HIGH PERFORMANCE EBIS FOR RHIC

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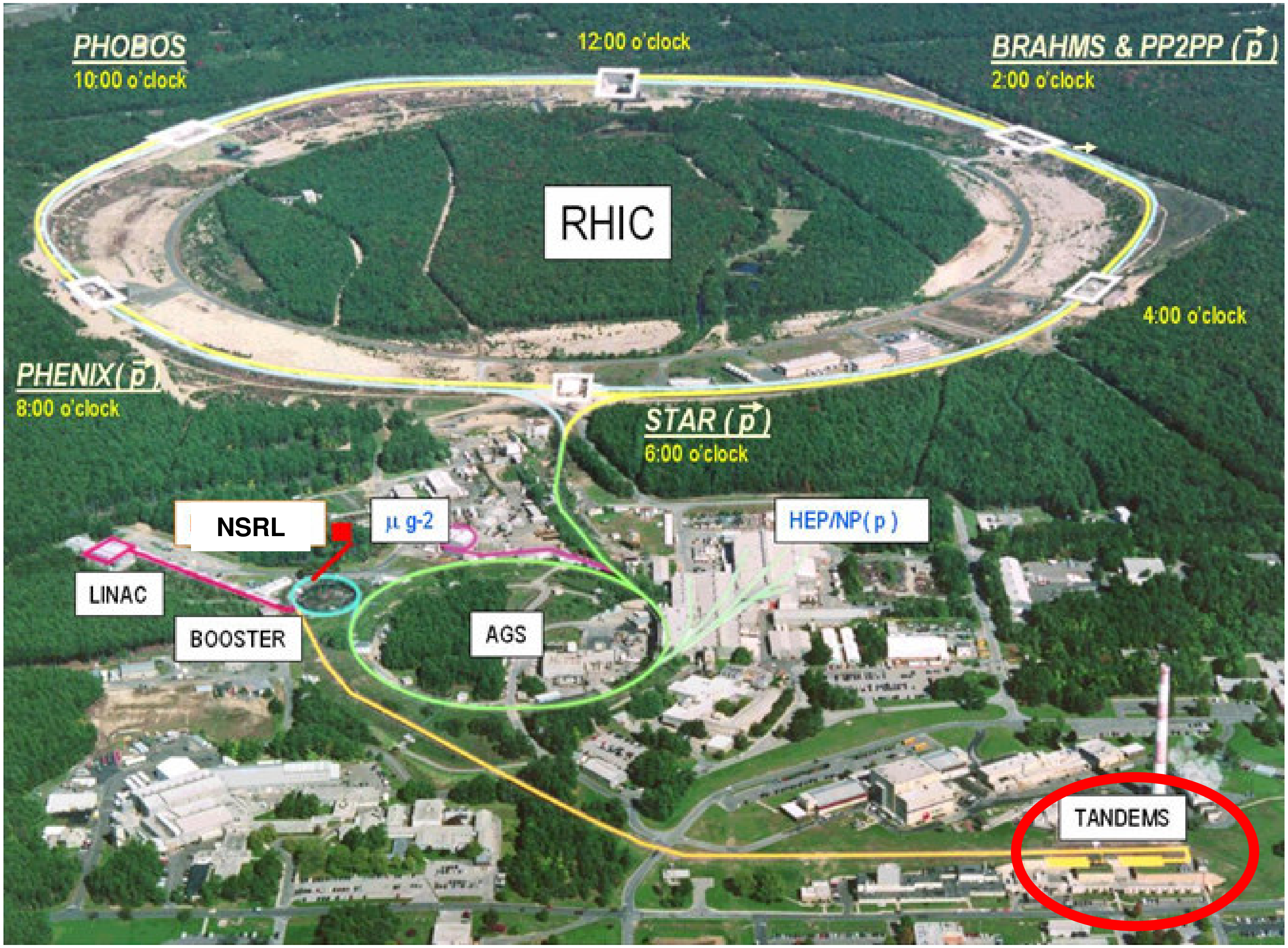
Overview

Presently, one or two ~35-year old Tandem Van de Graaff accelerators are used for RHIC pre-injection, but recent advances in the state of the art in EBIS performance by more than an order of magnitude now make it possible to meet RHIC requirements with a modern linac-based preinjector.

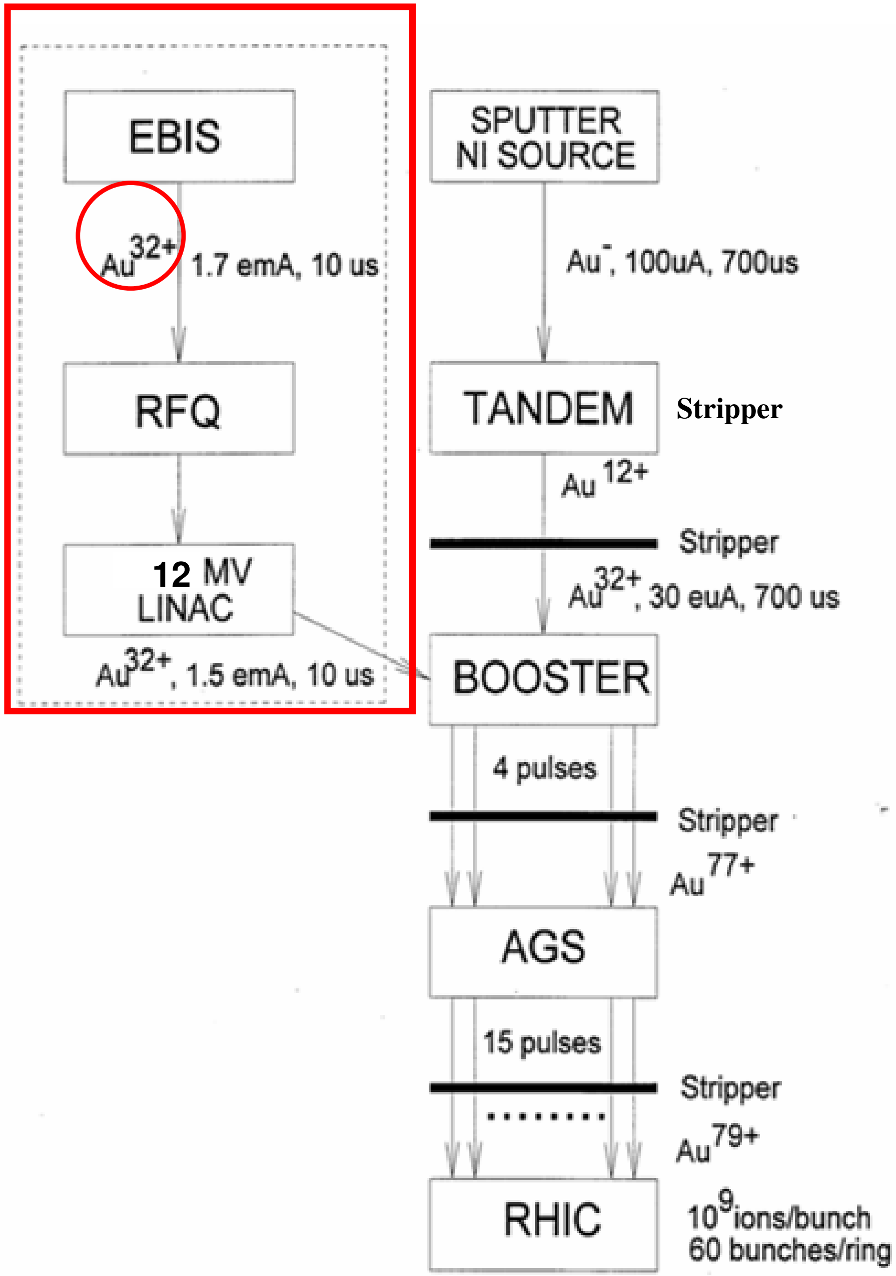
BNL now has DOE CD3 approval for new pre-injector for RHIC based on the Laboratory's development of an advanced Electron Beam Ion Source (EBIS).

The new preinjector would consist of an EBIS high charge state ion source, a Radio Frequency Quadrupole (RFQ) accelerator, and a short linac, to produce beams at 2 MeV/u.

Tandems are the present heavy ion preinjectors for RHIC



860 m long transport line from the Tandems to the Booster



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

REQUIREMENTS

It is desirable for the preinjector to 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

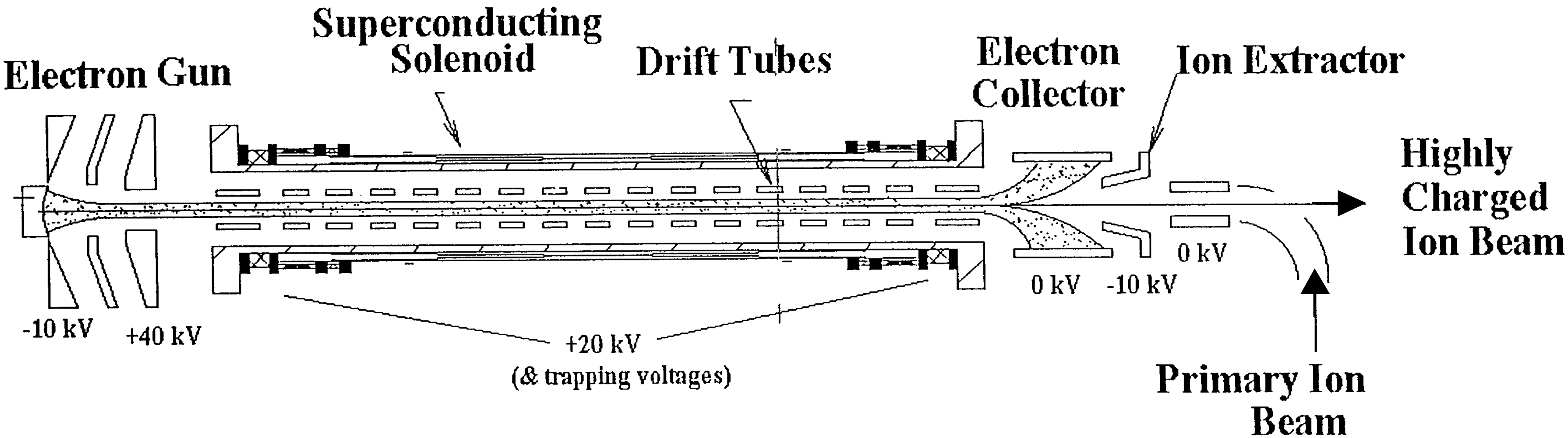
Performance Requirements of the Ion Source

Species	He to U
Output (single charge state)	≥1.1 x 10^{11} charges / pulse
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

- 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

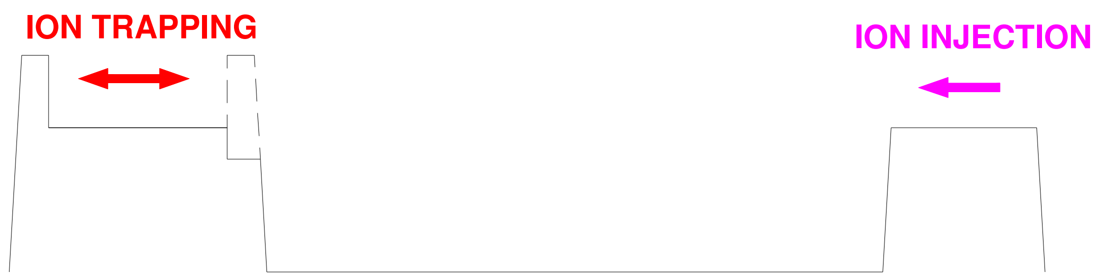
Principle of EBIS Operation



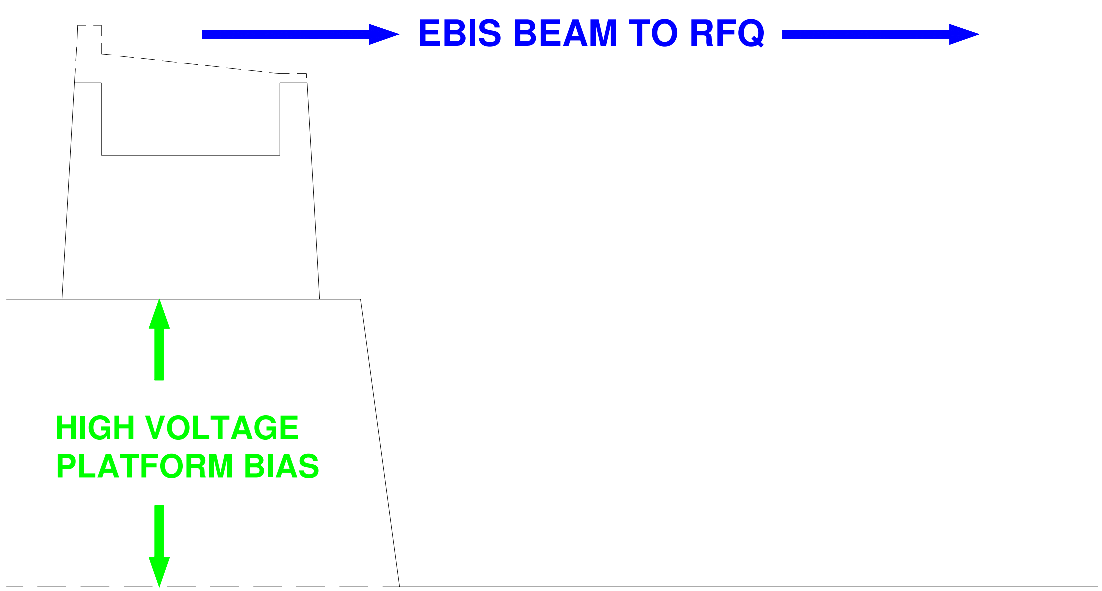
Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials on electrode at ends of trap.

- 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!

EBIS operation with Pulsed High Voltage Platform

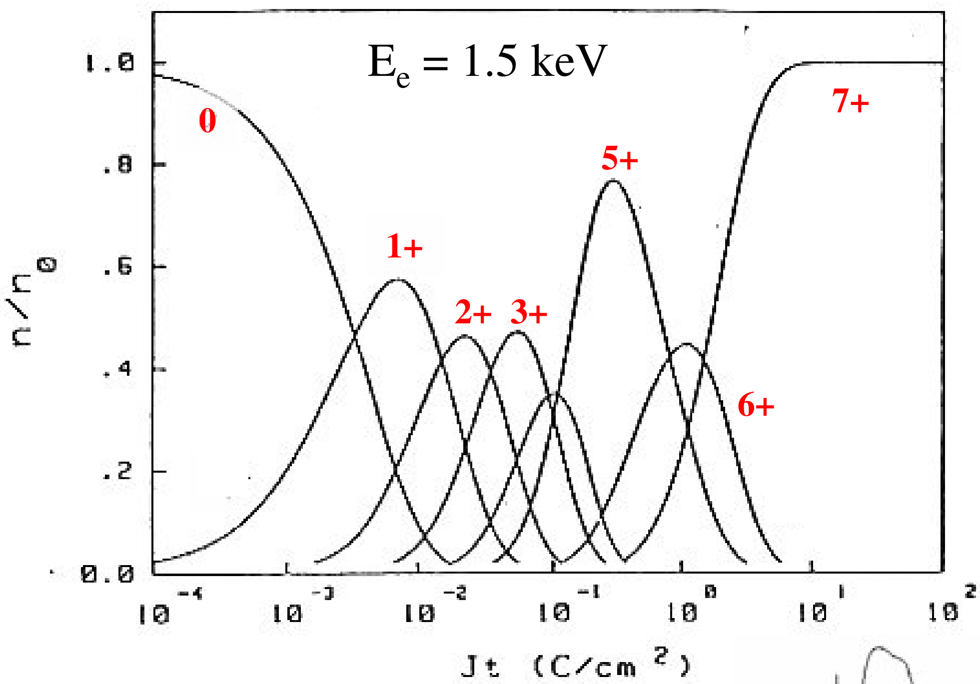


During injection and confinement the RHIC EBIS will operate at ground potential.



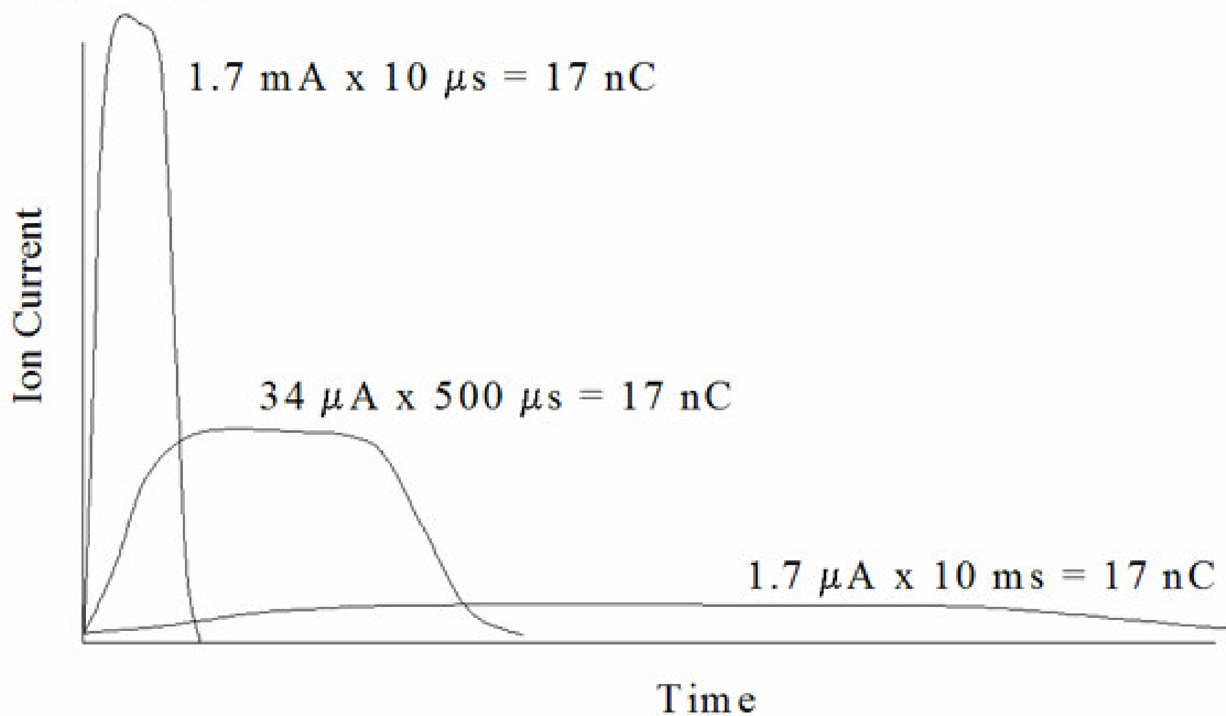
Just before ion extraction the EBIS Platform Voltage will be applied such that the ions are extracted through 100kV (nominal) to attain the ~17keV/amu needed for acceleration by the RFQ

Nitrogen Charge State Evolution

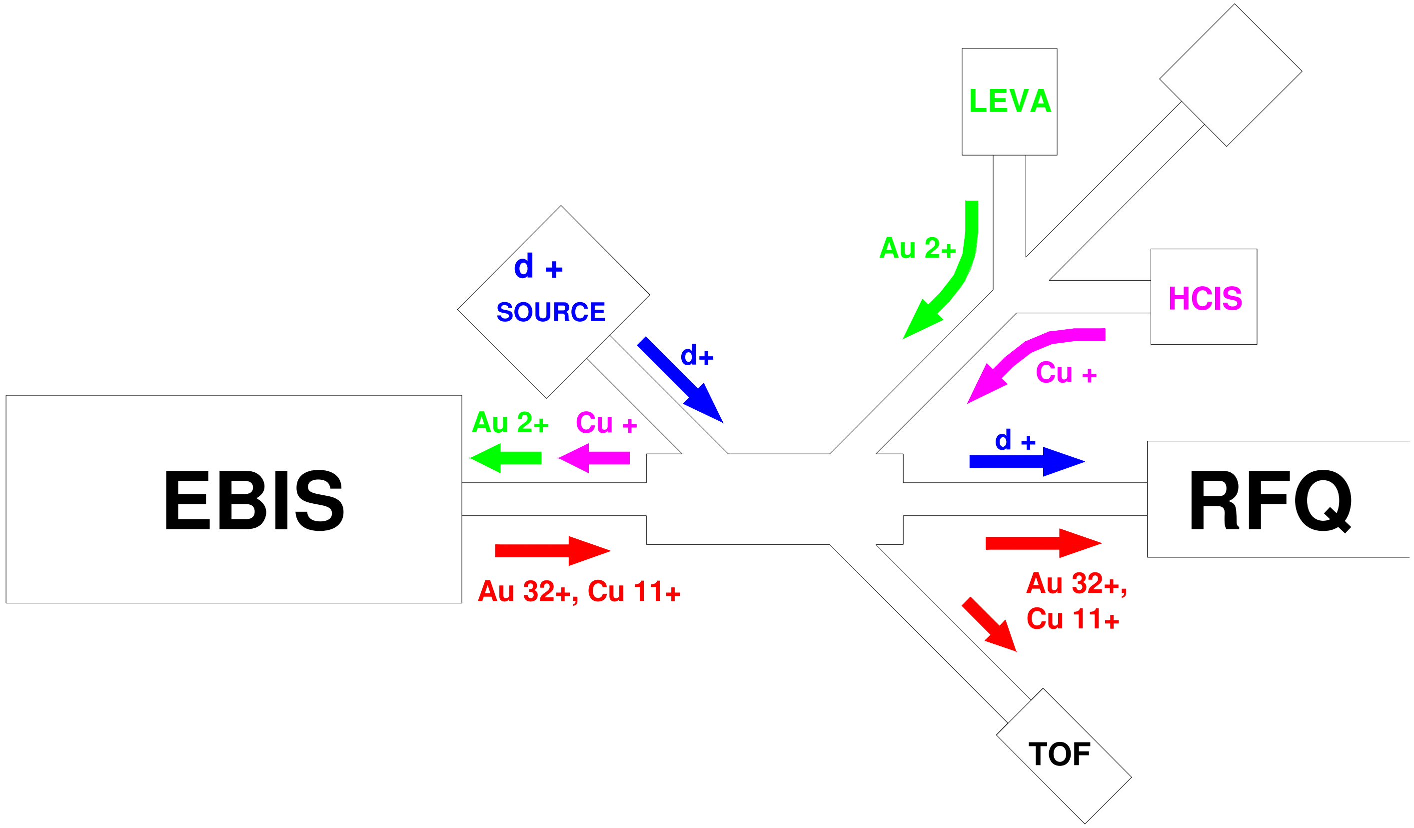


Charge state is selected by choosing the confinement time of ions in the trap

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



Ion Injection and Extraction from the RHIC EBIS



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

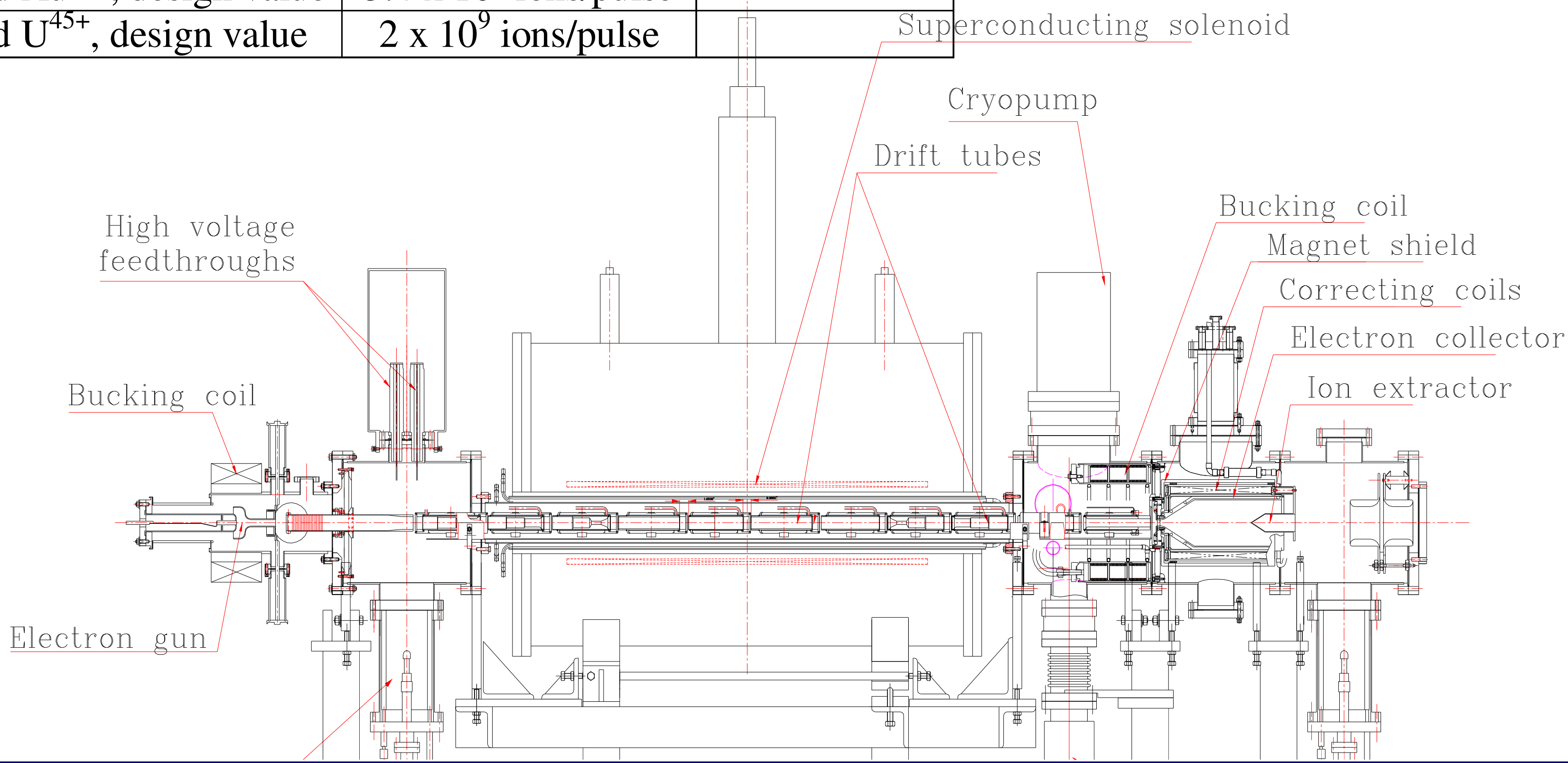
Advantages:

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.

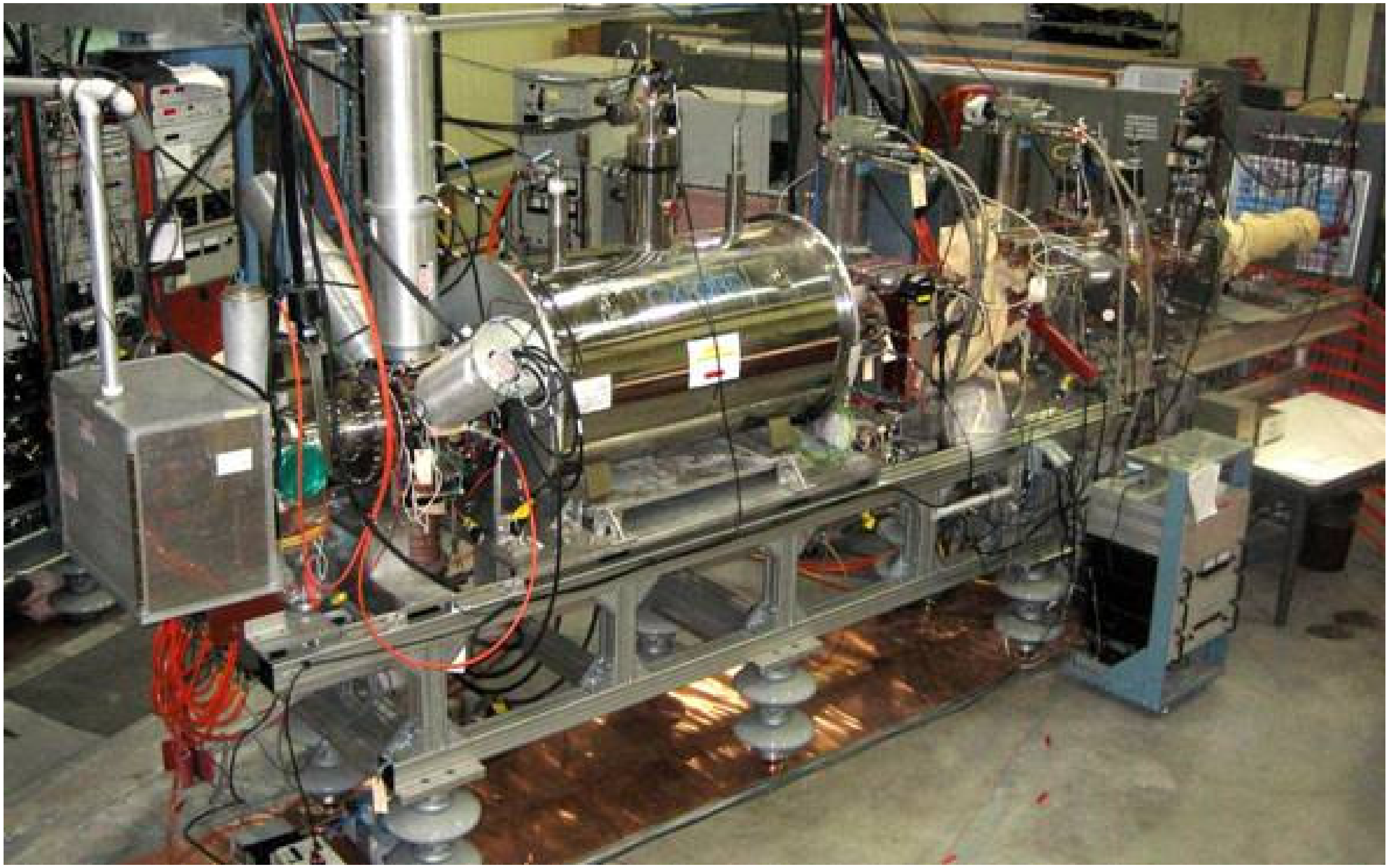
Test EBIS

Parameter	RHIC EBIS	Test EBIS
e-beam current	10 A	10 A
e-beam energy	20 keV	20 keV
e-beam density	~575 A/cm^2	~575 A/cm^2
Ion trap length	1.5 m	0.7 m
Trap capacity (charges)	1.1 x 10^{12}	5.1 x 10^{11}
Yield positive charges	5.5 x 10^{11}	2.6 x 10^{11}
Yield Au^{32+}, design value	3.4 x 10^9 ions/pulse	
Yield U^{45+}, design value	2 x 10^9 ions/pulse	

~1/2 length prototype, but with the full power electron beam



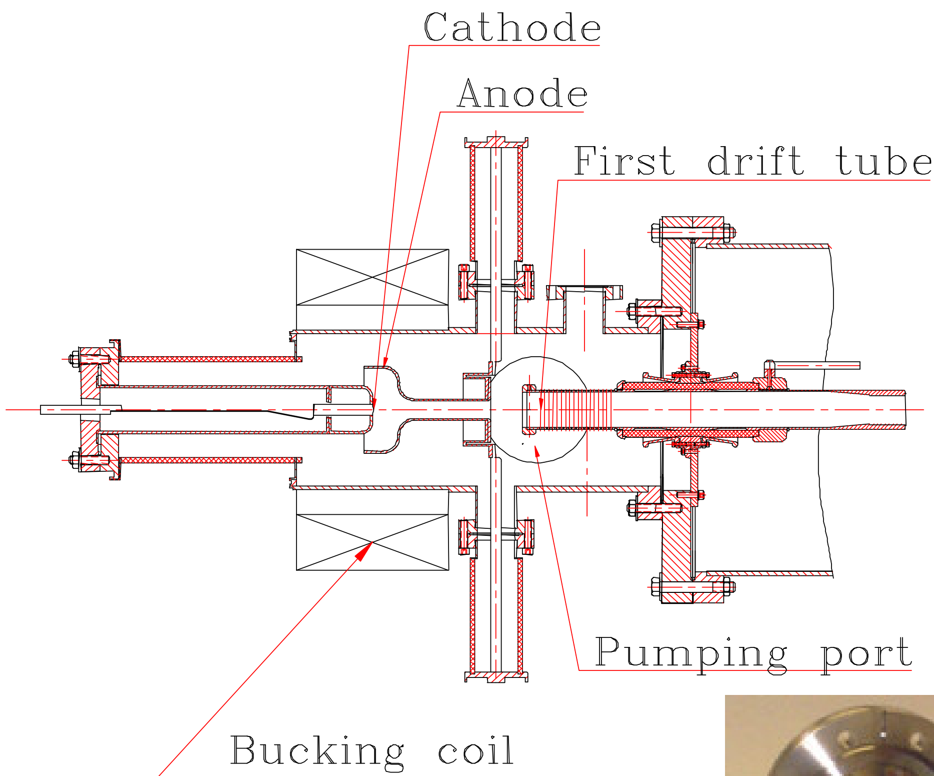
Test EBIS on stand with high voltage isolation



Operation of the Test EBIS at 80 kV extraction has been trouble-free.

No change in performance when platforms are pulsing.

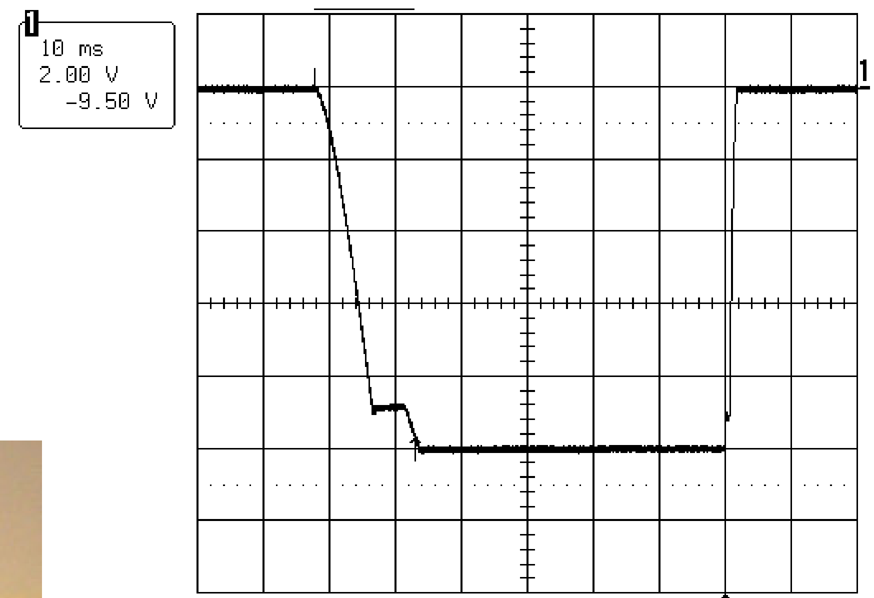
Operation of the Electron Beam



Perveance ~ 1.3 μP

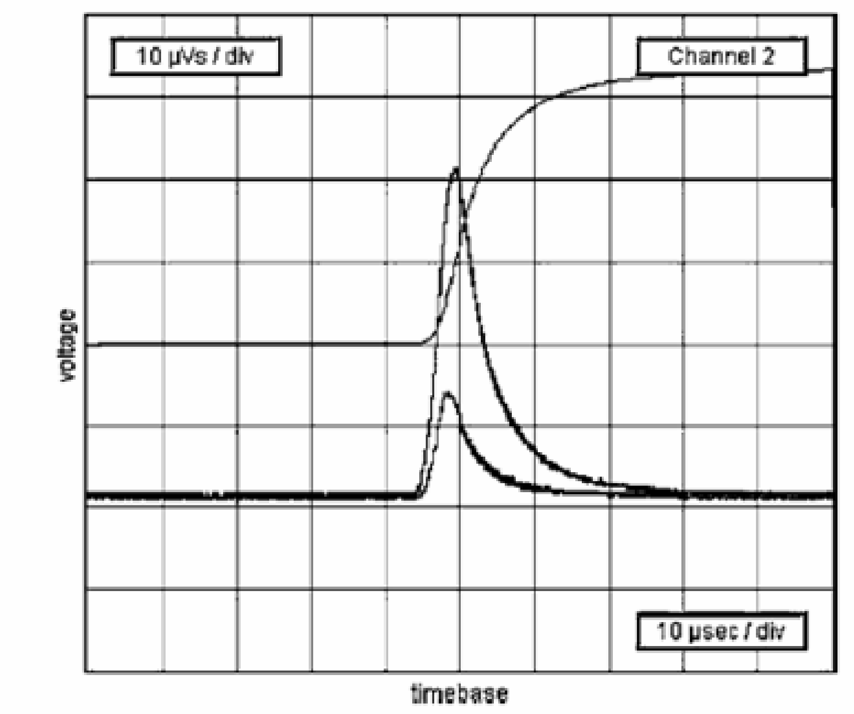
LaB_6 and IrCe cathodes

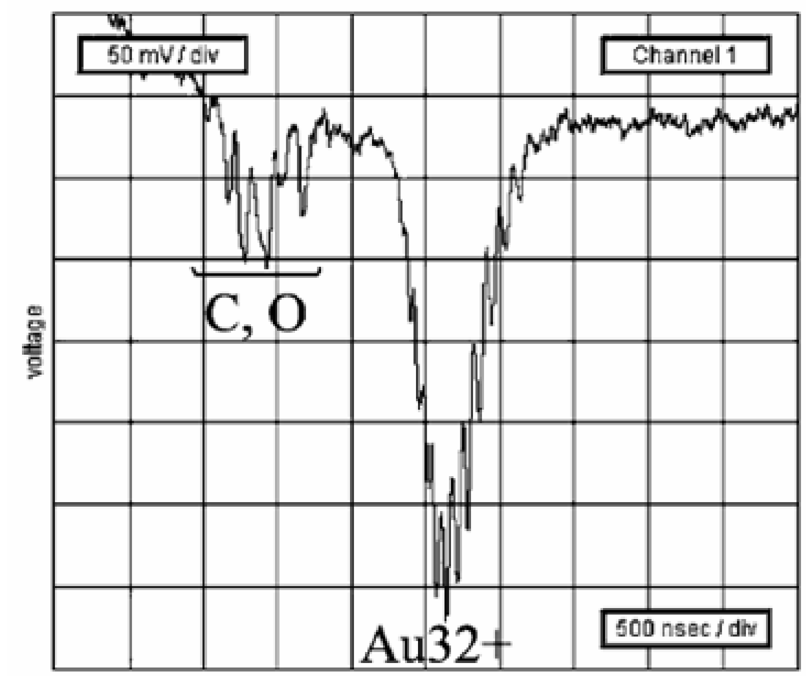
Propagation of a 10 A electron Beam through the EBIS trap



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

Highly charged Au extraction from Test EBIS after injection from the LMIS





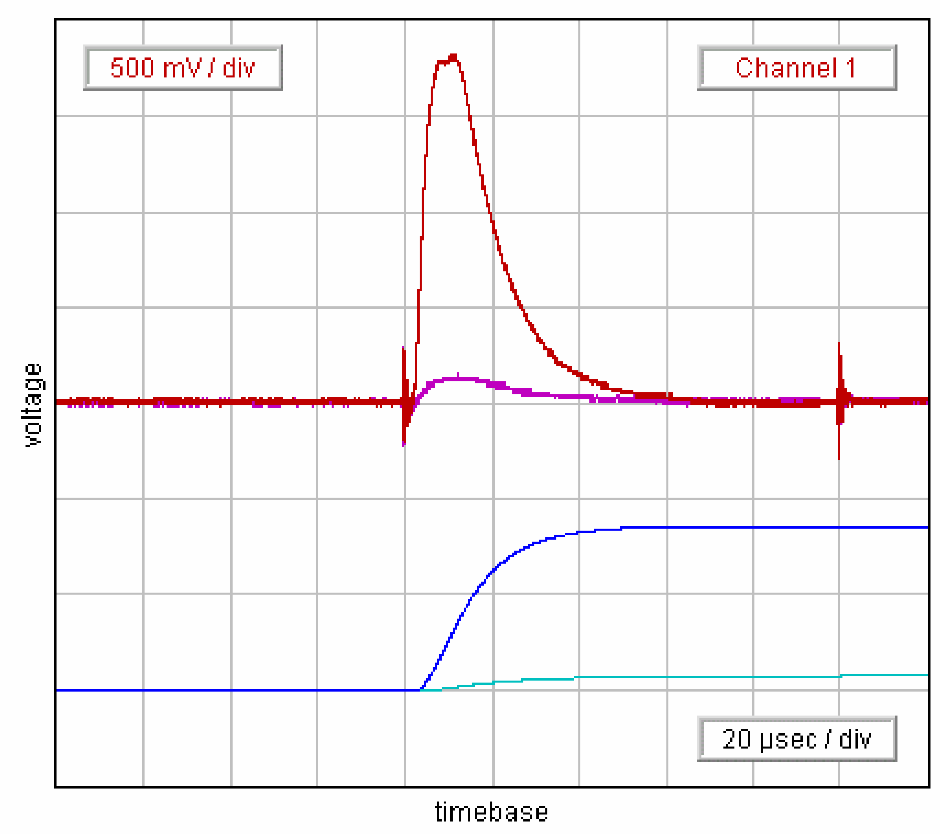
4.0mA, 8us FWHM, 32nC (2.0 x 10^{11} charges/pulse)

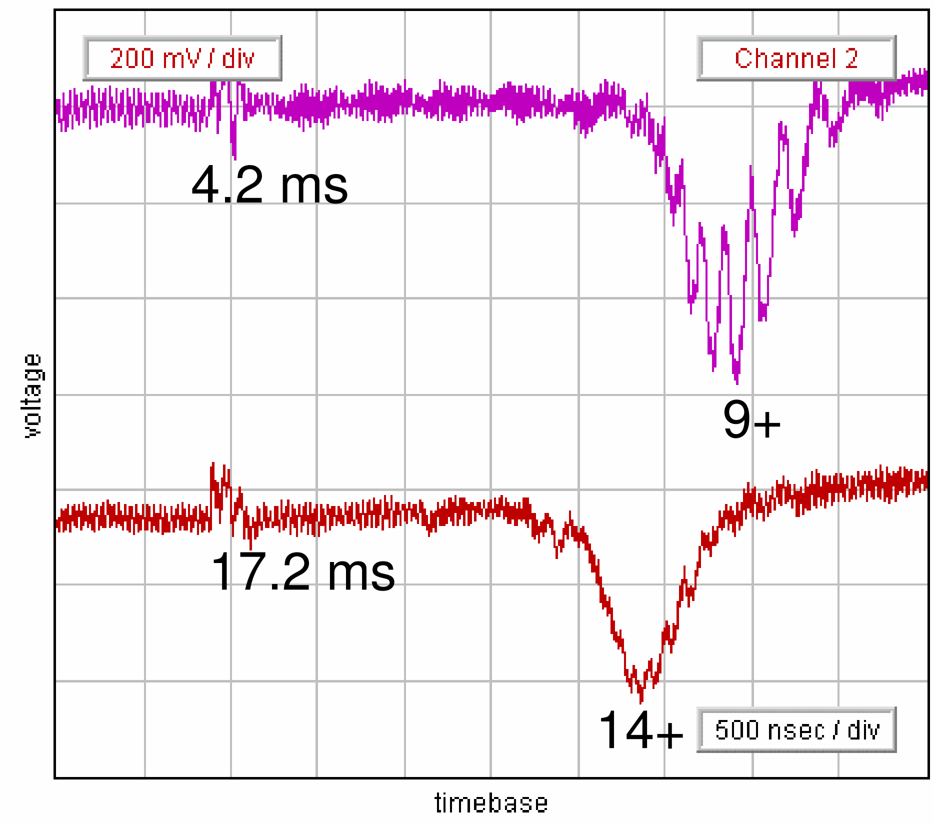
6.8A e-beam
36ms confinement

TOF charge state spectrum peaked around Au^{32+}

6.8A e-beam
36ms confinement

COPPER

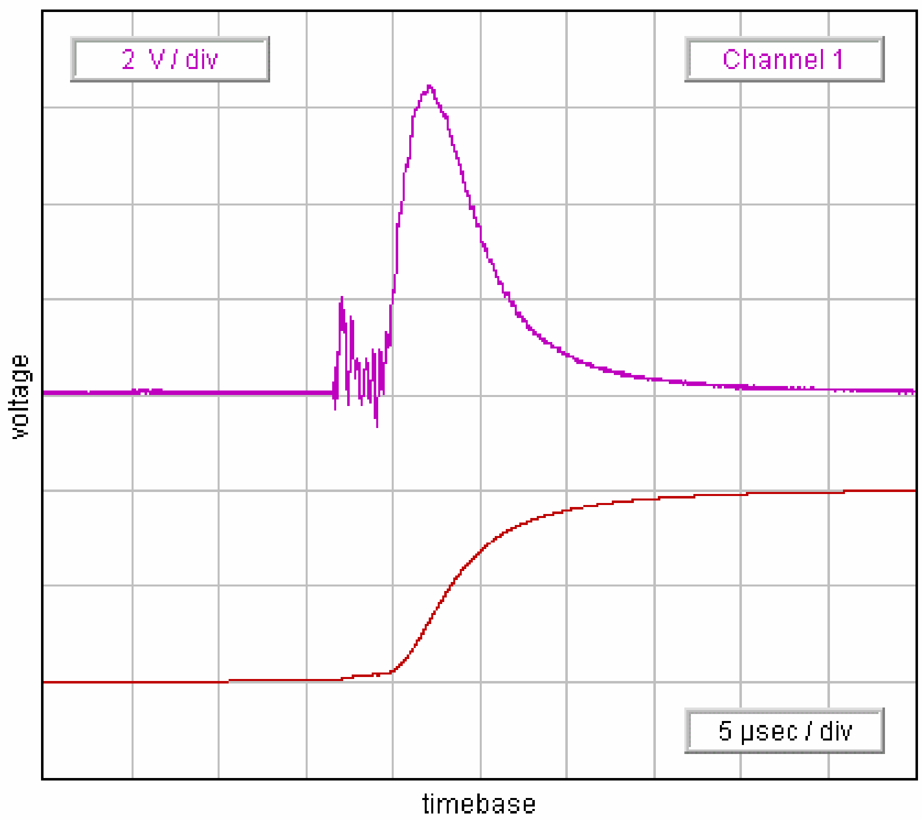




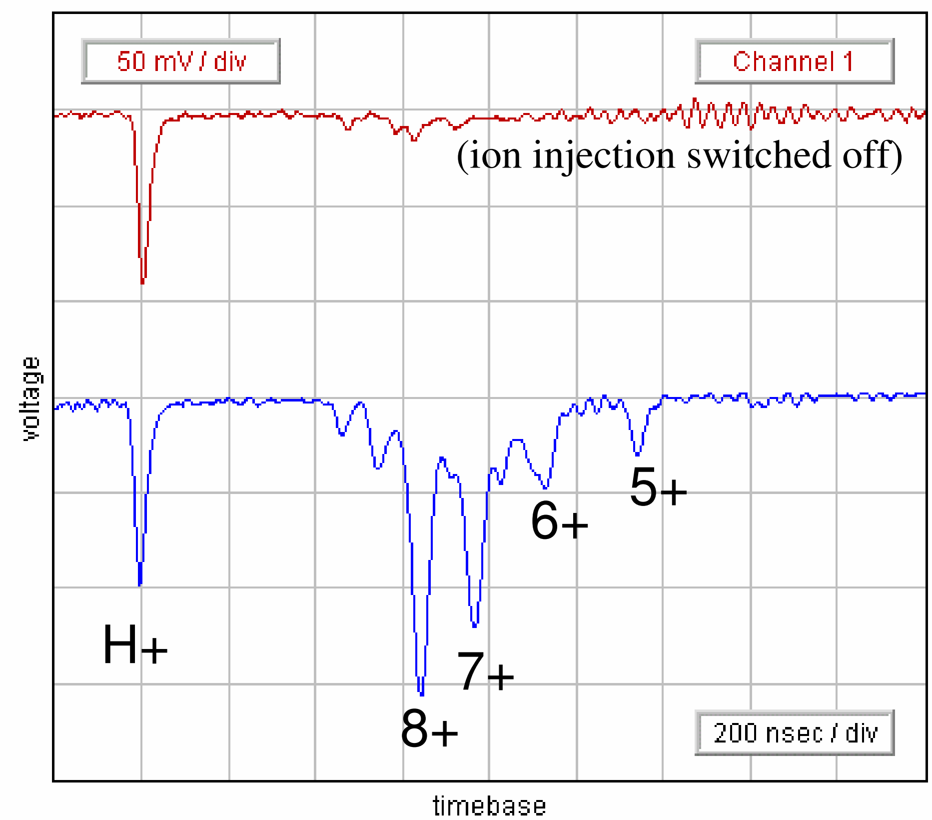
1.8 mA; 2.2x10^{11} charges/pulse,

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

NEON



I(e) ~ 6.8 A



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

14 ms confinement

NITROGEN

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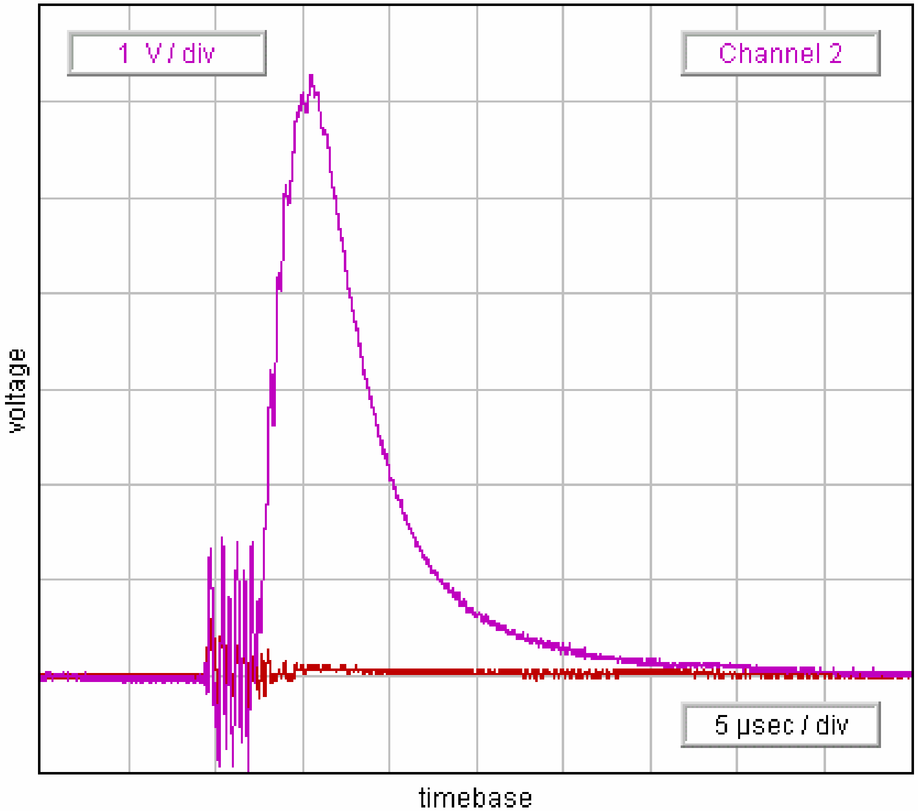
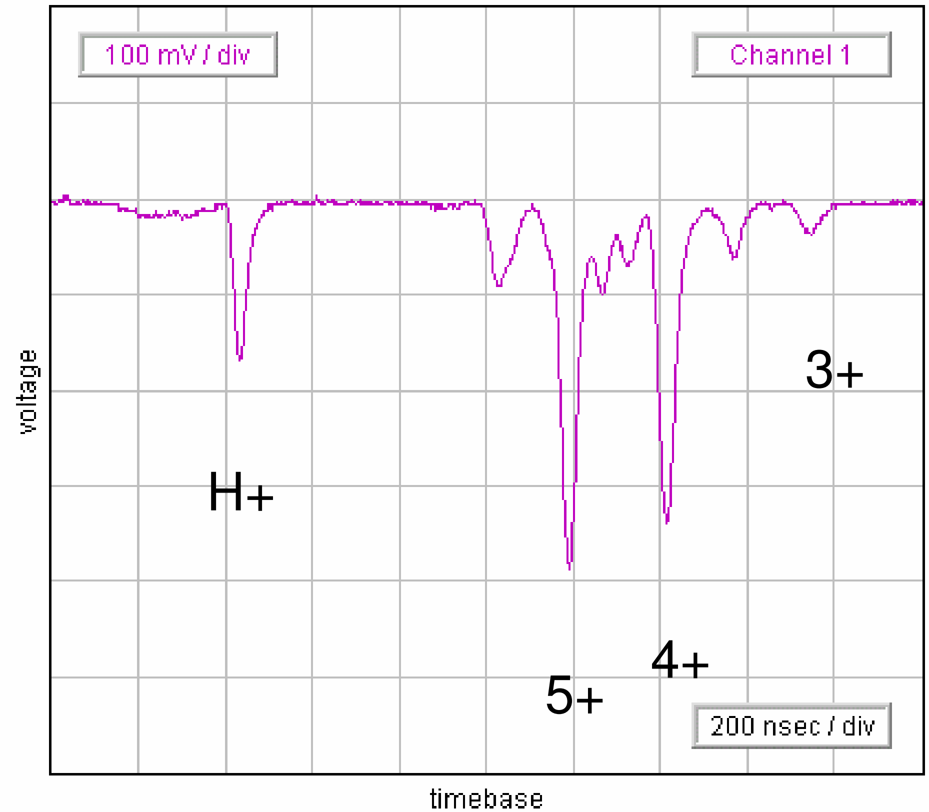


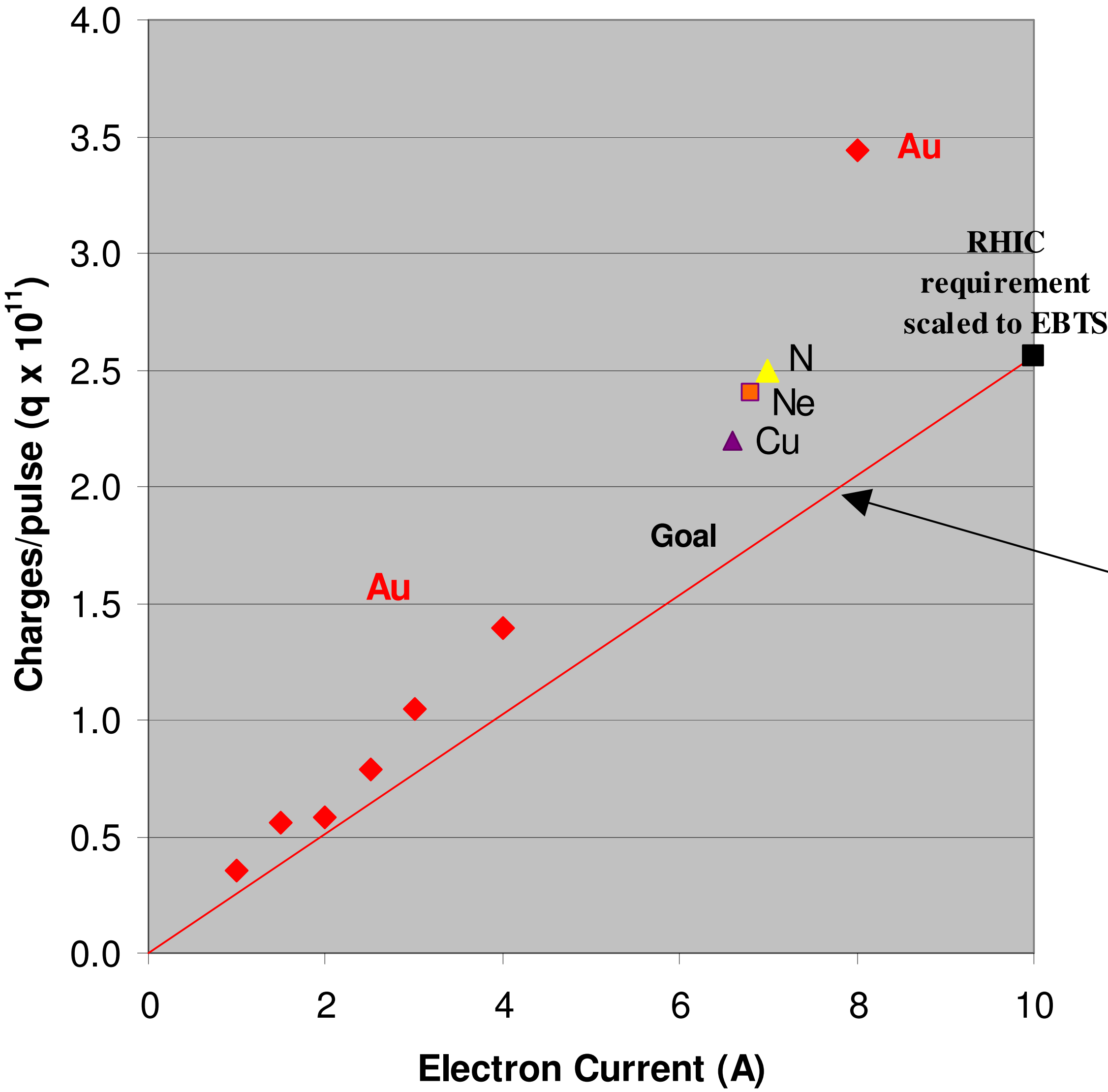
N_2^+ injected from HCIS
3 ms injection, 4 ms confinement
I(e) ~ 7A



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

In the RHIC EBIS, the pulse shape will be tailored by applying an appropriate voltage pulse to the well.

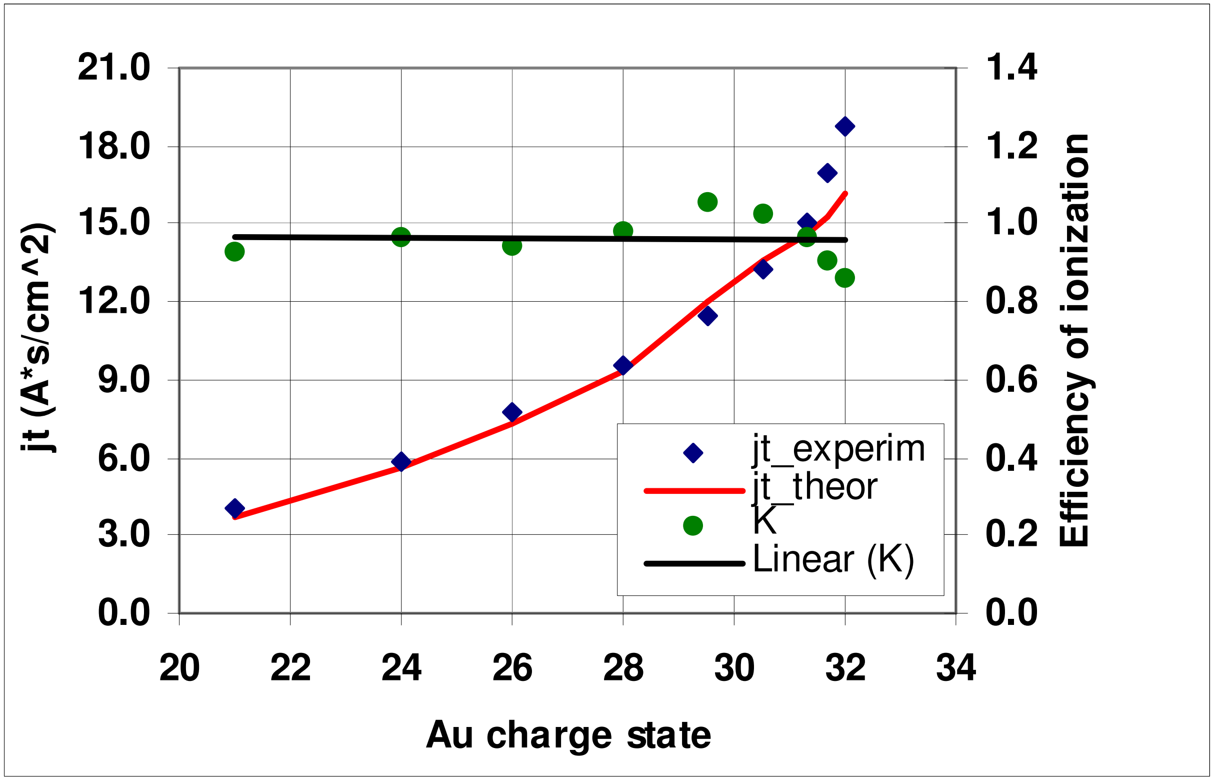
Charge extracted from Test EBIS



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

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

Ionization Efficiency



I_{el} = 6.8A

E_{el} = 20kV

J_e = 360 A/cm^2

Dependence of the most populated Au charge state in experimentally measured and calculated spectra on the ionization factor jτ and the ionization efficiency K

Electron Beam Perveance

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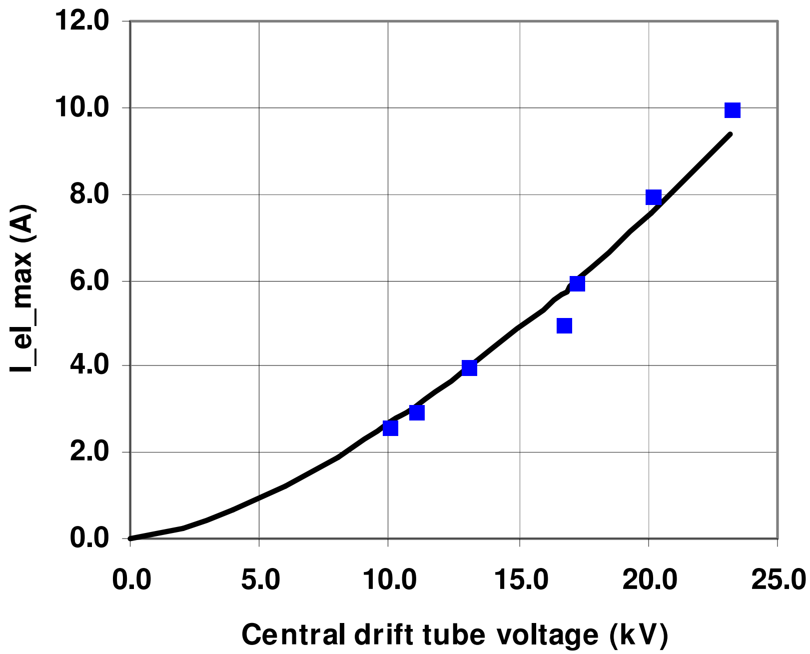
Drift Tube Region



Maximum perveance of the electron beam in the ion trap region of BNL EBIS. Solid line is a best fit of experimental data with perveance of 2.65×10^{-6} A/V$^{1.5}$

Collector Region

Test EBIS electron collector measured perveance:

$P_{col} = 18 \cdot 10^{-6}$ A/V$^{1.5}$

(For electron current I_{el} = 6.0 A the minimum collector voltage was 4.8 kV)

The RHIC EBIS design is more conservative:

$P_{col} = 11 \cdot 10^{-6}$ A/V$^{1.5}$

Emittances

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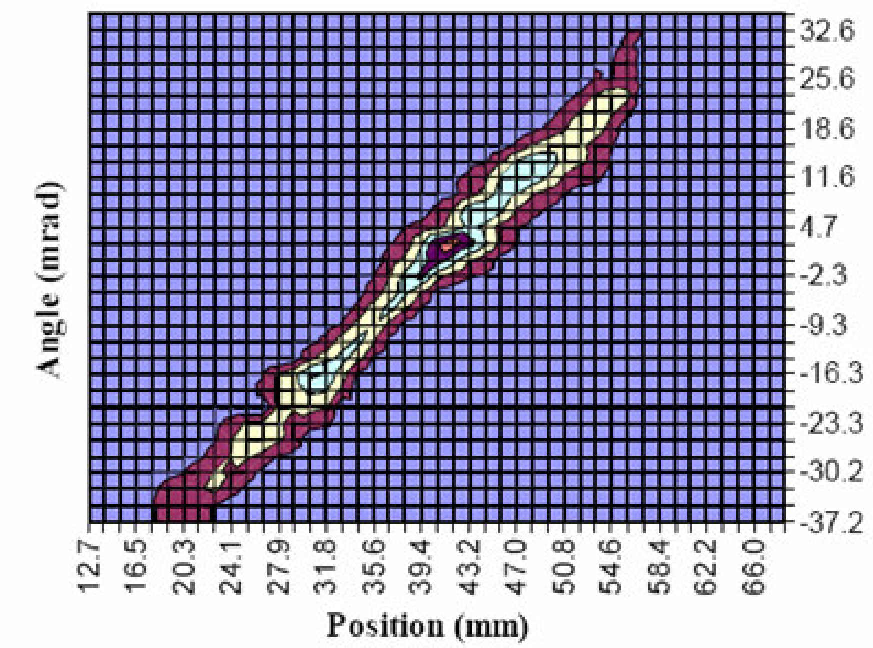
Measured emittance of a 1.7 mA Au beam



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 pi mm mrad, (n, rms)
- Lighter beams have emittances of ~ 0.3 pi mm mrad

Some key features responsible for the state-of-the-art performance of the Test EBIS

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•A novel electron gun 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

•Careful 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

•Very versatile controls allow one to easily apply a time dependent potential distribution to the ion trap

SUMMARY OF TEST EBIS PERFORMANCE

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- Electron beam currents greater than 10 A have been propagated through the Test EBIS with losses less than 1 mA.
- Au^{32+} has been produced in less than 35 ms, Ne^{8+} in 18 ms, N^{5+} in 4 ms, and Cu^{14+} in 15 ms. 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 10-20 µs 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.
- Operation of the EBIS is very stable, and very reproducible.

EBIS Results and RHIC Design Parameters

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	Achieved	RHIC
Ion	Au^{32+}	Au^{32+}
I_e	**10 A**	10 A
J_e	500 A/cm^2	500 A/cm^2
$t_{confinement}$	35 ms	35 ms
L_{trap}	0.7 m ↔	1.5 m
Capacity	5.1 x 10^{11}	11 x 10^{11}
% extracted ions	> 75%	50%
% in desired Q	20%	20%
Extracted charge	> 3.4 x 10^{11}	5.5 x 10^{11}
Ions/pulse	**> 1.5 10^9 (Au^{32+})**	3.3 x 10^9 (Au^{32+})
Pulse width	10-20 µs	10-40 µs

RHIC EBIS

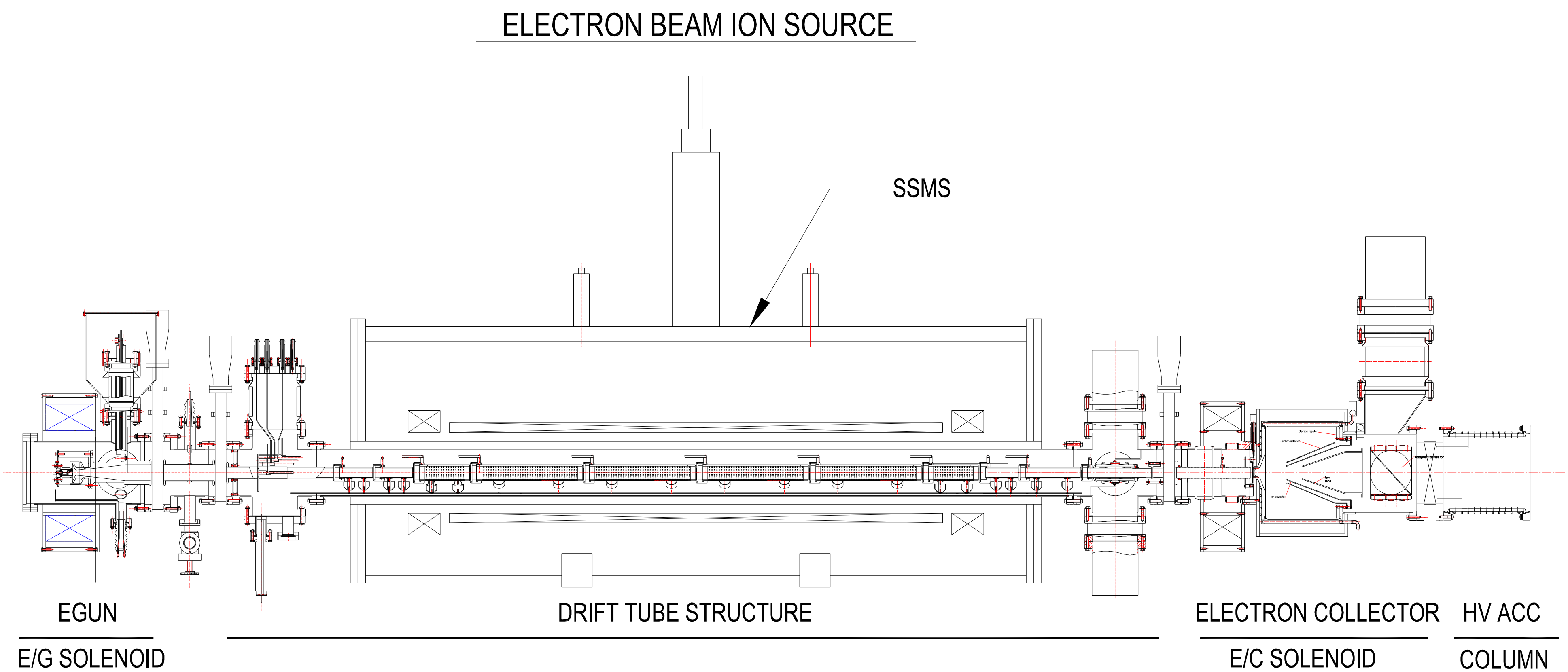
Design changes relative to the Test EBIS, needed to meet RHIC requirements:

1. Longer SC solenoid and ion trap region
2. Collector design for higher average power

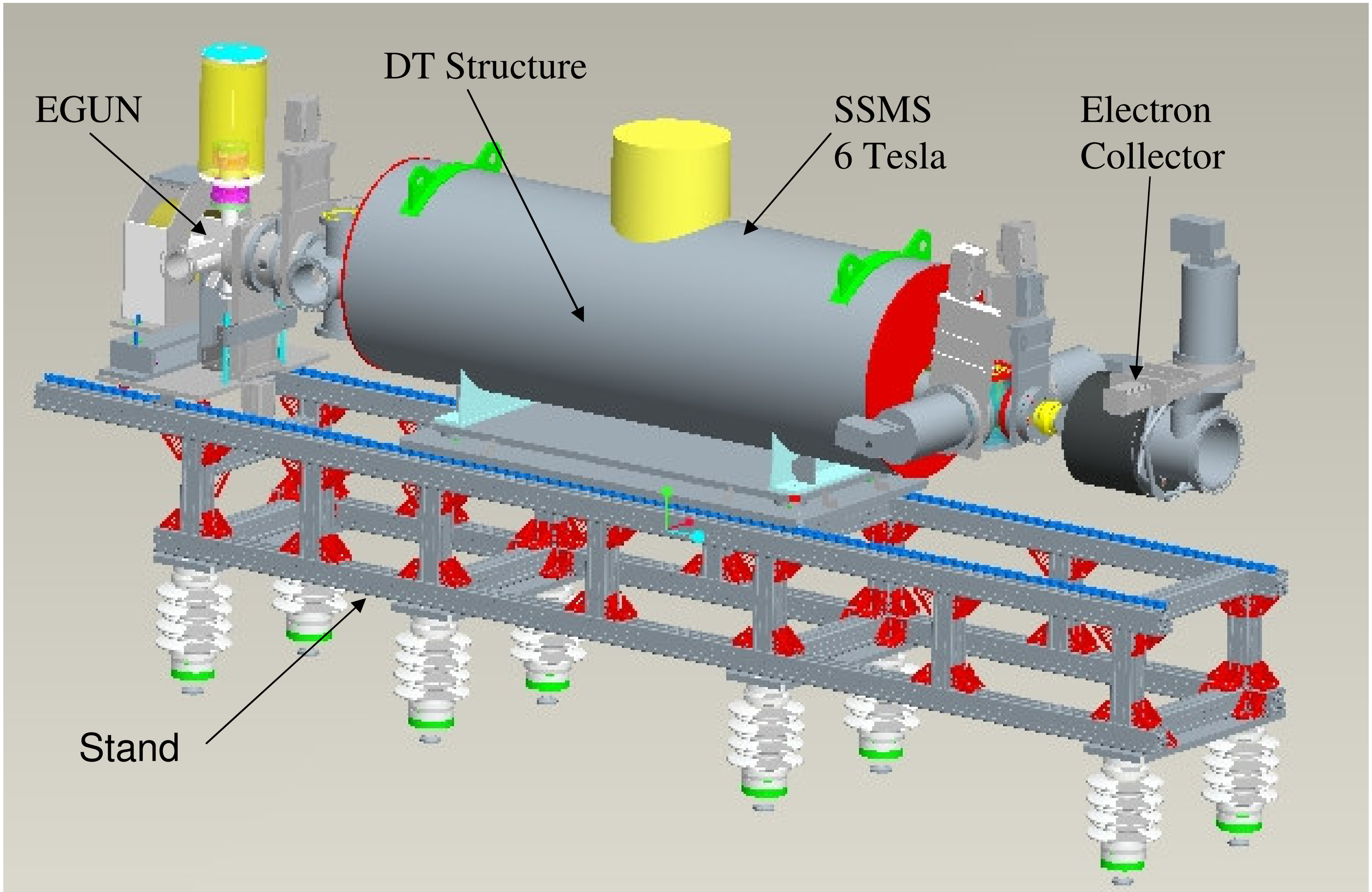
Improvements to increase operational reliability and safety margin:

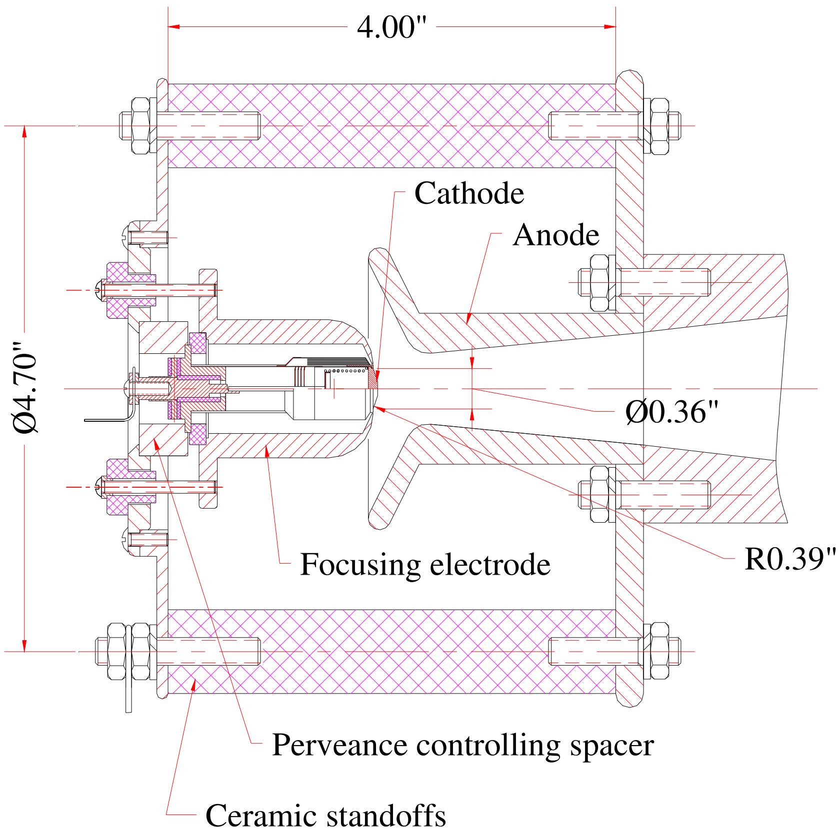
3. Collector design for higher peak power
4. Electron gun capable of 20 A operation
5. Increases to the solenoid bore and maximum field

RHIC EBIS – Cross Section



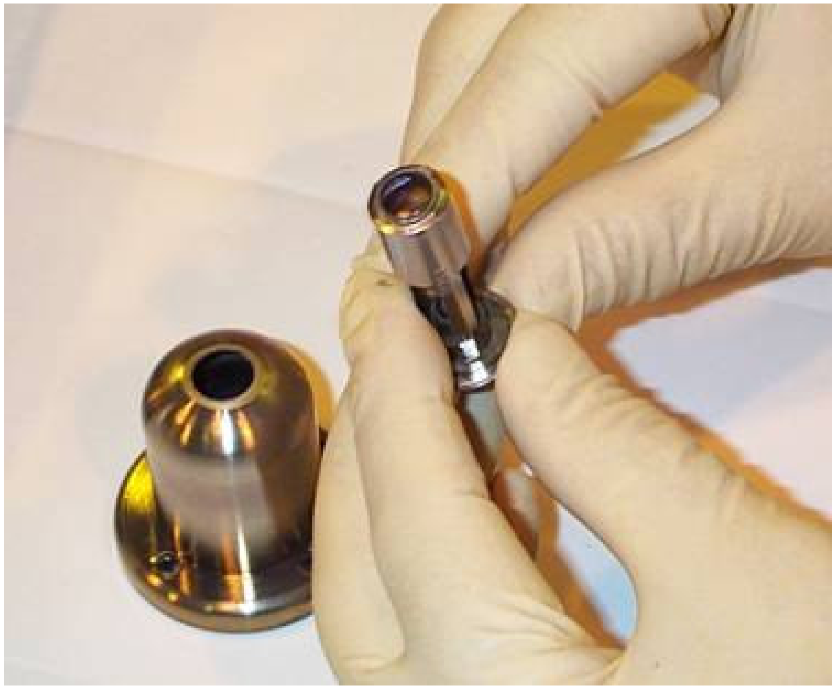
RHIC EBIS





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

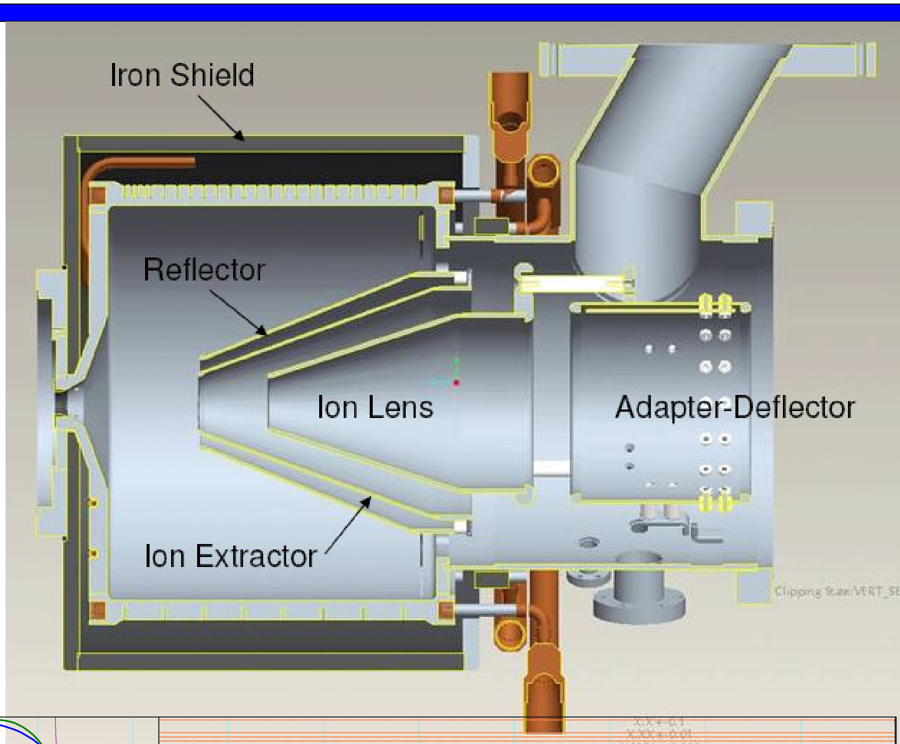


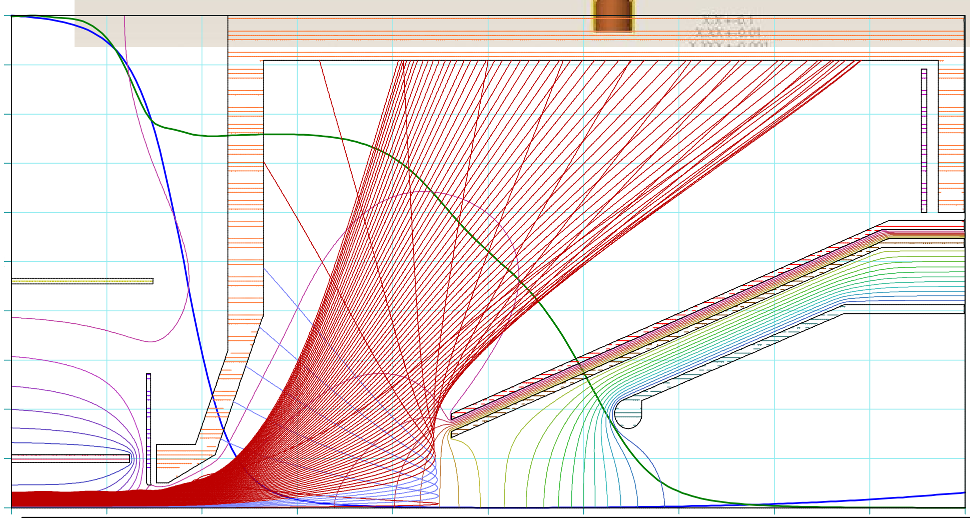
9.2 mm diameter convex cathodes (LaB_6 shown)

The present cathode is actually capable of operating at 20 A (J=30A/cm²) with lifetime of 3000-5000 hours. For possible future increase of the ion beam intensity, *we are building the electron gun electrodes and collector with the capability of operating at 20A*.

Perveance = 2.6 μP

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





- 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).
- The collector material will be 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 are also beginning the fabrication of a second collector from a Zr-Cr-Cu alloy).

RHIC EBIS Superconducting Solenoid

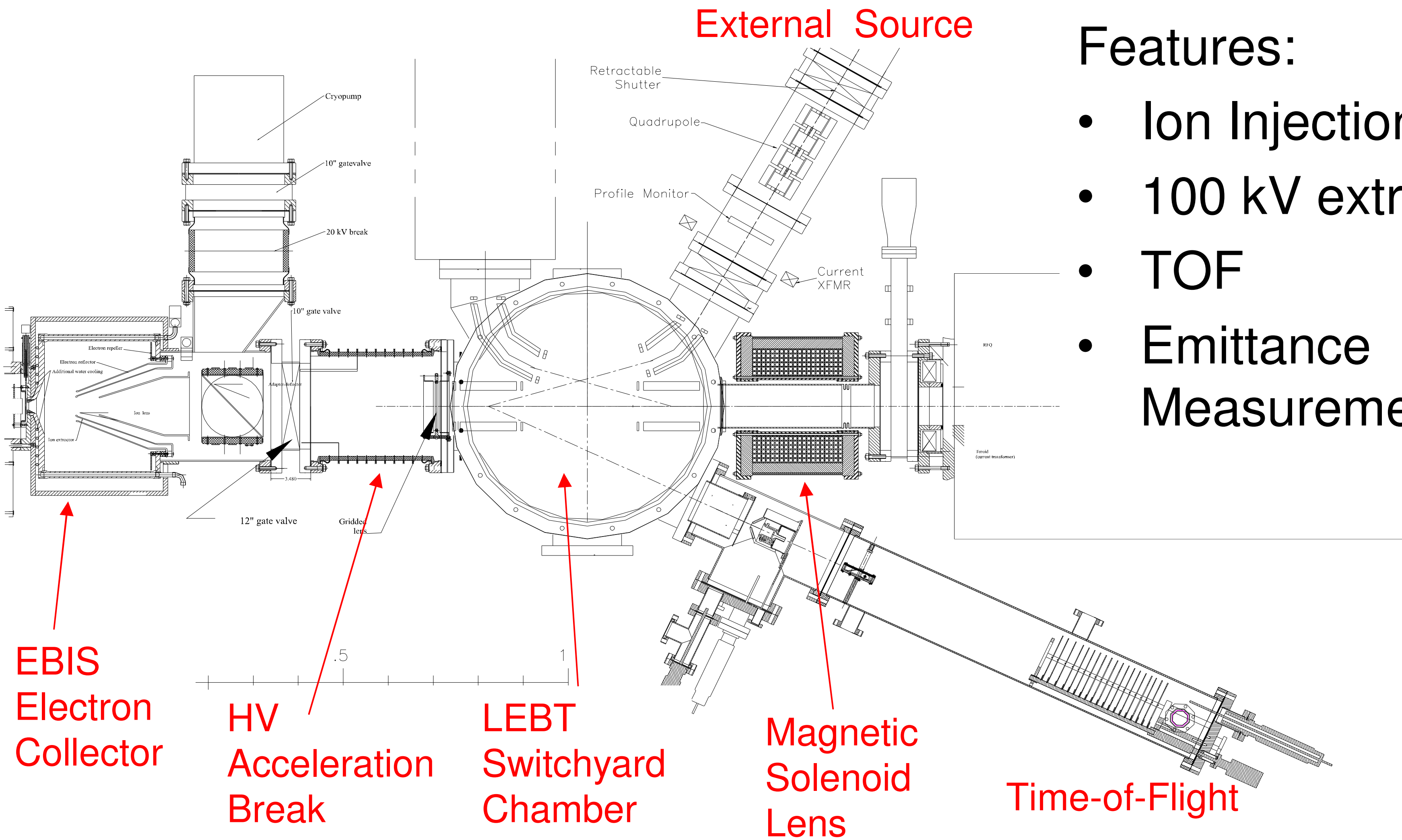
• Length of the SCS coil:	190 cm	Test EBIS: 100 cm
• Magnet field:	6 T	Test EBIS: 5T
• Warm bore inner diameter:	204 mm (8”)	Test EBIS: 155mm (6”)

  – 1.7 times increased vacuum conductance
  – more room for HV leads

- This solenoid is being fabricated by ACCEL. Factory acceptance testing planned for July, 2007.

Other EBIS components (stand, supports, drift tube structure, etc.) are now being fabricated. The present schedule has initial testing of the RHIC EBIS in the spring of 2008.

Prototype LEBT being installed on Test EBIS



Features:

- Ion Injection
- 100 kV extraction
- TOF
- Emittance Measurements

Prototype of Final LEBT

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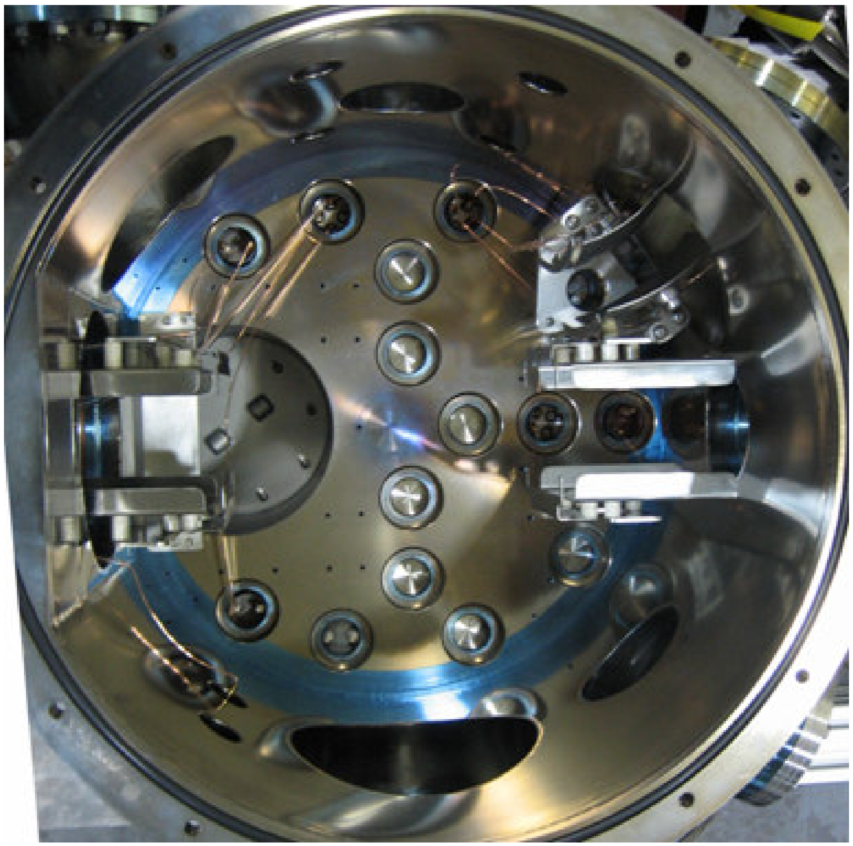
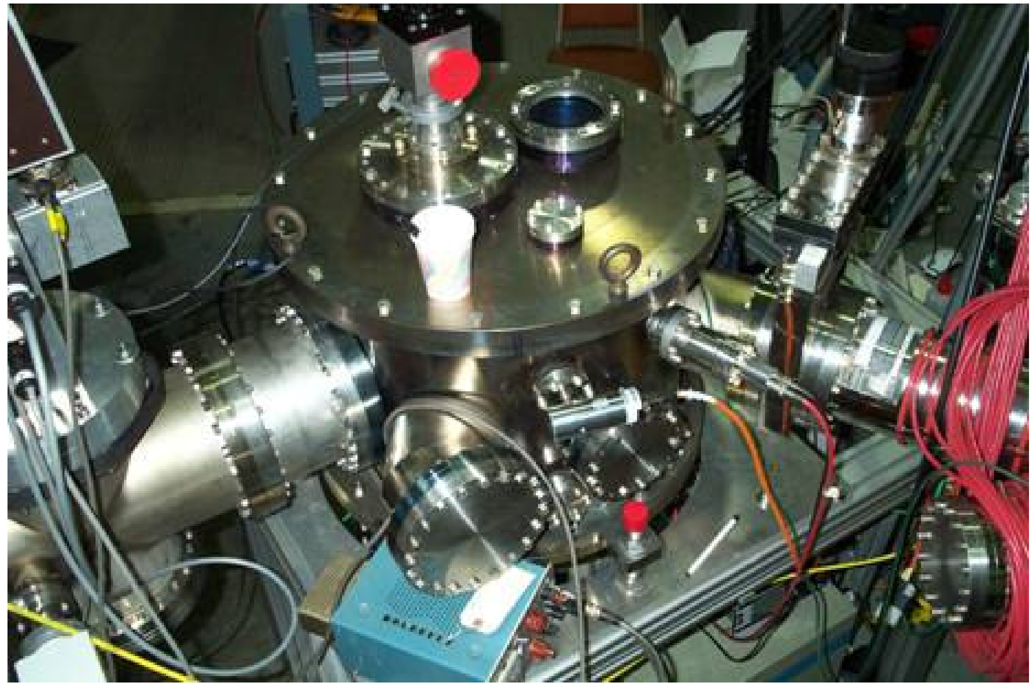
We are now injecting ions from an external source & measuring emittances at the "output" of the LEBT chamber.





Following these tests, the chamber will be installed on Test EBIS, and emittances measured at the RFQ input location.

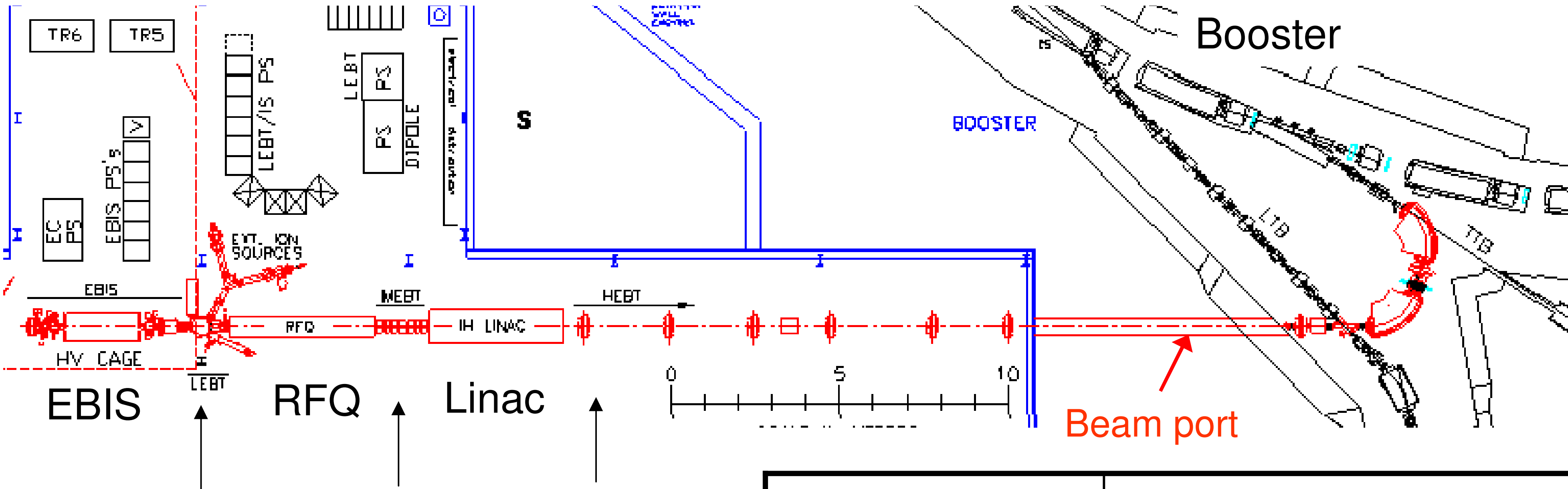
External Sources used for Primary Ion Injection on the Test EBIS

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.

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

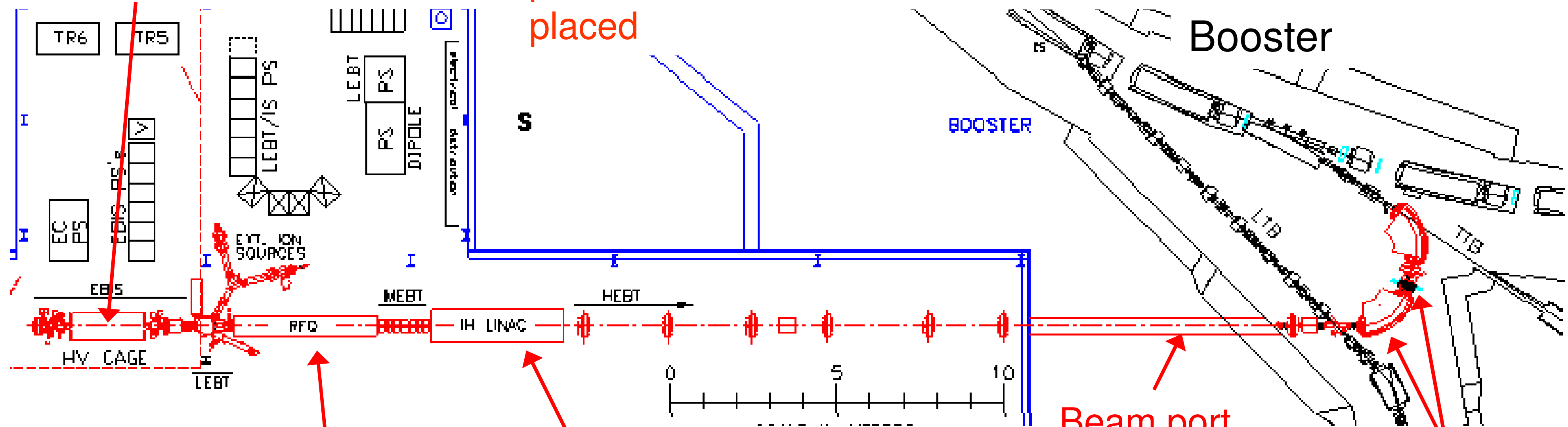


Ion	He - U
Q/m	≥1/6
Current	> 1.5 emA (for 1 turn inj)
Pulse Length	10 μs
Rep. Rate	5 Hz
Time to switch species	1 second

Status of Major Items

EBIS SC solenoid – acceptance testing in July (ACCEL)

RF Amps – procurement placed



Beam port - complete

Dipoles – preparing to place order

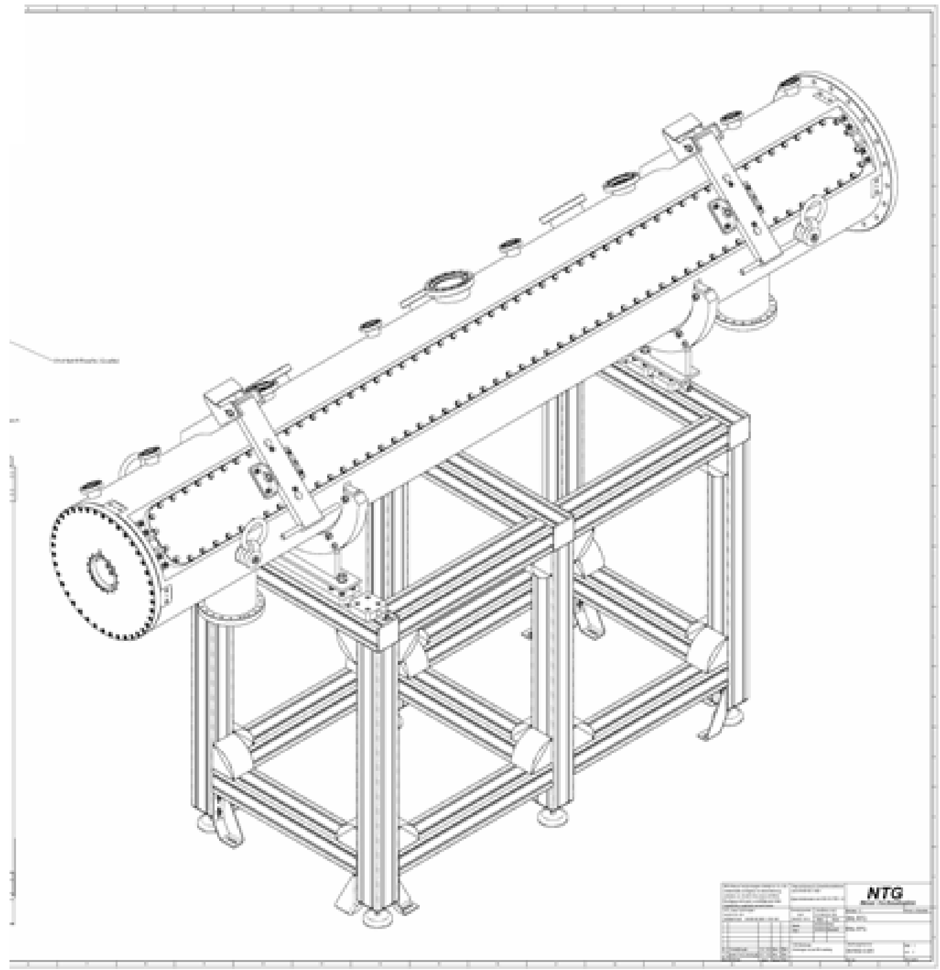
RFQ – being fabricated (IAP, Frankfurt)

Linac – design complete (IAP, Frankfurt)

RFQ

Design and Fabrication by IAP, Frankfurt

- Excellent physics design presented.
- Mechanically, based on well established design
- Delivery scheduled for January, 2008.



SUMMARY

- The EBIS-based preinjector is based on a modern technology, which will be simpler to operate and easier to maintain than the Tandems, and offers increased capabilities for RHIC and NASA.
- The Test EBIS has demonstrated that an EBIS meeting RHIC requirements can be built. The source performance is just as predicted.
  - 10 A e-beam; ~ 4 mA in 10 μs pulses; Au^{32+} in 36 ms; etc.
- No significant improvement in performance is required, other than the straightforward scaling of ion output with an increase in trap length.
- The success of this high current EBIS opens possibilities for other applications.
- The EBIS project received DOE CD3 approval (Construction start) in September, 2006.
- With joint funding from DOE and NASA, most large procurements have been placed.
- Our present schedule shows commissioning of the full preinjector in 2009.