

TEST EBIS Operation and Component Development for the RHIC EBIS[†]

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Abstract. Most design goals of the BNL Test EBIS Project have been exceeded and we are confident that an EBIS meeting RHIC requirements can be built. Achieved parameters include 10A electron beam current, ion charge state above Au³²⁺, and greater than 55nC total extracted ion charge. The Test EBIS utilizes the full electron beam power but has only half the trap length and operates at a reduced duty factor compared with an EBIS for RHIC, which would produce at least 85nC total ion charge in 10-40 microsecond pulses, containing $\sim 3 \times 10^9$ particles/pulse of Au³²⁺ ions. Normalized rms emittance values for 1-3mA extracted ion beams have been in the range of 0.08-0.1 pi mm mrad. Present development of the source is focused on establishing operational reliability and facilitating future upgrades in ion intensity and species, since the major emphasis is now on integrating the EBIS into a pre-injector facility, including an RFQ and linac. Recent progress towards this goal includes the following: 1) An IrCe electron gun cathode and modified anode have been installed in an electron gun chamber separable from the source ionization region by a gate valve. A very low loss 10A, electron beam has been propagated with the new configuration, with 100kW peak power dissipation at the electron collector. 2) A new electron collector power supply configuration has been tested which can lower the cost compared to our present setup, while improving the stability of the electron beam launch. This is an important first step towards placing the EBIS on a nominal 50kV platform, necessary for efficient highly charged ion transport to the RFQ. 3) A hollow cathode ion source obtained from CEA Saclay, [1] has been tested and is being installed. This will allow us to provide a variety of ion species to the RHIC and NASA Space Radiation Laboratory facilities, and is valuable at the present project stage for beamline development and emittance studies of heavy and light ion beams of highly charged ions from the EBIS. 4) An electron collector for RHIC has been designed which would allow operation exceeding 10A electron beams at 100% duty factor. The RHIC collector design could allow upgrades to 300kW electron beam power.[2] 5) Controls for pulse to pulse switching and diagnostics for charge state and charge fraction verification have been developed.

INTRODUCTION

The goal of the BNL EBIS program is primarily to supplying heavy ions such as gold to the Relativistic Heavy Ion Collider (RHIC). The NASA Space Research Laboratory (NSRL), uses beams such as iron and silicon, which are extracted directly from the Booster ring, the first of three synchrotrons in the RHIC complex. To obtain an intensity of 1×10^9 Au ions/bunch in RHIC, the source requirement for a linac based pre-injector such as an EBIS is $\sim 3 \times 10^9$ Au³²⁺ ions/pulse. In order to

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eliminate stripping (and associated losses) before the Booster ring, the source should deliver ions with $q/m > 0.16$ (e.g., Au³²⁺, Si¹⁴⁺, Fe²¹⁺). For 1-4 turn injection into Booster the EBIS pulse width should be 10-40 μ s. This results in peak currents between 0.4 and 1.6mA. The required repetition frequency is < 5 Hz and the emittance should be $\leq 0.35 \pi$ mm mrad, normalized, 90% for low loss at injection into the Booster.

An EBIS to meet these requirements would require ~ 20 times higher electron and ion charge than produced by other EBIS devices so a "Test EBIS" [3] was built at BNL to determine whether or not one could eventually meet the requirements for a RHIC EBIS. The Test EBIS is a $\sim 1/2$ length prototype of a RHIC EBIS, but with the full 10A electron beam. Descriptions of the Test EBIS and early results have been given in depth in earlier publications. [4, 5] In this article some of the notable source aspects are given and previous results are summarized. We will also present our most recent work which has shifted towards ensuring that one can deliver the required ions to the accelerator facility with very high reliability suitable for long term RHIC operation.

SOME DESIGN CHOICES AND FEATURES

In order to provide consistent performance, high reliability, and reduce downtime for maintenance, we have taken care to separate the functions of source components and remove as much of the complication as possible from the high vacuum ionization region. For example, we have decided to rely on external ion injection to provide the ion species. In this manner, the EBIS functions purely as a charge state multiplier, and the processes involved in low charge state ion production can be done in various easily accessible auxiliary ion sources. Only the necessary number of seed ions are injected into the ultrahigh vacuum EBIS ionization volume. This also avoids the need for cryogenic pumping within the ionization volume, which has been shown to be very valuable for "gas" injection techniques, but has also exhibited problems in long term EBIS operation such as memory effects which limit ion production when the ion species must be changed. In addition, for sources using high current electron beams the cryogenic vacuum can easily be destroyed by relatively low electron beam losses. The advantages of an EBIS working with ion injection are many: once the proper ion optics configurations are set up and stored, one can easily change species and charge state on a pulse to pulse basis, there is virtually no contamination or memory effect, and several relatively low cost external sources can be connected by gate valves and maintained independently of the EBIS.

A feature that is especially notable in the BNL Test EBIS is the extended axial magnetic field. This has been accomplished by using auxiliary warm solenoids in addition to the main Superconducting solenoid. A schematic of the axial magnetic field and electron beam radius with respect to the internal EBIS electrodes is given elsewhere in these proceedings [6] This configuration has proved useful for providing independent e-beam launch, compression, and collection; facilitating HV connections, pumping, and vacuum separation; and providing the possibility of including gate

valves for source partitioning during gun or collector servicing without the need for retractable gun or collector mechanisms.

BNL Test EBIS performance represents more than an order of magnitude improvement over past EBIS sources. At the same time, operation has been very reproducible and stable. Some of the key features, many of which are unique to this EBIS, are the following:

- Novel electron gun design by BINP [7] uses a convex LaB6 / IrCe cathode
- Warm bore, unshielded superconducting solenoid for the main trap region
- Vacuum separation of the trap region from the electron gun and electron collector regions aided by the use of auxiliary warm solenoids
- Large bore (32mm) drift tubes have been used (pumping, reduced alignment precision, fast extraction, reduced RF coupling)
- Transverse magnet coils for electron beam steering corrections
- Pulsed electron beam to reduce the average power on the electron collector
- Versatile controls allow one to easily apply a time dependent potential distribution to the ion trap.

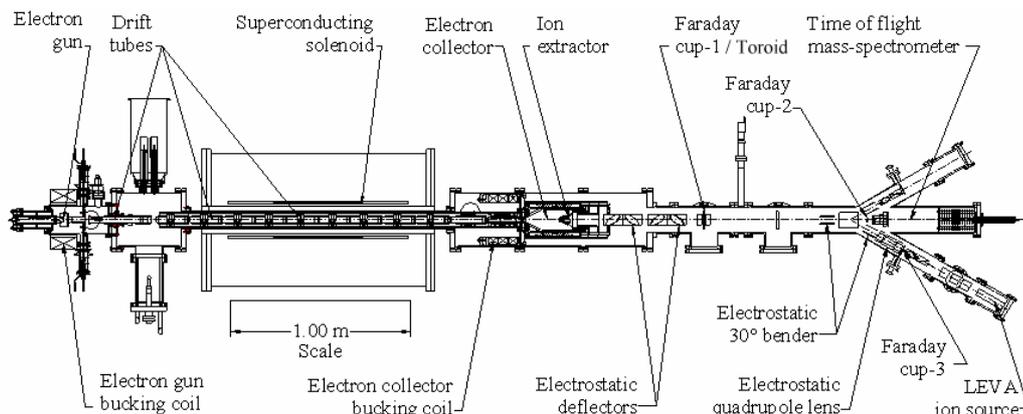


Figure 1. Test EBIS overview showing ion injection and extraction to the time of flight spectrometer.

A schematic of the BNL Test EBIS and external beamline is displayed in Figure 1, showing the auxiliary ion source in one arm of the “y-chamber” and the Mamyrin (energy focusing) high resolution time-of-flight (TOF) spectrometer at the end of the straight beamline. We have replaced the internal six segment Faraday cup-1 with an external Toroid current transformer. This allows us to make non-destructive total current measurements of both the injected and extracted beams, but has resulted in some loss of beam profile information. In addition, we have added a standard TOF in straight section. A high transparency gridded chopper can be inserted close to the exit of the collector and Faraday cup 2, which can capture the entire ion beam, serves as the detector. One of the challenges for the RHIC EBIS is to provide a compact EBIS to RFQ beamline that can accommodate ion injection (bend) optics, lenses, and beam diagnostics such as TOF, beam profile monitors, and emittance measurement. [8]

RESULTS

All EBIS results pertaining to gold ions were obtained using the Low Energy Vacuum Arc (LEVA) ion source obtained from LBNL. [9] In Figure 2 the data points show the number of charges per pulse obtained from the Test EBIS versus electron beam current. The solid line shows the RHIC requirement, scaled to account for the fact that the Test EBIS is only half the length of the RHIC EBIS.

- Electron beam – currents greater than 10A have been propagated through the Test EBIS with losses less than 1mA.
- Ion output – total ion charge after Au injection from the LEVA and a 30ms confinement in an 8A electron beam was more than 55nC.
- Charge state – Au³²⁺ has been produced in less than 35ms
- Pulse width – A 3.2mA, 12 μ s FWHM, (40nC) Au ion pulse was obtained at the source exit toroid using a 6.8A e-beam, after a 15ms confinement.
- Emittance – 0.1 π mm mrad rms normalized has been obtained for a 1.7mA beam extracted from the EBIS after Au injection from the LEVA source.

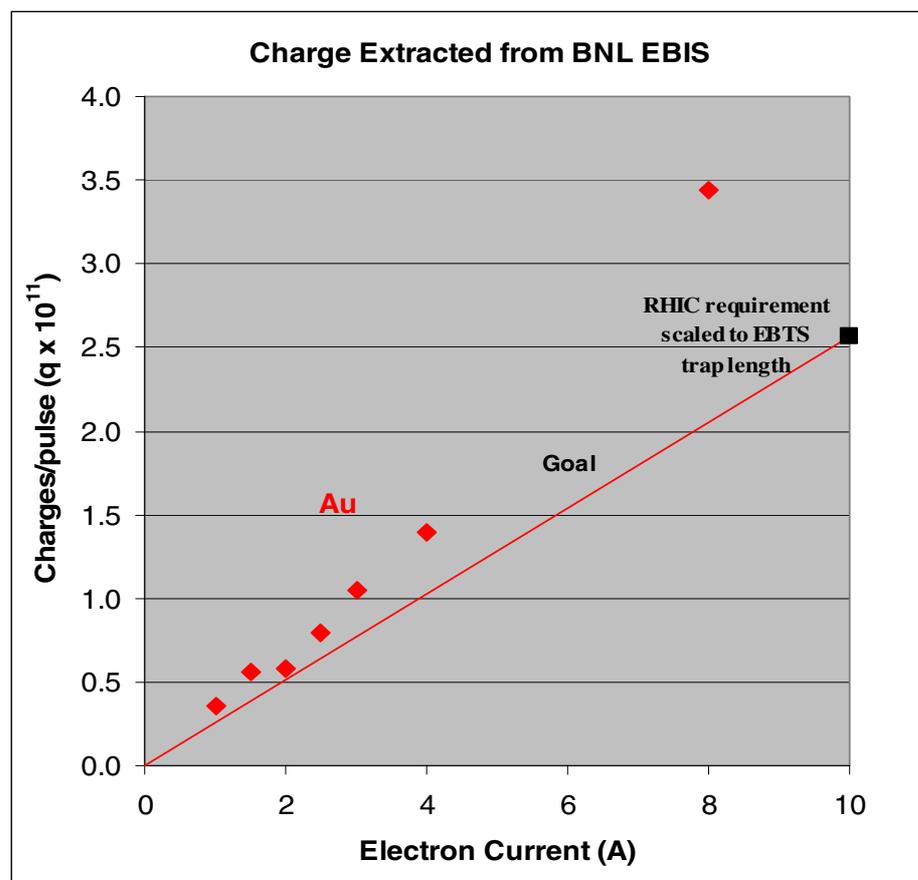


Figure 2. Au yield from the BNL Test EBIS versus electron beam current

Table 1

	Achieved	RHIC
Ion	Au ³²⁺	Au ³²⁺
I_e	10 A	10 A
J_e	500 A/cm ²	500 A/cm ²
t_{confinement}	35 ms	35 ms
L_{trap}	0.7 m	1.5 m
Capacity	0.51 x 10 ¹² charges	1.1 x 10 ¹² charges
% extracted ions	> 75%	50%
% in desired Q	20%	20%
Extracted charge	> 55 nC	85 nC
Ions/pulse	>1.5 x 10 ⁹ (Au ³²⁺)	3.3 x 10 ⁹ (Au ³²⁺)
Pulse width	10-20 μs	10-40 μs

Table 1 shows the parameters for an EBIS meeting RHIC requirements, as well as parameters already achieved on Test EBIS. For RHIC the straightforward doubling of the trap length by installing a longer superconducting solenoid is required. Linear scaling with trap length on the Test EBIS has been shown over a range of ~35-107 cm.

An in-line TOF spectrometer was developed to use in conjunction with the high resolution Mamyrin type TOF spectrometer developed earlier. Although it was not designed to have a high resolution, it has the advantage that the entire beam cross section is sampled and transported to a Faraday cup along the beam path between the EBIS and (future) RFQ. Thus, an accurate quantitative measurement of the charge distribution of the desired species and impurities can be made. Figure 3 shows an inline TOF spectrum of gold ions produced using a 7A electron beam and 10ms

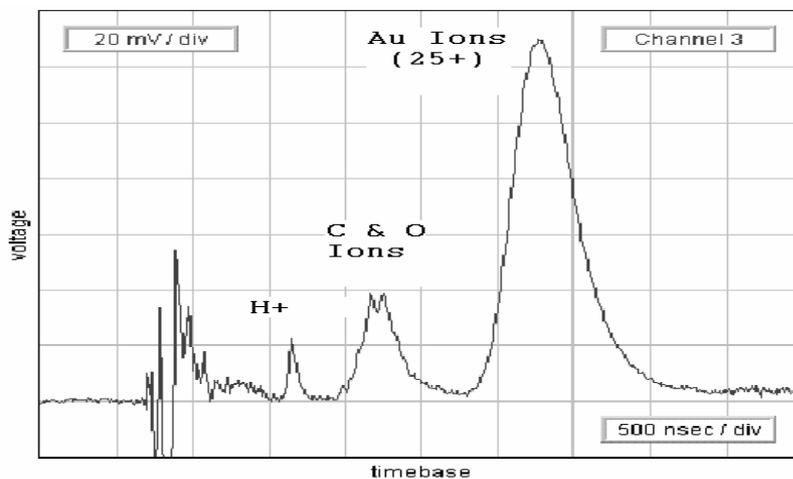


Figure 3. Inline Time-of-flight spectrum showing Au = 83%; C&O = 15%; H = 2%.

confinement period. A 100 ns sample of EBIS total extracted ion current pulse was made and measured on a Faraday Cup about 1.5 m downstream from a high transparency gridded chopper. One can see that the gold ion charge exceeded 80% of the total ion beam and is well separated from the light impurity ions.

COMPONENT DEVELOPMENT

During the past few years the “scientific” feasibility of building an EBIS that would meet RHIC requirements has been demonstrated. All parameters have been met or exceeded, assuming the doubling of the source trap length in the RHIC EBIS will provide a doubling of the total charge produced. In addition, the high power RHIC EBIS collector will allow operation at the 5 Hz repetition rate required for injection into the AGS booster ring. Therefore, work continues towards building an EBIS for RHIC, the emphasis is on component improvement and selection to produce a reliable “operational” device. To accomplish this we intend to:

- 1) increase engineering margins, especially the electron gun and collector, with the goal of increasing lifetime and also to accommodate future upgrades in electron current;
- 2) provide increased versatility, for example, develop the ability to change ion species on a pulse to pulse basis;
- 3) simplify source maintenance by making the source modular with gate valves to partition the gun, ionization and collector volumes in order to preserve ultra high vacuum in areas where maintenance is not required;
- 4) provide device protection through power supply fault detection, current limits and control system monitoring of currents and pressures.

IrCe Gun, Gun Chamber Gate Valve, and Anode Modification

During the past year we have modified the anode and first drift tube to accommodate the addition of a gate valve between the electron gun chamber and the ionization region, as shown in figure 4. The gate valve facilitates cathode replacement and electron gun upgrades without disturbing the ionization volume ultra-high vacuum. The anode and first drift tube were tapered to allow for electron beam to expansion in the resulting low magnetic field region between the launch solenoid and main solenoid. During the past few months, IrCe cathodes have been delivered from BINP, Novosibirsk. At our design electron current of 10A, the IrCe cathodes have lifetimes ~20,000 hours, several times longer than the LaB6 cathodes previously used. In addition, they provide the possibility of increased emission for either a marginal increase in electron current of a few amperes or a future upgrade of electron current up to 20A, via a modification of the gun electrode geometry. The IrCe cathode has been installed in the Test EBIS and electron beams up to 10A, and 100kW peak power dissipation on the electron collector have been propagated with very low loss. An in depth treatment of possible 20A electron gun and a 300kW electron collector design for the RHIC EBIS are given elsewhere in these proceedings.[2]

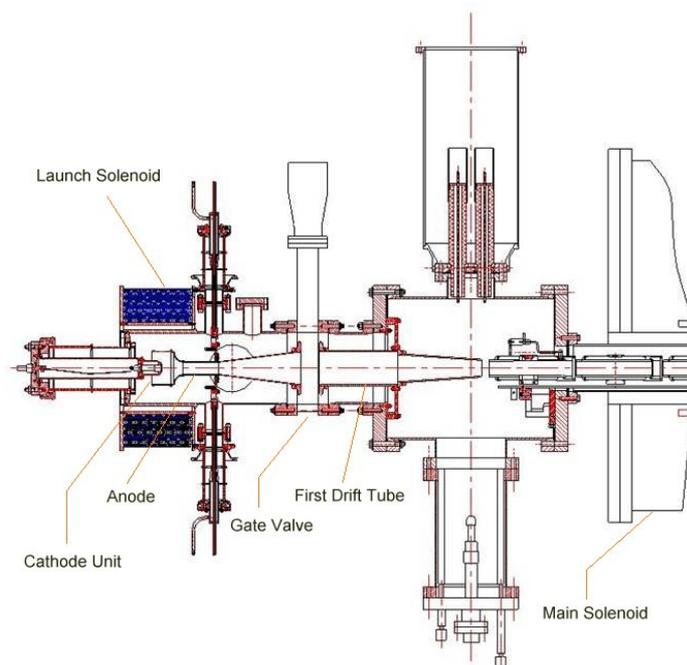


Figure 4. Test EBIS gun region configuration after electron gun gate valve installation.

RHIC EBIS Solenoid

The RHIC EBIS will have an ionization region 1.5m long, approximately twice the length of the Test EBIS. The design presently includes a 6-8 Tesla, 200mm warm bore, ~2m long superconducting solenoid. Discussions are in progress with the BNL Magnet Division concerning the design, construction, and cost of such a solenoid.

Electron Beam Platform Development

When work was started on the BNL Test EBIS, use was made of an existing, 30 year old, regulated, negative polarity 15 A, 15 KV power supply to provide the electron beam collection. This led to an electron gun platform design in which the electron collector is held at laboratory ground through a current fault sensing device and the supply voltage determines both the electron beam energy at collection and the cathode bias, see figure 4a.

Reconfiguration of our electron beam platform will provide both more versatile performance and cost savings for the RHIC EBIS through the use of a separate bias or “accelerator” supply and an unregulated high power (15kV, 15-20A) supply for the electron beam collection, as shown in figure 4b. The low current (~15mA, 15kV) regulated accelerator supply provides stable electron beam launch conditions, independent acceleration voltage (i.e., beam energy control), and built in electron beam fault protection, i.e., current limiting of the supply will cause a collapse of the cathode bias voltage if electron current is loss from the electron beam circuit exceeds ~15mA. An unregulated collector supply can be used since the electron beam collection conditions are much less stringent than the launch conditions. Ion optical effects of the time dependent collector voltage with electron beam loading on the injection and extraction of ions from the EBIS can be compensated through synchronization adjustments made with the EBIS voltage and timing controller. To

test the effect of collector voltage sag on electron beam propagation, the concept shown in figure 4b was implemented using a crude collector supply configured from a 50 μF capacitor and a charging supply. A 4A, 50ms pulsed electron beam was propagated through the EBIS, resulting in a collector voltage sag of $\sim 3.7\text{kV}$ from the nominal 10kV applied. Very low loss e-beam propagation was maintained, in contrast to the large losses that result with just a few hundred volt variation in the usual configuration shown in figure 4a.

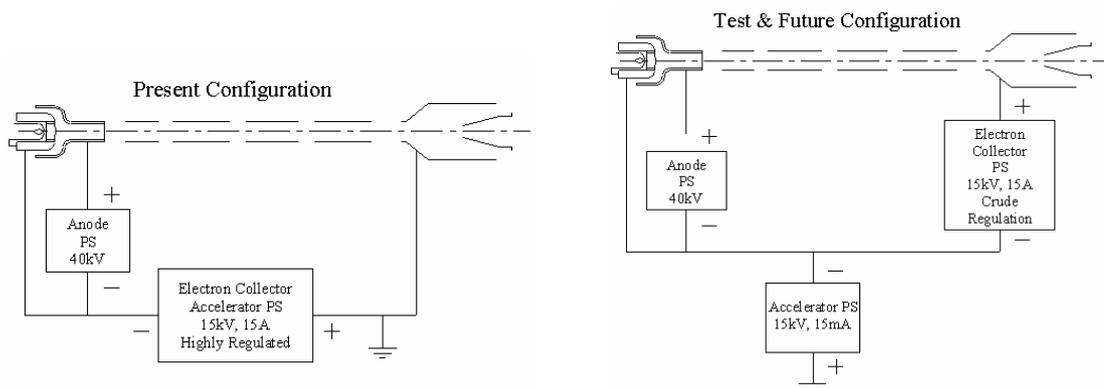
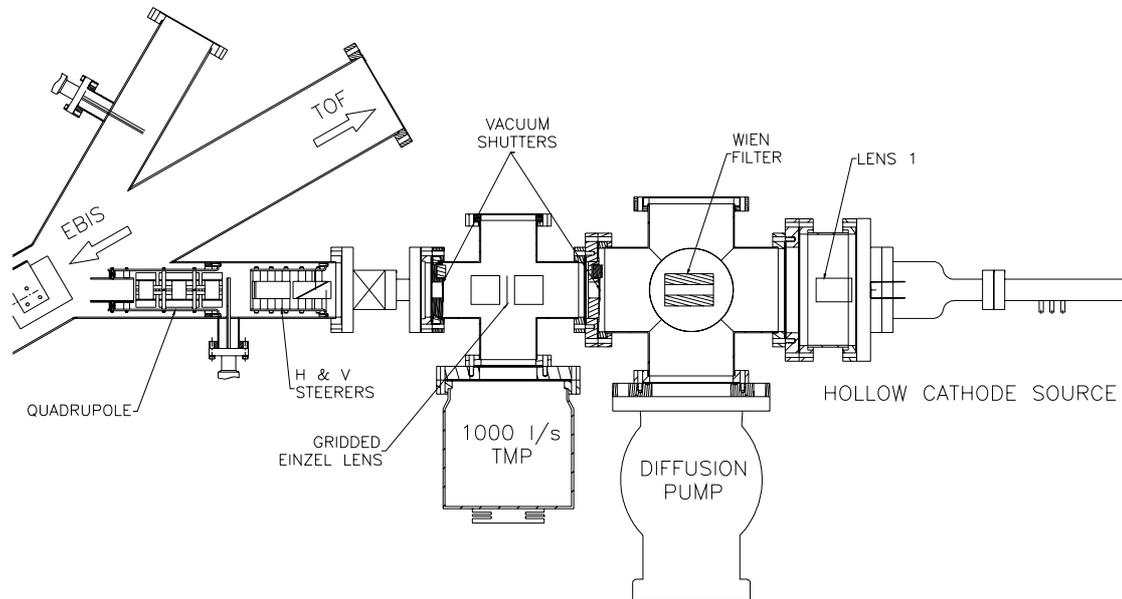


Figure 4. Electron beam platform configurations a) present (left) b) test and future (right).

Hollow Cathode Ion Source

We have recently obtained a Hollow Cathode Ion Source (HCIS) from CEA Saclay which was previously used as an ion injector for the EBIS “Dione” for ions such as Cu, Au, and U. [1] The source simultaneously produces ions of the working gas which is typically Ne, Ar, or Xe. The HCIS has been bench tested at BNL using a copper cathode with neon gas. Cu^{+1} beams of up to $15\mu\text{A}$, 15kV have been extracted from a pulsed 1ms, 3A discharge using a 1.5mm plasma electrode aperture. When optimized for Cu production, the Cu^{+1} and Ne^{+1} ion currents are similar. Up to $80\mu\text{A}$ of Ne^{+1} has been extracted (when copper is not optimized). An ExB (Wien) filter is used to select the 1+ species of interest (such as Cu^{+1}) for trapping in the EBIS electron beam, which is useful for maximizing the number of ions that can be injected. Species purity is desirable since an EBIS source has a fixed trap capacity for ion charge. The number of ions that can be captured during the roundtrip fast injection process is inversely proportional to the ion velocity in the ionization region. The emittance of the Cu^{+1} beam has been measured for a $10\mu\text{A}$, 10kV beam and is 16 pi mm mrad (rms) which is below the acceptance value determined by computer simulation of the Test EBIS. [6]

The HCIS has recently been installed at the test EBIS on a branch of a “y-chamber” which contains deflection plates for bending the ion beam into the EBIS beamline, figure 5. One of the challenges posed by the use of the HCIS is the necessity to provide adequate differential pumping between the HCIS which operates at ~ 1 mb and the EBIS ionization region which must be maintained at $\sim 1 \times 10^{-10}$ mb. Two 25mm Uniblitz[®] [10] electronically controlled fast shutters (minimum open time



$P \sim 4 \times 10^{-8}$ mB

$P \sim 4 \times 10^{-6}$ mB

$P \sim 8 \times 10^{-5}$ mB

$P \sim 0.8$ mB

Figure 5. HCIS beamline schematic showing ion optics, and pumping configuration. Pressures are given underneath the corresponding differentially pumped chambers. A pressure of $\sim 2 \times 10^{-10}$ mB has been obtained in EBIS Ionization region with the HCIS operating.

is ~ 6 ms) and restrictive apertures to help provide differential pumping. The HCIS will be useful for optimizing the beamline ion optics and will help us to measure the ion injection efficiency. An important result has already been obtained: we have verified that the EBIS ionization volume remains below 2×10^{-10} mb for a shutter open time of 10ms with a 1Hz repetition rate (i.e., 1% duty factor) and neon gas. For a 10% duty factor the pressure reaches 6×10^{-10} mb.

SUMMARY

With the Test EBIS, more than an order of magnitude improvement in EBIS performance has been achieved. For example, the electron beam current has been increased from ~ 0.5 A to >10 A, and the extracted ion charge has been increase from a few nano-Coulombs to >55 nC. The RHIC EBIS design will be very similar to the present EBIS operating at BNL. No significant improvement in performance is required, other than the straightforward scaling of ion output with an increase in trap length. Operation at the required duty factor will be made possible by introduction of an electron collector capable of higher average power dissipation. Beyond this, changes to the Test EBIS design, which was a device built to demonstrate feasibility, will make the RHIC EBIS an “operational” device, i.e. simpler to maintain, and more reliable due to increased engineering margins on components.

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