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RHIC EBIS: basics of design and status of commissioning[1]

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ABSTRACT: RHIC EBIS will be used for producing multicharged ions from helium to uranium using primary ions from various external ion sources. The EBIS is followed by an RFQ and short linac, forming the new preinjector which will produce beams used for physics at RHIC and the NASA Space Radiation Laboratory, The design of RHIC EBIS is based on the BNL Test EBIS, which was a successful 10A electron current prototype. Improvements have been made in the RHIC EBIS design to increase the capacity of the ion trap, repetition frequency of operation, electron current, acceptance for injected ions, and improve vacuum conditions in the ionization region. RHIC EBIS has been assembled and installed in its final position. Commissioning is now underway to reach its project parameters. The results of this commissioning stage are presented.

KEYWORDS: Ion sources (positive ions, negative ions, electron cyclotron resonance (ECR), electron beam (EBIS)); Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics)

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2010 JINST 5 C09003

Contents

1 Introduction

RHIC EBIS was built as a universal ion source for producing a variety of ions from polarized He_3^{2+} to multicharged ions up to U_{238}^{38+} for the Collider-Accelerator Department accelerator complex, including RHIC and NASA applications. The RHIC EBIS design is based on a successful full-electron current prototype Test EBIS, which operates with electron current up to 10 A [1–8]. RHIC requirement for intensity of ions Au^{32+} is 3x10^9 per pulse, which can be provided with ion trap capacity twice larger than the capacity of Test EBIS. Doubling the length of ion trap was the main goal of building RHIC EBIS. In RHIC EBIS the basic concept of electron beam forming by compressing it with magnetic field and flexible magnetic field control on the electron gun and at the entrance into electron collector are the same as in Test EBIS. However, for the purpose of maintaining the required cycle frequency, improving ion injection and extraction, minimising downtime for unit replacement, and improving vacuum in the interaction region, some systems have been modified.

2 Design of RHIC EBIS

The rendered 3D view of RHIC EBIS on its high-voltage platform is presented in figure 1.

RHIC EBIS utilizes a "warm" vacuum bore for the ionization region. The choice of "warm" bore over "cold" bore for Test and RHIC EBISs is based primarily on a need to have drift tubes at relatively high voltage ($\geq$20 kV) above ground. EBIS configuration of electric and magnetic fields can result in several discharge modes with subsequent molecular desorption from internal surfaces. The ability to "clean" them with bakeout and train them with discharge at room temperature is

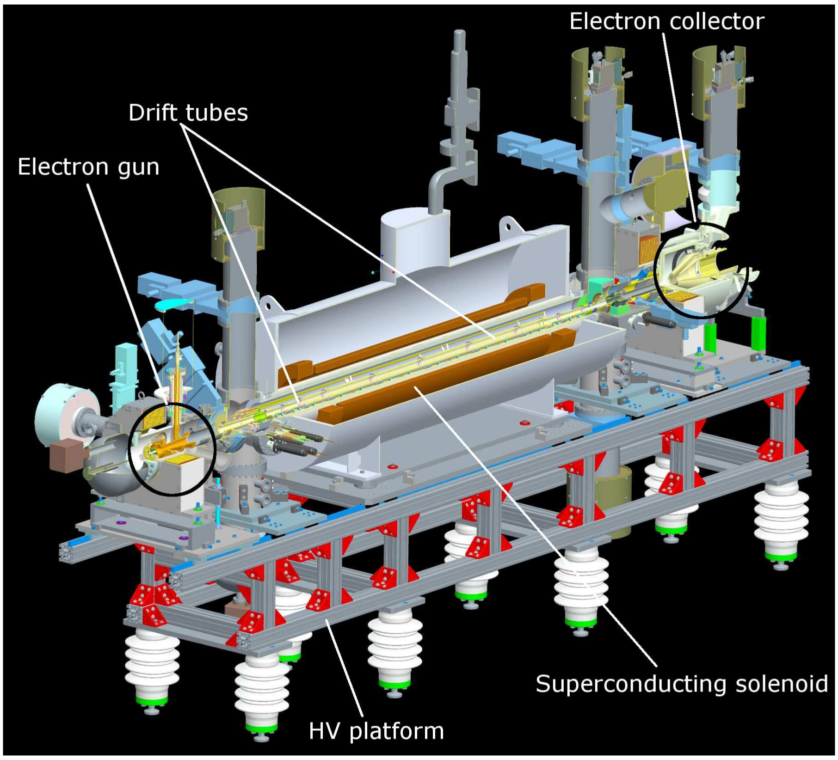

Figure 1. RHIC EBIS 3D assembly view.

an important advantage of the "warm" bore, since EBIS vacuum requirement is high ($P_{center} <$ $1\text{x}10^{-9}$ Torr).

Magnetic fields at the cathode of the electron gun and entrance into electron collector are produced with separate "warm" side solenoid coils, so the magnetic fields in these areas can be controlled independently from the main solenoid field. Such configuration of the magnetic coils allows providing sufficient vacuum pumping of the ionization region in gaps between the main solenoid and side coils and arranging high voltage leads for the drift tubes. The axial magnetic field distribution utilizes the fringe field of the unshielded main solenoid, which has a minimum of 600 Gs. The electron beam expands in this area and the drift tube has a sufficient inner diameter to accommodate the electron beam with its radial oscillations and halo. The structure of the RHIC EBIS magnetic system is presented in figure 2.

2.1 Electron gun

The design of RHIC EBIS electron gun is based on the same concept as the Test EBIS gun [1, 9, 10]: the cathode is immersed in the magnetic field and the cathode has spherical convex shape as providing more uniform electron emission density. The perveance has been increased from the original value of $1.4\text{x}10^{-6}$ A/V$^{3/2}$ to $2.5\text{x}10^{-6}$ A/V$^{3/2}$ by reducing the cathode-anode gap. Both cathode and anode are mounted on the same base. The new design [11] provides higher precision in assembly and stability of its position, and the anode has water cooling. There is also a replacement anode with the geometry of the original Test EBIS gun. The design of RHIC EBIS electron gun is presented in figure 3. The long-life IrCe cathode for this gun was provided by BINP, Novosibirsk.

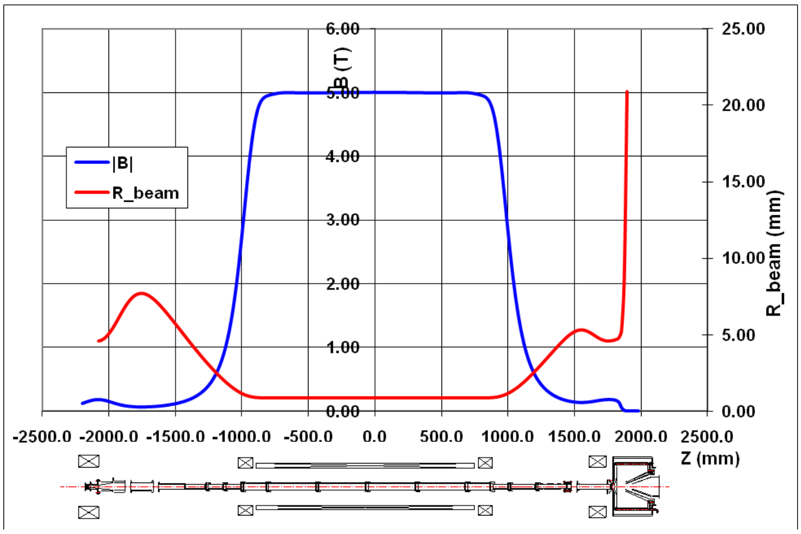

Figure 2. RHIC EBIS magnetic field distribution and electron beam envelope.

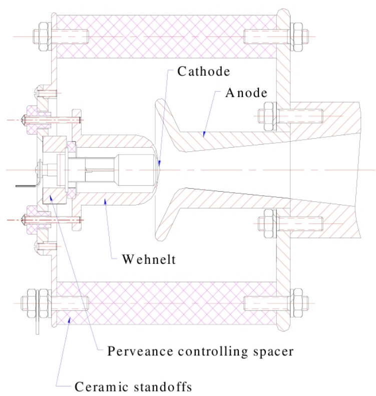

Figure 3. RHIC EBIS electron gun assembly.

The trajectory simulations of this electron gun demonstrated that increased perveance of the gun did not result in a significant increase of radial oscillations of the electron beam (figure 4).

$$I_{\text{electron}} = 20.0\text{A}, \qquad U_{\text{anode}} = 37.5\text{kV}, \qquad B_{\text{cathode}} = 1800\text{G}.$$

The simulation of the electron beam propagation in a low-magnetic field region demonstrates beam propagation with subsequent compression in the field of the main solenoid (figure 5).

2.2 Electron collector

The objective of the new electron collector design for RHIC EBIS was to provide an adequate capability of removing power of the electron beam and to increase acceptance of EBIS for injected primary ion beam as well as to reduce aberrations of the extracted ion beam compared to the existing Test EBIS collector design. The electron collector of RHIC EBIS was designed to dissipate

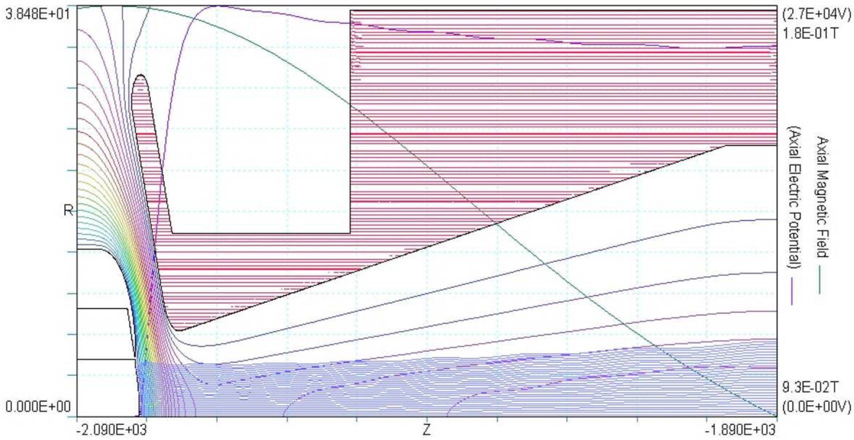

Figure 4. Simulated electron trajectories from the cathode of the RHIC EBIS electron gun.

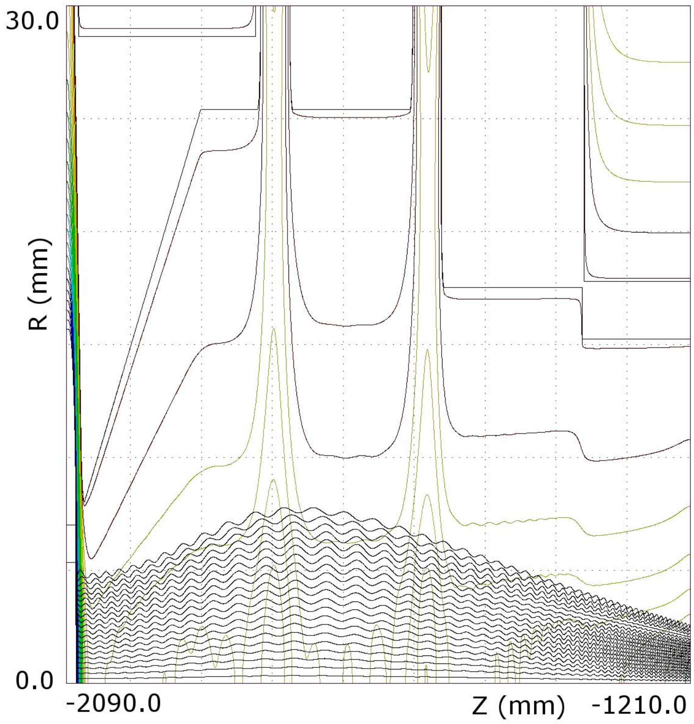

Figure 5. Simulation of electron beam transmission in a low-magnetic field region between electron gun and entrance into main solenoid. I_{el} =10.0 A.

power of a pulsed electron beam with current I_{el}=20.0 A, energy E_{el}=15.0 keV, pulse length t_{el}=50 ms, frequency f=5 Hz. To minimize the distance, which ions travel at low energy after decoupling from the electron beam, the ion extractor should be positioned close to the entrance aperture of the electron collector. The idea of spreading the electron beam over large area of inner cylindrical surface of the collector by partially shielding the electric field of ion extractor, located close to the entrance aperture, was proposed by G. Kuznetsov [10]. Comprehensive electro-optical, mechanical and thermal simulations of the RHIC EBIS electron collector are published in [12].

2010 JINST 5 C09003

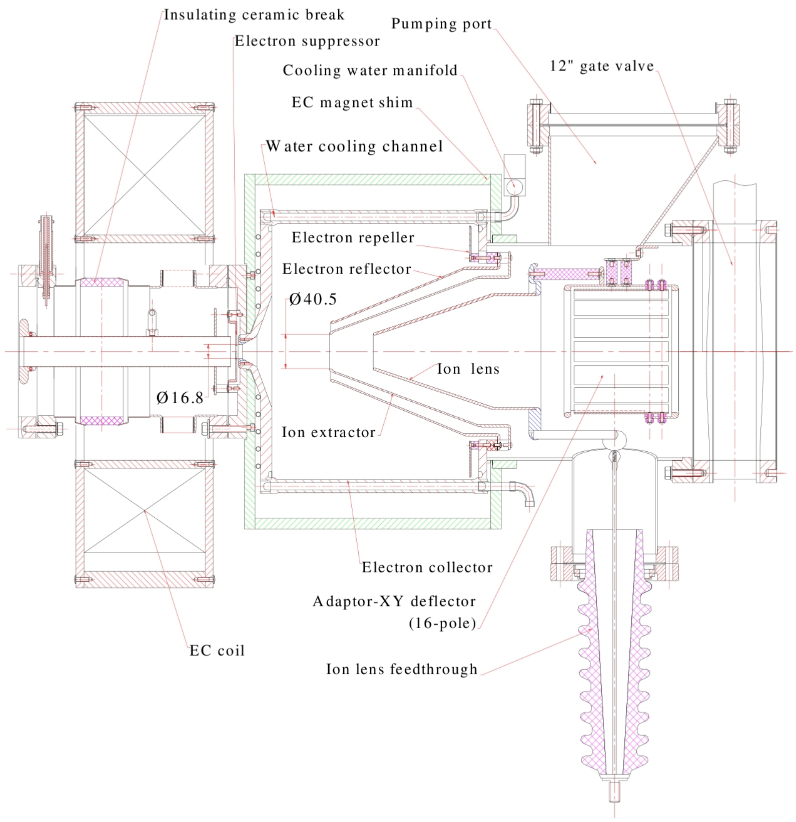

Figure 6. RHIC EBIS electron collector assembly with adjacent ion optics.

The design of this collector is presented in figure 6.

Trajectory simulation of electron beam transmission inside the electron collector has been done with secondary electrons and the results revealed significant heating of the conical ion reflector (with no water cooling) by a fast component of secondary electrons. This power dissipation on the electron reflector will be reduced by making this electrode as a semi-transparent wire frame structure and by applying a negative potential to it with respect to the electron collector (figure 7).

2.3 Drift tube structure

In RHIC EBIS the inner diameter of drift tubes is 42 mm, which is larger than in EBTS (31 mm). With larger diameter of drift tubes the beam-tube coupling is expected to be weaker and ion radial loss rate in the trap to be lower. The electron beam loss was not a concern in the choice of inner diameter of the drift tube. Cross-sectional views of central drift tubes are presented in figure 8.

The drift tubes are made double-walled with NEG strips inserted in a radial gap. The inner tube is perforated for exposing the NEG strips to the ionization volume. NEG strips are activated during high-temperature bakeout of the central chamber.

2.4 Vacuum

The schematic of RHIC EBIS vacuum system is presented in figure 9.

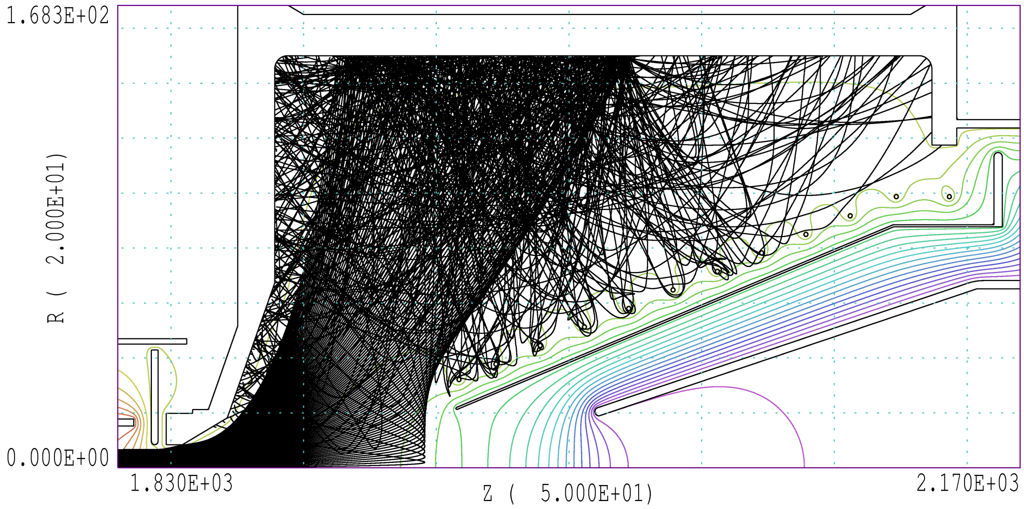

Figure 7. Trajectory simulation of the electron beam propagation into RHIC EBIS electron collector with wire-frame electron reflector. I_{el}=20.6 A, E_{el}=15 keV.

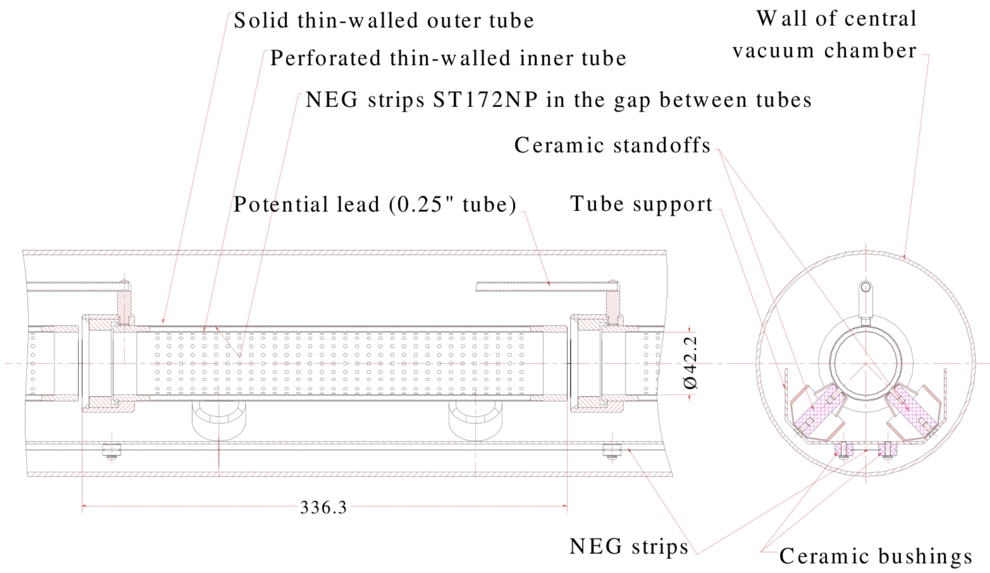

Figure 8. Central drift tubes in RHIC EBIS vacuum chamber.

The contamination of the extracted ion beam by the residual gas is lower than 10% if the pressure of residual gas is better than $1\text{x}10^{-9}$ Torr. Such vacuum condition in the ionization region is provided by conventional methods: pumping from both sides of the central vacuum chamber with cryopumps, limiting influx of gas from the electron collector and electron gun with vacuum separations, and using NEG strips inside the central chamber. An important potential source of gas income into the ionization region is a discharge provoked by the combination of high voltage drift tubes, electrical leads, and magnetic field. To reduce electric fields on surfaces of the HV leads these leads are made of stainless steel tubes with diameter of 6.35 mm and special attention was

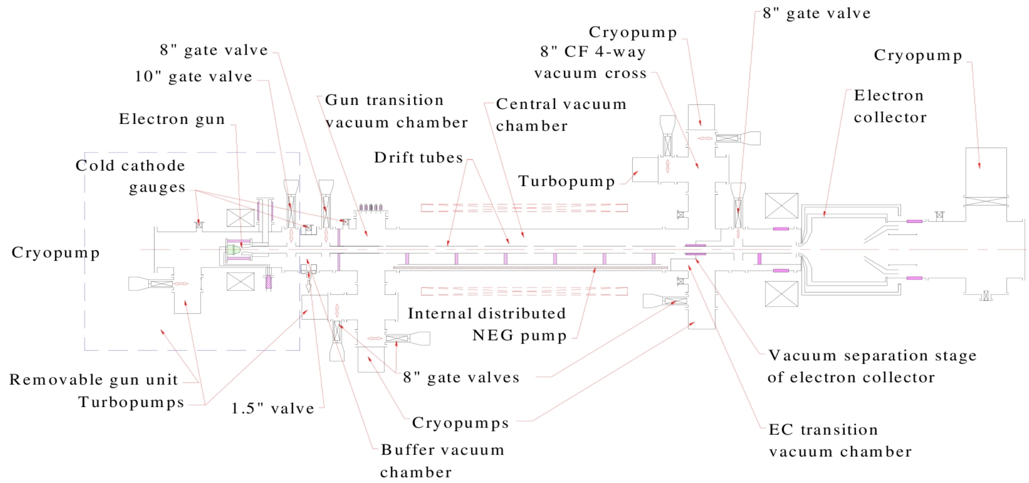

Figure 9. Schematic of RHIC EBIS vacuum system.

paid to the shape of all metal surfaces inside the ionization region. For the same reasons and for larger vacuum conductance the inner diameter of the central chamber was increased from 96 mm (on Test EBIS) to 146 mm. To reduce time for replacing the electron gun during operational periods the electron gun chamber is separated from the rest of EBIS with two gate valves. The whole gun platform with gun vacuum chamber will be replaced with a new one, with the gun chamber under vacuum. After evacuation of the small buffer chamber both gate valves will be opened and EBIS will be ready for operation. The electron collector can also be isolated from the rest of EBIS with a gate valve. Another gate valve separates the whole EBIS from the accelerating tube and LEBT.

2.5 Ion optics

The extraction ion optics of RHIC EBIS is presented in figure 10. It includes ion extractor, followed by a high voltage accelerating ion lens, adaptor-deflector, accelerating tube, gridded lens, magnetic solenoid lens at the entrance into RFQ, and electrostatic deflectors in the LEBT chamber. The voltage distribution on electrostatic ion optical elements can be changed from injection to extraction mode within one ionization cycle. RHIC EBIS can run for several users within one RHIC supercycle producing ion beams of different elements, and its ion optics allows connecting different external primary ion sources to the EBIS injection line using electrostatic benders in the switching chamber on external injection line. It takes less than 1 ms to switch any ion optical element from one regime to another, which is sufficient since the minimum ionization time is about 8 ms. The electrostatic adaptor-deflector is an optical element consisting of 16 isolated electrodes on a periphery of cylinder with inner diameter 141 mm. Such a structure can produce a uniform deflecting electric field within most of its cross-section. By changing the potential distribution on electrodes one can rotate the deflecting field and control its strength. All eight bipolar power supplies feeding 16 electrodes of deflector are mounted on an isolated platform and can be biased up to $\pm$20 kV with a TREK power supply. In effect this optical element can be used as an adaptor

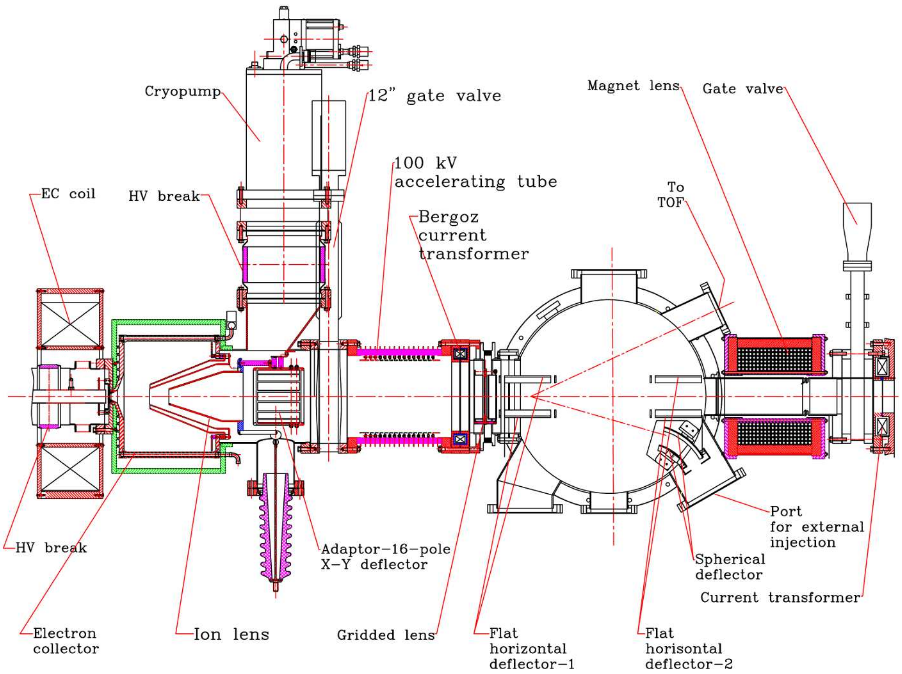

Figure 10. RHIC EBIS ion optics with LEBT chamber.

electrode between the ion lens and accelerating tube. By varying its voltage one can move axial position of the maximum radius of the extracted beam envelope.

The ion optics includes one gridded lens at the entrance into LEBT chamber. A gridded lens was selected for this position because it can do both focusing and defocusing of the ion beam depending on beam parameters. A combination of gridded lens and magnet lens allows optimizing the Twiss parameters of the ion beam at the entrance into RFQ with minimum spherical aberration.

There are four regimes of operation of the RHIC EBIS ion optics:

1. Ion injection from one of the external primary ion sources. In this regime the EBIS platform is at ground potential. Within this regime external ion optics is tuned to one of several ion sources.

2. Ion extraction from EBIS into RFQ. The platform has potential, which provides initial preacceleration of ions to 17.0 keV/nucleon for injection into the RFQ.

3. Ion extraction from an additional proton or deuteron ion source into RFQ. This ion source operates at the potential needed for injection of the specific ions into RFQ.

4. Ion extraction to a time of flight mass spectrometer. Platform is at ground potential.

To direct the primary ion beams into EBIS spherical, flat and cylindrical slanted electrostatic deflectors are used. The flat deflectors are used in LEBT chamber places where relatively small deflections (less than 25^0) in opposite directions are required. Cylindrical slanted deflectors are

2010 JINST 5 C09003

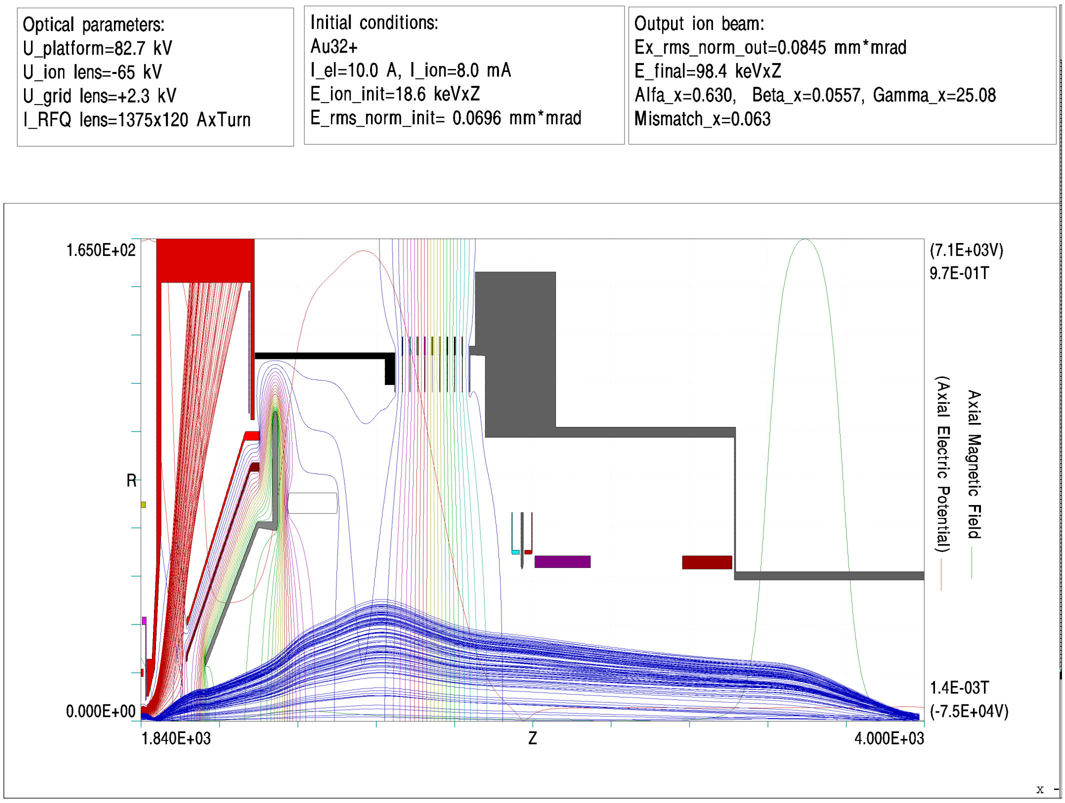

Figure 11. Simulated electron and ion trajectories for extraction of Au^{32+} ion beam with current I_{io}=8.0 mA from electron beam with current I_{el}=10.0 A.

selected for small corrections of angles in the low-energy lines because of maximum useful cross-sectional area with relatively small aberration. Spherical deflectors are used for bending ion beams to large ($>40^0$) fixed angles in the low-energy primary beam lines. Quadrupole lenses (quadruplets) are used in these beam lines for focusing and for partial correction of asymmetry caused by the flat deflector.

An example of simulation of ion beam extraction from the EBIS electron beam is presented in figure 11.

Based on simulations, the large aperture of ion optical elements contributes approximately 20% to the ion beam emittance growth from the point of origin inside the electron beam to the RFQ entrance with optimum setting of parameters.

3 Preliminary results of the RHIC EBIS commissioning

3.1 Electron beam

RHIC EBIS was been installed in its final position in the accelerator facility on June 30 2009. In first tests, an electron beam with current up to 8.0 A has been transmitted to the electron collector. The electron gun has perveance of P=2.2x10^{-6}A/$V^{1.5}$ with adequate heating. The largest electron beam loss of 500 μA has been detected only on the electron suppressor electrode at the entrance

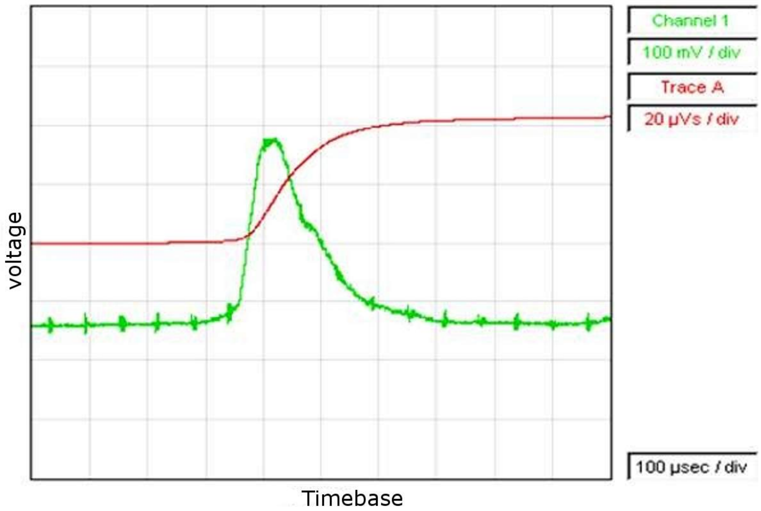

Figure 12. Waveform of the He ion pulse at the exit of the accelerating tube measured with a Bergoz current transformer. Green trace is an ion current pulse with calibration of 2 mA/V and red trace is an integral of the green trace.

into the electron collector. This electrode is used to monitor electron beam diameter and its transverse position at the entrance into the electron collector. EBIS operation has been tested with the frequency of 2 Hz.

3.2 Ion beams

EBIS has generated beams of He^{1+} and He^{2+} ions with gas injection and beams of Au ions with external injection from a Hollow Cathode Ion Source (HCIS). With helium gas injection maximum extracted ion charge was Q_{ion}=82 nC for electron current of I_{el}= 6.2 A with energy E_{el}=26.3 keV, which constitutes approximately 85.6% of electron charge in a volume of the ion trap. The waveform of this ion beam measure with Bergoz current transformer is presented in figure 12.

The content of the extracted ion beam has been measured with a low-resolution time of flight mass-spectrometer (TOF) mounted on a 25^0 off-axis arm of the LEBT chamber. The ion chopper is a 3-grid structure with blocking central grid. It has large acceptance and therefore its output signal represents the ion beam content at a given sample time. With a sampling time of 200 ns only groups of masses can be resolved, but it is sufficient to determine a share of injected heavy ions on a background of light ions from the residual gas and a charge state in a maximum of distribution. A TOF spectrum of the extracted ion beam with and without Au external ion injection is presented in figure 13. The ionization factor for electron current 5.6 A and confinement time 36 ms was 11.1 A·s/cm^2 and training of electron beam for higher current and longer pulse is in progress. The share of Au ions in a total extracted ion charge is approximately 60% in this case.

Ions extracted from EBIS have been accelerated through the RFQ. The result for He^{+1} is presented in figure 14.

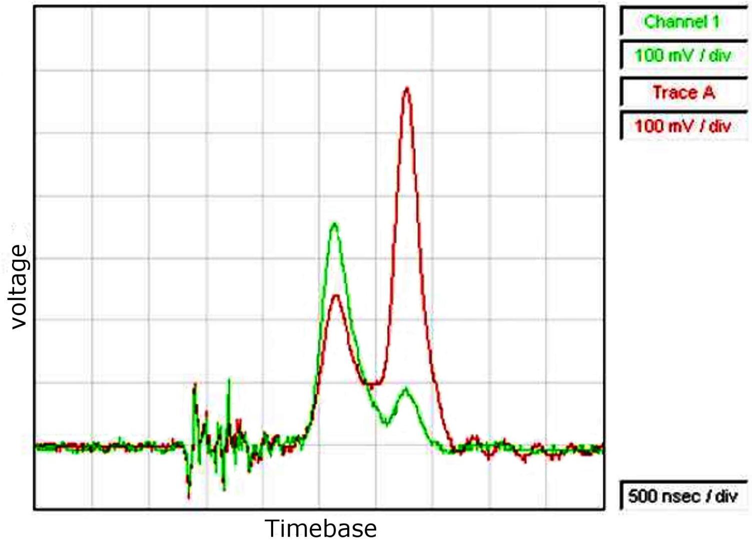

Figure 13. TOF spectra of the extracted ion beam from RHIC EBIS with Gold ion injection (red trace) and without ion injection (green trace). Electron current I_{el}=5.6 A, confinement time τ_{conf}=36 ms, dominant Gold ion charge state is 31+.

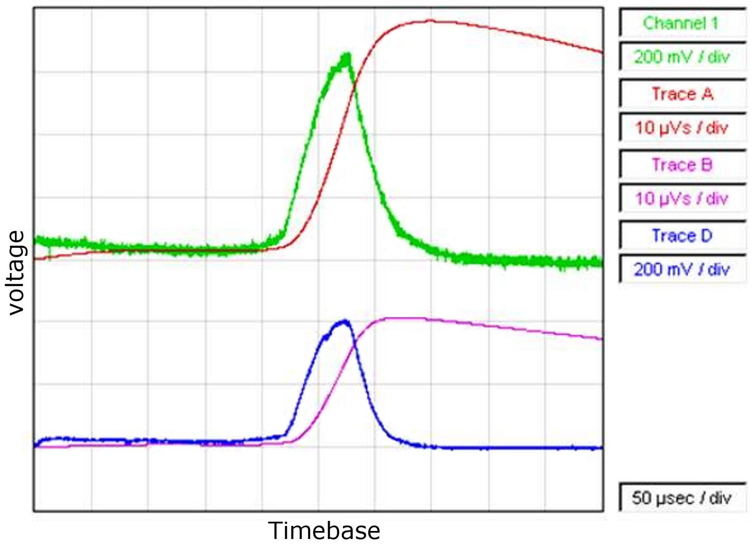

Figure 14. He1+ ion currents on Faraday cups at the entrance into RFQ (green and red traces) and at the exit from RFQ (blue and magenta traces). At the RFQ entrance ion current is I_{ionin}=612 μA and charge is Q_{ionin}=37 nC. At the RFQ exit I_{ionout}=390 μA and charge is Q_{ionout}=20 nC.

4 Summary

- RHIC EBIS has been assembled, drift tubes aligned, heaters and magnet deflectors of the central chamber have been tested.
- The ACCEL superconducting solenoid has been tested and is routinely used for EBIS oper-

ation.

- All EBIS part (including e-gun and collector) have been assembled with solenoid, pumped, and leak tested.
- Electron beam has been transmitted to the electron collector (currently maximum 8 A).
- Ion production tested with He gas injection with fast (20 μs) and slow (75 μs) extraction. Extracted ion charge with He gas injection reached 85.6% of the electron charge in the trap.
- External ion injection line assembled and ion beams (Ne and Au) from a HCIS transmitted to the EBIS entrance. Gold ions have been injected into the EBIS trap and extracted after reaching charge state up to 31+.
- The RFQ is attached to EBIS, and He and Au ions have been accelerated to energy of 300 keV/nucleon. Normalized RMS emittance of He1+ ion beam at the exit of RFQ was in a range 0.18-0.2 mm*mrad.

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