Injection and Ion Extraction Techniques at the Brookhaven High Current EBIS*

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Brookhaven National Laboratory

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Talk Outline

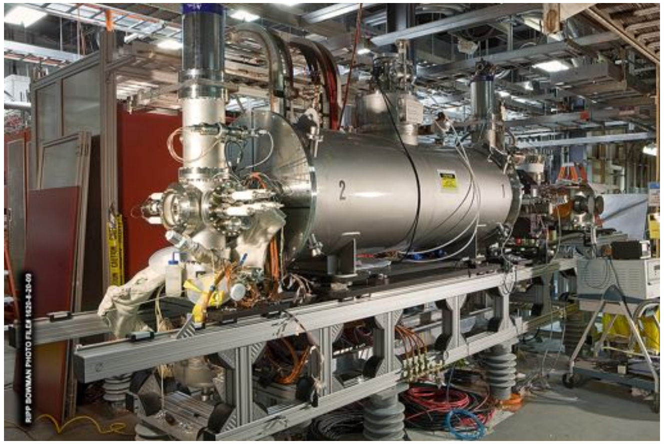
RhicEBIS Overview & Performance Recap

RhicEBIS Development Goals

Partitioned EBIS Trapping & Extraction

The EBIS replaces the Tandems and needs to serve two major users simultaneously

EBIS & RFQ & Heavy Ion Linac



Au, Fe, He, U, etc.

Relativistic Heavy Ion Collider

NASA Space Radiation Lab

In addition the EBIS must be able to diagnose operating performance and prepare for new beams, parasitically.

These considerations lead to a choice of electrostatic beam transport and switching in LEBT and a pulsed HV EBIS platform

Rhic EBIS Facility

High current EBIS multiply charge ion source on pulsed electrostatic platform

- Ion injection (primary mode)
- Neutral gas injection (secondary mode)

External Ion Sources for 1+ "seed" ions

- Laser Ion Source (mostly solid targets)
  - Fast injection mode
  - Fast target (species) switching
- Hollow Cathode Ion Sources (solids, gases, liquids)
  - Slow injection (accumulation) mode

RFQ

- Input 17 keV Nucleon
- Output 300 keV/Nucleon

LINAC

- Output 2 MeV/Nucleon

Project Goals Attained

Provide a variety of ion species in multi-milliampere pulses (10 - 40 microseconds) in 5Hz pulse trains for RHIC injection. (corresponds to ~3.4 E9 Au32+ ions per pulse)

Provide rapid switching of a variety of species to NSRL

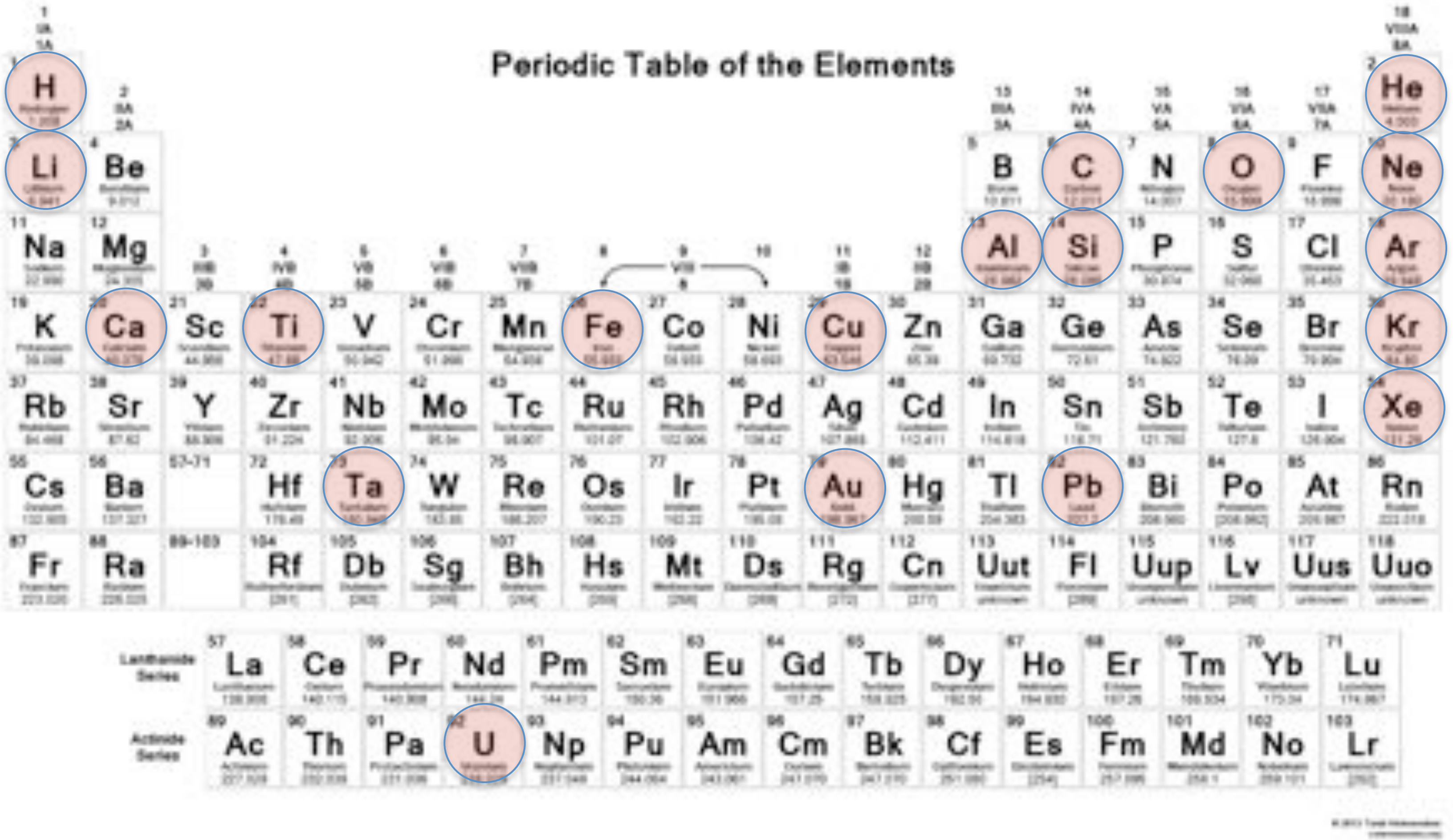
Preloaded Laser Ion Source Target system

Quasi - Simultaneous operation for RHIC Injection, NSRL and Setup tuning.

Switching between preloaded species requires 1 second due to HEBT limitations

(up to 3 different species in 5Hz pulse trains have been supplied to accelerator during a 5-7 second supercycle)

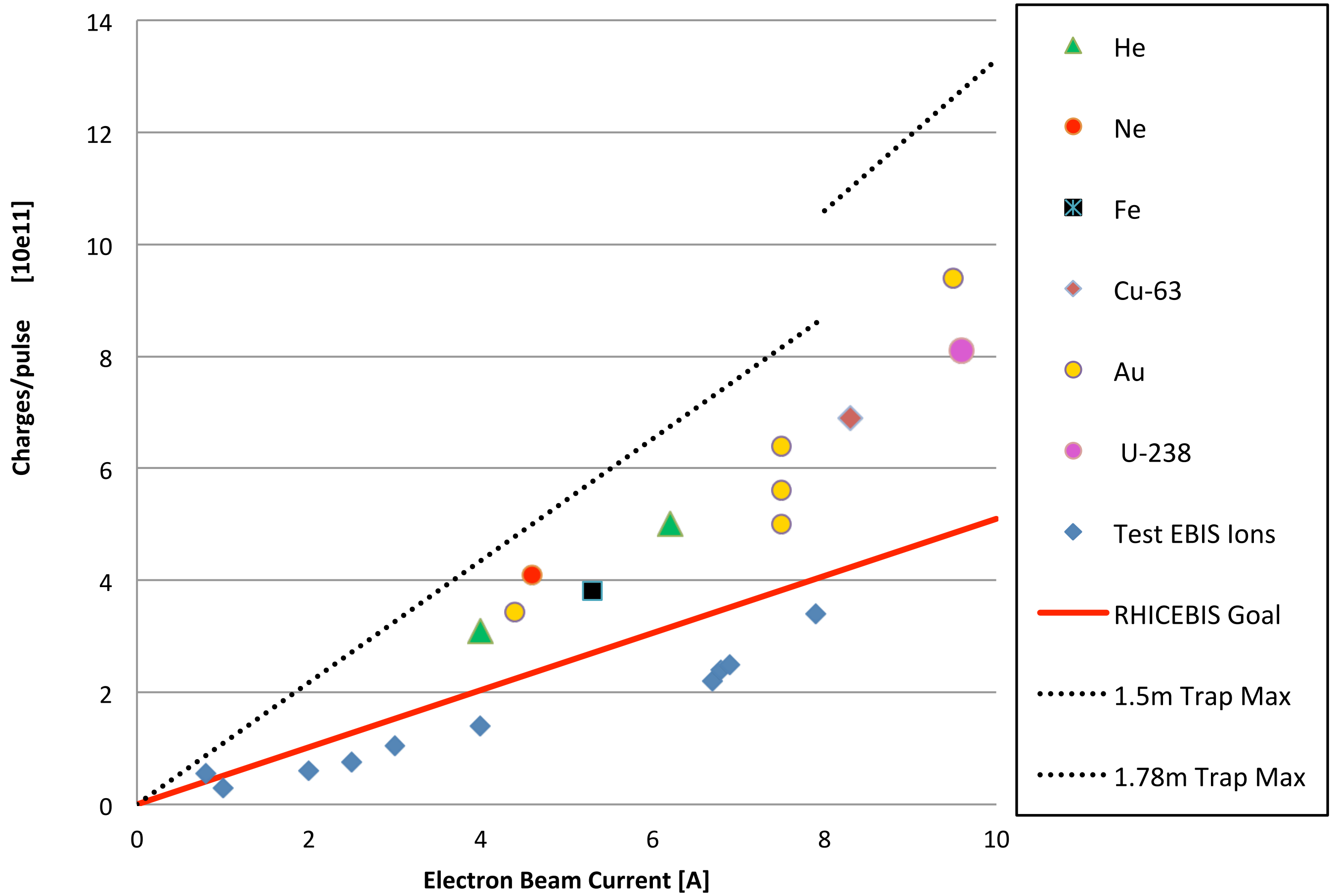
EBIS beams run to date



D, 3He^{2+}, 4$He^{1+,2+}$, Li^{3+}, C^{5+}, O^{7+}, Ne^{5+}, Al^{5+}, Si^{11+}, Ar^{11+}, Ca^{14+}, Ti^{18+}, Fe^{20+}, Cu^{11+}, Kr^{18+}, Xe^{27+}, Ta^{38+}, Au^{32+}, Pb^{34+}, U^{39+}

1 second switching between species (2, or more), alternating
<30 second switching among almost any 10

Ion yields from EBIS

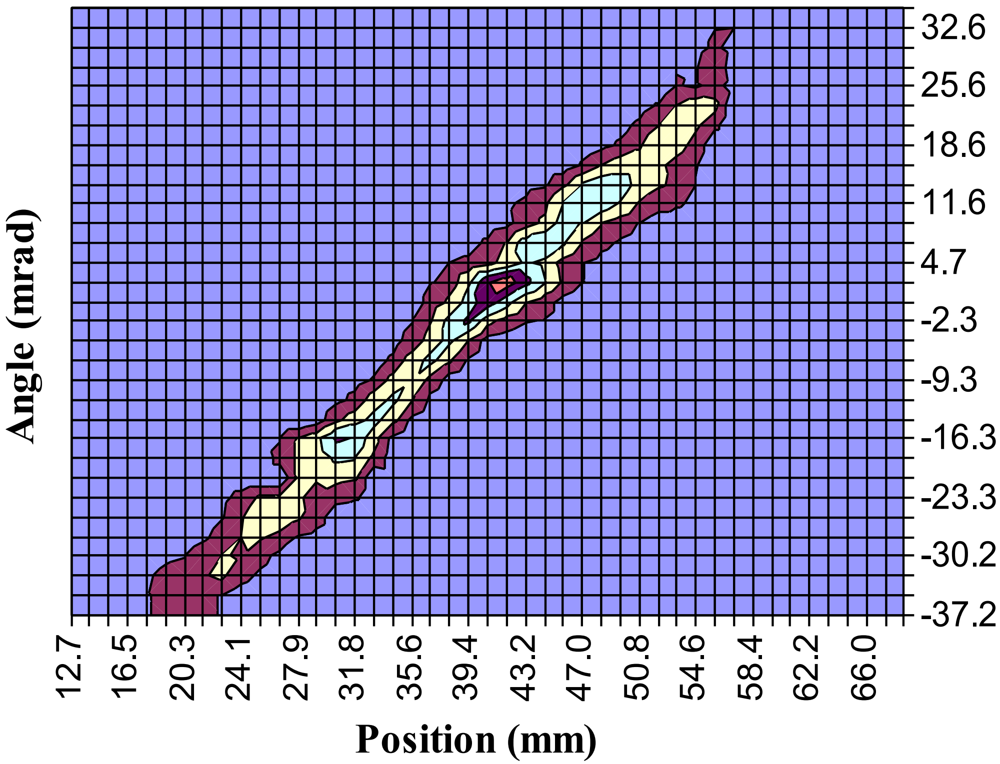


Dotted line is 100% neutralization of the electron beam space charge. Red line is 50% neutralization (design value)

(Jump in capacity at 8-10 A represents a lengthening of the trap)

EBIS source *charge* out exceeds the design value, but the % in desired charge state is lower than design. The result is that the *number of ions in the desired charge state is ~ the design value*.

Measured Emittance for a 1.7mA Gold Beam



Emittance of a 1.7 mA extracted beam from EBIS, with Au injection:

ε (n, rms)= 0.1 π mm mrad.

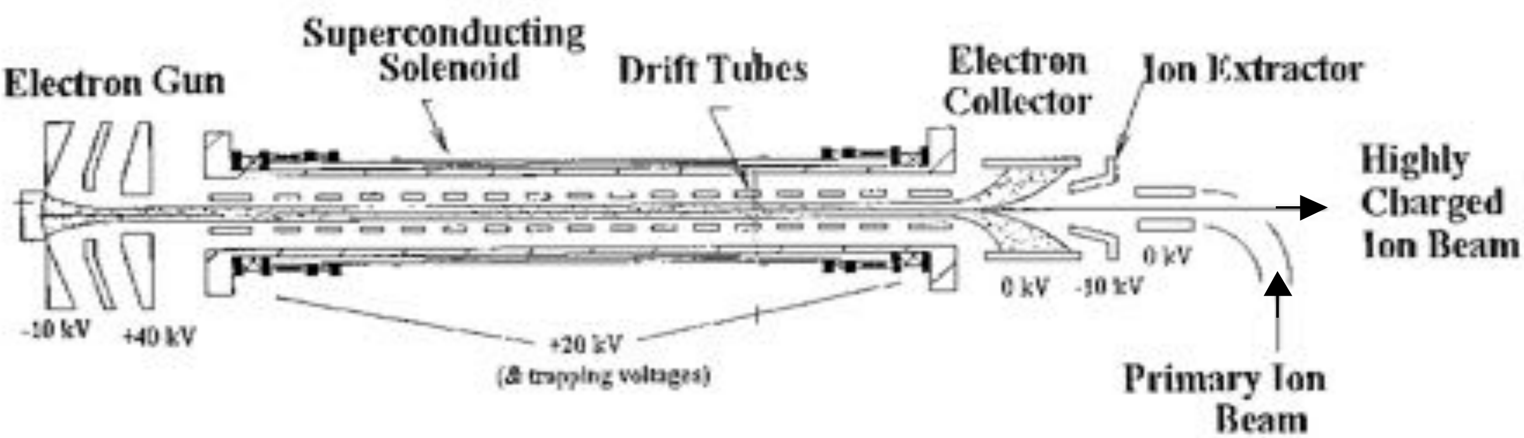
All charge states, peaked around Au^{25+}.

The emittance of light ions from EBIS is expected to be less due to less heating by the electron beam during relatively short confinement times necessary to reach charge states of interest.

EBIS as a RHIC Preinjector

- EBIS operates 7 days/week, 24 hours/day, for months at a time, very often with no operator present.
- First RHIC run with Uranium collisions
- First RHIC run with Au-Cu collisions
- Au - 3He
- Polarized p - Al (polarized protons not from EBIS)
- Goals were achieved for RHIC luminosity and bunch intensity - with the addition of bunch merging and higher duty factor EBIS operation.
- No major downtime from the EBIS preinjector
- Excellent stability

EBIS principle of operation



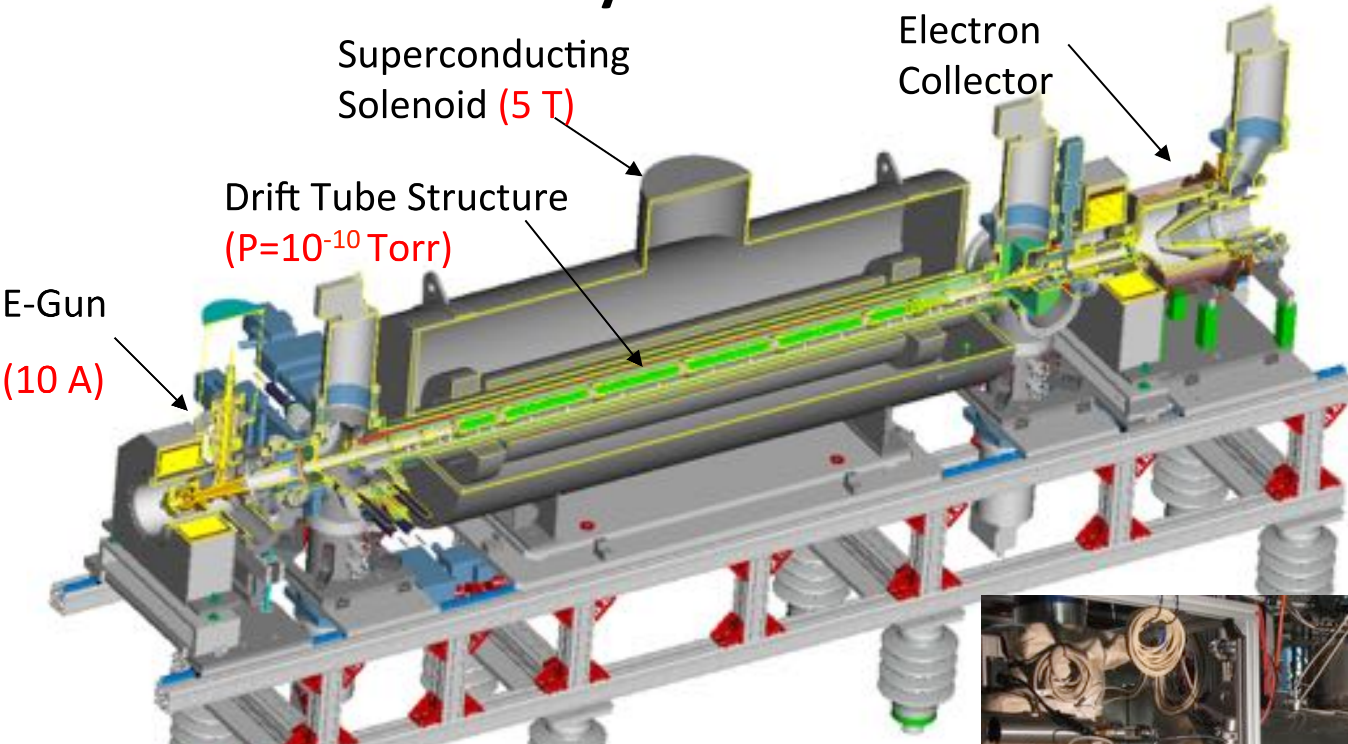
Yield of ions in charge state q:

$$N_q = \frac{I_e \times L}{q \times \sqrt{V_e}} \times K_1 \times K_2$$

I_e=electron beam current　　V_e=electron beam voltage　　L=trap length
K_1=neutralization factor　　K_2=fraction in desired charge state

Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrode electrostatic potentials.
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) ~ independent of species or charge state!

EBIS Source Assembly



Parameter		RHIC EBIS
Max. electron current	I_{el}=	10 A
Electron energy	E_{el}=	20 keV
Electron density in trap	j_{el}=	575 A/cm^2
Length of ion trap	l_{trap}=	1.5 m
Ion trap capacity	Q_{el}=	1.1x10^{12}
Ion yield (charges)	Q_{ion}=	5.5x10^{11} (10 A)
Yield of ions Au^{32+}	N_{Au}^{32+}=	3.4x10^9

EBIS: Accumulator and Charge State Multiplier with a widely programmable output pulse width

Typically operation is with ion injection from external sources:

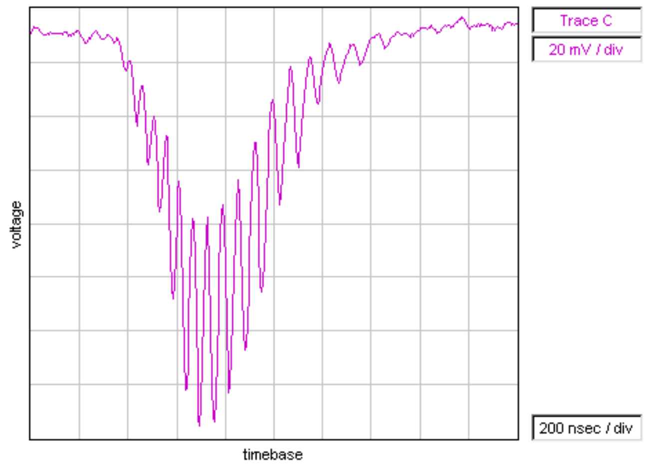
Fast injection: Laser Ion Source (LION) , ~100's uA – 1mA , 10-200 us

Slow injection: HCIS, 1-10's uA, 10-40 ms

(internal gas injection can be used in special cases)

Widely variable EBIS extraction pulse width 5uS to greater than 50ms possible

Booster/AGS/Rhic injection typically 5-40 us (High Intensity)



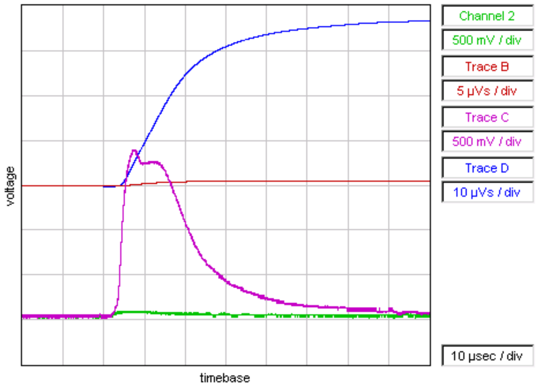
Above: Au Time-of-Flight Spectrum (Reflex mode – channeltron EM) Max peak is Au32+

Pure Beams (low contamination by unwanted ion species)

High utilization of relatively low charge capacity

Lower space charge beam transport to RFQ

Note very low background contamination characteristic of EBIS



Au pulse (all charge states)
With external Au1+ ion injection:

ChC Magenta **3.5mA**, 1 mA/div, 10 µs/div

ChD Blue: **70nC** , 20uVs/div

Without external ion injection

Ch2 Green: **0.2mA**, 1 mA/div, 10 µs/div

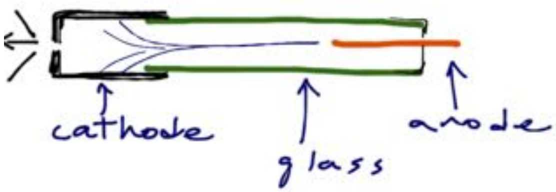
ChB Red: **1nC** , 10uVs/div

External 1+ ion production to feed the EBIS trap

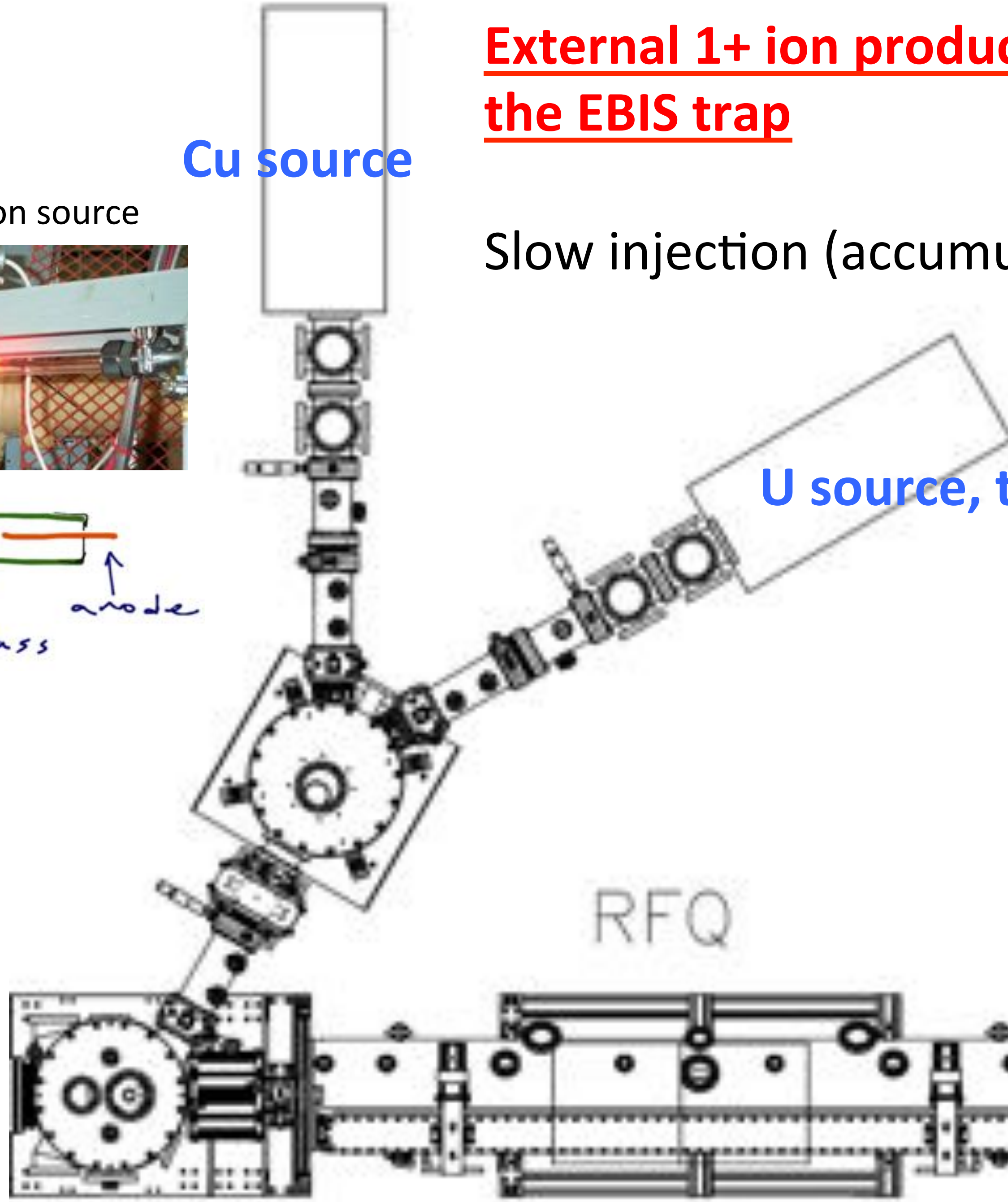
Slow injection (accumulation mode)

HCIS

Hollow cathode ion source

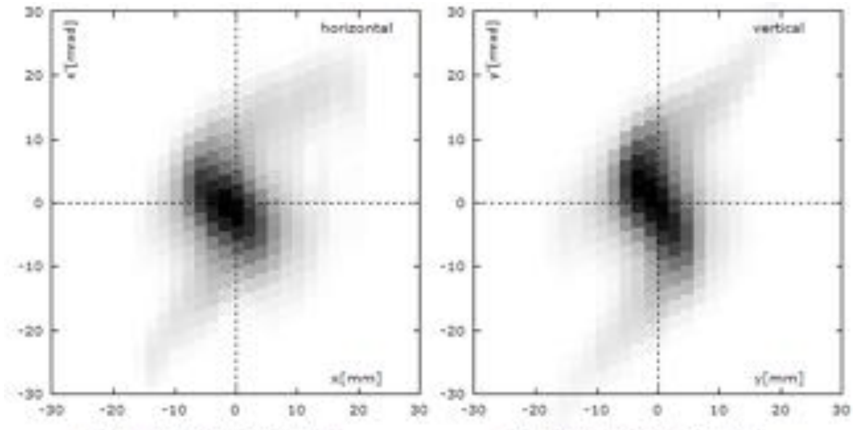


EBIS is a "charge breeder" of the injected 1+ ions



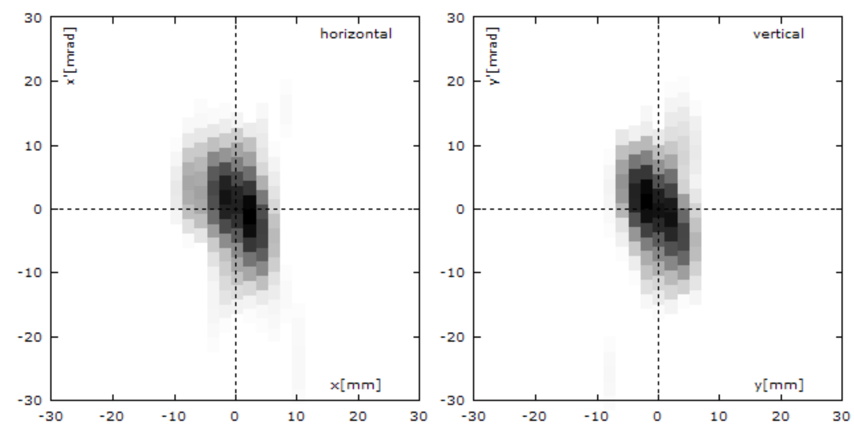
1+ Ions into EBIS

Pepperpot emittance measurements of injected 1+ ions



Emittance at the exit of the LEBT chamber, Cu^{1+}, 11 keV, 10 μA.

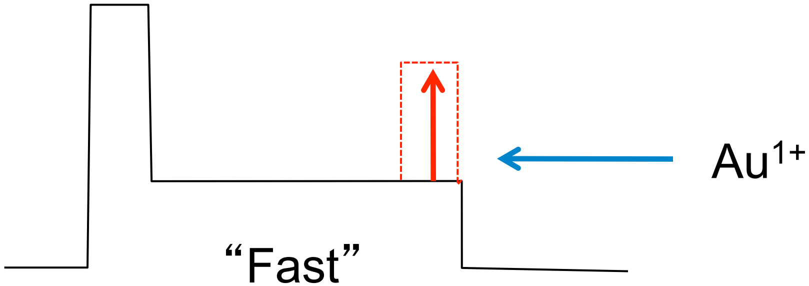
Aberrations observed when the beam fills the quadrupole aperture.

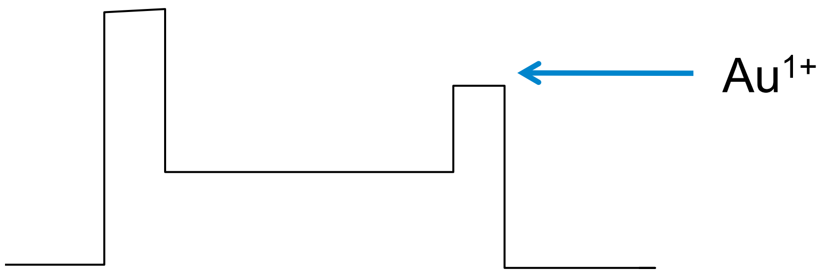


Emittance at the exit of the LEBT chamber when the beam is collimated between the ion source and the first quadrupole.

Output emittances with collimation are ≤0.02 π mm mrad, norm., rms.

INJECTION



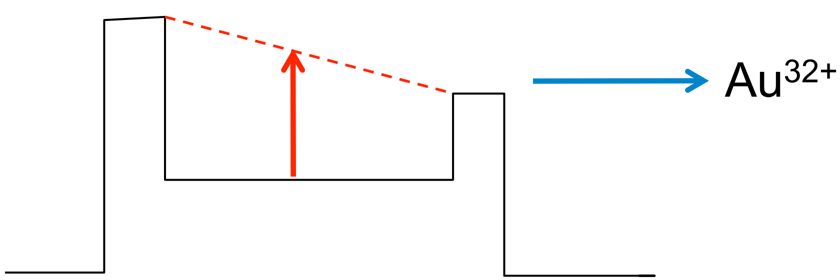


"Slow" or continuous

Fast injection – close the exit barrier to efficiently trap one "round-trip" worth of 1+ ions (~100-300 µs)

Slow injection – exit barrier is set just below the ion injection energy, such that if an ion goes from 1+ to 2+ before exiting, it will remain trapped.
Lower efficiency, but can inject for 10's of ms.

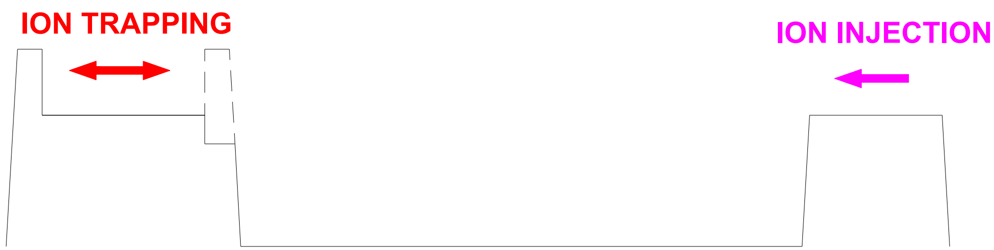
EXTRACTION



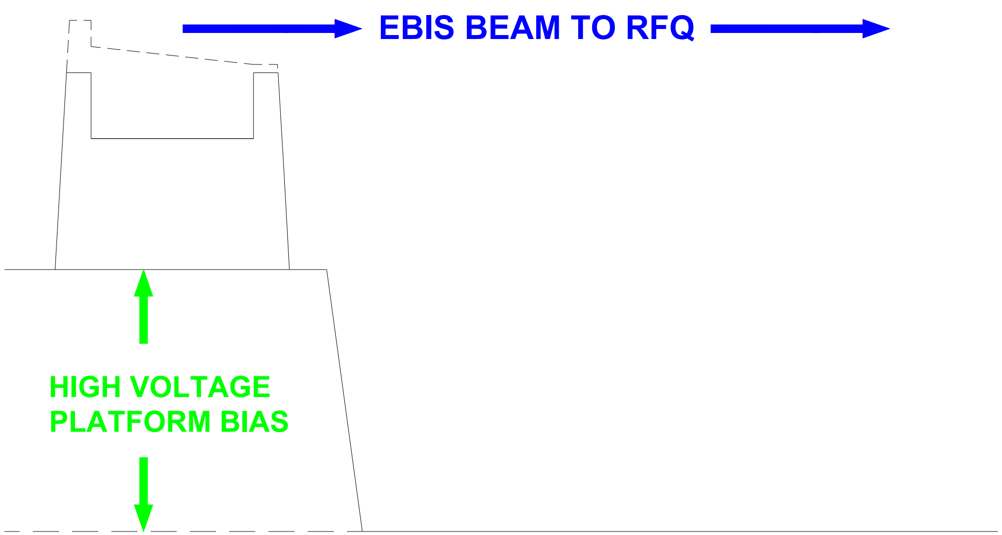
Fast – ~30 µA of Au^{1+}, ~100 µs
>500 µA of C^{1+}, ~300 µs

Slow - ~10 µA of either, but
~10 ms Au^{1+} to ~60 ms C^{1+}

Ion Elevators: Pulsed High Voltage Platforms



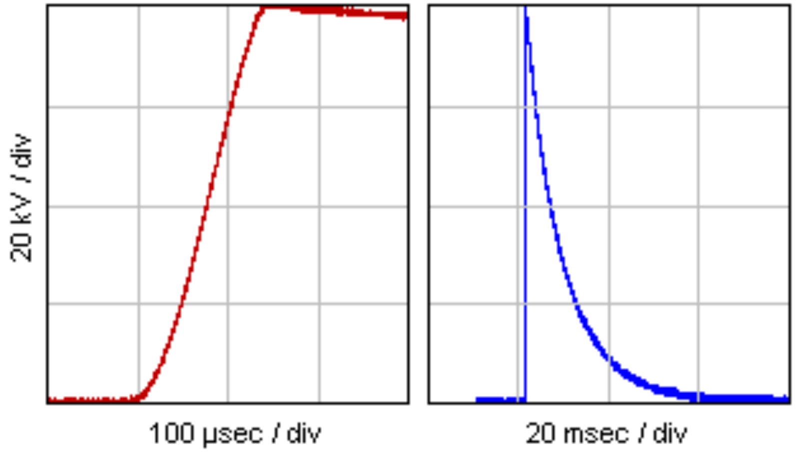
During injection and confinement the RHIC EBIS operates at ground potential.



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

(Platform pulsing is also useful for injection and TOF energy adjustments)

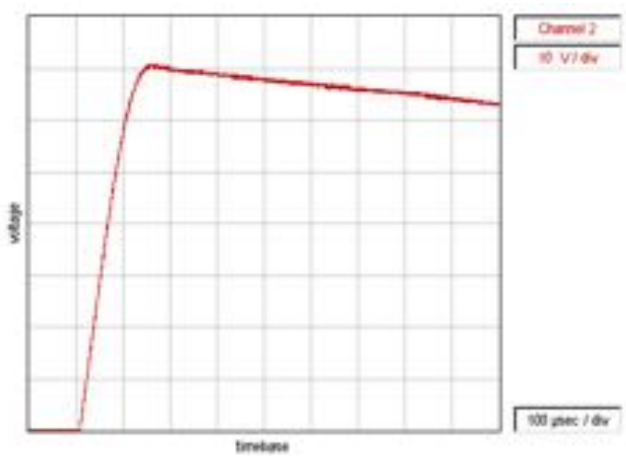
HV Platform Pulsing for EBIS ion beam injection into RFQ



80kV pulsing of Test EBIS Platform:

–100µs/div shows rise time and Flat Top (Far Left)

–20ms/div shows recovery to ground between EBIS cycles. (maximum EBIS Repetition frequency is 5Hz)



RHIC EBIS Platform pulsed to 100kV
(baseline is offset 30V below screen lower limit)

Red Trace: Platform potential (1V=1kV)

Horizontal scale is 100µs/div

20100104-04

Laser Ion Source (LION)

(M. Okumura, T. Kanesue)

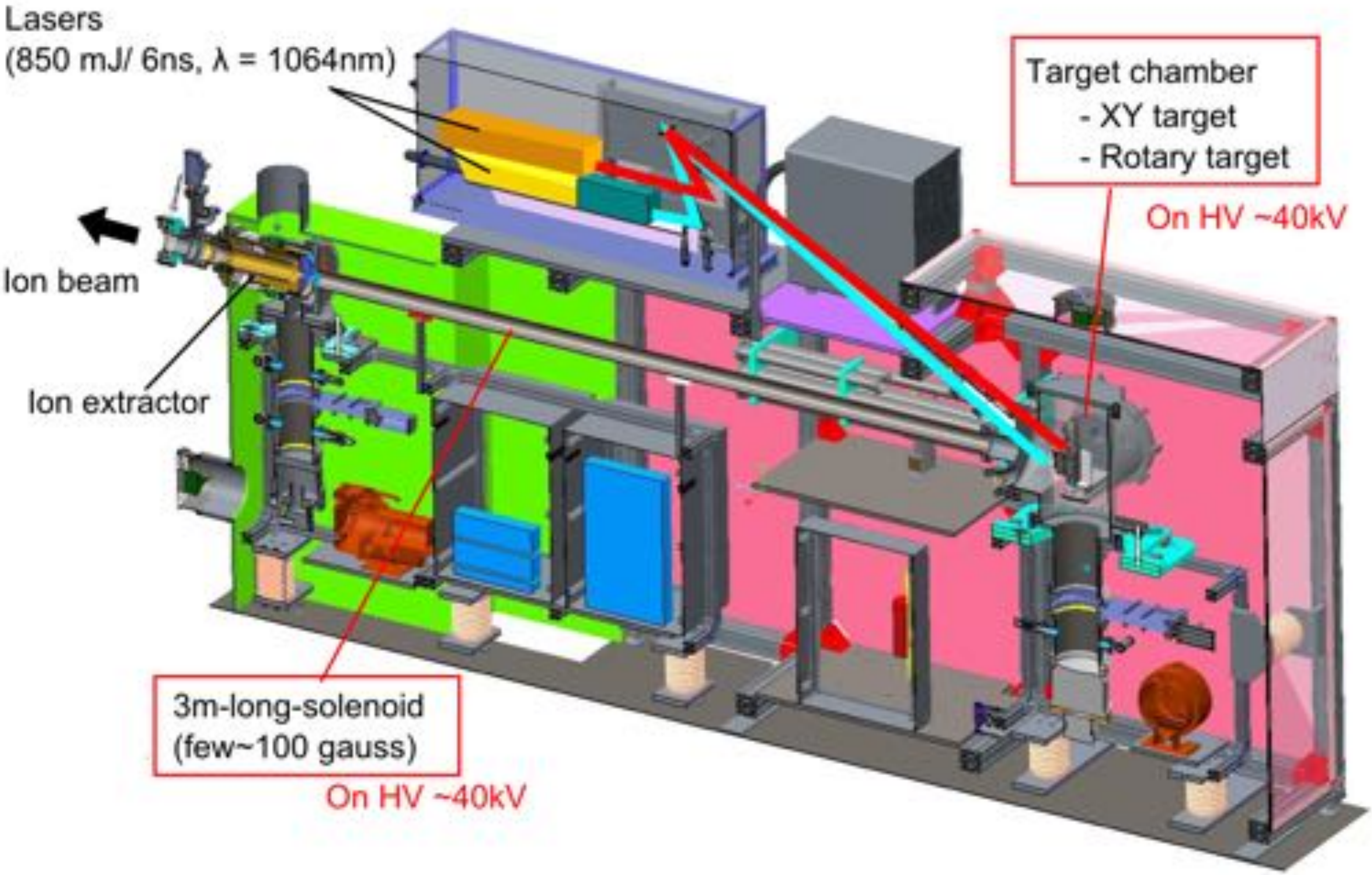
- One key factor in its role as reliable injector for the RhicEBIS, is that LION is the first operational Laser Ion Source with solenoid confinement of the ablation plasma. This keeps the extracted current high while allowing for a relatively long ion beam pulse.

- Optimized for 1+ ion production from solid targets
- Pulse widths from 10-200us (single laser pulse)
- Intensities ~ 100 microA to several mA
- Excellent pulse to pulse stability
- Fast switching between targets for species change
- LION has provided Li, C, Al, Si, Ca, Ti, Fe, Ta, Au
- High brightness: 0.043 π mm mrad rms (Au 120 μA)

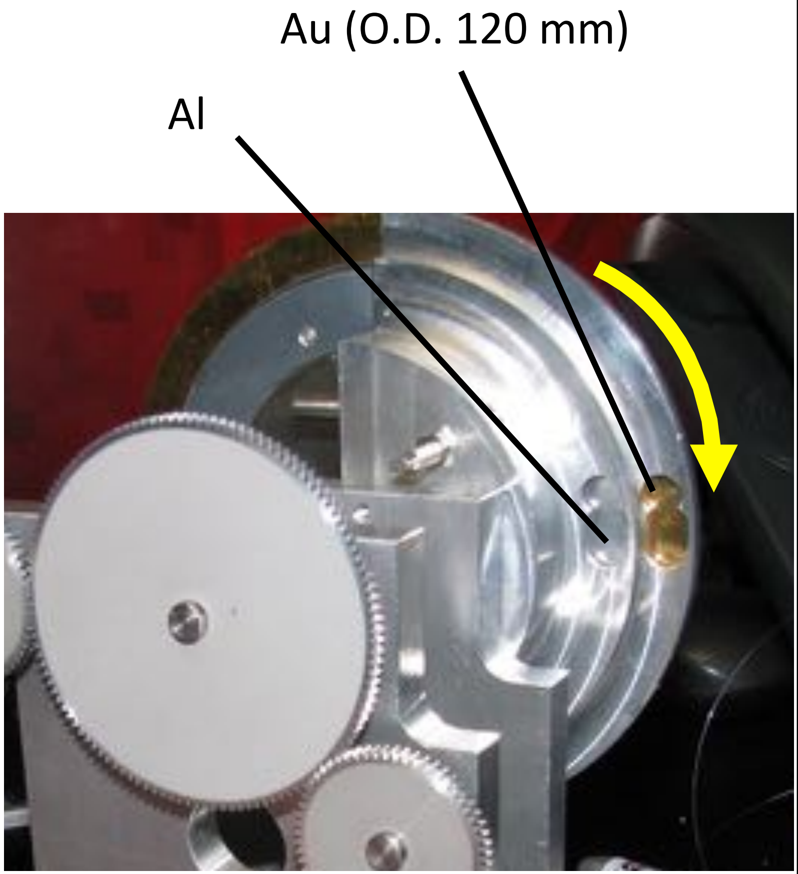
Fast injection: Short, injection time, high currents, relatively effiecient barrier based capture allows EBIS to produce narrow charge state distribution at low confinement time, e.g. Al5+

LION Key Features:

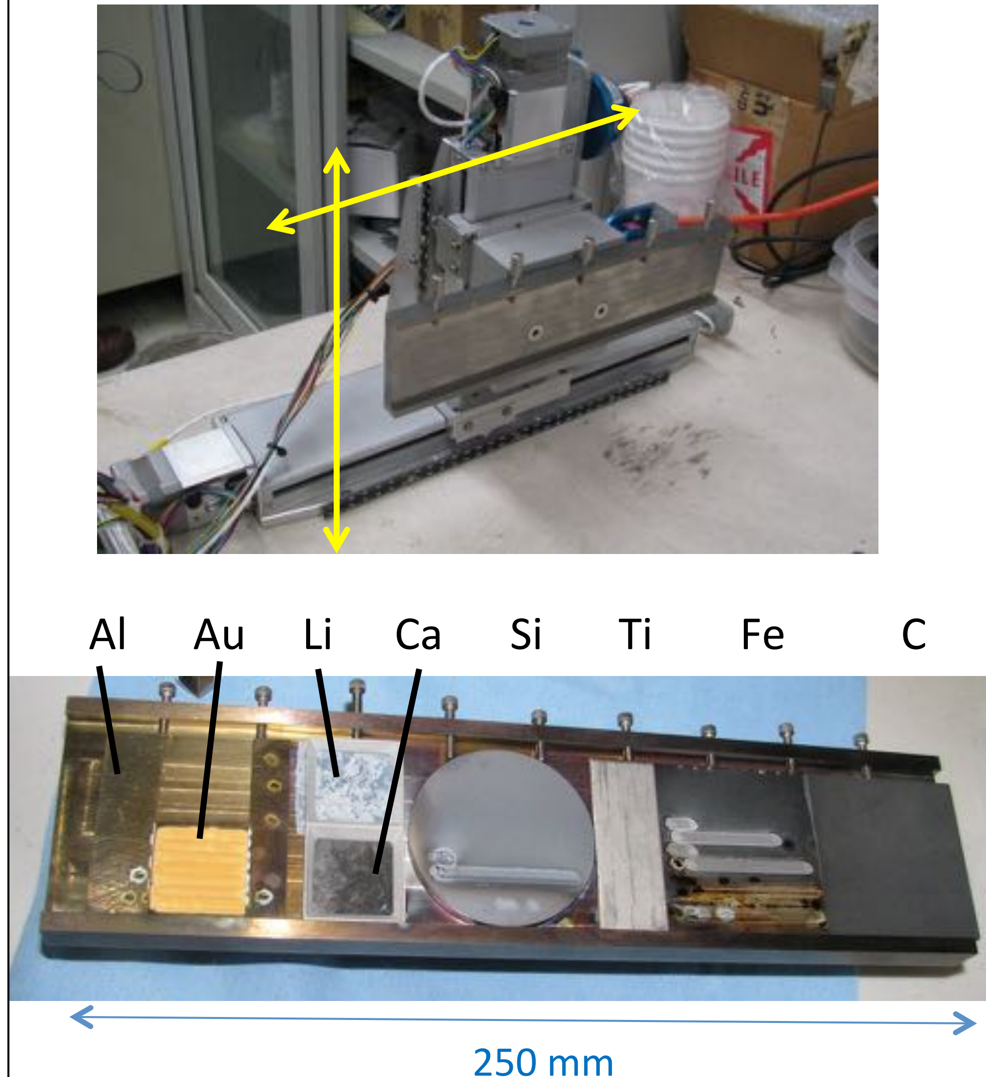
- 3 meter drift region with solenoidal confinement of plasma
- 2 Lasers and 2 targets systems for injection into RhicEBIS to permit *quasi-simultaneous* RHIC and NSRL operations.



Rotary target for RHIC



XY target for NSRL



Two Independent target systems with two dedicated lasers provide two different species of beams, almost simultaneously and allow switching to new beams within a few seconds.

RhicEBIS Charge Breeding of Stable Isotopes

Maximize output in single q/m species for injection into the AGS Booster ring.
(Seed ions typically not rare, space charge transport at low energy problematic)

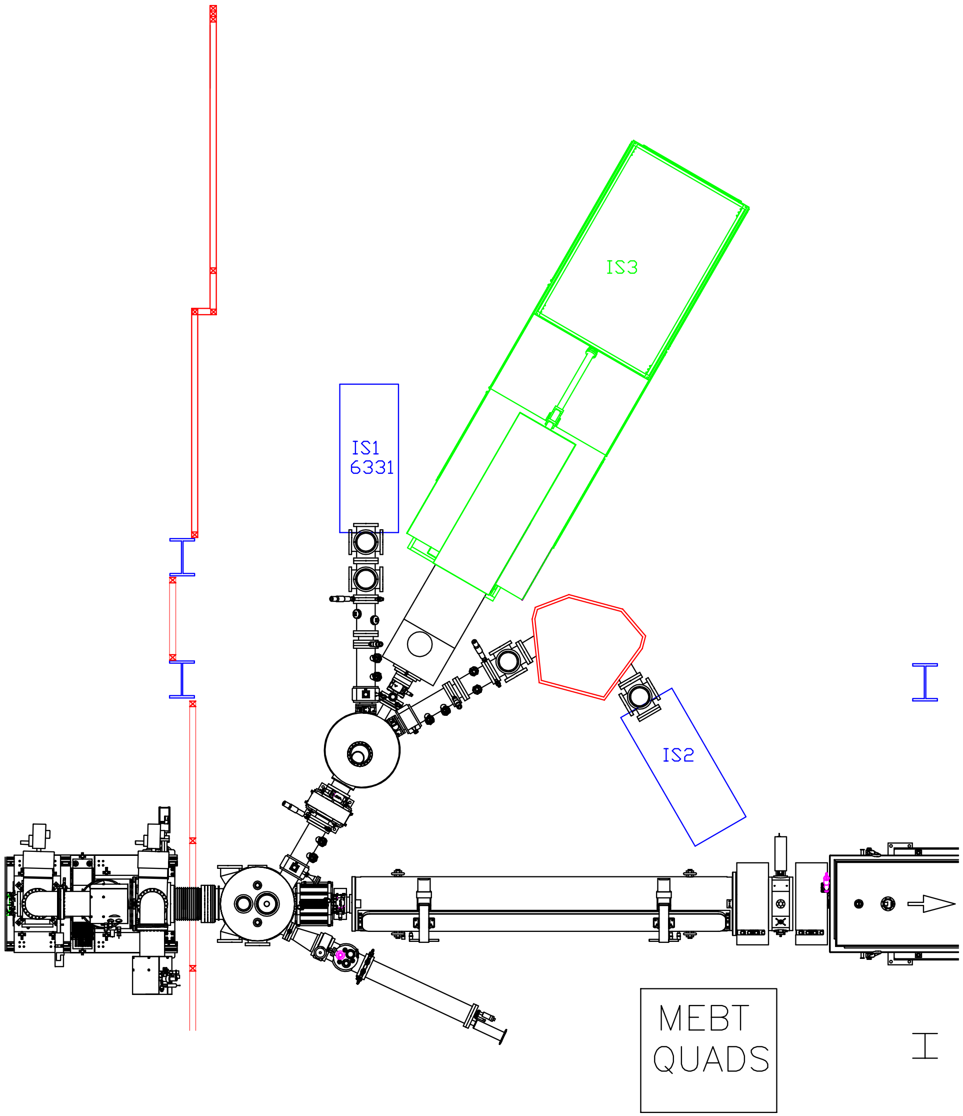
Avoid Wasting Limited EBIS Capacity:
Use isotopically pure or at least enriched material when possible

Proposed Isotope Separation for external ion sources

Proposed Efficient Neutral Gas injection system

(Breeding to closed shells is not usually effective in our electron beam current and ion charge state range)

Isotope Separator (possible near future upgrade)

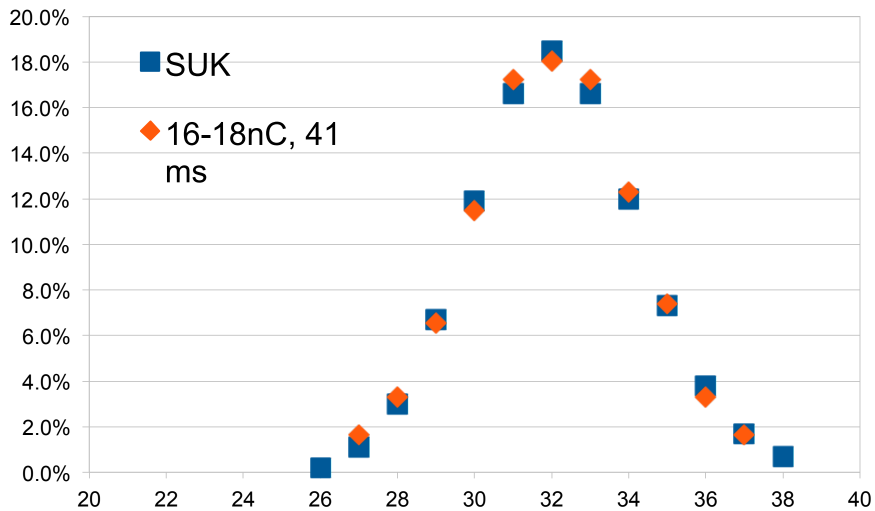


At RhicEBIS we also use wien filters to separate beams of different atomic species after each HCIS. This allows us to provide pulse to pulse switching between working gases such as He, Ne, Ar, Kr, and Xe and Solid elements such as Cu, Fe, Pb, and Au.

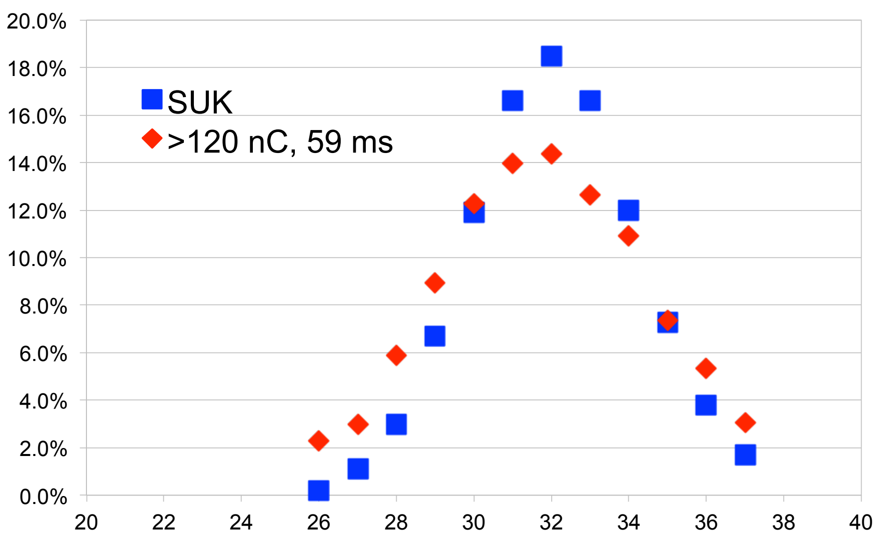
Use of a bending magnet after one of the HCIS would allow us to separate Isotopes of 1+ ions of a given species such as Xe or Zr, effectively boosting the output from EBIS.

(This can work well for slow mode injection in which the EBIS accumulates relatively weak beams).

Broadened Distribution peaked at Au32+ above ~25% neutralization



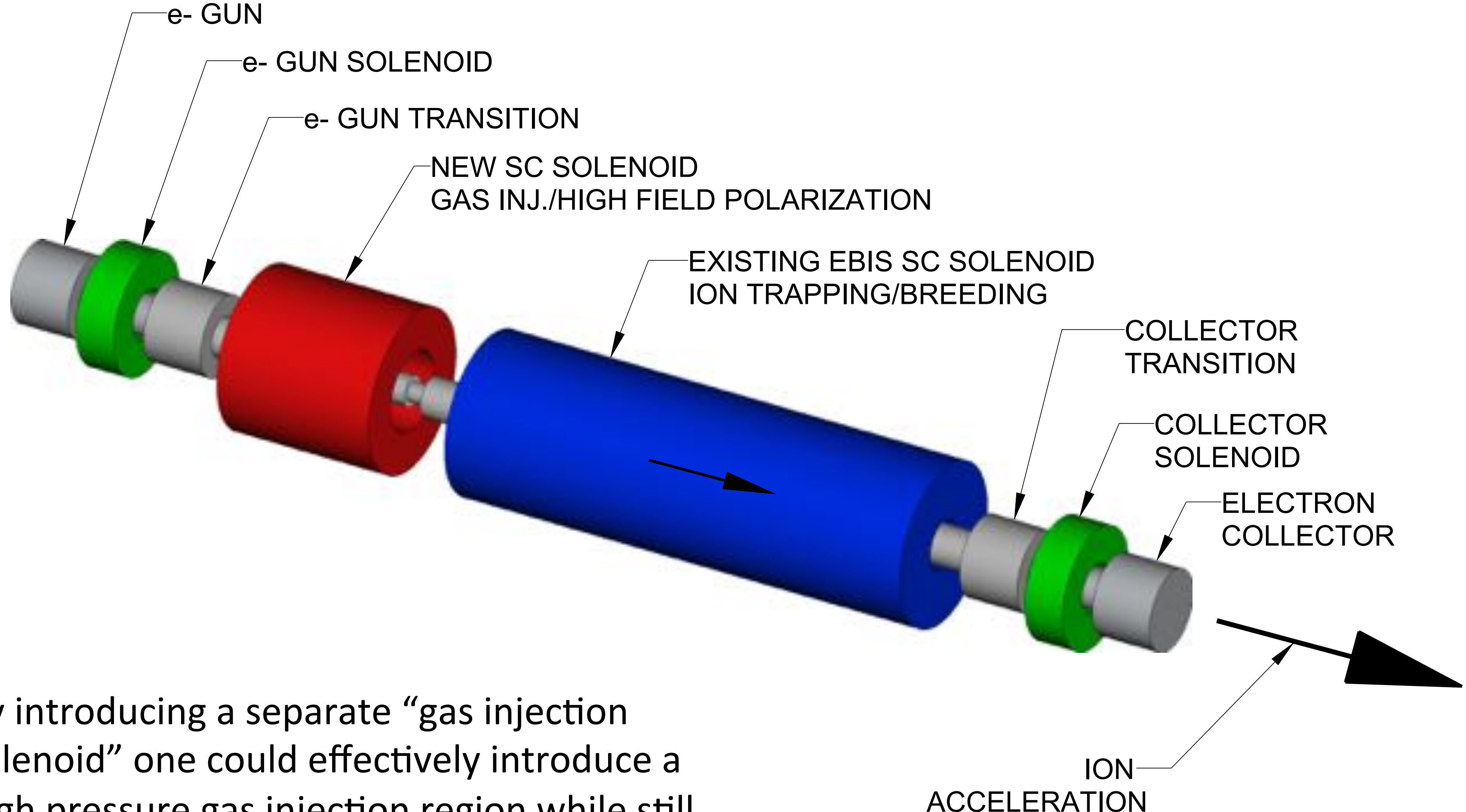
Test at reduced charge - measured distribution matches calculated



Normal running at >50% of capacity gives ~14% in desired charge state vs. 18.5% calculated.

Au ions - measured charge state distributions (orange), vs. calculated (blue, R. Becker code), which assumes 100% overlap of ions with electron beam

$^3He^{2+}$ Polarized Ion Production in EBIS – (proposed)

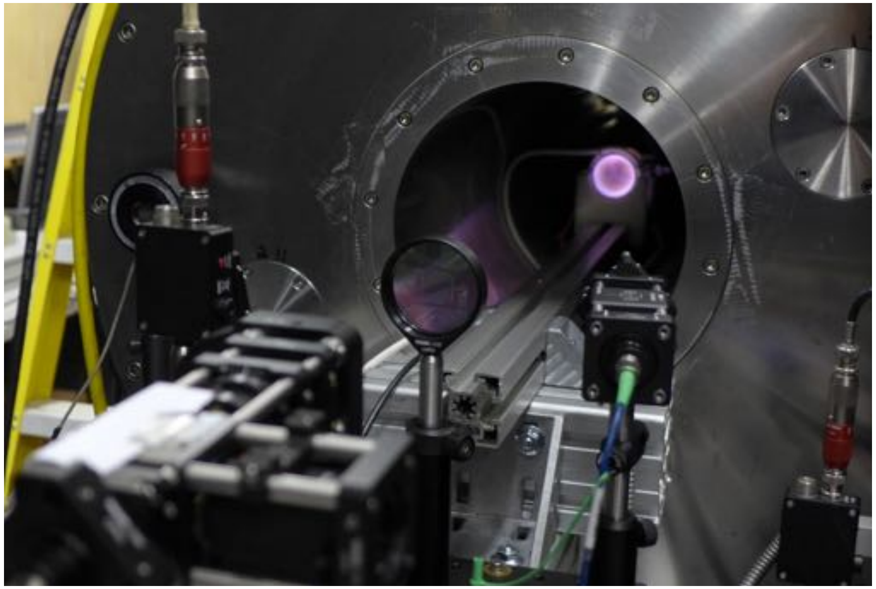


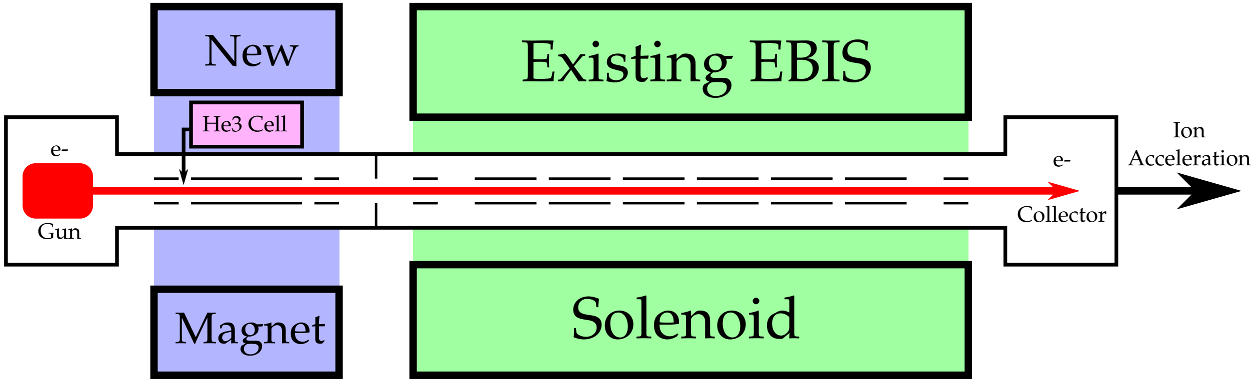
By introducing a separate "gas injection solenoid" one could effectively introduce a high pressure gas injection region while still maintaining a very low pressure existing trap region in which ionization to high charge state 3He2+ would occur with high efficiency.

High field Polarization Concept and Testing

J. Maxwell, C. Epstein, R. Milner(MIT)

J. Alessi, E. Beebe, A. Pikin,
J. Ritter, and A. Zelenski (BNL)

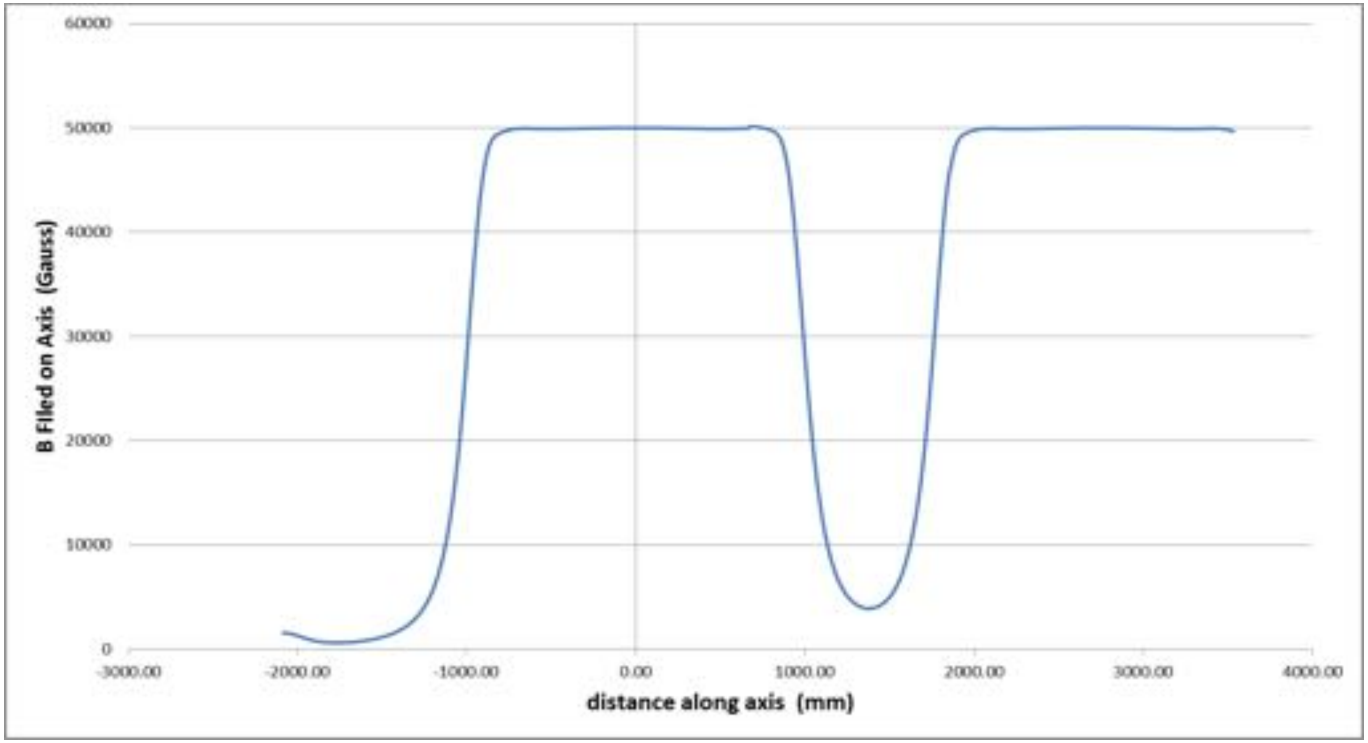




Conceptual diagram of EBIS with new magnet module, allowing high field polarization of 3He

RhicEbis Axial Magnetic Field with Identical main solenoid inserted

(5T each, Warm Bore 205mm, L=2300mm ---- shown with Gap=46cm)

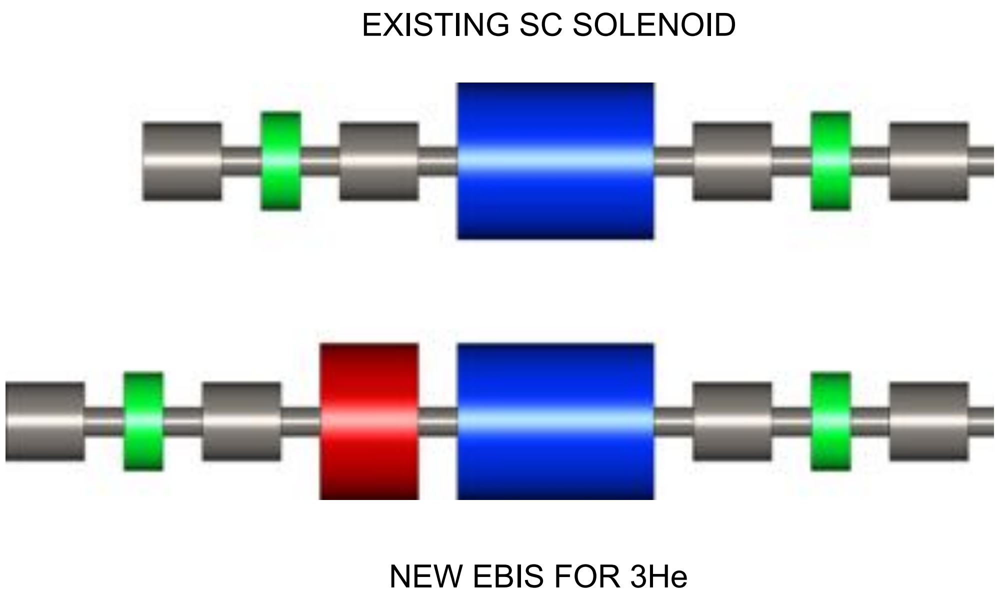


Gas would be polarized in the first superconducting solenoid and injected into the electron beam using a simplified. The ions travel along the beam to the second solenoid (existing EBIS trap) as 1+ ions using the electronic injection method, by suitable adjustment of drift tube voltages.

Nominal electron beam size based on 100A in existing gun coil:

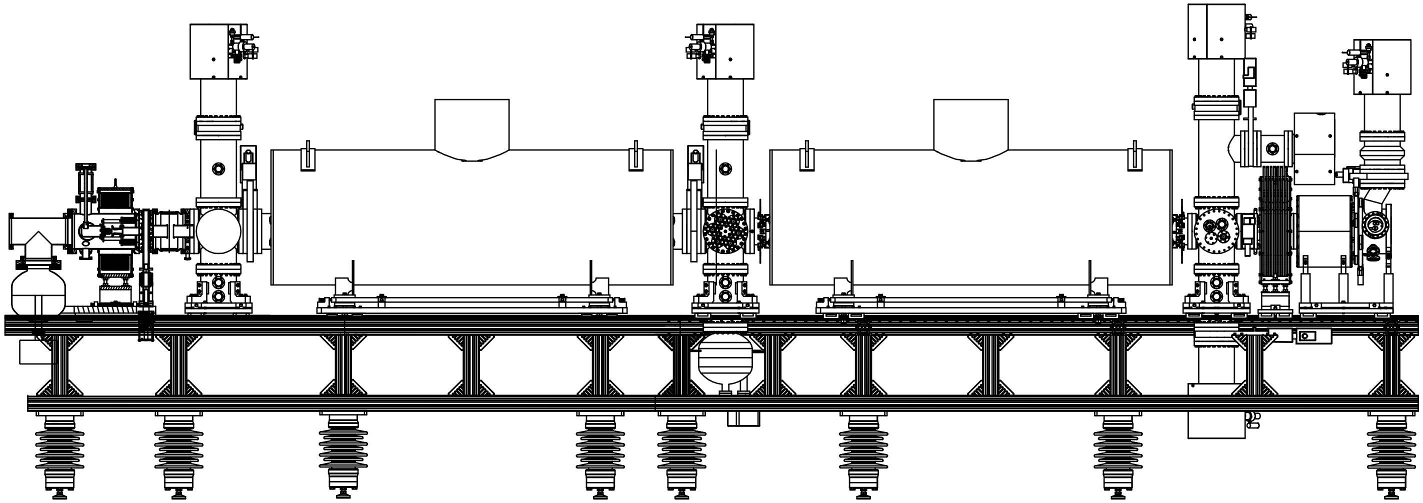
5T 1.6 mm (diameter)
2T 2.5 mm
0.5T 5 mm
0.4T 5.4 mm

Gas Injection Solenoid Option for Polarized 3He Source



Electron Beam Launching and Collection Modules would remain the same.
Addition of closely coupled solenoid containing reservoir vessel for high field polarization of 3He and pulsed gas valve.

Extended EBIS Design Concept



Two closely coupled reinforced RhicEBIS solenoids on the same axis could yield twice the charge capacity compared to the present RhicEBIS. **[This would give increased trap length without requiring one very long solenoid as required for the classical EBIS configuration]**

The electron gun and collector remain the same. **[Same electron beam power]**
(Similar to doubling of length from TestEBIS prototype to RHICEBIS)

Upcoming RHIC EBIS development work focused on increasing extracted ion intensities for RHIC (Au32+, etc). Should be consistent polarized 3He2+ capability.

See for example:
“Tandem EBIS” A simple concept for producing a longer EBIS region trap using existing, loosely coupled solenoids: HIAT2012 (poster)- A. Pikin, et. al.

“Intense Pulsed Heavy Ion Beams Production by EBIS and its Future Development“ New concept for internal polarization and 3He2+ production, closely coupled superconducting solenoids, and serial/parallel module solenoid configurations to provide intense beams and risk reduction (parallel configuration):
ICIS2015 (Invited Talk)- E. Beebe, et. al.

Increased Repetition Frequency by Long Trap Partitioning at Moderate Current Densities

High Capacity (i.e., high electron beam current) EBIS sources using very high electron beam current density (~5000 A/cm2) are desirable to reach high charge states using short confinement times.

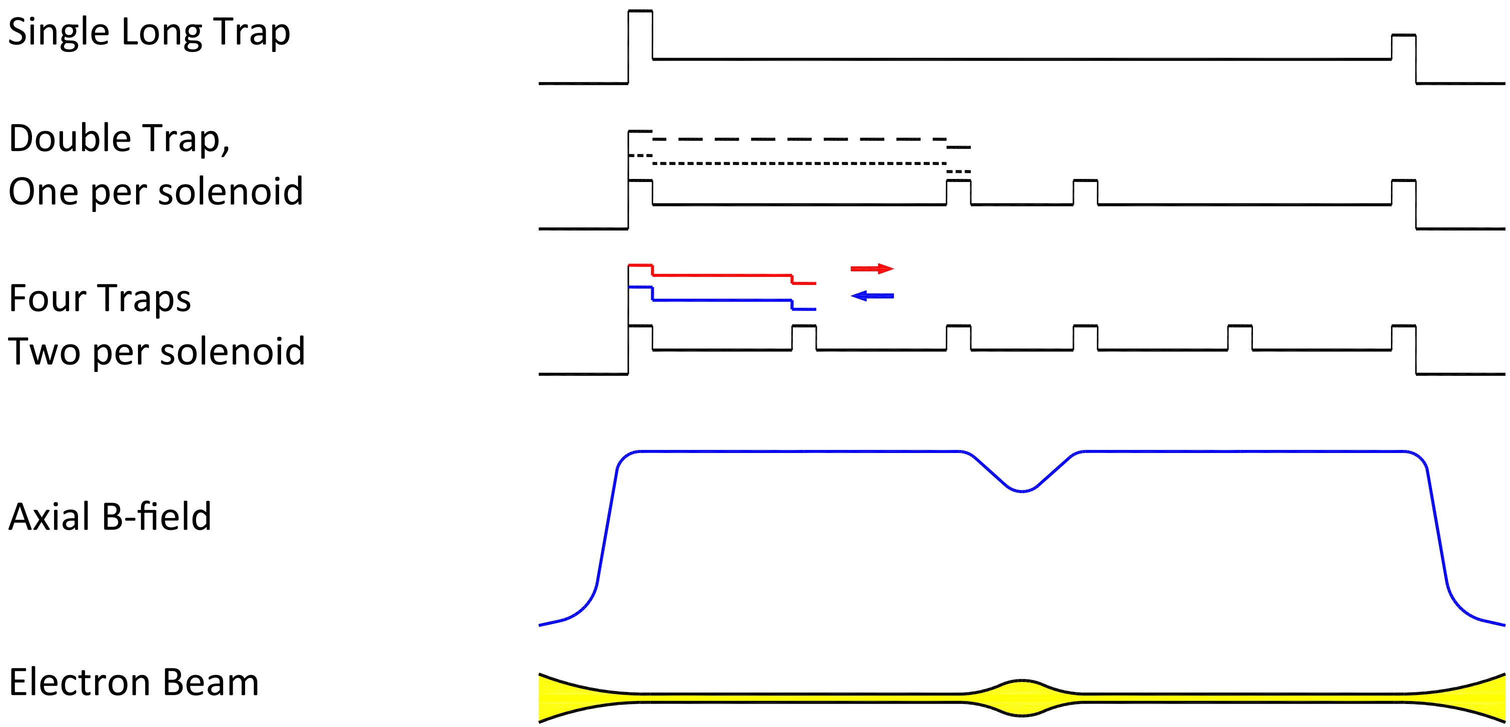
A high current, moderate electron beam current density EBIS (~500 A/cm2) using an extended trap region may provide some advantages for RIB facilities through the use of trap partitioning:

> Partition ionization region into up to four independent 0.5-0.7m ion traps.
> Independently trap and extract ions from each trap

For the RhicEBIS immersed flow electron beam launching concept the relatively large beam diameter and high electron current provide good acceptance for injected ions as well as maintaining a low electron beam neutralization factor. Narrow, more ideal extracted charge state distribution, ie., better breeding efficiency.

Ion production times are the same but effective repetition rate is multiplied by the partitioning factor.

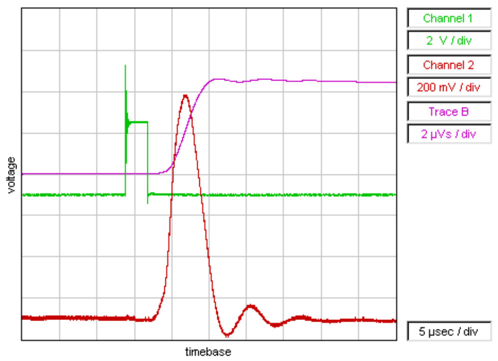
Extended Trap Using Two Solenoids with Partitions



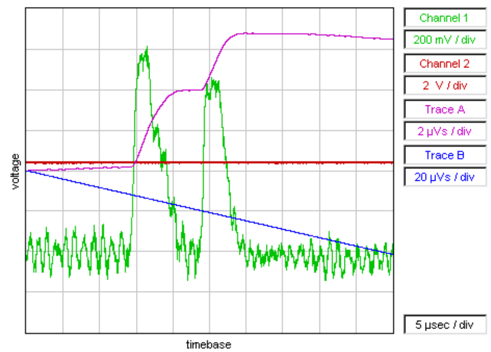
Ions injected from the Left as represented by the blue arrow. Potentials are adjusted such that the ions "fly over" other barriers and are captured in the fast mode in the trap of interest.

Ions extracted (red arrow) from each trap independently. Energy is determined by local extraction potential & global HV platform potential

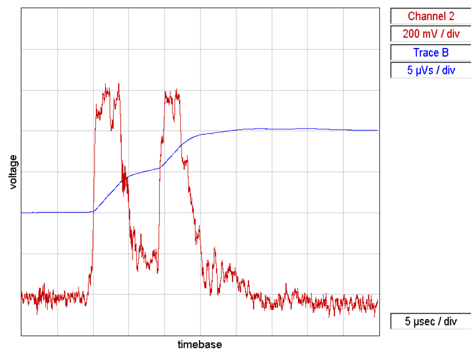
Trap Manipulation: Ion Extraction



110210-01_5us Au32 single pulse
Green Ch1: DT5-8 Trigger
Red Ch2: Bergoz Toroid[1v=2mA]
Magenta   Trace B: integral of 2 [1uVs=2nC]



111005-01_Au32 xf14_DoublePulsing5-8Behlke
Green Channel 1: xf14 (1.43mA/V)
Magenta   Trace A: integral of 1



File name: 120327-02_Au_xf14_2x Half trap
Red Channel 2: XF14   [1.43mA/V]
Blue   Trace B: integral of ch2 [1.43nC/uVs]

Extraction studies for half turn (5us) injection into the booster ring.
By using fast HV Behlke switches and RC networks to impose axial gradients, the Au ions can be extracted from EBIS in:

(1) a single 5us pulse from the full trap
(2) two 5us pulses from the full trap separated by 10us
(3) two 5us pulses from two halves of the EBIS trap

(normal Au extraction pulse widths are 15 – 20 uS)