Commissioning of the EBIS-Based Heavy Ion Preinjector

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Project Funding:

DOE

NASA

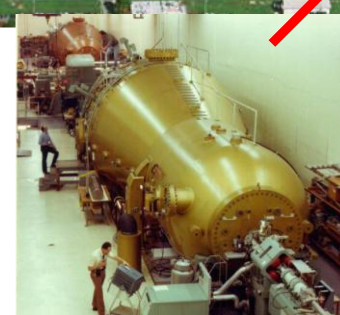
Outline of Talk

ELECTRON BEAM ION SOURCE

- Overview of the EBIS Preinjector project
  - What it is. Why we're doing it
- Electron Beam Ion Source (EBIS)
- Other key hardware
- System Performance
- Commissioning results with He^{+1},Au^{+32}, Fe^{+20}
- Next steps

Further details – M. Okamura "Beam Commissioning Results for the RFQ …" and D. Raparia "Commissioning of the IH Linac ….." at this conference.

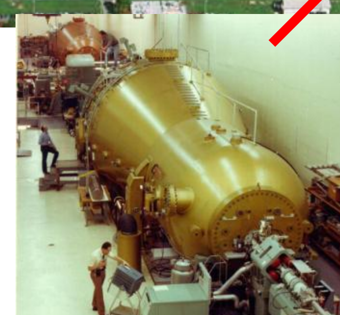
Heavy ions for RHIC



Two 14 MV Tandem Van de Graaffs

Heavy ions for NASA Space Radiation Lab

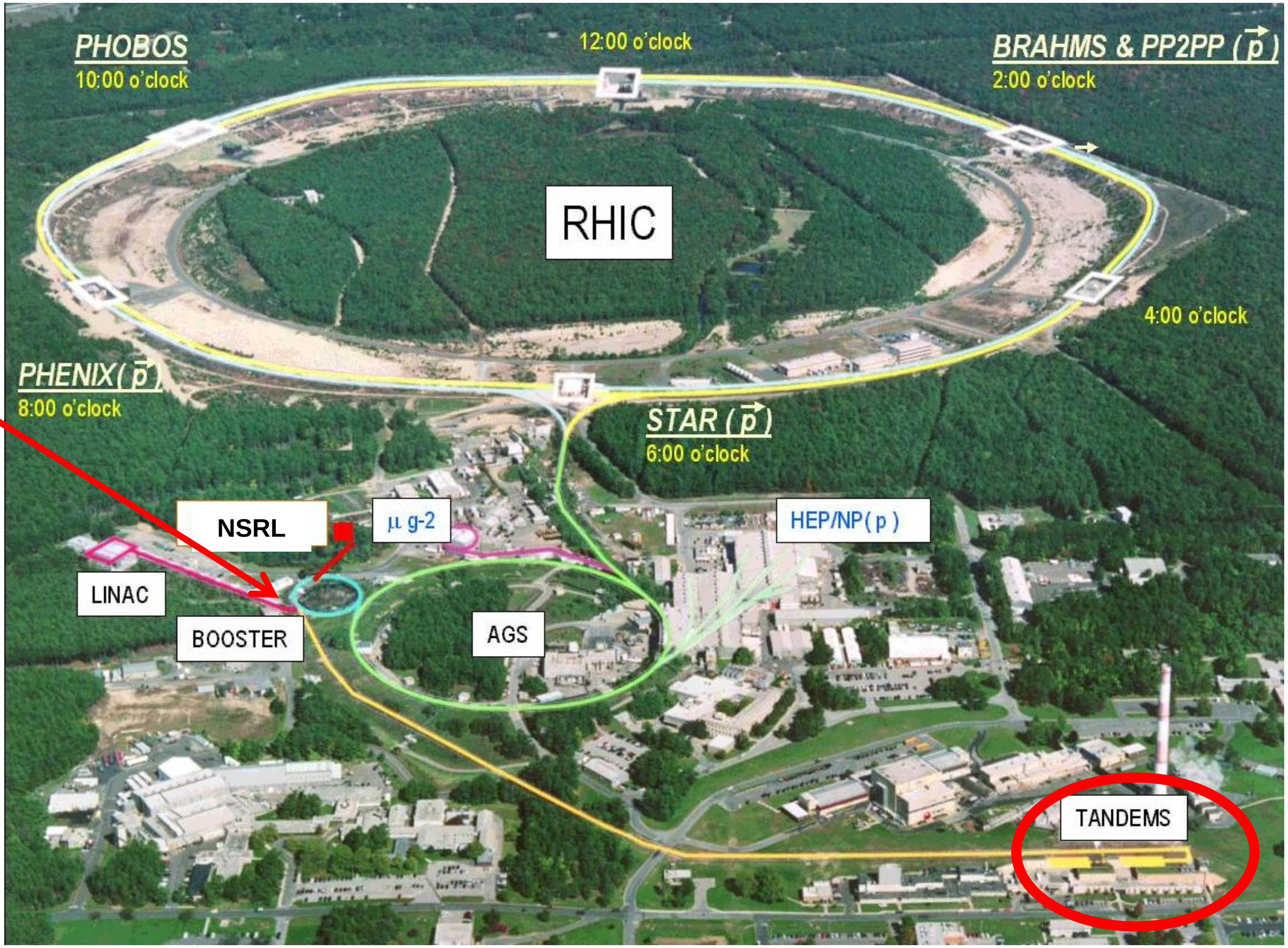
NSRL – biological effects of space radiation



Two 14 MV Tandem Van de Graaffs

EBIS Preinjector is located very close to the Booster

EBIS



860 m long transport line from the Tandems to the Booster

Motivation

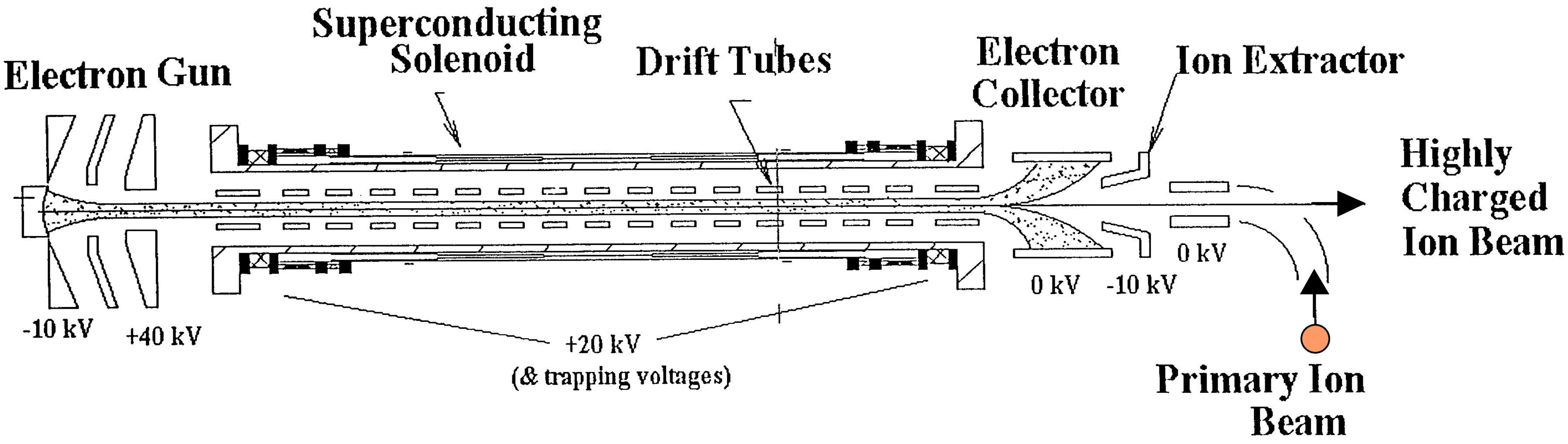
- Increased flexibility to handle the simultaneous needs of RHIC and NASA (fast switching between species)

- 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

Principle of EBIS Operation

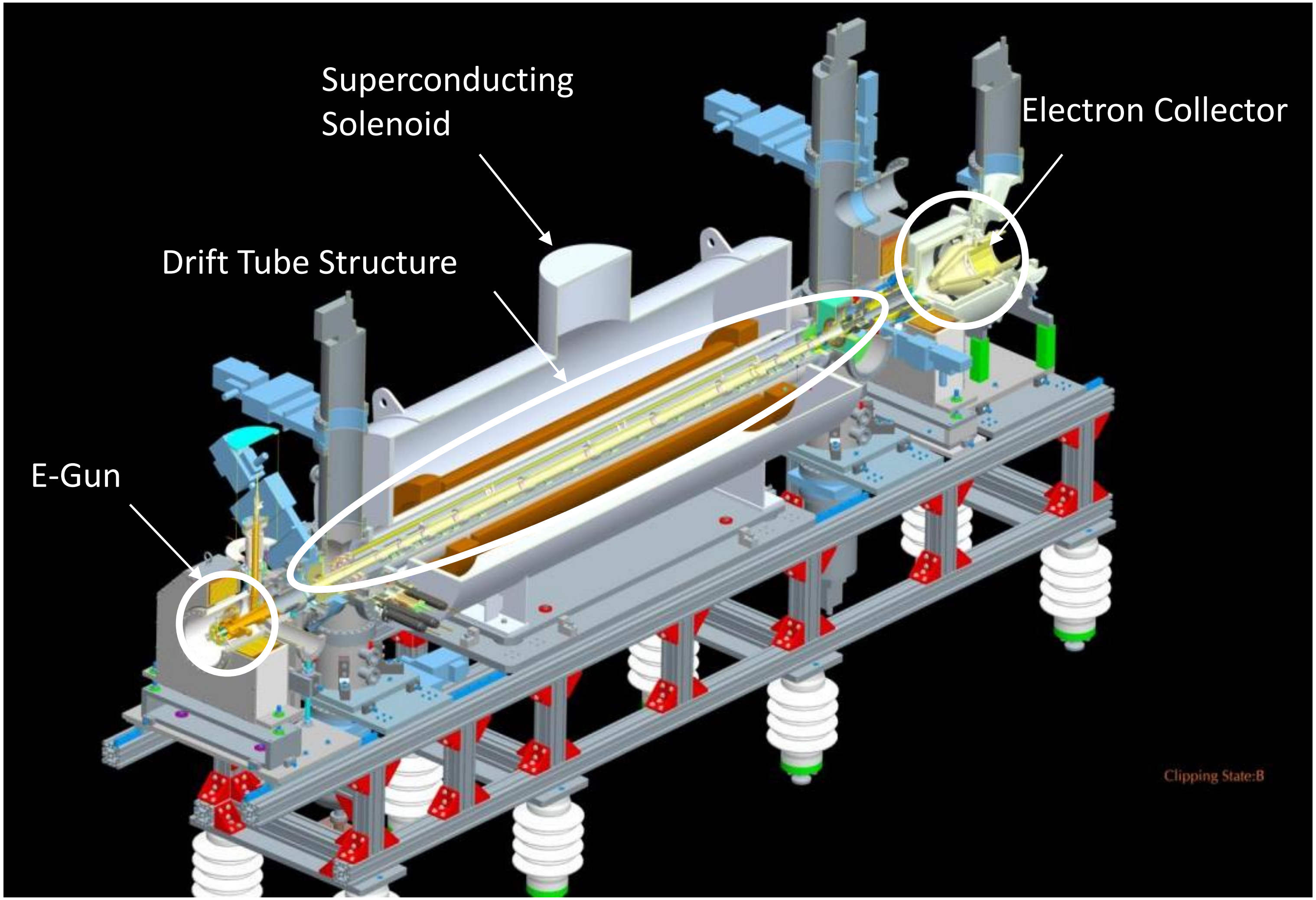


Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials at ends of trap.

- 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!

Electron Beam Ion Source (EBIS)

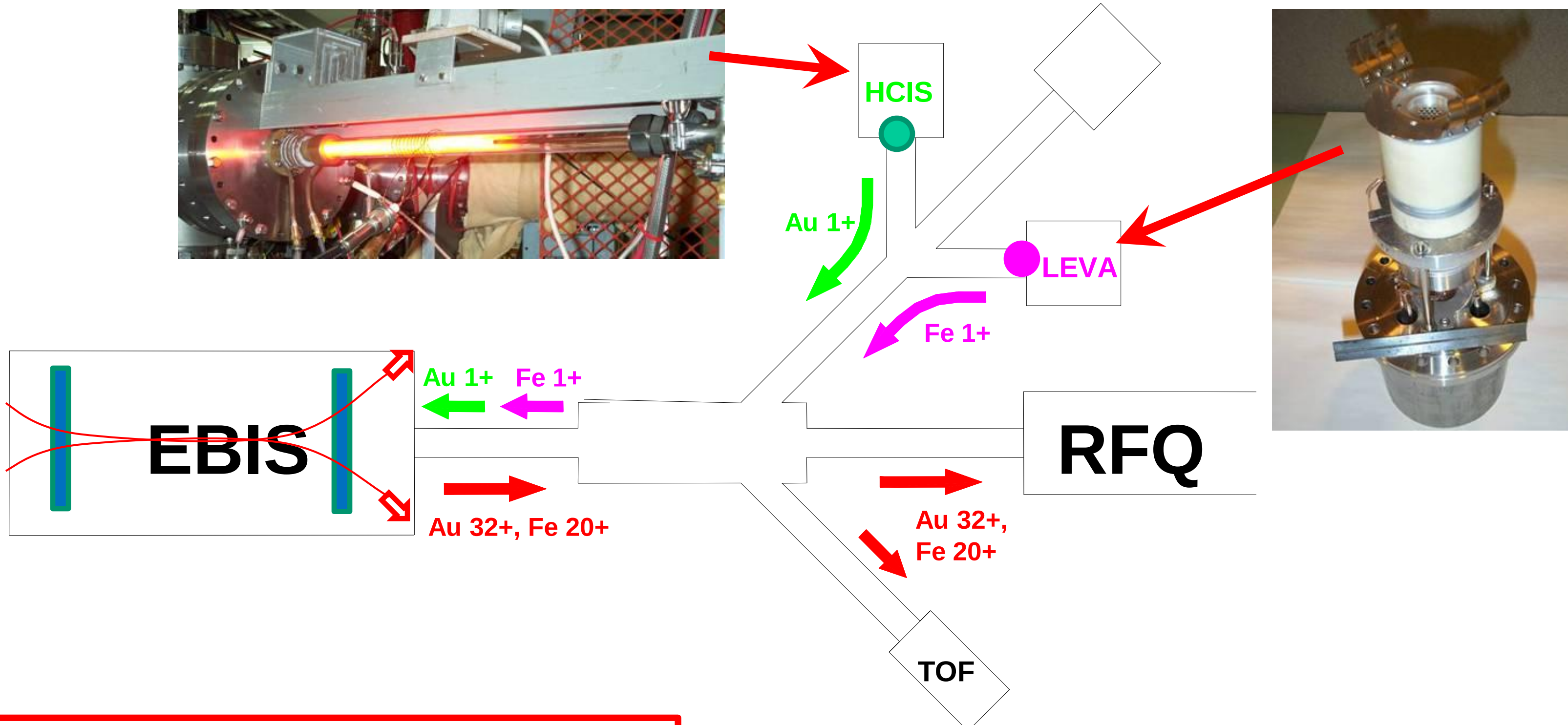
High charge state heavy ions produced by trapping and stepwise ionizing in an electron beam



BNL: 10 A electron beam; 5T magnet; 1.5 m long trap region

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

Test EBIS was half trap-length prototype at BNL

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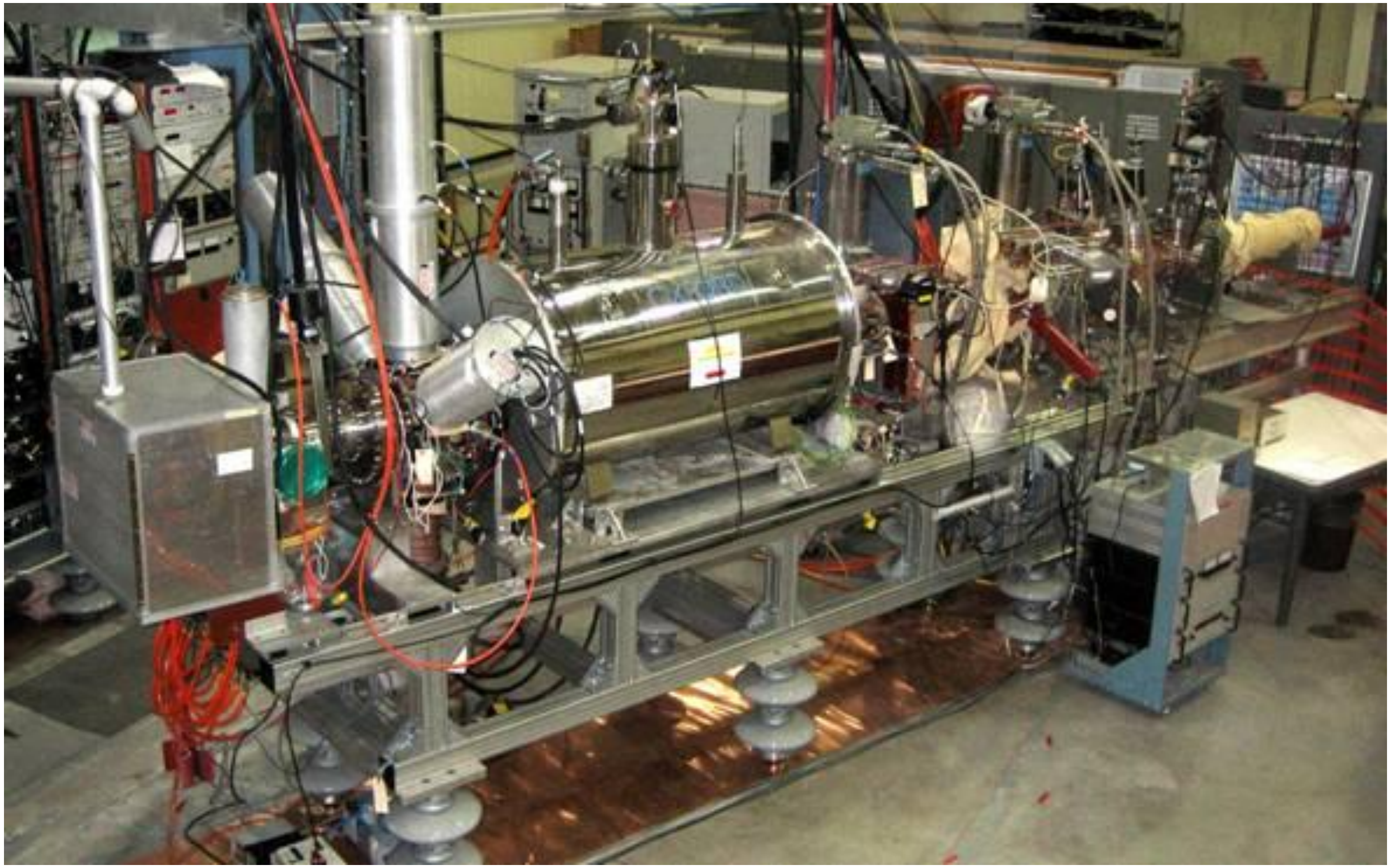
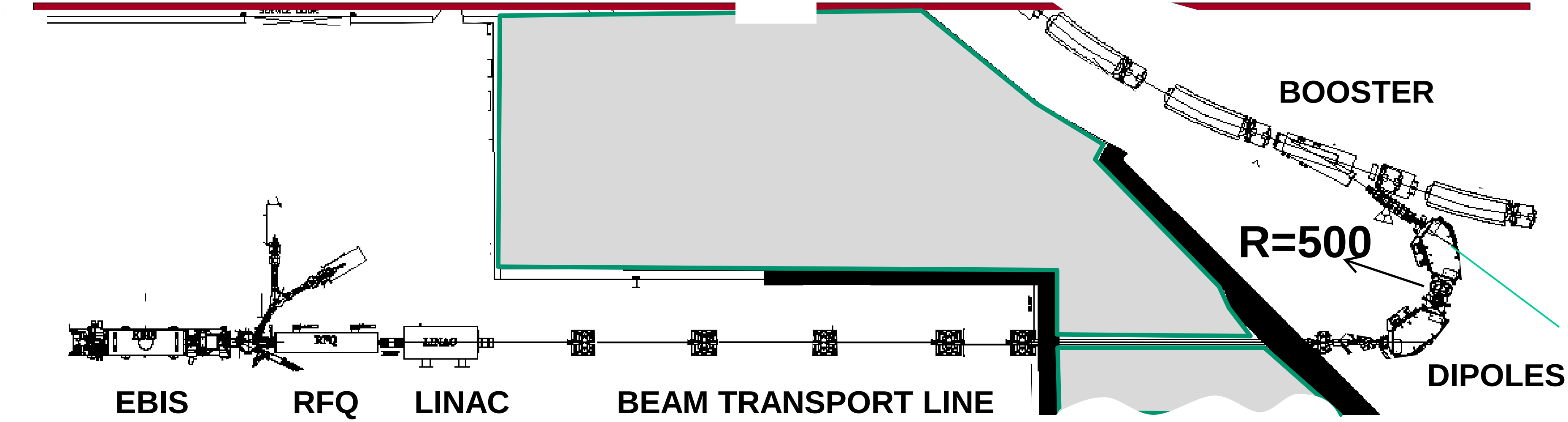
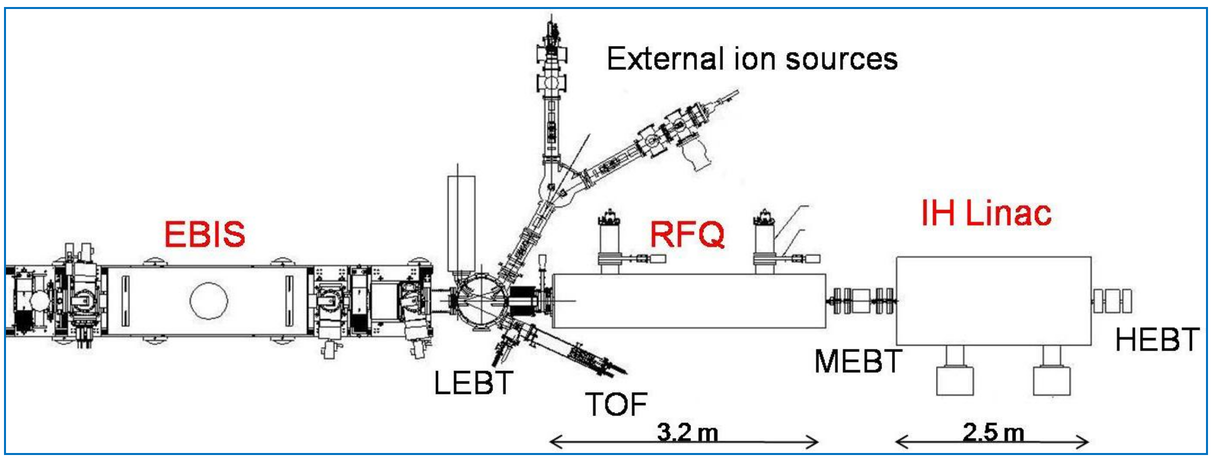


This proof-of-principle has been operating very successfully in the lab for many years.

10A electron beam; has produced mA's of beams such as Au, Cu, Ne, Ar, Cs, etc.

EBIS Preinjector in lower equipment bay of the 200 MeV Linac





Ions	He - U
Q / m	≥1/6
Current	> 1.5 emA (10 μS)
Pulse length	10-40 μs
Rep rate	5 Hz
Output energy	2 MeV / u
Time to switch species	1 second

Performance Requirements of the EBIS

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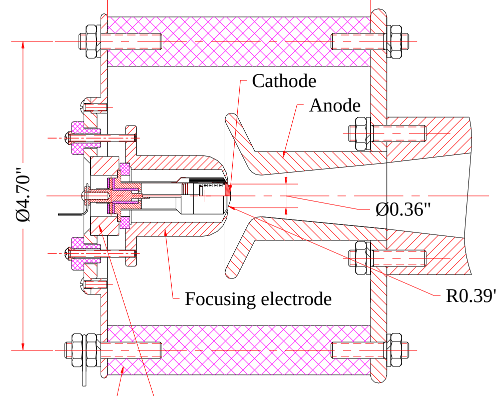
Species	He to U
Output (single charge state)	≥1.1 x 10^{11} charges
Intensity (examples)	3.4 x 10^{9} Au^{32+} / pulse (1.7 mA) 5 x 10^{9} Fe^{20+} / pulse (1.6 mA) 6.3 x 10^{10} He^{1+} / pulse (2.0 mA)
Q/m	≥ 0.16, depending on ion species
Repetition rate	5 Hz
Pulse width	10 - 40 μs
Switching time between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

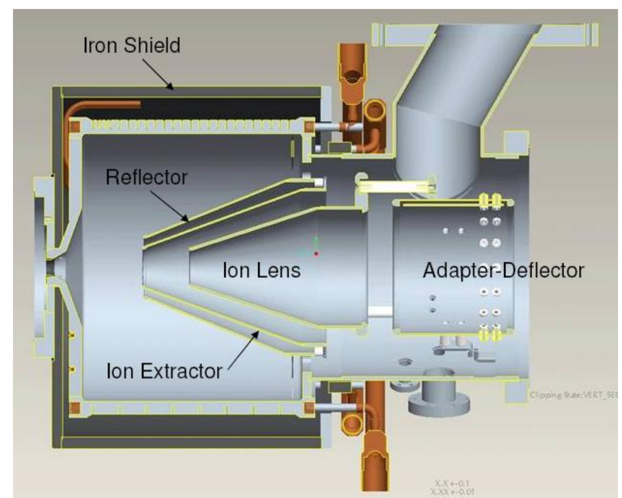
Key features of the EBIS

- High current electron gun (10-20A, IrCe cathode)



- Electron collector (design for 15A * 15 kV = 225 kW;

  50 ms* 5Hz = 25% df, to dc)



Key features of the EBIS (cont.)

- Superconducting solenoid (~5T, 2 meter, 8” warm bore)

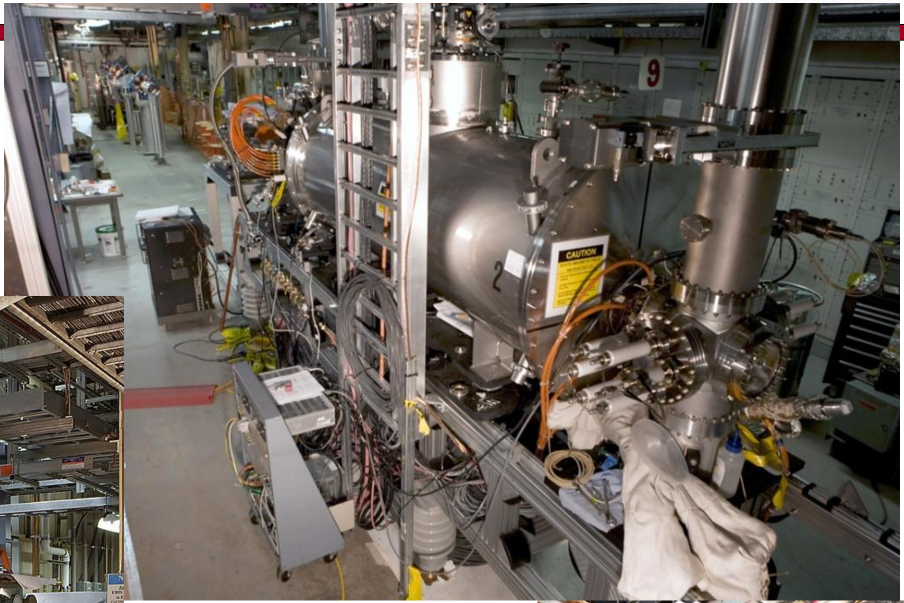
Made by ACCEL

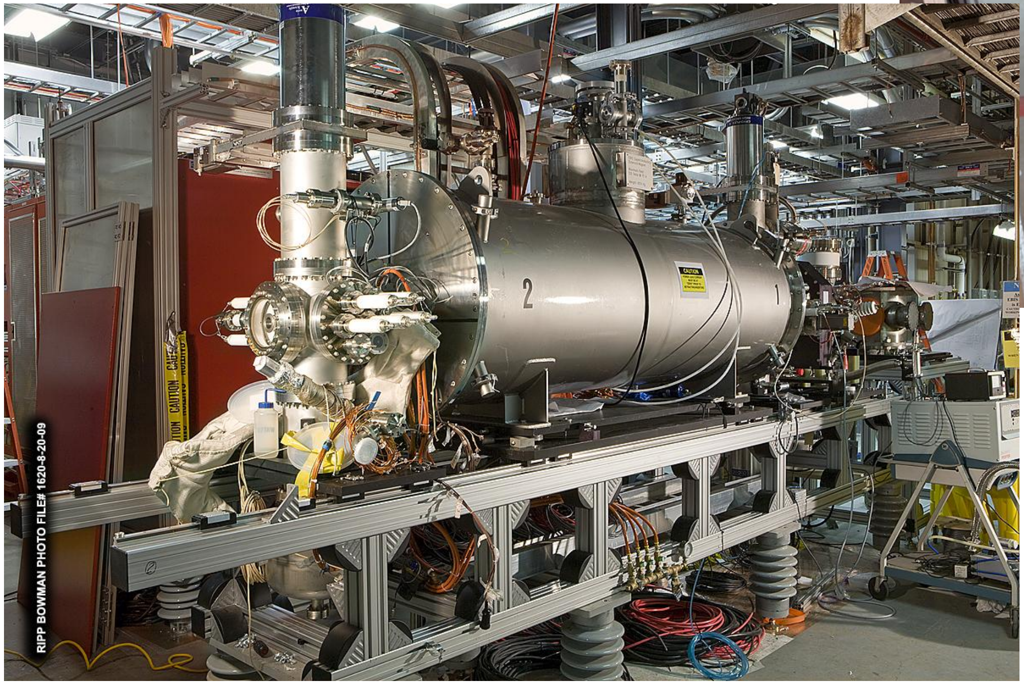
- Vacuum – ~10^{-10} in the trap region
- Controls – makes the complex programming of many electrode voltages during an EBIS cycle easy and reproducible

All preinjector hardware is in place and operating……..

shown in the following slides….

EBIS during installation





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

EBIS inside the high voltage cage

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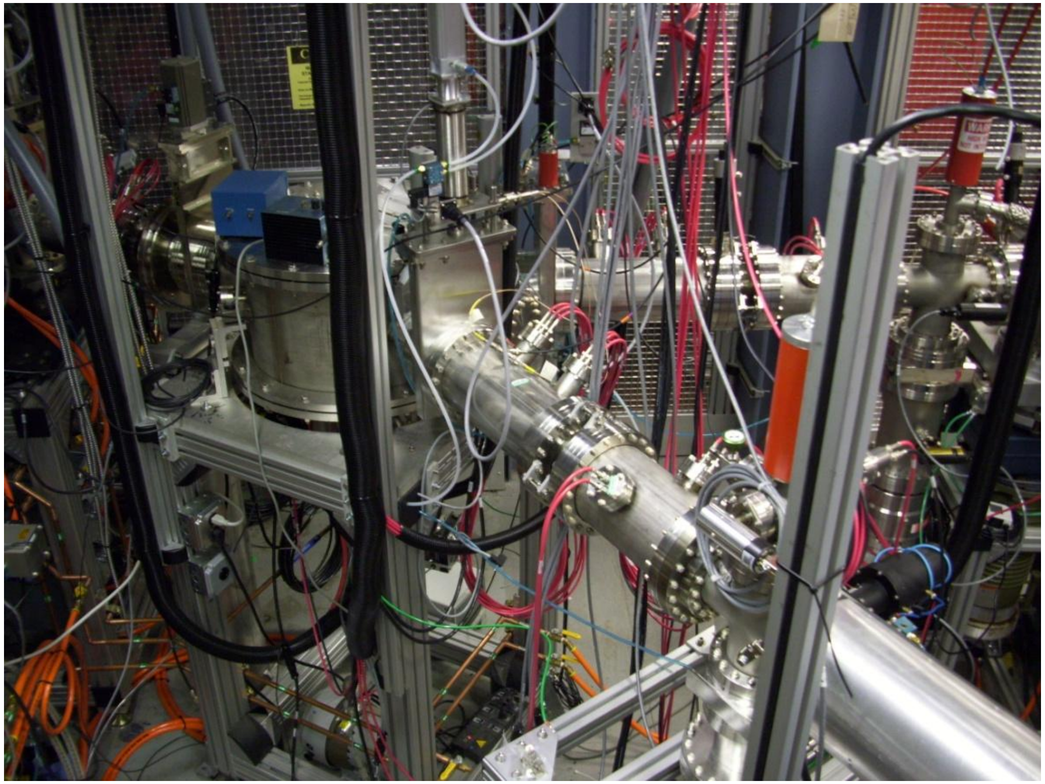
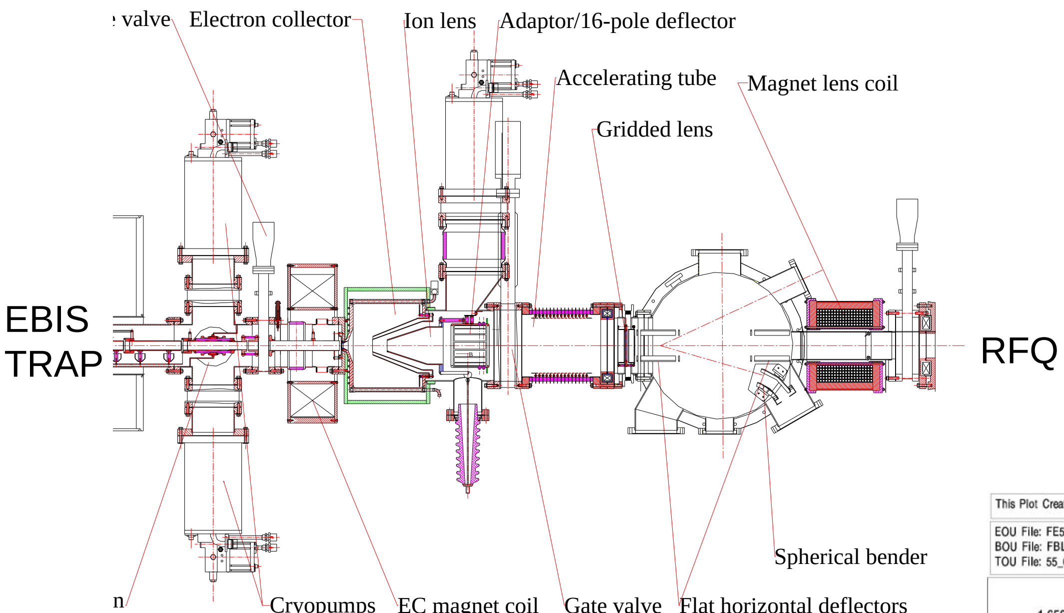
1+ ion injection lines

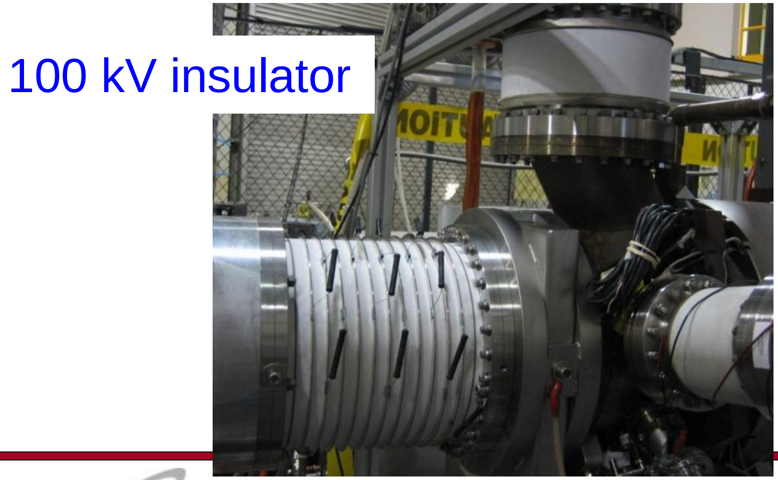


Hollow Cathode Ion Source based on design used on Saclay EBIS.

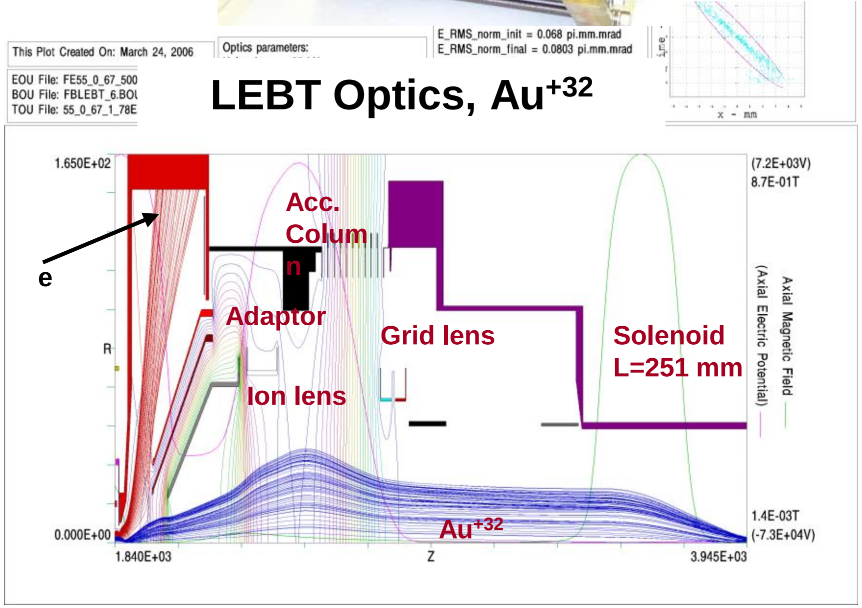
Low Energy Vacuum Arc Source (I. Brown);

Matching to the RFQ





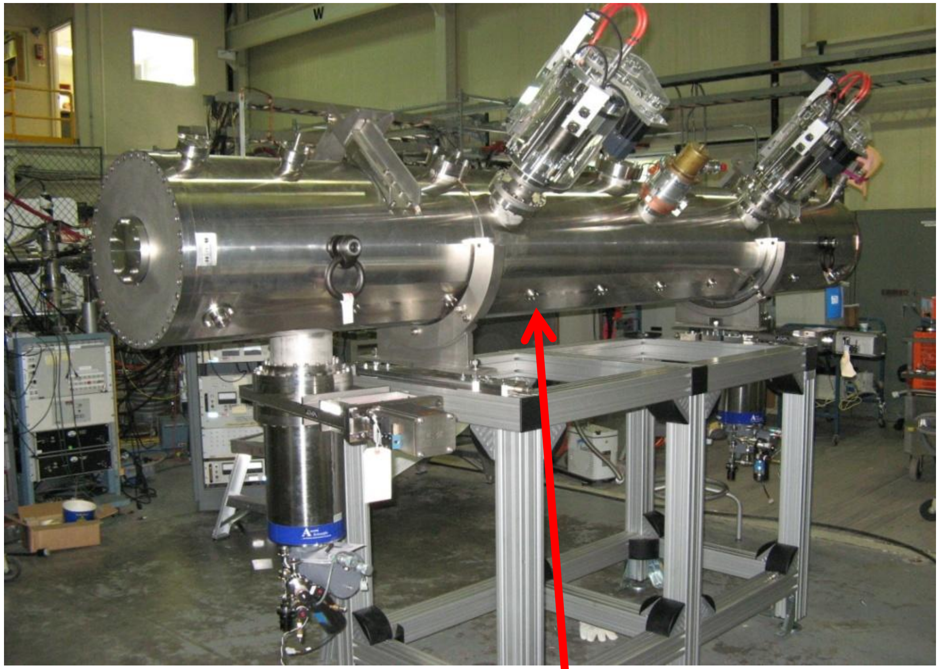
LEBT Optics, Au^{+32}



RFQ and Linac Design Specifications

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		%

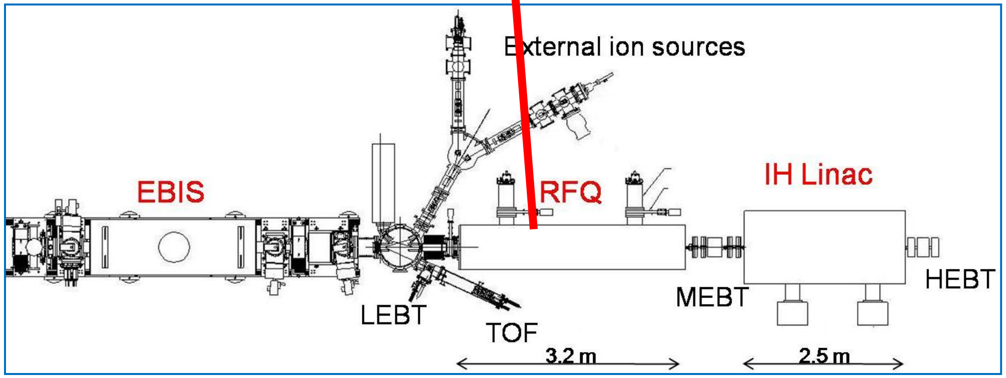
RFQ from IAP, Frankfurt (A. Schempp)

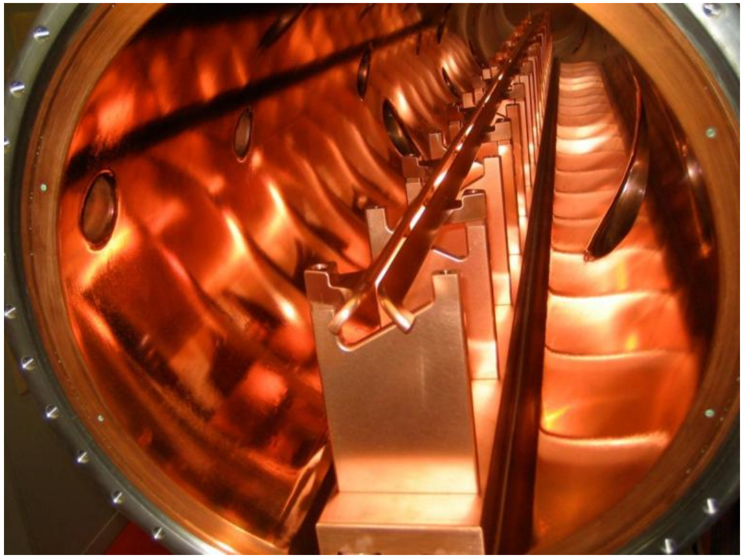


100 MHz

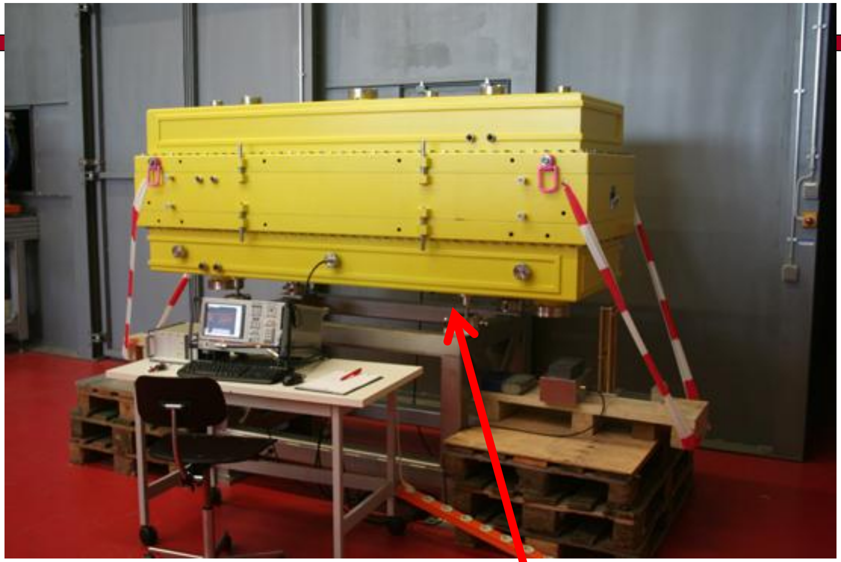
Accelerates the beam from 17 keV/u to 300 keV/u

Fabricated by NTG

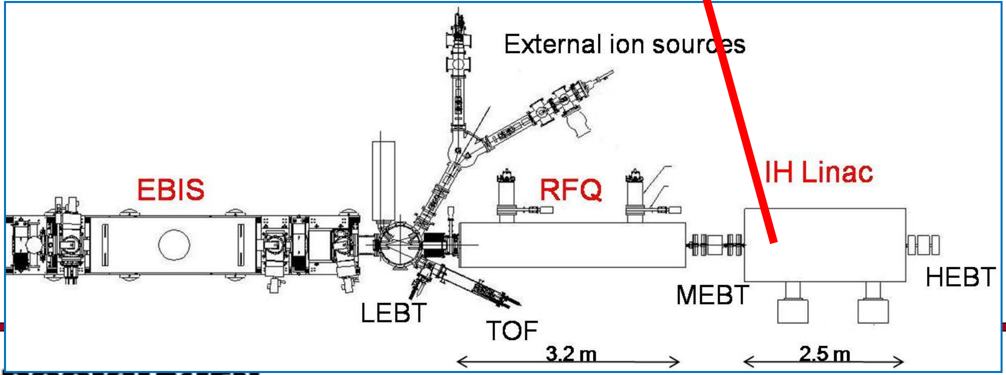




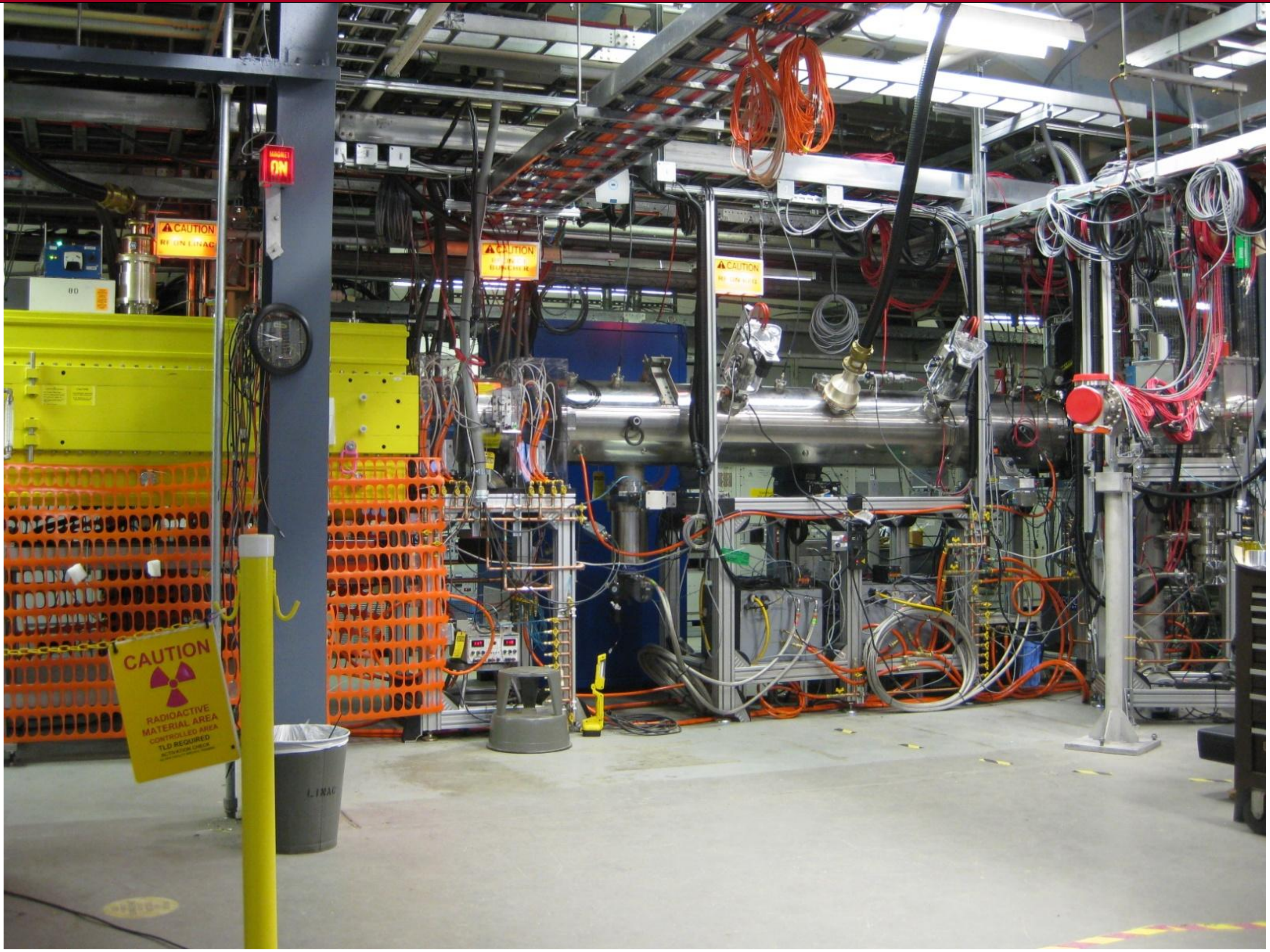
Linac from IAP, Frankfurt (U. Ratzinger)



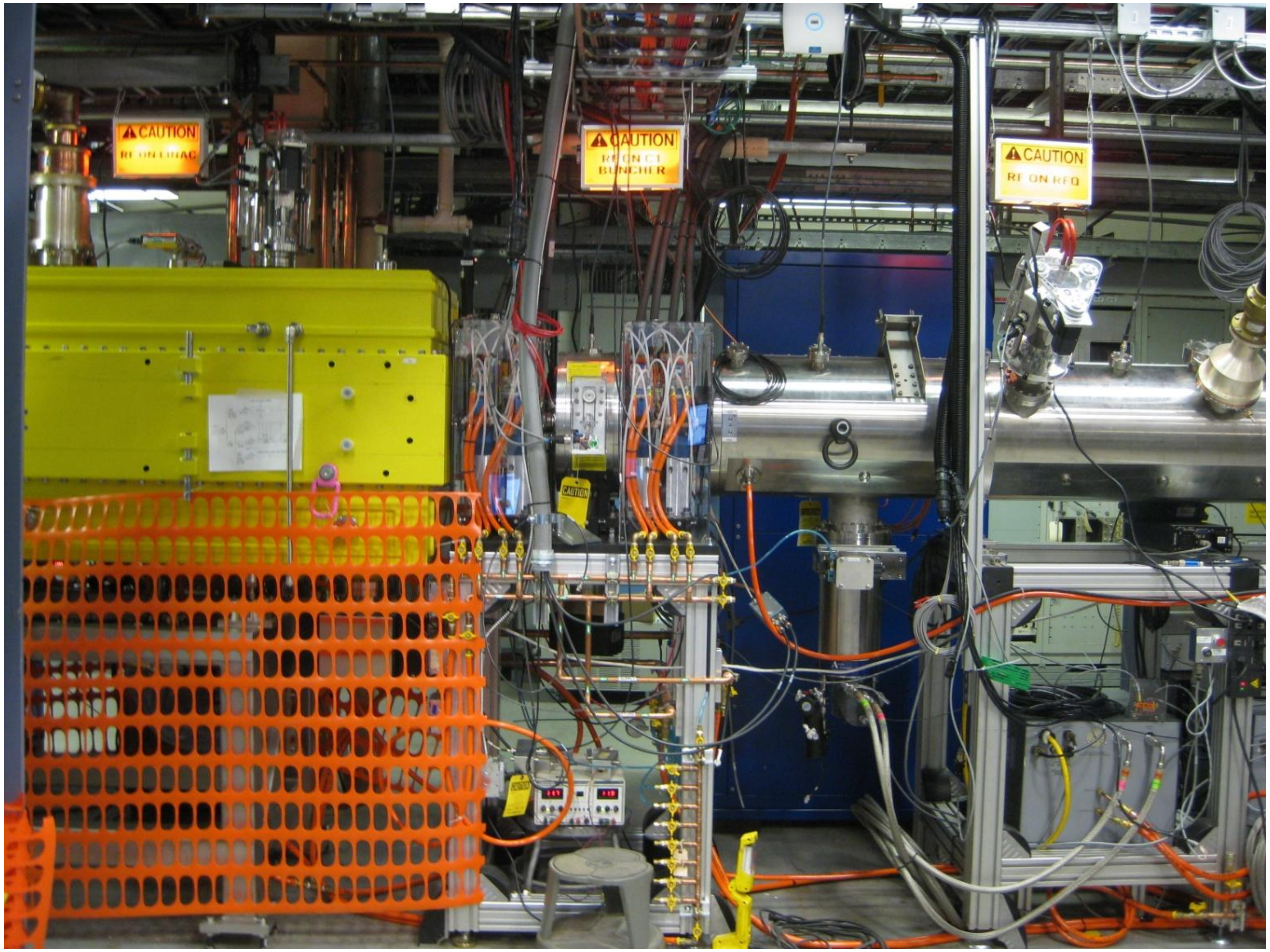
100 MHz
Accelerates the beam from 300 keV/u to 2 MeV/u
Cavity Fabricated by PINK; Quad by Bruker



RFQ. MEBT, and Linac
(moved into place in June, 2010)



RFQ, MEBT (C-1), and Linac



Linac and EBIS-to-Booster transport

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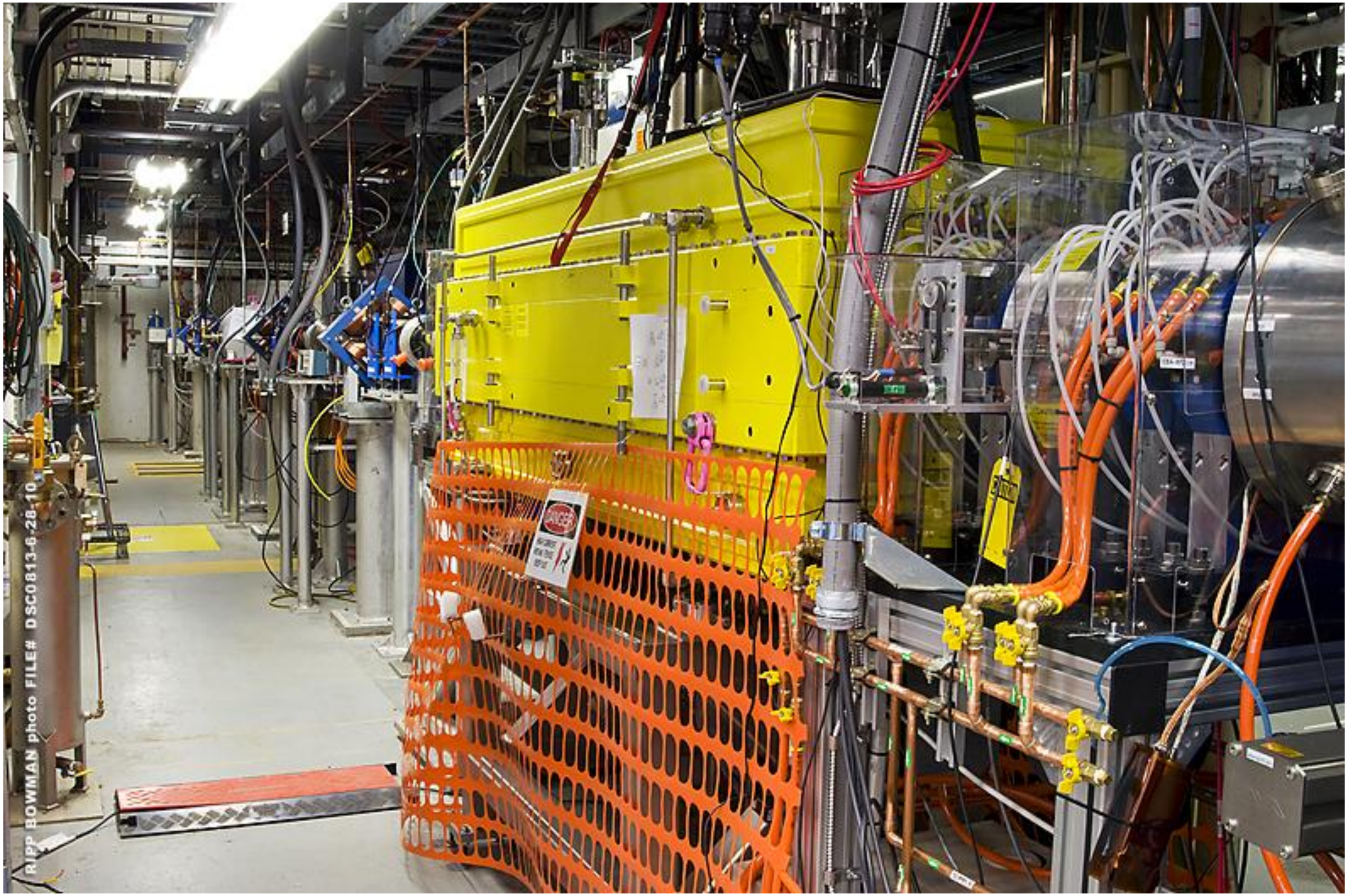
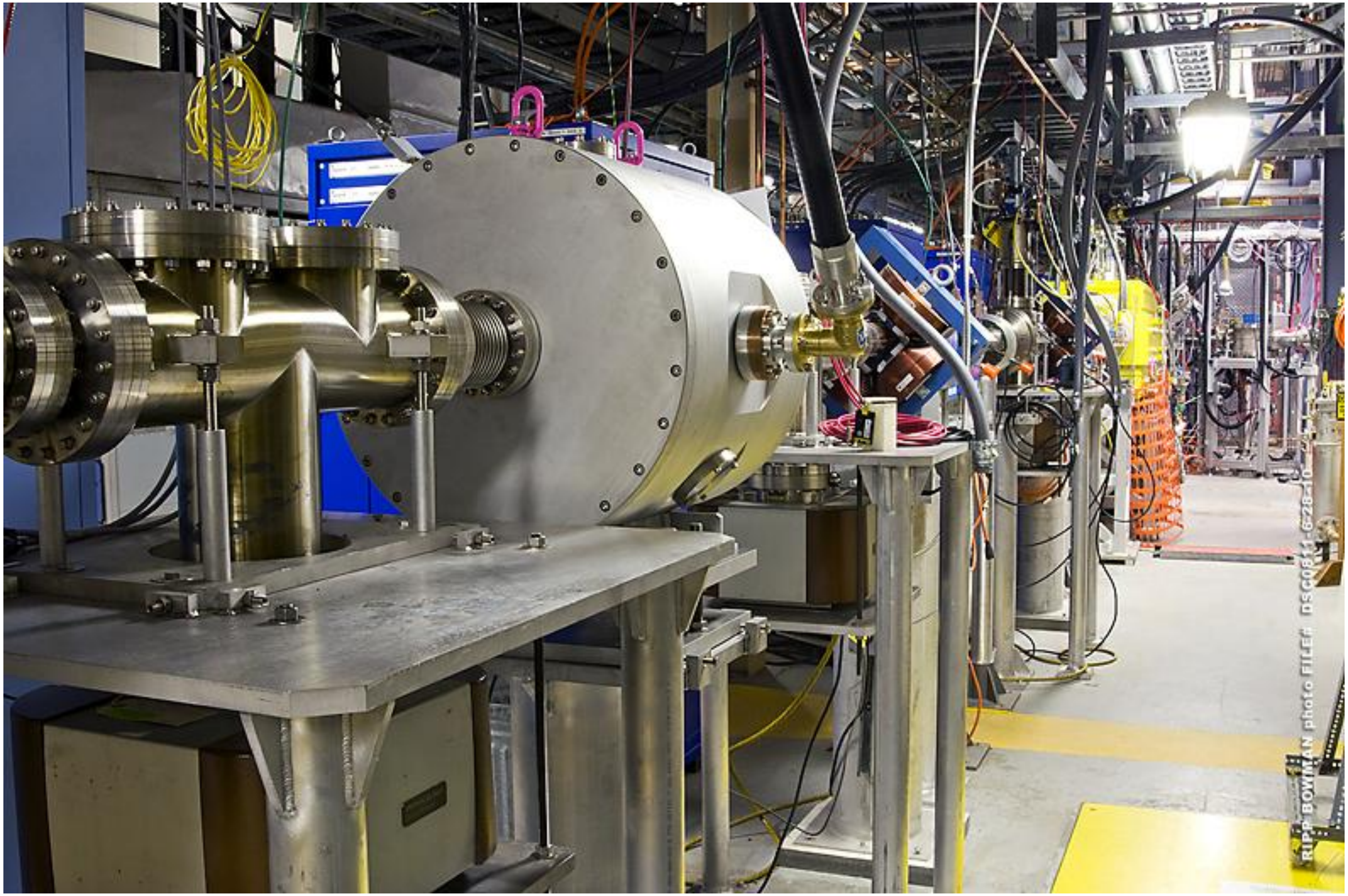
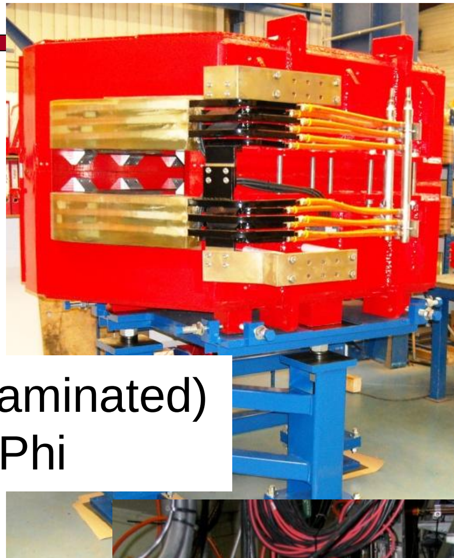


Buncher C-2 in transport line

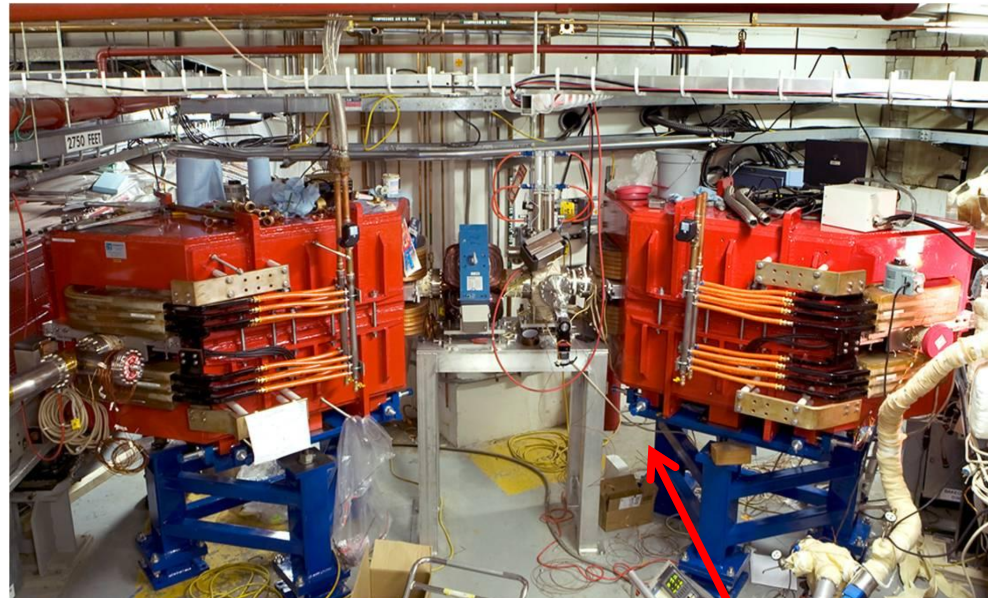


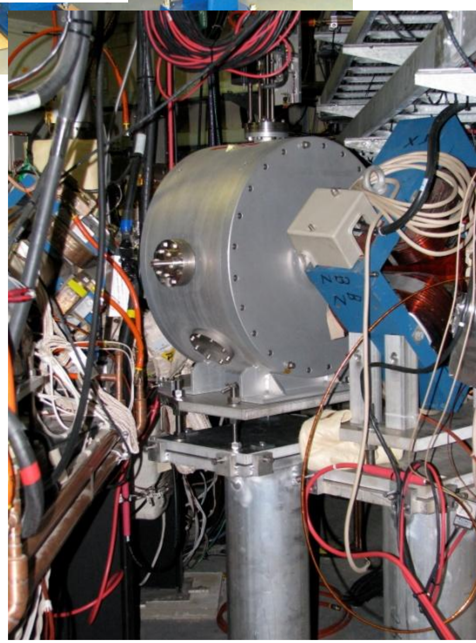
Beamline in Booster

ELECTRON BEAM ION SOURCE

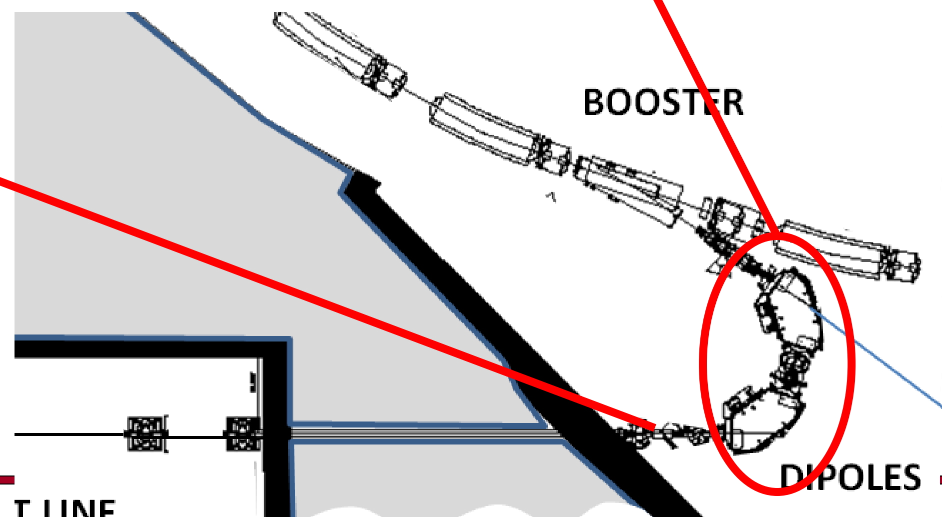


Dipole (laminated)
 - SigmaPhi





Buncher

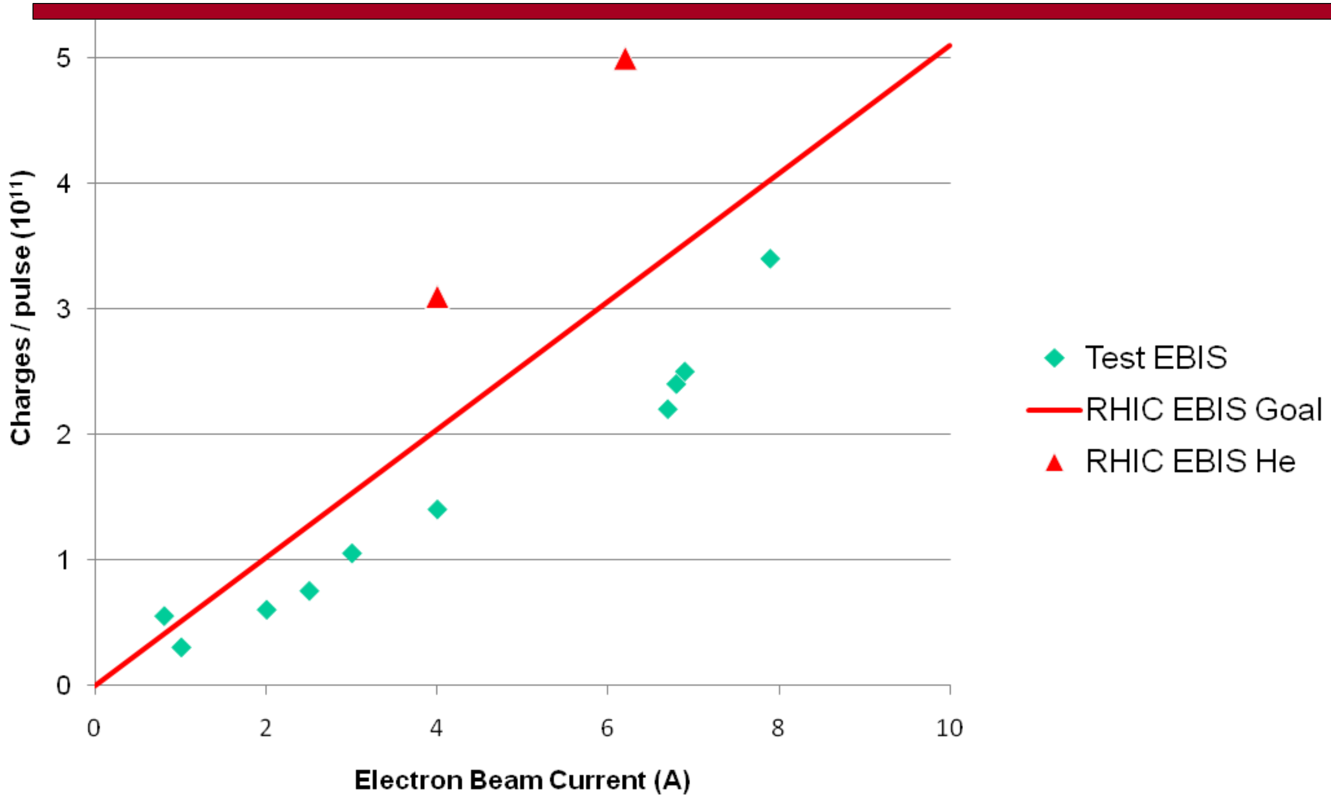


BROOKHAVEN
NATIONAL LABORATORY

RF Amplifiers

RFQ & Linac – 350 kW each (from Continental)
Bunchers – 2 @ 10 kW, 1 @ 20 kW   (from Armstrong)

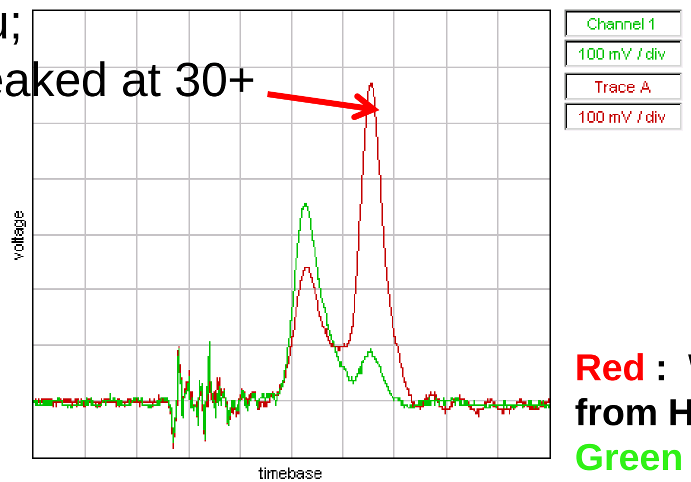
EBIS is operational



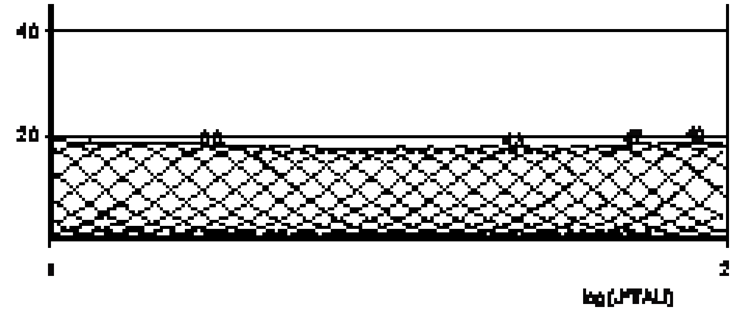
Helium ion yield vs. electron current is scaling properly –
RHIC EBIS has twice the trap length of Test EBIS
and is producing twice the output compared to Test EBIS (red points vs. green points)

EBIS Performance

Au;
peaked at 30+



Red : With Au+ injection from HCIS
Green : Au+ injection off



Computer calculation of successive ionization of Au with a 20keV electron beam:

•Low resolution TOF spectrum measured on a Faraday cup shows a gold fraction of extracted charge is approximately 60% (will improve after baking).

•We have operated electron current up to 8 A (design 10 A) . Typically operated so far at ~5A, up to 160 ms confinement times

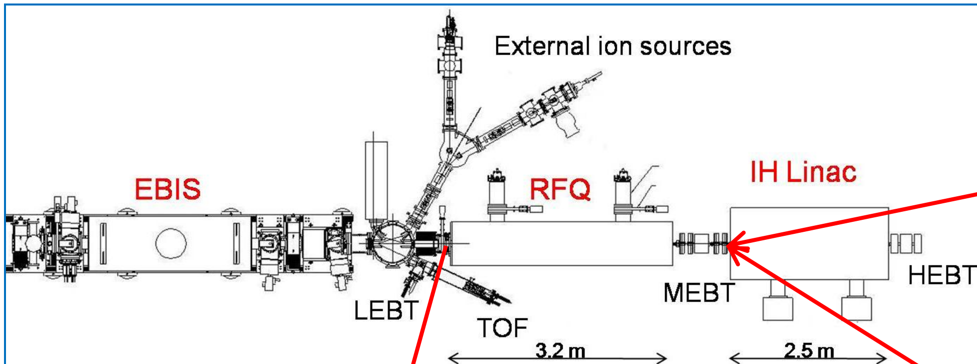
•100 kV platform voltage has been achieved (maximum required is ~90 kV)

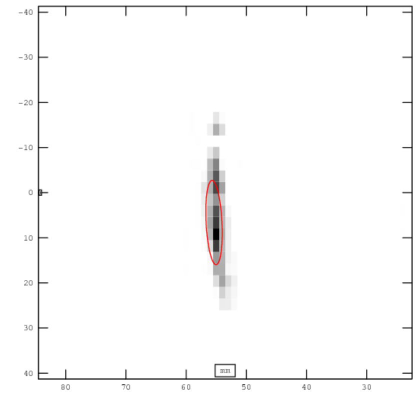
•Ion injection from both external sources (Au and Fe injection)

Timeline of commissioning

- RFQ on Test EBIS – He, Cu, Ne accelerated; measured E, dE
- LEBT – emittance of He^{1+} from RHIC EBIS
- RFQ & MEBT – emittances of He^{1+}; Au^{32+}, TOF
- Linac delivery 4/19/10; quad repaired 6/11/10
    - First accelerated beam – 6/19
- Beam transported around the bend (momentum analysis) – 6/24
    - RFQ energy around the bend, then RFQ & C1
    - Linac energy around the bend, then use C2 to adjust dE
- He^{1+} circulating in Booster (before summer shutdown) – 6/30-7/2
- Au^{32+} to middle of bend at CD-4 intensity - 8/17
- Fe^{20+} to the middle of the bend at CD-4 intensity – 8/29

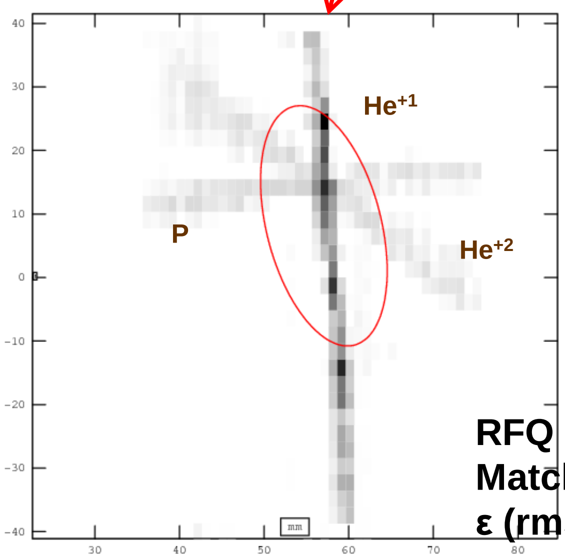
The LEBT and MEBT beam lines were each first commissioned with temporary diagnostics, before moving the RFQ, and then the linac, into place.





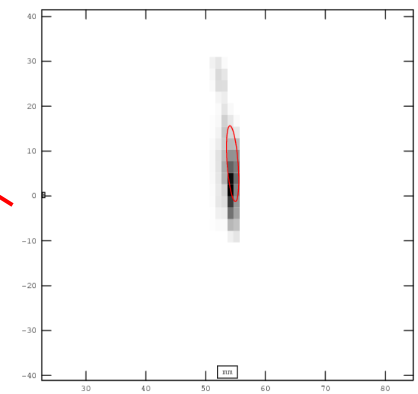
MEBT

Helium: matched condition into LINAC
ε(n,rms) 0.13 π mm mrad



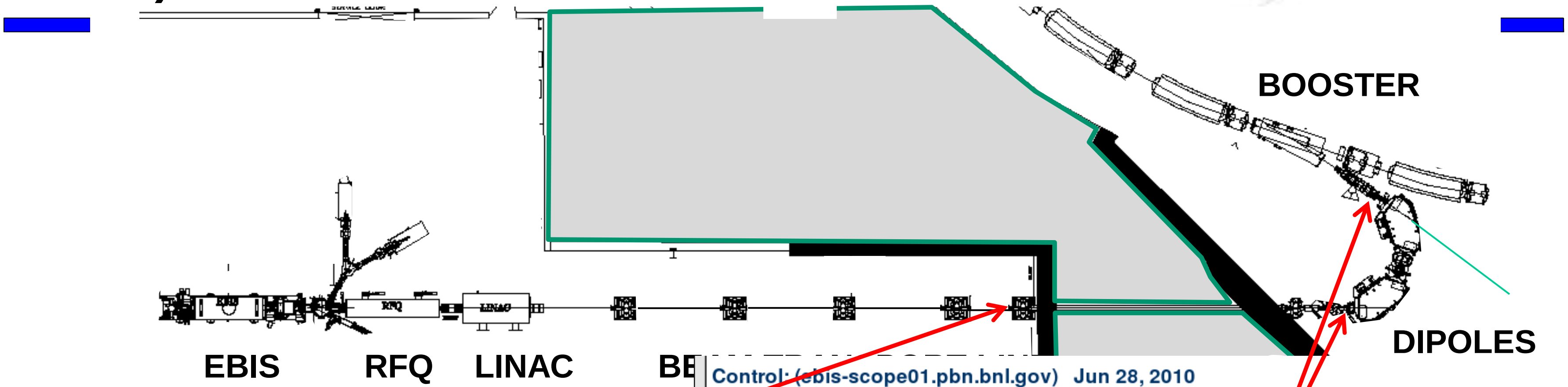
LEBT

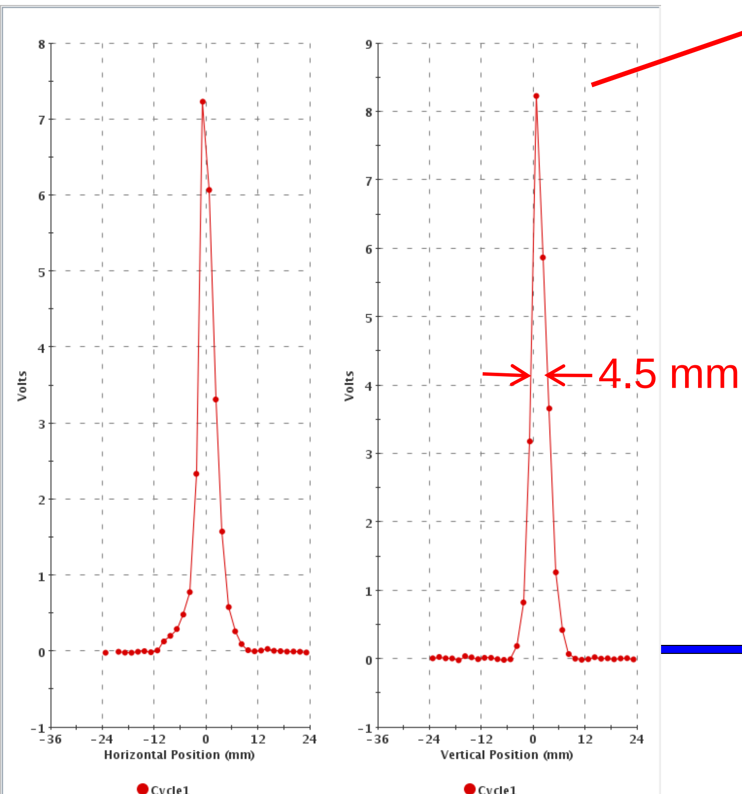
RFQ entrance for He^{+1}
Matched condition into the RFQ
ε (rms,N)= 0.09 πmm mrad

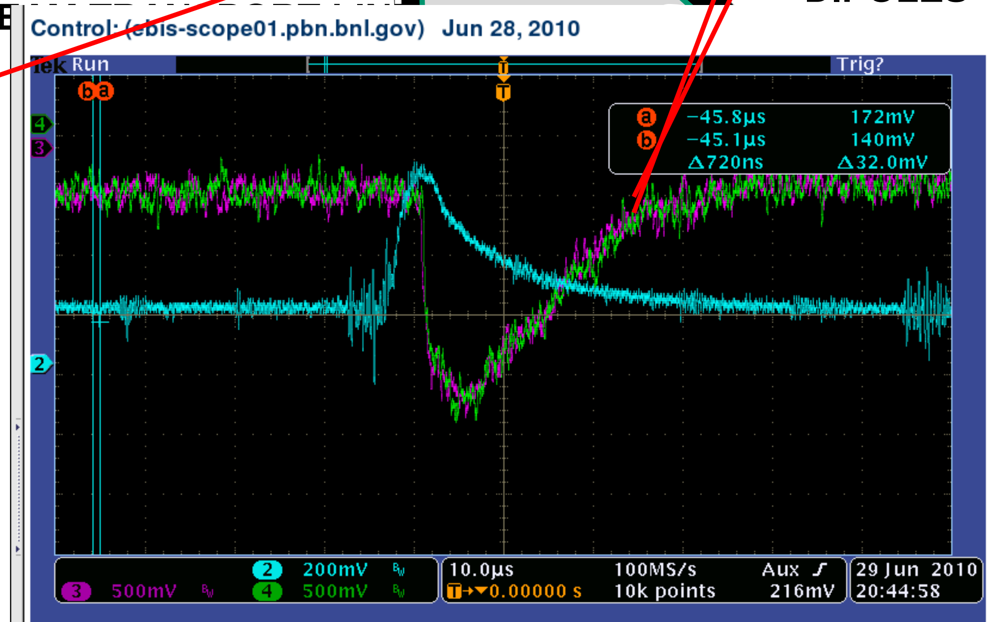


Gold: Matched conditions into linac
ε(n,rms) 0.19 π mm mrad

He^{1+} – first beam from EBIS transported to Booster (June 29)

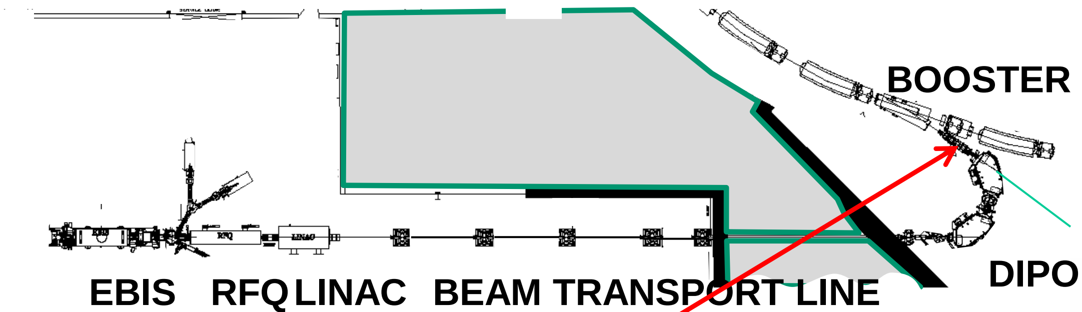




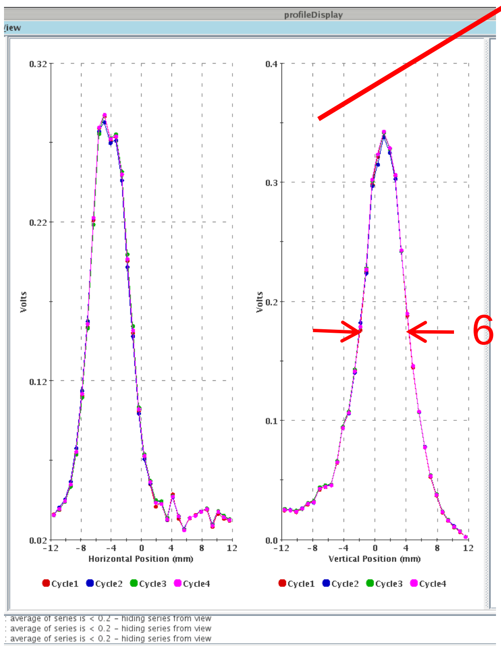


Green and pink traces are before and after the bends

First beam from EBIS circulating in the Booster (7/2/10)!

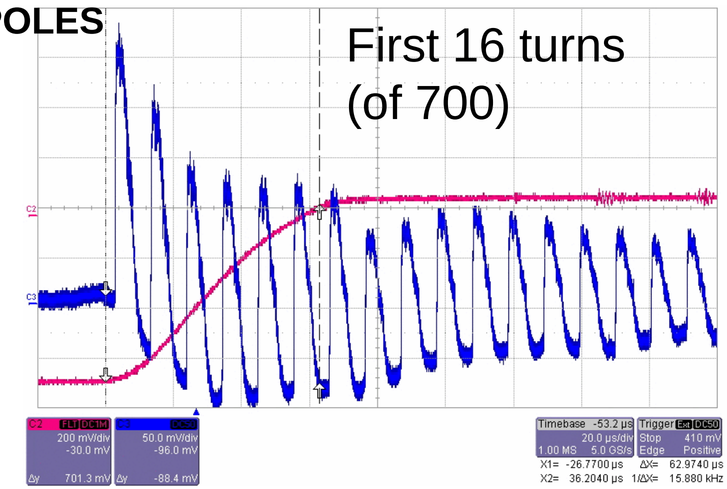


He+ beam from EBIS circulating in the Booster



Profiles right before the Booster injection

6 mm



First 16 turns (of 700)

From the measure of the beam debunching time in Booster

$\Delta p/p = 2.0\mathrm{x}10^{-4} \pm 1.0\mathrm{x}10^{-4}$

(Requirement $\leq 5.0 \times 10^{-4}$)

EBIS beams transported to middle of bend (2 MeV/u)

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He^{+1}

Conf. Time	2.5 ms
RFQ Power	40 kW
Linac Power	76 kW
Pulse width	<20 μs
Intensity	7×10^{10} ions / pulse

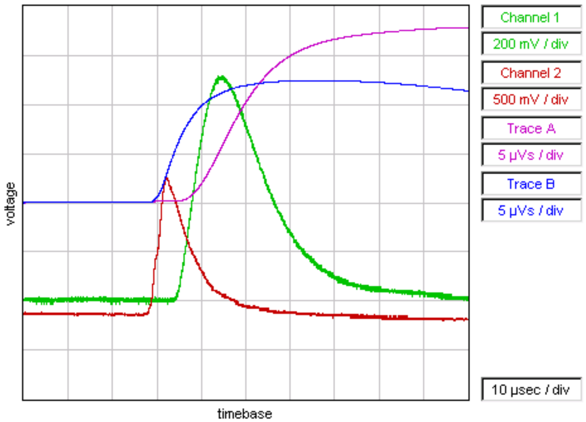
Transmission (helium):

RFQ Input FC	1.4 mA (18.5 nC)	
RFQ Output FC	1.4 mA (15.0 nC)	T=100%,(T=81% charge)
XF14 (after linac)	1.1 mA	T=79%
XF 89 (before bend)	1.1 mA	T=100%
XF108 (after ***both*** bends)	1.0 mA	T=91%

Between the two bends (continued)

Au^{+32}

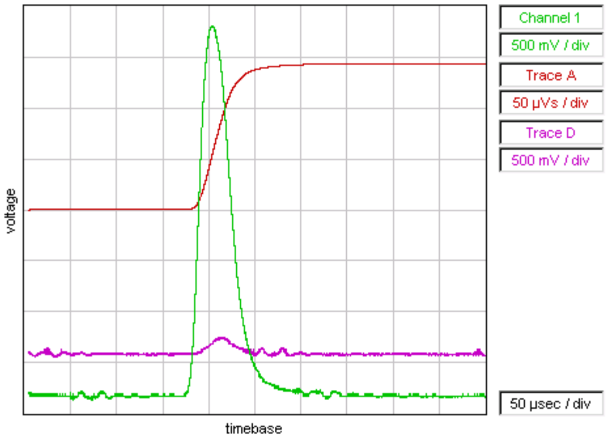
Conf. Time	65 ms
RFQ Power	95 kW
Linac Power	180 kW
Pulse width	20 µs
Intensity/pulse	3.7 x10^8 ions/pulse



Green trace is Au^{+32} between the bends (1V=109 µA).

Fe^{+20}

Conf. Time	130 ms
RFQ Power	20 kW
Linac Power	37 kW
Pulse width	36 µs
Intensity/pulse	4.75 x 10^8 ions/pulse



Green FC between dipole bends 10.9uA/V Fe
Red Integral of CH 1 [0.0109nC/uVs]
Magenta FC between dipole bends 10.9uA/V (background)

Beam switching

- Alternating injection – Fe from LEVA; Au from HCIS
- 65 ms / 130 ms confinement switching
- 92 kV / 32 kV platform voltage switching
- RF systems – all powers alternating a factor of 4.8
- Dipoles – 2270A / 1030 A switching in 1 second
- All transport lines switching values pulse-to-pulse
  - Ion injection line quads and deflectors
  - LEBT solenoid & deflectors
  - MEBT quads
  - Linac quads
  - HEBT quads & steerers

All CD-4 parameters have been demonstrated
(DOE requirement for project completion)

	CD-4 Performance	CD-4 Status
Species	Fe, Au	**Complete**
Intensity	3. 10^8 Au^{+32} /pulse 4. 10^8 Fe^{+20}/pulse	**3.7 x 10^8 Au^{+32} / pulse** **4.75 x 10^8 Fe^{+20} / pulse**
Charge-to-mass ratio (Q/m)	0.162 (Au) 0.357 (Fe)	**Complete**
Repetition rate	Demonstration of pulsing	**Complete**
Pulse width	10-40 μs	**Complete**
Switching time between species	Demonstration of switching	**Complete**
Output energy	2 MeV/amu	**Complete**

Plan for FY 2011 RHIC & NASA Running

- For further commissioning during the FY 2011 run, pulses from EBIS can be injected and accelerated in Booster <u>in parallel</u> with RHIC and NASA operation from Tandem.
- EBIS will provide He and Ne beams to NASA this Fall. Tandem will continue to provide the other beams for the Fall NASA run.
- Gold for RHIC will be tested / developed during the spring Au run.
- EBIS may provide a short run of Uranium for RHIC in the spring.

- Ramp-up of the preinjector intensity (~ factor of 10)
  - Full bake of EBIS
  - Transmission improvements
  - Routine operation at 10A electron beam
  - Increase of injected ion intensity (slow injection)

Summary

ELECTRON BEAM ION SOURCE

- All systems are operating, and performing as expected
  - good agreement between measurements and simulations
- EBIS has operated continuously for multi-day shifts; also, the full preinjector can be started up in ~1 hour
- He^{1+}, Au^{32+} and Fe^{20+} beams were transported to Booster, and helium was circulated in Booster
- Au/Fe back/forth switching every 2 seconds
- All CD-4 requirements (for project completion) have been achieved.
- Full design parameters (platform voltage, rf powers, magnet currents, etc.) are met routinely, except for full electron current and rep rate
  - no show-stoppers or new hardware needed, just further time
- Next phase is ramp-up of intensity

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