PROGRESS ON TEST EBIS AND THE DESIGN OF AN EBIS-BASED RHIC PREINJECTOR*

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Abstract

Following the successful development of the Test EBIS at BNL [1-3], we now have a design for an EBIS-based heavy ion preinjector which would serve as an alternative to the Tandem Van de Graaffs in providing beams for RHIC and the NASA Space Radiation Laboratory. This baseline design includes an EBIS producing mA-level currents of heavy ions (ex. Au^{32+}) in ~10-20 µs pulses, injecting into an RFQ which accelerates the beams to 300 keV/amu, followed by an IH linac accelerating to 2 MeV/amu. Some details of this design are presented, as well as recent experimental results on the Test EBIS.

INTRODUCTION

There are considerable advantages to the use of an EBIS+linac-based preinjector instead of the present Tandem Van de Graaffs for injection of beams into the Booster synchrotron for RHIC and the NASA Space Radiation Laboratory (NSRL). First is the replacement of the 35 year old Tandems by a modern injector which will be simpler and less costly to operate. In addition, Booster injection will become easier and more efficient since one will only need to inject over 1-4 turns, rather than the present 30-100 turn injection. While ion species from the Tandems are limited to those starting as negative ions, the EBIS can provide any ion species. Since the desired final charge state can be produced directly in the EBIS, two stripping stages are eliminated. This will result in more stable beam operation, eliminating present intensity variations coming from stripping foils aging and breaking. Finally, this preinjector, coupled to the Booster via a short transport line, will be able to rapidly switch beam species (1 second) to meet the needs of both RHIC and NSRL.

For RHIC, as an example, one may be asked to provide 1.7 emA of Au^{32+}, 10 µs pulse width, for 4 pulses at a 5 Hz repetition rate. In addition, a second, interleaved beam might be required for NSRL, which could be any one of the following: He^{2+}, C^{5+}, O^{8+}, Si^{13+}, Ti^{18+}, Fe^{20+} at ~2-3 emA, ~10 µs pulse width. The present control system supports "pulse-to-pulse modulation", i.e. the setpoint of any device can be changed pulse-to-pulse, depending on the "user". It will now be required from the new preinjector that within 1 second the EBIS will change species, the RFQ and linac will change gradient, and the transport line elements will switch to new field values.

*This manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH1-886 with the U.S. Department of Energy.
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SOURCE REQUIREMENTS

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

Requirements for the RHIC EBIS are the following:

Species: He to U
Output (single charge state): ≥1.1 x 10^{11} charges
Ion output (Au^{32+}): 3.4 x 10^9 particles/pulse
Q/m: ≥ 1/6, depending on species
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%
Switching time between species: 1 second

TEST EBIS RESULTS

The Test EBIS, built to demonstrate all essential features of an EBIS meeting RHIC requirements, is shown schematically in Figure 1. This half-trap length (half-yield), full power electron beam prototype is described in detail in [2]. The following are some key results:

- Electron beam currents greater than 10A have been propagated through the Test EBIS with losses less than 1mA.
- Au^{32+} has been produced in less than 35ms, Ne^{8+} in 18ms, N^{5+} in 4ms, and Cu^{15+} in 15ms. Charge state vs. confinement time agrees with calculations.
- With external ion injection, 3.5x10^{11} charges/pulse of Au ions, and ≥2x10^{11} charges/pulse of Ne, N, and Cu have been achieved. In all cases our goal of extracting charge of 50% of the trap capacity has been exceeded.
- The above yields can be extracted in pulses of 10-20µs FWHM, resulting in extracted currents for these ions of several mA's.

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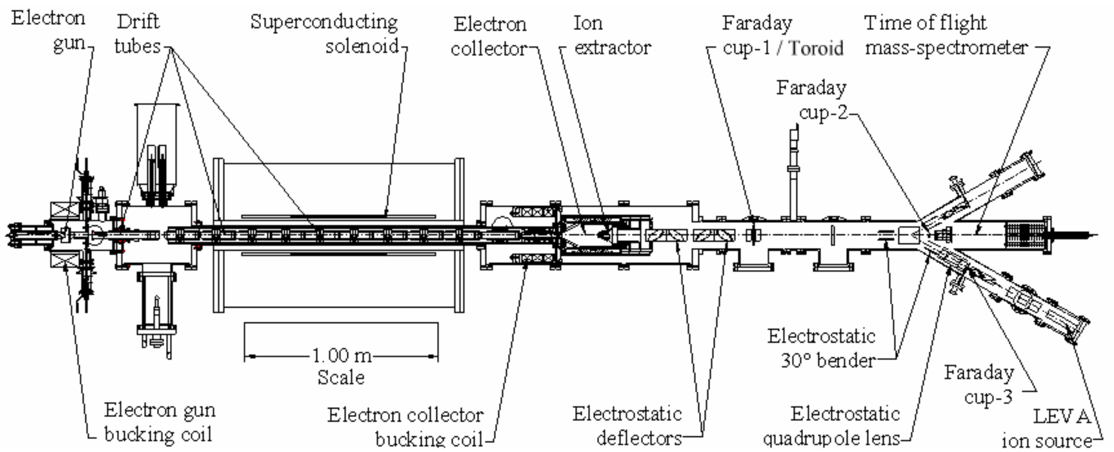

Figure 1: Schematic showing the Test EBIS, ion injection line, and extraction to time-of-flight diagnostic .

- Emittance = 0.1 π mm mrad (rms normalized) has been obtained for a 1.7 mA beam extracted from the EBIS after Au injection from the LEVA source.

For RHIC the straightforward doubling of the trap length by installing a longer superconducting solenoid is required. Linear scaling with trap length on the Test EBIS has been shown over a range of 35-107 cm.

EXTERNAL ION SOURCES

We have decided to rely on external ion injection to provide the ion species. In this manner, the EBIS functions purely as a charge state multiplier. The advantages of an EBIS working with ion injection are many: once the proper ion optics configurations are set up and stored, one can easily change species and charge state on a pulse to pulse basis, there is virtually no contamination or memory effect, and several relatively low cost external sources can be connected by gate valves and maintained independently of the EBIS.

A Low Energy Vacuum Arc (LEVA) ion source was obtained from LBNL [4] for all our initial experiments on the Test EBIS. It has performed very adequately for all our extensive initial testing, and all EBIS results pertaining to gold ions were obtained using LEVA.

Hollow Cathode Ion Source

We have tested a Hollow Cathode Ion Source (HCIS), similar to that used at CEA Saclay as an ion injector for the EBIS "Dione" for ions such as Cu, Au, and U. [5] The source simultaneously produces ions of the working gas which is typically Ne, Ar, or Xe, and the cathode material. To date, the HCIS has been tested at BNL using copper and stainless steel cathodes. With discharge currents from 0.5-4A, a 1mm diameter plasma electrode aperture, and 15kV extraction, the source has produced 45μA of Cu^+, 130μA of Ne^+, and 27μA of N_2^+. These currents are sufficient for seeding the EBIS trap.

One of the challenges posed by the use of the HCIS is the necessity to provide adequate differential pumping between the HCIS which operates at ~1 mb and the EBIS ionization region which must be maintained in the 10^{-10} mb range. Two 25mm Uniblitz [6] electronically controlled fast shutters (minimum open time ~6ms) and restrictive apertures help provide differential pumping. We have verified that the EBIS ionization volume remains below $2x10^{-10}$ mb for a shutter open time of 10ms with a 1Hz repetition rate (i.e., 1% duty factor) and neon gas. For a 10% duty factor the pressure reaches only $6x10^{-10}$ mb.

20 A ELECTRON GUN & COLLECTOR

An IrCe cathode, from BINP, Novosibirsk [7], is now routinely used on the Test EBIS, and electron beams up to 10A, and 100kW peak power dissipation on the electron collector have been propagated with very low loss. At our design electron current of 10A, the IrCe cathodes have expected lifetimes of ~20,000 hours, several times longer than the LaB_6 cathodes previously used. The performance required for the RHIC EBIS can be achieved with this 10 A electron gun already in use. Nevertheless it would be desirable to have a safety margin with electron beam current for EBIS operation at 10 A and some prospects for increase of output ion intensity in the future, and indeed, with this IrCe cathode one has the possibility of increased emission for either a marginal increase in electron current of a few amperes or a future upgrade of electron current up to 20A, via a modification of the gun electrode geometry. We have such a design of the electron gun and collector which would allow a possible future increase of electron current in RHIC EBIS to 20 A [8].

To reach electron current of I_{el}=20 A with existing 40 kV anode power supplies the perveance of the gun should be doubled relative to our present gun. The design of this 20 A gun is presented in Figure 2. The IrCe cathode can provide emission current density 40 A/cm^2, with an expected lifetime at this density of several thousand hours [7]. The diameter of the convex cathode is 9.2 mm and the radius of the sphere is 10 mm. This design is based on the inverted magnetron geometry of our existing electron gun of Novosibirsk design, which produces a laminar electron beam, allowing operation in a wide range of electron current, potential and magnet field distributions. It also allows substantial deceleration of the electron beam in the ion trap and electron collector regions. The cathode is immersed in a magnetic field of approximately 0.14 T. The perveance of this gun is ~$2.5 \cdot 10^{-6}$ A/$V^{3/2}$. The focusing electrode at zero voltage with respect to the cathode suppresses electron emission on the cathode periphery, resulting in a more homogeneous power density distribution on the electron collector.

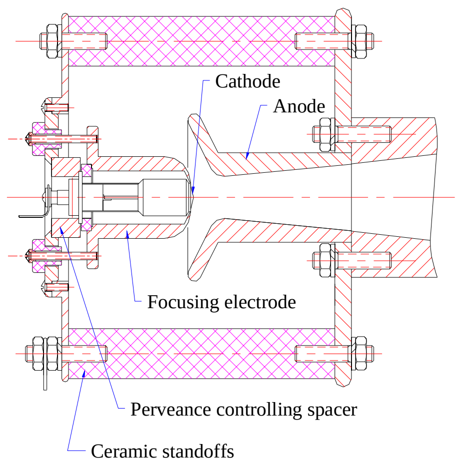

Figure 2: Schematic of the 20 A electron gun.

The problems of power dissipation on the electron collector (EC) include heat removal and fatigue of the EC material. The electron optics, cooling structure and material of the electron collector were optimized to reduce both the average temperature of EC surface and amplitude of its variations during the operation cycle. ANSYS simulations of collector temperature and stress distributions have been done for the electron energy 15 keV and current 20 A, and beam on for 30 ms, off for 170 ms. The maximum heat load on the inner surface is ~350 W/cm^2 during the pulse, and averaged over the area being hit, is ~ 200 W/cm^2 during the pulse. The peak power at the cooling channels is 45 W/cm^2. The collector material will be Hycon 3 HP (Brush-Wellman). This high conductivity BeCu, was chosen since it results in low stresses in the material. The calculated stresses are all well within the fatigue cycle limit for 10^8 cycles. More details on the gun and collector design can be found in [9].

PREINJECTOR SYSTEM DESIGN

A 100 MHz, 4-rod RFQ will accelerate the beam from an input energy of 17 keV/amu, to 300 keV/amu. This will be followed by a 100 MHz IH linac for acceleration to the final energy of 2 MeV/amu. The RFQ and linac will be designed to handle beams with $Q/m \geq 0.16$.

Ions get an initial ~20 keV*Q/m from the biasing of the internal (trap) electrodes. The remaining acceleration to the 17 keV/amu RFQ injection energy will be achieved by placing the EBIS on a high voltage platform of ≤ 80 kV (depending on Q/m). This platform is pulsed to high voltage for only ~100 μs, during ion extraction.

In the ~1.5 m straight transport line between the EBIS and RFQ, beam matching will be done via a combination of electrostatic focusing and a magnetic solenoid lens at the RFQ entrance. One electrostatic deflector in this line will be pulsed to high voltage to allow injection of singly charged ions into the EBIS from one of several external sources, while a second electrostatic deflector is pulsed to high voltage to allow the extracted EBIS beam to be deflected to a time-of-flight measurement line.

The ~4.4 m RFQ is followed by a ~1 m beam matching line which contains 4 magnetic quadrupoles and one rebuncher cavity. The 100 MHz linac, in the baseline design, is a single-cavity, 4m, IH structure. For the heavier ions, one charge state on each side of the desired one survives through the linac. These are separated out following the first of two 73^{o} magnetic dipoles in the matching line to the Booster.

PROJECT STATUS

The EBIS project received DOE CD0 approval (approval of mission need) in August, 2004. With joint funding expected from DOE and NASA, some long-lead procurements should begin in 2006. The present schedule shows commissioning of the full preinjector in 2009.

ACKNOWLEDGEMENTS

We would like to thank Dr. C. Meitzler of Sam Houston State University for his work on initial operation of the hollow cathode ion source at BNL, and A. Hershcovitch and G. Kuznetsov for their physics support. We would also like to thank D. Boeje, D. Cattaneo, D. McCafferty, and R. Schoepfer for their excellent technical support on this project.

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