

***ELECTRON BEAM ION SOURCE PRE-INJECTOR PROJECT
(EBIS)***

CONCEPTUAL DESIGN REPORT

J. Alessi, Editor

**D. Barton, E. Beebe, D. Gassner, R. Grandinetti, H. Hseuh,
A. Javidfar, A. Kponou, R. Lambiase, E. Lessard, R. Lockett,
V. LoDestro, M. Mapes, K. Mirabella, T. Nehring, B. Oerter, A. Pendzick,
A. Pikin, D. Raparia, J. Ritter, T. Roser,
T. Russo, L. Snyderstrup, M. Wilinski, A. Zaltsman, S. Zhang**

September 2005


Collider-Accelerator Department

Brookhaven National Laboratory

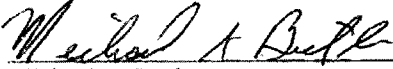
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

Managed by
Brookhaven Science Associates, LLC
for the United States Department of Energy under
Contract No. DE-AC02-98CH10886

CONCURRENCES:

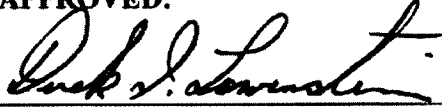

James Alessi
EBIS Contractor Project Manager

Date: 9/12/05


Michael A. Butler
Federal Project Director
DOE Brookhaven Site Office

Date: 9/12/05

APPROVED:


Derek I. Lowenstein
Chair, Collider-Accelerator Department

Date: 9/13/05

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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. <i>Features of an EBIS for RHIC</i>	<i>32</i>
5.2.2. <i>Electron Gun.....</i>	<i>32</i>
5.2.3. <i>Electron Collector.....</i>	<i>34</i>
5.2.4. <i>Drift Tube Structure</i>	<i>41</i>
5.2.5. <i>Superconducting Solenoid</i>	<i>41</i>
5.2.6. <i>EBIS Vacuum System</i>	<i>42</i>
5.2.7. <i>Seeding the EBIS Trap.....</i>	<i>44</i>
5.2.8. <i>EBIS Power Supply Requirements</i>	<i>46</i>
5.2.9. <i>EBIS Controls and Timing.....</i>	<i>49</i>
5.3. LEBT	50
5.4. RFQ.....	54
5.4.1. <i>Choice of Parameters</i>	<i>54</i>
5.4.2. <i>Specifications</i>	<i>54</i>
5.4.3. <i>Beam Dynamics</i>	<i>55</i>
5.5. MEBT	61
5.6. LINAC.....	62
5.6.1. <i>Specification of Parameters.....</i>	<i>63</i>
5.6.2. <i>Beam Dynamics</i>	<i>63</i>
5.7. HEBT	69
5.7.1. <i>Charge Discrimination</i>	<i>72</i>
5.8. BOOSTER INJECTION.....	73
5.8.1. <i>EBIS Beam</i>	<i>73</i>
5.8.2. <i>Space Charge Effect.....</i>	<i>74</i>
5.8.3. <i>Longitudinal Aspects.....</i>	<i>74</i>

5.8.4.	<i>Inflector Aperture Limit and Scraping Effect</i>	77
5.9.	DIAGNOSTICS	79
5.9.1.	<i>EBIS Time of Flight (High Resolution & Inline)</i>	80
5.9.2.	<i>EBIS Emittance</i>	81
5.9.3.	<i>Faraday Cups</i>	81
5.9.4.	<i>Current Transformers</i>	82
5.9.5.	<i>Profile Monitors</i>	82
5.10.	RF SYSTEMS	82
5.11.	MAGNETS	84
5.12.	CONTROLS	86
5.12.1.	<i>Timing & Infrastructure</i>	86
5.12.2.	<i>EBIS</i>	86
5.12.3.	<i>Accelerators & Beam Transport</i>	87
5.13.	VACUUM SYSTEM	87
5.14.	COOLING SYSTEMS	90
5.14.1.	<i>RHIC EBIS Water Cooling</i>	90
5.14.2.	<i>Water Cooling Requirements</i>	93
5.15.	FACILITY MODIFICATIONS	95
5.15.1.	<i>Beam Access Port</i>	95
5.15.2.	<i>Power Modifications</i>	95
5.16.	INSTALLATION	96
5.17.	ESSH	96
5.17.1.	<i>Review of ESSH Issues Associated with the EBIS Design</i>	96
5.17.2.	<i>ESSH Plans for Construction</i>	101
5.17.3.	<i>ESSH Plans for Commissioning, Operations and Decommissioning</i>	105
6.	COST AND SCHEDULE	108
6.1.	OVERVIEW	108
6.2.	COST	110
1.1	<i>Structural Components</i>	110
1.2	<i>Controls</i>	112
1.3	<i>Diagnostics</i>	113
1.4	<i>Magnet Systems</i>	114
1.5	<i>Power Supplies</i>	115
1.7	<i>Vacuum Systems</i>	116
1.8	<i>Cooling Systems</i>	117
1.9	<i>Facility Modifications</i>	117
1.10	<i>Installation</i>	117
1.11	<i>Project Services</i>	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 ^3He 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.

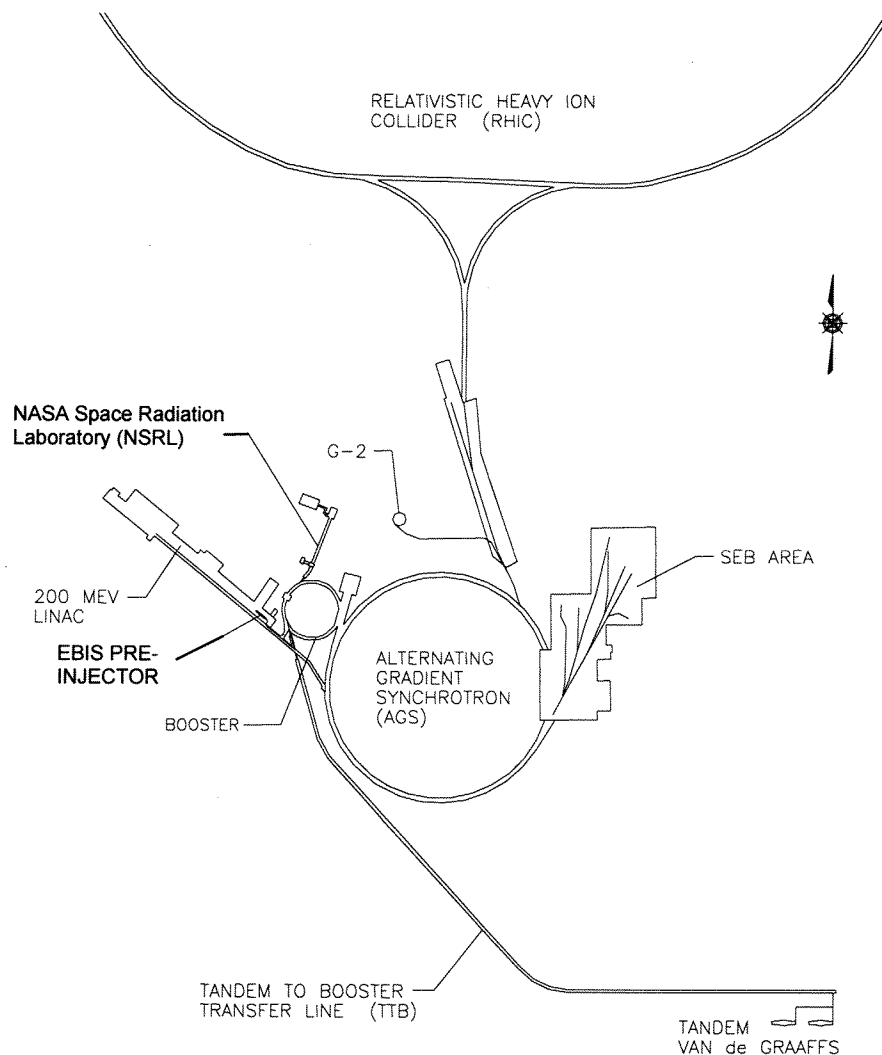


Figure 2.1 Schematic of the present Tandem injection and future EBIS injection lines.

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 3He , 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.

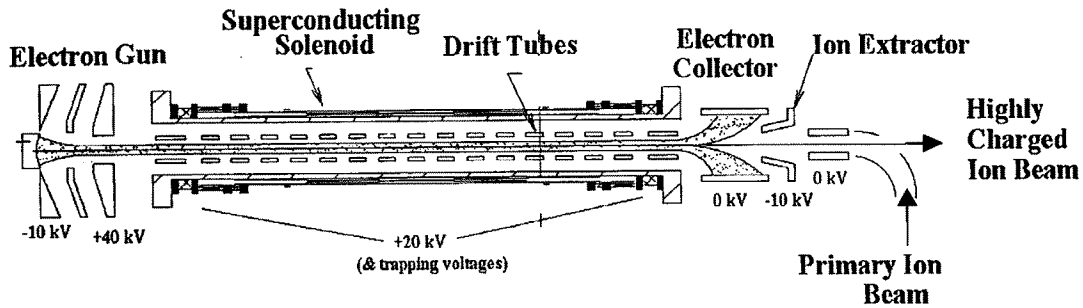
With the long-term commitment to heavy ions at BNL for RHIC, and increasing demands for different species and delivery of beams to different users, the EBIS pre-injector will enhance capabilities significantly. Undoubtedly, additional benefits of the EBIS pre-injector will appear as one gains experience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

PRINCIPLE OF OPERATION



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
 K_1 =neutralization factor

V_e =electron beam voltage
 K_2 =fraction in desired charge state

L =trap length

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	≤ 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, 3.4×10^9 Au³²⁺ ions in a 10 μs pulse corresponds to an Au³²⁺ 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 Au³²⁺ 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 μ A of Au^- in 500 μ s pulses. The beam is then accelerated to the 14 MV terminal, where ions are stripped by passage through a 2 $\mu\text{g}/\text{cm}^2$ 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 e μ A 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:
Au³²⁺ : 2.7×10^9 ions per pulse. (8.6×10^{10} charges/pulse). Sufficient to achieve 1.2×10^9 ions per bunch in RHIC.
D : 2.5×10^{11} ions/pulse. (From plasma source, for convenience)
Cu¹¹⁺ : 1.0×10^{10} ions/pulse. (1.1×10^{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+	2×10^{10}	1×10^{11}
O	8+	6.7×10^9	5.3×10^{10}
Si	13+	5×10^9	6.5×10^{10}
Ti	18+	1.3×10^9	2.4×10^{10}
Fe	20+	1.7×10^9	3.4×10^{10}

These numbers assume the expected efficiency from Booster injection to extraction of $\geq 85\%$ for few-turn injection. One needs $\leq 1.1 \times 10^{11}$ 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 μ s.** 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: 1.4π 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 $q/A \sim 0.16$ 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.

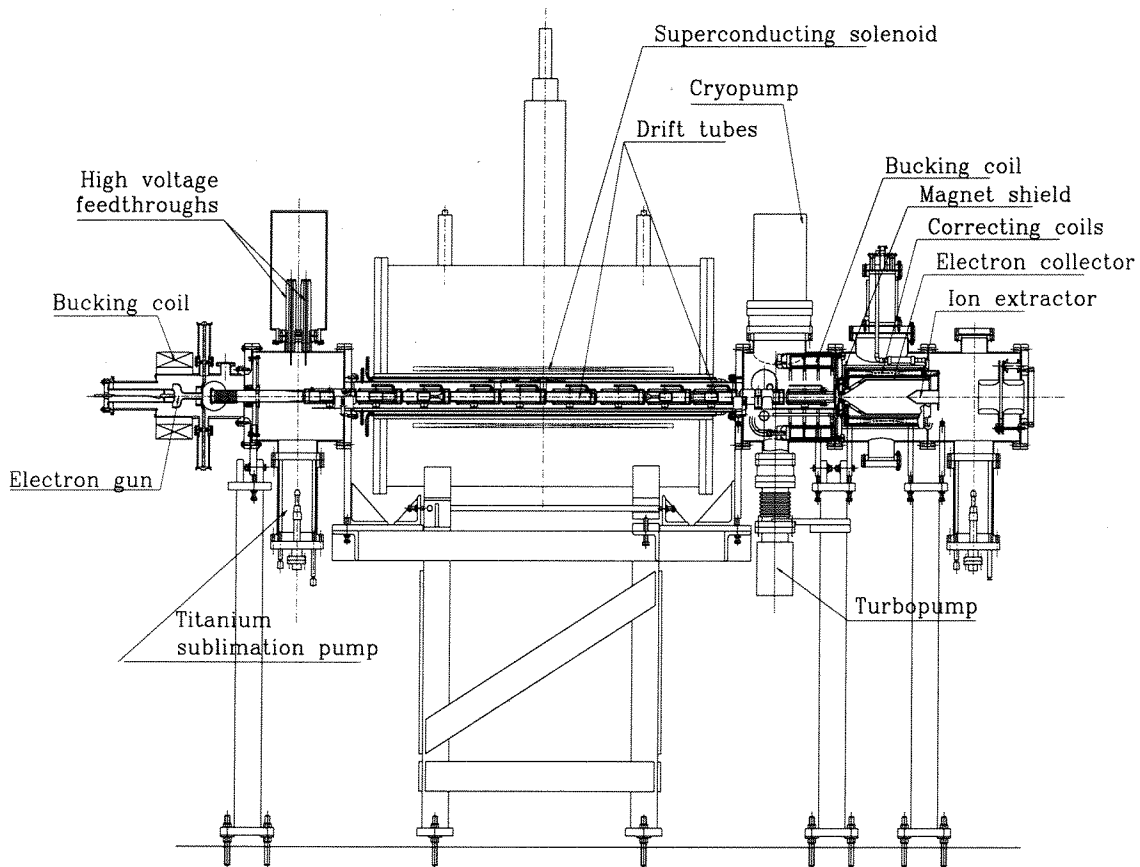


Figure 4.1 Schematic of the Test EBIS.

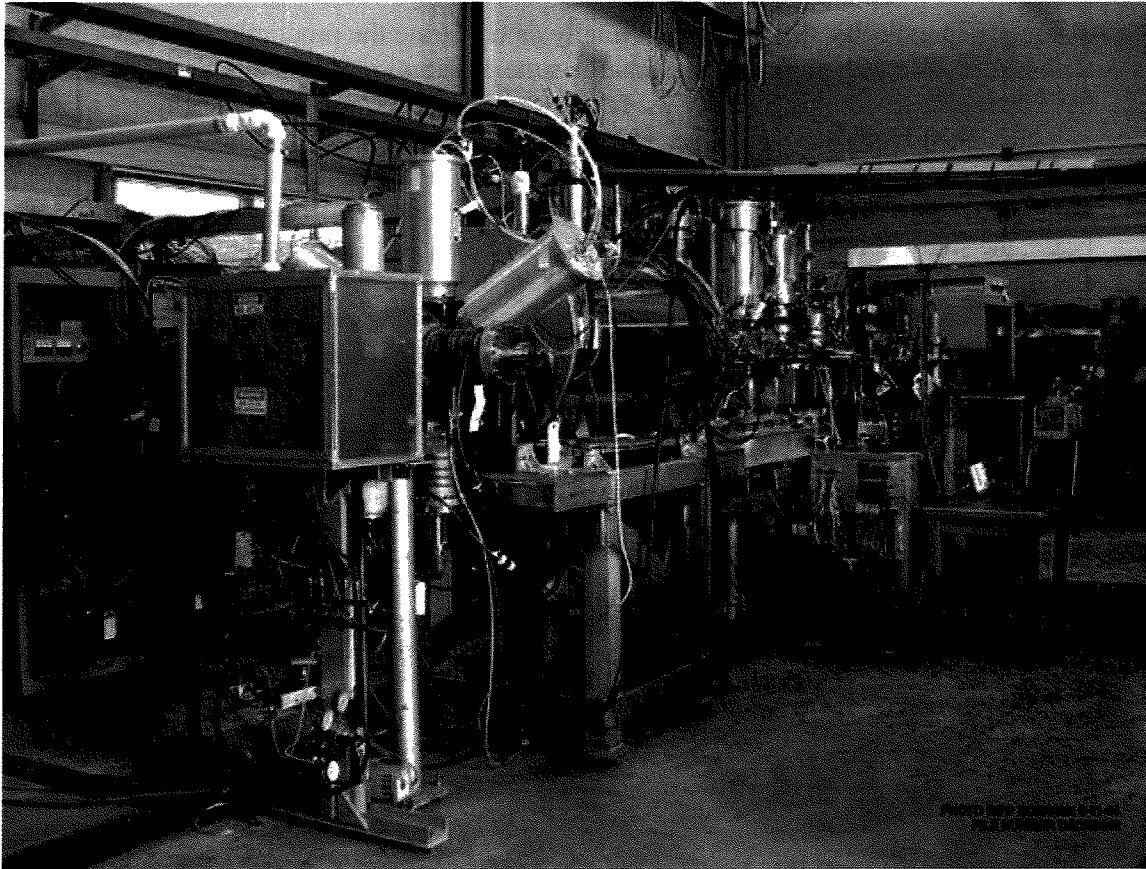


Figure 4.2 Photograph of Test EBIS

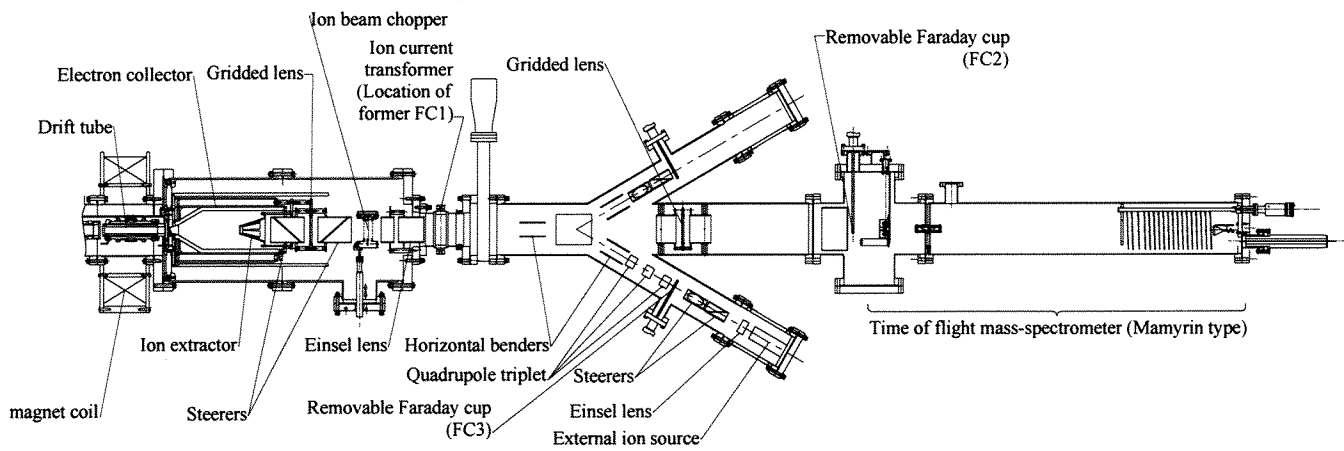


Figure 4.3 Schematic of the ion extraction, transport, diagnostics, and external injector

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 x 10 ⁻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 LaB₆ 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

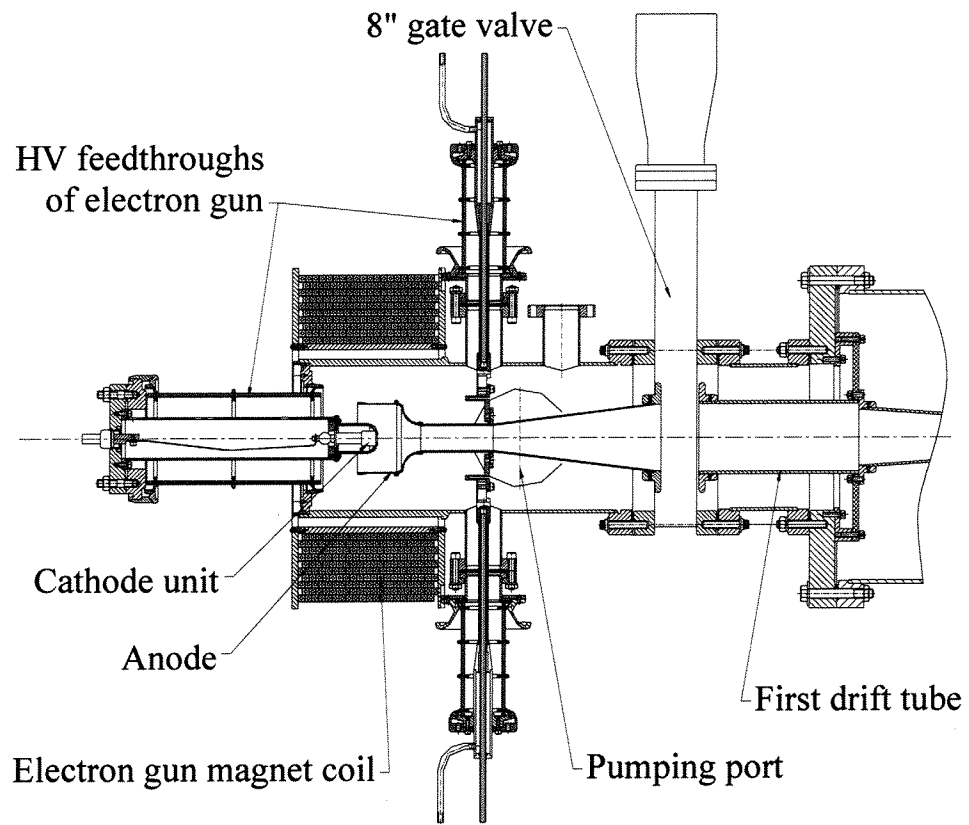


Figure 4.4 Electron Gun Assembly



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.

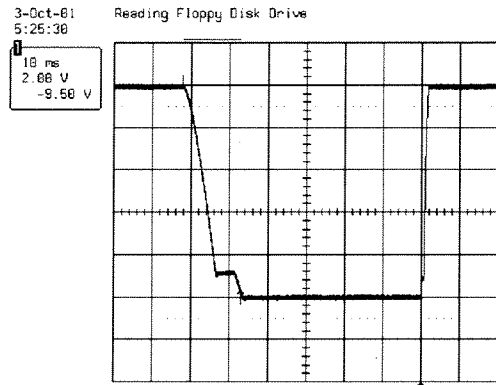


Figure 4.6 10A, 50 ms electron beam pulse. Vertical scale: 2A/div.

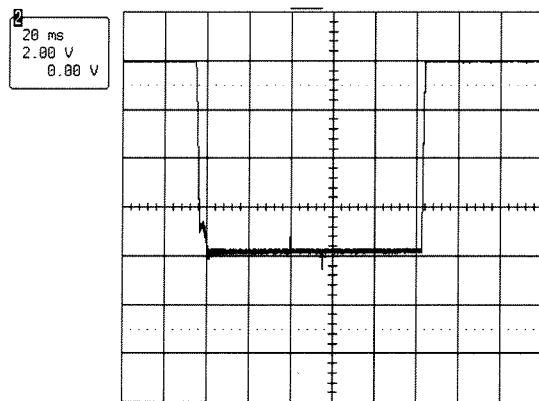


Figure 4.7 8A, 100 ms electron beam pulse

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 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 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.

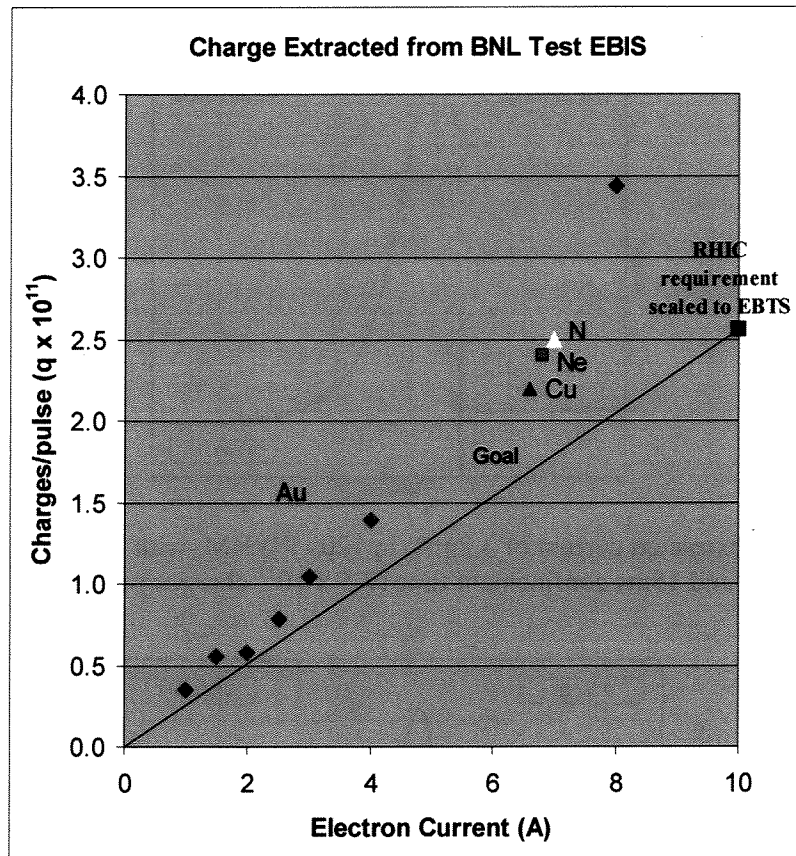


Figure 4.8 Extracted ion charge as a function of electron current for Test EBIS.

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 μ s long. Figure 4.9 is a 3.2mA, 12 μ s FWHM ion pulse, (2.5×10^{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.

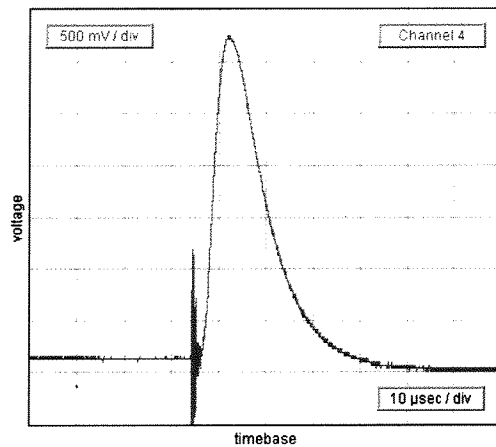


Figure 4.9 Total extracted current of 3.2mA, in 12 μ s FWHM, with $I_e=6.8$ A, Au injection, and 15ms confinement time (2.5×10^{11} charges/pulse).

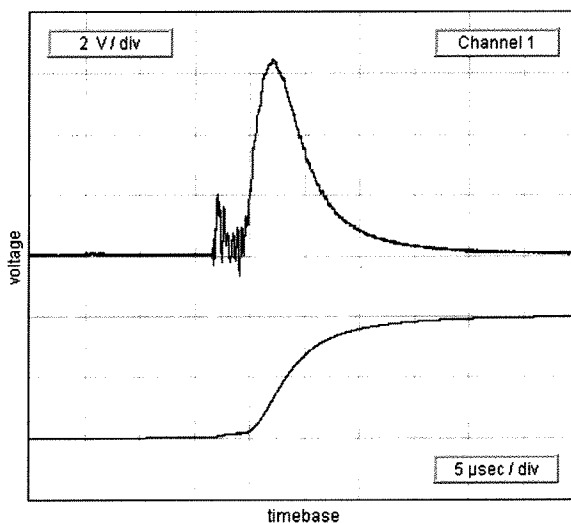


Figure 4.10 Total extracted current of 6.3 mA, Neon injection, $I_e=6.8$ A, 18 ms confinement time (2.4×10^{11} charges/pulse).

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 Au³³⁺ 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.

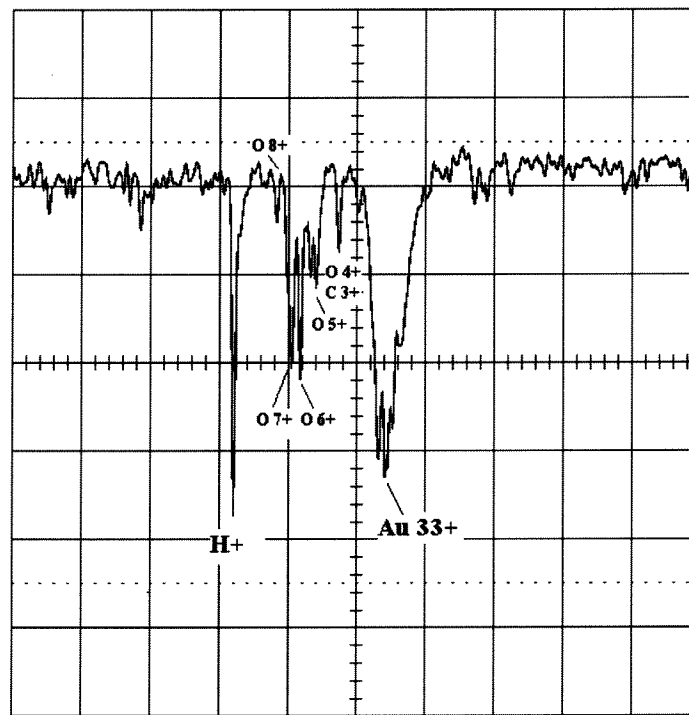


Figure 4.11 Narrow Au charge state distribution coming from external gold ion injection into the Test EBIS ($I_e=7.2$ A, confinement time=40 ms).

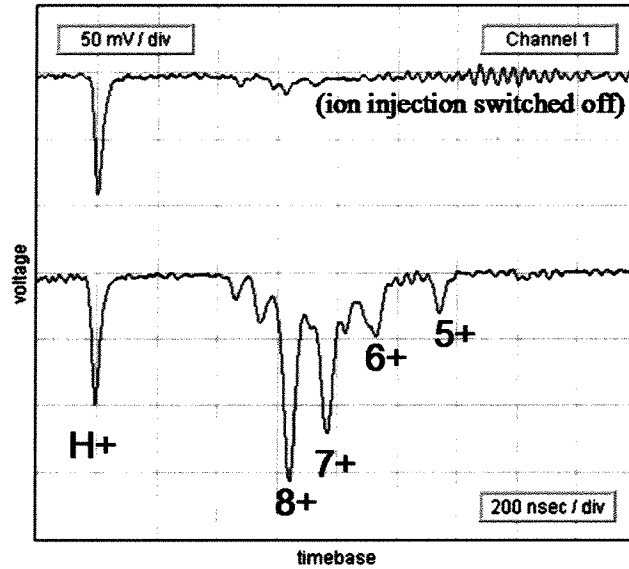


Figure 4.12 Neon charge state distribution ($I_e=6.8$ A, confinement time=14 ms)

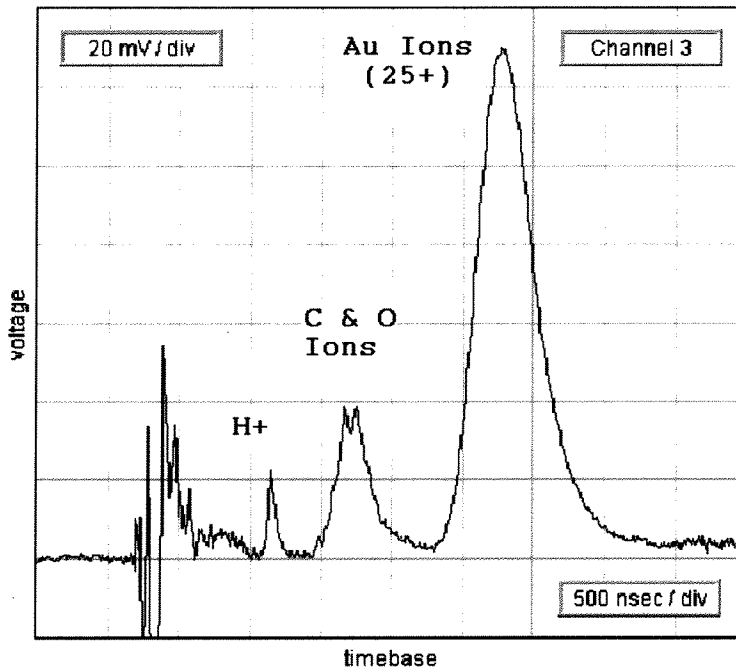


Figure 4.13 Inline Time-of-Flight spectrum showing Au=83%; C&O=15%; H=2%

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 μ s pulses at 10 kV. Up to 100 μ A 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 $\sim 25\%$ 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 $15\mu\text{A}$, 15kV have been extracted from a pulsed 1ms, 3A discharge using a 1.5mm plasma electrode aperture. The emittance of a $10\mu\text{A}$, 10kV Cu^{1+} beam has been measured as 16π mm mrad (rms) which is below the acceptance value determined by computer simulation of the Test EBIS.¹² Beams up to $80\mu\text{A}$ 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 $\sim 45\mu\text{A}$ and Ne^{+1} current of $130\mu\text{A}$ 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 $\sim 1\text{mb}$, the EBIS ionization volume remains below $2 \times 10^{-10}\text{mb}$ for shutter open time 10ms and 1Hz repetition rate.

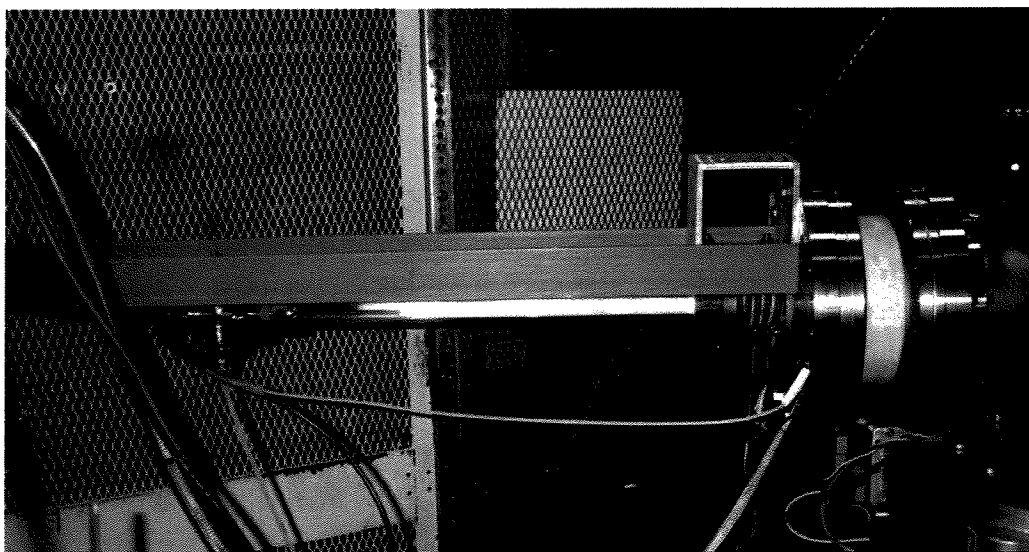
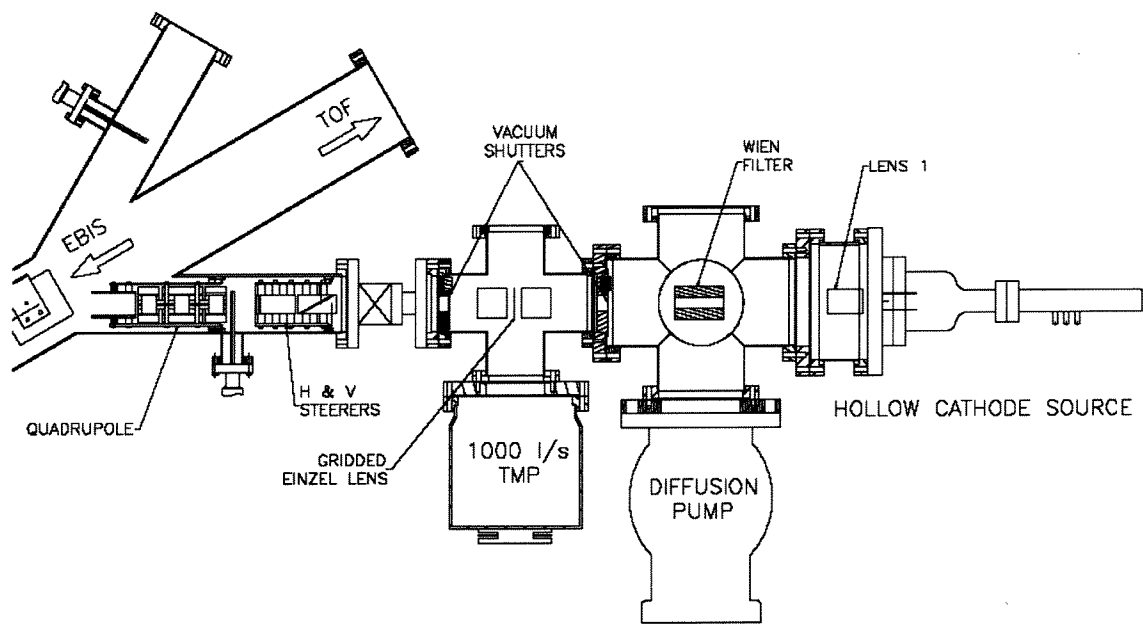


Figure 4.15 Hollow Cathode Ion Source with Ne discharge and Copper cathode.



$P \sim 4 \times 10^{-8}$ mB $P \sim 4 \times 10^{-6}$ mB $P \sim 8 \times 10^{-5}$ mB $P \sim 0.8$ mB

Figure 4.16 Schematic of the Hollow Cathode Ion Source beamline, with pressures in the differentially pumped chambers. With the source operating, $P \sim 2 \times 10^{-10}$ 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

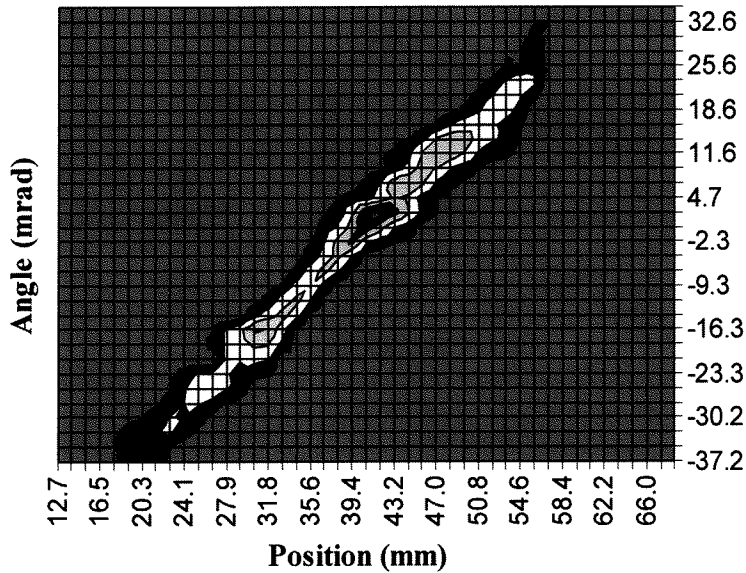


Figure 4.17 Emittance of a 1.7 mA extracted beam from EBIS, with Au injection.
 $\epsilon(n,rms) = 0.1 \pi$ mm mrad.

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 $\sim 10\mu s$ 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 Au³²⁺. 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 5×10^{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.

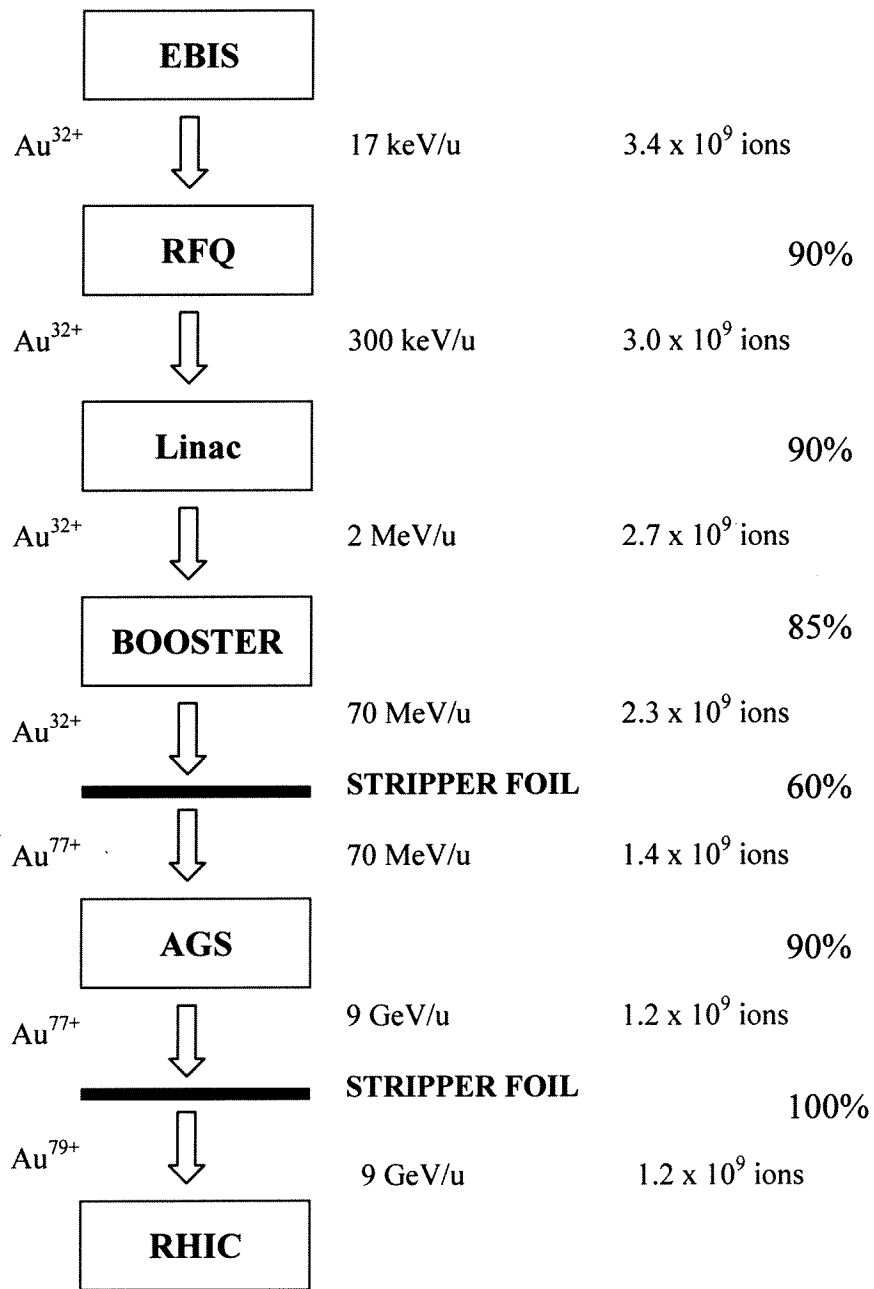


Figure 5.1 Schematic of Linac-based injection, showing ions per pulse, and efficiencies at various stages, for Au injection.

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)	1.1×10^{11}	charges/pulse
	Ion output (Au^{32+})	3.4×10^9	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	

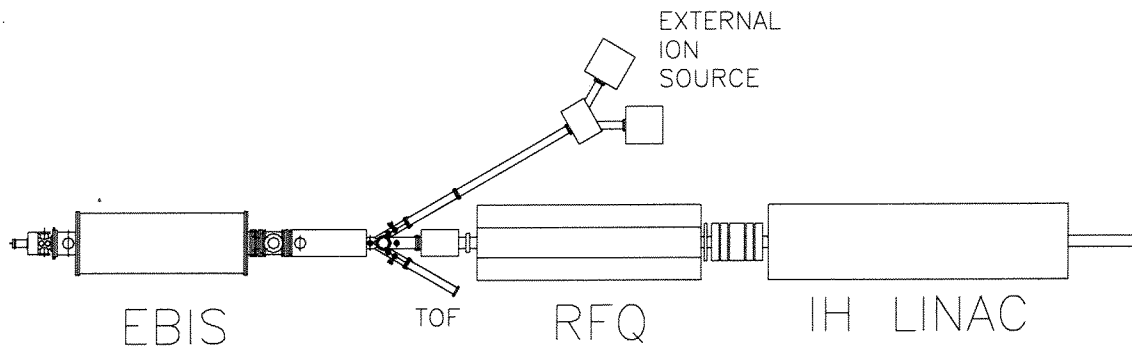


Figure 5.2 Conceptual layout of the pre-injector

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).

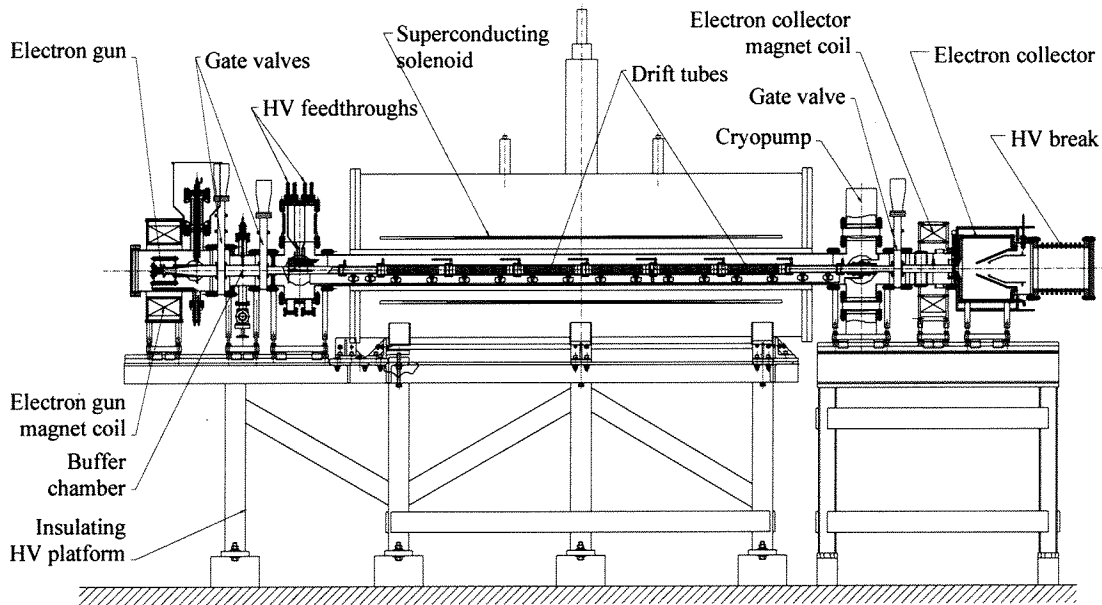


Figure 5.3 Schematic of the proposed EBIS for RHIC.

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 $\sim 1 \times 10^{12}$ 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 LaB₆ cathodes.

Published results of tests of IrCe cathodes show that even for an emission density as high as 30 A/cm² the lifetime is several thousands hours – much longer than we expect from our LaB₆ 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.

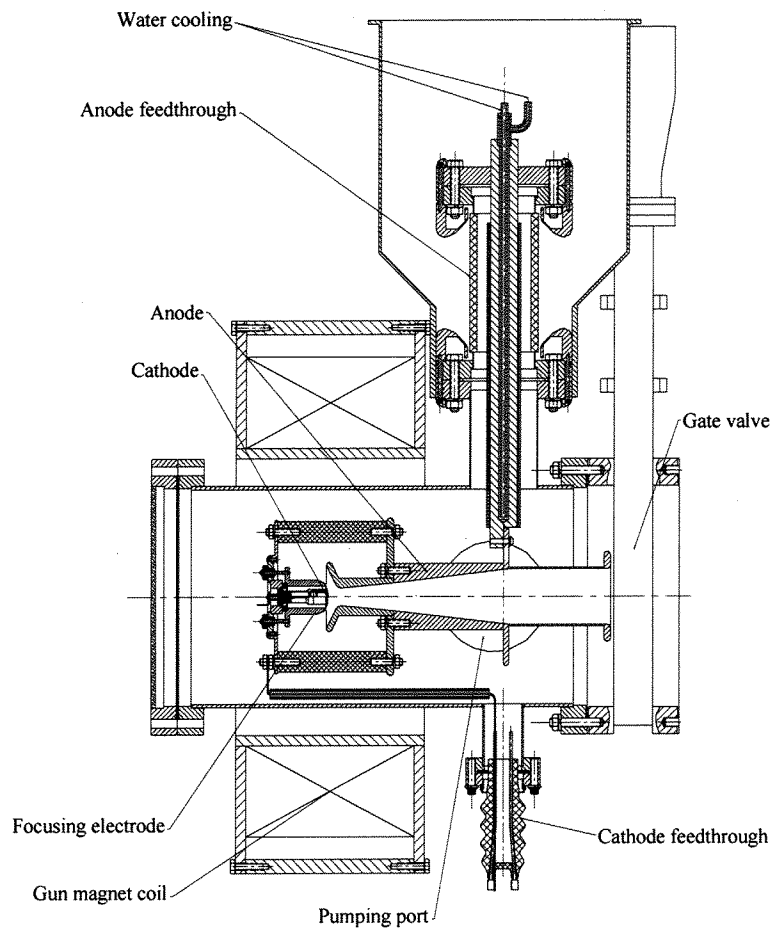


Figure 5.4. Replaceable electron gun unit of RHIC EBIS.

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/cm². 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.

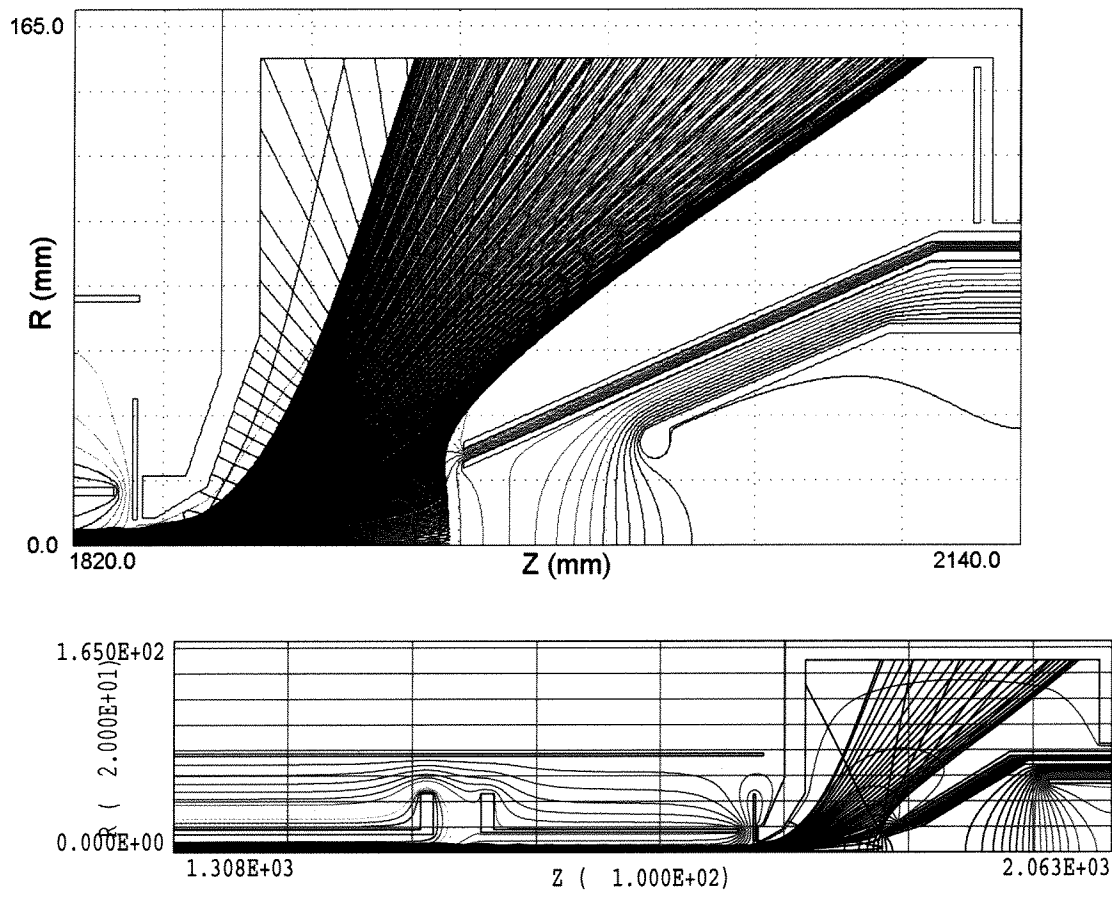


Figure 5.5 Simulated trajectories of electron beam with current 15 A entering the electron collector with energy 15 keV.

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%.

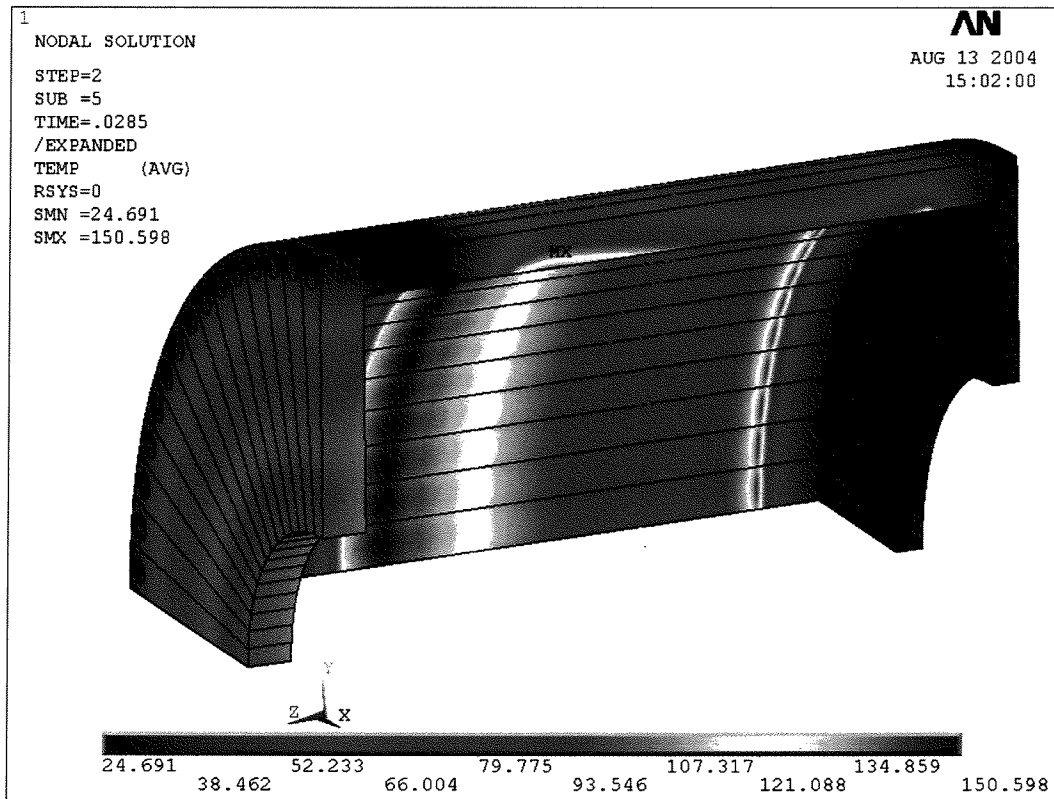


Figure 5.6 Simulated temperature distribution on the EC surface at the end of an electron pulse 20A, 15 keV, 50 ms. The average temperature reached equilibrium.

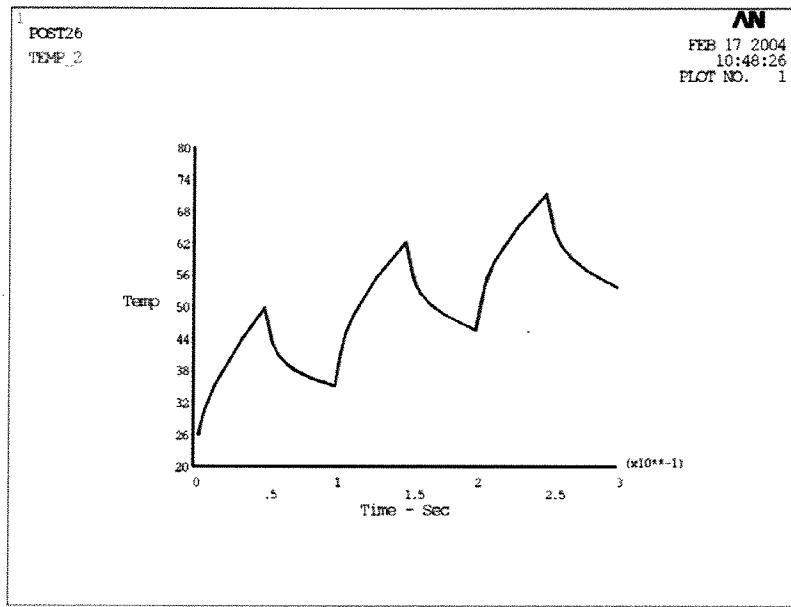


Figure 5.7 Temperature cycling in the hottest node at the beginning of the power load (20A, 15 keV, 50 ms on, 50 ms off).

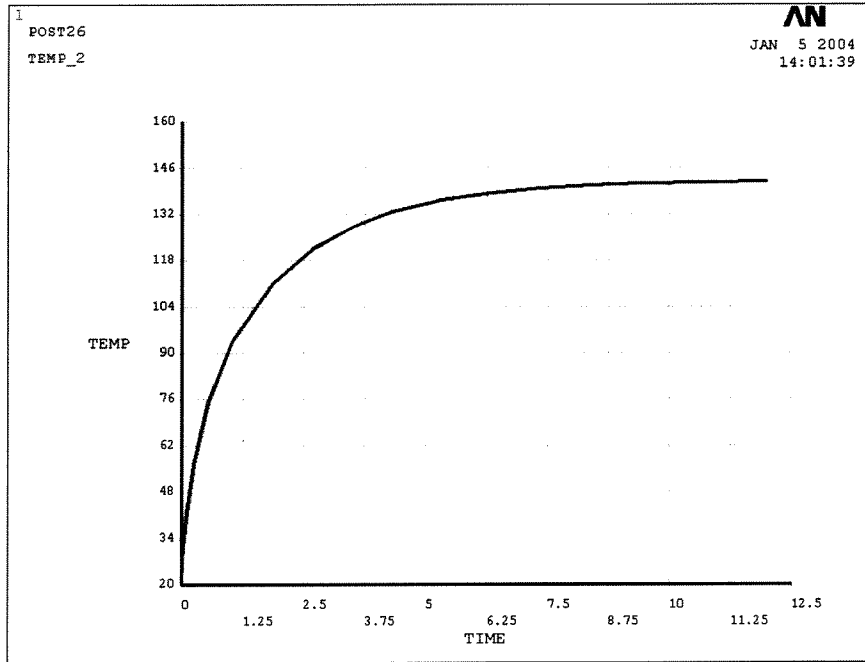


Figure 5.8 Average temperature rise from the beginning of the thermal load on the EC. Time scale – in sec (20A, 15 keV, 50 ms on, 50 ms off).

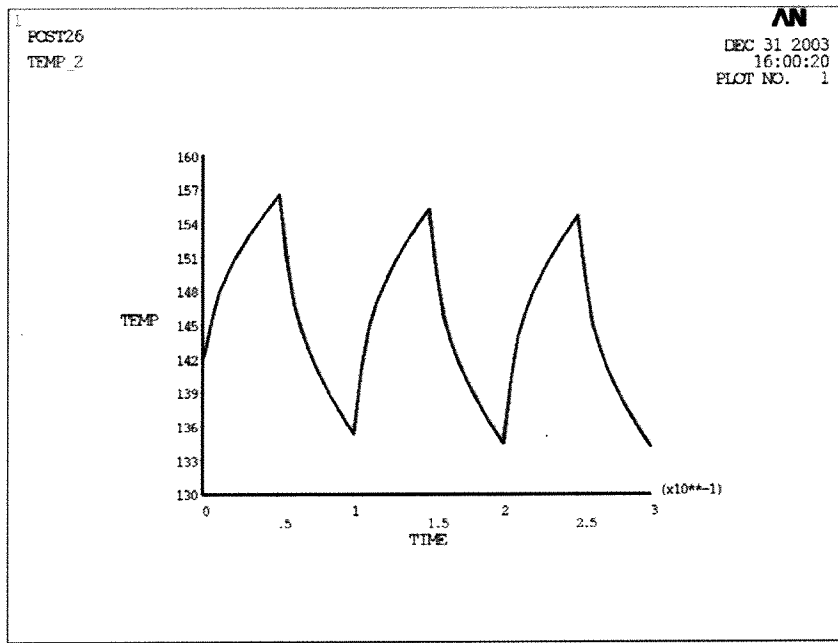


Figure 5.9 Temperature cycling at the hottest node of the EC in equilibrium of medium temperature. (20A, 15 keV, 50 ms on, 50 ms off)

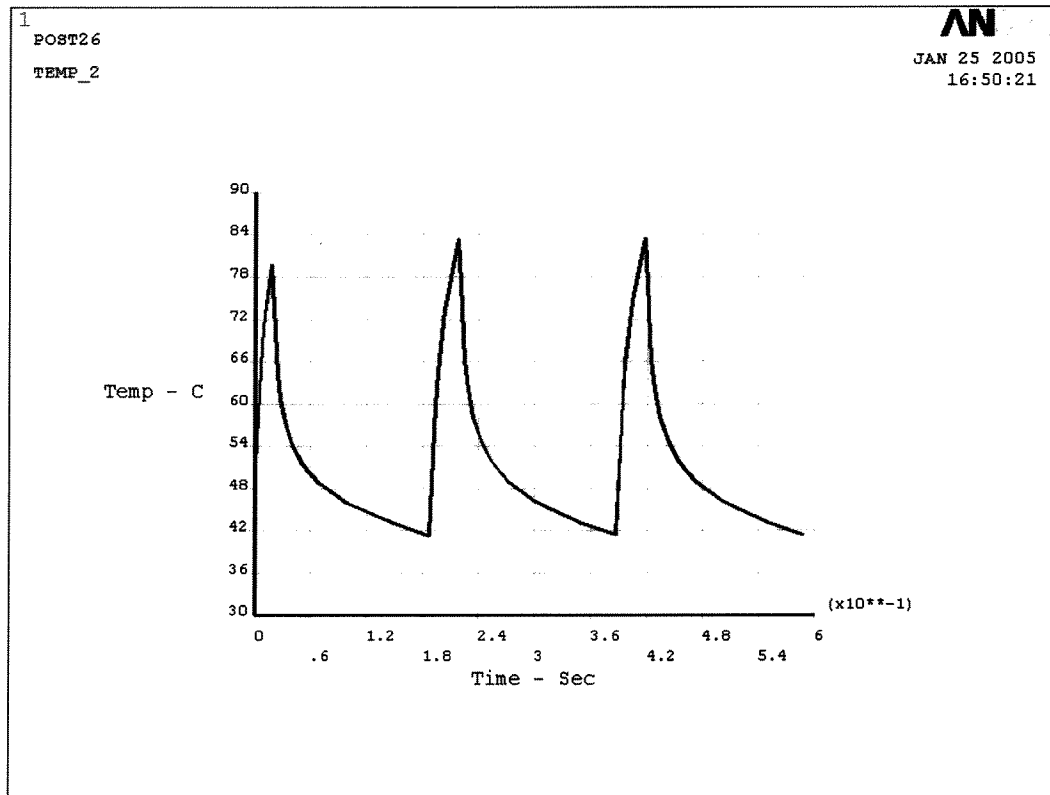


Figure 5.10 Temperature cycling at the location of maximum power density on the EC in equilibrium of medium temperature (20 A, 15 keV, 30 ms on, 170 ms off).

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 $(135-155)^{\circ}\text{C}$ for a 50% duty cycle and $(42-86)^{\circ}\text{C}$ 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.

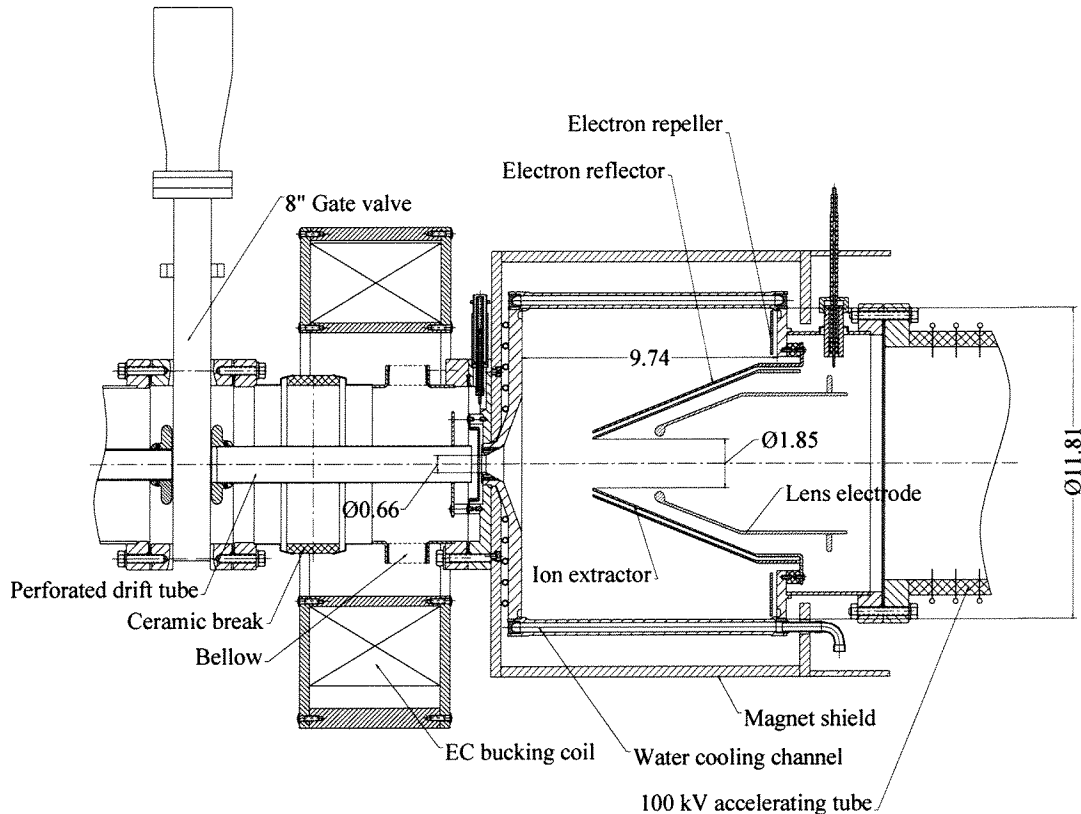


Figure 5.11 The Conceptual assembly drawing of the electron collector for RHIC EBIS.

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.

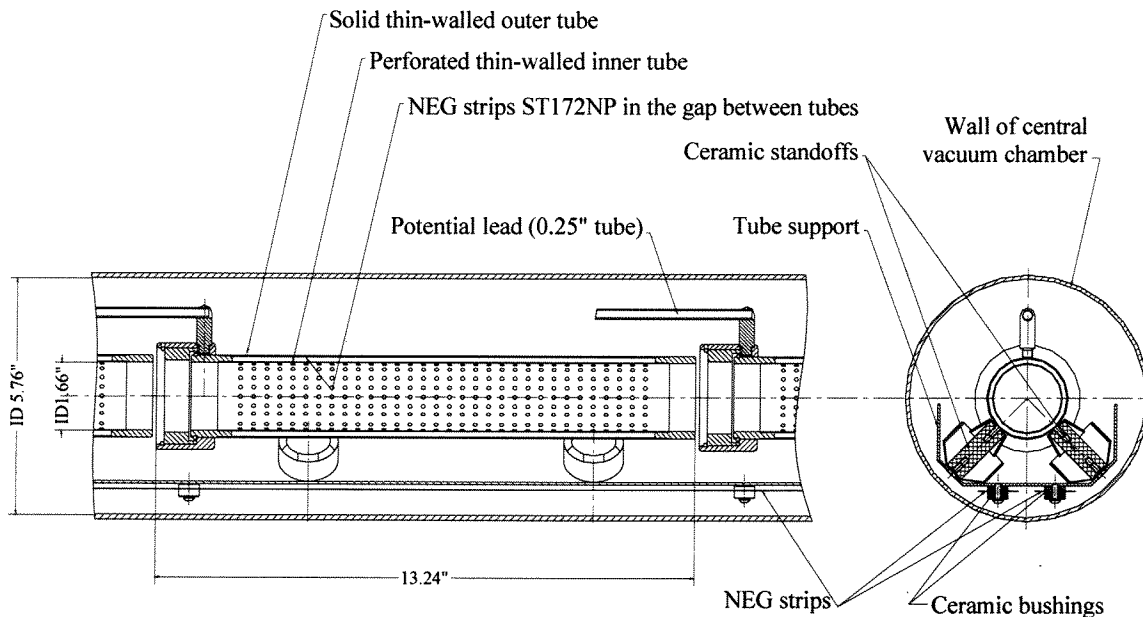


Figure 5.12 Central drift tube (ionization region).

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.	1×10^{-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 $P=1 \times 10^{-10}$ 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 900⁰ 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 300⁰C.
- 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.

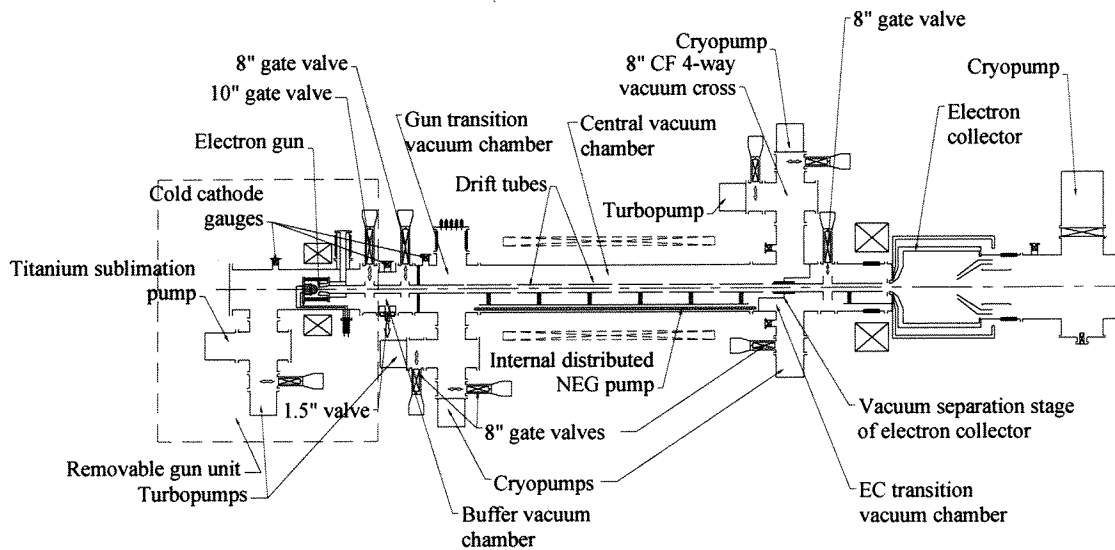


Figure 5.13 Vacuum system of RHIC EBIS

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.

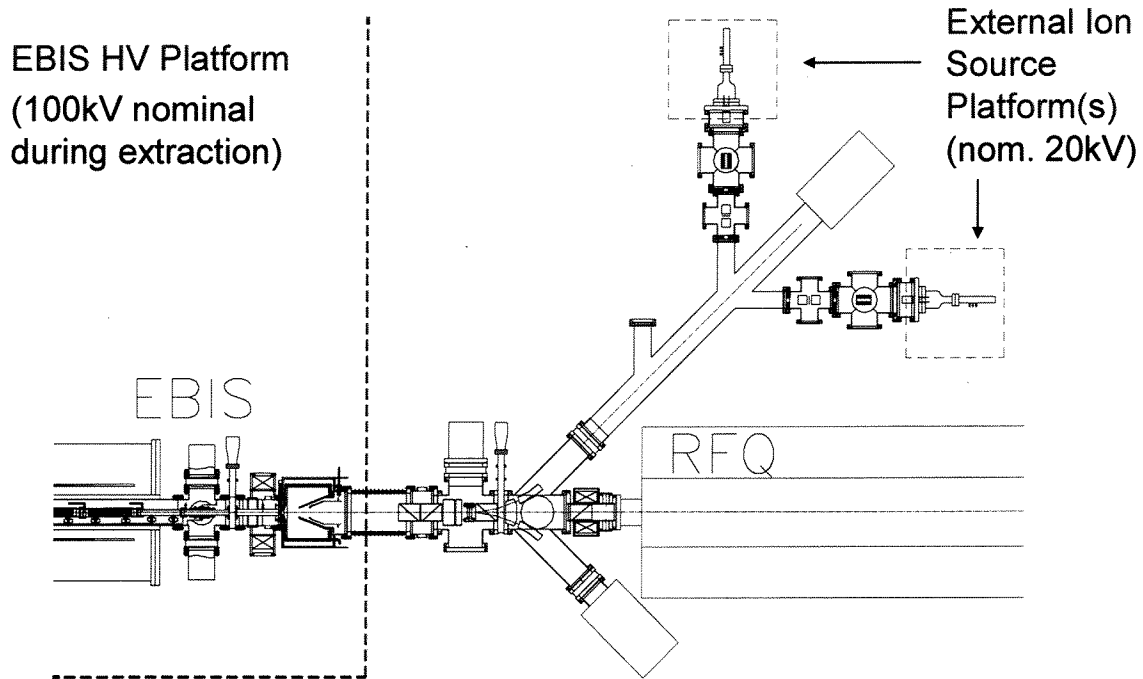


Figure 5.14 Schematic showing the external ion source beamline.

5.2.8. EBIS Power Supply Requirements

For injection into the RFQ at 17 keV/amu, Au³²⁺ 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.

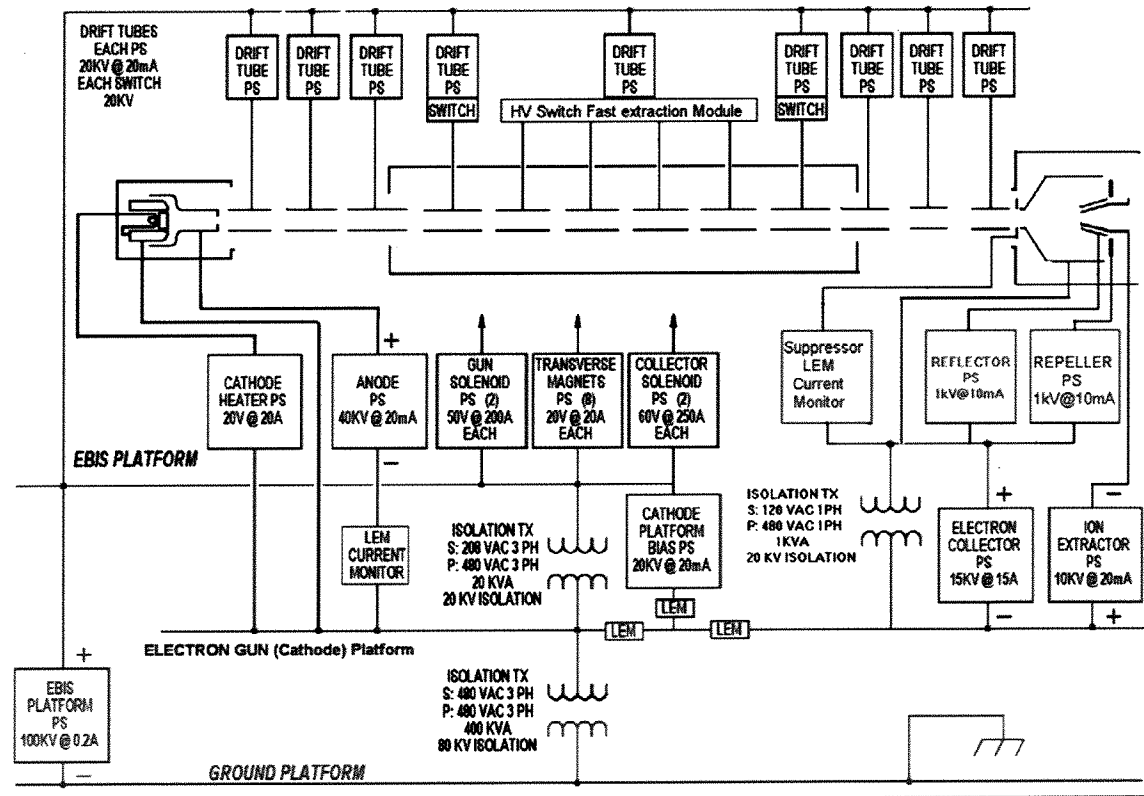


Figure 5.15 Schematic of the EBIS voltage platforms

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 (~10 μ s) 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 μ F 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.

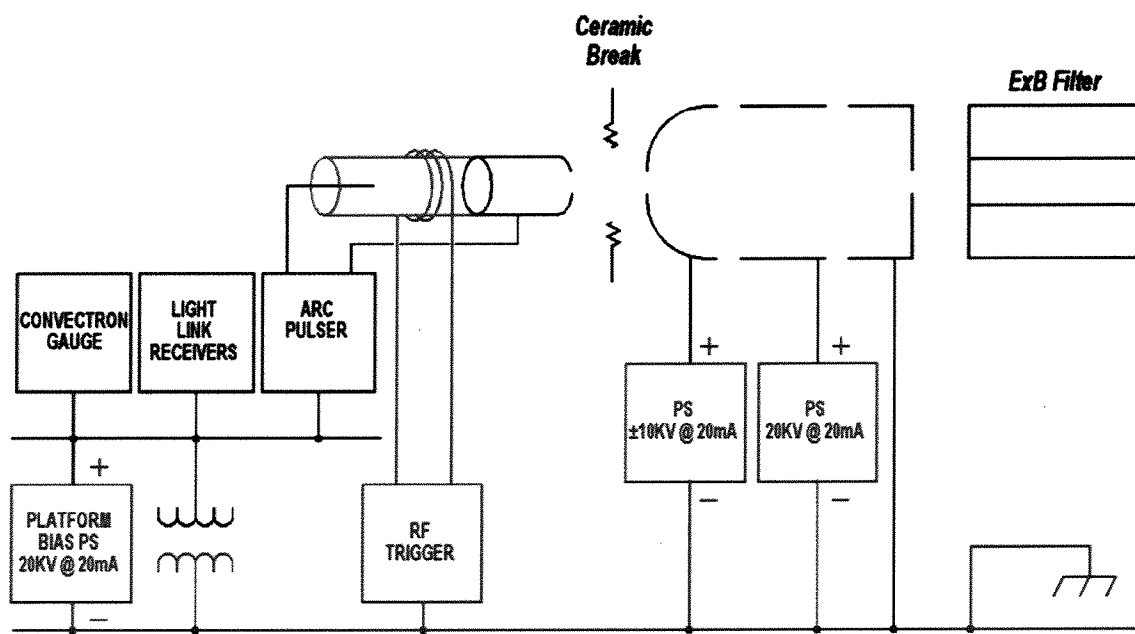


Figure 5.16 Schematic of the Hollow Cathode Source power supply configuration.

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 10 μ s). 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 μ s. 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.

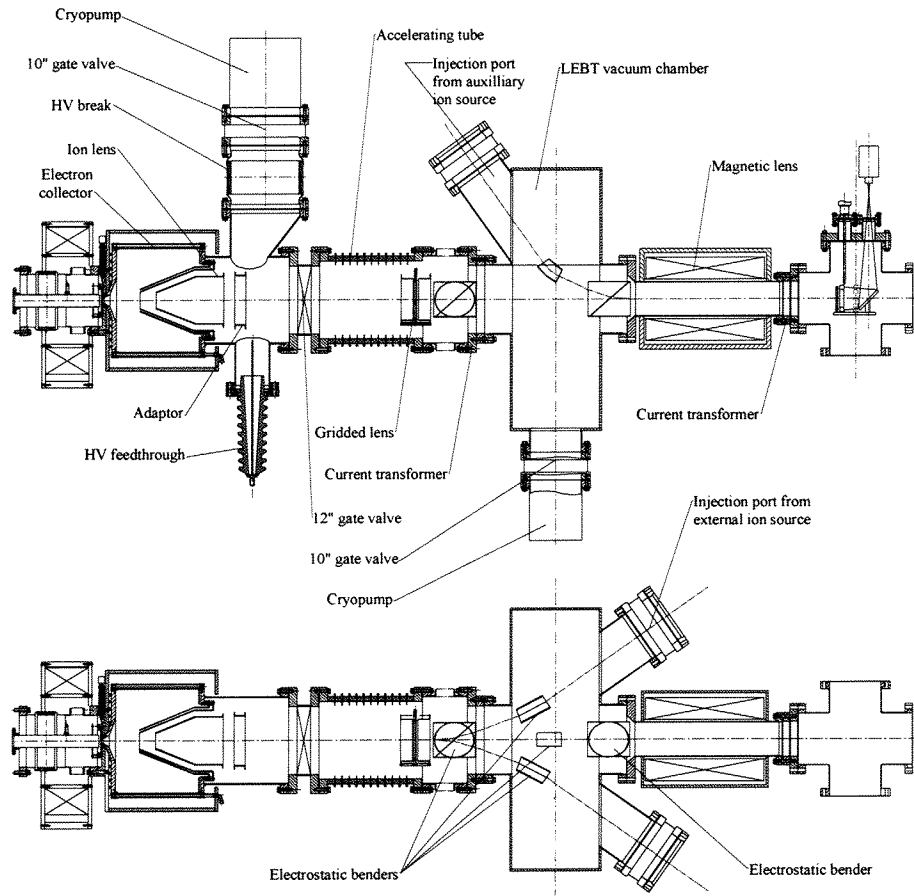


Figure 5.17 Schematic of the LEBT preliminary design

The beam from the EBIS source has to be matched into the RFQ, which needs a small, highly convergent beam. The beam out of EBIS is symmetric in x and y, as is the RFQ acceptance, so one needs control of only two degrees of freedom for matching. The starting condition of the beam for LEBT was obtained using the following formula

$$kT_i \left(\frac{R_i}{R_t} \right)^2 = q \cdot (U(R_i, z_0) - U(0, z_0))$$

Where R_t is ion beam radius inside the trap, R_i is beam radius at point of interest, and U is the ion beam space charge potential.

Table 5-4 shows the Twiss parameters of Au^{+32} and ${}^3\text{He}^{+2}$ for 10 mA of ion current at the collector.

Table 5-4 Twiss parameters of Au^{+32} and ${}^3\text{He}^{+2}$ at the collector, for 10mA.

	E (keV)	α	β (m)	ε (RMS,norm) π mm mrad
Au^{+32}	970	0.0	0.075	0.035
${}^3\text{He}^{+2}$	15	0.0	0.047	0.034

Figure 5.18 shows particle trajectories through the extraction/ acceleration system to the RFQ. Table 5-5 shows the Twiss parameters at the beginning, and end of the LEBT for Au^{+32} with a kinetic energy of 17 keV/amu. The magnetic field required for the 37.1 cm long transverse matching solenoid is 7.8 kG. There is ~ 1 meter between the two lenses for ion injection and diagnostics.

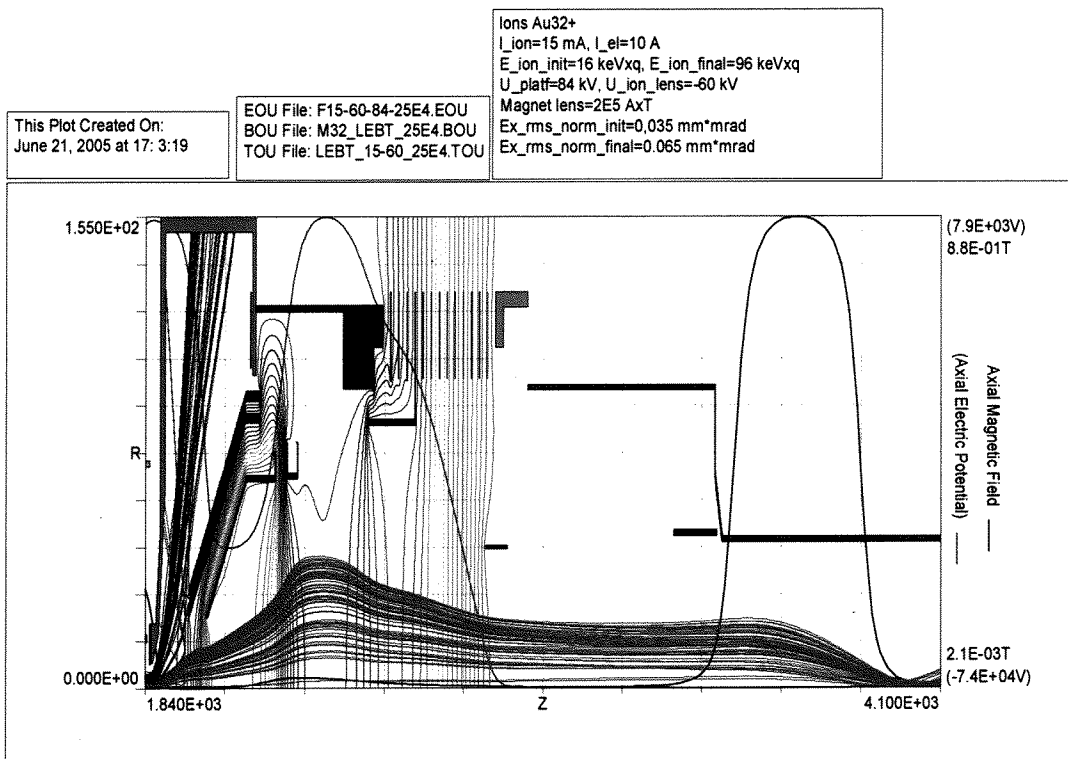


Figure 5.18 Ion (Au^{+32}) trajectories through the LEBT.

Table 5-5 Twiss parameters at the beginning and end of the LEBT.

Parameters	Beginning of LEBT	End of LEBT	Units
α_x	0.0	1.057	
β_x	0.075	0.0639	mm/mrad
ϵ_x (rms, norm)	0.035	0.072	π mm mrad
α_y	0.0	1.057	
β_y	0.075	0.0639	mm/mrad
ϵ_y (RMS, norm)	0.035	0.072	π mm mrad

These calculations have been done including the effects of the space charge at the full beam current of 10.0 mA (all charge states), since the pulse length is too short for neutralization to occur. If the charge-state distribution were broader, as in an ECR or LIS, the space charge from a much higher total beam current would present problems in matching. Simulations for the extraction/ acceleration system and gridded lens were done using the axially symmetric code TRAK. The results of an earlier calculation of the phase space ellipse of the different charge states at the entrance of the RFQ is shown in Figure 5.19.

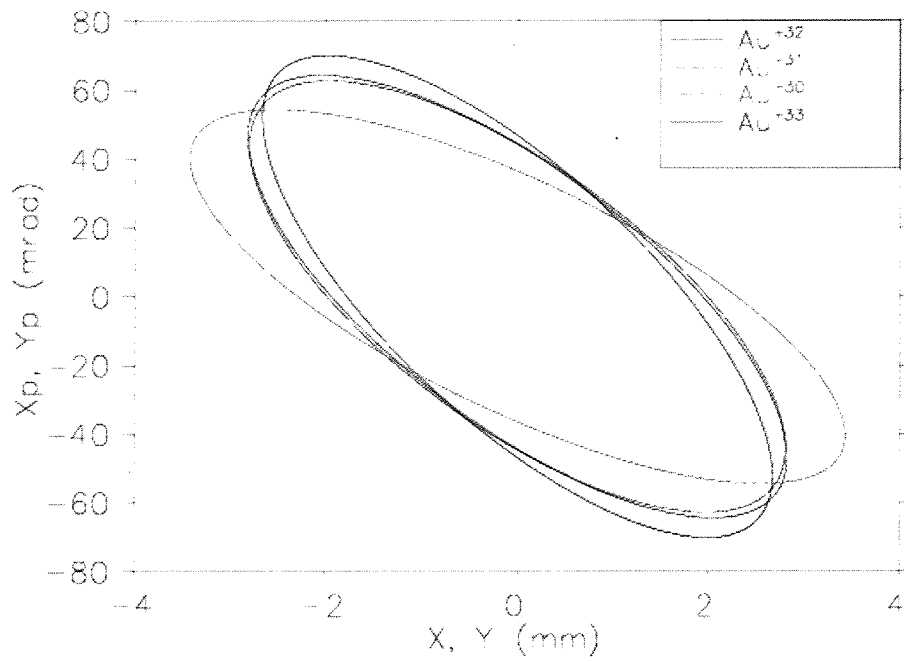


Figure 5.19 Phase space ellipses at the entrance of RFQ for different charge states of Au.

Calculations have also been done where the beam is matched into the RFQ with two solenoid lenses, and this may still be a viable option.

5.4. RFQ

5.4.1. Choice of Parameters

The EBIS output energy is 16.24 keV/amu. The RFQ output energy is 314.72 keV/amu, which is a comfortable input energy for the IH structure. The frequency chosen is 101.28 MHz. The focusing force in the RFQ is proportional to $1/(\text{rf wave length})^2$, and this frequency provides a good focusing for a relatively low q/m beam. Another consideration has been the fact that there are several existing RFQs operating at this frequency. The emittance from the EBIS source has not yet been fully determined, but based on the available data we estimate it to be about 0.35π mm mrad (normalized, 90%). The acceptance of the RFQ in the present design is comfortable, at 1.7π mm mrad (norm.), with an aperture radius of 5 mm.

5.4.2. Specifications

At a frequency of 101.28 MHz, a four rod RFQ can be easily designed and built, and would be very similar to the CERN heavy ion RFQ. Table 5-6 shows some parameters and specifications of the two RFQs. Figure 5.20, shows the beam optics relevant parameters along the length of the RFQ.

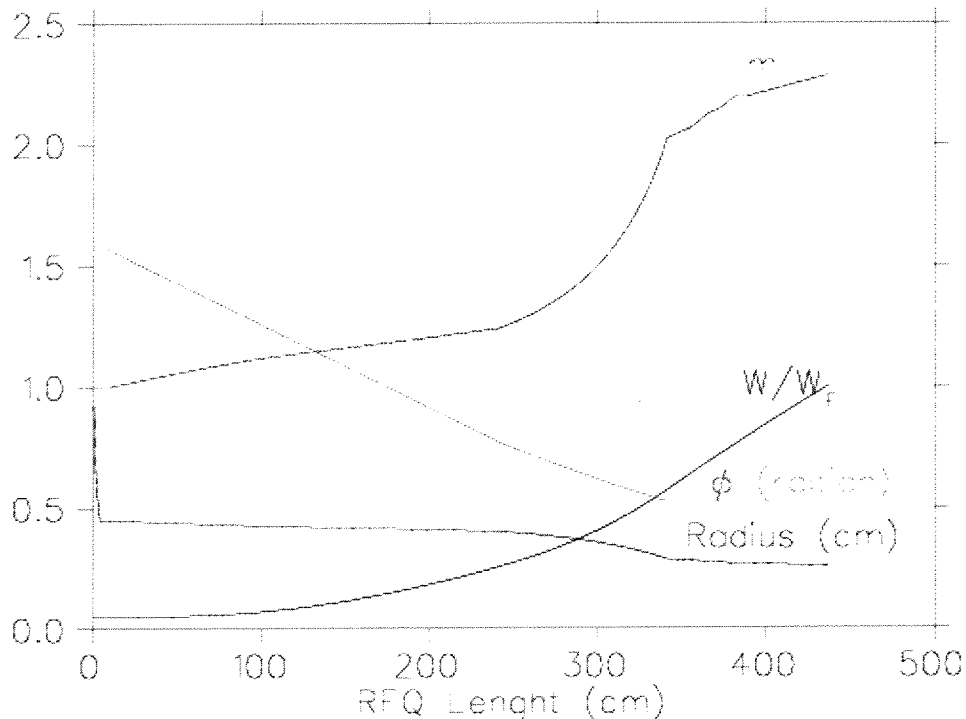


Figure 5.20 Optics design parameters for the RFQ

Table 5-6 Specifications for the RFQ

Parameters	BNL	CERN	Units
Type	4-rod	4-rod	
Q/m	0.16-0.5	0.12	
Input Energy	16.2	2.5	keV/amu
Output Energy	314.72	250	keV/amu
Frequency	101.28	101.28	MHz
Max rep rate	5	10	Hz
Length	4.37	2.5	meters
Number of cells	277		
Aperture Radius	0.005	.0045	meters
Voltage	69	70	kV
E (surface)	20.8	≤ 23	MV/m
RF Power	< 350	< 350	kW
Acceptance	1.7	> 0.8	π mm mrad (nor)
Input Emittance	0.35		π mm mrad, nor, 90%
Output Emittance (trans)	0.375		π mm mrad, nor, 90%
Output Emittance (longit)	33.6		π MeV deg, 90%
Transmission	91	93	%
Bravery factor	1.8	≤ 2	Kilpatrick

5.4.3. Beam Dynamics

To keep the length short, the RFQ is designed using a modified LANL algorithm.¹³ The RFQ has four sections, (1) radial matching section, (2) shaper (3) buncher and (4) accelerating section. The design of the first three sections follows the same principle as LANL's,¹⁴ but in the acceleration section, at first the current limit is kept constant while the modulation factor m grows by 2, after which m is kept constant. This reduces the RFQ length, which is only 4.37 meters.

Figure 5.21 shows the current limits along the RFQ and Figure 5.22 shows the various beam profiles along the RFQ. Simulations show that the beam losses are concentrated in the RFQ during the bunching process. Figure 5.23 shows the transmission as a function of input emittance. Calculation does not show any emittance growth. Figure 5.24 shows the transmission as the input energy is varied. This shows that the RFQ transmission will remain good even if the EBIS beam energy spread is increased (i.e. voltage in the EBIS trap is ramped to decrease ion pulse width). Simulations also show that transmission is high for charge states neighboring the design charge state, that is, the RFQ will not act as a good filter for the off-charge states. Figure 5.25 shows the transmission of different charge state. Figure 5.26 shows the transmission as a function of input current. The RFQ transmission remains > 80% even for currents in excess of 30 mA. Table 5-7 shows the beam parameters for different ions at the end of the RFQ. Figure 5.27 - Figure 5.29 shows the phase space plots (x - x_p , y - y_p and W - Φ) for different charge states at end of the RFQ.

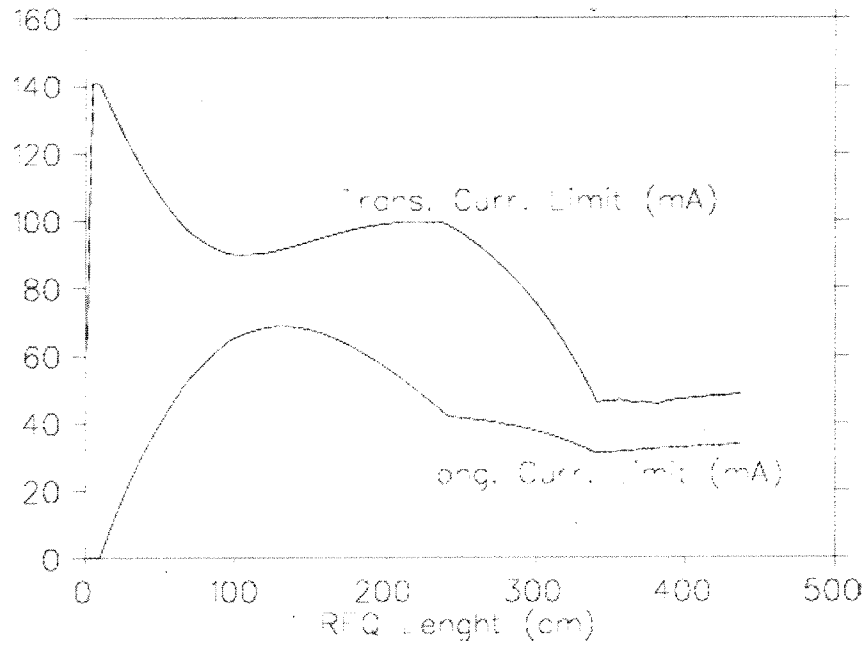


Figure 5.21 Current limits along the RFQ

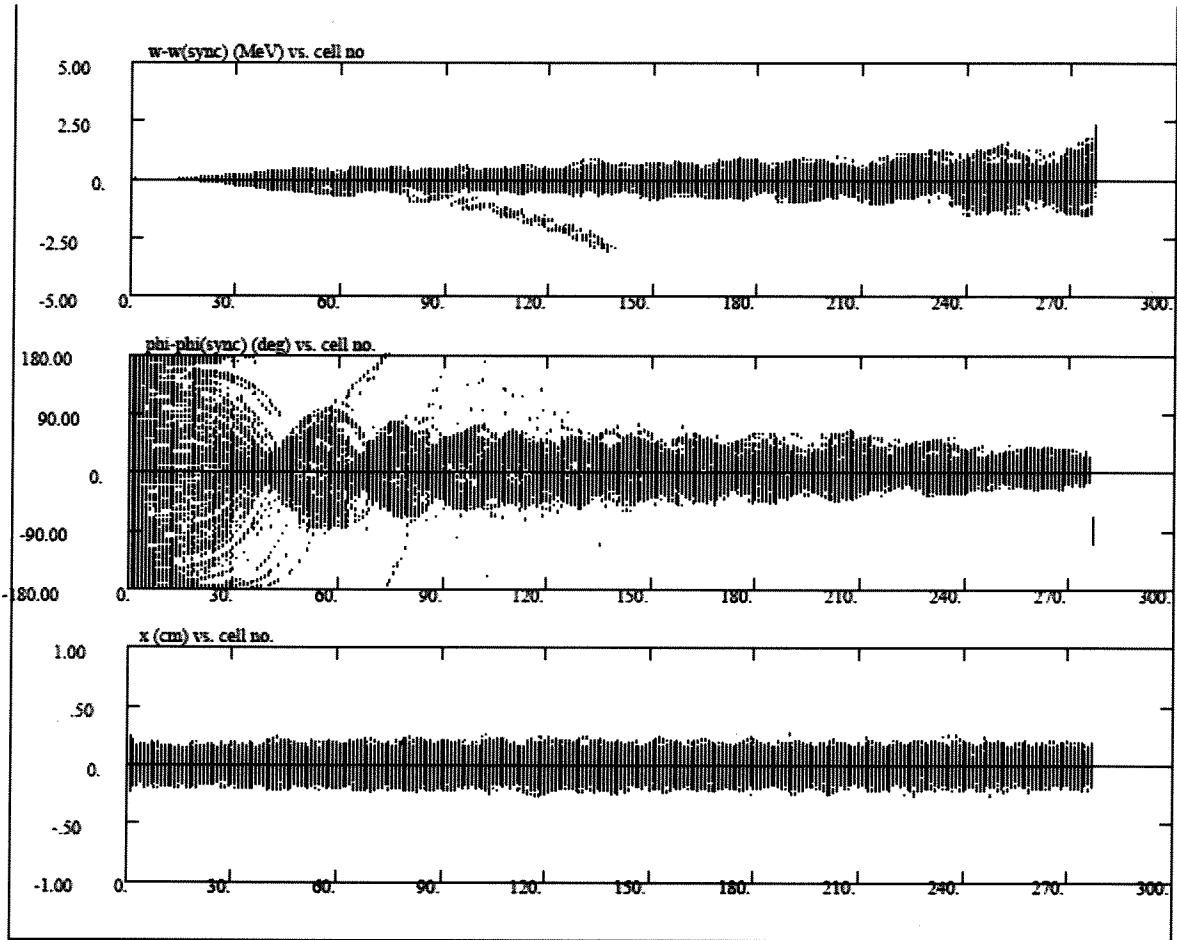


Figure 5.22 Variation of energy spread, phase spread, and x-profile along the RFQ

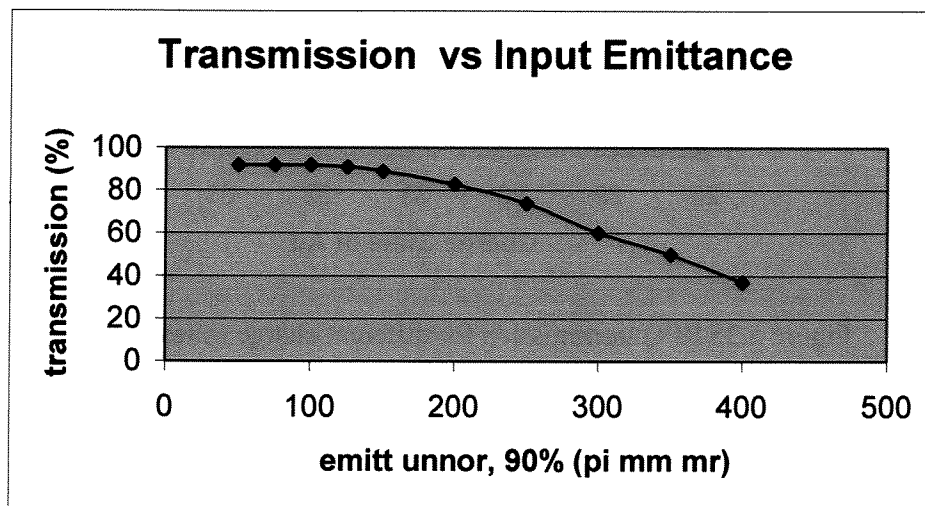


Figure 5.23 RFQ transmission vs. input emittance.

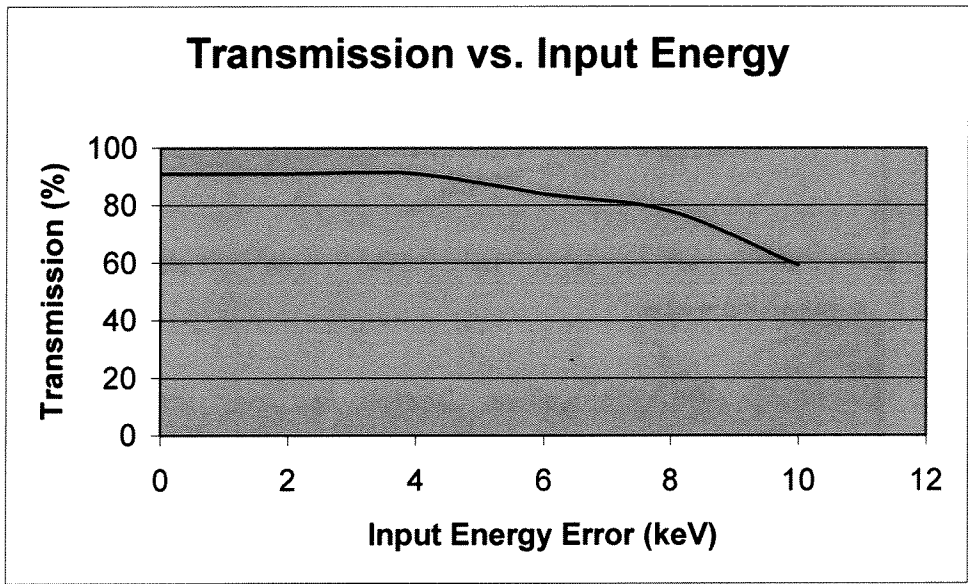


Figure 5.24 RFQ transmission vs. input energy.

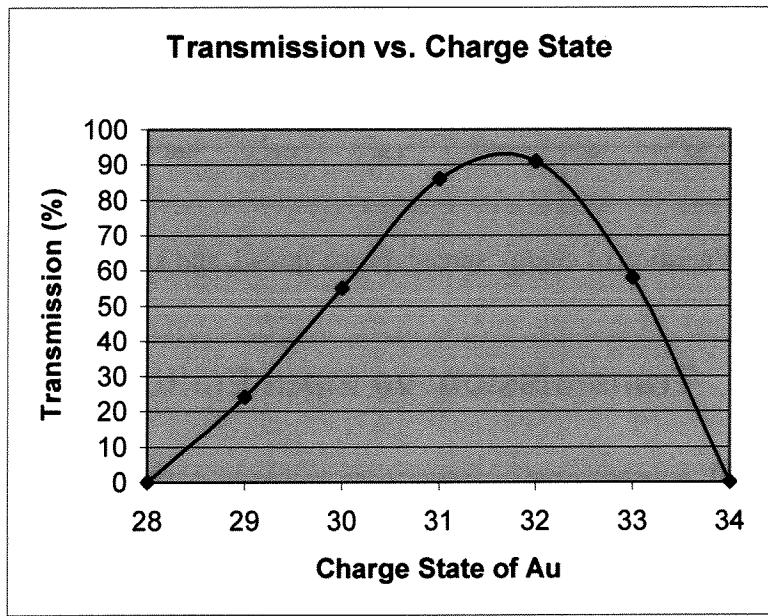


Figure 5.25 RFQ transmission for different charge states of Au.

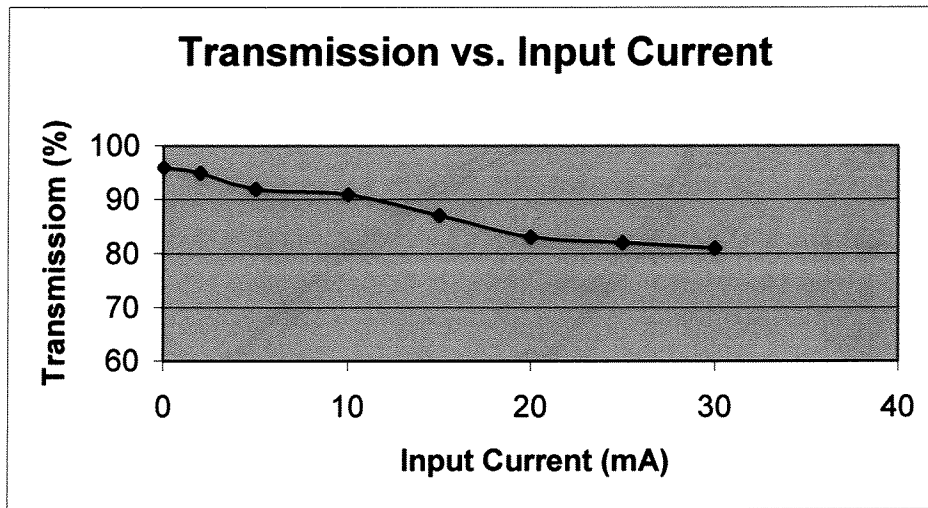


Figure 5.26 RFQ transmission vs. input current for Au⁺³².

Table 5-7 Beam parameters for different charges states of Au at the exit of RFQ.

Ions	Energy (MeV)	Curr. (mA)	Trans. (%)	X-XP Unnor, 90% (π mm mrad)			Y-YP Unnor, 90% (π mm mrad)			$\Delta E - \Delta \phi$ 90% (π MeV deg)		
				α	β (m)	ϵ	α	β (m)	ϵ	α	β (deg/MeV)	ϵ
Au ⁺³²	62.00	10	91	1.82	0.180	24	-1.59	0.142	22.5	-0.22	13.3	32.5
Au ⁺³¹	61.08	10	86	1.58	0.152	27	-1.25	0.138	20.5	-0.04	27.1	40.3
Au ⁺³⁰	62.08	10	55	1.63	0.162	30	-1.16	0.138	20	0.97	27.5	105
Au ⁺³³	61.87	10	58	1.53	0.164	26	-1.05	.108	21	-0.08	17.2	40.9
Au ⁺³⁴		10	0									
He ⁺²	1.259	10	91	1.78	0.28	24.5	-0.86	0.117	25.5	-0.13	615.9	1.055

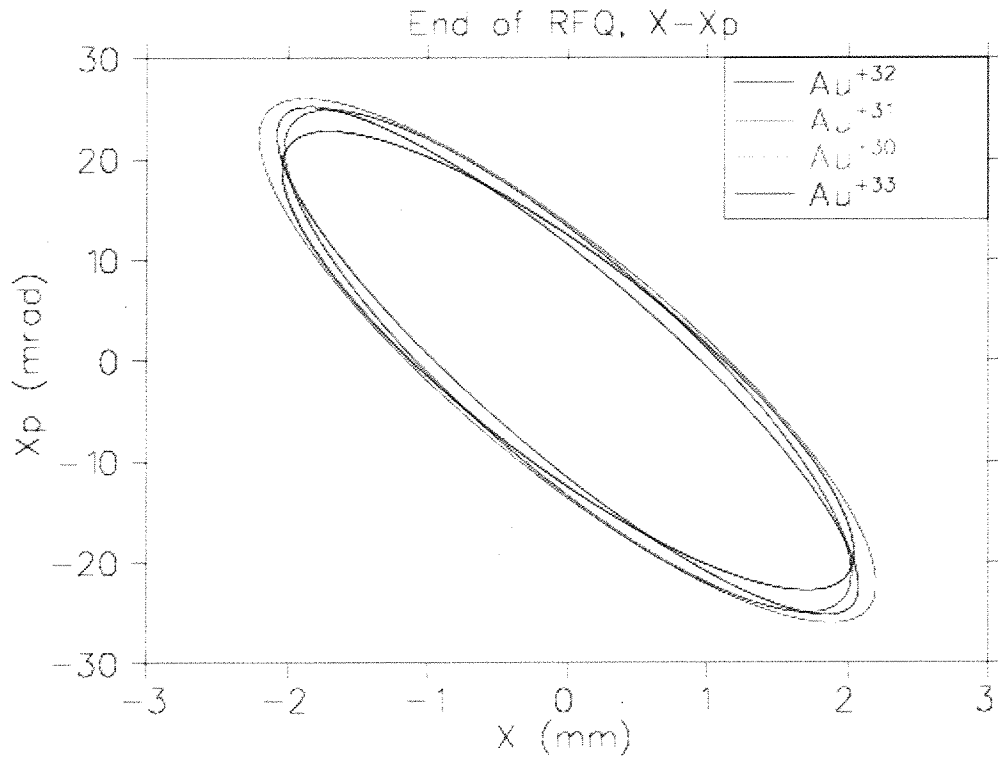


Figure 5.27 Phase space (X- X_p) at end of RFQ for different charge states of Au.

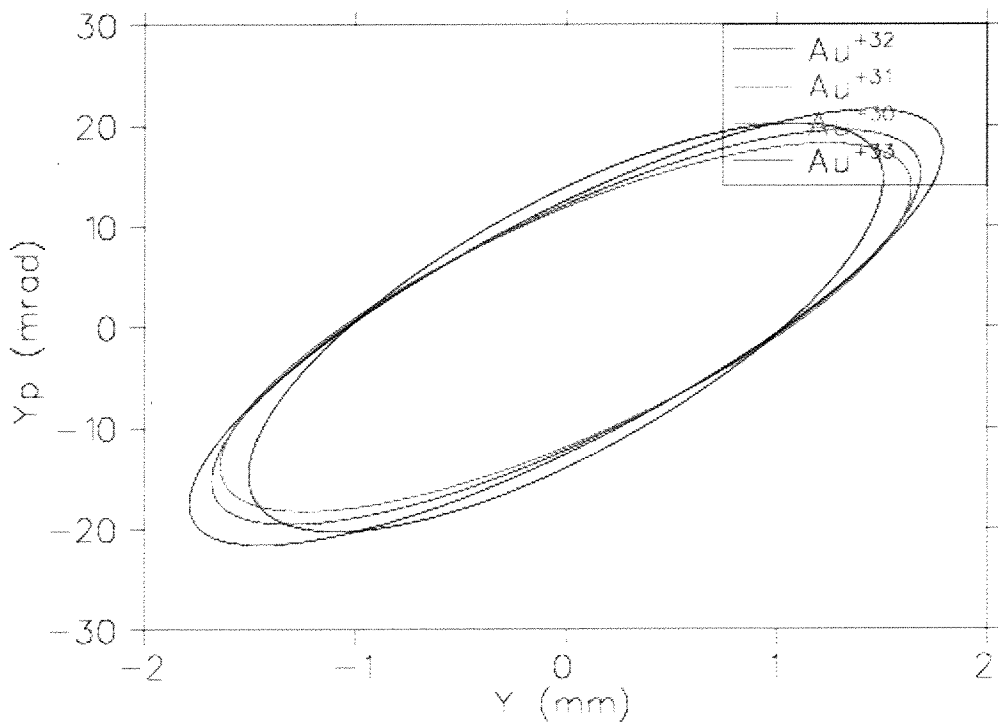


Figure 5.28 Phase space (Y- Y_p) at end of RFQ for different charge states of Au.

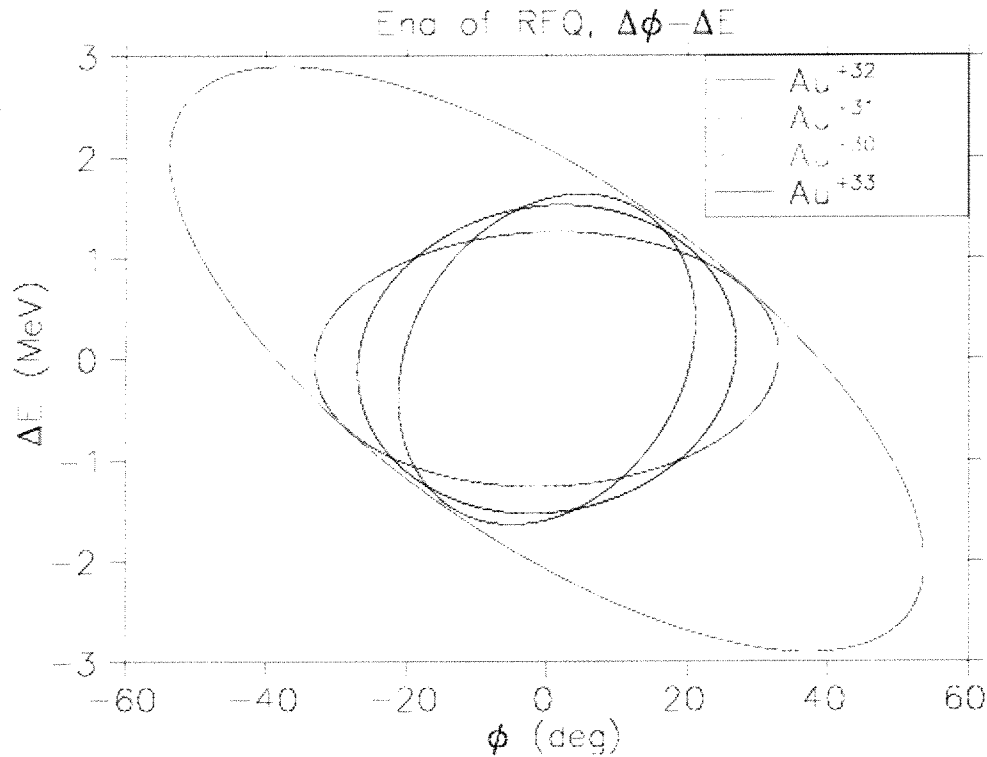


Figure 5.29 Phase space (W-Phi) at end of RFQ for different charge states of Au.

5.5. MEBT

The purpose of the Medium Energy Beam Transport (MEBT) is to match the beam from the RFQ to the IH structure in all three planes (two transverse, and one longitudinal). The RFQ has a FODO lattice with 1 $\beta\lambda$ period and the IH structure has quadrupole triplet focusing. The RFQ and the IH structure have the same RF frequency of 101.28 MHz. Table 5-8 shows the Twiss parameters at output of the RFQ and input of the IH structure.

Table 5-8 Twiss parameters at the end of the RFQ and entrance of the IH structure.

Parameter	End of RFQ	Entrance of IH	Units
α_x	0.0	1.80221	
β_x	1.0	1.01	mm/mrad
ϵ_x (90%, unnorm)	24.0	24	π mm mrad
α_y	0.0	0.60246	
β_y	0.05	0.59391	mm/mrad
ϵ_y (90%, unnorm)	22.0	22	π mm mrad
α_z	0.054	0.37	
β_z	0.0203	0.24	deg/keV
ϵ_z (90%)	34168	34168	π keV deg

The MEBT requires 6 controllable elements to match the beam in all three planes, four in the transverse plane and two in the longitudinal plane. Because the RFQ is a strong focusing structure, the beam from the RFQ is highly divergent in one transverse plane and highly convergent in the other transverse plane. After passing the RFQ high energy endflange, gate valve, and a current transformer, the beam has usually become divergent in the both planes by the time it reaches the first quadrupole. To avoid this problem we will modify the RFQ electrodes so that beam Twiss parameters will be as shown in Table 5-8. There are four quadrupoles to provide four degrees of freedom in the transverse plane. In the longitudinal plane we use one buncher and the position of the buncher to match the beam to the IH structure. Thus we have 5 active controls to match the beam instead of six. Figure 5.30 shows the TRACE3D output for the MEBT. There is enough space in the MEBT to accommodate the diagnostics.

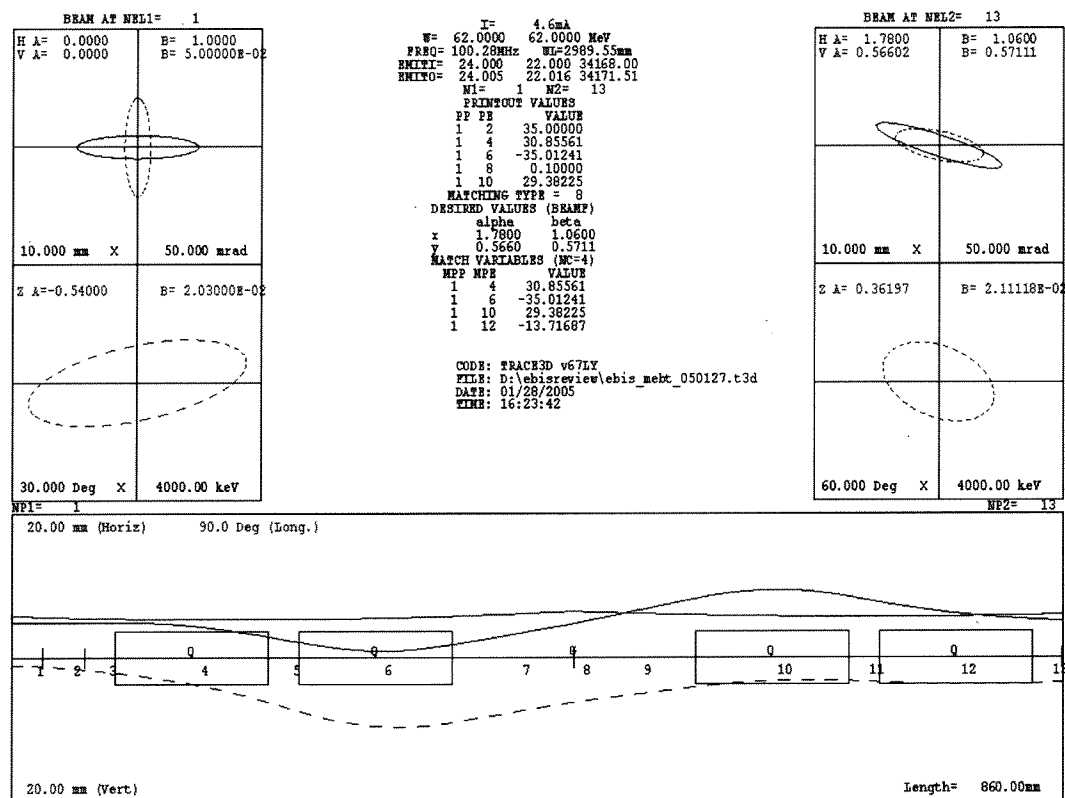


Figure 5.30 TRACE3D output showing the MEBT optics

5.6. Linac

For the baseline design, we have chosen an Interdigital-H (IH) structure, as been used at CERN for the Pb Linac, and at GSI. This will be a single-cavity, designed for a fixed output velocity, independent of the q/m of the desired beam (cavity gradient is adjusted for different q/m 's, to maintain a fixed velocity profile).

5.6.1. Specification of Parameters

As mentioned previously, we have selected a minimal final energy of 2 MeV/amu into the AGS booster, to reduce the space charge tune shift and the electron capture cross section at injection. The Linac frequency is chosen to be 101.28 MHz, which is the same as the CERN Pb IH Linac. This design is an extension of CERN Pb Linac in which the beam dynamics concept of "combined zero degree synchronous particle sections" is used.

The Linac has one tank, 4 meters long, with two quadrupole triplets inside for focusing. The maximum field on the axis will be 13.5 MV/m. The gap voltage distribution is adjusted by changing the capacity distribution between the adjacent drift tubes to match the velocity profile. Table 5-9 shows the main parameters of the IH Linac.

Table 5-9 Main parameters of the IH Linac

Parameters	BNL	CERN Tank 1	Units
Q/m	0.16-0.5	0.12	
Input energy	0.314	0.250	MeV/amu
Output Energy	2.08	1.87	MeV/amu
Frequency	101.28	101.28	MHz
Max rep rate	5	10	Hz
Length	4.0	3.57	Meters
Input emittance	0.55		π mm mrad, norm, 90%
Output emittance	0.61		π mm mrad, norm, 90%
Output energy spread	20.0		keV/amu
Transmission	100		%

5.6.2. Beam Dynamics

We have used the computer code LORAS¹⁵ to design and simulate the IH Linac. Figure 5.31 shows the beam profiles (x, and y) along the Linac. Figure 5.32 shows the phase width and energy width profiles along the Linac. Figure 5.33-Figure 5.35 show the input and output phase space projections in the x, y, and phase-energy planes, respectively. Table 5-10 shows the beam parameters for different charge states of Au at end of the Linac. Figure 5.36-Figure 5.38 shows the phase space plots for different charge state of Au at end of Linac.

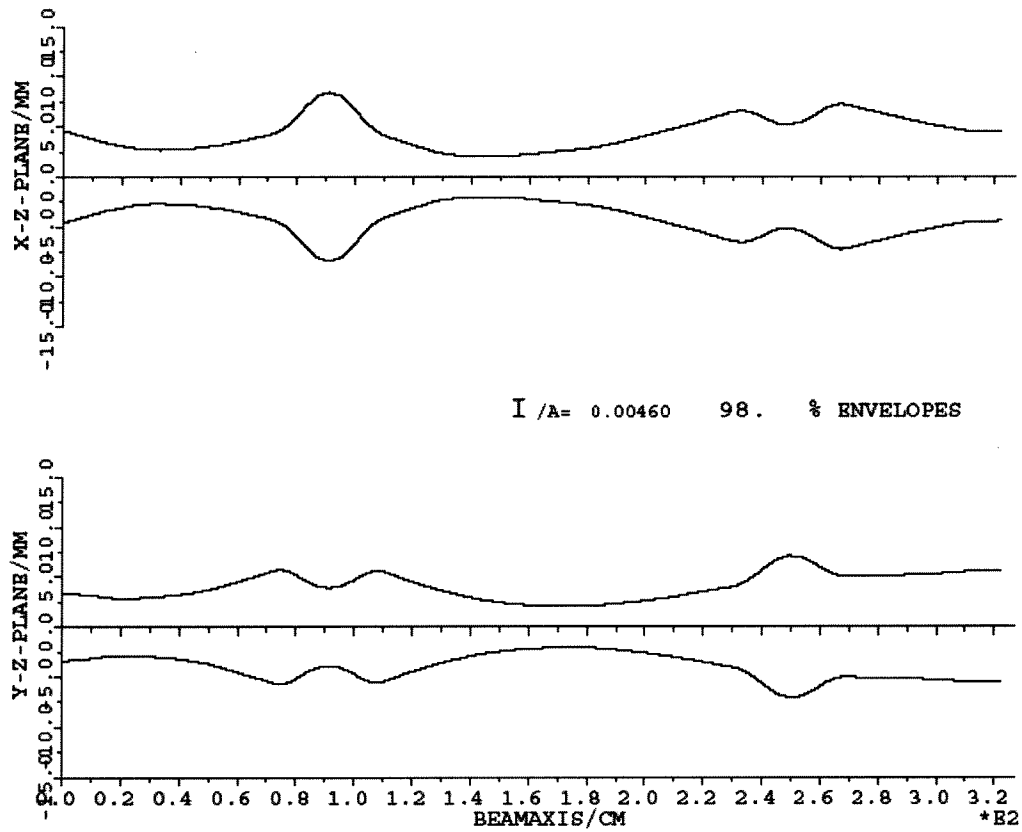


Figure 5.31 x and y beam profiles along the Linac

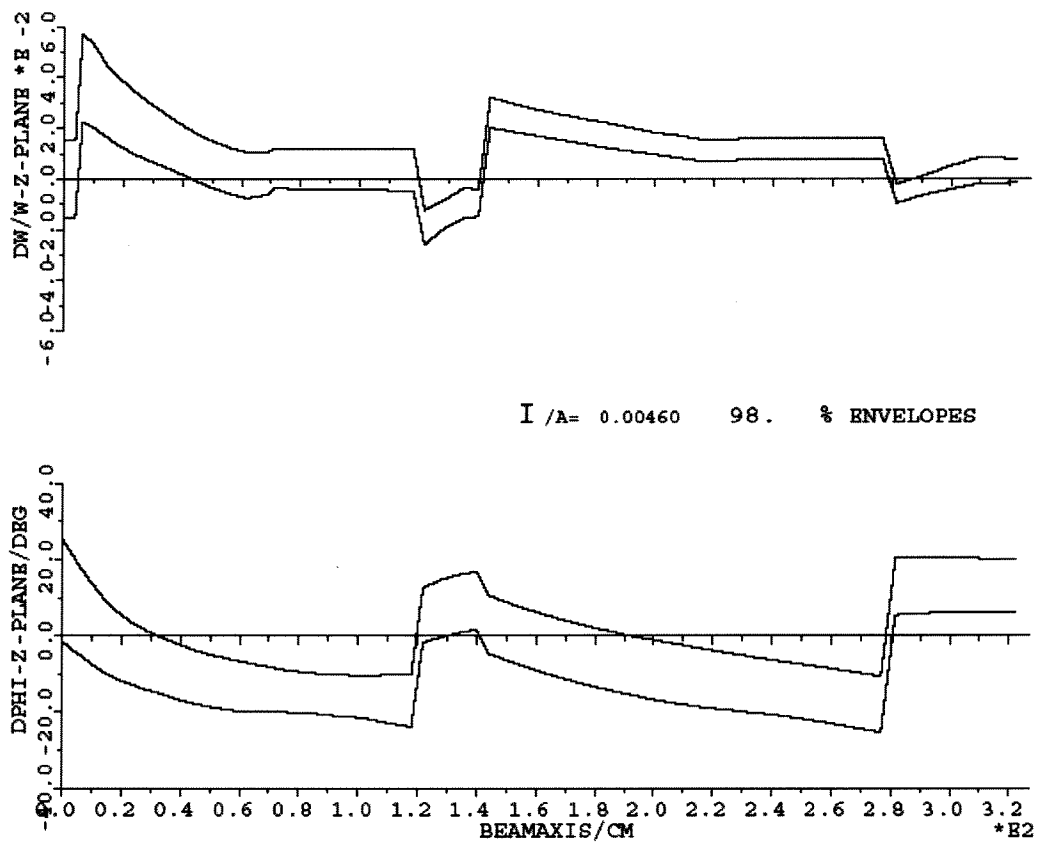


Figure 5.32 Phase width and energy width along the Linac

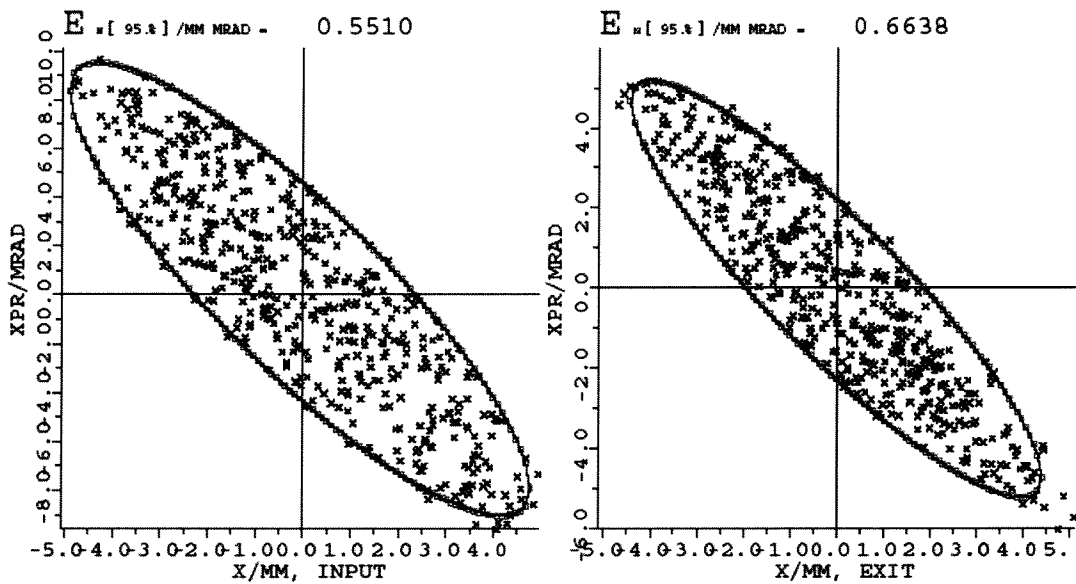


Figure 5.33 Input and output x-phase space

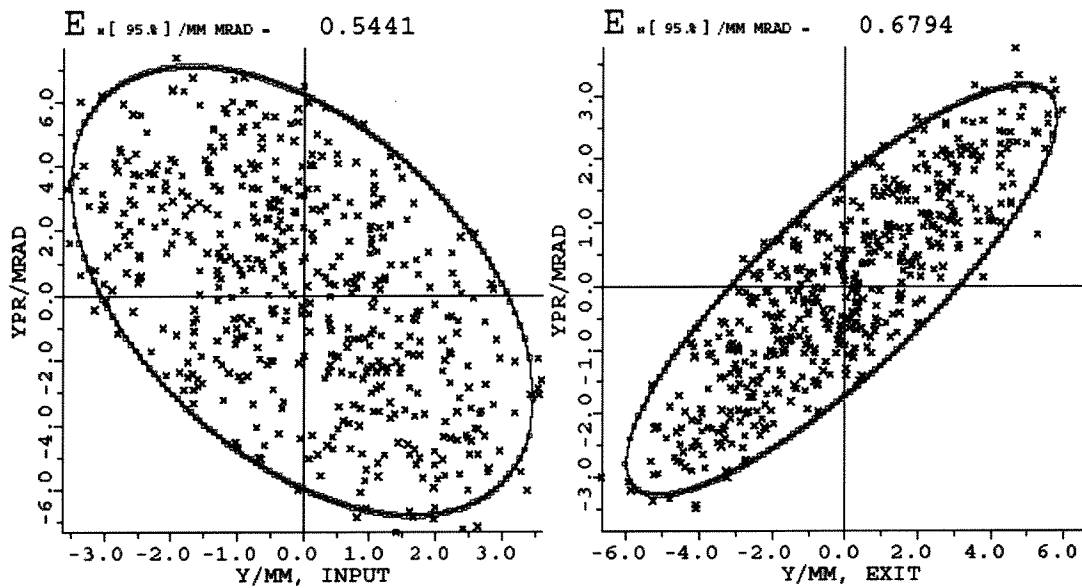


Figure 5.34 Input and output y-phase space

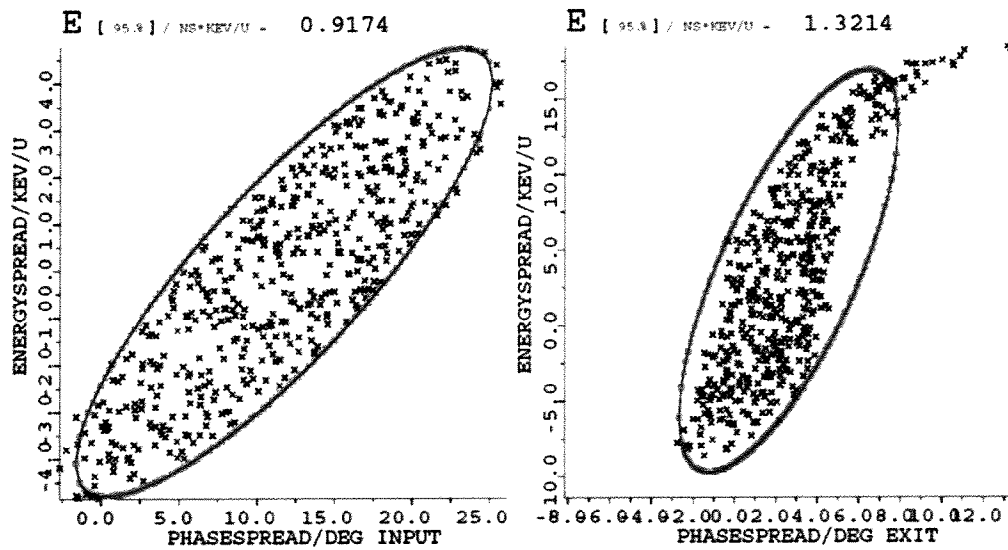


Figure 5.35 Input and output longitudinal phase space

Table 5-10 Beam parameters for different ions at end of the Linac.

Ions	Curr. (mA)	Trans. (%)	X-XP Unnorm, 90% (π mmmr)			Y-YP Unnorm, 90% (π mmmr)			$\Delta E - \Delta\phi$ 90% (π MeV deg)		
			α	β (m)	ϵ	α	β (m)	ϵ	α	β (deg/MeV)	ϵ
Au ⁺³²	4.6	100	2.1	1.97	11.0	-1.59	3.45	10.3	-0.68	5.4	35.0
Au ⁺³¹	4.6	55.8	1.01	0.60	41.0	0.025	1.47	31.3	5.21	14.5	90.72
Au ⁺³⁰	4.6	0									
Au ⁺³³	4.6	85	1.77	2.73	11.2	-1.12	3.61	10.0	0.71	3.5	54.8
Au ⁺³⁴	(lost in RFQ)										
He ⁺²	10	85	1.56	1.0	10.44	0.28	1.5	9.7	0.8	1.2	1.5

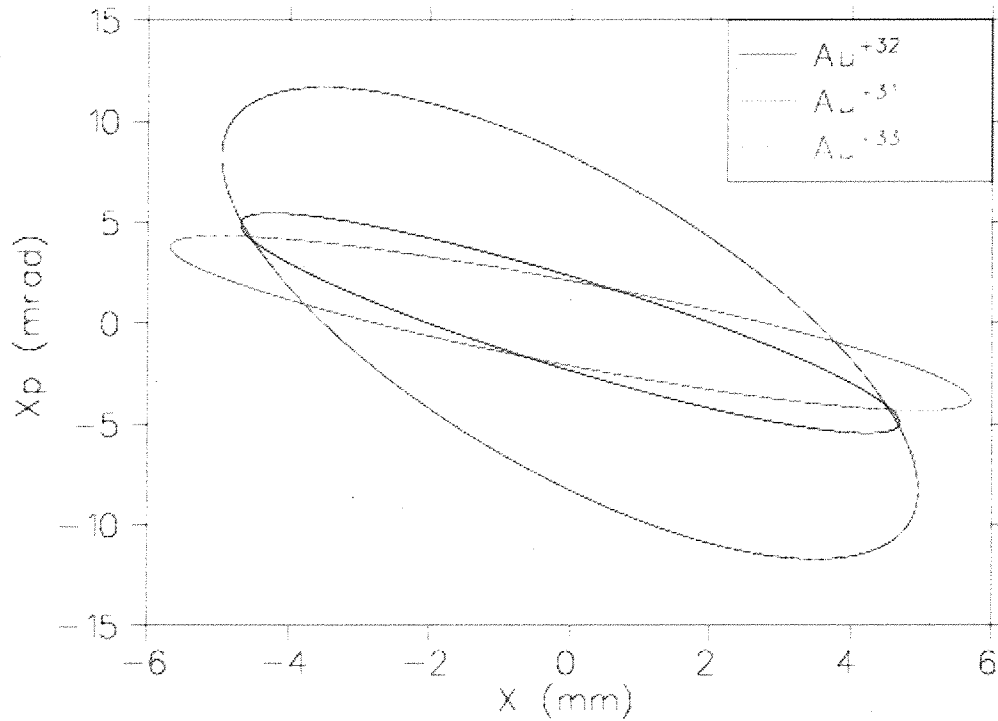


Figure 5.36 Phase space (X-XP) plots for different charge states of Au at end of Linac.

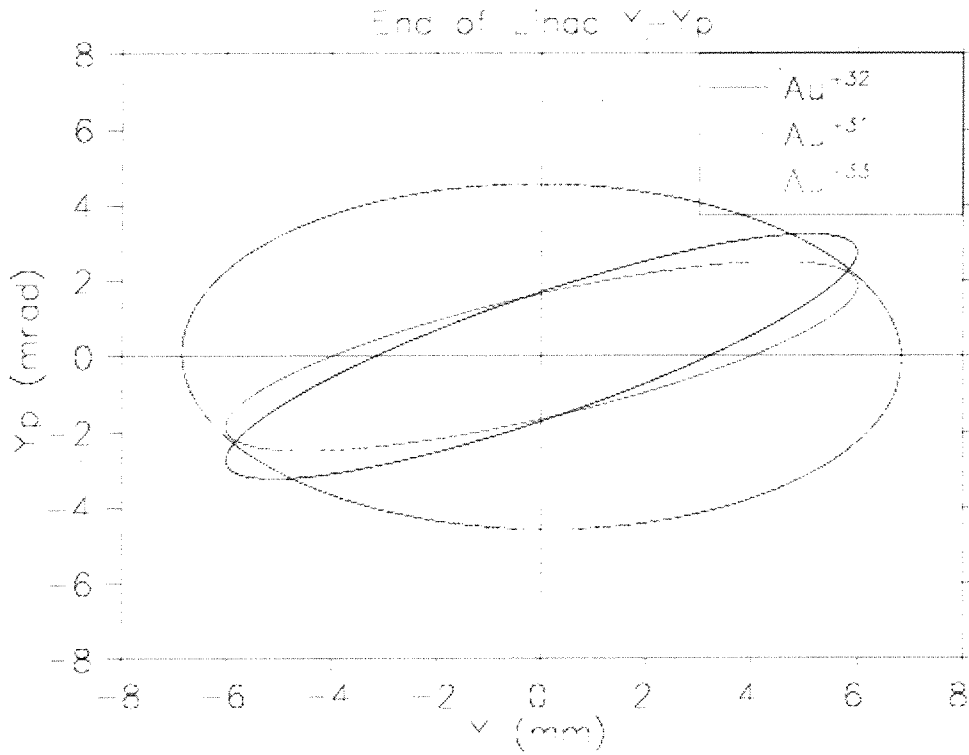


Figure 5.37 Phase space (Y-YP) plots for different charge states of Au at end of Linac.

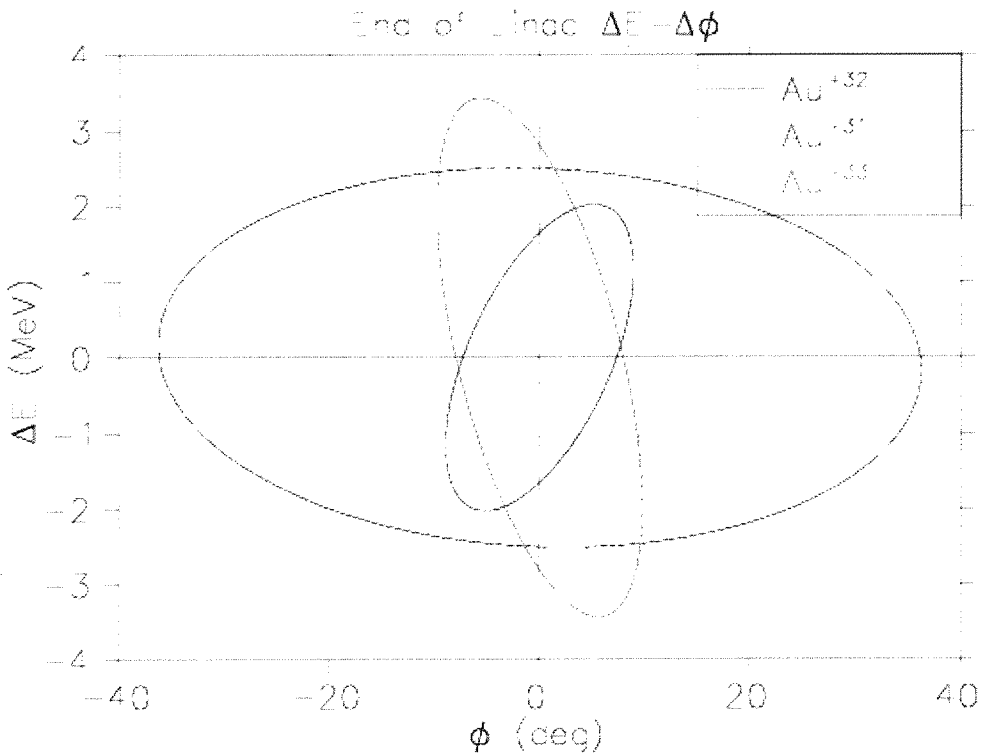


Figure 5.38 Phase space (W-Phi) plots for different charge states of Au at end of Linac.

5.7. HEBT

The High Energy Beam Transport (HEBT) matches beam transversely from the Linac to Booster injection, minimizes the energy spread at the injection, provides ion charge state discrimination, and provides space for diagnostics. The pre-injector is located in the lower equipment bay of the 200 MeV H^- Linac. A beamline penetration through the Linac shielding provides a short, direct path into the Booster allowing injection using the existing heavy ion inflector. The line is shown schematically in Figure 5-41. Since the RFQ and Linac will not eliminate all unwanted charge states, the line will be designed for charge discrimination. Two debuncher cavities will be used in HEBT to rotate the longitudinal phase space to minimize the energy spread at Booster injection. In the case of gold ions only one debuncher cavity is needed to rotate the phase space. Table 5-11 gives the Twiss parameters at the end of the Linac and entrance of the Booster for the mismatched injection scheme.

Figure 5.40 shows the beam envelopes (TRACE3D) through the HEBT for Au^{+32} . Figure 5.41 and Figure 5.42 show the beam envelopes for Au^{+31} and Au^{+33} , respectively.

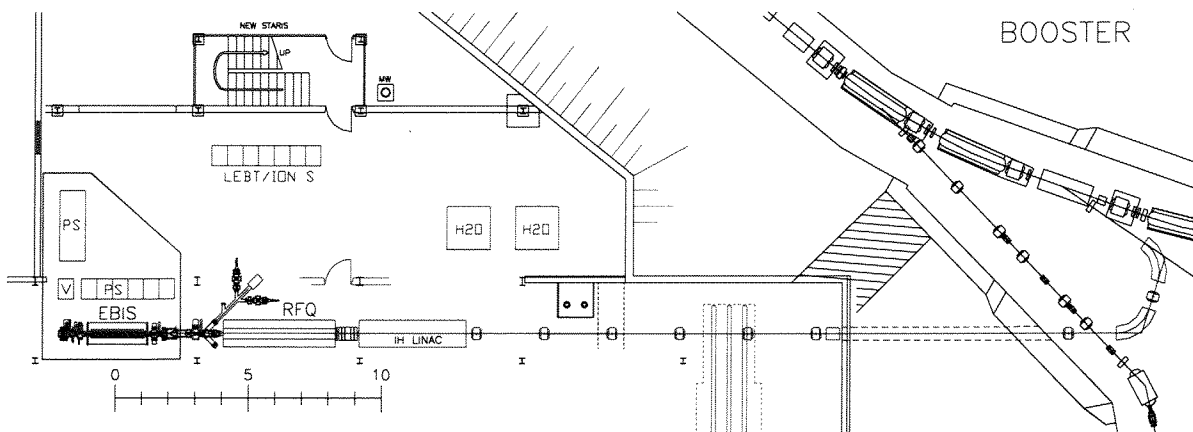


Figure 5.39 Schematic showing the pre-injector in the lower equipment bay of the 200 MeV Linac.

Table 5-11 Twiss parameters at end of the IH Linac and entrance of the Booster for mismatch injection scheme.

Parameters	End of IH Linac	Entrance to Booster	Units
α_x	2.1	-1.87	
β_x	3.0	2.5	mm/mrad
ϵ_x (90%, unnorm)	11.0	11.0	π mm mrad
α_y	-1.59	0.87	
β_y	3.45	4.8	mm/mrad
ϵ_y (90%, unnorm)	10.2	10.2	π mmrad
ΔE (90%) for Au ⁺³²	± 1345	± 363	keV
ΔE (90%) for He ⁺²	± 37.57	± 14.75	keV

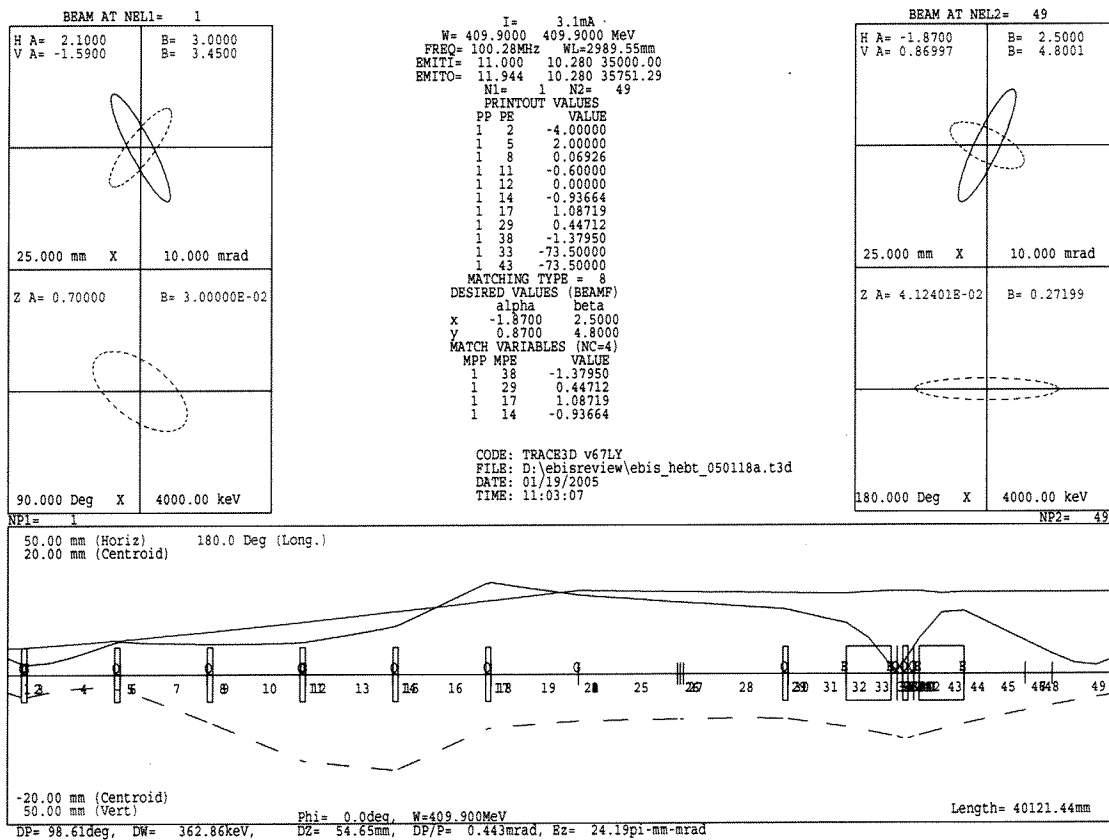


Figure 5.40 Beam envelope (TRACE3D) through the HEBT for Au⁺³².

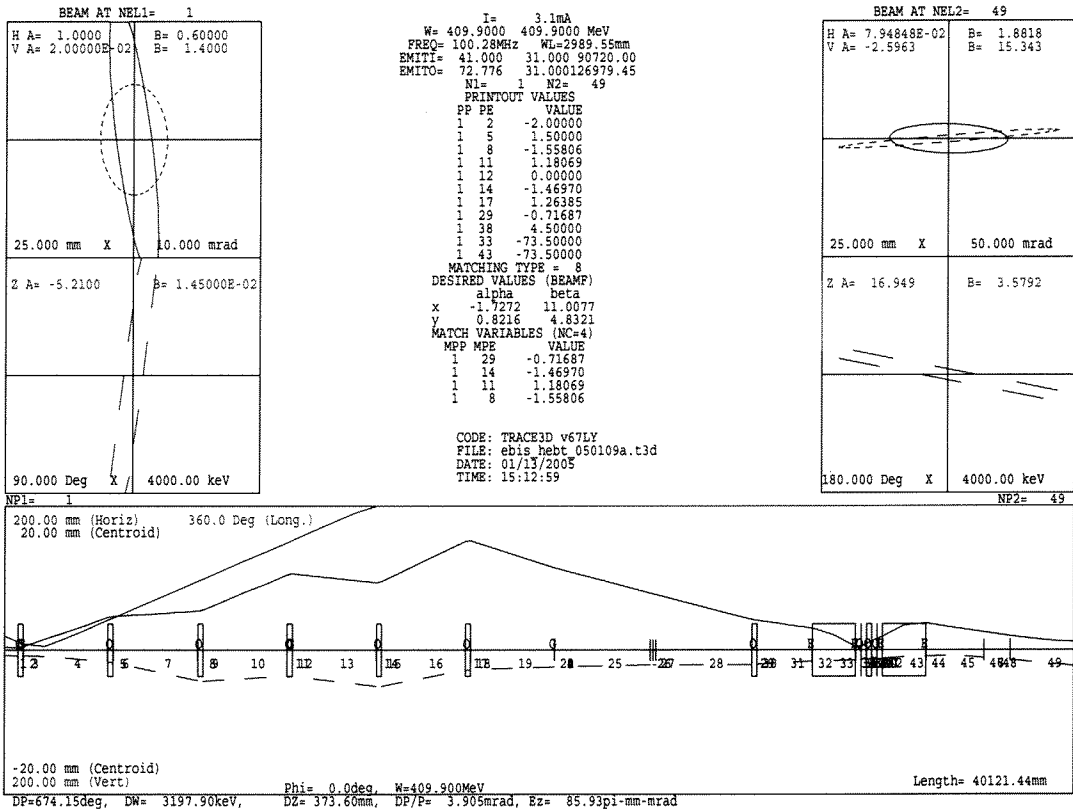


Figure 5.41 Beam envelope (TRACE3D) through the HEBT for Au⁺³¹.

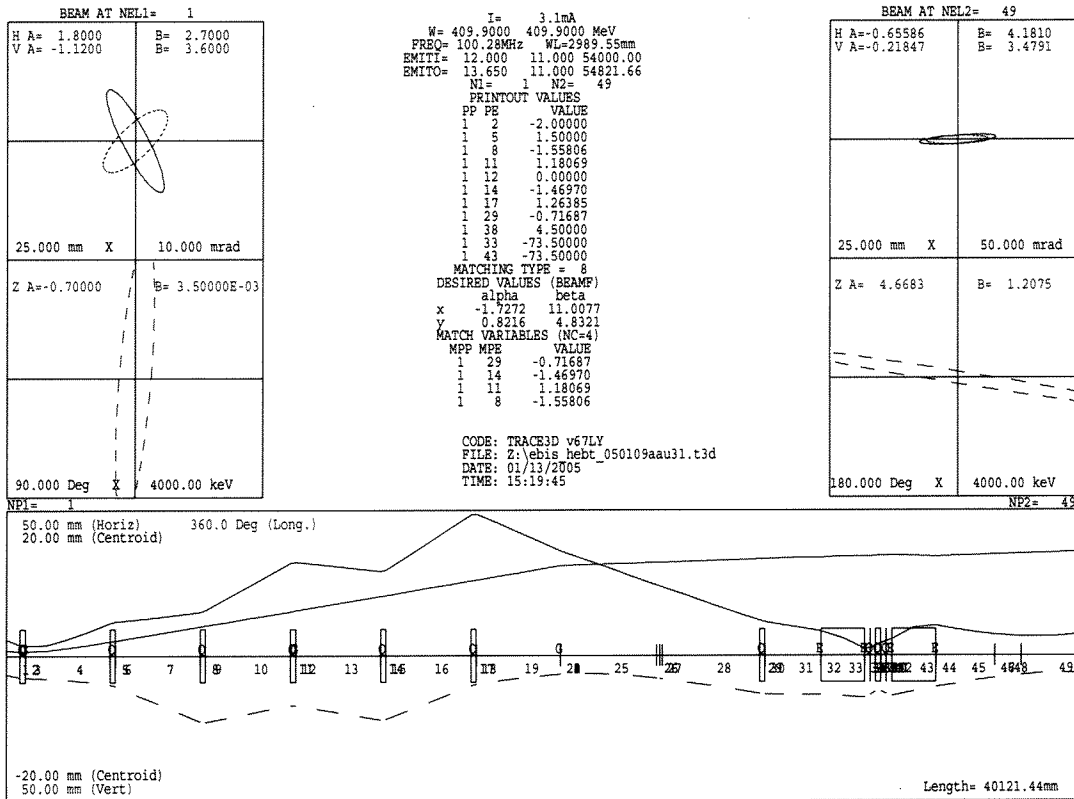


Figure 5.42 Beam envelope (TRACE3D) through the HEBT for Au⁺³³.

5.7.1. Charge Discrimination

Simulations have shown that while accelerating Au⁺³² neighboring charge states Au⁺³¹ and Au⁺³³ will also be accelerated and have to be dumped before injection into the Booster. TRACE calculations show that most of beam of Au⁺³¹ will be lost in first part of the HEBT. It may cause vacuum pressure to rise, so adequate pumping must be available in these regions. The dispersion function between the two dipoles is about 1.6 meters and the momentum of the neighboring charge states is about 3.14% off the center charge state. The neighboring charge state will be off center by 50.2 mm, which is radius of the beam pipe at that location. We will provide a beam absorber to catch these neighboring charge states without rise in the vacuum pressure. Figure 5.43 shows the location of these beam absorbers.

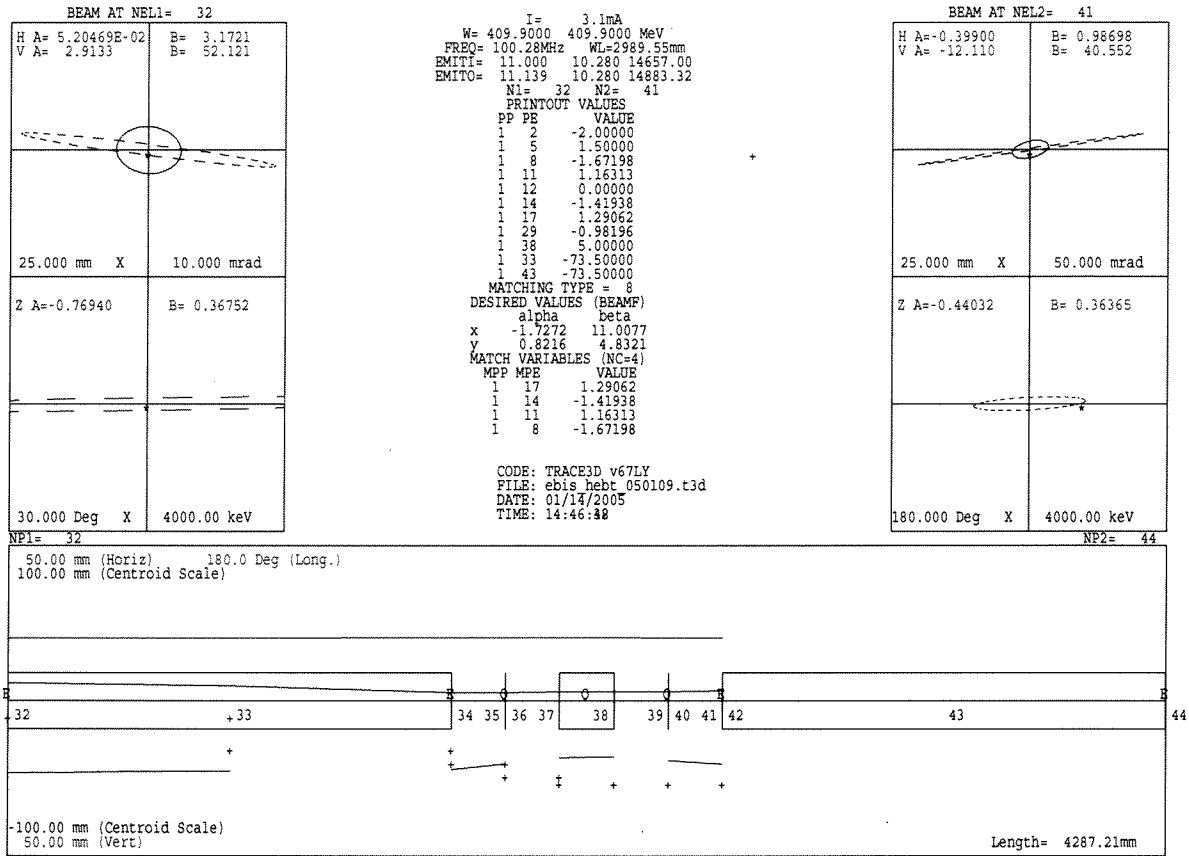


Figure 5.43 TRACE calculation showing charge separation.

5.8. Booster Injection

5.8.1. EBIS Beam

The expected parameters of the EBIS beam at Booster injection are presented in Table 5-12.

Table 5-12 Expected beam parameters at Booster injection

Au^{32+}		Au^{32+}	D^+	Unit
Particles per pulse	N	3	250	10^9
Kinetic energy	E_k	2	2	MeV/u
	β	0.0652	0.0652	
	γ	1.002	1.002	
Pulse width	d	10 - 40	10 - 40	μs
Energy spread	ΔE	± 2	± 3	keV/u
Momentum spread	$\Delta p/p$	± 0.05	± 0.075	%
Norm. 90% emittance	$\epsilon_{N,90}$	0.7	0.7	$\pi mm mrad$

The pulse width will allow for 1 to 4 turn injection at the Booster. It may also be possible to extract ions from the source in short bursts to match directly the Booster RF buckets. With the Booster RF harmonic number 4 or 6, this would require a bunch length about 1.23 μs or 0.83 μs , respectively. The energy spread and the transverse emittance should be unchanged with this “bunched” beam.

The beam energy spread at the exit of the Linac is ± 20 keV/u for Au^{32+} , which is reduced by a debuncher to ± 2 keV/u. This is crucial for keeping the Booster beam longitudinal emittance small. The transverse profile of the beam will be Gaussian-like.

5.8.2. Space Charge Effect

The space charge effect is estimated by the incoherent tune spread

$$\Delta\nu_{inc} = \frac{-3NQr_0}{2\pi AB_f \beta \gamma^2 \epsilon_{N,95}} \quad (1)$$

where Q and A are the charge state and atomic mass, respectively, r_0 is the classical radius of proton, and B_f is the bunching factor. The bunching factor at early acceleration is considered to be ≤ 0.4 .

With 1 to 4 turn injection, the calculated incoherent tune spread for Au^{32+} is 0.62 to 0.16 without any emittance dilution. Since the Booster acceptance of $70 \times 225 \pi \text{mm mrad}$ (VXH) is much larger than the injected beam, off-centered or mismatched injection results in the dilution of the transverse phase space and strongly reduces the incoherent tune spread. The beam emittance at the Booster exit can be expected to be several times larger than the injected beam. Present Booster beam with the Tandem injection of 40 turns usually has normalized horizontal and vertical 95% emittances of 6 and 3 $\pi \text{mm mrad}$, or 8 and 4 times larger than the EBIS beam. Therefore, the Booster beam transverse emittance with the EBIS injection will not be a problem. In fact, with a limiting incoherent tune spread of 0.1, the normalized 95% emittance would be 4 $\pi \text{mm mrad}$, which is smaller than with Tandem beam injection and might have a positive impact on the RHIC luminosity.

5.8.3. Longitudinal Aspects

5.8.3.1. Capture of Unbunched Beam

The RF capture and the resultant longitudinal beam emittance are important issues. The present optimized scheme for the Tandem beam injection is to use an RF voltage of about 200V, with harmonic number of 6, at the $B = 0$ porch to capture the beam. The adiabatic-like capture takes about 6 ms. The resultant longitudinal emittance is ~ 0.05 eVs/u for the one Booster pulse (6 bunches). Once this beam becomes a RHIC bunch, the longitudinal emittance is enlarged to 0.3 to 0.4 eVs/u. Therefore, with the EBIS

beam injection, the resultant Booster pulse longitudinal emittance should not be larger than $0.05 \text{ eVs}/u$.

The capture loss needs to be as small as possible. It is known that the lost beam may create a pressure increase, causing further beam loss.

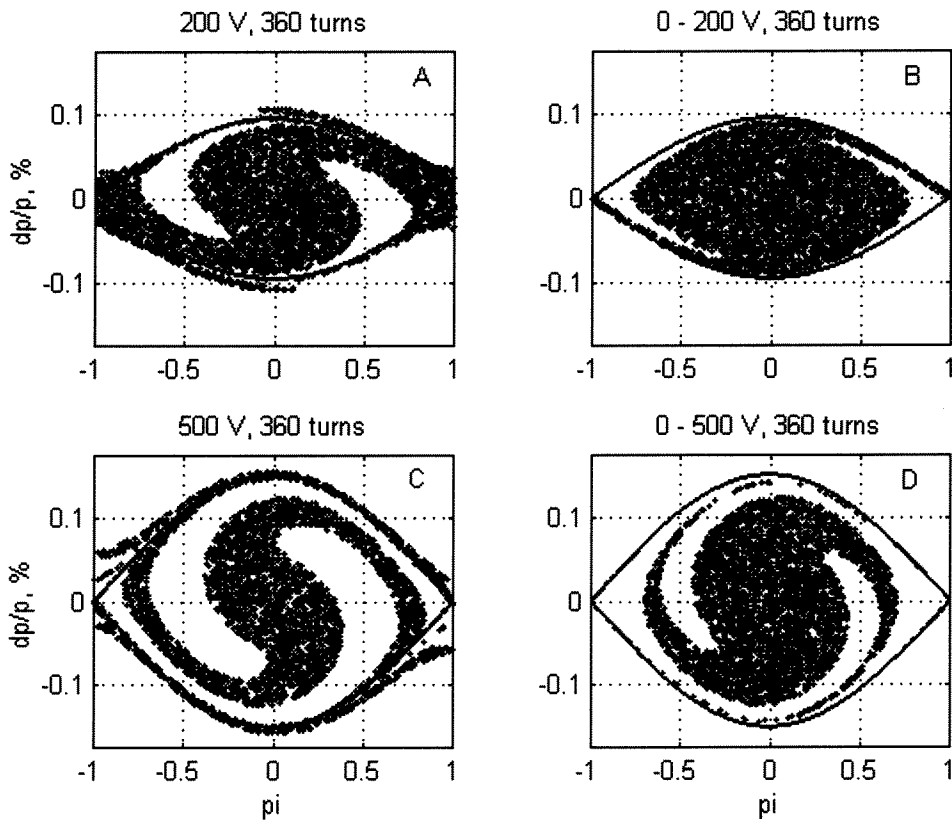


Figure 5.44 Simulation results for 4 different EBIS beam capture schemes

The injected beam momentum spread will have an impact on both aspects. Note that the Tandem beam momentum spread is very small, at about $\Delta p/p = \pm 0.01\%$. With the EBIS beam momentum spread of $\Delta p/p = \pm 0.05\%$ at the Booster injection, and much fewer turns injected, the injection scheme is substantially different from the existing one.

Simulation results for 4 different schemes of the EBIS beam capture are shown in Figure 5.44. In the cases A and B, an RF voltage of 200V is used, but the latter is adiabatic type capture, i.e. the RF voltage is linearly increased from 0 V to 200 V in 360 turns, or 3.7 ms. The cases C and D are similar to the A and B, but the voltage is 500V. In Figure 5.45, the mountain range of these captures is shown.

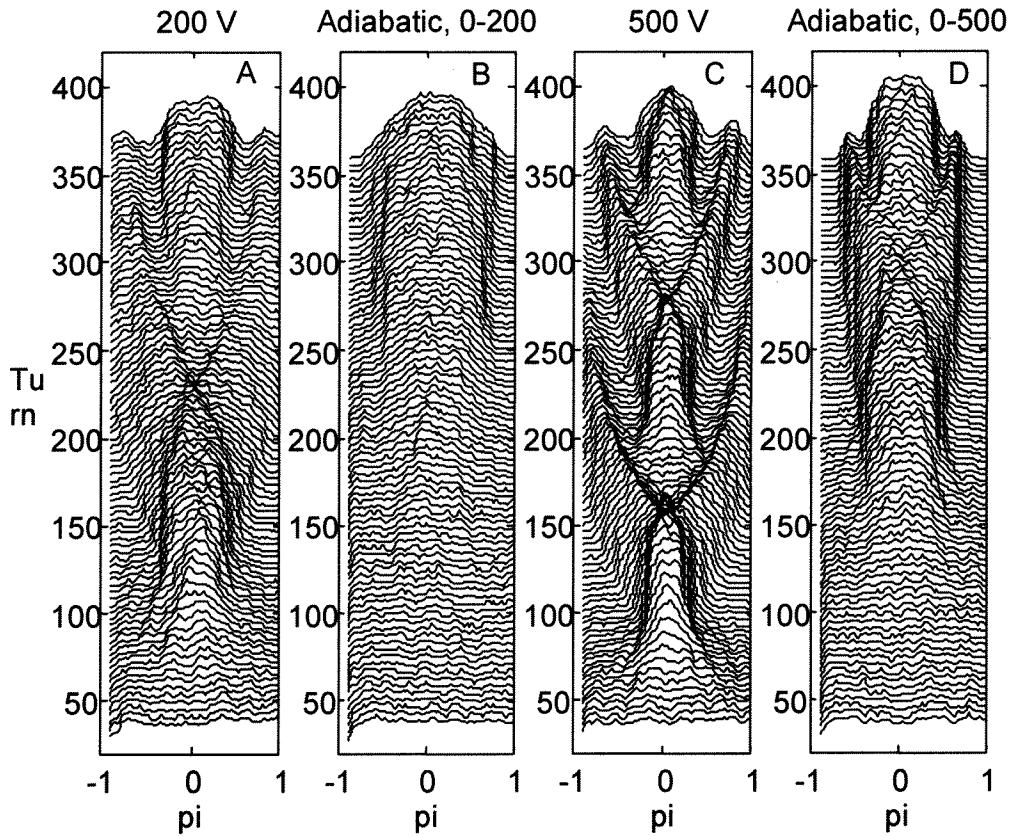


Figure 5.45 Mountain range of 4 EBIS beam capture schemes

It can be observed that in the case B and D, all particles have been captured, and also the resultant emittance is relatively small. In fact, there is almost no emittance growth in the capture. Taking the case B as an example, the bucket area for $V_{RF} = 200$ V is $0.0083 \text{ eVs}/u$. For a total of 6 buckets, the area is therefore $0.05 \text{ eVs}/u$. It is seen from Figure 5.44 that the bunch emittance is smaller than the bucket area, probably by 10% to 15%. On the other hand, the injected beam with the energy spread (for Au^{32+}) of $\pm 2 \text{ keV}/u$ and the pulse length of $10.3 \mu\text{s}$ gives rise to a total emittance of $0.041 \text{ eVs}/u$, which is almost the same as the emittance of the captured beam.

The voltage amplitude of the Booster RF cavities, with full voltage of 35 kV, cannot be well controlled at low level. In fact, under 1.5 kV, counterphasing is needed to generate the required voltage. Therefore, the adiabatic capture requires some effort to be achieved. On the other hand, using constant voltage, the beam loss is still not significant, and the resultant beam emittance is not much larger. It also can be observed that the capture using 500 V RF voltage results in less beam loss, but larger diluted emittance, than the one with $V_{RF} = 200$ V.

Another issue at the injection is the possible longitudinal microwave instability with the EBIS beam. For the normalized emittance of $0.7 \pi \mu\text{m}$ and the injection energy of $2 \text{ MeV} / u$, the Booster longitudinal space charge impedance Z_l/n is $-j13.5 \text{ k}\Omega$. The peak EBIS beam current is about 6 mA. Using the Keil-Schnell criterion,

$$\left| \frac{\Delta p}{p} \right| > \sqrt{\frac{QeI_p}{A\gamma m_0 c^2 |\eta|} \left| \frac{Z_l}{n} \right|} \quad (2)$$

it is required that $\left| \frac{\Delta p}{p} \right| = \pm 0.12\%$. This is satisfied by the EBIS injected beam with $\left| \frac{\Delta p}{p} \right| = \pm 0.05\%$.

The EBIS based Linac will provide the bunched beam, and can be transferred into the Booster RF bucket without adiabatic capture. Simulation shows that $V_{\text{RF}} = 1.75 \text{ kV}$ and $dB/dt = 0.3 \text{ T/s}$ results in the smaller longitudinal emittance.

We conclude that the beam longitudinal emittance requirement can be achieved. If further reduction of the longitudinal emittance is required, then smaller energy spread of the injected beam is needed.

5.8.4. Inflector Aperture Limit and Scraping Effect

The voltage required for the Booster C3 inflector is less than 50 kV for the EBIS beam injection, which is well within its operating range of 80 kV. The aperture of the inflector is 17 mm. For the matched beam, the horizontal β_H of the Booster at the inflector exit of $\beta_H = 11 \text{ m}$, $\alpha_H = -1.72$ and $\eta_x = 2.4 \text{ m}$ with $\Delta p/p = 0.05\%$ gives rise to the full size of the injected beam, $2a = 2\sqrt{\varepsilon_{90} \beta_H + (\eta_x \frac{\Delta p}{p})^2} = 22.1 \text{ mm}$, which is larger than the inflector aperture.

Twiss function mismatch injection can be used to avoid this beam scraping. The inflector gap is 17 mm and is 2.2 meters long. The geometrical acceptance of the inflector is $29 \pi \text{ mm mrad}$ with Twiss parameters of $\beta_H = 2.5 \text{ mm/mrad}$ and $\alpha_H = -1.87$ at exit of inflector. The mismatch injection results in bigger emittance in the ring for one turn injection given by

$$\frac{\varepsilon_i}{\varepsilon_m} = \frac{\sigma_i^2}{\sigma_m^2} = \frac{1}{2} (\beta_m \gamma_i + \beta_i \gamma_m - 2\alpha_i \alpha_m) = 7.1$$

where subscripts i and m represent Twiss parameters of injected beam and matched beam, respectively. The Linac normalized emittance of $0.7 \pi \text{ mm mrad}$ results in a Booster emittance of $5 \pi \text{ mm mrad}$ in one turn, which corresponds to an incoherent tune spread of 0.09 for Au^{32+} .

The most significant effect of the beam scraping is that the lost particles could generate a large number of ions and neutral particles, producing a local vacuum pressure

bump. At the present Booster injection of $0.9 \text{ MeV}/u$ gold beam with the loss of 2×10^9 ions, the pressure increased from $5 \times 10^{-11} \text{ Torr}$ to greater than $5 \times 10^{-8} \text{ Torr}$. The local vacuum pressure bump was longer than 10 meters in the Booster ring, in the vicinity of the exit of the C3 inflector. The circulating beam lifetime, therefore, was affected by the electron capture of the gold ions, and reduced from 200 ms to about 20 ms.

Given the much smaller amount of beam loss than the 2×10^9 ions, and also the fact that the sputtering effect is peaked below an energy of $1 \text{ MeV}/u$, the vacuum pressure increase is expected to be much lower with the EBIS beam. An equally important factor is that the capture cross section at $2 \text{ MeV}/u$ is much smaller than that at $0.9 \text{ MeV}/u$. In Figure 5.46, the electron impact cross sections are shown. The capture cross section at $2 \text{ MeV}/u$ is smaller than at $0.9 \text{ MeV}/u$ by a factor of 40. Ionization will take place and become larger than electron capture only at $> 2.5 \text{ MeV}/u$. We may expect, therefore, that the scraping of EBIS beam at the C3 inflector will have only a modest effect on the beam lifetime at injection.

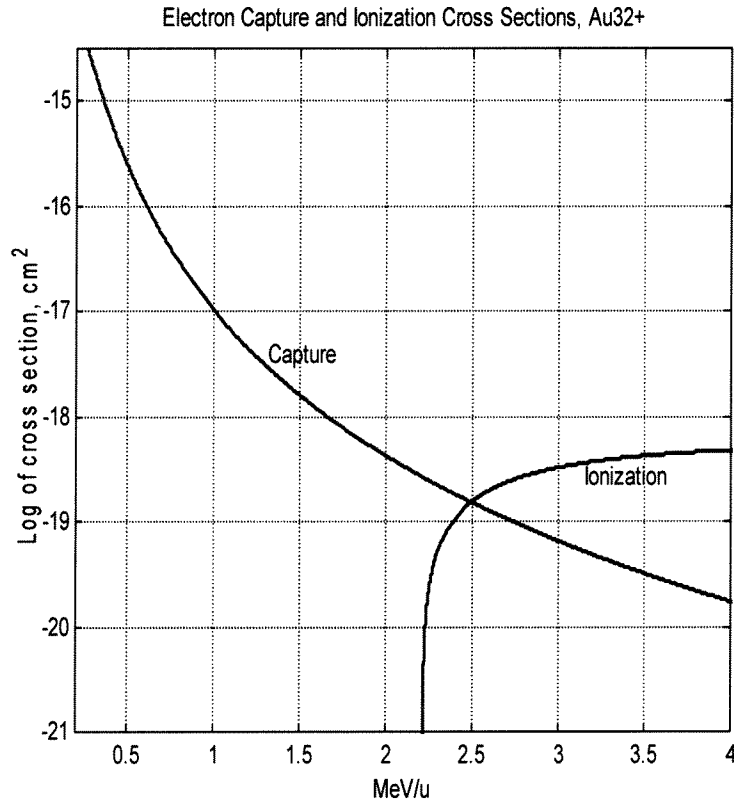


Figure 5.46 Electron capture and ionization cross-sections, for Au³²⁺.

5.9. Diagnostics

Diagnostics for the preinjector are shown in Figure 5.47 and Figure 5.48. A description of the various type diagnostics are given below.

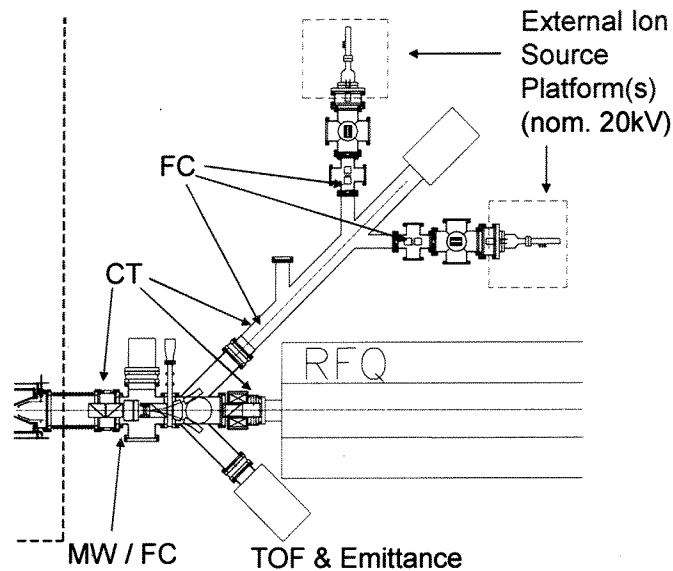


Figure 5.47 Layout of the diagnostics in the LEBT and external ion injection lines.
CT=current transformer; FC= Faraday cup; MW=multiwire; TOF=time-of-flight.

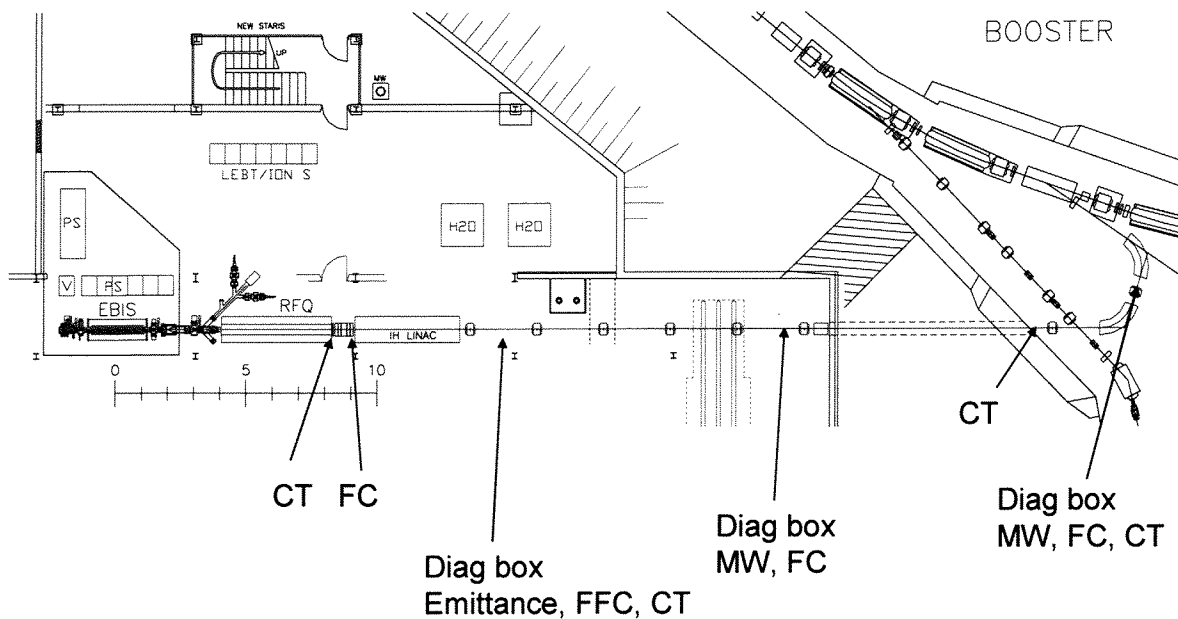


Figure 5.48 Layout of the diagnostics in the MEBT and HEBT.
CT=current transformer; FC= Faraday cup; FFC=fast Faraday cup; MW=multiwire.

5.9.1. EBIS Time of Flight (High Resolution & Inline)

EBIS is tuned by using two time-of-flight systems to measure different beam mass components and the charge/mass ratios of the desired beam component. After extraction from the source the dc beam is chopped to a single 10-100ns long pulse. To measure different beam-mass components, a fast Faraday cup intercepts this chopped pulse after a short drift. This measurement mode is the “inline” low-resolution TOF system.

After the source is tuned to maximize the desired mass component the high resolution TOF system is used to resolve different charge states. The chopped pulse is reflected from a Mamyryn electrostatic mirror¹⁶ and into a second fast Faraday cup after a much longer drift distance.

The Mamyryn mirror introduces different path lengths based on charge/mass ratios of the ions. The fast Faraday cups now in use at the EBIS development facility are channeltron electron multipliers. This diagnostic is shown in Figure 5.49. The present plan is to use an existing time-of-flight unit, taken from the Test EBIS.

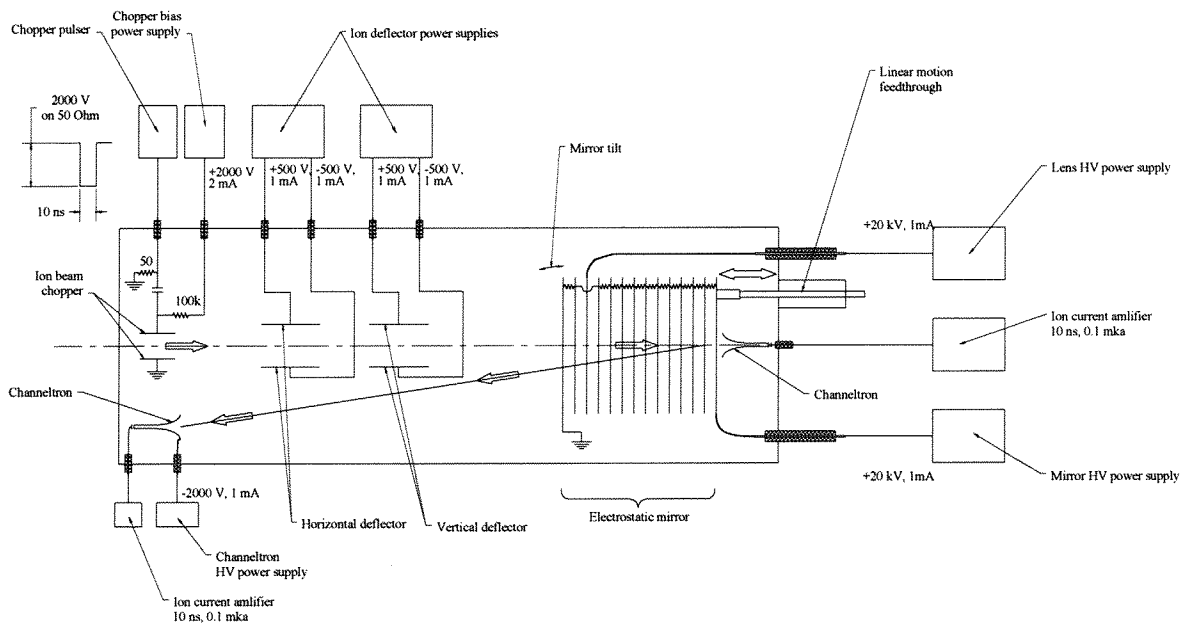


Figure 5.49 Schematic of the Mamyryn time-of-flight diagnostic.

5.9.2. EBIS Emittance

Measurement of the transverse ion beam emittance will be possible at two locations, between the EBIS and the RFQ, and in the HEBT. A pepperpot type mask will be plunged into the beam path; the beam that passes through the small holes in the mask will form an image on the downstream phosphor screen. By analyzing this image with a fast shutter CCD camera, an emittance measurement can be made in a single shot. Additional advantages of this technique are that coupling of horizontal and vertical phase planes can be measured, and pulse-to-pulse variations can be examined.

The imaging system can be calibrated by inserting a mirror to direct light from a low power laser through the pepperpot. A similar system shown below from GSI claims resolution of less than 0.5 mrad in divergence, and 0.1mm in size. The present plan is to use, during beam commissioning, a pepperpot device that is being developed for general use in the Preinjector Group.

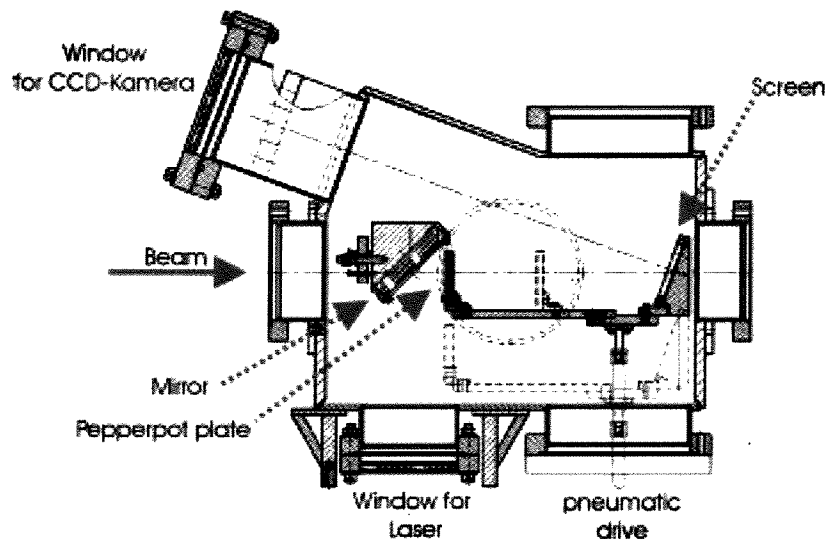


Figure 5.50 Drawing of pepper-pot emittance device and laser calibration system used at GSI.¹⁷

5.9.3. Faraday Cups

Eight Faraday Cup detectors will be distributed among each of the transports between the major system components which include the External Ion Source, EBIS, RFQ, IH Linac and 3 in the HEBT transport to the junction to the existing Booster injection beamline.

This destructive measurement is made when accelerated ions are stopped inside a Faraday cup that is pneumatically inserted into the transport aperture. The accumulated

electric charge is detected as a corresponding current that is processed by front-end electronics then digitized. Average current and pulse waveform data is made available via the Controls system.

Taking advantage of the fully destructive measurement, these devices can also be used as a beam stop. Princeton Scientific provides a commercially available detector head and plunge assembly, which has been used at a variety of places at the C-AD facility. The fast Faraday cup is an existing unit which has GHz bandwidth, and will allow one to observe the 100 MHz bunch structure of the beam coming out of the linac.

5.9.4. Current Transformers

Seven transformers will be installed, as shown in Figure 5.47 and Figure 5.48, one each at the following locations: EBIS output, external ion injection line, RFQ input, RFQ output, IH output and two in HEBT. The transformers will be fabricated at BNL and will be similar to the transformers currently installed in the TTB line. A calibration winding will be installed around each transformer so that each transformer's response can be measured independently. A commercial current source will be used to generate test currents for calibration. Electronics will be fabricated for signal conditioning and gain control. Each current transformer output will be digitized and read out through the Controls system.

5.9.5. Profile Monitors

Beam profile measurements will be made at three locations, between EBIS and RFQ, and two in the HEBT. We will use existing plunging multi-wire units with 32 X 32 wire resolution. Horizontal & vertical profile information can be obtained by processing the low level current signal generated when a small portion of the ion beam interacts with the wires. These 64 signals will be processed by a COTS Euro-card based multi-channel integrator electronics that will feed VME digitizers. This technique has been used successfully at many places throughout the C-AD facility. The data will be displayed using a modified version of an existing Controls application.

5.10. RF Systems

The EBIS project will require a total of five RF systems: Radio Frequency Quadrupole (RFQ), Interdigital-H structure (IH) Linac, and three buncher/debuncher cavities.

The RFQ and IH Linac RF systems will be pulsed 101.28 MHz systems with the pulse width of 1 ms running at 5 Hz, ~400 kW peak power. Although the present baseline plan is to buy commercial type stand-alone FM transmitters, engineers from MIT-Bates have also presented a nice design concept for these rf systems, and the possibility of these amplifiers being fabricated at MIT-Bates is being considered. Each of the three bunchers will use a 4kW water-cooled solid-state amplifier, which is also commercially available.

RF systems will be built to accommodate pulse-to-pulse modulation (PPM) with at least seven independent users, and amplitude and phase controls to compensate for the beam loading; they will not require beam locking or beam chopping. Commercially available circulators are included in the lines between the amplifiers and the cavities.

EBIS LLRF System

The LLRF systems for the EBIS program will comprise five essentially identical digital controllers. The primary function of the LLRF controller is to provide amplitude and phase (I & Q) control of each RF subsystem (RFQ, Linac and Buncher/Debuncher) to the specified regulation and dynamic range requirements. The digital controller will be a design based on both DSP and FPGA technologies, borrowing from both past designs (SNS Ring LLRF and Booster LLRF) as well as the current design effort underway for the RHIC and AGS LLRF upgrades.

All sub-systems are locked to a common reference, which may be internal to the system or from an external RF source. Control bandwidth achievable is difficult to specify without more specific details on things like cavity Qs, etc. Diagnostic data will be provided at the full 5 Hz rep rate, with throughput limited only by external factors (control system bandwidth). 5 Hz PPM capability will be provided for up to a minimum of seven users.

5.11. Magnets

Table 5-13 shows the parameters for all beamline magnets, for Au³²⁺ beam. All other beams will require reduced magnetic field values.

Table 5-13 Magnet Parameters (Au³²⁺)

SOLENOIDS	Type	Length (cm)	Aperture Radius (cm)	Field (T)	Current (A)	Voltage (V)
E-Gun Solenoid	SOL	15.24	12.7	0.22	300	80
Collector Solenoid	SOL	12.7	12.7	0.15	300	80
LEBT Solenoid	SOL	24.1	5.1	1.25	2000	?
QUADRUPOLES	Type	Length (cm)	Aperture Radius (cm)	Gradient (T/m)	Current (A)	Voltage (V)
MEBT	EMQ	10	2	33	450	10
MEBT	EMQ	10	2	38	450	10
MEBT	EMQ	10	2	36	450	10
MEBT	EMQ	10	2	38	450	10
Linac	EMQ	9.2	1.3	44	450	10
Linac	EMQ	16.2	1.3	42	450	10
Linac	EMQ	9.2	1.3	44	450	10
Linac	EMQ	9.2	1.3	44	450	10
Linac	EMQ	16.2	1.3	44.5	450	10
Linac	EMQ	9.2	1.3	44	450	10
HEBT	EMQ	20.32	5	1.5	25	35
HEBT	EMQ	20.32	5	1	25	35
HEBT	EMQ	20.32	5	2	25	35
HEBT	EMQ	20.32	5	1.4	25	35
HEBT	EMQ	20.32	5	1.6	25	35
HEBT	EMQ	20.32	5	1	25	35
HEBT	EMQ	20.32	5	1	25	35
HEBT	EMQ	20.32	5	5	25	35
DIPOLE	Bend Angle	Gap (cm)	Radius Curvature (mm)	Field (T)	Current (A)	Voltage (V)
HEBT	73°	10	1280	1.3	3285	12.6
HEBT	73°	10	1280	1.3	3285	12.6

The two warm EBIS warm solenoids are very similar to those already in use on the Test EBIS. Both are designed with water-cooled hollow conductors, pancake-style coils and no iron return. The design of the LEBT solenoid is pancake coils with a laminated iron return, similar in design to the BNL high current H- and polarized H- LEBT solenoids, shown in Figure 5.51.

The EBIS MEBT quadrupole magnets will be units that have been received from LANL, which were excessed from the LEDA Project. Since they are approximately half the length of the originally planned design shown in Table 5-13, eight of the LEDA quadrupoles will be used, in pairs powered in series.

HEBT dipoles are two similar 73° bending dipoles. The basic design of the dipole is a C style with the open end facing the outer curve to allow the chamber to have a port for the TTB line into booster. The magnet will be constructed of laminations of different sizes which when assembled will produce the required bend shape. The magnet coils will be wound of water-cooled hollow copper conductor.

The HEBT quadrupoles will be air-cooled Danfysik magnets. Originally used for other projects at BNL, these magnets are available for the EBIS beam line. These magnets will allow switching of values in ~ 1 second for running of different magnetic rigidity beams.

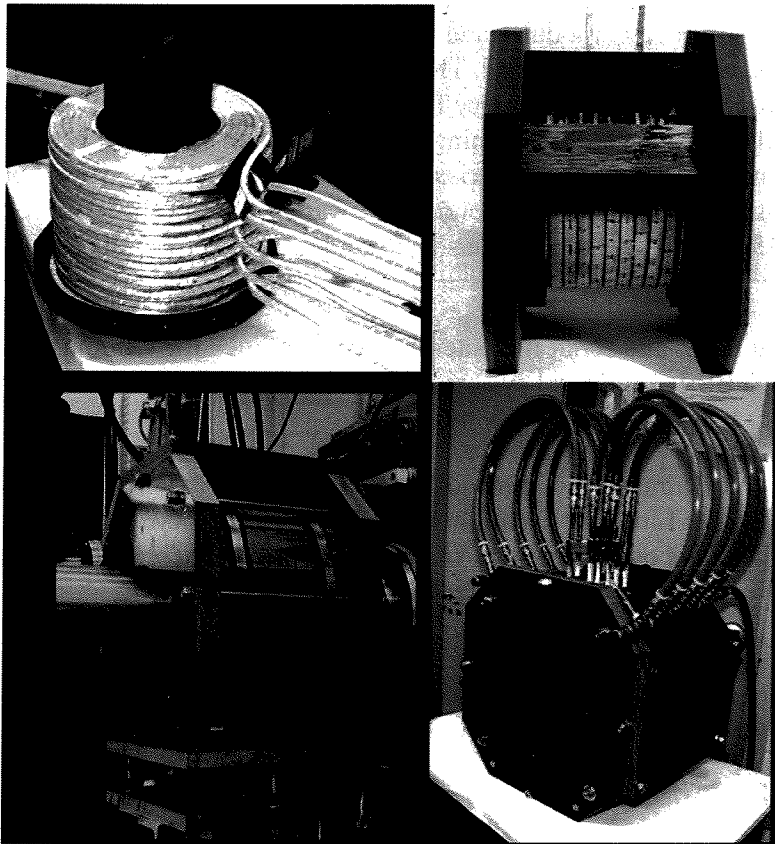


Figure 5.51 Photos showing construction of the H- LEBT solenoid.

5.12. Controls

The EBIS control system will be an extension of the RHIC control system¹⁸. The basic architecture of the system will comprise networked front-end interfaces connected via Ethernet to control console workstations and central C-AD servers. The standard controls hardware interface will be a front-end computer comprising VME-bus chassis, processor, utility link interface, battery-backed cache memory, and event decoder-delay modules. Extensive re-use will be made of existing interface module designs. Full pulse-to-pulse modulation functionality will be a feature of all beam control equipment interfaces.

General purpose and project-specific application software for operating and monitoring the equipment and beam characteristics will be provided. It is expected that a majority of the requirements will be met by existing software tools for simple device control and archiving, data logging, comfort displays, alarms, and e-log.

5.12.1. Timing & Infrastructure

Existing fiber optic infrastructure in building 930 will be extended to the two EBIS equipment areas. This will provide access to the C-AD controls subnet and standard links. Remote power reset modules and terminal servers, for serial port access to front-end processors, will also be provided. The C-AD Real-Time Data Link will provide the facility-standard, time-of-day reference for all front-end chassis. This time base will be common to all logged data. Pulse timing will be provided by a local version of the standard Event Link system with provision for 32 encoded events. It will provide a standard real-time clock and asynchronous, software- or hardware-initiated, encoded event signals for triggering equipment. The standard remote reset link will be provided also.

Networked PLCs and serial line interfaces are provided for vacuum system equipment in WBS 1.7. Control system access to these devices will be provided through the chassis that houses the event link modules.

Work consoles composed of a standard 19-inch rack with writing shelf attachment and equipped with a Linux workstation will be provided in the equipment rooms, two on the first floor and one on the second. An additional monitor screen for alarms and a color printer will also be provided on the first floor.

Front-end computer software effort will largely entail configuration of existing device driver software and accelerator device object (ADO) software. Database setup to match the specific instances of installed devices will also be required.

5.12.2. EBIS

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, many of which will be located on pulsed high voltage platforms. Waveform generation and data acquisition for EBIS will be provided using the fiber-optically isolated PSI interface developed for the Spallation Neutron Source (SNS) and already in use at the AGS and Booster. More detail may be found in section 1.5. For this application, the link speed of the PSI and matching VME function generator will be increased to handle one reference and two readbacks at a 100kHz update rate. This will entail some design modifications. A Faraday cup, and temperature and pressure sensors located on the high voltage platforms will also be controlled and monitored using the PSI interface.

All function generator channel references and readbacks will be synchronized to a common clock derived from the EBIS event link. Common event timing will initiate the EBIS cycle and schedule extraction. Fiber optic links will carry pulsed trigger signals to the high voltage platform.

The revisions to the function generator design are expected to necessitate minor modifications to the corresponding front-end software. A custom console application program will be provided for management of details of the EBIS cycle waveforms.

5.12.3. Accelerators & Beam Transport

Most power supplies will be controlled via the SNS PSC-PSI interface system. Any devices that require ramped operation will be controlled using the C-AD standard PSI-compatible function generator.

Beam instrumentation interfaces will be patterned after existing C-AD systems that utilize commercial modules wherever possible. A standard VME chassis assembly with event link decoder-delay modules and pulse fanout modules will provide trigger pulses to the data acquisition modules.

Custom VME control modules are part of the RF system (WBS 1.6). Control of the high-power RF system equipment will be implemented with networked PLCs that are likewise included in the RF system. The Controls contribution to this effort will comprise standard VME chassis and modules for timing and link interfaces, and commercial analog and digital I/O modules.

Front-end software effort will be mainly configuration and database setup. Existing console programs for beam line diagnostics will be modified to include the EBIS transport lines.

5.13. Vacuum System

In addition to the EBIS vacuum system, described in Section 5.2.6, there are several other regions, which make up the balance of the vacuum system that include the LEBT, RFQ, MEBT, IH Linac, and HEBT. Each region has its own vacuum pumps and gauges installed, and can be isolated from each other with the gate valves that are mounted at each end. A schematic layout of the vacuum system is shown in Figure 5.52. Vacuum

levels of 10^{-8} and 10^{-9} Torr are sufficiently low for the partially stripped low energy ion beams for all these regions due to the single pass nature, except at the downstream end of HEBT. Vacuum of 10^{-10} Torr is needed in the last section of HEBT to minimize the diffusion of residual gas into the 10^{-11} to 10^{-12} Torr Booster ultrahigh vacuum system.

Only UHV compatible materials such as metals and ceramics will be used throughout the vacuum system. No organic materials will be allowed. Conflat type flanges will be used throughout the vacuum system as the standard flanges since they are fully bakeable and provide a highly reliable vacuum joint with a reasonable cost. Stainless steel will be used for vacuum pipes and chambers wherever possible. All vacuum chambers and beam line components will be chemically cleaned and assembled in a clean environment to minimize contamination. To achieve the required design pressure, low outgassing rates are required for all vacuum chambers and components. This will be accomplished by vacuum degassing all chambers and components in a vacuum furnace at the highest allowed temperature prior to installation.

The RFQ will have two cryopumps each with their own gate valve so the pumps can be isolated from the system for regeneration and for protection from power dips. The LEBT and IH Linac regions will also have their own cryopumps and isolation valves.

The HEBT line will be baked in-situ at 150° C and be pumped with a combination of small ion pumps and NEG strips and cartridges. This region must be baked to provide a pressure differential from upstream high vacuum regions to the Booster ring ultrahigh vacuum of 10^{-11} Torr. Components in this line shall be bakeable to a temperature of 200° C or higher. In order to provide even heating of the vacuum chambers, the entire system will be wrapped with permanent fiberglass heating jackets. The in-situ bakeout will be controlled by programmable temperature controllers with individual PID loops. Two additional gate valves will be added at the 4-way cross between HEBT and LTB lines to minimize the total bleed-up length should the need of repair or upgrade arises. This feature will shorten the vacuum downtime, conserve manpower and reduce radiation exposure, since restoring ultra-high vacuum after venting is a very labor-intensive procedure.

A PLC based control system will be used to monitor and control the vacuum gauges, pumps and sector gate valves. One set of Pirani and cold cathode gauges will be installed at each vacuum sector. Gauge controller digital outputs in conjunction with vacuum pump setpoint outputs will provide inputs to the PLC logic to control the sector gate valves. The PLC will also provide inputs to the beam permit system to abort the beam in the event of a vacuum fault. An Ethernet network will connect the PLC to the VME type front-end computer for monitoring, logging and control of the vacuum devices. A residual gas analyzer will be installed on the EBIS chamber to provide a quick analysis of the partial pressures. The layout of the vacuum instrumentation and control system is shown in Figure 5.53.

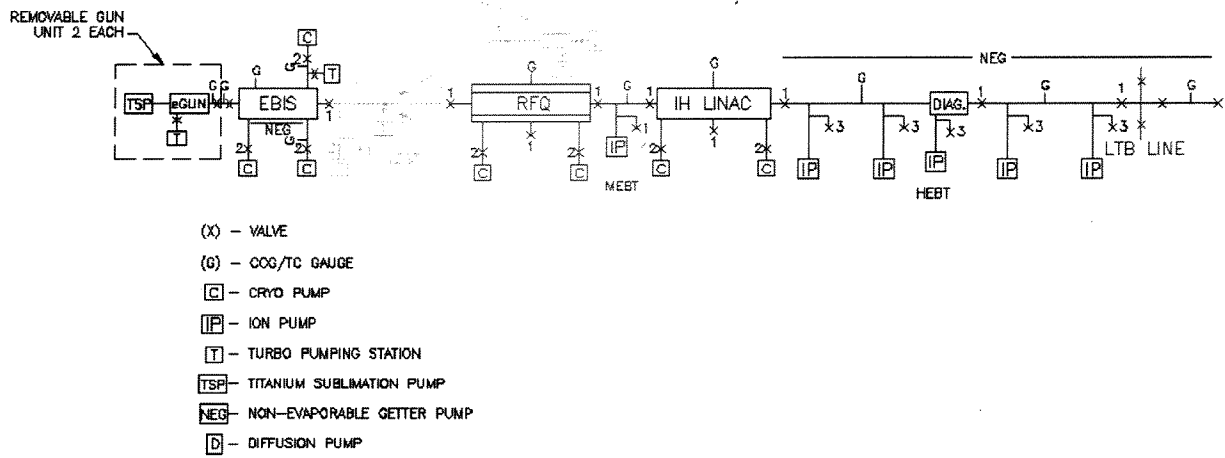


Figure 5.52 Schematic of the vacuum system

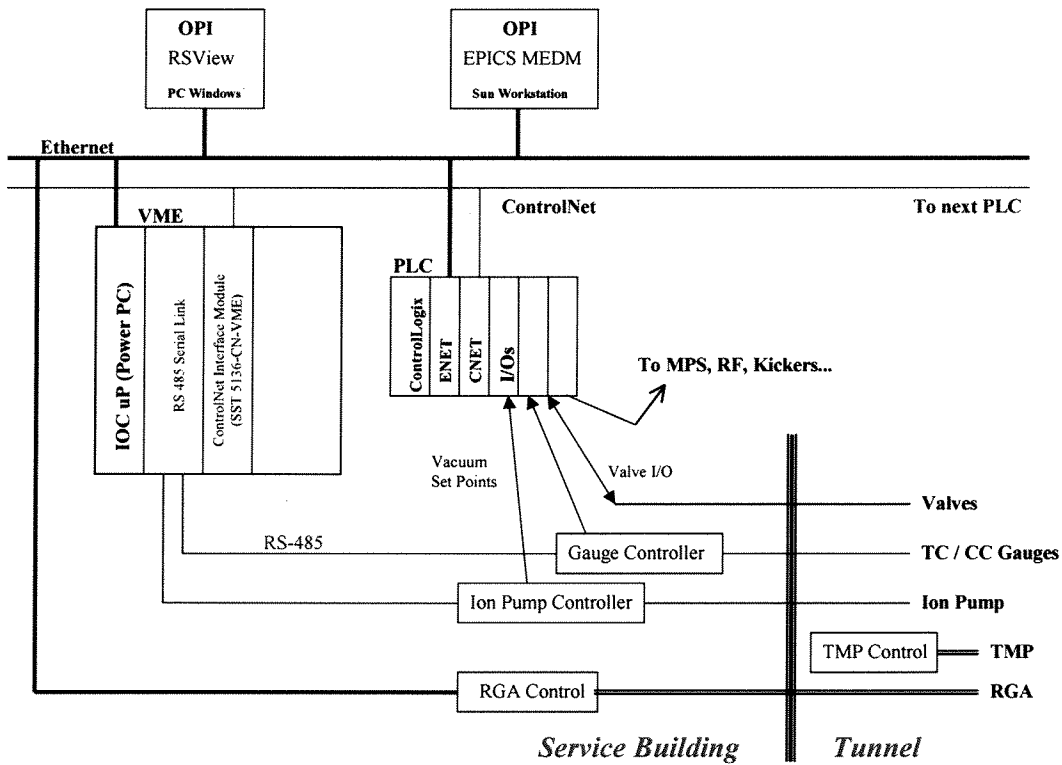


Figure 5.53 Schematic of Vacuum Instrumentation and Control

Table 5-14_EBIS Vacuum

Description	#	Unit Length
Design Vacuum Level		< 1×10^{-9} Torr
Beamline Length		40 m
Special Dipole Vacuum Chambers	2	1.8 m
Gate Valves, 10" CF	13	0.14 m
Gate Valve 8" CF	4	0.12m
Sputter Ion Pumps, 20 l/s	6	
Cold Cathode and Pirani Gauge Set	18	
Turbopump/Dry Pump Stations,	6	
Cryopumps	8	
Diffusion Pumps with Baffle	2	
NEG cartridge pumps	2	
Titanium Sublimation Pumps	2	
Insitu Bake Temperature for HEBT line		150 C

5.14. Cooling Systems

5.14.1. RHIC EBIS Water Cooling

In a process of EBIS operation a significant amount of heat is released. The primary source of heat is electron collector (EC) with peak power dissipation 300 kW and average amount up to 150 kW. The other sources are magnet coils (30 kW) and vacuum pumps and compressors (~6 kW). All sources except EC require cooling water with pressure about 4 bar. EC requires cooling water with pressure 20 bar, it is necessary to increase its boiling temperature to 200⁰C and this way avoid boiling on its hot surfaces at high (up to 500 watt/cm²) power density. All sources are located on an insulated platform that can go up to 100 kV in short (ms range) pulses with frequency up to 5 Hz. The schematic of RHIC EBIS cooling system is presented in Figure 5.54.

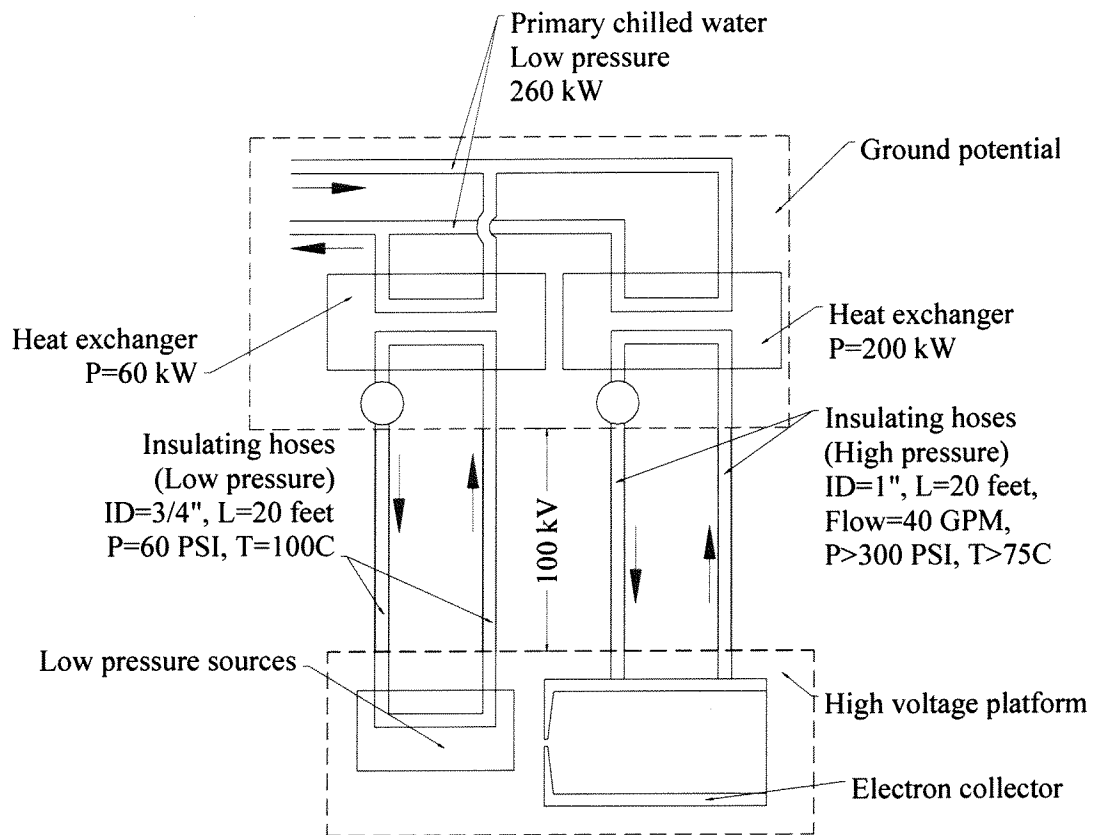


Figure 5.54 Schematic of RHIC EBIS water cooling

Description of the Heat Sources

1. Electron Collector

RHIC EBIS electron collector is designed to dissipate up to 300 kW of electron beam peak power in pulses with length 50 ms and duty factor up to 50% on its cylindrical surface with diameter 11.8" and length about 9.7". Special precautions are taken to prevent water boiling and heat fatigue of EC material. The schematic of RHIC EBIS EC is presented on Figure 5.55.

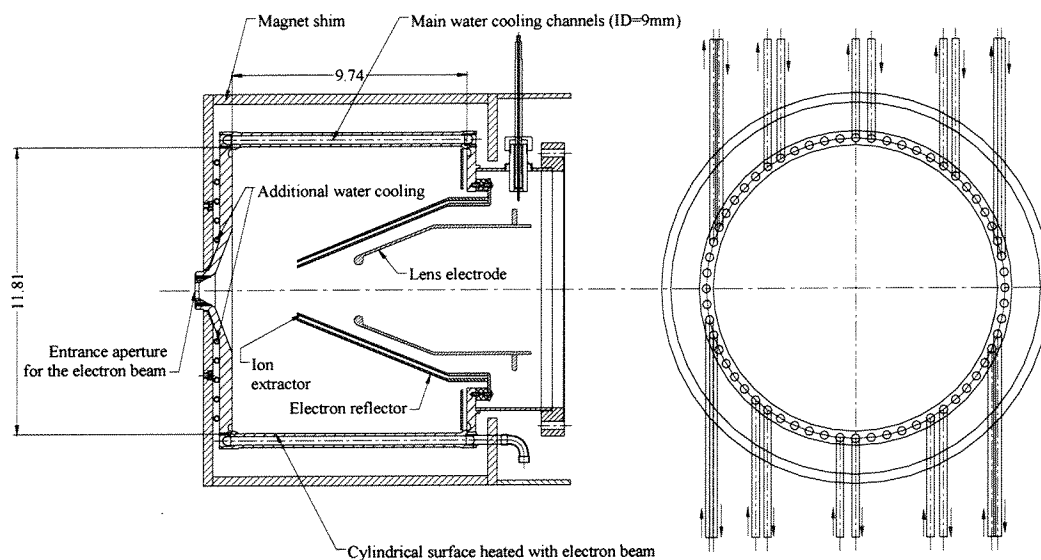


Figure 5.55 Schematic of RHIC EBIS electron collector.

60 water-cooling channels on its cylindrical wall have ID=9mm and are connected in branches. Each branch consists of 6 channels connected in series and has total length about 1.5 m and consumes 4 GPM of water. There are 10 such branches, which are connected in parallel for water flow, so the total water flow is 40 GPM. With 1-phase flow the expected value of pressure drop on EC is about 1 bar. Inclusion of vapor phase will increase this value depending on the fraction of vapor. The temperature of water will increase only by 14⁰C, but the high water flow is still needed to provide high turbulence on hot surfaces for effective heat removal. Even though the water pressure drop on EC is only 1 bar, we need to stabilize water against boiling. Therefore, the whole EC water cooling circuit should be elevated to 20 bar. Pressure loss for any reason will result in creating of vapor sheath on copper-water interface, loss of heat exchange and fast and uncontrolled rise of EC temperature.

The requirements for the insulating hoses:

- withstand this pressure (20 bar) while providing the required water flow (40 GPM) and temperature up to 100⁰C,

- pressure loss should be not higher than 2 bar. (With one way length L=18 feet and ID=1" the total pressure drop on EC hoses should be about 2 bar.)
- the length of these hoses and its ID should be chosen also considering the current loss of the high voltage power supply of the platform. This current loss can be satisfied with a combination of hoses dimensions and water resistivity. Water used in all secondary circuits should be distilled and deionized.

2. Low Pressure Circuit

This circuit includes 2 magnet coils (about 15 kW each), EC power supply (40 KW), Compressor for cryopumps (5 kW) and small other items like vacuum pumps (5 kW total), thermal shield of the central vacuum chamber (30kW, can only be used rarely, when other sources are OFF). Total power going to water in this low-pressure line of HV platform is estimated at 80 kW. The required water pressure in this circuit is 4-5 bar.

5.14.2. Water Cooling Requirements

There will be three separate and independent closed loop systems running off the present Linac chilled water system. This chilled water system dissipates heat into the existing Linac cooling tower. Each of the three basic systems consists of a pump/motor (with a spare), filter, heat exchanger, expansion tank, temperature and pressure control valves, and water treatment as required. All components will be individually skid mounted. The deionized water controls on two of the systems are separate active on-line control systems maintaining the required resistivity. The exception is the RFQ/Linac system, which will have a 4109 iron corrosion inhibitor control system. This system will be tested (monitored) periodically and manually adjusted as required (on present systems this is usually on a weekly basis).

The PLC system is an active on line control system. This system will individually monitor the controlled parameters of each of the five EBIS systems. The parameters which are monitored, and adjusted as required, are temperature, pressure, system water level, flow, and resistivity. The PLC will also monitor critical parameters with upper and lower alarms to initiate system alarm responses as required.

Total heat load is estimated at about 373 KW (106 Tons). A total of 268 KW (76 Tons) will require a 70 F supply temperature. This temperature will require a chilled water source. The Linac existing chilled water system has a 450 Ton chiller that is reported to be 50% to 75% utilized during maximum load conditions. Therefore, at this time, that is the preferred choice for the cooling source. The chilled water source is available in the Linac building, but the line size must be increased in size to handle the higher flow requirement of EBIS at that location.

Cooling system requirements are given in Table 5-15.

Table 5-15 Cooling water requirements for EBIS.

Electron Collector/Quads	Collector	Linac quads	System	
Flow	40 gpm	20 gpm	60 gpm	
Supply Pressure	425 psi (note 1)	375 psi	425 psi	
Heat Load	200 kW	1 kW	201 kW	
Inlet Supply Temp	70 F (21C)	85 F (30C)	70 F (21 C)	
Water Treatment	DI at <10 uS/cm or 0.1 MegOhms/cm			
Req'd Floor Area	70 ft ² excluding required aisle or wall space for electrical equipment			
High Voltage Platform / RF amplifiers / Circulators				
	Platform	RF Amplifiers	Circulator	System
Flow	60 gpm	70 gpm	5 gpm	135 gpm
Pressure	60 psi (note 2)	80 to 100 psi	80 psi	90 psi
Heat Load	60 kW	100 kW	5 kW	165 kW
Inlet Supply Temp	70 F (21C)	85 F (30C)	85 F (30C) +/-1F	70 F
Water Treatment	DI at <10 uS/cm or 0.1 MegOhms/cm			
Req'd Floor Area	70 ft ² excluding required aisle or wall space for electrical equipment			
RFQ & Linac				
Flow	20 gpm			
Pressure	100 psi	5 HP estimated		
Heat Load	7 KW			
Inlet Supply Temp	70 F (21C) +/- 1F			
Water Treatment	Water additive 4109, iron corrosion inhibitor			
Req'd Floor Area	50ft ² excluding required aisle or wall space for electrical equipment			
HEBT 73 degree dipoles magnets (2) – Use existing Booster magnet water system				
	Flow	22.9 gpm (2 x 11.45 ea)		
	Pressure	60 psi		
	Heat Load	90 kW		
	Inlet Supply Temp	90-870 F (30C)		
	Water Treatment	DI at <10 uS/cm or 0.1 MegOhms/cm		
	Req'd Floor Area	None		

Note 1: The overall static pressure in the system should be at least 25 Bars or 375 psi to prevent water vaporization at the target. The estimated system delta press is estimated at 2 to 3 Bar.

Note 2: The overall static pressure in the system should be at least 4 Bars or 60 psi to prevent water vaporization.

5.15. Facility Modifications

The conventional facility modifications required for the EBIS project include a new beam access port from the Linac building to the Booster, power modifications associated with equipment relocation, plus new power for EBIS.

5.15.1. Beam Access Port

A new beam access port will be installed from the Linac building to the Booster. This will be accomplished by saw cutting the existing concrete walls and jacking a ~18" diameter steel pipe through the earth shielding.

5.15.2. Power Modifications

Power modifications include the installation of new power for EBIS equipment. EBIS power will be obtained from an existing Linac substation. This work consists of re-distribution of substation power and running a dedicated power feed, distribution, and tray.

5.16. Installation

The EBIS facility will be installed in existing building 930, which will have been extended to accommodate support equipment and electronic racks. Provisions for clean power, HVAC, cooling water, and power and instrumentation cables (i.e., most of the tray and conduit) will be made prior to the installation phase. The installation will be done in the following sequence: major beam line components, then small beam components, diagnostic devices, and beam line sections, followed by electronic/electrical racks and utility support systems, such as air and water lines. The primary beam line components include the EBIS, RFQ, Linac, and dipole and quadrupole magnets. The primary components will be pre-assembled and, when feasible, operated and tested prior to final installation at the site. Special provisions for safely lifting and positioning these devices without an overhead crane will be determined in the design phase. The LEBT region between the EBIS and the RFQ is a complex assembly of ion sources, beam components and diagnostic devices that will also be assembled prior to installation to verify fit without interferences, then reassembled and aligned in the beam line. The HEBT region is an ultra-high vacuum region consisting of conventional beam line components. Support equipment for the facility, electronic racks, and power supplies will be installed in an equipment bay adjacent to the beam line and on the second level above this equipment bay. Stations for operating the EBIS, beam line controls, and diagnostics will also be placed in these areas.

Proper connection of power supplies, controls, and diagnostic electronics will be verified during the Installation phase. Operation, test, and checkout of the EBIS, ion sources, and beam line devices with beam will be conducted during the commissioning phase. The EBIS superconducting solenoid will have been acceptance tested at the factory and at BNL prior to installation in the facility.

5.17. ESSH

The purpose of this chapter is to briefly describe the rigorous environmental protection, safety, security, health and quality (ESSH) activities associated with the EBIS Project that will be completed prior to commencement of construction, commissioning and operations.

5.17.1. Review of ESSH Issues Associated with the EBIS Design

The shielding policy for this facility is the same as that for the rest of the Collider-Accelerator facilities since the new pre-injector and beam-line are to be the responsibility of the Department. Specifically, the Collider-Accelerator Department's Radiation Safety Committee will review facility-shielding configurations to assure that the shielding has been designed to:

- Prevent contamination of the ground water

- Limit annual site-boundary dose equivalent to less than 5 mrem
- Limit annual on-site dose equivalent to inadvertently exposed people in non-Collider-Accelerator Department facilities to less than 25 mrem
- Limit dose equivalent to any area where access is not controlled to less than 20 mrem during a fault event
- Limit the dose equivalent rate to radiation-workers in continuously occupied locations to ALARA but in no case would it be greater than 0.5 mrem in one hour or 20 mrem in one week
- Limit the annual dose equivalent to radiation workers where occupancy is not continuous to ALARA, but in no case would it exceed 1000 mrem.

In addition to review and approval by the Radiation Safety Committee, the Radiation Safety Committee Chair or the ESHQ Associate Chair must approve final shield drawings. Shield drawings are verified by comparing the drawing to the actual configuration. Radiation surveys and fault studies are conducted after the shield has been constructed in order to verify the adequacy of the shield configuration. The fault study methodology that is used to verify the adequacy of shielding is proscribed and controlled by Collider-Accelerator Department procedures.

The DOE ESHQ requirements applicable to the new pre-injector are listed in Table 5-16. All hazards, including radiological hazards, associated with DOE accelerator facilities are addressed comprehensively in DOE Order 420.2A, Safety of Accelerator Facilities. Appropriate and adequate protection of workers, the public, and the environment from ionizing radiation is also covered under 10CFR1035, "Occupational Radiation Protection," which applies to all DOE facilities regardless of the source and type of ionizing radiation.

Table 5-16 Current DOE ESHQ Requirements for BNL Accelerators

Topic	DOE Requirements Document
Authorization Basis Documents	DOE O 420.2B, Safety of Accelerator Facilities DOE O 420.1A, Facility Safety (Natural Phenomenon and Fire Protection Sections)
Conduct of Operations	DOE O 54100.19 Chg 2, Conduct of Operations Requirements for DOE Facilities
Quality Assurance	DOE O 414.1B, Quality Assurance
Maintenance Management	DOE O 430.1B, Real Property Asset Management DOE O 430.2A, Departmental Energy And Utilities Management
Training and Qualification Programs	DOE O 54100.20A Chg 1, Personnel Selection, Qualification, and Training Requirements for DOE Nuclear Facilities
Radiation Protection	Title 10, Code of Federal Regulations, Part 1035, Occupational Radiation Protection
Transportation and Packaging	DOE O 460.2 Chg 1, Departmental Materials Transportation and Packaging Management DOE O 460.1B, Packaging and Transportation Safety
Worker Protection	DOE O 440.1A, Worker Protection Management for DOE Federal and Contractor Employees
Environmental Protection	DOE O 450.1, Environmental Protection Program DOE O 451.1B Chg 1, National Environmental Policy Act Compliance Program - Change 1
ESH Reporting	DOE O 231.1A, Environment, Safety, and Health Reporting
ESH Standards	DOE O 54100.4 Chg 4, Environmental Protection, Safety, and Health Protection Standards
Accident Investigation	DOE O 225.1A, Accident Investigations
Radioactive Waste Management	DOE O 435.1 Chg 1, Radioactive Waste Management

The C-A Department implements the DOE requirements indicated in Table 1 using procedures and training. At the BNL level, the Standards Based Management System (SBMS) is used to keep DOE requirements current and to flow requirements down to the Department level. At the C-A Department level, SBMS requirements are flowed down into routine operations procedures. All ESHQ requirements and hazard controls are documented in detail in the C-A Operational Procedures (OPM) as follows:

- **Management Controls:** OPM Chapter 1, Authorizations, Environmental Management System, OSH Management System, Security

- **Operational Controls:** OPM Chapter 2, Conduct of Operations, LOTO, Maintenance, Work Planning
- **Emergency Response Controls:** OPM Chapter 3, Emergency Procedures
- **Access Controls:** OPM Chapter 4, Access Control System Testing, Sweep and Reset Requirements
- **ESH Review and Personnel Protective Equipment:** OPM Chapter 9, Radiation Safety, ESH Committees, ESH Review, ALARA, Safety Inspection, Cryogenic Safety
- **Occurrence Reporting:** OPM Chapter 10, Occurrence Reports, Notification Lists, Water Spill Procedures
- **Experiment Operations Controls:** OPM Chapter 11, Experimental ESH Procedures
- **Quality Controls:** OPM Chapter 13, Quality Assurance Procedures

The remaining chapters of the C-A Department OPM are devoted to specific operations tasks for accelerators pre-injectors and sub-systems.

In order to meet the requirements in DOE Order 420.2A, Safety of Accelerator Facilities, C-AD has incorporated a description and safety assessment of the new pre-injector into the current Safety Assessment Document for C-AD. At the appropriate time, C-A Department will obtain an approved Accelerator Safety Envelope for the new pre-injector from DOE and perform an Accelerator Readiness Review in accord with 420.2A prior to commissioning and operations.

The C-A Department conforms to the requirements of ISO 14001, Environmental Management System, and OHSAS 18001, Occupational Safety and Health Management System, and achieves third-party registration for these internationally recognized management systems. Thus, in addition to DOE requirements, documentation of environmental protection and occupational safety and health programs for new pre-injector facilities will be prepared and audited by independent parties. This documentation will include:

- Environmental Process Evaluations for all processes with significant environmental aspects
- Facility Risk Assessments for all facilities and areas
- Job Risk Assessments for all jobs

DOE O 420.1A, Facility Safety, has two sections that are applicable to accelerator facilities: Natural Phenomenon and Fire Protection Sections. DOE STD-1020-2002, Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities, describes the Performance Criteria (PC) to be used for evaluating building design for earthquake, wind and flood phenomena. DOE-STD-1020-2002 employs the graded approach in assigning PC categories to DOE buildings. The graded approach enables cost-benefit studies to be used to address categorization. It is noted that the radioactivity entrained within the new pre-injector components would not have a significant off-site impact as a result of an earthquake, high winds or flood. Based on the small amounts of hazardous materials that will be present at the new pre-injector facilities, the PC1 category is applicable. That is, BNL will use model building codes for the new pre-injector facilities that include earthquake, wind, and flood considerations. BNL is currently using PC1 for all other C-AD facilities for life safety issues.

Significant environmental aspects of the new pre-injector project include:

- Excavation
- Chemical Storage/Use
- Liquid Effluent
- Hazardous Waste
- Radioactive Waste
- Radiation Exposures
- New or Modified Federal/State Permits

Routine operation and maintenance actions associated with the new pre-injector facility would involve the use of chemicals or compounds, generally in small quantities. BNL's Chemical Management System would track the quantity, location, owner, and storage of any chemical inventory.

Although BNL is situated over a Sole Source Aquifer, operation of the Linac-based RHIC pre-injector should not affect the aquifer. This would include discharges to the BNL sanitary and storm water systems. Work planning, experimental review, and Tier I safety inspections are the three methods for ensuring that hazardous effluents do not make their way into the sanitary waste stream or storm water discharges. Any non-hazardous discharges associated with the pre-injector, including cooling tower effluent, would be managed according to the BNL Standards Based Management System Subject Area "Liquid Effluents".

Routine operation and maintenance actions associated with the new pre-injector would result in a small amount of hazardous or radioactive wastes being generated. The total volume generated would not be expected to exceed a few cubic feet per year and would not constitute a significant increase to Collider-Accelerator Department total waste volumes. All hazardous and radioactive wastes would be managed in accordance with established BNL procedures and subject areas. Work planning, experimental review, and Tier I safety inspections are the three methods for ensuring wastes are minimized and controlled.

Routine operation and maintenance actions associated with the new pre-injector would result in low-level radiation exposures to workers. Interlocks, access controls, training and procedure administration would be used to minimize exposures and employ ALARA principles.

Depending on the disposition of cooling tower discharge, the existing New York State Pollutant Discharge Elimination System (SPDES) permit would be revised as necessary. The cooling system would be a closed loop deionized water system using ion exchange beds that would be removed for regeneration or disposal by a contractor off site. In no case would the ion beam strike the water directly. At the proposed beam current and ion-beam energy, no induced activity would be expected. Discharge of contaminants to the ground or to the sanitary system would be neither planned nor expected from the cooling system. The closed loop cooling system would be connected to the cooling tower via a heat exchanger. Cooling-tower water would be treated either with ozone or with biocides and rust inhibitors, and would meet all SPDES effluent limits.

5.17.2. ESSH Plans for Construction

All requests for goods or services will be processed through a formal and well-documented system of review to incorporate any special ESSH requirements of the contractor or vendor. BNL will review the proposed contract scope of work using Work Planning and Control for Experiments and Operations Subject Area. The building modification and utility drawings for the new pre-injector will be sent to the BNL's Safety and Health Services Division for review by the appropriate ESH disciplines.

C-AD will define the scope of work with sufficient detail to provide reviewers and support personnel with a clear understanding of what is needed, expected, and required. This will include the type of work to be performed, location of work, defined contract limits, allowed access routes, and any sensitive or vulnerable Laboratory operations or infrastructure that may be impacted by this work. The C-AD will ensure that facility hazards are characterized and inventoried specific to the expected construction location and activities.

To protect valuable materials against theft or diversion that could result in significant financial impact or that could result in unauthorized release of radiological or chemical agents, the C-A Department will employ some or all of the following strategies:

- Permanently etch or mark valuable materials with "Property of U.S. Government", or apply permanent, tamper-proof tags with indelible marking stating "Property of U.S. Government"
- Register the materials and their location in an inventory system
- Use stickers to warn potential thieves of a theft protection system

- Enclose the materials in a storage area with locked fencing
- Use electronic security systems
- Keep heavy valuable materials and heavy-lifting equipment separated
- Secure heavy-lifting equipment with tire locks
- Secure material with chain and lock

The C-AD will ensure that minimum ESSH competency requirements for contractors are detailed and provided to the Procurement & Property Management Division (PPM). PPM will include those requirements in the bid and contract documents to qualify contractors for award. Competency requirements will be consistent with the project, facility and job to be performed.

Candidates for any contract award will be required to submit the following:

Comprehensive Corporate Environmental, Safety and Health (ES&H) Program - Candidates for contract award must submit an acceptable Corporate Health and Safety Program to be considered for award. This program must be sufficiently detailed to clearly define ES&H responsibility, accountability, and authority of the company's employees for the intended work to be performed and the hazards to be encountered. They should include: Policy Statement, Personnel Duties (Inspection, Reporting, Accident/Incident Investigation, and Enforcement) Training, and Communication.

Performance History - Injury/Illness reports for the previous three years (OSHA 200 logs, or Insurance C-2 loss runs), Experience Modification Rates (EMR), Incidence Rates, and Days Away or Restricted Time (DART) Rate must be submitted in order to be considered for award. EMR, Incidence Rate, and DART Rate must be equal to or better than industry average for award consideration. Exceptions may be allowed where candidates can prove that the causes of the higher than average rates have been, and will be rectified. Environmental compliance record for the latest 5-year period must be submitted.

Complex or Hazardous Activities - For projects involving complex or hazardous activities, submission of equivalent project experience, hazard-specific management programs, resumes and related work histories of field and supervisory personnel will be required. Examples of complex or hazardous activities include: Work in radiological areas, radiological construction work, working at height, hoisting and rigging operations, excavation, working in confined spaces, exposure to sources of hazardous energy, exposure to vehicular movement, exposure to hazardous materials, demolition, or site clearing. In addition, copies of any required certifications, registrations or applicable County, State, or Federal Permits must be submitted. Examples include Hazardous Waste Operations, Asbestos, Lead, and Dewatering.

Administration - Personnel responsibilities will include the obligation to obey the safe working practices for their trade, the frequency and scope of inspections for deficiencies, corrective actions to be taken, reporting of accidents, injuries, near-misses, spills, and leaks.

Enforcement, Reporting, and Evaluation - Corrective action will be clearly defined with abatement and punitive actions outlined. The reporting and record-keeping process will be outlined with specific responsibilities for notifying owner, contractor, and regulatory personnel, documenting the deficiency and its abatement. A process for periodic evaluation and improvement of the program shall be included in the Corporate Safety Program.

Project Environmental Safety and Health Plan - The Contractor will be required to submit a project safety plan that complies with the requirements of the Federal Acquisition Regulations, BNL SBMS requirements and 29 CFR 1926 Safety and Health Regulations for Construction. The plan will address the following:

- A Contractor/Vendor employee or designee shall be identified in writing as having responsibility for safety and health compliance at the project site.
- A Contractor/Vendor employee or designee shall be identified in writing as having responsibility for safety and health compliance over a particular hazardous activity.
- In addition to the Corporate ES&H Program requirements, specific hazard prevention and control programs will be included in the plan for routine, complex, and hazardous activities.
- Prime contractors shall award subcontracts based upon the evaluation criteria used to award prime contracts. Subcontractors shall comply with the Prime contractor's safety program, unless their own is more stringent.
- The plan will describe a process for ensuring that each employee entering the worksite receives initial worksite safety and health orientation and continued safety and health training addressing the hazards associated with the work and the measures necessary to control or eliminate the hazards. Weekly "Tool Box" safety and health training will be conducted and documented for the duration of the project.
- A process for documenting accidents, injuries, illnesses, near misses, and inspection results will be clearly outlined.
- Safe working practices shall be outlined for the hazards to be encountered. Punitive consequences for failure to follow safe working practices shall be commensurate with the severity of the violation, and shall include dismissal for serious or repeat violations.

- A written program including a company policy statement, prohibited activities, supervisor and employee responsibilities, enforcement actions, consequences for violations, on-going drug free awareness training, intervention procedures, employee assistance options.
- A list of BNL-specific permits, permissions, requirements, and instructions that are to be supplied to the contractor by BNL or its representative will be included in the plan.

The C-AD will ensure only authorized contractor personnel are allowed on the Laboratory property to perform work under the terms of their contract. They shall carry current BNL issued gate passes, identification badges, or be escorted by an authorized Laboratory employee. To obtain access, contractor employees must have received BNL site-specific training or be assigned an escort.

Materials to be disposed of, recycled or otherwise reused either on or off-site, shall pass through the vehicle radiation monitor in the presence of a Radiological Control Technician or equivalent.

Job sites will be inspected with sufficient frequency to accurately assess compliance with ES&H obligations, and to identify any weaknesses in the contractor's ES&H management of the site. Violations of ES&H requirements shall be cause for a work interruption on that portion of the work, and may be grounds for a Stop Work Order for the entire project. Inspections will be documented.

The C-AD will make periodic inspections to verify project ES&H performance is consistent with contractual obligations. The frequency of inspections shall be adequate to represent the effectiveness of the contractor's ability to manage the job safely.

During periods of active construction, the contractor will be required to conduct daily inspection of the worksite to identify hazards and instances of noncompliance with project ES&H requirements. Records will be kept of all daily inspections. Records will be kept of hazards and the corrective actions taken.

Imminent danger, or failure to adequately correct identified safety deficiencies in a timely manner will be cause for a Stop Work Order to be issued on part or the entire project. The Stop Work Order can only be lifted when the contractor has prevented or controlled the identified hazards, and corrected the ES&H management system deficiencies that allowed them to occur.

All accidents, injuries, illnesses, environmental hazards, imminent danger, and near misses will be reported to the appropriate BNL authority immediately. Investigation and reporting will be in compliance with BNL SBMS requirements.

Fire, accidents involving injury, illness or property damage, injury or illness of unknown origin, any quantity of pollutant dropped anywhere, the suspicion or discovery of

munitions will require immediate notification of BNL Emergency Services (x911). Thefts or vandalism will require immediate notification of the BNL Safeguards and Security Division.

Contractor employees will be required to maintain current permits for the activities being performed at the jobsite.

ES&H performance data will be collected during each phase of the project and summarized at the end. Data shall rank the seriousness of the violations, the responsiveness of the contractor, and the effectiveness of the contractors ES&H management system. The C-AD will forward this data to the Procurement & Property Management Division on a timely basis throughout the project life, and at project closeout. The Procurement & Property Management Division uses this data to qualify organizations for award of future contracts.

5.17.3. ESSH Plans for Commissioning, Operations and Decommissioning

The Collider-Accelerator Department (C-AD) has already identified hazards and associated on-site and off-site impacts to the workers, the public and the environment from the C-AD accelerator facilities, including the new EBIS based pre-injector, for both normal operations and credible accidents. Sufficient detail was provided to DOE in the current C-AD Safety Assessment Document (SAD) to ensure that C-AD has performed a comprehensive hazard and risk analysis. The amount of descriptive material and analysis in the SAD related to both the complexity of the facility and the nature and magnitude of the hazards. In addition, the SAD provides an understanding of radiation risks to the workers, the public and the environment.

The SAD provides appropriate documentation and detailed description of engineered controls, such as interlocks and physical barriers, and administrative measures, such as training, taken to eliminate, control or mitigate hazards from operation. The SAD demonstrates that controls are sufficient to satisfy requirements and manage identified conditions associated with hazards. The SAD also documents the methods used to mitigate the hazards to the extent prescribed by applicable requirements, codes or consensus standards.

The SAD describes the Department management organization, and the function and location of each pre-injector and accelerator in addition to details of major components and their operation. The descriptions are of sufficient depth and breadth that a reviewer familiar with accelerator operations but unfamiliar with this particular pre-injector can readily identify potential hazards and populations or environments at risk.

The risk analysis in the SAD addresses the hazards of the entire system of pre-injectors and accelerators. It also addresses hazards, controls and risks for all facilities such as pre-injectors, injectors, accelerators, experimental halls, experiments and their associated targets and detectors.

The C-AD SAD follows the generally accepted principles identified in DOE Order 420.2B that address the following eight topics:

1. The SAD has a description of the function of the integrated C-AD facilities and the protection afforded the public and worker's health and safety, and the protection of the environment and government property.
2. The SAD has an overview of the results and conclusions of the safety analysis including a description of the comprehensiveness of the safety analysis, appropriateness of the Accelerator Safety Envelopes, and the appropriateness of the occupational safety and health, environmental protection and security management systems used at C-AD.
3. The SAD documents a review of the land, water, air and wildlife environment within which the C-AD facilities operate, individual facility characteristics that are safety-related and the methods to be used to operate the pre-injectors, injectors, accelerators, beam-lines, targets and experiments. The following specific items are addressed:
 - Site geography, seismology, meteorology, hydrology, demography and adjacent facilities that may affect or may be affected by C-AD facilities
 - Design criteria and as-built characteristics for components with safety-significant functions
 - Features that minimize the presence of hazardous environments such as those that ensure radiation exposures are kept ALARA during operation and maintenance
 - BNL and C-AD organizational and management structures and a delineation of responsibilities for safety, security, health and environmental protection
 - The function of engineered and administrative controls both for routine operation and for emergency conditions
 - Critical operational procedures to prevent or mitigate accidents
 - Design criteria and characteristics of experimental equipment, systems and components having safety-significant functions
4. A documented safety analysis, including the systematic methods used to identify and mitigate hazards and risks is in the SAD. Hazardous materials, energy sources and potential sources of environmental pollution including radiological hazards were characterized and quantified. Coupled with the identification of hazards is a

description of the controls that are employed for their mitigation. The description of controls includes discussion of credible challenges and estimates of consequences in the event of corresponding failure. A discussion of the risk to workers, the public and the environment from radiation is also included. In addition, the methods to ensure radiation exposures are kept ALARA during operation, maintenance and facility modification are described.

5. The Accelerator Safety Envelope narrative in the SAD consists of a generic description of the engineered and administrative bounding conditions within which the C-AD operates its facilities. Specific ASEs for C-AD accelerators and experiments are prepared and approved separately from the SAD. An Accelerator Safety Envelope for commissioning and operating the new pre-injector will be prepared and approved by DOE.
6. The quality assurance program for C-AD facilities, focusing upon activities that influence protection of the worker, the public and the environment is described in the C-AD SAD.
7. The security program for C-AD facilities, focusing upon protection of property, the public and the environment is described in the SAD.
8. A decommissioning and decontamination plan that includes a description of structural and internal features of C-AD facilities, which facilitate decommissioning and decontamination is described in the SAD. Waste management of radiological and hazardous material generation from routine operations and from the decommissioning and decontamination operation were addressed.

6. Cost and Schedule

6.1. Overview

The EBIS Project contains four major systems: the Source and Accelerator Structures, Electrical Systems, Facilities and Installation Support, and Mechanical Systems. These comprise thirteen major WBS Level 2 components: Structural Components, Controls Systems, Diagnostic/Instrumentation, Magnet Systems, Power Supply Systems, RF Systems, Vacuum Systems, Cooling Systems, Facility Modifications, Installation, Project Services, Commissioning and R&D.

Table 6-1 shows the EBIS cost summary in Actual Year dollars. Appendices C & D contain tables separating the cost by funding source (DOE & NASA). These estimates include applicable BNL overheads on labor and material.

Figure 6.1 shows a high level schedule of some of the key elements in the EBIS schedule.

The contingency percentages were derived by estimating at the lowest level WBS/task item for cost, technical and schedule risks. The contingency rates are determined by considering the development status of the items, and the uncertainties plus risks in completing the construction and testing. Contingency percentages have been assigned to individual risk elements and vary from 10 to 40%. The guidelines used to establish the contingency percentages are listed in Table 6-2. Averages are used when the risk levels in the technical and cost categories are different for a given item.

Table 6-1 EBIS TPC in AY dollars

WBS	Title	M\$
1.1	Structural components	3.3
1.2	Controls Systems	0.6
1.3	Diagnostics/instrumentation	0.7
1.4	Magnet Systems	0.6
1.5	Power Supply Systems	2.0
1.6	RF Systems	2.3
1.7	Vacuum systems	1.5
1.8	Cooling Systems	0.3
1.9	Facility Modifications	0.7
1.10	Installation	1.9
1.11	Project Services	0.6
1.12	Commissioning*	
1.13	R&D / CDR	1.2
subtotal		15.6
	Contingency	3.7
Total		19.3

* Commissioning dollars are currently contained in the other WBS elements

Table 6-2 Contingency Percentages

Technical Risk Description	Cost Risk Description	Schedule Risk Description	Contingency Rate
Direct copy of an existing, working design	Off the shelf hardware or purchased from a catalog	No schedule impact on any other WBS item	10%
Based on an existing design but requiring extensive modifications	Based on a vendor quote using limited conceptual design sketches	Delays completion of only its own non-critical path subsystem item	20%
New design different from established designs or existing technology	Estimate for item with little in-house experience	Delays completion of other non-critical path subsystem items	30%
New design requiring R&D to develop advanced state-of-the-art technology	Top down estimate derived from comparable previous programs	Directly delays completion of critical path subsystem item	40%

6.2. Cost

The dollars shown in this section are AY totals for the EBIS project, inclusive of DOE and NASA funded items.

1.1 Structural Components

Structural Components	AY K\$			
	Material	Labor	Contingency	Total
	2015	1260	890	4165

1.1.1 EBIS Hardware

The mechanical components which comprise the EBIS source.

1.1.1.1 SC Solenoid

Superconducting solenoid is a major element of EBIS and its function is to focus the electron beam generated in the electron gun and maintain its diameter in a region of the ion trap. No shielding is planned for the solenoid to be able to use its magnet field "tails" for the electron beam transmission in areas where use of other coils is difficult. The required magnetic field in the center of solenoid is determined by the combination of parameters (cathode emission current density, ion confinement time, tolerated level of impurities, ability of the electron collector to dissipate certain power). The solenoid is

located on the EBIS platform and should require minimum maintenance for refilling of cryogenics. (A portion of this WBS is funded by NASA)

1.1.1.2 Electron Gun

The EBIS electron gun generates electron beam used for the ionization and confinement ions in a trap. Since the electron beam propagates through the areas with very low potentials and with different magnetic field the requirements to the laminarity of the electron beam are high. For this reason the magnetic field on the cathode is high enough to determine formation of the electron beam in a cathode-anode gap. The cathode material (IrCe) provides high emission current density with lifetime of several thousand hours. Electron gun chamber is separated from the rest of EBIS with two gate valves, which in a case of gun failure allows replacing the whole gun unit with a new one without venting the gun chamber and venting only small buffer volume between gate valves.

1.1.1.3 Drift Tube & Chamber Structures

Drift tubes are installed along EBIS axis to control ion trap operation and propagation of the electron beam. Drift tubes are electrically isolated from the ground and connected to the external power supplies via electrical feedthroughs on a vacuum jacket. Vacuum chambers form a vacuum envelope of EBIS with pressure of residual gas in a range of 1×10^{-10} Torr. Three gate valves separate different parts of EBIS for the purpose of maintaining high vacuum in parts that are not vented at that time for modification or repair.

1.1.1.4 Stands, Platform Hardware

This includes the mechanical support structures for the EBIS, the electron gun, the LEBT line, and the external ion sources. It also include the 100 kV insulating platform for the EBIS source and its associated power supplies, as well as the electrical system required for putting a ramp on the EBIS trap electrodes for fast ion extraction.

1.1.2 LEBT and External Ion Injection

The beamlines between the EBIS output and RFQ input.

1.1.2.1 LEBT

LEBT is a transitional portion of the pre-injector and is used for:

- transmission and forming for the injection into RFQ the ion beam extracted from EBIS,
- transmission the ion beam from the external ion injector into EBIS,
- diagnostics of the ion beams (total ion current measurements, ion beam content measurements),
- vacuum pumping of the electron collector.

LEBT consists of two vacuum chambers separated with a gate valve and contains optical electrostatic elements (deflectors, lens), magnetic lens for focusing the ion beam into RFQ and diagnostic elements.

1.1.2.2 External Ion Injection

A set of two or more ion sources generating low charge state ions for injection into EBIS. This also includes also ion optics, a switching station for electronically selecting the desired ion species for ion injection, ion current monitors, vacuum system and power supplies.

1.1.3 RF Structures

Resonant cavities used to accelerate or decelerate (for bunching) the ion beam. When radiofrequency power is fed into these resonant cavities, the appropriate electric fields for acceleration or deceleration are produced.

1.1.3.1 RFQ

The Radiofrequency Quadrupole (RFQ) is a resonant structure in which four long, continuous vanes or rods, machined with precise modulations and configured in a quadrupole geometry, provide bunching, focusing, and acceleration of the injected ion beam. This type structure is able to provide efficient rf acceleration at the low energies ion beams have when initially extracted from an ion source. A 4-rod RFQ operating at 101.28 MHz is planned. (A portion of this WBS is funded by NASA)

1.1.3.2 Linac

The Linac is a resonant structure which generates time dependent axial electric fields to accelerate ions. When the rf field direction is reversed, the ion bunches are shielded from the decelerating fields by internal drift tubes. An "Interdigital-H" - type linac operating at 101.28 MHz is planned. (A portion of this WBS is funded by NASA)

1.1.3.3. Buncher Cavities

A resonant cavity in which the time dependent field in a gap is adjusted to decelerate the front of a beam bunch arriving at the gap, and decelerate the back of the bunch, so that all particles in the bunch arrive at a downstream point more closely spaced in time. By changing the phase of the cavity by 180 degrees relative to the bunch, it can be used to remove energy spread in the beam instead ("debuncher"). (A portion of this WBS is funded by NASA)

1.2 Controls

Controls	AY K\$			
	Material	Labor	Contingency	Total
	435	165	135	735

1.2 Controls

Networked, front-end interfaces will be connected via Ethernet to control console workstations and central C-AD servers. Full pulse-to-pulse modulation functionality will be provided. Custom application software will be provided as needed, but extensive re-use will be made of existing software designs with EBIS database additions.

1.2.1 Timing & Infrastructure

C-AD fiber optic infrastructure will be extended to the EBIS equipment area and a standard network switch and timing chassis will be provided. Workstations and monitor screens will be provided for console-level control access, along with supporting software and database configuration.

1.2.2 EBIS

Waveform generation and data acquisition for EBIS will be provided using the fiber-optically isolated PSI interface and VME function generator. The fiber link interface of these standard C-AD modules will be modified to operate at 50 to 100 kHz for this application. Additional fiber optic links will carry pulsed trigger signals to the high voltage platforms. Standard VME chassis will be provided. Minor modifications will be required to existing front-end software for the function generator. A custom console application program will be developed for power supply waveform control.

1.2.3 Accelerators & Beam Transport

Commercial and C-AD standard VME modules will be used to control magnet power supplies and beam-line instrumentation. Standard VME chassis assembly and timing modules will be provided for these systems and also for RF system interfaces. Front-end software effort will be mainly configuration and database setup. Existing console programs for beam line diagnostics will be modified to include the EBIS transport lines.

1.3 Diagnostics

Diagnostics/Instrumentation	AY K\$			
	Material	Labor	Contingency	Total
	380	295	135	810

1.3 Diagnostics/Instrumentation

1.3.1 Faraday Cup

A fully destructive measurement is made when a detector head is plunged into the beam path to collect the entire ion beam. The captured charge is measured as a current in

the processing electronics. Several types of detector heads can be employed depending on the characteristics of the desired measurement. Channeltrons or multi-channel plates are used for fast high bandwidth response.

1.3.2 Current Transformers

A ferrite toroid wound with many turns of signal wire is positioned around a ceramic break in the beam transport, all enclosed in a protective shroud. This is used as a non-destructive technique to measure the ion beam current characteristics with respect to time. A separate set of wire turns on the toroid are used for injecting a calibration signal.

1.3.3 Profile Monitors

Transverse beam profiles are measured by plunging an array of thin wires into the beam path. Each of the wires collects the charge from the small portion of the ion beam it intercepts; this charge is detected as a current in the processing electronics.

1.4 Magnet Systems

Magnet Systems	AY KS			
	Material	Labor	Contingency	Total
	350	250	130	730

1.4.1 EBIS Warm Solenoids

The EBIS warm solenoids consist of three solenoid magnets. The electron gun solenoid is designed with water-cooled hollow conductors, pancake-style coils and no iron return. The electron gun coil provides the necessary field for proper electron beam launching and transport. The electron collector solenoid is similar in design to the electron gun solenoid. The electron collector solenoid focuses the beam to allow for proper electron collector operation. The remaining magnet, the LEBT solenoid, is a pulsed solenoid located directly in front of the RFQ. The LEBT solenoid focuses the EBIS beam into the RFQ. The design of the LEBT solenoid is pancake coils with a laminated iron return similar in design to the BNL OPPIS LEBT solenoid.

1.4.2 MEBT Quadrupoles

The quadrupole magnets for transverse matching between the RFQ output and Linac input. The present design is based on the use of quadrupoles excessed from the LEDA project at Los Alamos National Laboratory.

1.4.3 HEBT Dipoles

HEBT dipoles are two similar 73° bending dipoles. The basic design of the dipole is a C style with the open end facing the outer curve to allow the chamber to have a port for the TTB line into booster. The magnet will be constructed of laminations of different sizes which when assembled will produce the required bend shape. The magnet coils will

be wound of water-cooled hollow copper conductor. (A portion of this WBS is funded by NASA)

1.4.4 HEBT Quadrupoles

The HEBT quadrupoles will be air-cooled Danfysik magnets. Originally used for other projects at BNL, these magnets are available for the EBIS beam line. These magnets will allow switching of values in ~ 1 second for running of different magnetic rigidity beams.

1.5 Power Supplies

Power Supply Systems	AY K\$			
	Material	Labor	Contingency	Total
	1665	310	500	2475

1.5.1 EBIS

Power supplies to support EBIS itself:

- Solenoid, cathode, cathode heater, collector and grid supplies
- Platform bias supplies and the transformers to isolate them
- Drift tube supplies, Behlke switches, and transverse magnetic supplies
(A portion of this WBS is funded by NASA)

1.5.2 External Ion Injectors & LEPT

Power supplies to support two external ion sources, the transport from the ion sources to the LEPT, and the LEPT itself:

- Heater, arc pulser and extractor power grid supplies
- Platform bias supplies and the transformers to isolate them
- Supplies for electrostatic and electromagnetic steering elements and lenses
- Mass analyzer and focusing solenoid power supplies

1.5.3 MEPT, IH Linac, & HEBT

Power supplies for the MEPT, IH Linac, and HEBT

- Pulsed quads and steering magnet power supplies
- Linac drift tube quadrupole power supplies
- Pulsed bending magnet power supplies
(A portion of this WBS is funded by NASA)

1.6 RF Systems

RF Systems	AY K\$			
	Material	Labor	Contingency	Total
	1670	655	630	2955

1.6.1 High Level RF

The final rf amplifier stages powering the RFQ, Linac, and three bunchers. This also includes the coaxial transmission line connecting the amplifier outputs to the rf cavities.

1.6.2 Low Level RF

The low power rf systems which provide the phase and amplitude controls for the high level rf systems, and frequency control for the resonant cavities.

1.7 Vacuum Systems

Vacuum Systems	AY K\$			
	Material	Labor	Contingency	Total
	940	510	290	1740

1.7 Vacuum Systems

1.7.1 Beampipes/Chambers

Pipes or chambers that have vacuum pressure inside and provide a path for the ion to be transported, as well as provide a housing for special components inside the vacuum system.

1.7.2 Vacuum Instrumentation & Control

A PLC based control system used to monitor and control the vacuum system and components such as gauges, pumps and valves.

1.7.3 Vacuum pumps

Pumps used to evacuate or pump down a vacuum chamber from atmospheric pressure to the desired high vacuum or ultra-high vacuum range.

1.7.4 Vacuum valves

Manual or pneumatically operated valves used to isolate vacuum pumps and/or a section of the beamline from another section or vacuum chamber.

1.8 Cooling Systems

Cooling Systems	AY KS			
	Material	Labor	Contingency	Total
	240	60	60	360

The cooling system is comprised of three separate and independent closed loop systems that will run off the present Linac chilled water system and dissipate heat into the existing Linac cooling tower. Each system consists of individually skid-mounted components: a pump/motor, filter, heat exchanger, expansion tank, temperature and pressure control valves, and water treatment as required. The active on-line deionized water controls on 2 of the systems maintain the required resistivity. The exception is for the rf structures, which will have a 4109 iron corrosion inhibitor control system.

A chilled water source is required to supply the necessary 70F temperature. The existing Linac chilled water system is the preferred choice.

1.9 Facility Modifications

Facility Modifications	AY KS			
	Material	Labor	Contingency	Total
	475	225	180	880

1.9.1 Beam Access Port

A new access port for the EBIS beam line will be installed through the earth shielding from Linac to the Booster.

1.9.2 Power Modification

Provides for the relocation of existing power & tray in the Linac area where the EBIS beam line will be installed.

1.10 Installation

Installation	AY KS			
	Material	Labor	Contingency	Total
	180	1720	400	2300

The major systems and components of the EBIS are installed at the facility site in building 930, including structural components, control systems, diagnostic and instrumentation systems, magnets, power supplies, RF systems, vacuum systems, and

cooling systems. The installation effort also includes any minor additions or changes to the building and facility necessary to accommodate these systems and components.

1.10.1 Structural Components

The major structural components installed in the facility include the Electron Beam Ion Source (EBIS), RFQ, and Linac. Other components will include smaller devices located in the LEBT, MEBT, and HEBT beam transport regions, such as auxiliary ion sources (LEBT), bunchers, electrostatic beam transport devices, and beam monitoring devices.

1.10.2 Controls

Installation of controls for the entire project.

1.10.3 Diagnostics/Instrumentation

Installation and checkout of all diagnostics in the beamlines.

1.10.4 Magnet Systems

The magnet systems installed in the beam transport line include dipoles, quadrupoles, and solenoidal magnets, and steerers. Also includes survey of elements.

1.10.5 Power supply Systems

Installation of all power supplies in their final locations, the connection of power from breaker boxes to the supplies, and the connections from the power supplies to the elements.

1.10.6 RF Systems

Installation of the rf power supplies, as well as the connection of the coaxial transmission line between the rf amplifiers and the rf cavities.

1.10.7 Vacuum Systems

Installation of beampipes, chambers, pumps, and valves. Also includes the leak checking and bakeout of systems.

1.10.8 Cooling Systems

Installation of all cooling systems.

1.11 Project Services

Project Services	AY KS			Total
	Material	Labor	Contingency	
	0	625	125	750

Level of effort tasks associated with the daily management, oversight, and statusing of the project.

1.11.1 Project Management & Support

This WBS contains the effort associated with the Project Office at BNL for the EBIS. The effort includes: the Contractor Project Manager, Project Controls, installation and conventional facilities coordination, QA and ES&H, financial oversight, documentation and reporting, and the Project Office secretary.

Appendix A Parameter List

EBIS		
Solenoid length	1.5	m
Solenoid field	6 T	T
Electron beam current	10	A
Trap capacity	1.1e12	charges
Output (single charge state)	1.1e11	charges/pulse
Ion output (Au 32+)	3.4e9	particles/pulse
Pulse width	10-40	μ s
Max rep rate	5	Hz
Beam current	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
Type	4 rod	
Frequency	101.28	MHz
Max rep rate	5	Hz
Length	4.37	m
Number of cells	277	
Aperture radius	0.005	m
Voltage	69	kV
E (surface)	20.8	MV/m
RF power (total)	< 350	kW
Acceptance	1.7	π mm mrad, norm
Input emittance	0.5	π mm mrad, norm, 90%
Output emittance	0.5	π mm mrad, norm, 90%
Output emittance (longit.)	32.5	π MeV deg
Transmission	91%	(10 mA Au ³²⁺)
IH Linac		
Q/m	0.16 - 0.5	
Input energy	300	keV/amu
Output energy	2000	keV/amu
Frequency	101.28	MHz
Max rep rate	5	Hz
Length	4	m
RF power (total)	< 350	kW
Acceptance	4.3	π mm mrad, norm
Input emittance	0.55	π mm mrad, norm, 90%
Output emittance	0.7	π mm mrad, norm, 90%
Output energy spread	+/- 20	keV/amu
Transmission	100%	(Au ³²⁺)
Transport line		
dE after debuncher (Au)	+/- 2	keV/amu
dE after debuncher (He ²⁺)	+/- 5	keV/amu
Magnet/ps switching time	1	s
Injection		
# of turns injected	1-4	
Inflector voltage	48	kV (Au ³²⁺)
Inflector acceptance (H)	1.9	π mm mrad, norm
input mismatch injection (at inflector)		
Alphax	0	
Alphay	0	
Betax	4.0	
Betay	2.6	

Appendix B Summary Preliminary Cost Estimate Table

The following table gives the detailed preliminary cost estimate for the EBIS project. The breakdown is by WBS number, and the estimates are in AY dollars, and include applicable BNL labor rates and overheads.

WBS	Title	AY K\$			Average Contingency \$	Average Contingency %
		Labor	Material	Cost		
1.1	Structural components	1260	2015	3275	890	27%
1.2	Controls	165	435	600	135	23%
1.3	Diagnostics/instrumentation	295	380	675	135	20%
1.4	Magnet Systems	250	350	600	130	22%
1.5	Power Supply Systems	310	1665	1975	500	25%
1.6	RF Systems	655	1670	2325	630	27%
1.7	Vacuum systems	510	940	1450	290	20%
1.8	Cooling Systems	60	240	300	60	20%
1.9	Facility Modifications	225	475	700	180	26%
1.10	Installation	1720	180	1900	400	21%
1.11	Project Services	625	0	625	125	20%
1.12	Commissioning*					
1.13	R&D / CDR	785	415	1200	200	17%
	Subtotals/Average	6860	8765	15625	3675	24%

Estimated Total Project Cost = \$19300

*Commissioning Dollars currently contained in above WBSs.

Appendix C DOE Funding and TPC

The planned levels of DOE funding per fiscal year are as follows:

Fiscal Year	Funding Profile (M\$)
2005	0.7
2006	2.1
2007	7.5
2008	4.5
2009	0.0
Totals	14.8

The following table details the planned application of DOE funds.

WBS	Title	M\$
1.1	Structural components	1.8
1.2	Controls Systems	0.6
1.3	Diagnostics/instrumentation	0.7
1.4	Magnet Systems	0.3
1.5	Power Supply Systems	0.9
1.6	RF Systems	2.3
1.7	Vacuum systems	1.5
1.8	Cooling Systems	0.3
1.9	Facility Modifications	0.6
1.10	Installation	1.9
1.11	Project Services	0.6
1.12	Commissioning*	
1.13	R&D / CDR	0.7
subtotal		12.1
	Contingency	2.7
Total		14.8

* Commissioning dollars are currently contained in the other WBS elements

Appendix D NASA Items

Since CD-0 approval, a Statement of Work between BNL and NASA has been signed, in which NASA will contribute \$4.5M (AY \$) to the project costs. These funds allow the schedule to be accelerated to four years. Within the overall EBIS project, certain items have been identified for use of these funds. These include the Radio Frequency Quadrupole, the linac and bunchers, the EBIS superconducting solenoid, the HEBT dipoles, a beam access port, and various power supplies.

NASA Funding: the planned levels of funding per fiscal year are as follows:

Fiscal Year	Funding profile (M\$)
2005	0.5
2006	1.5
2007	1.5
2008	1.0
Totals	4.5

Application of NASA funds:

WBS	Title	M\$
1.1	Structural components	1.5
1.2	Controls Systems	0.0
1.3	Diagnostics/instrumentation	0.0
1.4	Magnet Systems	0.3
1.5	Power Supply Systems	1.1
1.6	RF Systems	0.0
1.7	Vacuum systems	0.0
1.8	Cooling Systems	0.0
1.9	Facility Modifications	0.1
1.10	Installation	0.0
1.11	Project Services	0.0
1.12	Commissioning*	
1.13	R&D	0.5
subtotal		3.5
	Contingency	1.0
Total		4.5

* Commissioning dollars are currently contained in the other WBS elements

GLOSSARY

AGS	Alternating Gradient Synchrotron
ALARA	As Low As Reasonably Achievable
ASE	Accelerator Safety Envelope
BHSD	Brookhaven Site Office
BINP	Budker Institute of Nuclear Physics
BNL	Brookhaven National Laboratory
C-A	Collider-Accelerator
C-AD	Collider-Accelerator Department
CCD	Charge-Coupled Device
CEA	Commissariat à l'Énergie Atomique
CERN	Conseil Européen pour la Recherche Nucléaire
CFR	Code of Federal Regulations
DART	Days Away or Restricted Time
DSP	Digital Signal Processing
EBIS	Electron Beam Ion Source
EC	Electron Collector
ECR	Electron Cyclotron Resonance
EMQ	Electromagnetic Quadrupole
EMR	Experience Modification Rates
ESH	Environment, Safety and Health
ESHQ	Environment, Safety, Health and Quality Assurance
ESSH	Environmental Protection, Safety, Security, Health and Quality
FODO	Focusing-Defocusing
FPGA	Field Programmable Gate Array
FWHM	Full Width Half Maximum
GPM	Gallons per Minute
HCIS	Hollow Cathode Ion Source
HEBT	High Energy Beam Transport
HV	High Voltage
IH	Inter-Digital H Structure
ISO	International Organization for Standardization
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkley National Laboratory
LEBT	Low Energy Beam Transport
LEVA	Low Energy Vacuum Arc
Linac	Linear Accelerator
LIS	Laser Ion Source
LLRF	Low Level Radio Frequency
LOTO	Lock-Out/Tag-Out
LTB	Linac to Booster
MEBT	Medium Energy Beam Transport

NASA	National Aeronautics and Space Administration
NEG	Non-Evaporable Getter
NSRL	NASA Space Radiation Laboratory
OHSAS	Occupational Health and Safety Assessment Series
OPM	Operational Procedures Manual
OPPIS	Optically Pumped Polarized Ion Source
OSH	Occupational Safety and Health
OSHA	Occupational Safety and Health Act
PC	Performance Criteria
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PPM	Pulse to Pulse Modulation
PSC	Power Supply Controller
PSI	Power Supply Interface
QA	Quality Assurance
RFQ	Radio Frequency Quadrupole
RHIC	Relativistic Heavy Ion Collider
SAD	Safety-Assessment Document
SBMS	Standards Based Management System
SC	Superconducting
SNS	Spallation Neutron Source
SPDES	State Pollutant Discharge Elimination System
STD	Standard
TOF	Time of Flight
TTB	Tandem to Booster
UHV	Ultra High Vacuum
VME	Versa Module Eurocard
WBS	Work Breakdown Structure

References

- ¹ A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec, and L. Snyderstrup, *Rev. Sci. Instrum.* 69, 697 (1998).
- ² A. Kponou, E. Beebe, A. Pikin, G. Kuznetsov, M. Batazova, and M. Tiunov, *Rev. Sci. Instrum.* 69, 1120 (1998).
- ³ A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec, *Proc. PIBHI-2000, Conference Proceedings series of the Italian Physical Society.*
- ⁴ E. Beebe, J. Alessi, A. Kponou, A. Pikin, K. Prelec, *Proceedings of EPAC-2000, Vienna, Austria* p. 1589 (2000).
- ⁵ A. Kponou, E. Beebe, A. Pikin, G. Kuznetsov, M. Batazova, and M. Tiunov, *Rev. Sci. Instrum.* 69, 1120 (1998).
- ⁶ E.N. Beebe, J.G. Alessi, O. Gould, D. Graham, A. Kponou, A. Pikin, K. Prelec, J. Ritter, "Extraction of highly charged Au ions from a multiampere electron beam EBIS at BNL", *Rev. Sci. Instrum.* 73, 699 (2002).
- ⁷ A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec, "Experimental study of ion injection into an extended trap of the Brookhaven National Laboratory EBIS", *Rev. Sci. Instrum.* 73, 670 (2002).
- ⁸ E. Beebe, J. Alessi, A. Kponou, A. Pikin, K. Prelec, "A New Generation of EBIS: High Current Devices for Accelerators and Colliders", *Proceedings of EPAC-2002, Paris, June 3-7, 2002*
- ⁹ A. I. Pikin, J. G. Alessi, E. Beebe, O. Gould, D. Graham, A. Kponou, K. Prelec, J. Ritter, V. Zajic, "Recent Results with Au Ions Extracted from an EBIS using an 8A Electron Beam at BNL", *Proceedings of EPAC-2002, Paris, June 3-7, 2002*
- ¹⁰ I. G. Brown et al, *Rev. Sci. Instrum.* 65 (1994) 1260.
- ¹¹ B. Visentin et al, *Physica Scripta T71*, 204-206, (1997).
- ¹² Kponou et. al., *Journal of Physics: Conference Series* 2 (2004) 164–173.
- ¹³ K.R. Crandall, R.H. Slokes, and T.P. Wangler, "RF Quadrupole beam dynamics studies", 1979 Linac Conf., BNL 51134, p. 205.
- ¹⁴ D. Raparia, "RFQ accelerator section and its optimization", 1988 Linac Conf., CEBAF-Report-89-001, p. 61.

-
- ¹⁵ U.Ratzinger and V.T. Mimje, "LORAS", description and manual
- ¹⁶ A. Kponou et al, "A Time-Of-Flight Spectrometer for SuperEBIS", AGS/AD/Tech. Note No. 390, January 1994.
- ¹⁷ T. Hoffman et al, "Emittance Measurements of High Current Heavy Ion Beams Using a Single Shot Pepperpot System", BIW 2000, Boston, Mass.
- ¹⁸ D. S. Barton et al, *RHIC control system*, Nuclear Instruments and Methods in Physics Research A 499 (2003) 356-371.

