Automated Operation of EBIS Injector at BNL


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Outline

• RHIC and NASA Space Radiation Laboratory (NSRL)
• Motivation for automated species change:
  – Galactic Cosmic Ray (GCR) simulator at NSRL
• RHIC-EBIS Pre-injector (2 MeV/u heavy ions)
• Operation mode
  – Beam for RHIC
  – Beam for NSRL
• Operational performance
  – Reliable >100 switched/day without EBIS experts
• Summary
RHIC accelerator complex

- RHIC-EBIS supplies all heavy ions for RHIC and NSRL “simultaneously” (sequentially)
NASA Space Radiation Laboratory (NSRL)

- **Mission:** Ground based high energy ion source for space radiation research

**Galactic cosmic Ray (GCR)**

- High-energy **protons and various heavy ion species** coming from outside of solar system.
- A few MeV/u to well above 1 TeV/u, with the peak of the distributions tend to be around 1 GeV/u
- Evaluation of risk is essential for interplanetary missions beyond Earth

**How to simulate?**

- Up to 1.5 GeV/u of heavy ions and 2.5 GeV of proton from AGS-Booster
- **Mixed radiation by sequences of exposures**
The 2 MeV/u RHIC-EBIS pre-injector

- Primary (1+) ions from external ion source
  - Laser ion source (LIS) and hollow cathode ion sources (HCIS)
- Electron Beam Ion Source (EBIS) as charge multiplier
- RFQ from 17 keV/u to 300 keV/u
- Rebuncher
- IH-Linac from 300 keV/u to 2 MeV/u
- 2 debunchers
- 2 of 72.5 degrees bending magnet (1 T)

Switching between species < 1 sec after EBIS
(Due to ramping of bending magnet)
• **EBIS can switch species within 200 ms**
• EBIS runs as charge multiplier
• Primary (+1) ion beams are from external sources
  • LION (Solid target) and HCIS (gas)
• No memory effect of previous ion

**Switching time depends on eternal ion sources**
Laser Ion Source (LION)

- Laser ablation
- Pressure $< 10^{-4}$ Pa
- No coupling between beam for RHIC and NSRL
- 1+ ions
- Norm. rms emittance $0.06 \pi$ mm mrad (Good)
- 100 $\mu$A $\sim$ 1 mA
- $\sim$200 $\mu$s

Nd:YAG laser (1064 nm, 200~500 mJ/6ns)
• XY target (multiple targets on a 2D linear stage)
• **Number of targets depends on target holder**
  – Typically 10 at a time
• Pure or compound (O from alumina (Al$_2$O$_3$))
• **Switching time depends on stage motion**
  – At most 25 sec (10 mm/s now)
  – Laser spot can be shifted if faster switch is required in the future
Hollow Cathode Ion Source

- Discharge gas ions
- Metallic ion beam from cathode
- Plasma induced by cathode sputtering in a glow discharge

- Normalized RMS emittance 0.03 \( \mu \text{mrmrad} \) (Good)
- Low peak current (5~50 \( \mu \text{A} \)) and long pulse (10~40 ms).
  - “Slow injection” scheme of EBIS
- Need to replace gas or cathode to change species (~30 min)

Primary ions provided by Hollow Cathode Ion Sources
Operation mode

1 sec between beam for RHIC and NSRL

“Supercycle” = 6.6 sec

- This is the highest load for RHIC EBIS
  - 12 pulses at 5 Hz for RHIC + 1 pulse for NSRL within supercycle
  - (12-6-2 merge in AGS)
- Minimum number of pulses is
  - 1 pulse as standby + 0 pulse for NSRL
- RHIC-EBIS always switch species between RHIC and NSRL within 1 second in a supercycle
- Stable and reliable with large variation of duty and amplitude
Beam for RHIC

- 12 pulses for >30 min for RHIC fill including setup at every 0.5-20 hours
- 12 pulses for injector setup during store
- 1 pulse/supercycle in other time (standby)

MCR use a sequencer

Automatically decrease the number of cycles and EBIS cathode heater current after RHIC fill

MCR use a automated sequencer to increase the number of pulses and increase cathode heater power
### Beam operation for NSRL

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<tr>
<th></th>
<th>Sep</th>
<th>Oct</th>
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<th>Dec</th>
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<tbody>
<tr>
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<td>NSRL</td>
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- **Heavy ion beams and proton beam** from AGS-Booster
  - Proton is from 200 MeV Linac or Tandem
- **One pulse per supercycle** (~4 sec during RHC shutdown, interleaved in RHIC (6 sec) when RHIC is running)

- **NSRL or MCR switches species automatically without assistance of EBIS experts**
  - 10 species from LION
  - 2 from 2 HCISs
  - Proton

- **In GCR simulator mode, species changes is controlled by a dosimetry system at NSRL**
  - Dose on sample is precisely controlled
  - Beam cut off time is ~ms order
How to automate NSRL species change?

- Optimized parameters are “archived” for each species
- Archived setting of “next” species is restored on “next” (or background) ppm user
  - “Ppm user” contains machine parameters for different beam
- Stop EBIS electron beam to avoid failure (e.g. timing glitch)
- **Switch ppm user to activate parameter change**
- Switch species of external source, start electron beam

- Above procedures are automated by the sequencer
- **Reliable and reproducible. Once archives are created, EBIS is unattended for routine operation**
NSRL interface for fast species switch

Just need to set here

This page is not used during the execution of a GCR sequence.
A day of GCR simulator + RHIC injection

- Beam for RHIC and injector at Booster input
- > 130 species changes for NSRL
- He, O, Si, Fe from EBIS
- Proton from 200 MeV linac
Switching performance for NSRL

- Au for RHIC at Booster input

- RHIC-EBIS beam for NSRL
  - Blue: Out of EBIS
  - Red: out of IH-Linac
  - Black: after bending magnet
  - **Switching time at RHIC-EBIS is ~40 sec**
  - **No assistance from EBIS experts**

- Beam at NSRL target room
- GCR mode: Dosimetry system cut off beam to control dose on sample, and initiate species change
### RHIC-EBIS for NSRL in Run-17 and Run-18

<table>
<thead>
<tr>
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<th>Sep</th>
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#### LION

<table>
<thead>
<tr>
<th>EBIS Days for NSRL</th>
<th>Li</th>
<th>C</th>
<th>O</th>
<th>Si</th>
<th>Ti</th>
<th>Fe</th>
<th>Zr</th>
<th>Nb</th>
<th>Ta</th>
<th>Au</th>
<th>Th</th>
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<tr>
<td>Run 17</td>
<td>104</td>
<td>5</td>
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<td>20</td>
<td>38</td>
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<td>1</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>2</td>
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<tr>
<td>Run 18</td>
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<td>0</td>
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#### HCIS

<table>
<thead>
<tr>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
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<tbody>
<tr>
<td>35</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>11</td>
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</table>

<table>
<thead>
<tr>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
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<tr>
<td>35</td>
<td>8</td>
<td>0</td>
<td>11</td>
<td>16</td>
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</tbody>
</table>

- This table contains not only for user operation but set up time
- EBIS routinely provide multiple heavy ion species for NSRL simultaneously with RHIC
### Species from RHIC-EBIS pre-injector

- Charge state is adjusted to match Q/M >1/6 for RFQ injection
- This is the list of ions delivered for NSRL
- In addition, Au, Cu, Pb, U were used for RHIC.

<table>
<thead>
<tr>
<th>Species</th>
<th>Charge state</th>
<th>Bst_input n per pulse</th>
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<tbody>
<tr>
<td>He</td>
<td>2</td>
<td>9.0E+09</td>
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<tr>
<td>C</td>
<td>5</td>
<td>4.4E+09</td>
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<td>Si</td>
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<td>2.7E+09</td>
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<tr>
<td>Fe</td>
<td>20</td>
<td>8.1E+08</td>
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<tr>
<td>Au</td>
<td>32</td>
<td>1.1E+09</td>
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</table>

<table>
<thead>
<tr>
<th>Species</th>
<th>Charge state</th>
<th>Q/M</th>
<th>Confinement time (ms)</th>
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<tbody>
<tr>
<td>He</td>
<td>2</td>
<td>0.500</td>
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<td>Li</td>
<td>3</td>
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<td>B</td>
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<td>Ta</td>
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<td>Th</td>
<td>39</td>
<td>0.168</td>
<td>130</td>
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</table>
Summary

- RHIC-EBIS pre-injector is providing heavy ion beam for RHIC and NSRL
- Switching time between RHIC beam and NSRL beam is ~1 sec
- Automated fast species change and GCR simulator mode for NSRL has been developed and now routinely used
- The number of species change can be > 100
- Available heavy ion species to switch is typically 12 (10 from LION and 2 from 2 HCISs)
- NSRL switches species at any time without EBIS experts
- Switching time for NSRL at RHIC-EBIS pre-injector is ~40 sec
- Reliability is very high and RHIC-EBIS is unattended for normal operation
End
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 $\sim (0.5 - 0.8) \times$ (# 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 $\sim$ independent of species or charge state!
- Switching time $< 200$ ms
- No memory effect from previous species with external ion injection
Electron Beam Ion Source

Max. Electron current 7~10 A
Length of ion trap 188 cm
Electron energy 20-24 keV
Electron density in trap 300—500 A/cm²
Length of ion trap 188 cm
Max. solenoid fied 5 T

Very reliable, excellent pulse-to-pulse stability, and long life time.
Laser Ion Source is the key for fast species change

Charge state 1+

- **Any solid target** by laser ablation in vacuum
- $10^8 \sim 10^9$ [W/cm$^2$] for 1+ ions
- Beam out of LION
  - $100 \mu A \sim 1$ mA, $\sim 200 \mu s$ ("fast injection" scheme of EBIS)

Low emittance

<table>
<thead>
<tr>
<th>Au beam Norm. RMS</th>
<th>X</th>
<th>0.067 $\pi$ mm mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y</td>
<td>0.058 $\pi$ mm mrad</td>
</tr>
</tbody>
</table>

Plasma transport by solenoid
Beam operation for RHIC

- RHIC runs from around January to the end of June
- RHIC-EBIS provides beam for >30 min to refill RHIC at every 0.5-20 hours
- For RHIC injection, 12 pulses at 5 Hz within a supercycle (overall repetitive sequence of the accelerator facility) of 6 s
- 12 pulses are also used for injector setup during store
- Other time, EBIS runs at 1 pulse/supercycle as standby mode to keep the system up. Cathode heater current is reduced to save life time

- Duty changes a lot from 1 to 12 cycles per supercycle (6 s)
- More chances of electron beam fault
- **MCR use the automated sequencer to change from standby to operational mode without EBIS experts’ help**