ELECTRON BEAM ION SOURCE

A High-Performance Electron Beam Ion Source

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Acknowledgements

Ed Beebe, Sasha Pikin, Ahovi Kponou – EBIS

Deepak Raparia, Masahiro Okamura – Linac, RFQ, etc.

Outline of Talk

- Overview of the EBIS Preinjector project
  - What we're doing, and why

- Electron Beam Ion Source (EBIS)
  - How an EBIS works
  - What we've achieved with the Test EBIS
    (full electron beam current, half-trap length of the RHIC EBIS)
  - Status of the EBIS for RHIC

EBIS Preinjector - Overview

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Presently, one or two >35-year old Tandem Van de Graaff accelerators are used for RHIC pre-injection.

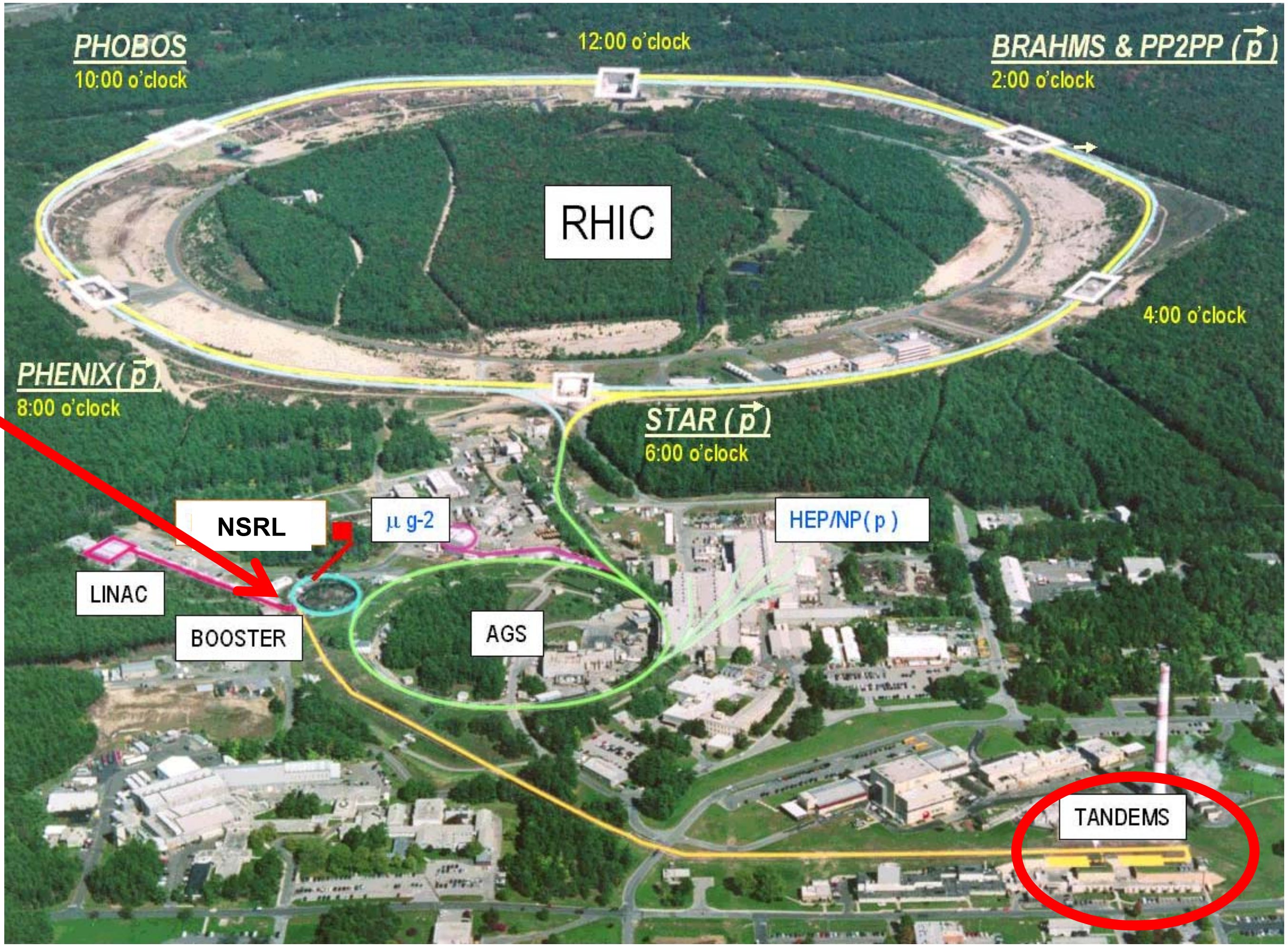
The "Test EBIS" at BNL has advanced the state of the art in EBIS performance by more than an order of magnitude, which now makes it possible to meet RHIC requirements with a modern linac-based preinjector.

BNL is in the construction phase of a new pre-injector for RHIC. The new preinjector consists of an EBIS high charge state ion source, a Radio Frequency Quadrupole (RFQ) accelerator, and a short linac.

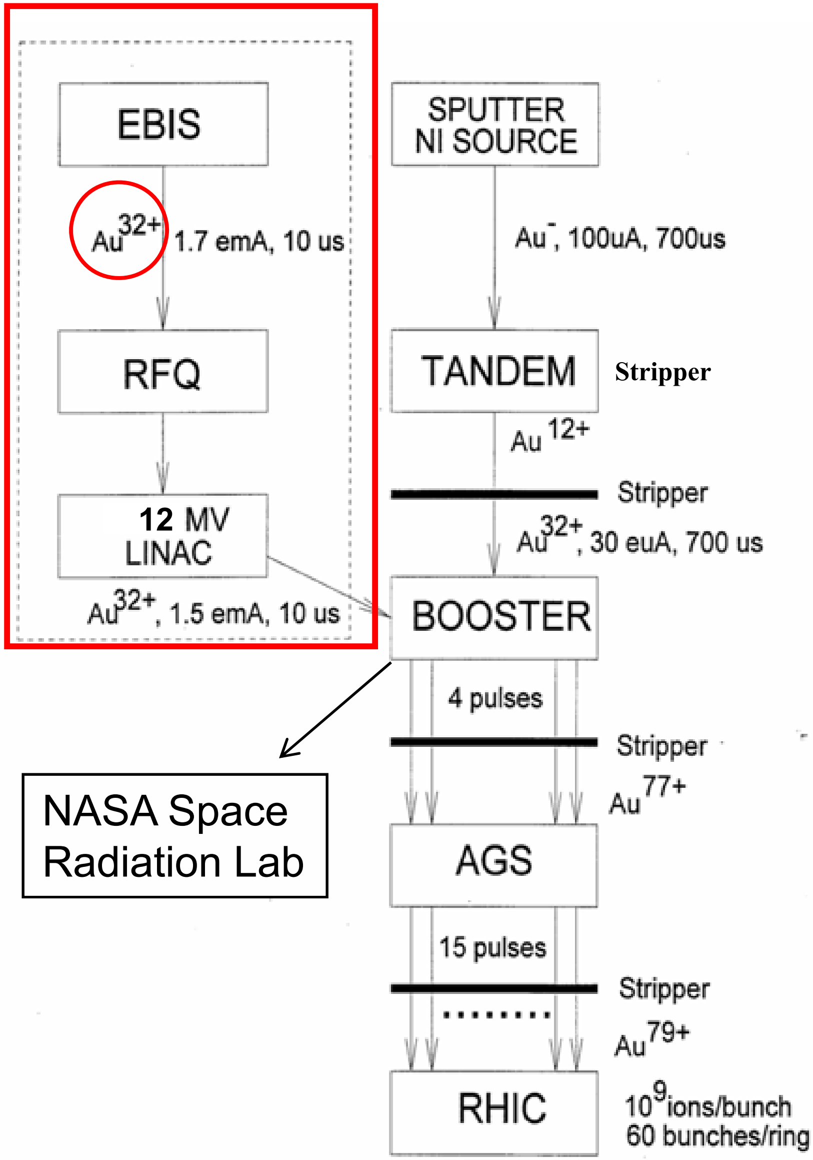
CD-4 date (project completion) is September, 2010.

Tandems are the present heavy ion preinjectors for RHIC

EBIS going here



860 m long transport line from the Tandems to the Booster



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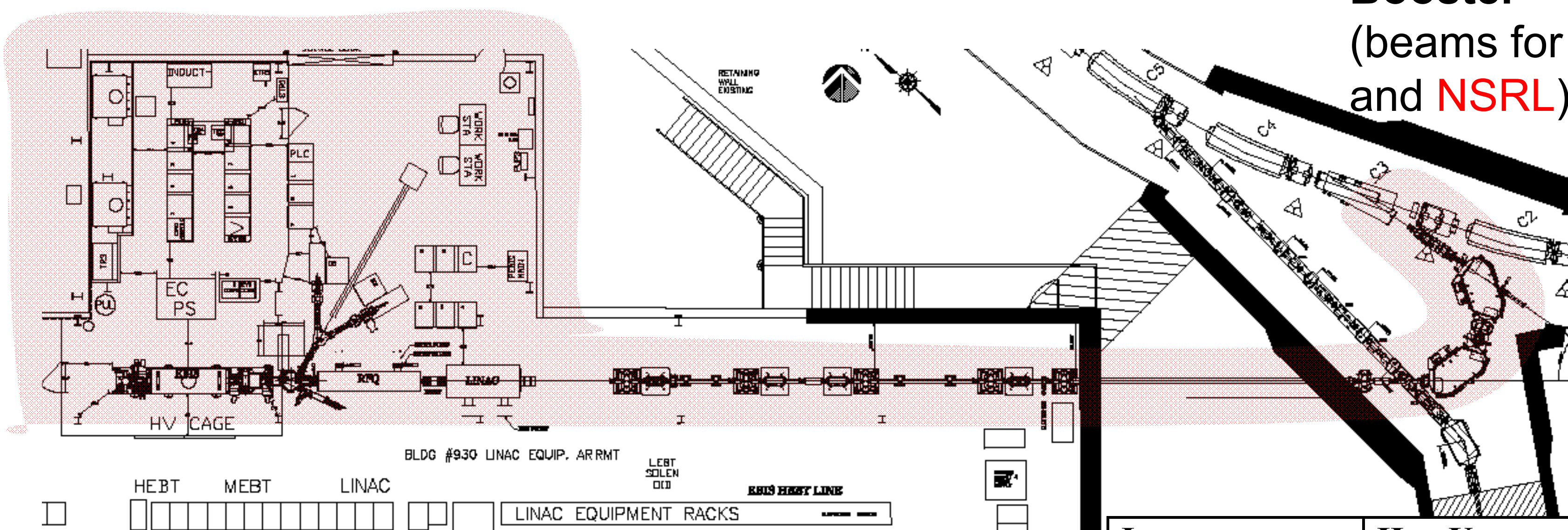
Operation for RHIC requires the preinjector to be available 24/7 for 4-6 months at a time, and the Tandems have done this for many years.

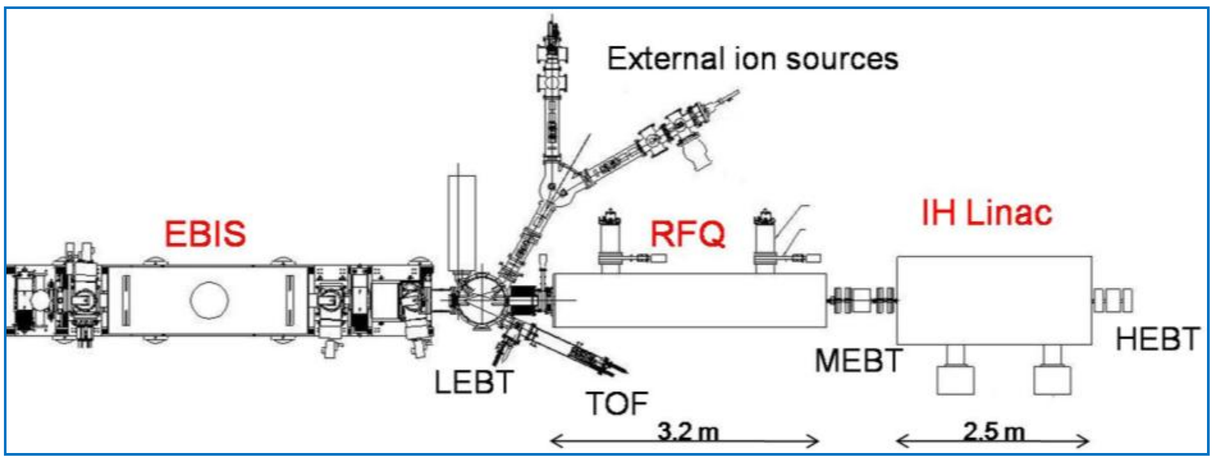
Advantages of the new preinjector:

- **Simple, modern, low maintenance**
- **Lower operating cost**
- **Can produce any ions (noble gases, U, He^3↑)**
- **Higher Au injection energy into Booster**
- **Fast switching between species, without constraints on beam rigidity**
- **Short transfer line to Booster (30 m)**
- **Few-turn injection**
- **No stripping needed before the Booster, resulting in more stable beams**
- **Expect future improvements to lead to higher intensities**

Placement of EBIS Preinjector in lower equipment bay of 200 MeV Linac

Booster
(beams for RHIC and NSRL)





Ions	He - U
Q / m	≥1/6
Current	> 1.5 emA
Pulse length	10 μs (for 1-turn injection)
Rep rate	5 Hz
Output energy	2 MeV / u
Time to switch species	1 second

Preinjector requirements

The preinjector must be able to switch both species and transport line rigidity in ~1 second, so that there are no restrictions on compatibility between RHIC and NSRL operations.

For example:

Requirement for RHIC : 1.7 emA of Au^{32+}, 10 μs; 5 Hz

plus….NSRL (NASA Space Radiation Laboratory) – *a* second species, 1 second later:

He^{2+}, C^{5+}, O^{8+}, Si^{13+}, Ti^{18+}, Fe^{20+}, Cu^{22+}, at ~2-3 emA, ~ 10 μs

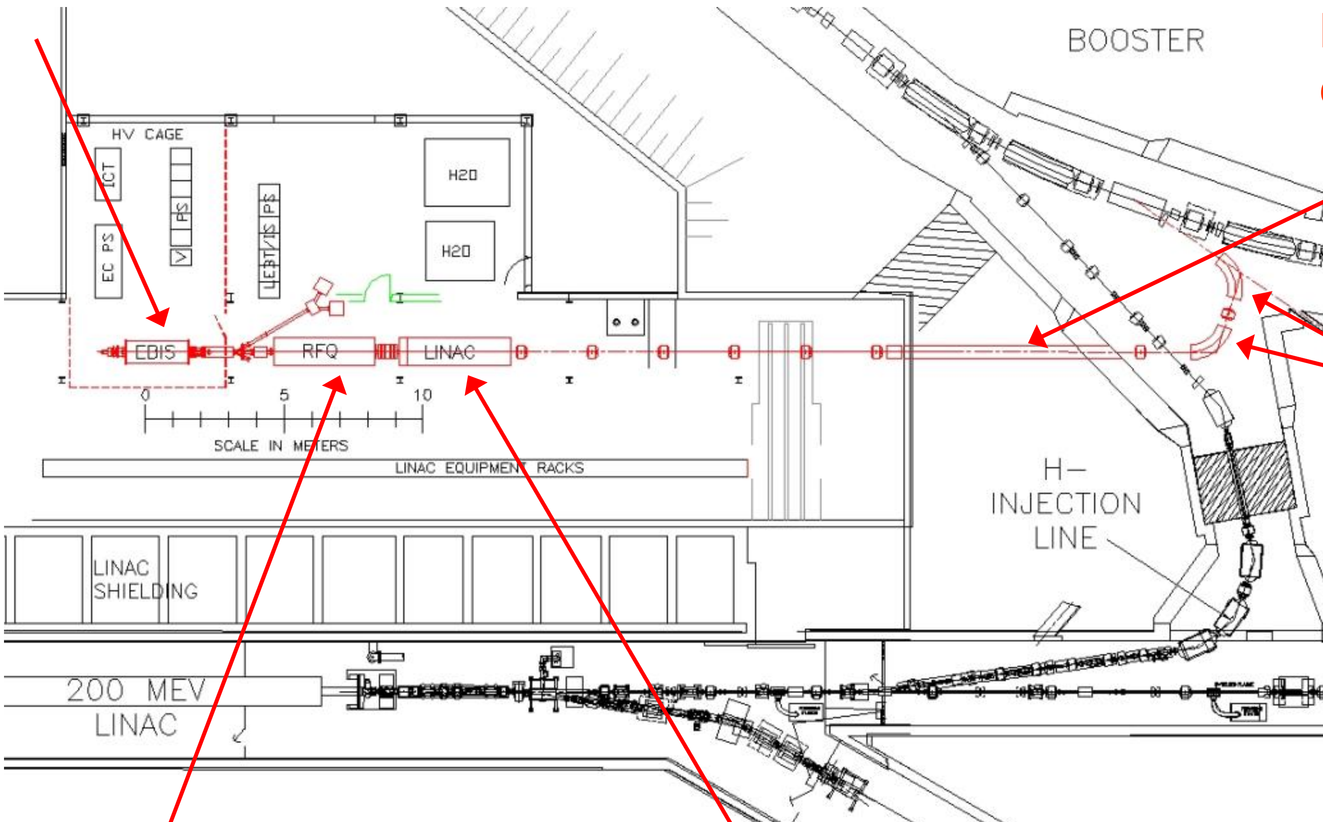
- **short pulses**
- **fast beam changes**
- **any species**

The EBIS was the key to the project – this will be covered for most of the talk…

A few minutes on the overall project….

EBIS SC solenoid – delivered

Beam port – completed



Dipoles – delivered and installed

RFQ – Frankfurt; delivered, being tested with beam

Linac – being manufactured (Frankfurt, 9/09 delivery)

RFQ and Linac Design Specifications

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Parameter	RFQ	Linac	Units
Type	4-rod	IH	
Operating Frequency	100.625		MHz
Design Beam Current	10	5	mA
Maximum Beam Current	>20	>10	mA
Q/m	0.16 – 1.0		
Repetition Rate, Max	5		Hz
Pulse Width	≤ 1.0		ms
Input Energy	17.0	300	keV/u
Input Emittance (rms, normalized, Au^{32+})	0.09	0.11	π mm mrad
Input Emittance, longitudinal (90%)	-	172	π keV/u-deg
Acceptance (normalized)	≥ 1.7	≥ 4.3	π mm mrad
Output Energy	300	2000	keV/u
Emittance Growth	≤ 20		%
Output Emittance, longitudinal (90%)	≤ 172		π keV/u-deg
ΔE (90%) for Au^{+32}		< ±10	keV/u
Transmission Efficiency	> 90		%

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RFQ from IAP, Frankfurt (Schempp)

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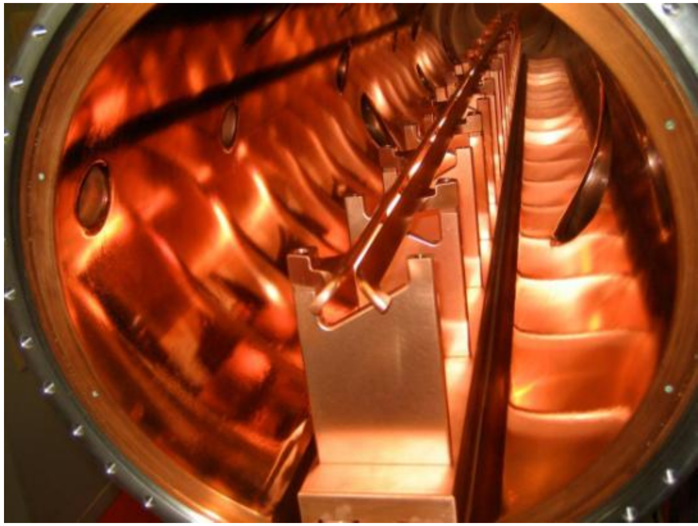
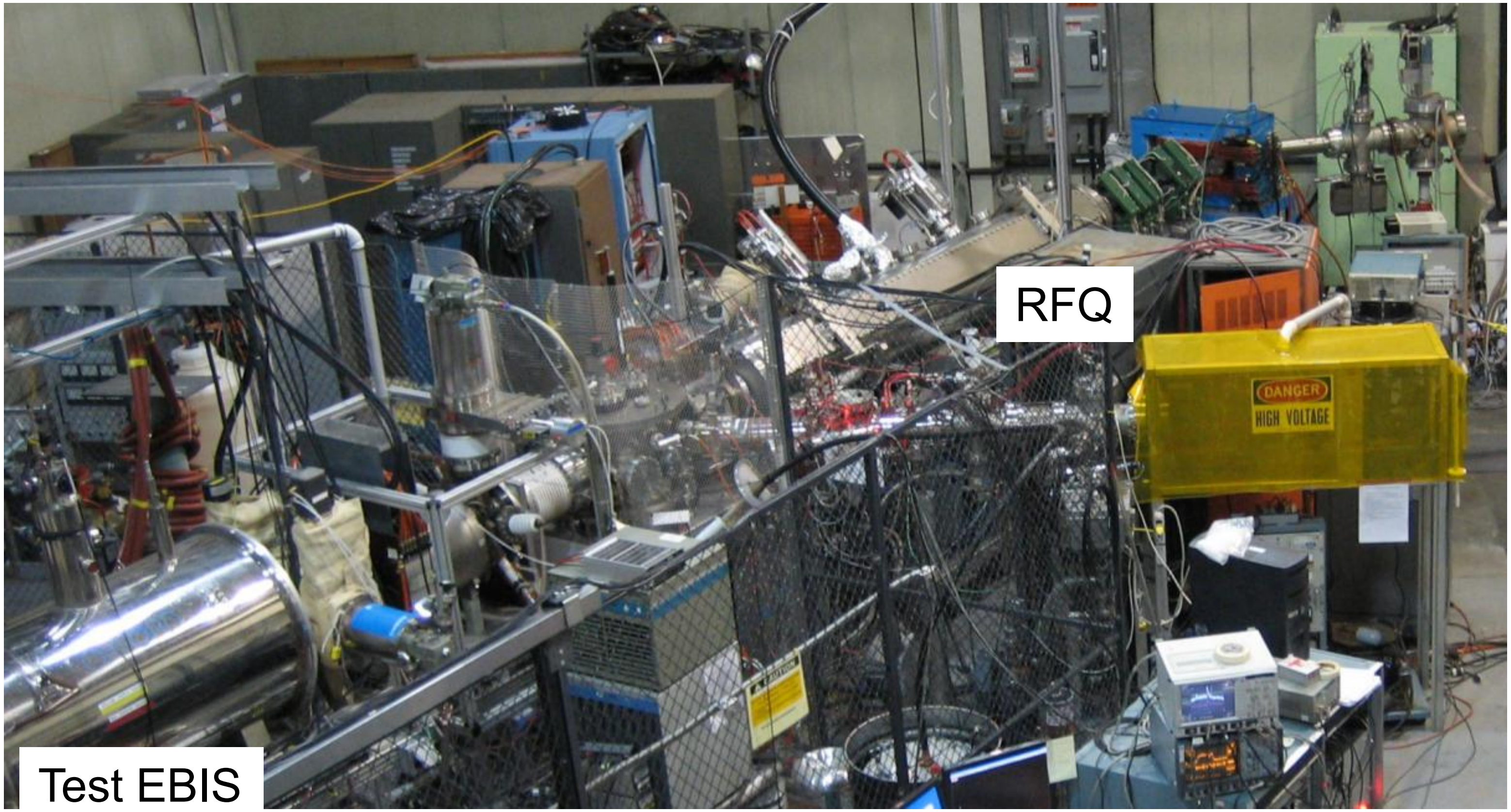
The RFQ has successfully accelerated He, Cu, & Ne from the Test EBIS at BNL.

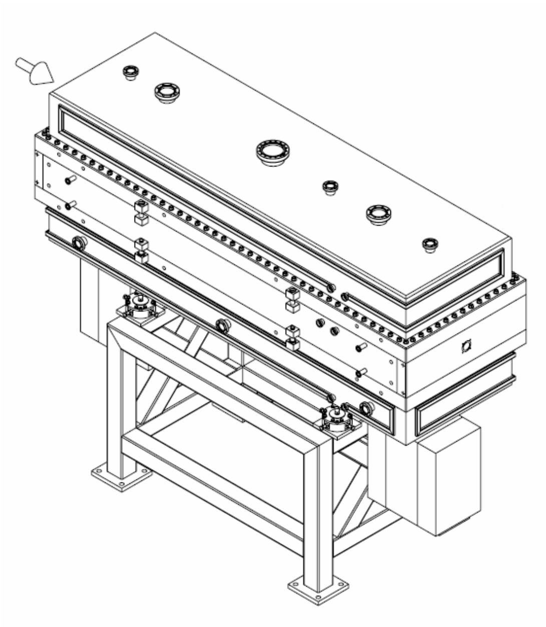


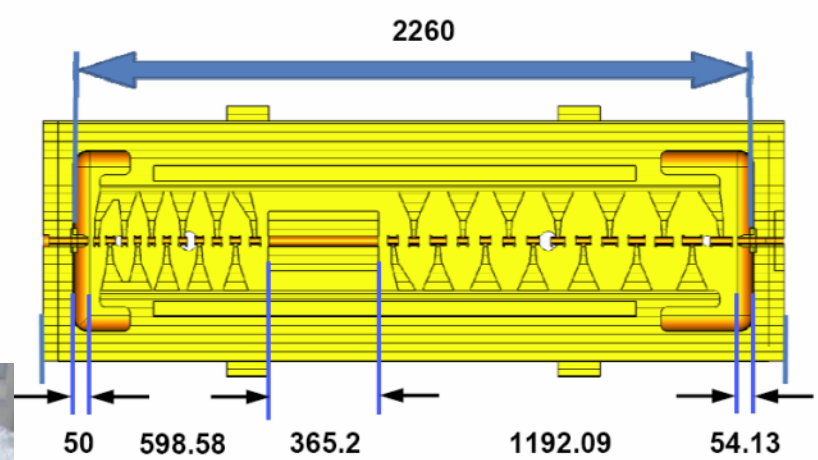
Delivered in September, 2008.

RFQ on Test EBIS



IH Linac from IAP, Frankfurt (Ratzinger)





Frequency	100.625 MHz
Input energy	300 keV/u
Output energy	2.0 MeV/u
Mass to charge ratio	6.25
Beam current	10 mA
Out. Energy spread 90%	< ± 2.0 keV/u
Tras. Emittance growth	< 20 %
Transmission	> 90%
RF power	300 kW
Tank length	2.46 m
Gap number	27
Aperture min - max	9 - 15 mm

Cavity is at GSI for Cu plating
Internal quads being manufactured by Bruker
Delivery to BNL scheduled for September, 2009.

Many other components in place

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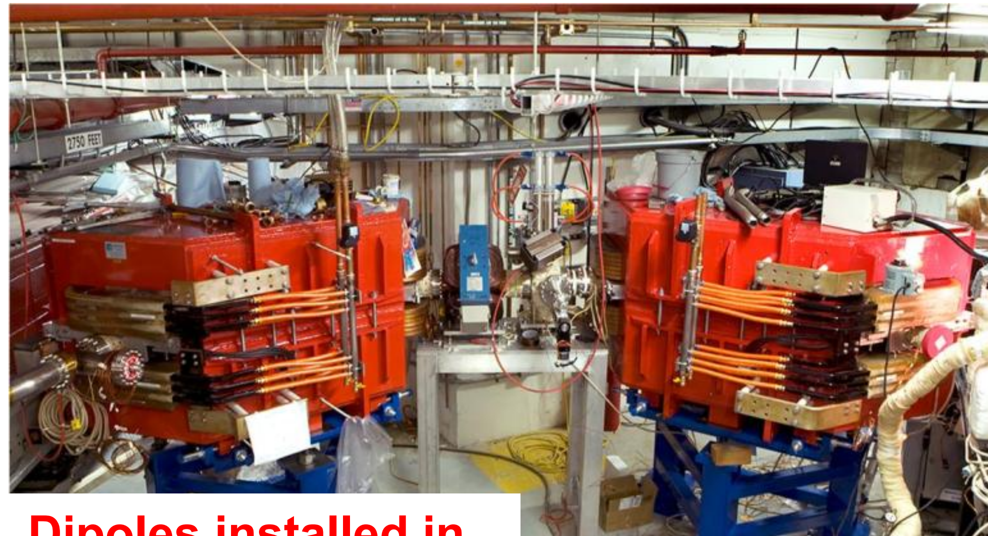
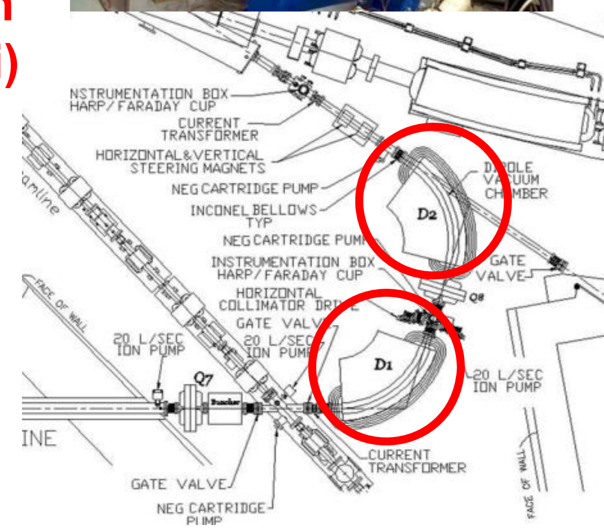
EBIS power supplies are being installed on the 100 kV platform



Dipoles installed in Booster (Sigmaphi)



350 kW, 100 MHz RF amplifiers

To meet the RHIC and NASA requirements…..

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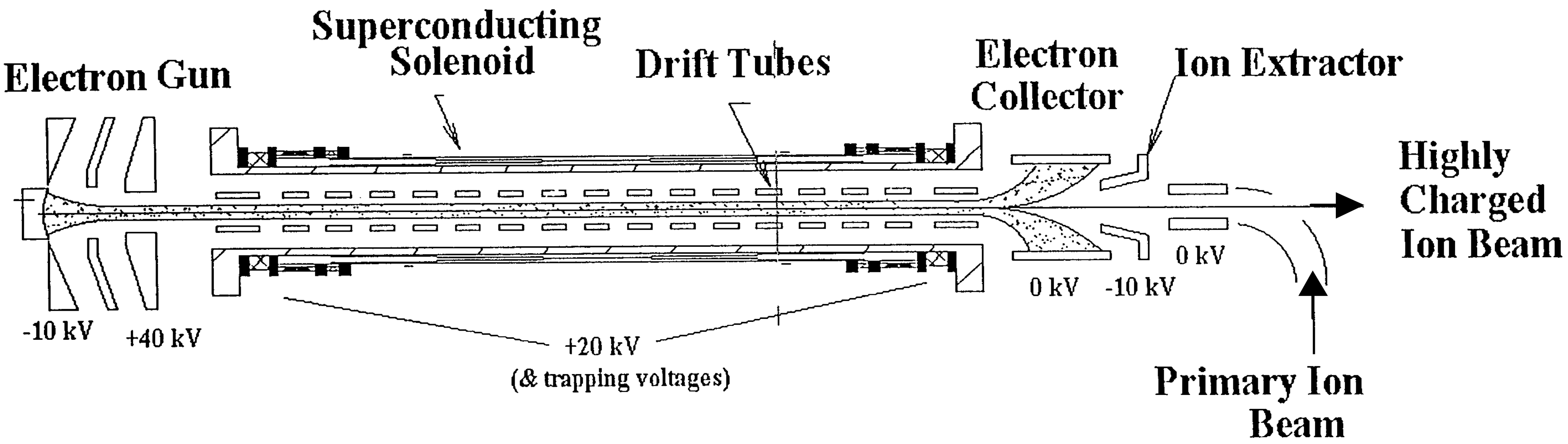
- Needed an ion source which could produce
  - Any species
  - “High” charge states
  - mA currents in the desired charge state in ~10 μs pulses
  - Switch species in 200 ms

The Test EBIS at BNL has demonstrated these requirements. It has achieved an order of magnitude higher intensity than all previous EBISs.

Performance Requirements of the EBIS

Species	He to U
Output (single charge state)	≥1.1 x 10^{11} charges
Intensity (examples)	3.4 x 10^9 Au^{32+} / pulse (1.7 mA) 5 x 10^9 Fe^{20+} / pulse (1.6 mA) 6.3 x 10^{10} He^{2+} / pulse (2.0 mA)
Q/m	≥ 0.16, depending on ion species
Repetition rate	5 Hz
Pulse width	10 - 40 μs
Switching time between species	1 second
Output emittance (Au^{32+})	< 0.18 π mm mrad,norm,rms
Output energy	17 keV/amu

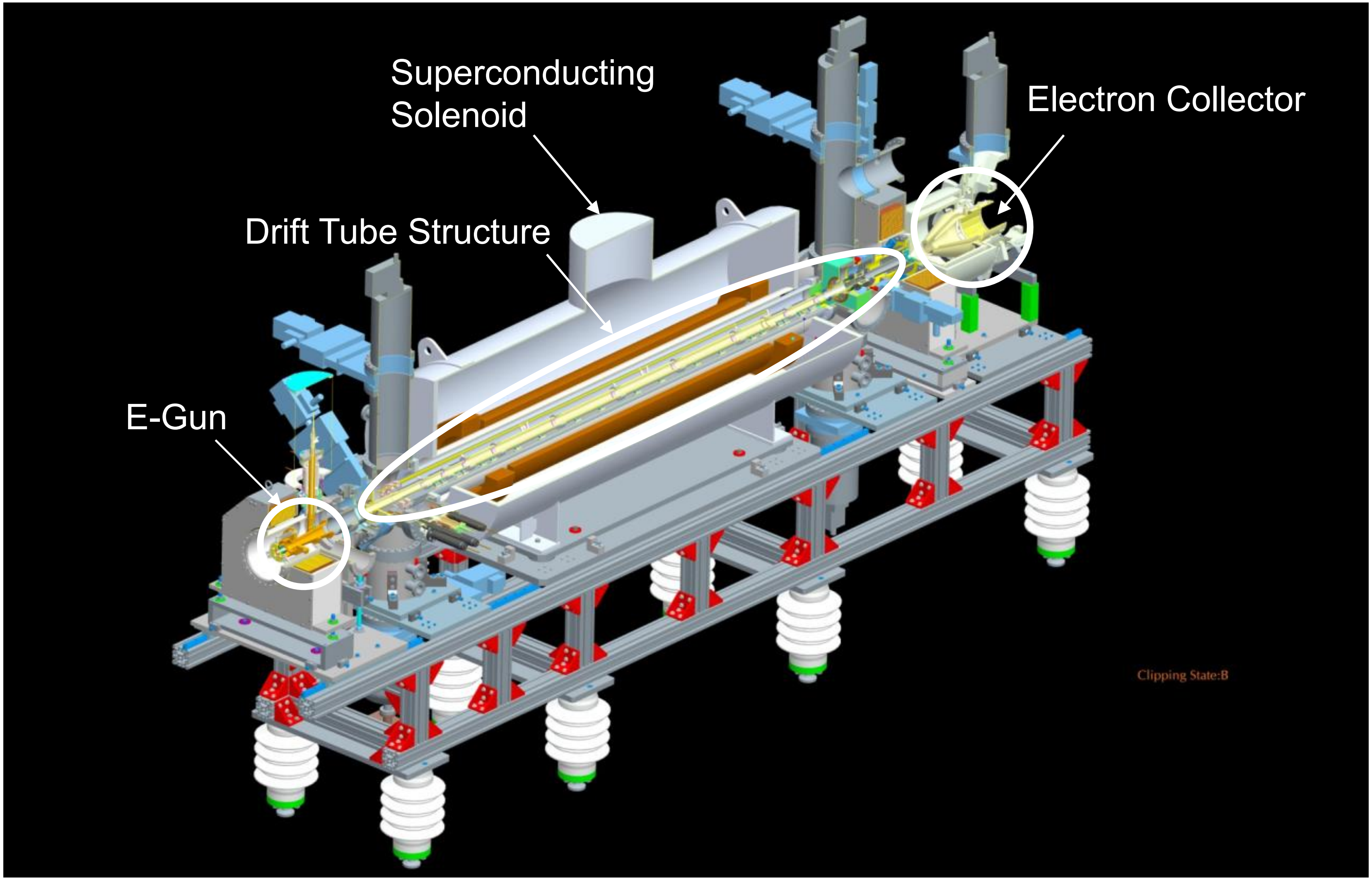
Principle of EBIS Operation



Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials on electrode at ends of trap.
The total charge of ions extracted per pulse is ~ (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.
- Charge per pulse (or electrical current) ~ independent of species or charge state!

Electron Beam Ion Source (EBIS)



Key Technologies

- High current electron gun (10-20A, IrCe cathode)
- Electron collector (design for 15A * 15 kV = 225 kW;
- 50 ms* 5Hz = 25% df, to dc)
- Superconducting solenoid (~5T, 2 meter, 8” bore)
- Vacuum – ~10^{-10} in the trap region
- Controls – makes the complex programming of many electrode voltages at different times during an EBIS cycle easy and reproducible

EBIS

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

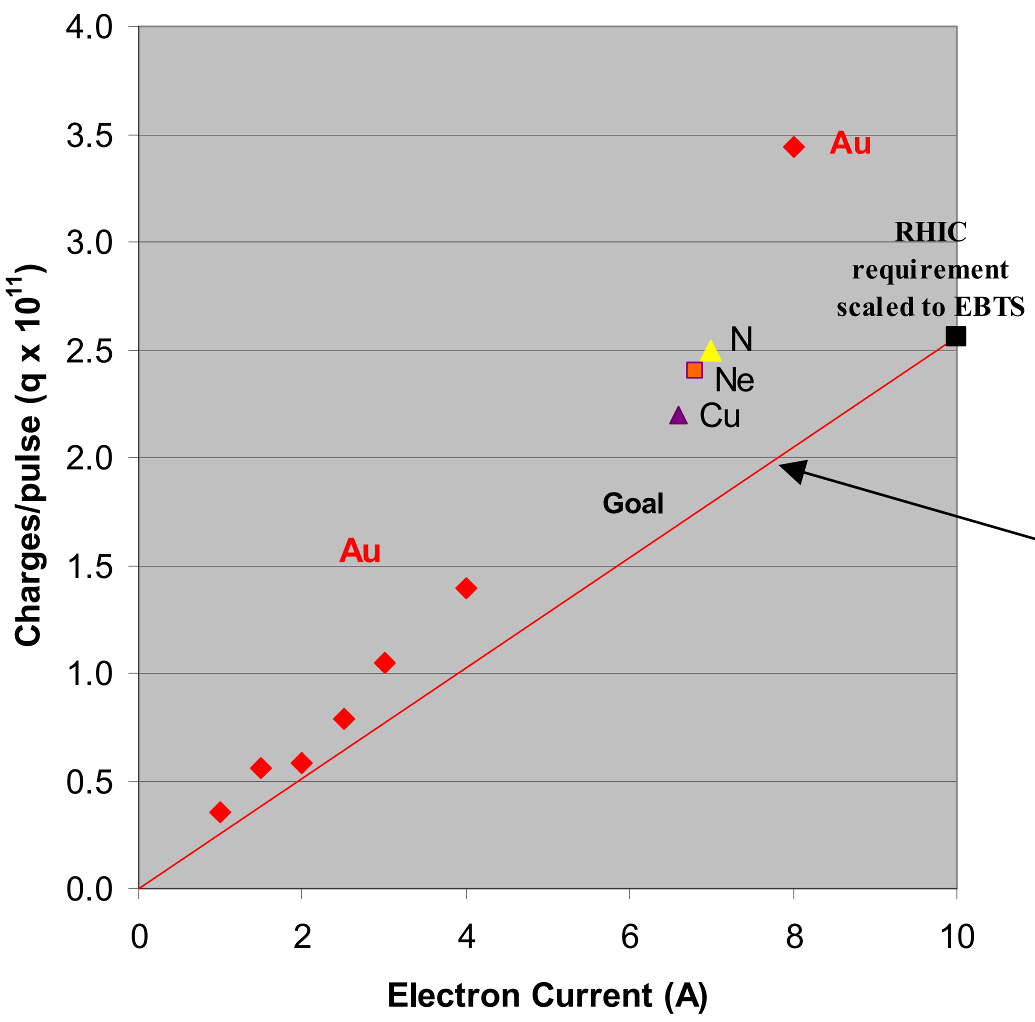
$K_1 \sim 0.5 – 0.8$

$K_2 \sim 0.2 – 0.8$

RHIC EBIS Trap length = 1.5 m
I(e) = 10 A
V(e) ~ 20 kV

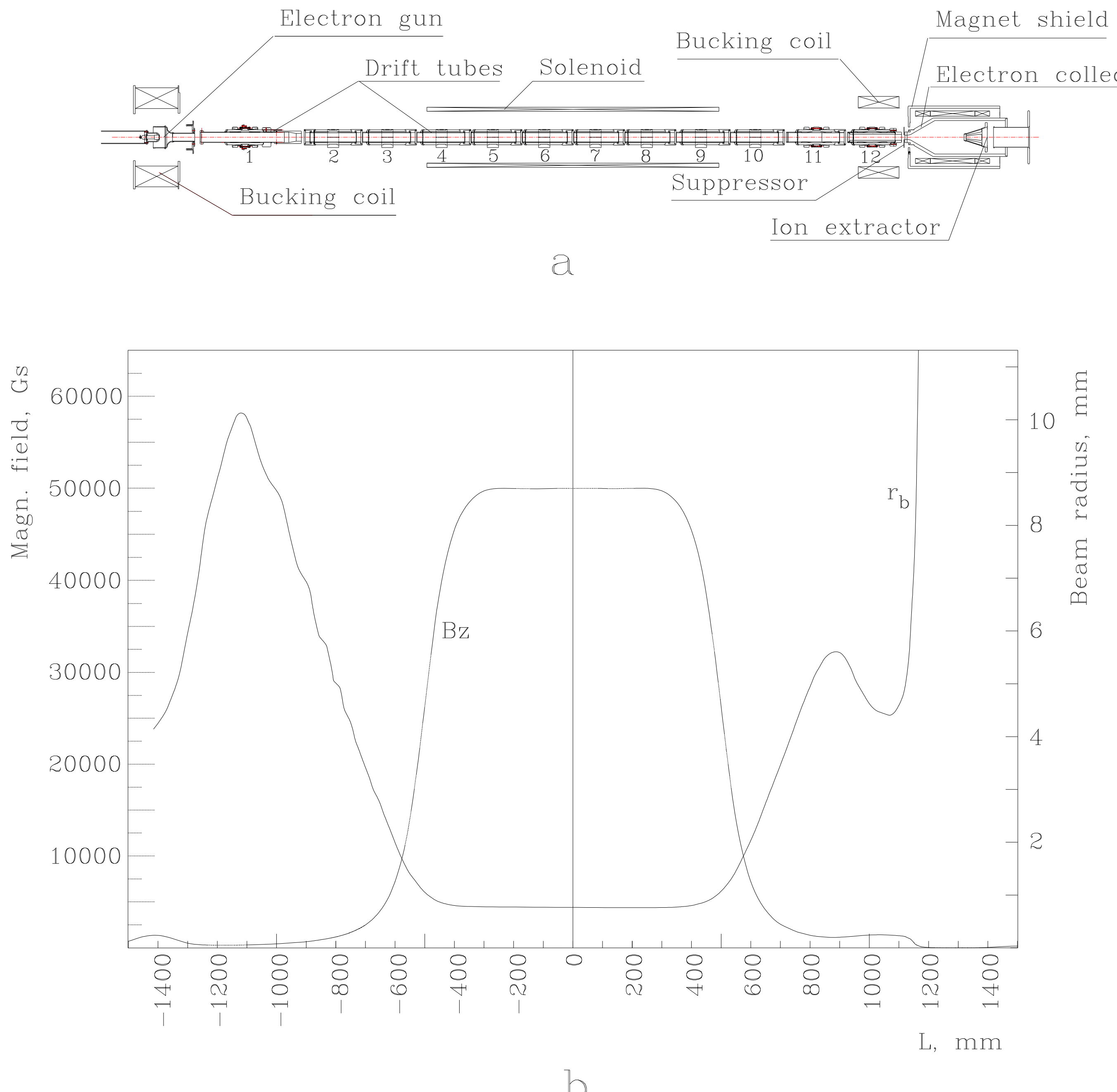
Electron beam charge in trap ~ 10^{12}
→ Extracted ion yield in a single charge state will be ~1–6 x 10^{11} charges/pulse

Charge extracted from Test EBIS



50% of "trap capacity"
(# of e's in trap)
= goal for Test EBIS

5 x 10^{11} (80 nC) required for RHIC
(with 2 x the trap length)



Electron beam current density:

15 A/cm^2 at cathode (B~0.15T)

500 A/cm^2 in the trap (B=5T)

r(e) ~0.7 mm in trap

Can easily change
J at fixed I, …
I at fixed r, … etc.

Operation of the Electron Beam

EBIS
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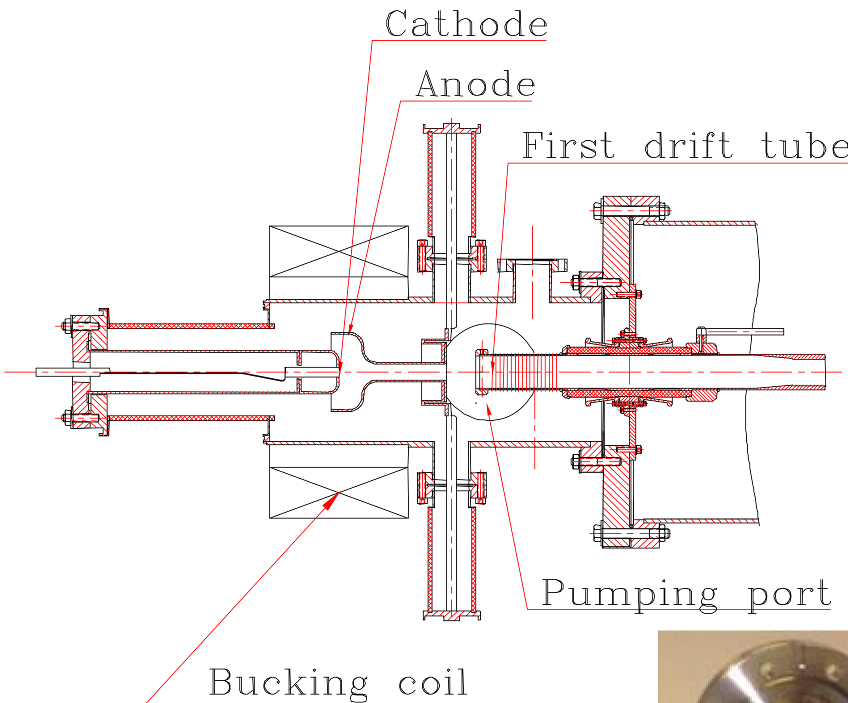
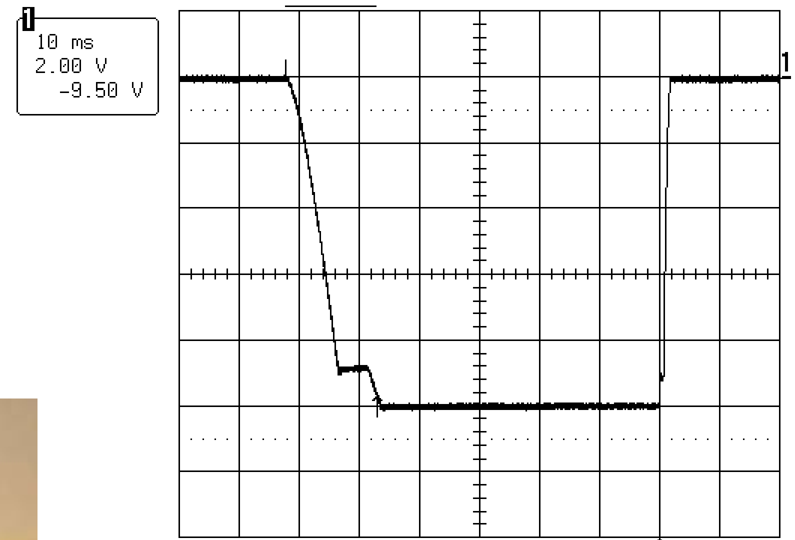


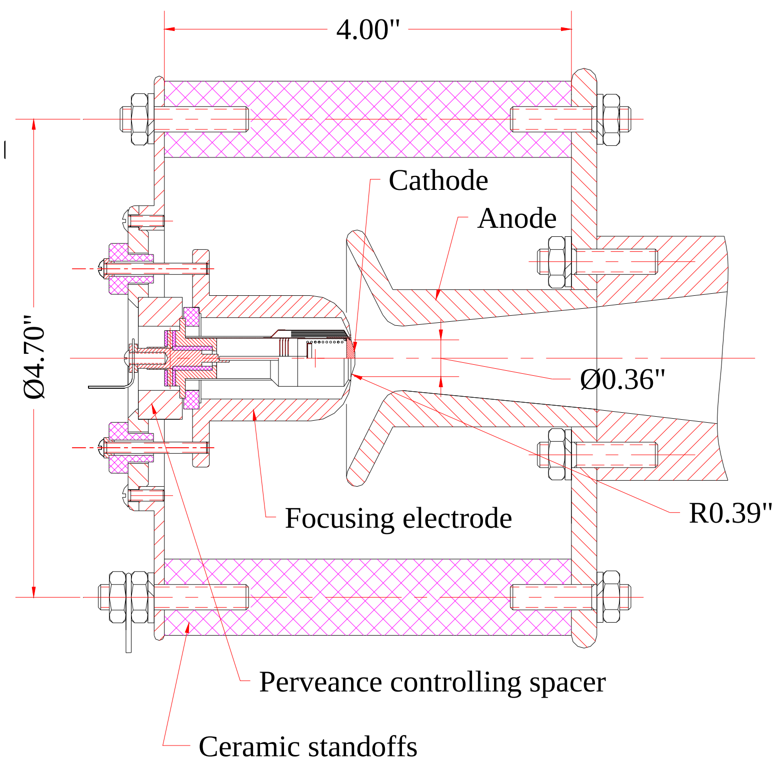
Propagation of a 10 A electron Beam through the EBIS trap



10 A, 50 ms electron beam pulse
Losses < 1 mA

Perveance ~ 1.3 μP
(Test EBIS gun)
LaB_6 and **<u>IrCe</u>** cathodes

RHIC EBIS Gun



Electron beams up to 10A, 100kW have been propagated with very low loss, using IrCe cathodes from BINP, Novosibirsk.

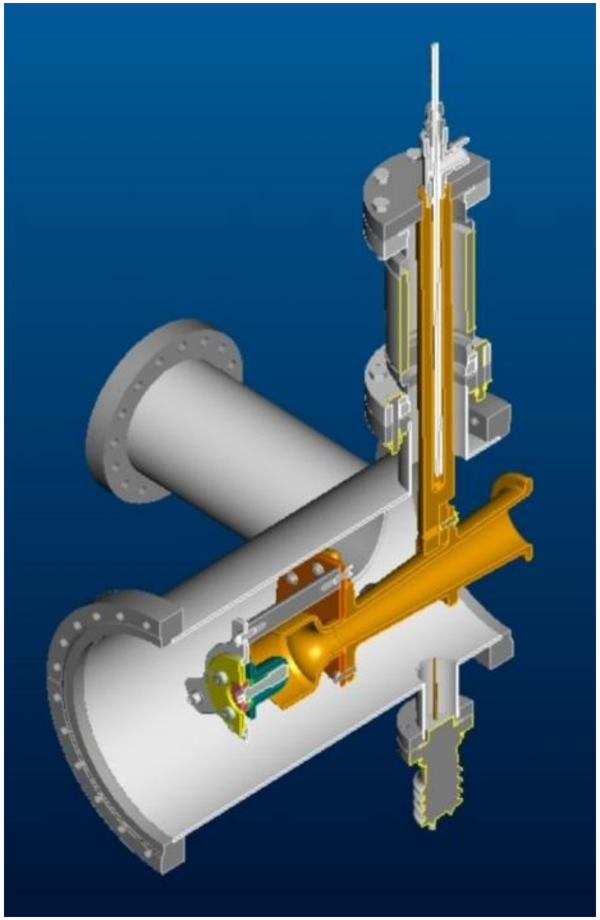
10 A electron gun with IrCe cathode meets the RHIC EBIS requirements, with an estimated lifetime of >20,000 hours

9.2 mm diameter convex cathodes (LaB_6 shown)

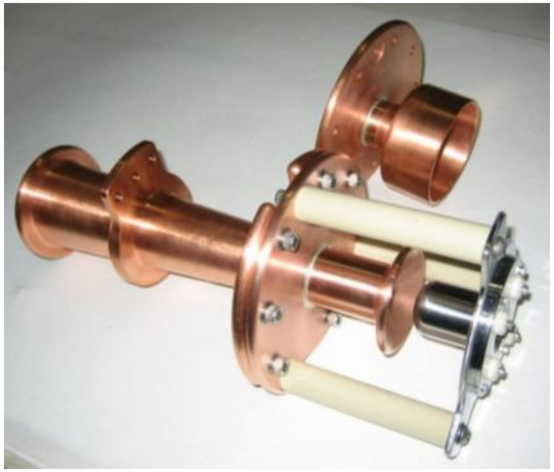
The present cathode is actually capable of operating at 20 A (J=30A/cm^2) with lifetime of 3000-5000 hours. For possible future increase of the ion beam intensity, we have built the electron gun electrodes and collector with the capability of operating at 20A.

Perveance = 3.1 μP

Electron gun assembly in a chamber



The new electron gun with the high perveance anode (~3μPerv) was installed and operated at the Test EBIS to produce electron beams up to 10A.



RHIC EBIS electron collector assembly design for pulsed 20 A, 15 kV beam

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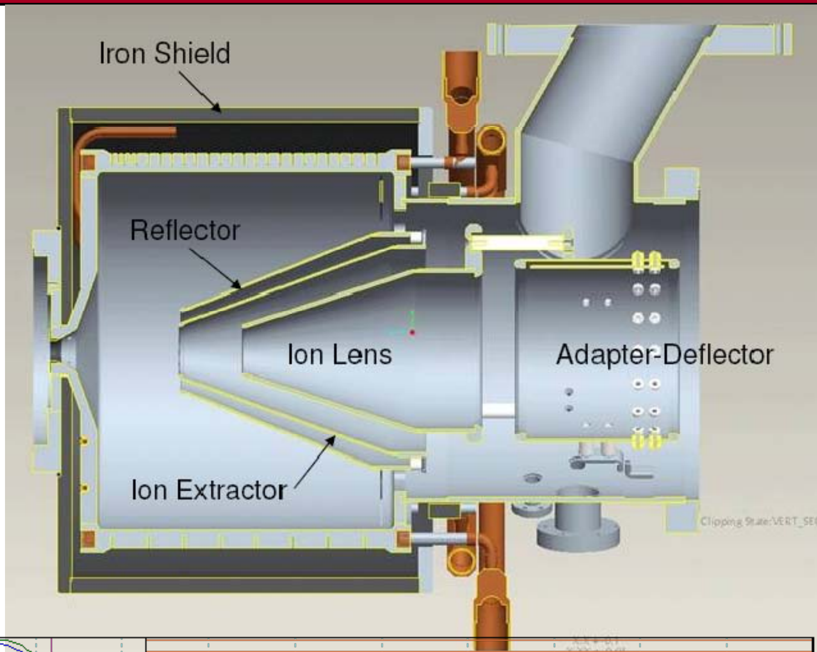

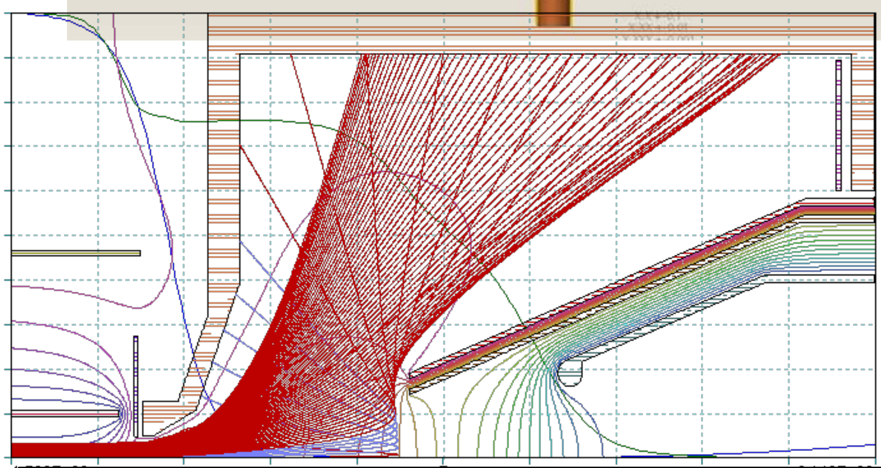

- Designed to dissipate P_{el}= 300 kW peak power (20 A, 15 kV e- beam)
- Calculated power density on EC surface (for 300 kW):
  P = 200 W/cm^2 , during the pulse
- Outer surface of collector is at atmosphere (no internal cooling lines).
- One collector is Hycon 3 HP (Brush-Wellman). This high conductivity BeCu was chosen because it provides longer fatigue lifetime.
  However, due to difficulties in electron beam welding of this material, we have also built a second collector from a Zr-Cr-Cu alloy. This is now in use on the Test EBIS.

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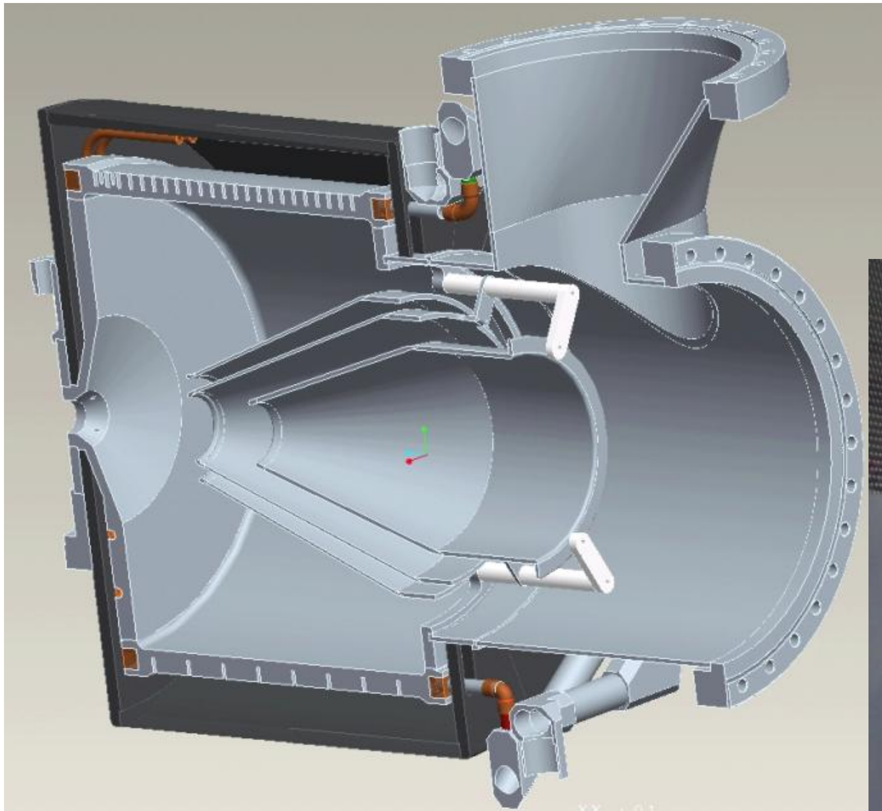
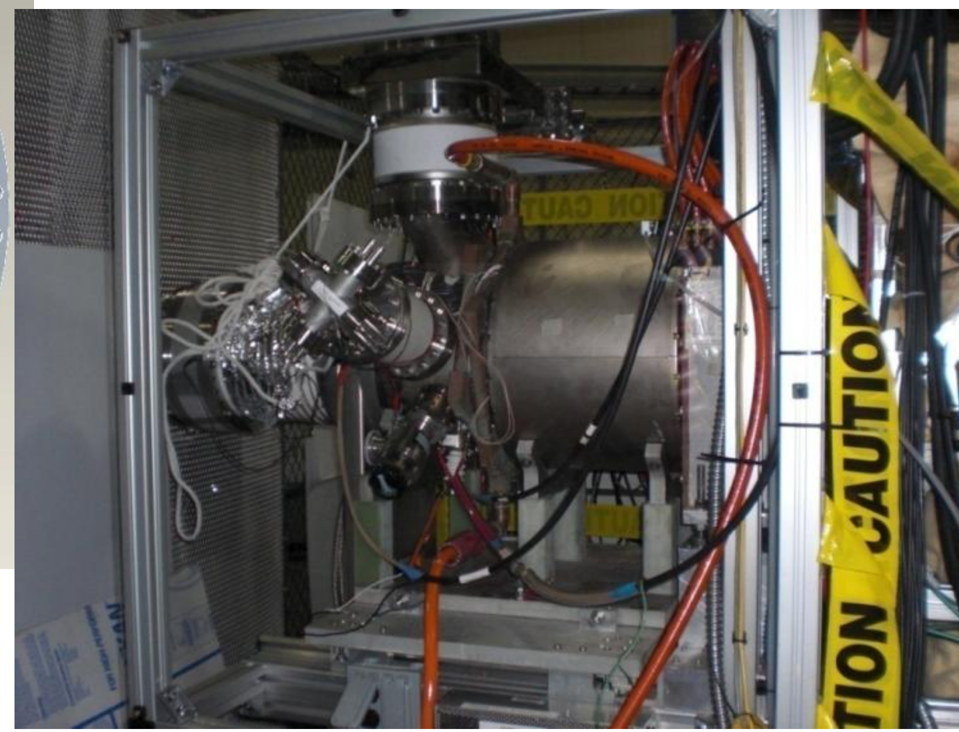
RHIC EBIS electron collector assembly, now in use on the Test EBIS





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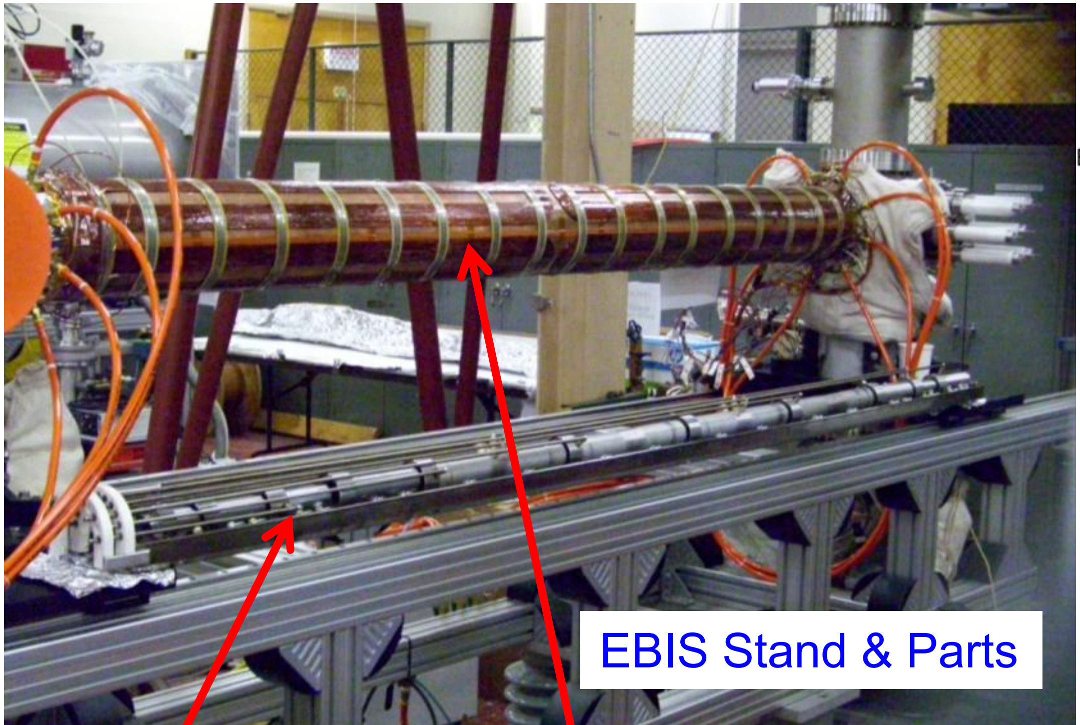
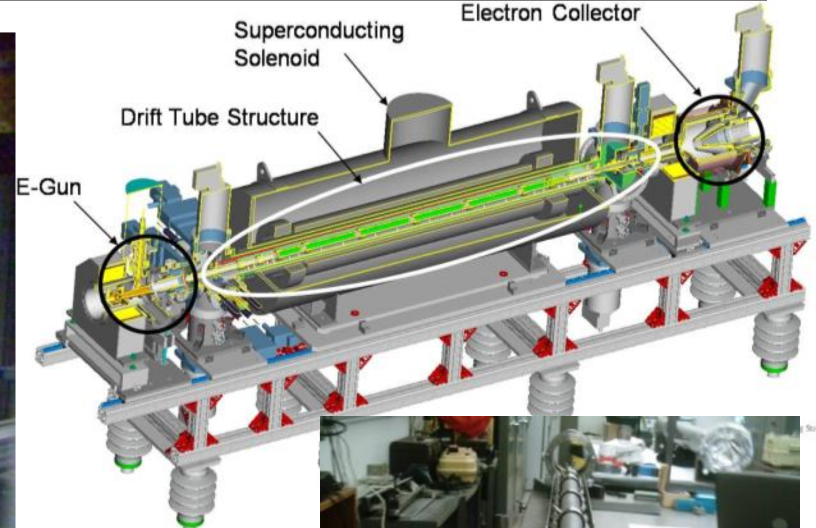
Drift tube structure





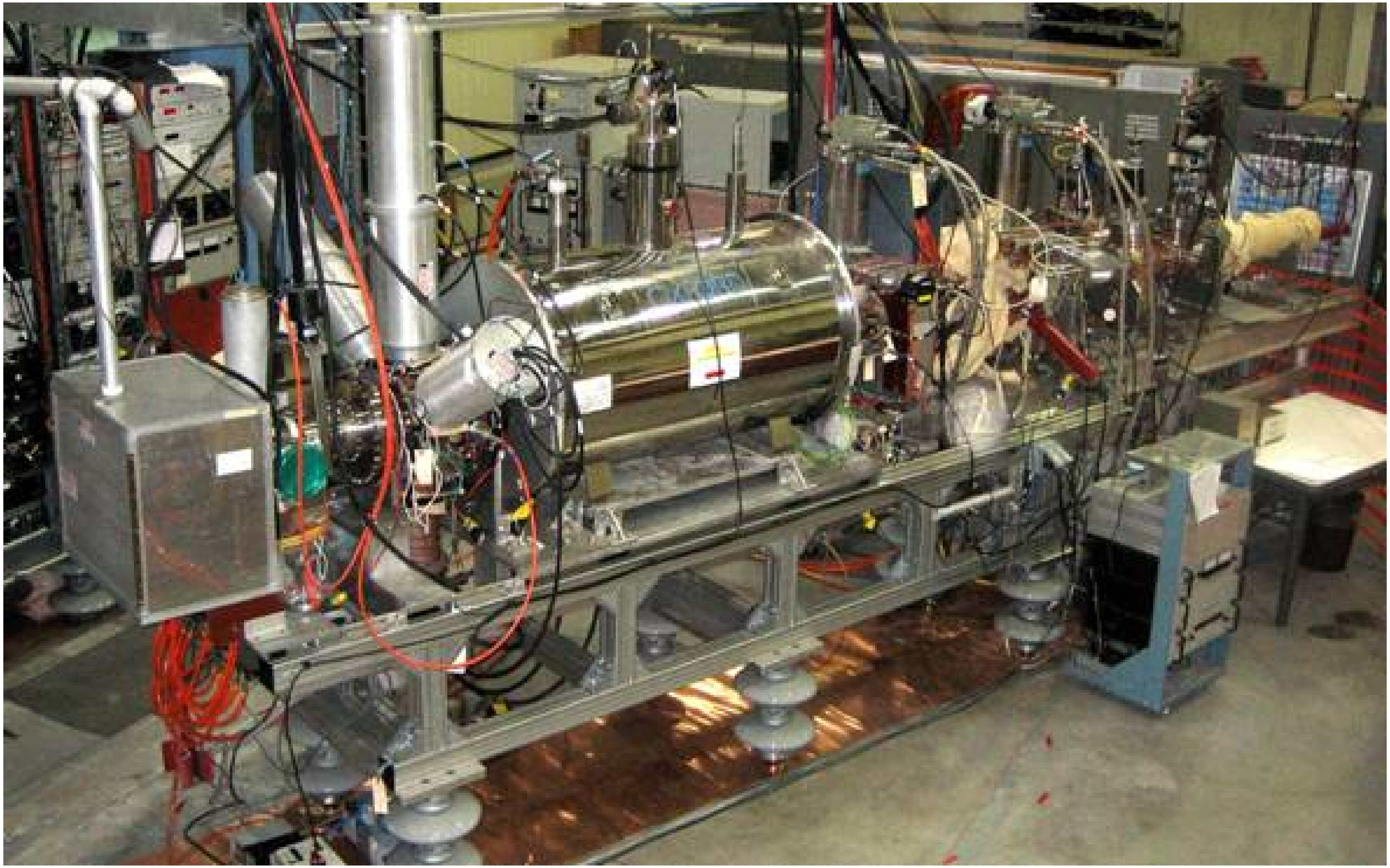
Drift tubes sit inside the central vacuum tube.
Heaters on the outside of the vacuum pipe allow baking to 450 C.
Outside of these heaters, there is a water cooled jacket to keep the magnet bore cool.
Outside the water cooled jacket, there are transverse steering coils.

RHIC EBIS Superconducting Solenoid (SCS)

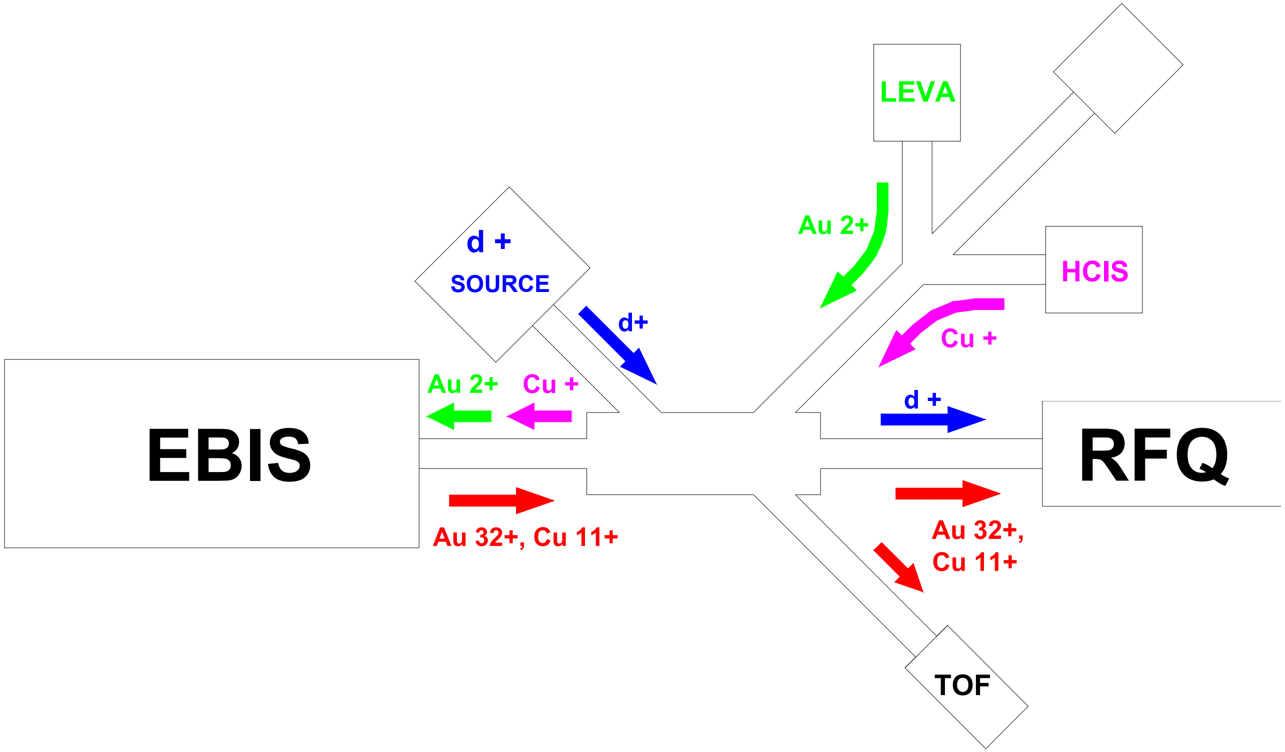
- Length of the SCS coil: 190 cm — Test EBIS: 100cm
- Magnet field: 5 T — Test EBIS: 5T
- Warm bore inner diameter: 204 mm (8”) — Test EBIS: 155mm (6”)
  - 1.7 times increased vacuum conductance
  - more room for HV leads

Made by ACCEL. The solenoid has passed acceptance tests and is at BNL.

Test EBIS on stand with high voltage isolation



Ion Injection and Extraction from the RHIC EBIS

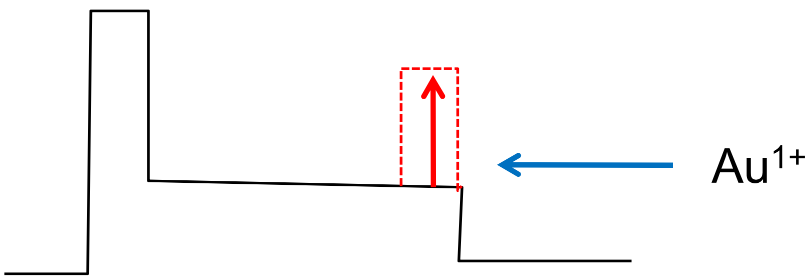


External ion injection provides the ion species; the EBIS acts purely as a charge breeder.

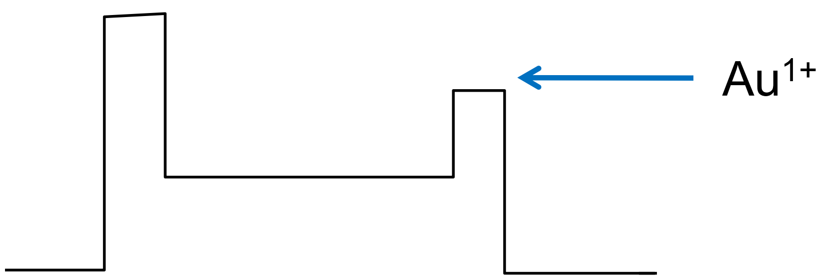
Advantages:

1. One can easily change species and charge state on a pulse to pulse basis
2. There is virtually no contamination or memory effect
3. Several relatively low cost external sources can be connected and maintained independently of the EBIS.

INJECTION

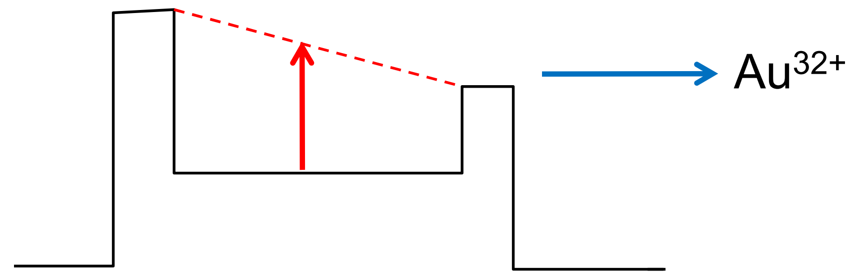


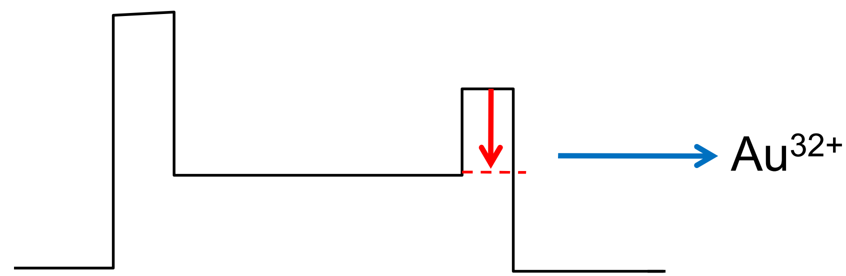
“Fast”



“Slow” or continuous

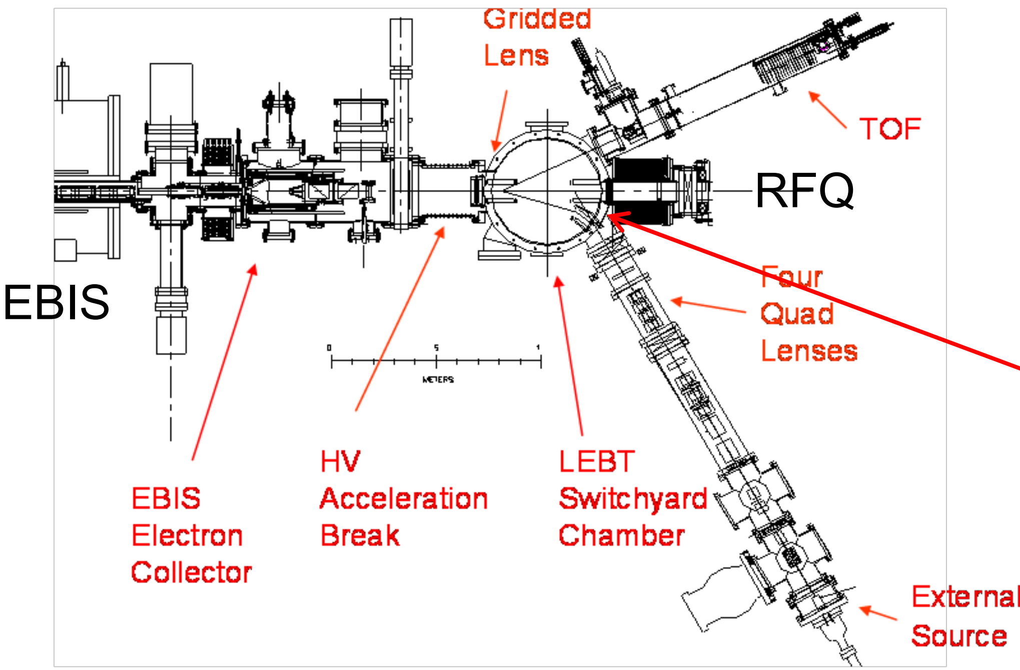
EXTRACTION

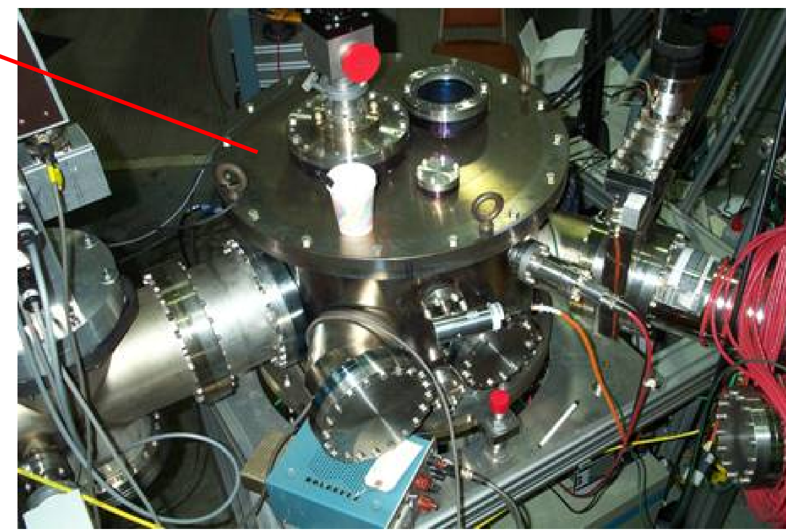




Adjust the time you take to raise/lower the barrier to change the extraction pulse width

LEBT Switchyard at Test EBIS





External Sources used for Primary Ion Injection on the Test EBIS

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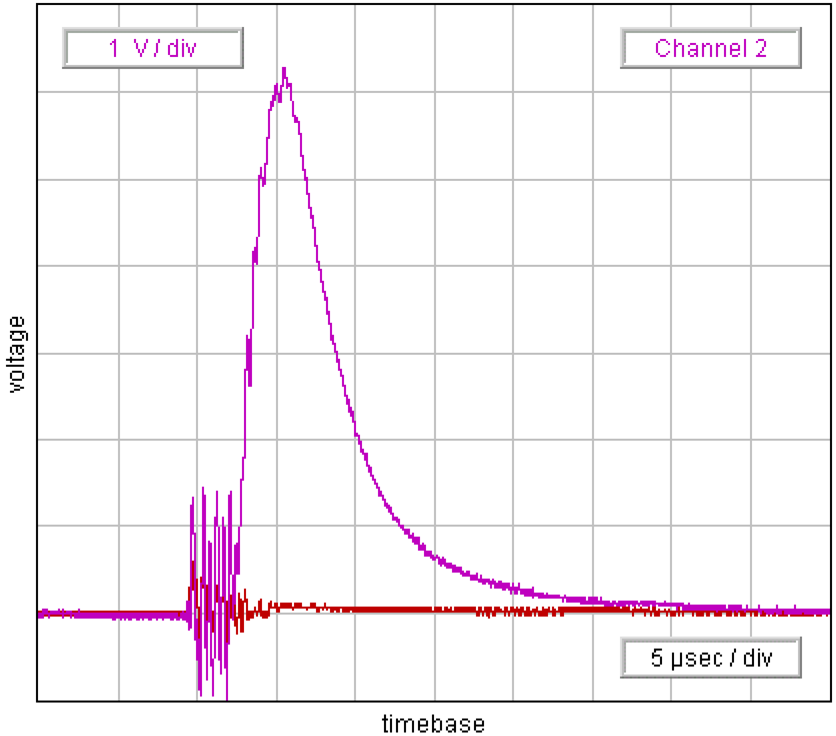
To date, we have operated the EBIS successfully with external ion injection from a Metal Vapor Vacuum Arc Source, a Hollow Cathode Ion Source, and a Liquid Metal Ion Source. In addition, for beams such as helium, we have used standard gas injection.

Low Energy Vacuum Arc Source (I. Brown);

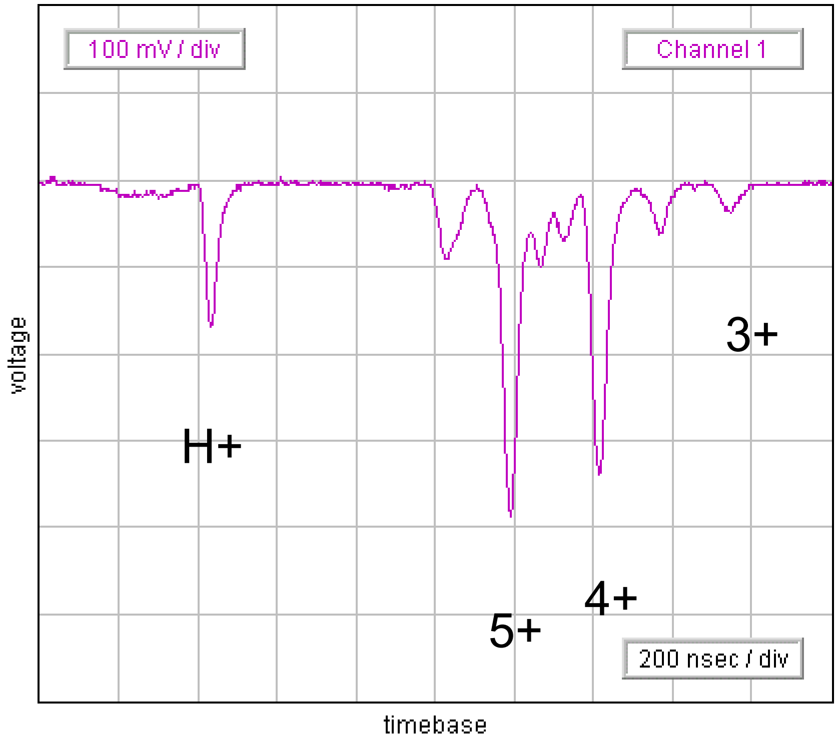
Hollow Cathode Ion Source (HCIS), based on design used on Saclay EBIS.

NITROGEN

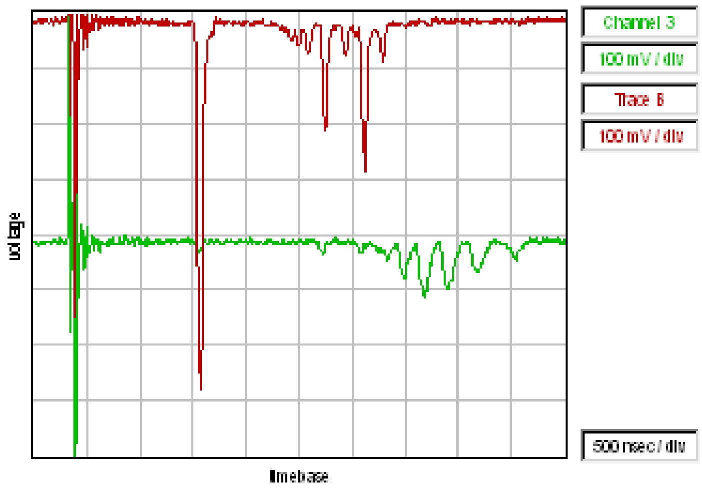


6 mA peak current
2.5 x 10^{11} charges/pulse

N_2^+ injected from HCIS
3 ms injection, 4 ms confinement
I(e) ~ 7A



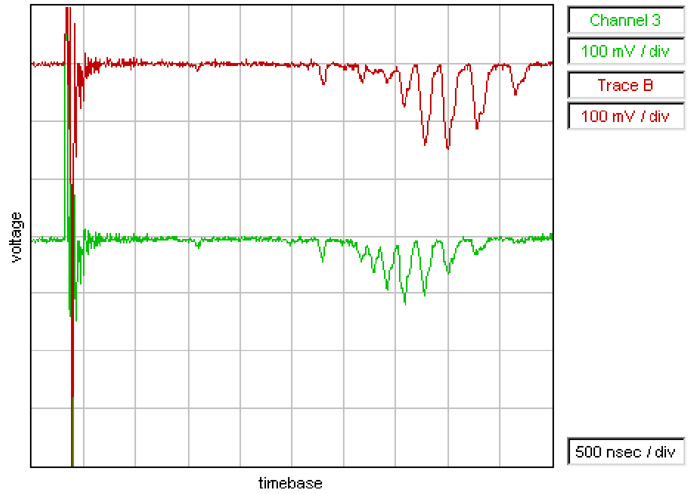
TOF spectra -- Cu+ injection (2.75A e-beam)



Upper trace: no injection
3.3ms confinement
(residual gas spectrum)

Lower trace Cu+ injection
3.3ms confinement

(Cu spectrum –residual gas displaced by Cu ions)



Upper trace: Cu+ injection
3.3ms confinement
(Cu spectrum)

Lower trace Cu+ injection
6.3ms confinement
(Cu spectrum shifted to higher charge states for longer time)

NEON from Test EBIS

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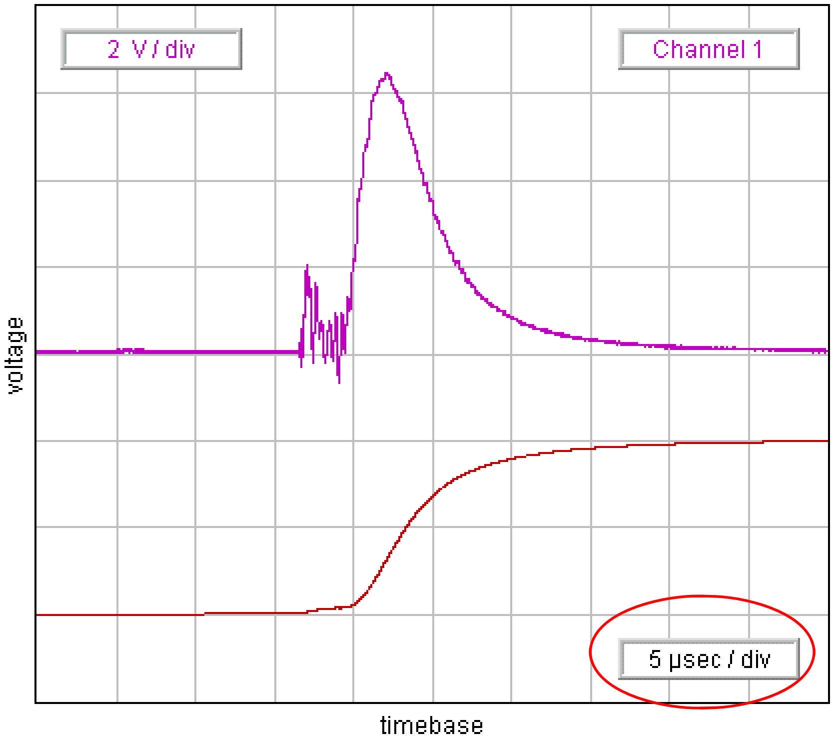
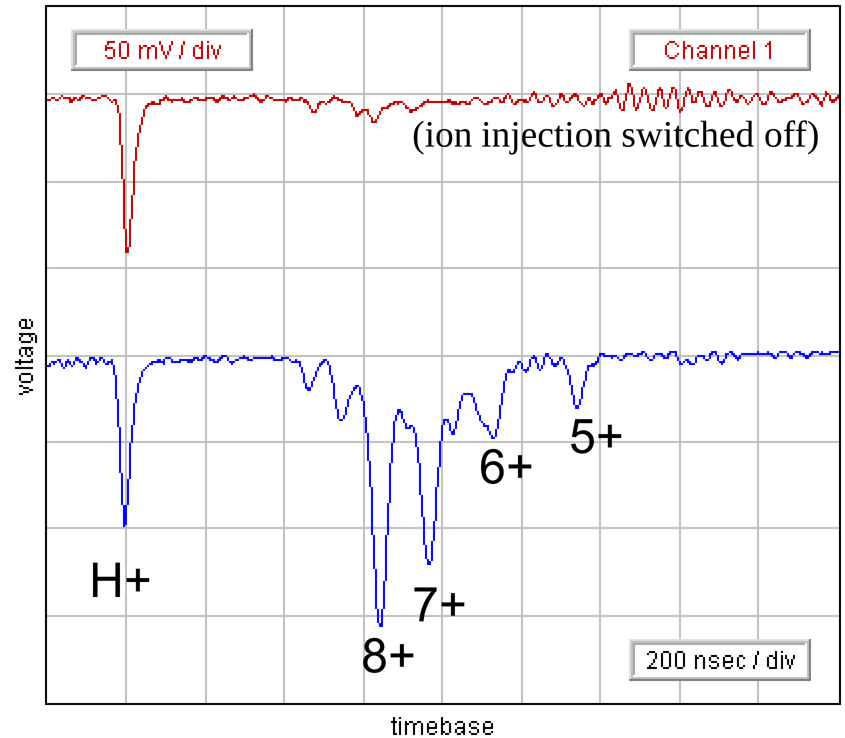


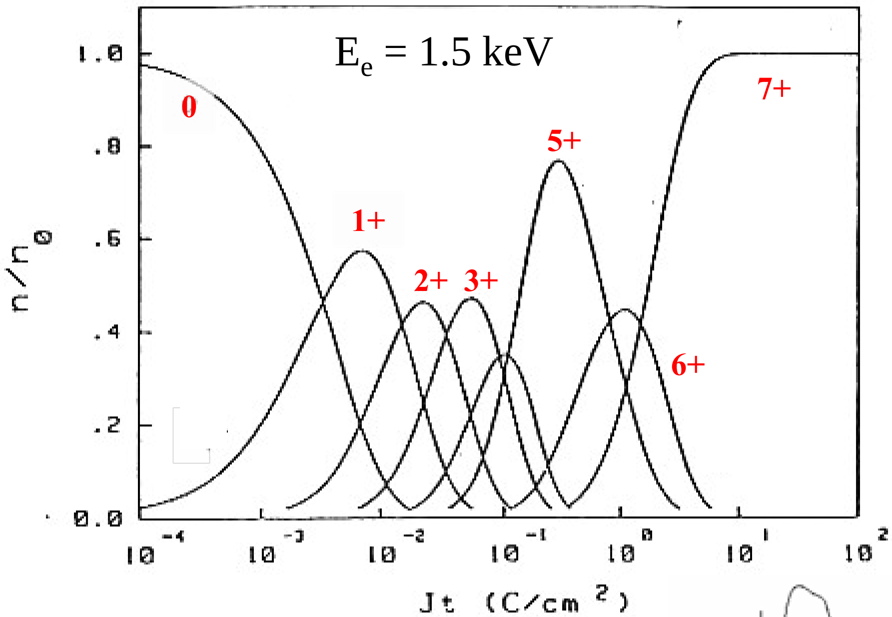
I(e) ~ 6.8 A



6.3 mA peak
2.4 x 10^{11} charges/pulse
18 ms confinement

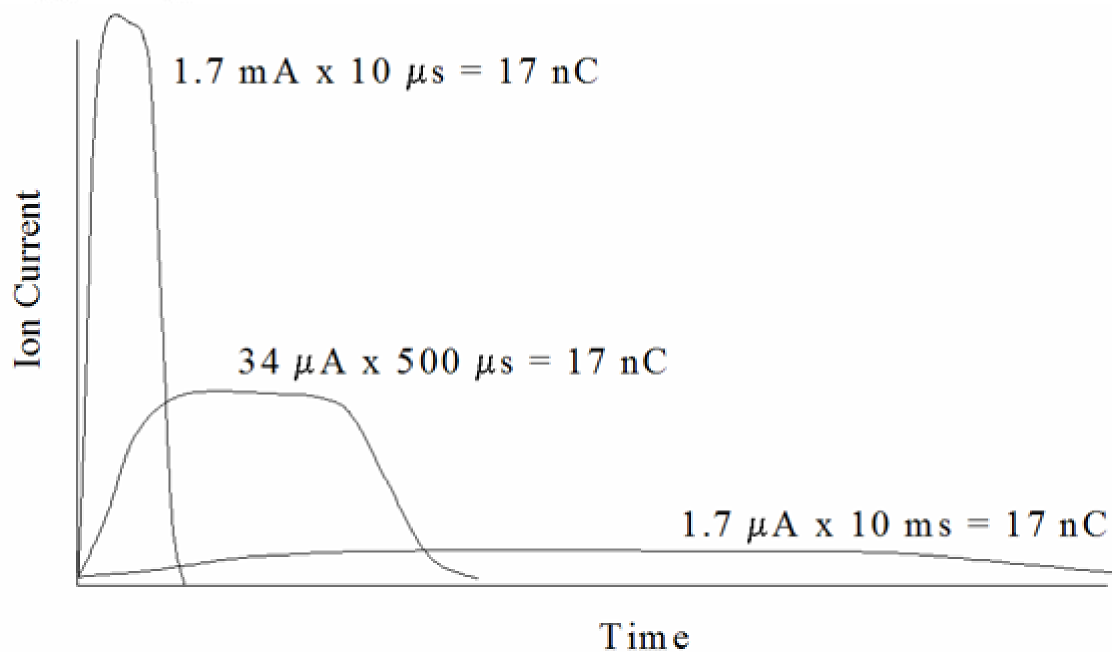
14 ms confinement

Nitrogen Charge State Evolution

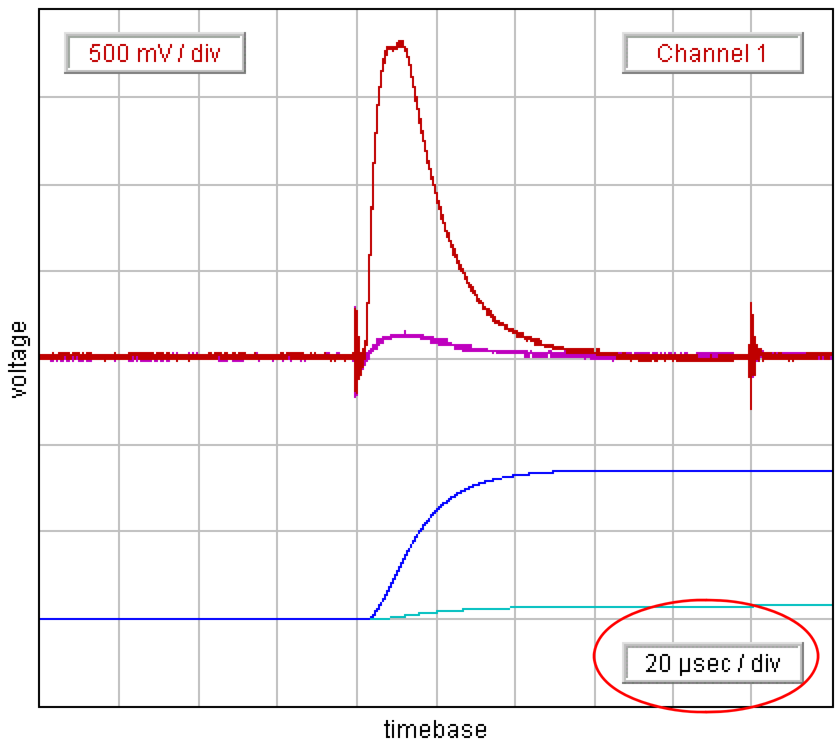


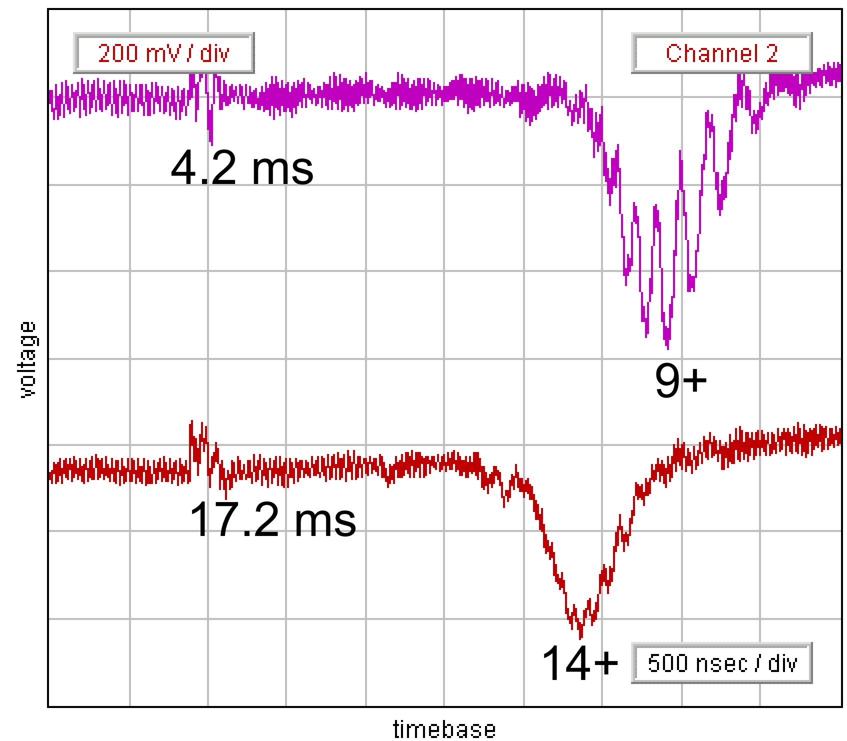
Charge state is selected by choosing the confinement time of ions in the trap

Ions are extracted from an EBIS in pulses of <u>constant charge</u>; one has control over the pulse width



COPPER



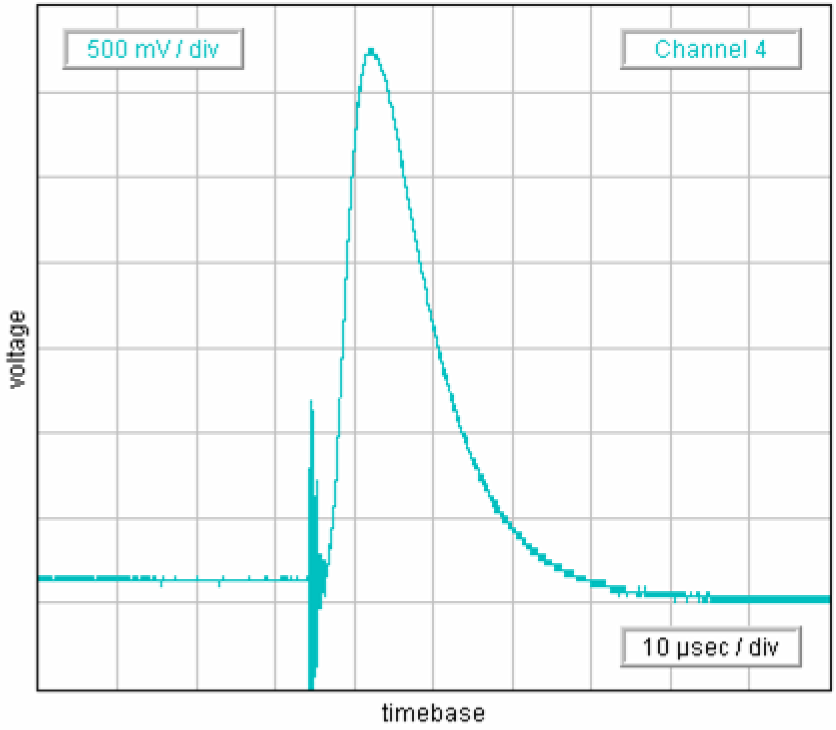


1.8 mA; 2.2x10^{11} charges/pulse,

15.3 ms confinement, I(e) = 6.6 A,

GOLD

Gold ions extracted from EBIS, with LEVA injection



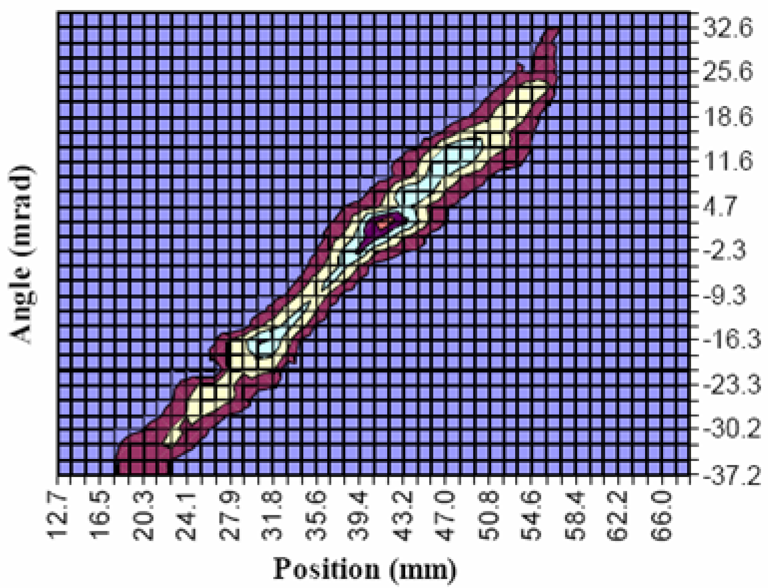
3.2mA, 12µs FWHM, (2.5 x 10^{11} charges/pulse)

6.8A e-beam

15ms confinement.

Emittances

Measured emittance of a 1.7 mA Au beam



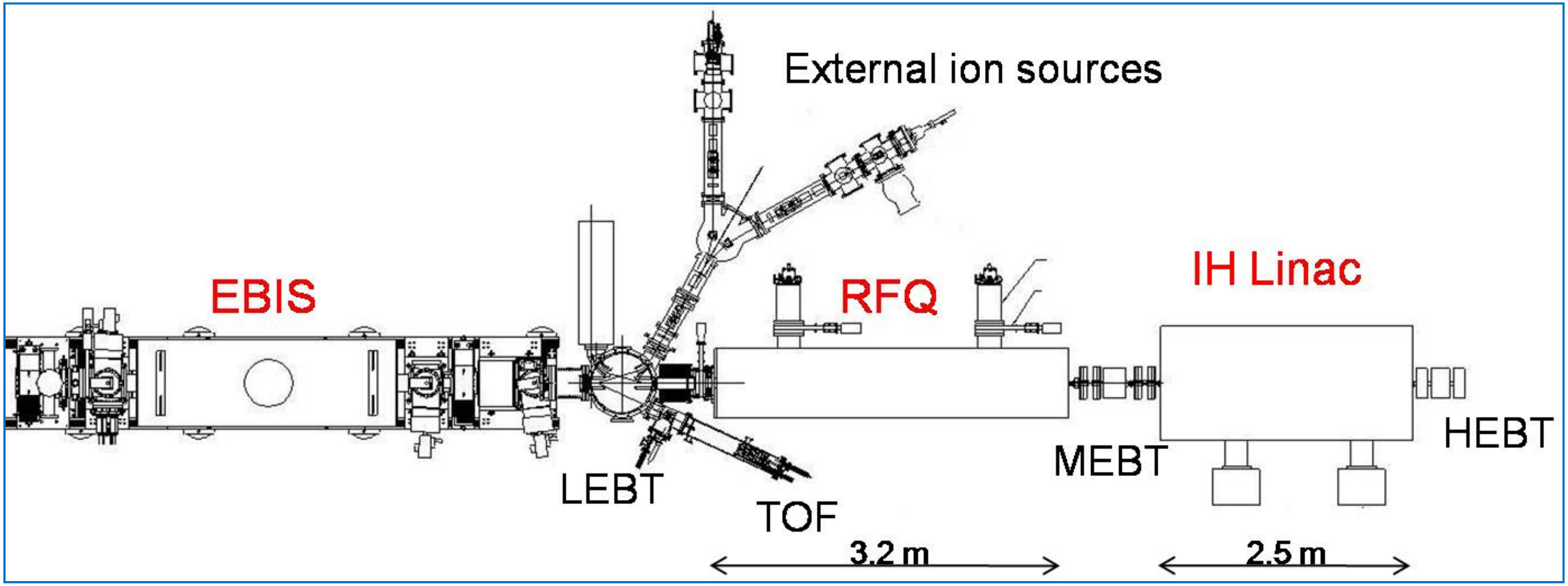
ε (n, rms)= 0.1 π mm mrad.

Emittance measurements for Au, Xe, He, H, Ar

Measurements always include all charge states

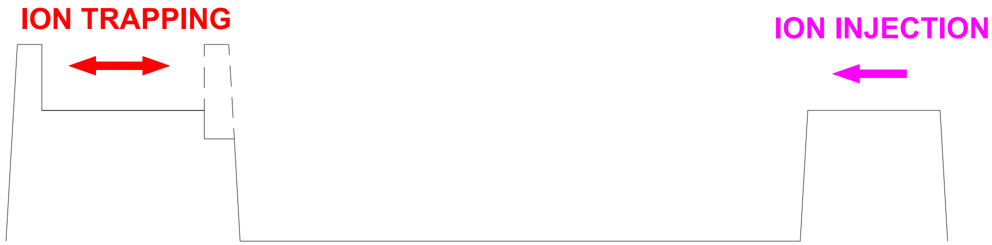
Au typically 0.1 – 0.15 π mm mrad, (n, rms)

Lighter beams have emittances of ~ 0.3 π mm mrad

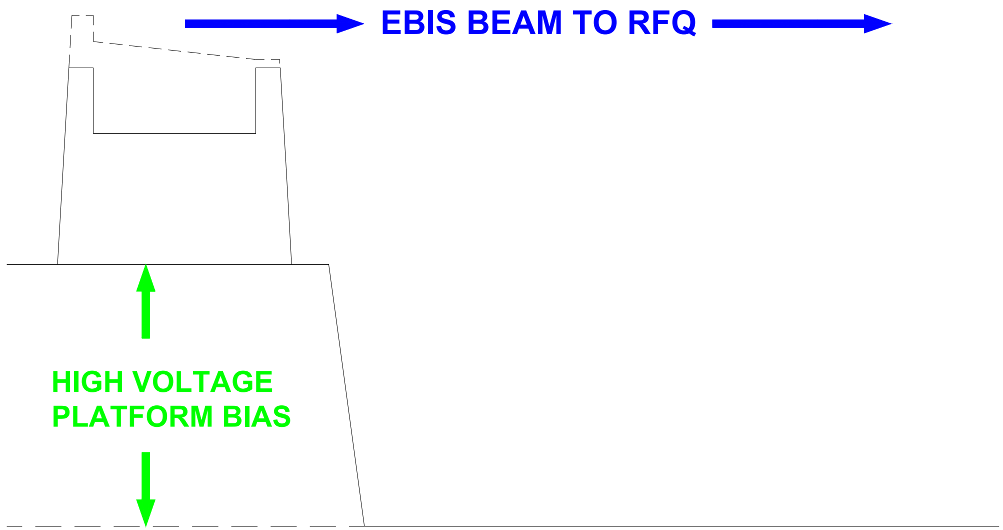

External ion sources
EBIS
RFQ
IH Linac
LEBT
TOF
MEBT
HEBT
3.2 m
2.5 m

EBIS operation with Pulsed High Voltage Platform

ELECTRON BEAM ION SOURCE

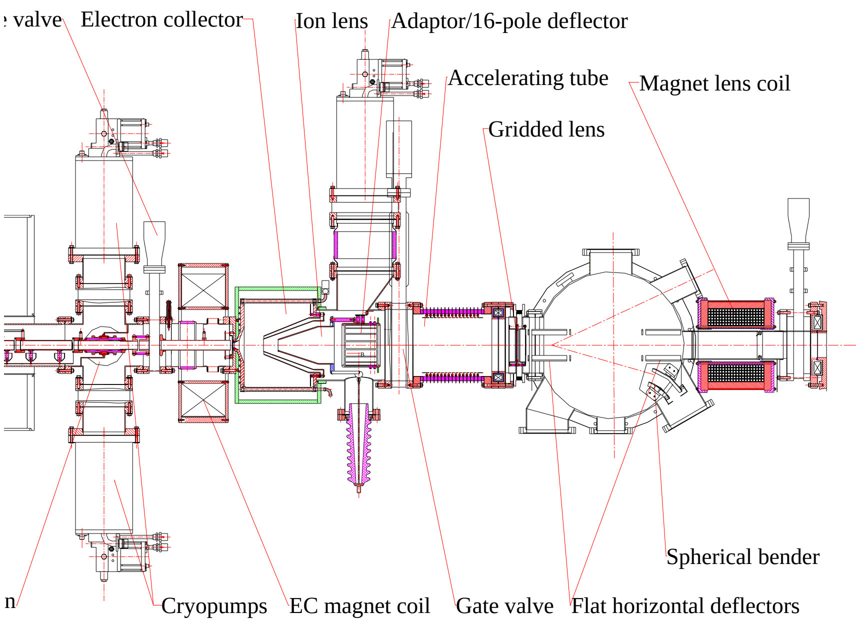


During injection and confinement the RHIC EBIS operates at ground potential.



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

EBIS TRAP

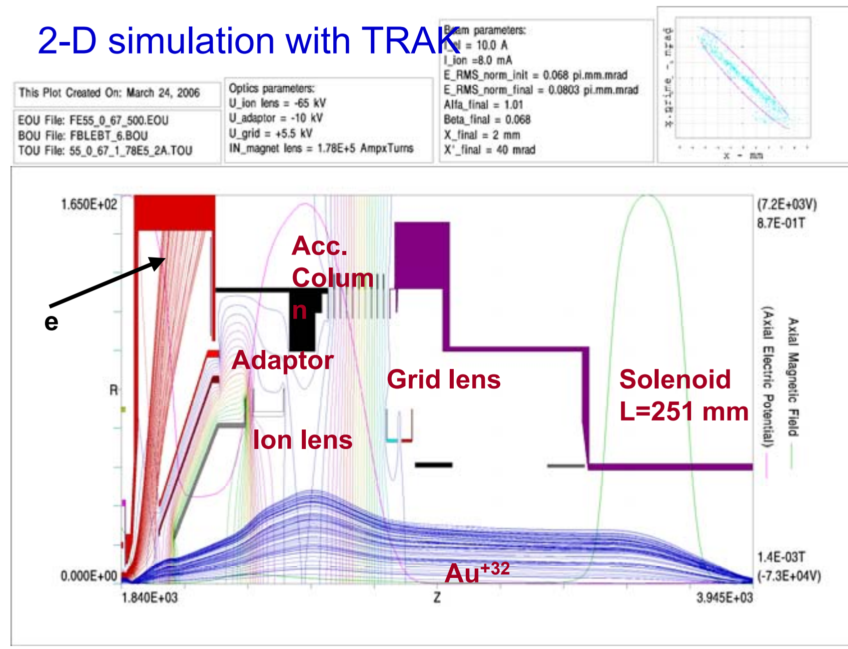


RFQ

LEBT Optics, Au^{+32}

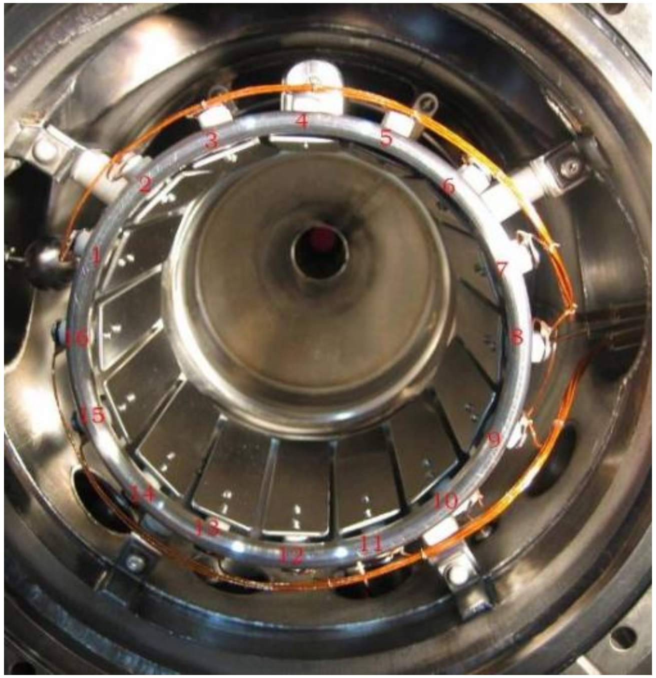
100 kV insulator

2-D simulation with TRAK

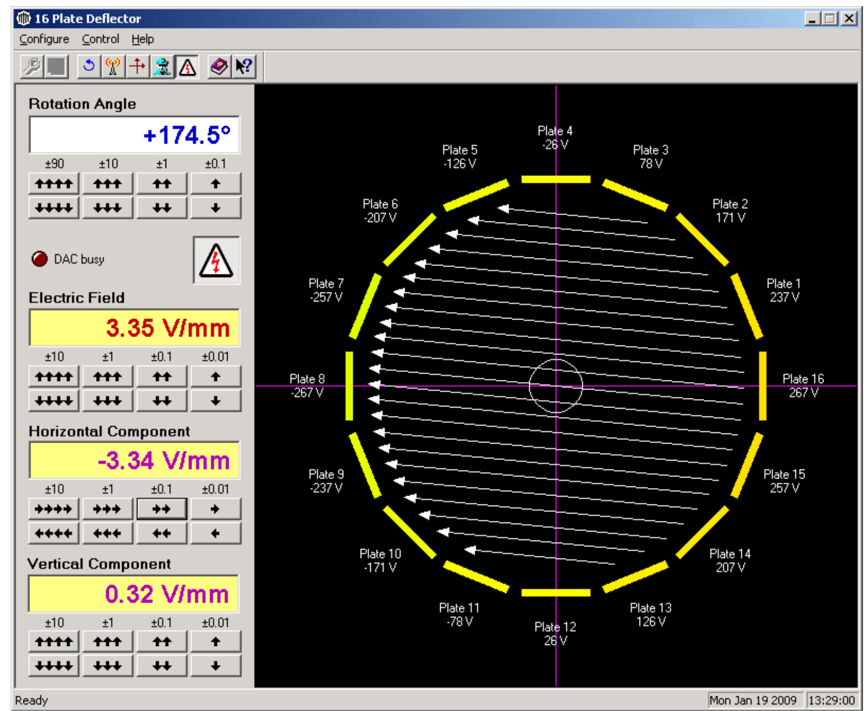


16 Pole Deflector / Adapter Lens

ELECTRON BEAM ION SOURCE

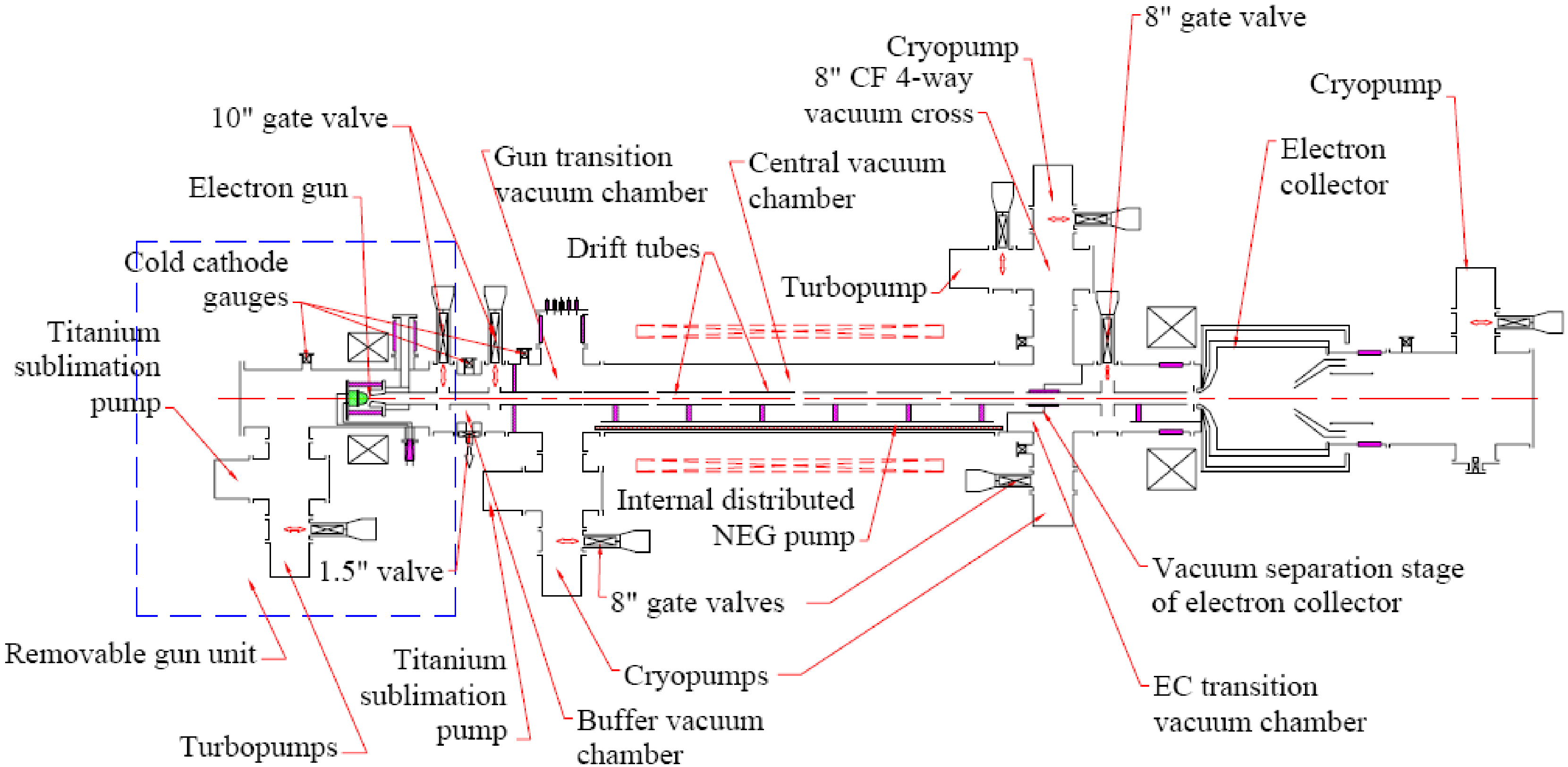


16 Pole Wide Aperture Deflector/Lens (left):
+/- 2kV fast deflector supplies are biased by a +/- 10kV power supply to provide both deflection and lens capabilities for ion injection and extraction.



Control Screen for 16 pole Deflector showing applied electric field (right):

Vacuum System



Want P(trap) ~ 1e-10 to minimize contaminant ions
On Test EBIS, P(trap) = 4e-11 when off
P(gun) – 3e-9 when running; P(collector)~1e-9

Vacuum system features

- UHV technology including preliminary vacuum firing at 900 C.
- Differential pumping between central chamber and electron gun and collector chambers.
- Increase ID of the central chamber from 4” to 6” for better pumping on sides and allow for placing strips with NEG (Non-Evaporable Getters) materials inside the central chamber.
- Additional differential pumping stage between EC and ionization region.
- Electron gun exchange without breaking vacuum

James Alessi
HIAT 2009
June 8-12, 2009

SUMMARY OF EXPERIMENTAL RESULTS

ELECTRON BEAM ION SOURCE

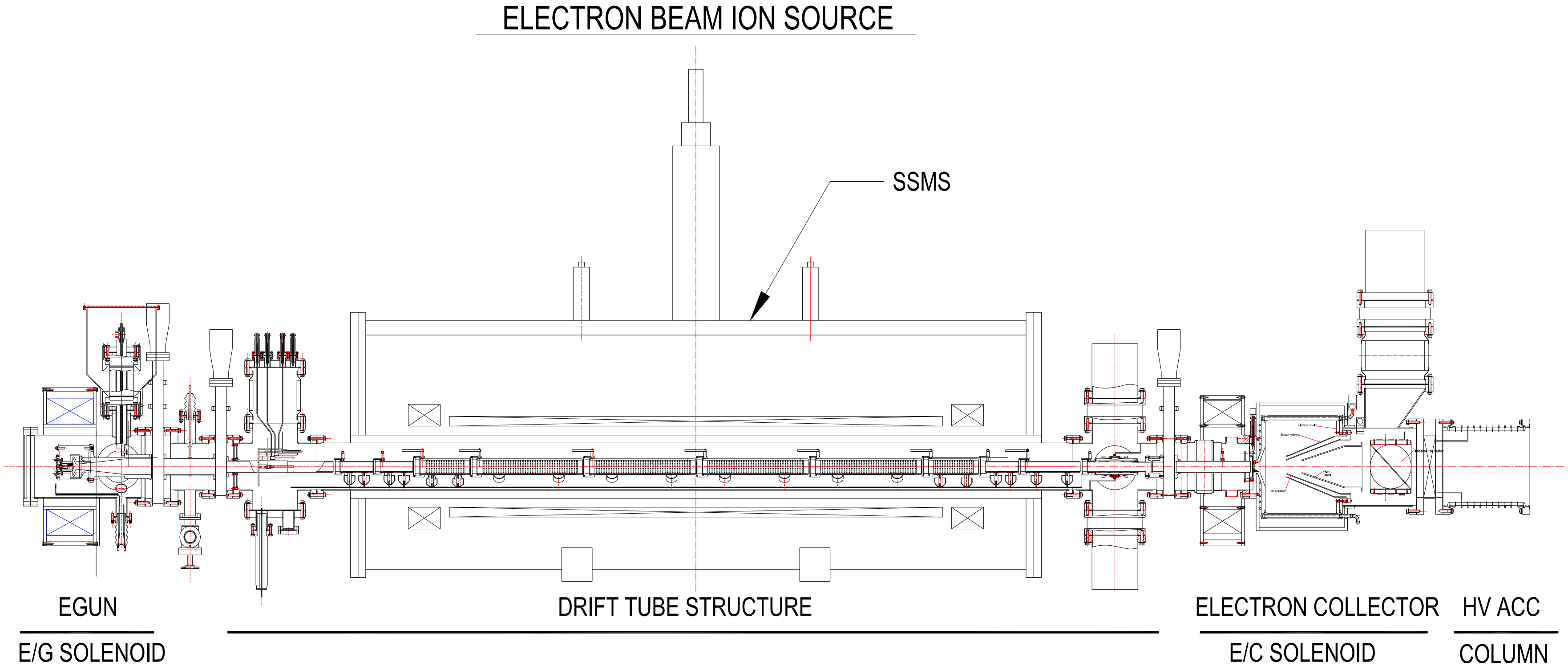
- Electron beam currents greater than 10A have been propagated through the Test EBIS with losses less than 1mA.
- Au^{32+} has been produced in less than 35ms, Ne^{8+} in 18ms, N^{5+} in 4ms, and Cu^{14+} in 15ms. Charge state vs. confinement time agrees with calculations.
- With external ion injection, 3.5×10^{11} charges/pulse of Au ions, and $\geq 2\times10^{11}$ charges/pulse of Ne, N, and Cu have been achieved. In all cases our goal of extracting charge of 50% of the trap capacity has been exceeded.
- The above yields can be extracted in pulses of 10-20μs FWHM, resulting in extracted currents for these ions of several mA's.
- Emittance = 0.1 π mm mrad (rms normalized) has been obtained for a 1.7 mA beam extracted from the EBIS after Au injection from the LEVA source.
- Beams have been accelerated off the EBIS platform to 17 keV/u, matched into the RFQ, and accelerated through the RFQ to 300 keV/u (early tests).

EBIS Results and RHIC Design Parameters

	Achieved	RHIC
Ion	Au^{32+}	Au^{32+}
I_e	**10 A**	10 A
J_e	575 A/cm^2	575 A/cm^2
$t_{confinement}$	35 ms	35 ms
L_{trap}	0.7 m	1.5 m
Capacity	5.1×10^{11}	11×10^{11}
% extracted ions	> 75%	50%
% in desired Q	20%	20%
Extracted charge	> 3.4×10^{11}	5.5×10^{11}
Ions/pulse	**> $1.5\ 10^9$ (Au^{32+})**	3.3×10^9 (Au^{32+})
Pulse width	10-20 μs	10-40 μs
Rep. Rate	**0.5-2 Hz**	5 Hz

RHIC EBIS – Cross Section

ELECTRON BEAM ION SOURCE



Summary of the advantages of an EBIS for the BNL Application

ELECTRON BEAM ION SOURCE

- **An EBIS can produce <u>any</u> type ions – from gas, metals, etc., and is easy to switch species (pulse-to-pulse!)**
- **One has control over the charge state produced (easy to get intermediate charge states, such as Au^{32+} or U^{45+})**
- **One has control over pulse width, extracting a fixed charge – can better match to synchrotron requirements**
- **EBIS produces a narrow charge state distribution (≥ 20% in the desired charge state), so there is less of a space charge problem in the extraction and transport of the total current**
- **The scaling laws are understood**
- **The source is reliable, and has excellent pulse-to-pulse stability, long life**

Status

- The Test EBIS performance has demonstrated all requirements, and is now being used for RHIC EBIS component testing, and RFQ beam tests.

- Commissioning of the RHIC EBIS will start this summer (but the final electron gun, collector, and full transport from collector to RFQ have already been tested).

- The RFQ and Linac are scheduled to be in place by December of 2009.

- CD-4 date for the project is September, 2010.