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ELECTRON BEAM ION SOURCE PRE-INJECTOR PROJECT (EBIS)

CONCEPTUAL DESIGN REPORT

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TABLE OF CONTENTS

1. SUMMARY 6
2. INTRODUCTION 7
   - 2.1. FEATURES AND ADVANTAGES OF THE NEW PRE-INJECTOR 8
   - 2.2. THE EBIS SOURCE 9
3. FUNCTIONAL REQUIREMENTS AND PERFORMANCE SPECIFICATIONS 11
4. BACKGROUND 14
   - 4.1. RESULTS OF THE TEST EBIS 14
   - 4.2. DEMONSTRATION OF HIGH CURRENT ELECTRON BEAM FORMATION AND PROPAGATION 17
   - 4.3. EXTRACTION OF IONS FROM THE TEST EBIS TRAP 20
   - 4.4. FAST EXTRACTION OF IONS FROM THE TEST EBIS TRAP 21
   - 4.5. MEASUREMENT OF CHARGE STATE DISTRIBUTION OF IONS FROM TEST EBIS 22
   - 4.6. EXTERNAL ION INJECTION 24
   - 4.7. ADDITIONAL TEST EBIS RESULTS 27
   - 4.8. SUMMARY OF TEST EBIS PERFORMANCE 28
5. TECHNICAL DESIGN 29
   - 5.1. DESIGN OF THE NEW PRE-INJECTOR 31
   - 5.2. RHIC EBIS 32
     - *5.2.1. Features of an EBIS for RHIC* 32
     - *5.2.2. Electron Gun* 32
     - *5.2.3. Electron Collector* 34
     - *5.2.4. Drift Tube Structure* 41
     - *5.2.5. Superconducting Solenoid* 41
     - *5.2.6. EBIS Vacuum System* 42
     - *5.2.7. Seeding the EBIS Trap* 44
     - *5.2.8. EBIS Power Supply Requirements* 46
     - *5.2.9. EBIS Controls and Timing* 49
   - 5.3. LEBT 50
   - 5.4. RFQ 54
     - *5.4.1. Choice of Parameters* 54
     - *5.4.2. Specifications* 54
     - *5.4.3. Beam Dynamics* 55
   - 5.5. MEBT 61
   - 5.6. LINAC 62
     - *5.6.1. Specification of Parameters* 63
     - *5.6.2. Beam Dynamics* 63
   - 5.7. HEBT 69
     - *5.7.1. Charge Discrimination* 72
   - 5.8. BOOSTER INJECTION 73
     - *5.8.1. EBIS Beam* 73
     - *5.8.2. Space Charge Effect* 74
     - *5.8.3. Longitudinal Aspects* 74

5.8.4. *Inflector Aperture Limit and Scraping Effect* 77
5.9. DIAGNOSTICS **79**
5.9.1. *EBIS Time of Flight (High Resolution & Inline)* 80
5.9.2. *EBIS Emittance* 81
5.9.3. *Faraday Cups* 81
5.9.4. *Current Transformers* 82
5.9.5. *Profile Monitors* 82
5.10. RF SYSTEMS **82**
5.11. MAGNETS **84**
5.12. CONTROLS **86**
5.12.1. *Timing & Infrastructure* 86
5.12.2. *EBIS* 86
5.12.3. *Accelerators & Beam Transport* 87
5.13. VACUUM SYSTEM **87**
5.14. COOLING SYSTEMS **90**
5.14.1. *RHIC EBIS Water Cooling* 90
5.14.2. *Water Cooling Requirements* 93
5.15. FACILITY MODIFICATIONS **95**
5.15.1. *Beam Access Port* 95
5.15.2. *Power Modifications* 95
5.16. INSTALLATION **96**
5.17. ESSH **96**
5.17.1. *Review of ESSH Issues Associated with the EBIS Design* 96
5.17.2. *ESSH Plans for Construction* 101
5.17.3. *ESSH Plans for Commissioning, Operations and Decommissioning* 105

6. COST AND SCHEDULE **108**

6.1. OVERVIEW **108**
6.2. COST **110**
1.1 Structural Components 110
1.2 Controls 112
1.3 Diagnostics 113
1.4 Magnet Systems 114
1.5 Power Supplies 115
1.7 Vacuum Systems 116
1.8 Cooling Systems 117
1.9 Facility Modifications 117
1.10 Installation 117
1.11 Project Services 118

APPENDIX A PARAMETER LIST **120**

APPENDIX B SUMMARY PRELIMINARY COST ESTIMATE TABLE **121**

APPENDIX C DOE FUNDING AND TPC **122**

APPENDIX D NASA ITEMS **123**

GLOSSARY **124**

REFERENCES **126**

Summary

This report describes a new heavy ion pre-injector for the Relativistic Heavy Ion Collider (RHIC) based on a high charge state Electron Beam Ion Source (EBIS), a Radio Frequency Quadrupole (RFQ) accelerator, and a short Linear accelerator (Linac). The highly successful development of an EBIS at Brookhaven National Laboratory (BNL) now makes it possible to replace the present pre-injector that is based on an electrostatic Tandem with a reliable, low maintenance Linac-based pre-injector. Linac-based pre-injectors are presently used at most accelerator and collider facilities with the exception of RHIC, where the required gold beam intensities could only be met with a Tandem until the recent EBIS development. EBIS produces high charge state ions directly, eliminating the need for the two stripping foils presently used with the Tandem. Unstable stripping efficiencies of these foils are a significant source of luminosity degradation in RHIC. The high reliability and flexibility of the new Linac-based pre-injector will lead to increased integrated luminosity at RHIC and is an essential component for the long-term success of the RHIC facility. This new pre-injector, based on an EBIS, also has the potential for significant future intensity increases and can produce heavy ion beams of all species including uranium beams and, as part of a future upgrade, might also be used to produce polarized ^{3}He beams. These capabilities will be critical to the future luminosity upgrades and electron-ion collisions in RHIC.

The proposed pre-injector system would also provide for a major enhancement in capability for the NASA Space Radiation Laboratory (NSRL), which utilizes heavy-ion beams from the RHIC complex. EBIS would allow for the acceleration of all important ion species for the NASA radiobiology program, such as, helium, argon, and neon which are unavailable with the present Tandem injector. In addition, the new system would allow for very rapid switching of ion species for NSRL experiments, reducing delays due to the interference with RHIC injection operations, and allowing enhanced mixed field radiation studies.

The new RFQ and Linac that are used to accelerate beams from the EBIS to an energy sufficient for injection into the Booster are both very similar to existing devices already in operation at other facilities. Injection into the Booster will occur at the same location as the existing injection from the Tandem.

2. Introduction

The present pre-injector for heavy ions for the Alternating Gradient Synchrotron (AGS)/RHIC uses the Tandem Van de Graaff, built around 1970. The beam is transported to the Booster via an 860 m long line, as shown schematically in Figure 2.1. The proposed replacement consists of an Electron Beam Ion Source, followed by a Radio Frequency Quadrupole accelerator, and a short Linac. This new pre-injector offers improvements in both performance and operational simplicity, as described below.

The present state of EBIS development is discussed in Section 4. In Section 5 the design of the new pre-injector is presented, including features of the EBIS for RHIC, and details of the following acceleration stages. A description of injection into the Booster is also given in Section 5.

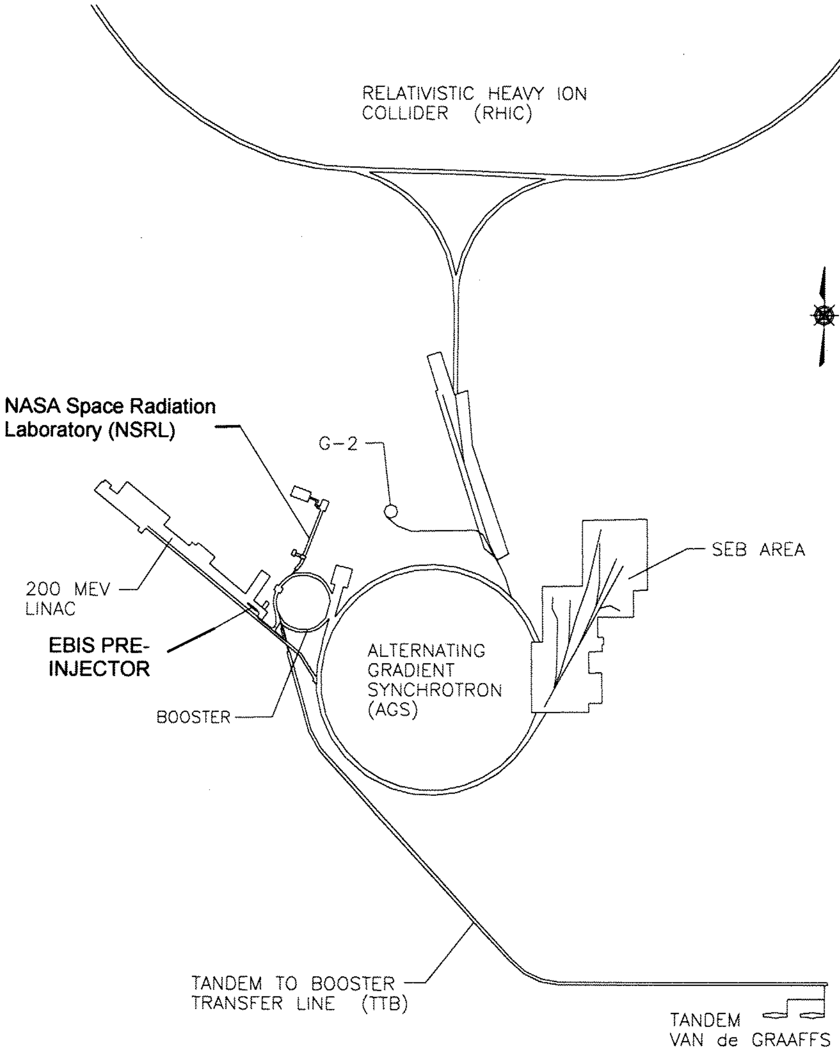


Figure 2.1 Schematic of the present Tandem injection and future EBIS injection lines.

2.1. Features and Advantages of the New Pre-Injector

Linac-based pre-injectors are presently used at most accelerator and collider facilities with the exception of RHIC, where the required gold beam intensities could only be met with a Tandem until the recent EBIS development. The high reliability and flexibility of a new Linac-based pre-injector will be an essential component for the long-term success of the RHIC facility. The Linac-based pre-injector offers the following advantages:

- While the Tandem has proven to be reliable, quite a few of its systems are becoming obsolete, and would have to be replaced to maintain reliable long-term operation for RHIC and NSRL. The RFQ and Linac are a simpler, modern, more robust technology, which will require less maintenance. This is similar to our very favorable experience of replacing a large electrostatic device, the Cockcroft –Walton preaccelerator, with a compact RFQ accelerator for H^- ions in the 200 MeV Linac. In that case, one went from a device that occupied one person full time with maintenance, to the RFQ, which requires almost no maintenance and has had almost no downtime over its 15 years of operation.

- The Tandem requires stripping foils at two locations. Increased energy spread in the Tandem beam as the foils age (thicken), and foil lifetime reduces reproducibility and integrated luminosity of RHIC operation. The EBIS requires no stripping before the Booster, which will result in more stable beam intensities.

- The 860 m long Tandem-to-Booster transport is difficult to tune, especially when changing the species. The new line will be only about 30 m long, and will use a more stable FODO lattice, reducing setup times.

- The EBIS will inject only 1-4 turns into the Booster, as opposed to 30-40 from Tandem, so injection will be much easier.

- The higher Booster injection energy for heavy beams will reduce losses at injection.

- Tandem species are limited to ions starting as negatives, while the EBIS can produce all ions. This give the ability to provide ions not presently available for the NASA program, such as noble gas ions (major components of galactic cosmic rays), as well as more massive ions such as uranium and, with additional enhancements, polarized ^{3}He, for the RHIC program.

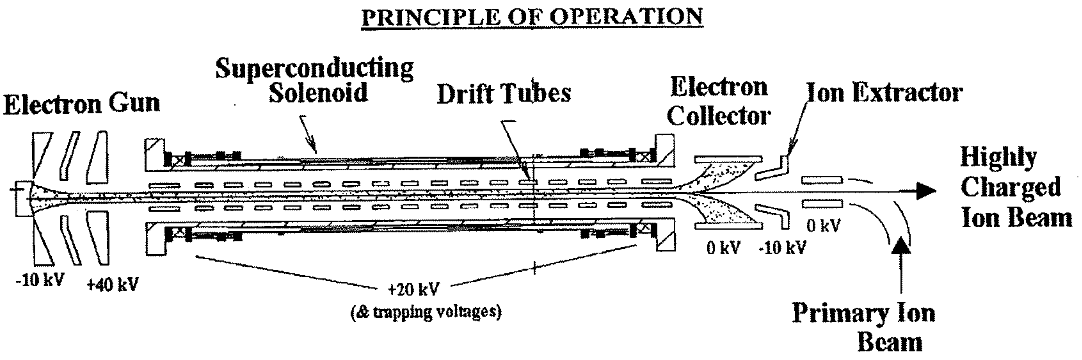
- The EBIS can switch species very quickly, for filling RHIC with two different ions, or for fast switching between RHIC and NSRL. Fast switching with the Tandem requires the use of the two BNL Tandems, leaving no spare Tandem.

With the long-term commitment to heavy ions at BNL for RHIC, and increasing demands for different species and delivery of beams to different users, the EBIS pre-injector will enhance capabilities significantly. Undoubtedly, additional benefits of the EBIS pre-injector will appear as one gains experience and explores the new parameter space it will present.

2.2. The EBIS Source

The principle of operation of an Electron Beam Ion Source is shown schematically in Figure 2.2. At one end an electron beam is produced, and then compressed to high density as it enters a strong solenoidal magnetic field. The beam passes through the solenoid, is decelerated, and then stopped in the electron collector. The EBIS trap region is a series of cylindrical electrodes in the main solenoid. Electrostatic barriers for ions are produced on the ends of the trap region by applying positive voltages on the end electrodes. Ions are confined radially by the space charge of the electron beam. The trap is seeded either by injecting neutral gas of the desired species, or by axial injection and trapping of singly charged ions produced in an external ion source. As the ions are held in the trap, they are step-wise ionized, until the desired charge state is reached, at which time the voltage on one end electrode is reduced and the ions are extracted. They pass axially through the electron collector and into a beam transport line.

One essential feature of the EBIS is that it produces a narrow charge state distribution, with the charge state in the peak increasing as the product of electron beam current density and ion confinement time, $j\tau$, increases. It is therefore straightforward to achieve any desired charge state; this is especially the case for an EBIS for RHIC where the needed charge states are very modest. A second feature of EBIS is that it produces a fixed amount of positive charges per pulse. The number of trapped charges can increase only to the point where the space charge of the electron beam is neutralized. The maximum yield of positive charges therefore roughly equals the electron beam charge in the trap (trap capacity). Neutralization efficiency is the ratio of extracted ion charge to trap capacity, and is usually greater than 50%, but can be as high as 100%. As shown in the equation in Figure 2.2, the yield of the desired charge state is the product of trap capacity, neutralization efficiency, and fraction in the desired charge state.



Yield of ions in charge state q:

$$N_q = \frac{I_e \times L}{q \times \sqrt{V_e}} \times K_1 \times K_2$$

I_e=electron beam current
V_e=electron beam voltage
L=trap length
K_1=neutralization factor
K_2=fraction in desired charge state

Figure 2.2 Principle of EBIS Operation

An EBIS delivers ion pulses having a constant total positive charge, and one has control over the pulse width by controlling the release of the trap voltage. Ions can be extracted in short pulses of high current, which is desirable for synchrotron injection. With the properties of an EBIS being well understood, one can arrive at design parameters for an EBIS meeting RHIC requirements. These parameters are given in Table 2-1. While this combination of parameters is not unique, based on past and present experience we feel that they represent the most straightforward path to the design goals. Also given in the table are some of the presently achieved parameters from the BNL Test EBIS.

Table 2-1 EBIS Parameters

Parameter	RHIC EBIS	Test EBIS (Achieved to Date)
e-beam current	10 A	10 A
e-beam energy	20 keV	20 keV
e-beam density	~575 A/cm^2	>575 A/cm^2
Ion trap length	1.5 m	0.7 m (solenoid limit)
Trap capacity (charges)	11 x 10^{11}	5.1 x 10^{11} (10A)
Yield positive charges, total	5.5 x 10^{11} (Au, 10 A)	3.4 x 10^{11} (Au, 8 A)
Pulse length	$\leq$ 40 μs	20 μs
Yield Au^{32+}, design value	3.4 x 10^9 ions/pulse	> 1.5 x 10^9 ions/pulse

The electron beam neutralization efficiency for RHIC EBIS is assumed to be 50%, a value that has been consistently exceeded on our Test EBIS, as well as in many other EBISs. The yield in the desired charge state is assumed to be 20%, again a value that is frequently achieved in EBISs.

We have also considered other sources for the production of pulsed currents of intermediate charge state ions for synchrotron injection – specifically the Electron Cyclotron Resonance (ECR) ion source, and the Laser Ion Source (LIS). These sources have a more difficult time achieving the desired charge state, so while with an EBIS one is using the peak charge state from a narrow distribution, with the ECR and LIS one is typically using a charge state on the tail of a much broader distribution. Thus, for the same current in the desired charge state, one has to deal with much higher total extracted currents, and their accompanying problems of transport and matching into the RFQ of these higher total currents. For example, 3.4 x 10^9 Au^{32+} ions in a 10 μs pulse corresponds to an Au^{32+} current of 1.7 mA. The total extracted current from the EBIS will be 8.5 mA, assuming 20% in the desired charge state. For the same Au^{32+} currents, total current from an ECR or LIS would have to be up to 10 times higher (this is considerably above what an ECR has achieved). If one goes to a lower charge state from the ion source, then in addition to the accelerator becoming longer, the total current required becomes even higher because an additional stripping would be required after acceleration.

Both sources also have some limitations in the ions that can be produced. The LIS requires high melting point solids and the ECR has difficulty producing ions from high melting point solids. The LIS has additional obstacles, such as large emittance due to a large energy spread, target erosion and coating of mirrors, state of the art laser requirements, and very large pulse-to-pulse fluctuations in beam current.

Unlike these two sources, an EBIS can easily produce any type of ions – from gas, metals, etc., with essentially the same intensity for any species. The EBIS can quickly switch species (even pulse-to-pulse) without a memory effect. One can easily control the width of the extracted pulse. Scaling laws for EBIS are well understood, and the source is reliable, with excellent pulse-to-pulse stability.

3. Functional Requirements and Performance Specifications

The performance of the new pre-injector must be able to meet the requirements of both the RHIC and NSRL experimental programs. When filling RHIC, four pre-injector pulses, spaced 200 ms apart, are delivered every ~3 seconds. NSRL takes 1 pulse every ~3 seconds. There are presently several operating scenarios for RHIC and NSRL:

MODE	PRESENT TANDEM OPERATION
Dedicated RHIC running; same species in both rings	5 Hz, 4 pulses every ~3 seconds; single Tandem
Dedicated RHIC running; two species	5 Hz, 4 pulses every ~3 seconds; 2 minute switching time between species; two Tandems
Dedicated NSRL running	~0.3 Hz; single Tandem
RHIC single species & NSRL same species, energy, charge state	5 Hz, 4+1 pulses every ~3 seconds; single Tandem
RHIC single species; NSRL different species of same magnetic rigidity	4 pulses at 5 Hz, ~1.5 second switching, then 1 NSRL pulse; two Tandems
RHIC single species; NSRL different species of different rigidity	~2 minute switching; two Tandems

To achieve the above operating modes, the new pre-injector must be able to switch beam species in ~1 second. To improve upon the present Tandem performance, it is desirable for the pre-injector to be able to switch both species and transport line rigidity in this time, so that there are no restrictions on compatibility between RHIC and NSRL operations.

The present scheme for filling RHIC uses one ion source pulse (and one Booster pulse) to fill one bunch in RHIC. Using Au as the most common example, for the required 10^9 ions per bunch in RHIC, and with a transfer efficiency of about 50% (including stripping after the Booster) from Booster to AGS (and RHIC), one needs to achieve 2×10^9 Au ions per pulse extracted from the Booster.

Present heavy ion injection into the Booster from the Tandem Van de Graaff starts with a sputter negative ion source on a 150 kV high voltage platform, which can deliver approximately 200 μA of Au^- in 500 μs pulses. The beam is then accelerated to the 14 MV terminal, where ions are stripped by passage through a 2 $\mu g/cm^2$ carbon foil, and then accelerated to ground potential, where the total current (all charge states) is ~ 1 emA, with approximately 20% of that being in the desired 12^+ charge state. The beam then passes through a second carbon stripper foil, with ~ 70 eμA in the desired Au^{32+} charge state, with an energy of about 0.92 MeV/amu. This beam is transported 860 m to the Booster, where it is injected over ~ 35 turns, with a capture efficiency of about 50%.

The present alternative scheme, using a high charge state heavy ion source such as EBIS, produces, directly from an ion source, the charge state desired for Booster injection. This eliminates the inefficiencies due to stripping, and makes the initial preacceleration more efficient. In addition, Booster injection is more efficient if one can inject over fewer turns, so it is also desirable for the source to produce shorter pulses of higher currents.

Some of the parameters required from a new pre-injector are listed as follows:

1. **Species**: All stable species from d to U are desired. Helium to U will be produced in EBIS. For convenience, deuterium beam may be produced in a simple plasma source injecting directly into the RFQ.

2. **Intensity at injection into the Booster:**
In order to provide ions/bunch in RHIC the same as those already run, the following intensities are required at Booster input:
Au^{32+} : 2.7 x 10^9 ions per pulse. (8.6 x 10^{10} charges/pulse). Sufficient to achieve 1.2 x 10^9 ions per bunch in RHIC.
D : 2.5 x 10^{11} ions/pulse. (From plasma source, for convenience)
Cu^{11+} : 1.0 x 10^{10} ions/pulse. (1.1 x 10^{11} charges/pulse)

Similarly, in order to provide species and intensities for NSRL matching the best previous runs, the following intensities are required at Booster input:

Species	**Q**	**Ions/pulse**	**Charges/pulse**
C	5+	2 x 10^{10}	1 x 10^{11}
O	8+	6.7 x 10^9	5.3 x 10^{10}
Si	13+	5 x 10^9	6.5 x 10^{10}
Ti	18+	1.3 x 10^9	2.4 x 10^{10}
Fe	20+	1.7 x 10^9	3.4 x 10^{10}

These numbers assume the expected efficiency from Booster injection to extraction of ≥ 85% for few-turn injection. One needs ≤ 1.1 x 10^{11} charges/pulse in all cases for the beams to be produced by EBIS. With a trap capacity in the EBIS of 10^{12} charges, these intensities should be readily achievable.

3. **Injected pulse width: variable, 10 – 40 μs.** This allows 1-4 turn injection into the Booster. This simplifies the injection, and should greatly reduce the sensitivity to small beam losses at injection, which could otherwise lead to a pressure bump resulting in further beam loss.

4. **Repetition rate: 5 Hz.** This keeps overall RHIC fill times to only a few minutes

5. **Injection energy: 2 MeV/amu.** Present tandem injection is at 0.92 MeV/amu for Au. At this energy, there is a significant beam loss due to electron capture during Booster injection. By raising the injection energy to 2 MeV/amu, the capture cross section is reduced by a factor of 20-40. In addition, the higher energy reduces the space charge tune shift at injection. At even higher injection energies one would approach the voltage limit of the inflector, and losses due to ionization would begin to become important. While for light ions this injection energy is lower than that from the Tandem, it is shown in Section 5.8 that it is sufficient even for deuteron injection.

6. **Q/m: 0.16 or greater.** This ratio equals that presently delivered for Au from the Tandem. For lighter ions a higher q/m is required (Si^{13+}, Fe^{20+}) to achieve the desired Booster output energy for NSRL, within rigidity constraints in the Booster and extraction transport.

7. **Emittance (full beam, normalized) at Booster input: 1.4 π mm mrad or less.** This emittance is acceptable for the few-turn injection, but if one were to inject over 10's of turns, as with the tandem, the emittance requirement is stricter.

8. **dp/p : 0.05% or less.** This is a requirement for RHIC injection, but can be relaxed for NSRL beams.

9. **Switching time between two species: 1 second**. There are presently several operating scenarios for RHIC and NSRL, depending on, among other things, whether either is running alone, or the two are running concurrently. To allow operation with the desired flexibility, the new pre-injector must be able to switch beam species and transport line rigidity in 1 second.

Table 3-1 gives performance specifications for the new pre-injector. The required performance can be achieved with the EBIS source, followed by an RFQ and short Linac, as will be described in Section 5.

Table 3-1 Summary of Performance Specifications

Species	He to U
Intensity in desired charge state	$\geq 1 \times 10^{11}$ charges/pulse (Booster input)
Charge-to-mass ratio, Q/m	$\geq 1/6$, depending on ion species
Repetition rate	5 Hz
Pulse width	10 – 40 μs
Switching time between species	1 second
Output energy	2 MeV/amu
Emittance (full beam, normalized)	$\leq 1.4\ \pi$ mm mrad
Momentum spread, dp/p	$\leq \pm 0.05\%$

4. Background

4.1. *Results of the Test EBIS*

The requirements for the RHIC EBIS were given in Table 2-1. These parameters were considerably beyond the previous state of the art, since most EBIS sources were designed for atomic physics applications, where much lower intensities of very high charge state ions were usually desired. The objective of the BNL EBIS development program has been to demonstrate that an EBIS capable of meeting the RHIC requirements can be built. Our approach has been to construct a prototype at half the final length, show that each subsystem can work, demonstrate ion production and extraction in expected quantities, and finally demonstrate the production of heavy ions with q/A~0.16 centered in a narrow charge state distribution. With this Test EBIS, we have been able to develop many of the relevant technologies, and study the physics aspects of a high intensity EBIS. A number of issues have been addressed, among them the technology of high current electron beam formation and launching, development of primary ion injection into the trap, the study of ion formation in and loss from a high current electron beam, the study of fast ion extraction, and the development of appropriate source controls and diagnostics. There are some practical aspects in the present design that limit the performance of Test EBIS, such as the power handling limit of the electron collector, the Limits of the available electron collector power supply (a 25 year old supply that had been out of service for 15 years), and power supply and design limits to voltages which can be applied to various trap electrodes. The Test EBIS is shown schematically in Figure 4.1. A photo of the source is shown in Figure 4.2. A schematic for ion extraction, transport, external ion injection, and diagnostics is shown in Figure 4.3.

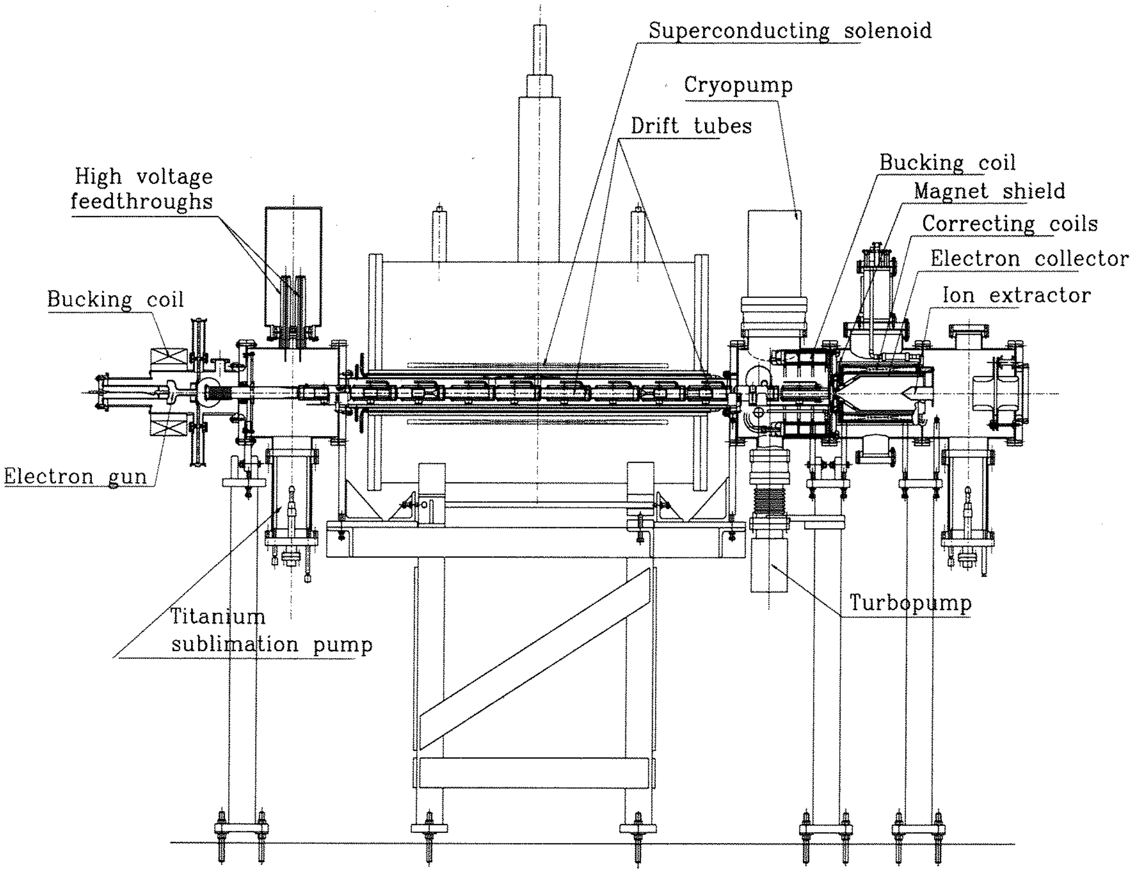


Figure 4.1 Schematic of the Test EBIS.

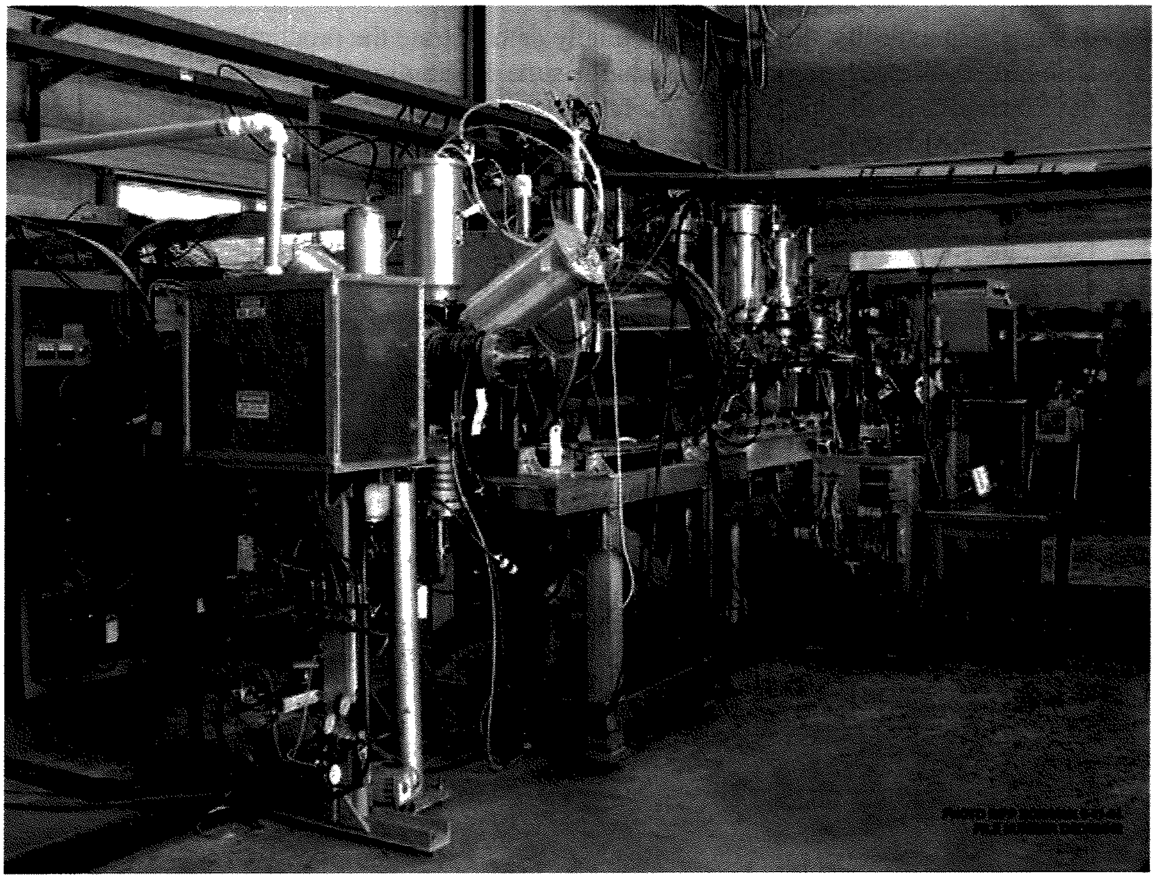


Figure 4.2 Photograph of Test EBIS

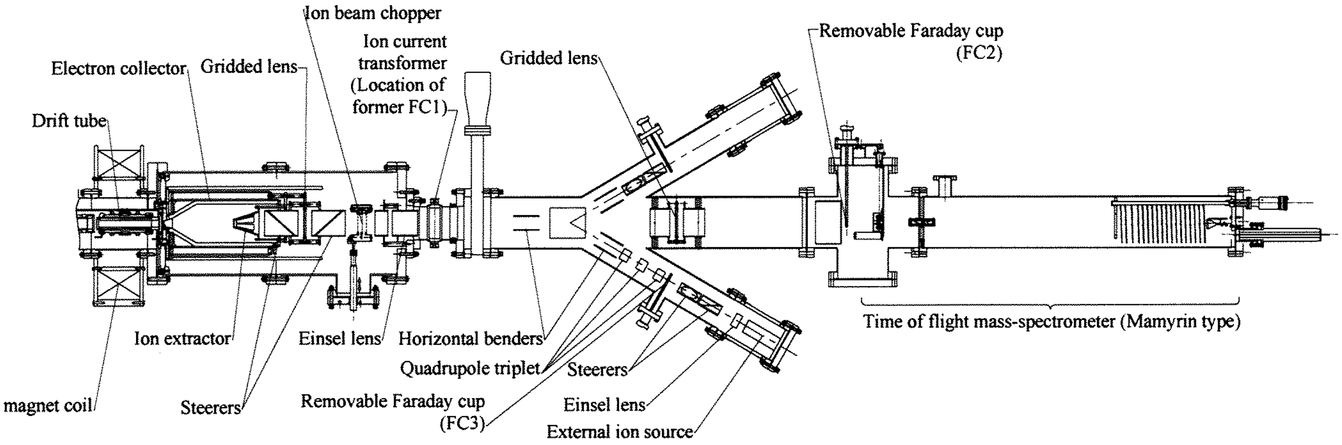


Figure 4.3 Schematic of the ion extraction, transport, diagnostics, and external injector

Table 4-1 Key Hardware Features of the Test EBIS

Superconducting solenoid:	
Length	1 meter
Maximum field	5 Tesla
Bore	155 mm diameter, warm
Helium consumption	0.12 l/hr
Drift tubes	
No. of electrodes	12
Bore diameter	31 mm
Trap length	0.7 m
Electron gun cathode	LaB$_6$ or IrCe, 8.3 mm diameter
Electron collector power	50 kW
Vacuum	1 x 10^{-9} to 4 x10^{-10} Torr in most regions (most sections bakeable to 200C, central DT's to 450 C)
Diagnostics	
Time-of-flight	Mamyrin-type, 2 m from ion extractor
Faraday cups	0.5 and 1.5 m from ion extractor
Harp	1.6 m from ion extractor
Emittance	1.6 m from ion extractor

Details of the Test EBIS design and experimental results have been presented in references.[1, 2,3,4,5,6,7,8,9] Table 4-1 gives some parameters for the test stand. Some of the key achievements will be mentioned in the following discussion.

4.2. Demonstration of High Current Electron Beam Formation and Propagation

The 10A electron beam current required to reach ion beam yields for RHIC was an order of magnitude higher than achieved in any previous EBIS. The design of the electron gun was of crucial importance not only because of the requirement for such a high current, but also because of the need for a flexible control of the electron beam parameters. After performing an extensive study of different electron gun geometries it was decided to adopt a coaxial diode with magnetic insulation, positioned in the field of a separate solenoid (Figure 4.4). The novel spherical convex LaB$_6$ cathode has a radius of curvature of 10.6 mm and transverse diameter of 8.3 mm. A photo of the gun cathode assembly is shown in Figure 4.5. The gun was designed and fabricated at the Budker Institute of Nuclear Physics (BINP), Novosibirsk.[5]

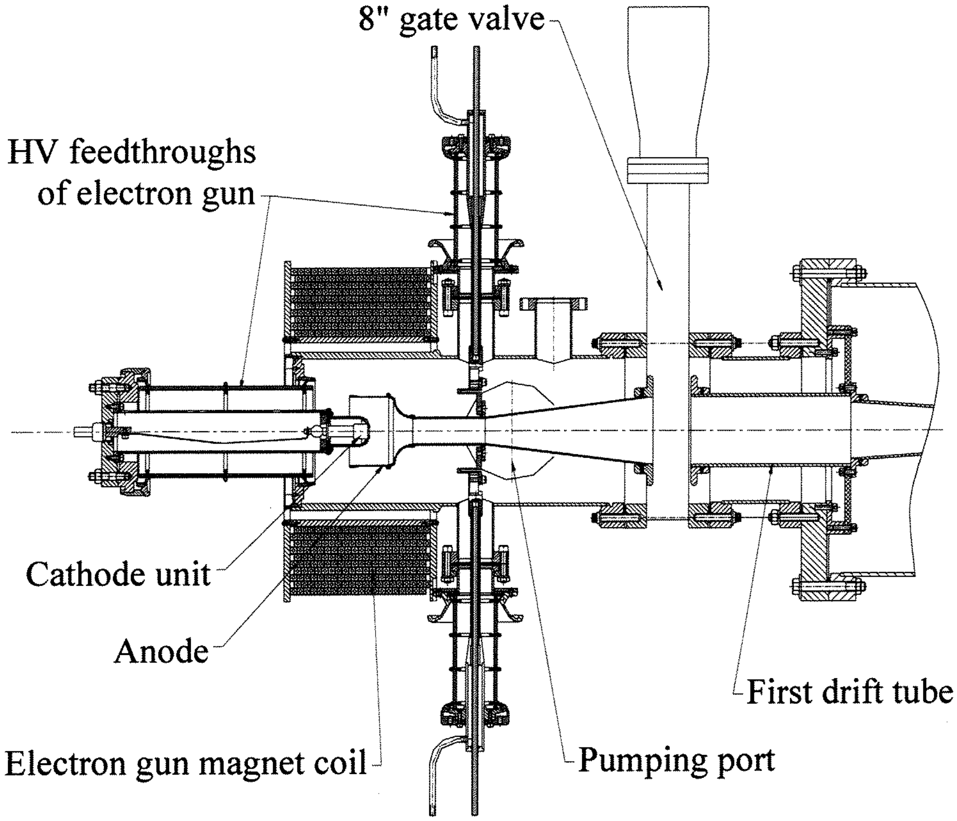


Figure 4.4 Electron Gun Assembly

Figure 4.5 Photo of the electron gun cathode assembly

The performance of this novel electron gun has been excellent. It has provided very stable operation over a wide range of gun operating parameters, with very satisfactory lifetime and reliability. With this gun we have reached our design goal, and propagated a 10A electron beam through the EBIS solenoid to the collector, with very low beam loss (<0.5%), in ~50 ms pulses. Figure 4.6 and Figure 4.7 show two examples of electron beam pulses propagating through the EBIS trap.

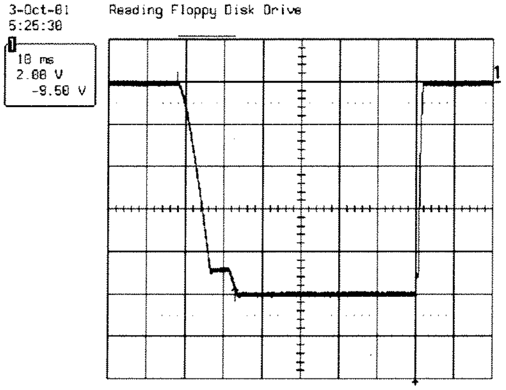


Figure 4.6 10A, 50 ms electron beam pulse. Vertical scale: 2A/div.

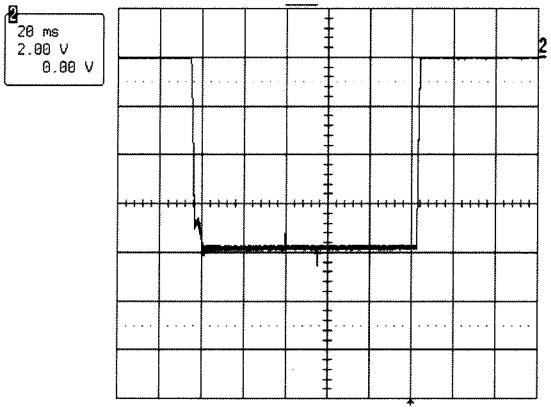


Figure 4.7 8A, 100 ms electron beam pulse

Upgrade to IrCe Cathodes:

During the past year, the Test EBIS has operated using IrCe cathodes manufactured at BINP, Novosibirsk. For Test EBIS design electron current of 10A, the IrCe cathodes have lifetime ~20,000 hours, several times longer than the LaB_6 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 to 20A, via a modification of the gun electrode geometry. Using the IrCe cathode, electron beams up to 10A, and 100kW peak power dissipation on the electron collector have also been propagated in the Test EBIS with very low loss.

4.3. *Extraction of Ions from the Test EBIS Trap*

Our design goal of extraction of the total ion charge corresponding to 50% of the electron beam space charge has consistently been met or exceeded. Trapping and ionization with continuous injection of Xe gas into the Test EBIS demonstrated good operation as a first test, although Test EBIS was not designed for gas injection. Subsequently, we have achieved excellent operation with Au, Cu, N, Cs, Ne, and Ta ions. In these cases, low charged ions were produced in an external ion source, and then injected into the EBIS trap for ionization to much higher charge states. Table 4-2 shows some ion yields under various operating conditions. The RHIC EBIS requires 5×10^{11} charges/pulse, at 10A but with slightly over twice the trap length of Test EBIS.

Table 4-2 Ion yields from the Test EBIS

Ion	Electron current	Ion yield, total charges/pulse	Neutralization
Gold	8.0 A	3.4×10^{11}	85 %
Xenon	7.0 A	1.9×10^{11}	55 %
Copper	6.6 A	2.2×10^{11}	64%
Neon	6.8 A	2.4×10^{11}	68%
N	7.0 A	2.4×10^{11}	69%

We have not measured ion yields at the full electron beam current due to power supply limitations.

Figure 4.8 shows how Test EBIS ion yield has scaled properly with electron beam current. Also shown is the design goal for Test EBIS, i.e. achieving 47% of the RHIC requirement from 47% of the trap length.

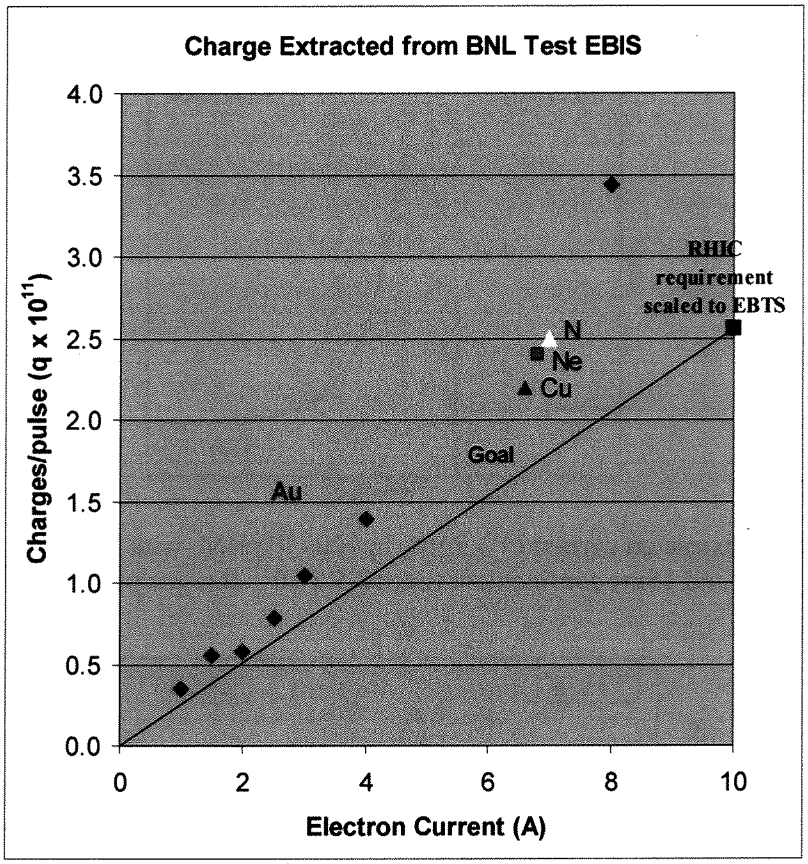


Figure 4.8 Extracted ion charge as a function of electron current for Test EBIS.

4.4. Fast Extraction of Ions from the Test EBIS Trap

For 1-4 turn injection into the Booster, the extracted ion pulse should be 10-40 μs long. Figure 4.9 is a 3.2mA, 12 μs FWHM ion pulse, (2.5 x 10^{11} charges/pulse), obtained at the source exit toroid using a 6.8 A e-beam and Au external ion injection, after a 15ms confinement period. This result was achieved by raising the voltage of the trap region above the level of the barrier electrode, with an additional voltage tilt in the trap produced via a fixed resistor/capacitor RC network. In a RHIC EBIS, with programmable control of electrode voltages, and an adjustable RC network, the shape and duration of the pulse will be more controllable. Figure 4.10 is a similar result (6.3 mA peak current) with Ne external ion injection.

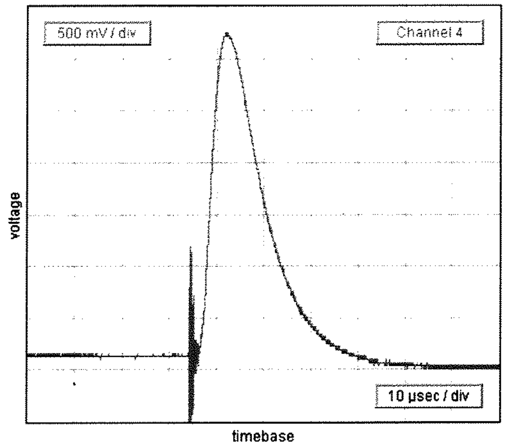


Figure 4.9 Total extracted current of 3.2mA, in 12μs FWHM, with Ie=6.8A, Au injection, and 15ms confinement time (2.5 x 10^{11} charges/pulse).

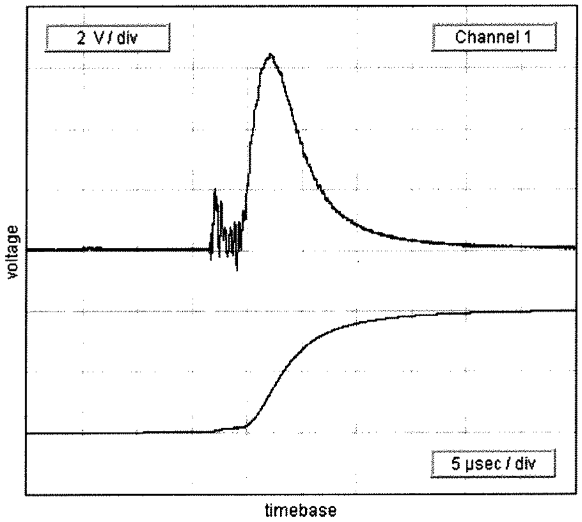


Figure 4.10 Total extracted current of 6.3 mA, Neon injection, Ie=6.8 A, 18 ms confinement time (2.4 x 10^{11} charges/pulse).

4.5. Measurement of Charge State Distribution of Ions from Test EBIS

Charge state distributions were measured on the Test EBIS with a time-of-flight (TOF) spectrometer located 1.5 m from the ion extraction electrode. Narrow charge state distributions have been demonstrated on EBISs such as those in Stockholm and Saclay using injection of singly charged ions from an external source into the trap. In the Test EBIS, we have reached this major milestone by injecting ions from external sources for ions of Cs^{1+}, Ta^{1+}, Ne^{1+}, Cu^{1+}, N_2^+ and Au^{1+}. These ions were transported over ~2 m to the EBIS, where they were trapped and further ionized. This external injection was very successful. Figure 4.11 shows a narrow gold charge state distribution, with the desired 20% of the gold ions in a single charge state. Contaminant peaks will eventually be reduced with improved baking of the system. The peak charge state of Au^{33+} after only 40 ms confinement with a 7.2 A electron beam already exceeds our requirement. A similar result for Neon injection is shown in Figure 4.12.

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 4.13 shows an inline TOF spectrum of gold ions produced using a 7A electron beam and 10 ms 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 an insertable, high transparency 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.

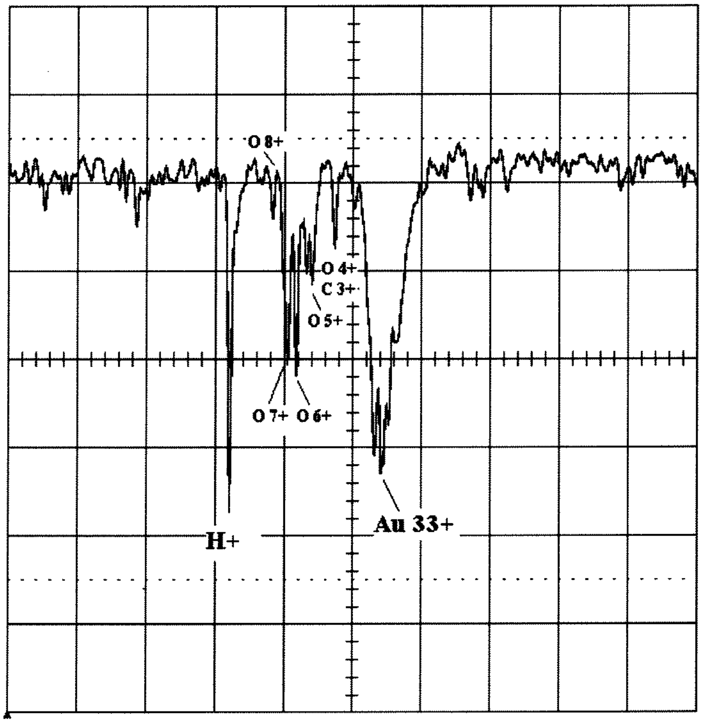


Figure 4.11 Narrow Au charge state distribution coming from external gold ion injection into the Test EBIS (Ie=7.2 A, confinement time=40 ms).

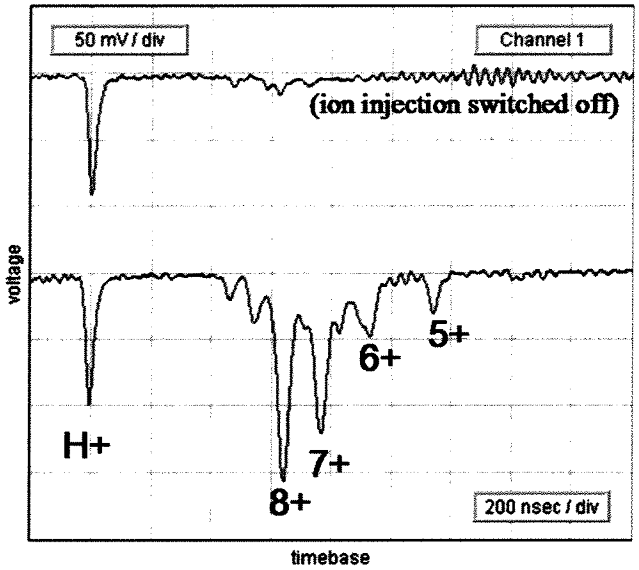


Figure 4.12 Neon charge state distribution (Ie=6.8 A, confinement time=14 ms)

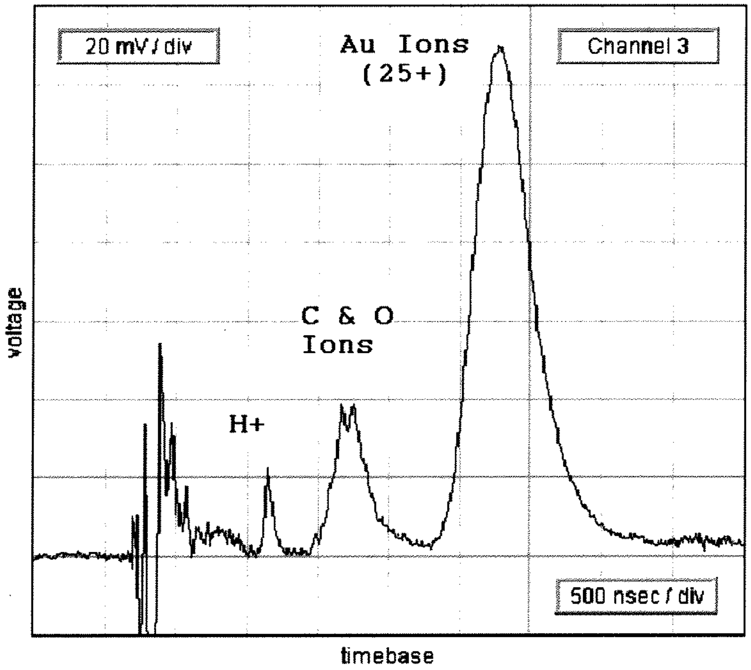


Figure 4.13 Inline Time-of-Flight spectrum showing Au=83%; C&O=15%; H=2%

4.6. External Ion Injection

All initial EBIS results pertaining to gold ions were obtained using the Low Energy Vacuum Arc (LEVA) ion source obtained from LBNL.[10] Low charged Au ions were produced in a LEVA source using 7 apertures, each of ~1.5 mm diameter. These ions were extracted in ~500-700 μs pulses at 10 kV. Up to 100 μA of low charged Au ions from the LEVA could be transported to the ion current transformer just outside of the Test EBIS (see Figure 4.3). Typically, 20 μA currents were sufficient to provide ~25% neutralization of the Test EBIS trap with low charged Au ions after < 2 ms confinement times. The LEVA source is shown in Figure 4.14.

Figure 4.14 Low Energy Vacuum Arc ion source.

A Hollow Cathode Ion Source (HCIS) was obtained from CEA Saclay.[11] It was previously used as an ion injector for the EBIS "Dione" for ions such as Cu, Au, and U. In bench tests using a copper cathode with neon working gas, Cu^{1+} beams of up to 15μA, 15kV have been extracted from a pulsed 1ms, 3A discharge using a 1.5mm plasma electrode aperture. The emittance of a 10μA, 10kV Cu^{1+} beam has been measured as 16 π mm mrad (rms) which is below the acceptance value determined by computer simulation of the Test EBIS.[12] Beams up to 80μA beams of Ne^{+1} have also been extracted. At BNL a modified source has been constructed from a straight quartz tube, Figure 4.15. Cu^{+1} currents ~45μA and Ne^{+1} current of 130μA have been achieved in this configuration for 12 kV extraction voltage, 1.5A discharge current, and 1.5mm plasma aperture. Figure 4.16 shows the HCIS installed at the Test EBIS on a branch of a "y-chamber". Differential pumping is aided by apertures and two 25mm electronically controlled fast shutters. We have verified that for HCIS Ne pressure ~1mb, the EBIS ionization volume remains below 2×10^{-10} mb for shutter open time 10ms and 1Hz repetition rate.

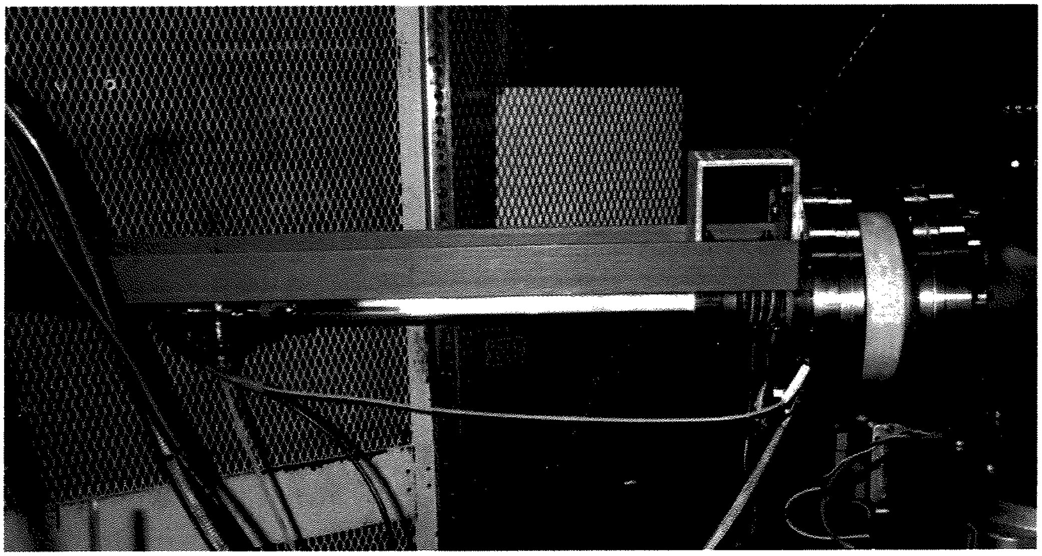


Figure 4.15 Hollow Cathode Ion Source with Ne discharge and Copper cathode.

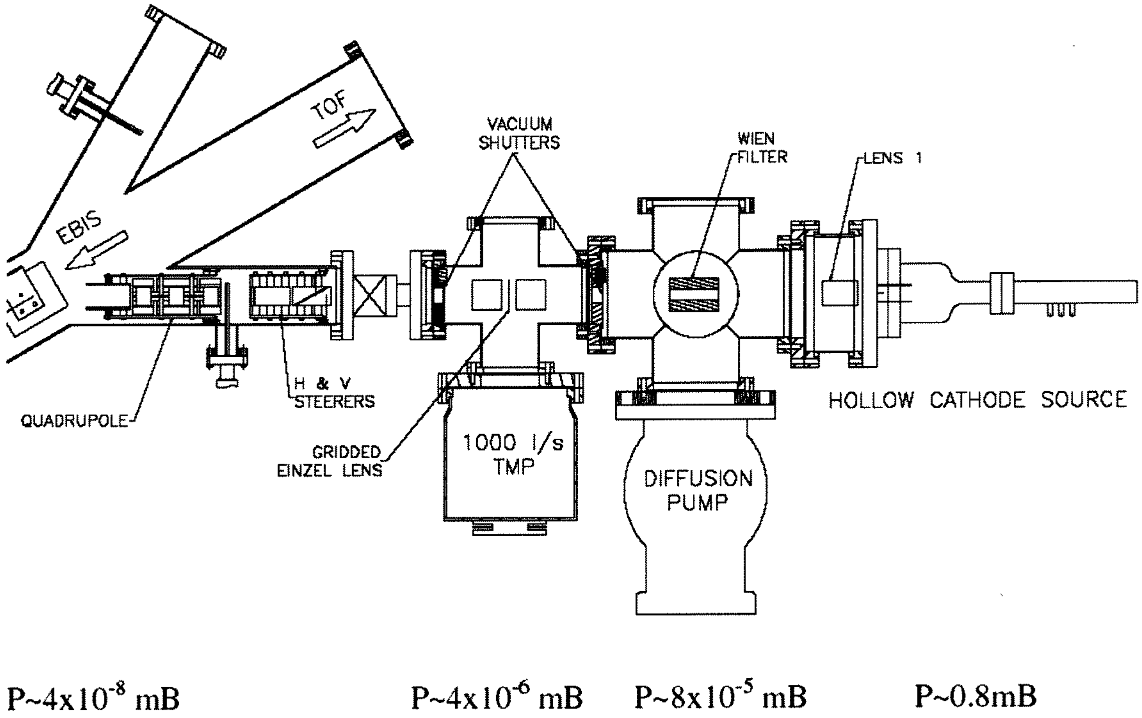


Figure 4.16 Schematic of the Hollow Cathode Ion Source beamline, with pressures in the differentially pumped chambers. With the source operating, $P\sim2\times10^{-10}$ mB (1.5×10^{-10} Torr) in the EBIS trap region.

4.7. Additional Test EBIS Results

1. Trap length can be varied by changing the trap electrodes used to form the end barriers. Measurements of extracted ion yield as a function of trap length show the expected linear dependence.

2. Source performance has confirmed the advantages of a warm bore solenoid.

3. The design philosophy was correct with regard to vacuum requirements and to maintaining vacuum separation between regions of the source.

4. Good progress has been made regarding controls and fast voltage pulsing, allowing flexible programming of electrode voltages during the EBIS cycle.

5. The design incorporated transverse steering coils at all chamber locations, including the central drift tube region. These have proved to be extremely effective in optimizing electron beam transmission through the EBIS.

6. Preliminary emittance measurements were taken under a variety of source conditions, with a 6.8 A electron beam, extracted charge of 20-40 nC, and extracted currents of 1-3 mA. Normalized rms emittance values were typically measured to be in the range of 0.08–0.1 π mm mrad.[9]

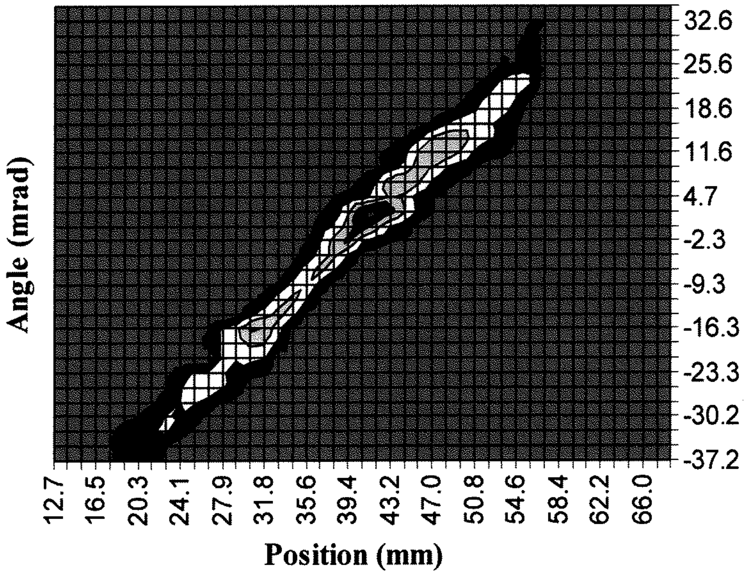


Figure 4.17 Emittance of a 1.7 mA extracted beam from EBIS, with Au injection. ε(n,rms)= 0.1 π mm mrad.

4.8. *Summary of Test EBIS Performance*

- The Test EBIS is operating with parameters more than an order of magnitude above previous EBIS sources.

- We have achieved the design goal of transporting a 10A electron beam through the 0.7 m EBIS trap with low losses.

- The extraction of Au ion pulses of 3.4×10^{11} charges with an 8A electron beam is less than a factor of 2 below the RHIC requirement for charge, and has demonstrated proper operation of an EBIS at high currents.

- The required Au charge state has been achieved with less than 40 ms confinement time.

- Au ions have been extracted in pulses of amplitude 3.3mA and duration ~10us FWHM, which is important for meeting our goal of 1-4 turn injection into the AGS Booster ring.

- Au, Cu, Ta, Ne, N and Cs ions from an auxiliary ion source were successfully injected into the trap of the Test EBIS with a good efficiency.

- To date, all results of the Test EBIS have agreed with EBIS scaling laws, and continue to confirm the parameters for a RHIC EBIS that were presented approximately 10 years ago.

Practical constraints rather than physics issues have limited performance of the Test EBIS, and therefore, while the test stand will benefit from further design optimization, we are now confident that an EBIS can be scaled to meet RHIC requirements. This is discussed in the following section.

5. Technical Design

A schematic of the injection scheme with the new injector is shown in Figure 5-1, with intensities given for Au^{32+}. A detailed parameter list for the injector is given in Appendix A. The EBIS, as described in this section, will operate with a 10A electron beam, and will produce in excess of 5 x 10^{11} charges/pulse, for any desired species. For heavy ions, ~20% of these ions will be in the desired single charge state, while for light ions this fraction can reach ~ 50%. This intensity will meet all requirements as given in Section 2. In addition, key components (electron gun and collector) will be designed with the capability of operating at up to 20 A electron beam current, so one will have the potential of a factor of ~1.6 improvement in electron trap capacity and ion charge yield.

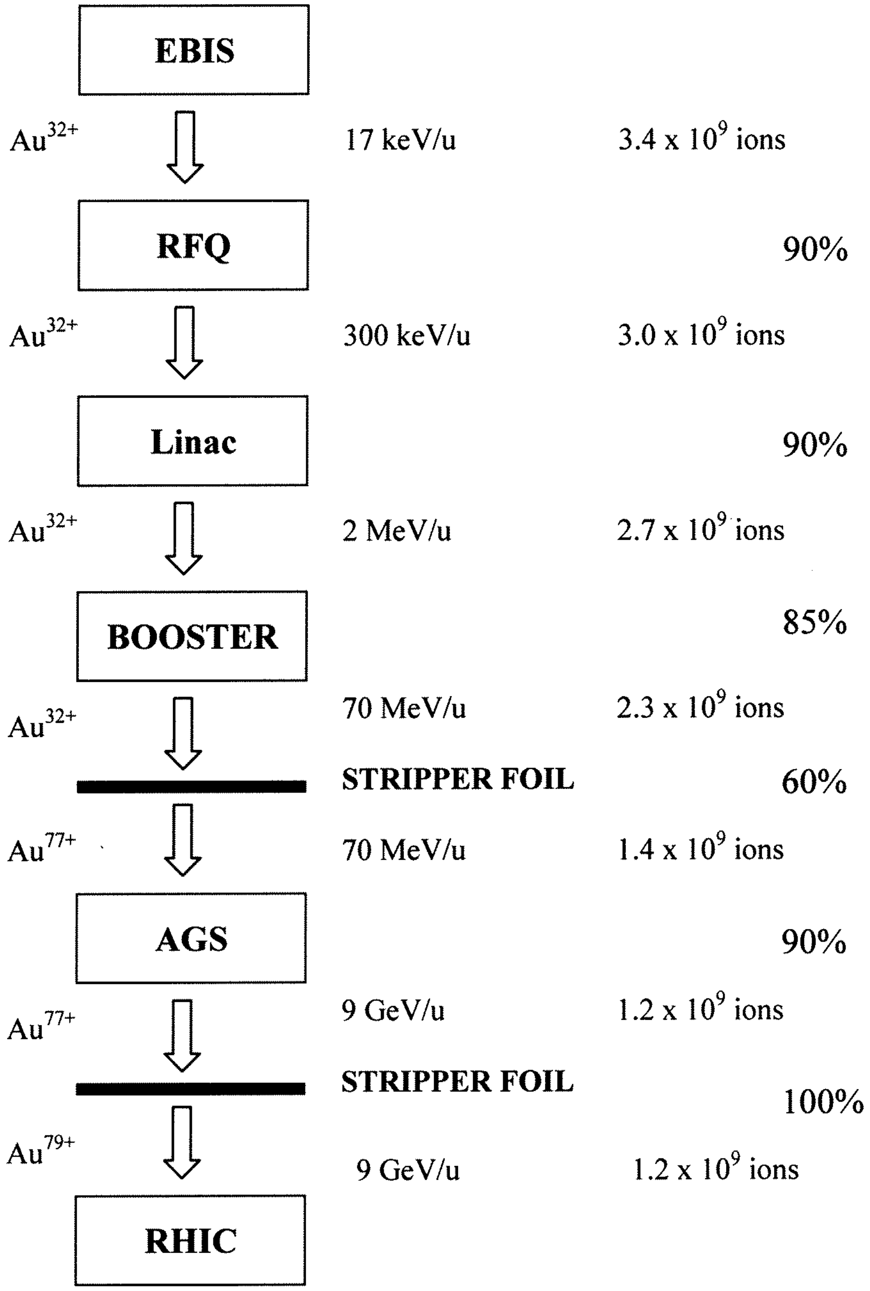


Figure 5.1 Schematic of Linac-based injection, showing ions per pulse, and efficiencies at various stages, for Au injection.

5.1. *Design of the New Pre-Injector*

Some parameters of the pre-injector are given in Table 5-1. The details of the subsystems are given in the following sections. A layout of the pre-injector is shown in Figure 5.2.

Table 5-1 Beam Parameters of the Proposed Pre-Injector

EBIS			
	Output (single charge state)	1.1 x 10^{11}	charges/pulse
	Ion output (Au^{32+})	3.4 x 10^{9}	particles/pulse
	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
	Output emittance	0.35	π mm mrad, norm, 90%
RFQ			
	Q/m	0.16 - 0.5	
	Input energy	17	keV/amu
	Output energy	300	keV/amu
Linac			
	Q/m	0.16 - 0.5	
	Input energy	300	keV/amu
	Output energy	2000	keV/amu
Injection			
	# of turns injected	1-4	

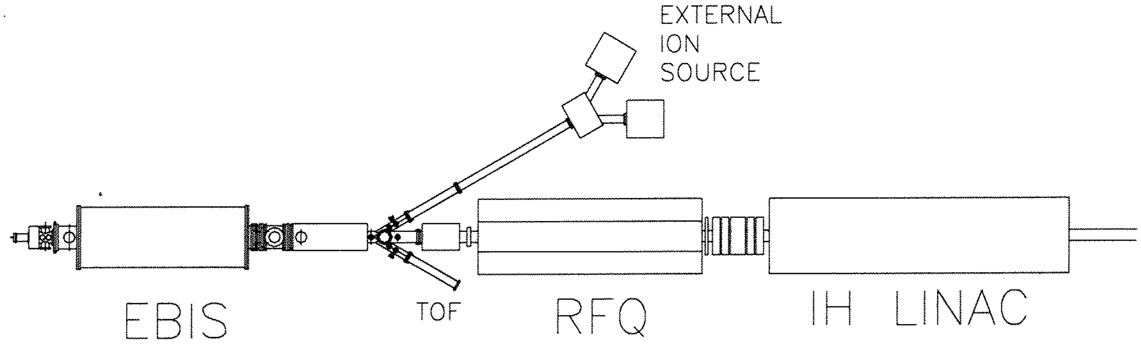


Figure 5.2 Conceptual layout of the pre-injector

5.2. *RHIC EBIS*

5.2.1. Features of an EBIS for RHIC

Our experience so far in the operation of the Test EBIS has confirmed the validity of our approach to the design of the RHIC EBIS. New features we plan to incorporate into the final EBIS will be made in order to make the final EBIS more robust. A schematic of the RHIC EBIS is shown in Figure 5.3. Presented below is our present concept for several key EBIS components. (Details may still change as a result of future Test EBIS studies).

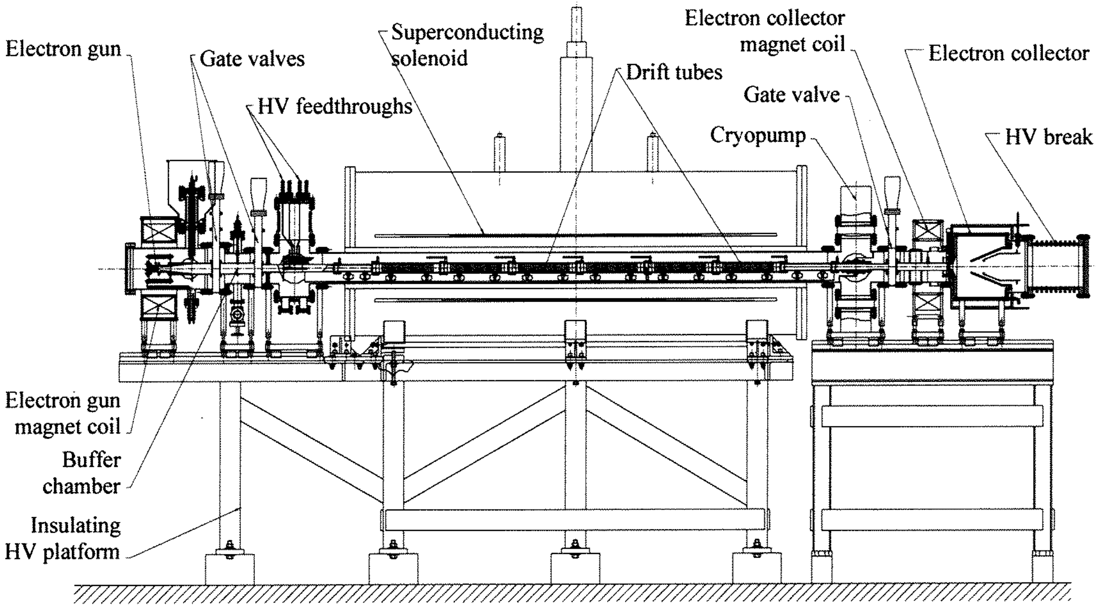


Figure 5.3 Schematic of the proposed EBIS for RHIC.

5.2.2. Electron Gun

As it has been mentioned previously, the required intensity of 3.4×10^9 of Au^{32+} ions per pulse can be provided with a trap containing ~1×10^{12} electrons. If the trap is 1.5m long and energy of electrons is 20 keV, the electron beam current should be 10 A. The microperveance of this electron beam is 3.5. There are several strict requirements to the electron beam, such as having the ability to strongly decelerate the beam in the strong magnetic field and in the collector region, and having the ability to operate over a wide parameter range. The existing electron gun with convex cathode and pure magnetic compression of the electron beam has proven to satisfy all our requirements.

The existing electron gun with a LaB_6 cathode can generate an electron current of 10 A for 1000 hours, with an emission density of 13.5 A/cm^2 for 10A electron beam. With further operation, the quality of electron beam becomes unsatisfactory due to deterioration of the cathode unit, and a simple replacement of the cathode is required. The existing unit meets our requirements, and it could be used for the RHIC EBIS. However, to have a more comfortable safety factor and a reserve for a possible future increase of the ion beam intensity, it would be advantageous to have an electron gun which is capable of generating an electron beam with a current of 20 A. To be able to extract electron current in excess of 10A while at the same time increasing the lifetime of the gun, we plan to use a cathode unit based on IrCe rather than our initial LaB_6 cathodes.

Published results of tests of IrCe cathodes show that even for an emission density as high as 30 A/cm^2 the lifetime is several thousands hours – much longer than we expect from our LaB_6 cathodes. These IrCe cathodes, obtained from BINP, have now been tested very successfully on the Test EBIS. The cathode unit design has been modified to reduce the heating power of the cathode and the area of the hot surfaces of the gun. The new electron gun will also have the anode water-cooled by heat conductance to reduce outgassing from the anode surface. BINP could again do detailed gun design and fabrication, as was the case for our 10A gun.

To allow replacement of gun cathodes without exposing the rest of the EBIS to atmosphere, a gate valve between the gun and gun transition chamber will be installed. Simulations of the electron beam transmission demonstrate that any adverse effect on the electron beam of adding a gap in the drift structure to accommodate the removable valve is negligible. This propagation of the electron beam through a gate valve region was also successfully demonstrated on the Test EBIS.

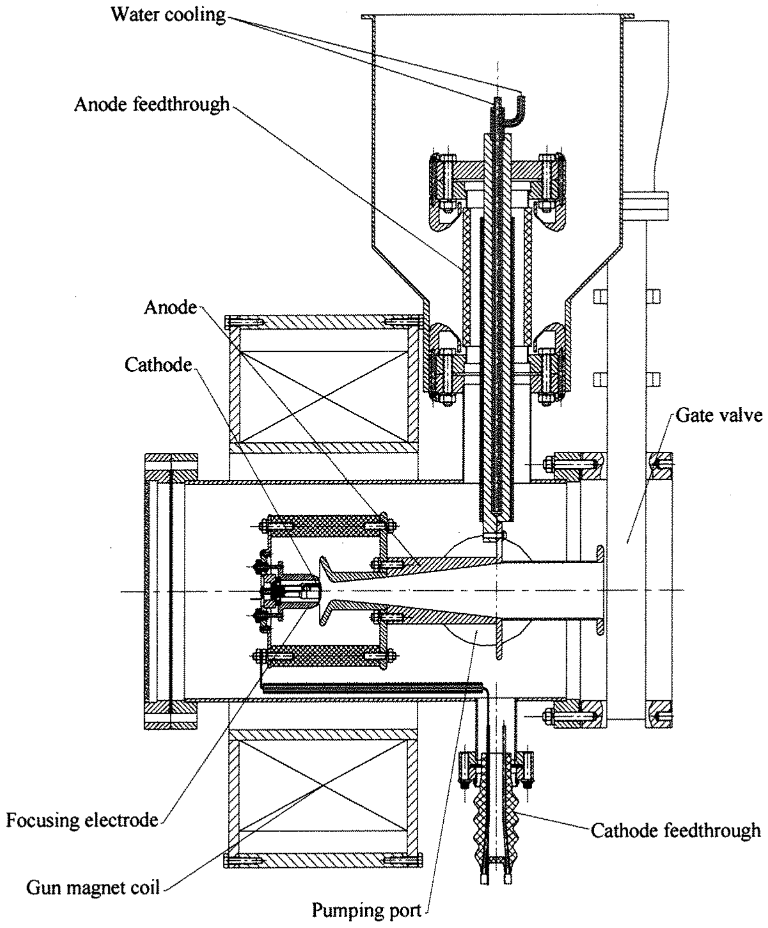


Figure 5.4. Replaceable electron gun unit of RHIC EBIS.

5.2.3. Electron Collector

5.2.3.1. Capacity of the Electron Collector to Dissipate the Power of the Electron Beam

The main improvement in the new electron collector (EC) for the RHIC EBIS is an increase in its capacity to dissipate power, compared with the existing EC on the Test EBIS. The new EC will be designed to dissipate the power of a 300 kW, 20A, 15 kV electron beam in DC or pulsed mode. This is 3 times higher peak power and 80 times higher average power than can be dissipated by the present EC. To increase the capacity of the EC, three approaches will be used – the peak power density at the surface of the cooling water channels will be reduced relative to the inner collector surface power density, the heat exchange by cooling water will be increased, and the pressure of the cooling water will be increased.

To reduce the maximum power density on the inner collector surface, the longitudinal distribution of the electron beam on this surface will be made more homogeneous than in the existing EC by optimizing the shape of the magnetic field. The total area of the cylindrical water-cooled inner surface of the EC will also be increased, with the new collector having an inner diameter of ~30 cm and a length of ~24 cm. The ratio of the surface area of the cooling channels to the area of the inner EC cylindrical surface will also be increased. The flow rate of cooling water will be 4 gallons per minute (GPM) through a single channel, two times higher than in the existing Test EBIS. Raising the pressure of the cooling water to 20 bar increases its boiling temperature to 200 C, making possible a heat exchange without creating a vapor sheath on the surface for a local power density up to 700 W/cm^2. The main parameters of the new and existing EC are compared in Table 5-2.

Table 5-2 Parameters of the new and present electron collectors

Parameter	**New EC**	**Existing EC**
Design power dissipation, kW (actual beam power = 100 kW)	300	50
Area of inner cylindrical surface, cm^2	2300	1000
Maximum removable power density, W/cm^2 (reduced area) (actual estimated max. pwr. density = 485 W/cm^2)	700	200
Water flow through the single channel, GPM	4	2
Diameter of the cooling channel, mm	9	6.4
Length of one cooling loop, m	1.6	1.8
Number of parallel cooling loops	10	4
Pressure drop of cooling water on channels, bar	5	2.7
Output pressure of cooling water, bar	20	1
Total water flow through all cooling channels, GPM	40	10.8
Diameter of entrance diaphragm, mm	16.8	17.8

5.2.3.2. Collector Optics

The electron beam optics in the vicinity of the electron collector and its injection into the EC entrance diaphragm are controlled independently of the main solenoid field with an electron collector magnet coil located outside of the vacuum. The diameter of the electron collector entrance diaphragm is 16.8 mm, and is close to that of Test EBIS (17.8 mm). The optics of the electron beam in the new EC is made versatile, accepting the electron beam over a wide range of operating parameters (electron current, electron energy and magnetic compression). The ion optics through the new EC is optimized to achieve a larger acceptance of the ion beam; one will be able to extract ion currents up to 15 mA without losses on the EC or ion extractor. Higher acceptance of the extraction optics of the new EC is achieved with larger diameter of the extracting diaphragm (46 mm in a new EC compare to 20 mm in an old design) and smaller distance between entrance and exit diaphragms. Electron trajectories in the new EC, simulated for an electron current of 15 A, are presented in Figure 5.5.

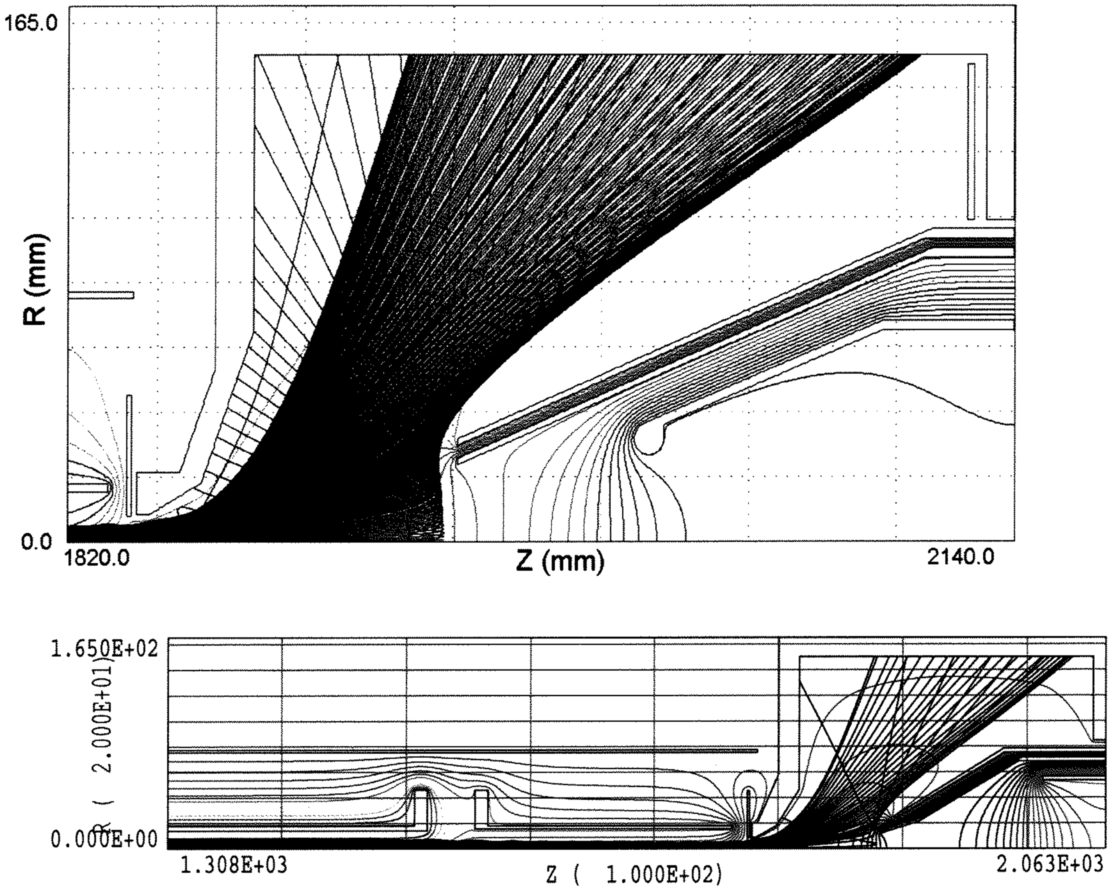


Figure 5.5 Simulated trajectories of electron beam with current 15 A entering the electron collector with energy 15 keV.

5.2.3.3. Collector Thermal Regime

Since a very high power density load on the EC surface is expected the thermal regime and stresses were simulated with the ANSYS program to evaluate the lifetime of the EC due to thermal fatigue. These simulations were done for an electron beam current of 20 A and energy of 15 keV on the EC surface. Electron beam pulses are 50 ms long and the duty cycle is 50%.

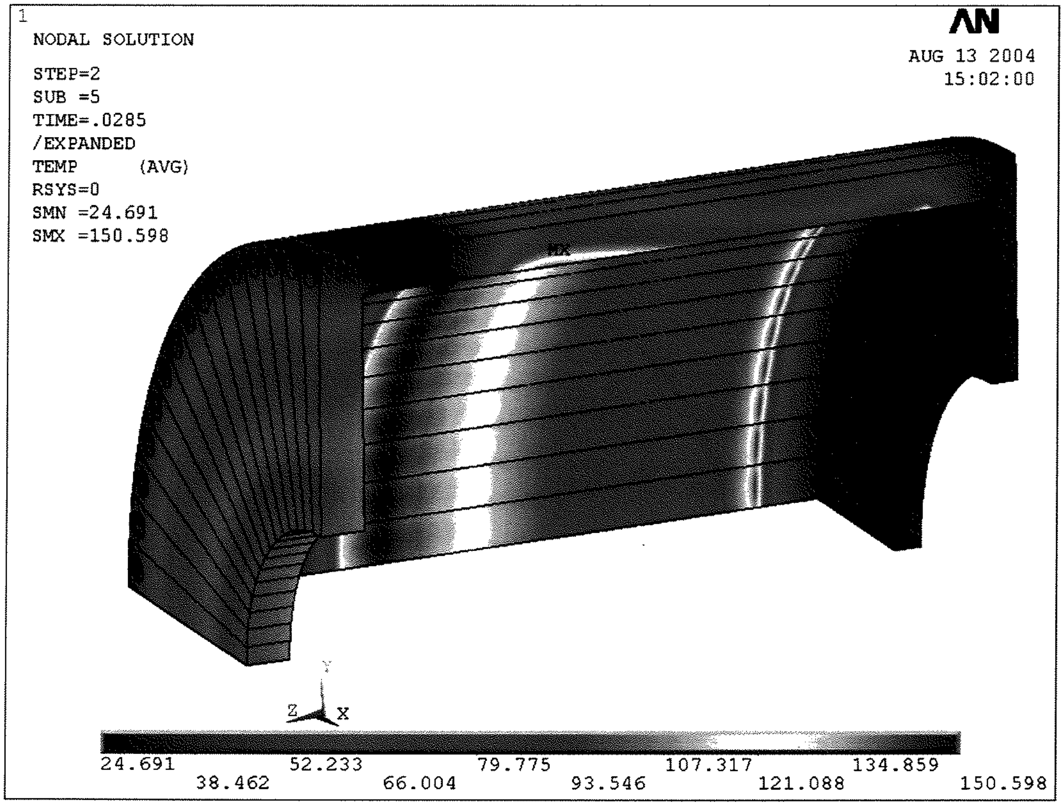


Figure 5.6 Simulated temperature distribution on the EC surface at the end of an electron pulse 20A, 15 keV, 50 ms. The average temperature reached equilibrium.

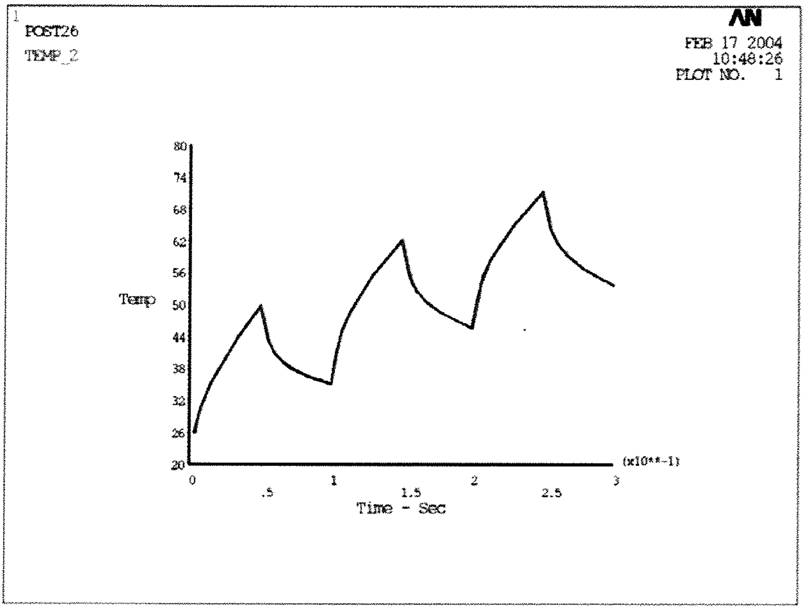


Figure 5.7 Temperature cycling in the hottest node at the beginning of the power load (20A, 15 keV, 50 ms on, 50 ms off).

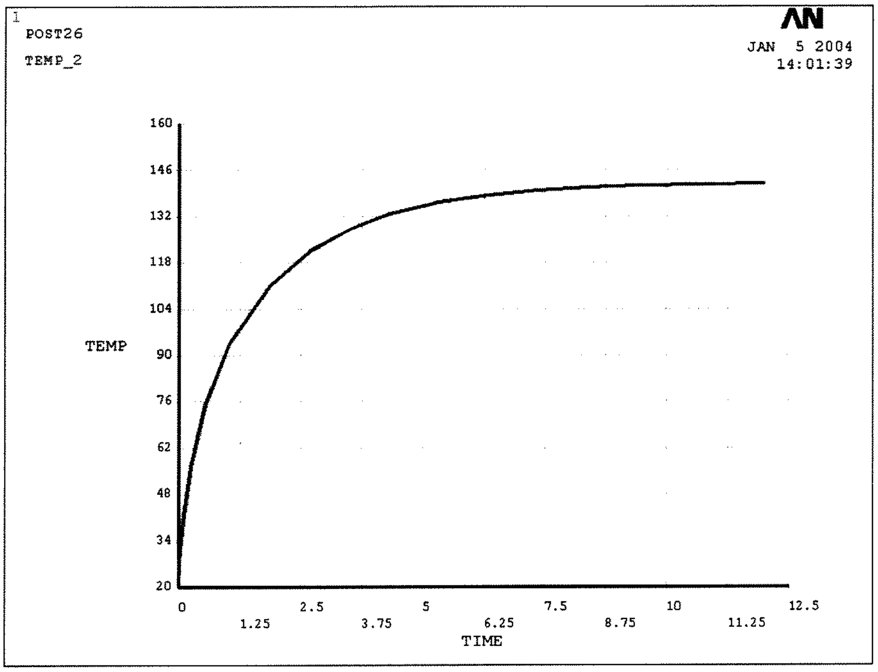


Figure 5.8 Average temperature rise from the beginning of the thermal load on the EC. Time scale – in sec (20A, 15 keV, 50 ms on, 50 ms off).

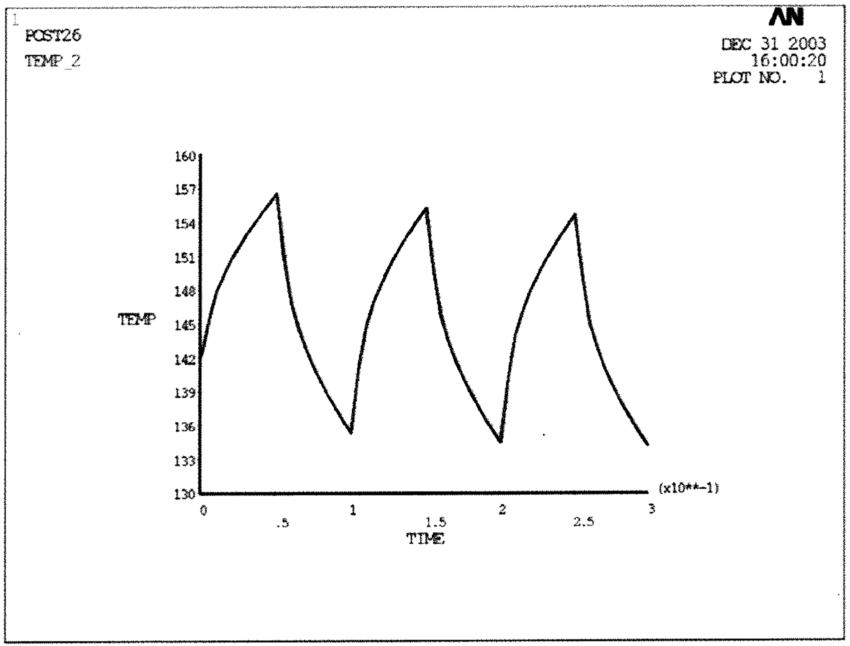


Figure 5.9 Temperature cycling at the hottest node of the EC in equilibrium of medium temperature. (20A, 15 keV, 50 ms on, 50 ms off)

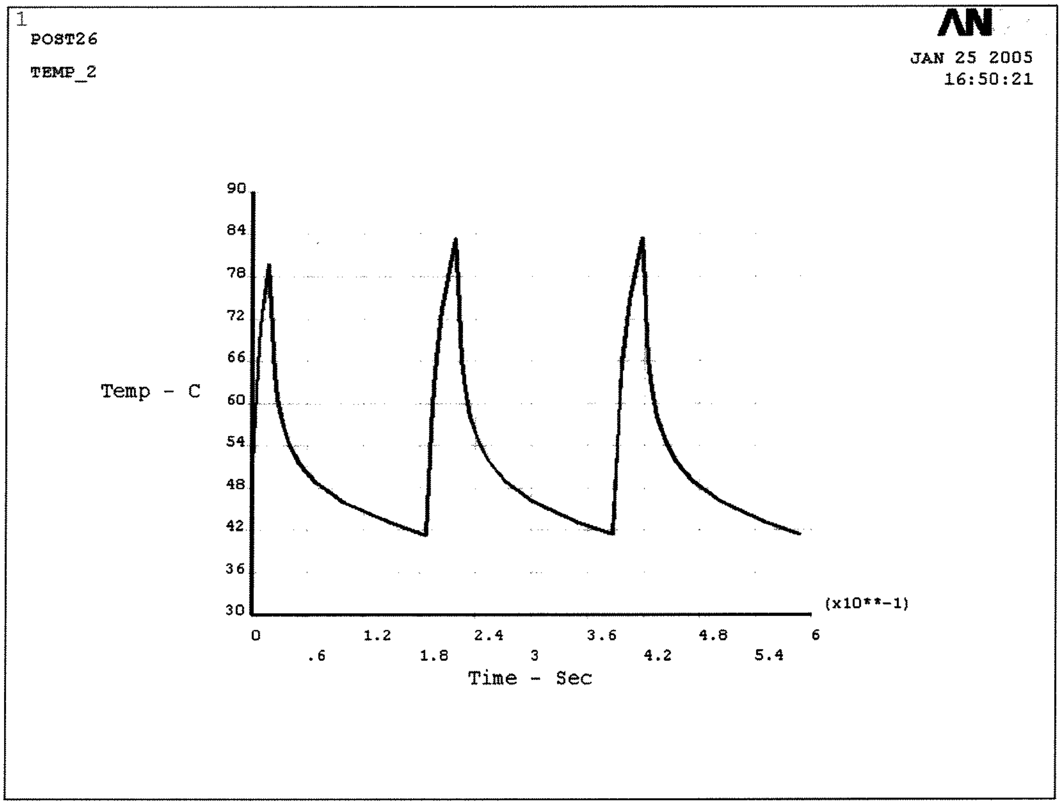


Figure 5.10 Temperature cycling at the location of maximum power density on the EC in equilibrium of medium temperature (20 A, 15 keV, 30 ms on, 170 ms off).

From Figure 5.8 one can see that temperature equilibrium on the EC is reached in approximately 10 sec. In equilibrium the temperature variations at the hottest node are within (135-155)^{0}C for a 50% duty cycle and (42-86)^{0}C for a 15% duty cycle.

To evaluate the lifetime of EC in a pulsed mode due to thermal fatigue the values of mechanical stresses were applied to Goodman diagram for Brush Wellman beryllium copper alloy Hycon-3. The results of simulation demonstrate that for all analyzed regimes the calculated amplitudes of stresses are several times lower than that required for lifetime of 10^8 pulses.

5.2.3.4. Mechanical Design of the Collector

Unlike in the Test EBIS, the outer surface of the new EC will be outside vacuum. This concept allows us to practically eliminate any probability of water leaks into the vacuum volume, because no water-cooling tubes will be exposed to the vacuum volume.

It also allows easy access to the EC body for monitoring the distribution of power dissipation on the EC surface by measuring the temperature distribution on the outside surface. The concept of vacuum separation between the EC and central vacuum chamber, used in the Test EBIS, will be preserved. The EC will be electrically isolated from other vacuum chambers with insulators capable of holding a DC voltage of up to 25 kV. The conceptual view of the EC assembly is presented in Figure 5.11.

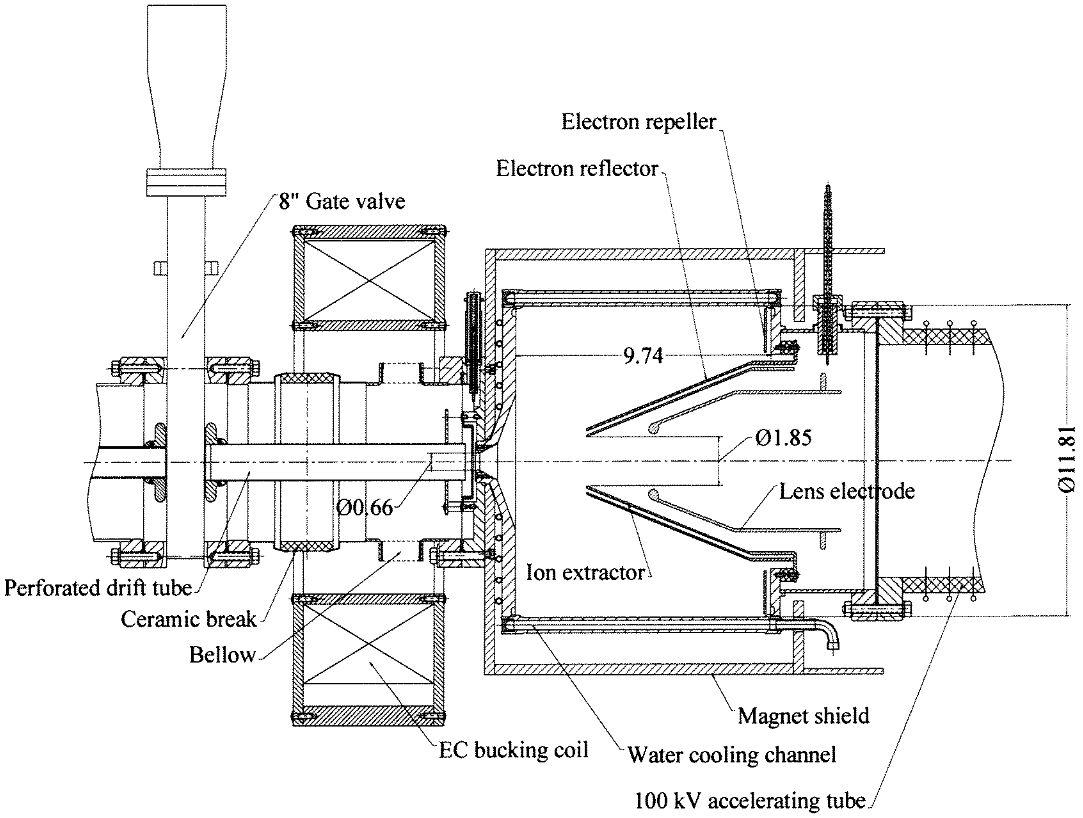


Figure 5.11 The Conceptual assembly drawing of the electron collector for RHIC EBIS.

5.2.3.5. EBIS Electron Collector Cooling System

As presently envisioned, the EBIS electron collector cooling system will dissipate heat from the collector by the flow of water at 20 bar pressure through cooling channels in the collector. The 20 bar water pressure serves to increase the boiling point of the cooling water, which reduces the chance of reaching the critical heat flux or burnout, caused by formation of a vapor film. In other words, the critical power density to wall-water interface is increased. To compensate for pressure losses in water hoses and the EC cooling channels, an initial pressure of 25 bar on the pumping station is required. The cooling system capacity of 200 kW exceeds with good safety margin the maximum heat load for a 50% duty cycle electron beam. The 40 GPM flow rate produces turbulent flow in the cooling channels, promoting high Reynolds numbers and good convective heat transfer.

5.2.4. Drift Tube Structure

To match a higher electron beam current the inner diameter of the drift structure within the ion trap region will be 42 mm (12 mm larger than in the Test EBIS). An increase of the distance between the electron beam and the wall will reduce beam - wall interaction and will result in only a small increase of the radial potential well. The inner wall of the double-walled drift tube is perforated and the space between the walls contains Non-Evaporable Getter (NEG) strips, providing additional pumping for the trap region. Also, NEG strips are mounted in a gap between the cylindrical wall of the vacuum chamber and the semi-cylindrical support of the central drift tube structure.

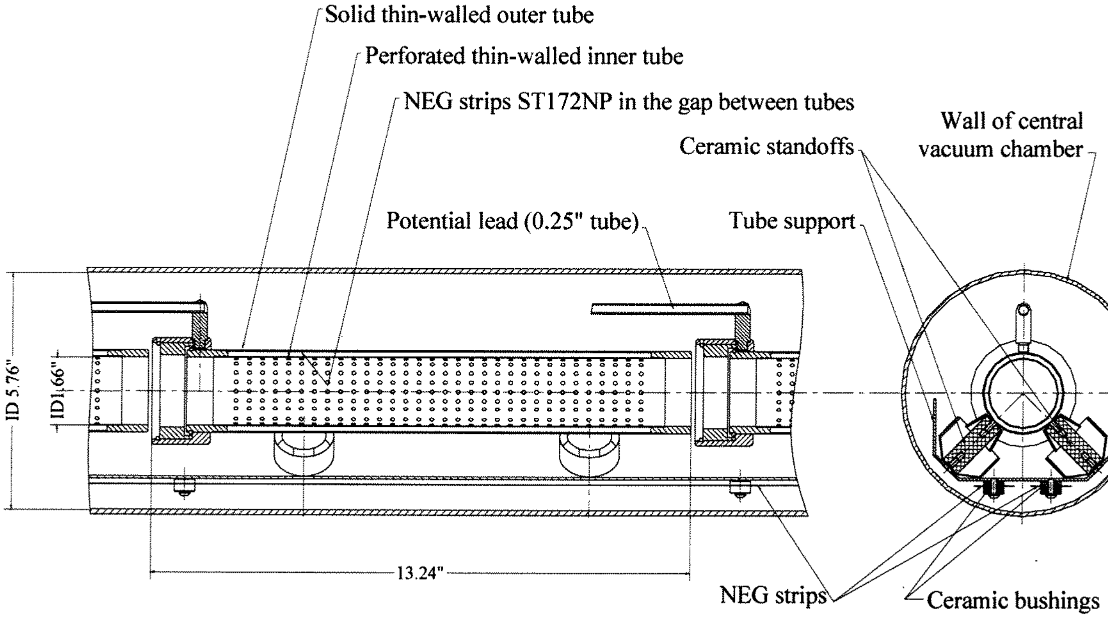


Figure 5.12 Central drift tube (ionization region).

5.2.5. Superconducting Solenoid

Table 5-3 shows the parameters of the new solenoid, as well as the parameters of the existing Test EBIS solenoid. The diameter of the warm bore of the solenoid will be increased to facilitate pumping, and to provide more space to reduce the likelihood of high voltage breakdowns.

Table 5-3 Required parameters of the superconducting solenoid, as well present Test EBIS solenoid parameters

	RHIC EBIS	**Test EBIS**
Guaranteed maximum magnet field:	6 T (tested to 6.3 T)	5T (tested to 5.5)
Inner diameter of the warm bore	204 mm (clearance for 8" flange)	155 mm (clear for 6")
Total length of solenoid	2000 mm	1000 mm
Homogeneity over region 1300x10mm	0.25%	0.25%
Maximum radial shift of magnet field axis over full length of the magnet (documented)	0.2 mm	0.2 mm
Maximum radial deviation of position of solenoid axis from the position of warm bore axis	0.2 mm	0.2 mm
Decay rate of magnet field in coils of solenoid, operating with current leads removed.	$1x10^{-6}$ per hour	1×10^{-5} per hour
Length of vacuum jacket	~ 2300 mm	1300 mm
Period between liquid helium refills	30 days	23 days
Period between liquid nitrogen refills	10 days	12 days

The helium cryostat will have an option of using a helium recondenser on a boil-off tube to simplify operation.

5.2.6. EBIS Vacuum System

5.2.6.1. Vacuum Requirements for the Ionization Region

Ion confinement times as long as 100 ms may have to be used to reach the charge states of interest. The background pressure in the trap region should be low enough that one does not produce a significant number of ions from the background gas. For a residual gas pressure $P=1x10^{-10}$ Torr, one estimates that less than 2% of the accumulated ions in the trap will be background gas ions. One can tolerate values even a factor of 10 above this, so this gives a range of acceptable vacuum conditions in EBIS ($10^{-9} - 10^{-10}$ Torr) and determines requirements to the vacuum technology. Requirements for the concentration of hydrogen are less rigorous, and its partial pressure can be 5 times higher.

Since background gas ions are typically lighter than injected ions, their presence may result in a beneficial cooling of the injected ions. However, it is advantageous to be able to inject cooling ions into the electron beam in a controlled way, so the estimate above for the vacuum is still desirable. Requirements on the pressure of residual gas in the electron gun region are dictated primarily by the need for proper conditions for operation of the cathode, and in the electron collector by the need for stable transmission of the electron beam without plasma formation. Normally, the pressure in the regions of electron gun and electron collector can be higher than in the ionization region, provided there is efficient vacuum separation between the sections.

5.2.6.2. Requirements to the Vacuum System

Based on our experience with the Test EBIS the requirements to the vacuum system are:

- All parts with surfaces exposed to the central chamber should be vacuum fired (baked in a vacuum oven to 900^0 C for 2 hours) before installation in EBIS. This requires use of steel 316LE for ConFlat flanges.

- Materials of all other parts should allow baking to 300^0C.

- Regions with high outgassing rate (electron collector, electron gun) should be separated as much as possible from the central chamber containing the ion trap. Practically, the area of direct connection between the central chamber and the adjacent electron gun and electron collector chambers should be approximately 50% larger than the cross-sectional area of the electron beam in the regions of separation. This means that the conductivity between the central chamber and adjacent chambers should be ~100 l/s.

- To improve the vacuum in the ionization region we are planning to reduce the flow of residual gas from the electron collector and introduce additional pumping inside the central chamber. For the same reason the central region containing the ion trap should be preserved from venting to atmosphere during maintenance or upgrade operations of the electron gun and electron collector by separating it from these regions with gate valves.

5.2.6.3. Structure of the RHIC EBIS Vacuum System

Our experience in the operation of Test EBIS has proven that high vacuum in the ionization region of the EBIS can be achieved without having the drift structure at cryogenic temperatures, by using conventional vacuum technology and pumps. Still, the vacuum system of the RHIC EBIS will include some improvements to reduce further the flow of residual gas to the ion trap and improve the pumping of gas created in the central chamber. These modifications include:

- Increase vacuum conductivity between the middle part of the central chamber and the side parts of this chamber where pumps are located, by increasing the diameter of the central chamber from 4" (as it is now in Test EBIS) to 6". It follows that a larger diameter of the bore of the solenoid is required.

- Reduce the turnaround time for the vacuum system by using thermo resistant materials on the exterior of vacuum chambers, so there will be no need to remove sensitive elements prior to bakeout. One should make a permanent system of electrical heaters and temperature sensors connected to a bakeout station.

- Introduce an additional stage of vacuum separation between the electron collector and the central vacuum chamber, to reduce the flow of residual gas from the heavily outgassing electron collector into the central region by another factor of 10.

- Increase the pumping speed in the central chamber by using Non-Evaporable Getters in the region of the ion trap.

- Separate the electron gun and electron collector from the central vacuum chamber with two gate valves.

The proposed structure of the vacuum system of the RHIC EBIS is presented in Figure 5.13.

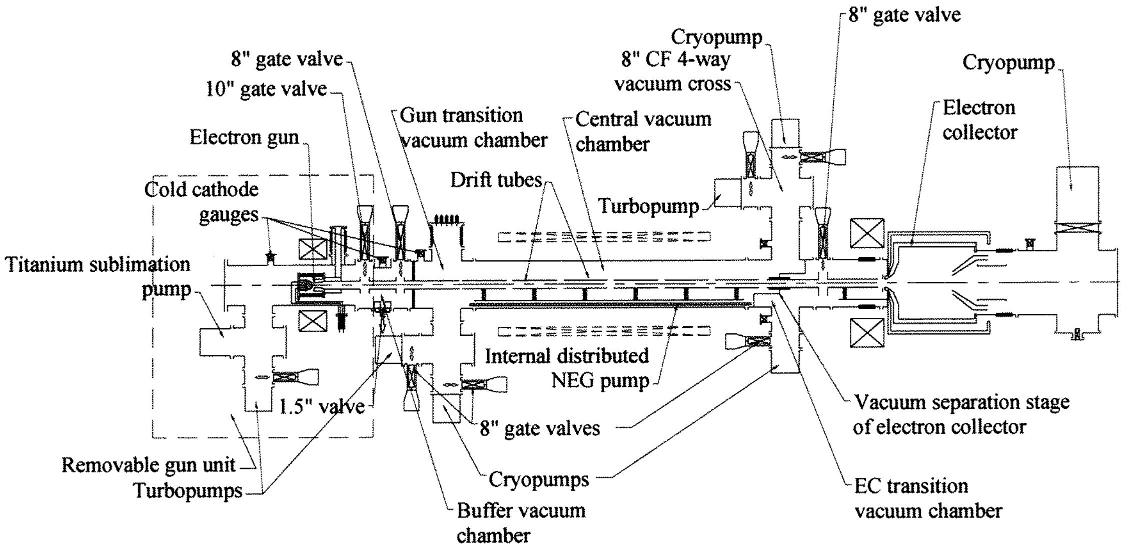


Figure 5.13 Vacuum system of RHIC EBIS

5.2.7. Seeding the EBIS Trap

The primary means of seeding the trap of the RHIC EBIS will be injection and trapping of single (or low) charged ions from an external ion source. This technique has been used very successfully on other EBISs, as well as on Test EBIS, and allows one to produce a very narrow charge state distribution. With ion injection, 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 external ion sources. Only the necessary numbers 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, although very valuable for "gas" injection techniques, also sometimes leads to memory effects that limit ion production when the ion species must be changed. The requirements of the external source are relatively modest, needing to produce currents of

10-100 μA of singly charged ions. The advantages of an EBIS working with ion injection are many: once the proper ion optics configurations are set up and stored, the ion species and charge state can be easily changed on a pulse to pulse basis, there is no contamination or memory effect, and several relatively low cost external sources can be connected by gate valves and maintained independently of the EBIS. If one needs to switch quickly (pulse-to-pulse) between two species, two external injection sources could be used. The transport line from the external source to the EBIS is shown schematically in Figure 5.14.

As described previously in Section 4.6, we have successfully used both the LEVA ion source and the Hollow Cathode source for injection of beams into EBIS. In addition, the commercially available Chordis source has been used successfully on the Stockholm EBIS to produce a wide range of beams from both solids and gasses. As also described in Section 4.6, electronically controlled fast shutters in the external beamline, along with restrictive apertures and differential pumping, will isolate the external source vacuum from the EBIS.

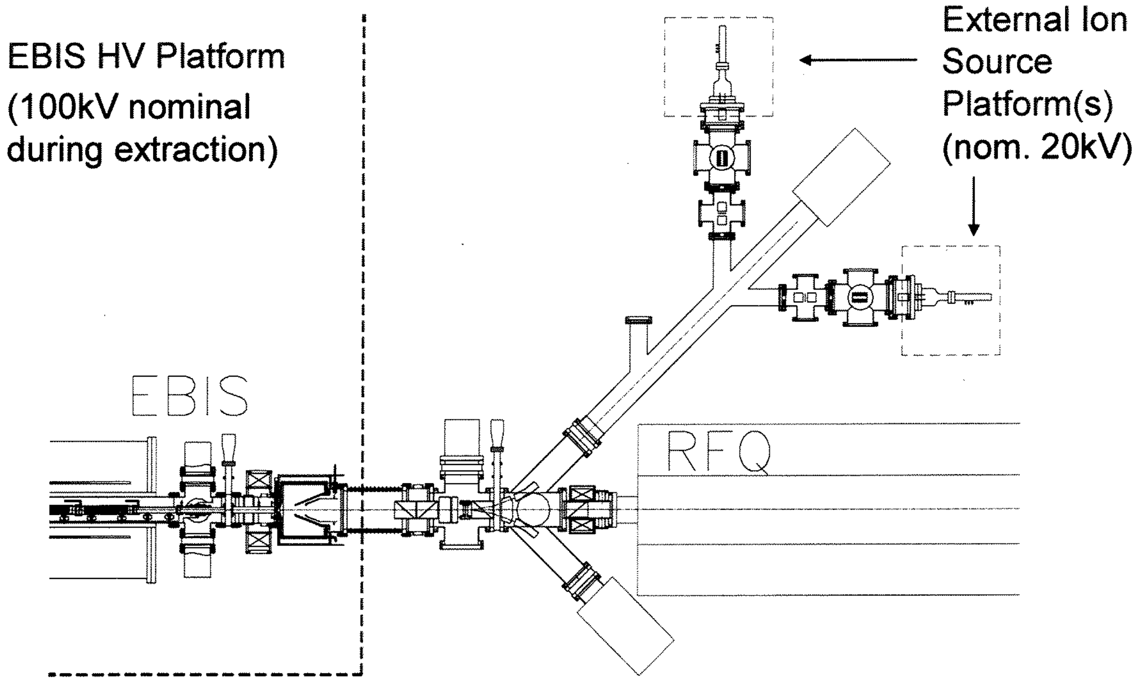


Figure 5.14 Schematic showing the external ion source beamline.

5.2.8. EBIS Power Supply Requirements

For injection into the RFQ at 17 keV/amu, Au^{32+} ions must be accelerated from +100 kV to ground potential. Part of this energy comes from the biasing of the trap region relative to the rest of source. The remainder of the energy must come from a biasing of the entire source with respect to ground. Applying all voltages internally would be more convenient, but it leads to more difficult design issues due to the presence of high voltages in a strong magnetic field. Therefore, we will incorporate both internal and external biasing in the design. The mode of operation can be summarized as follows: With the EBIS platform at ground potential, the primary ions are injected into the EBIS at 10-20kV energy from an auxiliary ion source. The ion energy for capture by the EBIS can be adjusted by using both the EBIS drift tube power supplies and the auxiliary ion source bias supply. The ions are then confined within the EBIS and their charge multiplied to the proper state Q during a period of approximately 30 ms. Before the highly charged ions are expelled from the trap for transport to the RFQ, the EBIS platform voltage is pulsed on such that the extracted ion energy is ~100 kV*Q. The various voltage platforms are described below, and are shown schematically in Figure 5.15.

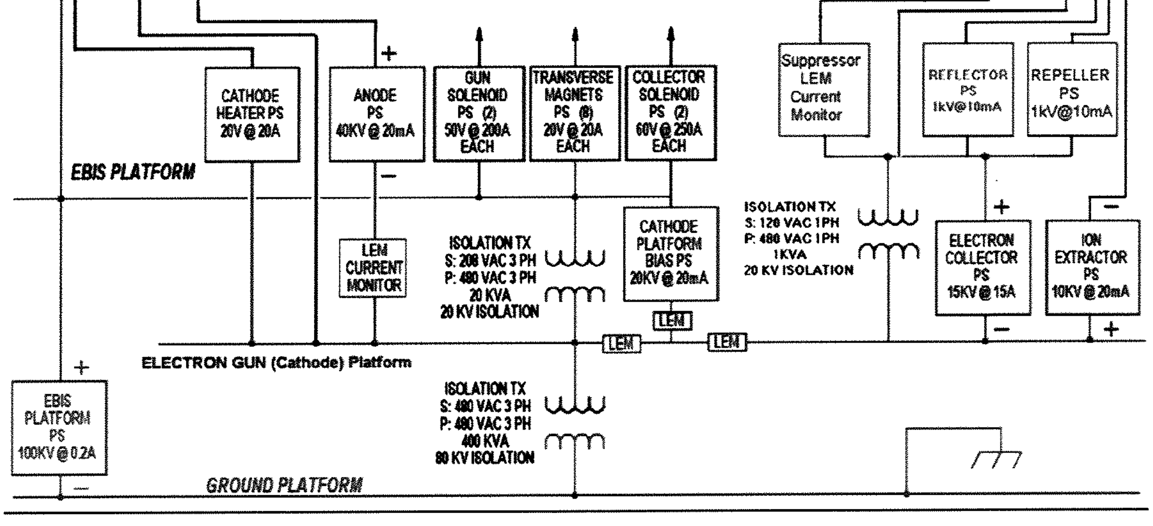


Figure 5.15 Schematic of the EBIS voltage platforms

Laboratory platform (ground):

This platform contains the operator interface for the EBIS controls and diagnostics. The Low Energy Beam Transport (LEBT) and external ion source(s) vacuum systems will also be referenced to laboratory ground where applicable. Individual power supplies will be used to bias the EBIS and each external ion source to their operating potentials with respect to laboratory ground. Several independent platforms, high voltage cages, and bias supplies will allow maintenance on unused ion sources while the EBIS is delivering beams. The EBIS platform bias supply to attain the full extracted ion energy and the external ion source bias supply for seeding the EBIS via external ion injection will be referenced to the Laboratory platform. Power supplies on this platform are:

EBIS platform bias supply
External ion source bias supply
Mass analyzer supply (for external ion source)
External beamline optics power supplies

EBIS source platform:

With this platform the EBIS, including the vacuum chamber and solenoid, will be elevated briefly to as much as +80 kV for extraction and transport of highly charged ions to the RFQ. The remaining 20 kV necessary to achieve the required 17 keV/amu RFQ injection energy would then be provided by biasing internal electrodes. Active bipolar supplies allow short pulse high energy extraction. In order to produce very fast (~10μs) extracted ion pulses, custom built supplies based on 20 kV Behlke switches would reside on this platform, to quickly raise and apply a slope to the internal trap electrodes. Fast extraction has already been demonstrated on our Test EBIS using a prototype Behlke-based supply. Power supplies will be controlled by the EBIS voltage controller via digital and analog optical links. During the ion injection and confinement periods, the EBIS source is nominally at laboratory ground potential. The source support will be constructed to hold off up to 100 kV. Power supplies on this platform are:

Cathode bias supply (biases electron gun platform)
Drift tube power supplies
Behlke fast injection and extraction modules
Gun, main, and collector solenoid power supplies
Correction solenoids and transverse magnetic steering coil supplies.

Electron gun (cathode) platform:

This platform contains the main electrodes responsible for establishing and collecting the electron beam. The power required for collecting the electron beam is provided directly to this platform by a 400 KVA (nominal) isolation transformer. Power supplies belonging to this platform are the cathode heater, anode, electron collector and ion extractor. The suppressor, reflector, and repeller electrodes are connected via the electron collector sub-platform which resides on the electron gun platform.

In this concept, the low current (20kV, ~20mA) cathode bias supply is used to establish electron beam energy in the trap region, while a high current collector supply (~15A, 15kV) is used to collect the electron beam. The cathode bias supply provides stable electron beam launch conditions, and protects against excessive electron beam loss since the capability of the power supply to provide current is low. In this configuration, it should be possible to relax the voltage stability requirement for the high power electron collector supply. The ion injection and extraction will be synchronized with the line frequency, since the collector voltage is still an element influencing the optics of the extracted ion beam. The effect of collector voltage sag on electron beam propagation in this configuration was tested using a 50 μF capacitor and a charging supply. A 4A, 50ms pulsed electron beam was propagated through the Test EBIS, resulting in a collector voltage sag of ~3.7kV from the nominal 10kV applied. Very low loss e-beam propagation was maintained since despite the collector voltage sag, stable electron beam launching potentials were maintained at the cathode.

External ion source platform:

This platform contains the ion source used to seed the EBIS with primary low charged ions of the selected species. Ion injection into the EBIS occurs during the interval when the EBIS platform is at ground; hence, the platform need operate only at 10-20 kV to produce ions with energy matched to the EBIS trap potential. The platform houses supplies relevant to the specific type source, such as heaters, arc pulsers and internal lenses. An electrical schematic of the Hollow Cathode Ion Source used in our laboratory on the Test EBIS is given in Figure 5.16. In this case the platform is relatively simple, and few elements reside on the HV platform.

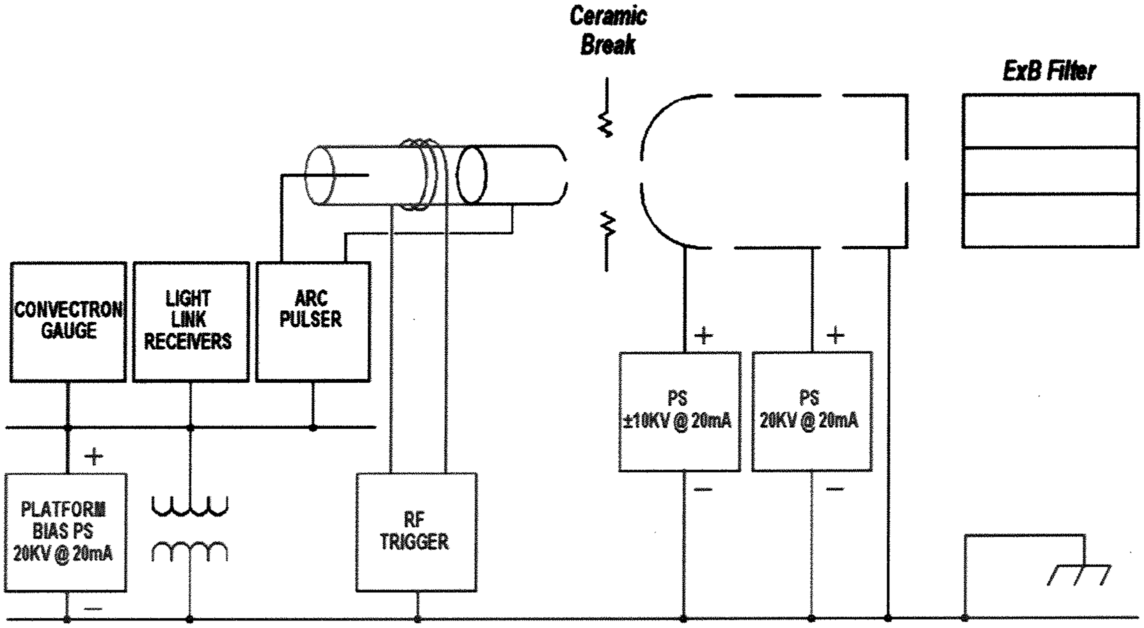


Figure 5.16 Schematic of the Hollow Cathode Source power supply configuration.

5.2.9. EBIS Controls and Timing

The EBIS system consists of power supplies for magnets, electrostatic lenses and drift tubes. Primary control for EBIS consists of timing and waveform generation for the power supplies. Waveform generation will be accomplished mainly with the use of digital-to-analog converters (D/A). Primary data acquisition for EBIS will be voltage and/or current read backs from the high voltage power supplies and read backs from beam instrumentation devices. The EBIS system will have approximately 100 signals that will need to be acquired. Out of these 100 signals, 20 will be fast pulsing signals (approximately l0 µs). Data acquisition will be accomplished mainly with the use of analog-to-digital converters (A/D). Secondary data acquisition needs for EBIS are temperature and pressure sensor readbacks.

The EBIS voltage controller issues all internal timing signals relevant to ion source operation. In particular, it controls EBIS trap electrode timing and voltage references, external ion source timing and switching of optics in the beam lines of the EBIS subsystem. Analog and digital signals are sent to power supplies and timing devices over optical links where necessary. The analog optical links for the fast power supplies must be good to about 20 µs. This allows monitoring by an oscilloscope at the ground platform. Timing will also be an important input to an EBIS data acquisition system since data must be taken from the EBIS system at precise times.

5.3. LEBT

The Low Energy Beam Transport (LEBT), transports the beam from the EBIS and matches it to the RFQ. A baseline layout is shown in Figure 5.17. The LEBT is 1.5 meters long and consists of an extraction / acceleration system, a gridded lens and solenoid magnet for transverse matching, two sets of transverse steerers, and a Y-chamber in the middle of the line. One arm of this chamber allows ions from an external ion source to be injected into the EBIS trap. In the second arm extracted ions can be deflected into a time-of-flight diagnostic. The gridded lens at the exit of the EBIS has the advantage of allowing fast changes in focusing, to accommodate the differing requirements of the injected and extracted ion beam optics. (Not shown in the figure is a third arm, coming vertically out of the page, which allows a source to be used for direct injection of ions into the RFQ, for beams such as deuterons). While only this baseline LEBT design will be discussed below, we will also be considering alternative layouts, including the use of a magnetic dipole between the EBIS and RFQ.

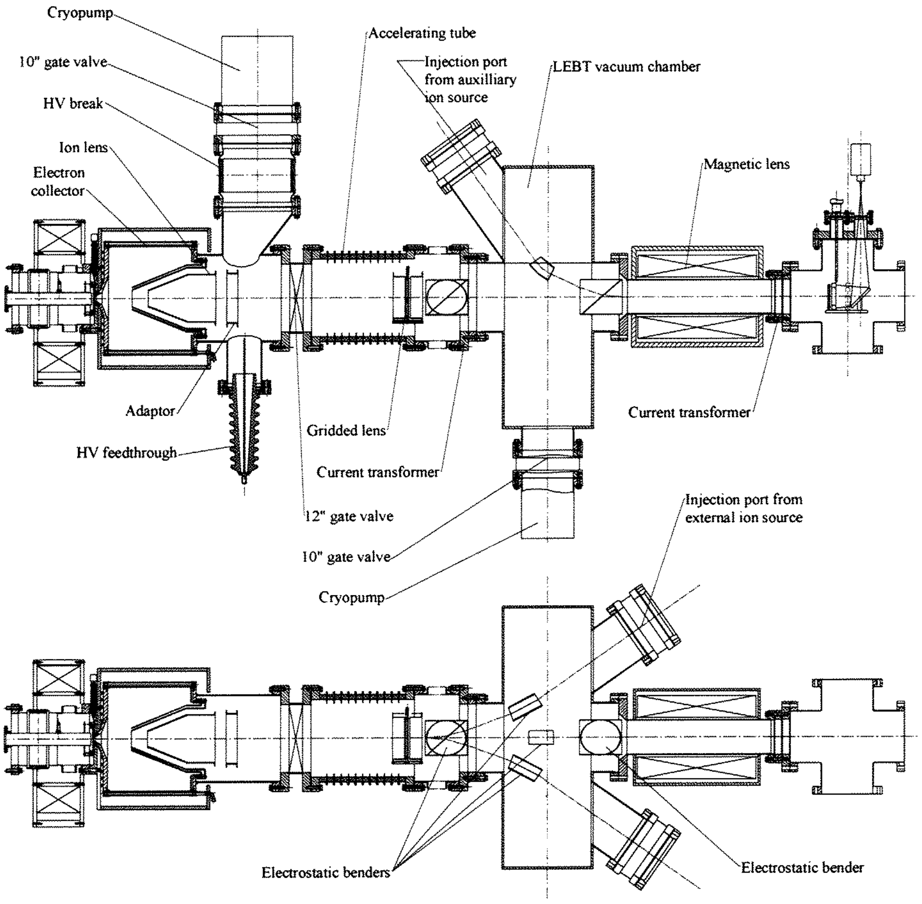


Figure 5.17 Schematic of the LEBT preliminary design