn injection into the Booster. Species from EBIS can be changed on a pulse-to-pulse basis, by changing the 1+ ion injected into the EBIS trap from the external ion sources. The switching time for the magnets in the beam transport line following the linac will be 1 second. Table 1 shows high-level parameters for the preinjector. In addition to it being a modern replacement for the aging Tandems, and its ability to produce any ion species rather than only those starting as negative ions, it also eliminates the need for any stripping foils before Booster injection, which will result in more stable beams.

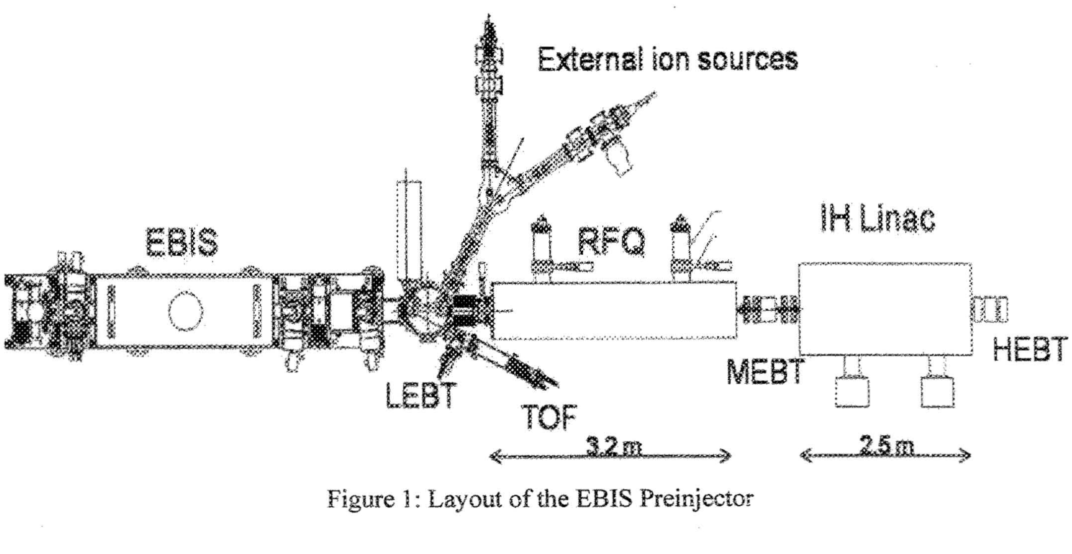

Figure 1: Layout of the EBIS Preinjector

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Table 1: Preinjector Parameters.

Ions	He – U
Q / m	≥1/6
Current	> 1.5 emA
Pulse length	10 µs (for 1-turn injection)
Rep rate	5 Hz
Final energy	2 MeV/u
Time to switch species	1 second

PREINJECTOR SYSTEMS STATUS

The EBIS source will be covered in detail in the later sections. Here, a brief status of the remaining components is presented.

RFQ

A 100 MHz, 4-rod RFQ will accelerate the beam from an input energy of 17 keV/amu, to 300 keV/amu. Some RFQ parameters are given in Table 2. The RFQ was built by A. Schempp, et.al. at the Institute of Applied Physics at the University of Frankfurt [1], with most of the fabrication by NTG [2].. The RFQ is now at Brookhaven (Fig. 2). Beams from the Test EBIS have been used for initial testing of the RFQ [3]. In early tests, we have accelerated He, Ne, and Cu beams, and while exact measurements of performance are complicated by the presence of multiple charge states entering the RFQ, results to date are consistent with the calculated performance.

Table 2: Parameters of the RFQ.

Input Energy	17 keV/u
Output energy	300 keV/u
Q / m	> 1 / 6
Frequency	100.625 MHz
Length	3.2 m
Power (with beam loading)	~ 200 kW

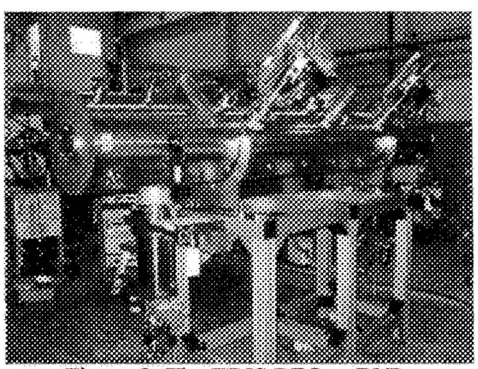

Figure 2: The EBIS RFQ at BNL.

Medium Energy Beam Transport

Following the RFQ, there is a ~1m matching section which consists of four pulsed magnetic quadrupoles for transverse matching, and one rebuncher cavity for longitudinal matching into the linac. The rebuncher cavity was built by IAP, Frankfurt, and is now ready for installation.

IH Linac

The IH Linac is being built by U. Ratzinger, et.al. at IAP, Frankfurt. Linac parameters are given in Table 3. The linac is designed for a beam current of up to 10 mA. Fabrication of the cavity by PINK [4] is complete, and the cavity is now at GSI for copper plating. The internal quadrupole triplet is being built by Bruker [5]. Linac drift tubes are complete, and the structure was assembled (with a dummy drift tube for the internal quadrupole triplet) for low level rf measurements, as shown in Fig. 3. The linac is scheduled for delivery in the fall of 2009.

Table 3: Parameters of the IH Linac.

Input energy	300 keV/u
Output energy	2 MeV/u
Q / m	> 1 / 6
Frequency	100.625
Cavity Length	2.46 m
Power (with beam loading)	~ 300 kW

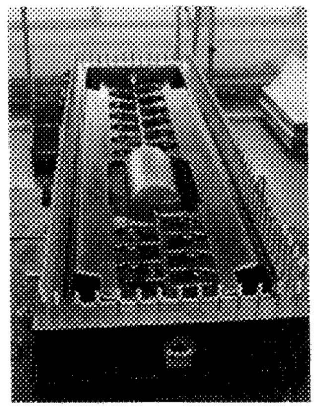

Figure 3: IH linac during initial rf testing.

High Energy Beam Transport

Following the linac, there is a 37 m long transport line to match beam into the Booster Synchrotron. This line consists of one pulsed quadrupole triplet, seven quadrupole singlets, and two 73 degree magnetic dipoles. Two debuncher cavities in the line reduce the beam energy spread going into Booster. The dipoles, made by Sigmaphi [6], have been installed in the Booster tunnel, as shown in Figure 4.

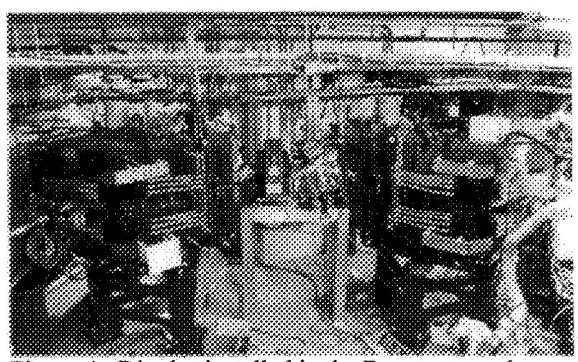

Figure 4: Dipoles installed in the Booster tunnel.

SOURCE REQUIREMENTS

The source requirements are shown in Table 4. An EBIS is well suited for meeting RHIC requirements. An EBIS can produce any type ions - from gas, metals, etc., and is easy to switch species, even pulse-to-pulse, when feeding the trap by injection of singly charged ions from external sources. One has precise control over the charge state produced, and it is easy to produce a distribution peaked at intermediate charge states such as Au^{32+} or U^{45+}. One has control over pulse width, extracting a fixed charge, so one can better match synchrotron requirements. EBIS produces a narrow charge state distribution (≥20% in the desired charge state), so there is less of a space charge problem in the extraction and transport of the total current. Finally, the source is reliable, has excellent pulse-to-pulse stability, and long lifetime.

Table 4: Source Requirements for the RHIC Preinjector

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	≥ 1/6, depending on ion
Pulse width	10 - 40 µS
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

TEST EBIS RESULTS

The Test EBIS was built to demonstrate all essential features of an EBIS meeting RHIC requirements. This half-trap length (half-yield), full power electron beam prototype is described in detail in [7]. The following are some key results:

- Electron beam currents greater than 10A have been propagated through the Test EBIS with losses less than 1mA.
- Au^{32+} has been produced in less than 35ms, Ne^{8+} in 18ms, N^{5+} in 4ms, and Cu^{15+}in 15ms. Charge state vs. confinement time agrees with calculations. A sample result for Ne is shown in Fig. 5,6.
- With external ion injection, 3.5×10^{11} charges/pulse of Au ions, and $\geq 2 \times 10^{11}$charges/pulse of Ne, N, and Cu have been achieved. In all cases our goal of extracting charge of 50% of the trap capacity has been exceeded (Fig. 7). ("Trap capacity" is the total number of electrons beam charges in the trap region, i.e. full space charge neutralization of the electron beam in the trap by ions).
- The above yields can be extracted in pulses of 10-20µs FWHM, resulting in extracted currents for these ions of several mA's.
- Emittance = 0.1 π mm mrad (rms normalized) has been obtained for a 1.7 mA beam extracted from the EBIS after Au injection, while lighter beams have emittances up to ~0.3 π mm mrad. (Since there is no separation of beam components, the emittance of all charge states were measured; individual charge state emittance could be smaller).
- The EBIS has operated on the pulsed high voltage platform at > 100 kV, producing the required 17 keV/u. The EBIS only has to be at high voltage during the < 50 µs ion extraction time, so pulsing of the high voltage reduces the likelihood of breakdowns, and allows the external ion sources and injection lines to sit at laboratory potential.
- Extracted beam has been matched into the RFQ with a LEBT including a gridded einzel lens and pulsed magnetic solenoid after the HV acceleration.

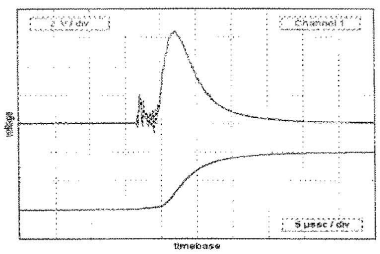

Figure 5: Neon beam pulse, 6.3 mA peak (upper) and integrated charge, 2.4×10^{11} (lower). I_e=6.8 A.

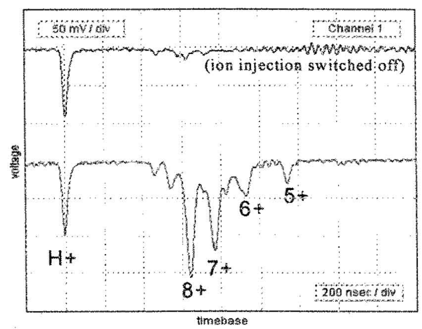

Figure 6: Ne time-of-flight spectra without and with ion injection (upper and lower), for 14 ms confinement time.

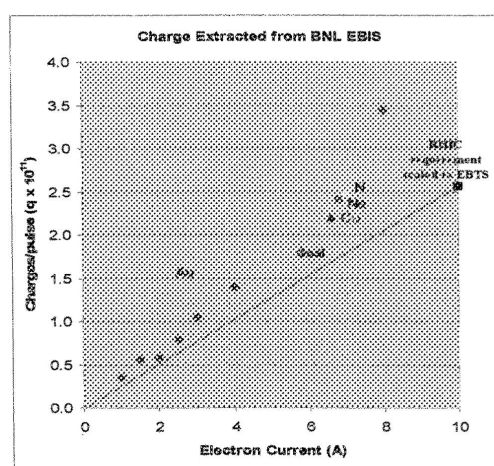

Figure 7: Ion yield vs. electron beam current, for various species

RHIC EBIS

The design of the RHIC EBIS is very similar to the prototype Test EBIS. For the RHIC EBIS, a straightforward doubling of the trap length by installing a longer superconducting solenoid is required, in order to double the ion output. Linear scaling of output with trap length has been shown on the Test EBIS over a range of 35-107 cm.

The design value of the electron beam current of 10 A is the same as run on the Test EBIS. The source is shown schematically in Fig. 8, and some key parameters are given in Table 5. All EBIS subassemblies have been fabricated, and have either already been tested, or are in the final assembly stages.

Table 5: RHIC EBIS Source Design Parameters.

Electron gun current	10 A
Solenoid field	5.5 T
Trap length	1.5 m
Pressure in the trap region	low 10^{-10} Torr
Total extracted charges per pulse	5 x 10^{11} (80 nC)
Total current per pulse (all charge states)	~8 mA in 10 μs
Output energy	17 keV/u

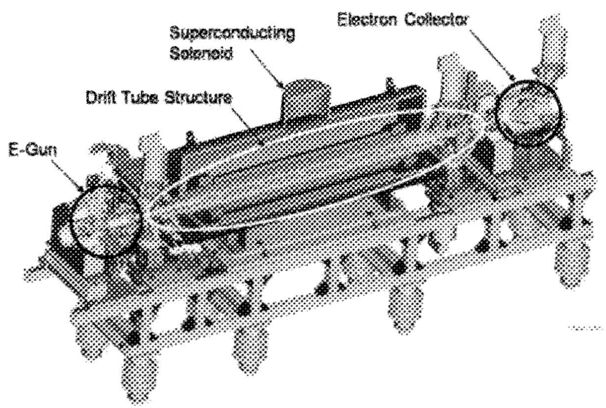

Figure 8: Drawing of the RHIC EBIS.

Electron Gun

The performance required for the RHIC EBIS can be achieved with the 10 A electron gun originally used on the Test EBIS. Nevertheless, it was desirable to have a safety margin with electron beam current for EBIS operation at 10A plus some prospects for increase of output ion intensity in the future. The electron gun cathode is a 9.2 mm diameter IrCe unit, made for BNL by BINP [8], and with this IrCe cathode one has the possibility of increasing emission and producing an electron current up to 20A. To reach electron current of I_{el}=20 A with existing 40 kV anode power supplies the perveance of the gun is doubled relative to our earlier gun, to ~$2.5 \cdot 10^{-6}$ $A/V^{3/2}$. The IrCe cathode can provide emission current density 40 A/cm^2, with an expected lifetime at this density of several thousand hours [9]. At 15 A/cm^2 required for 10A operation, the estimated lifetime is >20,000 hours. The design is based on the inverted magnetron geometry of our first electron gun of Novosibirsk design, which produces a laminar electron beam, allowing operation in a wide range of electron current, potential and magnet field distributions. It also allows substantial deceleration of the electron beam in the ion trap and electron collector regions. The cathode is immersed in a magnetic field of approximately 0.14 T.

The final electron gun has been successfully tested to 10 A on the Test EBIS, and has been in routine use there for ~ 6 months. It is shown schematically in Fig. 9.

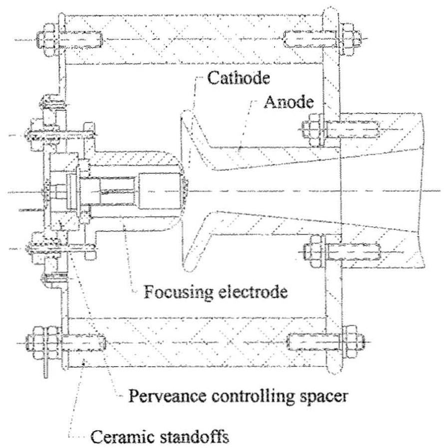

Figure 9: Schematic of the 20 A electron gun.

Electron Collector

The electron collector is designed to handle a nominal electron beam of 20 A, 15 kV dc, i.e. 300 kW, but since ionization times are typically < 50 ms, the electron beam can be pulsed at a duty factor < 25%, for a lower average power. The maximum heat load on the inner surface is ~350 W/cm^2 during the pulse, and averaged over the area being hit, is ~ 200 W/cm^2during the pulse. A collector fabricated from a Zr-Cr-Cu alloy is completed and has been in use on the Test EBIS, although the duty factor is low on Test EBIS due to power supply limitations. A second, spare collector has been completed which is identical, except that it is made from a high conductivity Be-Cu (Hycon3 HP). This should have somewhat better thermal fatigue lifetime. The collector is shown in Figure 10.

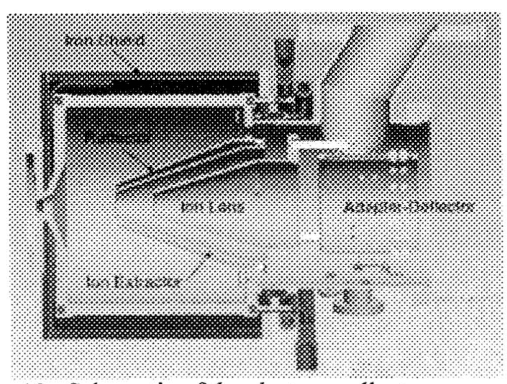

Figure 10: Schematic of the electron collector.

Superconducting Solenoid

The superconducting solenoid for the EBIS is 2 m long, with a 5 T field, and field uniformity sufficient to allow a 1.5 m trap length. The solenoid has a 204 mm diameter warm bore, to allow sufficient space for the vacuum pipe, which also has heating rods and water cooled shield for baking of the central trap region. The solenoid was fabricated by ACCEL Instruments [10], and following a failure during a quench test in 2007, it was repaired and passed factory acceptance testing in January, 2009. Some damage during shipping to Brookhaven has now been repaired, and the magnet has passed all acceptance tests. It is shown at BNL in Fig. 11.

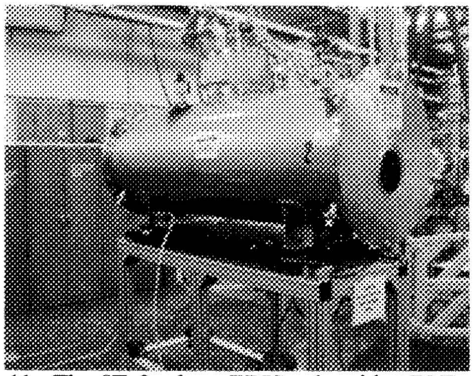

Fig. 11: The 5T, 2m long EBIS solenoid at BNL.

Central Trap

The central trap region consists of six cylindrical electrodes of ~42 mm diameter. The electron beam radius in the trap is ~0.8 mm (J_e~500 A/cm^2). There is NEG material running the length of the central vacuum pipe to provide extra pumping in this region. A pressure of ~10^{-10} T is required in this region to minimize contaminant ions. This inner trap electrode assembly is complete, and is shown in Fig. 12. Also shown in Fig. 12 is the outer vacuum chamber, with heating elements for baking, an outer cooling jacket, and steering coils. This unit has been successfully tested, reaching a central drift tube temperature in excess of the required 450 deg C, while maintaining the outer skin at room temperature.

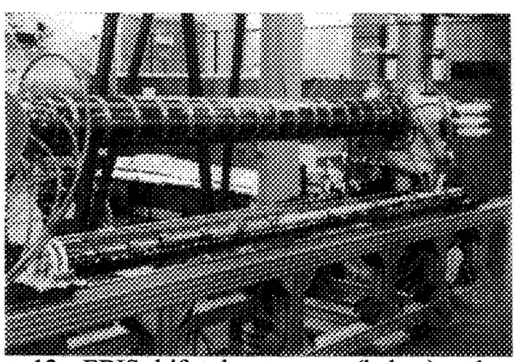

Figure 12: EBIS drift tube structure (below) and central vacuum chamber (above) where it will be inserted.

EXTRACTION AND TRANSPORT TO THE RFQ

The entire EBIS and its power supplies sit on a voltage isolated platform, and can be pulsed at up to ~ 100 kV to provide 17 keV/u for any ion species at Q/m > 1/6. This platform is pulsed to high voltage for only ~100 µs, during ion extraction. Matching into the RFQ is via one gridded einzel lens, and one pulsed magnetic solenoid. This matching section has been installed and operated on Test EBIS, to verify the performance of this LEBT. Emittance measurements are complicated by the presence of multiple charge states, but generally are consistent with expectations (rms values of ~0.1 – 0.3 pi mm mrad at the RFQ entrance location, depending on species).

EXTERNAL ION SOURCES

We rely on external ion injection to provide most ion species. In this manner, the EBIS functions purely as a charge state multiplier. One can easily change species and charge state on a pulse to pulse basis, and there is virtually no contamination or memory effect. To date, we have operated the EBIS successfully with external ion injection from a Metal Vapor Vacuum Arc Source, a Hollow Cathode Ion Source, and a Liquid Metal Ion Source. Injected 1+ ion currents of 10's to 100's of microamperes are required for seeding the EBIS trap, and these ions are transported to the EBIS at ~15 kV. In addition, for beams such as helium, we have used standard gas injection.

For the RHIC EBIS, we are building two ion sources plus injection lines, as can be seen in Fig. 1, which can be selected on a pulse-to-pulse basis. There is also a third port where 1+ ions from a laser ion source may be injected in the future [11], which offers the possibility of producing almost any desired 1+ beam from a single ion source.

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