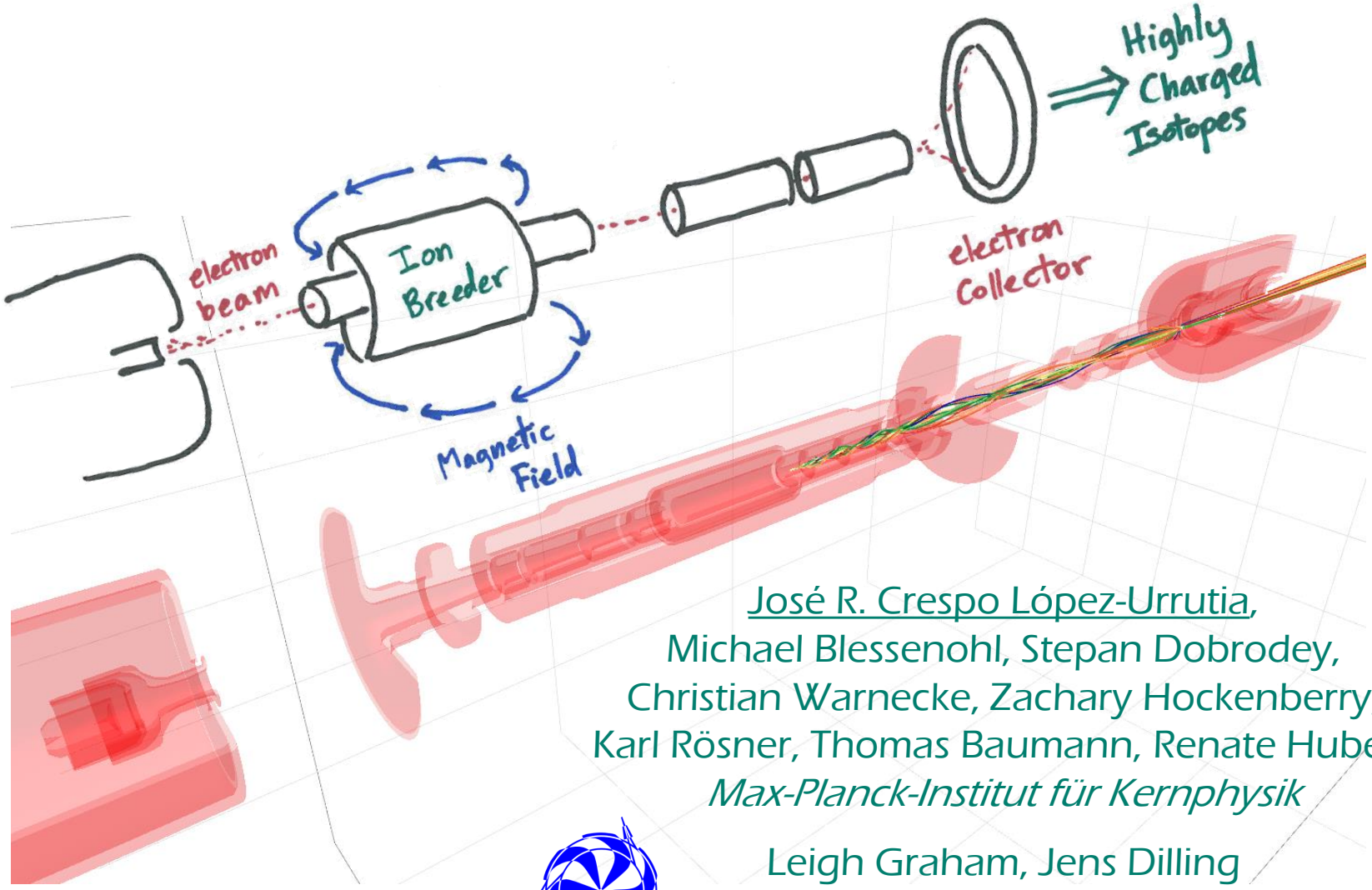
Design and test of the CANREB-EBIS



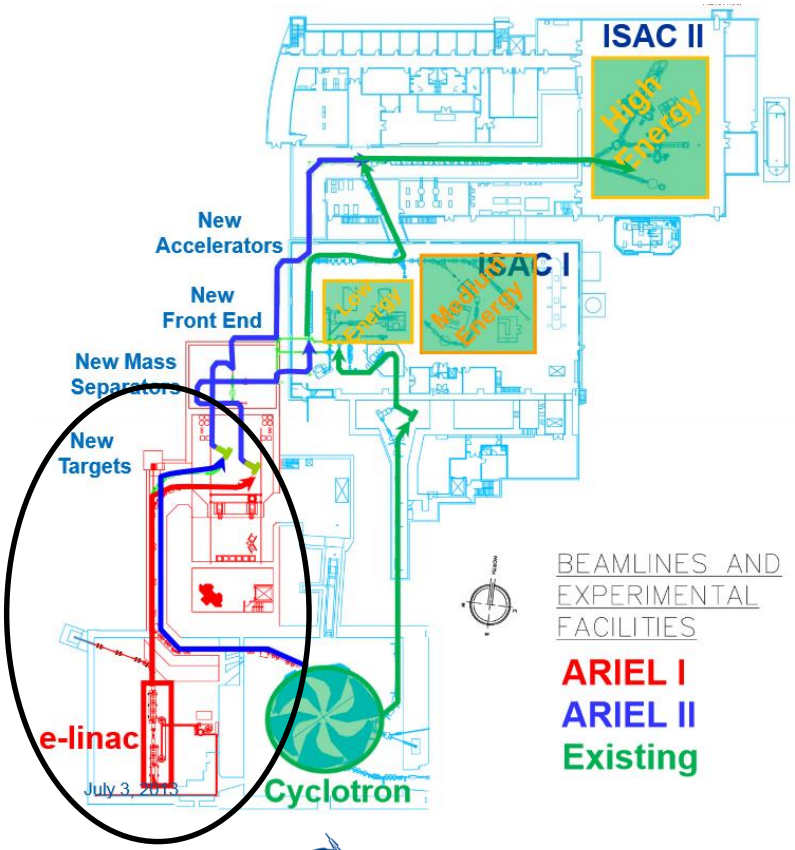
José R. Crespo López-Urrutia,
Michael Blessenohl, Stepan Dobrodey,
Christian Warnecke, Zachary Hockenberry,
Karl Rösner, Thomas Baumann, Renate Hubele
Max-Planck-Institut für Kernphysik

Leigh Graham, Jens Dilling
TRIUMF

ARIEL Extension

- Advanced Rare IsotopE Laboratory
- New facility to expand capabilities of TRIUMF

- E-linac (photo-fission)
  - Isotope distribution
  - Neutron heavy isotopes
  - More controlled

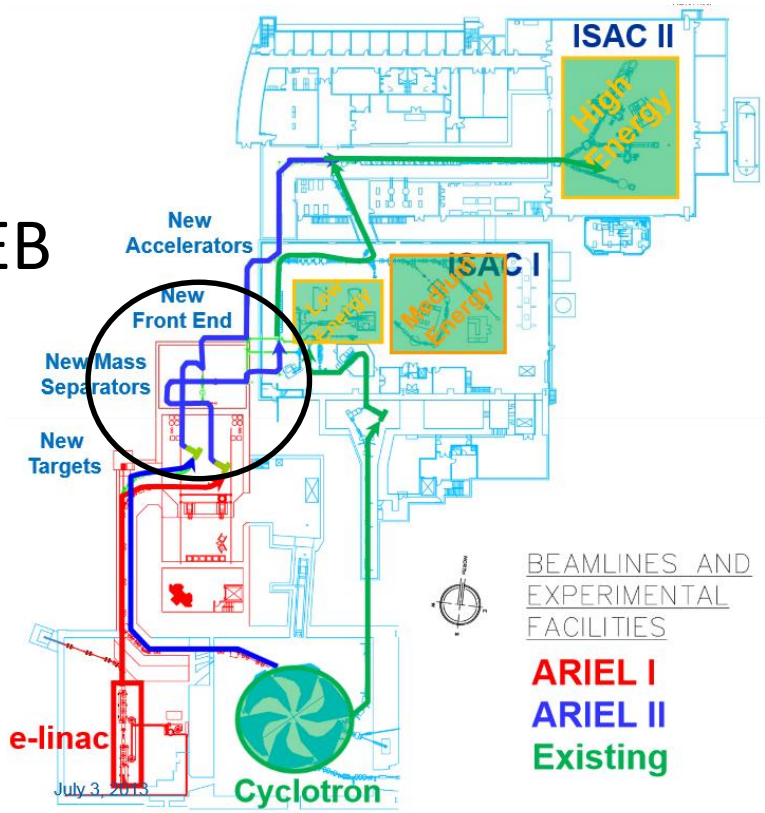


TRIUMF

ARIEL Extension

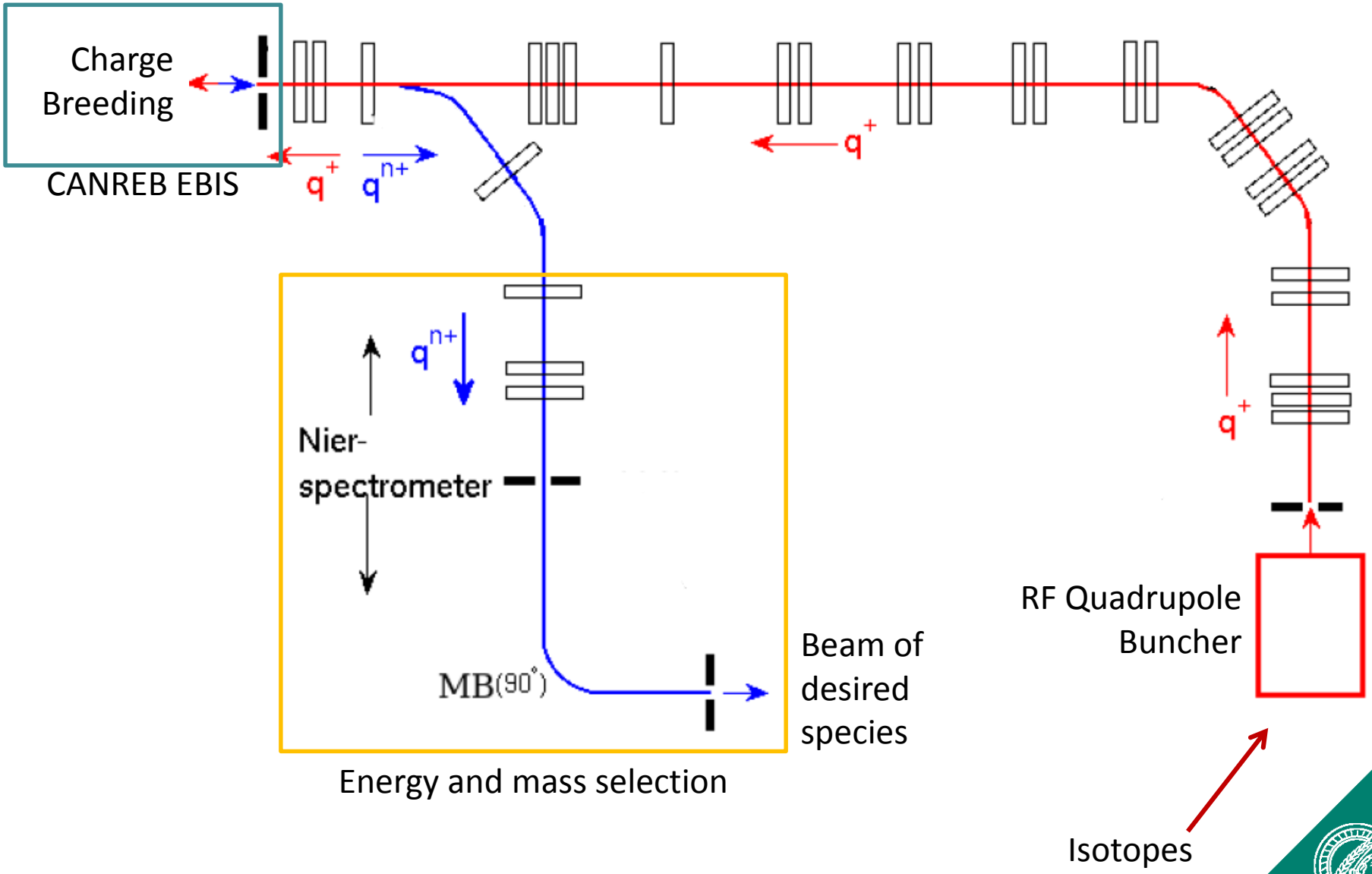
- Advanced Rare IsotopE Laboratory
- CANadian Rare isotope beam with EBIS
- Charge breeder and high resolution mass separator
  - Efficient filtering
  - Efficient post acceleration

CANREB

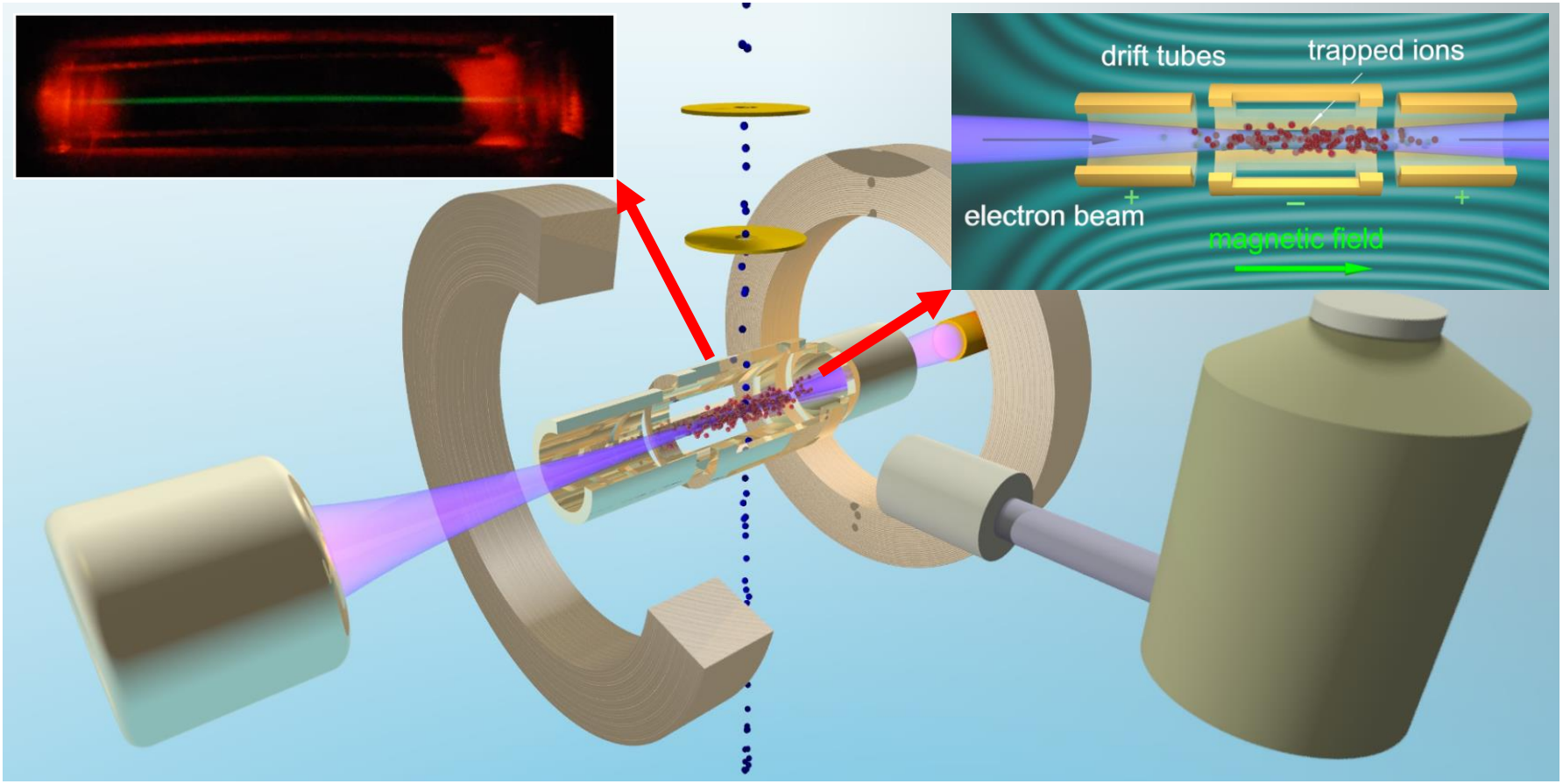


TRIUMF

CANREB

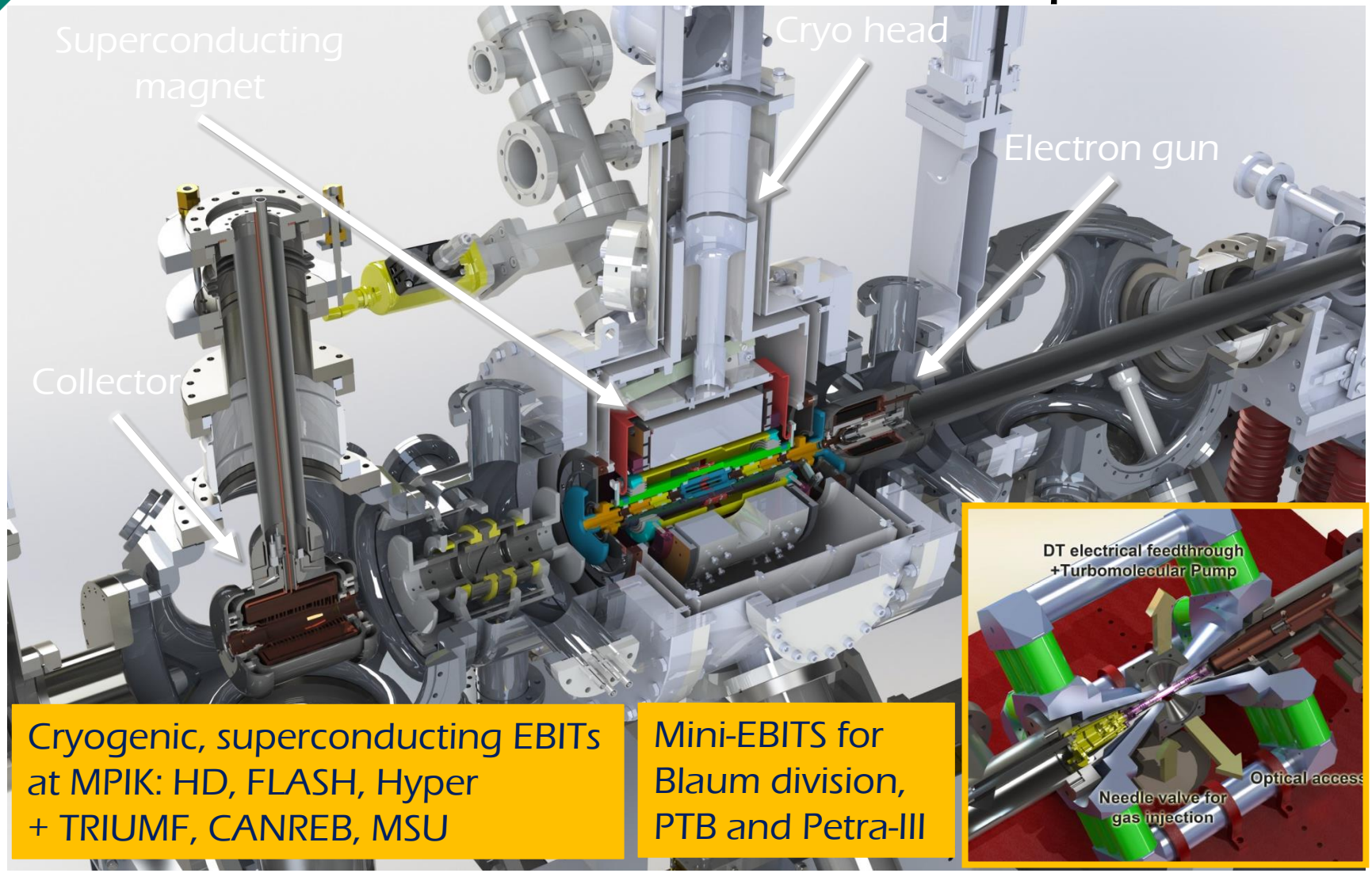


Electron Beam Ion Source (EBIS)



The cryogenic MPIK-EBIS are based on the MPIK-EBIT design and equipped with spectroscopic diagnostics

MPIK Electron beam ion traps



Cryogenic, superconducting EBITs at MPIK: HD, FLASH, Hyper + TRIUMF, CANREB, MSU

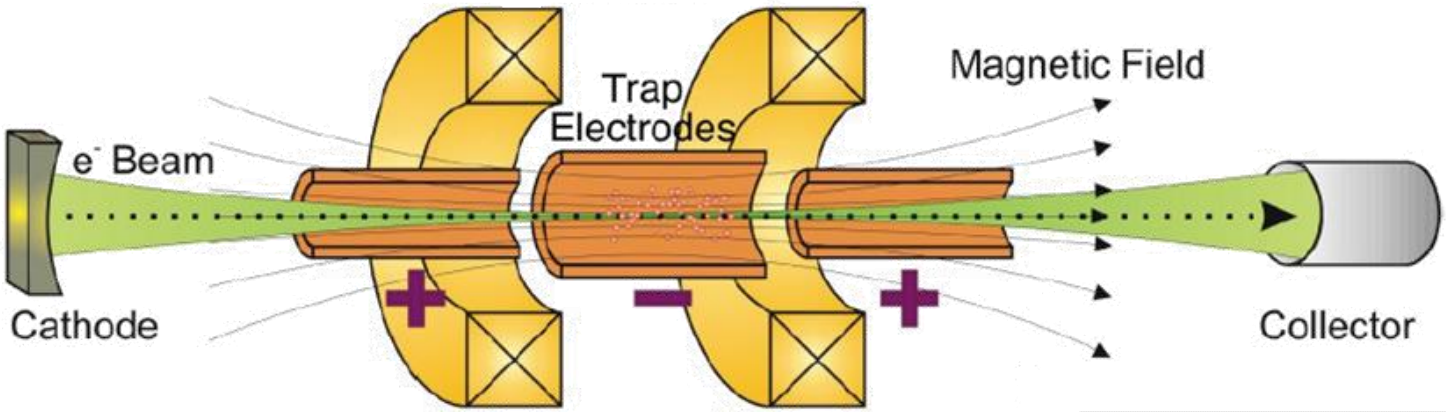
Mini-EBITS for Blaum division, PTB and Petra-III

- Facility at MPIK supports Pfeifer and Blaum division (
- Out of ~20 research EBITs worldwide, 10 are at or come from MPIK

Challenges and requirements

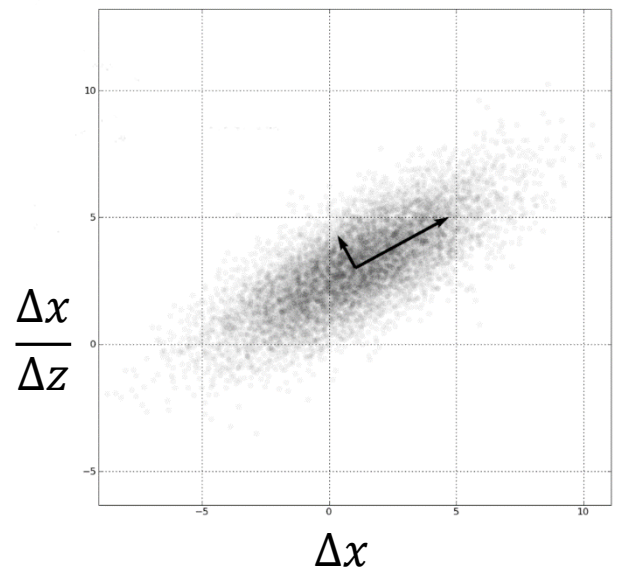
- ${}^{A}/_{Q} \leq 7$
- 10-20 % in charge state distribution
- 100 Hz repetition rate
- Isotopes with lifetimes down to few ms
- 10^6 ions/bunch, energy < 15 keV, long. length 1 µs, **90 % acceptance**
- **Emittance** energy < 14 keV $\times$ Q, energy spread d$E < 100$ eV, bunch up to 1 ms
- **EPICS controls**, compatible to TRIUMF control system

CANREB EBIS Requirements

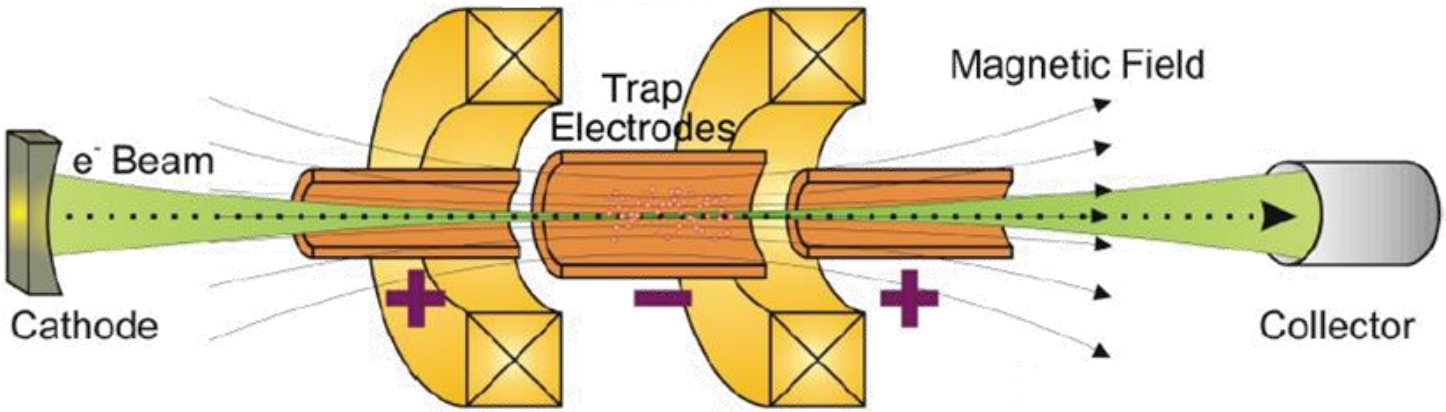


10^6 ions in bunch

- Accepts beams with a phase space area of 5π



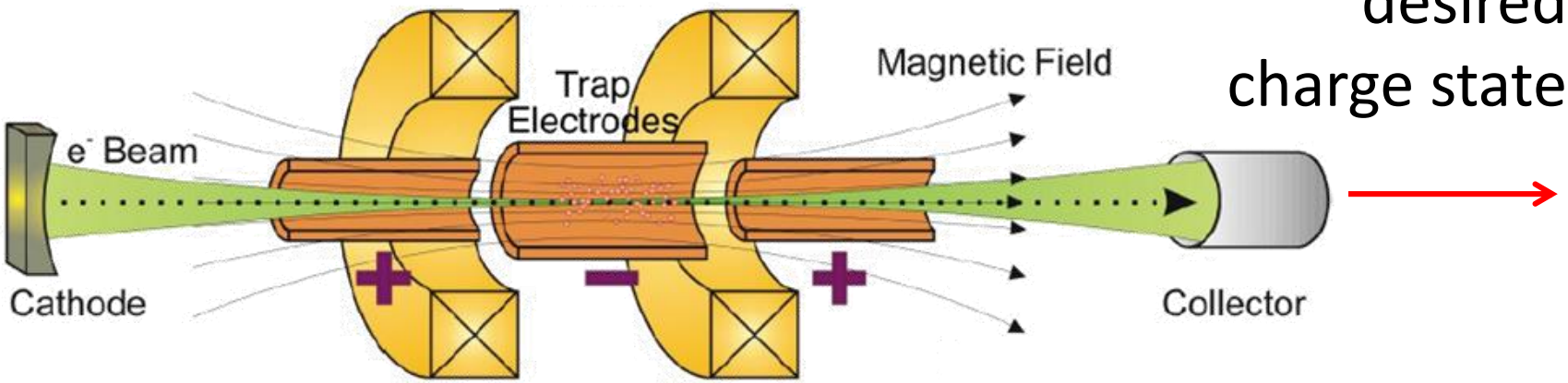
CANREB EBIS Requirements



- Must reach a mass-to-charge ratio ≤ 7 within 10 ms
- Charge state is about 6+ for potassium

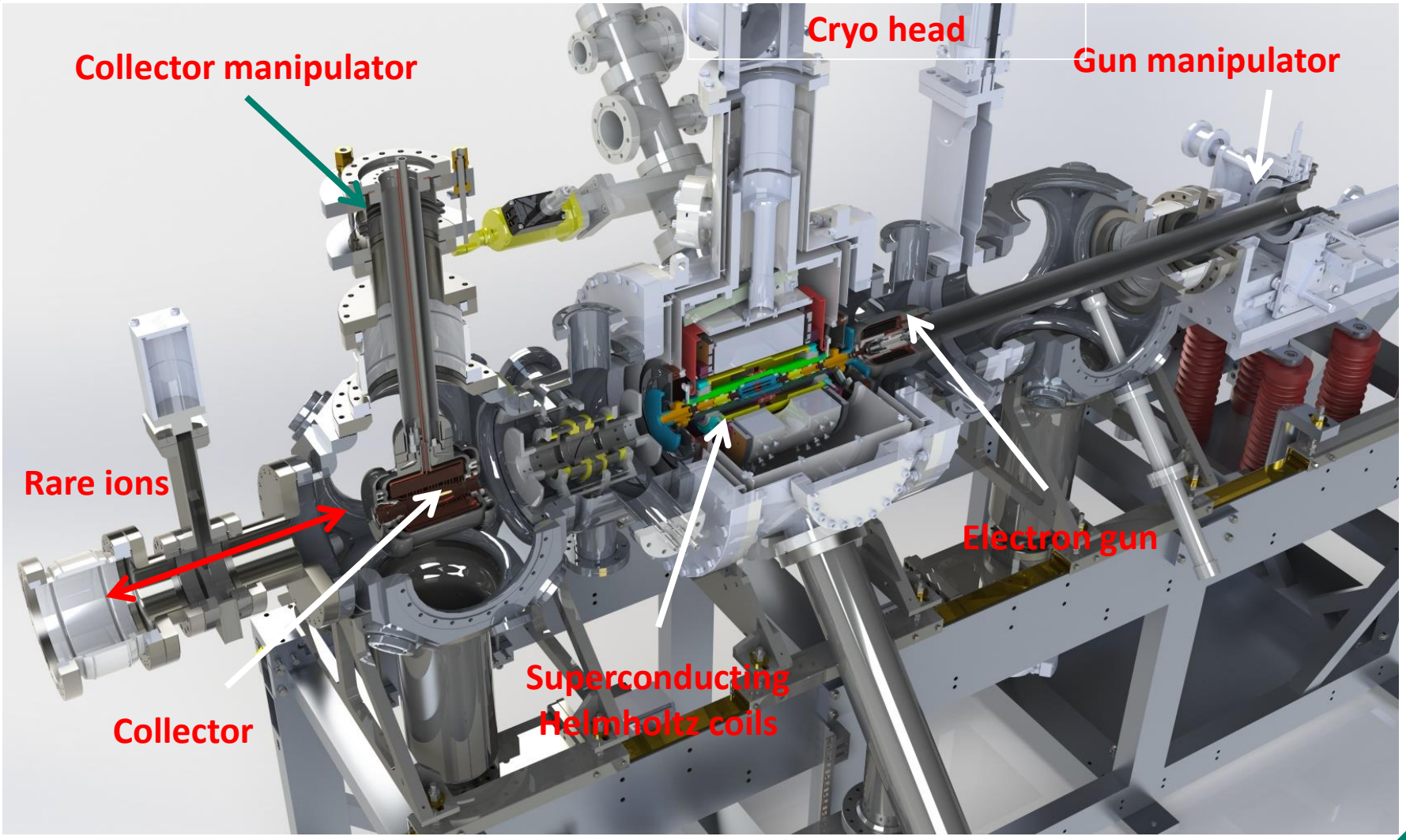
CANREB EBIS Requirements

$\sim 10^5$ ions in desired charge state

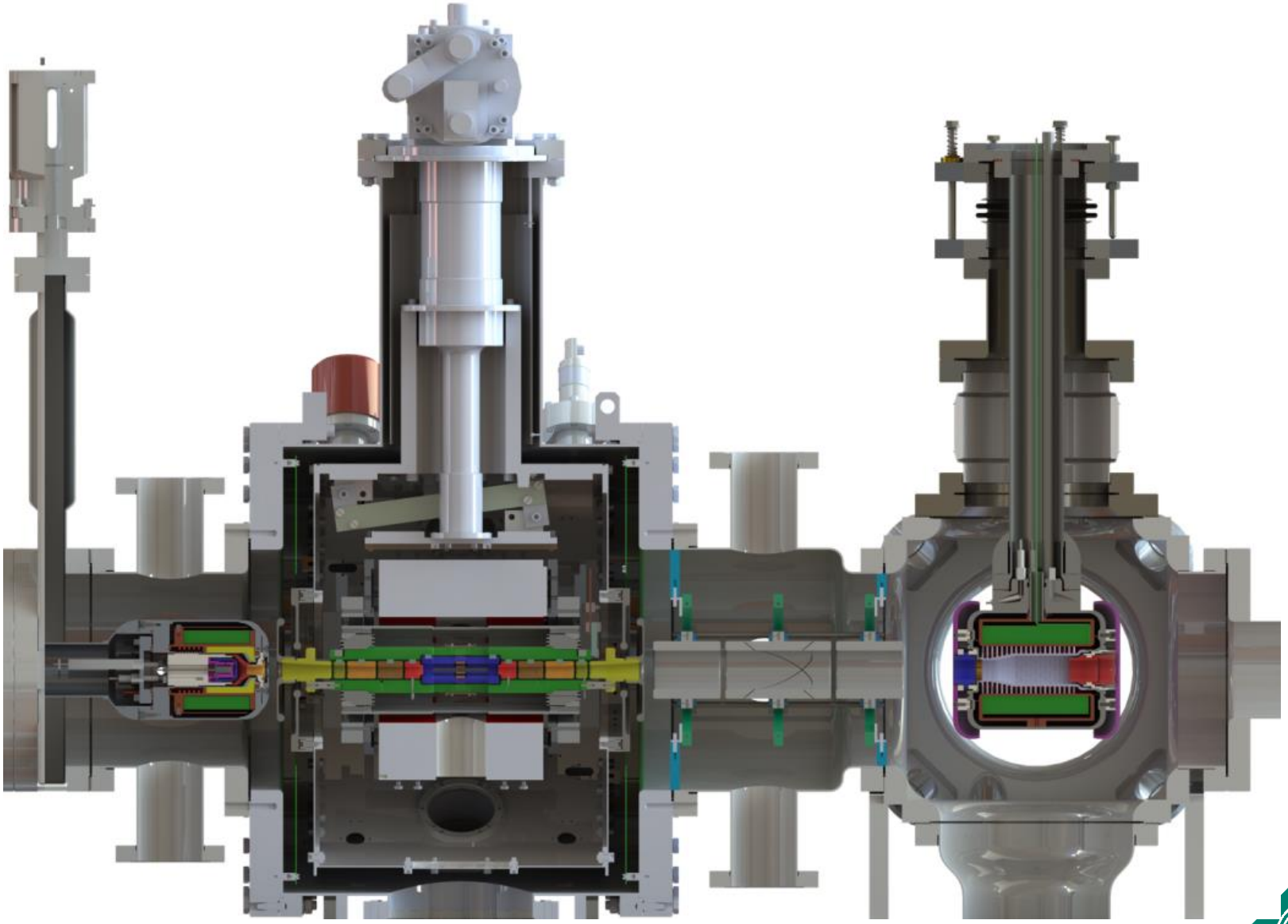


- Extraction must contain 10-20% in desired charge state
- ΔE< 100eV (for the next device)

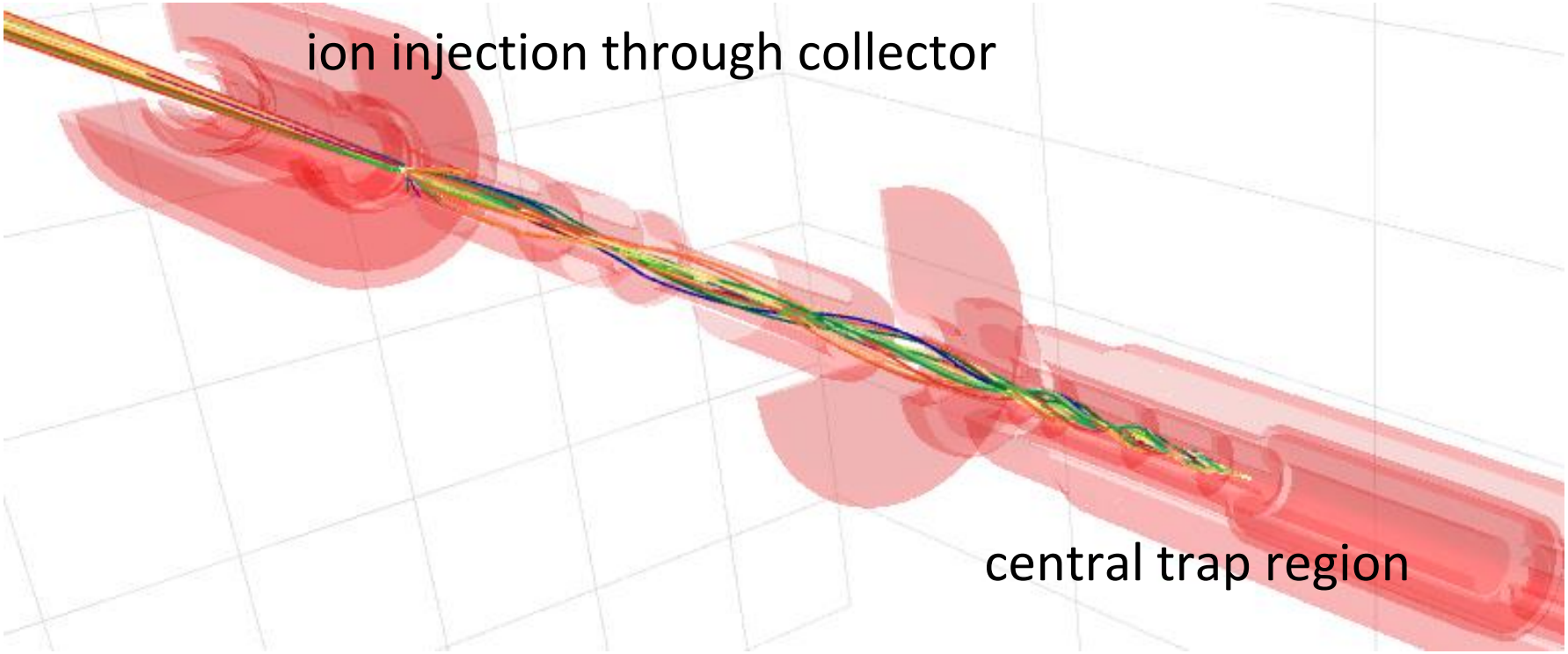
Design



Design



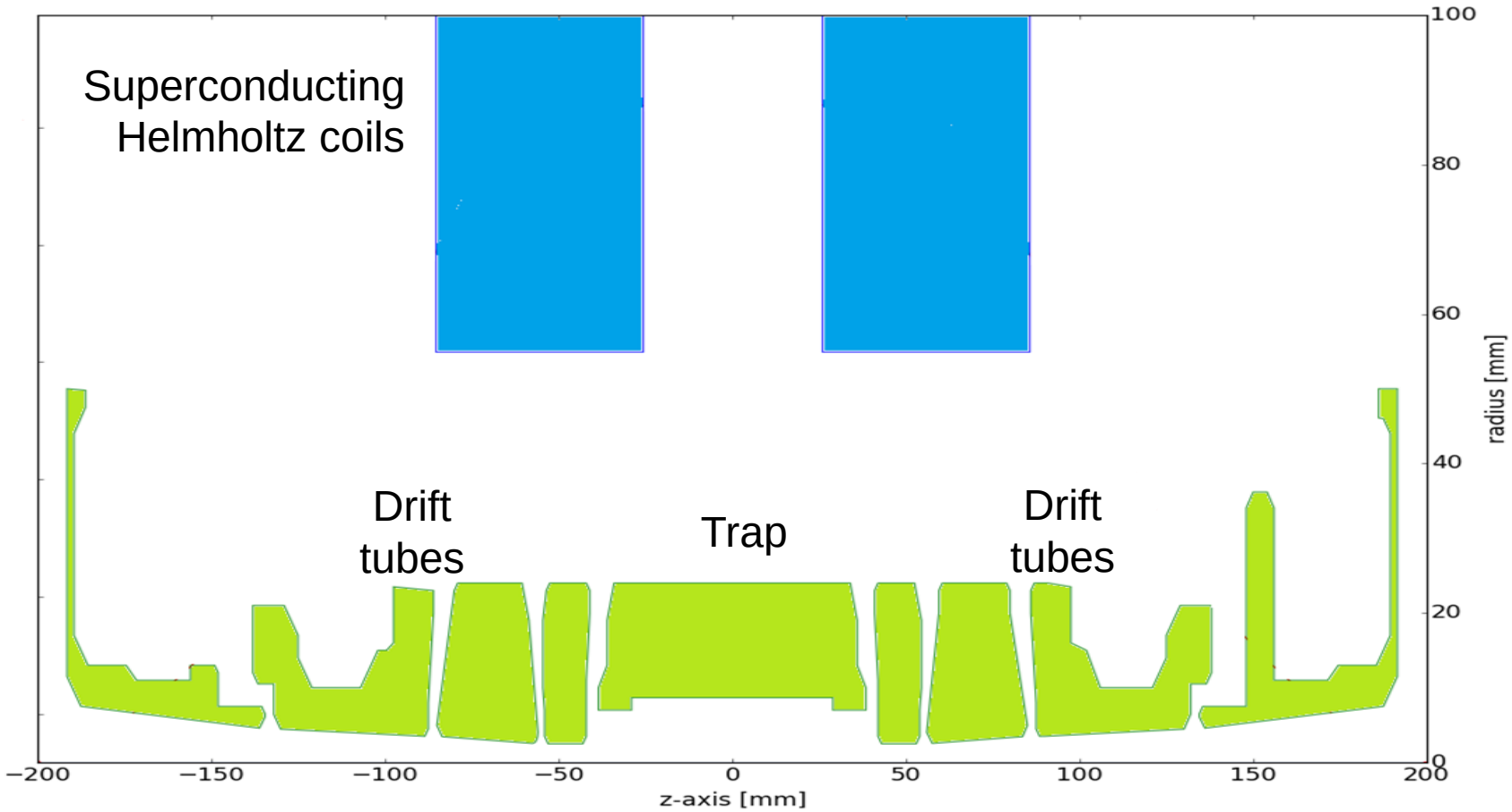
Simulation



Simulations aimed at optimization of

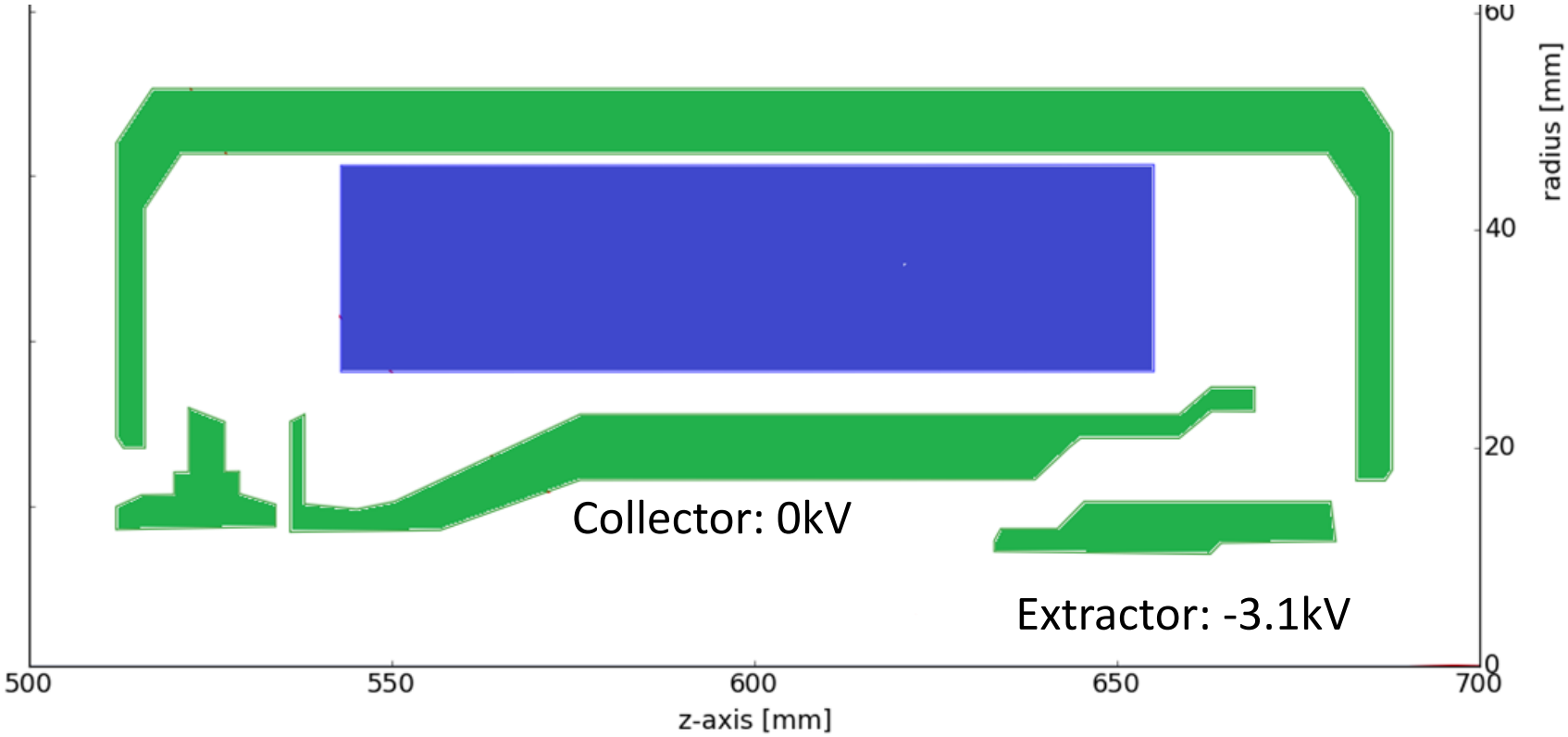
- electron beam for higher currents
- ion injection and extraction efficiency

Electrostatic simulation



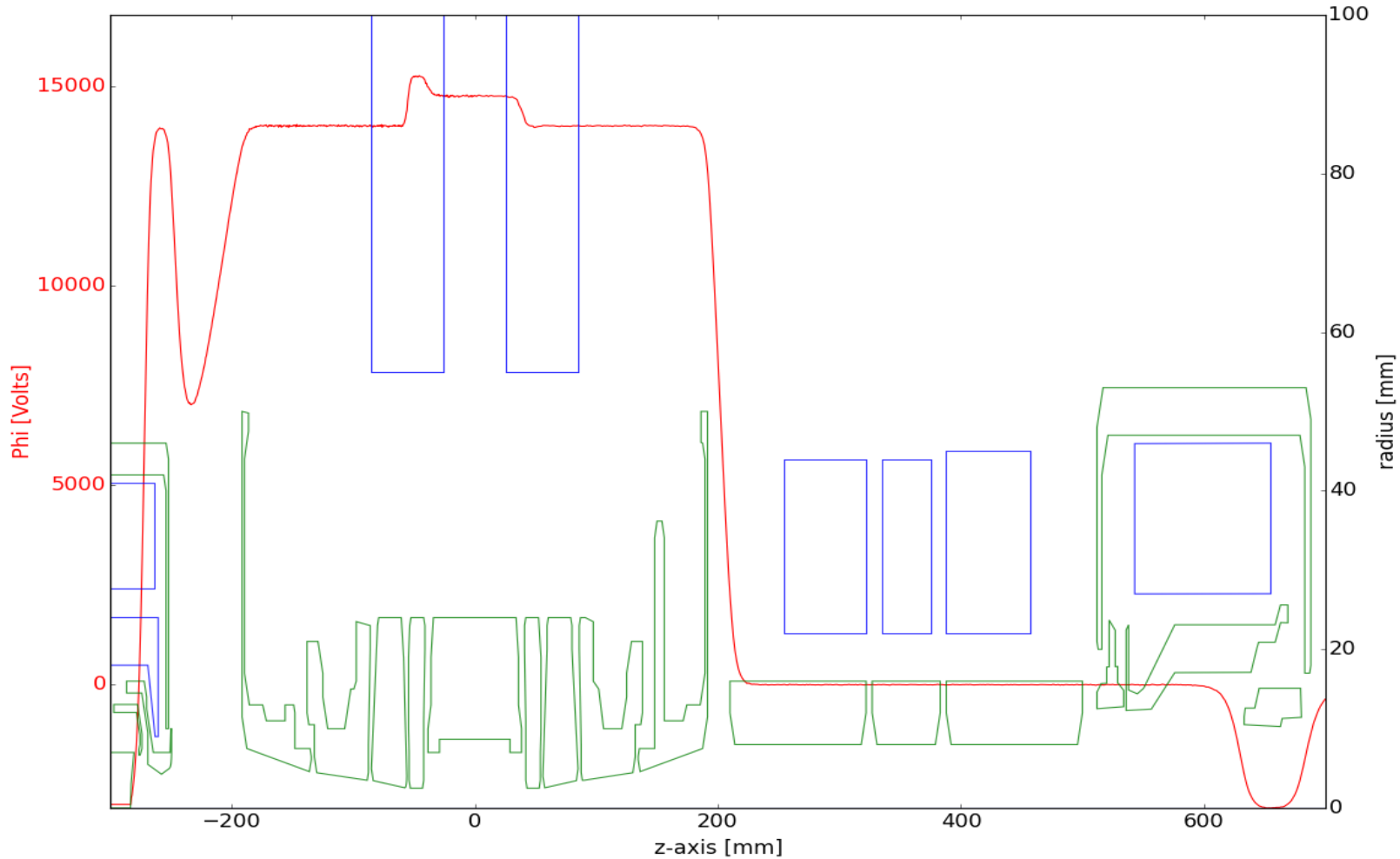
- Set of 9 individually biased drift tubes
- Central drift tube has eight radial RF electrodes

Collector



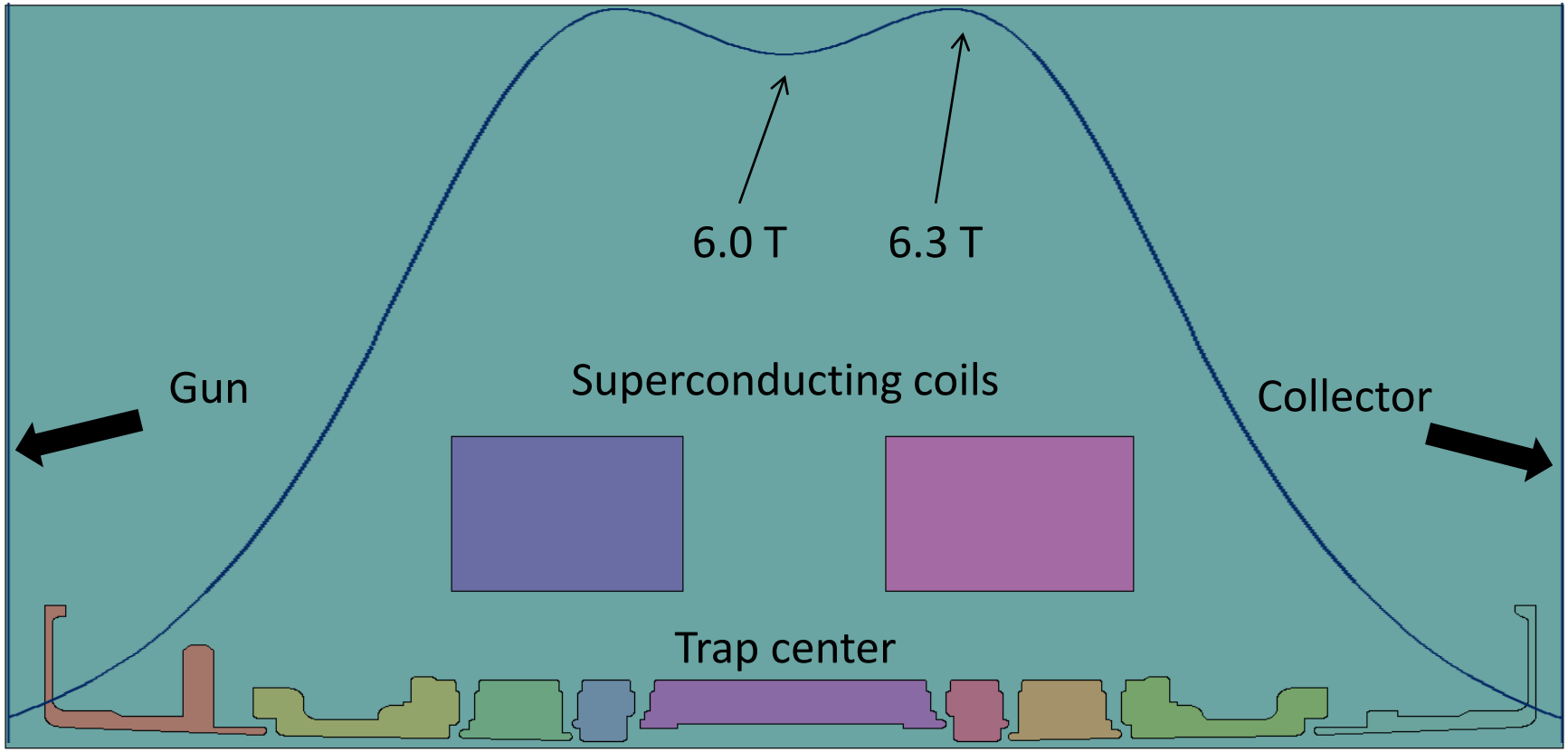
Collector uses water cooling for 3 kW DC thermal load

Electrostatic simulation



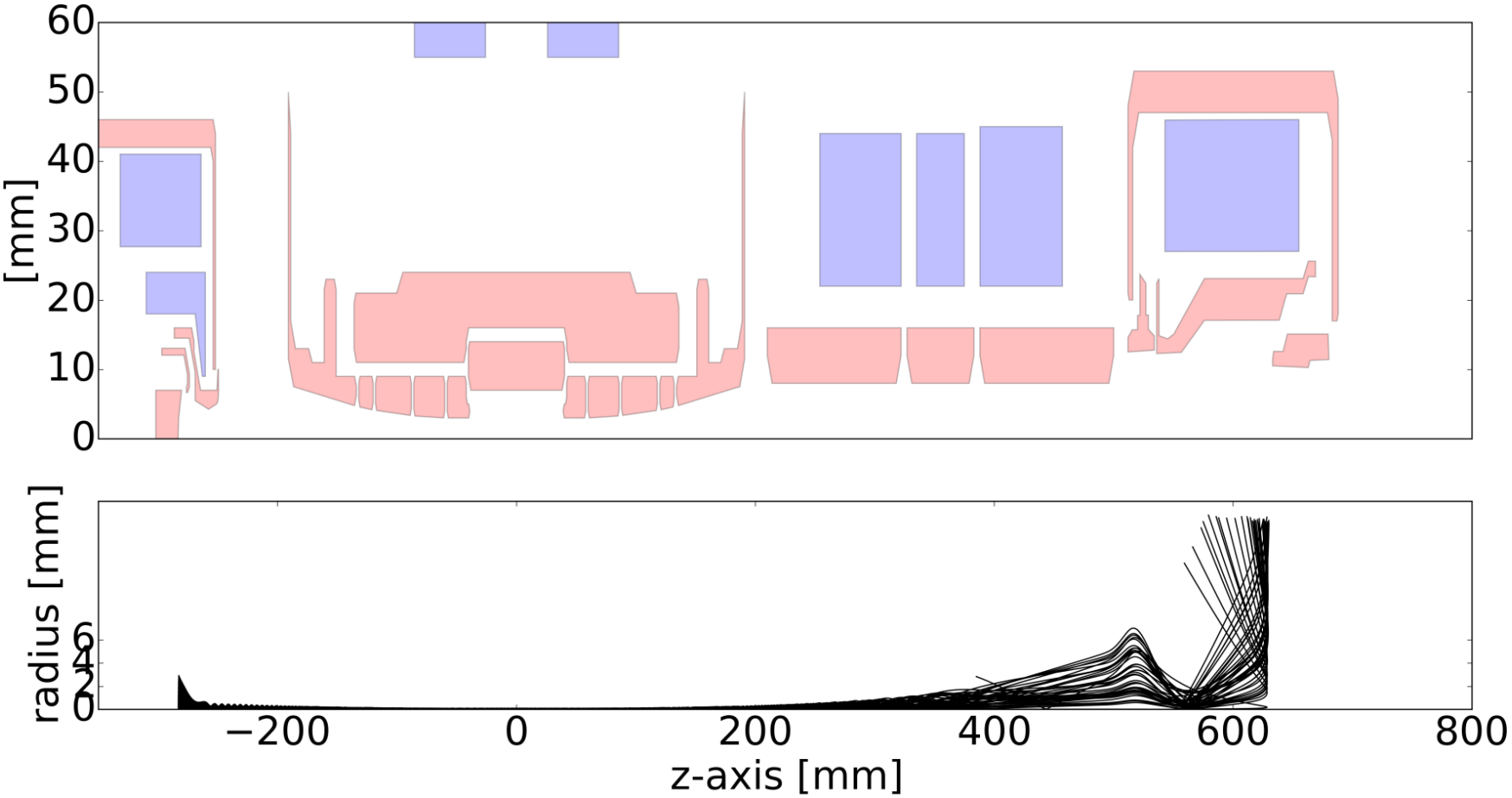
Specified for TRIUMF for 18 kV drift tube bias, but capable of higher values

Magnetostatic simulation



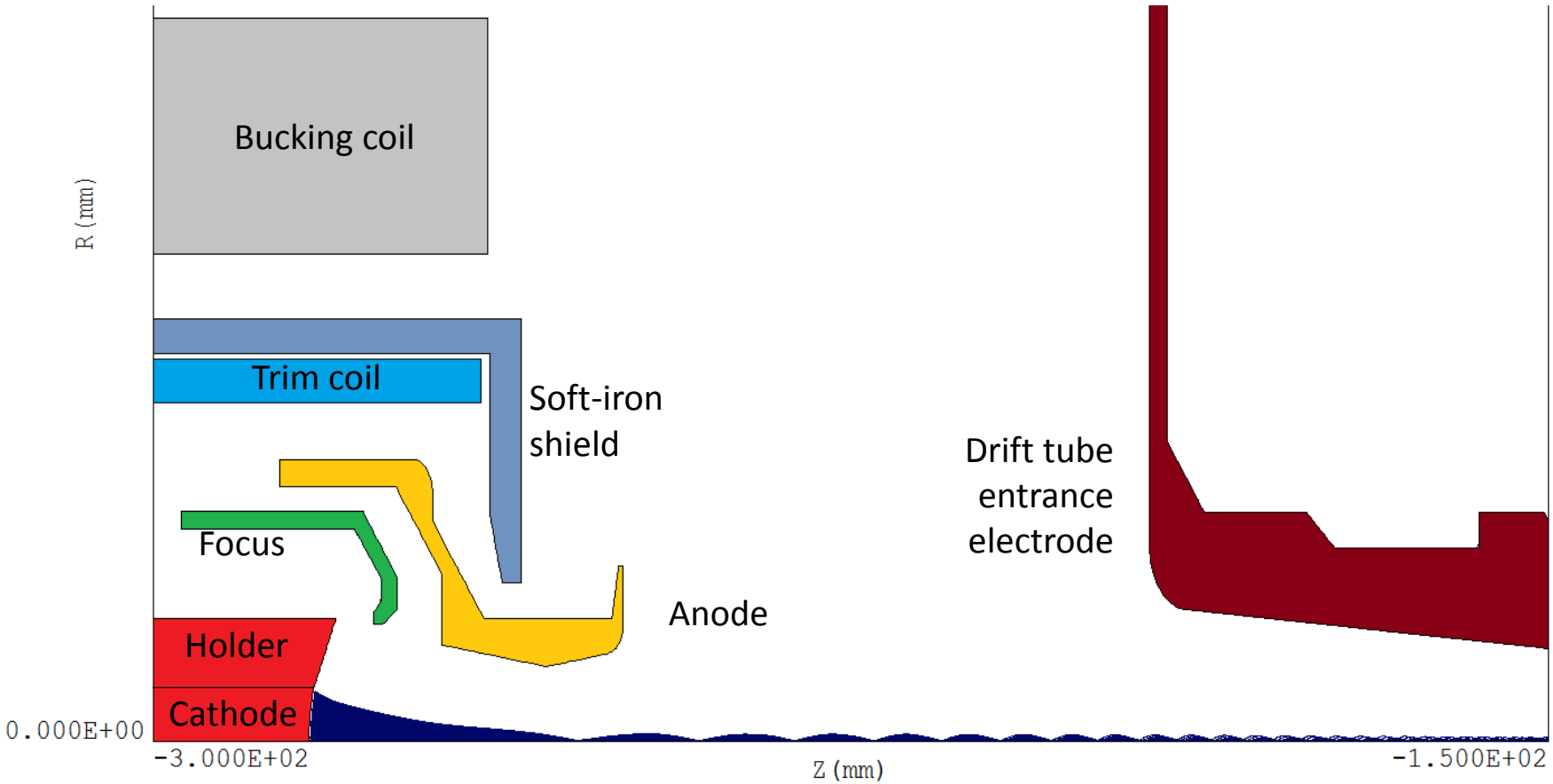
- 6 T central magnetic field
- Helmholtz configuration

Electron beam simulations



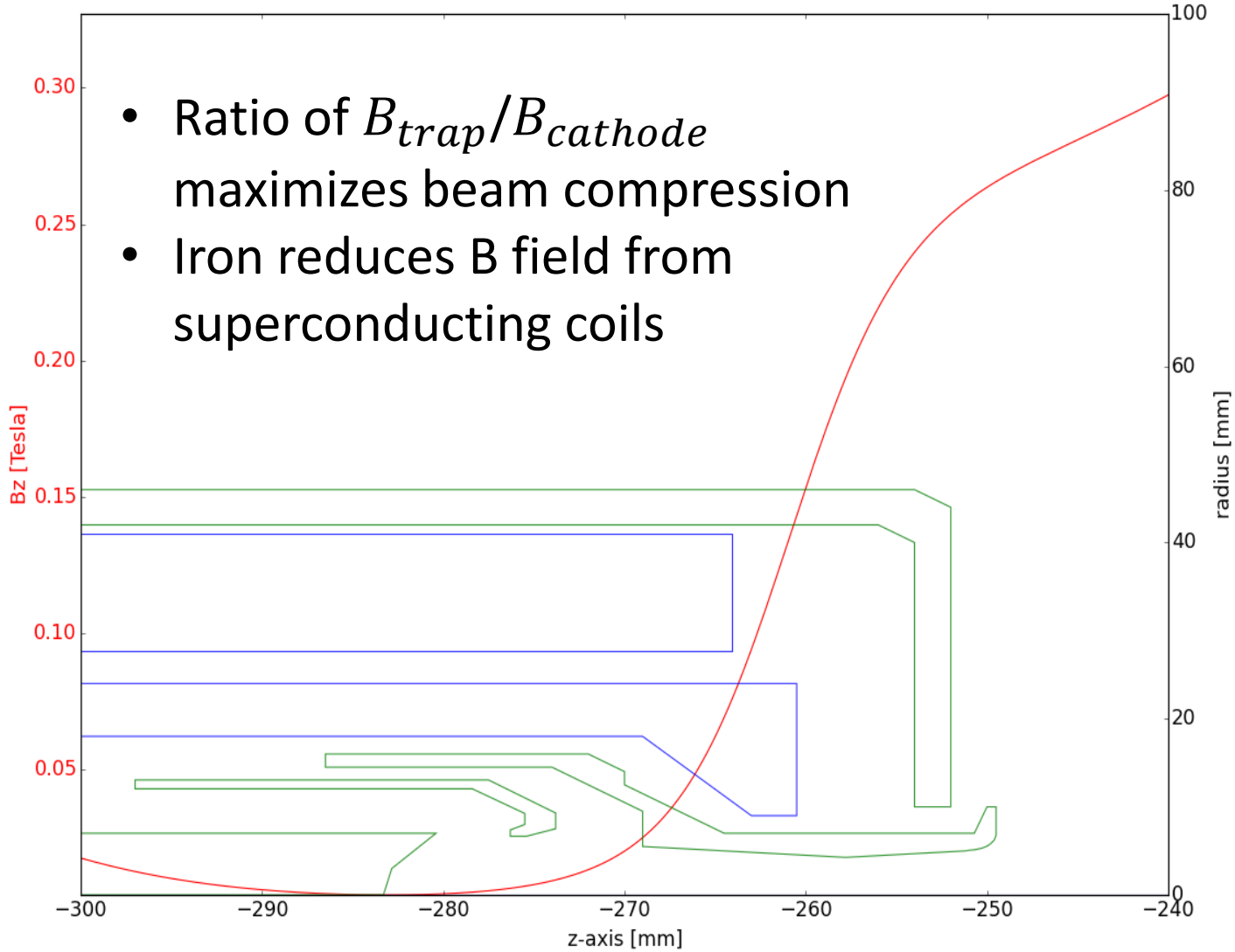
Electron beam simulations with TriCOMP, COMSOL, SimIon

Electron beam simulation



- Space charge limited Pierce gun design
- Non-immersed

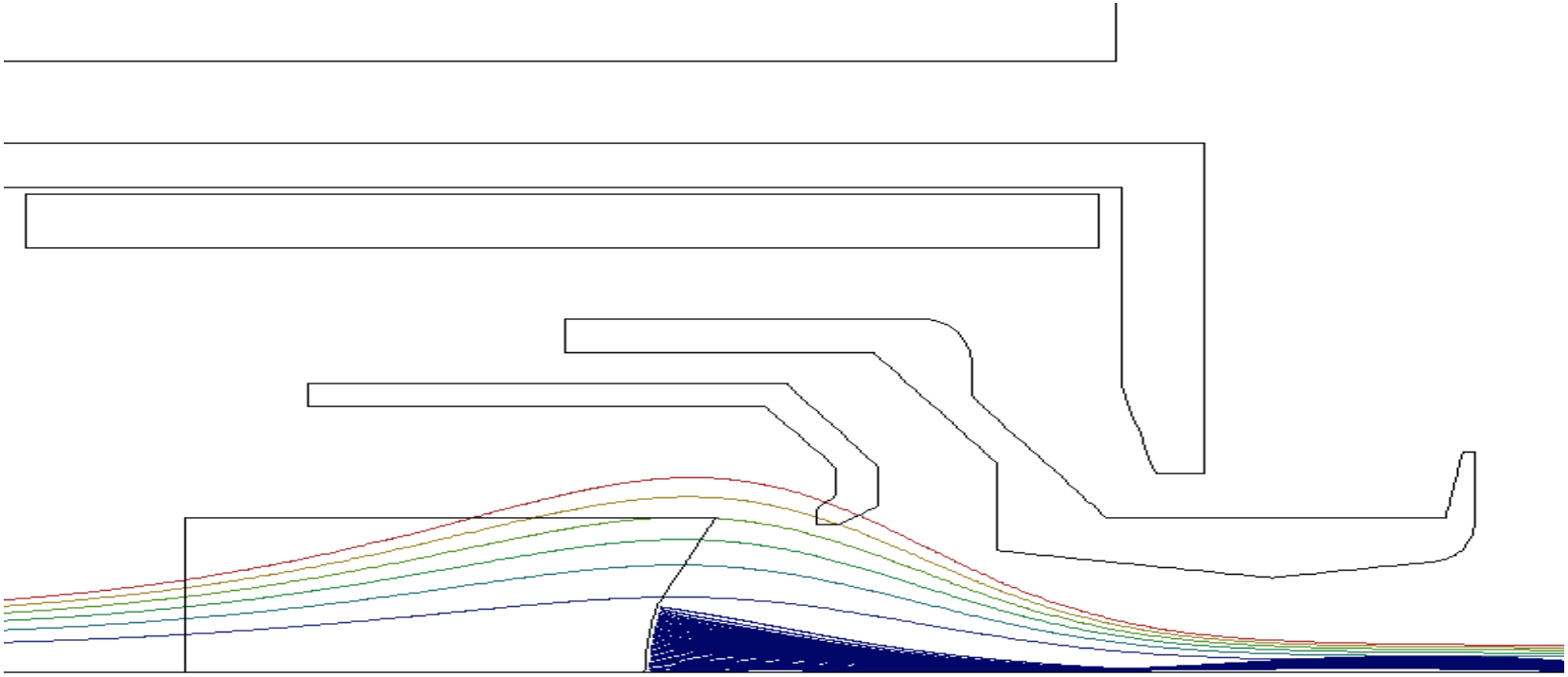
Magnetostatic simulation



- Ratio of $B_{trap}/B_{cathode}$ maximizes beam compression
- Iron reduces B field from superconducting coils

- Non-immersed design for very high compression

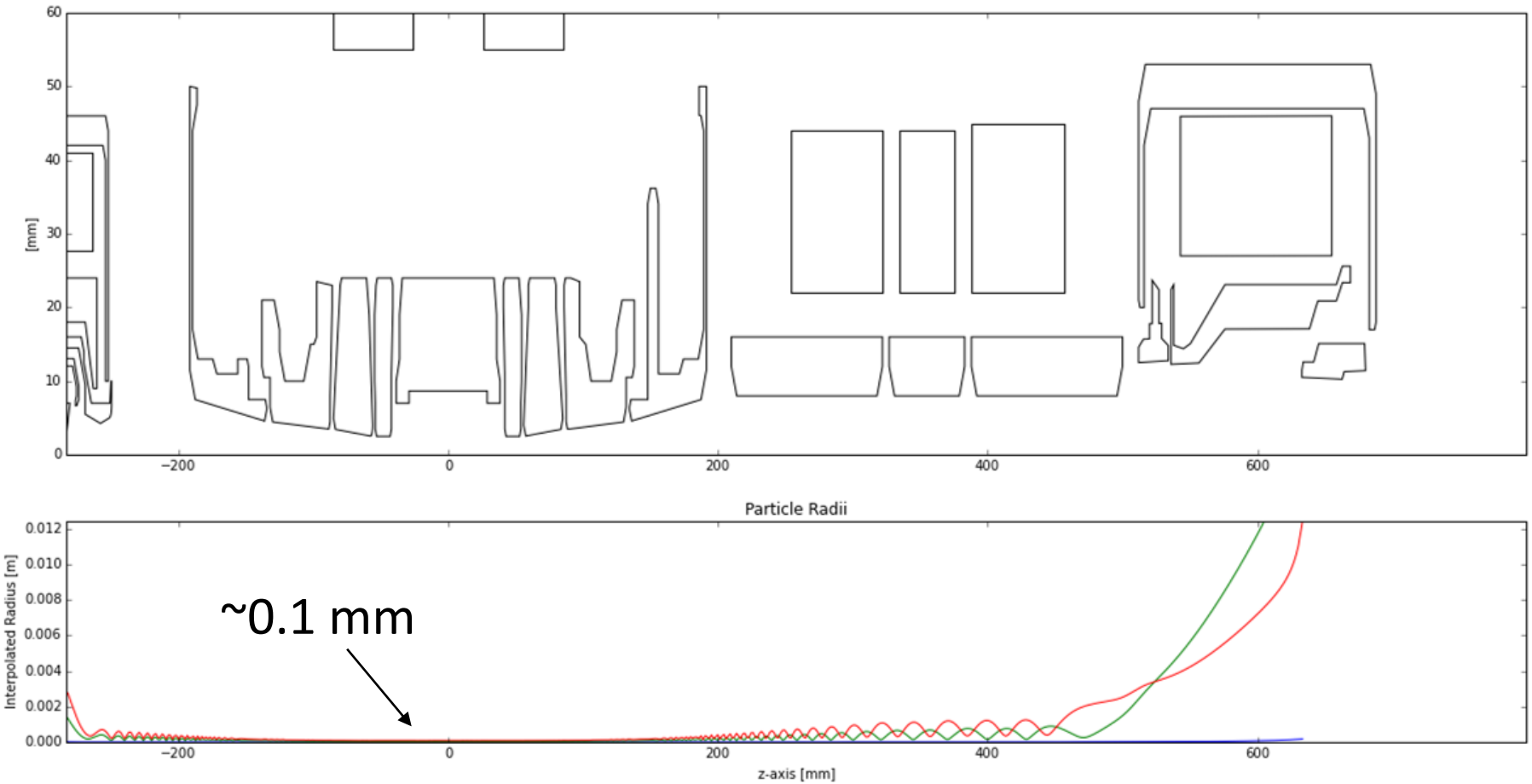
Electron beam emission



Emission parameters:

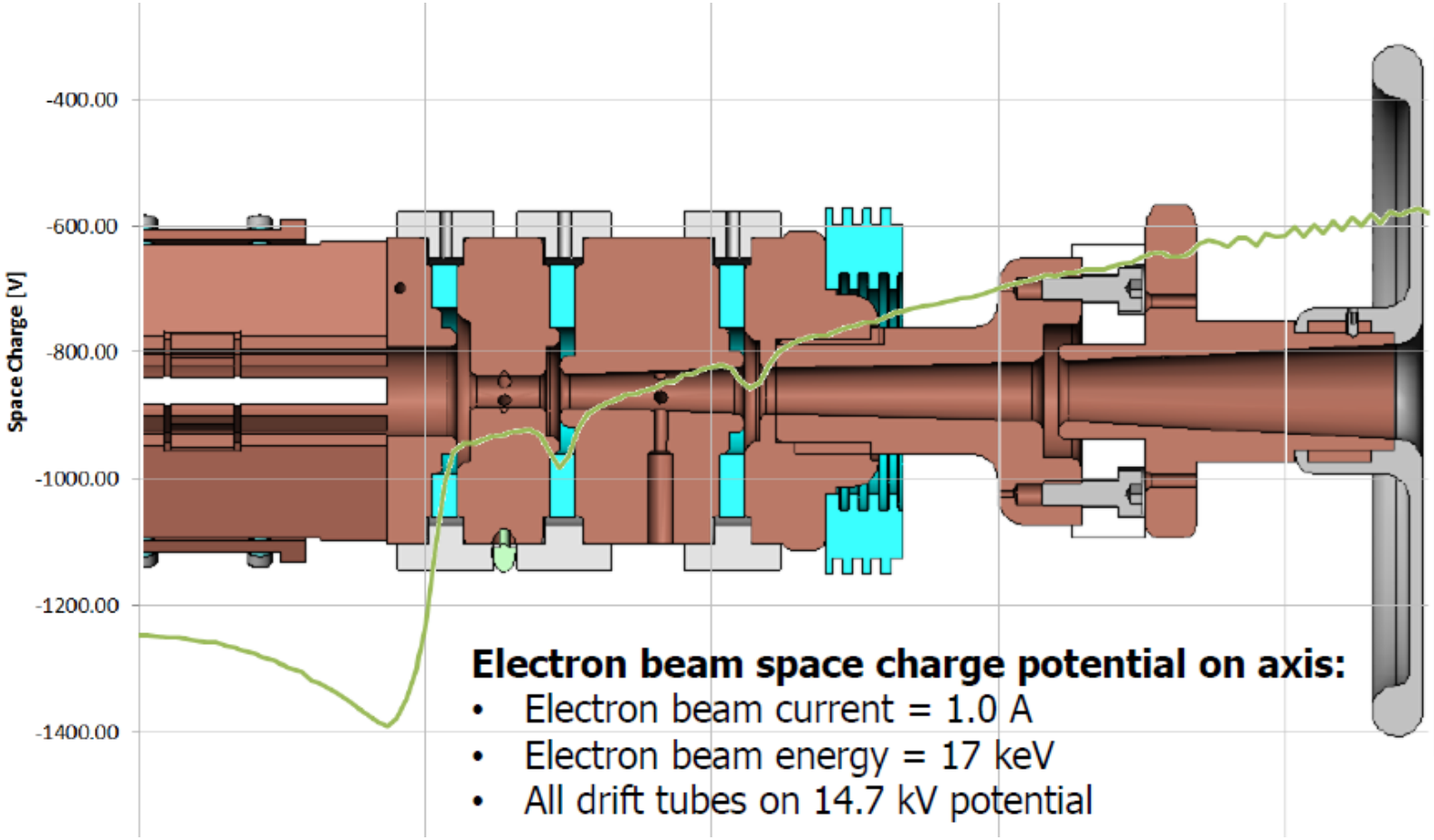
- Cathode radius: 3mm
- Maximum beam current: 1.0 A
- Bucking coil 8000 A×windings, trim coil -400 A×windings

Electron trajectories



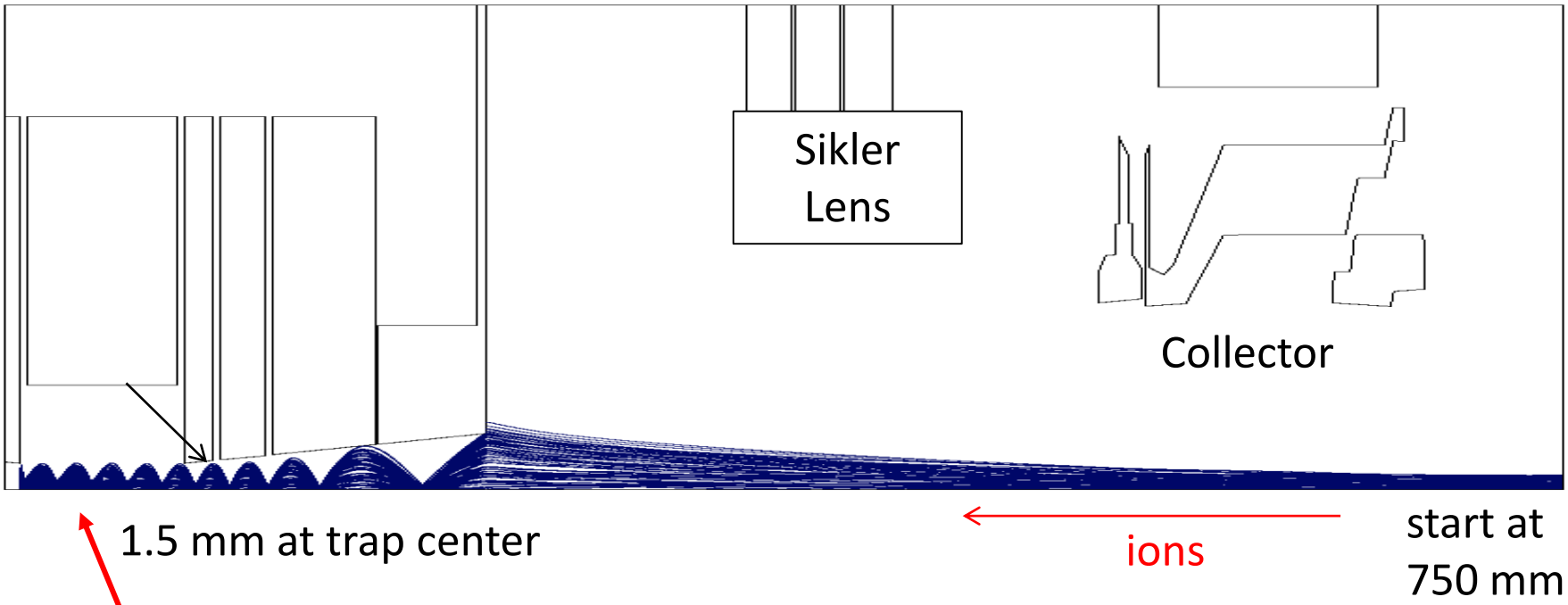
Examples for three complete electron trajectories

Space charge potential



At 1 A space charge potential on axis surpasses -1 kV

Injection (without ionization)



If not optimized:

Comparison of injected ion distribution (blue) to 0.1 mm radius electron beam (red)

Herrmann radius and acceptance

The electron beam radius (containing 80% of the electrons) can be calculated in the magnetic field, using Herrmann's formula:

$$r = r_B \sqrt{0.5 + \sqrt{0.25 + \frac{8 m_e k_B T_c r_c^{\,2}}{e^2 B^2 r_B^{\,4}} + \frac{B_c^{\,2} r_c^{\,4}}{B^2 r_B^{\,4}}}} \qquad r_B = \sqrt{\frac{I m_e}{\pi \varepsilon_0 v e B^2}}$$

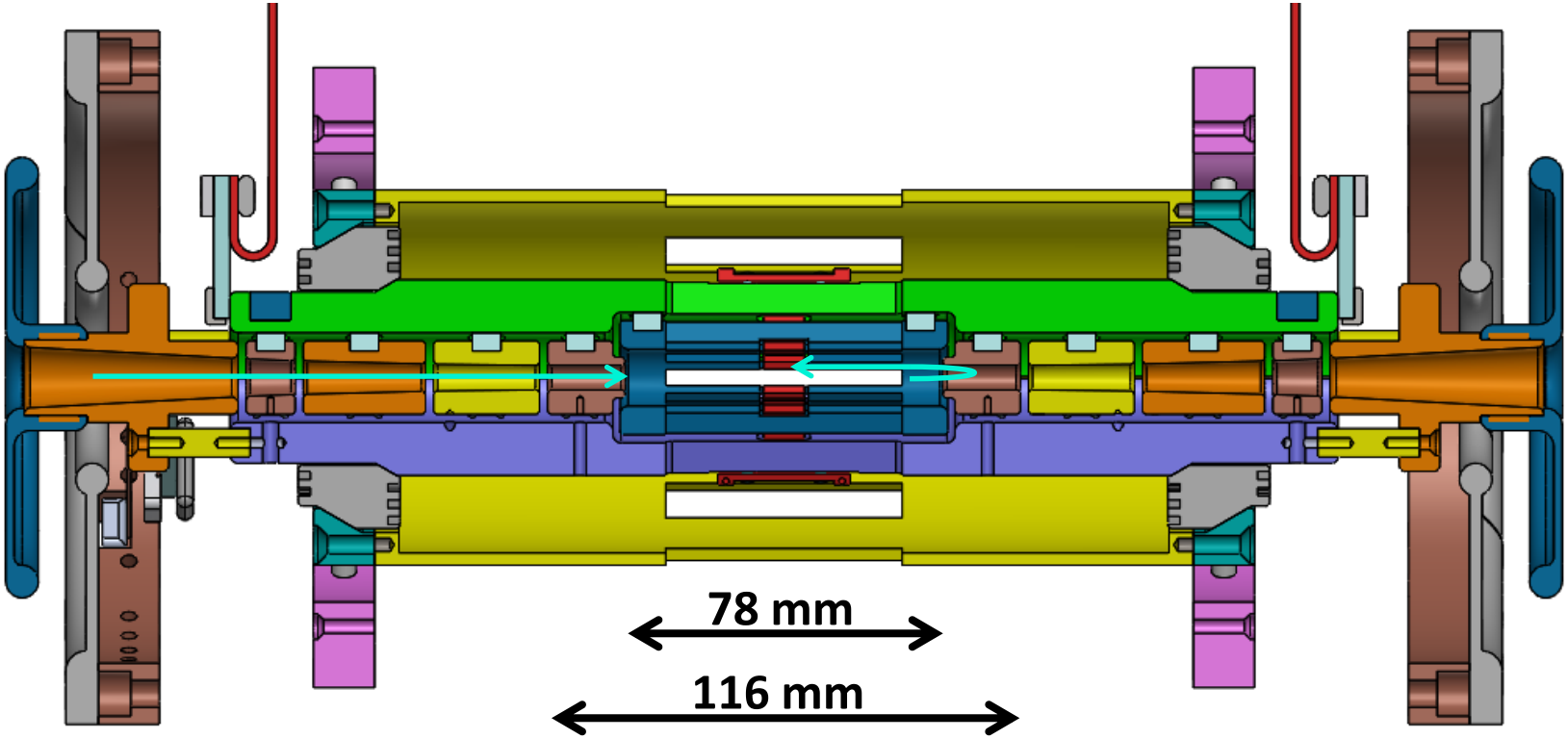
A maximum acceptance can be estimated by calculating the geometric phase space area of the non-compensated electron beam:

$$\alpha = \pi \frac{r^2}{\sqrt{2U}} \left(B \sqrt{\frac{Q}{M}} + \sqrt{\frac{QB^2}{4M} + \frac{j}{2v\epsilon_0}} \right)$$

I = electron beam current
j = electron beam current density
v = electron velocity
B = magnetic flux density on axis
Tc = cathode temperature
rc = cathode radius
Bc = cathode magnetic flux density
Q/M = ion charge over mass in As/kg
U = ion acceleration potential

e = electron charge
me = electron mass
ε0 = vacuum peritivity
kB = Boltzmann constant

Ion time of flight in the trap

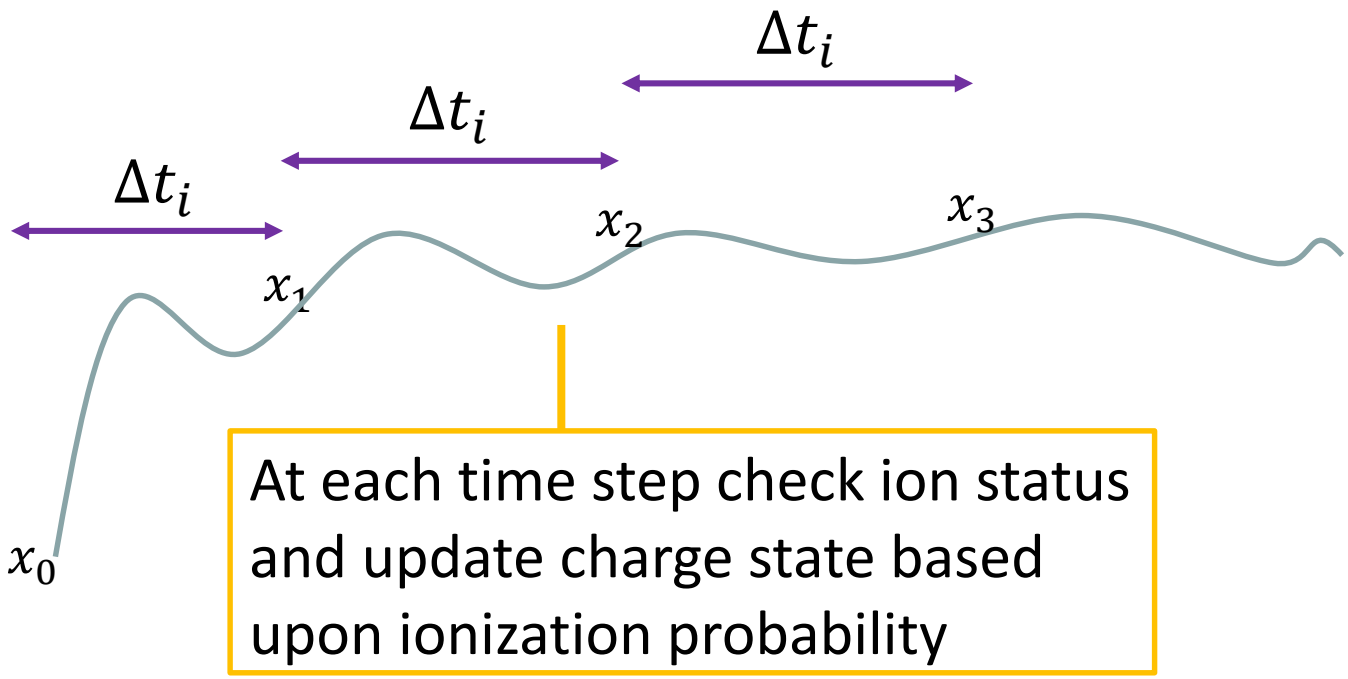


Example calculations of time-of-flight (TOF):

- Kinetic energy in the trap: 500 eV
- TOF for 2 x 78 mm: 2.2 µs (M = 20); 5.8 µs (M = 132)
- TOF for 2 x 116 mm: 3.3 µs (M = 20); 8.6 µs (M = 132)

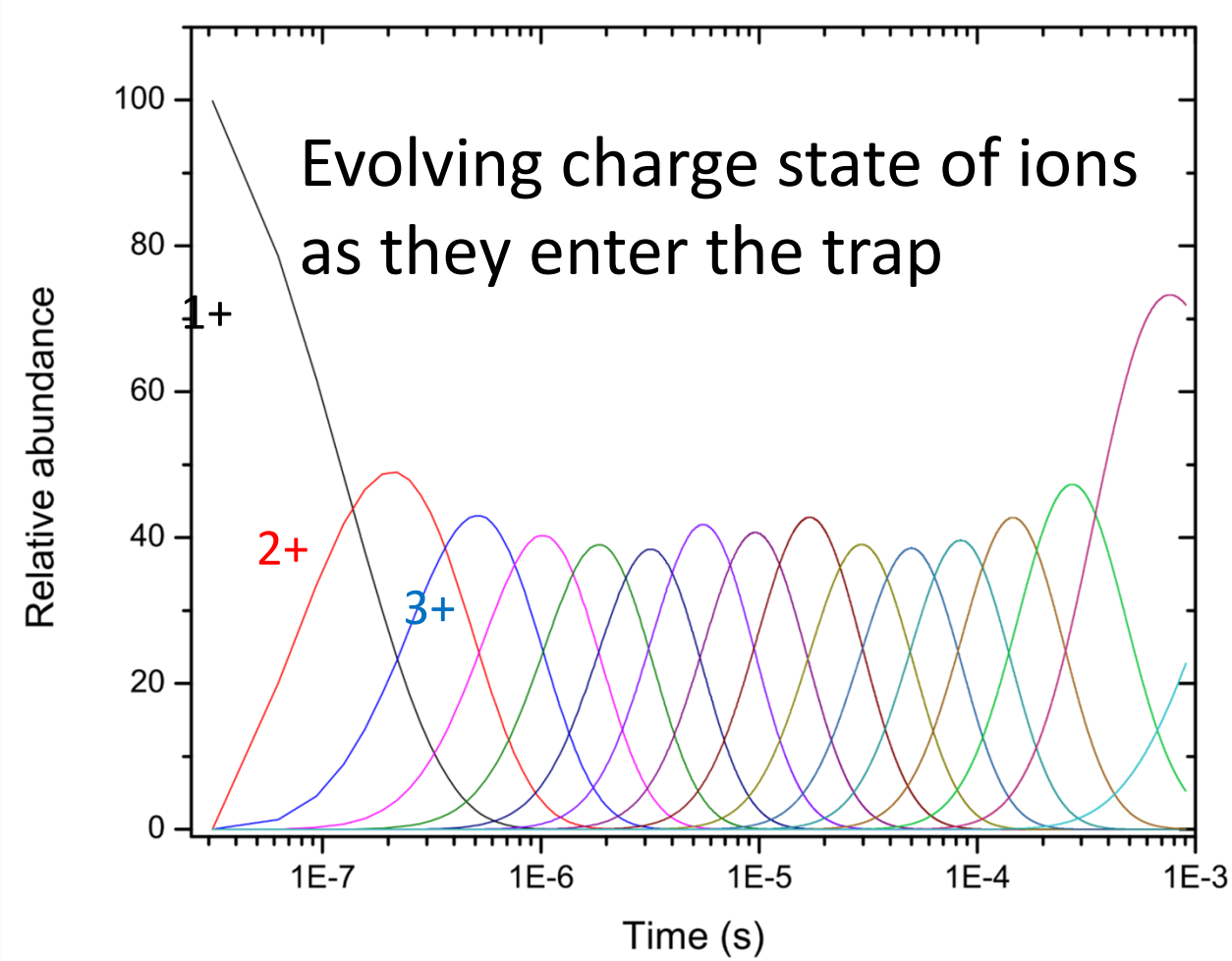
Implementation / Monte Carlo

Single injected ion trajectory



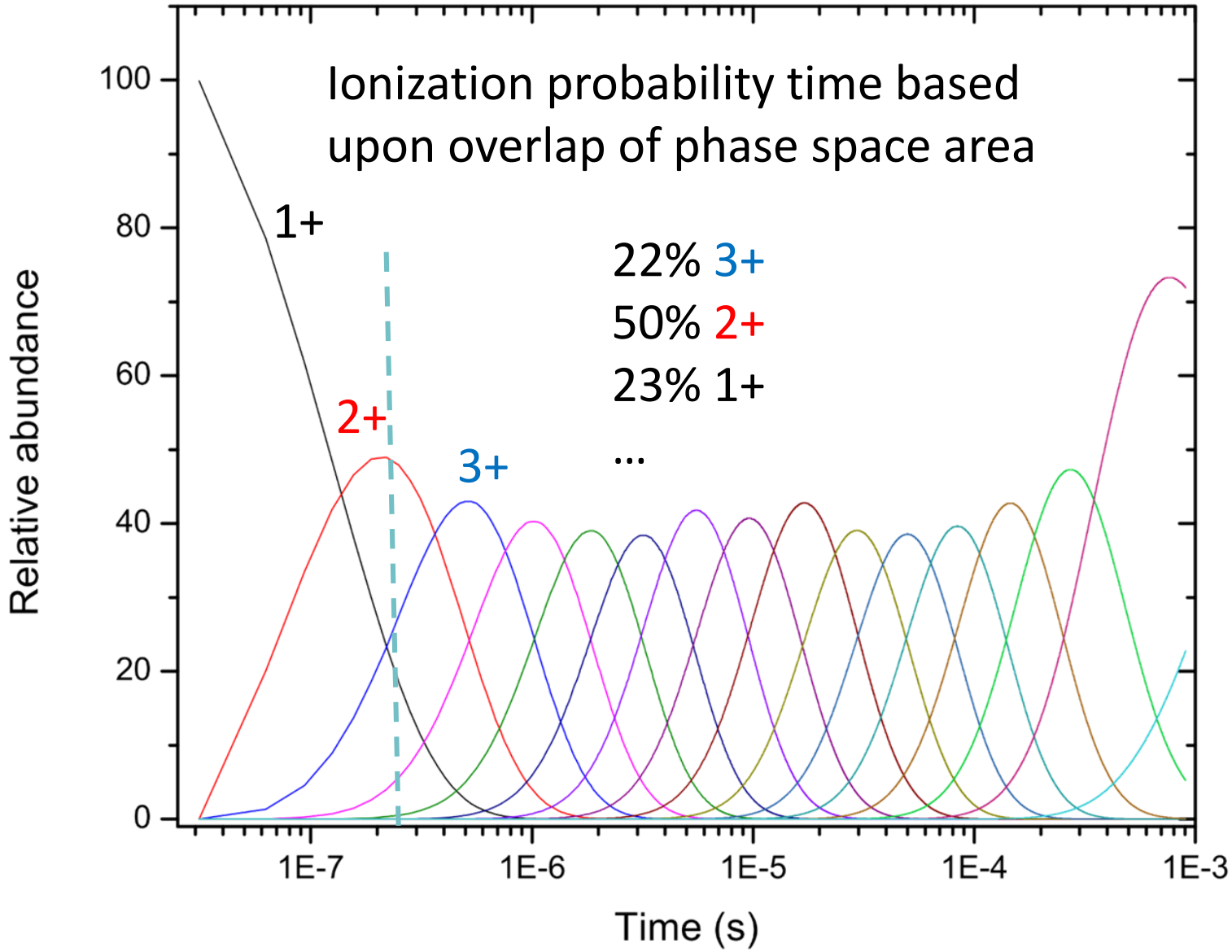
Injection efficiency simulation considers time-dependent ionization events

Ionization simulations

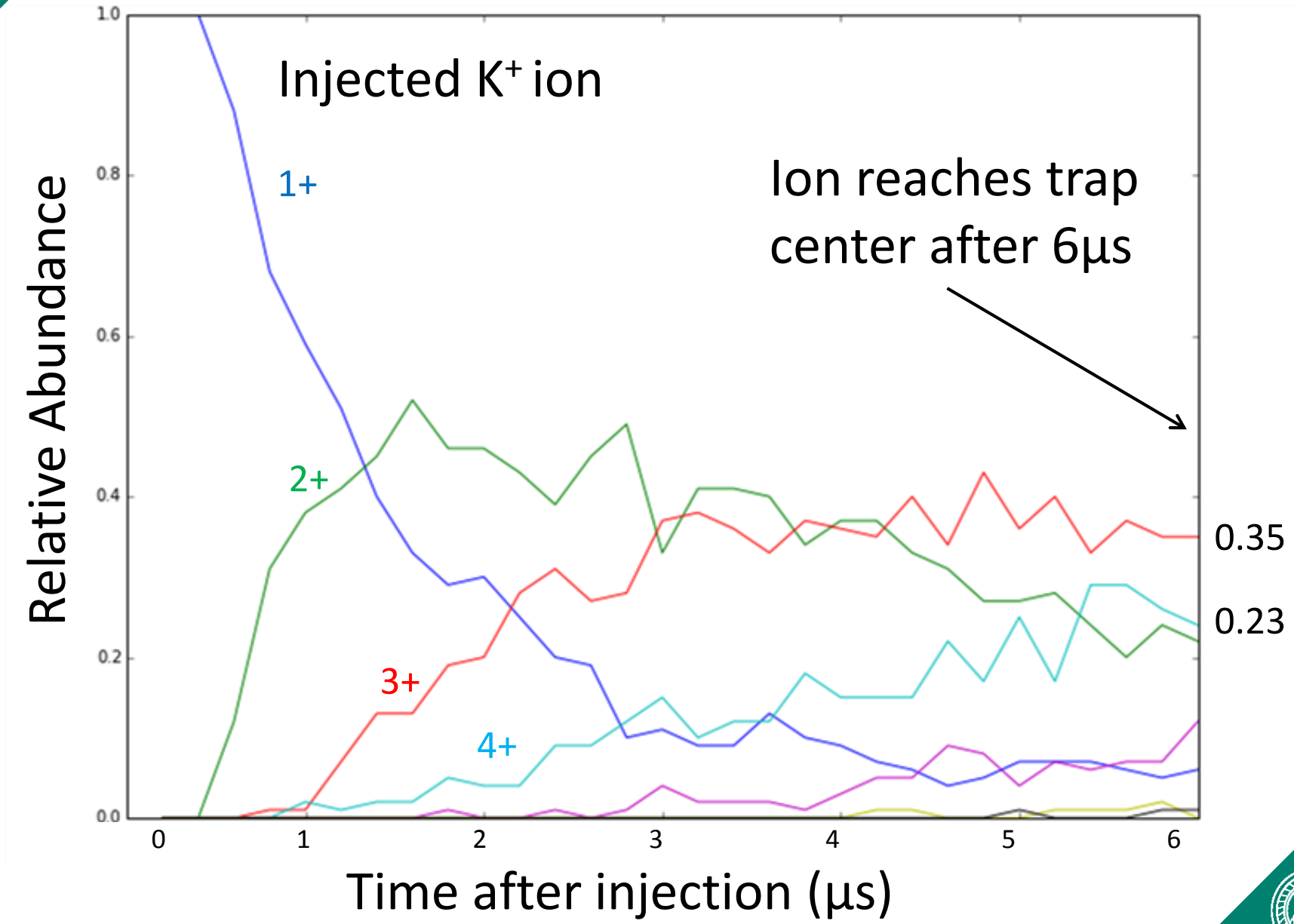


Runge-Kutta ionization state evolution including electron impact ionization and radiative recombination

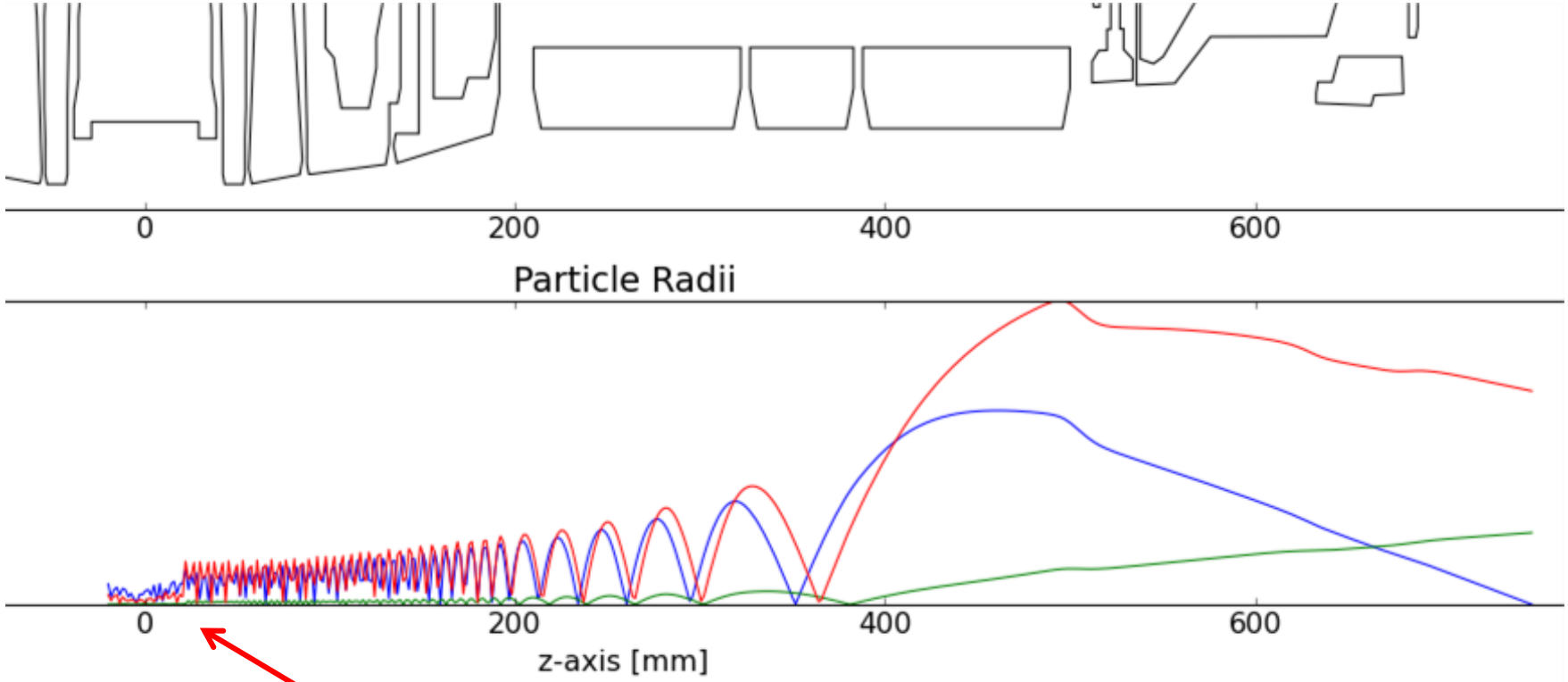
Capture simulation

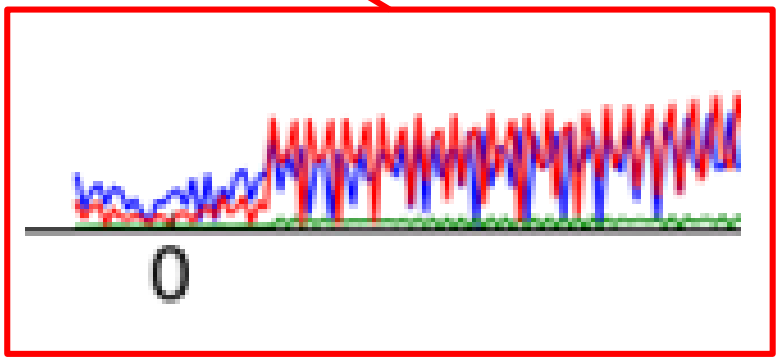


First Results



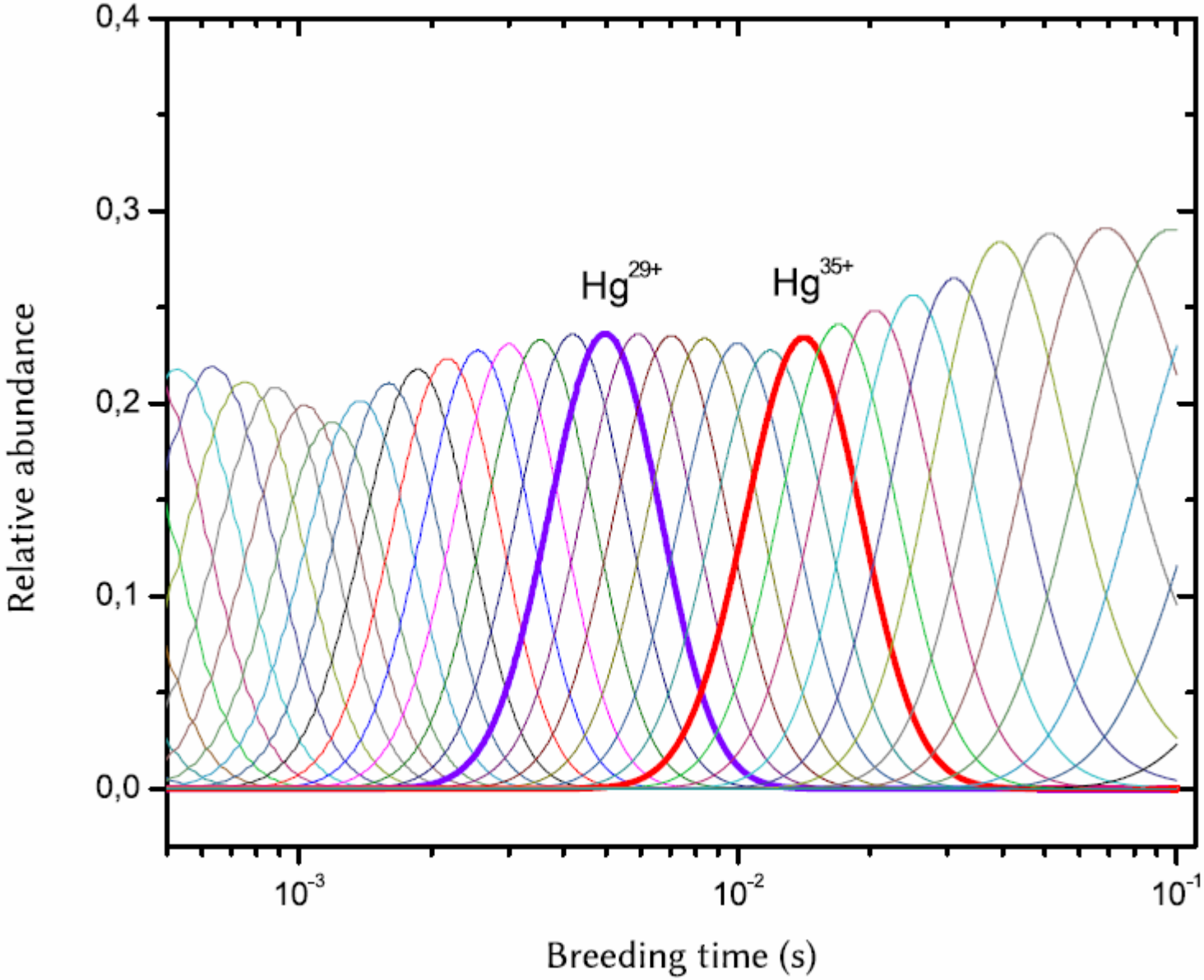
Results for capture efficiency



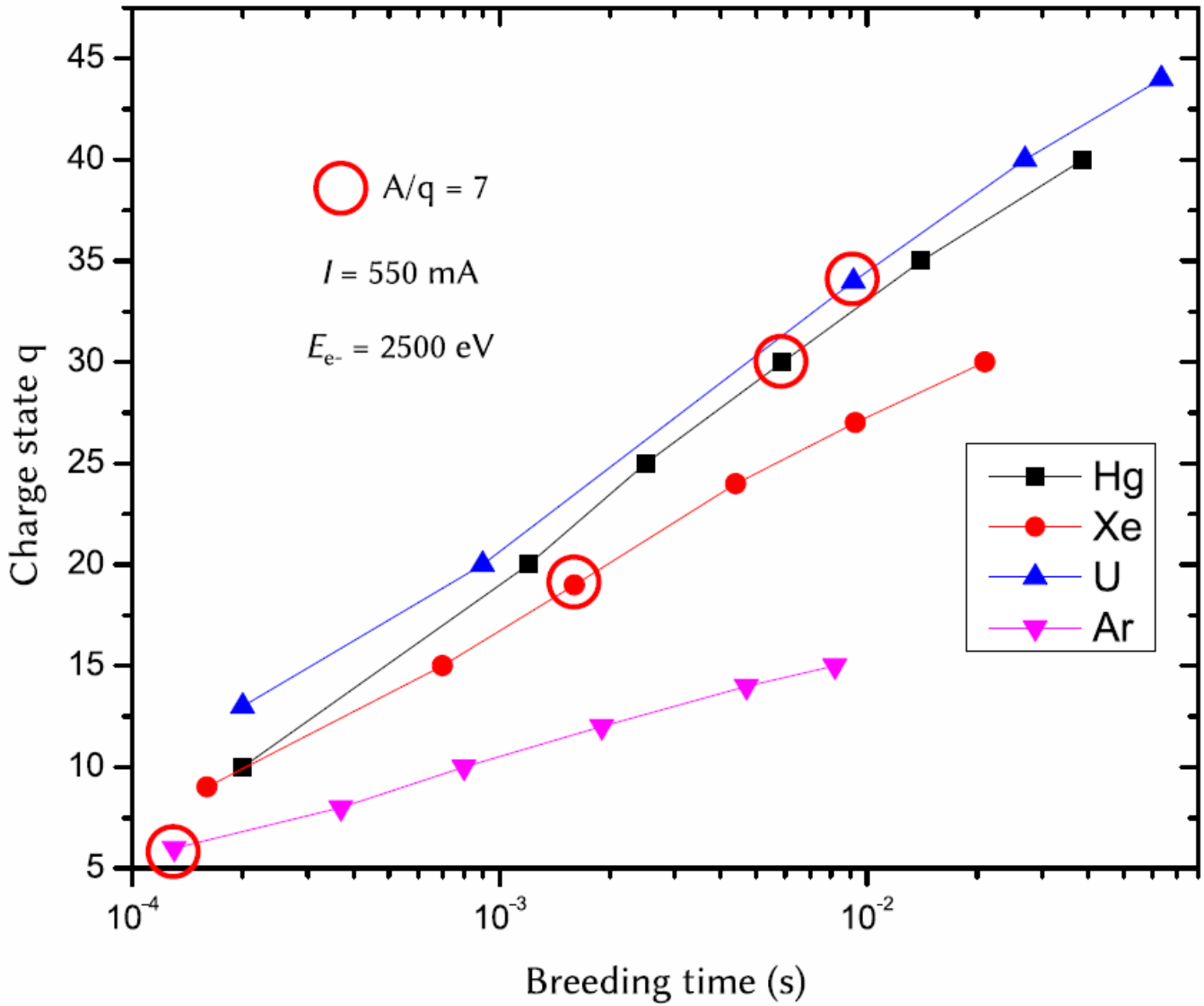


With increasing ionization stage, injected ion catching improves

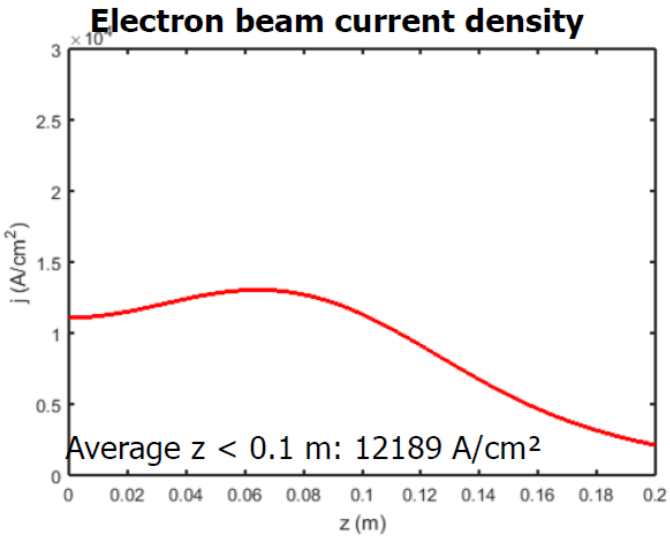
Charge breeding simulation

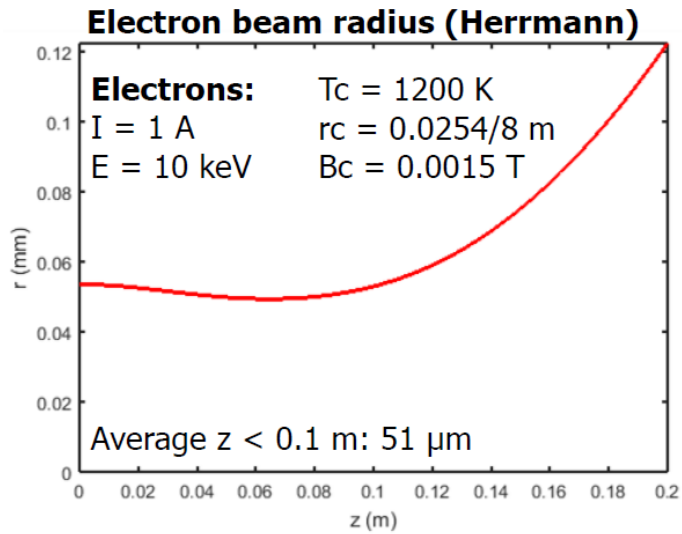


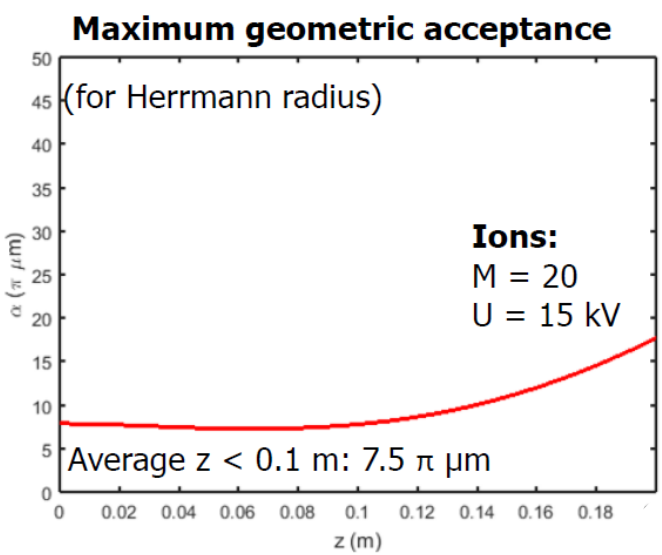
Breeding times required for A/q=7



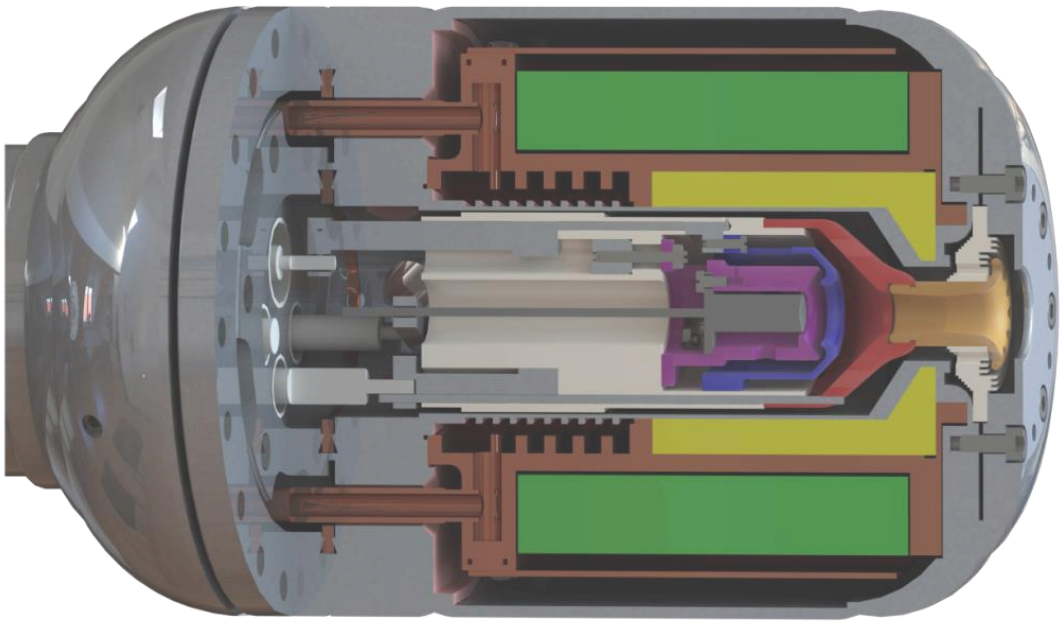
Acceptance and beam radius





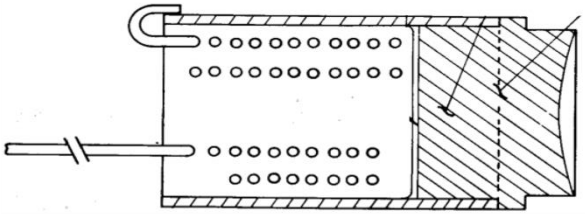


Electron gun

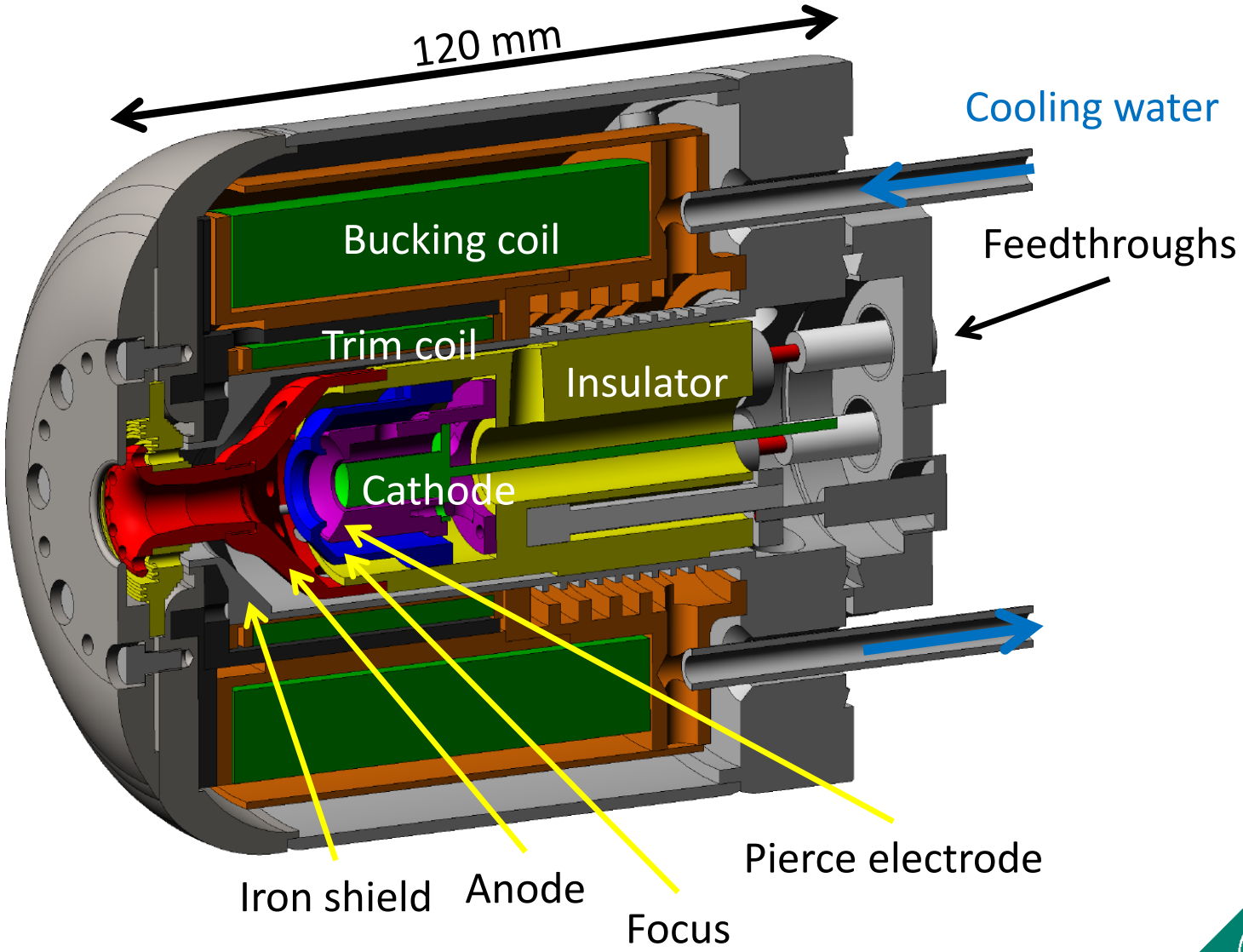


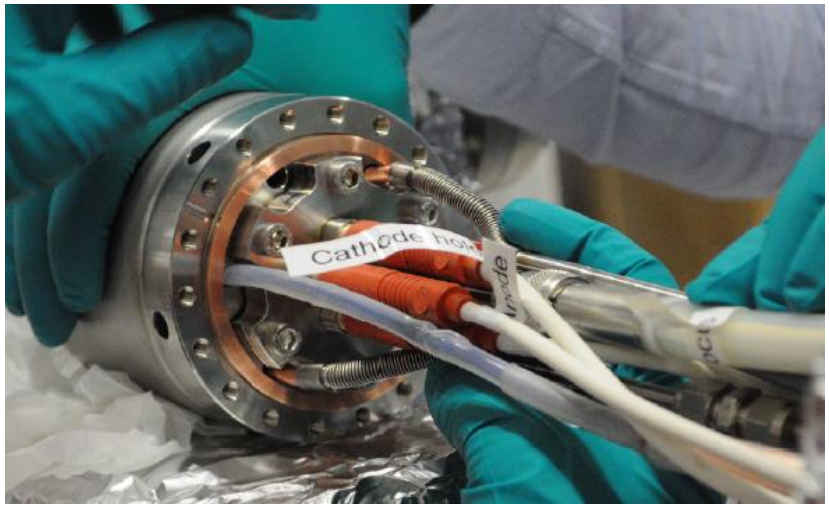
- $r_c = 3.175\ \mathrm{mm}$
- max. emission $I_c > 1\ \mathrm{A}$
- Soft iron shield

Dispenser-type Ba M-coating thermoionic cathode

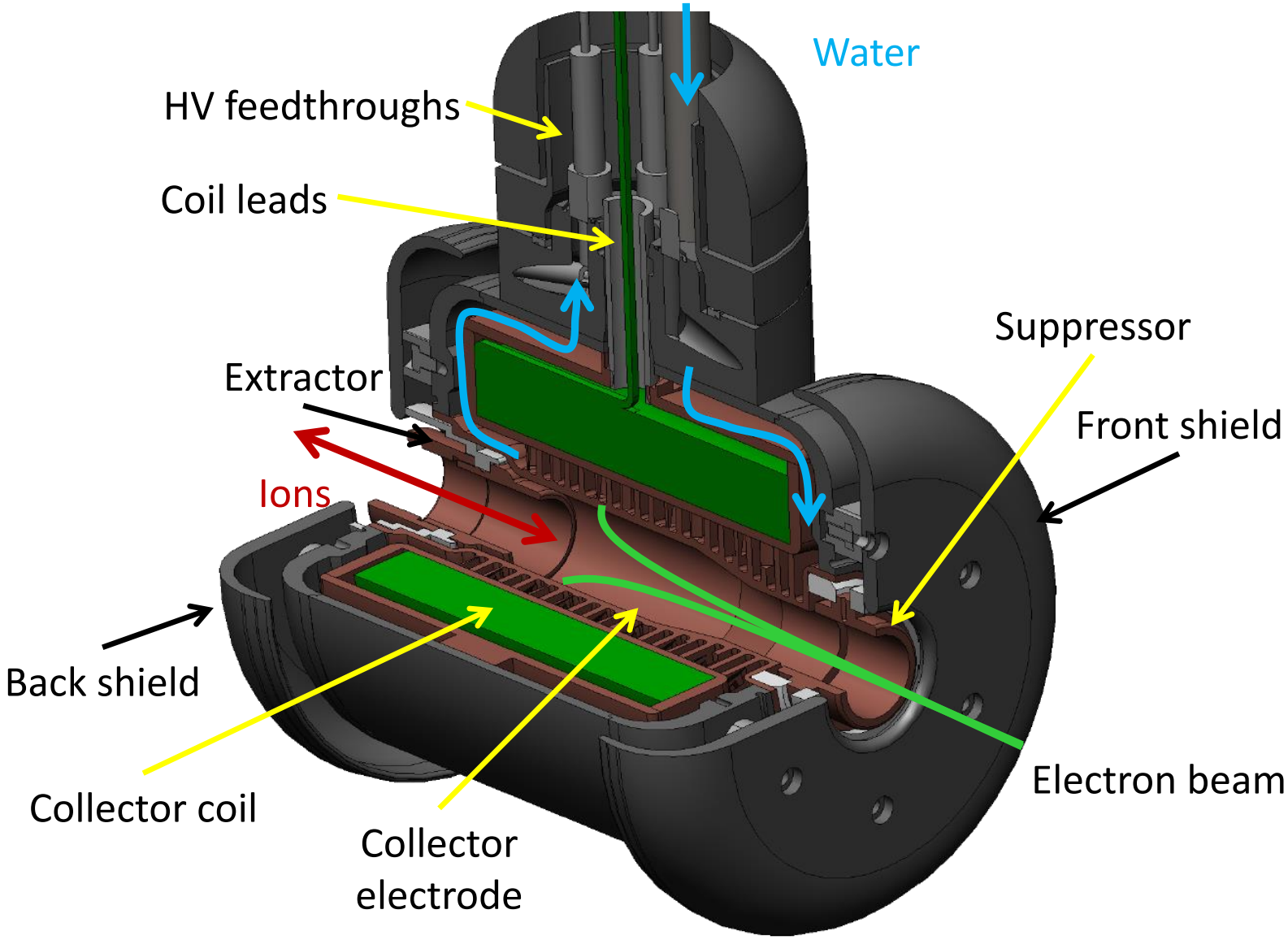


Electron gun



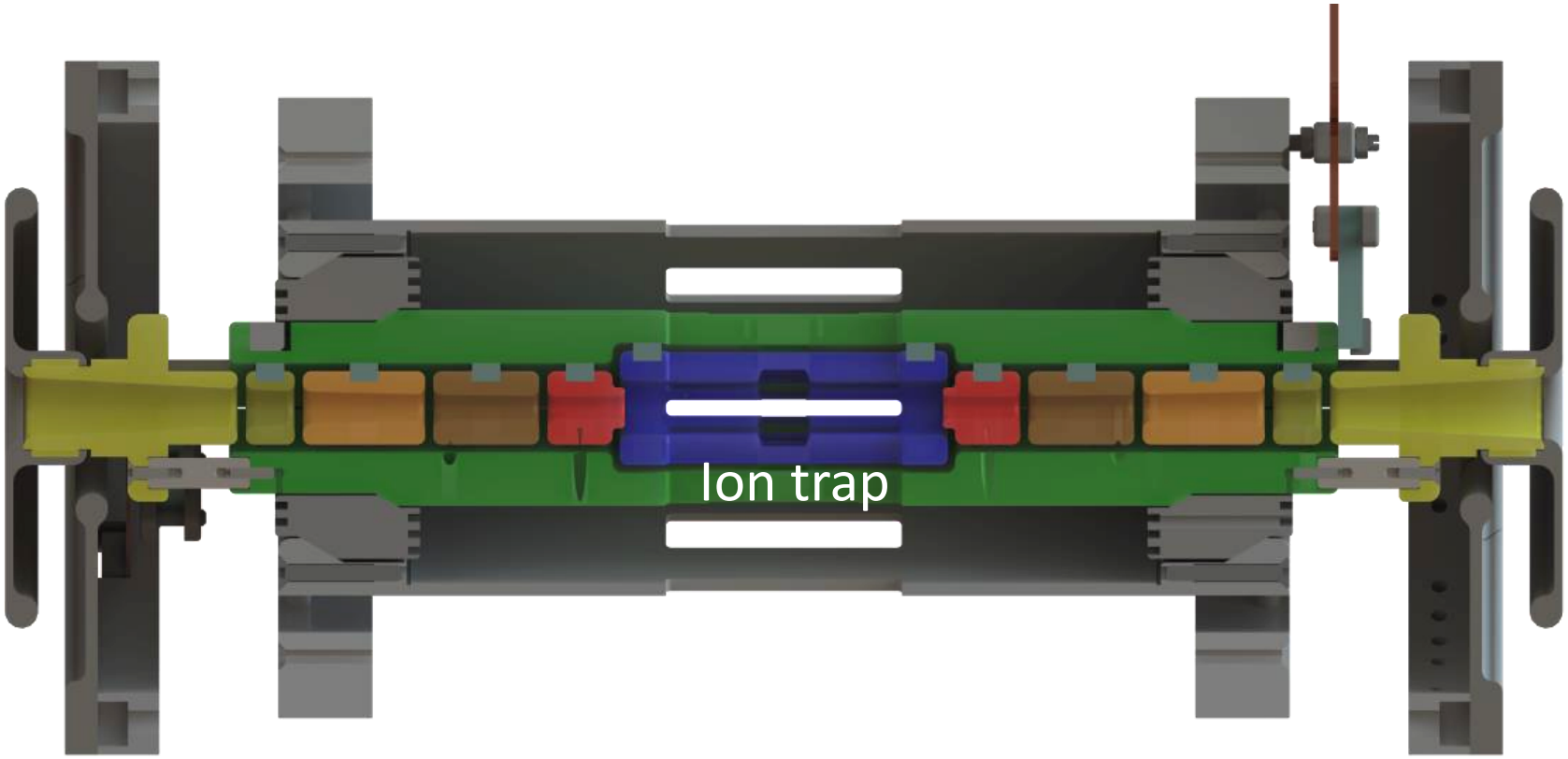

Cathode

Electron collector



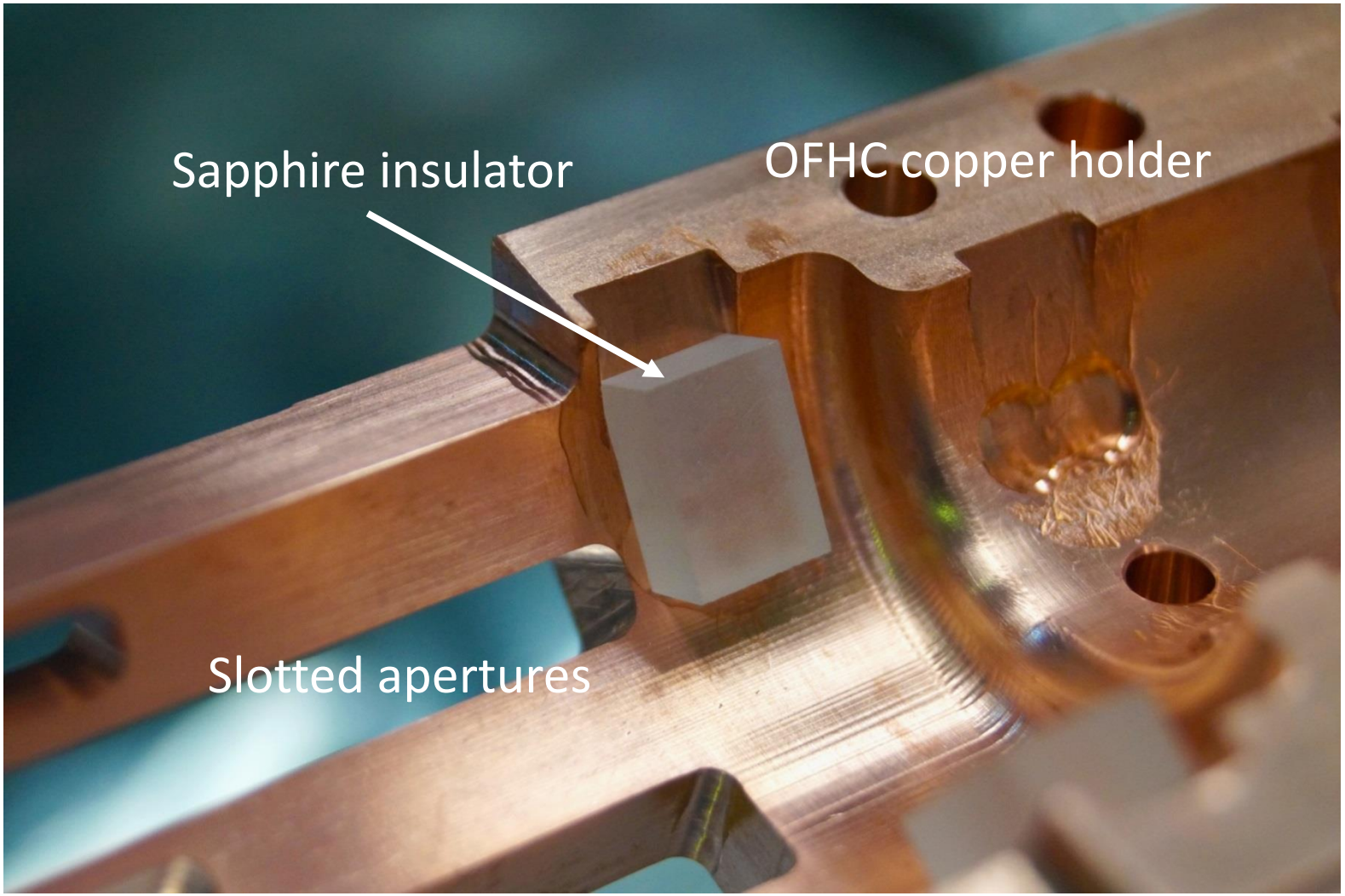
Electron collector

Drift tube assembly

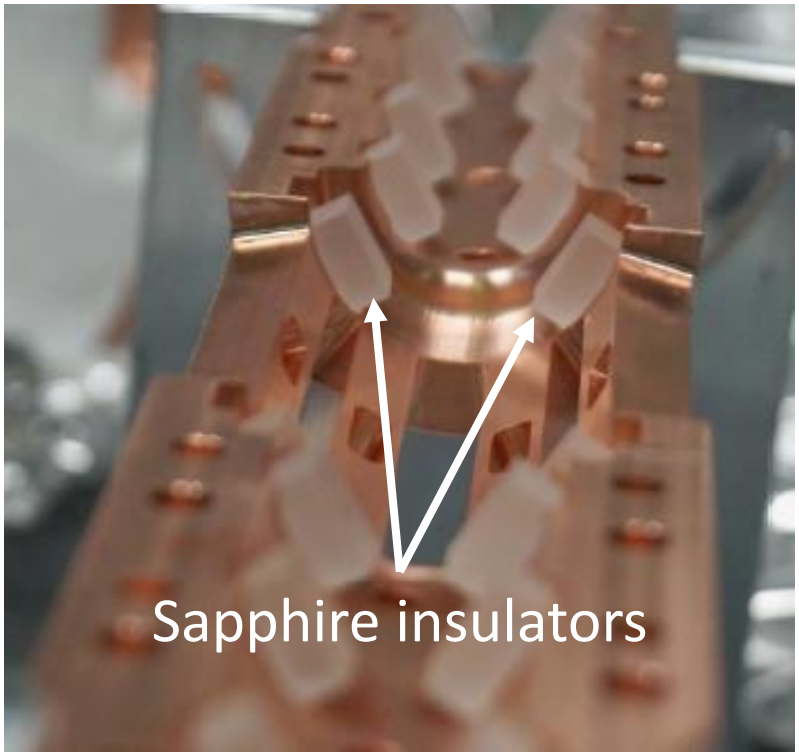


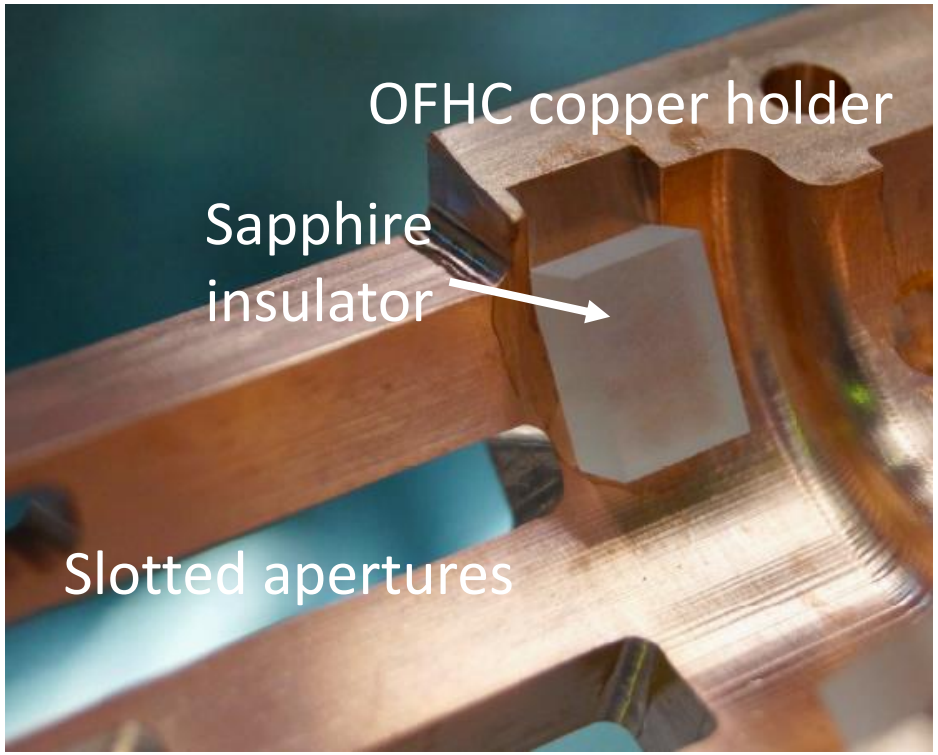
- Trap region lenght 80-270 mm
- 4 K operation
- Fast HV switching in sub-µs range possible

Drift tube supports

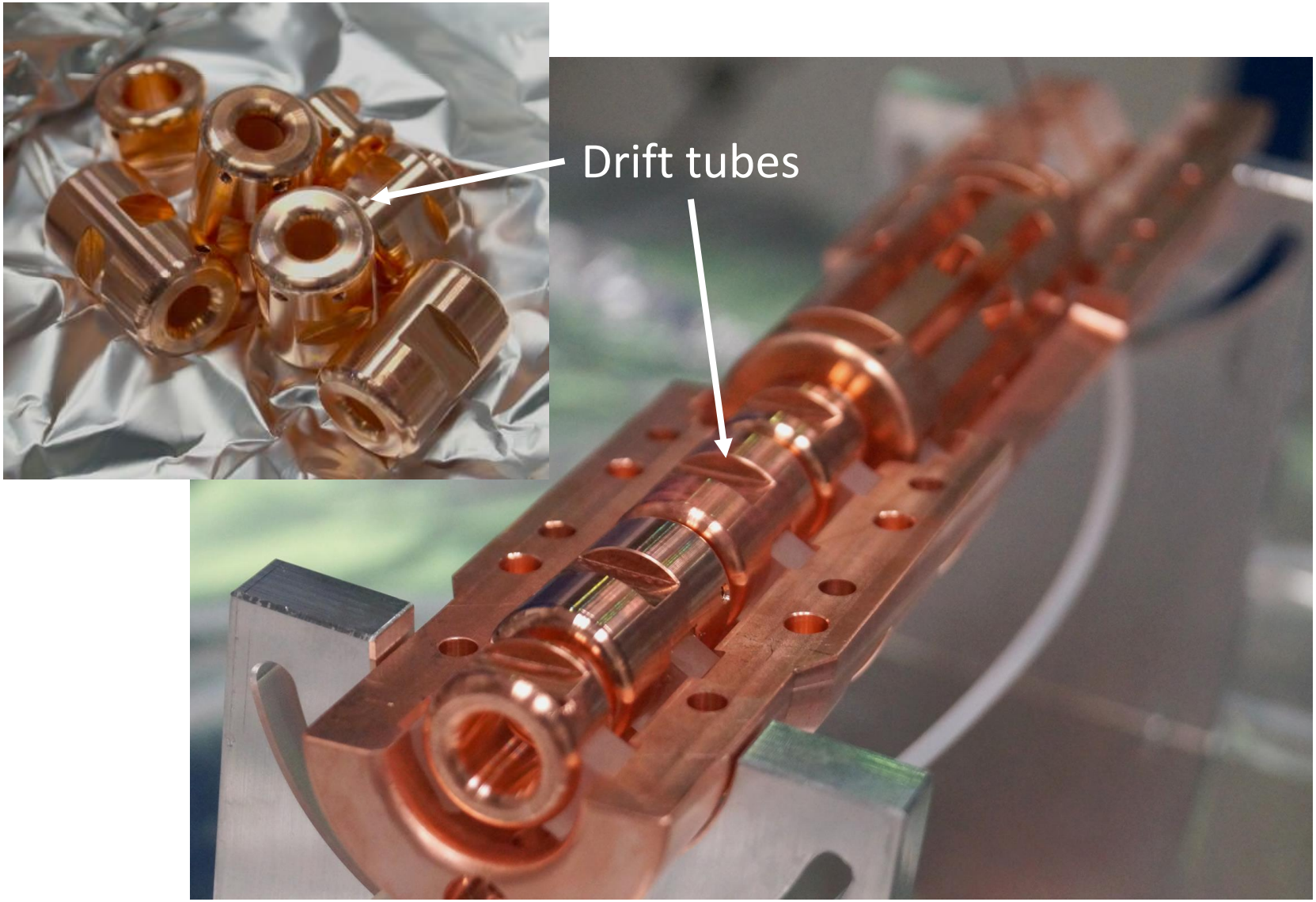


Drift tubes, electrode assembly

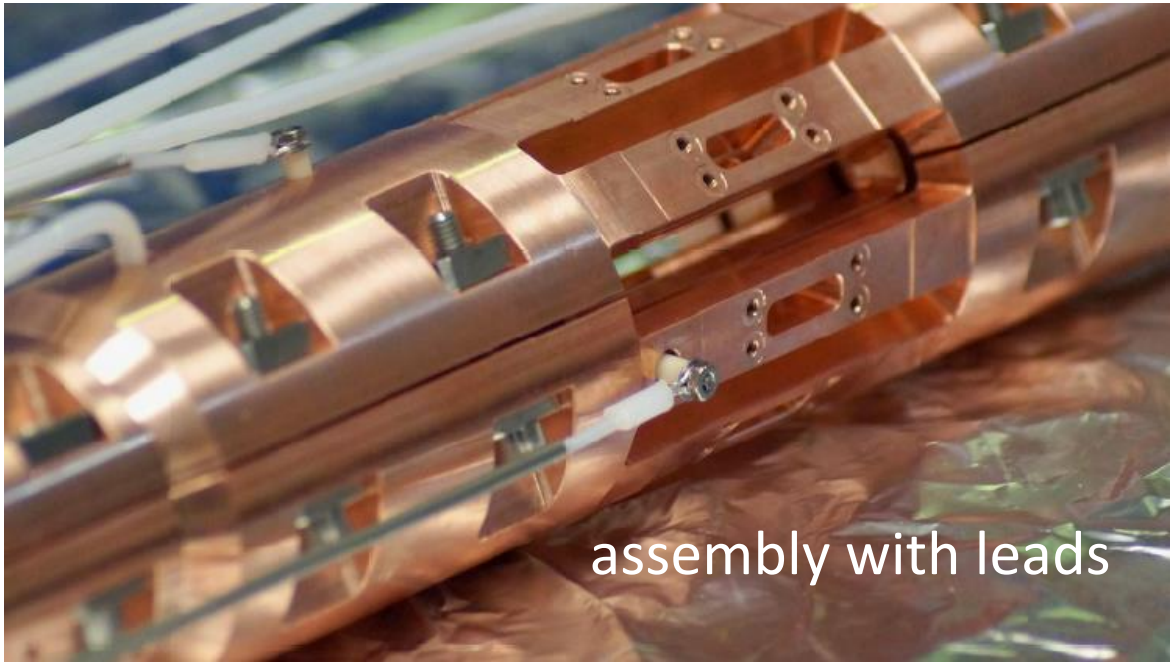




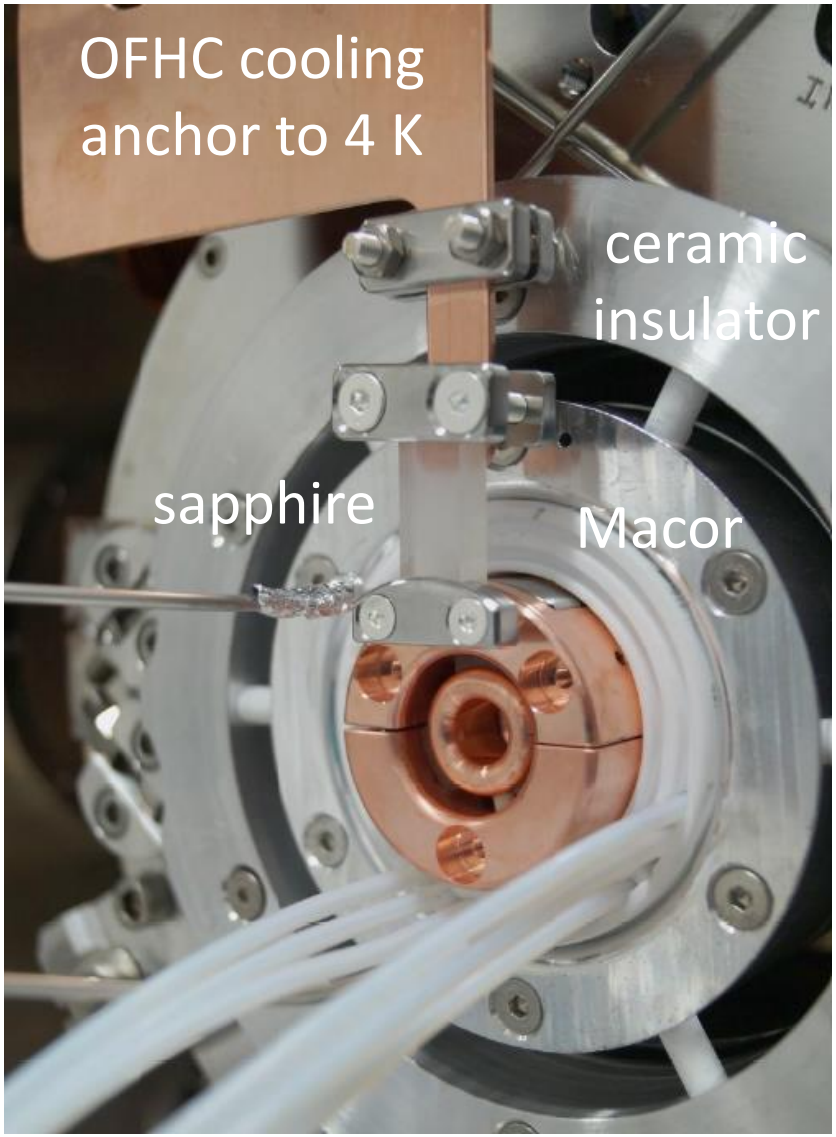
Drift tubes, electrode assembly



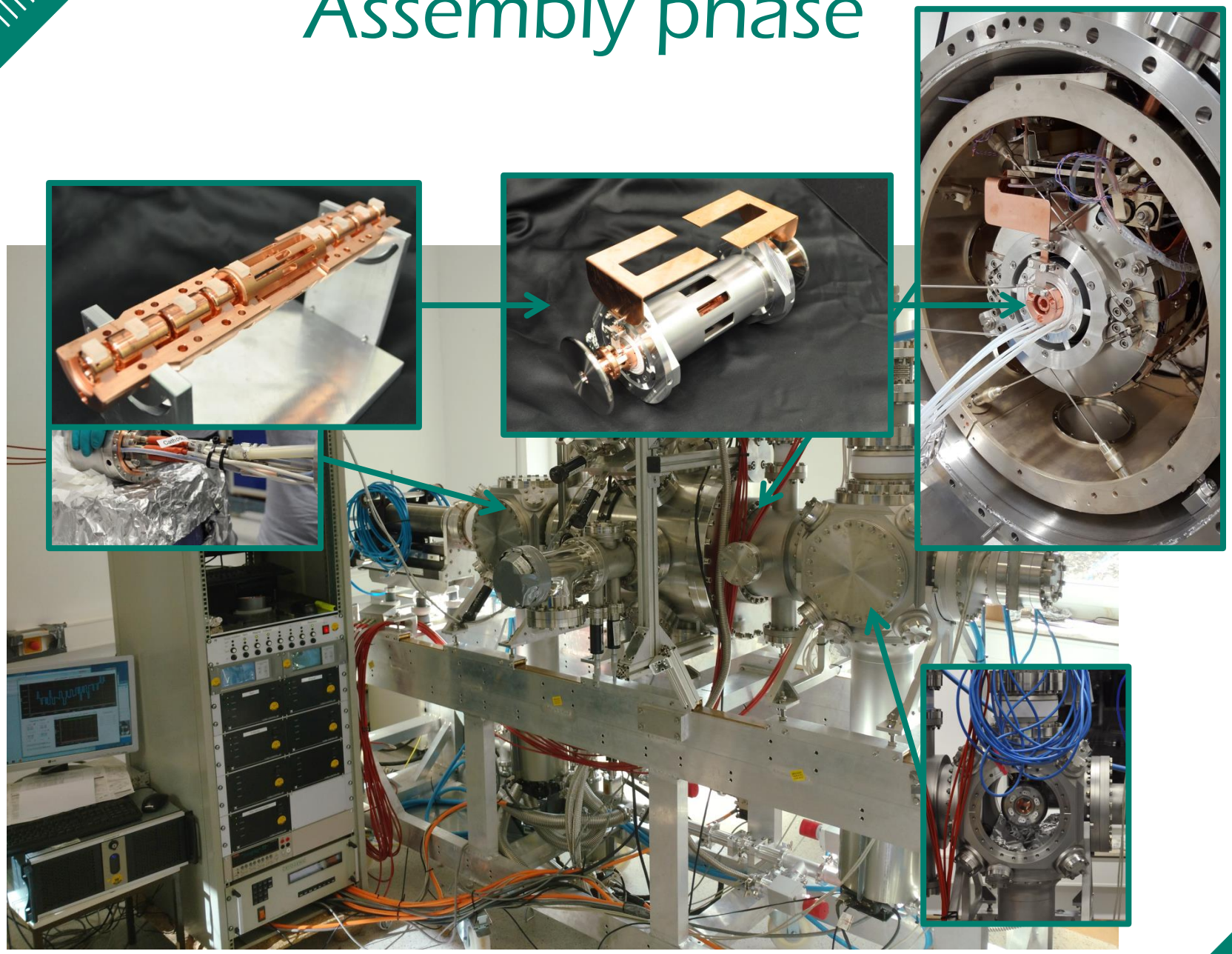
Slotted central drift tube



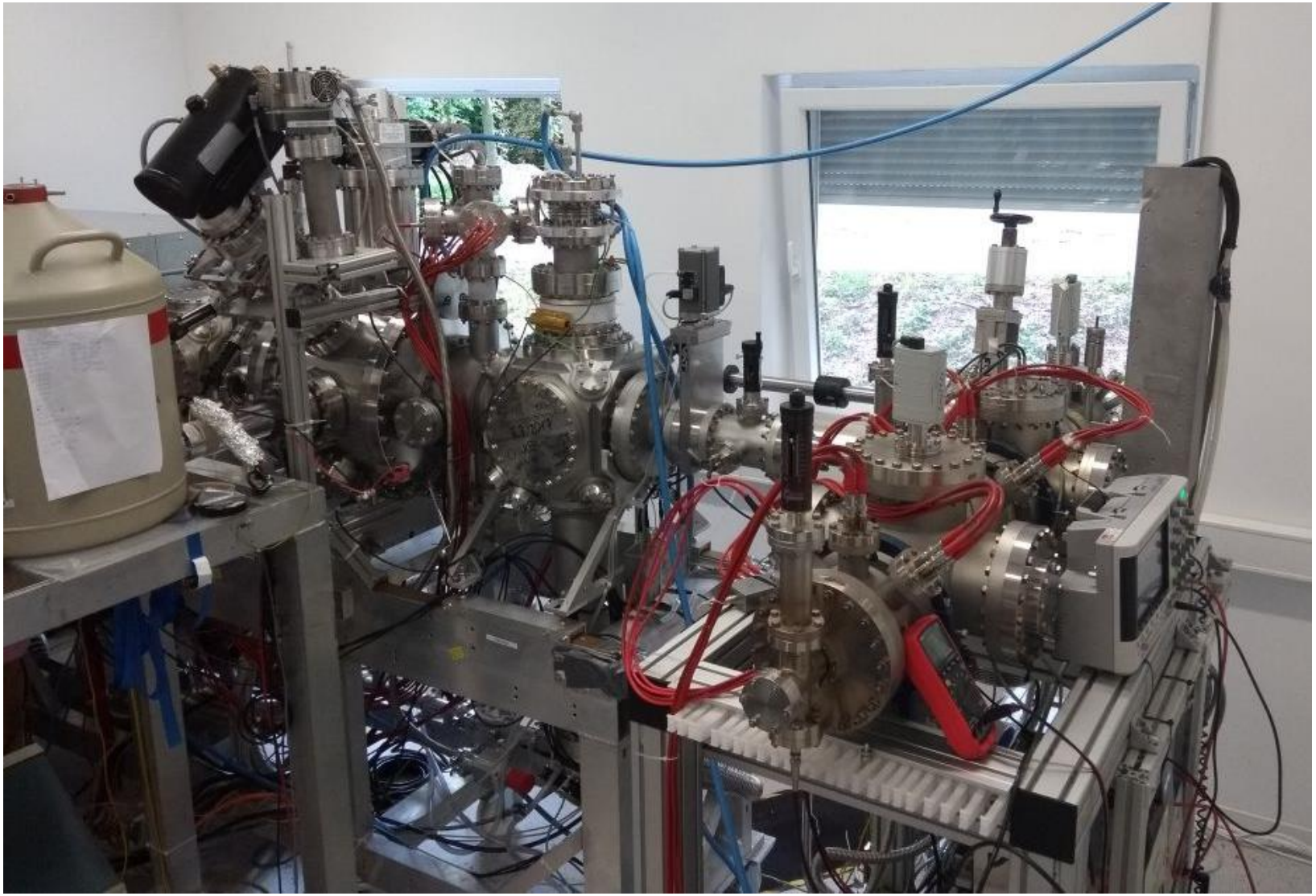
Drift tube assembly in magnet bore



Assembly phase

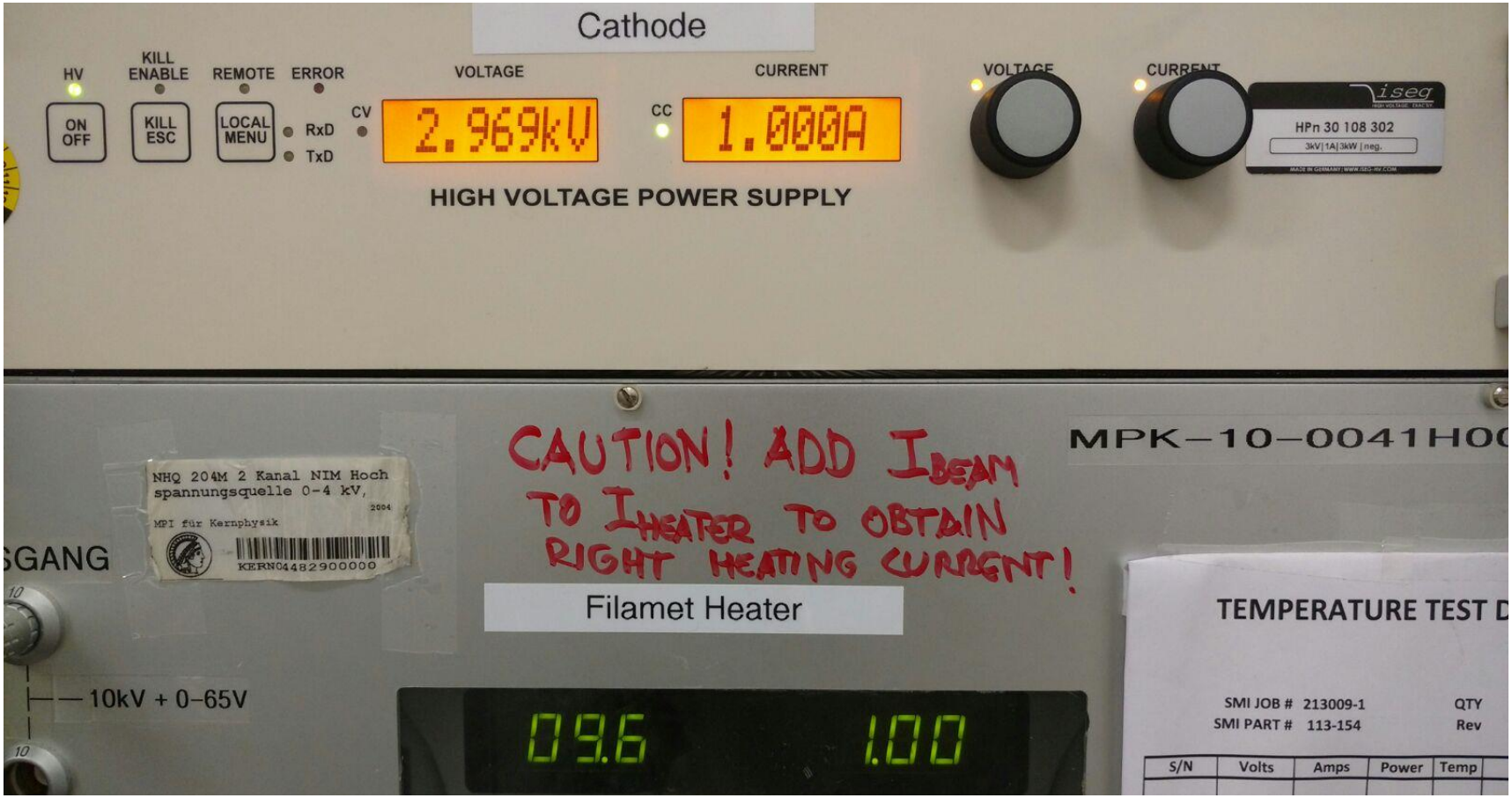


Assembly lab

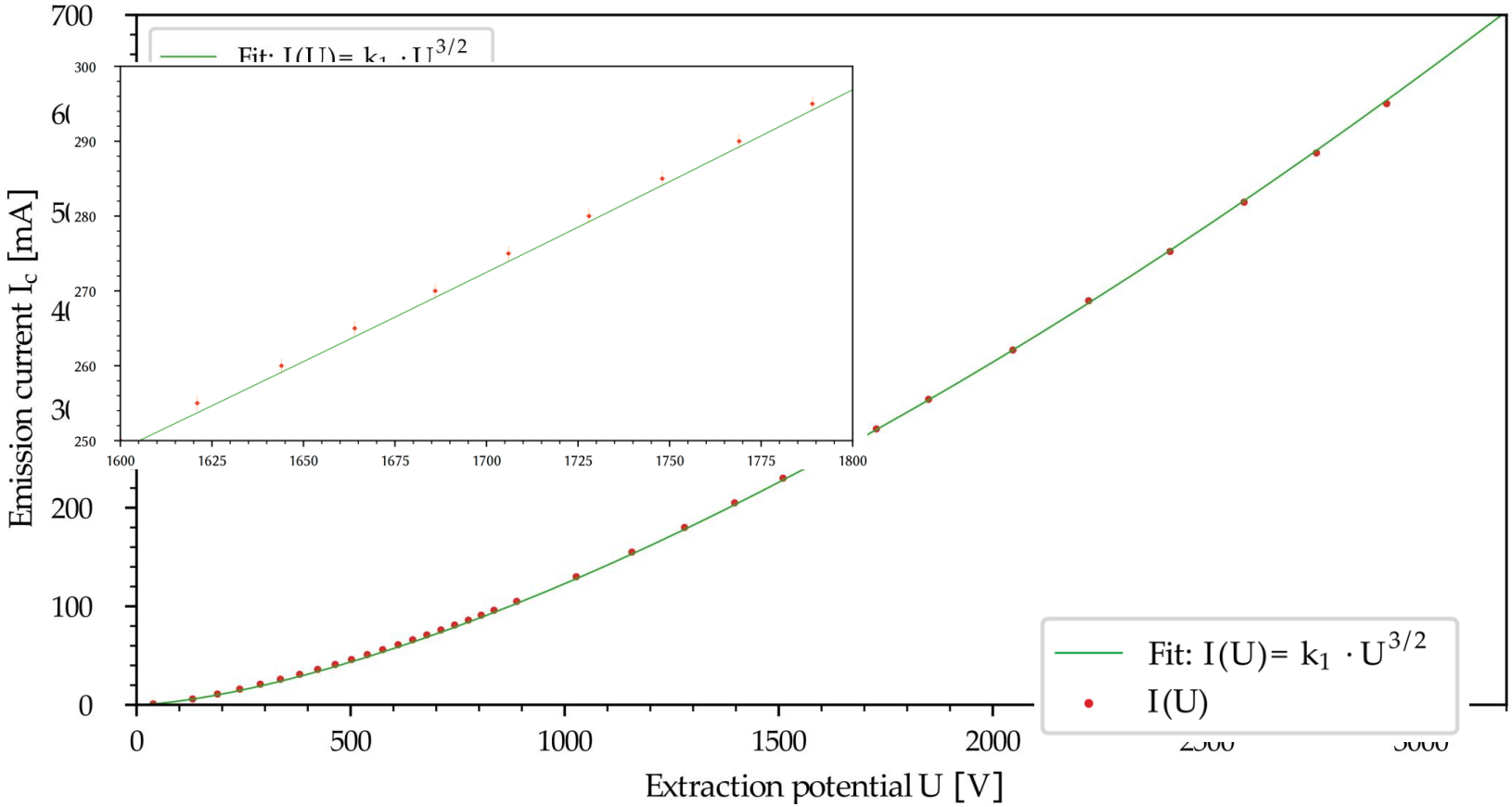


First beam 3.3.2017

First 1 A beam!

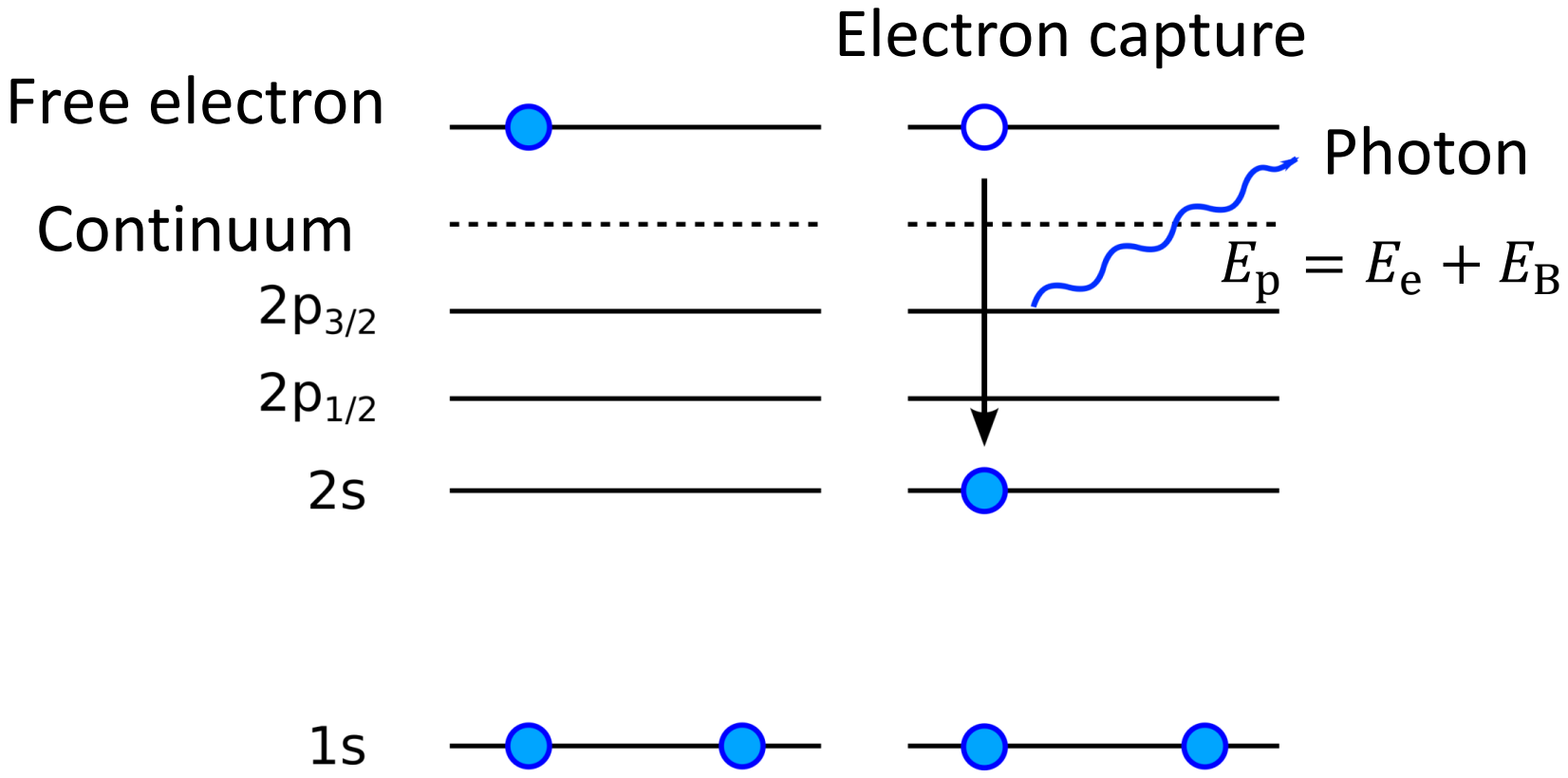


Measured perveance

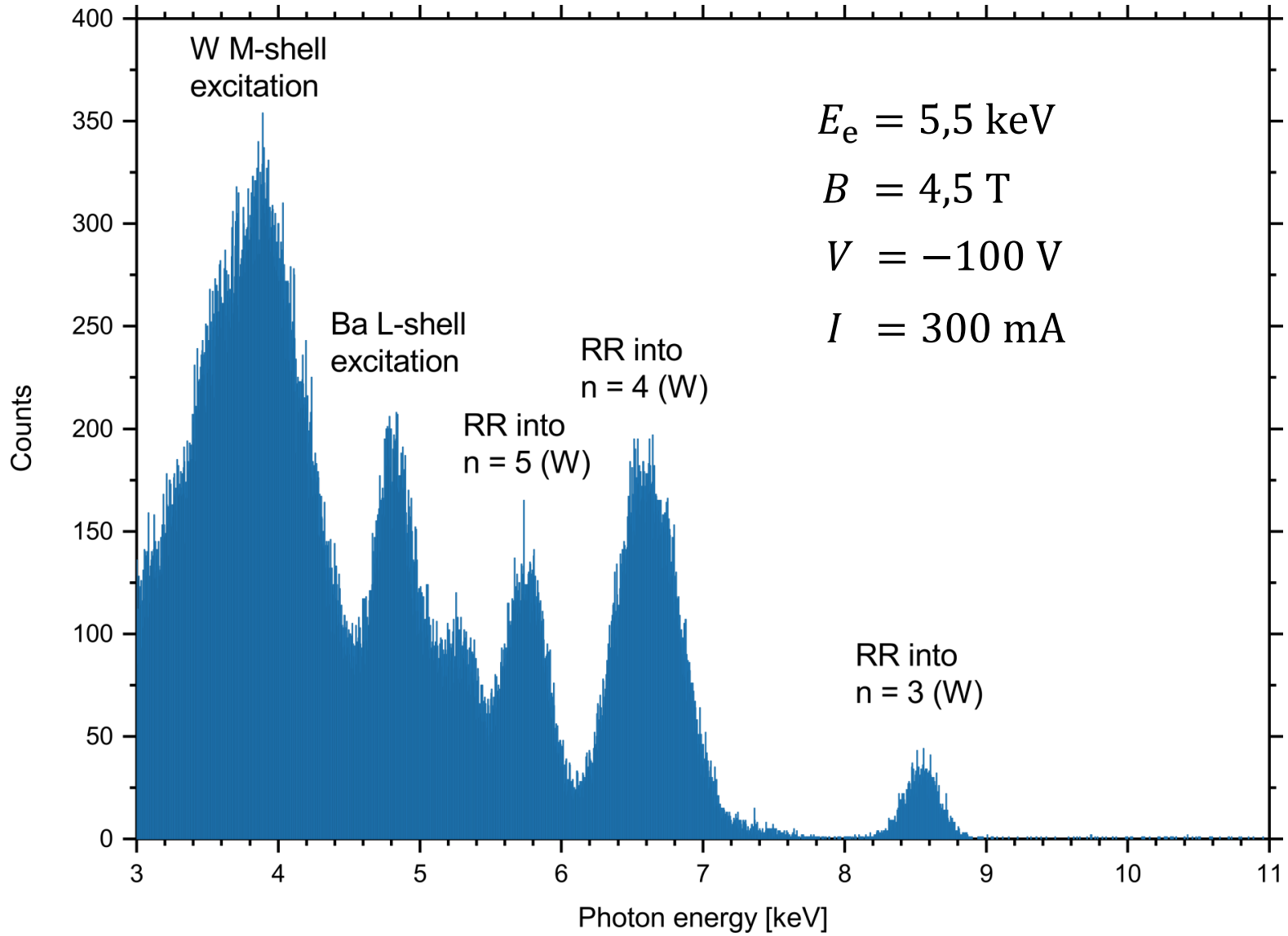


$$k_1 = (3.887 \pm 0.0024) \cdot 10^{-6} \frac{\mathrm{A}}{\mathrm{V}^{3/2}}$$

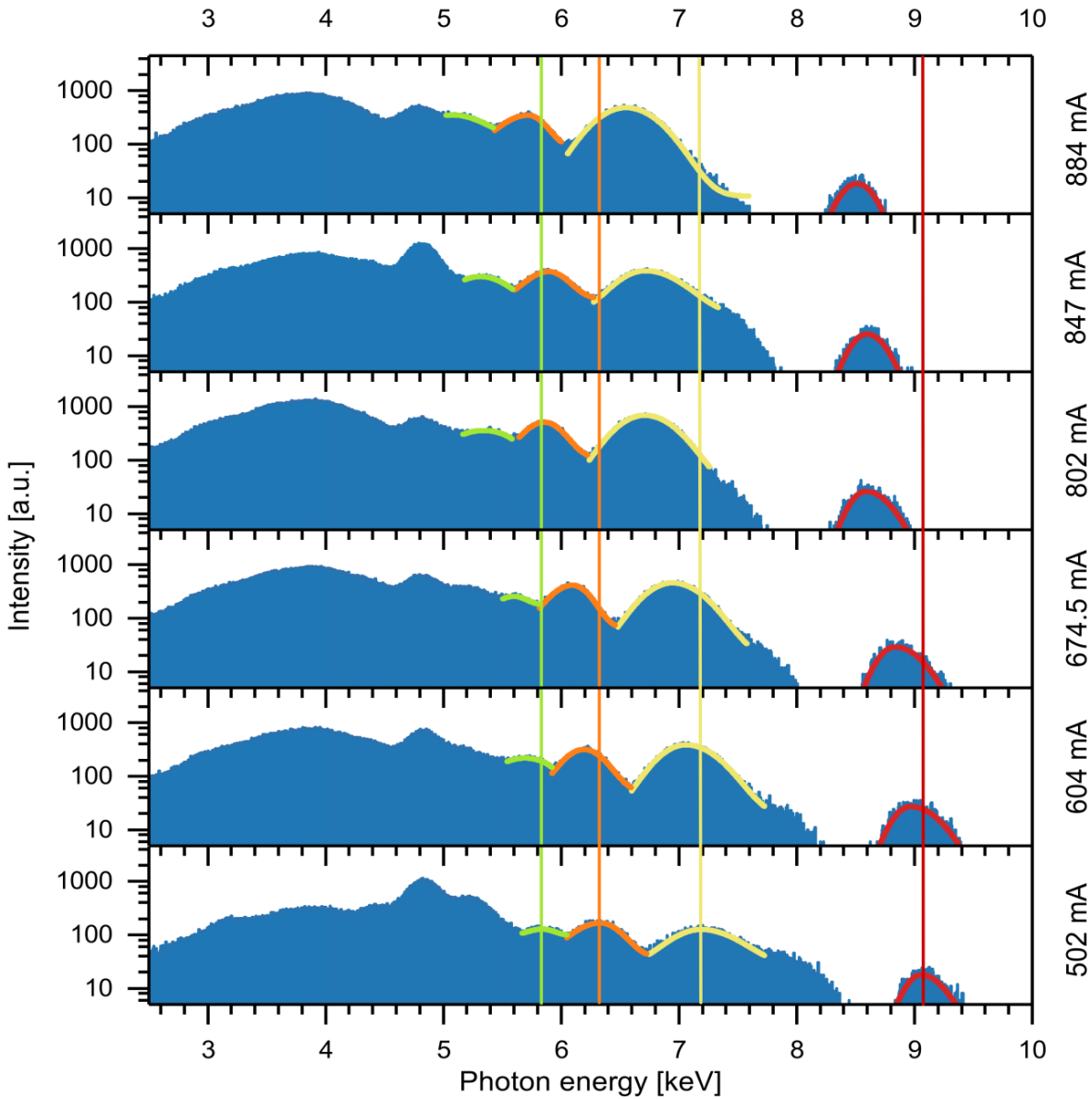
Radiative recombination



X-ray diagnostics



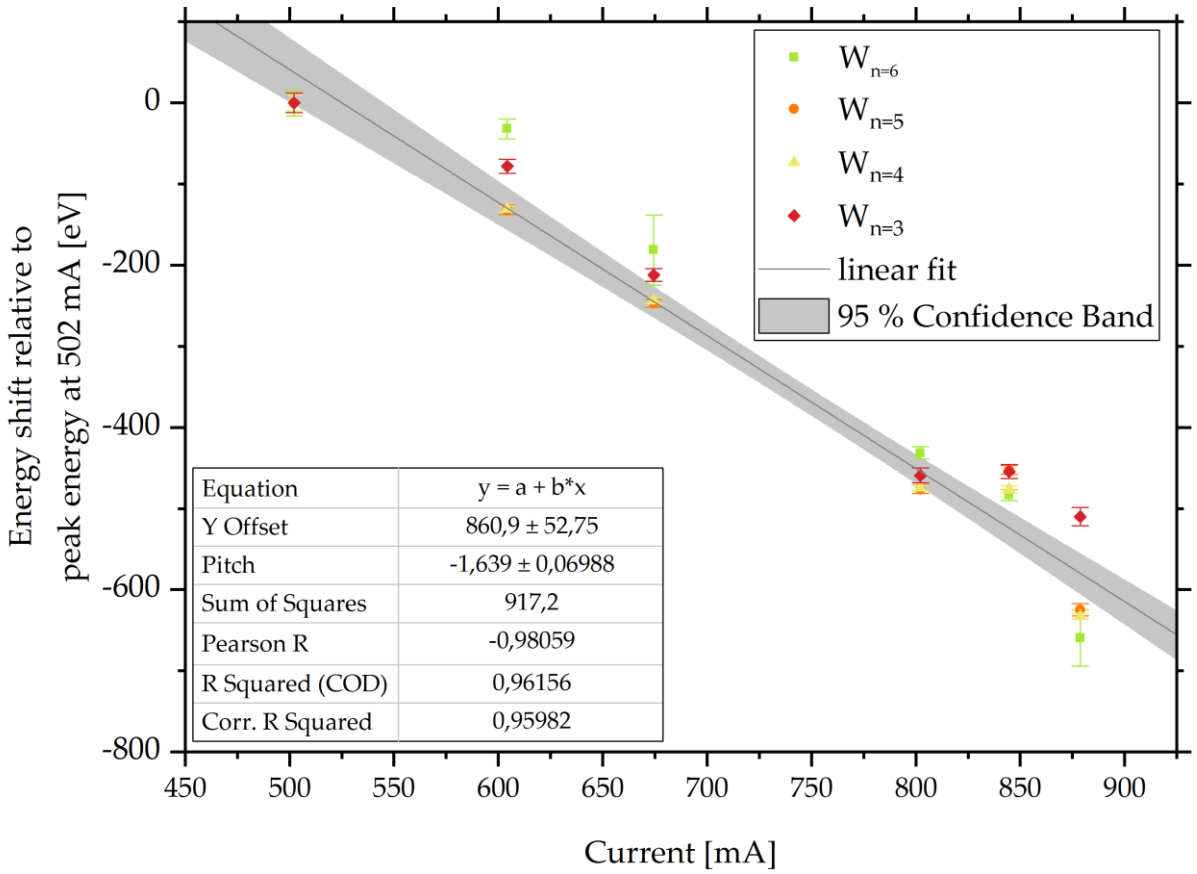
Spache charge shift



Shifts of RR peaks with beam current show value of space-charge potential

$$E_e = 5{,}8\ \mathrm{keV}$$
$$B = 4{,}5\ \mathrm{T}$$
$$V = -100\ \mathrm{V}$$

Space charge shift

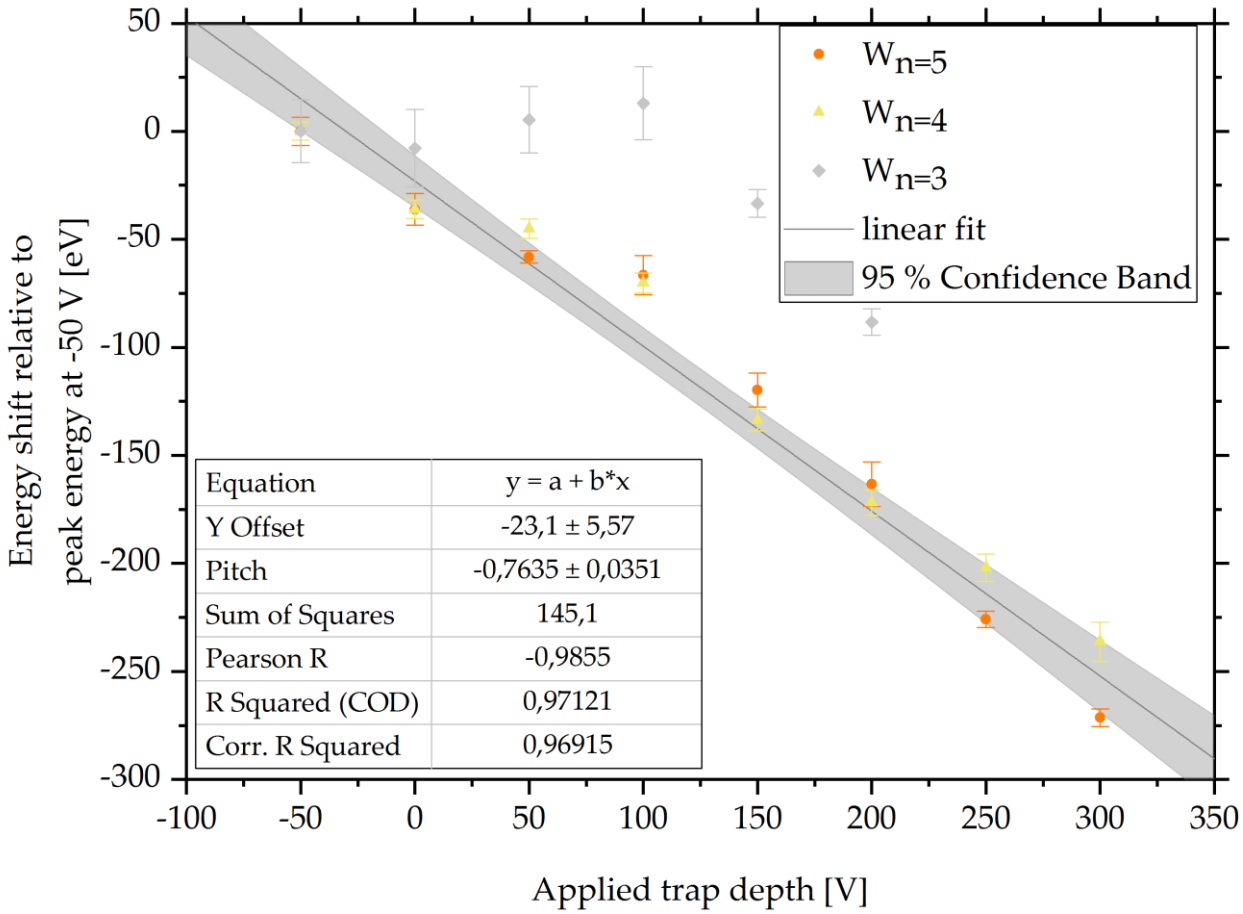


Equation	y = a + b*x
Y Offset	860,9 ± 52,75
Pitch	-1,639 ± 0,06988
Sum of Squares	917,2
Pearson R	-0,98059
R Squared (COD)	0,96156
Corr. R Squared	0,95982

Shifts of RR peaks with beam current show value of space-charge potential

$$\Delta V_e = (-1.639 \pm 0.070)\,\frac{\mathrm{eV}}{\mathrm{mA}}$$

Space charge shift



Equation	y = a + b*x
Y Offset	-23,1 ± 5,57
Pitch	-0,7635 ± 0,0351
Sum of Squares	145,1
Pearson R	-0,9855
R Squared (COD)	0,97121
Corr. R Squared	0,96915

Shifts of RR peaks with axial-well depth show ion space charge compensation

$$E_e = 5{,}5\ \mathrm{keV}$$
$$B = 4{,}5\ \mathrm{T}$$
$$V_{\mathrm{CDT}} = 2{,}5\ \mathrm{kV}$$
$$I = 812\ \mathrm{mA}$$

$$\Delta V_i = (-0.763 \pm 0.035)\ \frac{\mathrm{eV}}{\mathrm{V}}$$

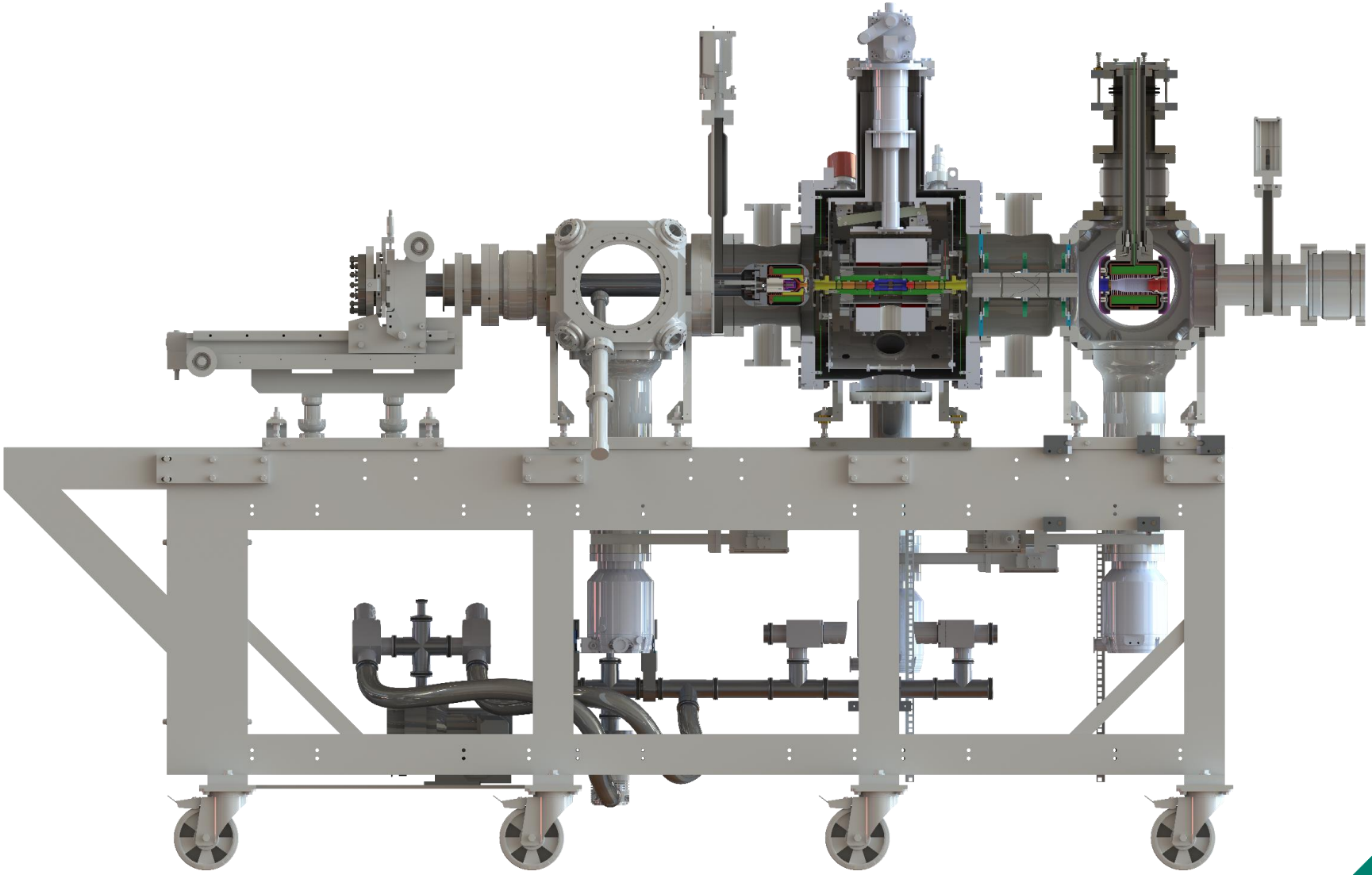
Summary

- Design, construction and assembly of CANREB-EBIS
- Test up to 4.5 T
- Emission currents up to 1 A with 6 mm diameter cathode

- Perveance determination $k_1 = (3.887 \pm 0.0024) \cdot 10^{-6} \frac{\mathrm{A}}{\mathrm{V}^{3/2}}$

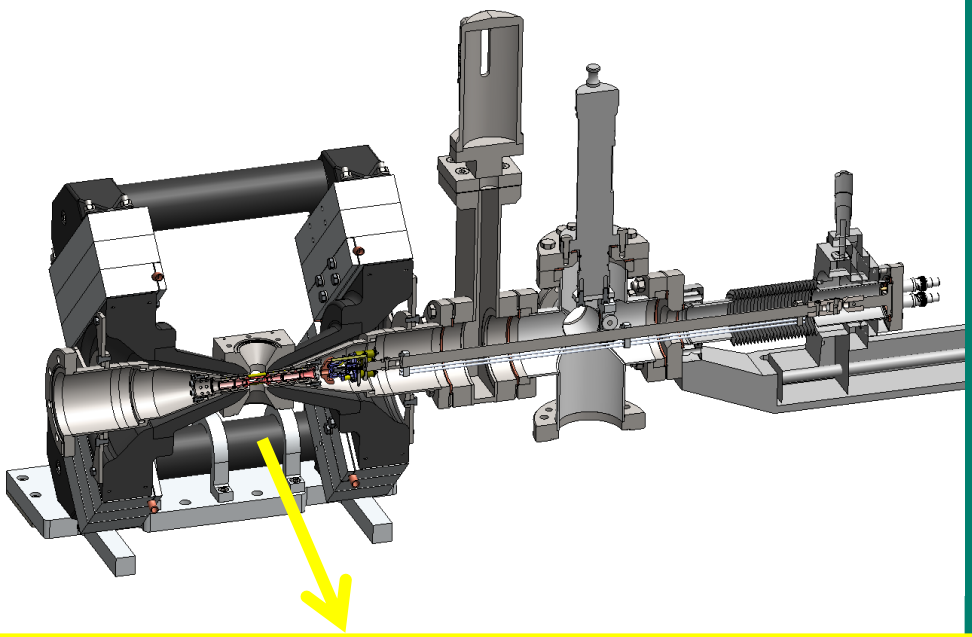
- Space charge potential determination dependence
  - electron beam current $\Delta V_\mathrm{e} = (-1.639 \pm 0.070) \frac{\mathrm{eV}}{\mathrm{mA}}$
  - trap potential depth $\Delta V_\mathrm{i} = (-0.763 \pm 0.035) \frac{\mathrm{eV}}{\mathrm{V}}$

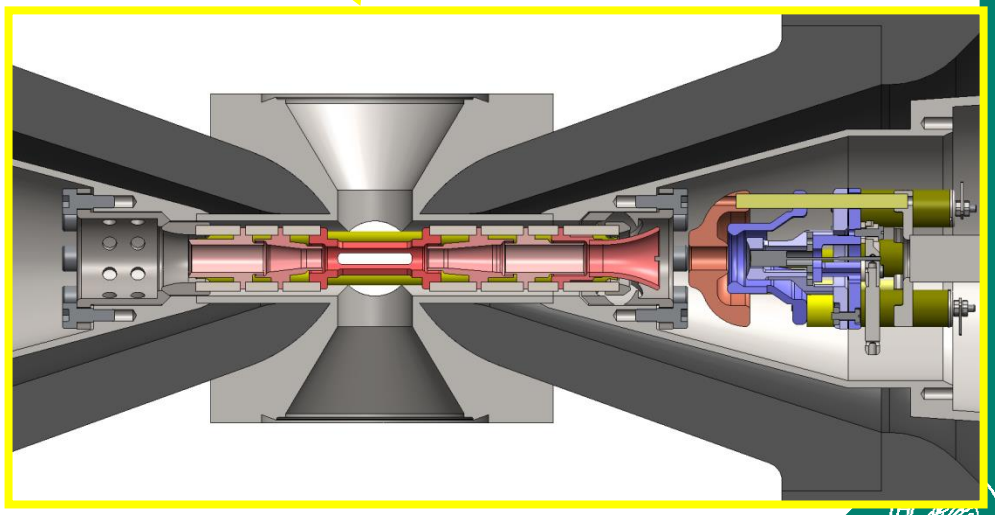
Support frame



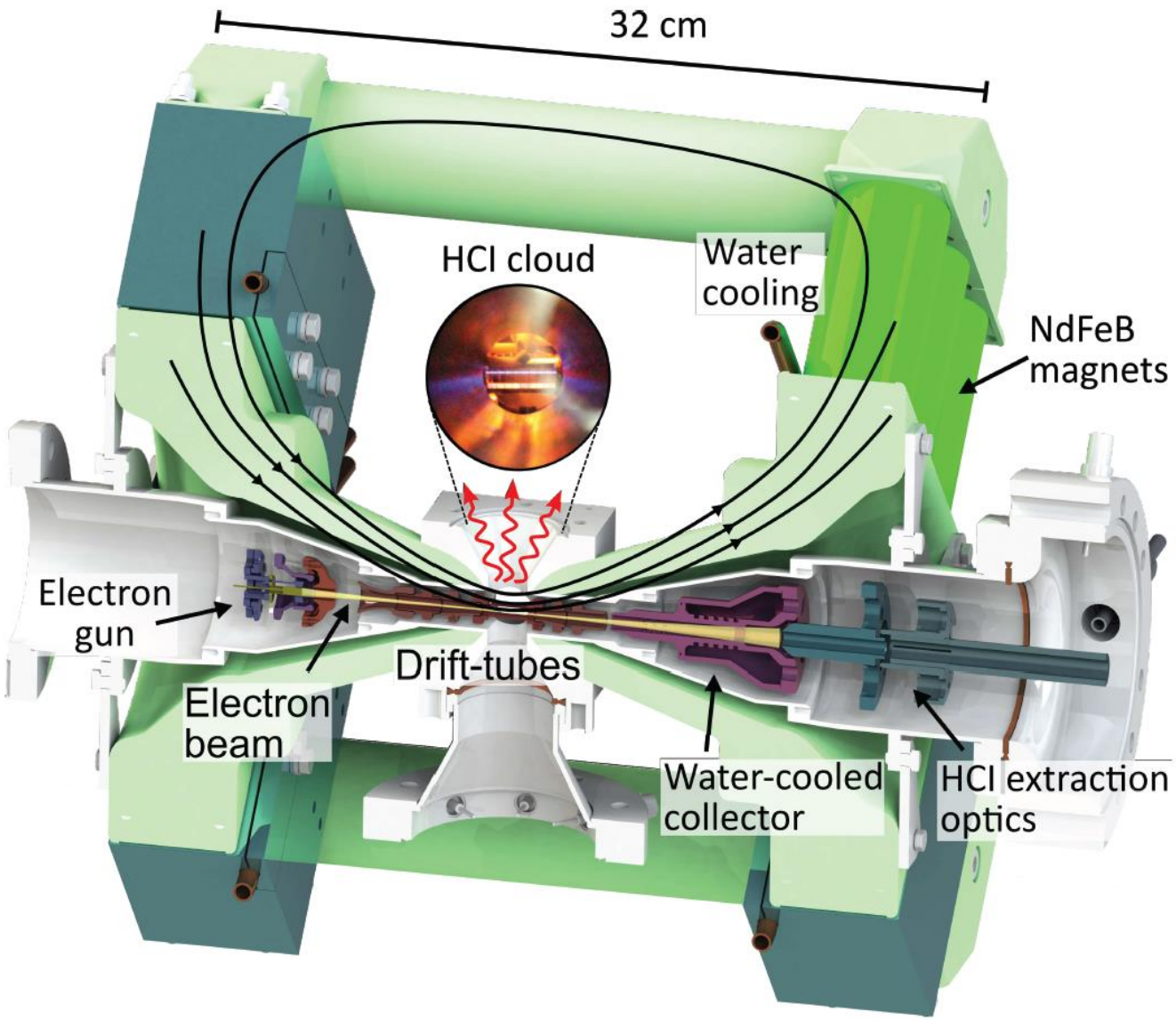
Final tests before shipping

Table-top EBITs for PTB, Petra-III, MPIK

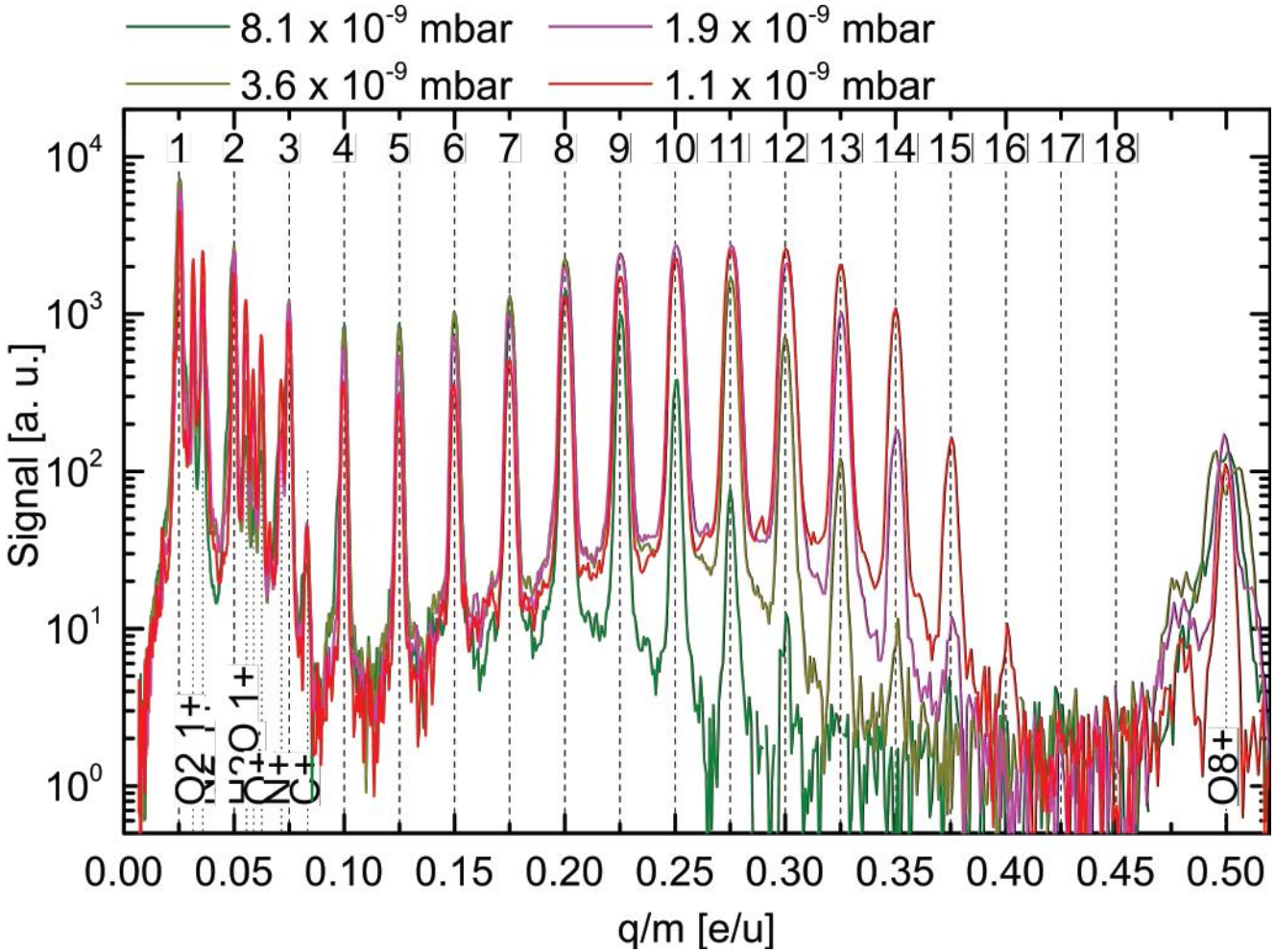




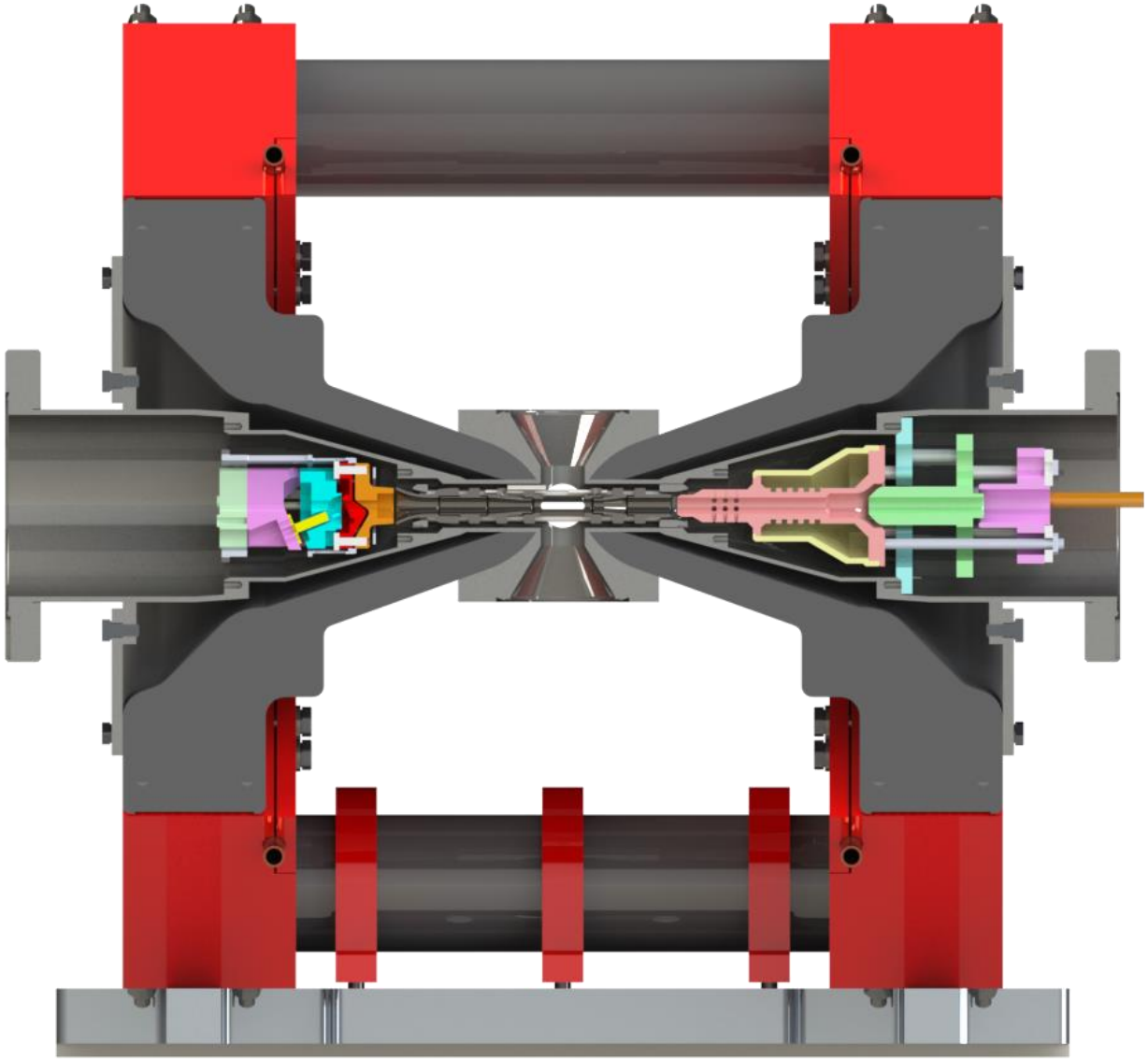
Mini EBITS



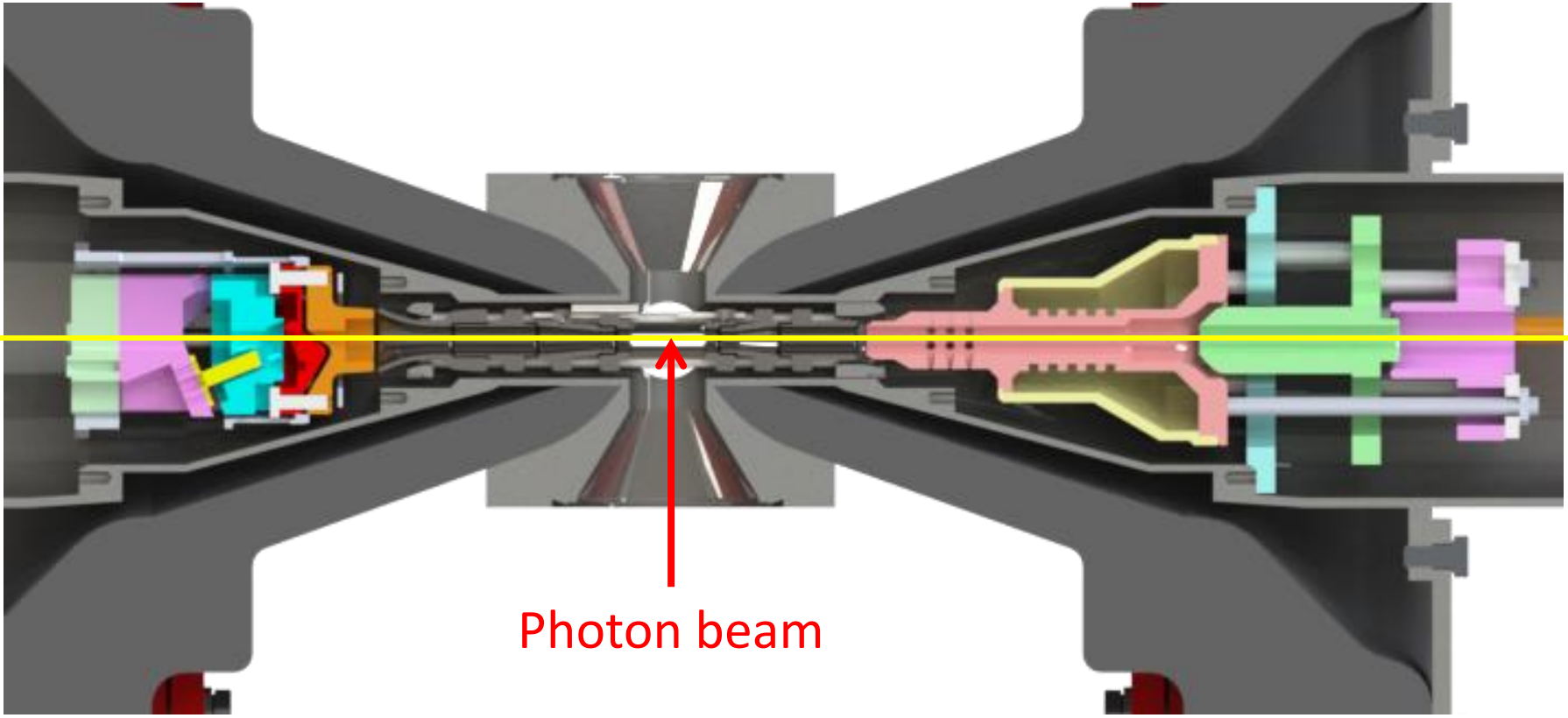
Mini EBITS



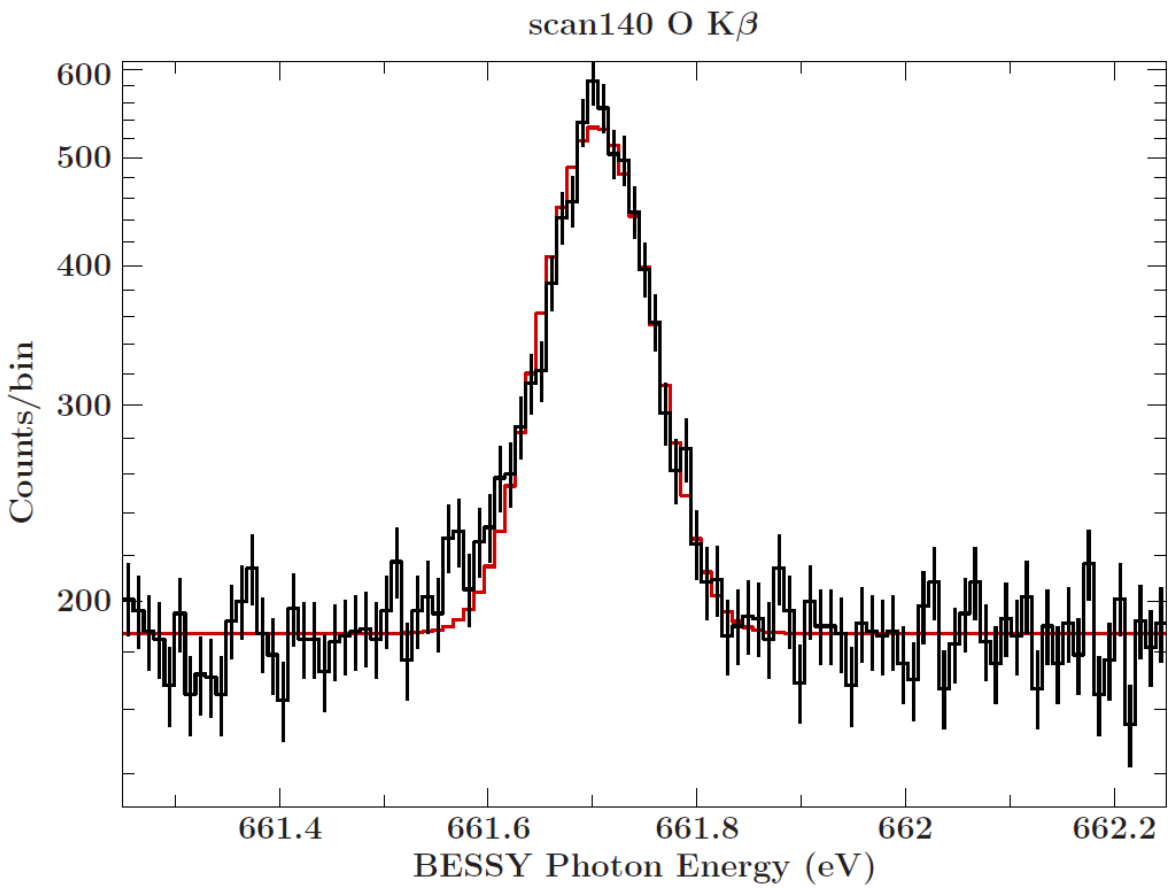
Off-axis electron gun



Off-axis electron gun



Fluorescence of He-like O^{6+} *1s-3p*

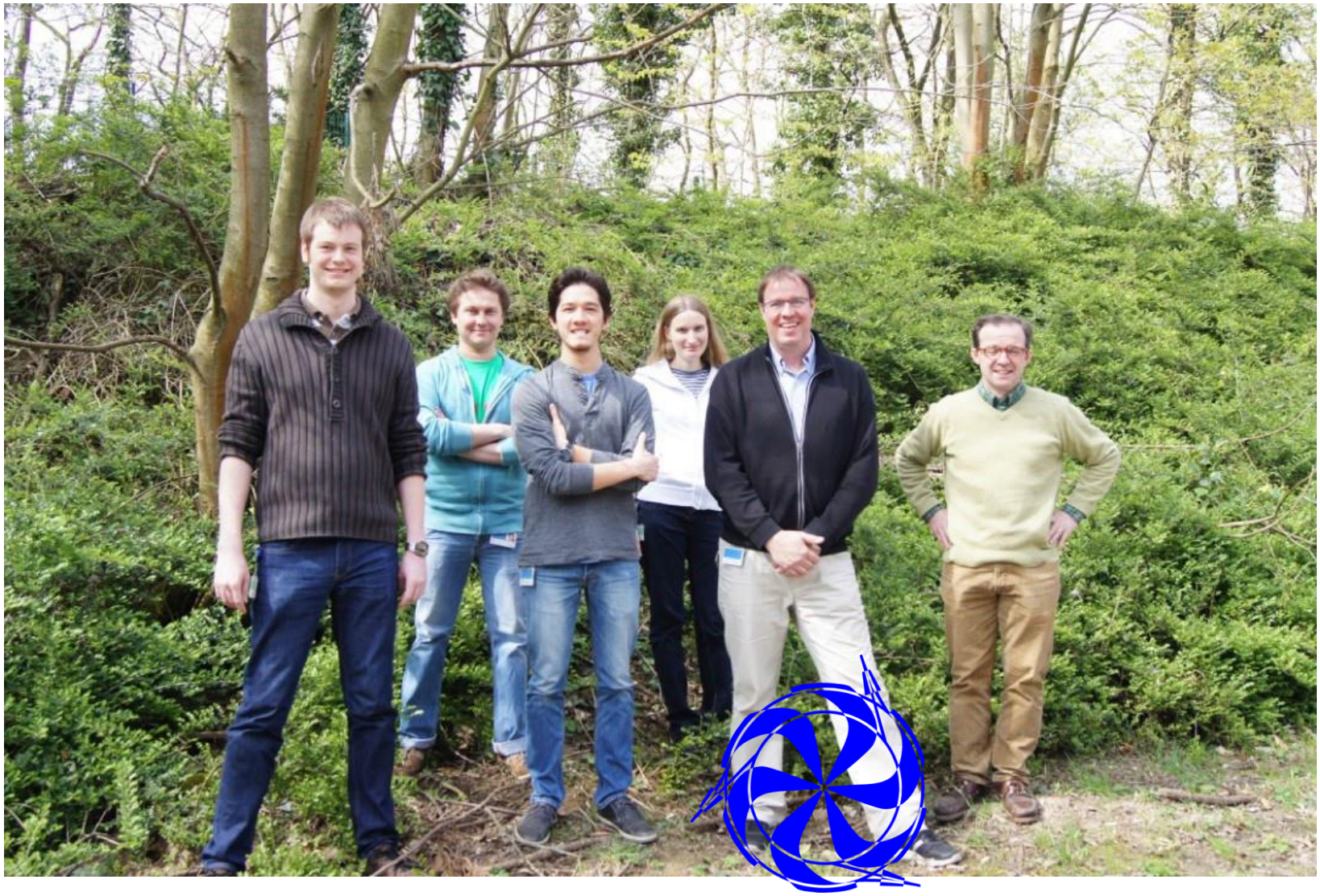


Miniature PolarX-EBIT succesfully operating with synchrotron radiation at BESSY-II

Outlook

- Preparation for HV-floating operation
- Tests of injection from laser ion source
- Test of gas injection system
- Transfer to TRIUMF

CANREB EBIS Team



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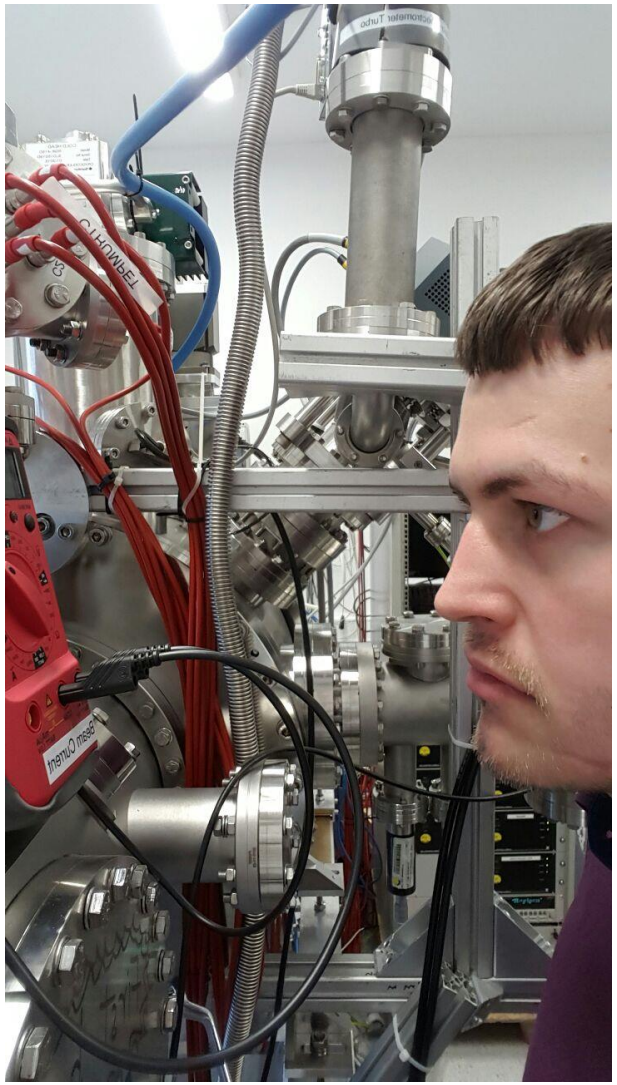

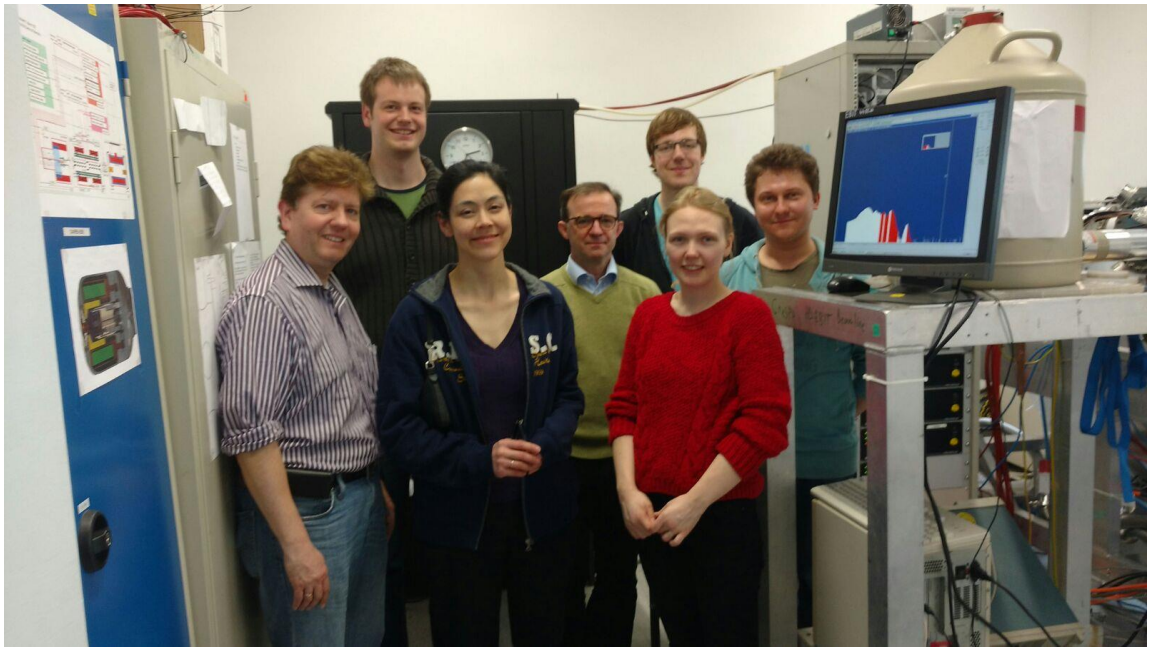

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