Submitted to ICIS 2001
September 2-7, 2001
Berkeley, CA

BNL-68744

EXTRACTION OF HIGHLY CHARGED AU IONS FROM A MULTIAMPERE ELECTRON BEAM EBIS AT BNL*

E.N. Beebe†, J.G. Alessi, O. Gould, D. Graham, A. Kponou, A. Pikin, K. Prelec, J. Ritter,

BNL, Upton, NY 11973, USA

Abstract

Excellent progress has been made in the operation of the BNL Electron Beam Ion Source (EBIS), which is a prototype for an EBIS that could meet requirements for a RHIC preinjector. We have achieved very stable operation of the electron beam at 10 A through the EBIS trap. Ion injection of low charge gold ions from a LEVA [1] ion source and subsequent extraction of these ions with most probable charge state Au^{34+} has been demonstrated with electron beams up to 8A. The total ion charge for gold measured on current transformer at the EBIS exit was 55nC after a 30ms confinement period. This corresponds to ~85% of the theoretical ion trap capacity and exceeds our goal of 50% neutralization. The collected ion charge is proportional to the electron current and the gold charge state scales with the electron current density. Details of the EBIS configuration, total charge measurements, and TOF spectra are given

1 INTRODUCTION

The present preinjector for heavy ions for AGS/RHIC uses the Tandem Van de Graaff. An alternative to this can be an Electron Beam Ion Source (EBIS), followed by a Radiofrequency Quadrupole accelerator and a short Linac. This new preinjector offers improvements in both performance and operational simplicity. In this case, one would produce, directly from the ion source, the charge state desired for Booster injection. This eliminates the particle loss from any subsequent stripping efficiencies, and makes the initial preacceleration more efficient. In addition, Booster injection will be more efficient if one can inject over fewer turns than presently used, so it

*This work was performed under the auspices of the U.S. Department of Energy, Contract No. DE-AC02-98CH10886.

is also desirable for the source to produce shorter pulses of higher currents. Some of the source requirements are:

- Intensity: 3.4 x 10^9 Au^{32+} ions per pulse
- Pulse width: variable, 10 – 40 μs, to allow 1-4 turn injection into the Booster
- Repetition rate: 5-10 Hz
- q/m: 0.16 or greater. Equals that presently used for Au from the Tandem. For lighter ions, higher q/m is required (Si^{14+}, Fe^{21+}) to achieve the desired Booster output energy.

We have chosen to develop an EBIS to meet the above requirements. The charge state requirements are modest for an EBIS. An EBIS delivers pulses having a constant total positive charge, and one has control over the ion pulse width by controlling the trap voltages. Ions can be extracted in short pulses of high current, which is desirable for synchrotron injection. The narrow charge state distribution from an EBIS has an advantage vs. other types of high charge state heavy ion sources when considering the beam transport line. For the same current in the desired charge state, one has to deal with much higher total extracted currents in sources having broad charge state distributions, which can lead to space charge problems in transport. Finally, an EBIS can easily produce ions of any species, and can rapidly switch between species (even pulse-to-pulse).

A conservative approach has been chosen for the RHIC EBIS concept. The EBIS would operate in a "traditional" mode, have a 1.5 m long trap, a warm bore, an unshielded superconducting solenoid, and a 10A, 20 keV electron beam with current density < 600 A/cm^2. The goal ion yield of 3.4 x 10^9 ions of Au^{32+} will be reached with the above parameters if the neutralization of the electron beam by the ion species of interest is 50%, a value exceeded in the BNL EBIS, as well as in other EBISs. It is also assumed that 20% of that charge is in the desired charge state, again a condition frequently achieved in EBISs. The recent progress at BNL in demonstrating the required performance is presented below.

2 DESCRIPTION OF EBTS

The EBIS Test Stand (EBTS) is a full-power, half length prototype of the RHIC EBIS. It has the following main components:

SC solenoid: A 1 m long, unshielded, warm bore magnet with an inner diameter of 154 mm. The solenoid, manufactured by Oxford Instruments, Inc., has a maximum operating field of 5 T.

Drift structure: This consists of 12 insulated stainless steel tubes (32 mm ID), sitting at room temperature. The four central tubes form an ion trap of length 71 cm.

Electron Collector: This is water cooled, and designed for a maximum average electron beam power dissipation of 50 kW. The collector is partially surrounded by an iron magnetic shield, and a coil in front of the collector is used to adjust the field at the entrance. Operating the electron beam in pulsed mode (100 ms), the collector has operated at instantaneous powers in excess of 120 kW.

Electron gun: 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. The gun has an 8.3 mm diameter, single crystal LaB_6 cathode, and is a coaxial diode with magnetic insulation, positioned in the field of a separate solenoid. The gun was designed and fabricated at the Budker Institute of Nuclear Physics, Novosibirsk [2].

There are separate bucking coils for the electron gun and electron collector, which decouple the electron beam launching, compression and collection from the main solenoid. Five sets of external transverse magnet coils allow versatile adjustment of the electron beam transmission in different regions, and their use significantly reduces electron beam losses on elements of the drift structure.

EBTS operates in the pulsed mode for both the electron gun and the drift tube high voltages, which extends the range of our 50 kW electron collector, and allows us to freely explore source parameters while still maintaining ultrahigh vacuum. A detailed description of the EBTS design and earlier results is presented in [3].

3 SUMMARY OF PREVIOUS EBTS RESULTS

The performance of the novel electron gun has been excellent. It has provided very stable operation over a wide range of gun operating parameters. With this gun we have reached our design goal, and propagated a 10 A electron beam through the EBIS solenoid to the collector, with very low beam loss (<0.5%), in 10 ms pulses. We have propagated electron beams up to 8.6A, 100ms and have confined and extracted ions with electron beams up to 8.0 A. We will continue with ion production with electron beams up to 10A after some reconfiguration of our power supplies.

Our design goal of extraction of a total ion charge corresponding to 50% of the electron beam space charge has consistently been met or exceeded. Trapping and ionization of background gas ions and injected neutral gas were tried first to demonstrate proper EBIS operation without the added complexities of external ion injection. Since EBTS was not designed to separate the gas injection region from the main trap region, we obtained the broader charge state distributions associated with a constant neutral density. The ion yield for Xe gas injection is given in Table 1. The RHIC EBIS requires a yield of 5×10^{11} positive charges/pulse, at 10 A and at twice the trap length of EBTS, so our results to date have exceeded the EBTS design goal.

For 1-4 turn injection into the Booster, the extracted ion pulse should be 10-40 μs long. Using a 6 A electron beam, a 10 μs FWHM ion pulse was extracted from EBTS, having a peak ion current of 3.3 mA. The yield was 1.9×10^{11} charges, corresponding to 57% neutralization. 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 resistor/capacitor network. While this result was with ions produced from background gas, this fast extraction can be similarly achieved for any ions. Once demonstrated, however, the fast power supplies used were reconfigured for use for ion injection experiments, to be described in the next section.

Finally, charge state distributions were measured using time-of-flight (TOF) for Ar, and Xe introduced as gases, and Cs injected from an external ion source. The distributions are consistent with the expected values based on the electron current density and ion confinement time.

4 RECENT RESULTS WITH EXTERNAL INJECTION OF AU IONS

The ion optical system, shown in Fig. 1 is used both for injection of singly charged ions into the EBIS trap from an auxiliary ion source, and for diagnostics of the ion beam extracted from EBTS. The transport line includes 30° pulsed electrostatic deflectors, which allow use of multiple auxiliary sources and provides for time-of-flight (TOF) analysis of the extracted EBTS beam in the straight section. The injected ion beam was monitored with removable Faraday cup FC3 at the exit of Au ion source, and FC1, close to the exit from EBTS. The extracted ion beam from the EBTS was measured on FC2, 160 cm from the exit of EBTS.

Low charged Au ions were produced in a LEVA source [1] having 7 apertures, each of ~1.5 mm diameter. These ions were extracted in ~500-700μs pulses at 10 kV. With an initial flat potential distribution on trap drift tubes, injected ions make a round trip traversal of the trap region, reflecting from the gun barrier. A flat potential distribution is imposed in the trap region and the potential can be adjusted to retard the injected Au ion beam to <100 eV in the EBTS trap region, thereby increasing the linear charge density of the injected Au ion beam. With the Au ion beam present, the potential on the trap drift tubes is then lowered, resulting in axial trapping of traveling ions, which find themselves confined between two axial barriers. In this method of injection, ions do not have to be further ionized to be trapped; therefore the efficiency of trapping can be high and the injection times are rather short. Up to 100μA of low charged Au ions from the LEVA could be transported to the Faraday cup 1 just outside EBTS (see fig. 1). Typically, 20μA currents were sufficient provide ~25% neutralization of the EBTS trap with low charged Au ions after <2ms confinement times.

Figure 2 shows measured Au ion yields for electron beam currents up to 8A. For electron currents up to 4A the data were obtained using a 2.3 cm diameter Faraday cup located 1.6 m from the extractor. For electron beams >4A ion yield could be measured using a recently installed current transformer closer to the ion extractor (see fig. 1). The current transformer allows non-destructive measurement of both the injected and extracted ion beams. The yield as a function of electron current exceeds the goal of 50% neutralization. The measured yield of 3.4×10^{11} charges per pulse at 8 A electron beam current corresponds to a 85% neutralization. Figure 3 shows the ion yield vs. confinement time at 8A with and without external Au ion injection. Figure 4 shows a Au TOF spectrum measured at 7.2A and 50ms ion confinement time with a most abundant charge state of Au^{34+}. By using spectra and neutralization data obtained with 7-8A electron beams, and the assumption that Au ions comprise only half the total charge, it is conservatively estimated that the EBTS is presently producing $>10^9$ Au^{32+} ions per pulse.

5 CONCLUSIONS

The output of EBTS is now close to the RHIC requirement for charge, with ½ the trap length – demonstrating proper operation of an EBIS at high currents. Ions can be injected, confined, and extracted just as in other EBISs operating below 1 A. To date, all results of the EBTS have agreed with EBIS scaling laws, and continue to confirm the parameters for a RHIC EBIS that were presented about 10 years ago. The observed ionization efficiency indicates that for a 10A electron beam, Au^{32+} , the required charge state for RHIC, can be obtained in less than 30ms, which will help in reducing the average power dissipation on the electron collector.

The progress made at BNL on the EBIS development has increased our confidence that such a source injecting into a Linac-based preinjector can reach the pulsed Au beam intensity required for RHIC, and offers significant advantages in meeting long-term requirements for performance and reliability for the RHIC program.

6 ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy. We would like to thank D. Boeje, D. Cattaneo, R. Lockey, D. McCafferty, R. Schoepfer, and W. Shaffer, for their excellent technical support and G. Smith for his assistance with the current transformer diagnostic.

7 REFERENCES

[1] I.G. Brown, et.al., Rev. Sci. Instrum. **65** (1994) 1260.

[2] A. Kponou, et.al., Rev. Sci. Instrum. **69**, (1998) 1120.

[3] A. Pikin, et.al., "EBTS: Design and experimental study", Proc. 8th Int. Symp. on Electron Beam Ion Sources and Traps (Nov., 2000), AIP Conf. Proc., to be published.

Figure Captions

Figure 1: Schematic of the EBIS test stand and ion injection.

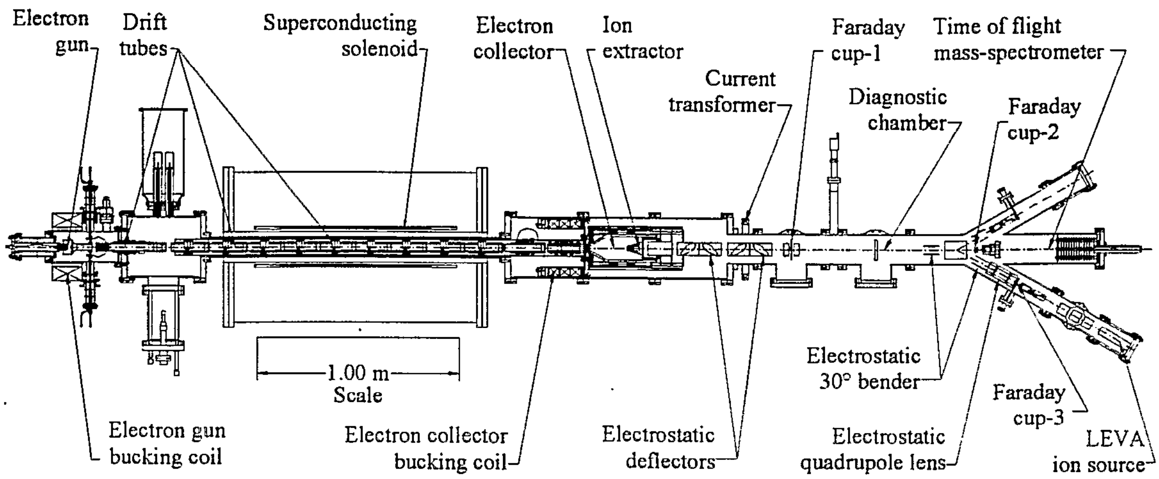
Figure 2: Gold ion yield vs. electron current.

Figure 3: Au and residual ion yield vs. confinement time for a 8A electron beam.

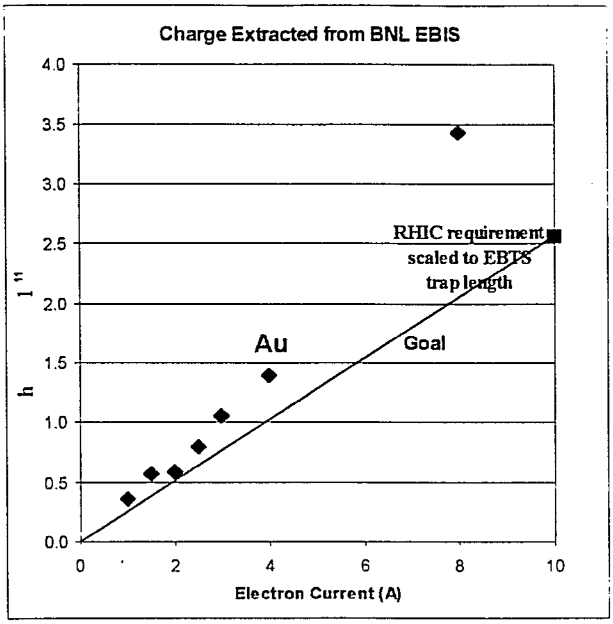
Figure 4: TOF spectrum for gold external ion injection into the EBTS (Ie=7.2A, confinement time=50ms).

TABLE 1. Ion yields from EBTS

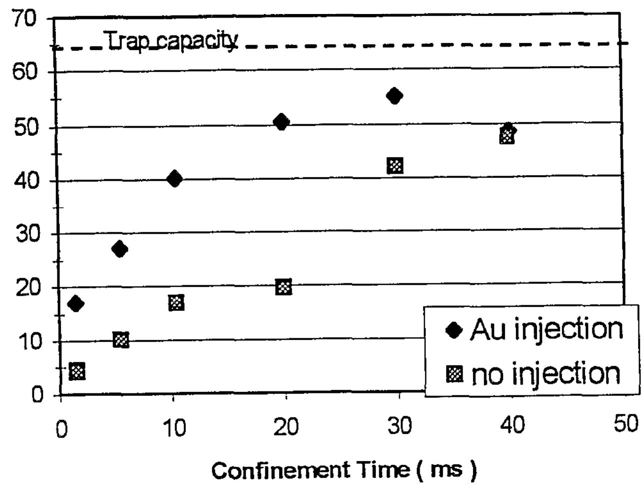
Ion	I_e	Charges/pulse	Neutralization
Au	8 A	3.4×10^{11}	85%
Xenon	7 A	1.9×10^{11}	55%



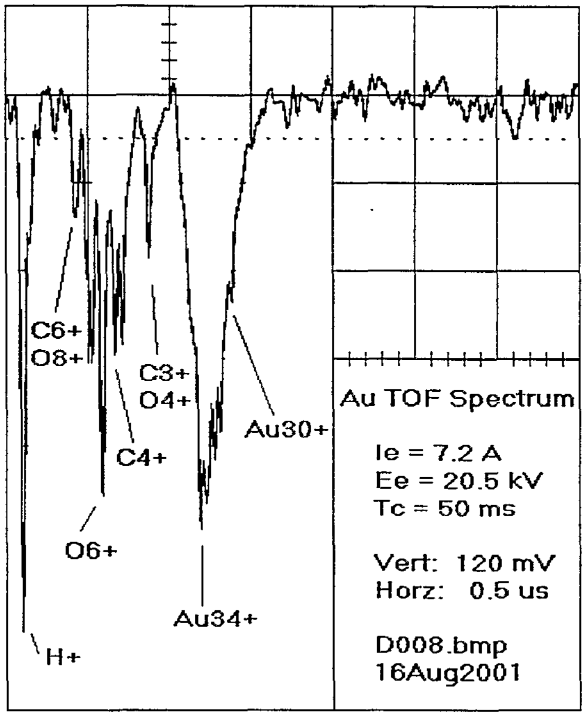
Electron gun
Drift tubes
Superconducting solenoid
Electron collector
Ion extractor
Current transformer
Faraday cup-1
Diagnostic chamber
Time of flight mass-spectrometer
Faraday cup-2
1.00 m
Scale
Electrostatic 30° bender
Faraday cup-3
Electron gun bucking coil
Electron collector bucking coil
Electrostatic deflectors
Electrostatic quadrupole lens
LEVA ion source



Charge Extracted from BNL EBIS
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
Electron Current (A)
RHIC requirement
scaled to EBTS
trap length
Au
Goal



70
60
50
40
30
20
10
0
Trap capacity
Au injection
no injection
0
10
20
30
40
50
Confinement Time (ms)


C6+
O8+
C3+
O4+
Au30+
C4+
O6+
Au34+
H+
Au TOF Spectrum
Ie = 7.2 A
Ee = 20.5 kV
Tc = 50 ms
Vert: 120 mV
Horz: 0.5 us
D008.bmp
16Aug2001