RhicEbis Design and Performance*

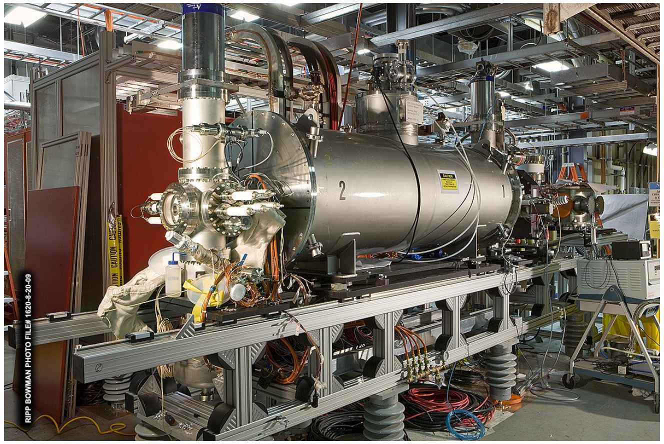
E. Beebe, J. Alessi, A. Pikin

Brookhaven National Laboratory

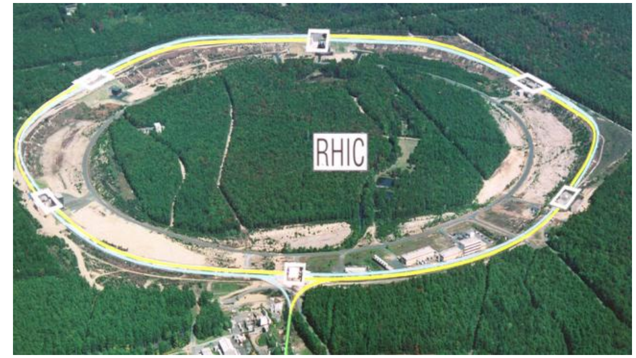
***Project funded by US Department of Energy and the National Aeronautics and Space Administration**

Two simultaneous users of RhicEbis ions

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 based preinjector vs Tandem

- Increased flexibility to handle the simultaneous needs of RHIC and NASA (fast switching between species)

- Capability to provide ions not presently available, such as noble gas ions (for NASA), uranium (RHIC).

- Simpler technology, robust, more modern

- Elimination of two stripping stages and an 860 m long transport line, leading to improved performance (stability, easier tuning).

RhicEBIS OverView

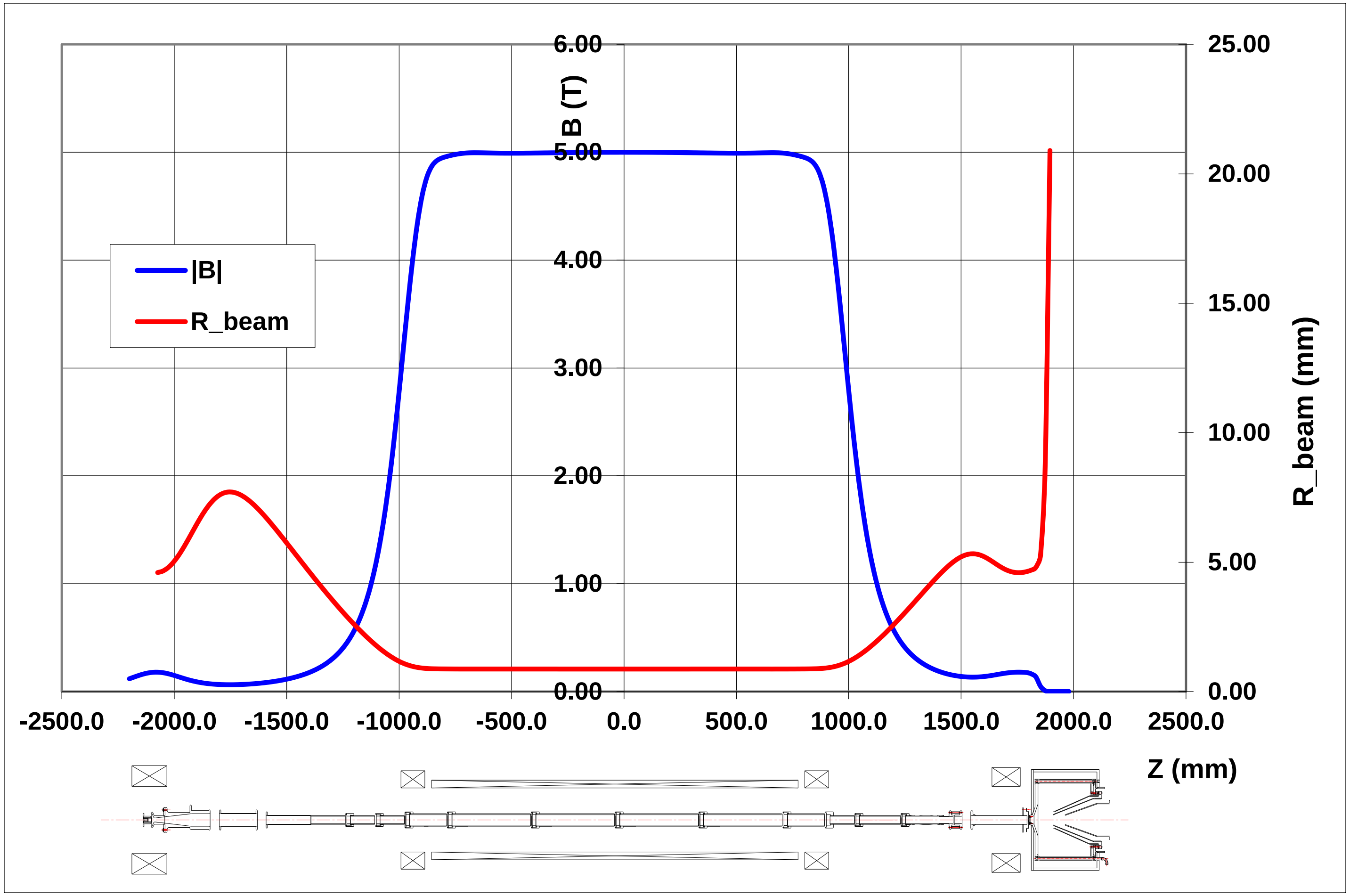
- High current electron beam (~10A), current density ~600A/cm2
- The goal is to produce high particle currents in intense charge pulses, which are well matched to the acceleration scheme.
- For an EBIS, the charge state is moderate (e.g. Au32+), but the ion currents are high (~10mA) for total extracted charge >100nC and short pulses ~10 to 40 microseconds.
- In order to maintain high vacuum in the face of electron beam losses and potential high voltage discharges, a warm, baked vacuum system design was used.
- Pumping includes Cryopumps, turbo pumps, sublimation pumps as well as passive and electrically heated NEG pumps. The pressure achieved currently is 2E-10 at the gun and 7e-11 in the trap.

Some key features of Rhic EBIS

- A novel electron gun based on a design from Novosibirsk, which uses a convex cathode
    - **produces a low rotational electron beam well suited for the accelerations and decelerations common in the EBIS transport system**
- A warm bore, unshielded superconducting solenoid for the main trap region
- Vacuum separation of the trap region from the electron gun and electron collector regions
- Large bore (32mm) drift tubes have been used (pumping, reduced alignment precision, fast extraction, reduced RF coupling)
- The use of auxiliary (warm) solenoids & many transverse magnet coils for steering corrections on the electron beam
- The electron beam is pulsed to reduce the average power on the electron collector
- Versatile controls and hardware allow one easily manipulate the time dependent potential distribution to accommodate various injection and extraction techniques.

Magnetic geometry and electron beam envelope

RHIC EBIS operates with the electron gun cathode immersed in the magnetic field of a launching coil. The electron beam is then compressed by the main magnetic field.



External ion injection modes:

Fast Injection: Ions are injected into the electron beam in an ion beam pulse typically ranging from a few uS to a few hundred uS. Raising a potential barrier traps the ions axially while terminating further injection. Retarding the incoming beam can greatly increase the linear charge density, lowering the required injector current. The efficiencies can be very high, typically above 50%, and there is a well defined beginning of confinement period.

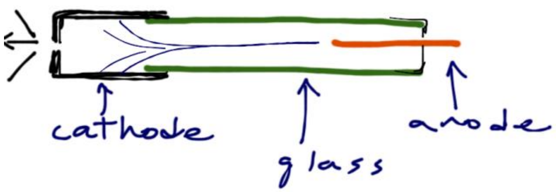
Slow injection: (accumulation mode) allows trap filling with much lower current beams. The injected ion energy is adjusted so that ions pass over a potential barrier on the way into the trap, but if they are further ionized during a round trip transit and if ionized during a round trip, they will be trapped. In general, this type of injection is much less efficient with trapping rates typically a few percent or less.

This mode can be useful when efficiency is not important or when the incoming beam is very low intensity and accumulation is essential. High electron beam current densities help improve the efficiency.

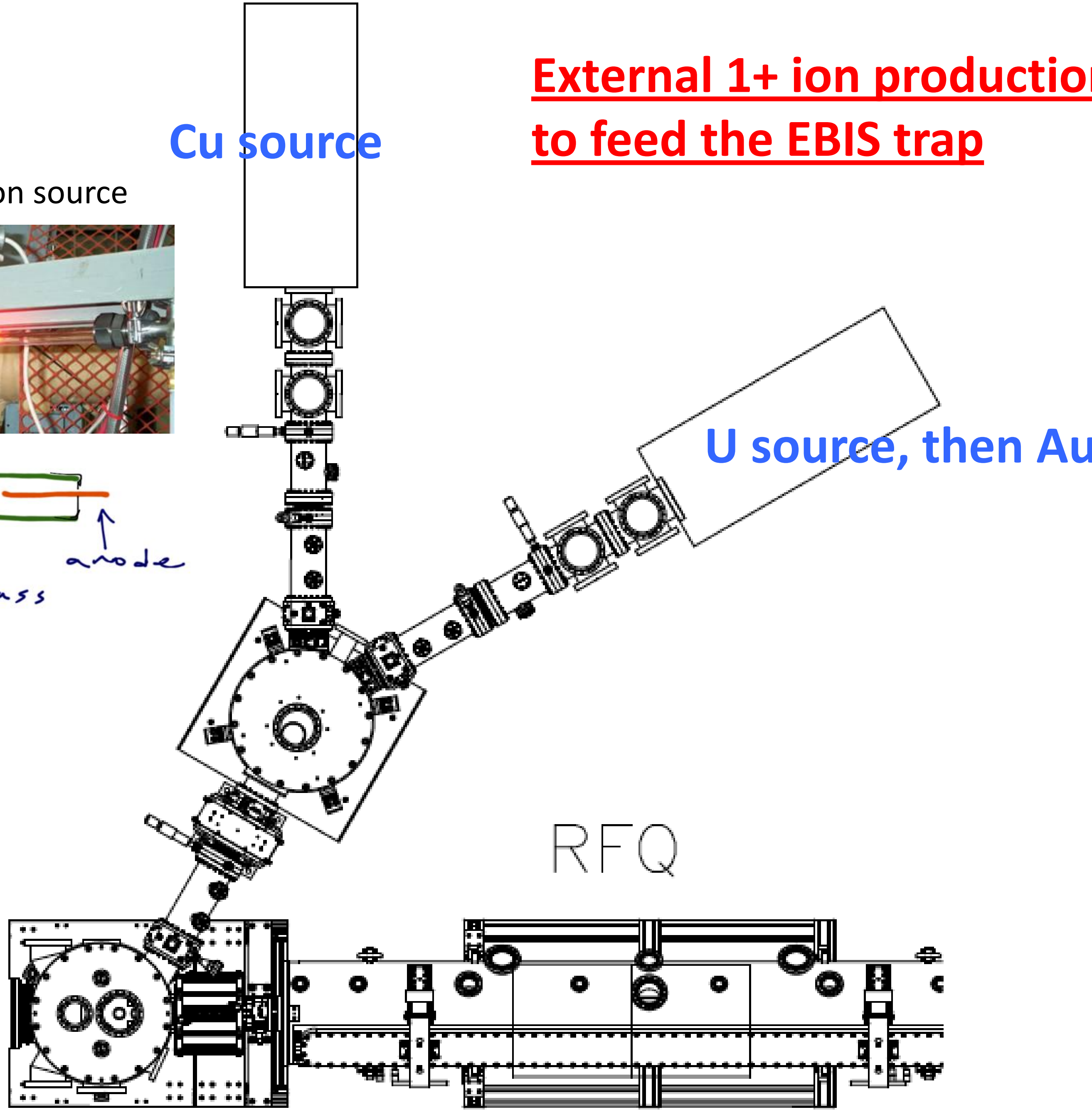
RhicEbis usually operates in the accumulation mode which places less demand on the external injection sources and beam transport.

External 1+ ion production to feed the EBIS trap

Hollow cathode ion source



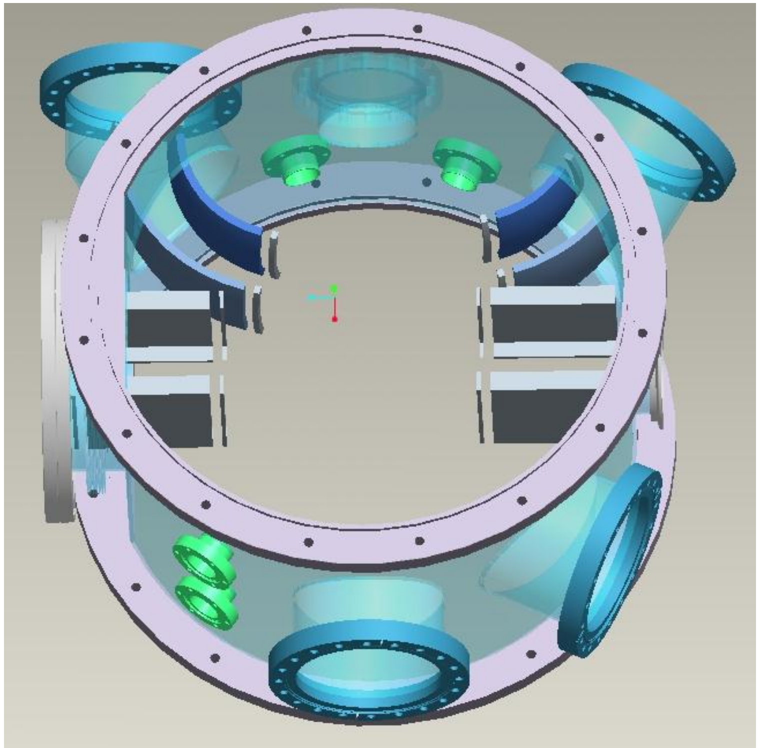
EBIS is a “charge breeder” of the injected 1+ ions

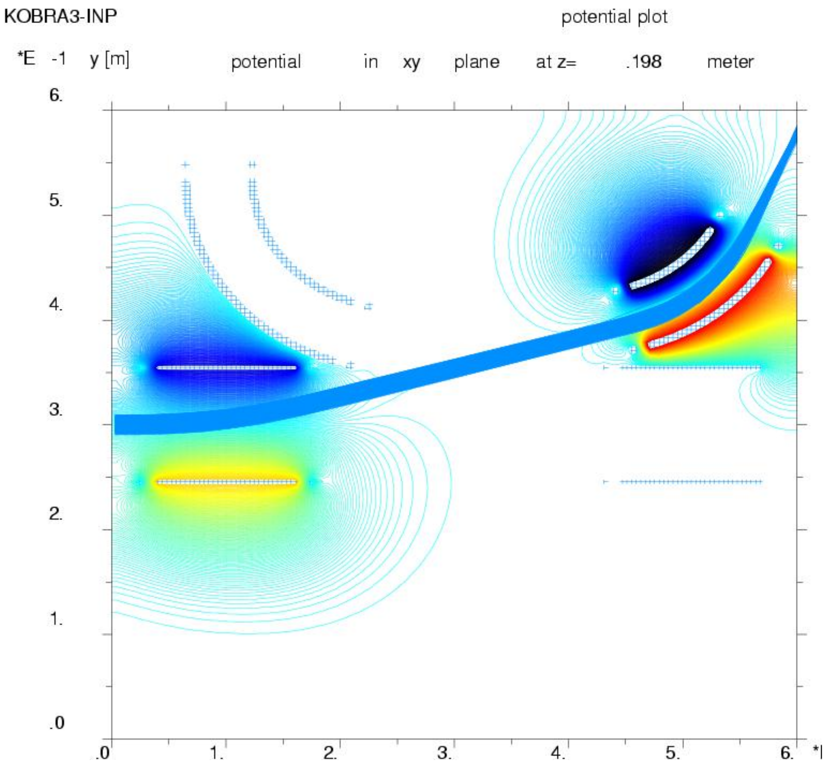


1+ Ions into EBIS

LEBT Switchyard and Diagnostic Chamber

BROOKHAVEN NATIONAL LABORATORY

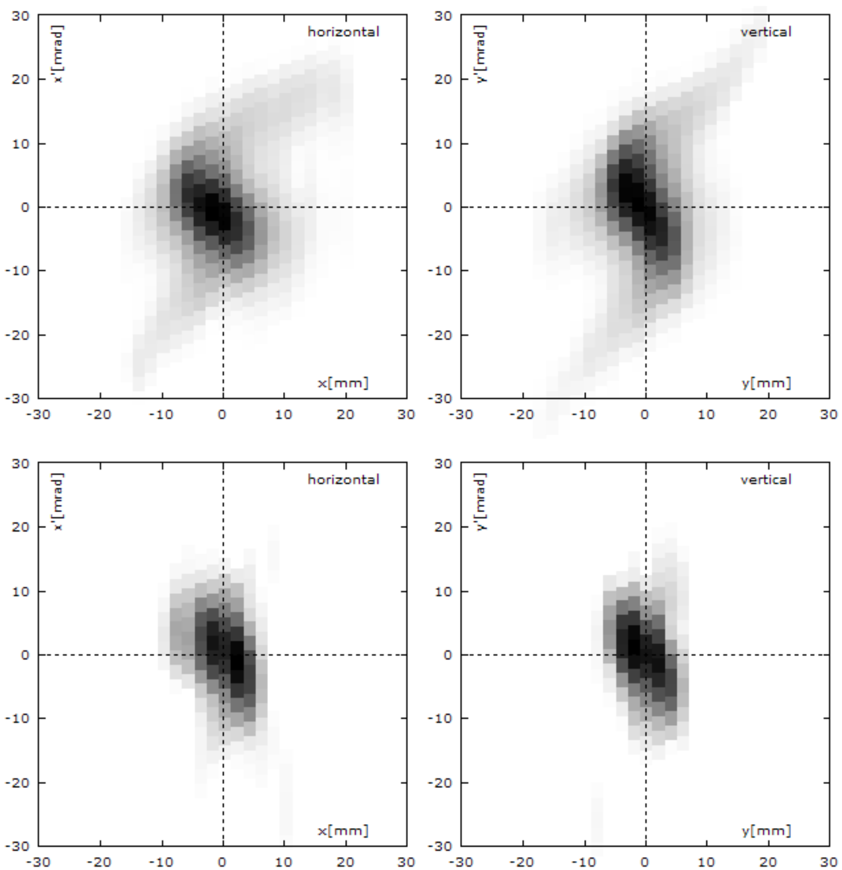




Left: Multi-port LEBT chamber with spherical & flat bending elements for ion injection into EBIS

Right: Simulated 15keV beam trajectory for injection into the EBIS

Pepperpot emittance measurements of injected 1+ ions



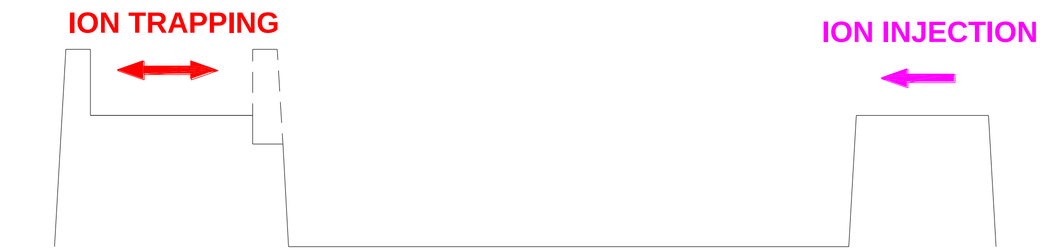
Emittance at the exit of the LEBT chamber, Cu^{1+}, 11 keV, 10 μA.

Aberrations observed when the beam fills the quadrupole aperture.

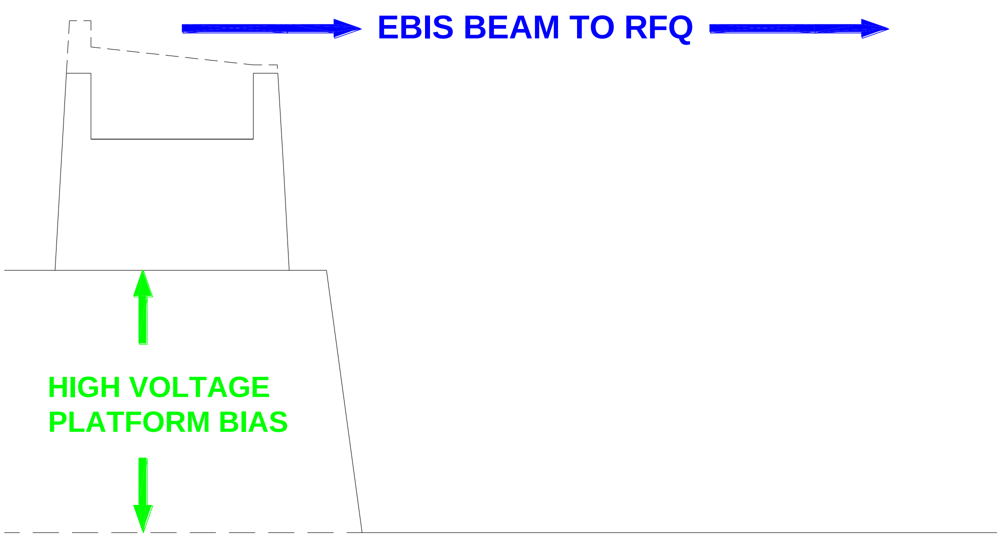
Emittance at the exit of the LEBT chamber when the beam is collimated between the ion source and the first quadrupole.

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

Ion Elevators: Pulsed High Voltage Platforms



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

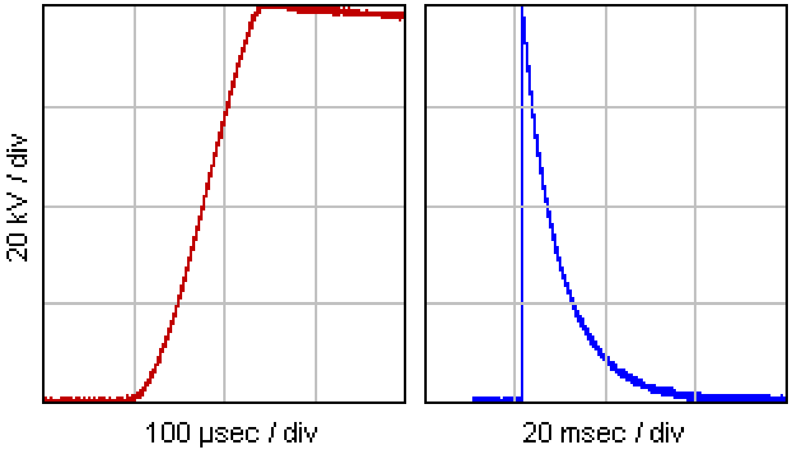


Just before ion extraction the EBIS Platform Voltage is applied such that the ions are extracted through 100kV (nominal) to attain the ~17keV/amu needed for acceleration by the RFQ

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

HV Platform Pulsing for EBIS ion beam injection into RFQ

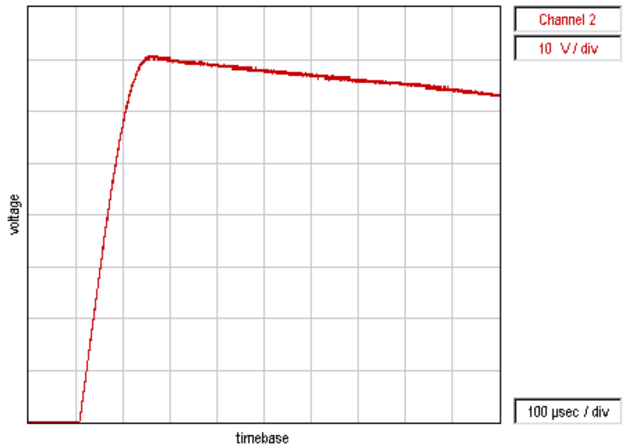
BROOKHAVEN NATIONAL LABORATORY



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)

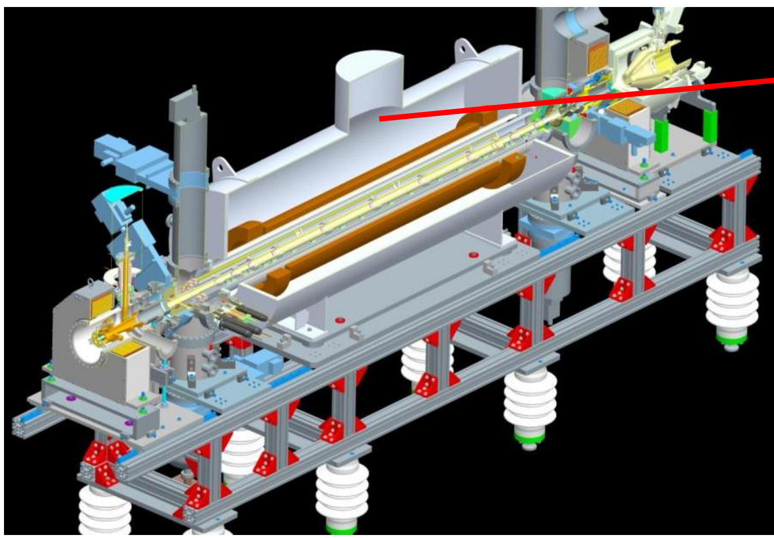
Horizontal scale is 100µs/div

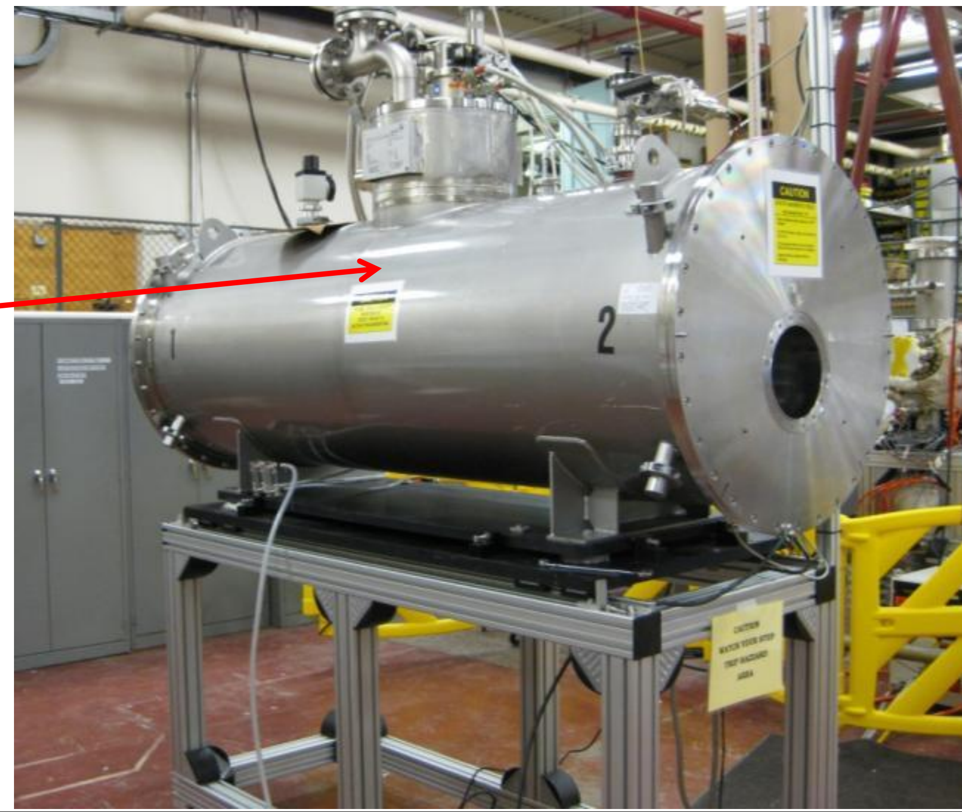
20100104-04

EBIS Superconducting Solenoid

- Length of the SCS coil: 190 cm
- Magnet field: 5 T
- Warm bore inner diameter: 204 mm (8”)

Solenoid is twice the length of that used for R&D prototype EBIS





RHIC EBIS design parameters

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

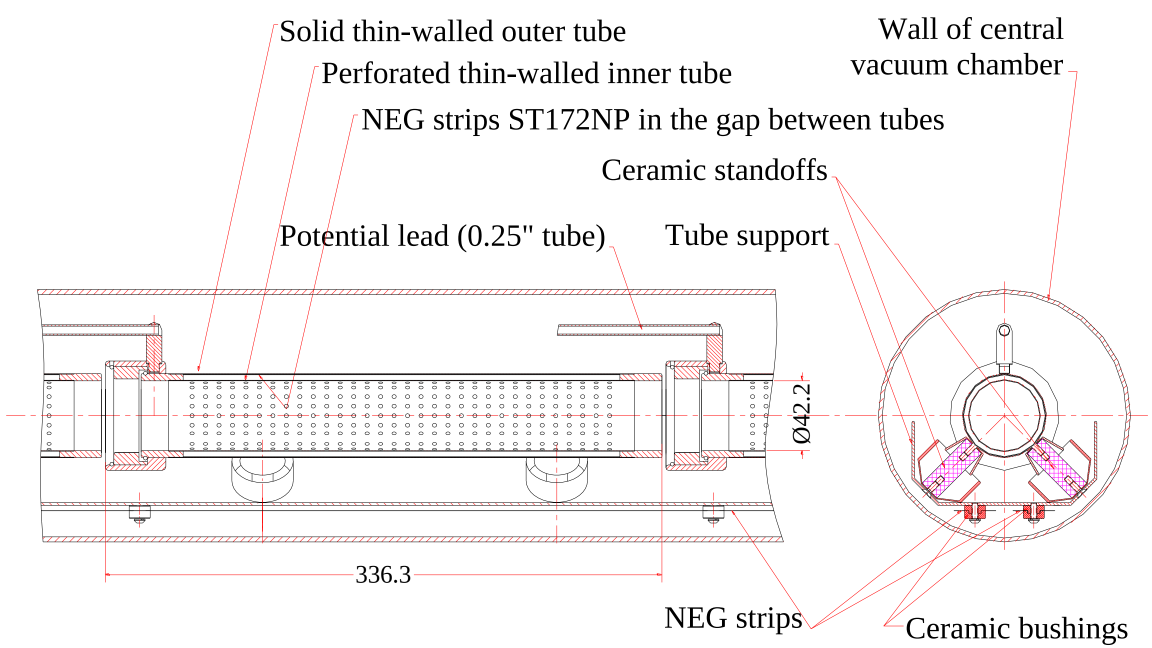
RHIC EBIS unshielded superconducting solenoid manufactured by ACCEL:

Maximum magnet field	5.0 T
"Warm" ID	204 mm
Length of solenoid	1900 mm
He refilling period	30 days

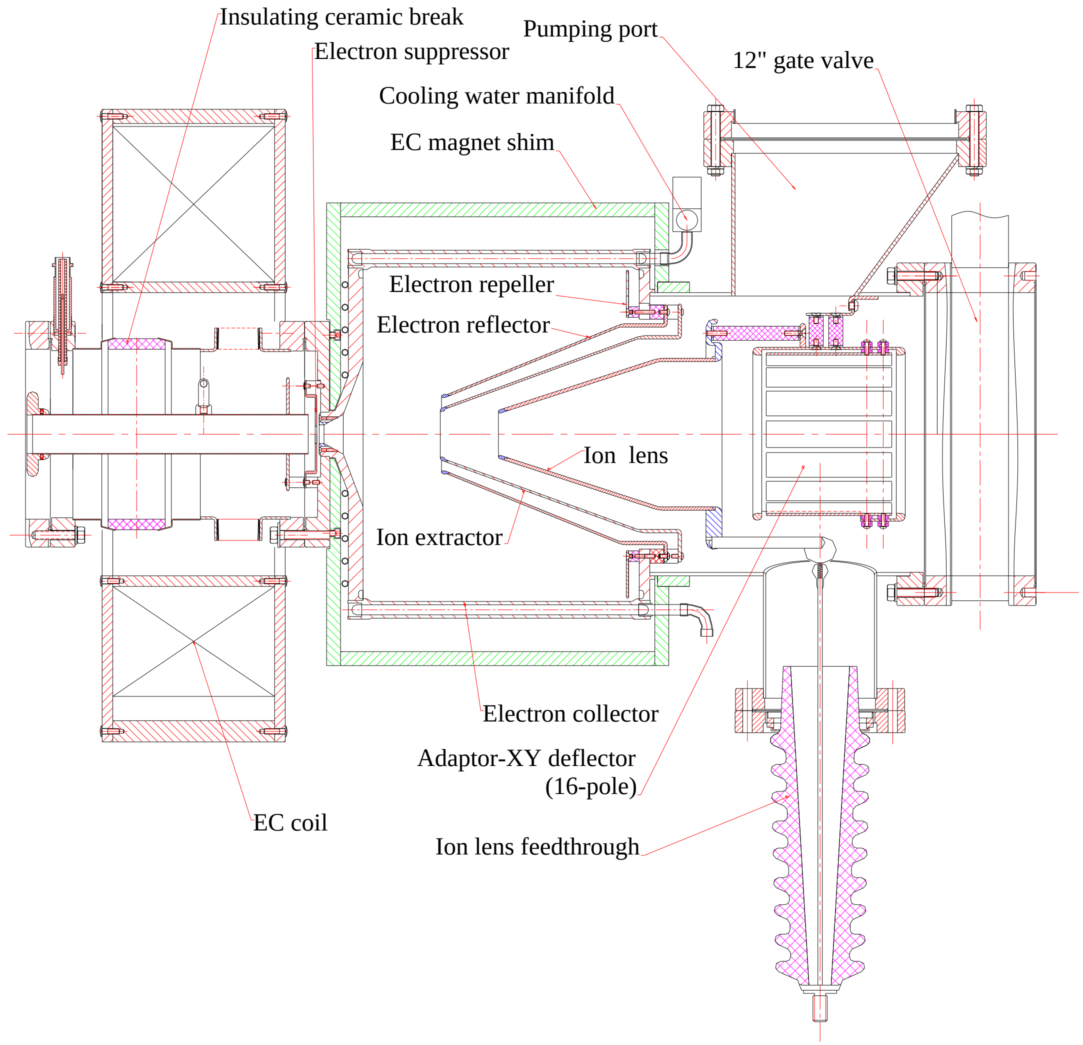
Rhic EBIS Upgraded pumping capabilities compared with Test EBIS :

-Larger inner diameter of drift tubes (42 mm instead of 31 mm) to reduce ion losses and further reduce electron beam – wall coupling (which may be important for higher electron current)

-Added actively heated NEG strips in the central chamber and passive NEGs on inner surface of drift tubes to improve vacuum conditions in the ionization region

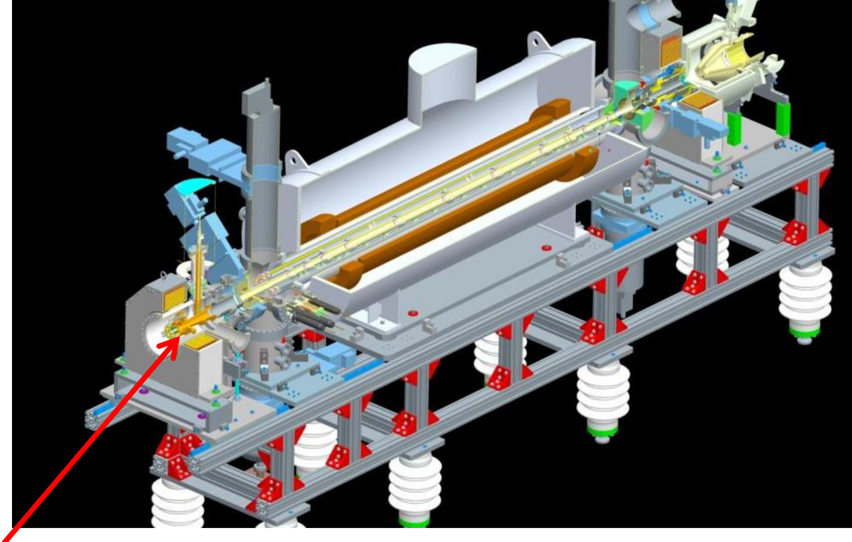


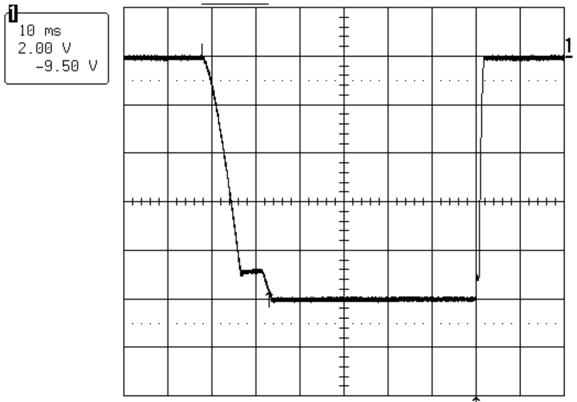
- Improved ion optics for extraction and injection with larger apertures to accomodate larger angles



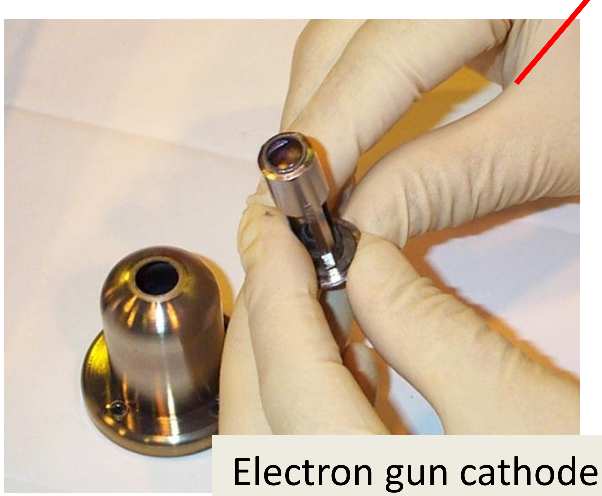
The EBIS 10A electron gun

- This was a key development. Previous EBIS operation was typically at 0.5A or less
- Electron beams up to 10A, 100kW have been propagated with very low loss, using IrCe cathodes from BINP, Novosibirsk.

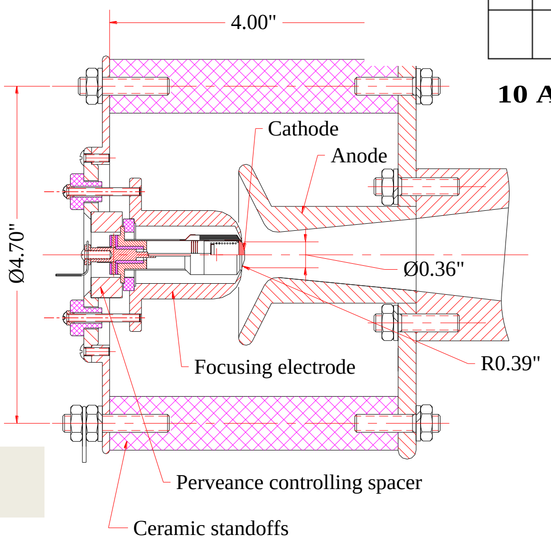




10 A, 50 ms Electron Beam Pulse (R&D EBIS)

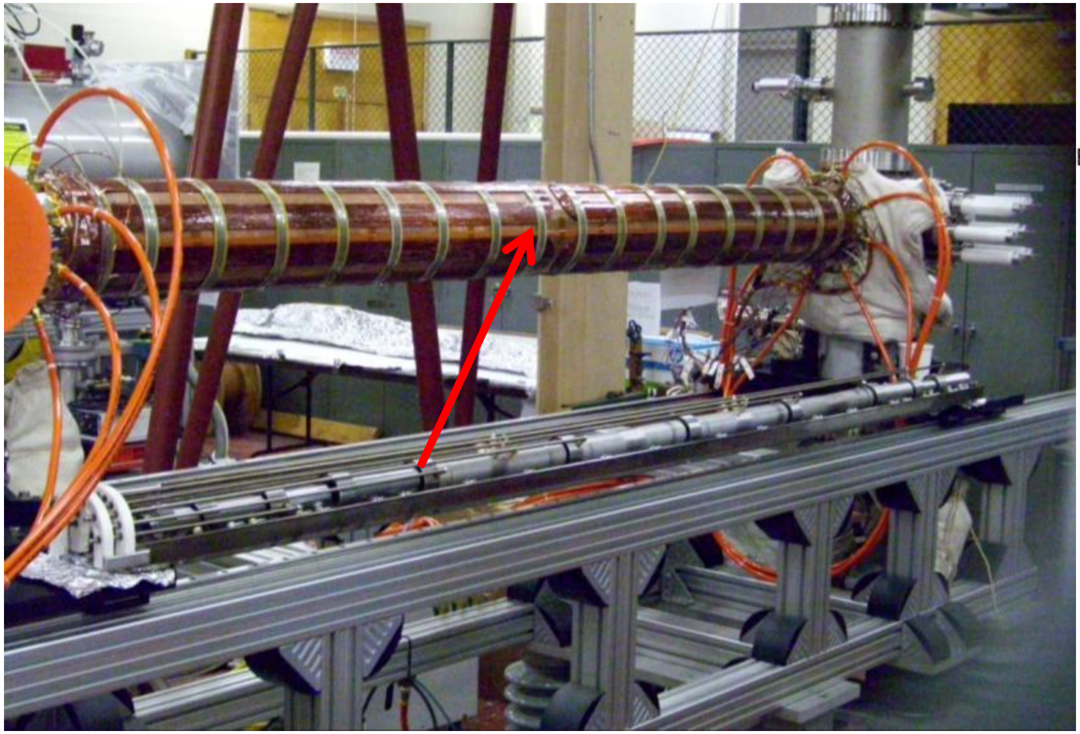


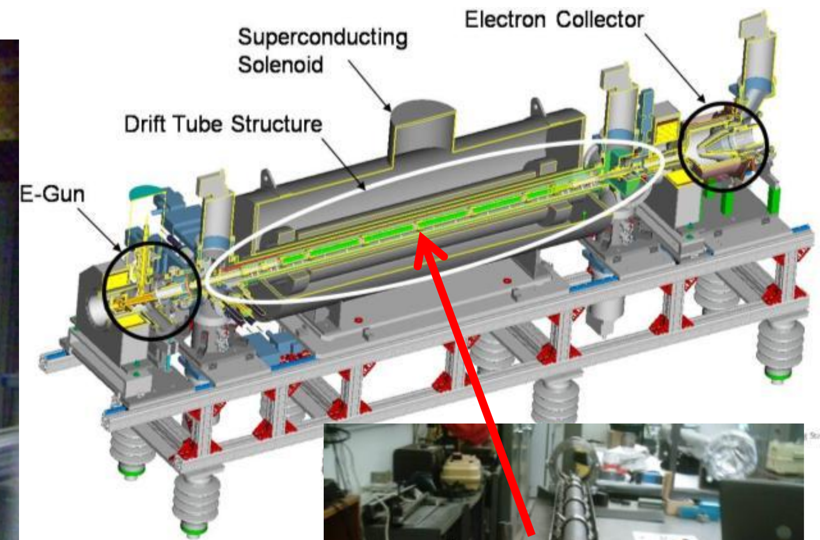
Electron gun cathode



Drift tube structure

BROOKHAVEN NATIONAL LABORATORY





Large-bore drift tubes sit inside the central vacuum tube.

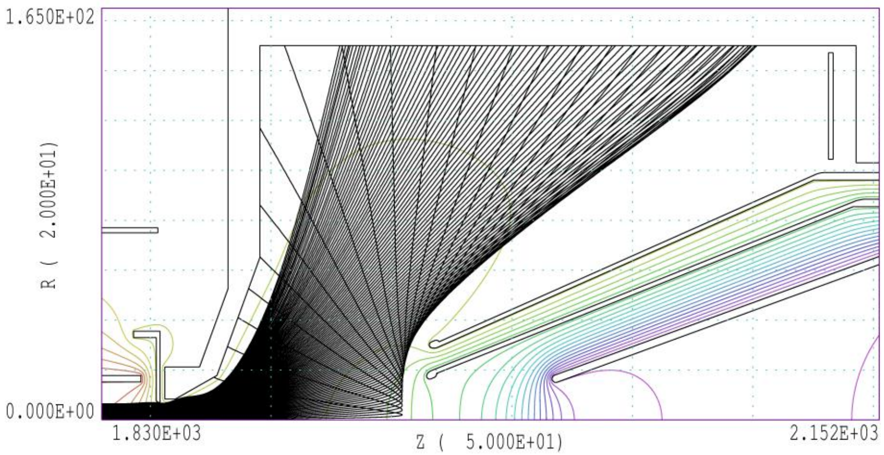
Heaters on the outside of the vacuum pipe allow baking to 450 C.

Outside the water cooled jacket, there are transverse steering coils.

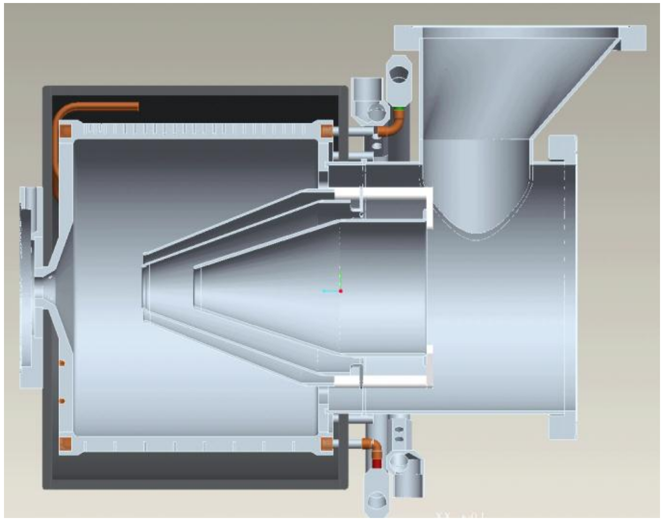
EBIS electron collector

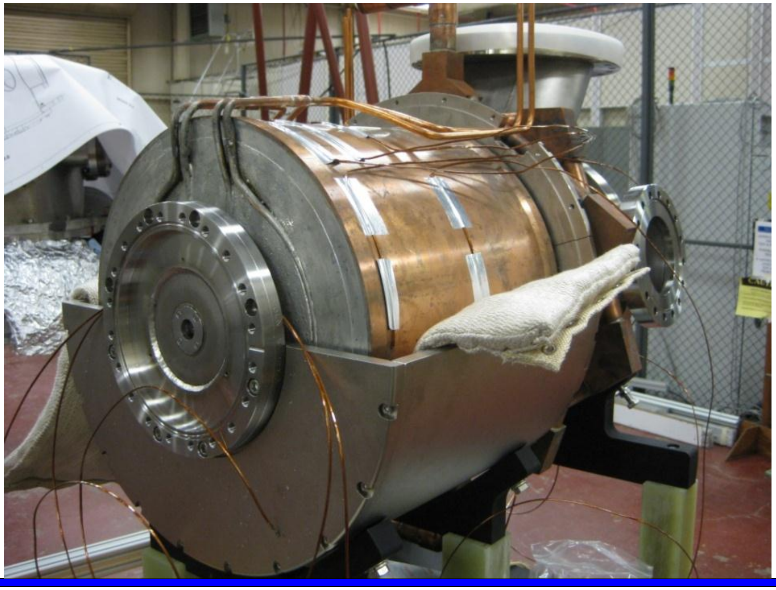
Another key development.

Electron collector capable of dissipating electron beam up to 20 A (300 kW peak power) with length 50 ms and frequency 5 Hz



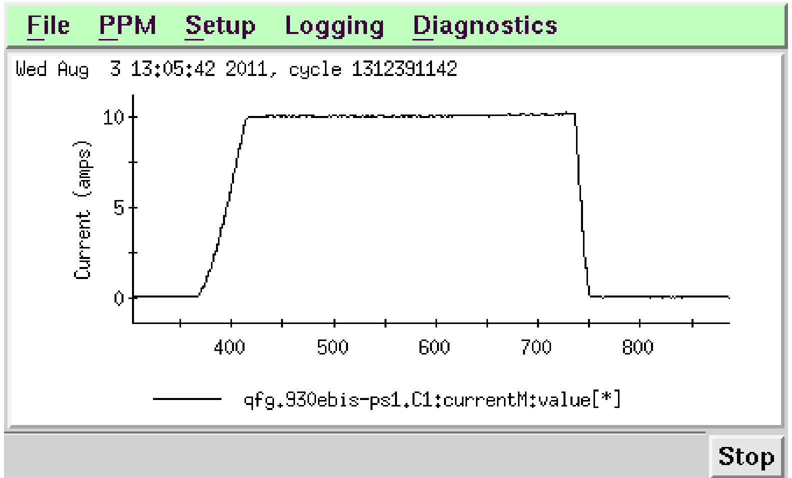
Trajectory simulations in RHIC EBIS electron collector. I_{el}=20.6 A, E_{el}=15 keV



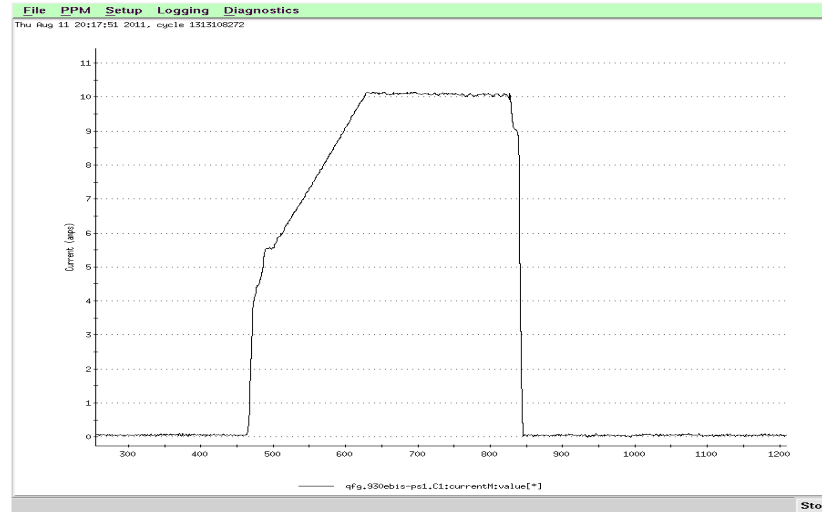


BeCu collector is installed on the RHIC EBIS

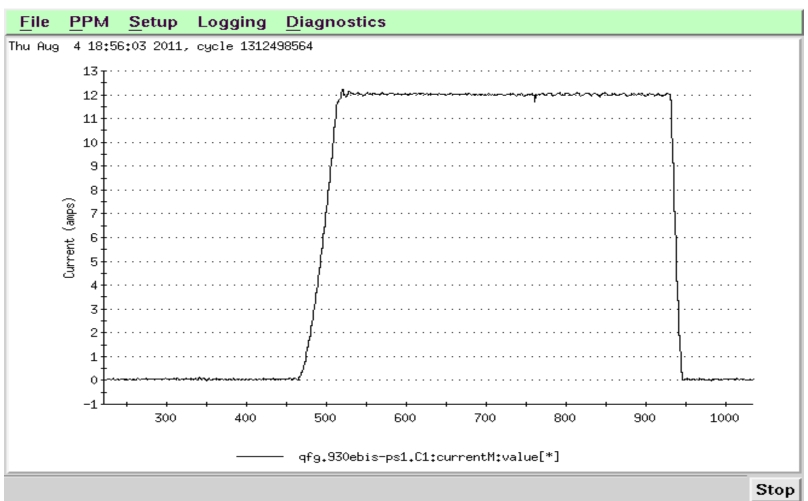
EBIS high electron beam current traces



First 10.1A 32ms e-beam in RhicEBIS



10A, 35ms used for Au ion production (82nC)

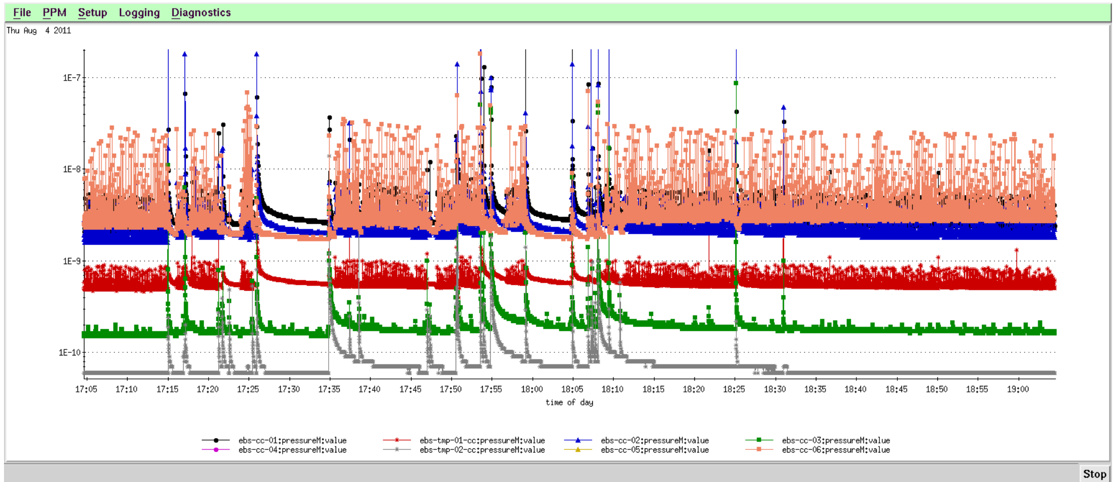


12A 40ms ebeam

Initially, propagation of high electron beam current is obtained using rather simple drift tube electrode voltage and electron current distributions.

Later, when ion trapping is added, more complex distributions are used to accommodate ion injection, ion trapping, and ion extraction, while maintaining a very low loss electron beam propagation.

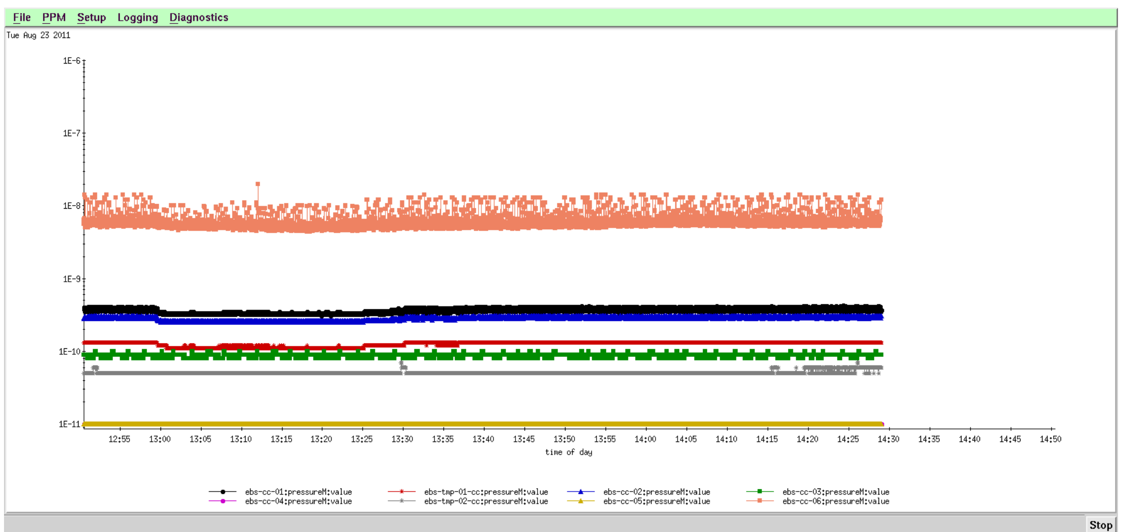
EBIS Pressures with high electron beam current



Pressures log for a 12A, 40ms beam

Pgun = 5 E-10
Ptrap =2 E-9
Pcol = 3 E-9

20110804



Pressure log for 7.6A e-beam with a 65ms ion confinement

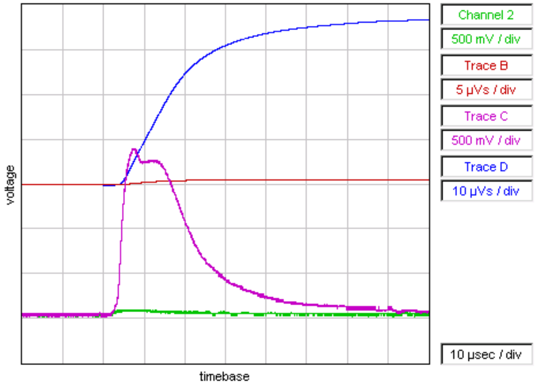
Extracted ions:
70nC Au with inj, 1nC no inj

Pgun = 1.5 E-10
Ptrap =9 E-11
Pcol = 5 E-9

20110823

Highly charged Au extraction from RhicEBIS after fast injection from the HCIS

BROOKHAVEN NATIONAL LABORATORY

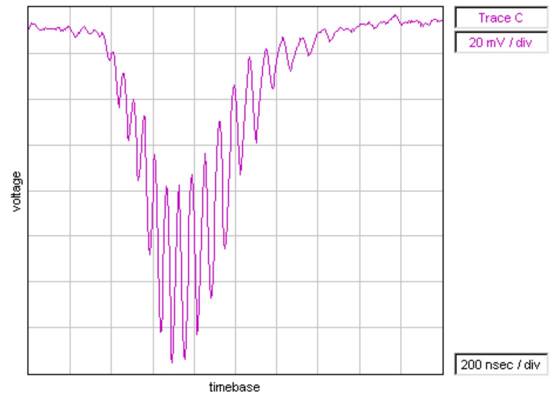


Au pulse (all charge states), slightly slowed extraction

ChC Magenta: (Current with Au+ inj) 3.5mA, 1 mA/div, 10 µs/div
ChD Blue: (Total extracted charge) 70nC , 20uVs/div

Ch2 Green: (Current without Au+ inj) 0.2mA, 1 mA/div, 10 µs/div
ChB Red: (Total extracted charge) 1nC , 10uVs/div

File name: 110823-08_Au__70nC_7.5Ae_65ms_on_neg_8kV _platform_fast_Inj_HCIS1_16kV_pulser_at_63__1nC_wo_inj.wfm



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

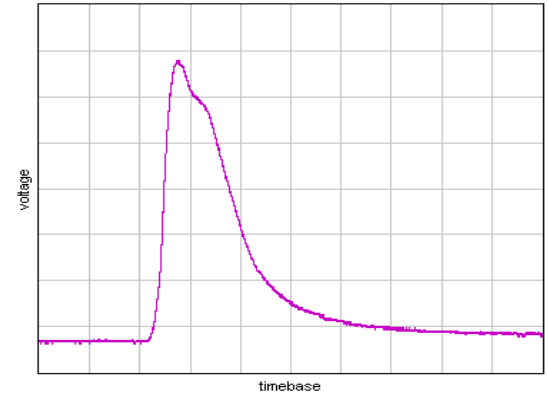
File name: 110823-09_Au__high_res_65ms_conf _8kV_retardation_7.6A__Au32.wfm

Right: Au pulse (all charge states), faster extraction

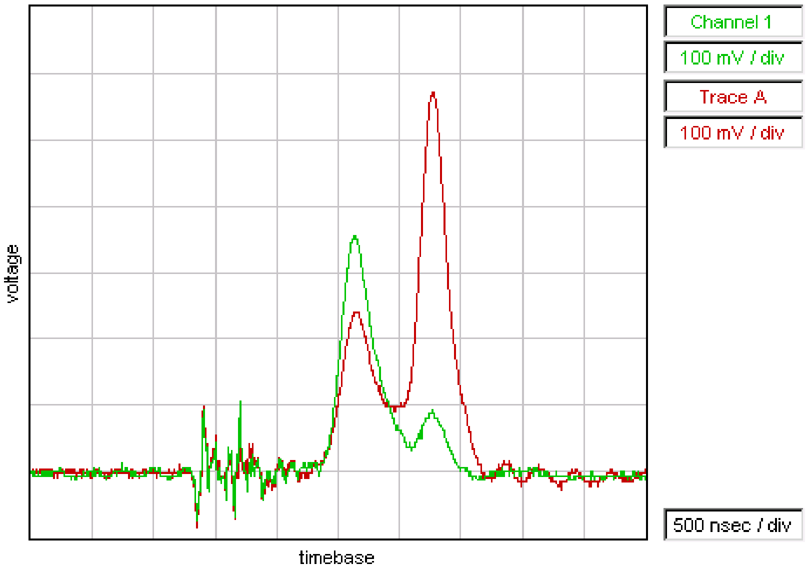
~6 mA peak, at EBIS output

1 mA/div, 10 µs/div

I(e)=7.6A, 65 ms confinement



Rhic EBIS Low resolution TOF after 15 degree bend



Red Trace: With Au+ injection from HCIS

Green Trace: reduced Au+ injection (Au injection not completely "off")

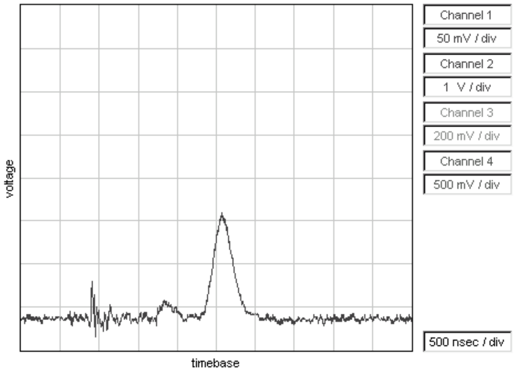
High background; unbaked system

Low resolution TOF spectrum measured on a Faraday Cup shows a gold fraction of extracted charge is approximately 60%.

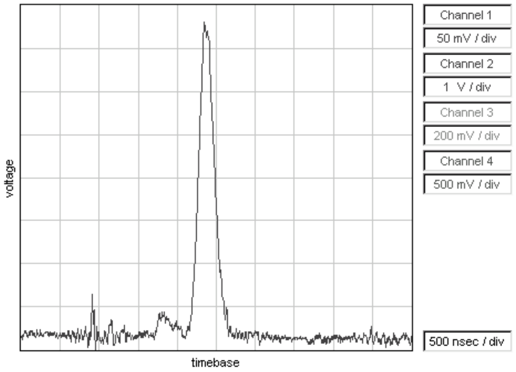
Electron current I_{el}=5.6 A, confinement time τ_{conf}=36 ms, dominant Gold ion charge state is ~30+.

Low Resolution TOF on a Faraday Cup (15 deg off axis)

BROOKHAVEN NATIONAL LABORATORY



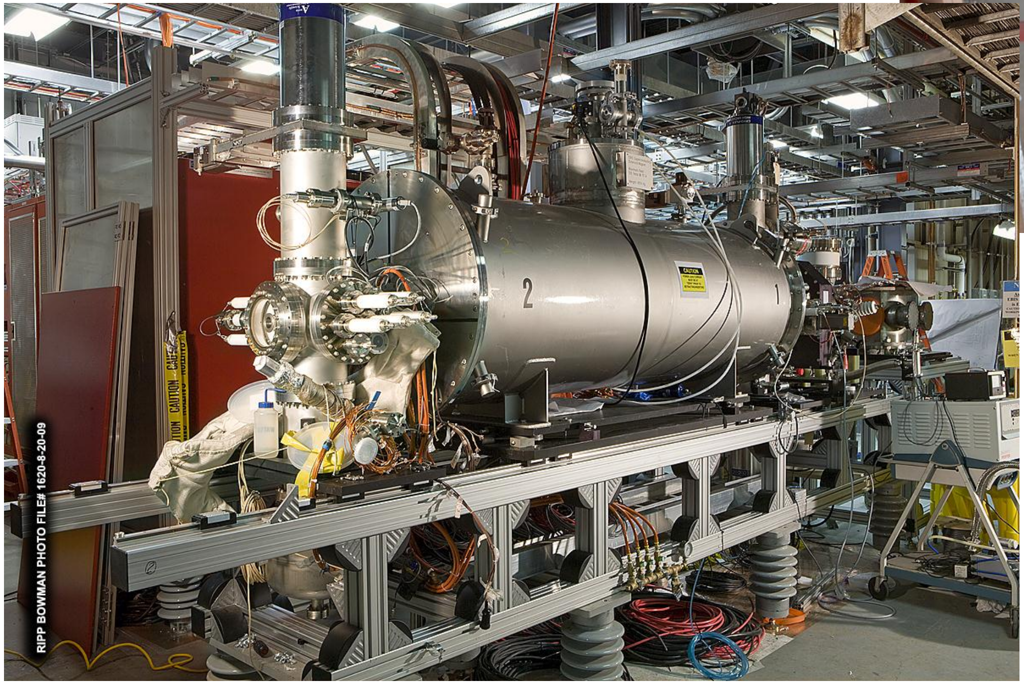
Au Time-of-Flight (25ms confinement)
(peaked at Au25+)



Au Time-of-Flight (65ms confinement)
(peaked at Au32+)

Well baked system and excellent electron beam propagation result in very pure Au spectrum.

EBIS during installation

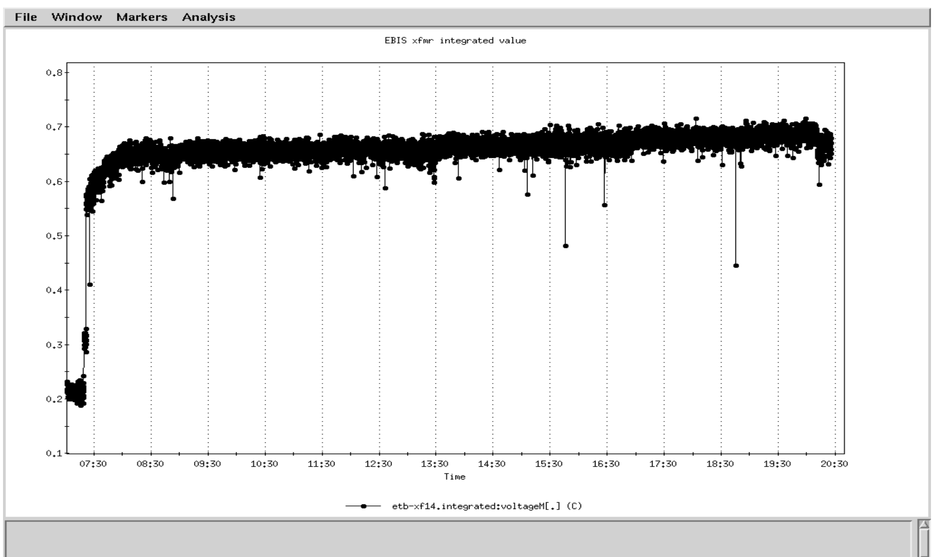


11 Racks of power supplies for EBIS, all pulsing to 100 kV along with the EBIS, during ion extraction.

Summary of First Run to NSRL (Mar-Jun 2011)

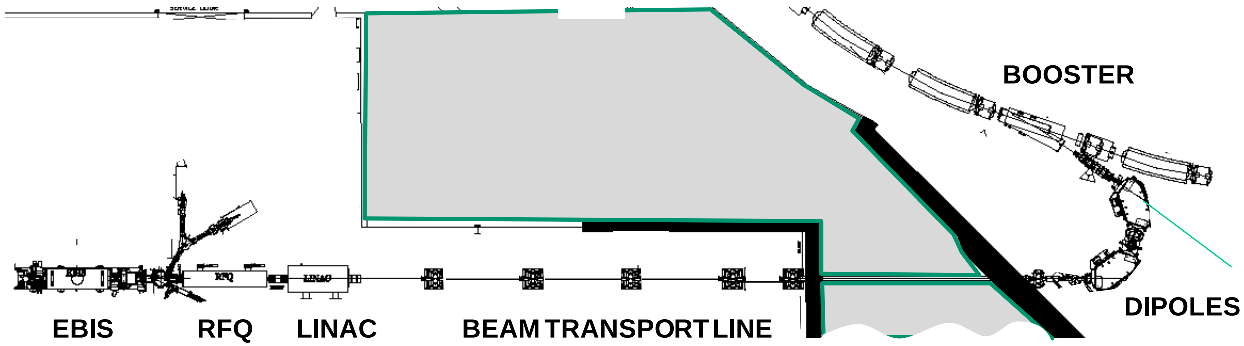
BROOKHAVEN NATIONAL LABORATORY

- EBIS operated ~ 6 days/ week, 12-16 hours/day, from ~ March through June
  - Delivering beam to NSRL, and working on adding species and increasing intensities
- Ran 38 days for NSRL biology experiments
  - Delivered Fe 20+, He 2+, Ne5+, Ar10+, and Ti18+ beams
    - (He, Ne, Ar were new beams for NSRL)
    - No downtime
    - Excellent stability (eventually got to where it ran for days without any adjustments)
- All RF systems and transport magnets ran 24/7 for ~ 4 months
- All EBIS source, rf system, and transport magnet settings are very reproducible



Fe20+ to NSRL:
Each point on the plot is the integrated current in one EBIS pulse
13 hours without a missed pulse

Rapid switching between ion species

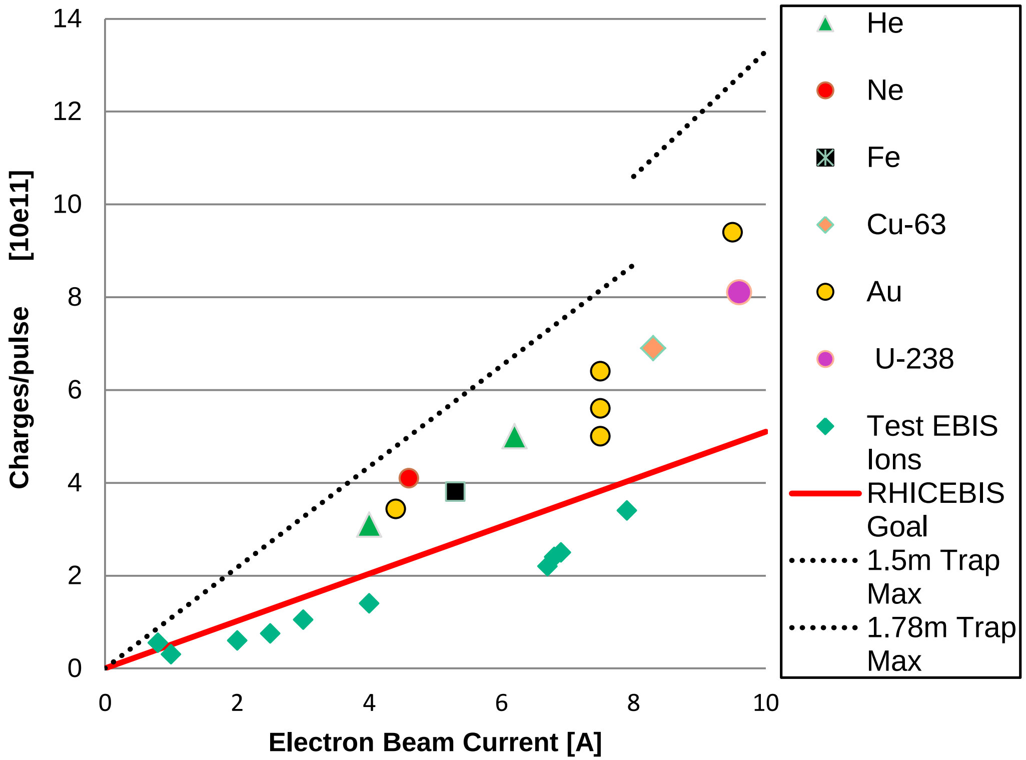


- Ion injection into the EBIS trap was tested first with Fe^{1+} and Au^{1+} (two sources)
- EBIS confinement time was switching between 65 ms for Au^{32+} and 130 ms for Fe^{20+}
- Also switching pulse-to-pulse: platform high voltage, power to all RF systems, current to the large dipoles, and all transport line elements.

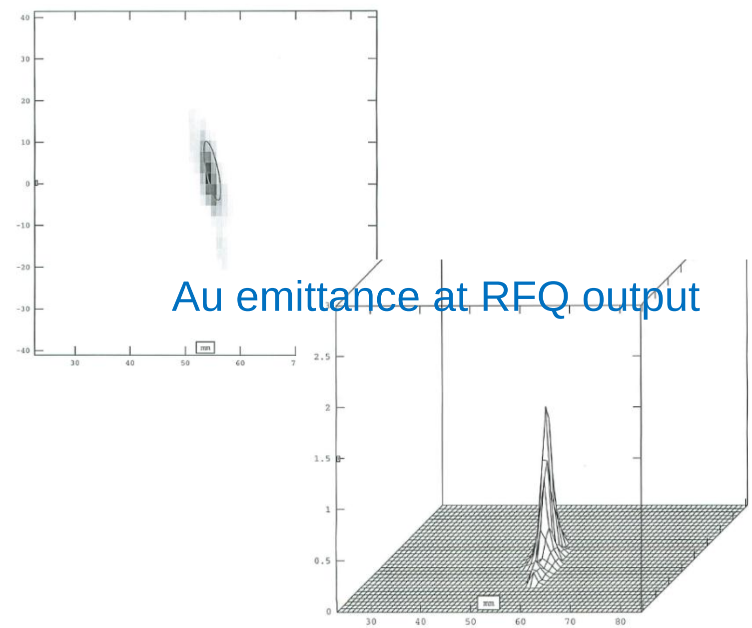
This rapid switching of species has been a frequent mode of operation during the RHIC run when both Au32+ and Cu11+ were delivered by EBIS. Switching will also be necessary when beams are delivered to both RHIC and NSRL.

Ion Yields from RhicEBIS (and TestEBIS)

BROOKHAVEN NATIONAL LABORATORY



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

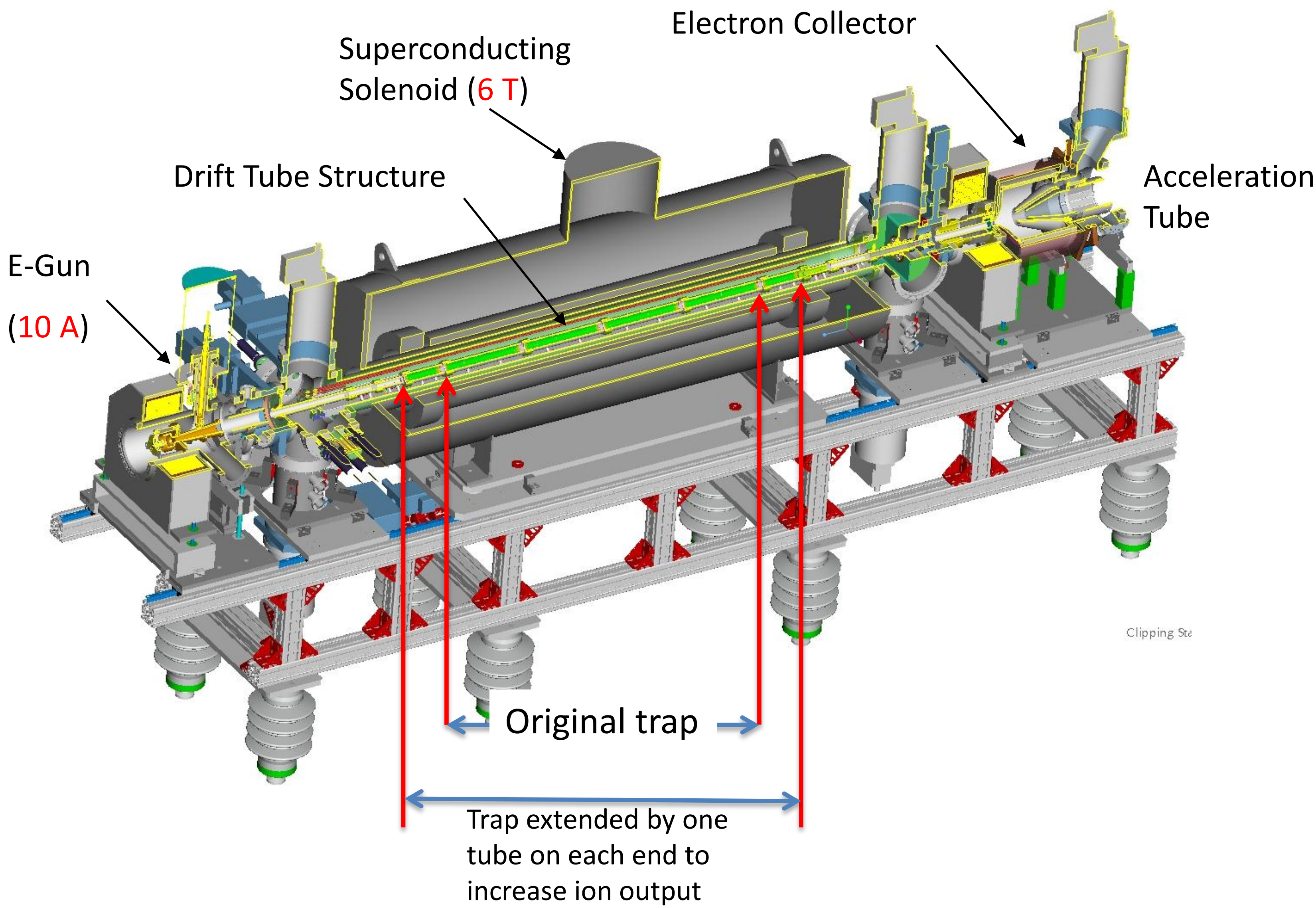


Au emittance at RFQ output

- **Ions produced with e- beams up to 10A**
- **Ion yield scales properly with Ie-**
- **Cu, Au, U beams using electron beams > 8A benefit from an increased source capacity of ~19% due to a longer axial trap configuration**

ε(n, rms) = 0.19 π mm mrad
(2-3 mm beam width)

Lengthened trap region from 1.5m to ~1.8m. Ion output increased proportionally.



EBIS Ions in Booster (per EBIS extraction)

BROOKHAVEN NATIONAL LABORATORY

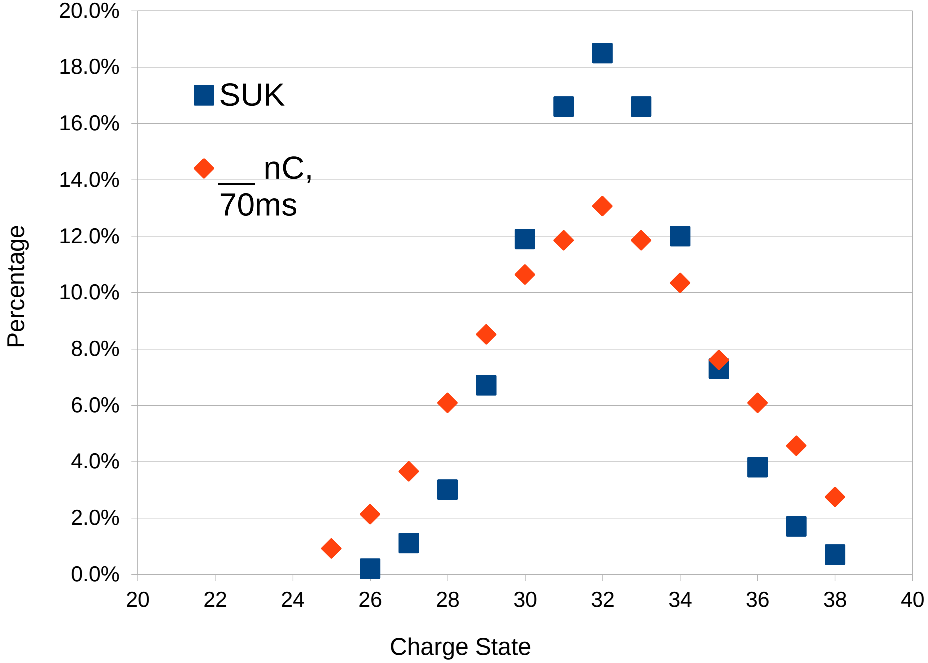
Charge for a single species charge state is measured close to the Booster ring input after the RFQ and Linac and Two dipole bends plus collimation. Measurement is made for best transmission through the rest of the complex rather than for maximizing the charge delivered by EBIS at that location.

EBIS electron Current [A]	Ion	Booster Input (ions)	Booster Input One Ch State (Charges)	EBIS All Ch States (Charges)	Charge Fraction EBIS to Booster
8.3	63Cu11+	6.1e9	6.7e10	6.9e11	9.7%
9.5	Au32+	1.5e9	4.7e10	9.4e11	5.0%
9.6	238U39+	1.1e9	4.2e10	8.1e11	5.2%

Transport to Booster/AGS/Rhic rings with nominal 10A EBIS electron beam operation:

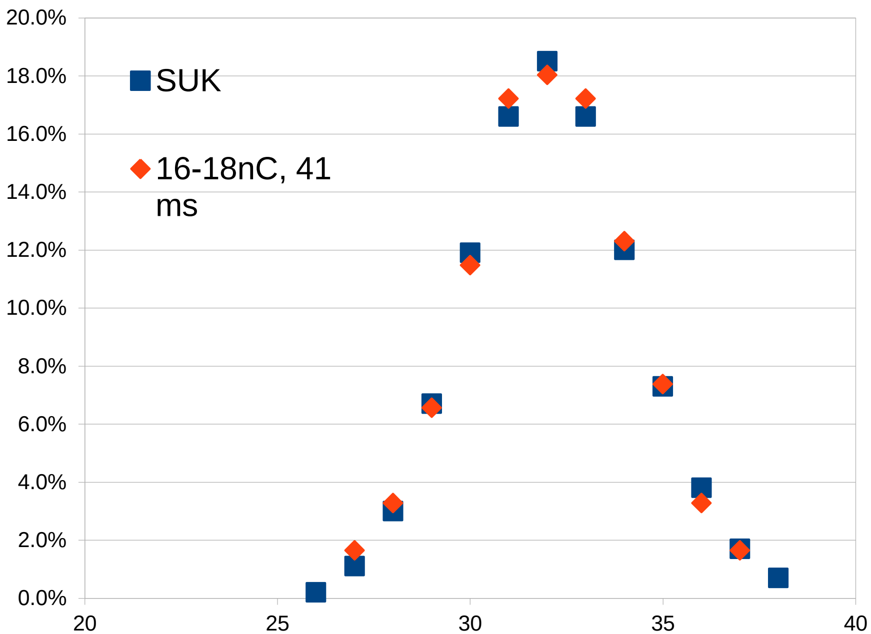
Transmission to Booster input is ~56% of what is expected, and there are additional shortfalls in the the Booster/AGS rings. We believe that the early losses are due to a broadening of the EBIS charge state distribution with high neutralization coupled with a 30% decrease in the RFQ/Linac transmission efficiency due to mismatch and/or emittance growth due to misalignment.

The RHIC injection goals have been met by extending the EBIS trap, doubling the number of EBIS pulses per injection cycle, and performing an extra bunch merge in the AGS ring.



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

Normal running at >50% of capacity gives ~13% in desired charge state vs. 18.5% calculated.



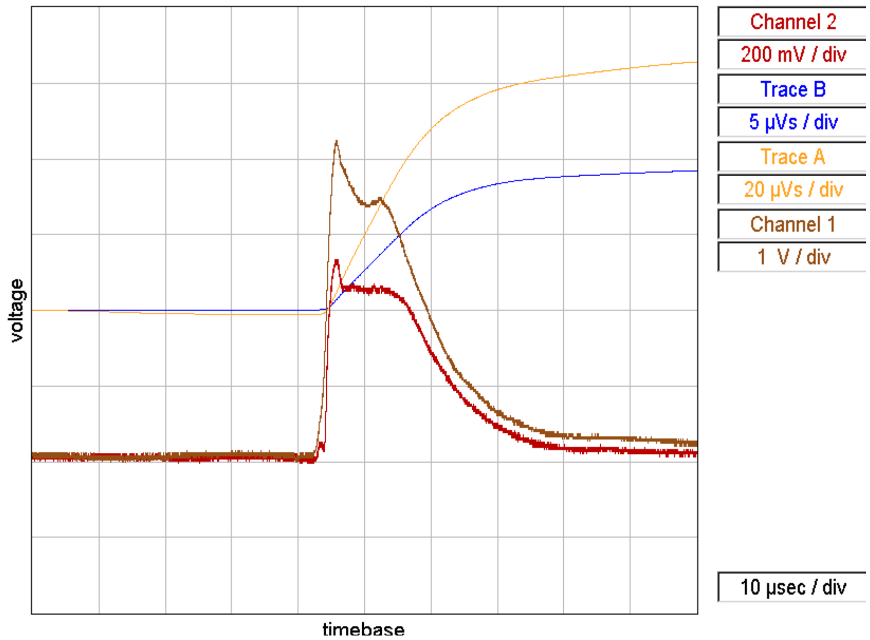
Test at reduced charge - measured distribution matched calculated

13% in 32+ * 75% of capacity =9.75% vs. design values of
18.5% in 32+* 50% capacity=9.25%
→ Should still be ok

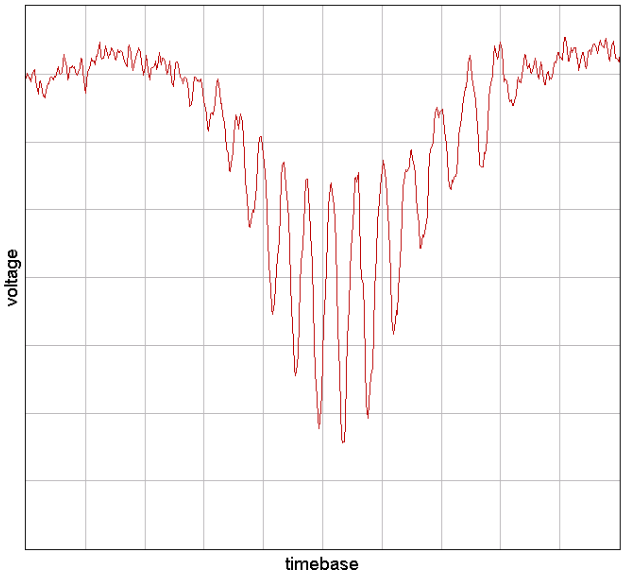
First RHIC Run with EBIS

- EBIS operated 7 days/ week, 24 hours/day, from ~ April through June
- First RHIC run with Uranium collisions
- First RHIC run with Au-Cu collisions
- 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 new preinjector
- Excellent stability, eventually getting to where it would run for days without needing any adjustments

Uranium from EBIS

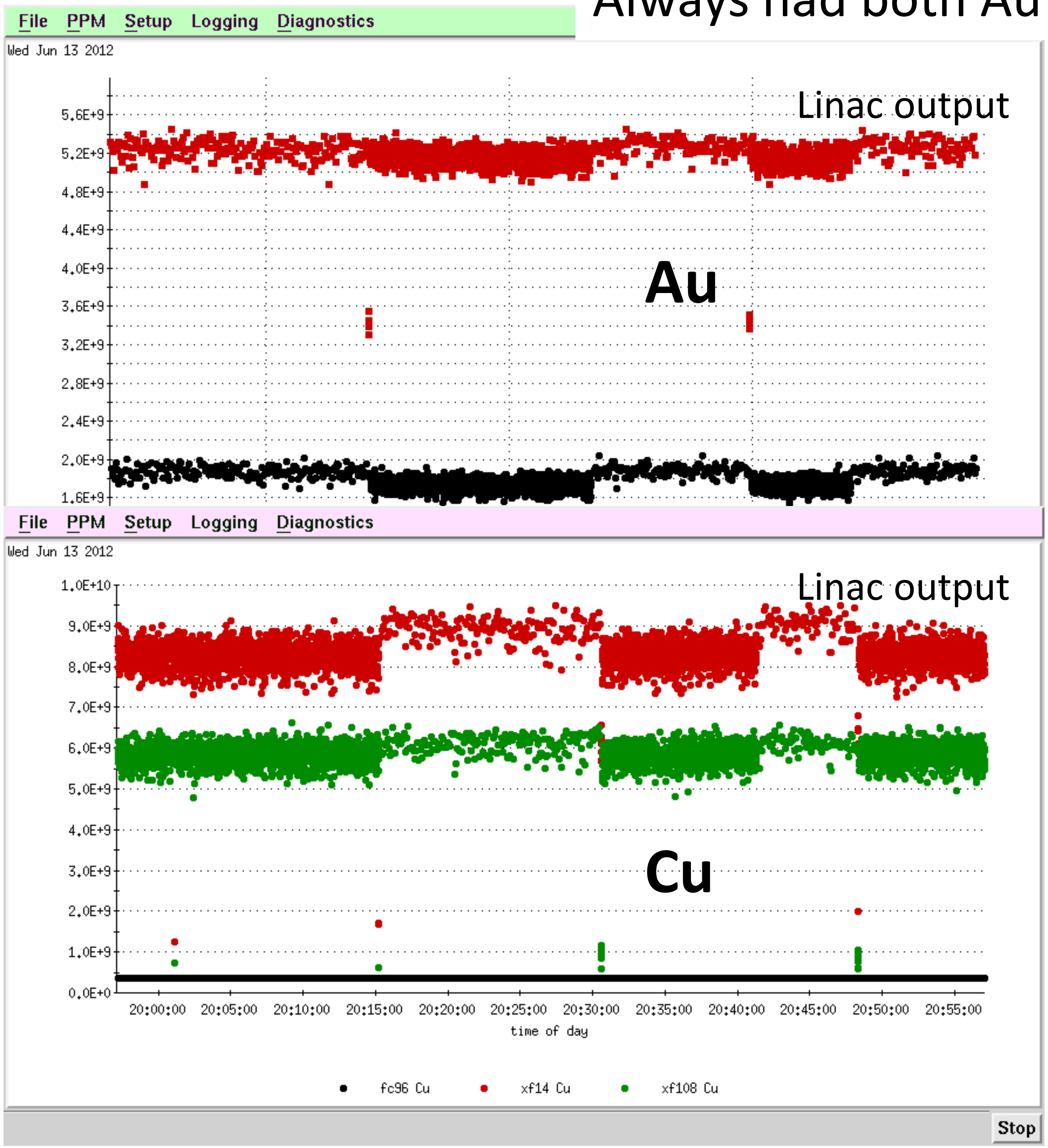


Uranium (all charge states) at EBIS output and RFQ input (both 2 mA/div)



Uranium time-of-flight charge state distribution; Peak at U 39+ (~13% in the desired charge state)

Always had both Au and Cu running



Each 5 second “supercycle”
8 Au & 1 Cu or
8 Cu & 1 Au or
1 Au & 1 Cu
(during stores)

EBIS confinement time was switching between 55 ms for Au^{32+} and 5 ms for Cu^{11+}

Also switching pulse-to-pulse: platform high voltage, power to all RF systems, current to the large dipoles, and all transport line elements.

Note – single pulse intensity is higher than the 8-pulse (difference is even larger when tuned for single pulse)

Fourteen EBIS beams delivered to date

BROOKHAVEN NATIONAL LABORATORY

He-3	2+	AGS
He-4	1+, 2+	NSRL
C	5+	NSRL
O	6+	NSRL
Ne	5+	NSRL
Ar	11+	NRSL
Ti	18+	NSRL
Fe	20+	NSRL
Cu	11+	RHIC
Kr	18+	NSRL
Xe	27+	NSRL
Ta	38+	NSRL
Au	32+	RHIC & NSRL
U	39+	RHIC

Carbon (and silicon ?) are new beams this fall

Future developments the BNL EBIS program

BROOKHAVEN NATIONAL LABORATORY

- Polarized He-3 source
- Brillouin gun tests on Test EBIS
- Brillouin gun / Fe^{26+} for NSRL
- Laser Ion Source for 1+ injection into EBIS

Summary

- RhicEBIS and all systems making up the new EBIS preinjector are operating as expected.
- EBIS has delivered a variety of ion beams to both NSRL and RHIC
- EBIS has operated above its design value of 10A electron beam (12A).
- Extracted ion charge with He gas injection reached 85.6% of the electron charge in 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 *current in the desired charge state is ~ the design value*.
- Several improvements are being implemented to increase the intensity at Booster extraction. (MEBT steering, additional matching quad at Booster, and increased gap of the inflector).
- Ion intensity at electron beams ~10A has been developed meeting the design goal for acceleration of ions such as U39+, Au32+ and Cu11+ for RHIC. Intensity and luminosity goals have been met with the help of bunch merging and increased EBIS duty factor.