Intense Pulsed Heavy Ion Beam Production by EBIS and its Future Development *

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Brookhaven National Laboratory

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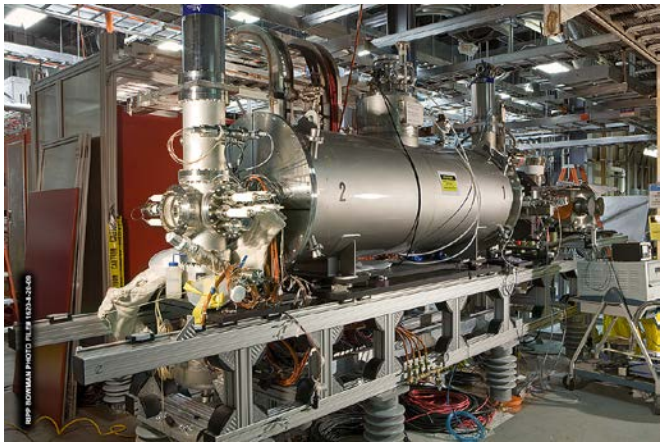
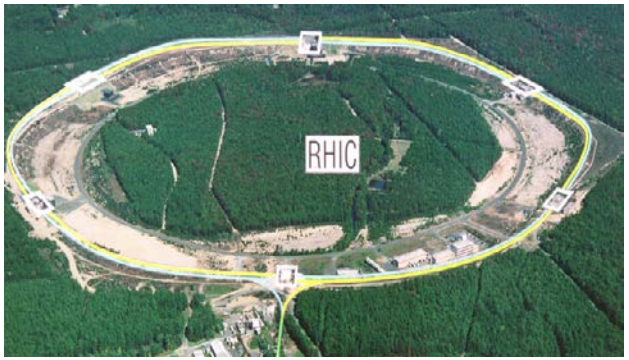
and the National Aeronautics and Space Administration**

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

EBIS & RFQ & Heavy Ion Linac



Au, Fe, He, U, etc.



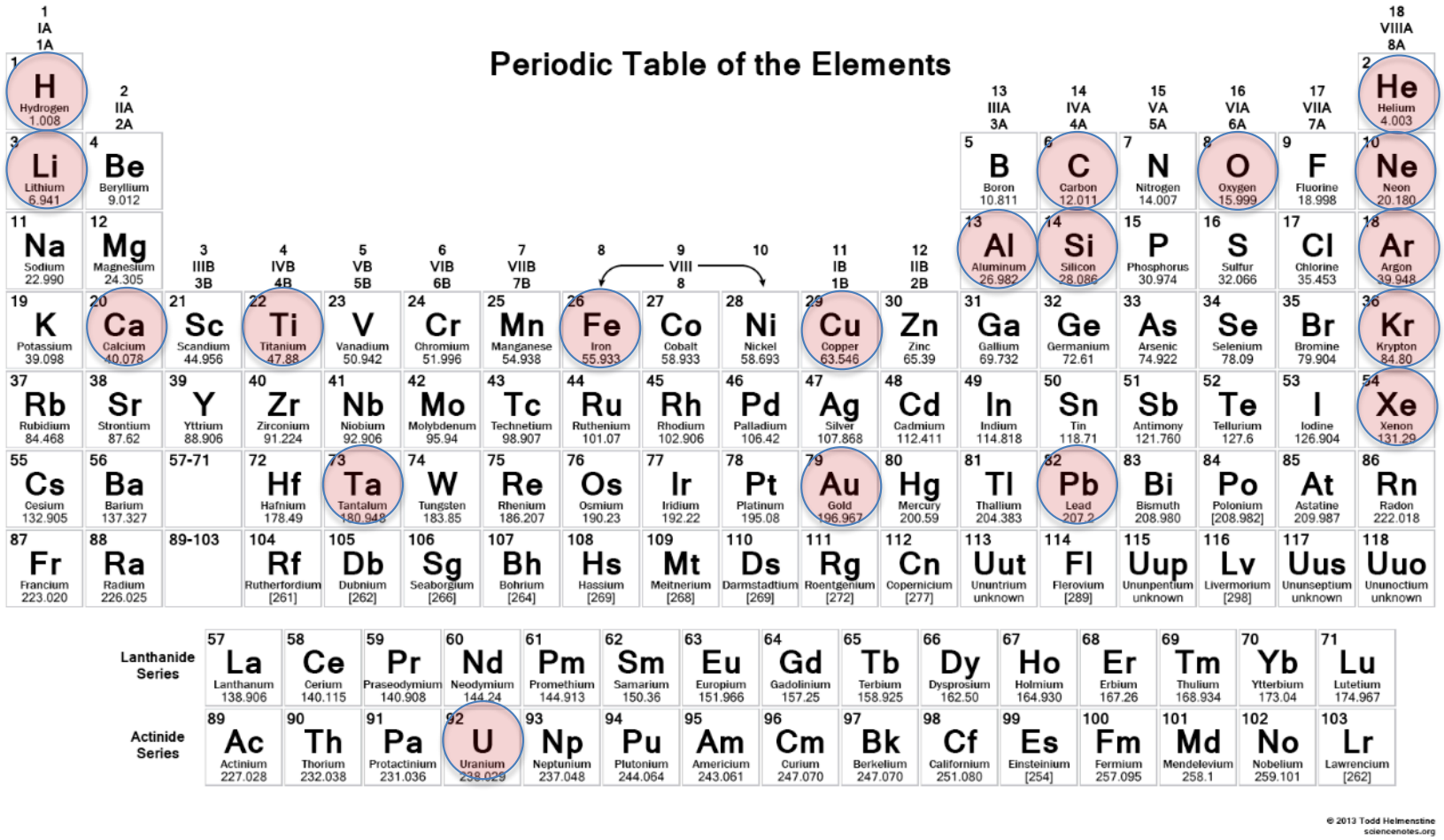
Relativistic Heavy Ion Collider

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

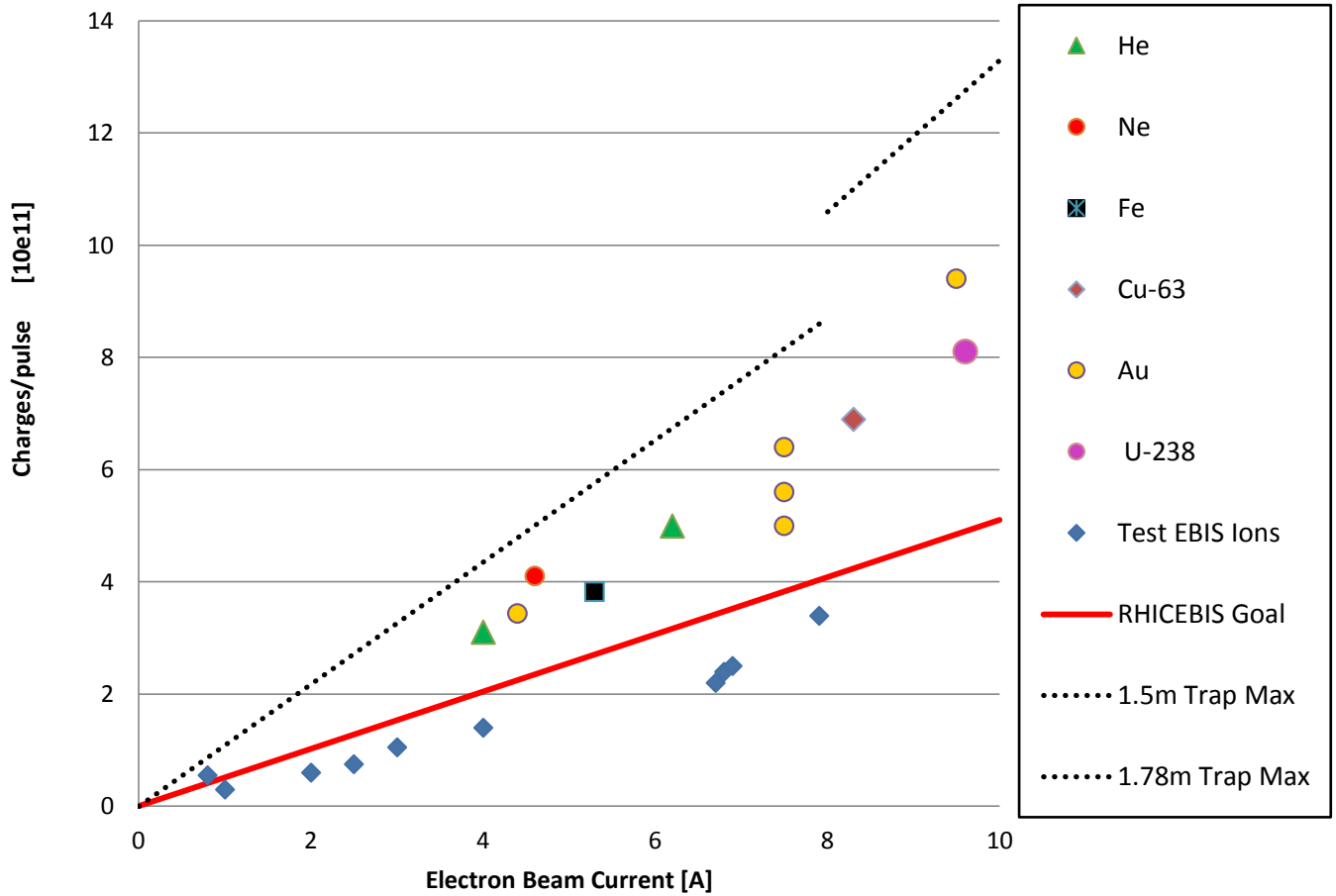
EBIS beams run to date



D, $3He^{2+}$, $4He^{1+,2+}$, 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)

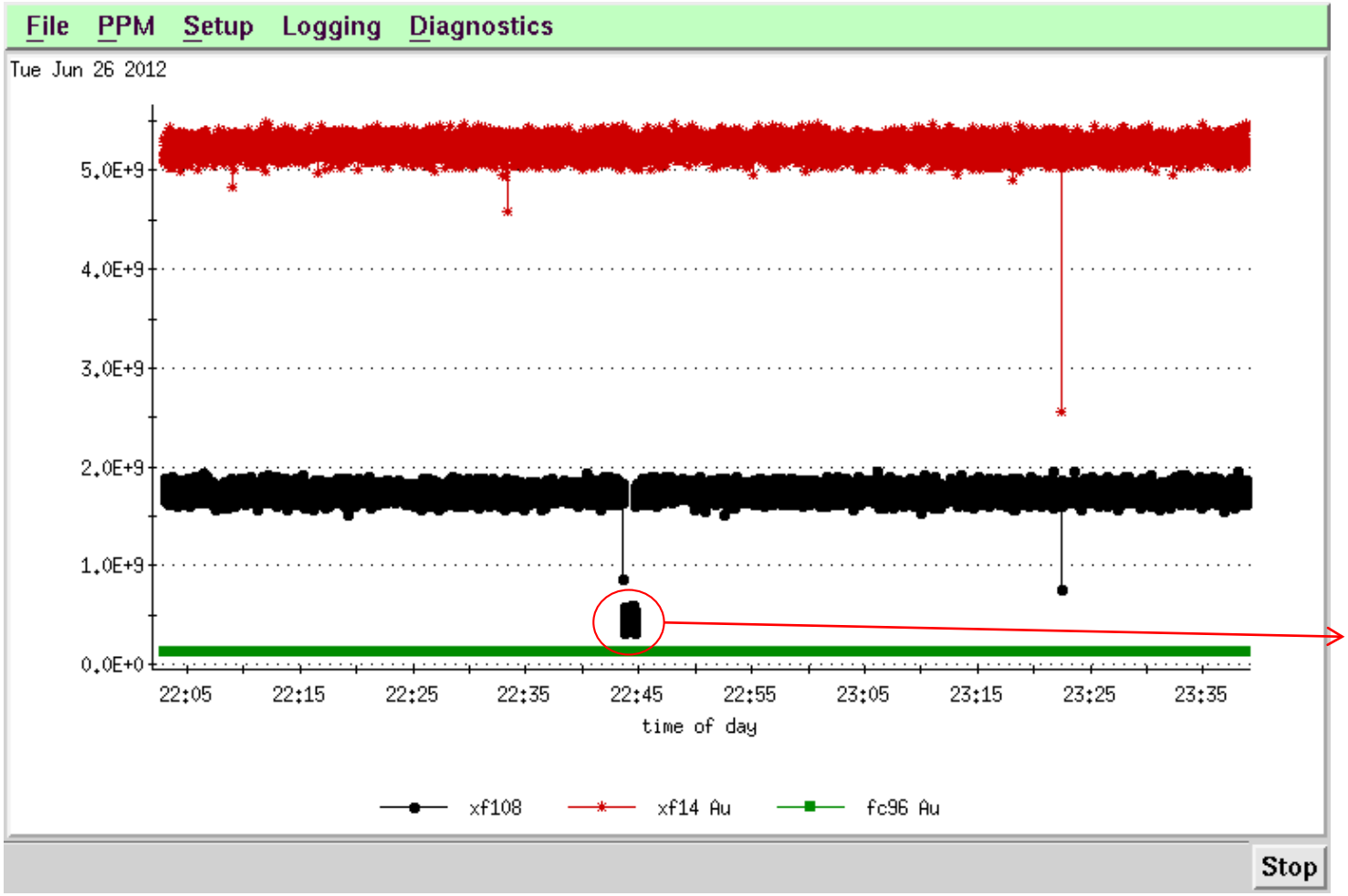
EBIS source *charge* out exceeds the design value, but the % in desired charge state is lower than design. The result is that the *number of ions in the desired charge state is ~ the design value*.

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
- 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

Example of beam stability – 8 pulses/supercycle of Au32+

For RHIC low energy Au run, we ran 8 pulses continuously for ~48 hours



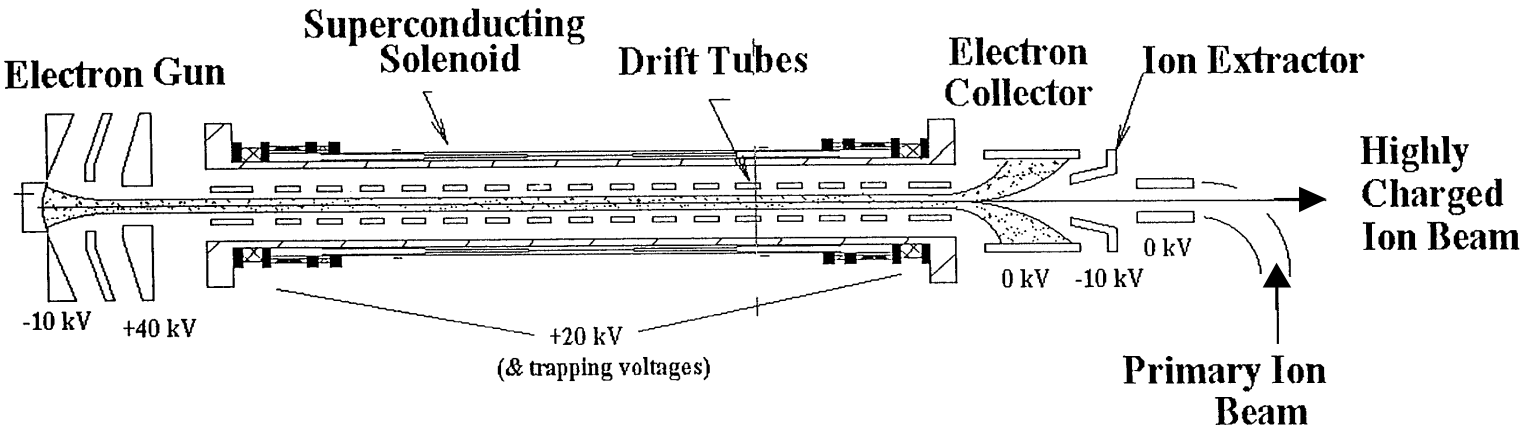
Transformer at linac output

Transformer at Booster input

Beamstop inserted (note noise width on transformer when no beam)

Estimate ~0.05% missed pulses

EBIS principle of operation



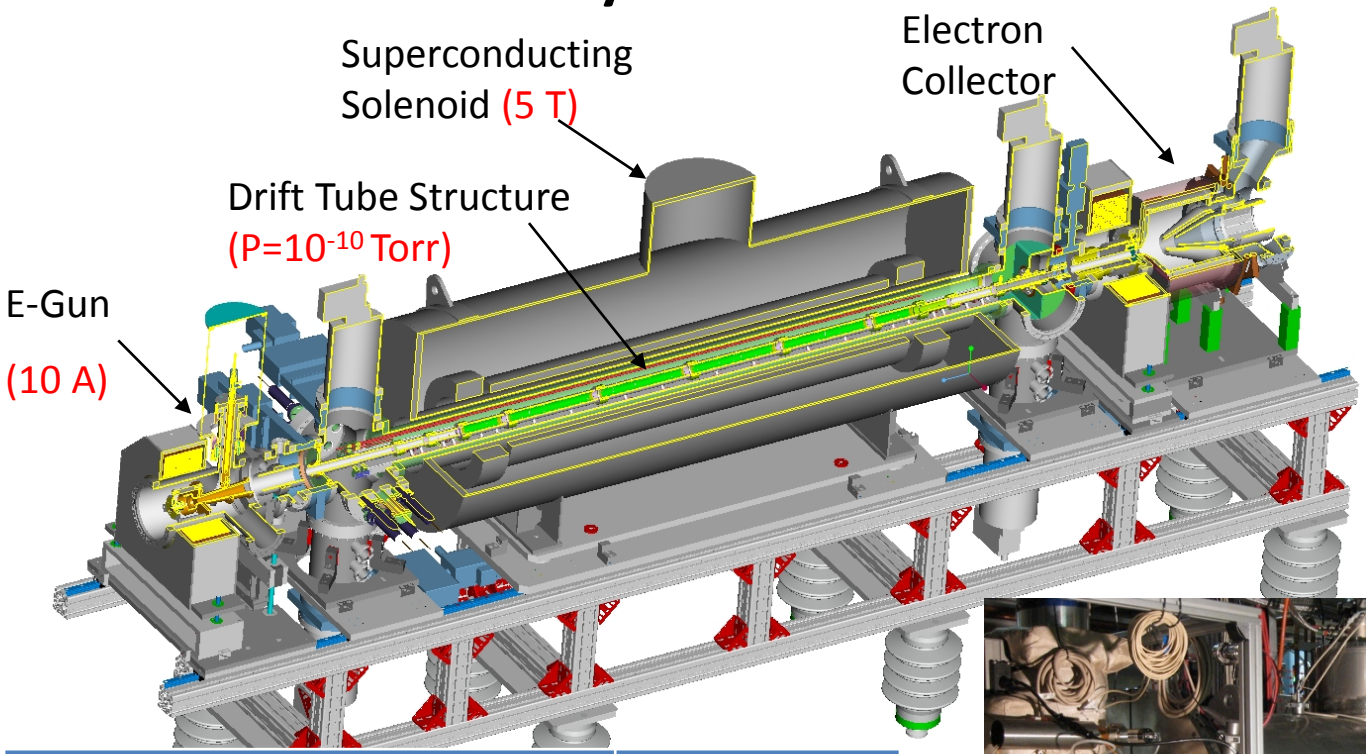
Yield of ions in charge state q:

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

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

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

Increasing the EBIS capacity:

The EBIS capacity for trapping positive charge can be increased by:

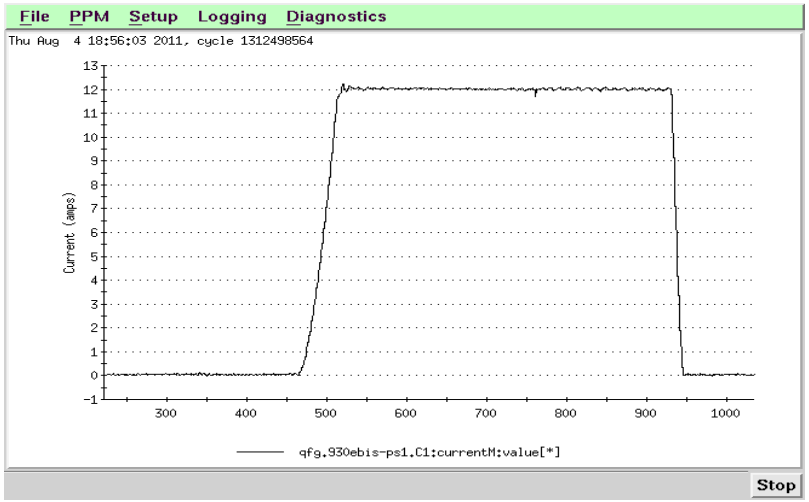
1) Increasing the trap length (done once from 1.5m to 1.78m)
2) Increasing the electron beam current (also increases current density)

The EBIS has operated with electron beams of 12A, above the design value of 10A. To effectively produce ions at this and higher currents some changes need to be implemented.

Steps for higher e-beams:

1) **Reconfigure trap HV supplies**. (Bipolar TREKs running in unipolar mode, have factor of 2 in voltage available.
2) Increase some transverse magnetic power supply currents
3) Implement electrostatic clearing of oscillating/reflected electrons

12A electron beam exceeds the design value



12A 40ms ebeam

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 extraction pulse width 5uS to greater than 50ms

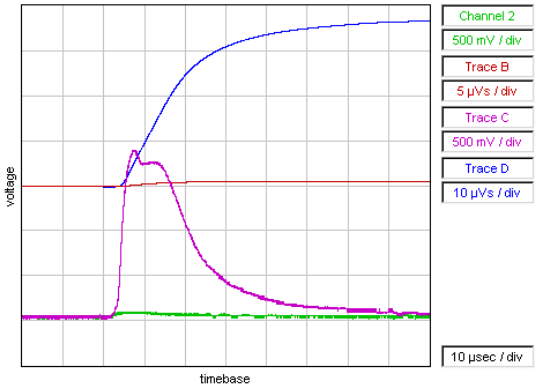
Booster/AGS/Rhic injection typically 5-40 us (High Intensity)

Pure Beams (low contamination by unwanted ion species)

High utilization of relatively low charge capacity

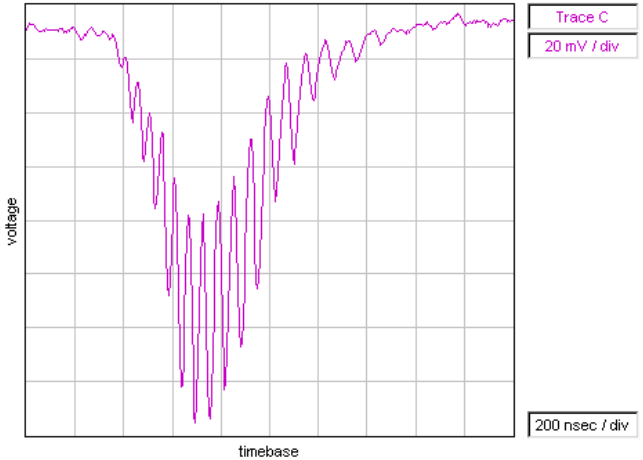
Lower space charge beam transport to RFQ

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



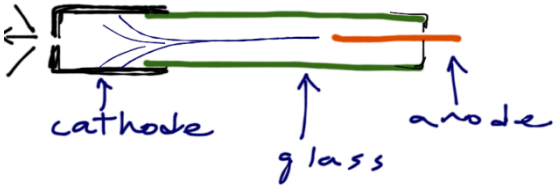
Above: Au Time-of-Flight Spectrum
(Reflex mode – channeltron EM)
Max peak is Au32+

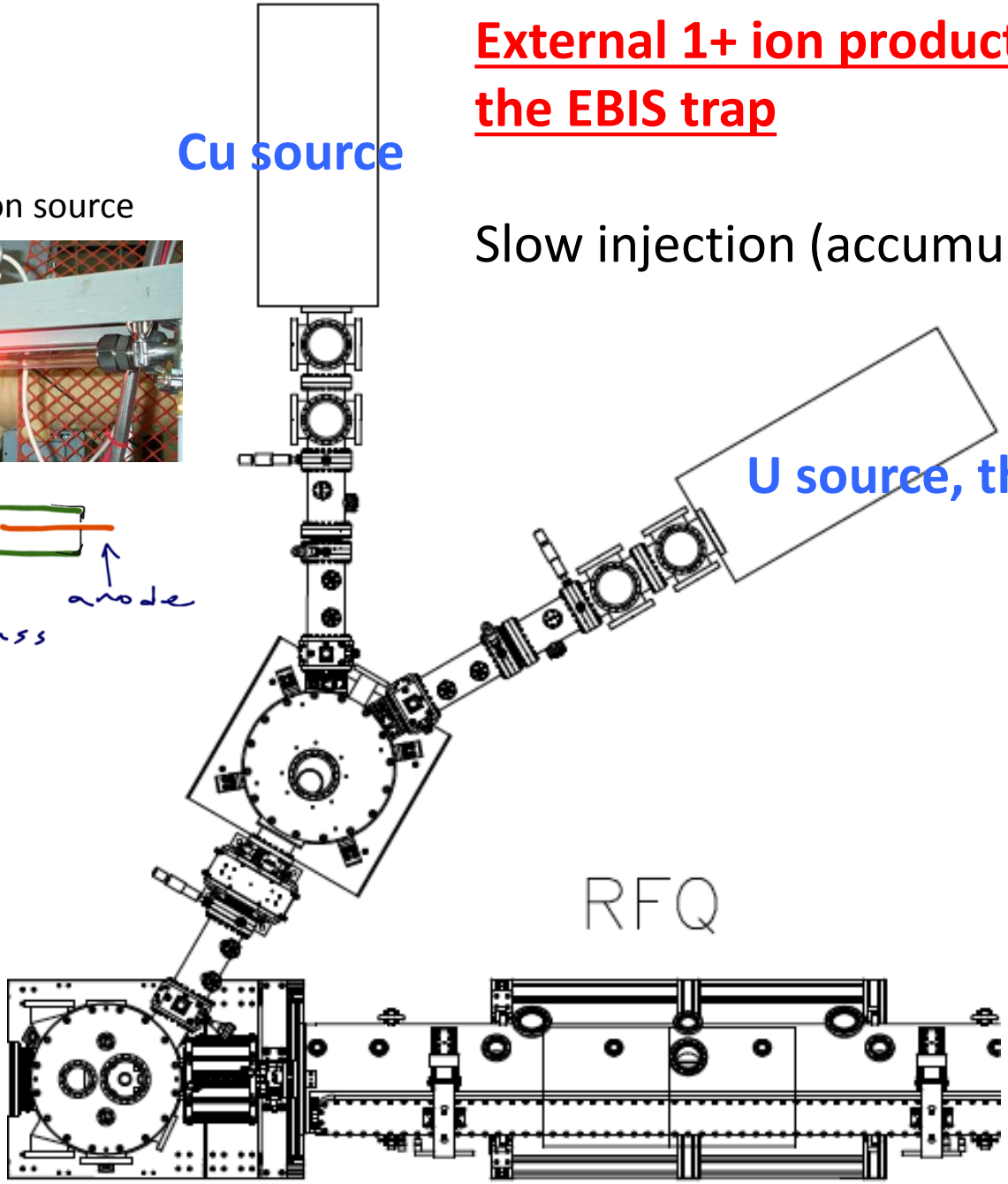
External 1+ ion production to feed the EBIS trap

Slow injection (accumulation mode)

HCIS

Hollow cathode ion source



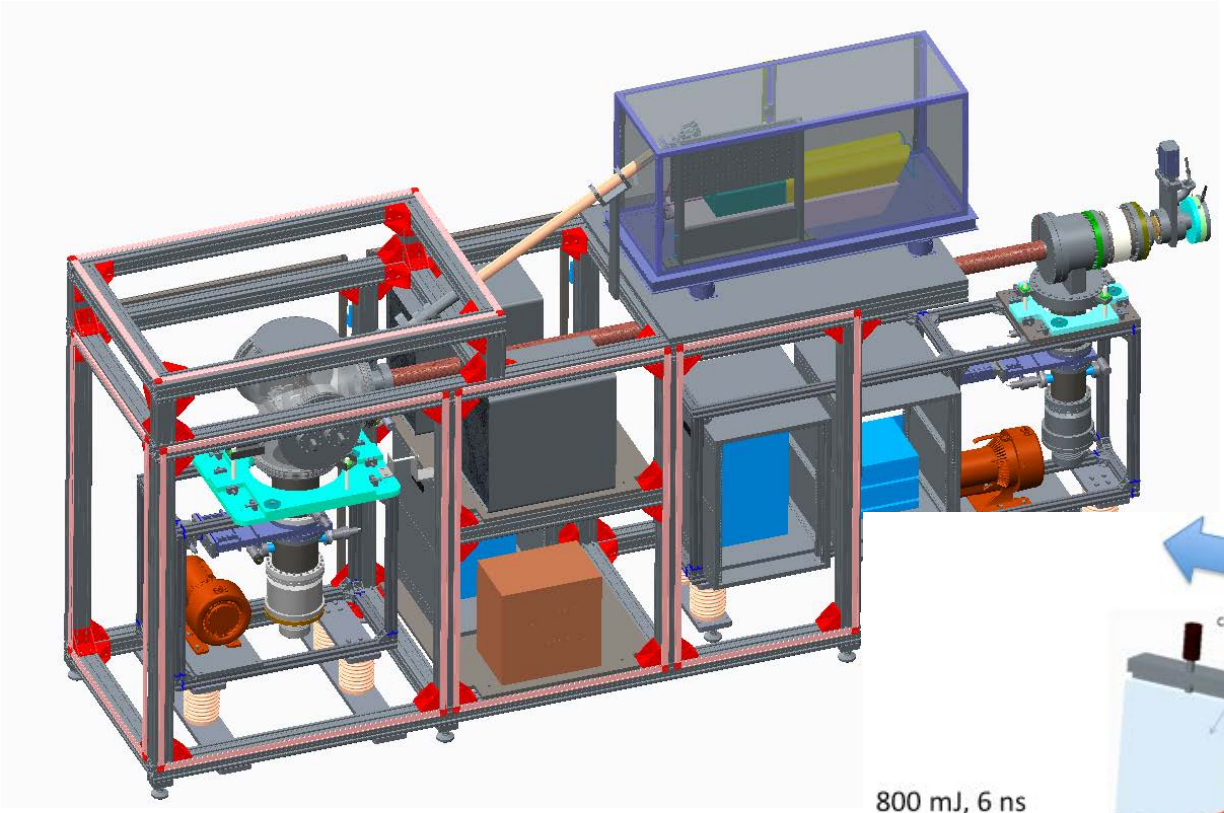


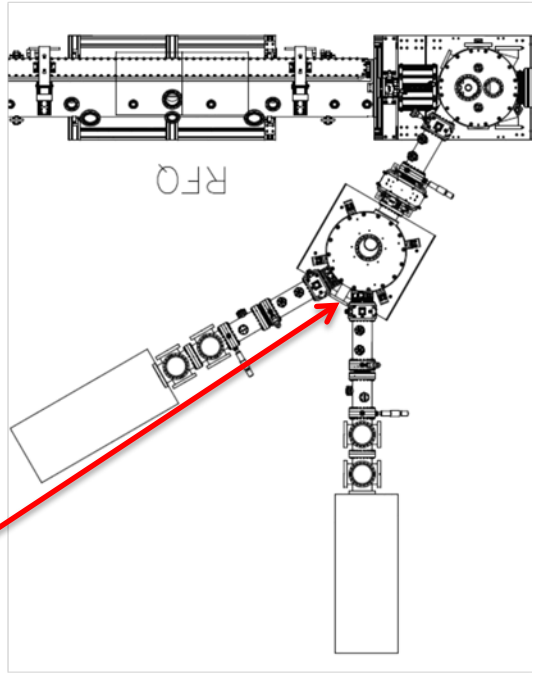
EBIS is a "charge breeder" of the injected 1+ ions

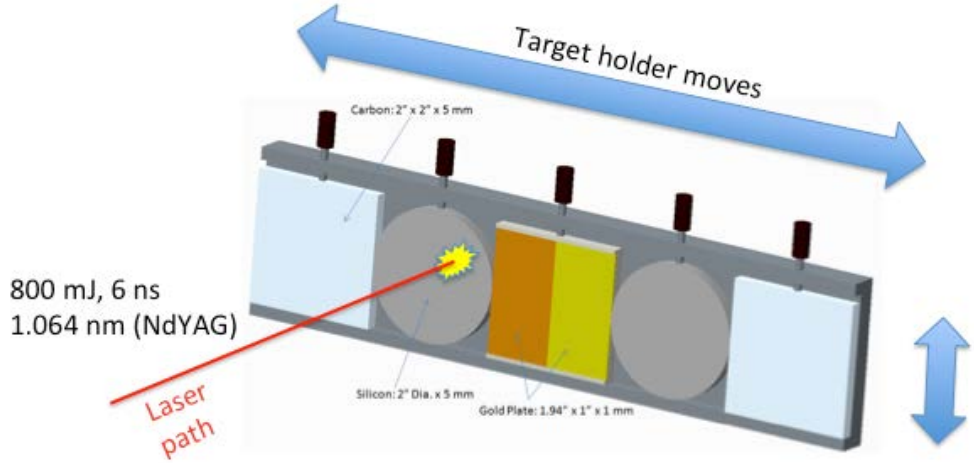
1+ Ions into EBIS

3rd injection line - Laser Ion Source:
improved flexibility (multiple species)

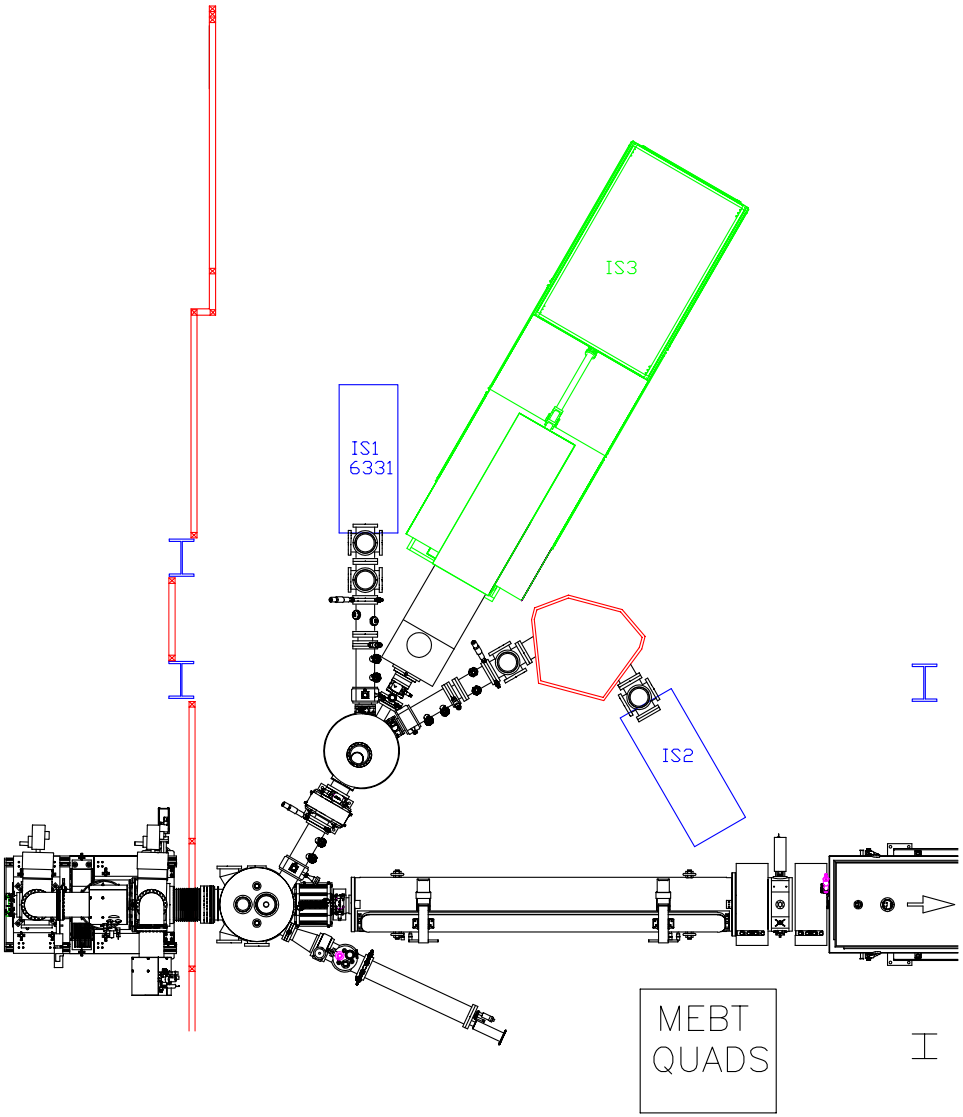
- low gas load
- Fast injection into EBIS







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).

Laser Ion Source (LION)

(M. Okumura, T. Kanesue)

Early in 2014, the Laser Ion Source (LION) was successfully commissioned and used intensively for providing injection of +1 ions of solid species into RhicEBIS for multiplication to high charge state for use by both the NASA Space Radiation Laboratory (NSRL) and the Relativistic Heavy Ion Collider (RHIC). 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 plasma

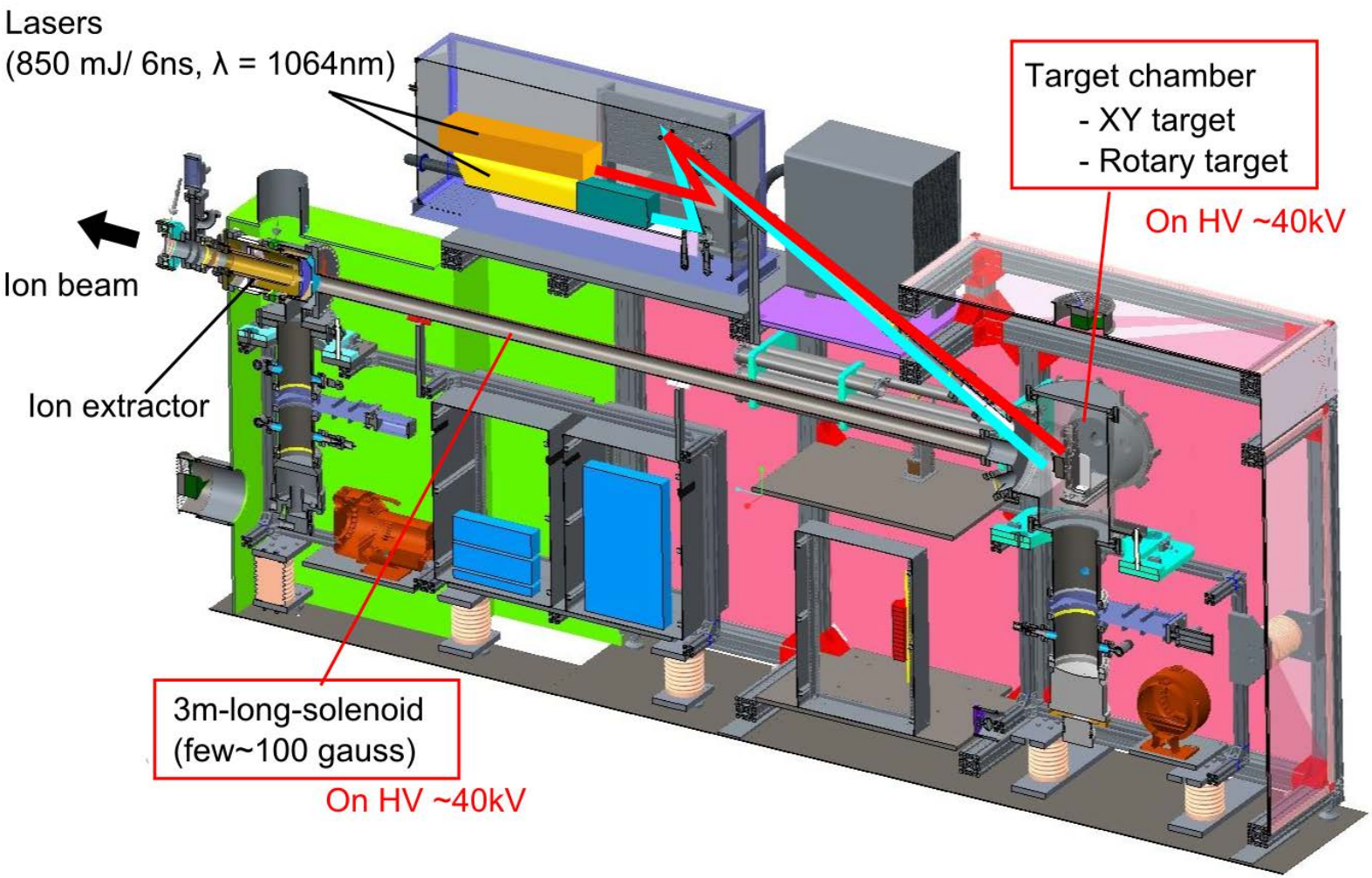
- Optimized for 1+ ion production from solid targets
- Pulse widths from 10-200us (single laser pulse)
- Intensities ~ 100 microA to several mA
- Excellent pulse to pulse stability
- Fast switching between targets for species change
- LION has provided Li, C, Al, Si, Ca, Ti, Fe, Ta, Au
- High brightness: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

In Run-15, LION was the EBIS injector source for most of solid based beams for RHIC (8 weeks) and NSRL (Sep 2014~Nov 2014, Mar 2015~Jul 2015)

Fast injection: EBIS can produce low charge states such as Al^{5+}

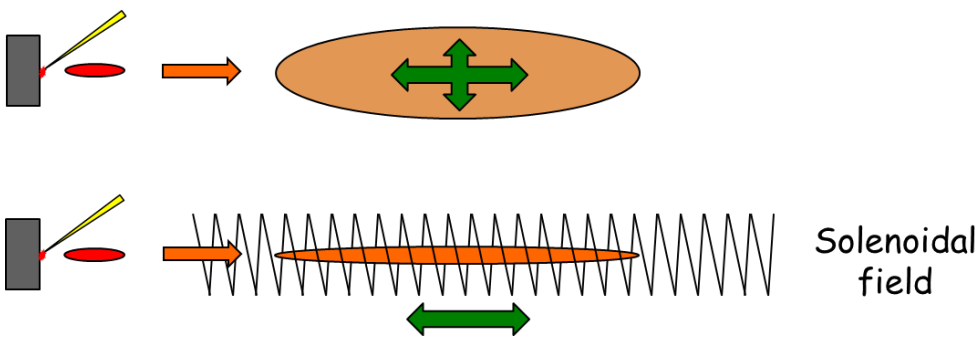
LION Key Features:

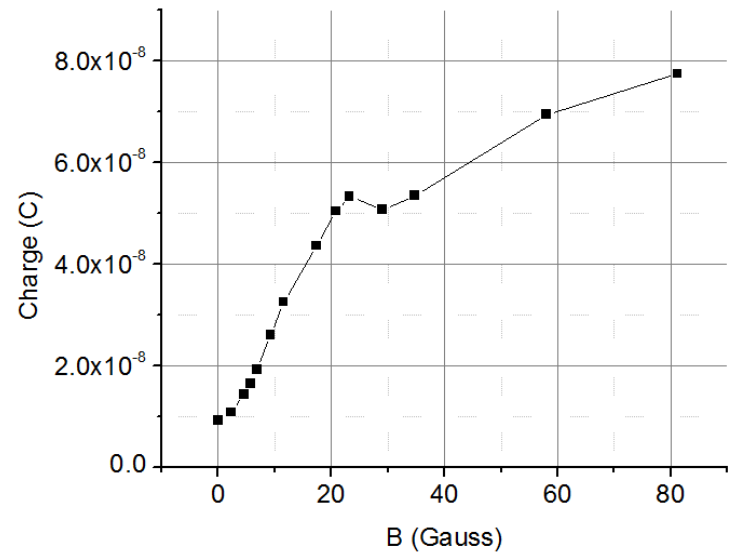
- 3 meter drift region with solenoidal confinement of plasma
- 2 Lasers and 2 targets systems for injection into RhicEBIS to permit *quasi-simultaneous* RHIC and NSRL operations.



Principle of operation

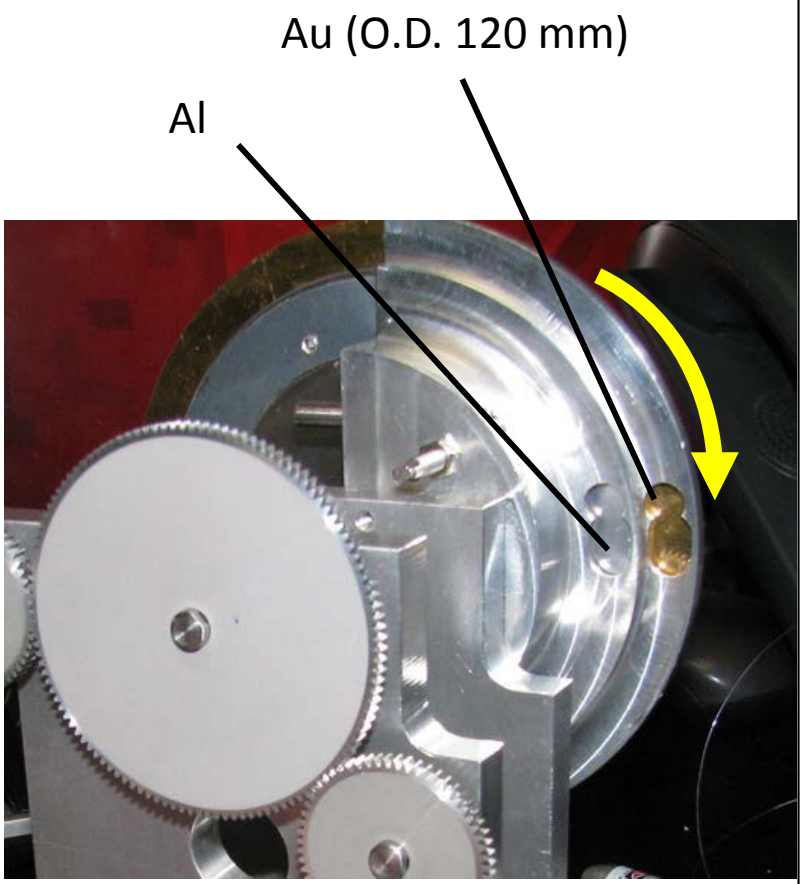
1. Laser is moderately focused (~ϕ4 mm) on a solid target (laser power density ~3E8 W/cm^2)
2. Plasma is generated by laser ablation
3. **Longitudinal magnetic field suppresses diverging angle** of **expanding plasma**
4. Ions are extracted at the end of the solenoid



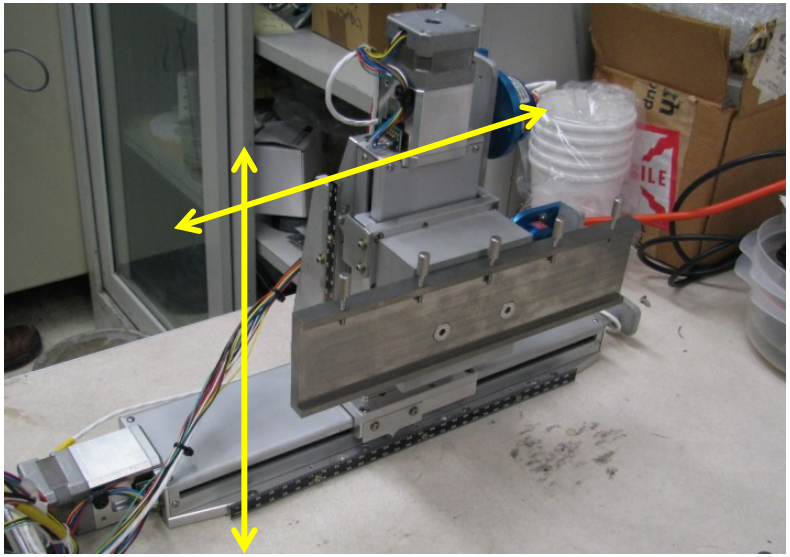


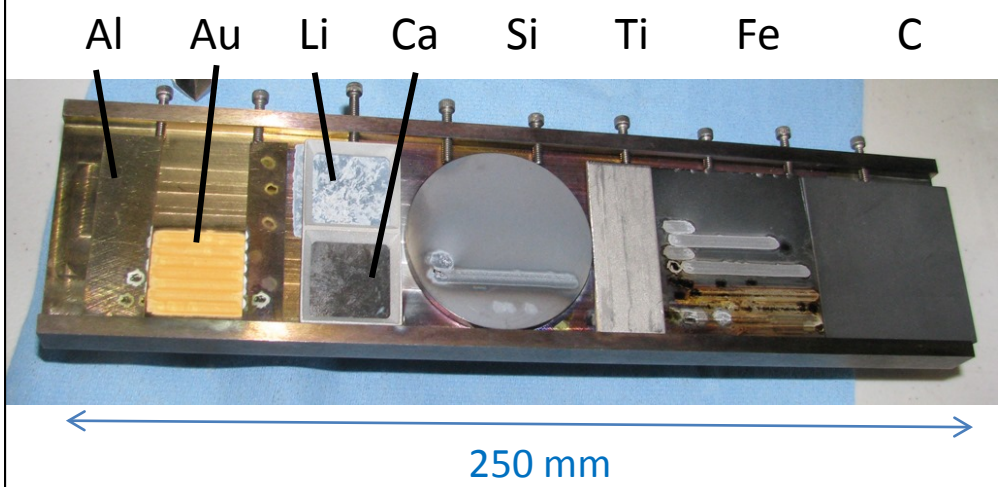
DC solenoid keeps ablation plasma current high and produces long pulse ion beam.

Rotary target for RHIC

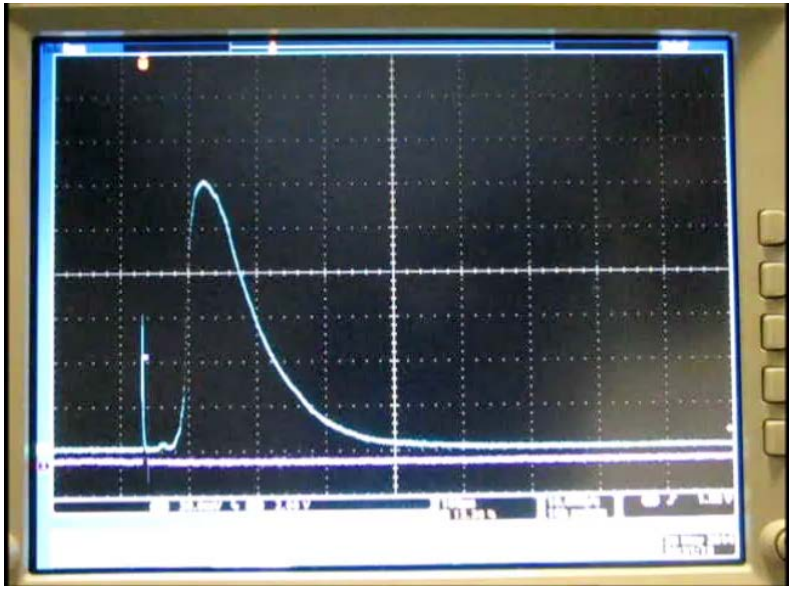


XY target for NSRL



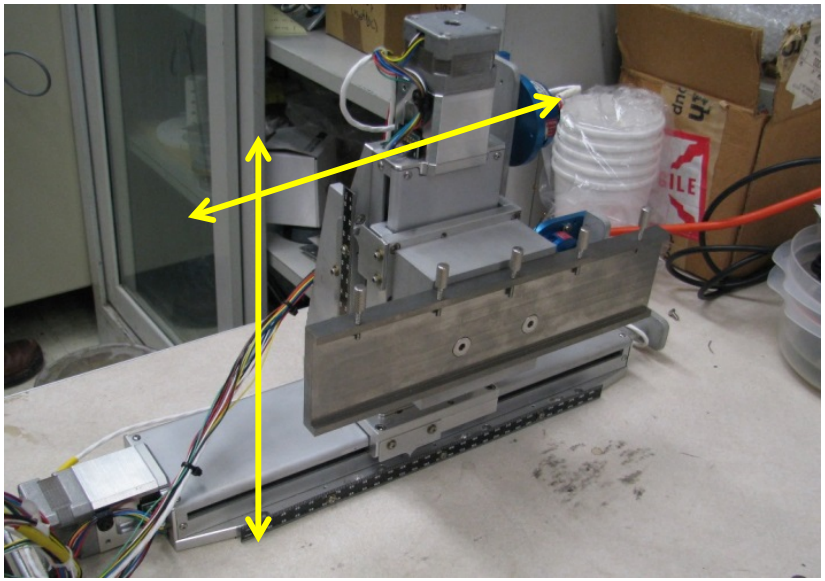


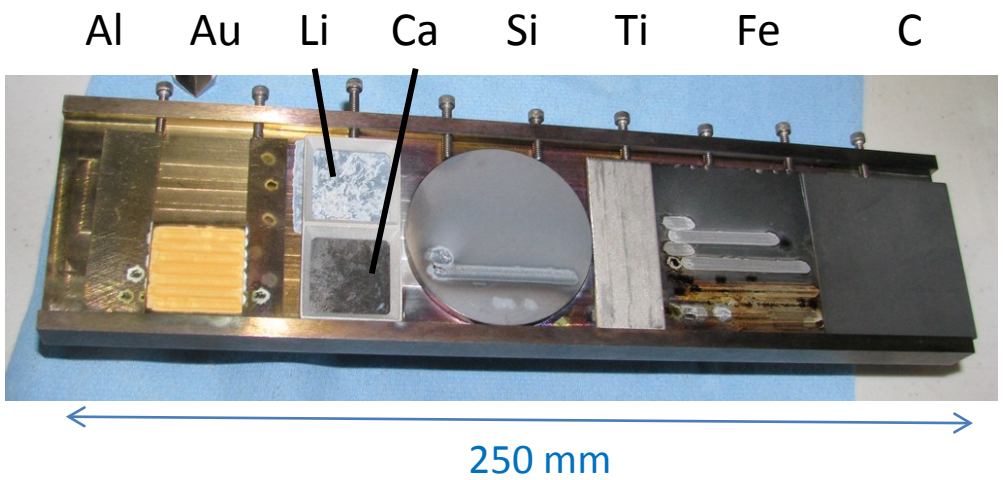
Two Independent target systems with two dedicated lasers provide two different species of beams, almost simultaneously and allow switching to new beams within a few seconds.



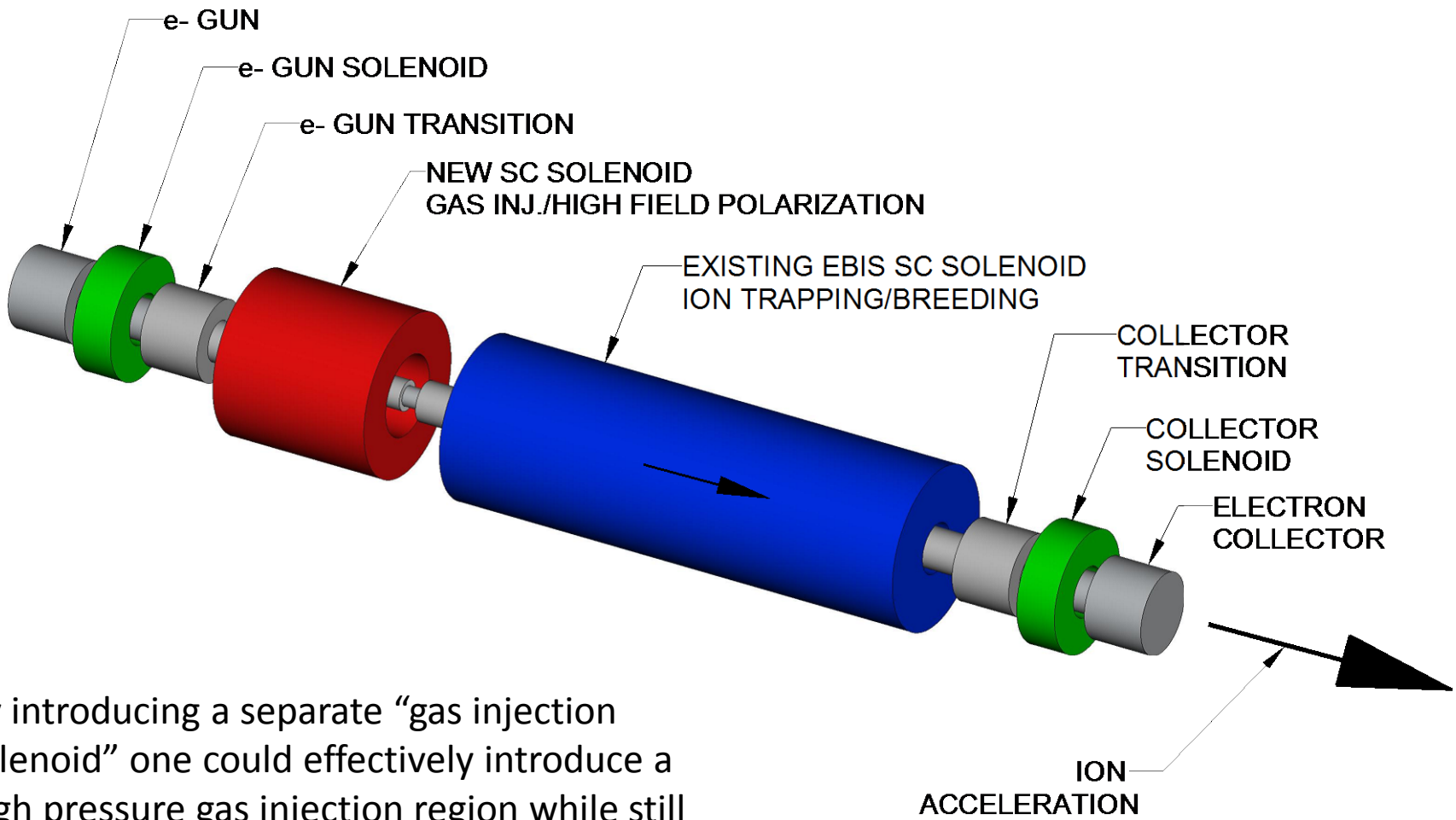
Fast species switching
Ti (1st species, higher peak))
Au (2nd species, lower peak)

XY target for NSRL





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

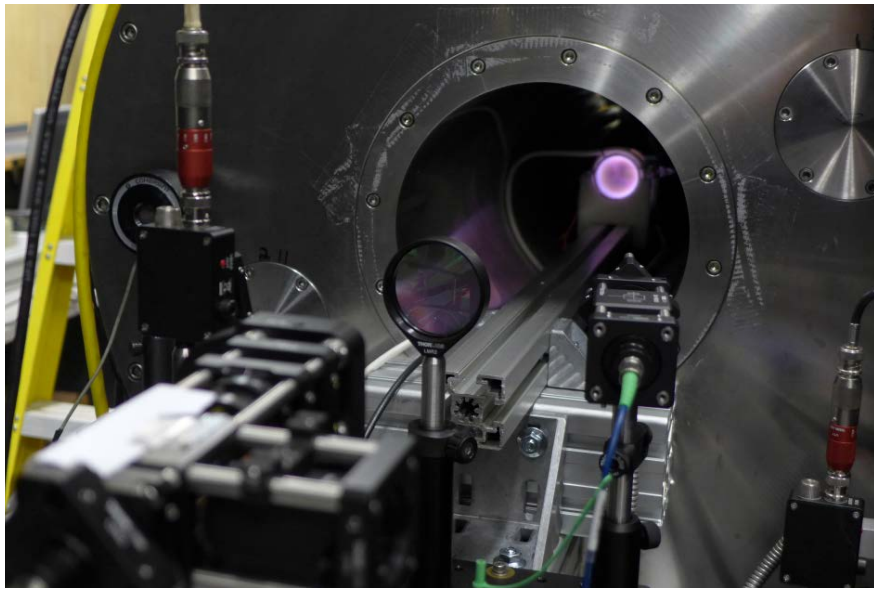


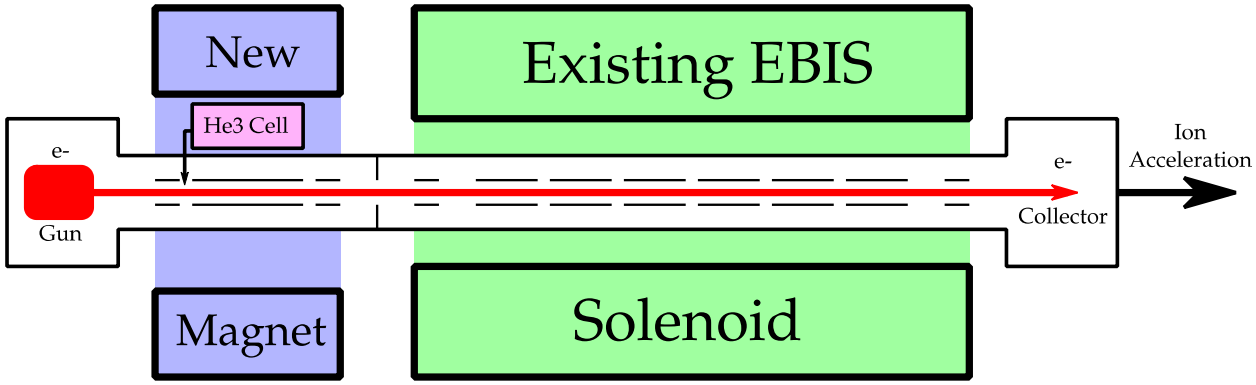
By introducing a separate "gas injection solenoid" one could effectively introduce a high pressure gas injection region while still maintaining a very low pressure existing trap region in which ionization to high charge state 3He2+ would occur with high efficiency.

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 Modification for high field polarization of 3He polarized gas in an external solenoid followed by electronic injection into the main RhicEBIS trap

New Components:

Additional superconducting solenoid:

Nominal 5T, 205mm Warm Bore, 500-700mm long, 200mm injection region

(A longer solenoid could be useful for other upgrades of RhicEBIS capacity)

Injection/trapping DT structure

reduced diameters (improved voltage and differential pumping)

possible integration with vacuum system containment

Accessible polarization cell and pulsed valve

Concept Benefits

The new system could be built up and tested as a test bench before integrating with RhicEBIS, with minimal interruption of existing RhicEbis operation and development:

Same electron gun and launching geometry

Same RhicEBIS internal components ---little or no modifications to internal drift tubes, pumping, heating jacket, etc.

Minor modification to drift tubes to optimize transport between added and existing solenoid.

Improved EBIS Trap region vacuum:

Less loading of EBIS Trap by neutral (and depolarized) gas

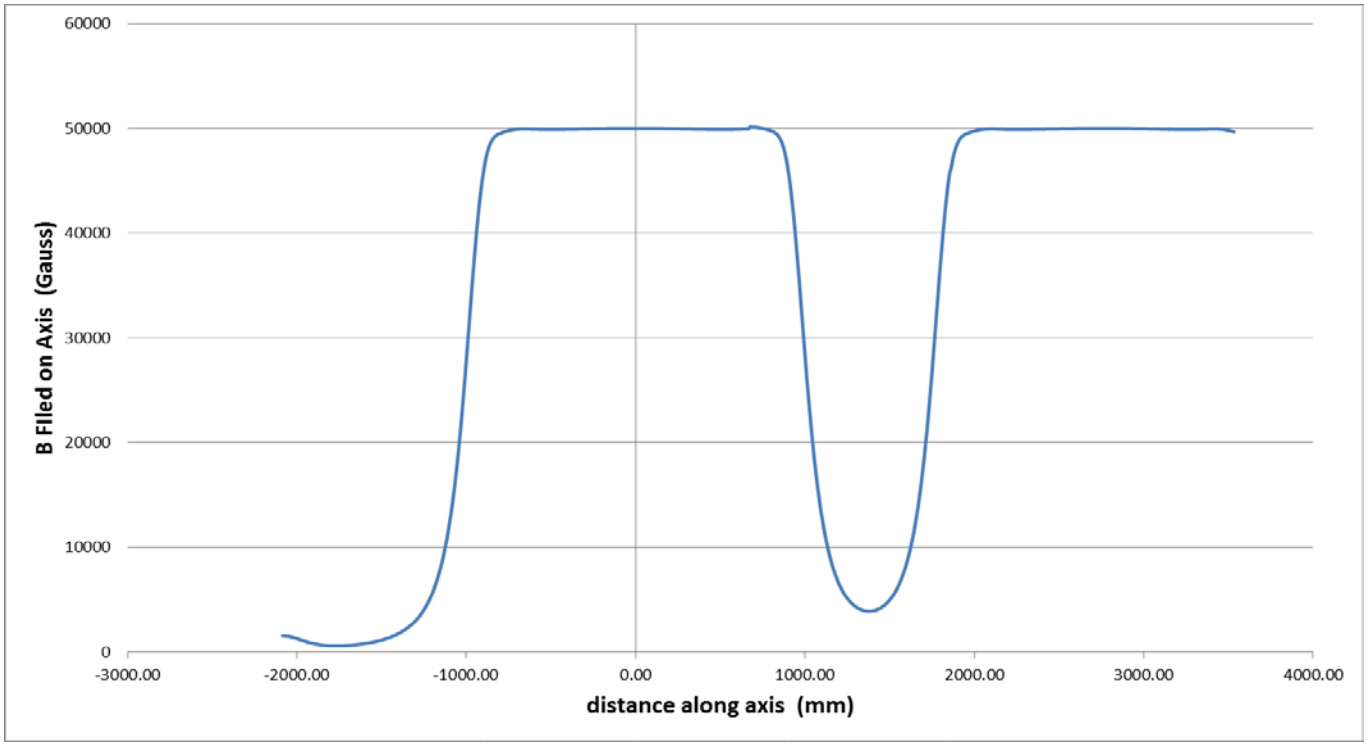
Improved Vacuum Separation between EBIS Trap and Electron Gun

Could retreat to current configuration, and upgrade hardware (offline) to:

1) adjust or improve 3He strategy
2) upgrade RhicEbis neutral injection concepts
3) Increase RhicEbis capacity per extraction cycle.

RhicEbis Axial Magnetic Field with Identical main solenoid inserted

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



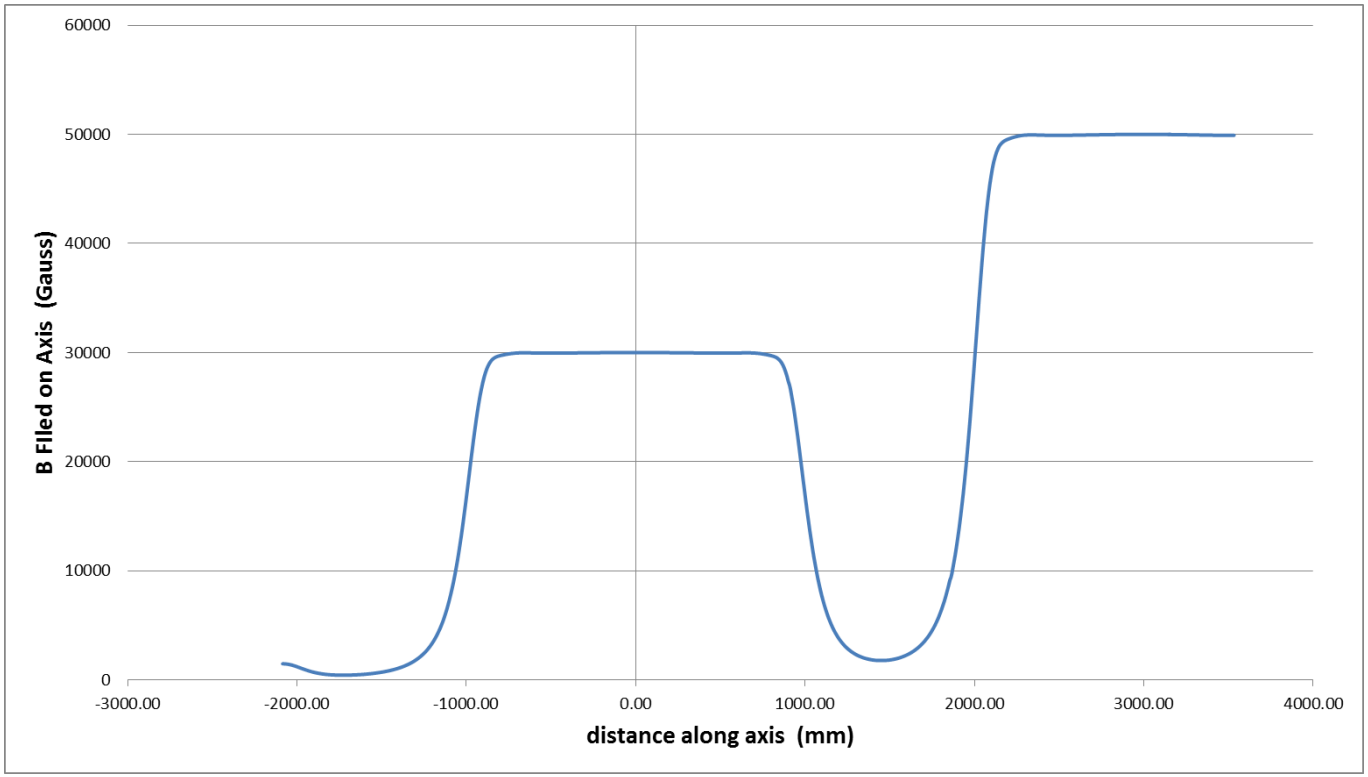
Gas would be polarized in the first superconducting solenoid and injected into the electron beam using a simplified. The ions travel along the beam to the second solenoid (existing EBIS trap) as 1+ ions using the electronic injection method, by suitable adjustment of drift tube voltages.

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

3T polarizing/injection field 5T Existing EBIS Trap Field

(Gap between SC solenoids 70cm)

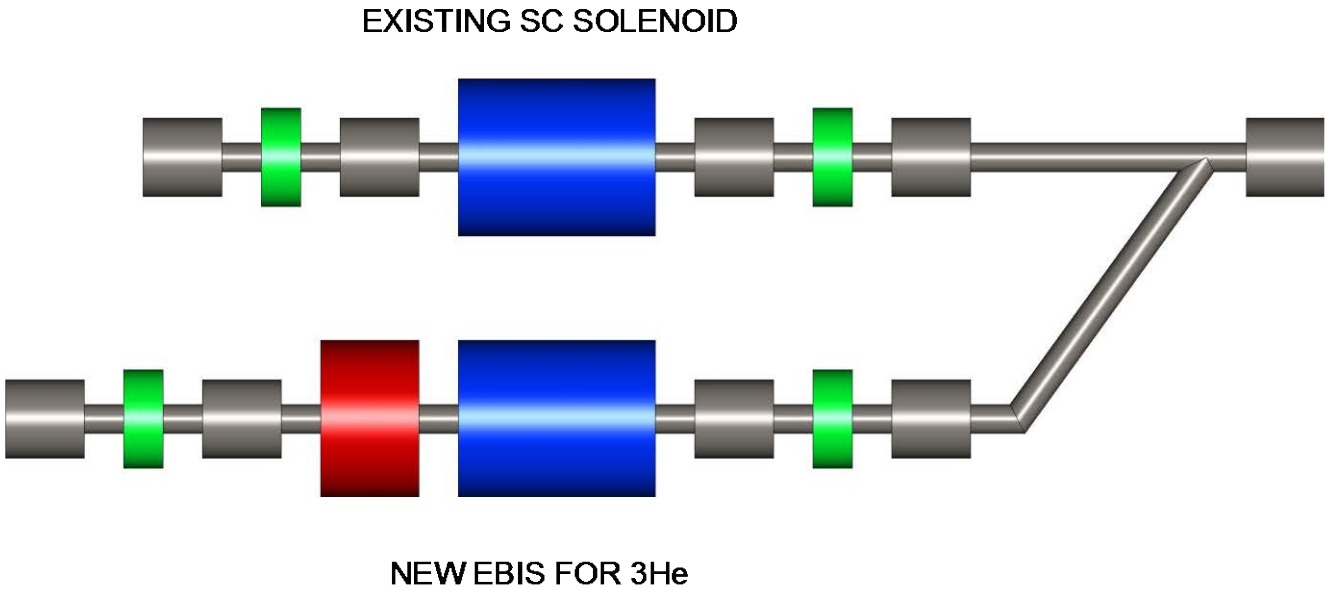


Length, Bore size, and Gap can be chosen based on optimization studies.
Magnetic field could be varied during experiments.

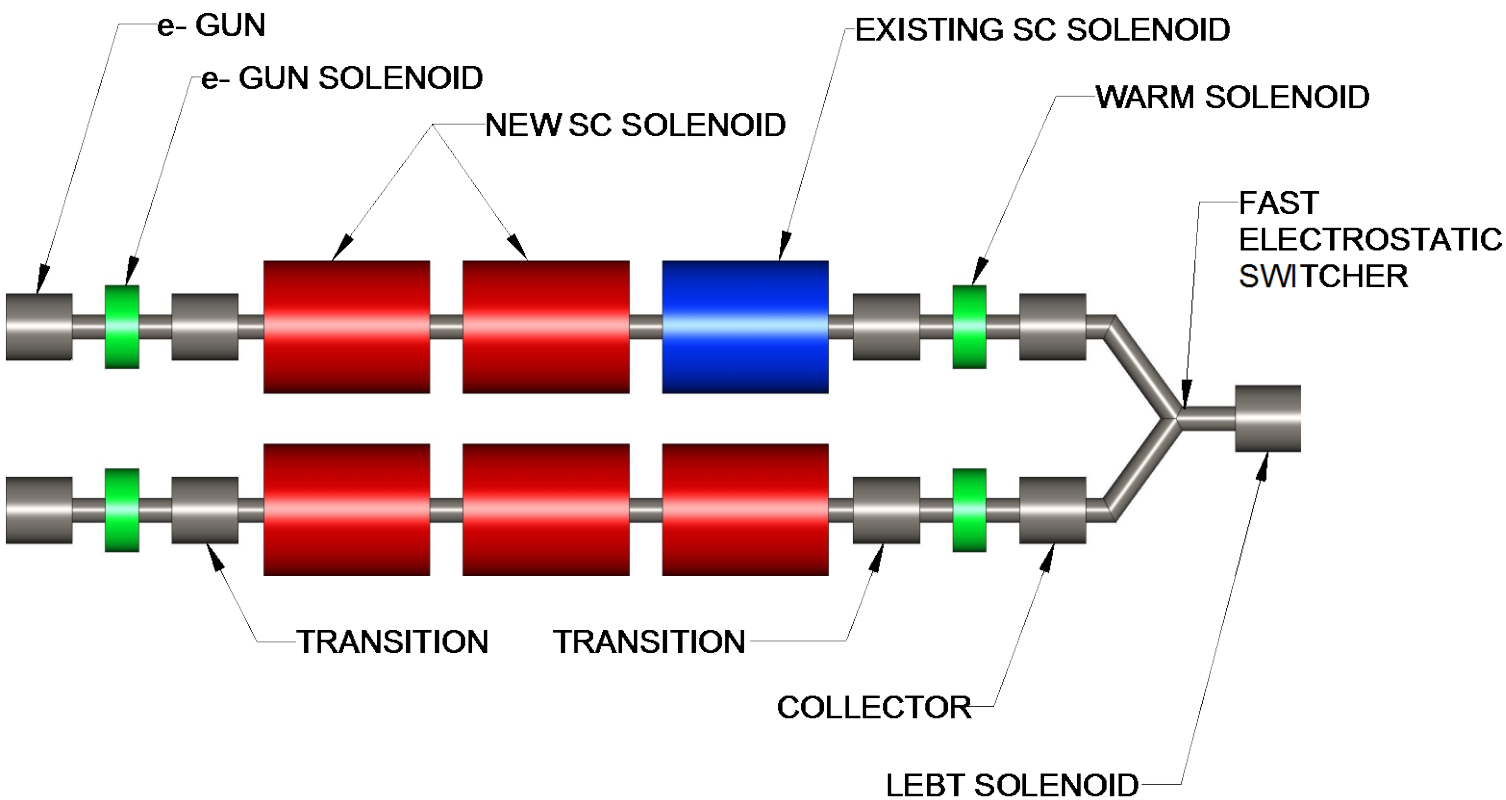
Main Issues:

1) Polarized 1+ survival ---- transits through the magnetic trough during a fill time ~1ms
2) Magnetic Forces between solenoid (might need to reinforce RhicEbis axial support s)

Possible Parallel Installation of 3He Source

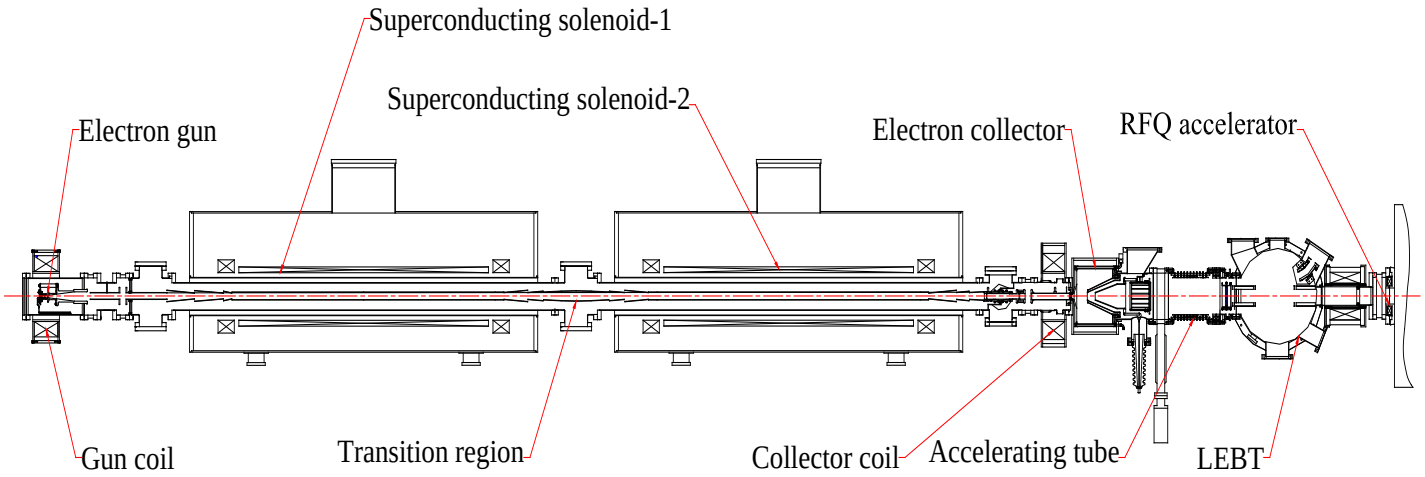


High Intensity EBIS Concept: Working Spare with Beam Merging



Increase length by adding EBIS Solenoid and Trap modules
(no change to Sophisticated Launch and Collection Sections)

Tandem EBIS (HIAT2012-A. Pikin)



Two RhicEBIS Solenoids on the same axis gives twice the charge capacity (or more) of the present RhicEBIS. **[Increased trap length]**

The electron gun and collector remain the same. **[Same electron beam power]**

(Similar to doubling of length from TestEBIS prototype to RHICEBIS)

Boosting the RHICEBIS Intensity

Mini-WS on HCI
IMP, Lanzhou
July 9-10, 2014

Can source achieve 1E11 U34+, in 400us pulse?

(Removing BNL 40microsec pulse width restriction reduces LEBT Transport problems)

	Au32+ ions/pulse	Total Au ions/pulse	40 microsec Avg Current [mA]	400 microsec Avg Current [mA]
RHICEBIS (8A ebeam, 1.8m Trap)	3.4E+09	2.7E+10	3.5	0.35
1 Tandem EBIS (4m total trap)	7.6E+09	6.0E+10	7.7	0.77
Add parallel Twin (8m total trap)	1.5E+10	1.2E+11	15.5	1.55
Increase ebeam to 20A	3.8E+10	3.0E+11	38.7	3.87
1 Tandem or single trap (10m total trap)	1.9E+10	1.5E+11	19.3	1.93
Add Parallel Twin (20m total trap)	3.8E+10	3.0E+11	38.7	3.87
Increase ebeam to 20A	9.4E+10	7.6E+11	96.7	9.67

For RHICEBIS U55+ is also possible without any more development, especially with increased current density of e-beam current. (~100M$ savings in accelerator)