A New Generation of EBIS: High Current Devices for Accelerators and Colliders*

E. Beebe, J. Alessi, A. Kponou, A. Pikin, K. Prelec,
BNL, Upton NY 11973, USA

*Work performed under the auspices of the U.S. Department of Energy.
The demand for high intensity, highly charged ions

With the advent of heavy ion colliders, such as RHIC at BNL and LHC at CERN, the demand for high charge state ion beam intensities was raised by more than an order of magnitude compared to fixed target operation of existing accelerators.*

Previously, the focus for EBIS sources at accelerator facilities e.g., Dubna, Saclay and Stockholm has been to produce very highly charged ions (charge to mass ratio q/m between 0.25 and 0.5). With those sources, the required intensity was within the bounds available with electron beam operation up to 0.5A.

In the proposed BNL acceleration scheme, more moderate charge states such as Au32+ can be used (q/m~0.16). The BNL EBIS program focus has been to increase EBIS heavy ion yields from a few nC/pulse to >85nC/pulse in a RHIC EBIS.

Heavy Ion Preinjector for RHIC

Tandem Van de Graaff presently used
860 m transport line to Booster
Stripping foils at terminal and high energy
Injection over > 40 turns is required
Limitations on ion species
Maintenance, manpower, upgrades, ….

Quite a while ago, we began to investigate alternatives.

The ion source is the key component.
Attractive features of an EBIS

- One has control over pulse width, extracting a fixed charge – a good match to 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

- One has control over the charge state produced (easy to get intermediate charge states, such as $\text{Au}^{32+}$ or $\text{U}^{45+}$)

- An EBIS can produce any type ions – from gas, metals, etc., and is easy to switch species

- The scaling laws are understood

- The source is reliable, and has excellent pulse-to-pulse stability, long life
Proposed Linac–Based RHIC Preinjector

**RFQ:** 8.5 - 300 keV/u; 100 MHz

**Linac:** 0.3 - 2.0 MeV/u; 100 MHz
Linac-based Preinjector - Source “requirements”

1. Intensity for $1 \times 10^9$ Au ions/bunch in RHIC : $\sim 3 \times 10^9$ Au$^{32+}$ ions/pulse from the source

2. No stripping before Booster injection : $q/m > 0.16$ (Au$^{32+}$, Si$^{14+}$, Fe$^{21+}$)

3. 1-4 turn injection into Booster : pulse width $10-40 \mu$s

   (Note - 1 & 3 result in a Au$^{32+}$ current of $1.6 - 0.4$ mA)

4. Rep rate : $\sim 10$ Hz

5. Emittance : $\leq 0.35 \pi$ mm mrad, normalized, 90%
   (for low loss at Booster injection); source emittance $\sim 0.1 \pi$ mm mrad, normalized, 90%
### Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RHIC EBIS</th>
<th>EBTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-beam current</td>
<td>10 A</td>
<td>10 A</td>
</tr>
<tr>
<td>e-beam energy</td>
<td>20 keV</td>
<td>20 keV</td>
</tr>
<tr>
<td>e-beam density</td>
<td>~575 A/cm²</td>
<td>~575 A/cm²</td>
</tr>
<tr>
<td>Ion trap length</td>
<td>1.5 m</td>
<td>0.7 m</td>
</tr>
<tr>
<td>Trap capacity (charges)</td>
<td>1.1 x 10^{12}</td>
<td>5.1 x 10^{11}</td>
</tr>
<tr>
<td>Yield positive charges</td>
<td>5.5 x 10^{11}</td>
<td>2.6 x 10^{11}</td>
</tr>
<tr>
<td>Yield Au^{32+}, design value</td>
<td>3 x 10^9 ions/pulse</td>
<td></td>
</tr>
<tr>
<td>Yield U^{45+}, design value</td>
<td>2 x 10^9 ions/pulse</td>
<td></td>
</tr>
</tbody>
</table>

**EBIS Test Stand** - ~1/2 length prototype, but with the full power electron beam
Design Choices for a Reliable, Low Maintenance EBIS

The basic principle that has been followed is to separate the functions of source components and remove as much of the action as possible from the high vacuum ionization region.

Electron Gun: (Designed in Novosibirsk: Kuznetsov, Tiunov)
A convex cathode produces a low rotational electron beam well suited for the accelerations and decelerations common in the EBIS transport system

Magnetic System:
Warm bore superconducting solenoid: pumping separate from cryosystem
Auxiliary launch and Collection solenoids: differential pumping
Transverse Steering coils for corrections

Large diameter drift tubes (32 mm diameter):
Pumping, RF coupling, fast extraction, alignment precision

External ion injection:
EBIS acts as a charge state multiplier, low contamination, high reliability

(Poster THPRI002 Recent Results…Pikin et. al.)
Development of the 10 A electron gun –
Collaboration with BINP on the development of a LaB$_6$–based electron gun. This gun has produced currents of up to 13A, has a good lifetime, and excellent beam optics. The unique optics for extraction and matching into the strong magnetic field allows a very stable operation over a broad range of electron beam currents.

Propagation of a 10 A electron beam through the EBIS trap

10 A, 50 ms Electron Beam Pulse

8 A, 100 ms Electron Beam Pulse
Gold Injection from Leva: FC2 Current and Charge Extracted from EBTS

( Ie = 4A, Tinj ~ 200 µs, Tc = 2ms )

d000.bmp
2Apr2001
$5.5 \times 10^{11}$ charges/pulse are required for RHIC. By doubling the EBIS trap length to 1.5 m, we will exceed this requirement. (The ion yield has been shown to scale linearly with trap length).
Emittance of a 1.7 mA extracted beam from EBIS, with Au injection. $\varepsilon (n, \text{rms})= 0.1 \pi \text{ mm mrad.}$
**Extraction of ions from the EBIS trap**

We have achieved excellent ion yields from the trap, with very high neutralization efficiencies.

<table>
<thead>
<tr>
<th>Ion</th>
<th>$I_e$ (A)</th>
<th>Charges/pulse</th>
<th>Neutralization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>8</td>
<td>$3.4 \times 10^{11}$</td>
<td>85%</td>
</tr>
<tr>
<td>Xenon</td>
<td>7</td>
<td>$1.9 \times 10^{11}$</td>
<td>55%</td>
</tr>
</tbody>
</table>

$5.5 \times 10^{11}$ charges/pulse are required for RHIC, from a trap length of 1.5 m, and assuming operation at 10 A electron current. (The ion yield has been shown to scale linearly with trap length and electron current).
A 3.2mA, 12µs FWHM, (40nC) ion pulse was obtained at the source exit toroid using a 6.8A e-beam and Au external ion injection, after a 15ms confinement. (85 nC required for RHIC)

Faster extraction has been obtained earlier by applying a gradient to the well floor during extraction. In the future, the pulse shape will be tailored by applying an appropriate voltage pulse to the well.
## Au32+ Pulsed Ion Currents

<table>
<thead>
<tr>
<th></th>
<th>Routine Extraction 100 µs</th>
<th>Extraction 40µs</th>
<th>Fast Extraction 10µs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EBTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8A e-beam</td>
<td>55 µA</td>
<td>138 µA</td>
<td>550 µA</td>
</tr>
<tr>
<td>0.7m trap</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RHIC EBIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10A e-beam</td>
<td>80 µA</td>
<td>400 µA</td>
<td>1600 µA</td>
</tr>
<tr>
<td>1.5m trap</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

By manipulation of the EBIS trap electrodes, the EBIS extracted charge can be delivered in pulse widths necessary to meet single to multi-turn injection requirements of the synchrotron.
An LHC EBIS Option

It has been pointed out previously, that the use of Pb\textsuperscript{54+} directly from an EBIS may offer several advantages:*,#

- elimination of the first stripping stage required by a lower charge state source such as an ECR
- elimination of the need to use LEIR for ion accumulation and electron cooling
- 10 Hz linac operation would not be required
- single turn injection into the PSB
- any ion species, with fast switching, becomes possible


## EBIS Applications

<table>
<thead>
<tr>
<th></th>
<th>Achieved</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ion</strong></td>
<td>$\text{Au}^{32+}$</td>
<td>$\text{Au}^{32+}$</td>
<td>$\text{Pb}^{54+}$</td>
</tr>
<tr>
<td>$I_e$</td>
<td>10 A</td>
<td>10 A (15)</td>
<td>20 A</td>
</tr>
<tr>
<td>$J_e$</td>
<td>500 A/cm$^2$</td>
<td>500 A/cm$^2$</td>
<td>3000 A/cm$^2$</td>
</tr>
<tr>
<td>$t_{\text{confinement}}$</td>
<td>35 ms</td>
<td>35 ms</td>
<td>150 ms</td>
</tr>
<tr>
<td>$L_{\text{trap}}$</td>
<td>0.7 m</td>
<td>1.5 m</td>
<td>2.0 m</td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
<td>$0.51 \times 10^{12}$</td>
<td>$1.1 \times 10^{12}$</td>
<td>$2.4 \times 10^{12}$</td>
</tr>
<tr>
<td>% extracted ions</td>
<td>$&gt; 75%$</td>
<td>50%</td>
<td>20%</td>
</tr>
<tr>
<td>% in desired Q</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Extracted charge</td>
<td>$&gt; 55 \text{nC}$</td>
<td>85 nC</td>
<td>77 nC</td>
</tr>
<tr>
<td>Ions/pulse</td>
<td>$&gt; 10^9 \ (\text{Au}^{32+})$</td>
<td>$3.3 \times 10^9 \ (\text{Au}^{32+})$</td>
<td>$1.8 \times 10^9 \ (\text{Pb}^{54+})$</td>
</tr>
<tr>
<td>Pulse width</td>
<td>10-20 $\mu$s</td>
<td>10-40 $\mu$s</td>
<td>5-10 $\mu$s</td>
</tr>
</tbody>
</table>
Summary

With EBTS, more than an order of magnitude improvement in EBIS performance has been achieved.

10 A electron beam. (>10 improvement over previous EBISs).

>55 nC pulses of ions extracted from the EBIS trap (less than a factor of 2 is needed for RHIC requirement, at less < 50% of the final trap design length.

Au$^{32+}$ will be produced in only ~30ms. (original design was for 100ms. Less average power on electron collector).

More modest increases in well understood parameters are needed to meet RHIC and LHC requirements.

The EBIS scaling has worked as expected. The design parameters for the RHIC EBIS are still the same as proposed more than 8 years ago.

A Linac-based preinjector will offer significant advantages in meeting long-term requirements for performance and reliability for the RHIC program.
Appendix (extra slides)
EBTS - showing ion injection, and extraction to TOF
EBIS inj scheme with tandem comparison