A High-Performance Electron Beam Ion Source

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Acknowledgements
Ed Beebe, Sasha Pikin, Ahovi Kponou – EBIS
Deepak Raparia, Masahiro Okamura – Linac, RFQ, etc.
Outline of Talk

• Overview of the EBIS Preinjector project
  – What we’re doing, and why

• Electron Beam Ion Source (EBIS)
  – How an EBIS works
  – What we’ve achieved with the Test EBIS
    (full electron beam current, half-trap length of the RHIC EBIS)
  – Status of the EBIS for RHIC
Presently, one or two >35-year old Tandem Van de Graaff accelerators are used for RHIC pre-injection.

The “Test EBIS” at BNL has advanced the state of the art in EBIS performance by more than an order of magnitude, which now makes it possible to meet RHIC requirements with a modern linac-based preinjector.

BNL is in the construction phase of a new pre-injector for RHIC. The new preinjector consists of an EBIS high charge state ion source, a Radio Frequency Quadrupole (RFQ) accelerator, and a short linac.

CD-4 date (project completion) is September, 2010.
Tandems are the present heavy ion preinjectors for RHIC

860 m long transport line from the Tandems to the Booster

EBIS going here
Advantages of the new preinjector:
- Simple, modern, low maintenance
- Lower operating cost
- Can produce any ions (noble gases, U, He³↑)
- Higher Au injection energy into Booster
- Fast switching between species, without constraints on beam rigidity
- Short transfer line to Booster (30 m)
- Few-turn injection
- No stripping needed before the Booster, resulting in more stable beams
- Expect future improvements to lead to higher intensities

Operation for RHIC requires the preinjector to be available 24/7 for 4-6 months at a time, and the Tandems have done this for many years.
Placement of EBIS Preinjector in lower equipment bay of 200 MeV Linac

- Booster (beams for RHIC and NSRL)
- Ions: He - U
- \( Q/m \geq 1/6 \)
- Current: > 1.5 emA
- Pulse length: 10 \( \mu s \) (for 1-turn injection)
- Rep rate: 5 Hz
- Output energy: 2 MeV / u
- Time to switch species: 1 second

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HIAT 2009
June 8-12, 2009
Preinjector requirements

The preinjector must be able to switch both species and transport line rigidity in ~1 second, so that there are no restrictions on compatibility between RHIC and NSRL operations.

For example:

Requirement for RHIC: 1.7 emA of $\text{Au}^{32+}$, 10 µs; 5 Hz

plus….NSRL (NASA Space Radiation Laboratory) – a second species, 1 second later:

$\text{He}^{2+}$, $\text{C}^{5+}$, $\text{O}^{8+}$, $\text{Si}^{13+}$, $\text{Ti}^{18+}$, $\text{Fe}^{20+}$, $\text{Cu}^{22+}$, at ~2-3 emA, ~ 10 µs

• short pulses
• fast beam changes
• any species

The EBIS was the key to the project – this will be covered for most of the talk…
A few minutes on the overall project…. 

EBIS SC solenoid – delivered

Beam port – completed

RFQ – Frankfurt; delivered, being tested with beam

Dipoles – delivered and installed

Linac – being manufactured (Frankfurt, 9/09 delivery)
# RFQ and Linac Design Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RFQ</th>
<th>Linac</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>4-rod</td>
<td>IH</td>
<td></td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>100.625</td>
<td>MHz</td>
<td></td>
</tr>
<tr>
<td>Design Beam Current</td>
<td>10</td>
<td>5</td>
<td>mA</td>
</tr>
<tr>
<td>Maximum Beam Current</td>
<td>&gt;20</td>
<td>&gt;10</td>
<td>mA</td>
</tr>
<tr>
<td>Q/m</td>
<td>0.16 – 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repetition Rate, Max</td>
<td>5</td>
<td>Hz</td>
<td></td>
</tr>
<tr>
<td>Pulse Width</td>
<td>≤ 1.0</td>
<td>ms</td>
<td></td>
</tr>
<tr>
<td>Input Energy</td>
<td>17.0</td>
<td>300</td>
<td>keV/u</td>
</tr>
<tr>
<td>Input Emittance (rms, normalized, Au$^{32+}$)</td>
<td>0.09</td>
<td>0.11</td>
<td>π mm mrad</td>
</tr>
<tr>
<td>Input Emittance, longitudinal (90%)</td>
<td>-</td>
<td>172</td>
<td>π keV/u-deg</td>
</tr>
<tr>
<td>Acceptance (normalized)</td>
<td>≥ 1.7</td>
<td>≥ 4.3</td>
<td>π mm mrad</td>
</tr>
<tr>
<td>Output Energy</td>
<td>300</td>
<td>2000</td>
<td>keV/u</td>
</tr>
<tr>
<td>Emittance Growth</td>
<td>≤ 20</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Output Emittance, longitudinal (90%)</td>
<td>≤ 172</td>
<td></td>
<td>π keV/u-deg</td>
</tr>
<tr>
<td>ΔE (90%) for Au$^{+32}$</td>
<td>&lt; ±10</td>
<td></td>
<td>keV/u</td>
</tr>
<tr>
<td>Transmission Efficiency</td>
<td>&gt; 90</td>
<td></td>
<td>%</td>
</tr>
</tbody>
</table>
RFQ from IAP, Frankfurt (Schempp)

The RFQ has successfully accelerated He, Cu, & Ne from the Test EBIS at BNL.

Delivered in September, 2008.
RFQ on Test EBIS
IH Linac from IAP, Frankfurt (Ratzinger)

Cavity is at GSI for Cu plating
Internal quads being manufactured by Bruker
Delivery to BNL scheduled for September, 2009.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>100.625 MHz</td>
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<tr>
<td>Input energy</td>
<td>300 keV/u</td>
</tr>
<tr>
<td>Output energy</td>
<td>2.0 MeV/u</td>
</tr>
<tr>
<td>Mass to charge ratio</td>
<td>6.25</td>
</tr>
<tr>
<td>Beam current</td>
<td>10 mA</td>
</tr>
<tr>
<td>Out. Energy spread 90%</td>
<td>&lt; ± 2.0 keV/u</td>
</tr>
<tr>
<td>Tras. Emittance growth</td>
<td>&lt; 20 %</td>
</tr>
<tr>
<td>Transmission</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>RF power</td>
<td>300 kW</td>
</tr>
<tr>
<td>Tank length</td>
<td>2.46 m</td>
</tr>
<tr>
<td>Gap number</td>
<td>27</td>
</tr>
<tr>
<td>Aperture min - max</td>
<td>9 - 15 mm</td>
</tr>
</tbody>
</table>
Many other components in place

EBIS power supplies are being installed on the 100 kV platform

Dipoles installed in Booster (Sigmaphi)

350 kW, 100 MHz RF amplifiers
To meet the RHIC and NASA requirements…..

- Needed an ion source which could produce
  - Any species
  - “High” charge states
  - mA currents in the desired charge state in ~10 µs pulses
  - Switch species in 200 ms

The Test EBIS at BNL has demonstrated these requirements. It has achieved an order of magnitude higher intensity than all previous EBISs.
# Performance Requirements of the EBIS

<table>
<thead>
<tr>
<th>Species</th>
<th>He to U</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output (single charge state)</strong></td>
<td>≥1.1 x 10^{11} charges</td>
</tr>
<tr>
<td><strong>Intensity (examples)</strong></td>
<td>3.4 x 10^9 Au^{32+} / pulse (1.7 mA)</td>
</tr>
<tr>
<td></td>
<td>5 x 10^9 Fe^{20+} / pulse (1.6 mA)</td>
</tr>
<tr>
<td></td>
<td>6.3 x 10^{10} He^{2+} / pulse (2.0 mA)</td>
</tr>
<tr>
<td><strong>Q/m</strong></td>
<td>≥ 0.16, depending on ion species</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>5 Hz</td>
</tr>
<tr>
<td><strong>Pulse width</strong></td>
<td>10 - 40 µs</td>
</tr>
<tr>
<td><strong>Switching time between species</strong></td>
<td>1 second</td>
</tr>
<tr>
<td><strong>Output emittance (Au^{32+})</strong></td>
<td>&lt; 0.18 π mm mrad, norm, rms</td>
</tr>
<tr>
<td><strong>Output energy</strong></td>
<td>17 keV/amu</td>
</tr>
</tbody>
</table>
Radial trapping of ions by the space charge of the electron beam. Axial trapping by applied electrostatic potentials on electrode at ends of trap. The total charge of ions extracted per pulse is \( \sim (0.5 - 0.8) \times (\# \text{ electrons in the trap}) \)

- Ion output per pulse is proportional to the trap length and electron current.
- Ion charge state increases with increasing confinement time.
- Charge per pulse (or electrical current) \( \sim \) independent of species or charge state!
Electron Beam Ion Source (EBIS)
Key Technologies

- High current electron gun (10-20A, IrCe cathode)
- Electron collector (design for 15A * 15 kV = 225 kW; 50 ms* 5Hz = 25% df, to dc)
- Superconducting solenoid (~5T, 2 meter, 8” bore)
- Vacuum – ~10^{-10} in the trap region
- Controls – makes the complex programming of many electrode voltages at different times during an EBIS cycle easy and reproducible
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  \hspace{1cm} V_e$=electron beam voltage  \hspace{1cm} L=trap length

$K_1$=neutralization factor  \hspace{1cm} $K_2$=fraction in desired charge state

**RHIC EBIS Trap length = 1.5 m**

$I(e) = 10$ A

$V(e) \sim 20$ kV

Electron beam charge in trap $\sim 10^{12}$

$\rightarrow$ Extracted ion yield in a single charge state will be $\sim 1-6 \times 10^{11}$ charges/pulse
Charge extracted from Test EBIS

50% of “trap capacity”
(# of e’s in trap)
= goal for Test EBIS

5 x 10^{11} (80 nC) required for RHIC
(with 2 x the trap length)
Electron beam current density:

- 15 A/cm^2 at cathode (B~0.15T)
- 500 A/cm^2 in the trap (B=5T)

r(e) ~0.7 mm in trap

Can easily change J at fixed I, ... I at fixed r, ... etc.
Operation of the Electron Beam

Propagation of a 10 A electron Beam through the EBIS trap

Pervance ~ 1.3 μP
(Test EBIS gun)
LaB₆ and IrCe cathodes

10 A, 50 ms electron beam pulse
Losses < 1 mA
Electron beams up to 10A, 100kW have been propagated with very low loss, using IrCe cathodes from BINP, Novosibirsk.

10 A electron gun with IrCe cathode meets the RHIC EBIS requirements, with an estimated lifetime of >20,000 hours.

The present cathode is actually capable of operating at 20 A (J=30A/cm²) with lifetime of 3000-5000 hours. For possible future increase of the ion beam intensity, we have built the electron gun electrodes and collector with the capability of operating at 20A.

Perveance = 3.1 μP

9.2 mm diameter convex cathodes (LaB₆ shown)
The new electron gun with the high perveance anode (~3μPerv) was installed and operated at the Test EBIS to produce electron beams up to 10A.
RHIC EBIS electron collector assembly design for pulsed 20 A, 15 kV beam

- Designed to dissipate $P_{\text{el}} = 300$ kW peak power (20 A, 15 kV e-beam)

- Calculated power density on EC surface (for 300 kW):
  \[ P = 200 \text{ W/cm}^2, \] during the pulse

- Outer surface of collector is at atmosphere (no internal cooling lines).

- One collector is Hycon 3 HP (Brush-Wellman). This high conductivity BeCu was chosen because it provides longer fatigue lifetime. However, due to difficulties in electron beam welding of this material, we have also built a second collector from a Zr-Cr-Cu alloy. This is now in use on the Test EBIS.
RHIC EBIS electron collector assembly, now in use on the Test EBIS
Drift tube structure

Drift tubes sit inside the central vacuum tube. Heaters on the outside of the vacuum pipe allow baking to 450 C. Outside of these heaters, there is a water cooled jacket to keep the magnet bore cool. Outside the water cooled jacket, there are transverse steering coils.
### RHIC EBIS Superconducting Solenoid (SCS)

- **Length of the SCS coil:** 190 cm  
  - **Test EBIS:** 100 cm

- **Magnet field:** 5 T  
  - **Test EBIS:** 5 T

- **Warm bore inner diameter:** 204 mm (8”)  
  - 1.7 times increased vacuum conductance
  - more room for HV leads  
  - **Test EBIS:** 155mm (6”)

Made by ACCEL. The solenoid has passed acceptance tests and is at BNL.
Test EBIS on stand with high voltage isolation
External ion injection provides the ion species; the EBIS acts purely as a charge breeder.

Advantages:
1. One can easily change species and charge state on a pulse to pulse basis
2. There is virtually no contamination or memory effect
3. Several relatively low cost external sources can be connected and maintained independently of the EBIS.
INJECTION

“Fast”

EXTRACTION

Adjust the time you take to raise/lower the barrier to change the extraction pulse width
LEBT Switchyard at Test EBIS
External Sources used for Primary Ion Injection on the Test EBIS

To date, we have operated the EBIS successfully with external ion injection from a Metal Vapor Vacuum Arc Source, a Hollow Cathode Ion Source, and a Liquid Metal Ion Source. In addition, for beams such as helium, we have used standard gas injection.

Low Energy Vacuum Arc Source (I. Brown);
Hollow Cathode Ion Source (HCIS), based on design used on Saclay EBIS.

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HIAT 2009
June 8-12, 2009
NITROGEN

$\text{N}_2^+ \text{ injected from HCIS}$

3 ms injection, 4 ms confinement

$I(e) \sim 7A$

6 mA peak current

$2.5 \times 10^{11}$ charges/pulse

H+ 3+

5+ 4+

1 V/div

5 μsec/div

100 mV/div

200 nsec/div

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TOF spectra -- Cu+ injection (2.75A e-beam)

Upper trace: no injection
3.3ms confinement
(residual gas spectrum)

Lower trace Cu+ injection
3.3ms confinement
(Cu spectrum – residual gas displaced by Cu ions)

Upper trace: Cu+ injection
3.3ms confinement
(Cu spectrum)

Lower trace Cu+ injection
6.3ms confinement
(Cu spectrum shifted to higher charge states for longer time)
NEON from Test EBIS

6.3 mA peak
2.4 x 10^{11} charges/pulse
18 ms confinement

I(e) ~ 6.8 A

(ion injection switched off)
Ions are extracted from an EBIS in pulses of constant charge; one has control over the pulse width.

Nitrogen Charge State Evolution

Charge state is selected by choosing the confinement time of ions in the trap.

$E_e = 1.5 \text{ keV}$
1.8 mA; \(2.2 \times 10^{11}\) charges/pulse,
15.3 ms confinement, \(I(e) = 6.6\) A,
Gold ions extracted from EBIS, with LEVA injection

3.2 mA, 12 μs FWHM, (2.5 x 10^{11} charges/pulse)

6.8A e-beam

15ms confinement.
Emittances

Measured emittance of a 1.7 mA Au beam

\[ \varepsilon (n, \text{rms}) = 0.1 \ \pi \text{ mm mrad.} \]

Emittance measurements for Au, Xe, He, H, Ar Measurements always include all charge states
Au typically 0.1 – 0.15 \( \pi \) mm mrad, (n, rms)
Lighter beams have emittances of \( \sim 0.3 \ \pi \) mm mrad
EBIS operation with Pulsed High Voltage Platform

During injection and confinement the RHIC EBIS operates at ground potential.

Just before ion extraction the EBIS Platform Voltage is applied such that the ions are extracted through 100kV (nominal) to attain the ~17keV/amu needed for acceleration by the RFQ.
LEBT Optics, Au$^{+32}$

2-D simulation with TRAK

100 kV insulator
16 Pole Deflector / Adapter Lens

16 Pole Wide Aperture Deflector/Lens (left):
+/- 2kV fast deflector supplies are biased by a +/-10kV power supply to provide both deflection and lens capabilities for ion injection and extraction.

Control Screen for 16 pole Deflector showing applied electric field (right):
Vacuum System

Want $P(\text{trap}) \sim 1e-10$ to minimize contaminant ions
On Test EBIS, $P(\text{trap}) = 4e-11$ when off
$P(\text{gun}) - 3e-9$ when running; $P(\text{collector}) \sim 1e-9$
Vacuum system features

- UHV technology including preliminary vacuum firing at 900 C.
- Differential pumping between central chamber and electron gun and collector chambers.
- Increase ID of the central chamber from 4” to 6” for better pumping on sides and allow for placing strips with NEG (Non-Evaporable Getters) materials inside the central chamber.
- Additional differential pumping stage between EC and ionization region.
- Electron gun exchange without breaking vacuum
SUMMARY OF EXPERIMENTAL RESULTS

- Electron beam currents greater than 10A have been propagated through the Test EBIS with losses less than 1mA.

- \( \text{Au}^{32+} \) has been produced in less than 35ms, \( \text{Ne}^{8+} \) in 18ms, \( \text{N}^{5+} \) in 4ms, and \( \text{Cu}^{14+} \) in 15ms. Charge state vs. confinement time agrees with calculations.

- With external ion injection, \( 3.5 \times 10^{11} \) charges/pulse of Au ions, and \( \geq 2 \times 10^{11} \) 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 10-20\( \mu \)s FWHM, resulting in extracted currents for these ions of several mA's.

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

- Beams have been accelerated off the EBIS platform to 17 keV/u, matched into the RFQ, and accelerated through the RFQ to 300 keV/u (early tests).
### EBIS Results and RHIC Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>RHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>Au^{32+}</td>
<td>Au^{32+}</td>
</tr>
<tr>
<td>I&lt;sub&gt;e&lt;/sub&gt;</td>
<td>10 A</td>
<td>10 A</td>
</tr>
<tr>
<td>J&lt;sub&gt;e&lt;/sub&gt;</td>
<td>575 A/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>575 A/cm&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>t&lt;sub&gt;confinement&lt;/sub&gt;</td>
<td>35 ms</td>
<td>35 ms</td>
</tr>
<tr>
<td>L&lt;sub&gt;trap&lt;/sub&gt;</td>
<td>0.7 m</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Capacity</td>
<td>5.1 x 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>11 x 10&lt;sup&gt;11&lt;/sup&gt;</td>
</tr>
<tr>
<td>% extracted ions</td>
<td>&gt; 75%</td>
<td>50%</td>
</tr>
<tr>
<td>% in desired Q</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Extracted charge</td>
<td>&gt; 3.4 x 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>5.5 x 10&lt;sup&gt;11&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ions/pulse</td>
<td>&gt; 1.5 x 10&lt;sup&gt;9&lt;/sup&gt; (Au&lt;sup&gt;32+&lt;/sup&gt;)</td>
<td>3.3 x 10&lt;sup&gt;9&lt;/sup&gt; (Au&lt;sup&gt;32+&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Pulse width</td>
<td>10-20 μs</td>
<td>10-40 μs</td>
</tr>
<tr>
<td>Rep. Rate</td>
<td>0.5-2 Hz</td>
<td>5 Hz</td>
</tr>
</tbody>
</table>
Summary of the advantages of an EBIS for the BNL Application

- An EBIS can produce any type ions – from gas, metals, etc., and is easy to switch species (pulse-to-pulse!)
- One has control over the charge state produced (easy to get intermediate charge states, such as Au$_{32}^{+}$ or U$_{45}^{+}$)
- One has control over pulse width, extracting a fixed charge – can better match to synchrotron requirements
- EBIS produces a narrow charge state distribution ($\geq 20\%$ in the desired charge state), so there is less of a space charge problem in the extraction and transport of the total current
- The scaling laws are understood
- The source is reliable, and has excellent pulse-to-pulse stability, long life
Status

• The Test EBIS performance has demonstrated all requirements, and is now being used for RHIC EBIS component testing, and RFQ beam tests.

• Commissioning of the RHIC EBIS will start this summer (but the final electron gun, collector, and full transport from collector to RFQ have already been tested).

• The RFQ and Linac are scheduled to be in place by December of 2009.

• CD-4 date for the project is September, 2010.