Electron Beam Ion Sources, Traps, and Strings: Versatile Devices to Meet the High Charge State Ion Needs of Modern Facilities *

E. Beebe, J. Alessi, A. Pikin

Brookhaven National Laboratory

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Talk Outline

- Introduction to EBIS/T
    - Basic Principles
- Applications and Example Sources
- RHIC EBIS Recent Results

EBIS, EBIT and ESIS are closely related devices which produce highly charged ions through successive electron impact ionization in a high density electron beam.

All are ultra high vacuum devices which ionize carefully introduced neutrals (gas or ballistic injection) or further ionize low charge state ions injected from external sources.

The ion sources are precisely controlled with respect to electrode voltages and timing.

EBIS/T Gymnastics

The flexibility with which injection, confinement and extraction can be performed makes the devices extremely versatile for both injectors in accelerators or sources for atomic physic experiments.

Ion Confinement:

TOF Mode

Leaky over barrier mode

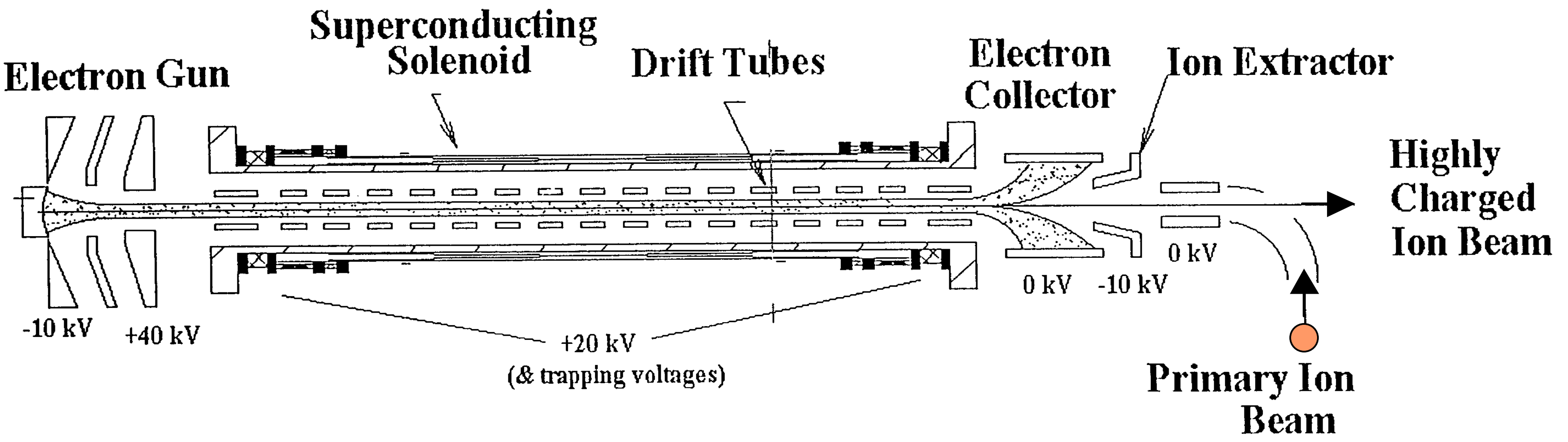
(ions come out when ready)

Pulsed Mode: (forced extraction after a prescribed confinement)

Fast extraction: Several mA in a few uS (VERY INTENSE)

or slow extraction: <<uA for many milliseconds

Principle of EBIS Operation

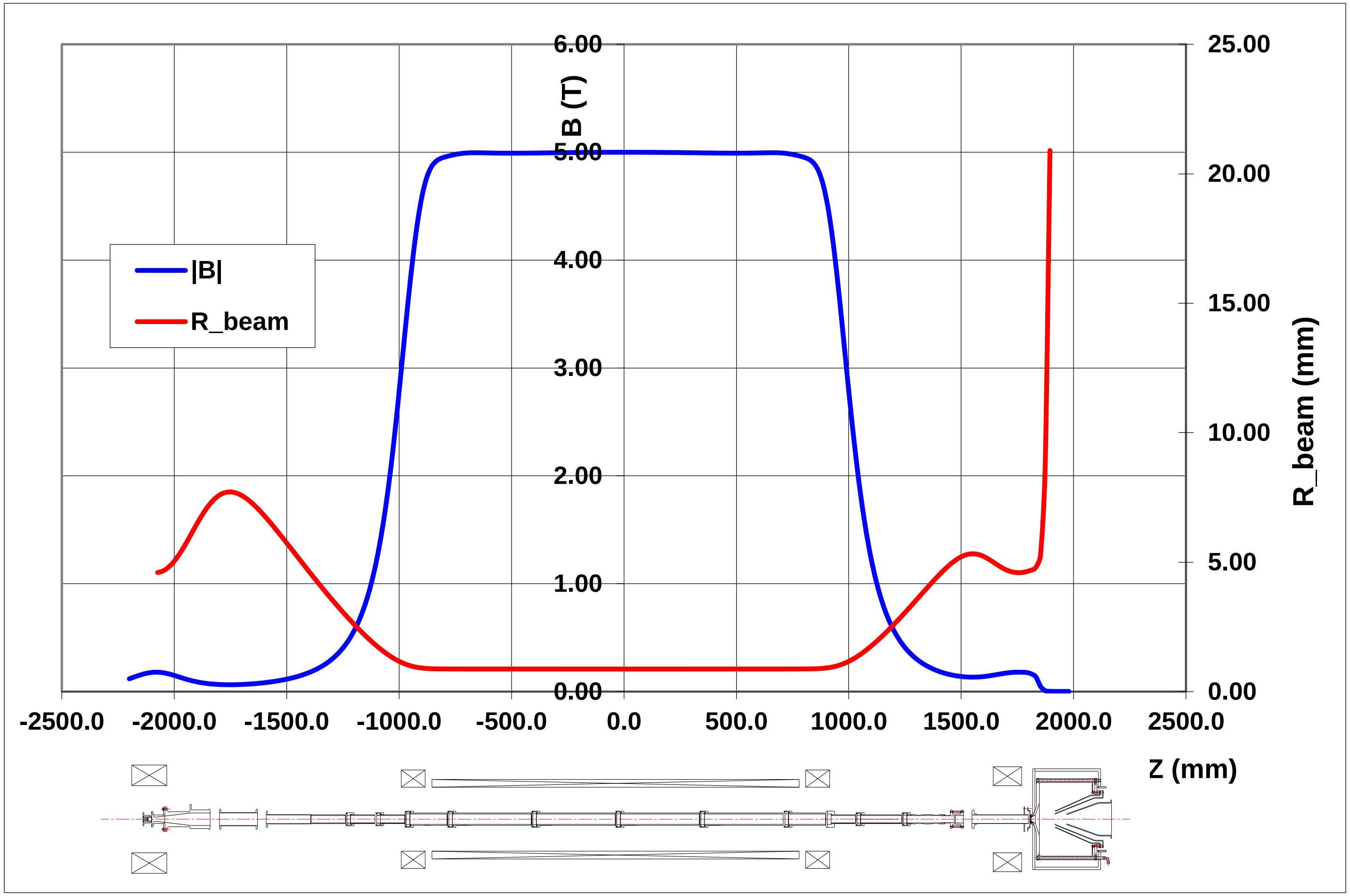


Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials at ends of trap.

- The total charge of ions extracted per pulse is ~ (0.5 – 0.8) x (# 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.
- Output current pulse is ~ independent of species or charge state!

Magnetic geometry and electron beam envelope

The RHIC EBIS method of forming the electron beam is the same as in Test EBIS: The Electron gun cathode is immersed in the launching coil magnetic field and the electron beam is compressed by the main magnetic field.



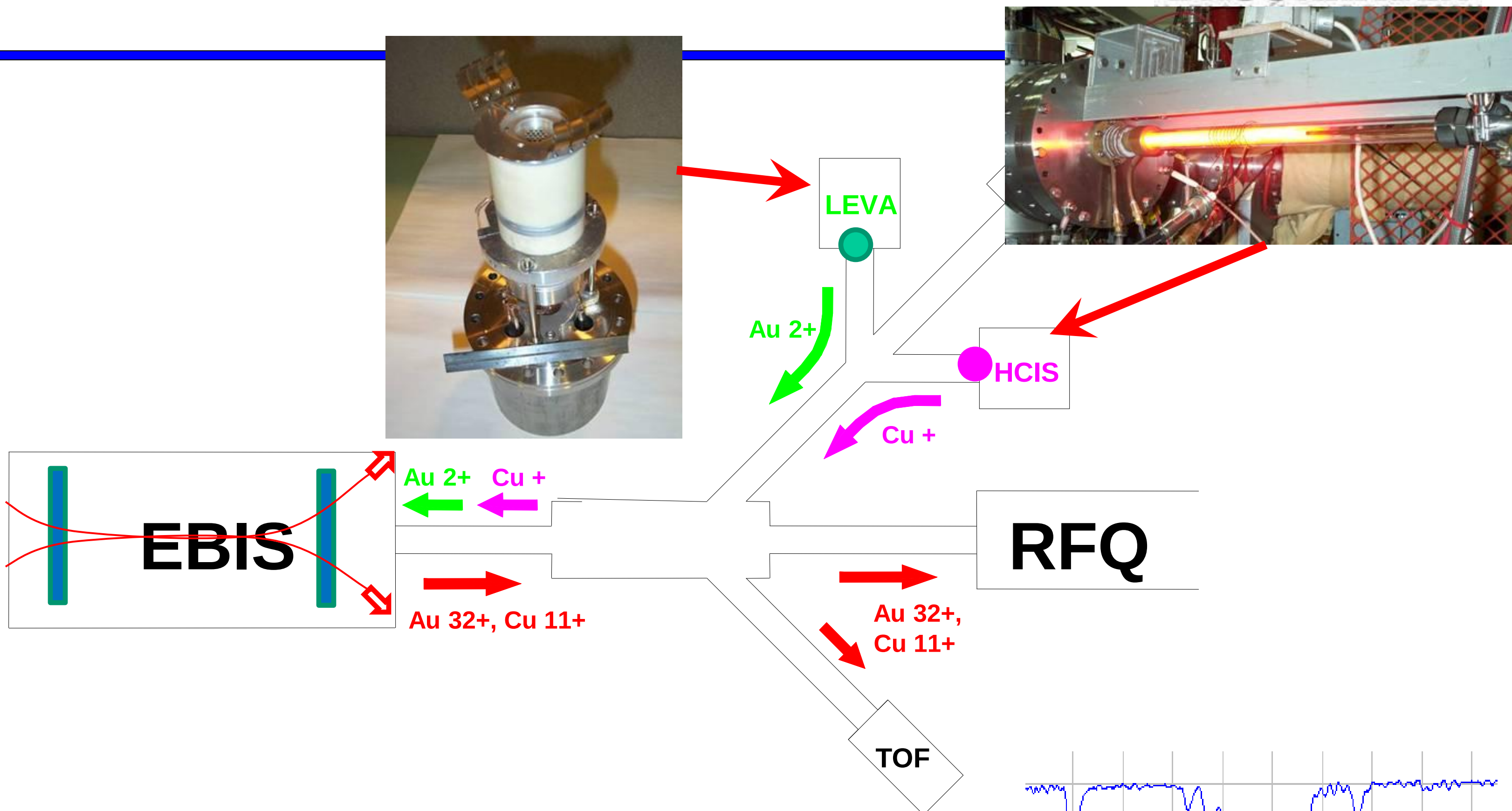
External ion injection modes:

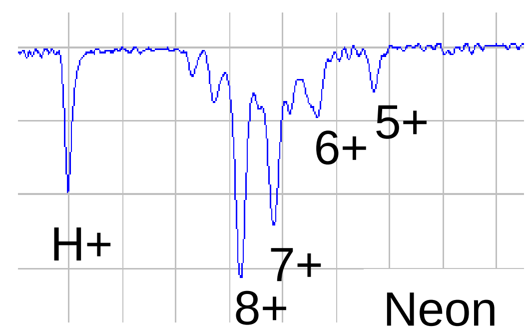
Fast Injection: Ions are injected into the electron beam in an ion beam pulse typically ranging from a few uS to a few hundred uS. Raising a potential barrier traps the ions axially while terminating further injection. Retarding the incoming beam can greatly increase the linear charge density, lowering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

Ion Injection and Extraction from the EBIS

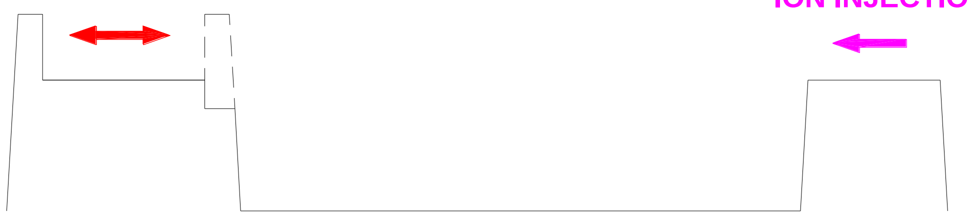




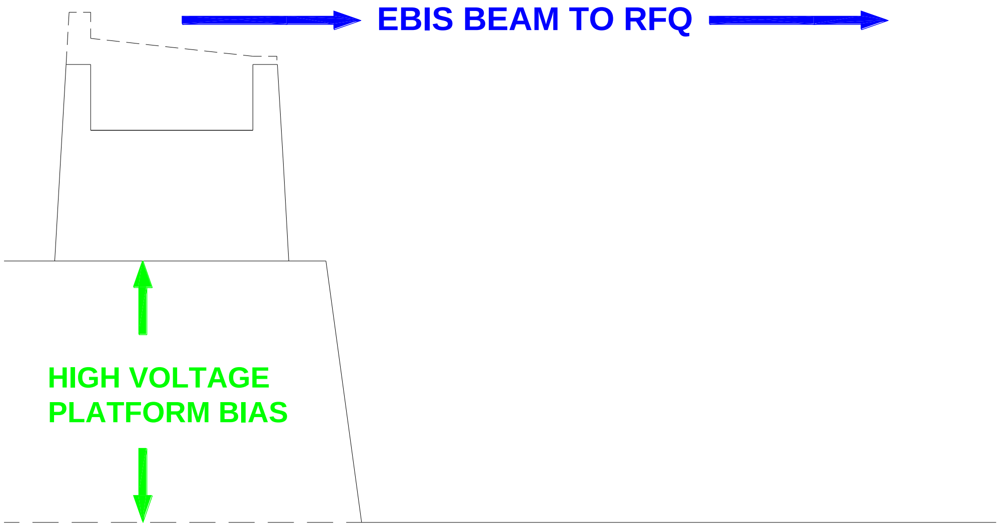
External ion injection provides most ion species.

One can change species and charge state
on a pulse to pulse basis

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)

Very High Energy EBITs:

SuperEBIT (LLNL): Ee ~200keV , Ie < 240mA, Je~6000 A/cm2

J. W. McDonald, et. al., RSI 73 (2002)

(extracted U90+ ~100 ions/s, Xe54+~1000 ions/s; U91+ to bare U ionization cross section measurement @ 198keV,200mA, 4s confinement)

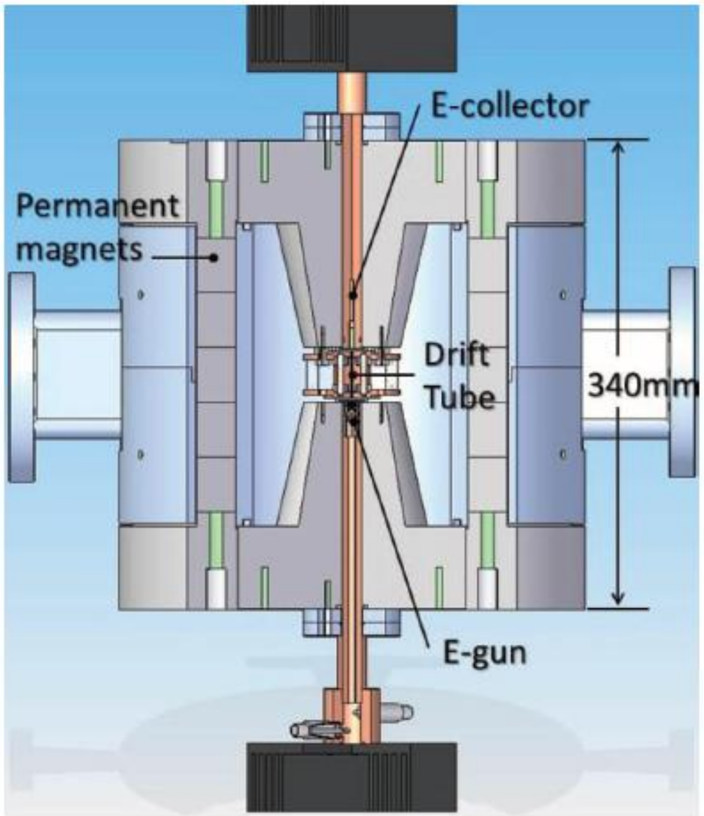
Tokyo EBIT Ee ~180keV , Ie < 330mA

N. Nakamura, et. al., JINST 5 (2010)

(Dielectric Recombination Studies, Extracted Bi81+ interaction with surfaces)

For internal experiments the electron beam serves both to produce the ions, and then to probe or stimulate atomic processes.

…….And very low energy, too!



Shanghai Compact EBIT
RSI 83 (2012) J. Xiao *et. al.*

Spectroscopy, no ion extraction
Permanent magnets, no cryogens

Low energy down to 60eV

TABLE I. Parameters of the SH-PermEBIT.

Parameter	Value
Energy range	60–5000 eV
Maximum beam current	10.2 mA
Beam width	93–103 μm
Center magnetic field	0.48 T

There has been a tremendous amount of development, especially of compact, turnkey EBIS/T sources by the Dresden Group (G. Zschornack, et. al)

They are making inexpensive sources relatively available to universities and research groups around the world.

In addition, they continue to vigorously pursue the important application of EBIS to Hadron Therapy for Cancer treatment.

Charge state Breeders

RexEBIS at Isolde (CERN): F. Wenander, JINST 5 (2010)

Works in conjunction with a gas filled Penning Trap requiring at least 10ms for cooling and bunching. (Typical operation 200mA, 100A/cm2, Warm bore with NEG & Turbomolecular drag pumping achieves <10E-10 mBar)

>72 radioactive isotopes of 25 elements reaccelerated for physics (pulsed injection)

CW injection test----bypass (fly through) RexTrap:

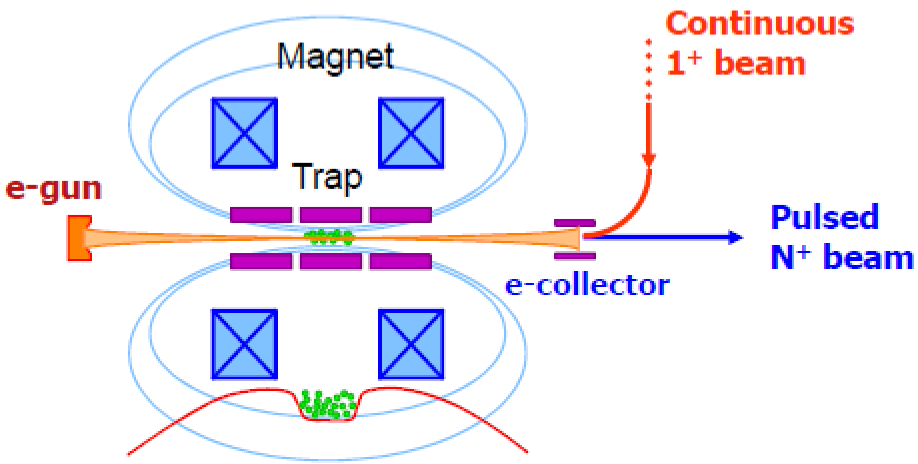
4% efficiency for 39K9+ was reached for 9.5 ms breeding time, compared with 15% efficiency for 39K10+ in the normal trap+EBIS mode.

However, no drop in efficiency when the 39K+ current was increased from 50-500pA

Titan EBIT (TRIUMF): First EBIT based charge breeder

Breeds short lived isotopes from ISAC isotope separator and accelerator and sends them to TITAN, the TRIUMF ion trap for atomic and nuclear science.

ReA3 – EBIS/T charge breeder



Expected performance

- Breeding times << 50 ms
- Efficiency > 50%
- Beam rates > 10^9/s
- Variable duty cycle
- Clean beams

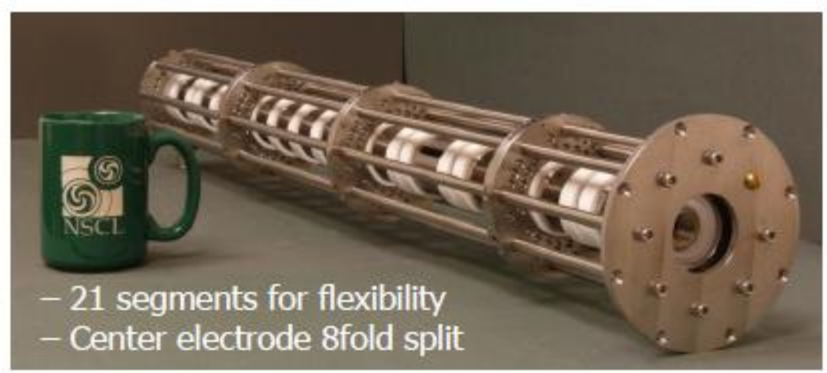
EBIT: Key parameters:

- magnetic field: up to 6 T
- **I_e= 0.5…5 A, E_e < 30keV**
- **current density: up to ~10^4 A/cm^2**

Unique Adjustable Magnetic structure: will provide both high acceptance for incoming beam and fast breeding for captured beam.

Moderate compression + large e-beam current
+ longer trap needed = good acceptance
→ Two traps for high acceptance and fast breeding

Trap: ~ 0.8m long



CARIBU EBIS Charge Breeder at ANL (S. Kondrashev et. al.)

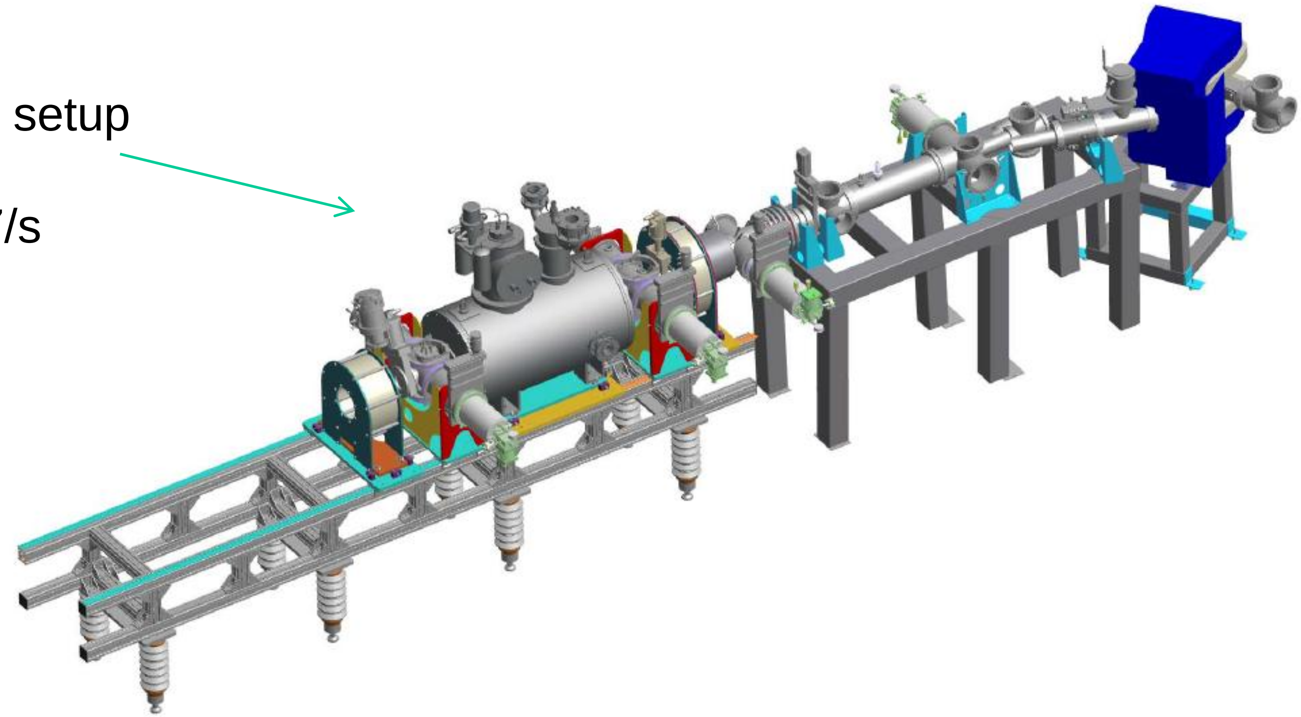
Parameter	Low current e-gun	High current e-gun
Superconducting solenoid: length/ field	1 m/6 T	1 m/6 T
Diameter of the IrCe thermocathode	1.6 mm	4 mm
Electron beam current	0.2 A	2 A
Electron beam energy	~ 2 keV	~ 5 keV
Electron beam diameter in the trap	~ 230 μm	~ 580 μm
Electron beam current density in the trap	$\sim 480\ A/cm^2$	$\sim 750\ A/cm^2$
Ion trap length	0.5 m	0.5 m
Trap capacity (in elementary charges)	$\sim 4 \bullet 10^{10}$	$\sim 2 \bullet 10^{11}$

Main parameters

Off-line commissioning setup

Gas catcher output <10e7/s

EBIS expected to provide High efficiency, High purity Charge breeding for reacceleration q/A>=1/7



"New" concept already operating for several years.

Provided beams for Nuclotron such as Ar16+ 200uA, and Fe24+ in 8us pulses using a 3T magnetic field.

Demonstrated in many EBIS laboratories including Stockholm, Frankfurt and BNL

Used low current multipass electron beam to build up beam-like electron space charge.

Greatly reduces power dissipation of collected beam

Tubular ESIS --Dubna (D.E. Donets et. al. EPAC08)

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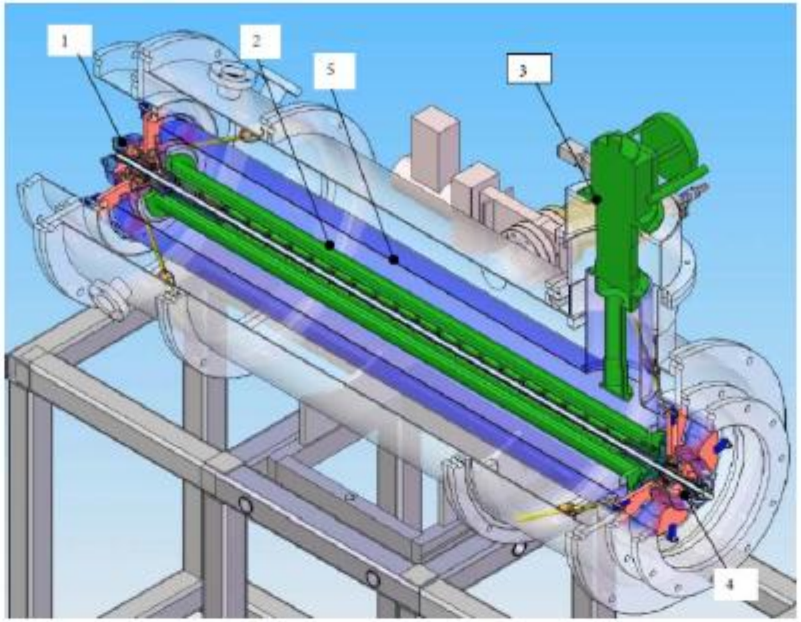


Table 1: Parameters of electron string ion source

Ion source	Krion-2 Ar^{16+}	TESIS Ar^{16+}
Electron energy, keV	3-5	5-7
Number of electrons	$5{\cdot}10^{10}$	$2{\cdot}10^{12}$
Magnetic field, T	3	5
Ion current, mA	0.15	10
Pulse duration, µs	8	8
Number of extracted ions	$5{\cdot}10^{8}$	$3{\cdot}10^{10}$
Injection frequency, Hz	1	5
Average current, µA	0.15	10

Figure 1: General view of the tubular electron string ion source, 1-electron gun, 2-superconducting solenoid, 3-cryocooler, 4- reflector electrode, 5- thermal shielding at temperature of 40 K.

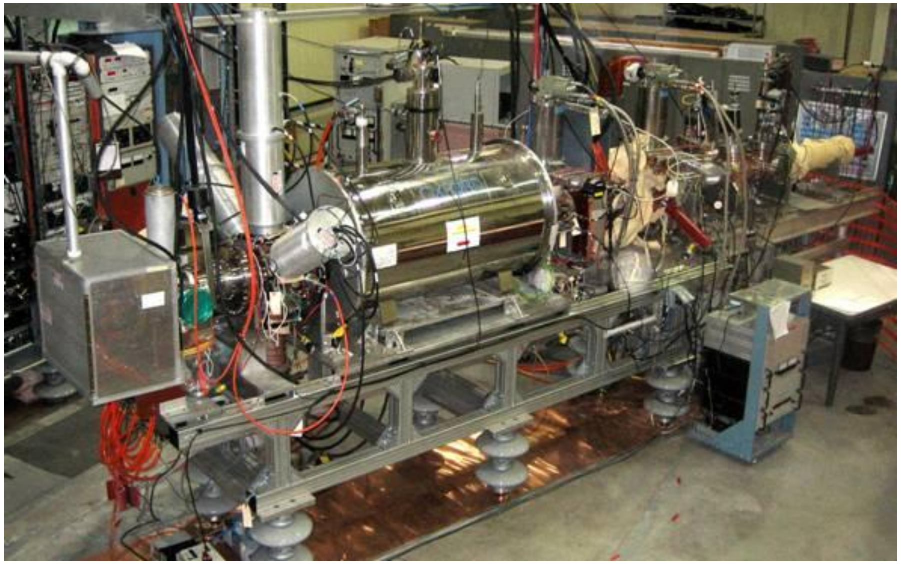
Projected currents 10-100 times that of (cylindrical) ESIS

BNL RHIC EBIS: Development of a High Current EBIS

More than 20 years ago, it was proposed to use an EBIS source as part of a new heavy ion preinjector for RHIC.

Existing EBIS intensities were a few nanocoulombs per pulse, rather than the required ~80 nC/pulse (8 mA, 10 μs pulse).

Over a period of about 10 years, the state-of-the-art in the **TestEBIS** (1/2 trap length) prototype was increased by a factor of **20**, making the **RhicEBIS**-based preinjector feasible.

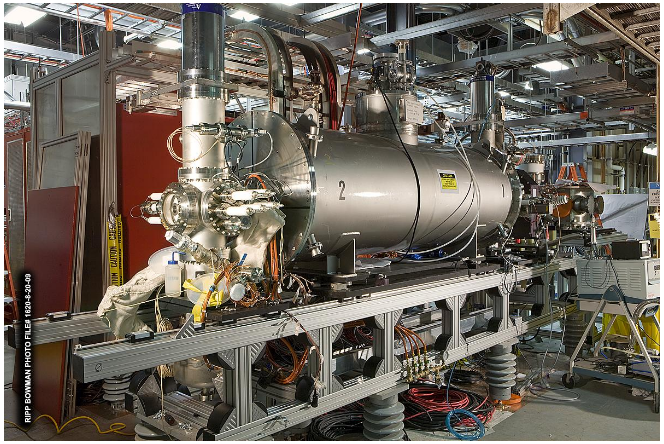


Knock off multiple electrons from each atom in the source, so each particle has <u>higher charge</u>, making them easier to accelerate to higher energy

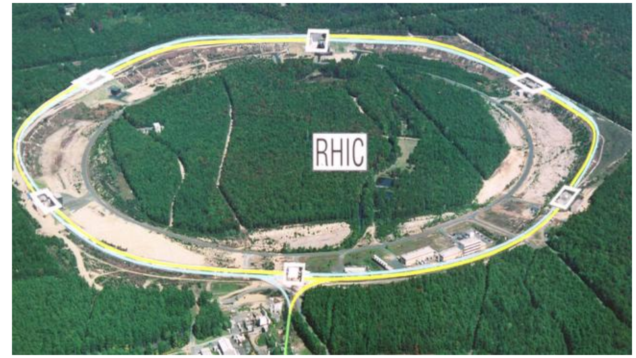
(Au^{1+} * 14 MV = Au^{28+} * 0.5 MV)

The RHIC EBIS 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

The preinjector will be able to switch both species and transport line magnet settings in 1 second, so there will be no restrictions on compatibility between RHIC and NASA Space Radiation Laboratory operations.

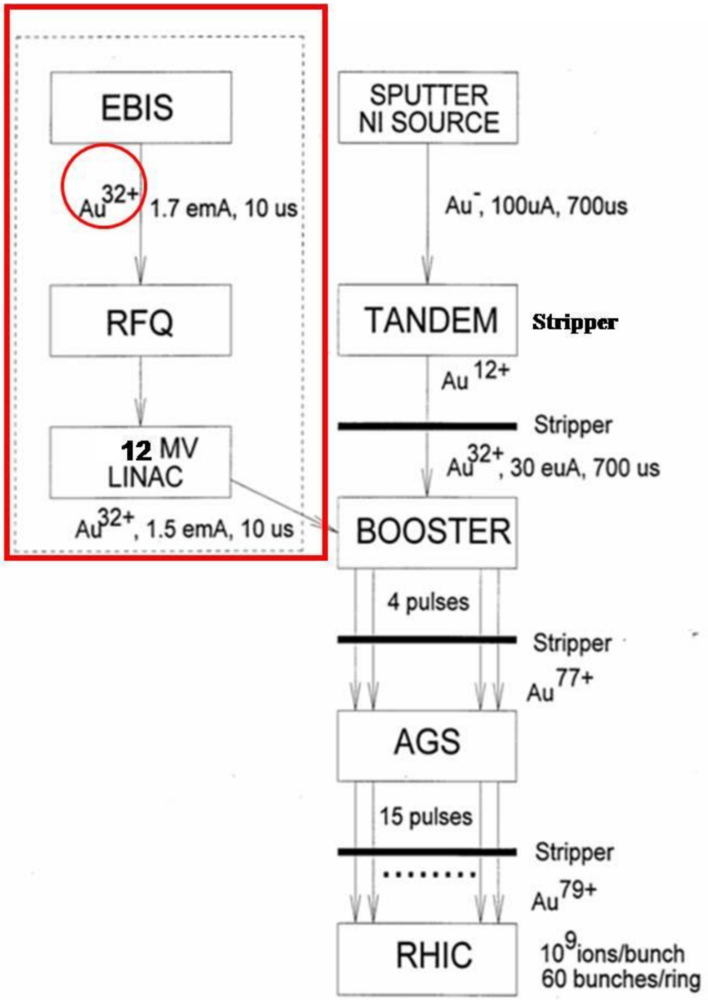
For example:

for RHIC : 1.7 mA of Au^{32+}, 10 μs pulses

plus…. NASA Space Radiation Laboratory – *a* second species, 1 second later, which could be:

~2-3 mA of He^{2+}, C^{5+}, O^{8+}, Si^{13+}, Ti^{18+}, Fe^{20+}, or Cu^{22+}

Advantages of EBIS Based Preinjector



EBIS can produce *any* ion species for NSRL

Fast switching between species (pulse-to-pulse)

No stripping needed before the Booster, resulting (more stable beams)

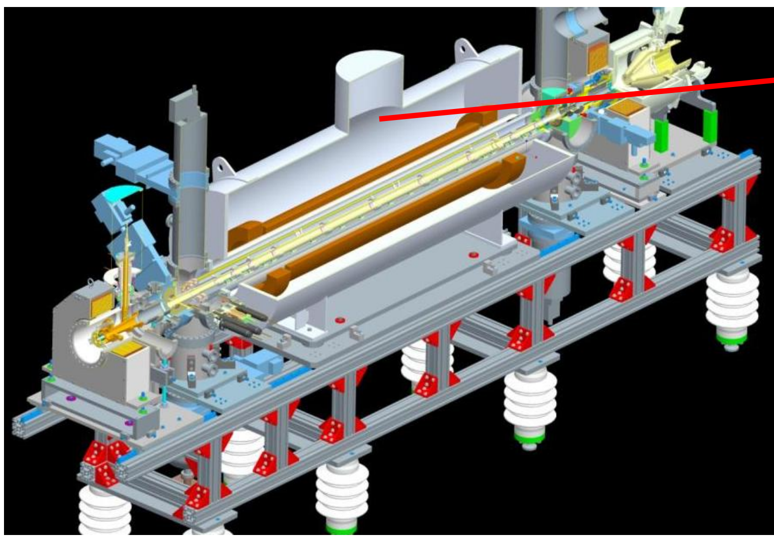
Simple, modern, low maintenance, (lower operating cost)

Ions	**He – U**
Q / m	**≥1/6**
Current	**> 1.5 emA**
Pulse length	**10–40ms (few-turn injection)**
Rep rate	**5 Hz**
EBIS output energy	**17 keV/u**
RFQ output energy	**300 keV/u**
Linac output energy	**2 MeV/u**
Time to switch species	**1 second**

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	$Q_{el}=$	1.1×10^{12}
Ion yield (charges)	$Q_{ion}=$	5.5×10^{11} (10 A)
Yield of ions Au^{32+}	$N_{Au}{}^{32+}=$	3.4×10^{9}

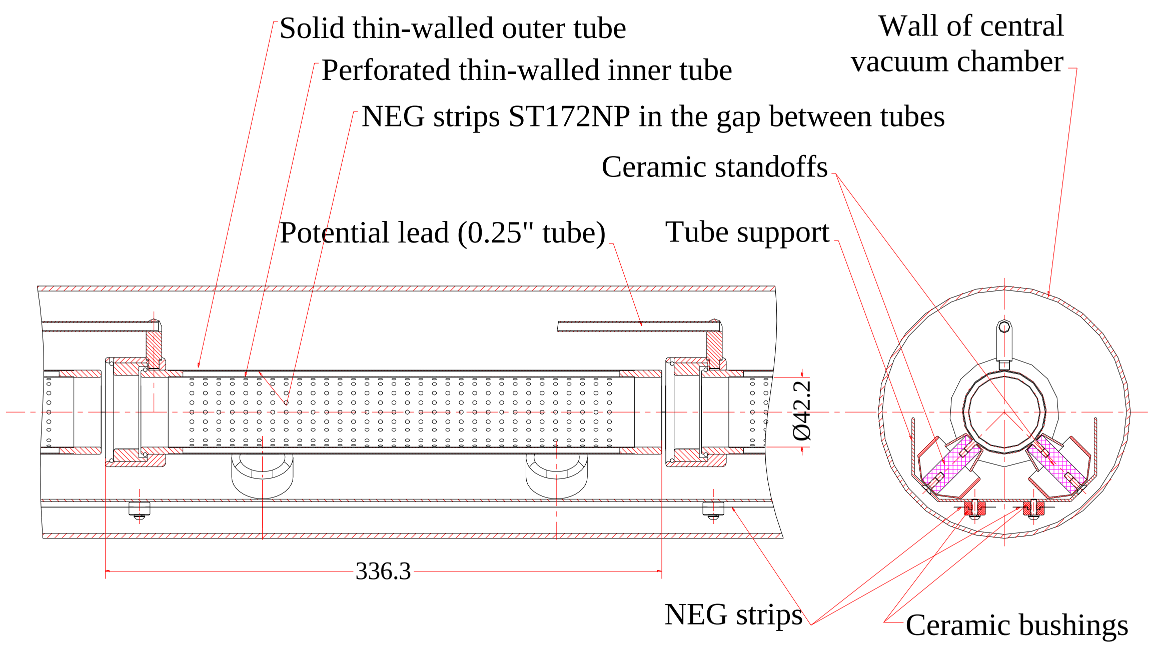
RHIC EBIS unshielded superconducting solenoid manufactured by ACCEL:

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

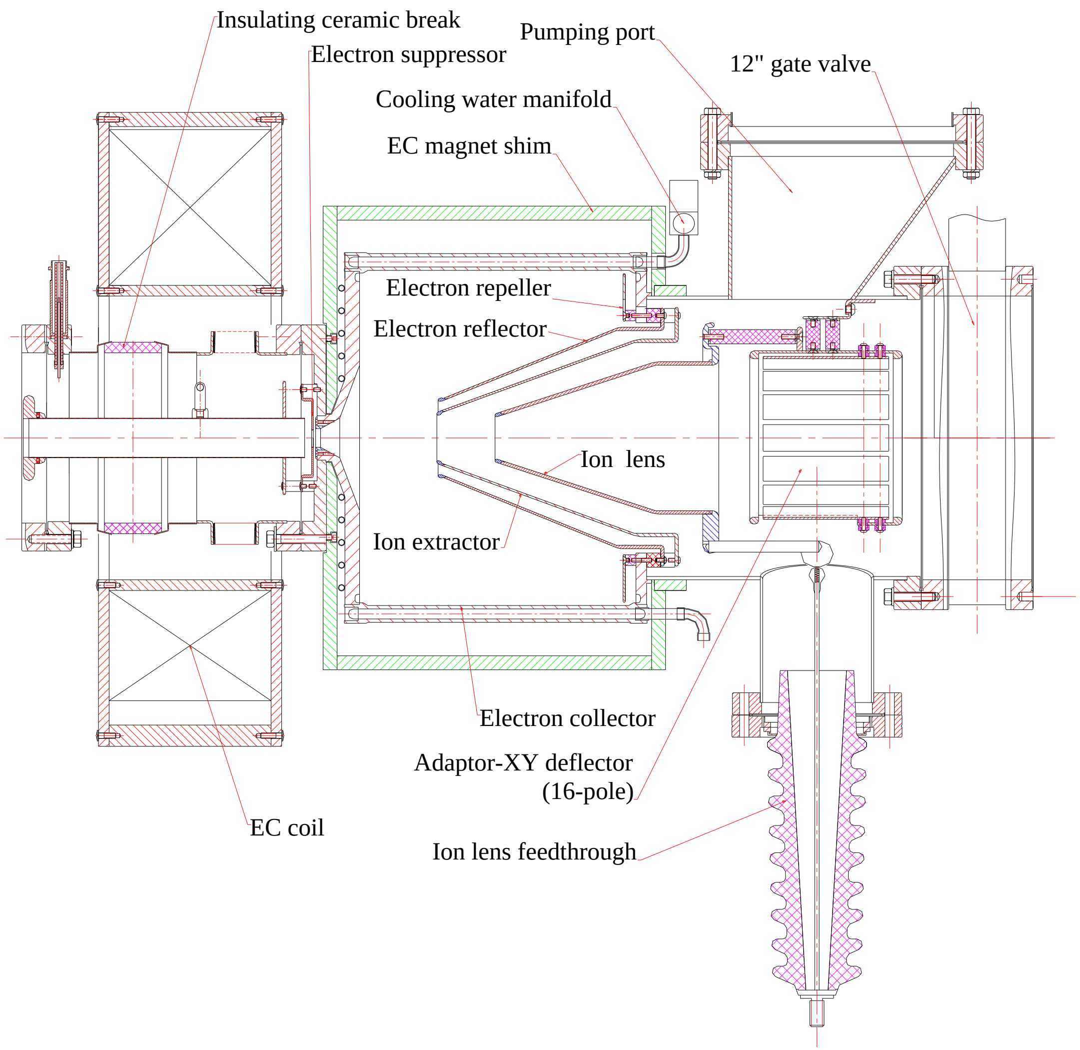
Rhic EBIS Upgraded pumping capabilities compared with Test EBIS :

-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

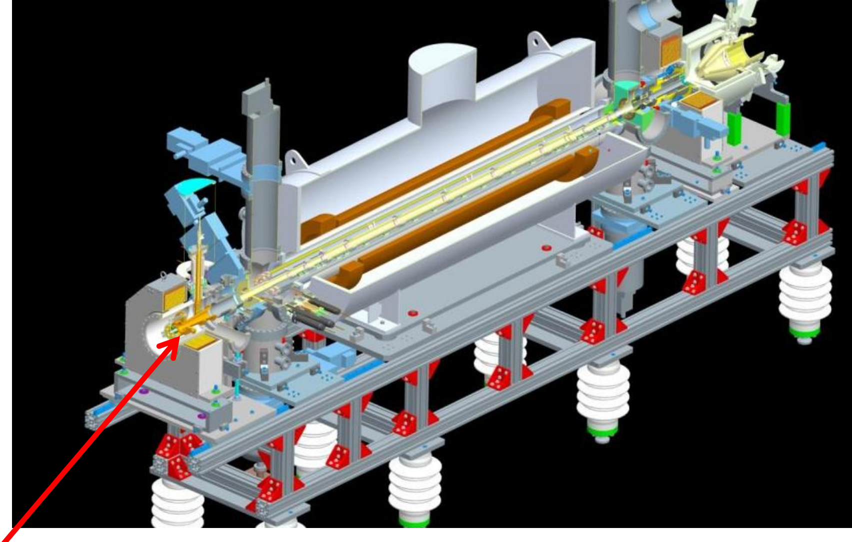


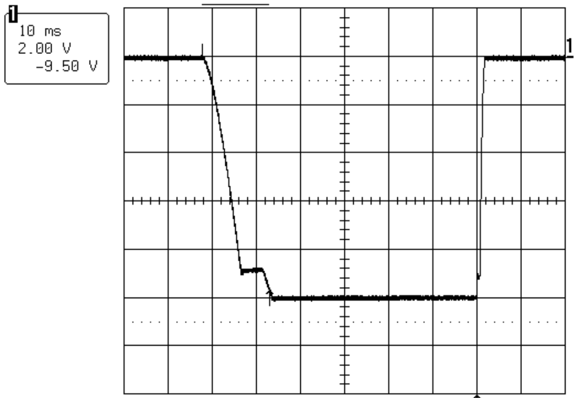
- Improved ion optics for extraction and injection with larger apertures to accomodate larger angles



The EBIS 10A electron gun

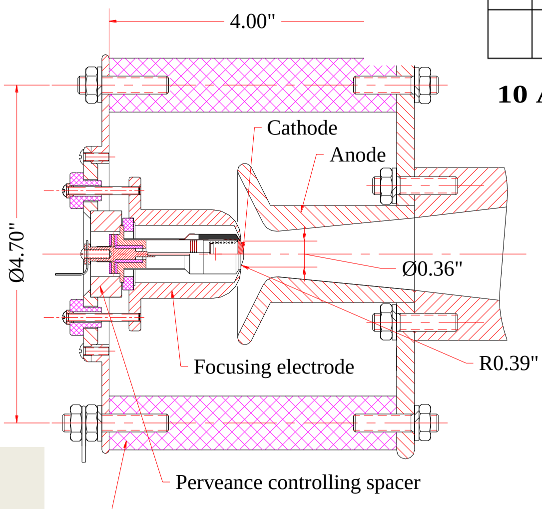
- This was a key development. Previous EBIS operation was typically at 0.5A or less
- Electron beams up to 10A, 100kW have been propagated with very low loss, using IrCe cathodes from BINP, Novosibirsk.



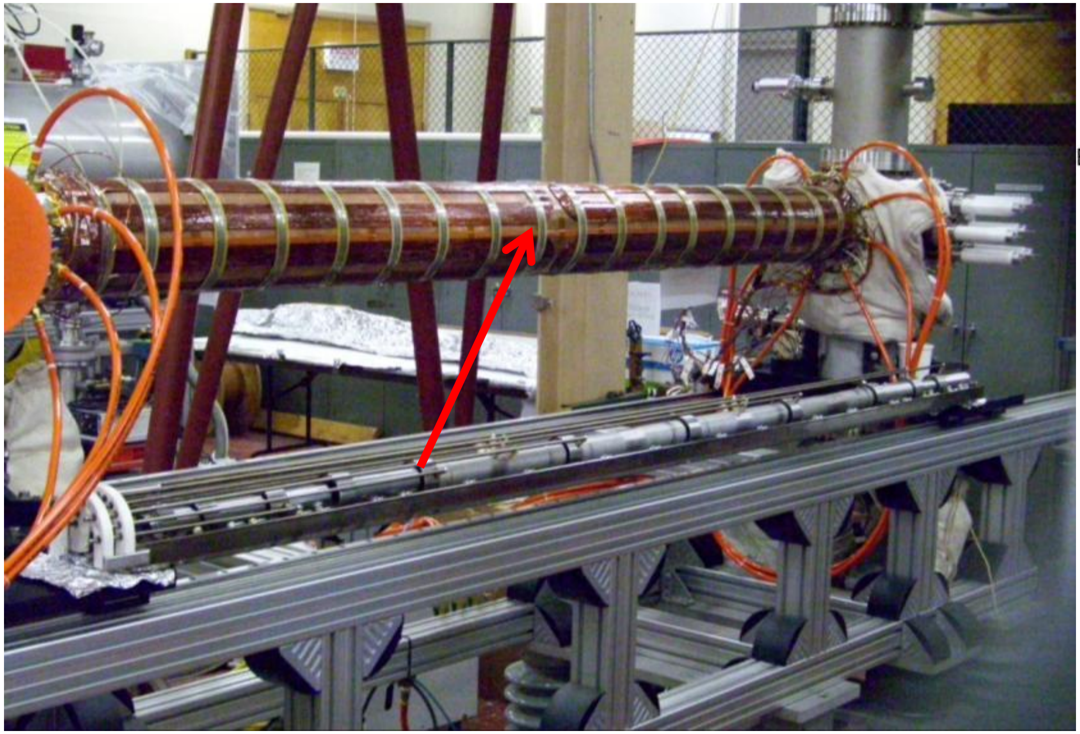


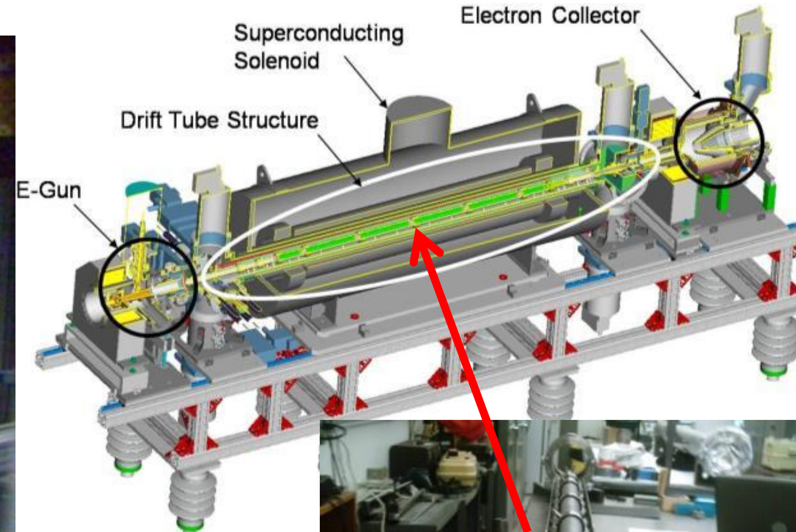
10 A, 50 ms Electron Beam Pulse (R&D EBIS)

Electron gun cathode



Drift tube structure





EBIS Drift tubes

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

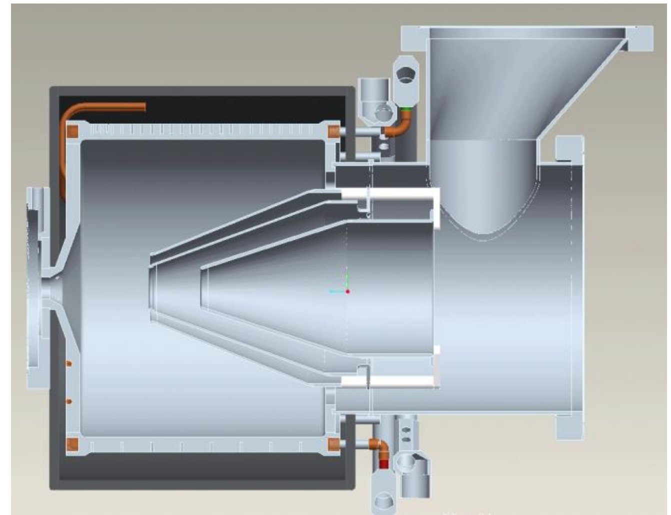
Heaters on the outside of the vacuum pipe allow baking to 450 C.

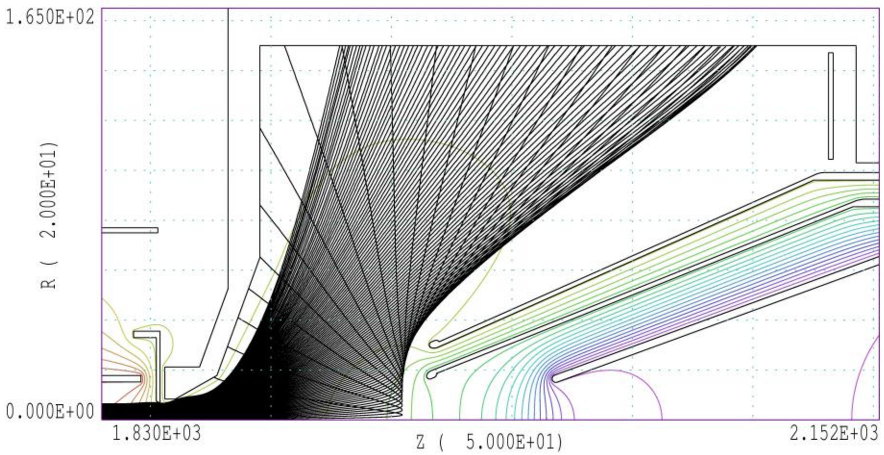
Outside the water cooled jacket, there are transverse steering coils.

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

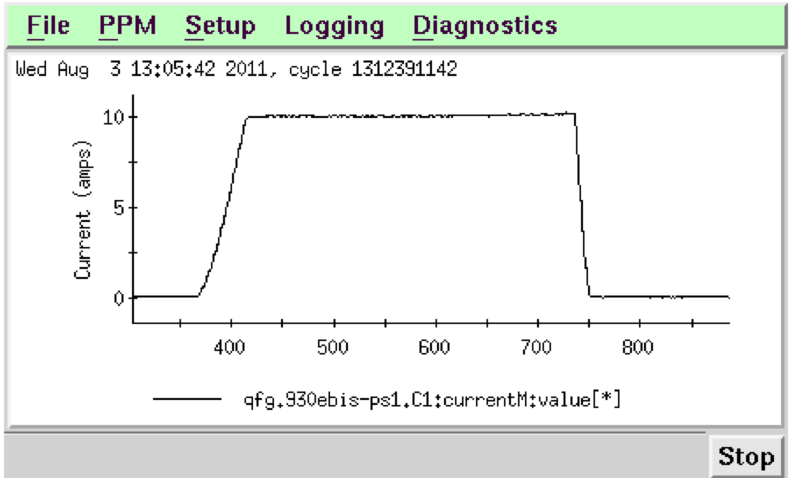




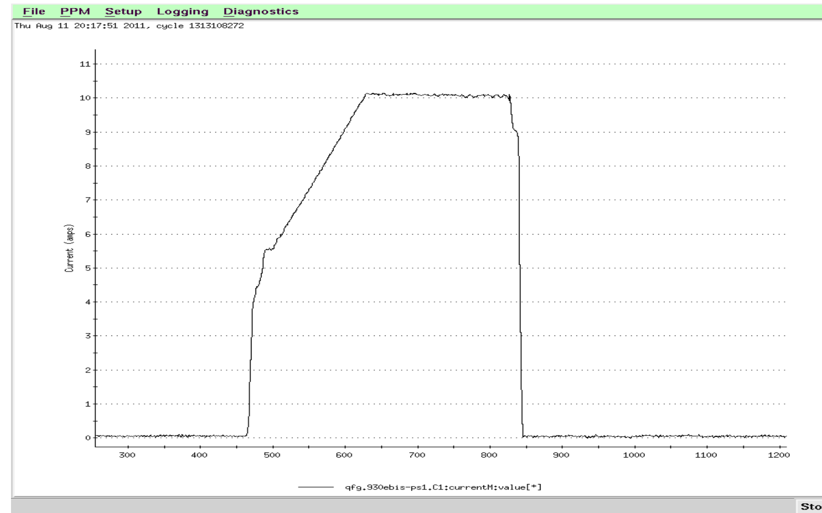
Trajectory simulations in RHIC EBIS electron collector. I_{el}=20.6 A, E_{el}=15 keV

BeCu collector is installed on the RHIC EBIS

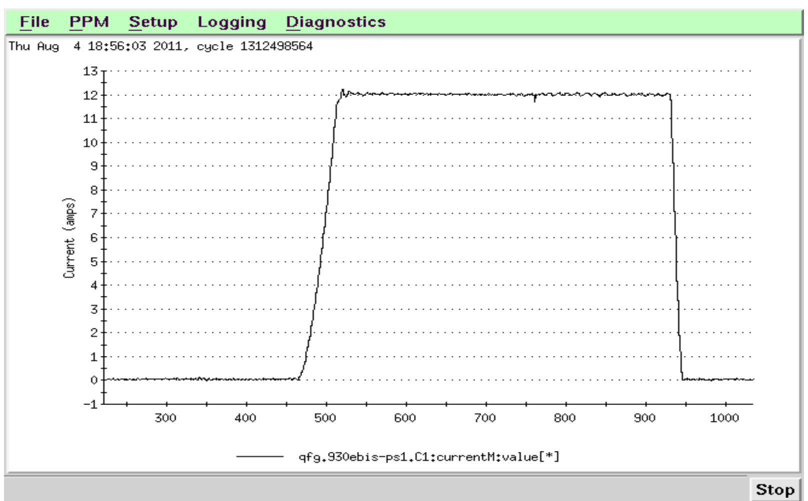
EBIS high electron beam current traces



First 10.1A 32ms e-beam in RhicEBIS



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

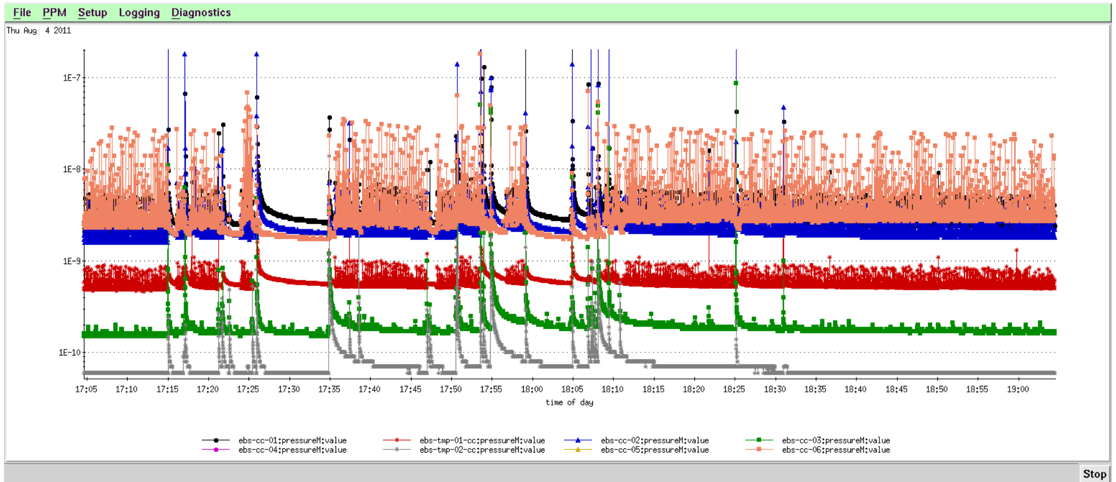


12A 40ms ebeam

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

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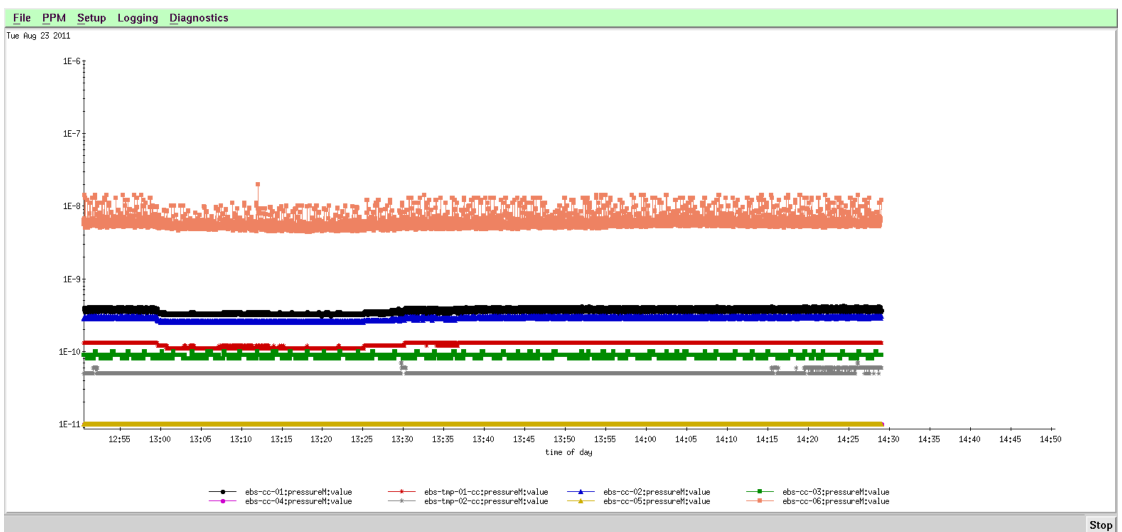

Pressure log for 7.6A e-beam with a 65ms ion confinement

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

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

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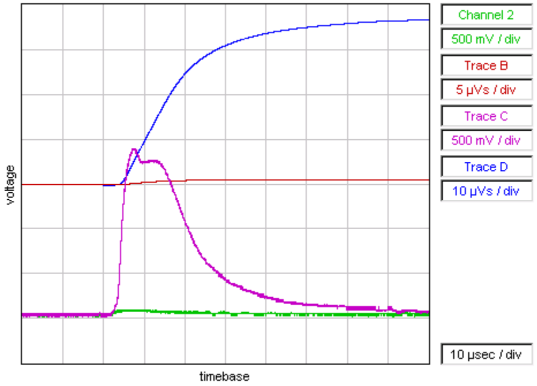
Highly charged Au extraction from RhicEBIS after fast injection from the HCIS

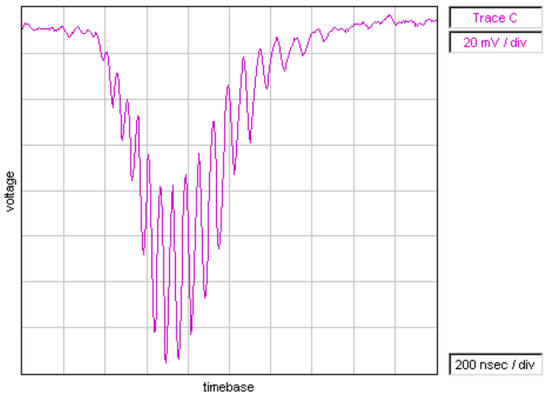


Au pulse (all charge states), slightly slowed extraction

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+

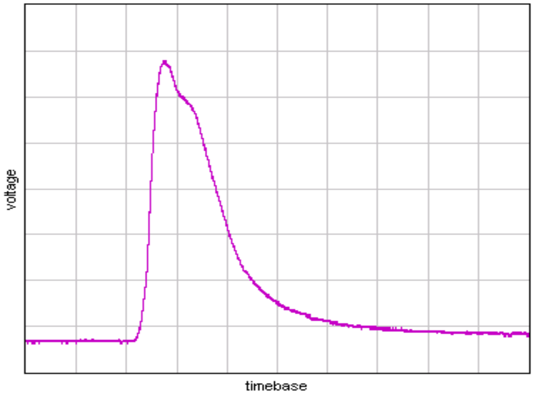
File name: 110823-09_Au__high_res_65ms_conf _8kV_retardation_7.6A__Au32.wfm

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

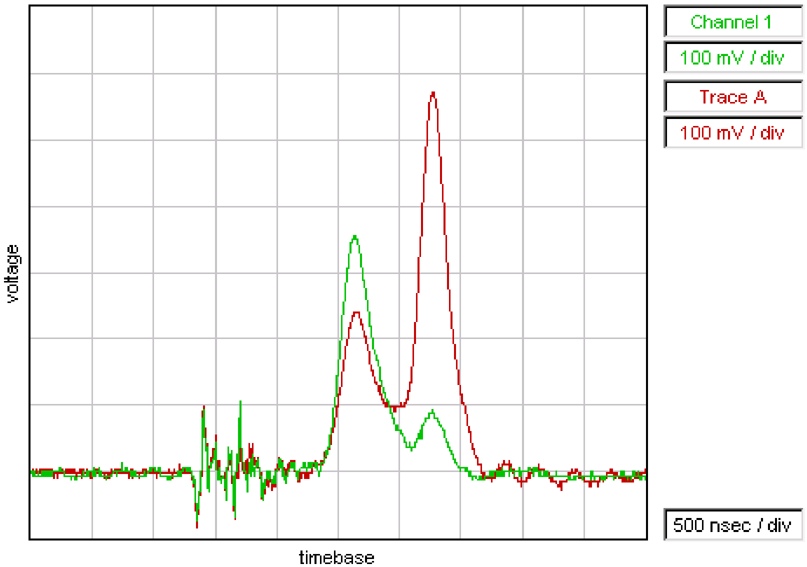
~6 mA peak, at EBIS output

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)

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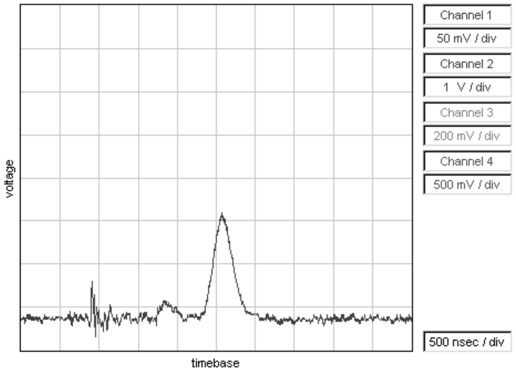
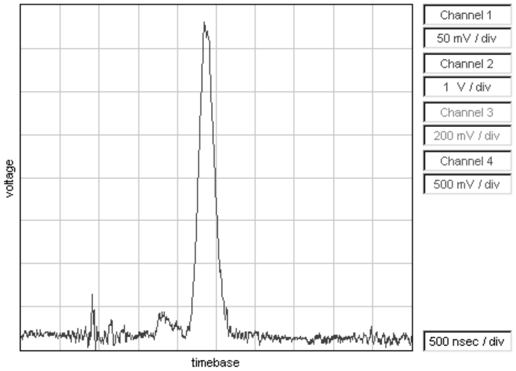


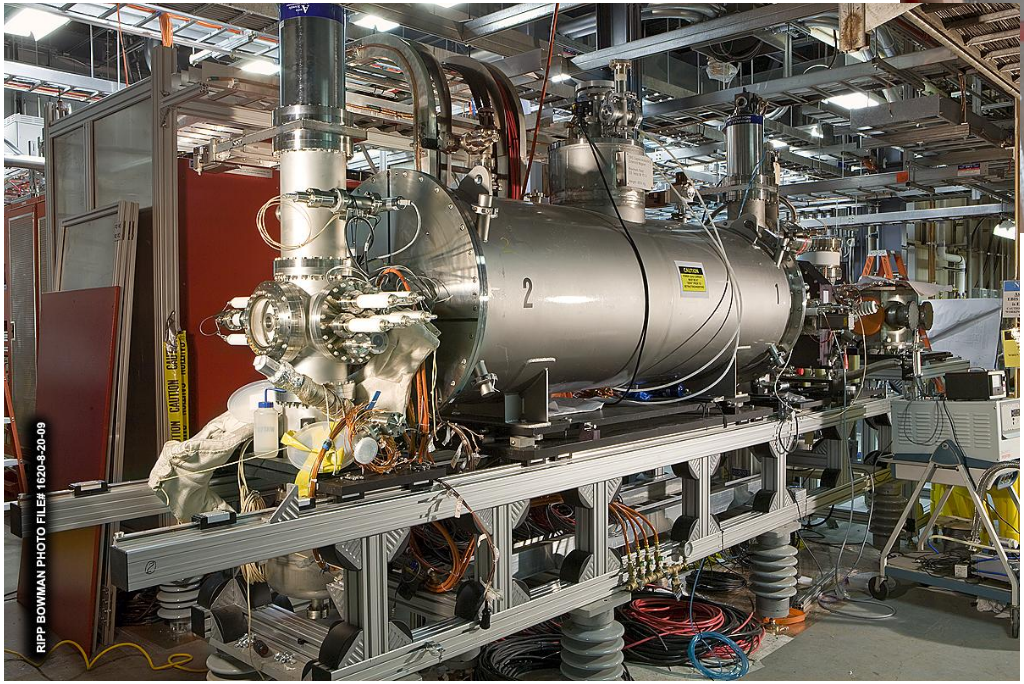
Au Time-of-Flight (25ms confinement)
(peaked at Au25+)



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

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

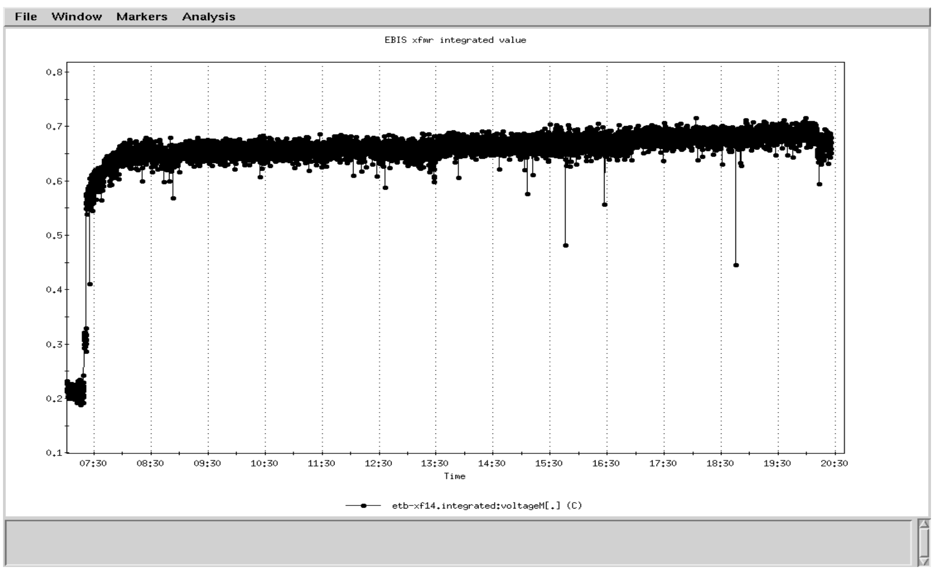
EBIS during installation



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

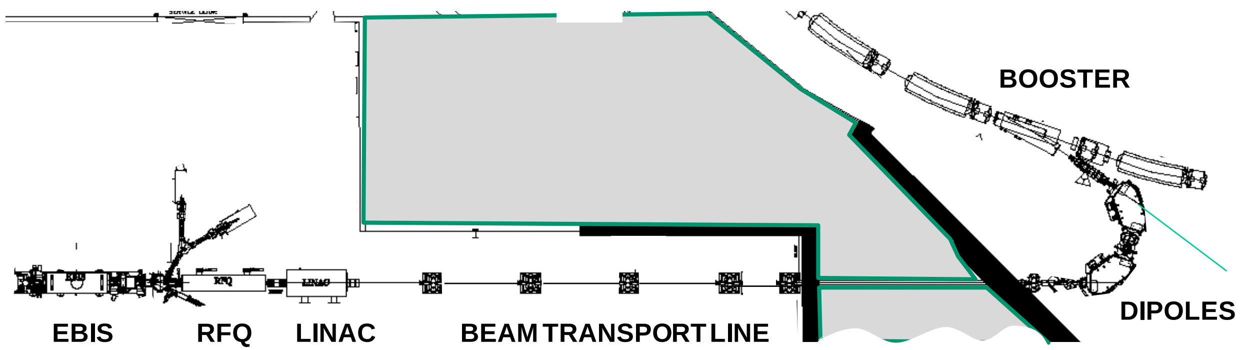
Summary of First Run to NSRL (Mar-Jun 2011)

- 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)

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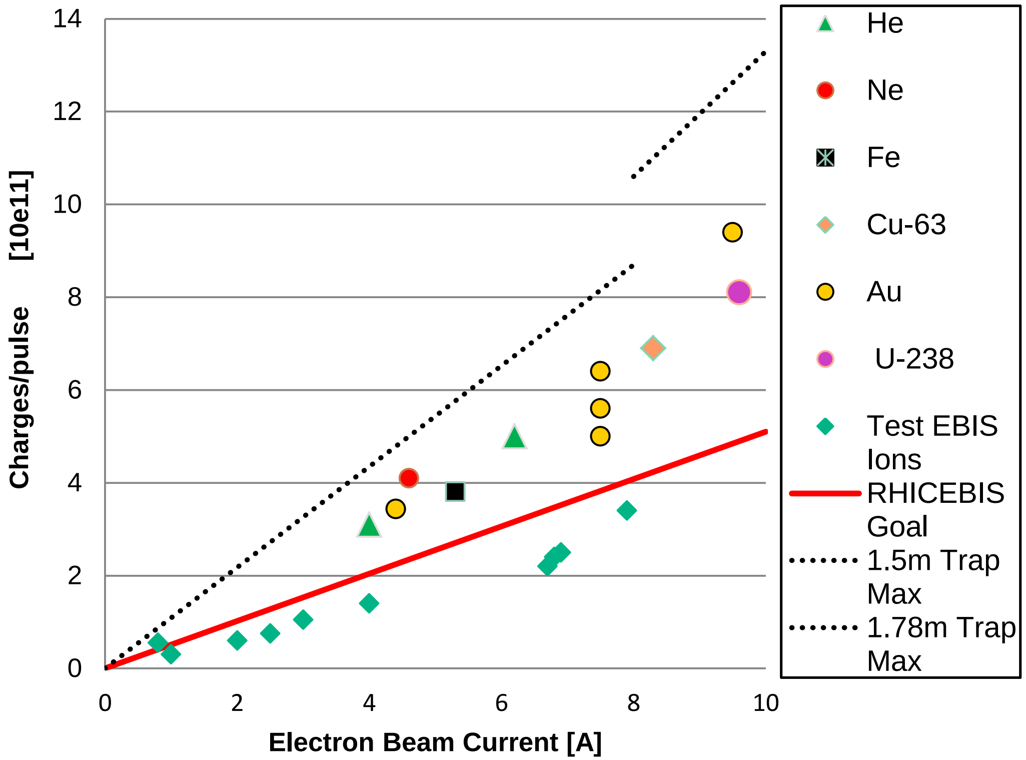
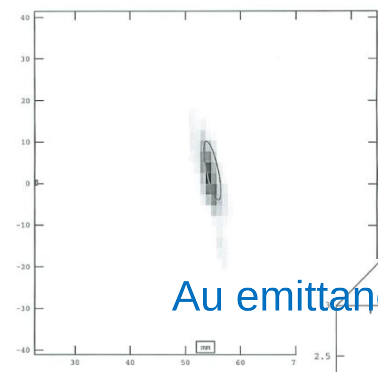
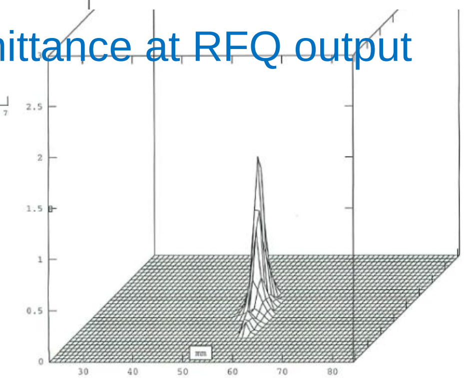




Au emittance at RFQ output



- •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)

EBIS Ions in Booster (per EBIS extraction)

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.

Summary

- RhicEBIS and all systems making up the new EBIS preinjector are operating as expected.
- EBIS has delivered beams to NSRL (He^{2+}, Ne^{5+}, Ar^{10+}, Fe^{20+}, and Ti^{18+}).
- 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
- Intensity at Booster so far has met the project goals, but 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.