# Brookhaven EBIS program: operation and development

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**Brookhaven National Laboratory**

**CERN**

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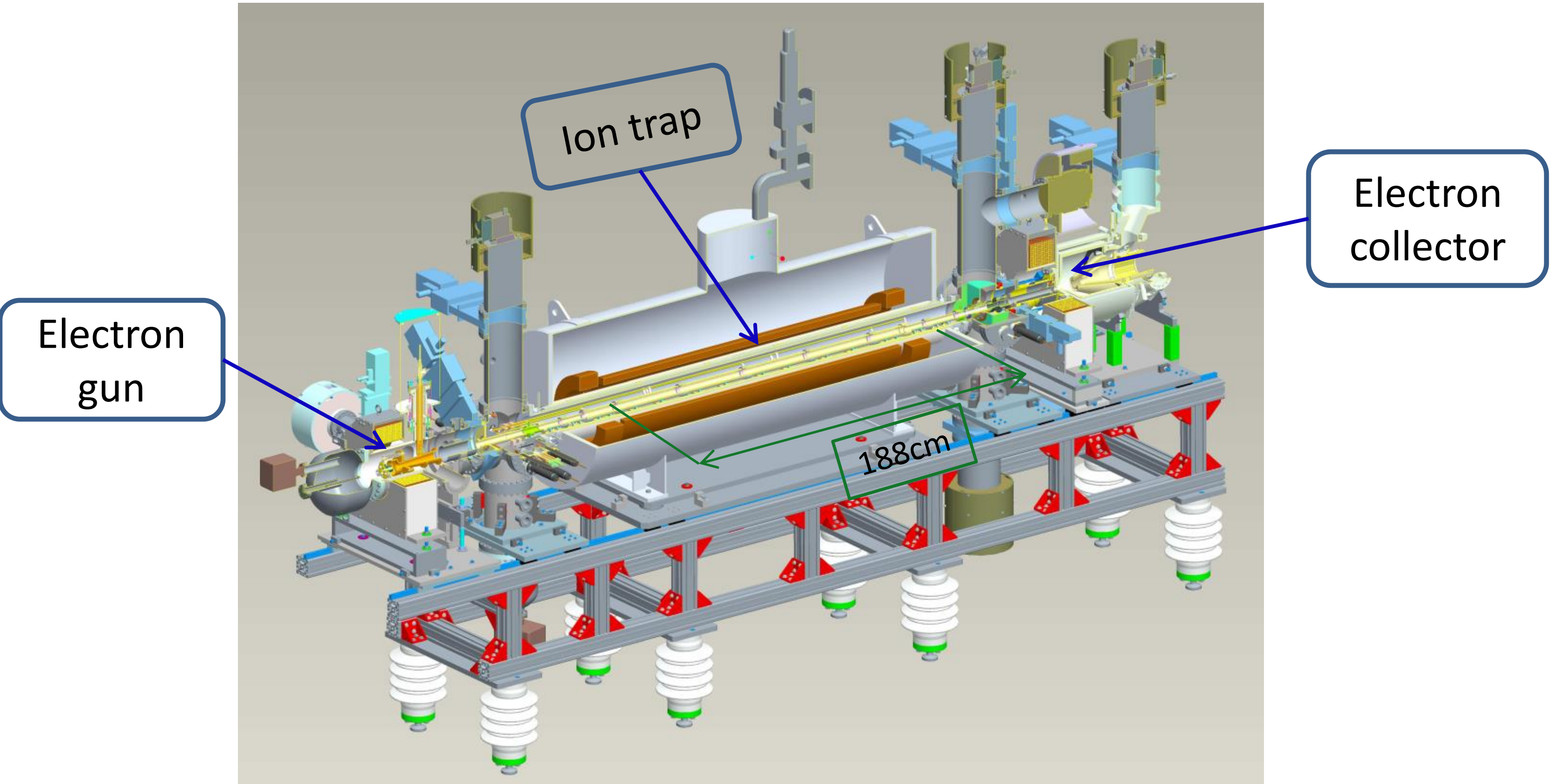
# RHIC EBIS: overview




RHIC EBIS parameters:

- $I_{el}$ = (7 – 10) A
- $E_{el}$ = (20 – 24) kV
- $j_{el}$ = (300 – 500) $A/cm^2$
- $L_{trap}$ = 1880 mm (increased from initial 1500mm, $\Delta B/B$=20%)
- $B_{trap}$ = 5 T
- $Q_{trap\_max}$ =220 nC (for 10A, 20 kV)

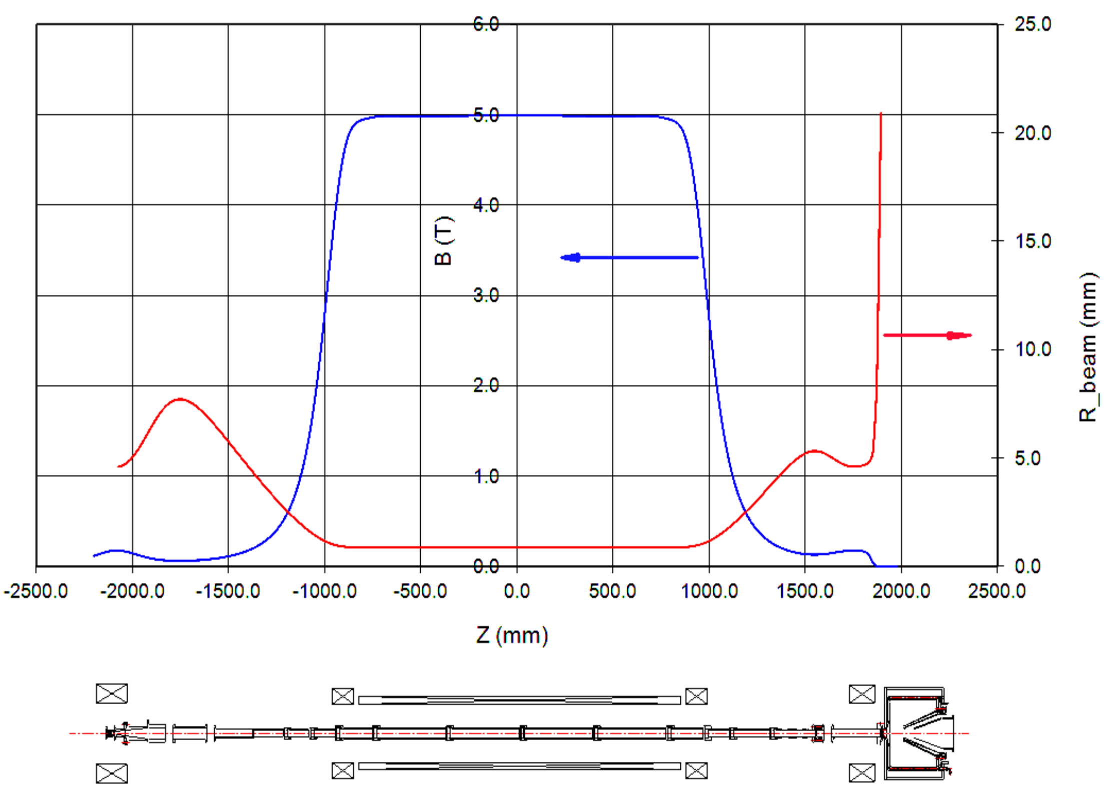
<u>**Optical system of RHIC EBIS**</u>

RHIC EBIS magnetic and electrostatic structures are based on its prototype: Test EBIS.

- Separate magnetic control of ionization region, electron gun and electron collector regions.

It provides good vacuum conductance from pumps to the central region in a conventional ("warm") vacuum system and a good voltage hold-off for high-voltage leads.

- Immersed electron beam: the cathode of the gun is in a strong magnetic field (1.4 kGs), the electrons propagate along magnetic field lines, the magnetic flux is conserved within the beam cross-section.

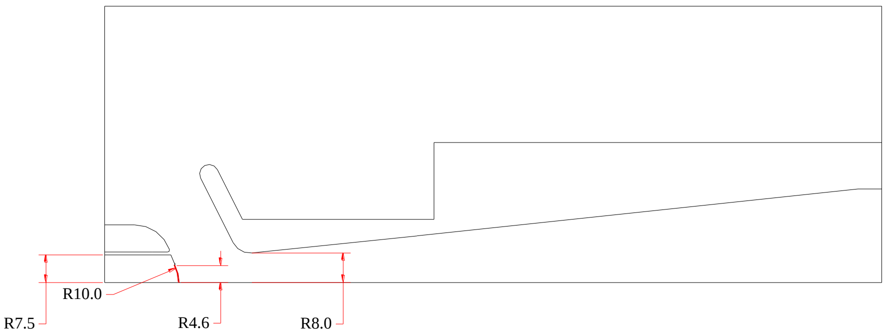



$$r(z) = r_c \cdot \sqrt{\frac{B_c}{B(z)}}$$

$$j_{el}(z) = j_c \cdot \frac{B(z)}{B_c}$$

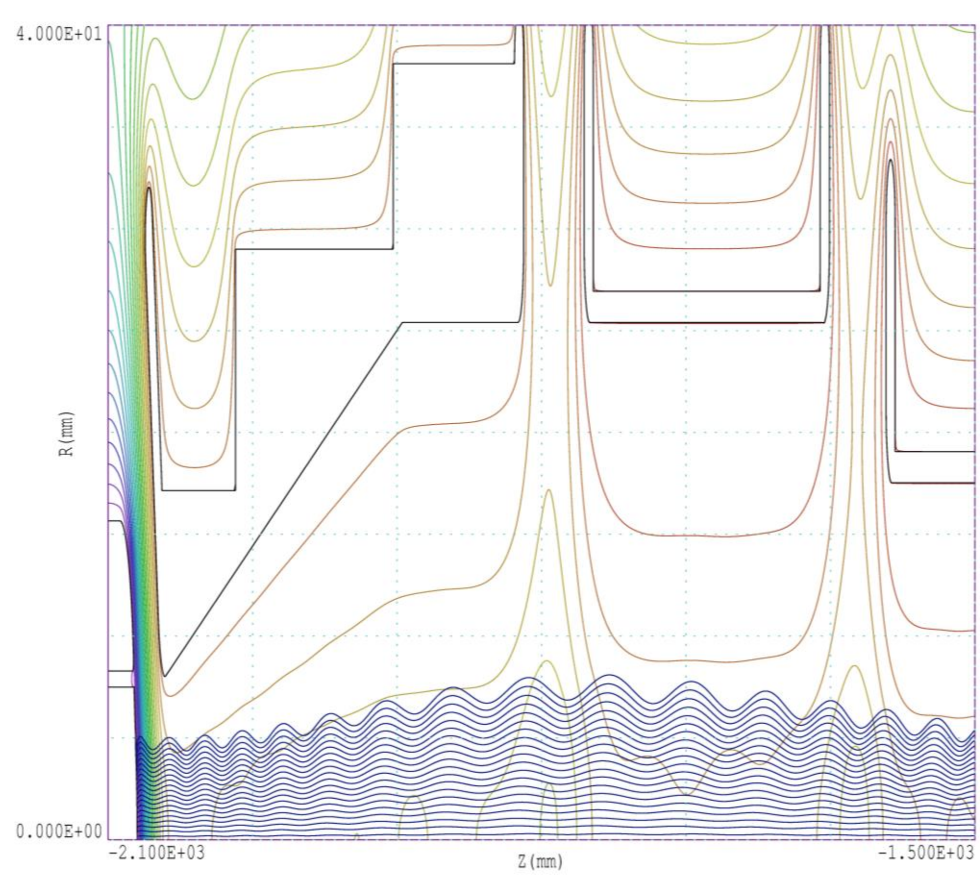
# Electron gun simulations

Electrostatic model:

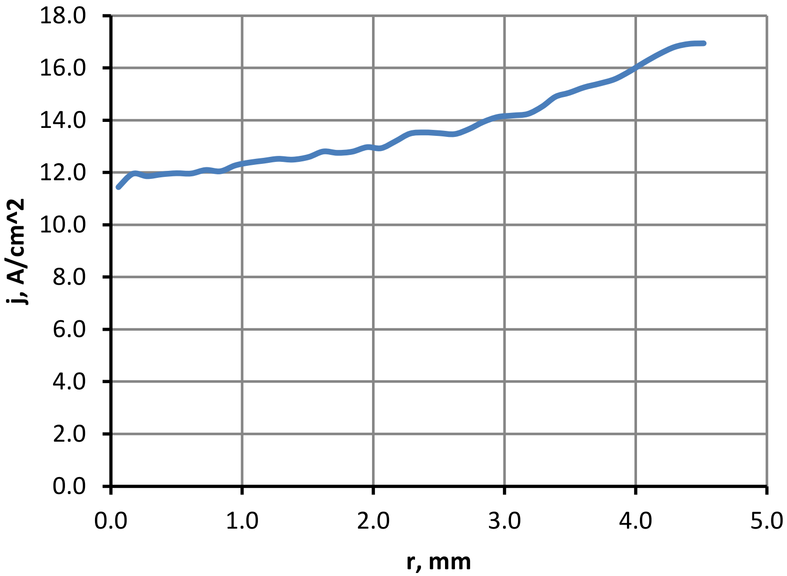



Simulated trajectories

$I_{el}$=10A, $P_{\mu}$=2.6, $B_{cath}$=1.4 kGs

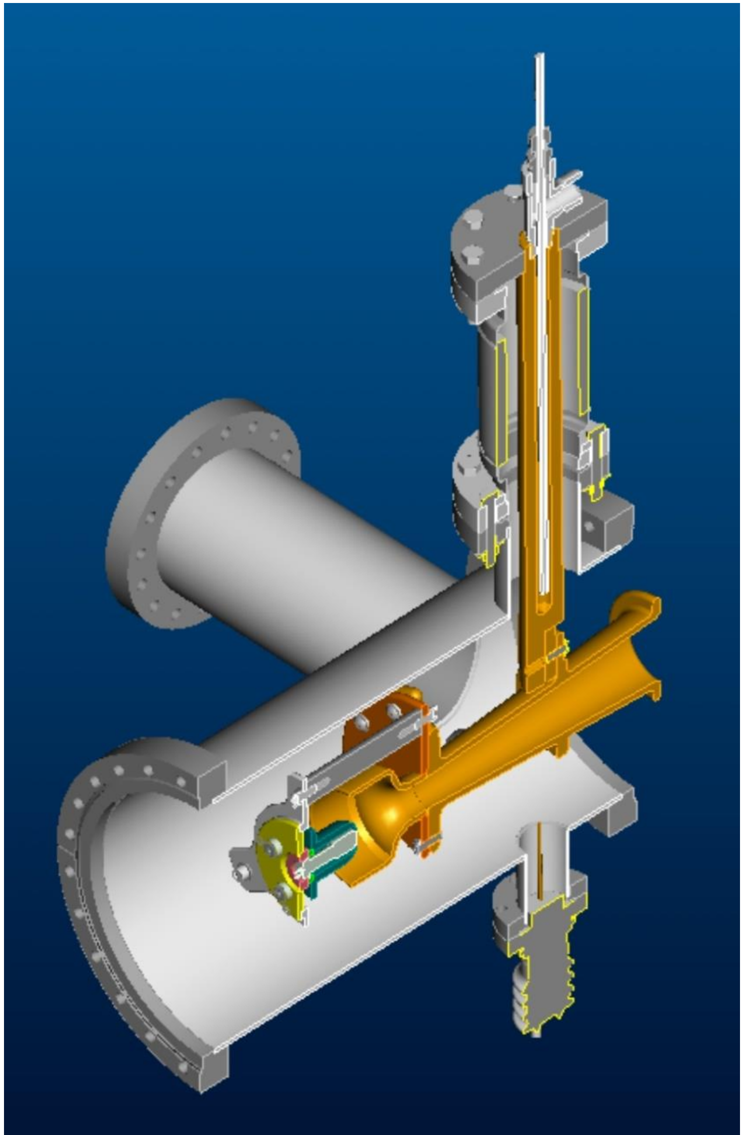



Simulated emission current density distribution. $I_{el}$ = 10 A.



# Electron gun design

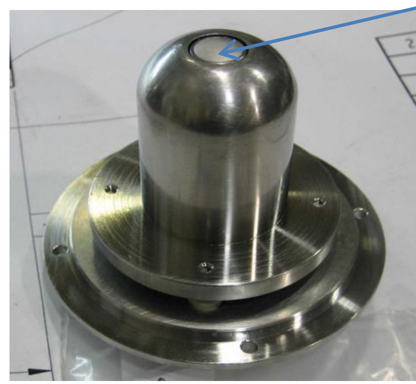
Electron gun in its chamber



Gun assembly

Cathode unit

IrCe cathode

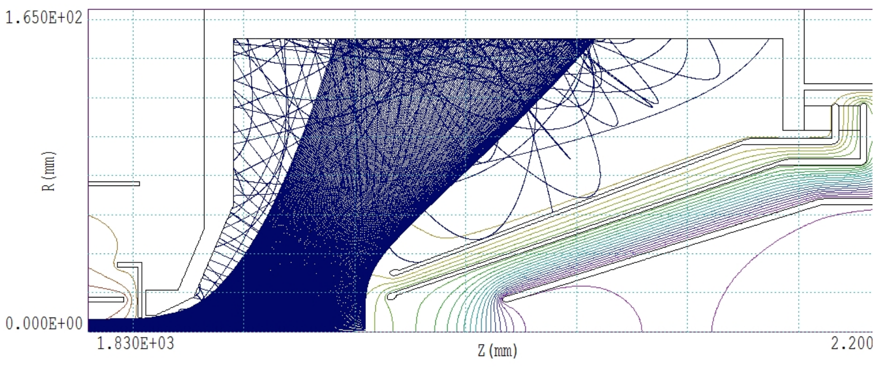


We replace cathodes once a year during maintenance works as a precaution

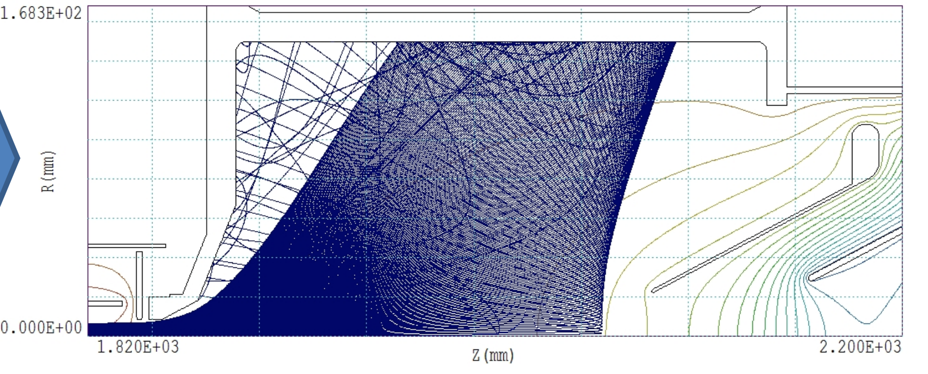
## Electron collector

Maximum electron beam power to the collector: 300 kW (20Ax15 kV)

Previous version of the electron collector




Present version of the electron collector

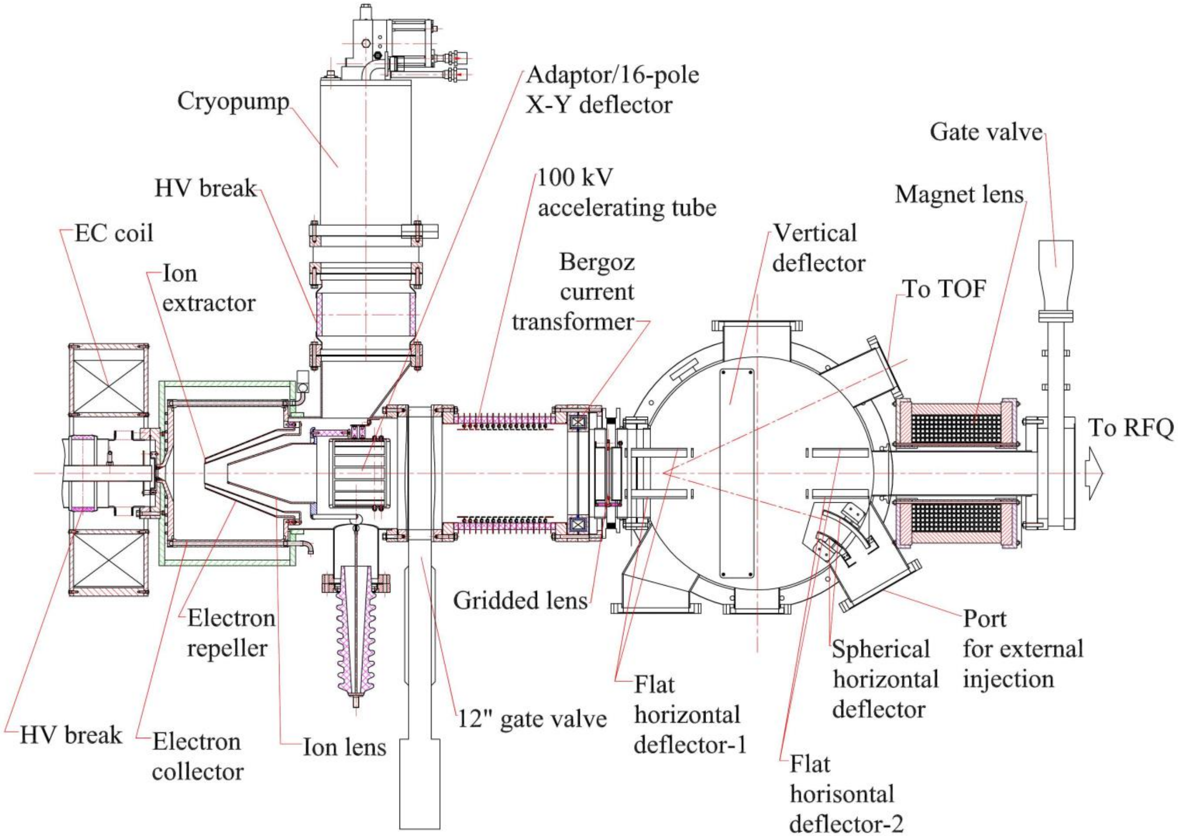



The purpose of modification was to eliminate the heating of the internal electrode inside the electron collector.

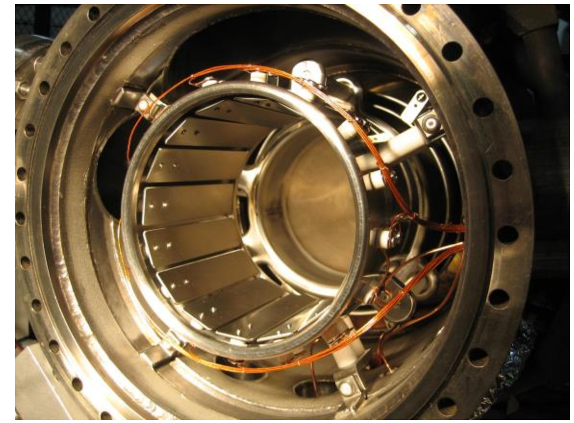
Relatively small change of optics practically preserved the ion beam transmission and the effect on its emittance.

# Ion optics

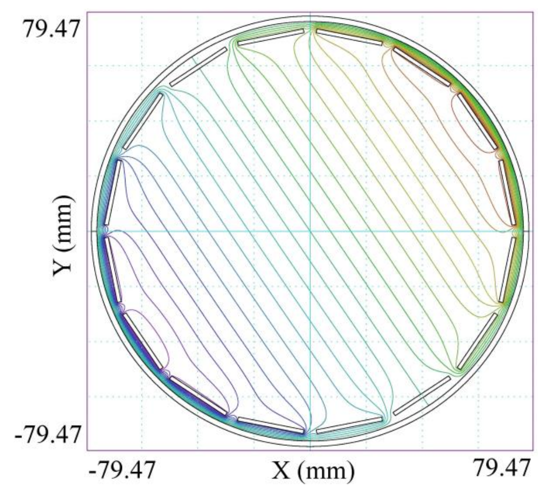
Structure of RHIC EBIS ion optics



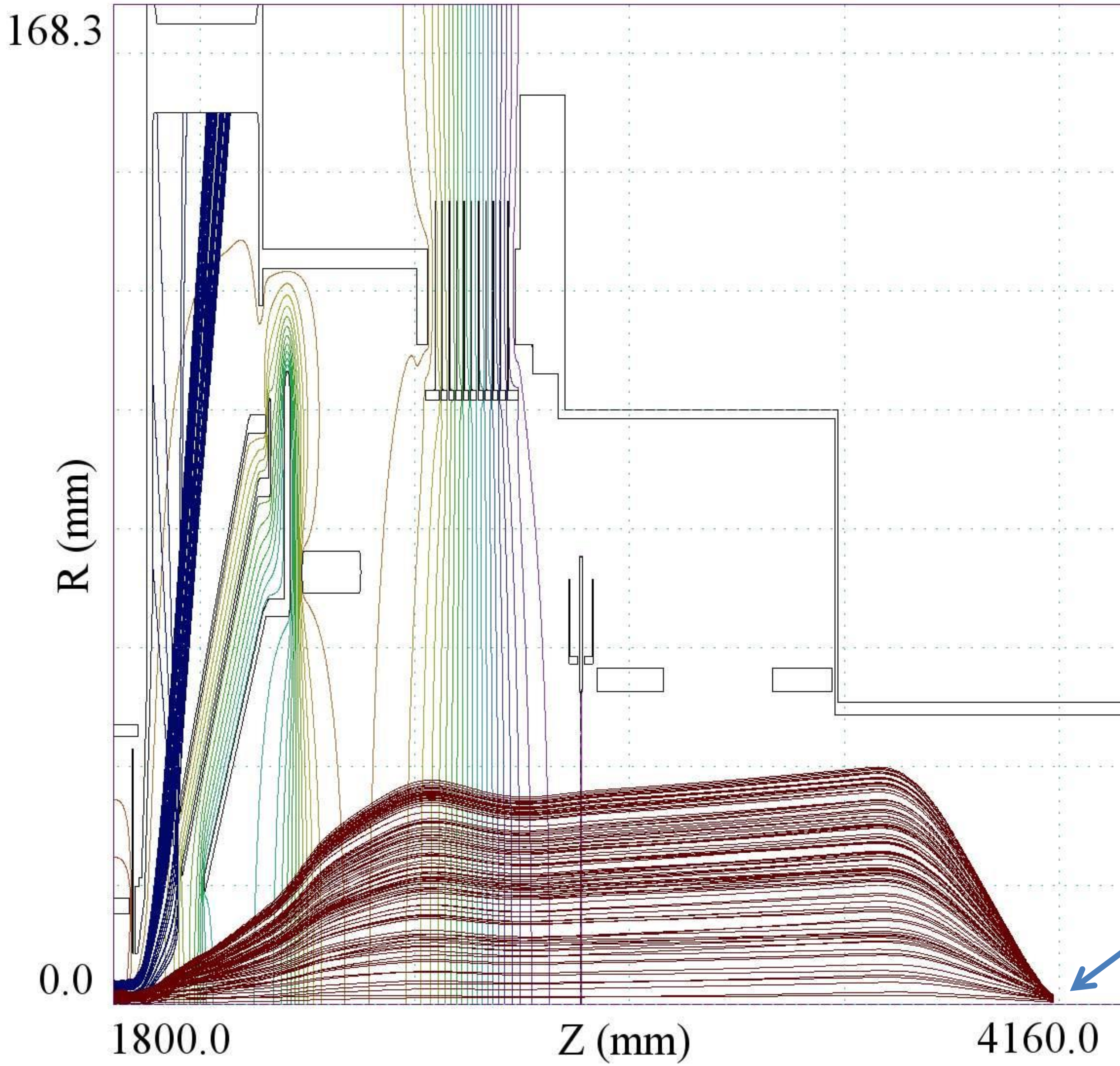

16-pole adaptor-deflector



Electrostatic field distribution
Inside 16-pole adaptor-deflector



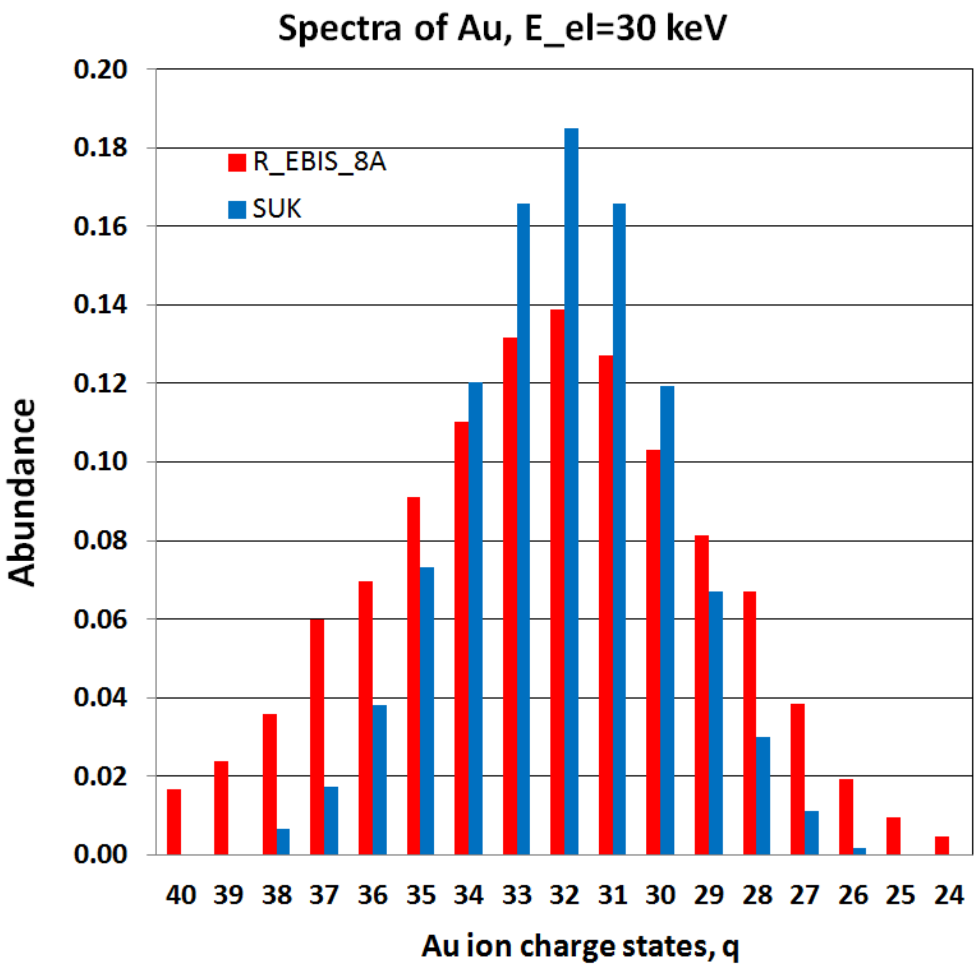
## Ion extraction simulations




$Au^{32+}$
$I_{el}$ = 15.0 A,
$I_{ion}$ = 3.0 mA

Entrance into RFQ

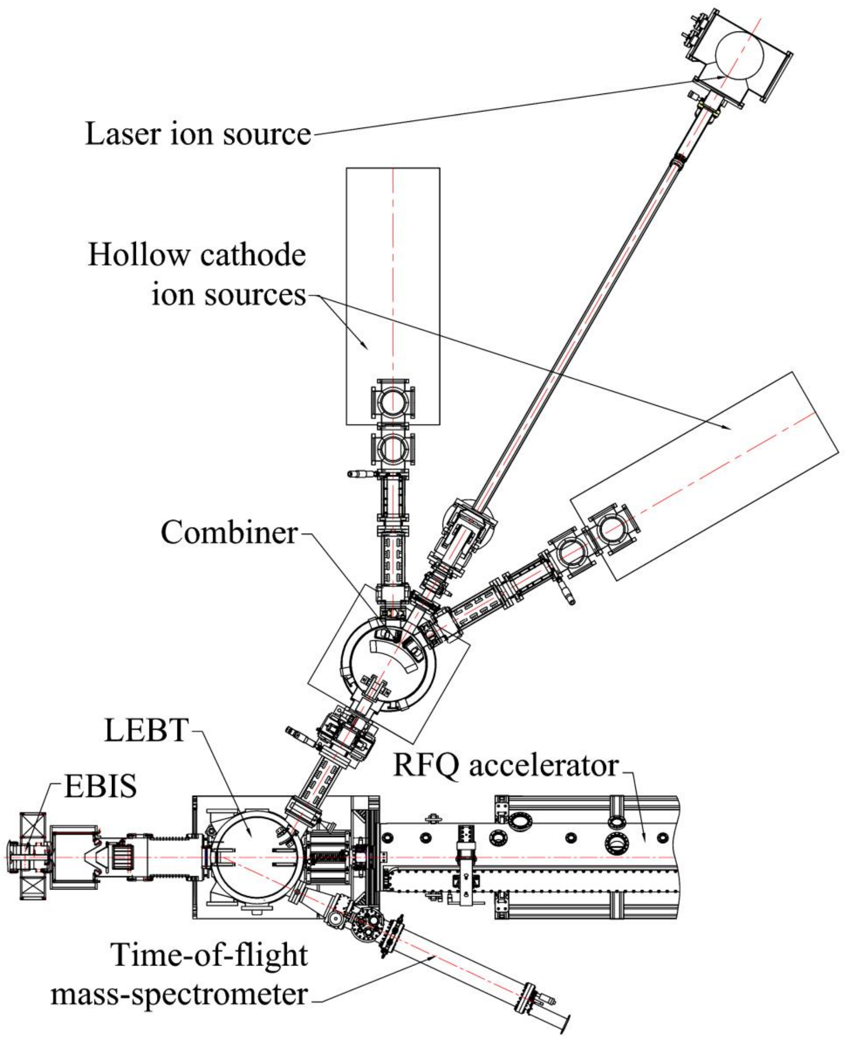
# Ion charge state distribution



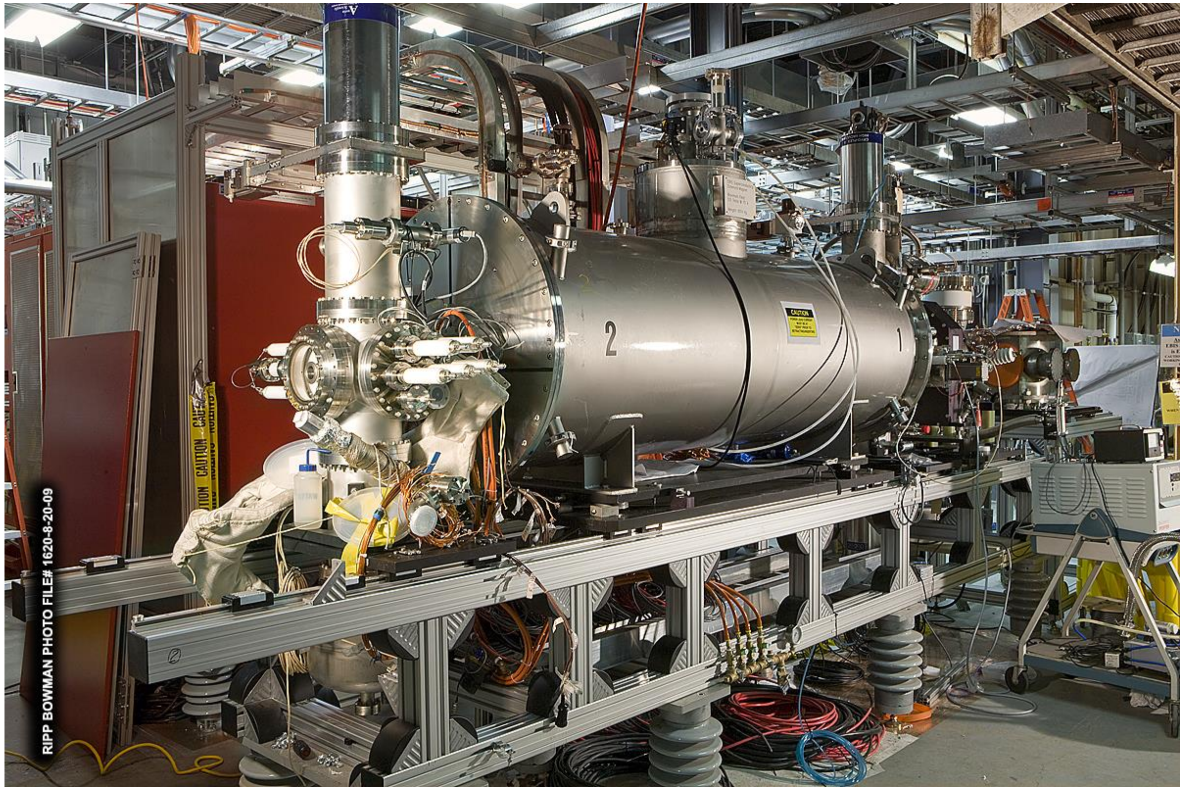

The width of the ion charge state distribution depends on the degree of neutralization of the electron beam in the trap. For the neutralization higher than 25% it is broader than predicted by the model of successive ionization (SUK, CBSIM).

The abundance of $Au^{32+}$ drops from 18% to 12%.

Schematic of ion optics for external ion injection




3 external ion sources allow us to switch ion species in 0.2 seconds using electrostatic ion optics.
The laser Ion source came in line this year and proved to be a versatile and reliable primary ion source.




After its commissioning in September of 2010 RHIC EBIS routinely supplies multicharged ions to RHIC accelerating facility.
The main users are RHIC and NASA Research Laboratory (NSRL).
While RHIC takes ion beams from EBIS only during its run, NSRL uses beams from EBIS most of the time.

## Ion beams from RHIC EBIS to users

| | | |
|---|---|---|
| He-3 | 2+ | AGS |
| He-4 | 1+, 2+ | RHIC & NSRL |
| C | 5+ | NSRL |
| O | 6+ | NSRL |
| Ne | 5+ | NSRL |
| Si | 11+ | NSRL |
| Ar | 11+ | NRSL |
| Ti | 18+ | NSRL |
| Fe | 20+ | NSRL |
| Cu | 11+ | RHIC |
| Kr | 18+ | NSRL |
| Xe | 27+ | NSRL |
| Ta | 38+ | NSRL |
| Au | 32+ | RHIC & NSRL |
| Pb | 34+ | AGS |
| U | 39+ | RHIC |

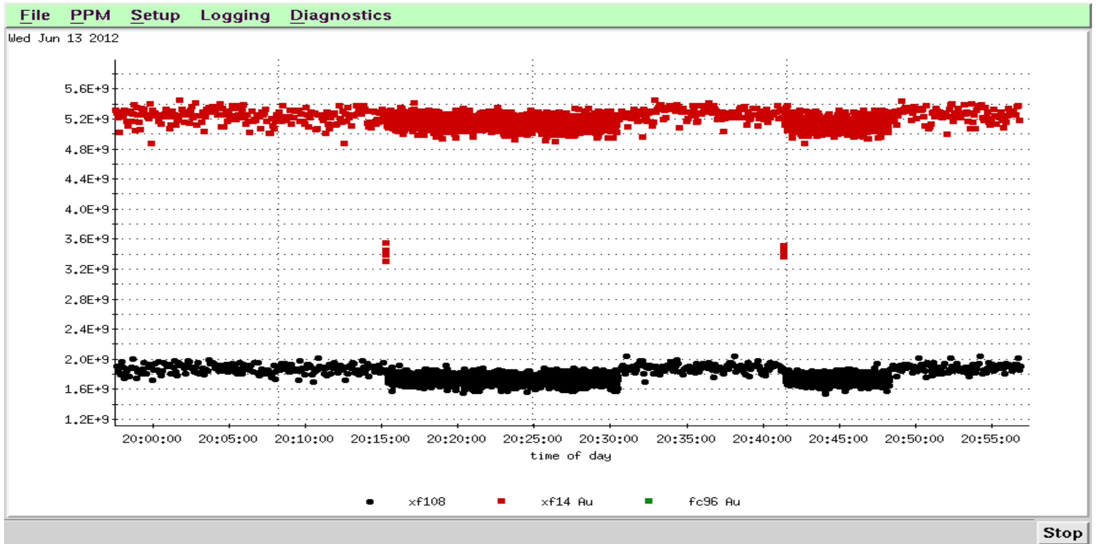
Gas injection (He-3, He-4)

To date ions of 16 elements, 18 ion species have been delivered to accelerator for users

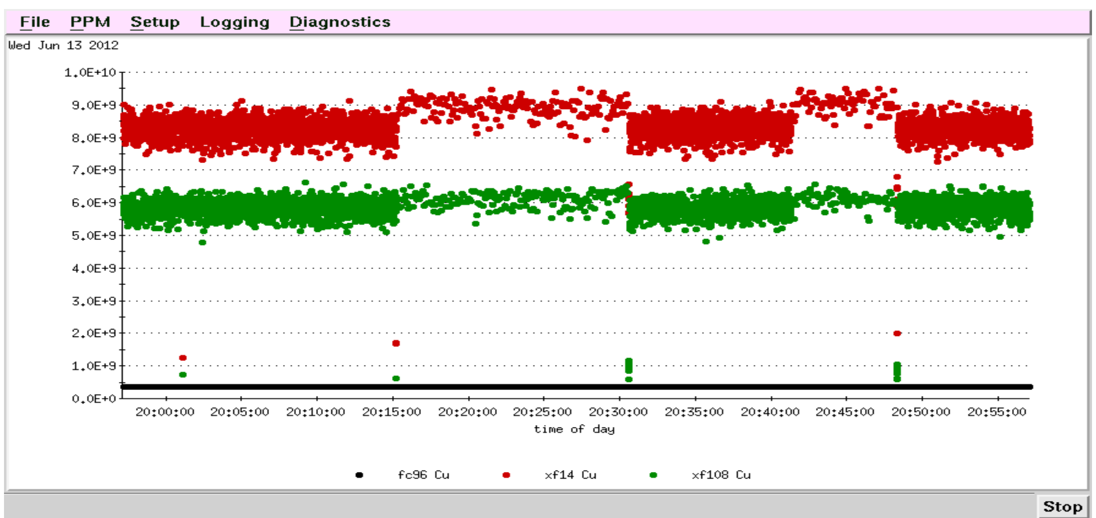
2.3E9 ions/pulse from EBIS (Au)

# Cu-Au run: beam intensity traces

Au




Cu




Two regimes of RHIC EBIS operation:

For RHIC run EBIS produces 8 pulses with frequency 5 Hz in each supercycle (4-5 s)during the rings fill.

Between fills RHIC EBIS either runs for NSRL (1 pulse per supercycle) or runs for itself with 1 pulse per supercycle, just to keep EBIS ready for fills.



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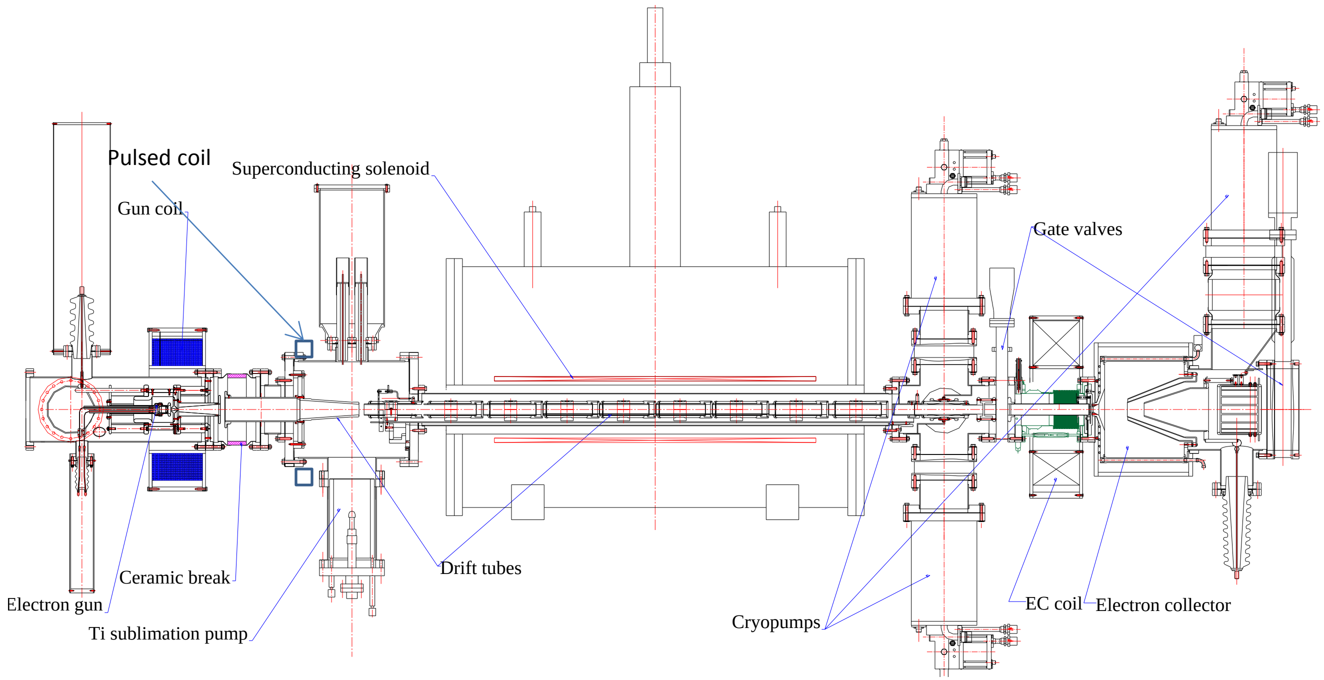
# Vital EBIS data

1. Total extracted ion charge from EBIS is typically > 100 nC/pulse (6.25E11 el. charges).
2. Only the gun cathode requires regular replacement (once a year, just as a precaution).
3. Liquid Helium refill in Superconducting solenoid is done every 25 days and takes approx. 1.5 hours.
4. Small maintenance works (cryo-pump regeneration, flushing the Ti sublimation pumps) are usually done during RHIC stores and do not affect the RHIC schedule.
5. The most frequent stops were due to the electron collector and RFQ power supplies trips.
6. RHIC EBIS operation is fully automated. Even for runs with He - Au collisions, involving both He gas and Au ion injection and when substantial modification of vacuum system was necessary for each species, EBIS was running practically without operator interference.
7. The availability of the ion beam from EBIS during the RHIC run was 99.8%.

Both BNL and CERN are interested in developing of EBIS with high-current density electron beam:

1. Increase the ion charge state and therefore the ion energy after the BNL Booster for NSRL experiments.
2. Reduce the confinement time and therefore the contamination of the ion beam.
3. Reduce the power consumption and improve the vacuum conditions.
4. Possible reduction of the ion beam emittance due to a smaller electron beam radius .
5. Possibility of generating very high ion charge states for ISOLDE even for heavy elements.

The experiments with the new electron gun are done on BNL Test EBIS




This is essentially the original structure of the Test EBIS with few new elements:

- A new Brillouin electron gun.
- A new ceramic break replaced a gate valve between the gun and the rest of Test EBIS to isolate the gun chamber from the ground.
- Degraded superconducting solenoid has B= 3.5 T instead of 4.6 T.



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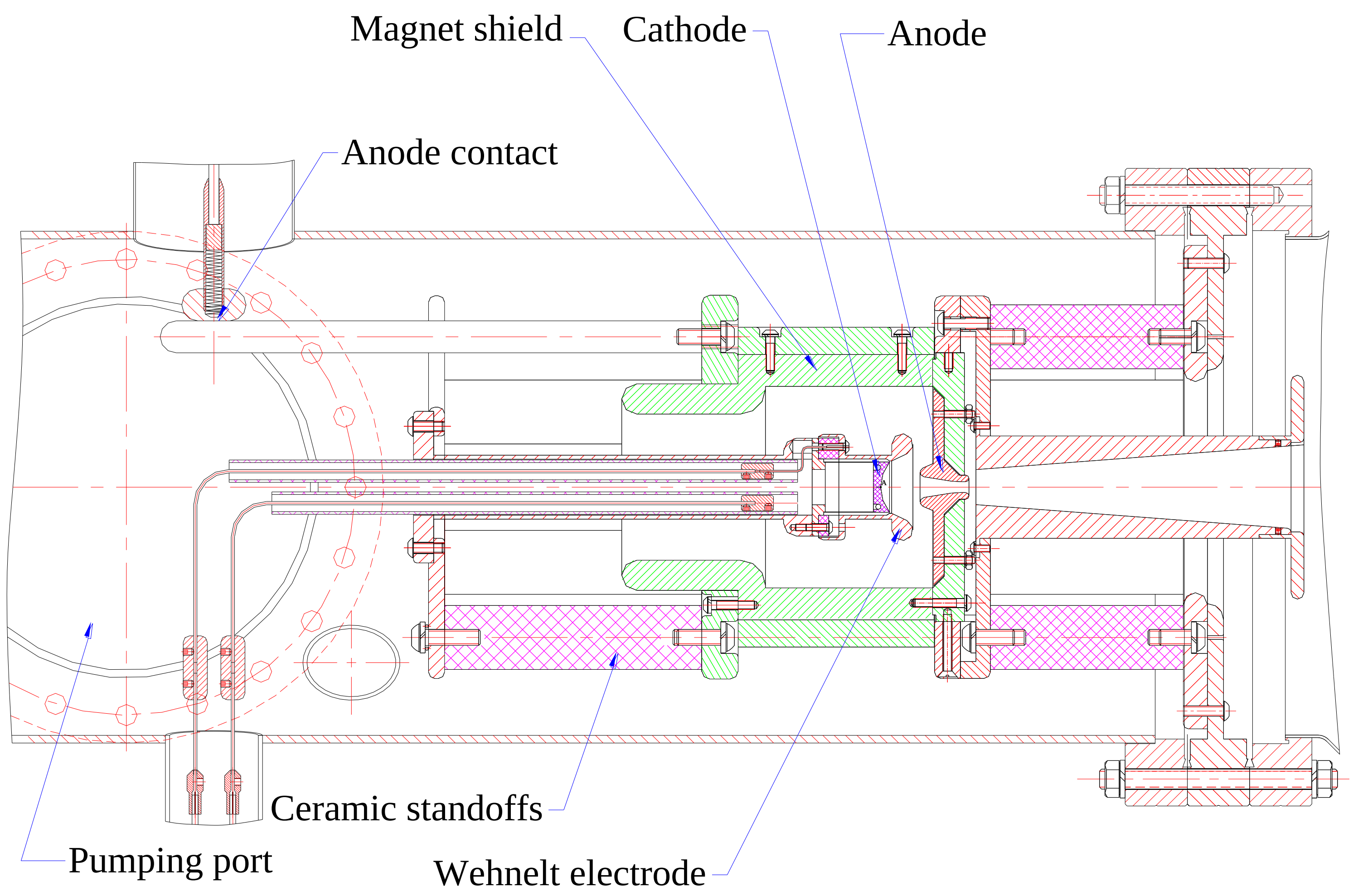
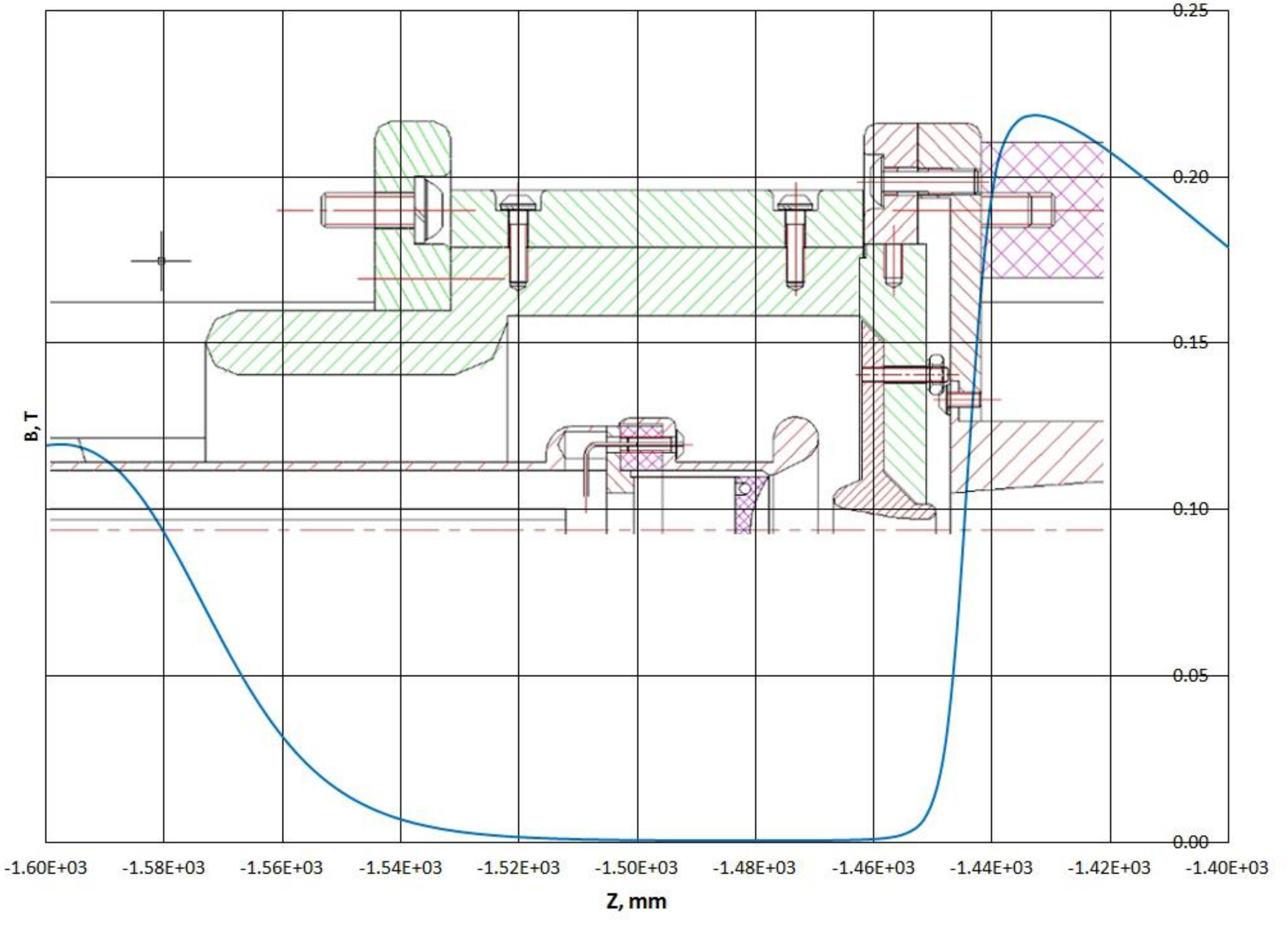
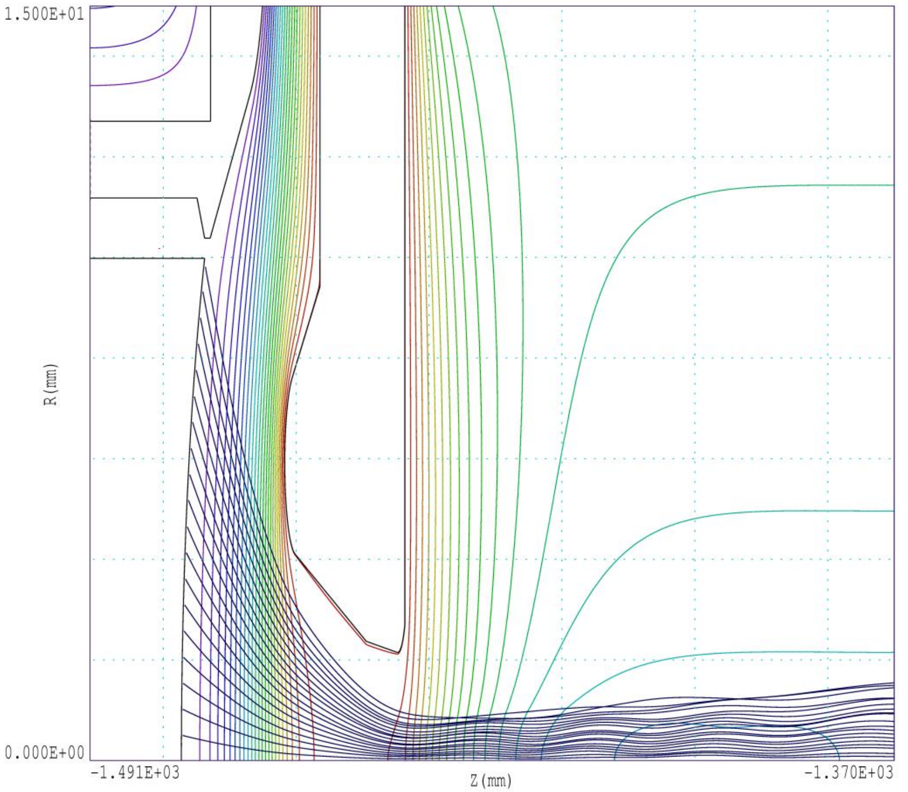
# Electron gun design



# Magnetic field distribution within the gun

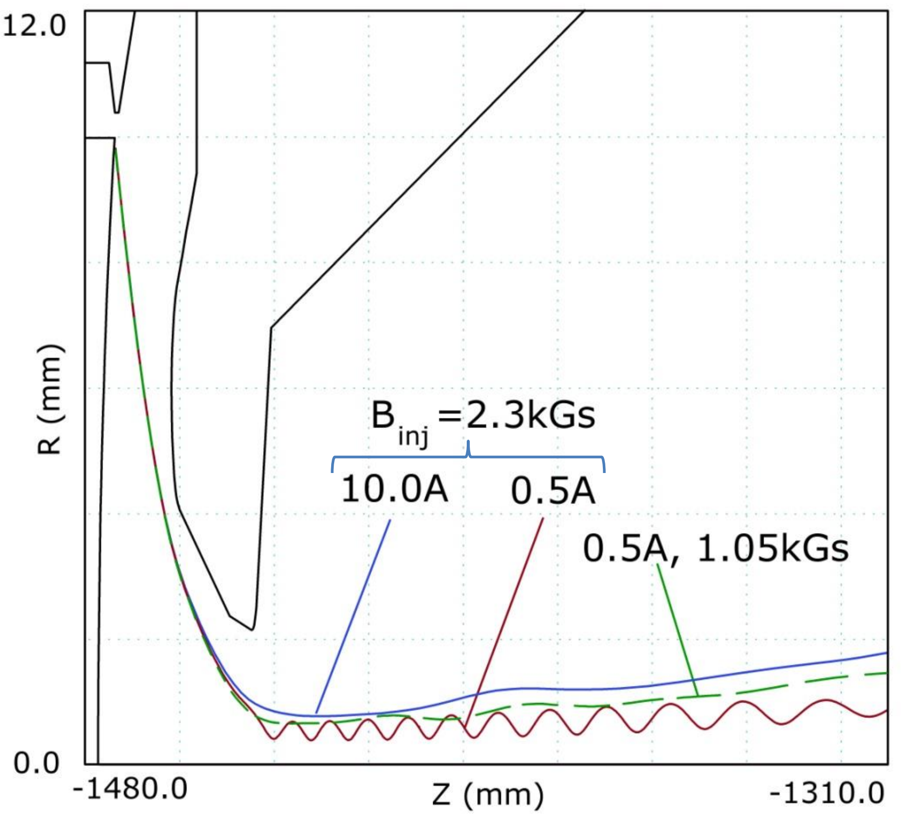


Electron beam with optimum magnetic field




$I_{el}$=8.0A, $U_{an}$ =41.8 kV, B=2.2 kGs

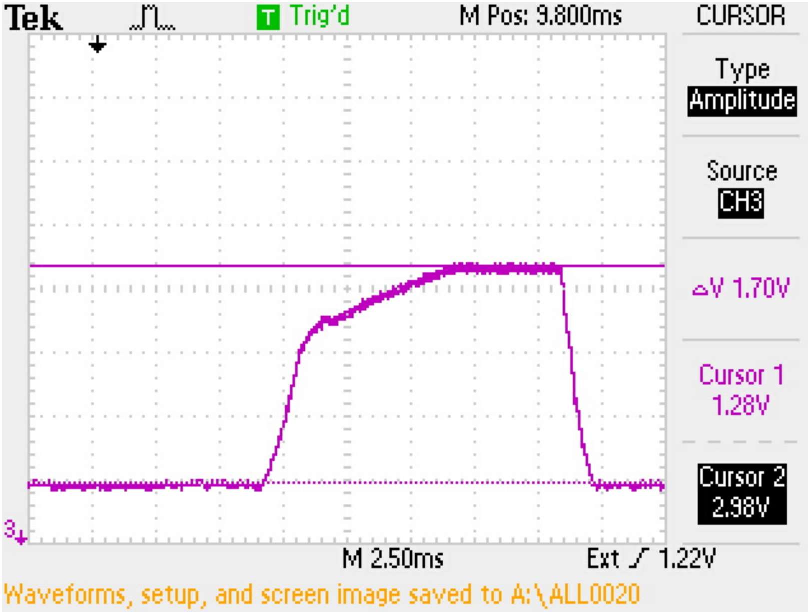
Radial oscillations at fixed magnetic field and different electron current



Experimental conditions:

1. We used a HeatWave dispenser cathode with diameter 20 mm.
2. Vacuum with hot cathode: $P_{gun\_chamber}$=($2\cdot10^{-8}$ – $1.4\cdot10^{-7}$) Torr, $P_{gun\text{-}transition}$ =($1\cdot10^{-8}$ – $3\cdot10^{-8}$)Torr
3. Wehnelt electrode is internally connected to the cathode.
4. Cathode heating current: (7.5 – 8.8) A (maximum of 72 watt).
5. Magnetic field of the main solenoid is B=3.5 T
6. The cathode of the gun is connected to the gun chamber: $U_{cath}$= $U_{gun\_chamber}$=-10 kV

## Results of experiments with electron beam transmission




Trace of the electron beam current on a collector CT (0.5 A/div)

$I_{el}$=1.7 A,
$U_{an}$=15.6 kV,
$P_{beam}$=0.87E-6A/$V^{1.5}$

1. Maximum electron current transmitted to the electron collector is 1.7 A
2. With higher electron current  the beam loss on anode reaches 20 mA, which is a current limit for TREK 20/20. It seems such load is manageable and outgassing from the anode can be reduced by training. Which means that a power supply with higher acceptable load can be used for the anode.
3. With sufficient heating power the perveance of the electron gun is $P_{exp}$ =0.93E-6 A/$V^{1.5}$ (simulated value $P_{sim}$ = 0.934E-6 A/$V^{1.5}$)

Observations:

1. Best electron beam transmission requires maximum available voltage on drift tubes inside the superconducting solenoid (DT4-DT9) (up to 20 kV): requires highest electron energy.

2. Strong dependence of the beam transmission on the gun coil current with the best coil current close to the simulated optimum for a running electron beam current (1.3 kGs).

3. Both potentials on the transition drift tubes (between the gun and SC the central drift tubes) and the current on a pulsed magnet coil in this transition region affect the electron beam transmission.

4. Our preliminary attempts to detect RF generation by the electron beam so far did not show any excitation in a range of (10 – 100) MHz (axial oscillations of the electron beam in the gun-transition region).

## Possible interpretation of the results

Our experimental results and observations give reason to believe, that the current load on the anode of the gun is caused primarily by reflecting of some primary electrons from the magnetic mirror at the entrance into the superconducting solenoid on their way to the trap:

$$r_{mirror} = \frac{B_{max}}{B_{min}}$$

Transmission cone: $\frac{v_\perp}{v_\parallel} < \frac{1}{\sqrt{r_{mirror}}} [< 0.17]$ (for $I_{el}$=1 A)

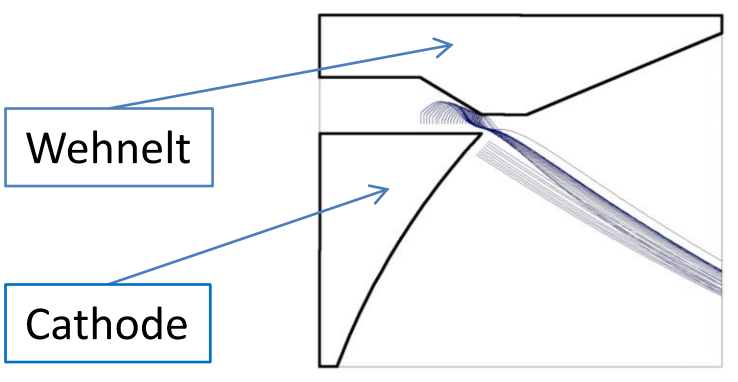
The electrons with larger angles are reflected back.
The most susceptible for reflection are the peripheral electrons with the largest angles.

Possible reasons of electron beam quality degradation in our case:

1. Axial movement of the gun parts due to thermal expansion (up to 1.5 mm). It can result in a not optimum position of the cathode with respect to the anode and magnetic shim, causing increase of radial oscillation.

1. Cathode edge aberrational effect with relatively large radial gap between the cathode and the Wehnelt electrode (0.4 mm).

2. Emission from the side of the cathode produces a beam component with large aberration and with current reaching several percents of the total beam:




Simulation for the existing conditions: $U_{Cath} = U_{Wehnelt}$

With existing magnetic and vacuum structures in Test EBIS the best way to increase current of the transmitted electron beam can be improving the electron beam quality – reducing the amplitude of radial oscillation.

1. Modify the electron gun: make the axial cathode position adjustable from outside to optimize the electron beam launch.
2. Disconnect the Wehnelt electrode from the cathode and have it energized independently.
3. Eliminate electron emission from the cathode periphery and increase the distance from the emission edge to the cathode-Wehnelt gap (make a sleeve on the cathode periphery).
4. Energize a pulsed coil in the gun-transition area with higher current, to be able to control the phase of the reflected electrons coming back to the anode.
5. Substantially Increase the injecting magnetic field on the gun (with accordingly higher electrostatic compression) to reduce the magnetic mirror.

## Summary

1. A Brillouin electron gun has been tested and electron beam up to 1.5 A has been transmitted to the electron collector. The anode load was the only beam loss component after EBIS tuning.

2. Based on our experimental data we can suggest, that the reason of the anode load is reflection of primary electrons from the magnetic mirror, caused by a combination of poor beam quality and high magnetic mirror ratio (16 – 27).

3. Modification of Test EBIS with a goal to increase the current of the transmitted electron beam according to our understanding of its physics is in progress.

4. The test of isolated gun vacuum chamber was a success. This method of suppressing the magnetron discharge by eliminating the radial electric field will be implemented in RHIC EBIS.

5. Experiments with ions from the residual gas started and confirmed a proper operation of the EBIS trap.