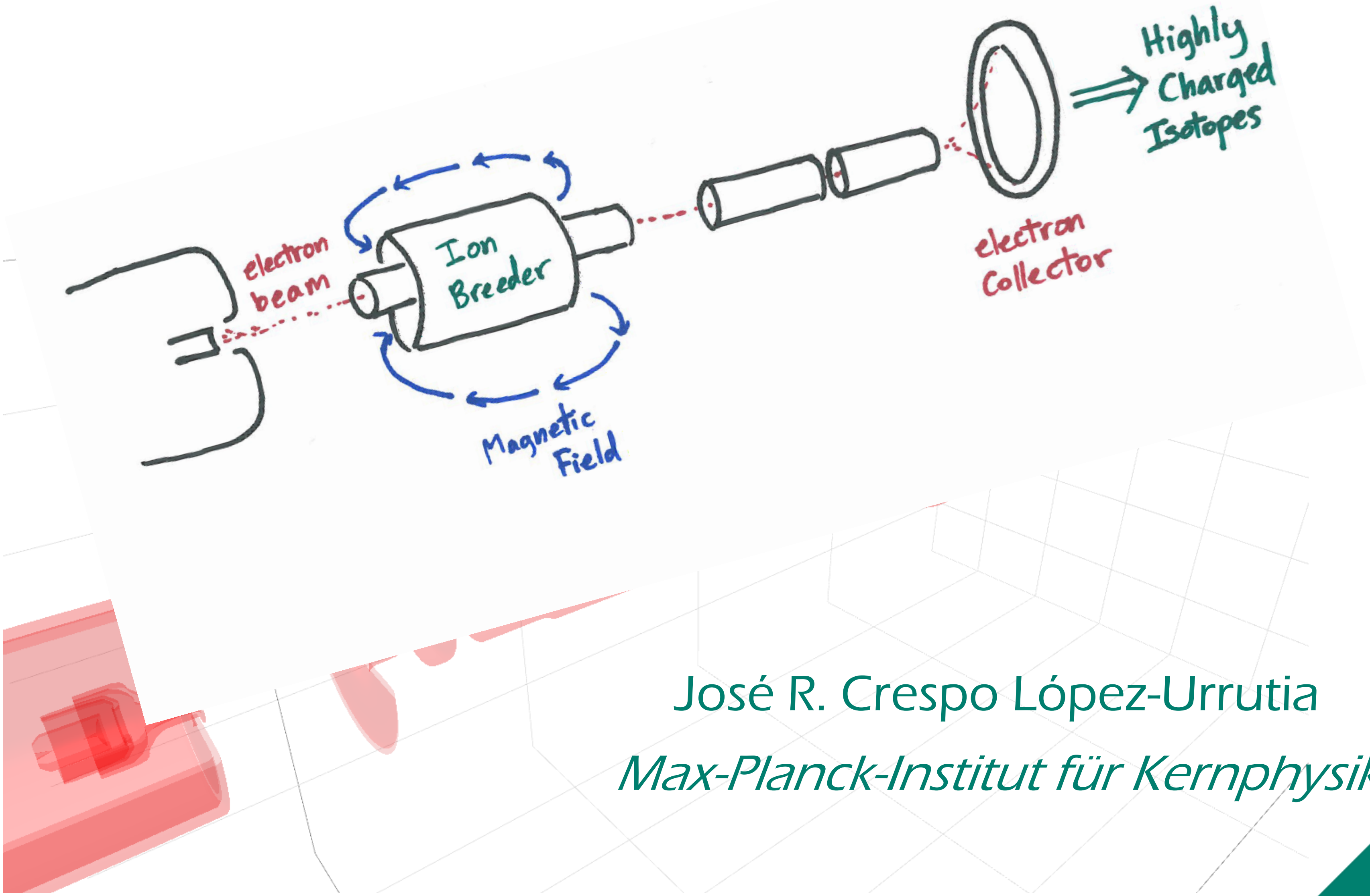
How to make, trap and observe microscopic star plasmas in the laboratory, and us clocks

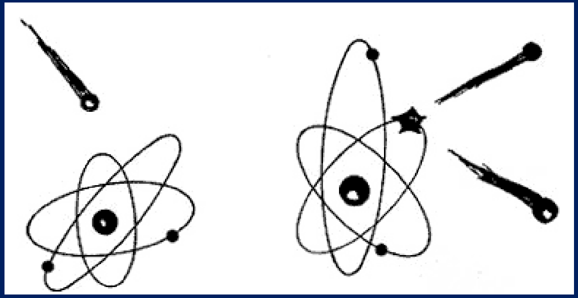


José R. Crespo López-Urrutia

Max-Planck-Institut für Kernphysik

What are highly charged ions?

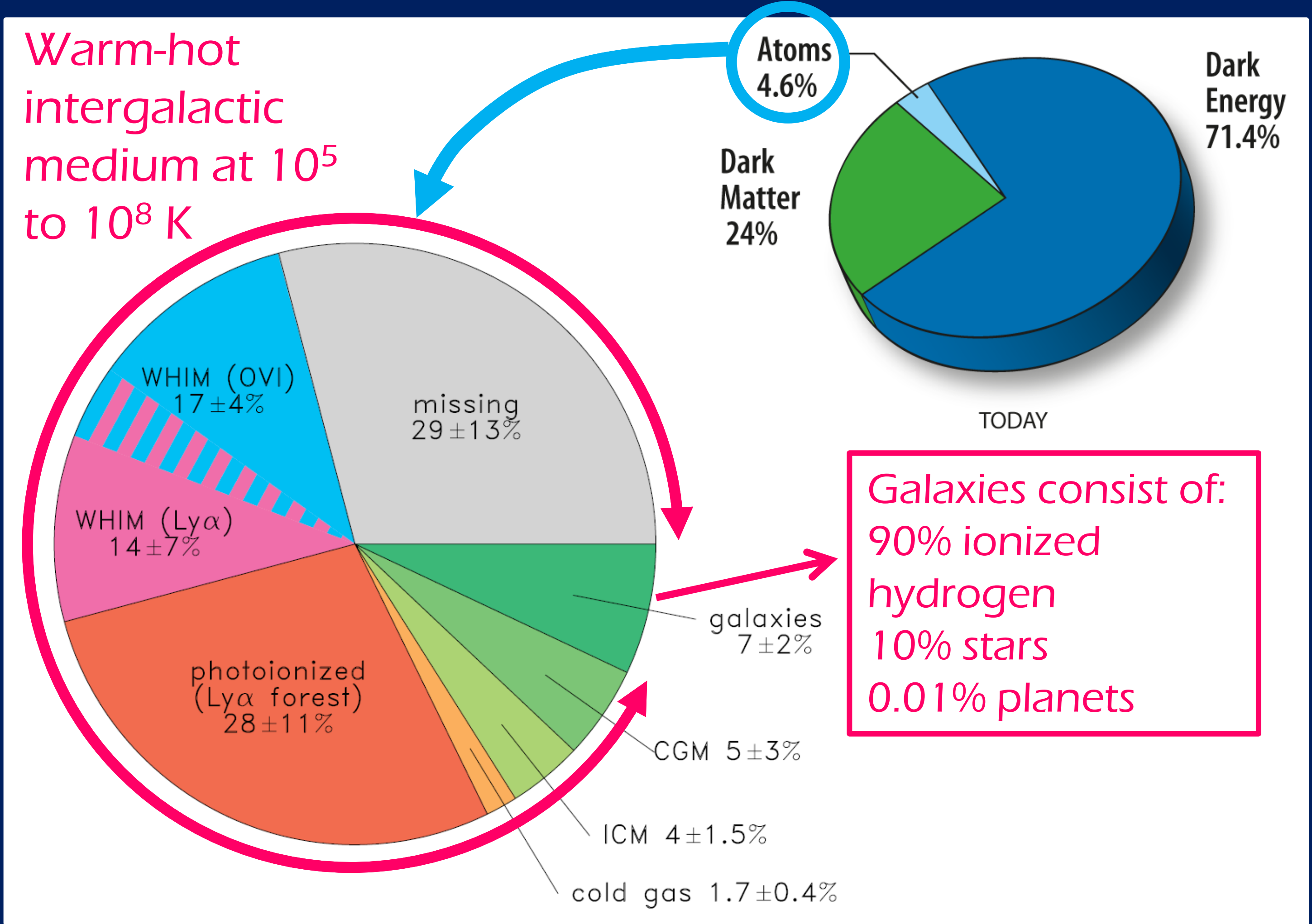
- Atoms loose many electrons at high temperatures < 100000 K due to collisions



- The incomplete electronic shell does not compensate the positive nuclear charge
- The electronic structure of such positive ions with few electrons behaves like that of an atom

Example: Fe XXV = Fe^{24+} ion
From 26 electrons to only two electrons: Helium-like $1s^2$

Baryonic matter (atoms) ist mostly highly ionized in intergalactic medium, galaxy clusters and galaxies



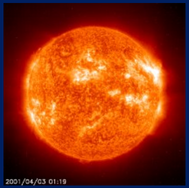
Warm-hot intergalactic medium at 10^5 to 10^8 K

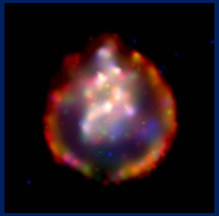
Galaxies consist of:
90% ionized hydrogen
10% stars
0.01% planets

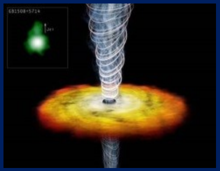
Compilation of current observational measurements of the low redshift baryon census (Shull, Smith, & Danforth, ApJ 2012)

In the Universe, elements are mostly highly ionized: Highly charged ions (HCI)

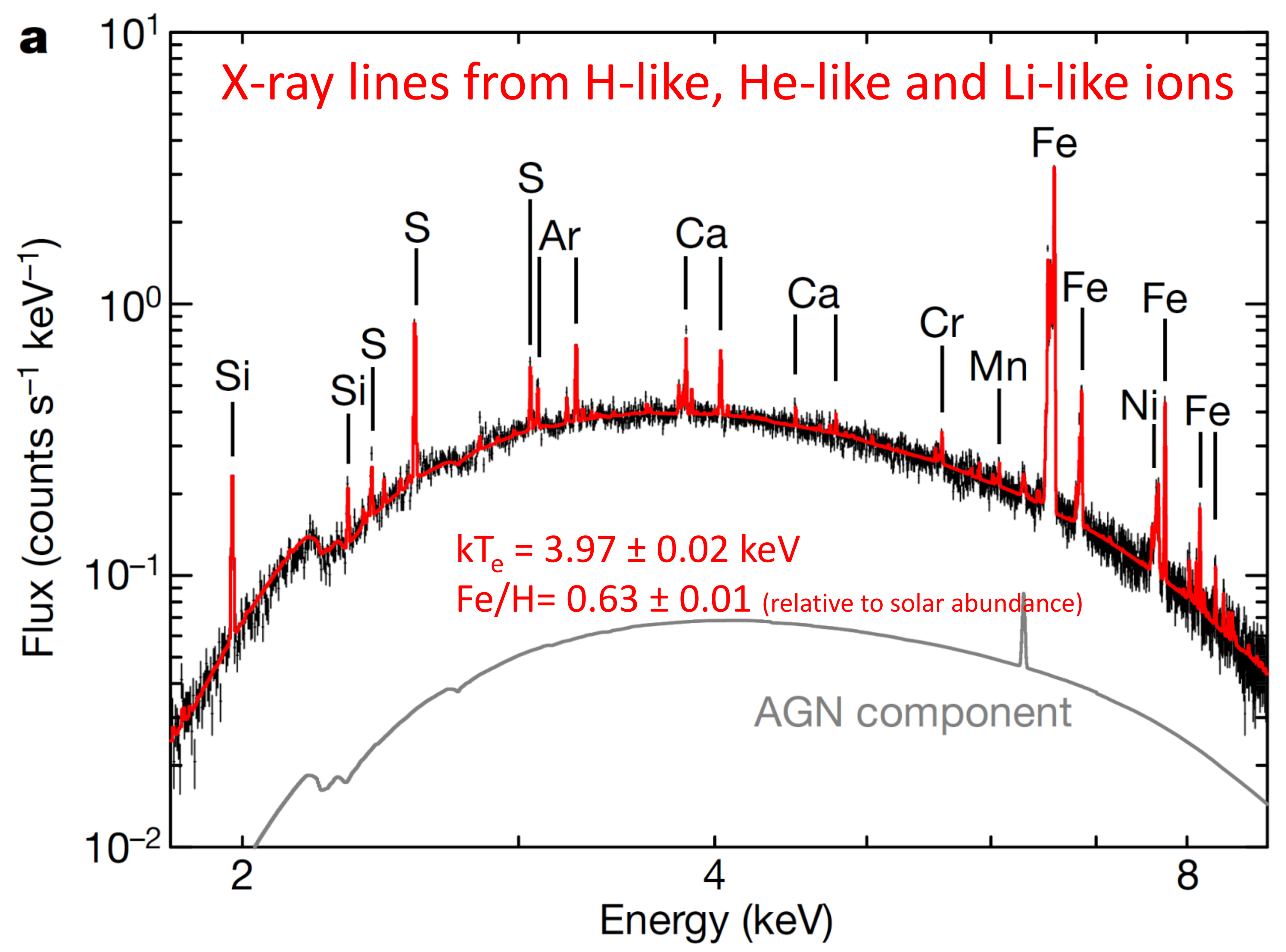
- Interior of the Sun (15 MK)
- Solar corona (2 MK)
- Solar wind (MK)
- Supernova remnants
- Active galactic nuclei (100 MK)
- Warm-hot intergalactic medium (0.1-1 MK)







Hitomi SXS spectra of the Perseus cluster of galaxies



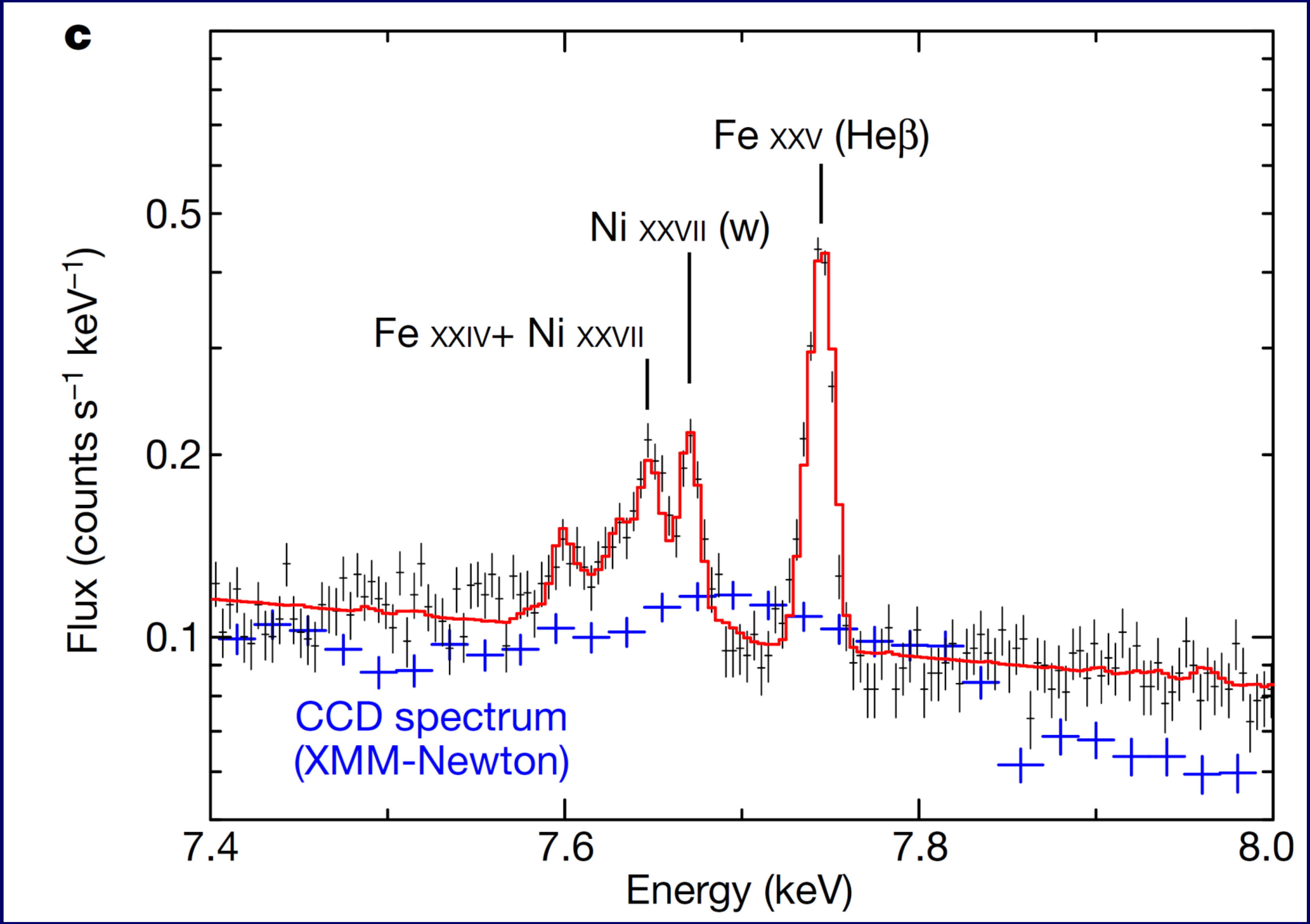
X-ray lines from H-like, He-like and Li-like ions

kT_e = 3.97 ± 0.02 keV

Fe/H= 0.63 ± 0.01 (relative to solar abundance)

Solar abundance ratios of the iron-peak elements in the Perseus cluster
Hitomi Collaboration, Nature (2017)

Hitomi SXS spectra of the Perseus cluster of galaxies



Solar abundance ratios of the iron-peak elements in the Perseus cluster
Hitomi Collaboration, Nature (2017)

State of the art in the field of HCI

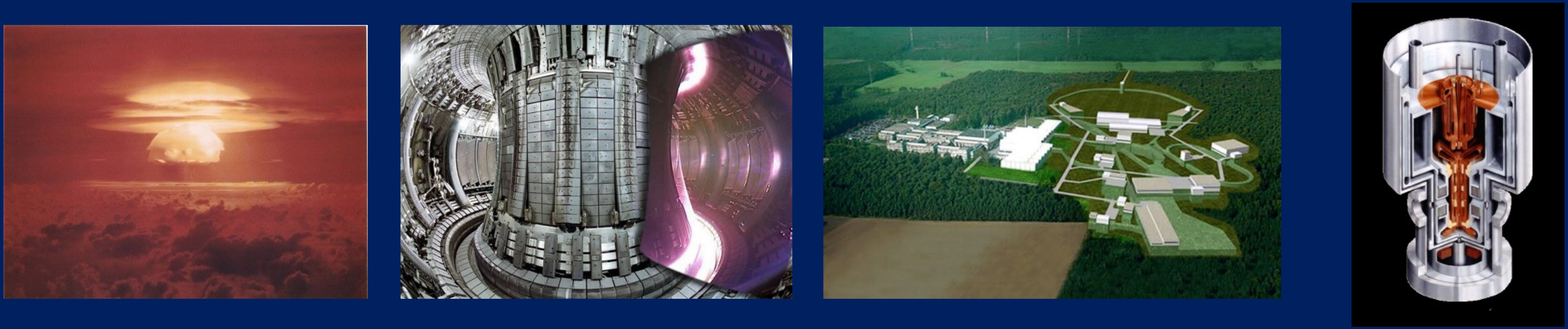
X-ray photon energies	1.5 ppm
VUV photon energies	4 ppm
Optical photon energies	0.3 ppm
Lifetimes (ns... ms)	0.15 %
Natural linewidths X-rays:	resolved

Accuracy is 10 orders of magnitude lower than in frequency metrology

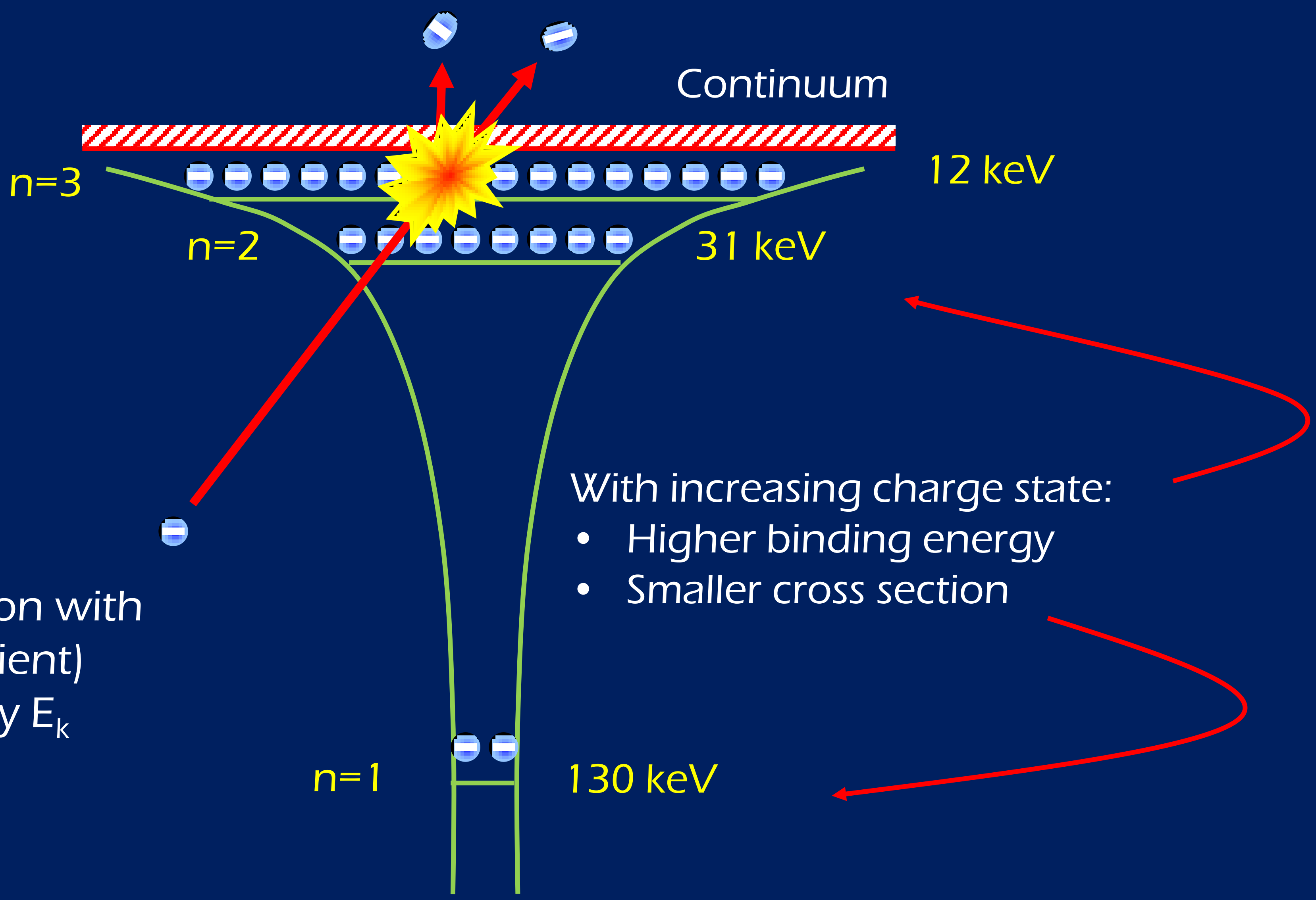
Stone-age spectroscopy at the 10^{-6} level

How do we make them in the laboratory?

- Fusion machines, magnetically confined plasmas
- High power lasers, X-ray lasers
- Ion accelerators
- Electron beam ion traps (Levine & Marrs 1986)



Making HCI by electron impact ionization

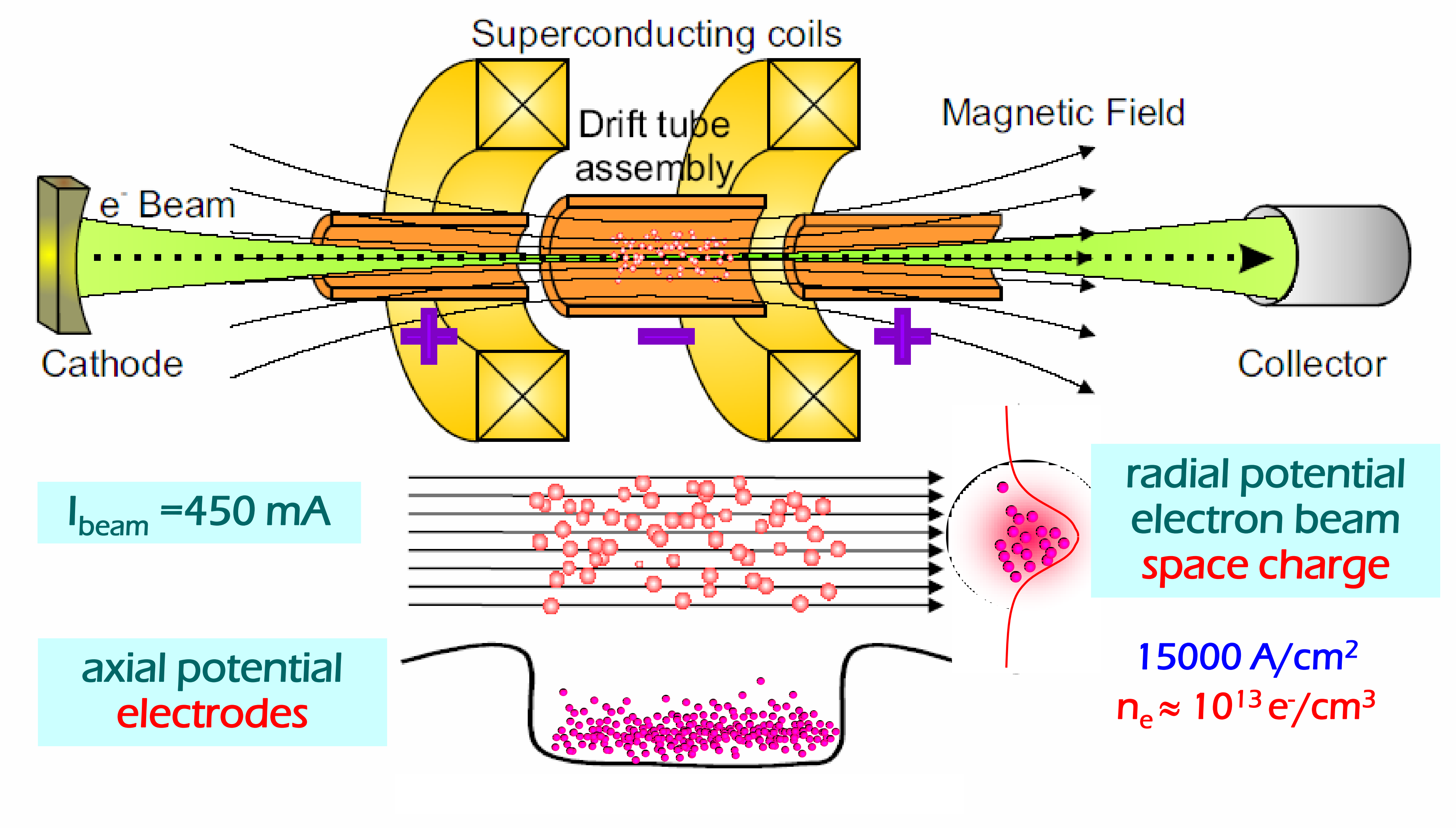


Electron with (sufficient) energy E_k

With increasing charge state:

- Higher binding energy
- Smaller cross section

HCI production with electron beam ion trap



I_{beam} =450 mA

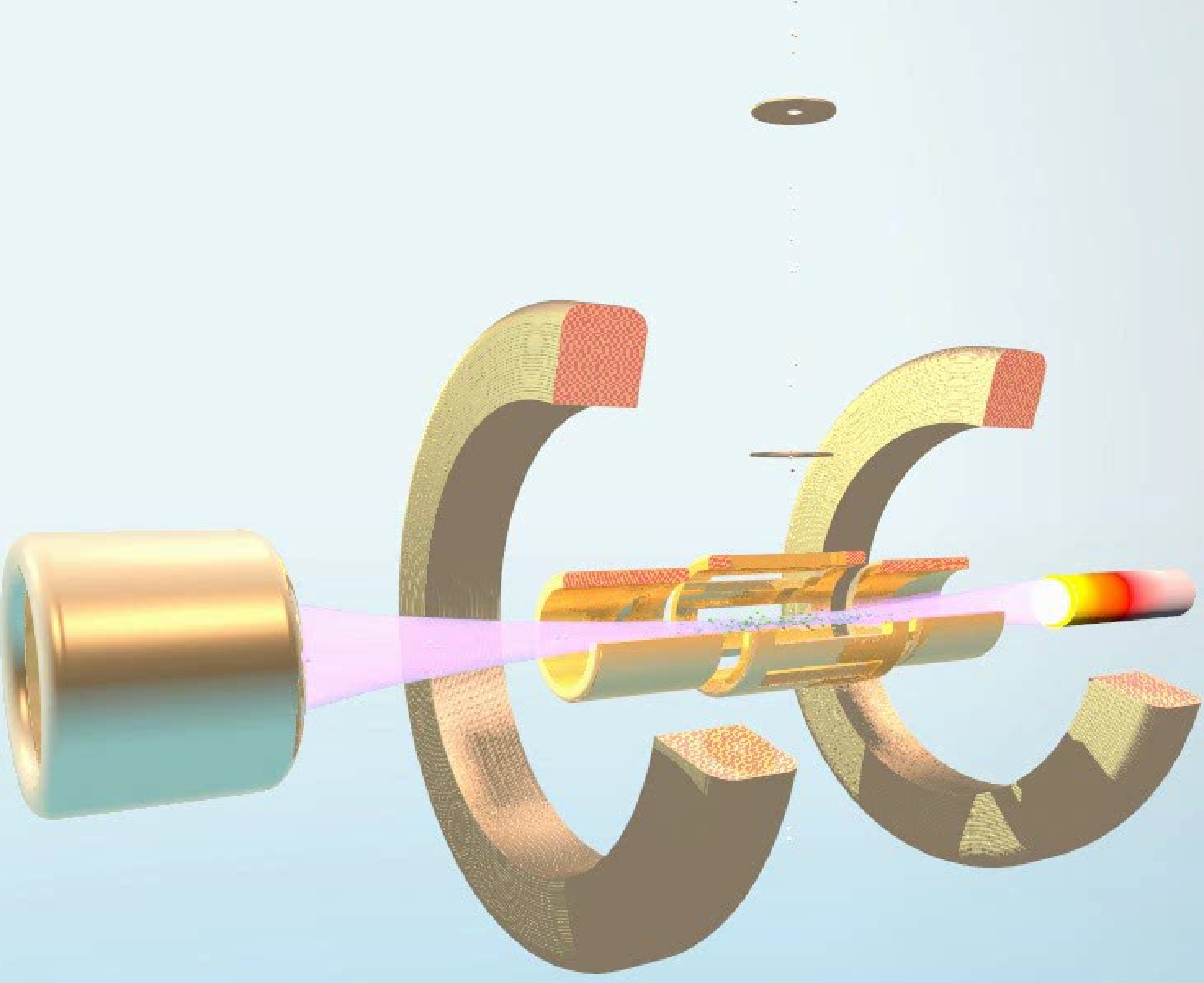
axial potential
electrodes

radial potential
electron beam
space charge

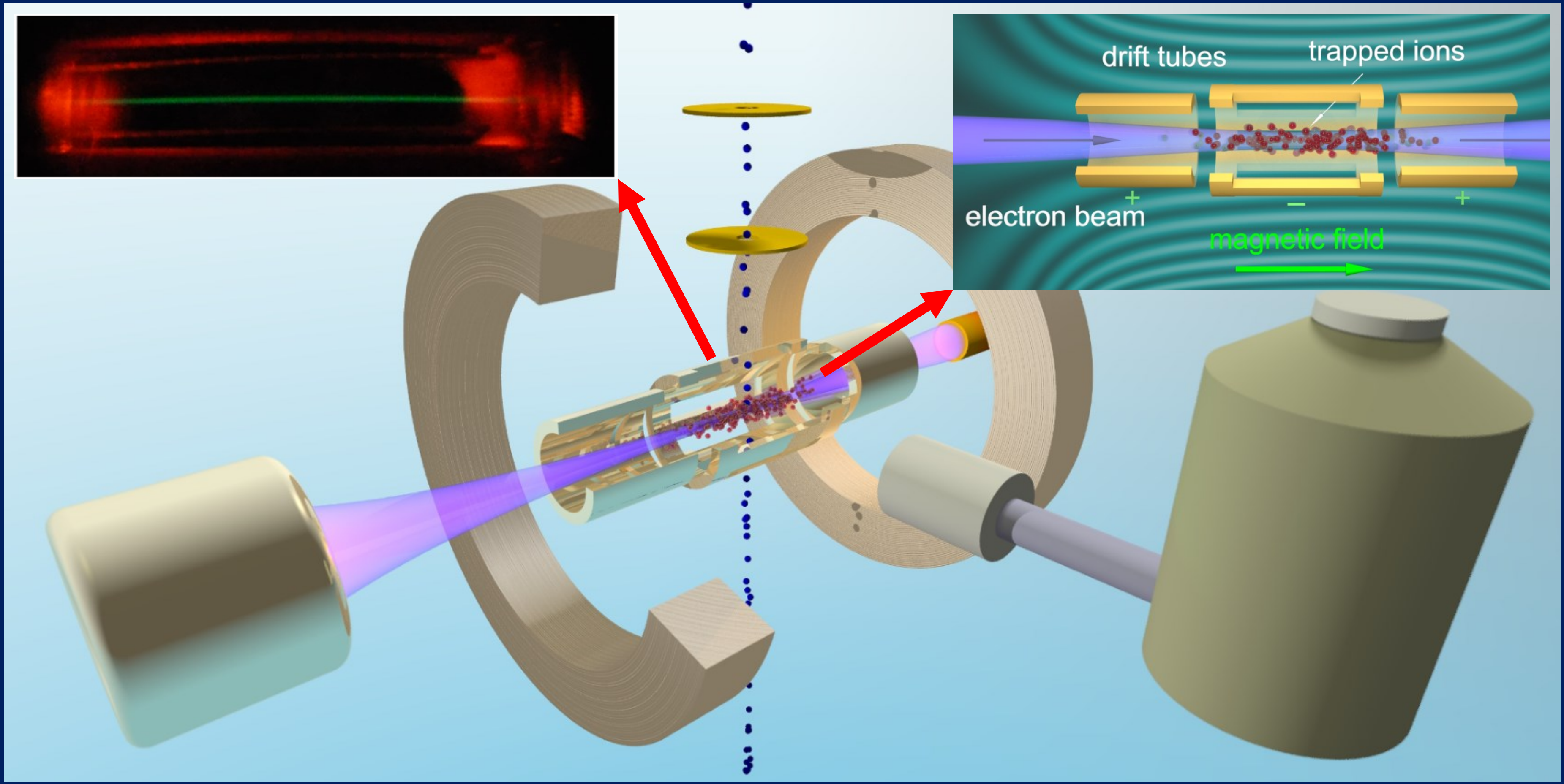
15000 A/cm²

$n_e \approx 10^{13}$ e-/cm³

Electron beam drives ionization, excites and traps the ions inside a cylindrical volume

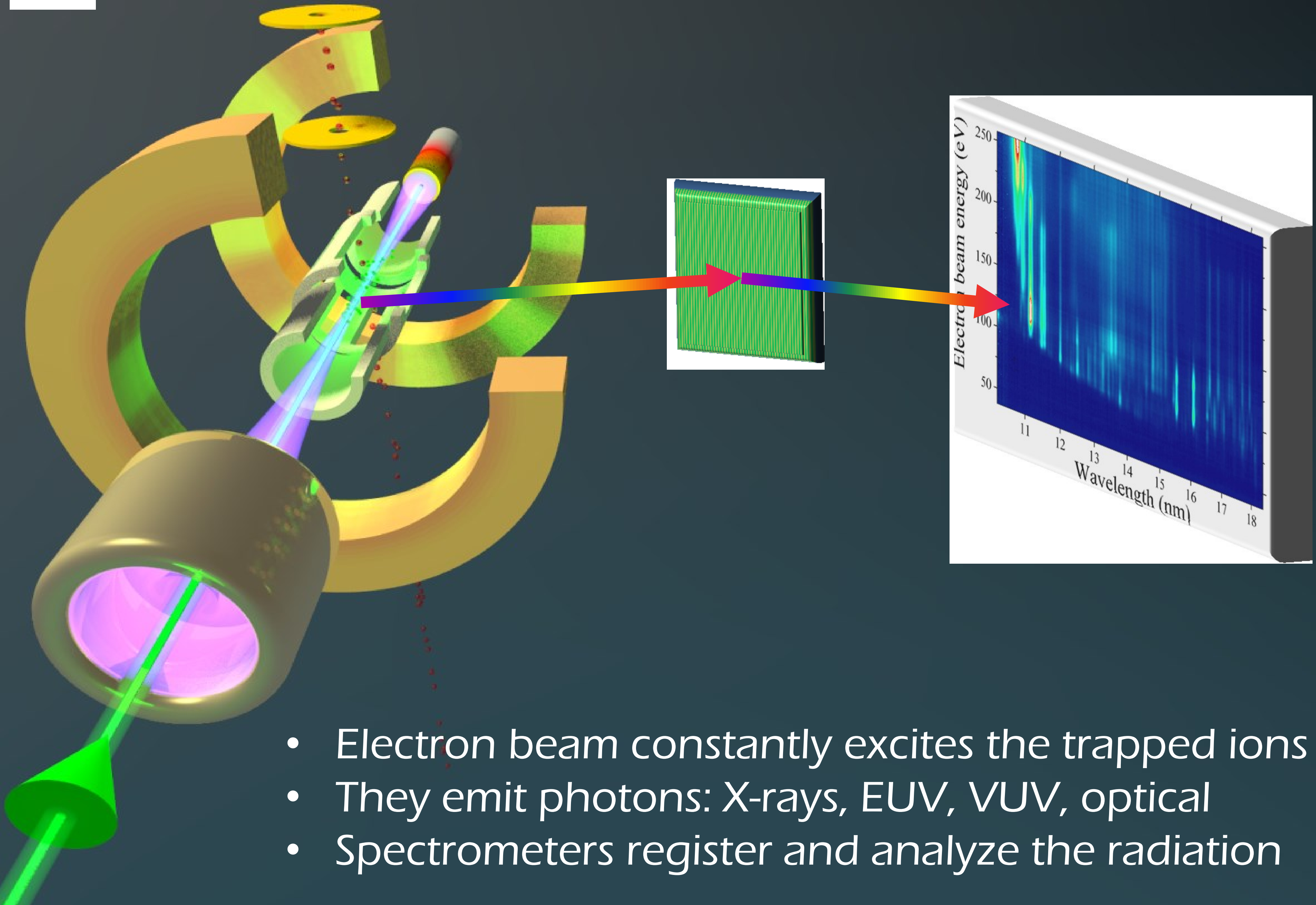


Electron beam ion traps



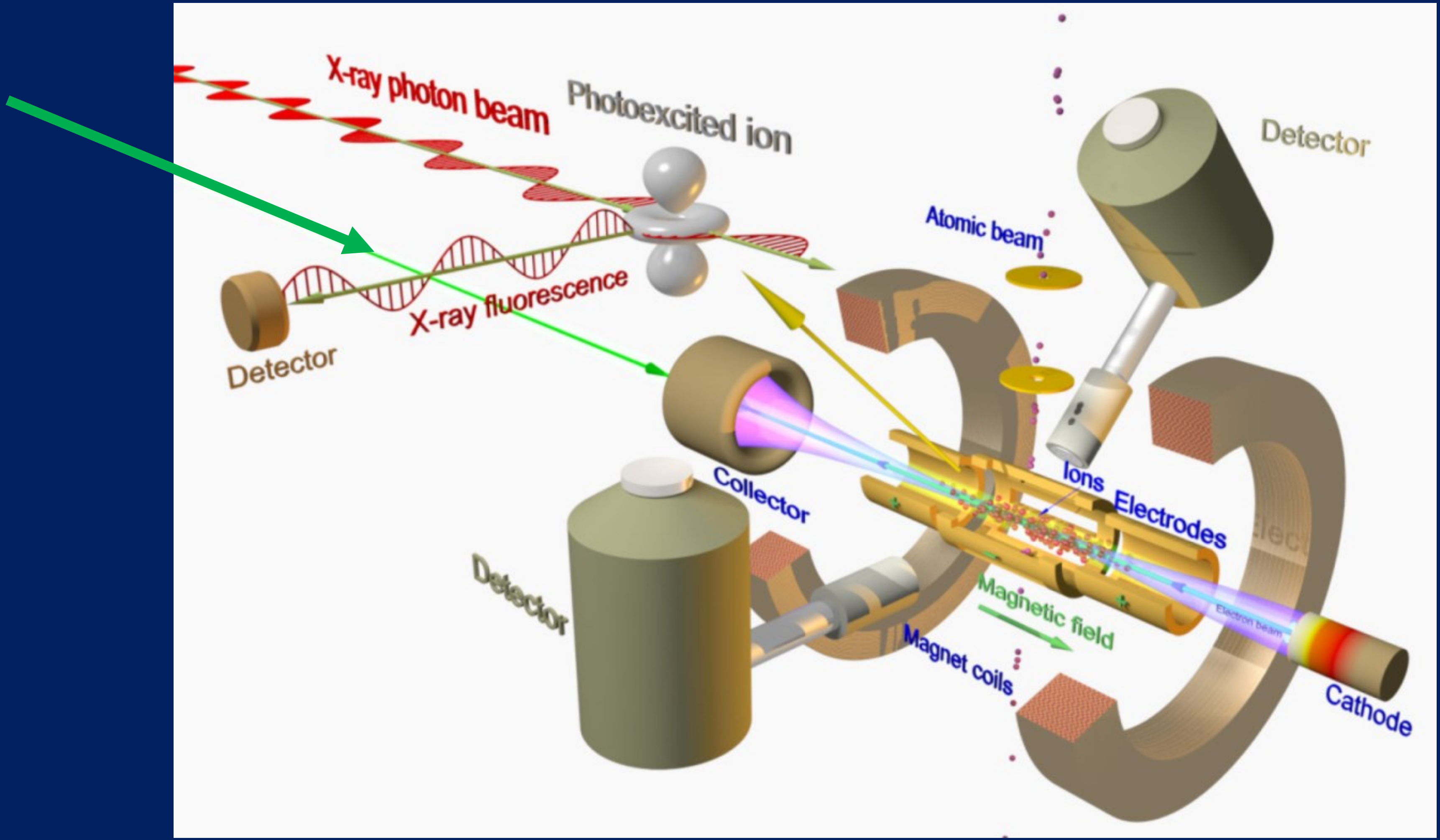
- An electron beam produces, traps and excites HCI
- Diagnostics from the optical to the hard x-ray range
- Additional ionic species particle diagnostics
- Studies from N^{3+} to Hg^{78+}

In-trap spectroscopy



- Electron beam constantly excites the trapped ions
- They emit photons: X-rays, EUV, VUV, optical
- Spectrometers register and analyze the radiation

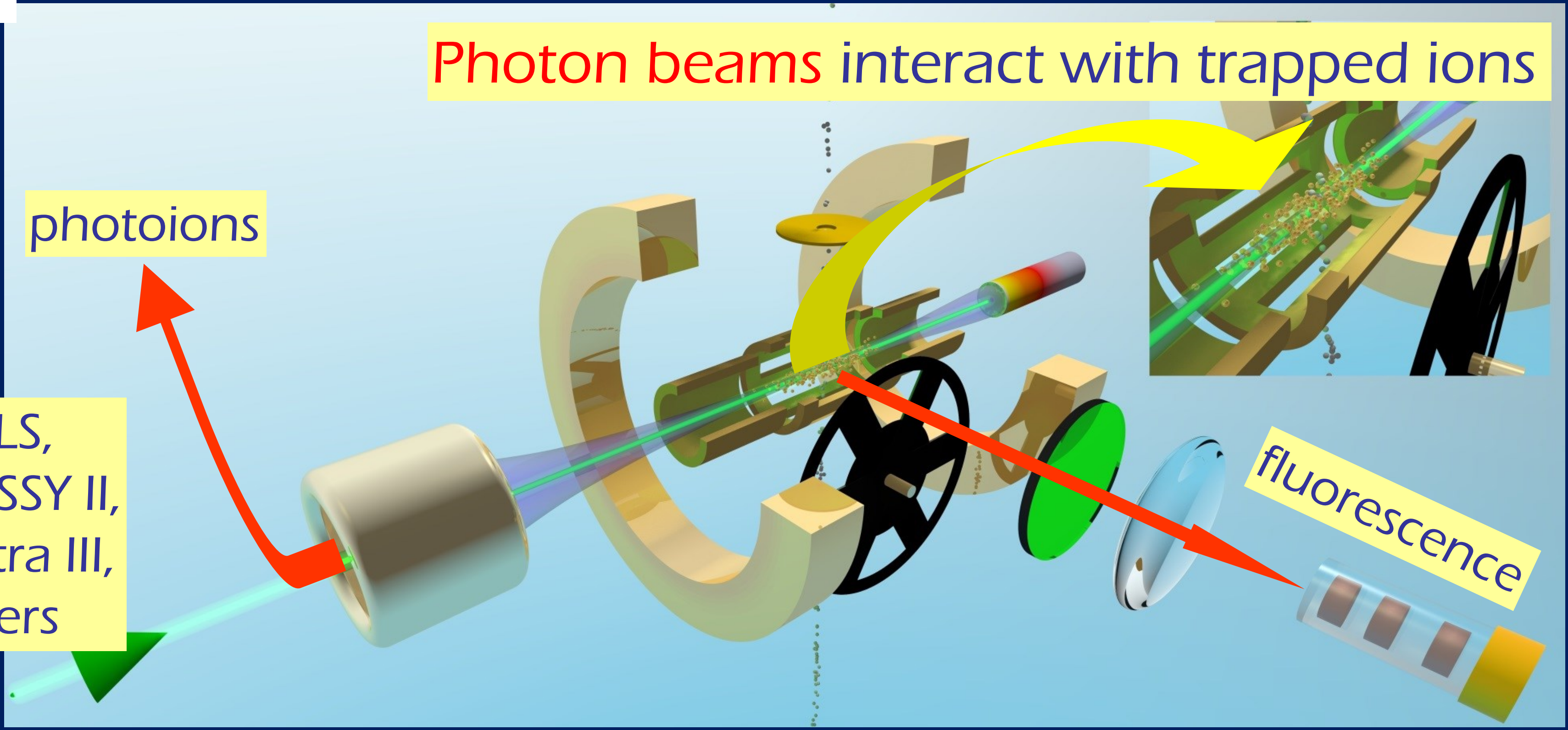
X-ray laser spectroscopy in EBIT



- Synchrotron radiation (PETRA-III, BESSY-II),
- Free-electron lasers (LCLS, FLASH) ,

provide X-rays with high power and energy resolution

Resonant photon excitation in EBITs



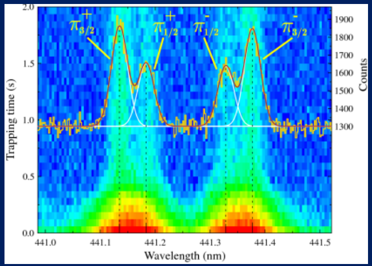
Photon beams interact with trapped ions

photoions

LCLS,
BESSY II,
Petra III,
lasers

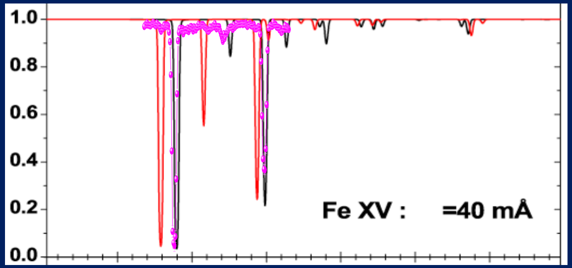
fluorescence

Visible M1
Ar^{13+}



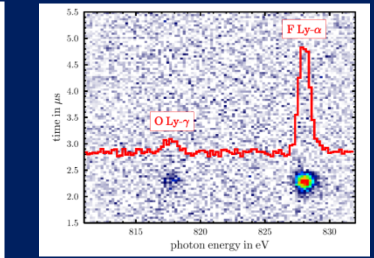
V. Mäckel et al.,
PRL **107** 143002 (2011)

Soft X-ray photoionization
Fe^{14+}



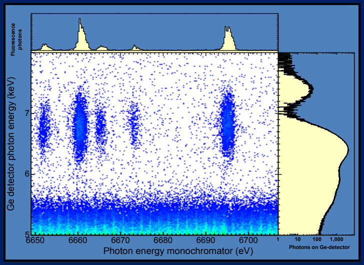
M. C. Simon et al.,
PRL **105** 183001 (2010)

FEL 800 eV
Fe^{16+}



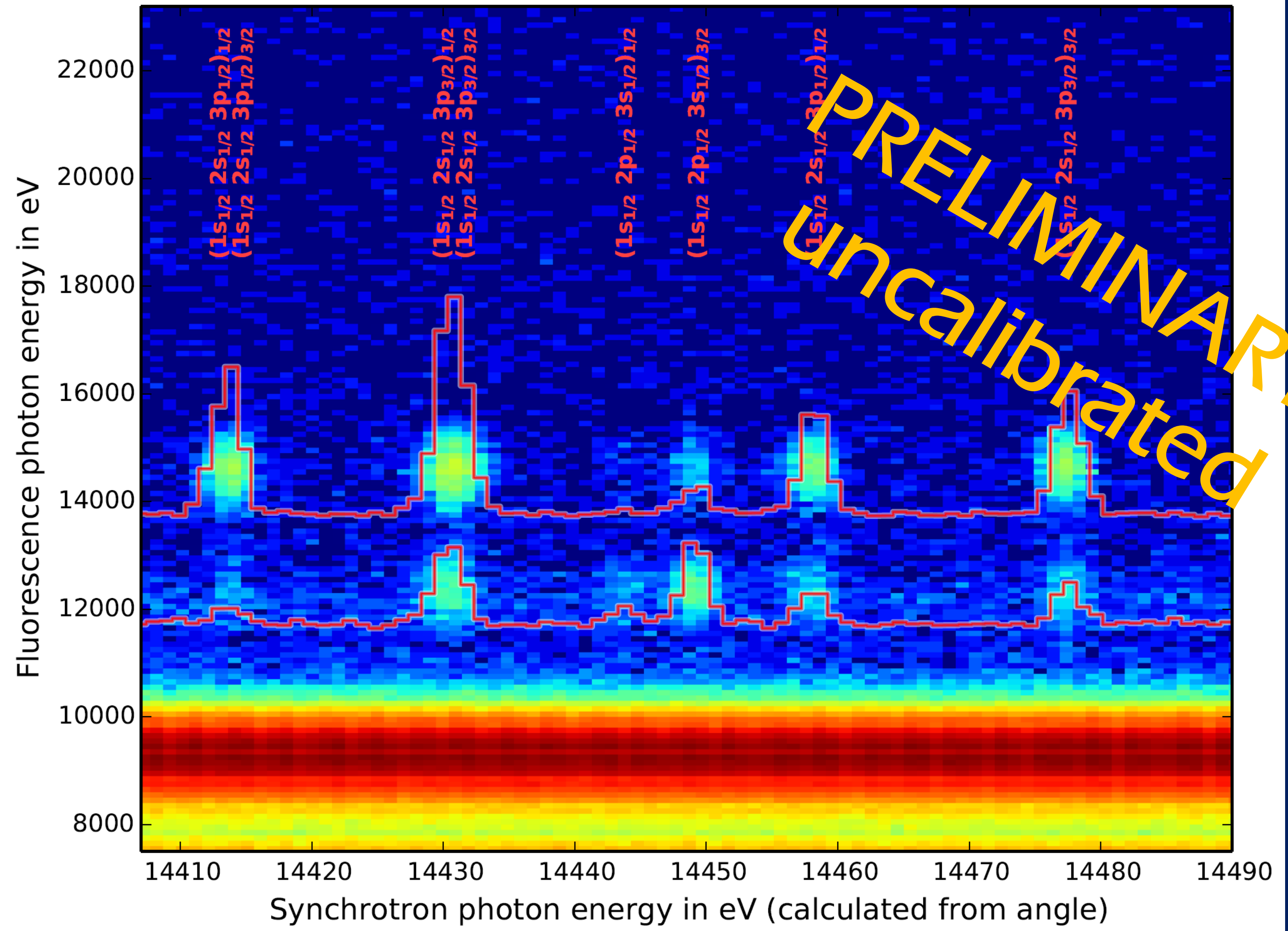
S. Bernitt et al.,
Nature **492**, 225 (2012)

Synchrotron 6 keV
Fe^{24+}, 13 keV Kr^{34+}



J. Rudolph et al.,
PRL **111**, 103002 (2013)

New results: Overview spectra of Br^{33+} (Li-like)

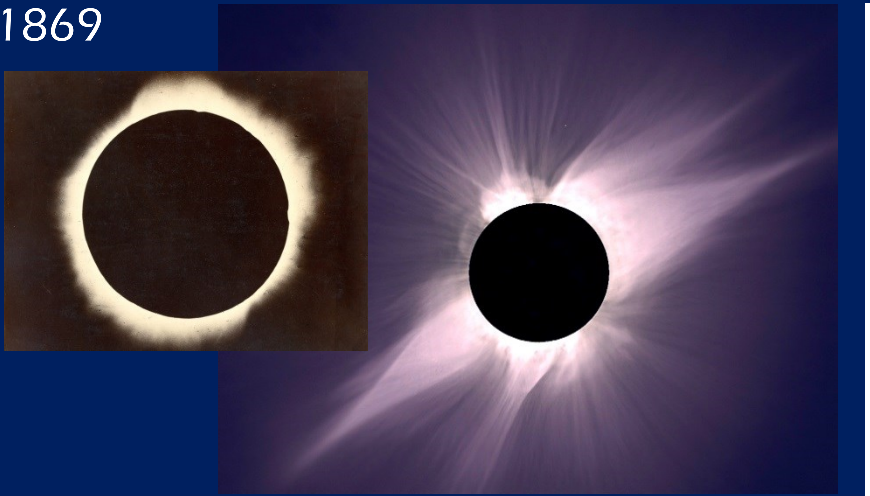


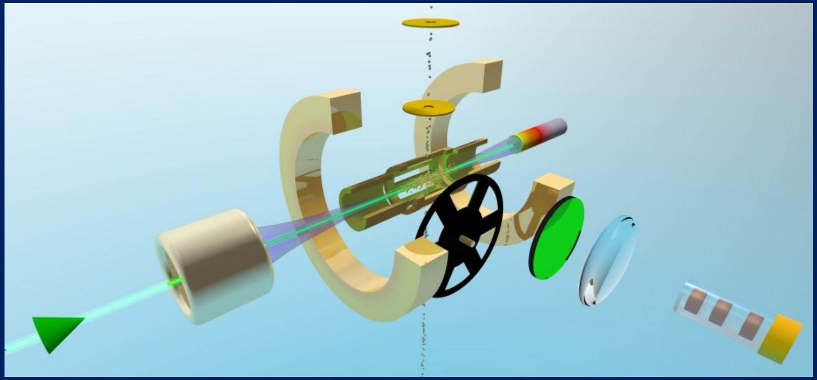
S. Bernitt, MPIK (2016)

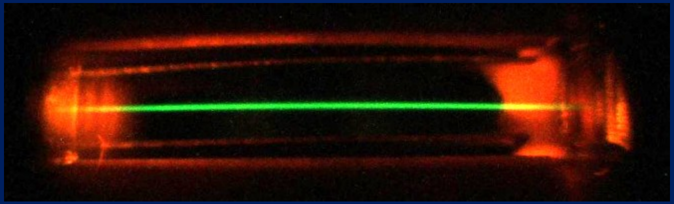
Laser spectroscopy of forbidden M1 lines

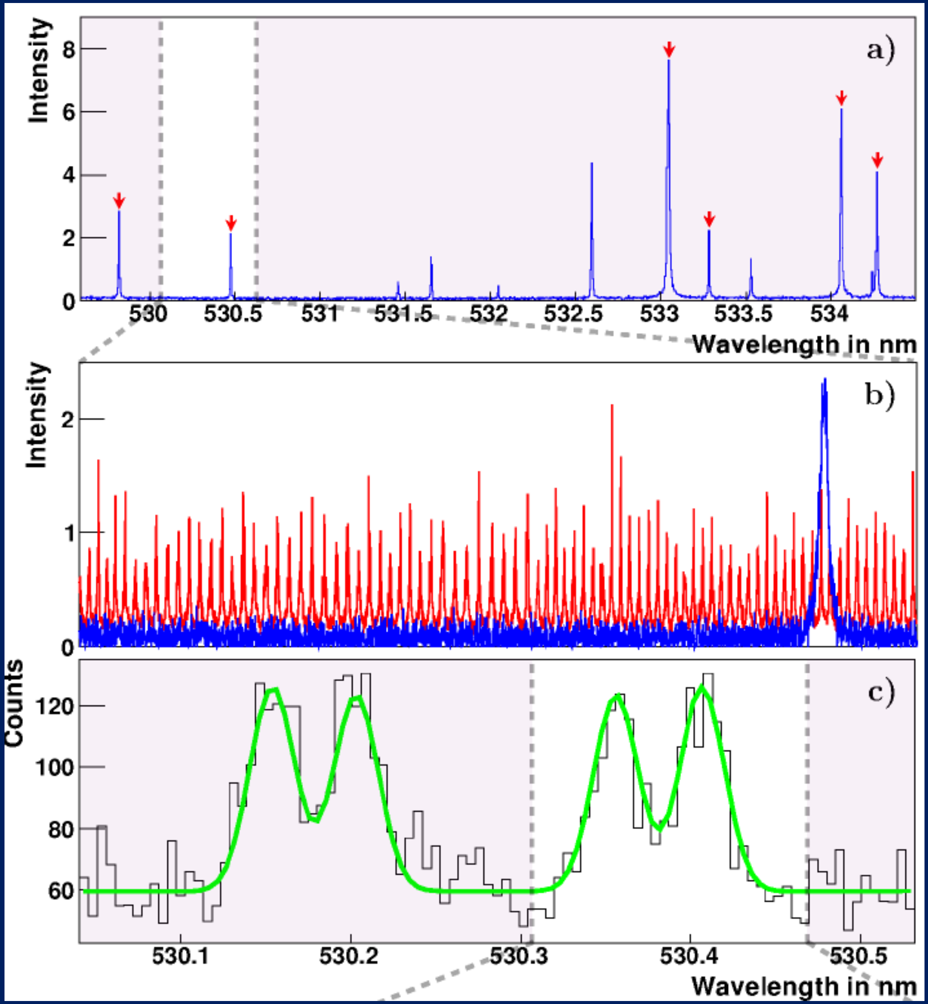
Fe^{13+} (Fe XIV), the *"green coronal line"*

First "coronium"
1869





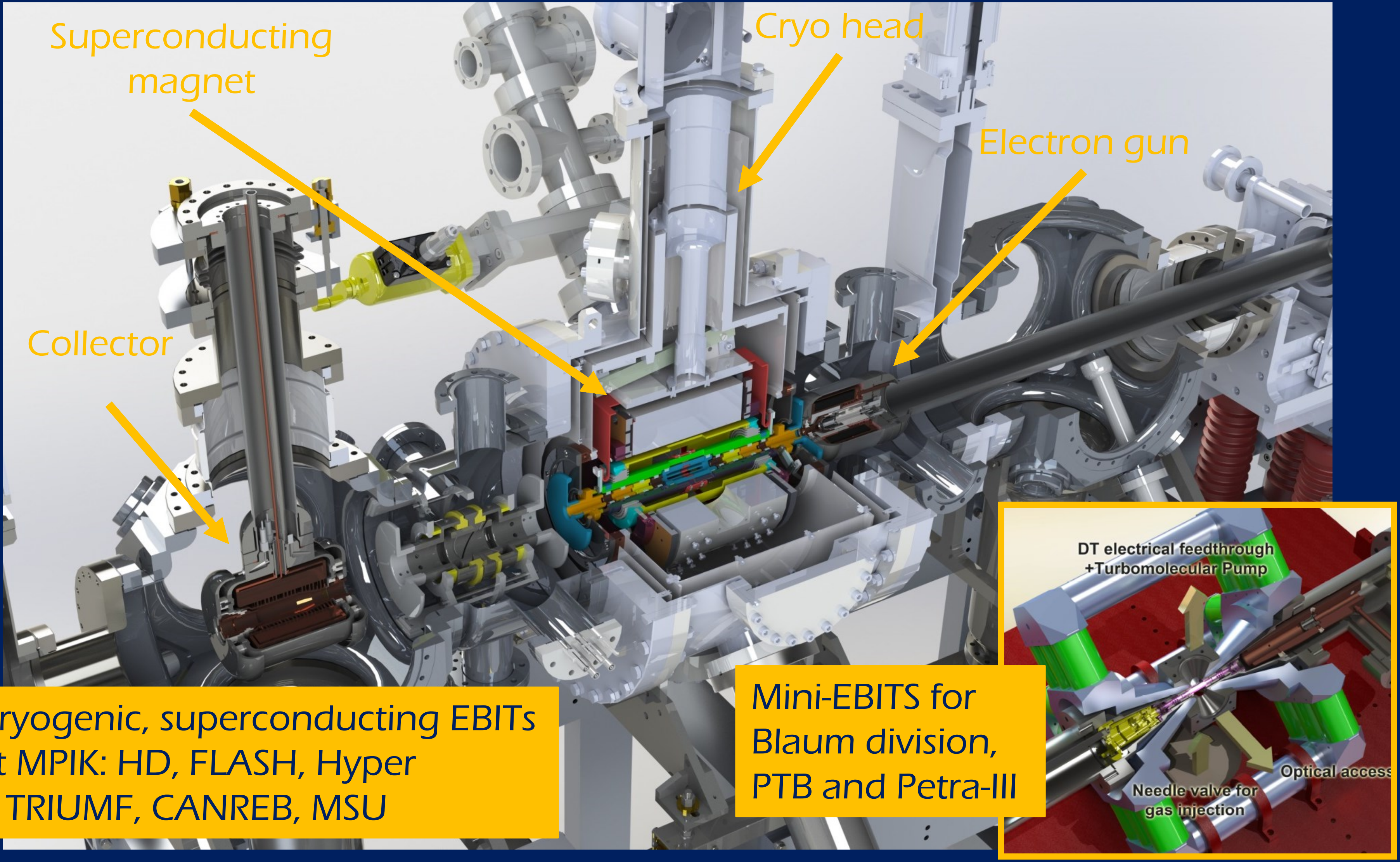




Still at $2\cdot10^5$ K ion temperature!

V. Mäckel, ... JRCLU et al., PRL 107, 143002 (2011), K. Schnorr... JRCLU et al., ApJ 776, 121 (2013)

Electron beam ion traps big and small

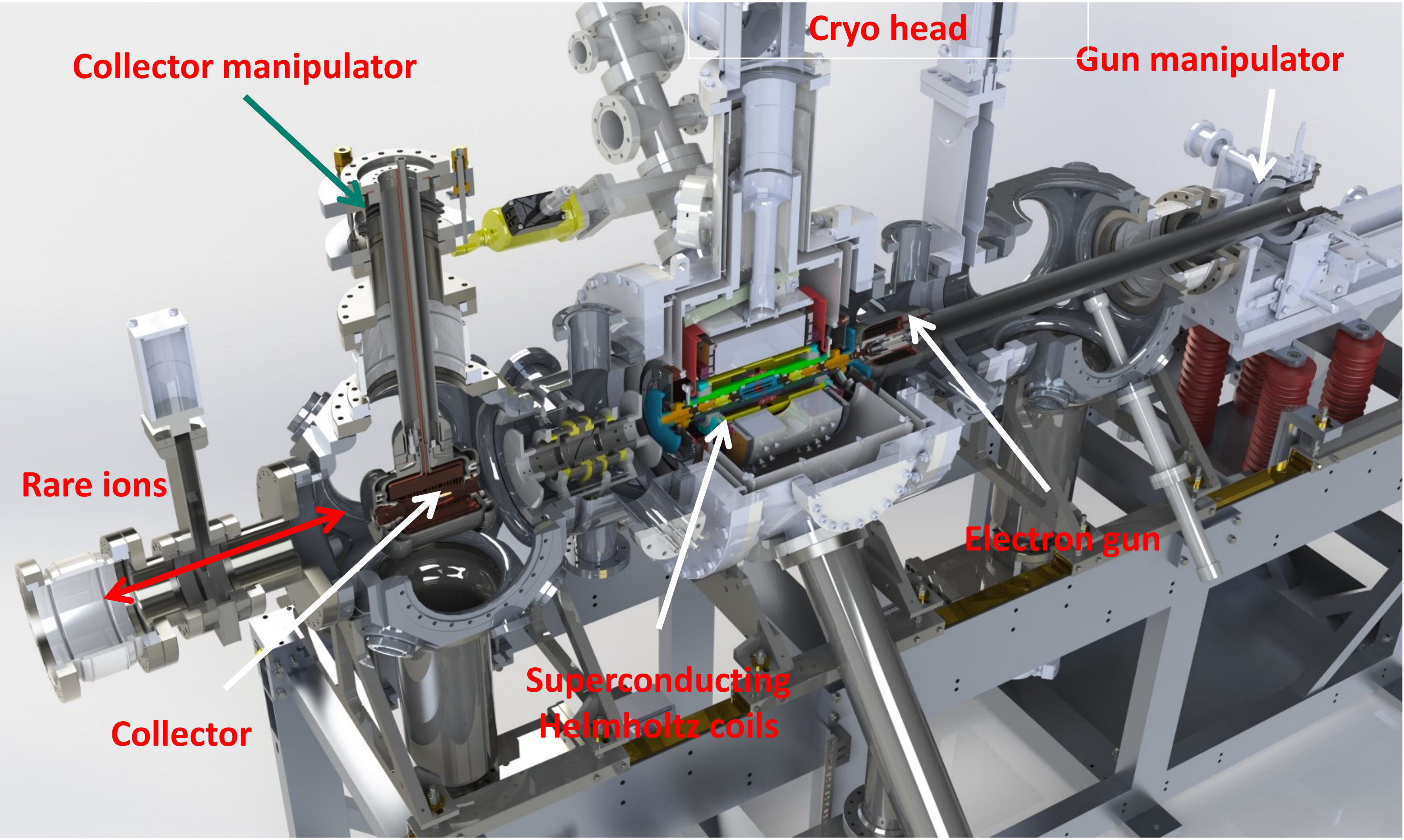


Cryogenic, superconducting EBITs at MPIK: HD, FLASH, Hyper + TRIUMF, CANREB, MSU

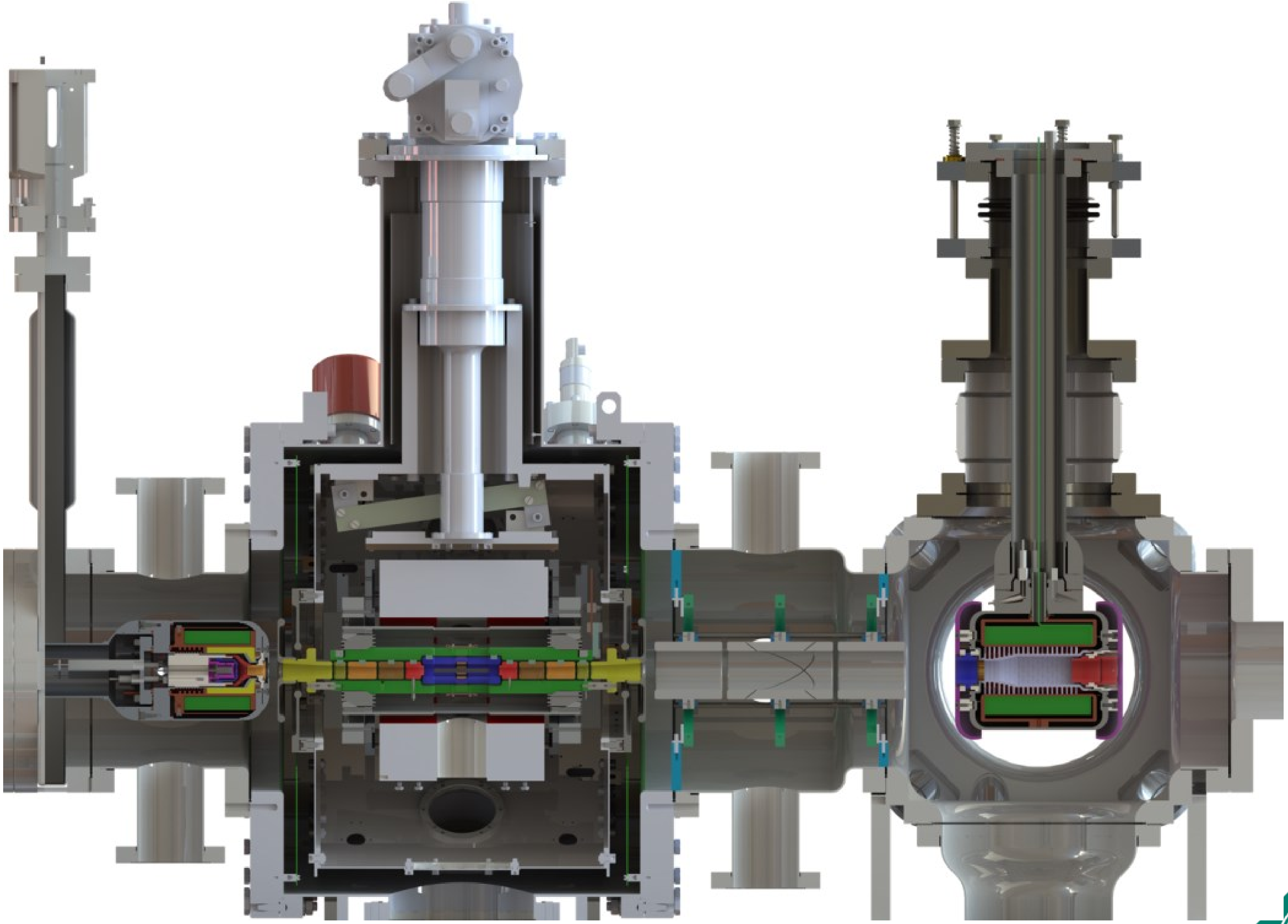
Mini-EBITS for Blaum division, PTB and Petra-III

- Unique facility at MPIK, supporting Pfeifer and Blaum division
- Out of ~20 research EBITs worldwide, 10 are at or come from MPIK

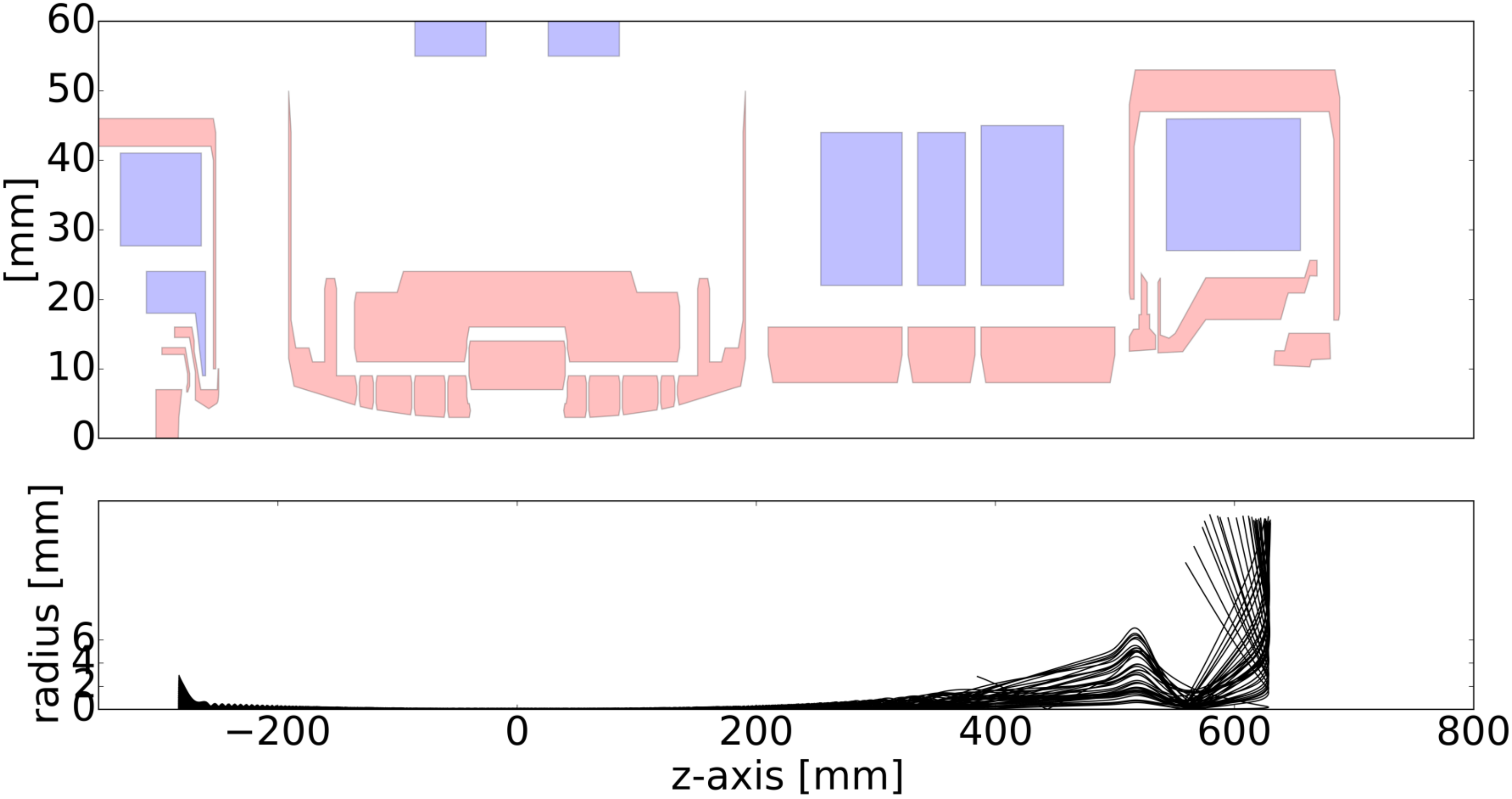
Design


Collector manipulator
Cryo head
Gun manipulator
Rare ions
Electron gun
Collector
Superconducting
Helmholtz coils

Design

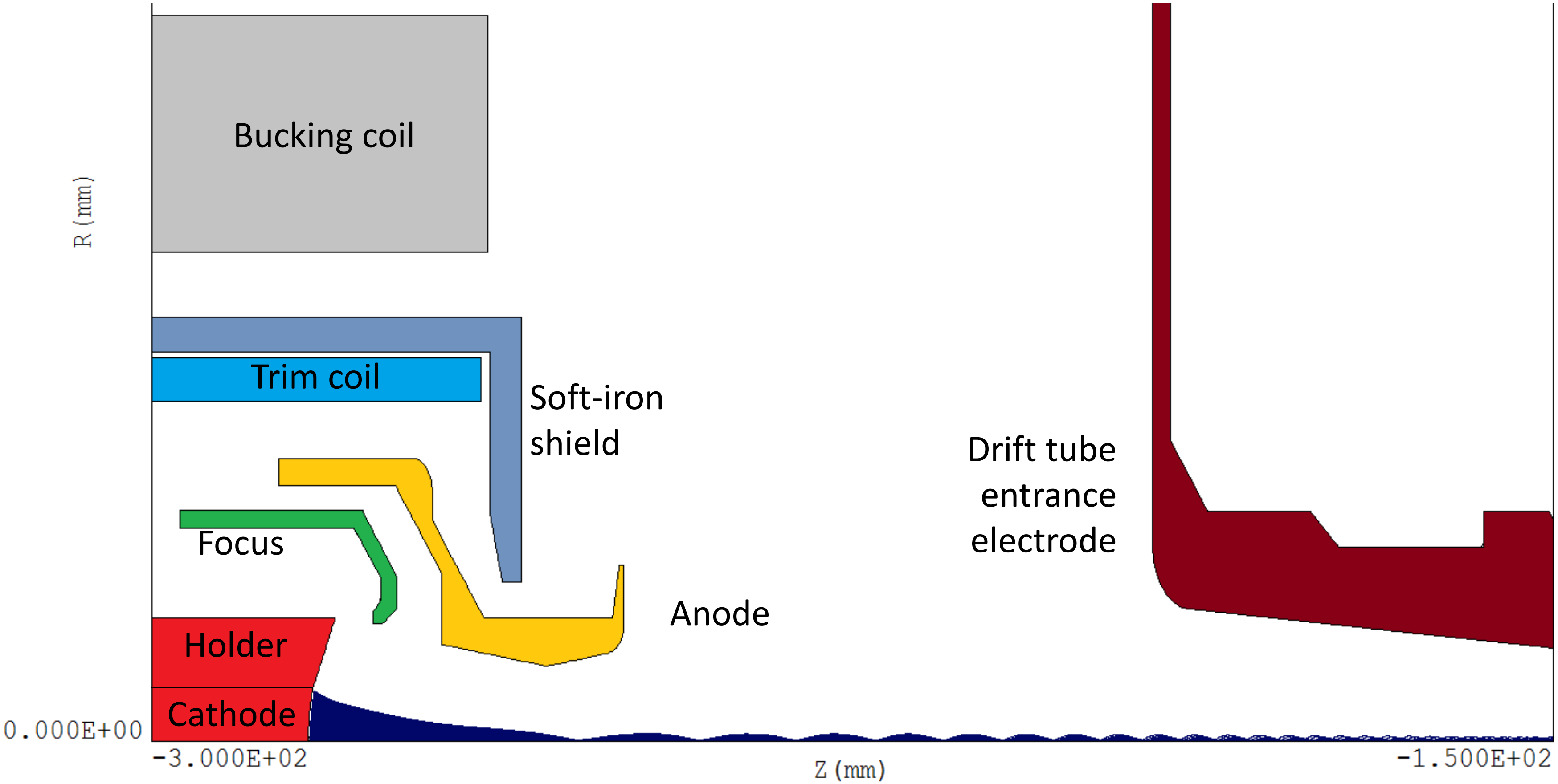


Electron beam simulations



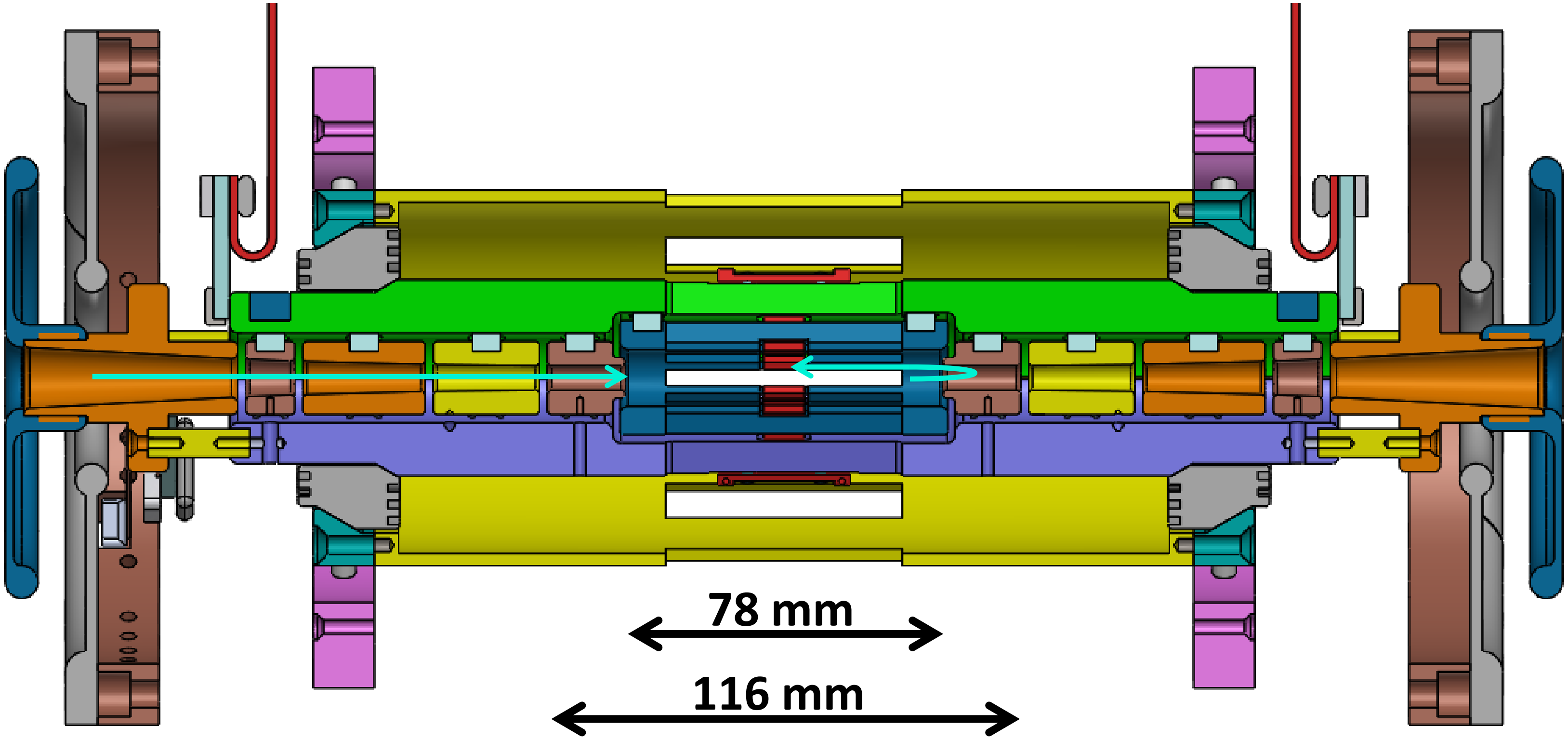
Electron beam simulations with TriCOMP, COMSOL, SimIon

Electron beam simulation



- Space charge limited Pierce gun design
- Non-immersed

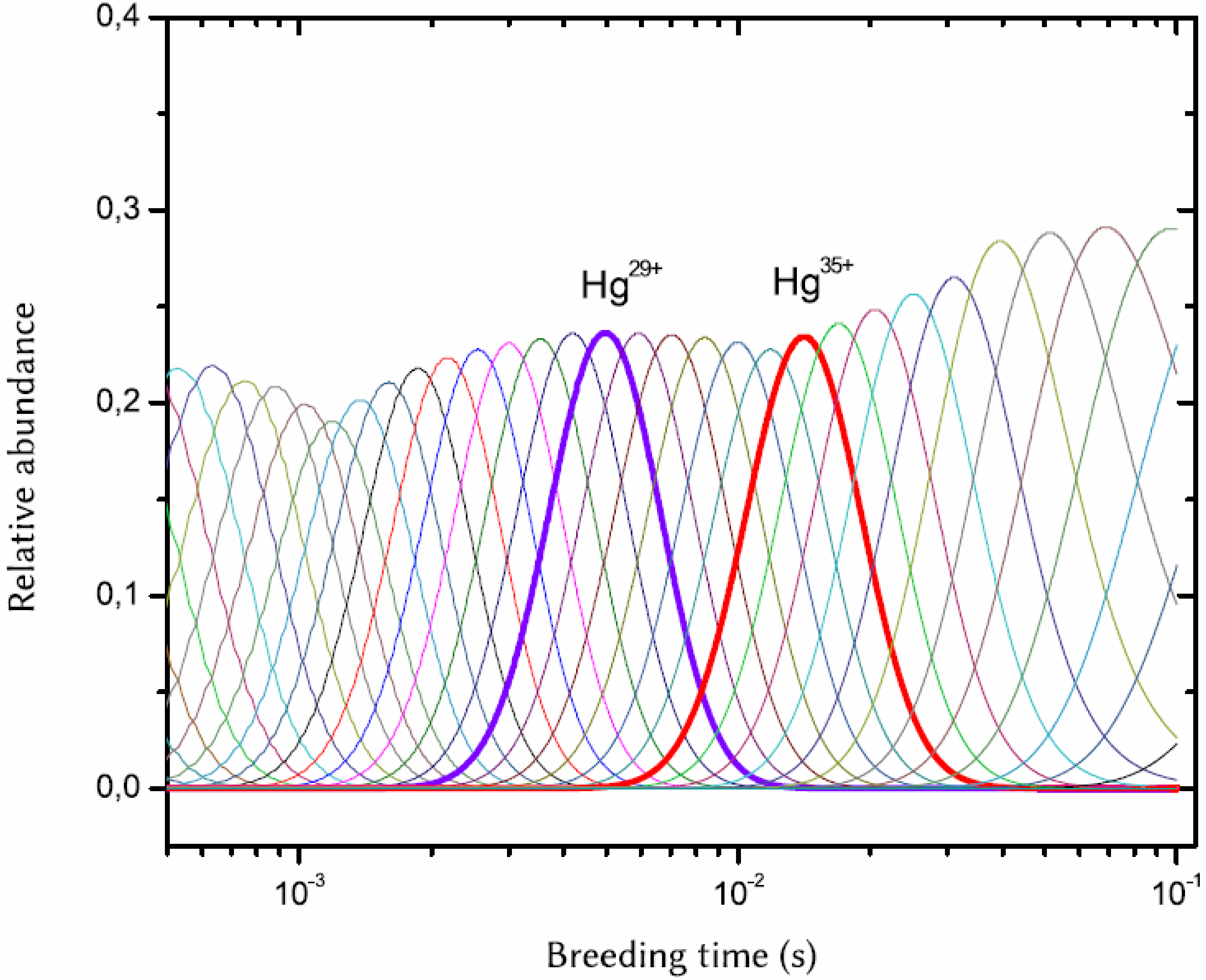
Ion time of flight in the trap



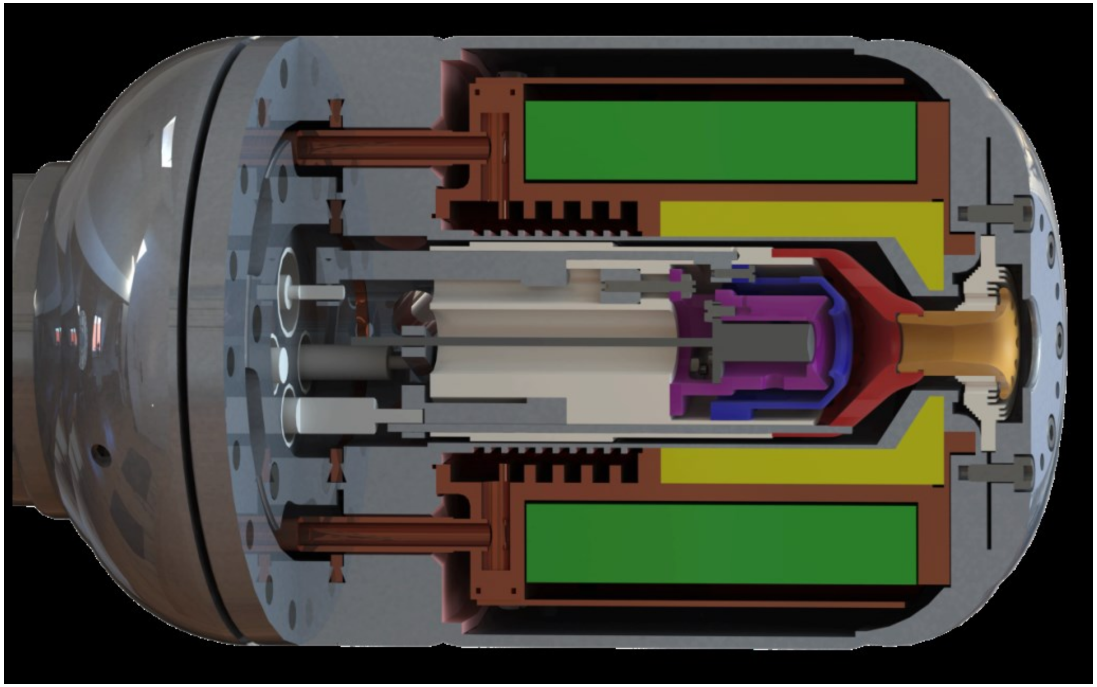
Example calculations of time-of-flight (TOF):

- 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)

Charge breeding simulation

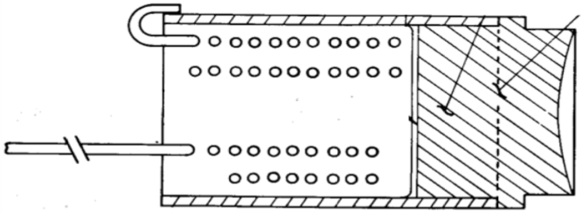


Electron gun

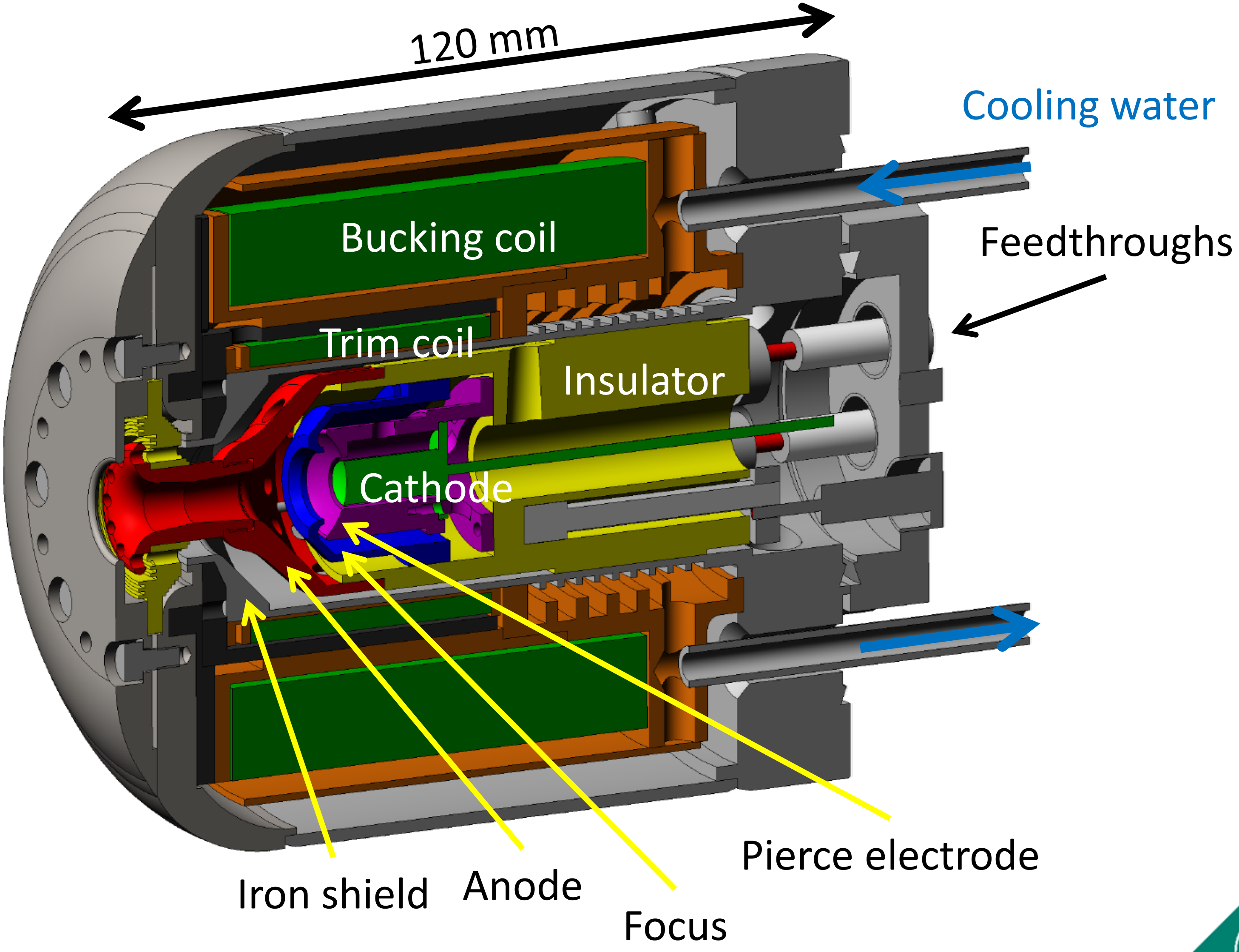


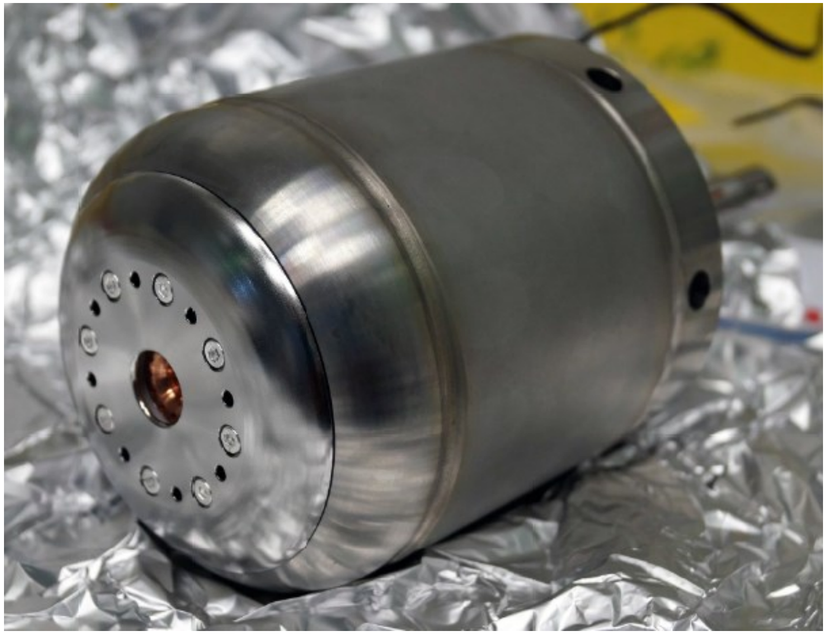
- $r_c = 3.175\ \mathrm{mm}$
- max. emission $I_c > 1\ \mathrm{A}$
- Soft iron shield

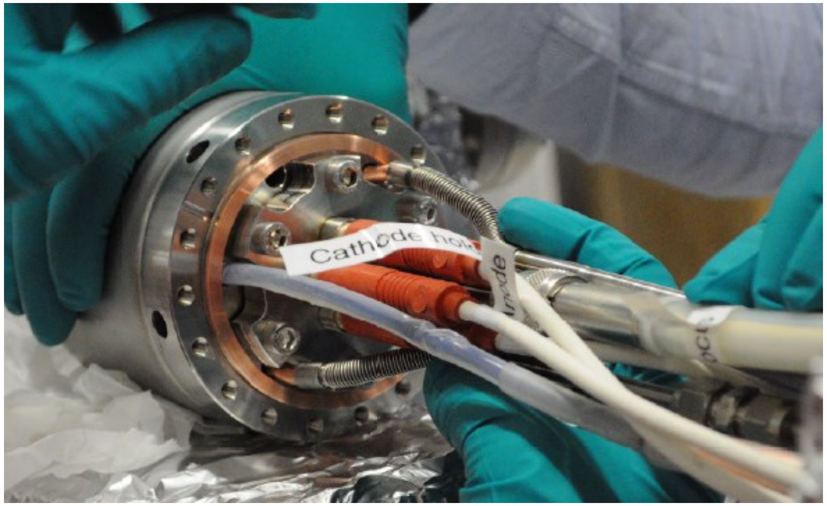
Dispenser-type Ba M-coating thermoionic cathode



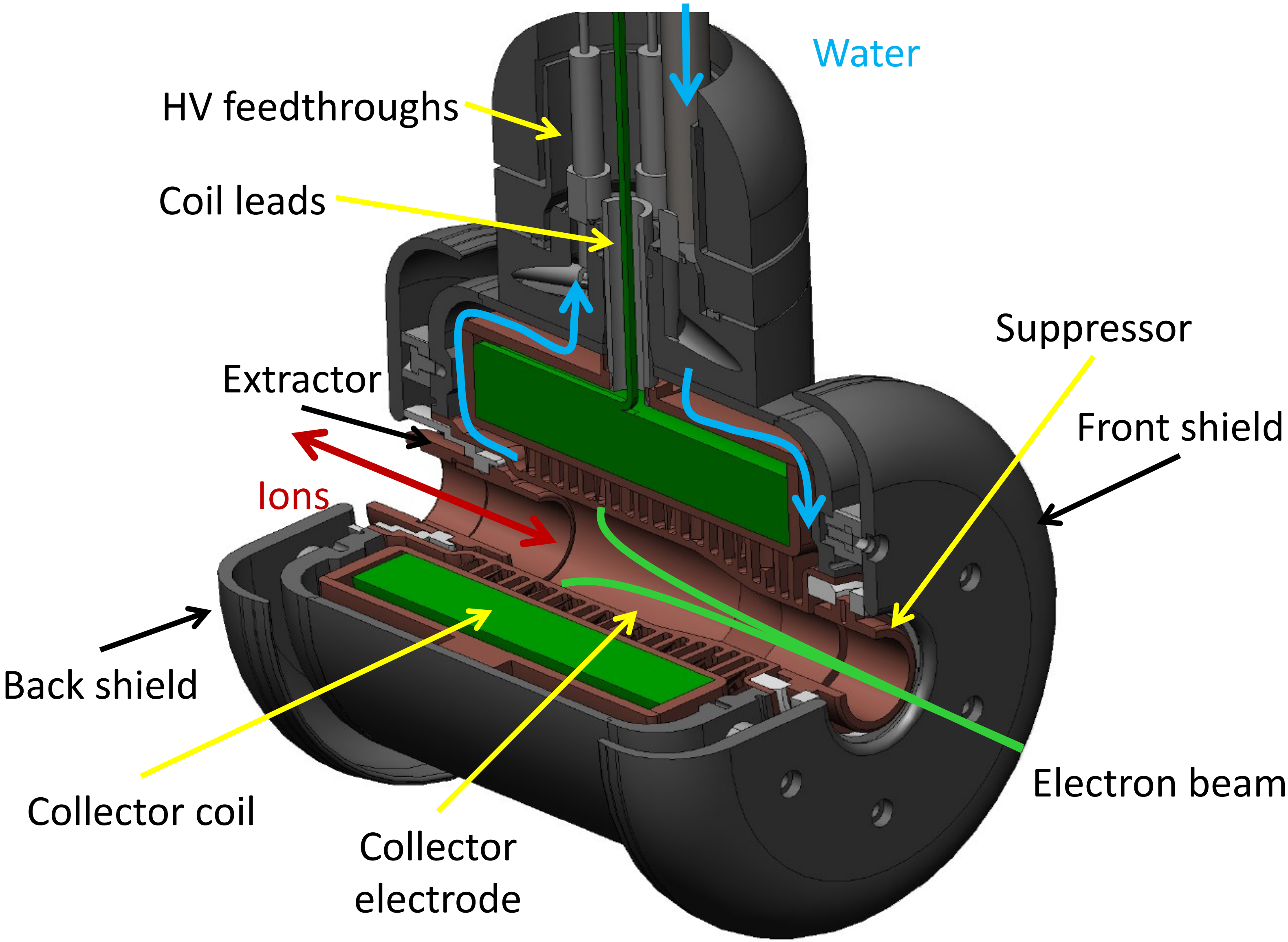
Electron gun



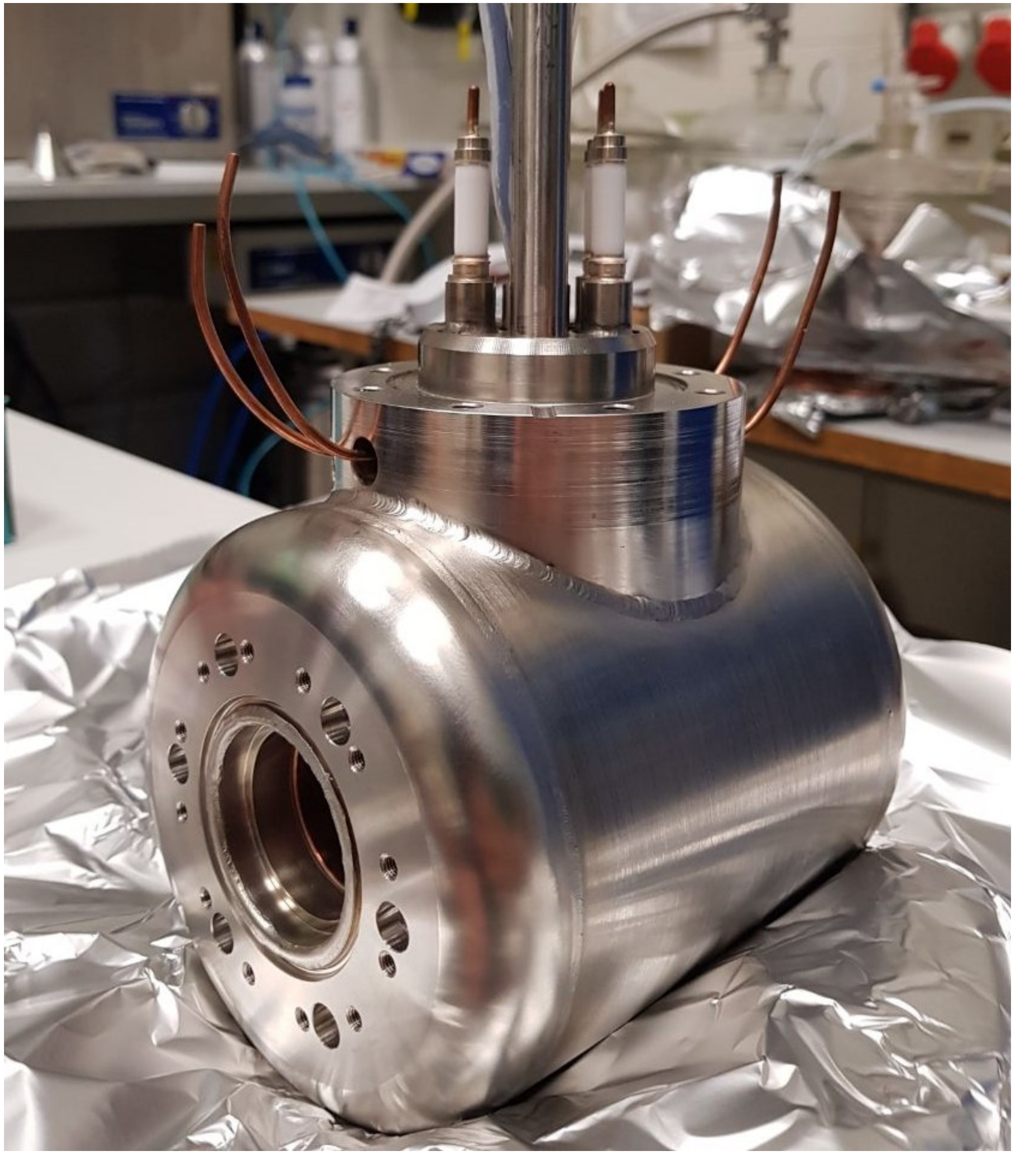



Cathode hol
Anode

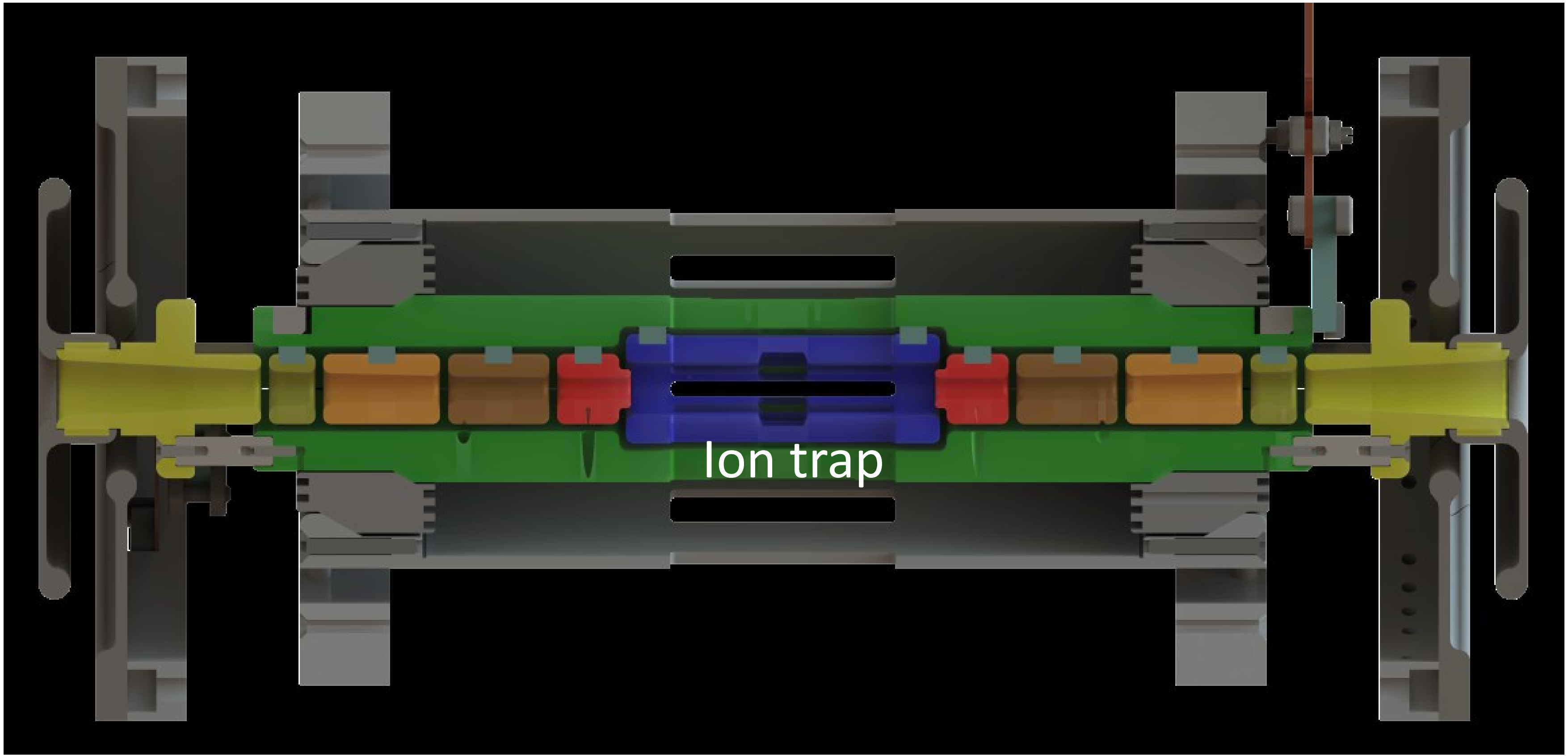
Electron collector



Electron collector

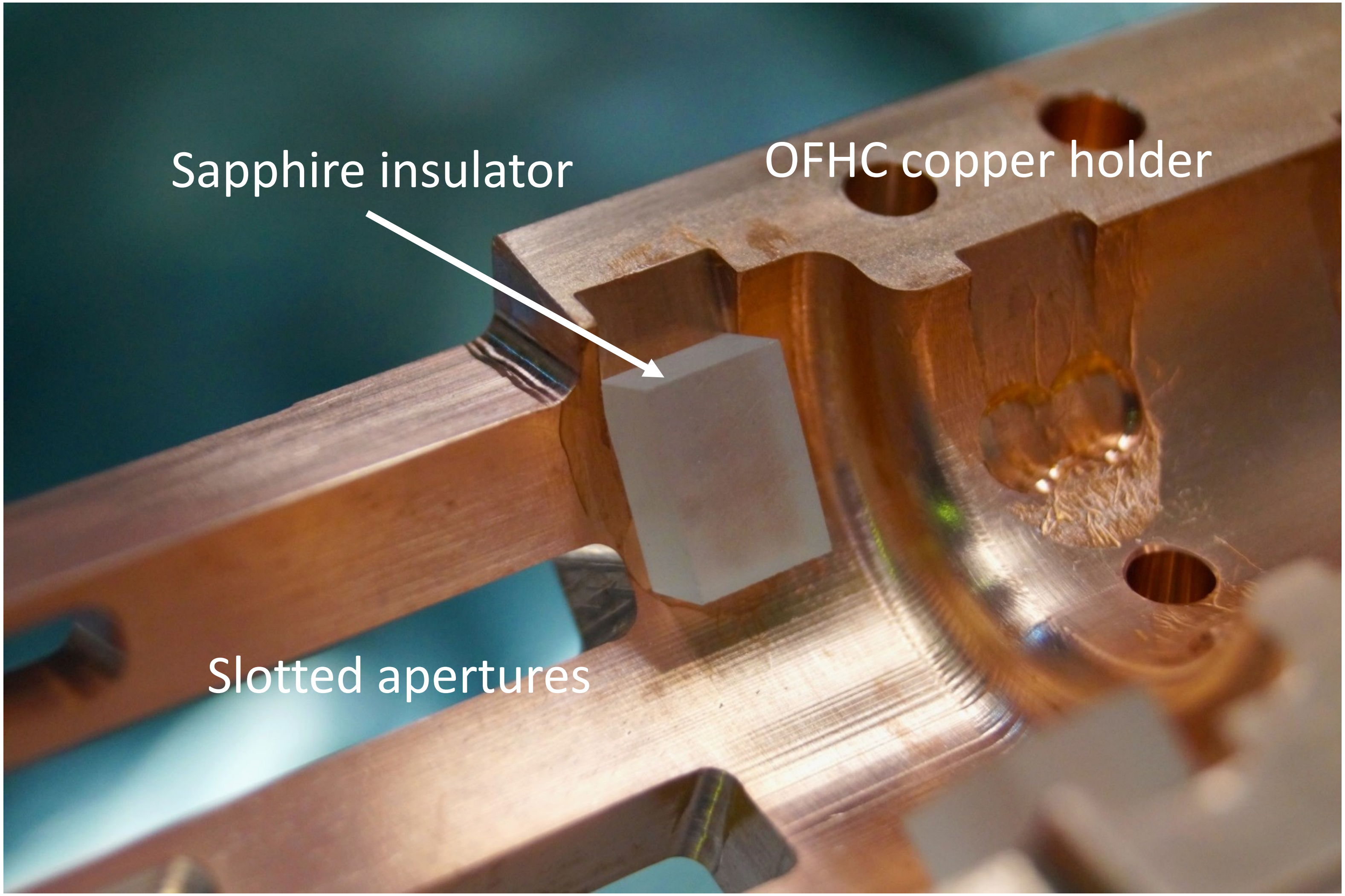


Drift tube assembly

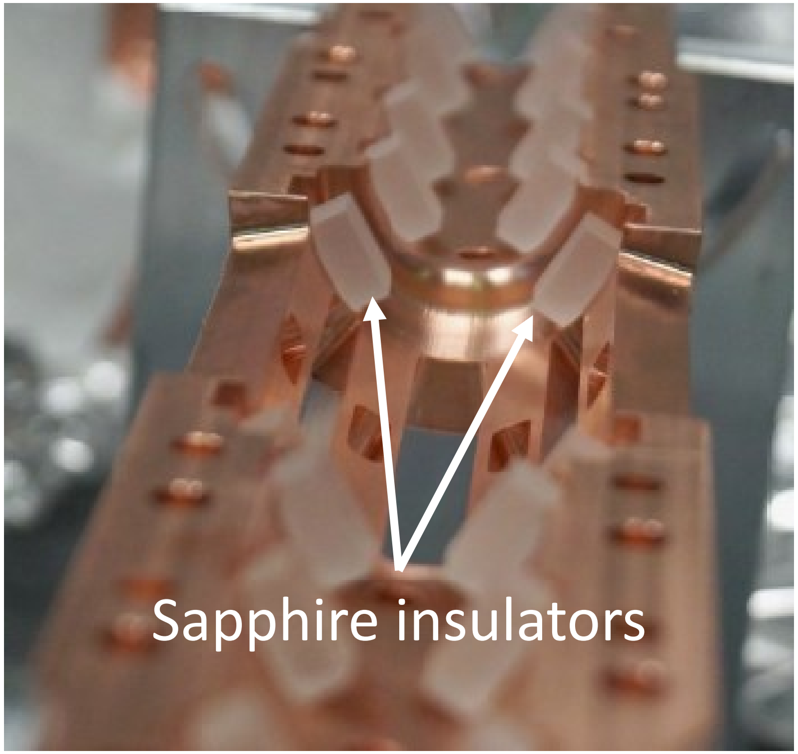


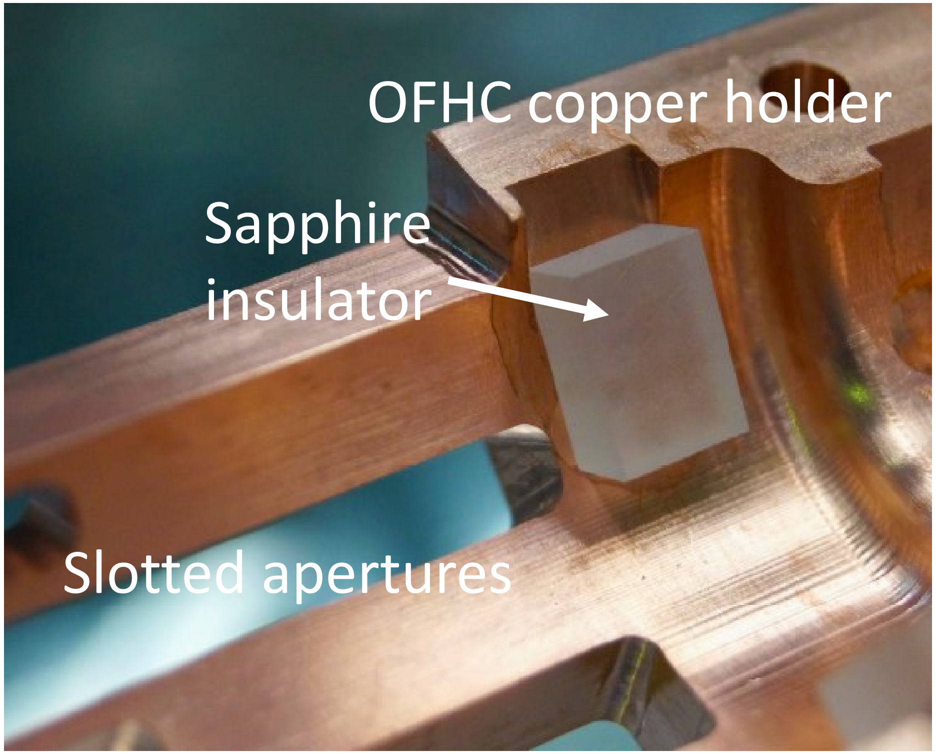
- Trap region lenght 80-270 mm
- 4 K operation
- Fast HV switching in sub-µs range possible

Drift tube supports

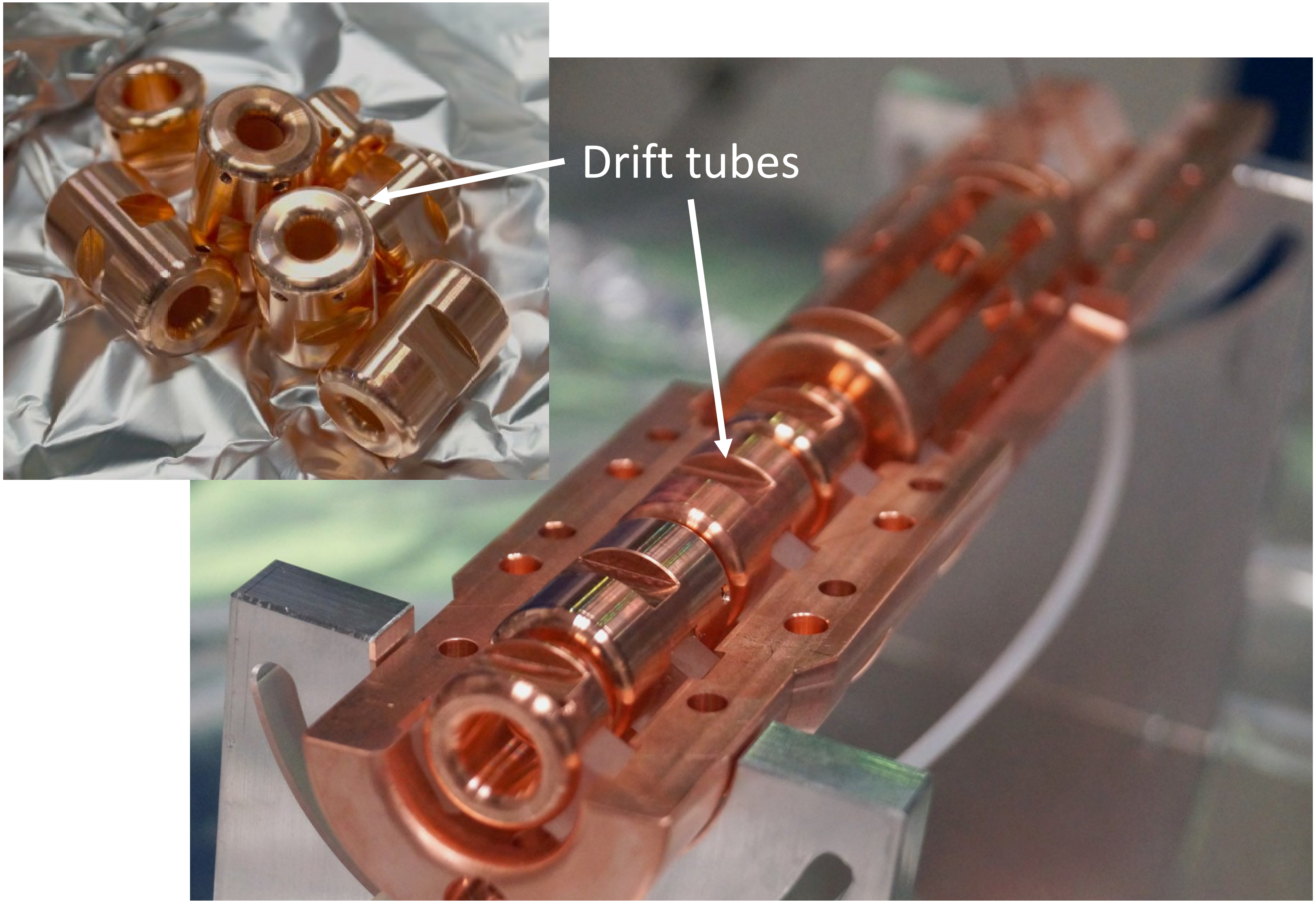


Drift tubes, electrode assembly

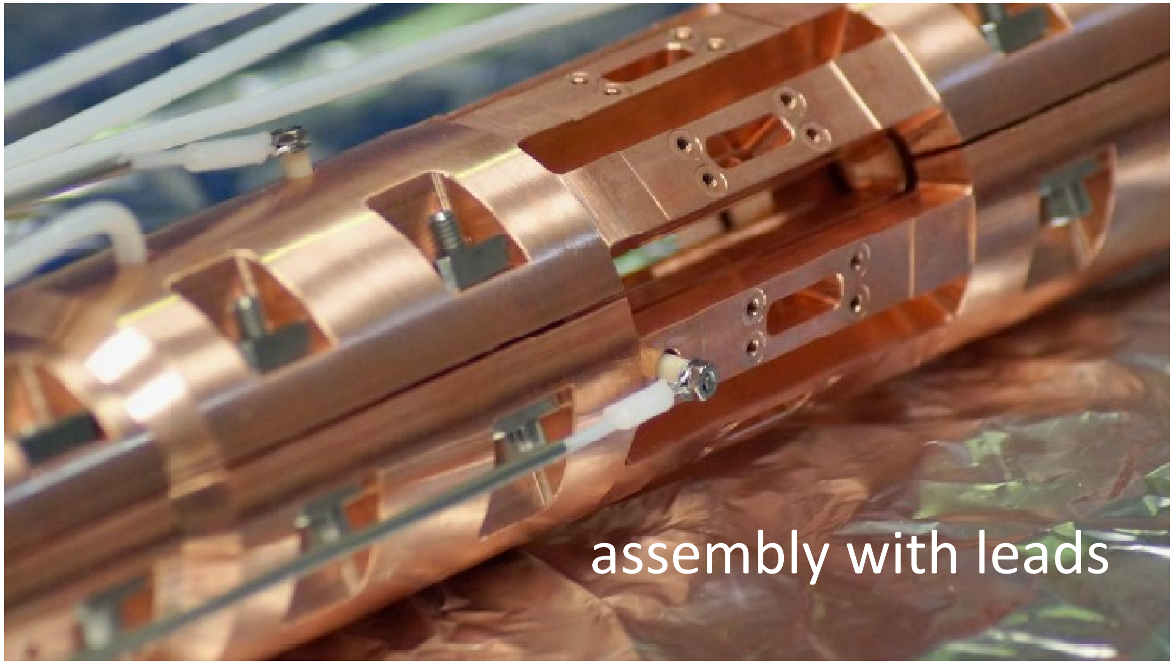




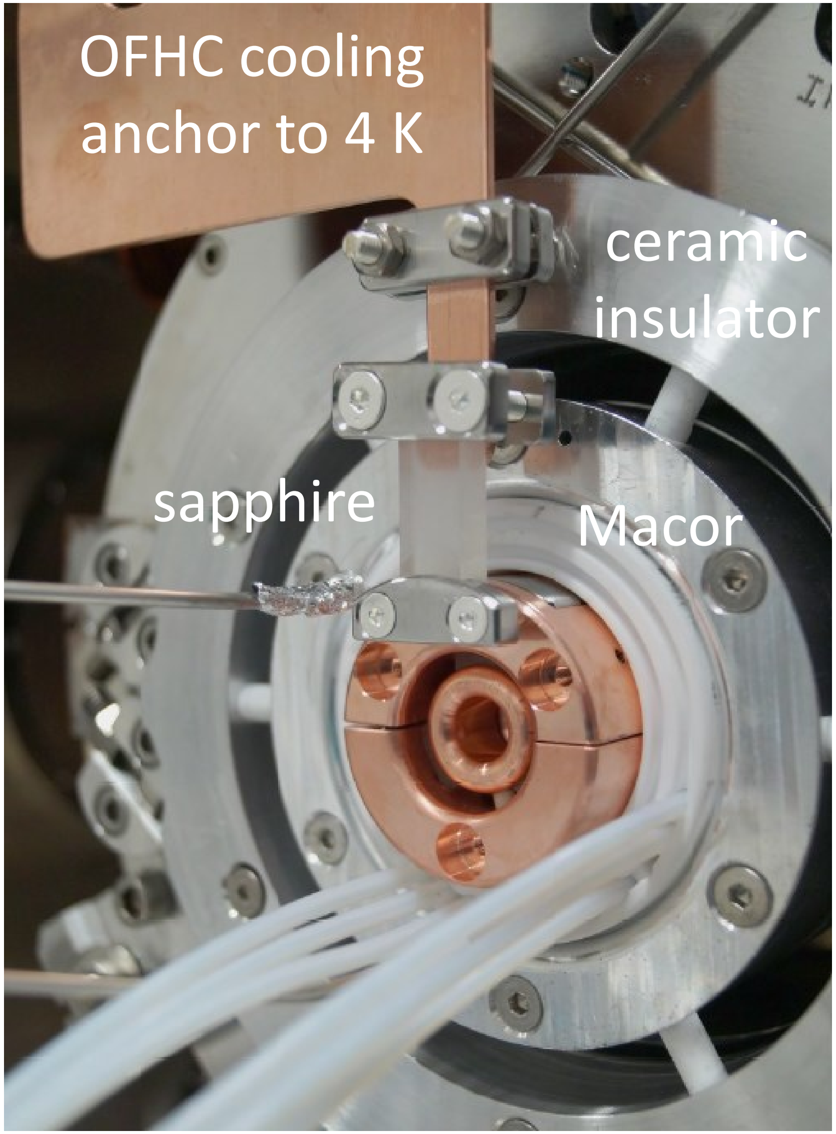
Drift tubes, electrode assembly



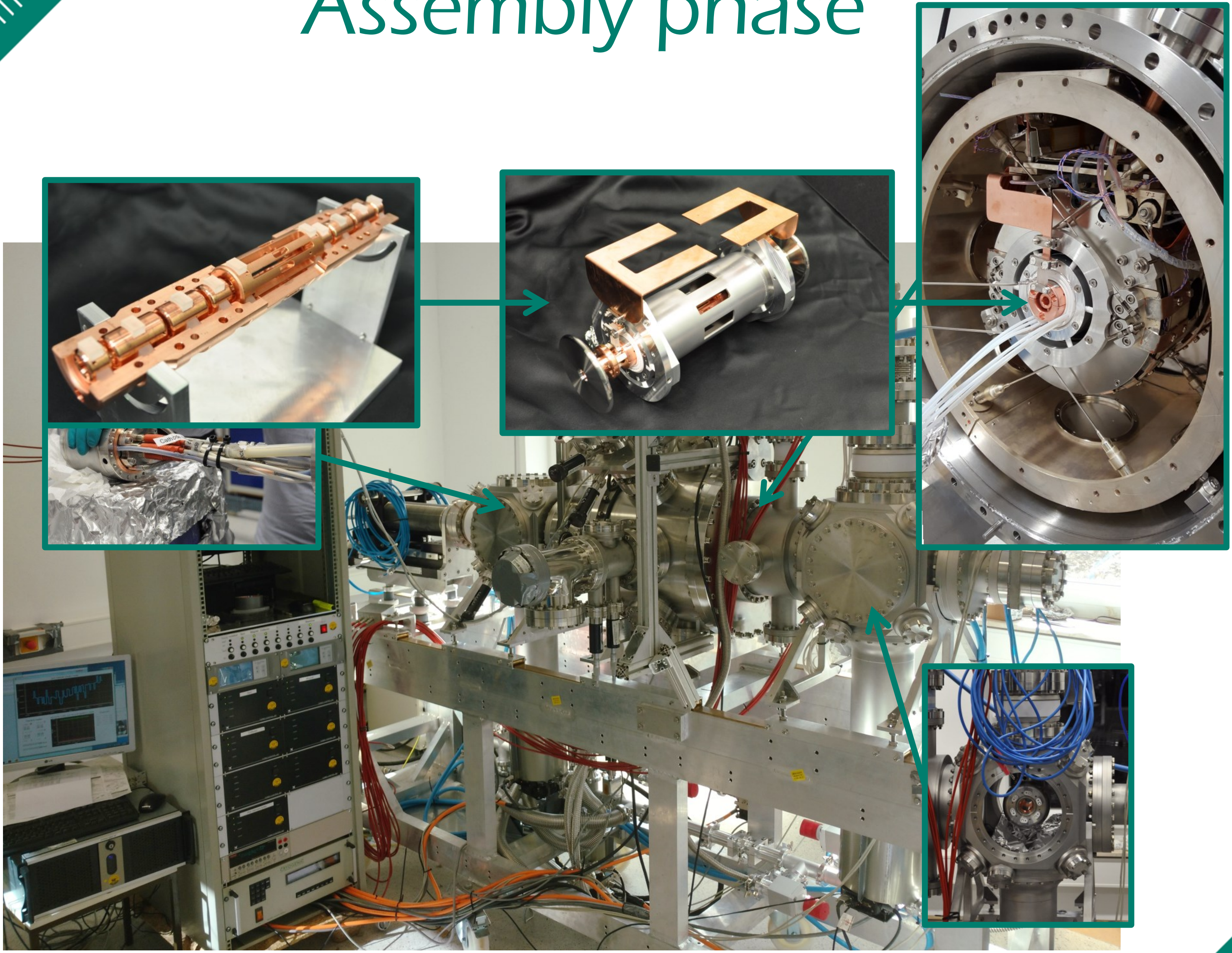
Slotted central drift tube



Drift tube assembly in magnet bore



Assembly phase



Assembly lab

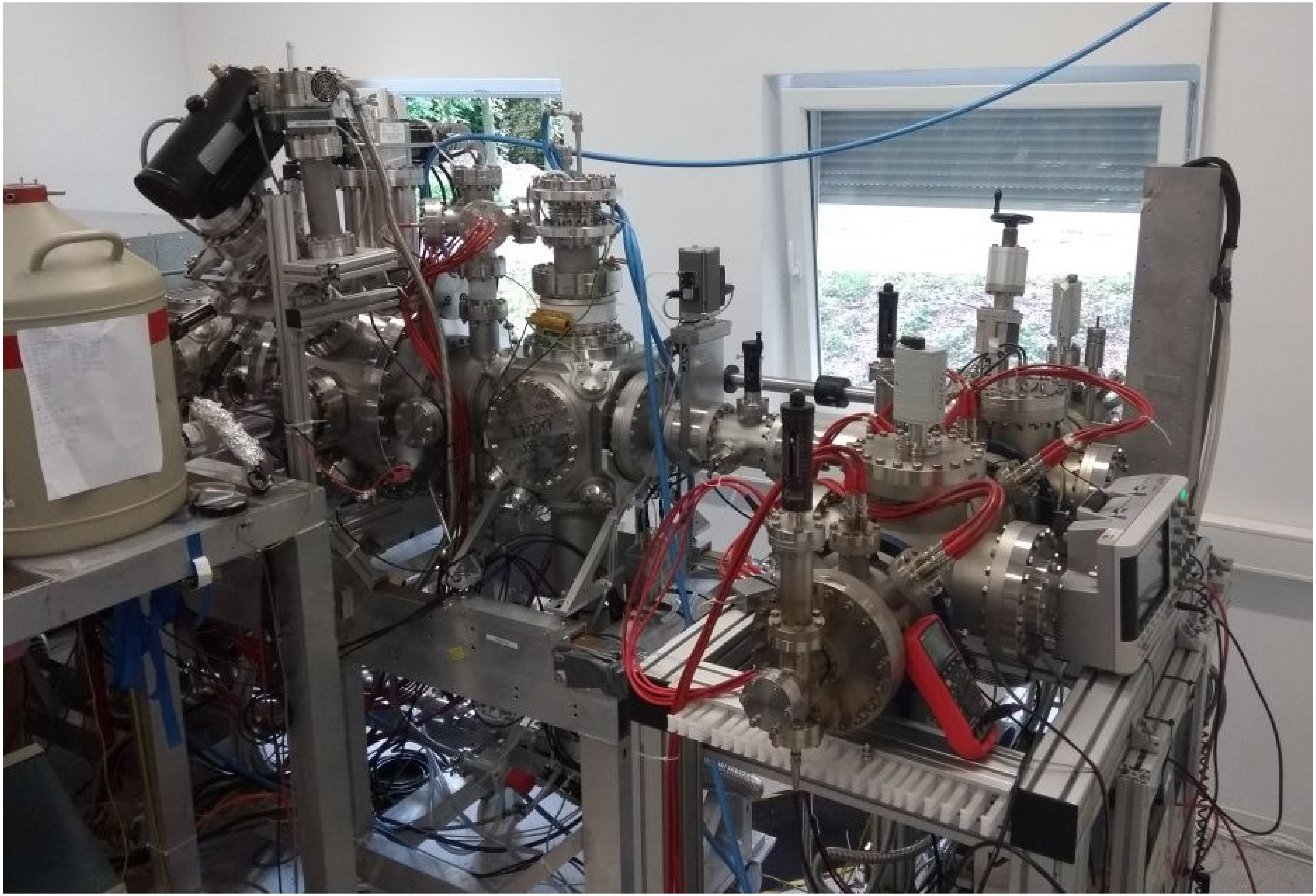
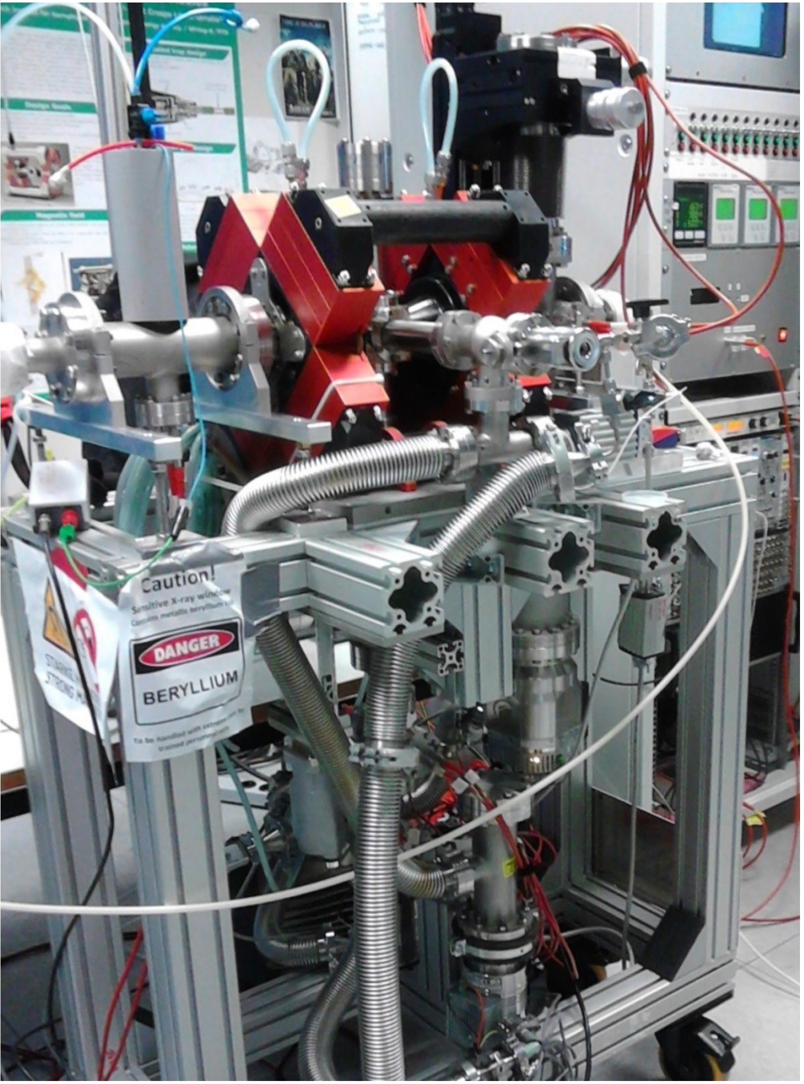
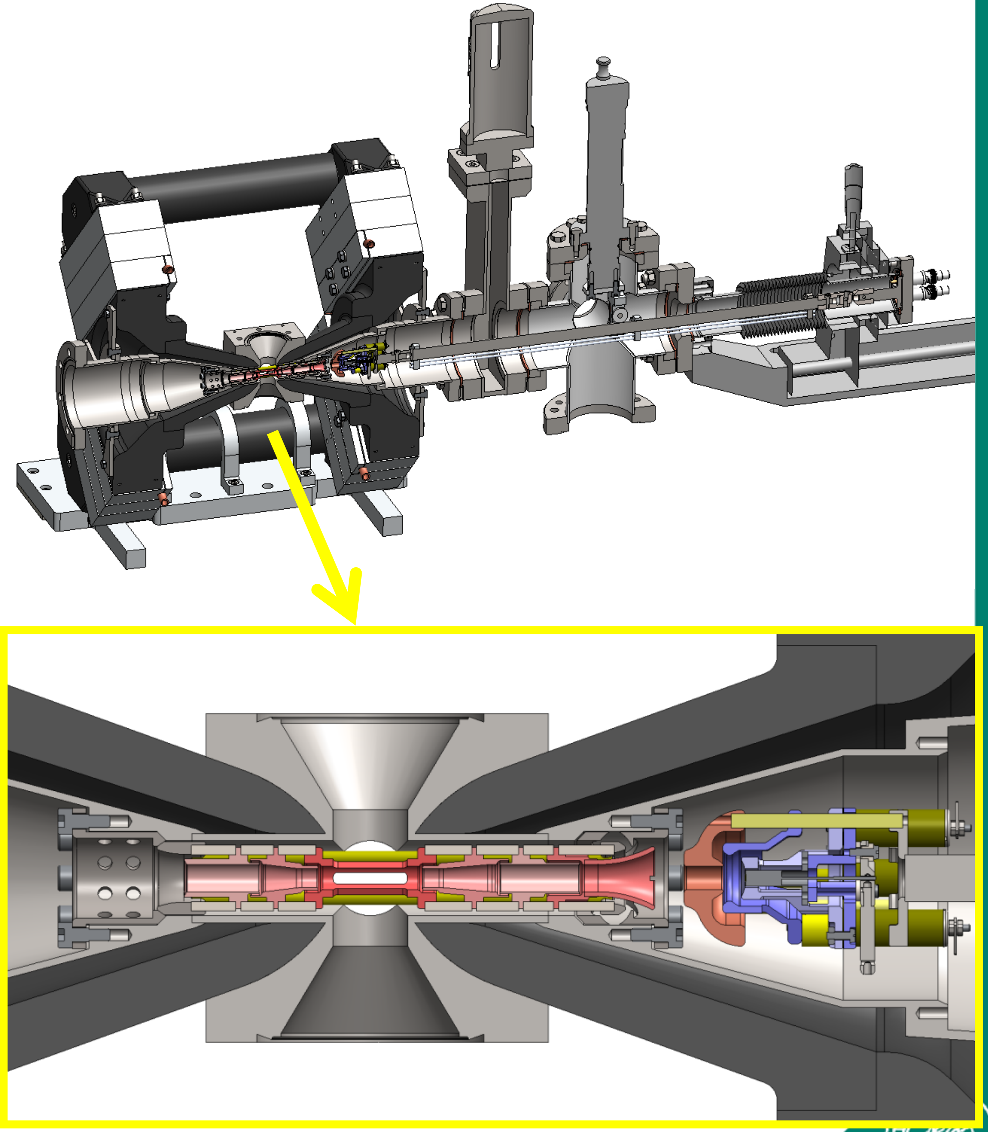
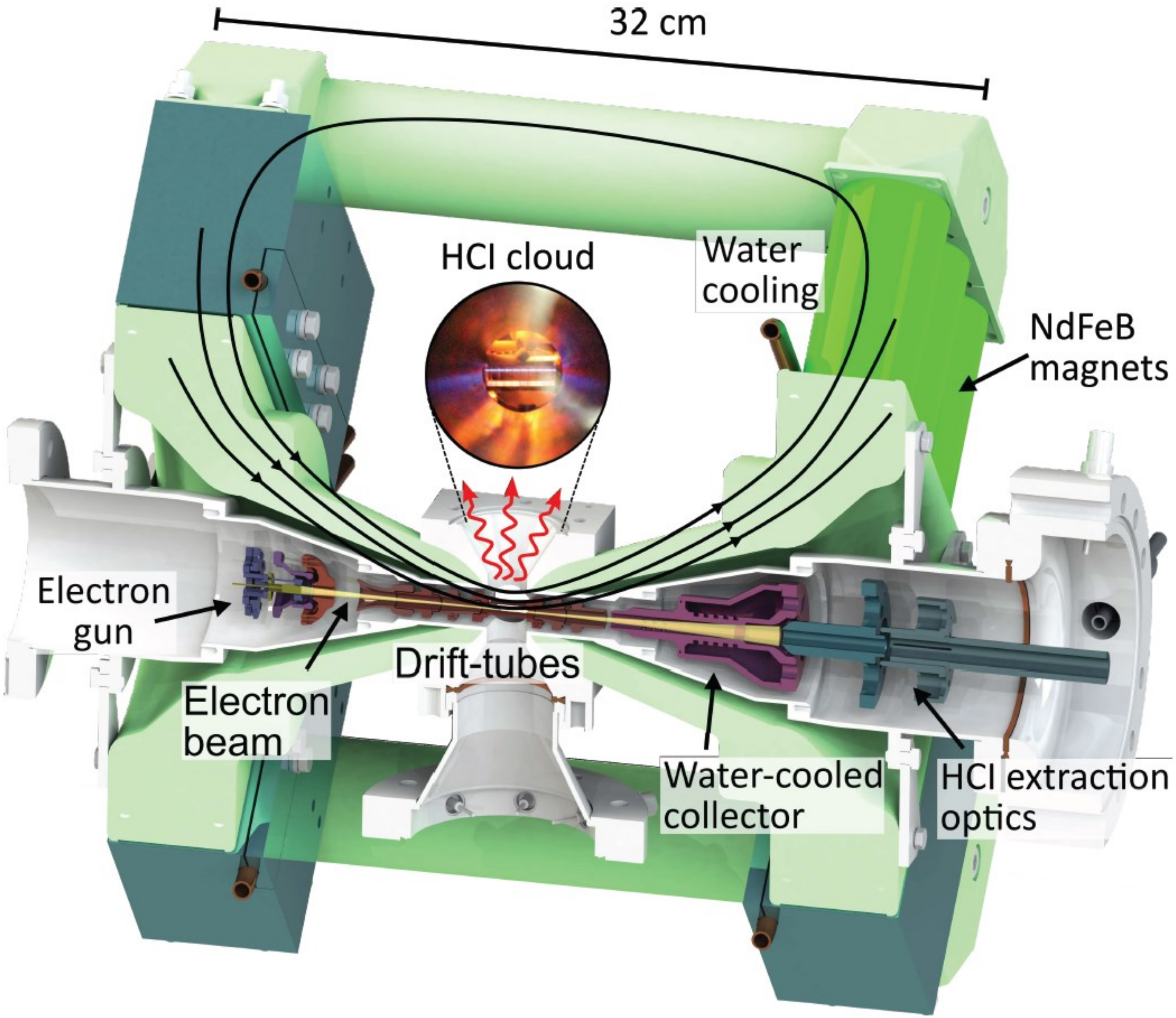


Table-top EBITs for PTB, Petra-III, MPIK

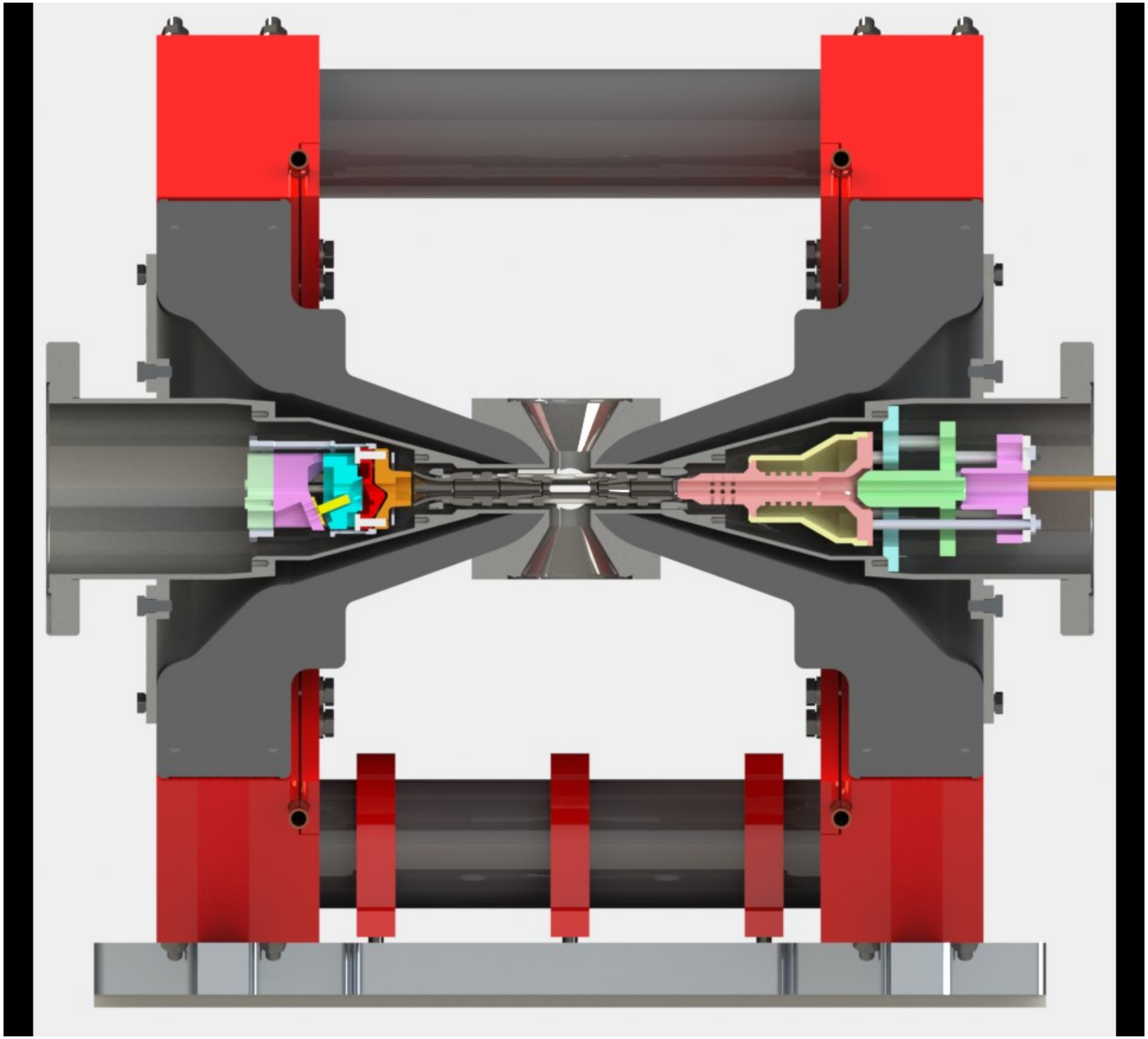




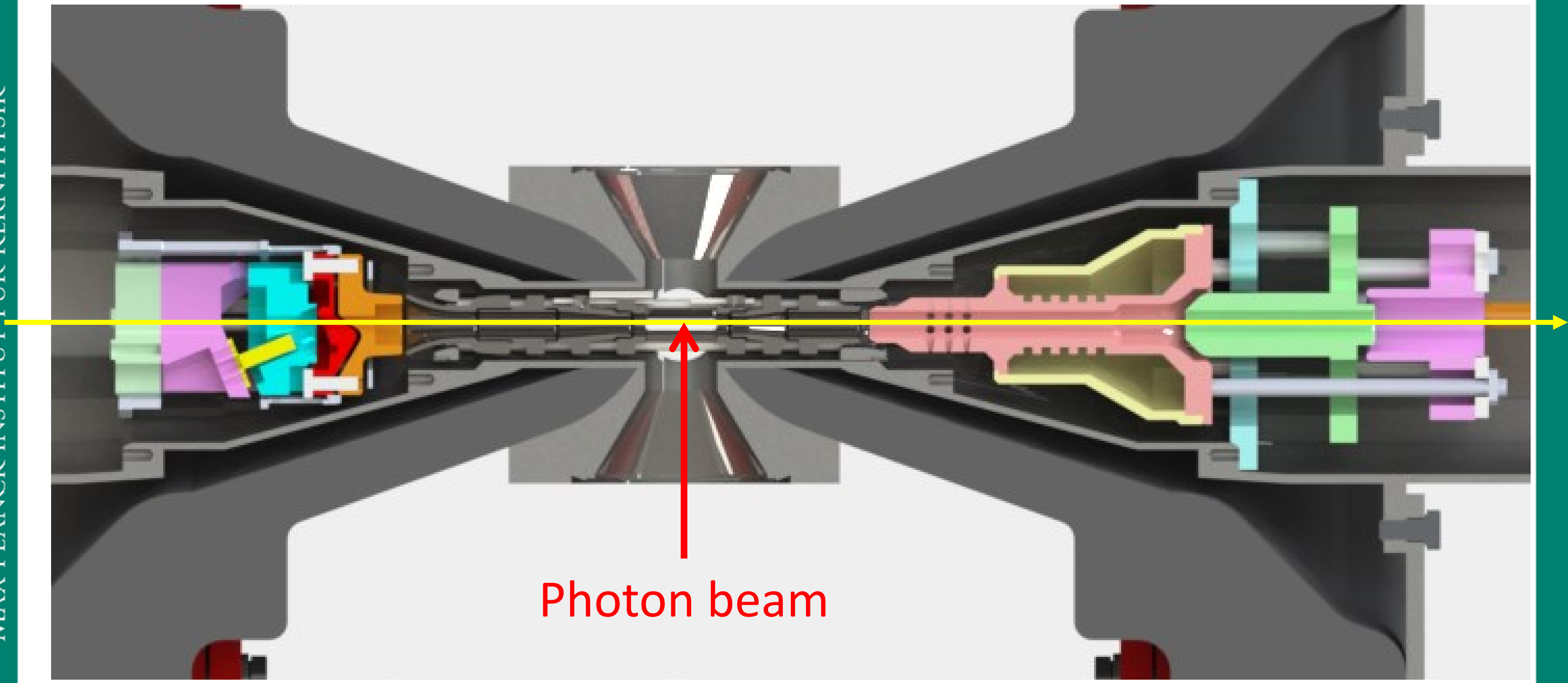
Mini EBITS


32 cm
HCl cloud
Water cooling
NdFeB magnets
Electron gun
Electron beam
Drift-tubes
Water-cooled collector
HCI extraction optics

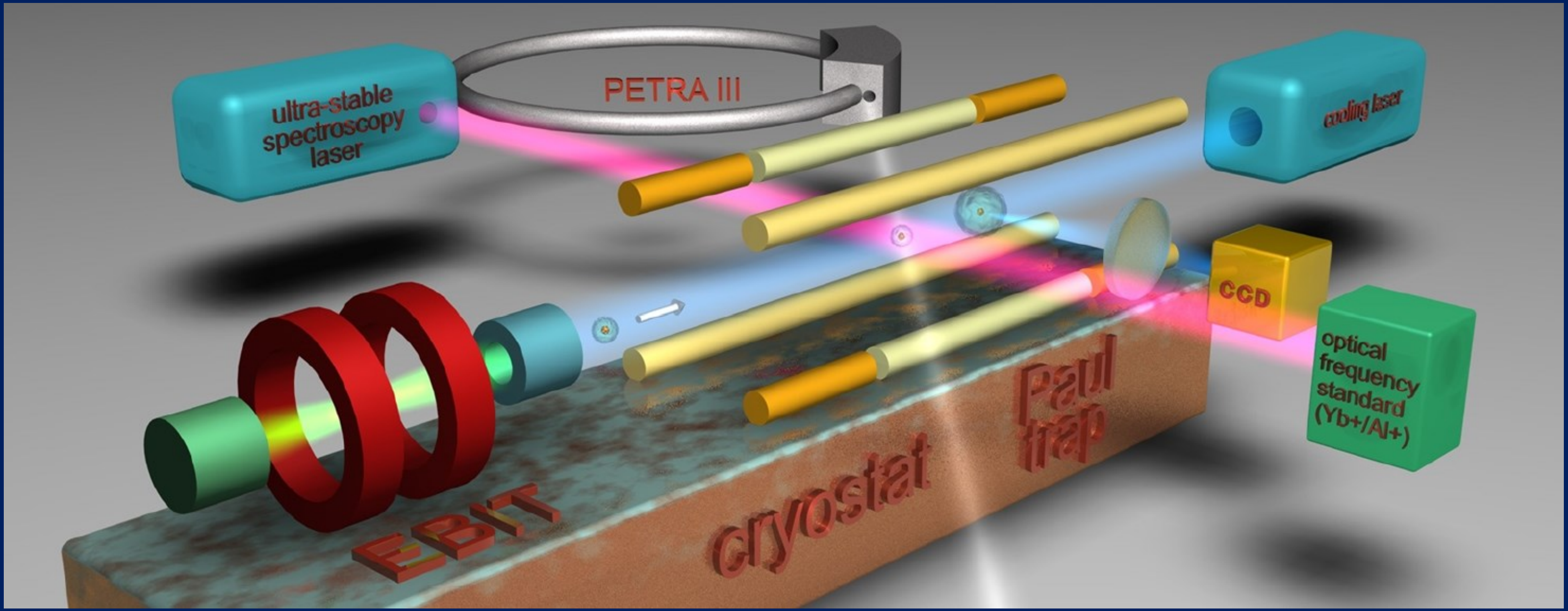
Off-axis electron gun



Off-axis electron gun



Coulomb crystals with HCI for optical clocks



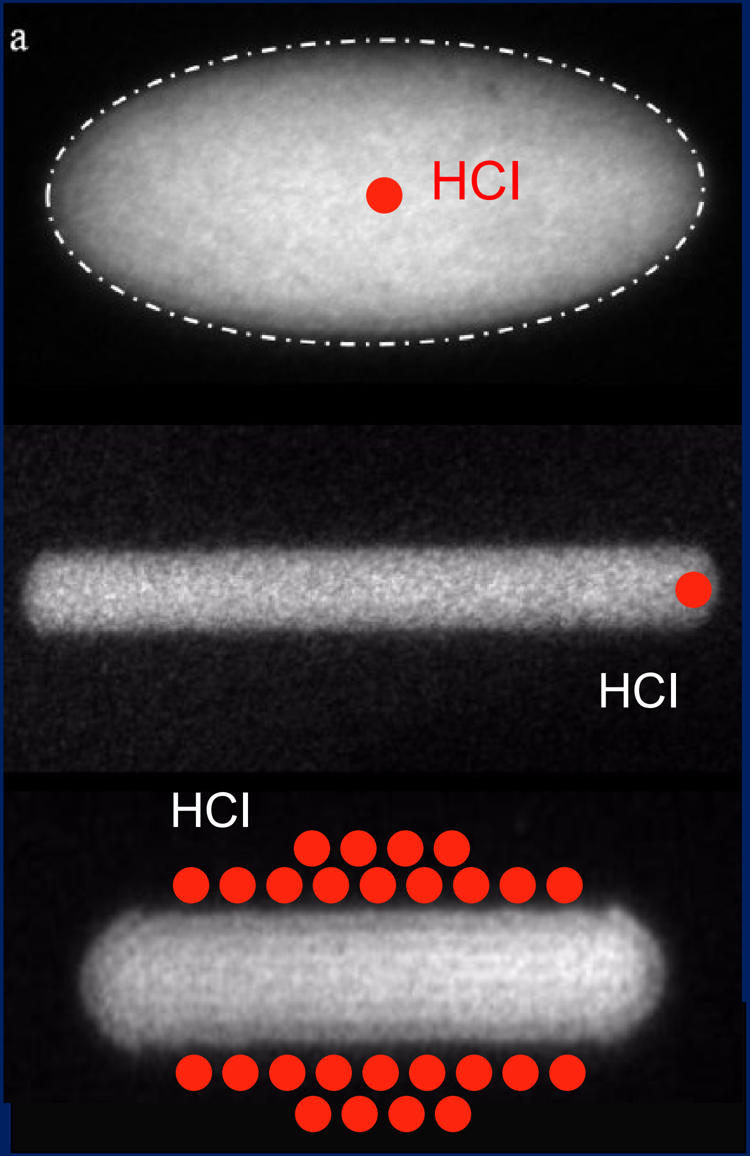
Collaboration with PTB (Piet O. Schmidt) for building an optical clock with an HCI as timekeeper

Deceleration, precooling, and multi-pass stopping of HCI in Be$^+$ Coulomb crystals
L. Schmöger, ... JRCLU et al., Rev. Sci. Instrum. 86, 103111 (2015)

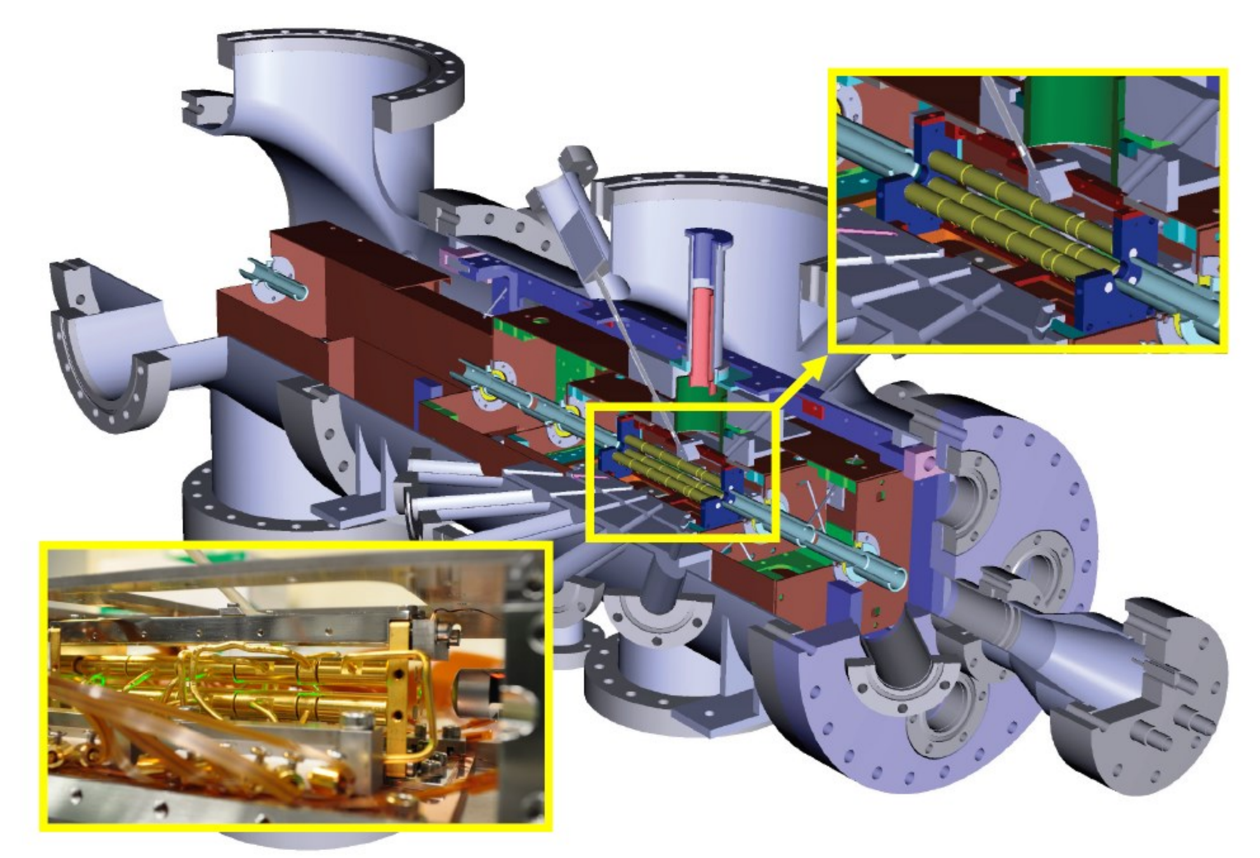
Cryogenic Linear Paul Trap...
M. Schwarz, ... JRCLU et al., Rev. Sci. Instrum. 83, 083115 (2012)

Laser cooling in Paul trap: Ion crystals

- Ion crystals (Be^+) at T=5 mK sympathetically cool HCI
- $T_{HCI} = 10^6\ K \rightarrow 0.1\ K$
- Doppler width reduction
- Low polarizability of HCI suppresses black-body and light shifts
- Improved clocks: search for time-variation of α
- Cooling applicable to X-ray laser spectroscopy



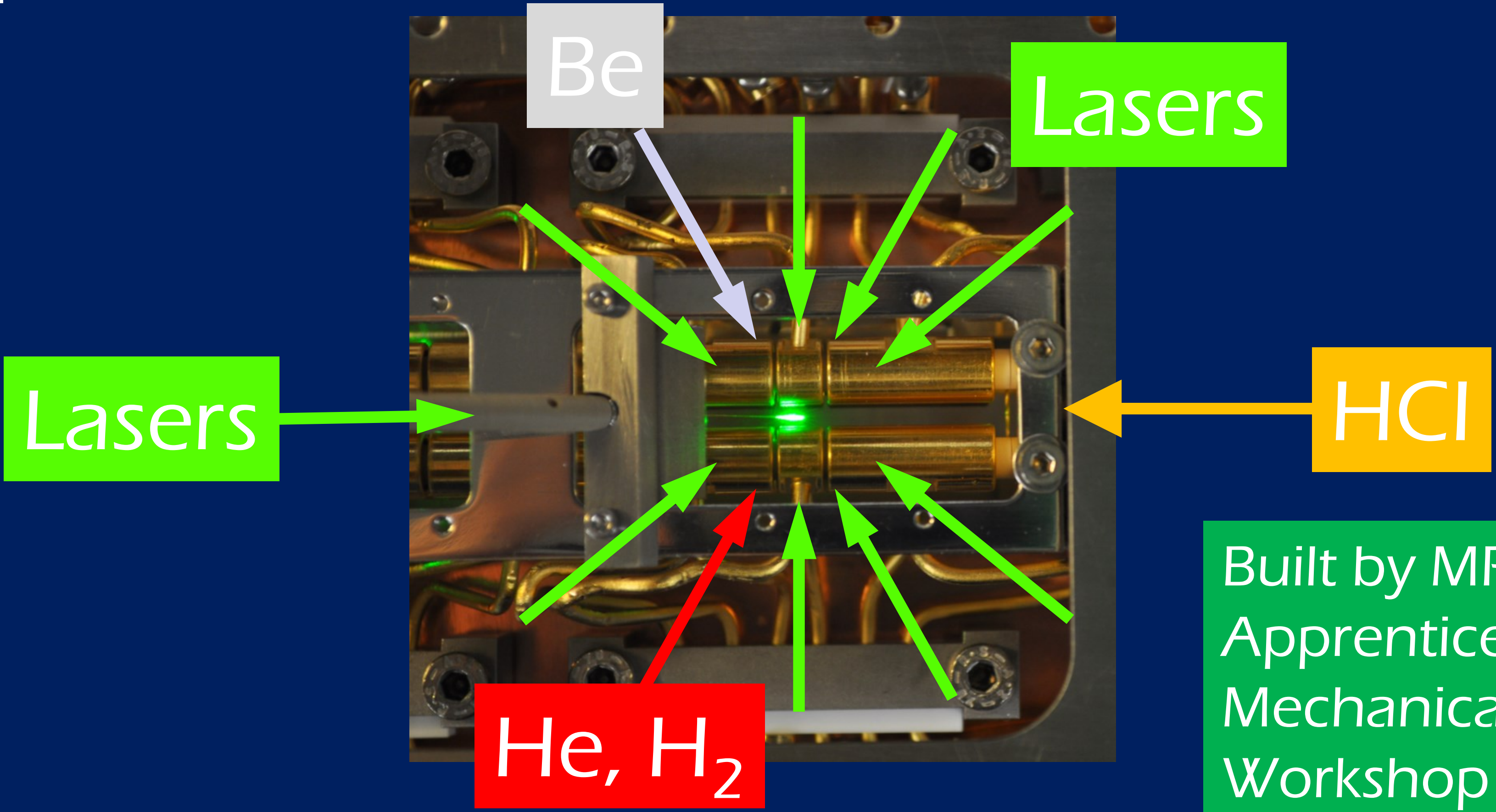
CryPTEx: Cooling T_{ion} down to 100 mK



The "Cryogenic Paul Trap Experiment" was designed for sympathetic laser cooling of highly charged and molecular ions

Design, construction 2010 (M. Schwarz, F. Brunner), tests 2011, operation 2012
M. Schwarz et al. RSI (2012); O.O.Versolato et al., Hyperfine Int. (2013)

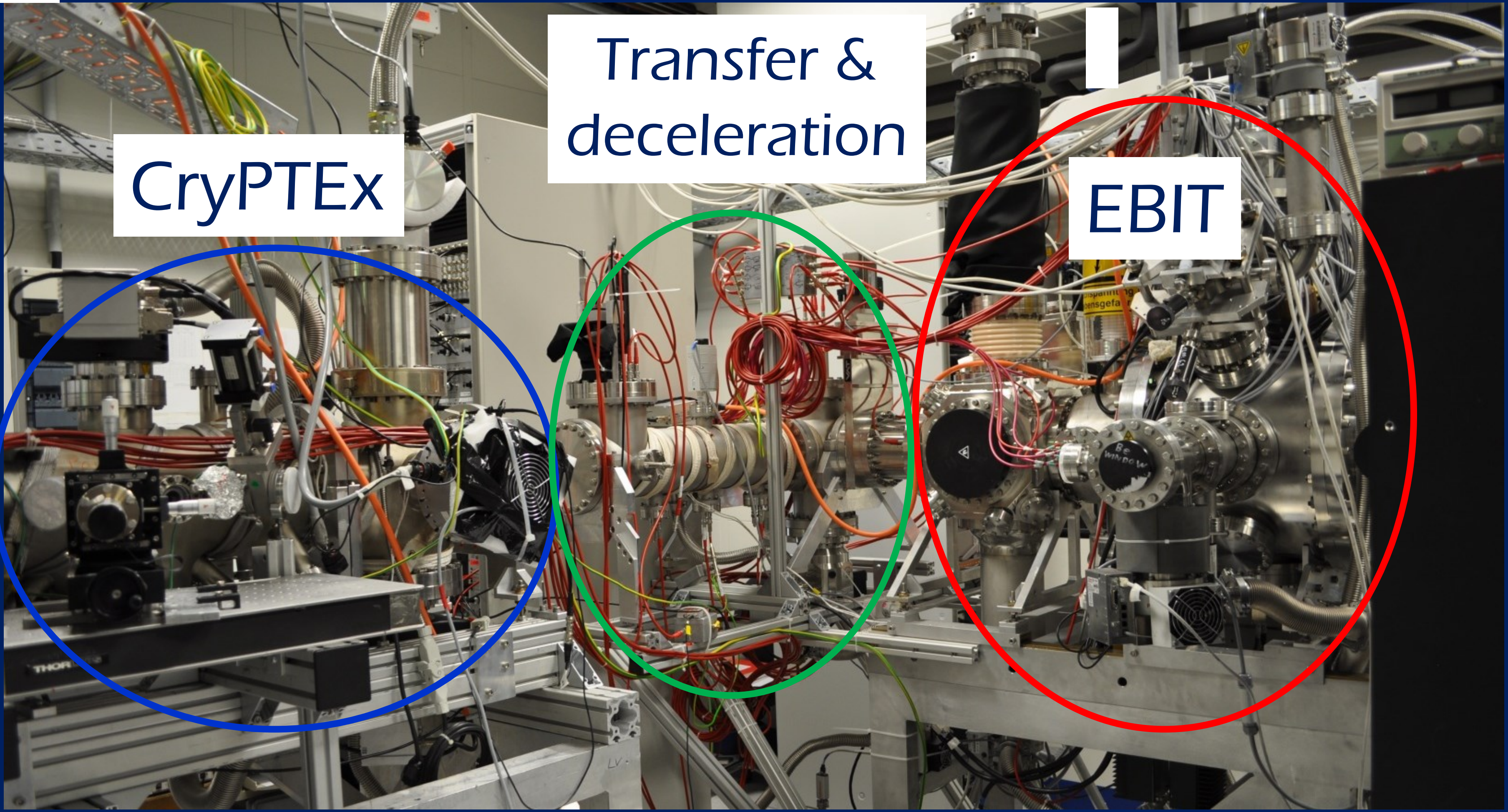
4K trap region accessible for HCI injection



Built by MPIK Apprentice Mechanical Workshop

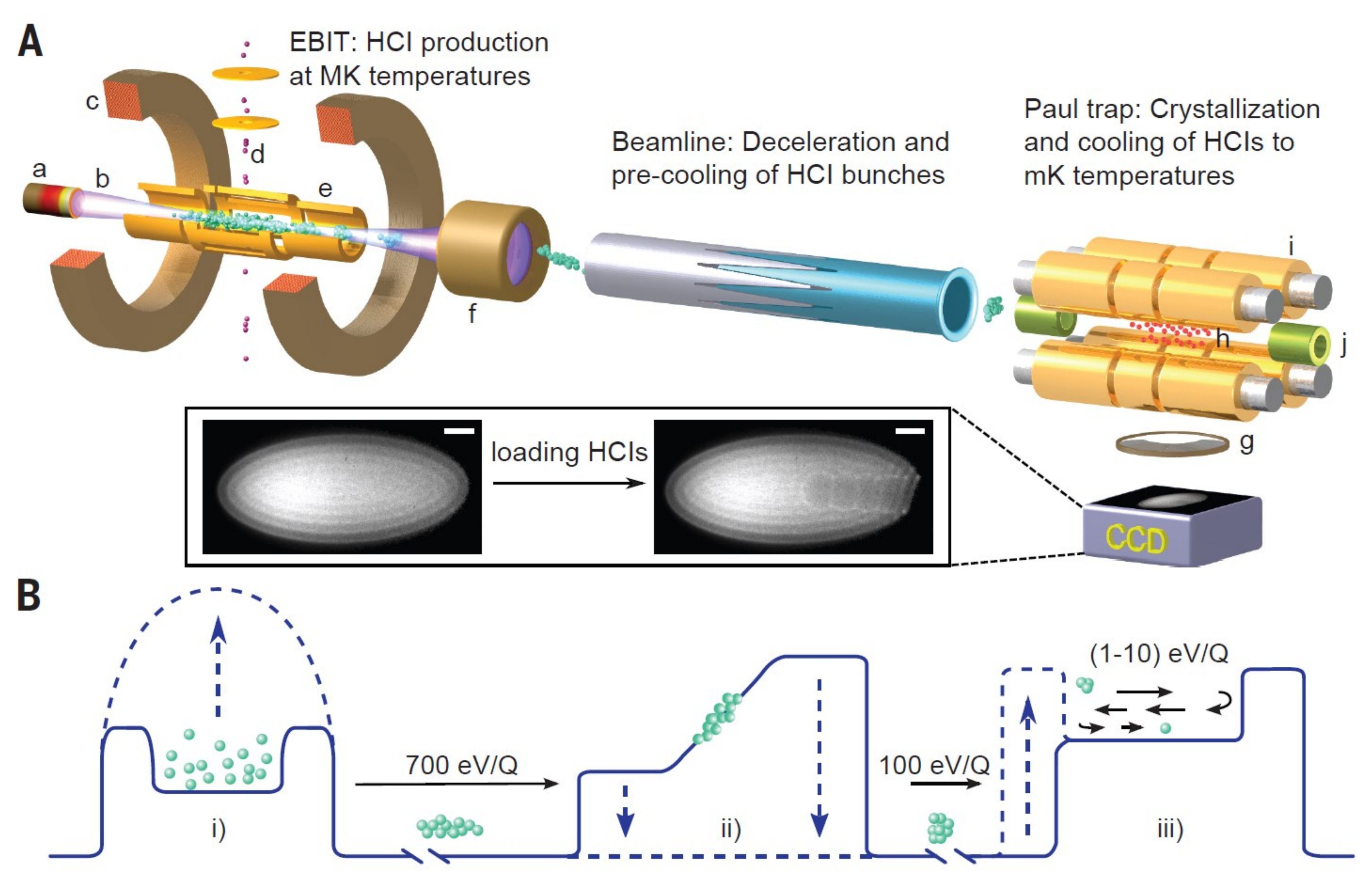
- 16 access ports to 4K trap: lasers, imaging, atoms, ions
- External ion sources + in-trap photoionization
- Measured pressure 10^{-15} mbar
- "Effective" black-body radiation temperature ~7.6 K

HCI transfer and deceleration at MPIK

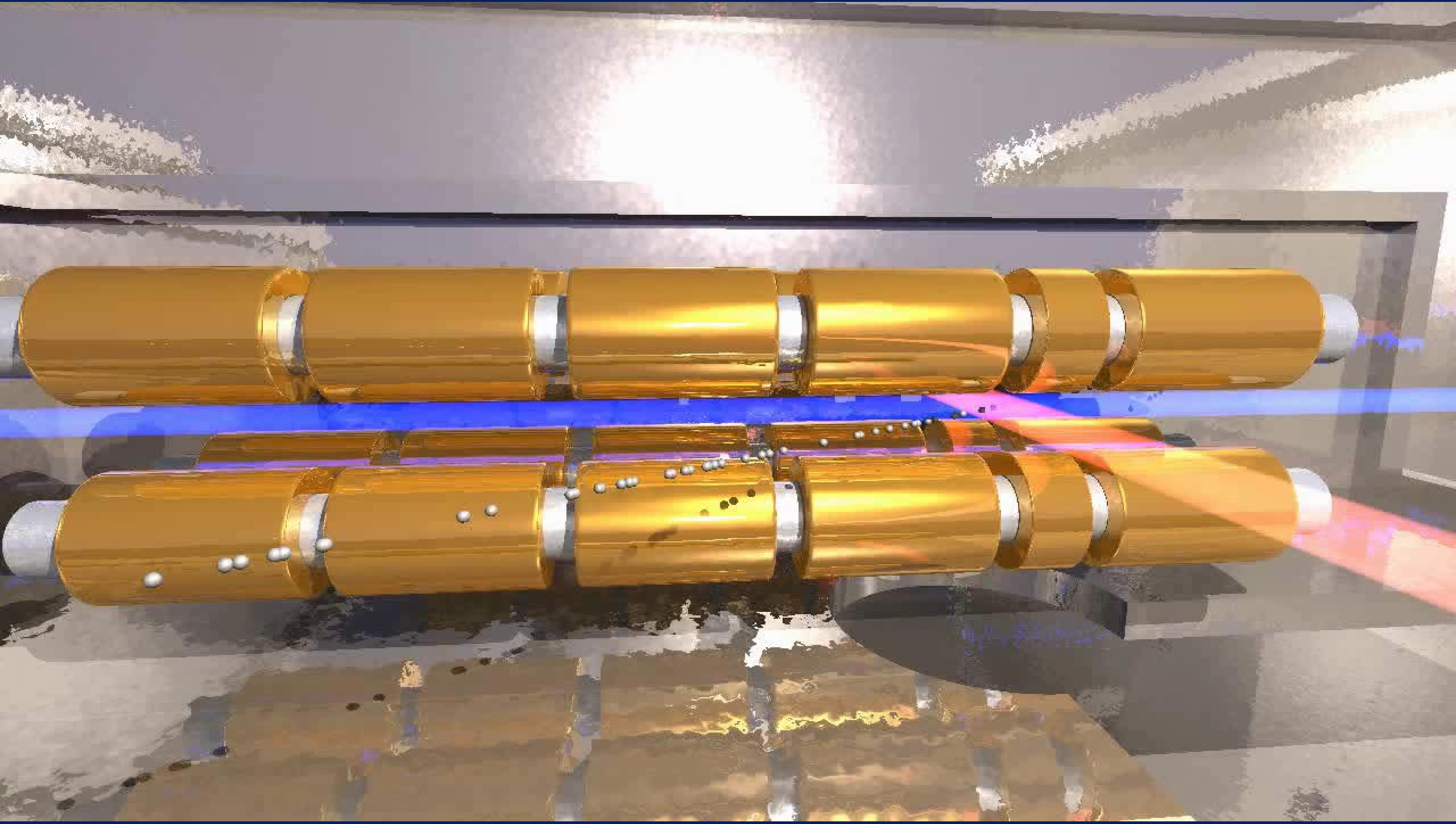


- HCI extraction from Hyper EBIT,
- Deceleration (pulse tube buncher)
- Injection into CryPTEx

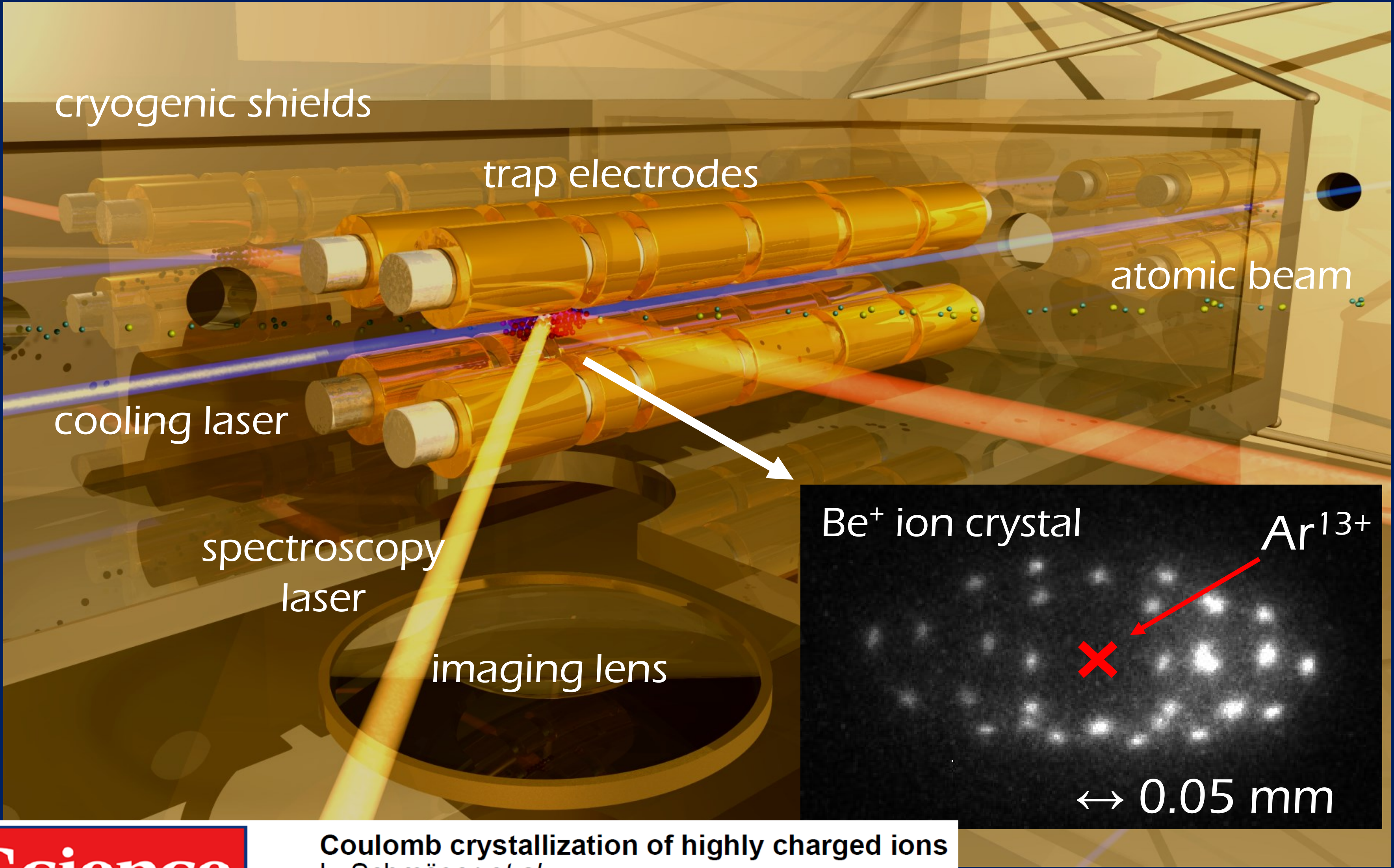
HCI production, deceleration, implantation



Lisa Schmöger et al., Science **347**, 1233 (2015)

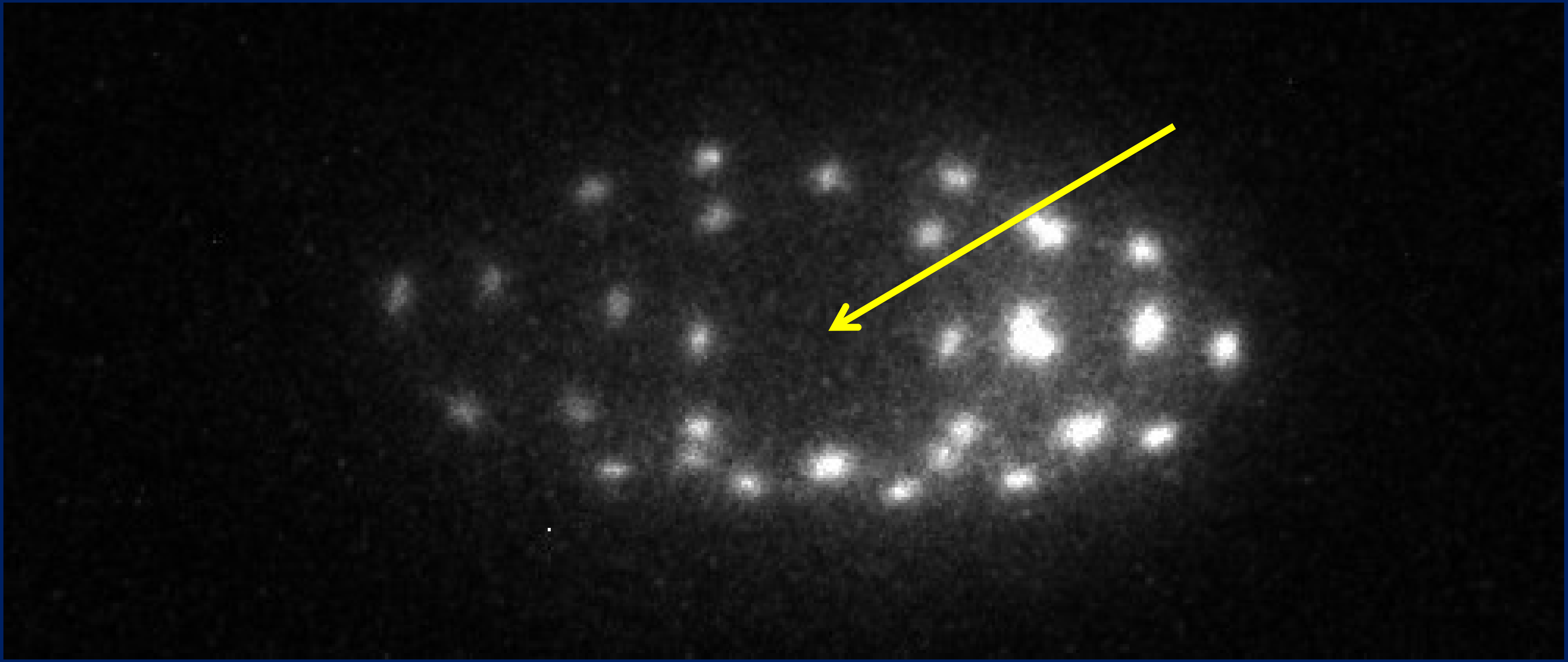


HCl production, deceleration, implantation



Coulomb crystallization of highly charged ions
L. Schmöger *et al.*
Science **347**, 1233 (2015);
DOI: 10.1126/science.aaa2960

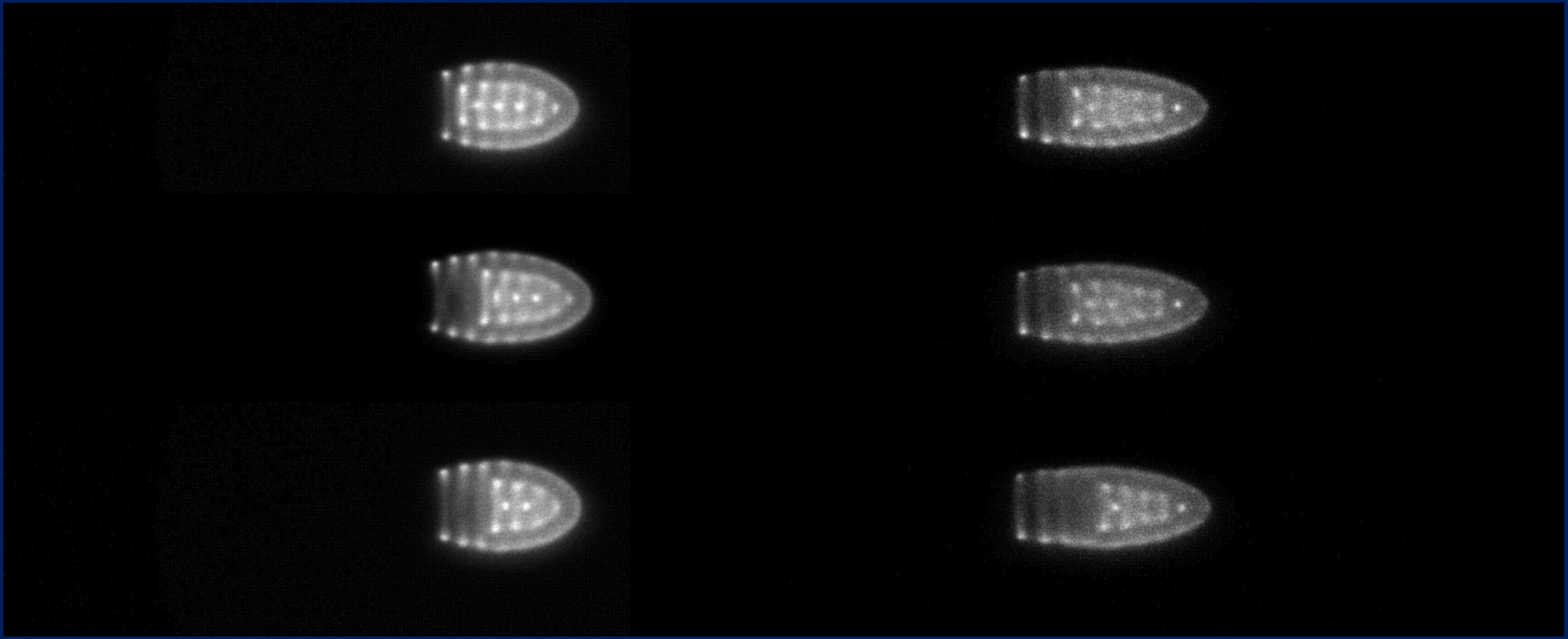
HCl identification by image analysis



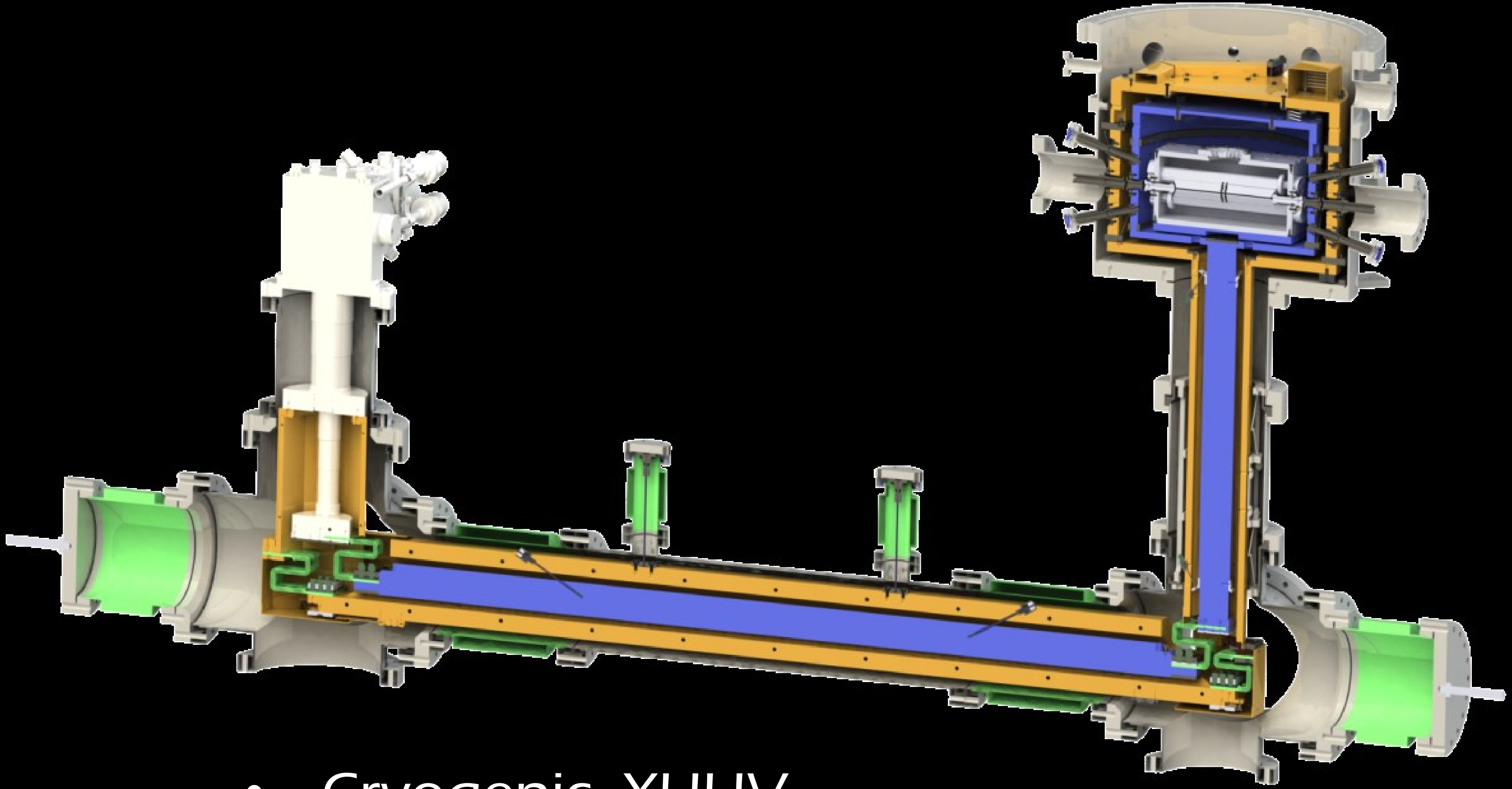
- The single HCI (here Ar^{13+}) repels Be^+ ions and produces a hole in the Coulomb crystal
- *Addressing a single ion in the trap with a focused* beam is possible due to large separation.

Lisa Schmöger et al., Science **347**, 1233 (2015)

Nice crystals

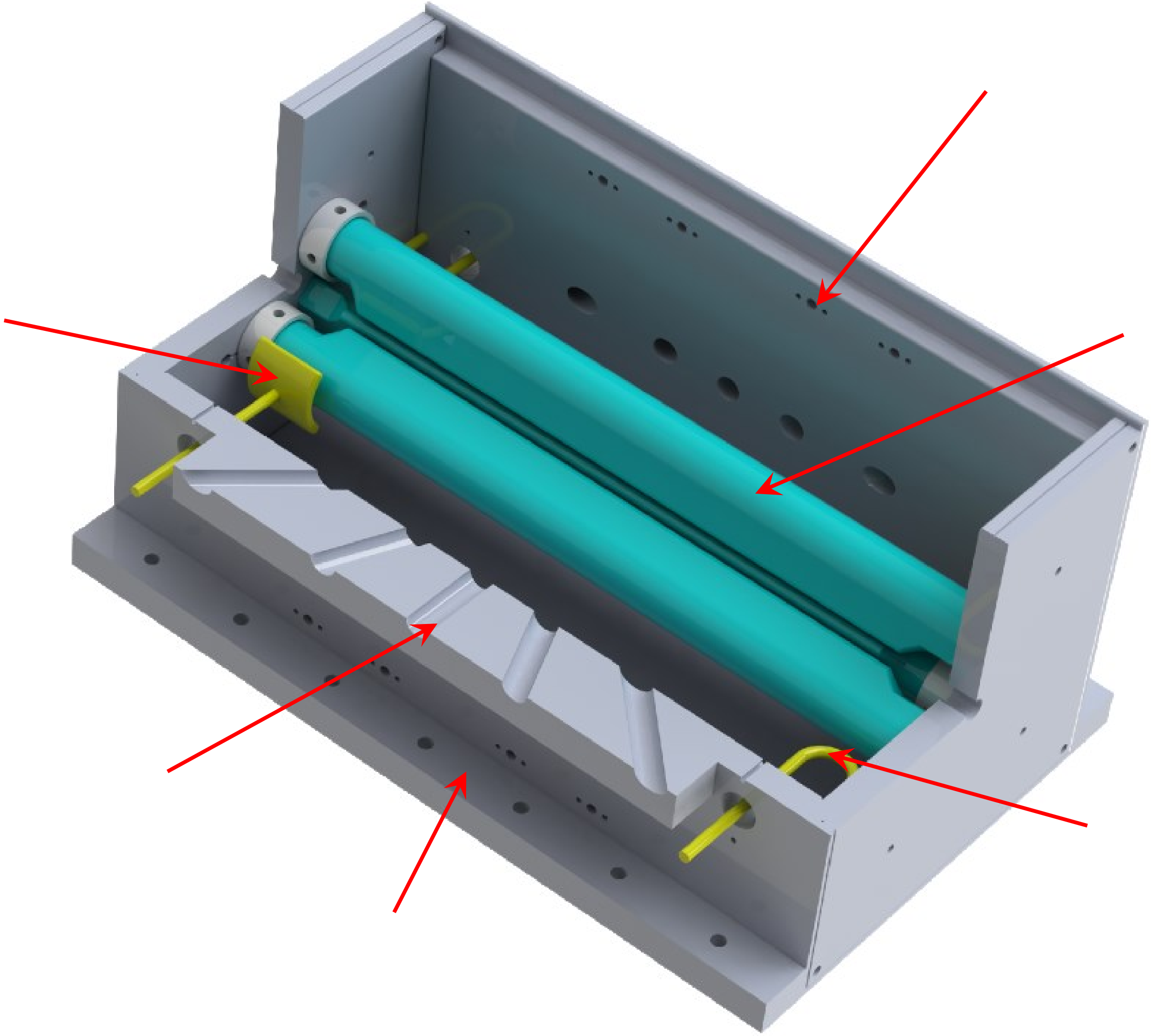


Next generation cryogenic trap



- Cryogenic, XUHV
- Ultra-low vibration
- Superconducting high-Q RF resonator

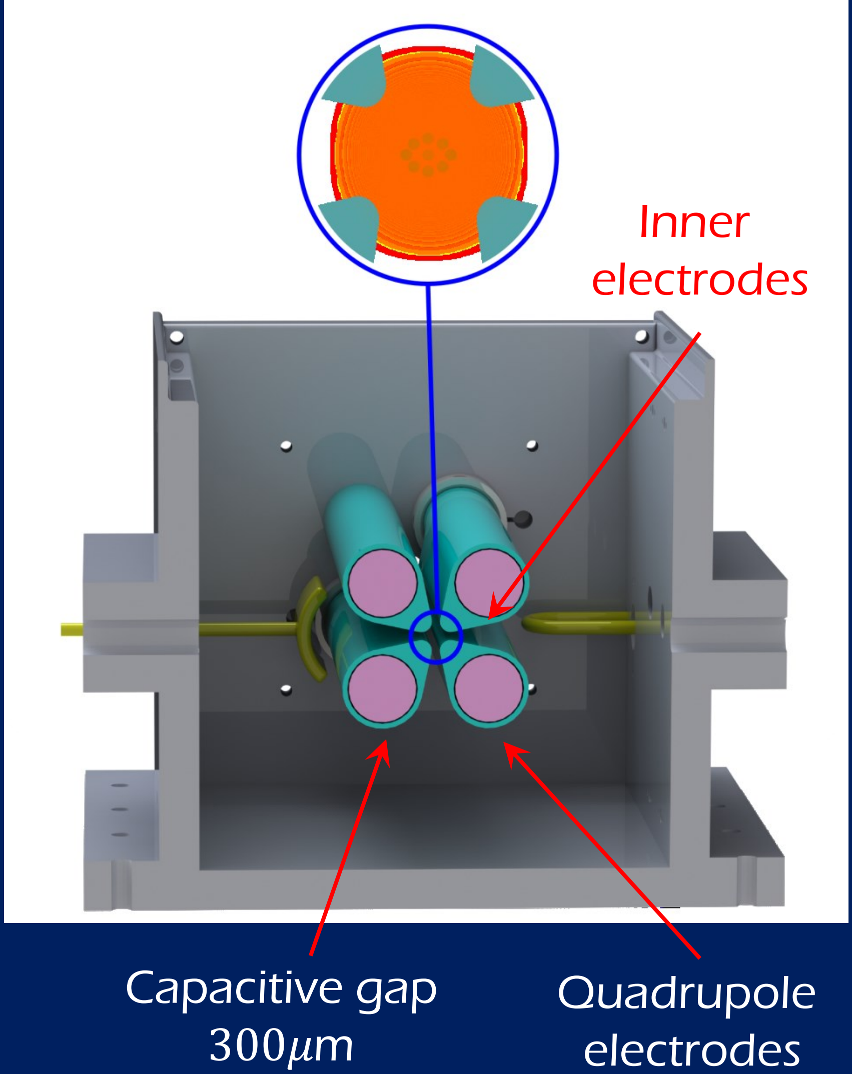
Cryogenic RF resonator for Paul trap



Design by Julian Stark (MPIK)

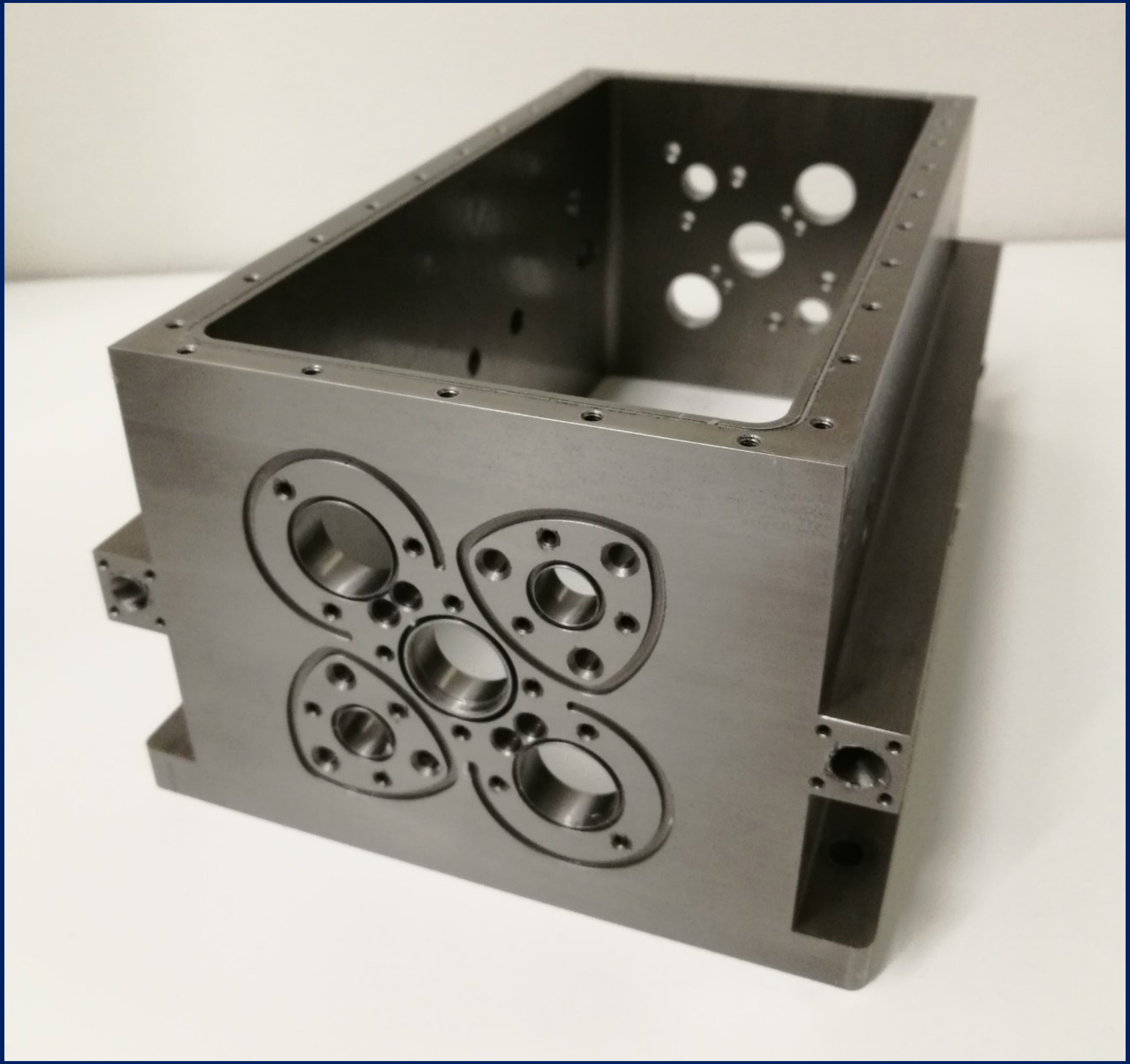
A prototype for a cryogenic resonator

- Integrated electrodes for high Q value and low coupling losses
- All RF electronics at T = 4K



Design by Julian Stark (MPIK)

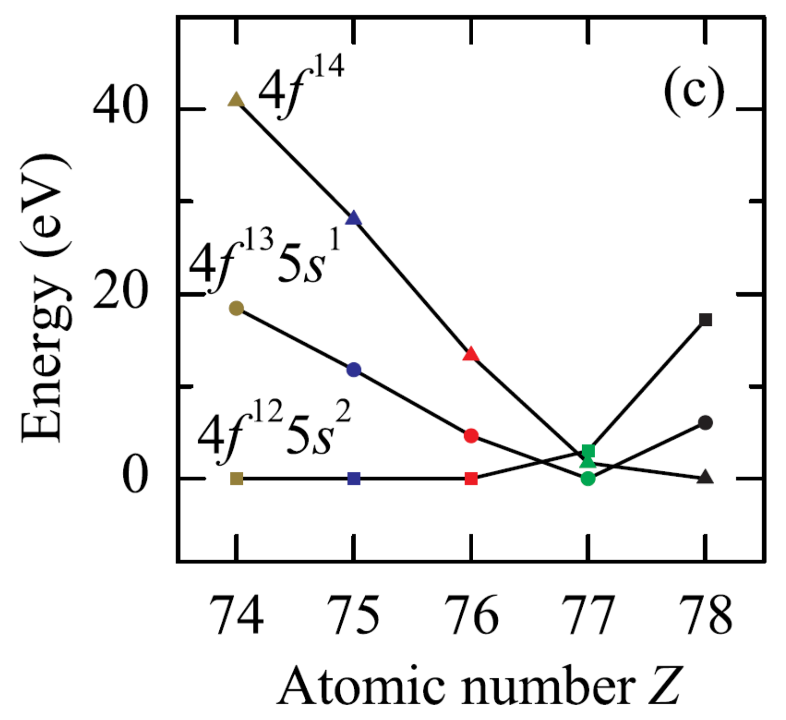
Next generation cryogenic trap



- Superconducting high-Q RF resonator

Time variation of α

- Limits for the time stability of α are based on claimed astrophysical observations too small for checking them with the currently best optical clocks at a relative accuracy of 10^{-17} / y.
- Forbidden optical transitions in HCl are very insensitive to external spurious fields, while scaling up the effect of a change in α due to much larger relativistic effects than in atoms



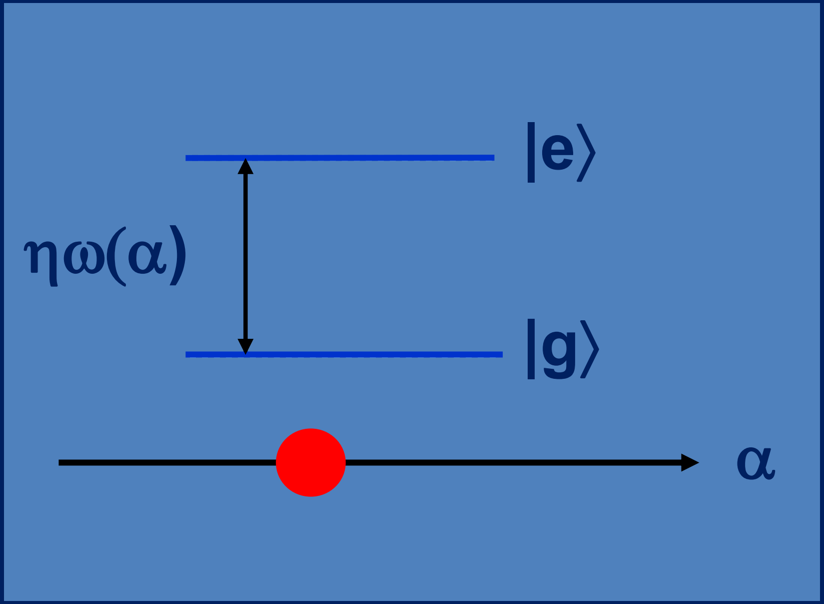
- The highest possible sensitivity to α is reached at specific *5s-4f* level crossings (e. g., at Z=77 with Ir^{17+}ions)

Search for a time variation of α with cold HCI

- Astrophysical hints of an spatial dependence

  Webb et al., PRL (2011)

- Test by comparing laser transitions that depend differently on α

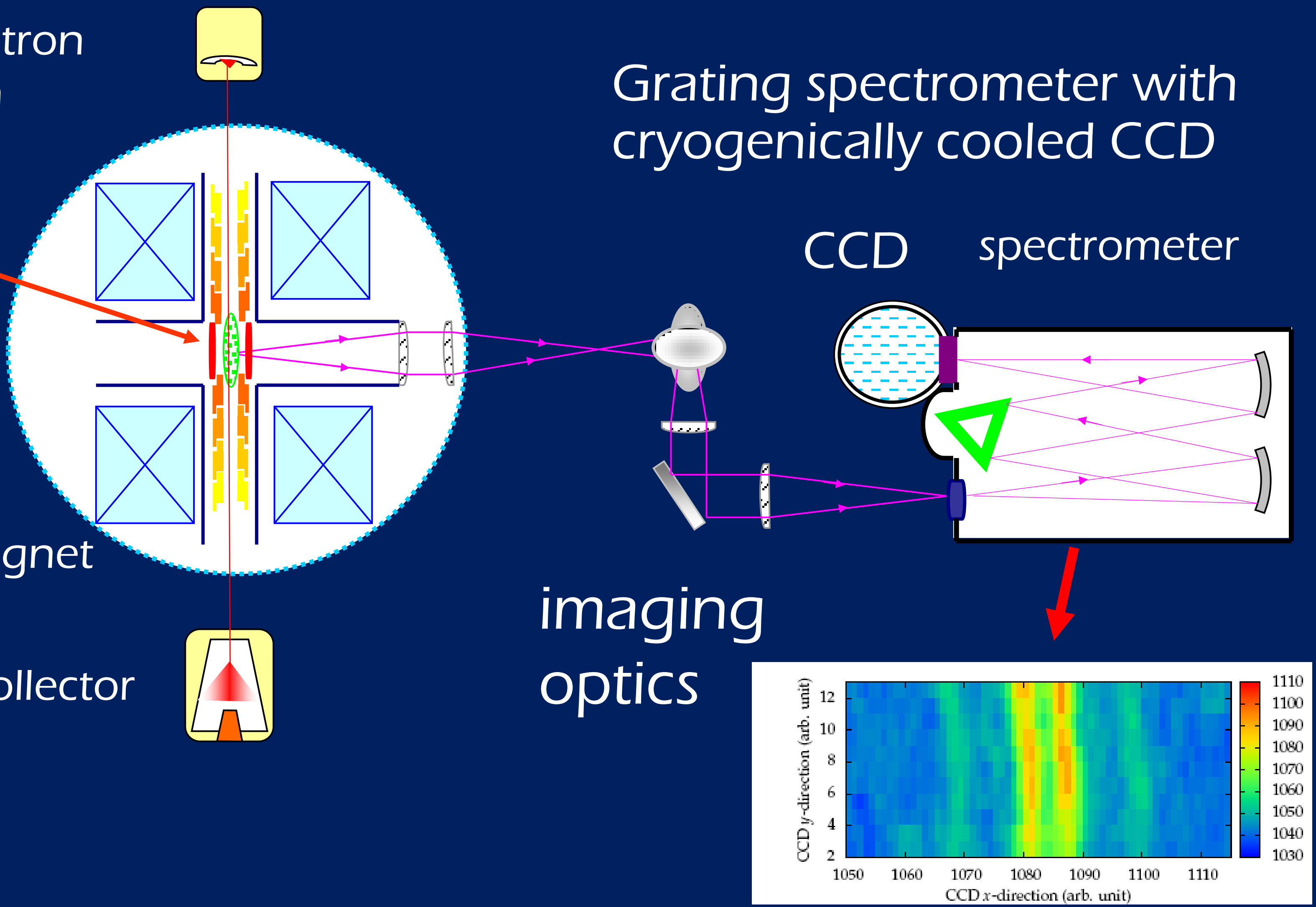


- Sensitivity coefficient q ~relativistic contributions

$$\omega(\alpha) \approx \omega_0 + 2q\, \Delta\alpha/\alpha$$

- HCI extremely sensitive: Frequency metrology on forbidden transitions between nearly degenerate states (e. g. Ir^{17+})

Spectroscopy of few-electron ions in the visible range



electron gun

trap

SC magnet

collector

Grating spectrometer with cryogenically cooled CCD

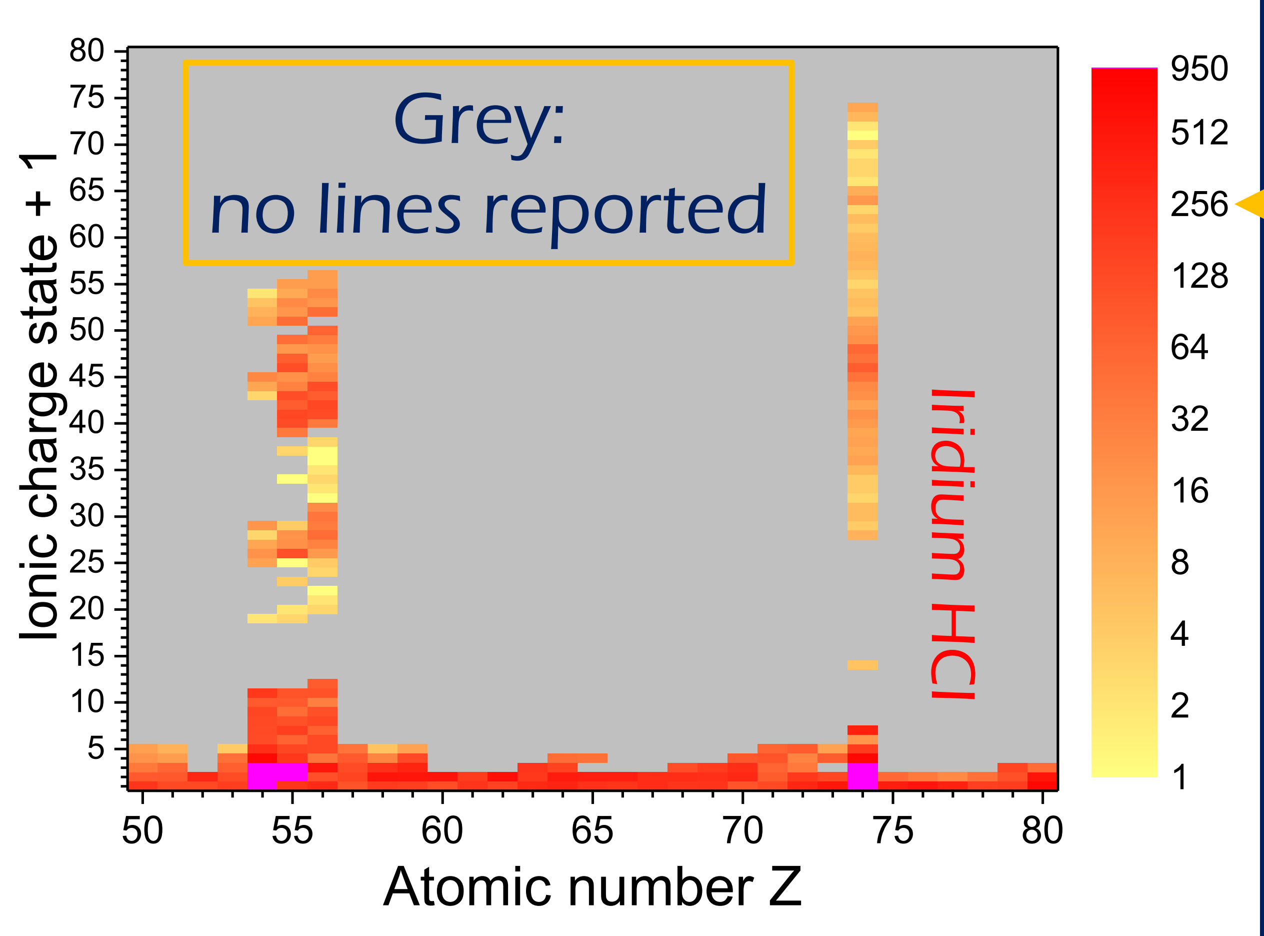
CCD

spectrometer

imaging optics

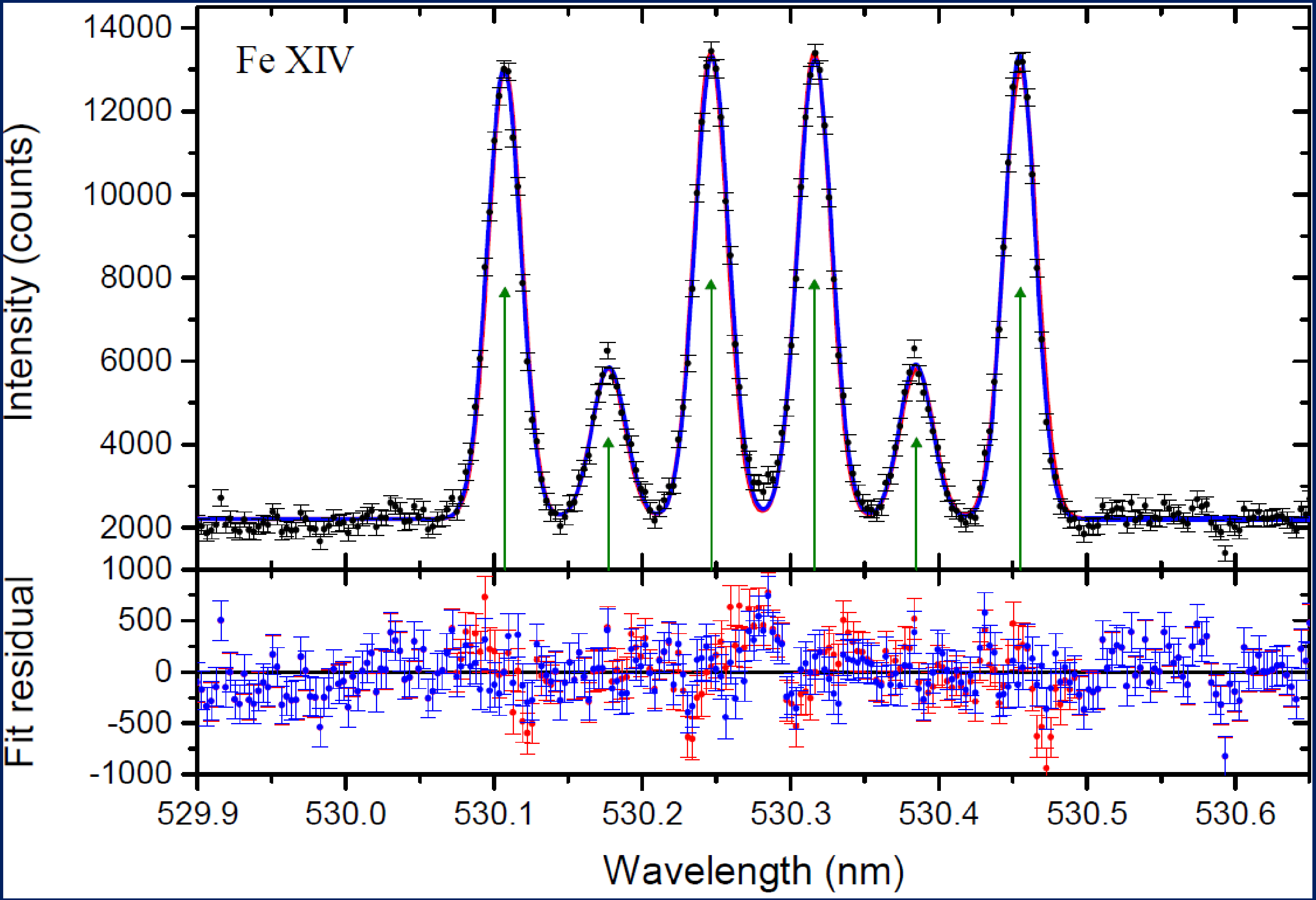
Under way in the spectral desert

- No reports about the ions of interest and no transition data available for most ions!
- HCI production in EBIT easy, identification much harder



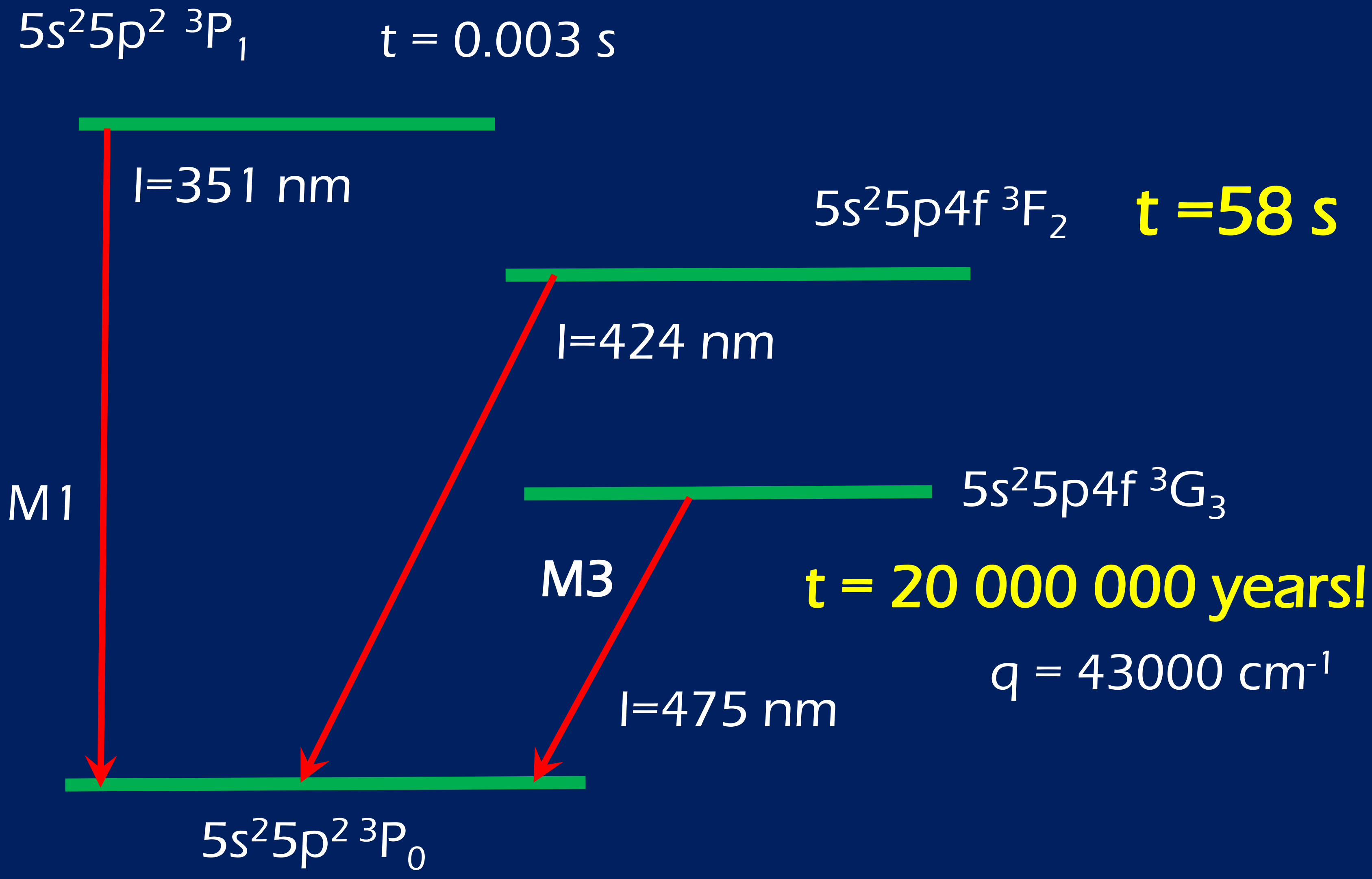
Color scale: Number of known transitions

Fe^{13+} (Fe XIV): the *"green coronal line"*



Hendrik Bekker, in preparation (for too long!)

Pr^{9+}: four valence electrons (Sn-like)



$5s^25p^2\ ^3P_1$ t = 0.003 s

l=351 nm

$5s^25p4f\ ^3F_2$ **t =58 s**

l=424 nm

M1

$5s^25p4f\ ^3G_3$

M3

t = 20 000 000 years!

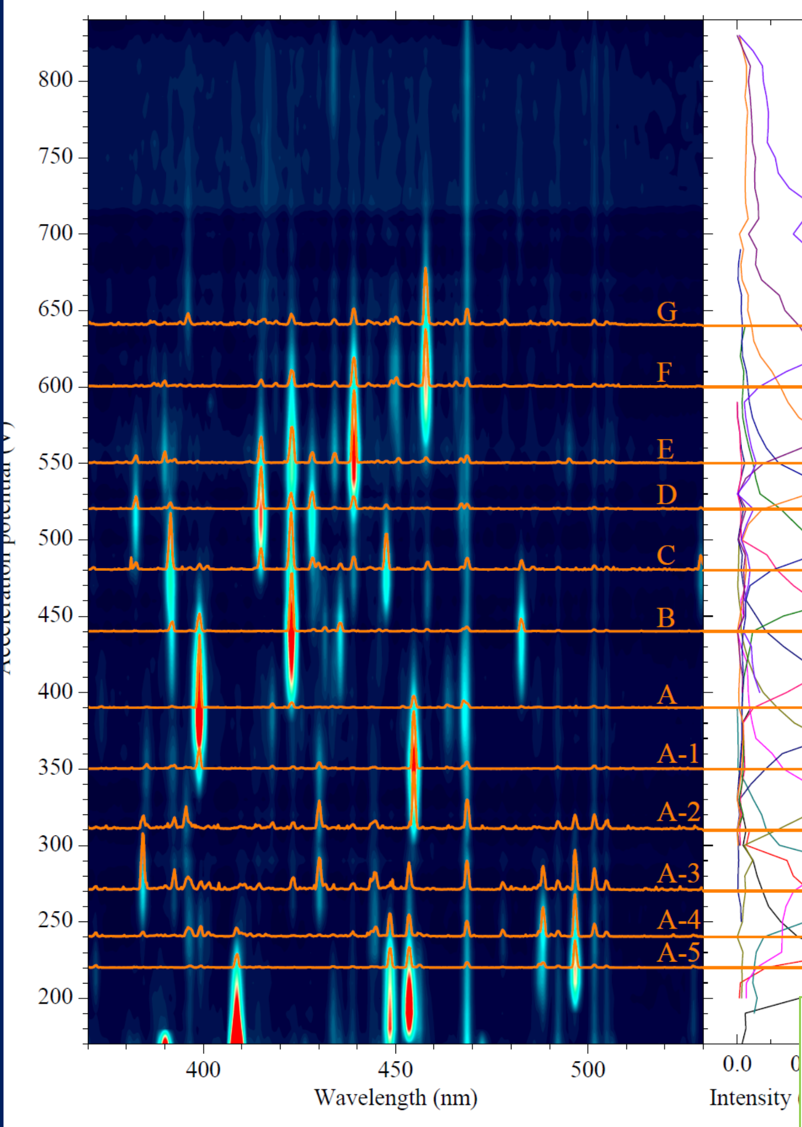
q = 43000 cm^{-1}

l=475 nm

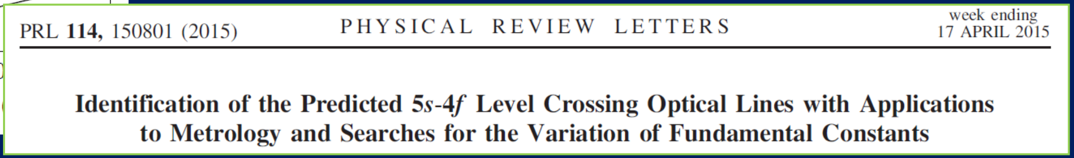
$5s^25p^2\ ^3P_0$

Courtesy of M. S. Safronova

Level crossings at Ir^{17+} provide α sensitivity



- At certain charge state levels change order
- *4f* goes below *5s* in Ir^{17+}
- Opposite parities degenerate: $4f^{12}\,5s^{2}$, $4f^{13}\,5s$, $4f^{14}$
- Many slow M1, E1, E2, M2, M3 transitions become possible
- Several long lived „ground states“ available

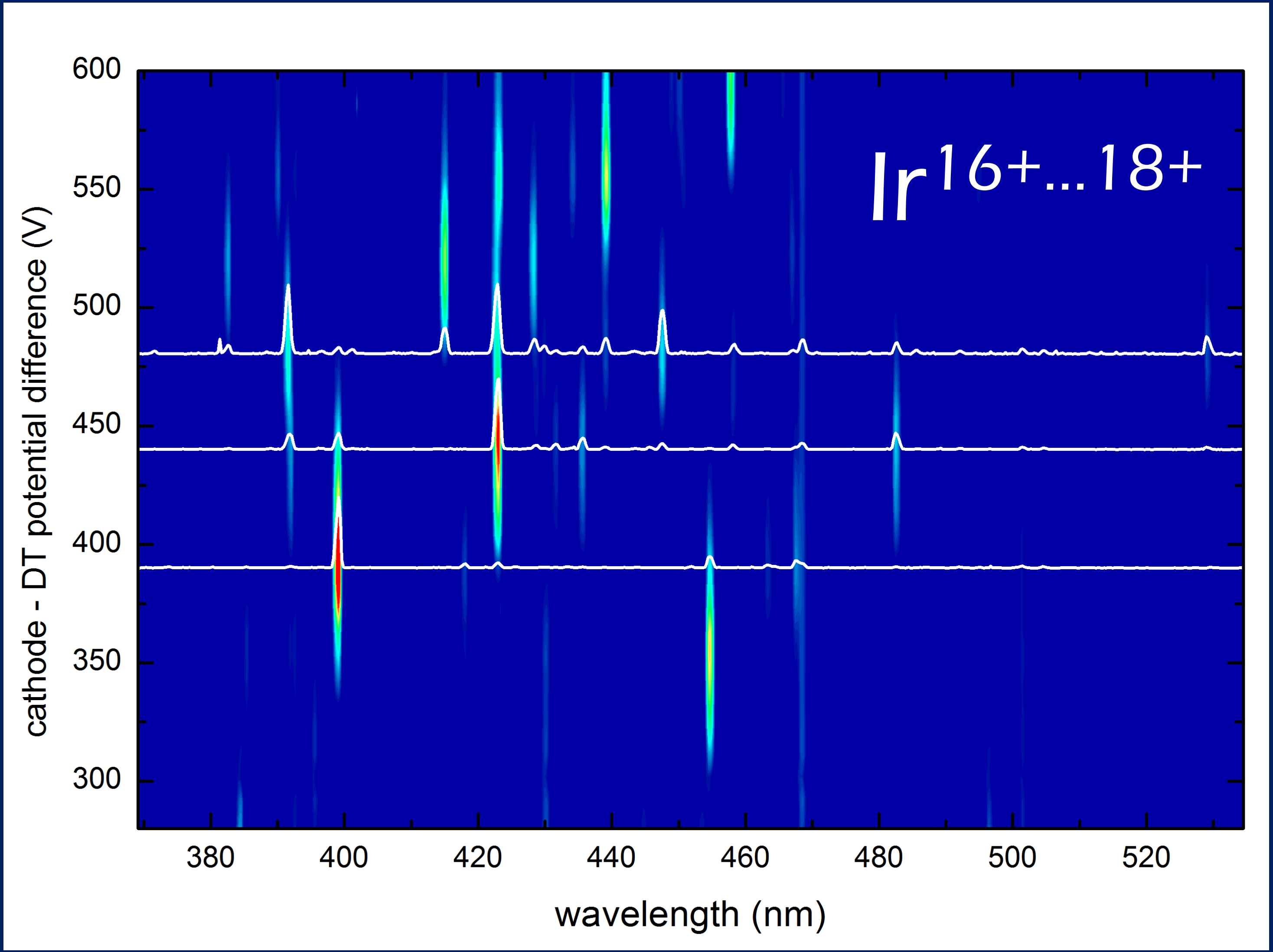


PRL **114,** 150801 (2015) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2015

Identification of the Predicted 5*s*-4*f* Level Crossing Optical Lines with Applications to Metrology and Searches for the Variation of Fundamental Constants

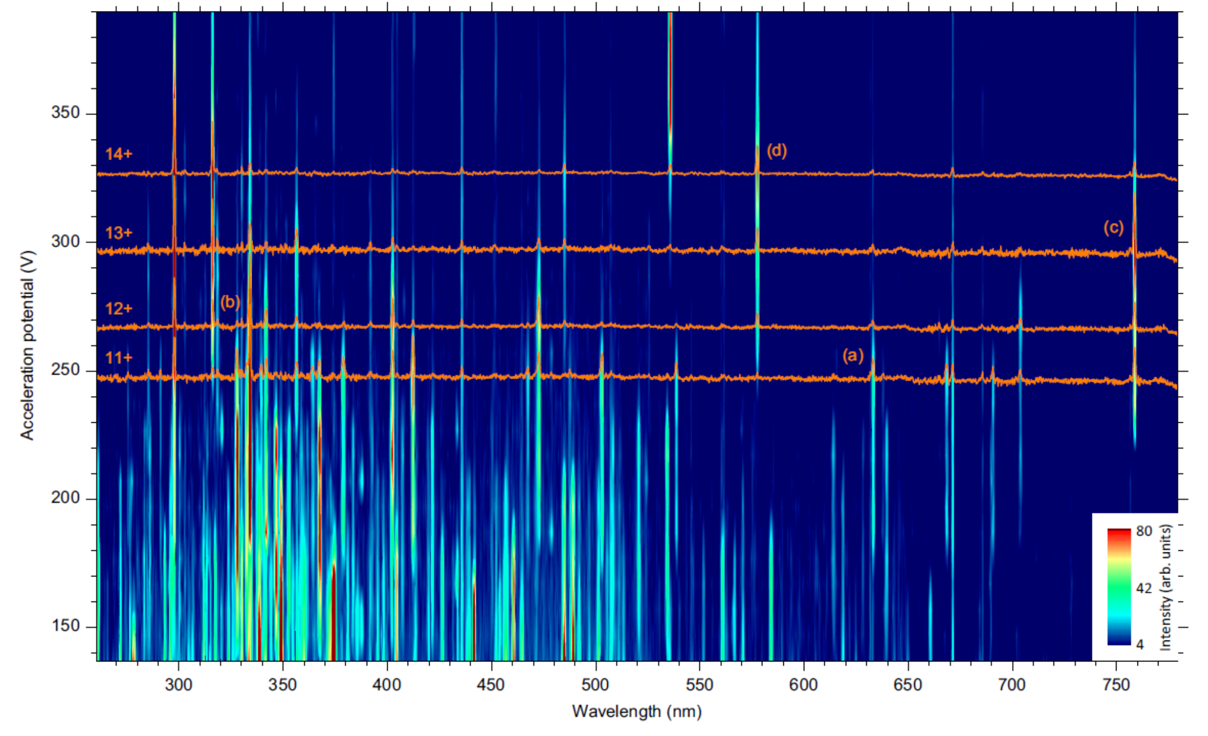
Windberger et al., PRL **114**, 150801 (2015)

Visible spectra of M1 lines in Ir ions



First observations; line identification difficult

Application to Sn HCI for EUV nanolithography



Collaboration ARCNL: EUV light-sources for nanolithography (ASML)

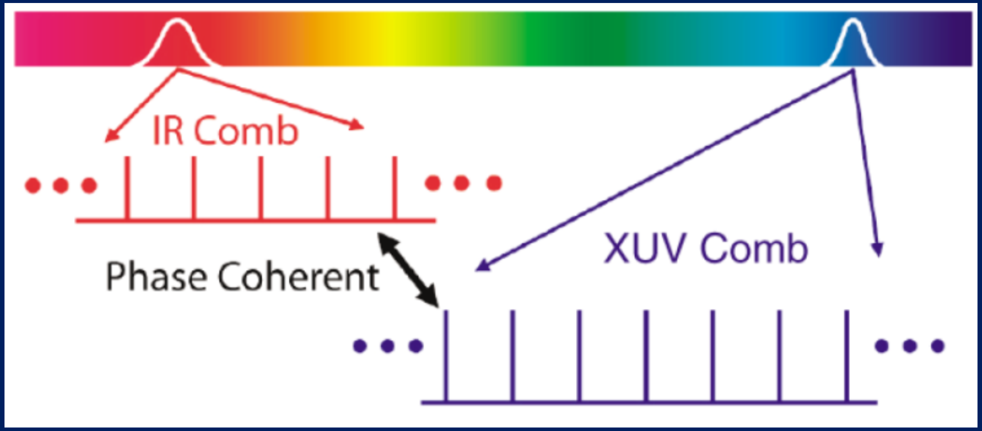
Analysis of the fine structure of Sn^{11+} – Sn^{14+} ions by optical spectroscopy in an electron-beam ion trap, A. Windberger…, JRCLU et al., PRA 94, 012506 (2016)

Identifications of and EUV transitions of promethium-like Pt, Ir, Os and Re
H. Bekker, …, JRCLU et al., J. Phys. B 48, 144018 (2015)

Optical spectroscopy of complex open 4d-shell ions Sn^{7+}-Sn^{10+}
F Torretti, …, JRCLU et al., arXiv:1612.00747, accepted, Phys. Rev. A

Towards ultra-high precision spectroscopy in the ultraviolet regime (XUV)

- Use HHG as light source for spectroscopy in XUV
- Coherently transfer comb modes from IR to XUV
- Perform direct frequency comb spectroscopy (DIFCOS)



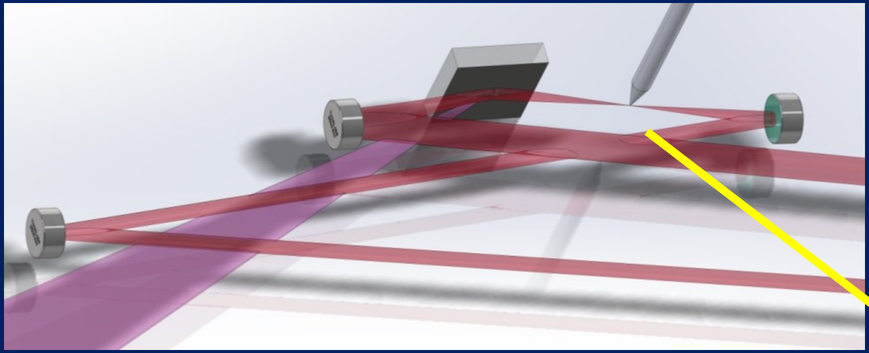
- Challenge: Obtain enough intensity in XUV

→ use enhancement cavity

A Cingöz et al. Nature 482, 68-71 (2012)
R. Jason Jones et al. Phys. Rev. Lett. 94, 193201 (2005)

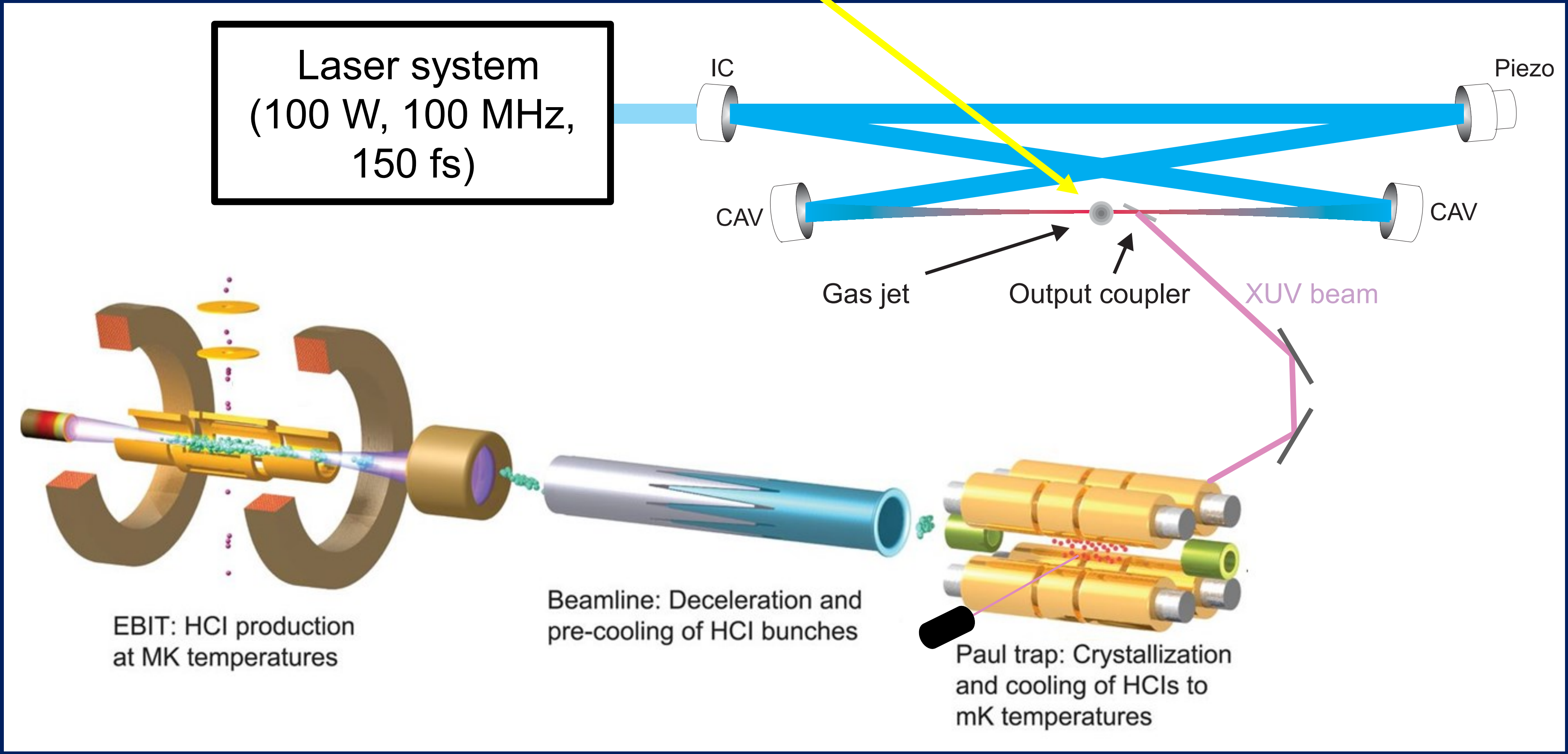
Experiment by Janko Nauta
and Andrii Borodin, MPIK

High harmonics and HCI

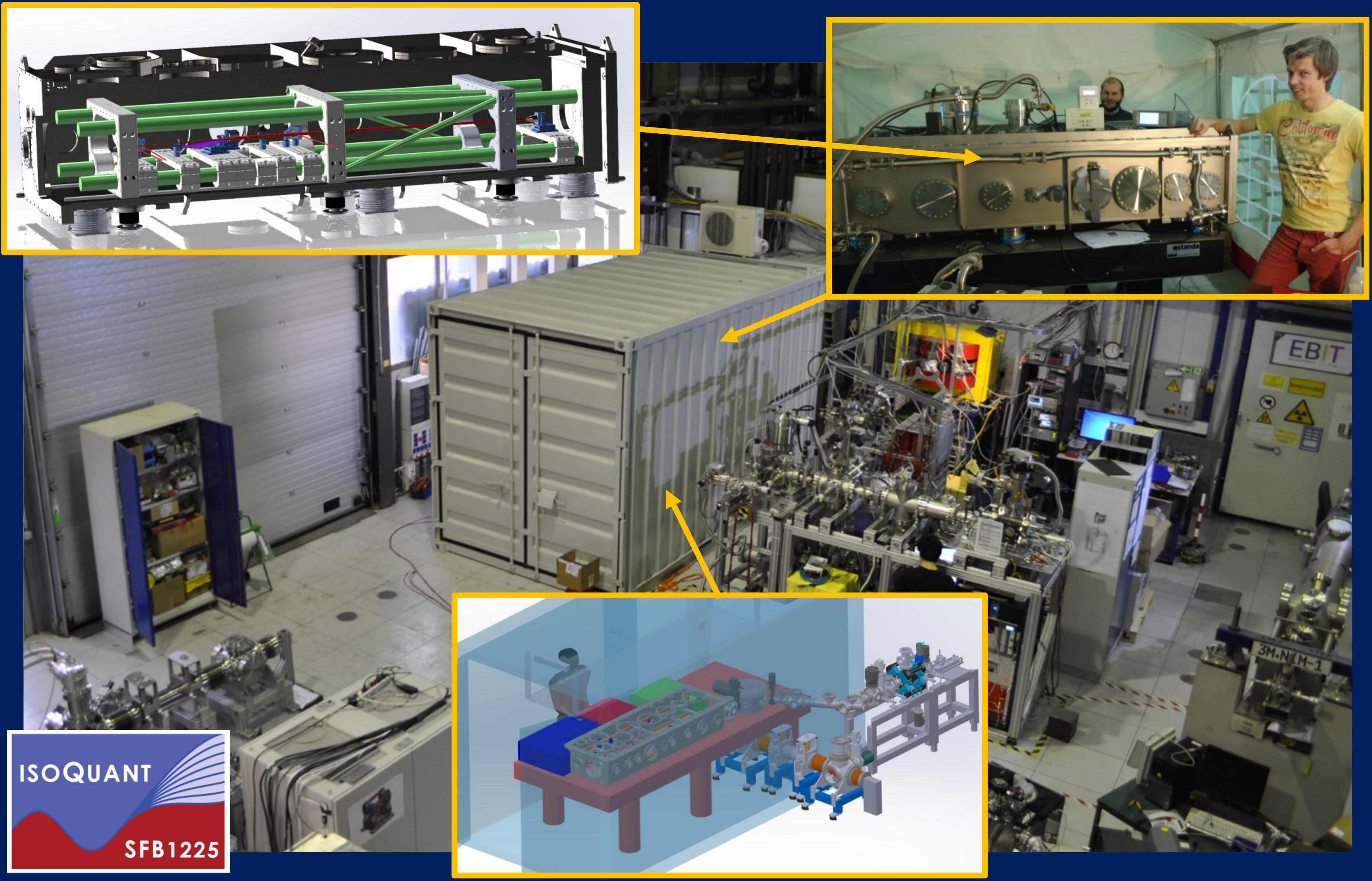


VUV frequency comb

- in-vacuo enhancement cavity
- in 15 µm focus ≈ 10^{13} W/cm^2
- 100 MHz repetition rate
- Under development



Temperature-controlled container for HHG-frequency comb



ISOQUANT SFB1225

Summary

- HCI are ultra-stable, universal and reproducible probes of fundamental physics with effects magnified by *Z*-scaling laws

- Insights into QED, relativistic as well as nuclear interactions and few-electron correlations in “tunable” admixtures

- Laboratory benchmarks for interpreting astrophysical X-ray observations

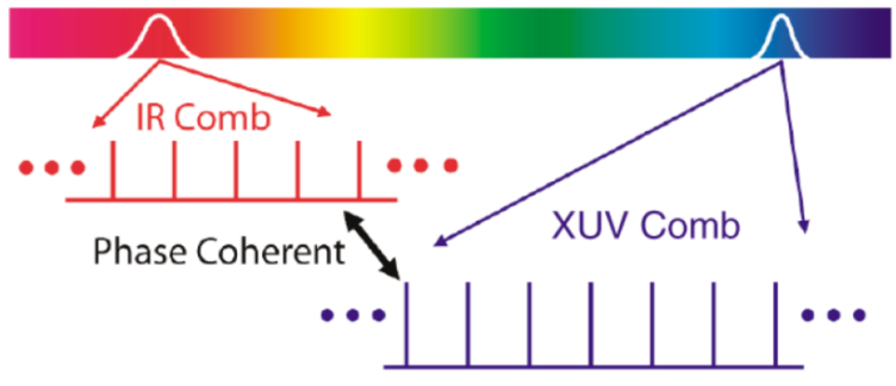
- HCI frequency metrology enabled by sympathetic cooling

- Optical clocks for studies of e. g., α variation, Lorentz invariance benefit from insensitivity of HCI to perturbations

- Extending frequency metrology to the high-energy photon range with HCI is a promising perspective

Towards ultra-high precision spectroscopy in the ultraviolet regime (XUV)

- Use HHG as light source for spectroscopy in XUV
- Coherently transfer comb modes from IR to XUV
- Perform direct frequency comb spectroscopy (DIFCOS)



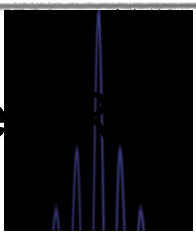
- Challenge:
  - Obtain enough intensity in XUV

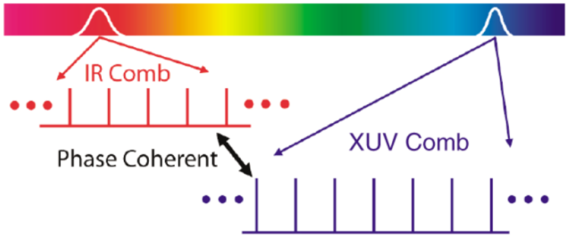
  → use enhancement cavity

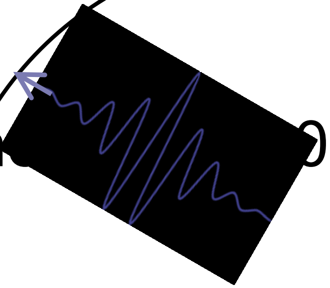
A Cingöz et al. Nature 482, 68-71 (2012)
R. Jason Jones et al. Phys. Rev. Lett. 94, 193201 (2005)

HHG: high harmonic generation

- Transfe[illegible]ht to UV light

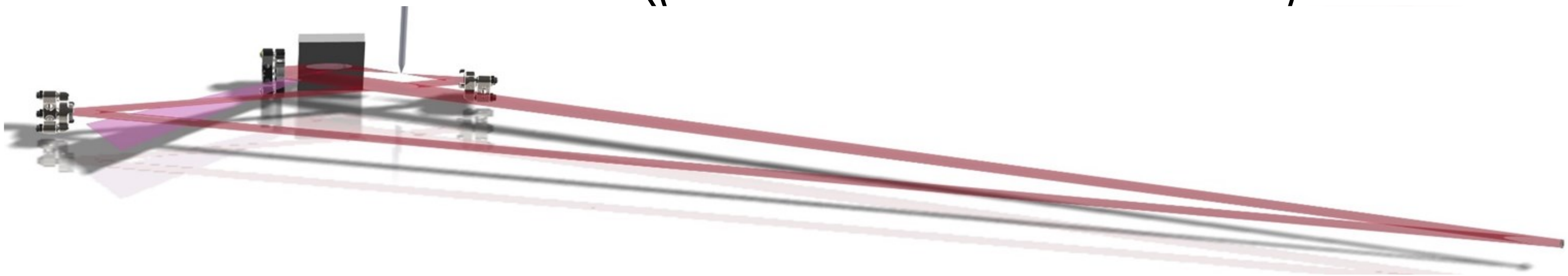






- But very high intensity n[illegible]0^{13} W/cm^{2}!

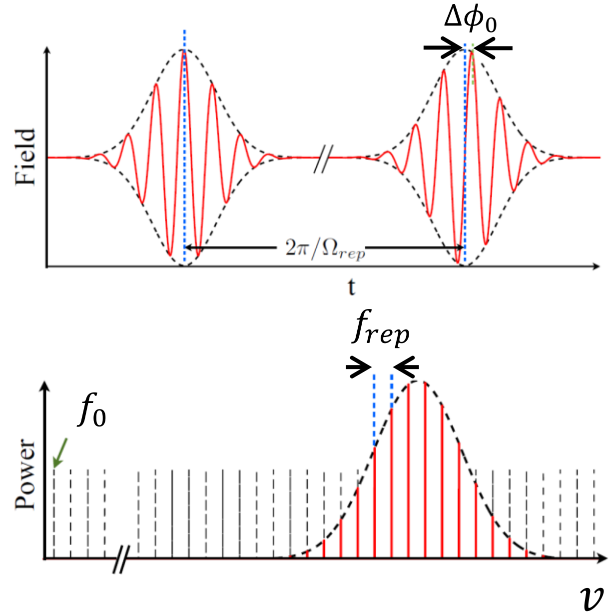
→ *use enhancement cavity to amplify pulses*



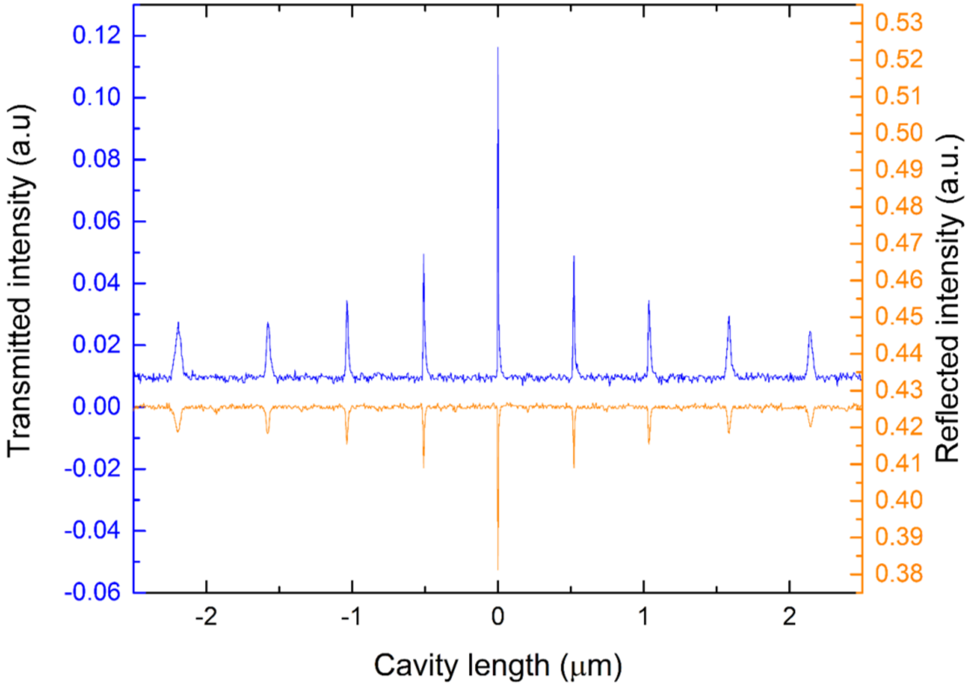
A Cingöz *et al. Nature* **482**, 68-71 (2012) doi:10.1038/nature10711

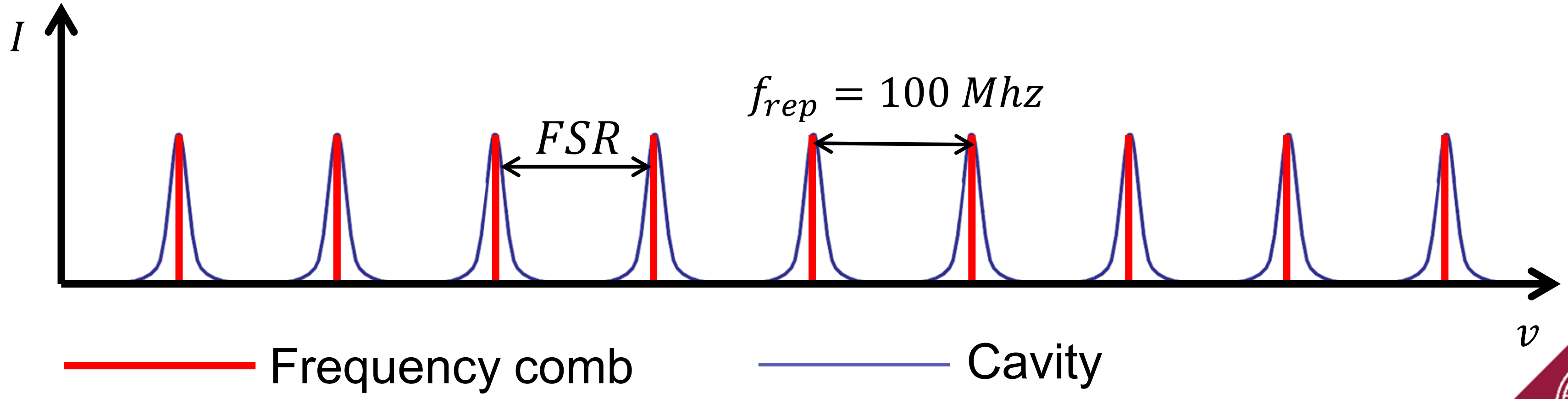
Frequency comb in optical cavity

QUANTUM DYNAMICS

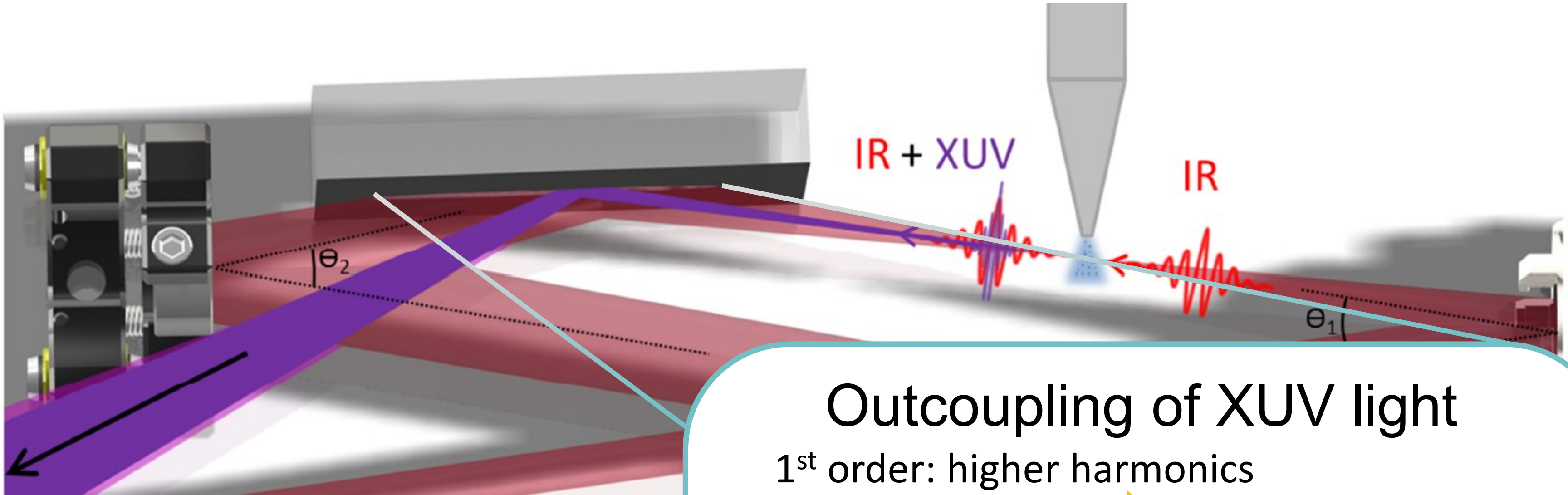


$$f_n = f_0 + n \cdot f_{rep}$$





Design of enhancement cavity



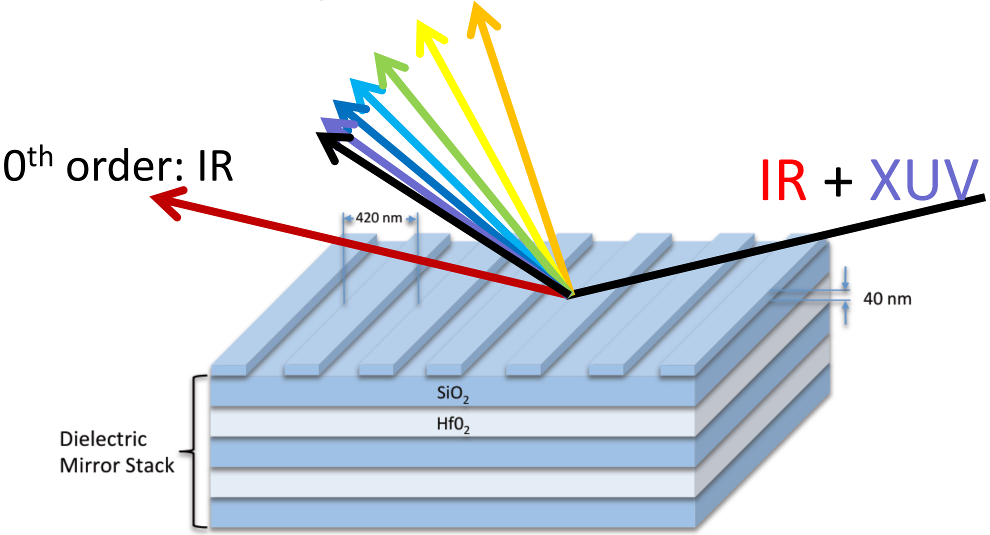
- Feed target gas at cavity focus
- Tight focus enables HHG
- High harmonics are coupled out via grating
- XUV light available for ultra-high precision metrology

D. C. Yost *et al.* Opt. Lett. **33**, 1099-1101 (2008)

Outcoupling of XUV light

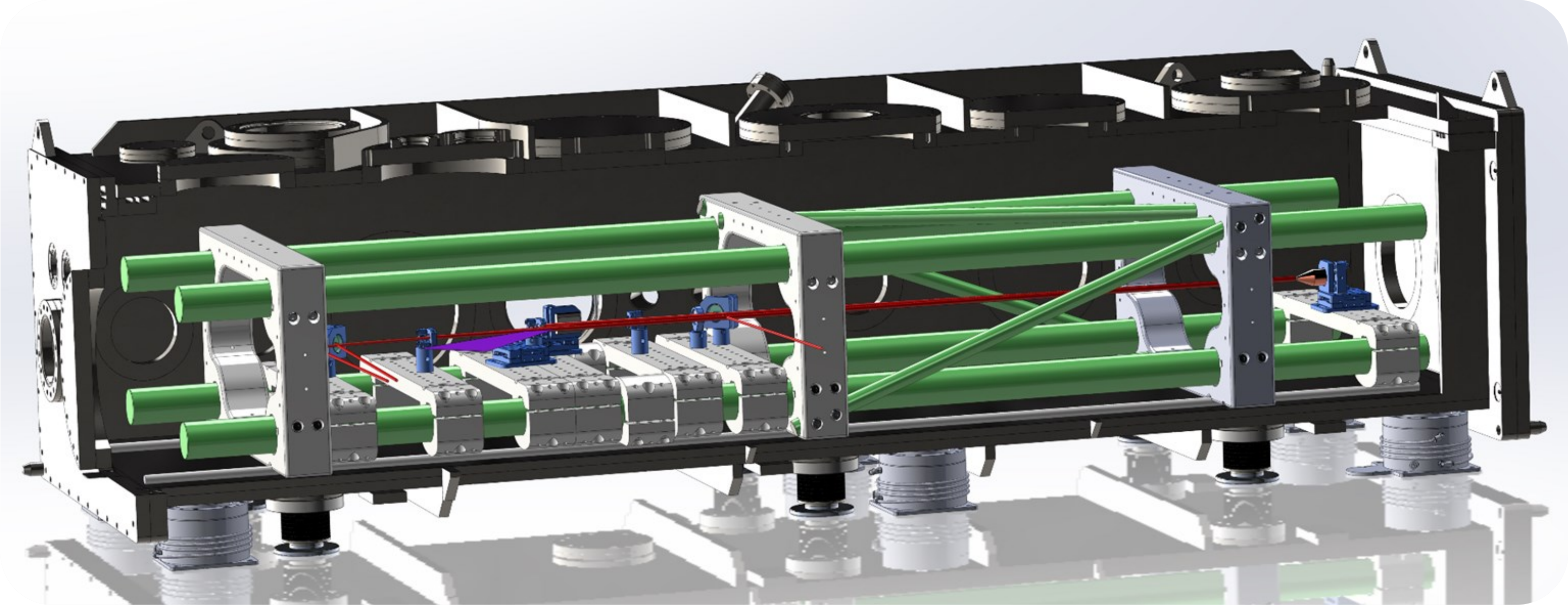
1st order: higher harmonics

0th order: IR

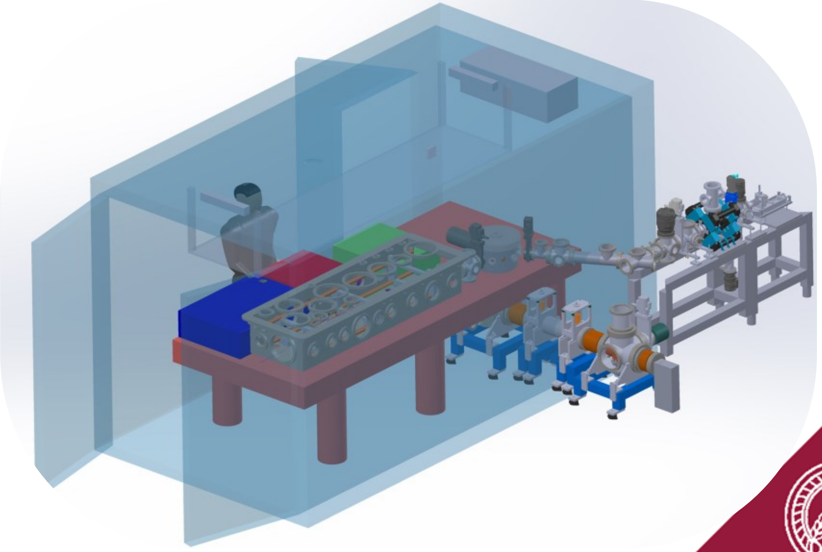


small period, shallow diffraction grating separates XUV from IR

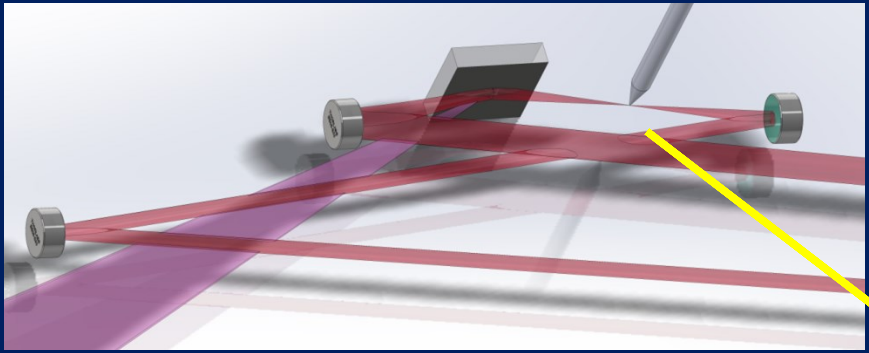
Experimental setup



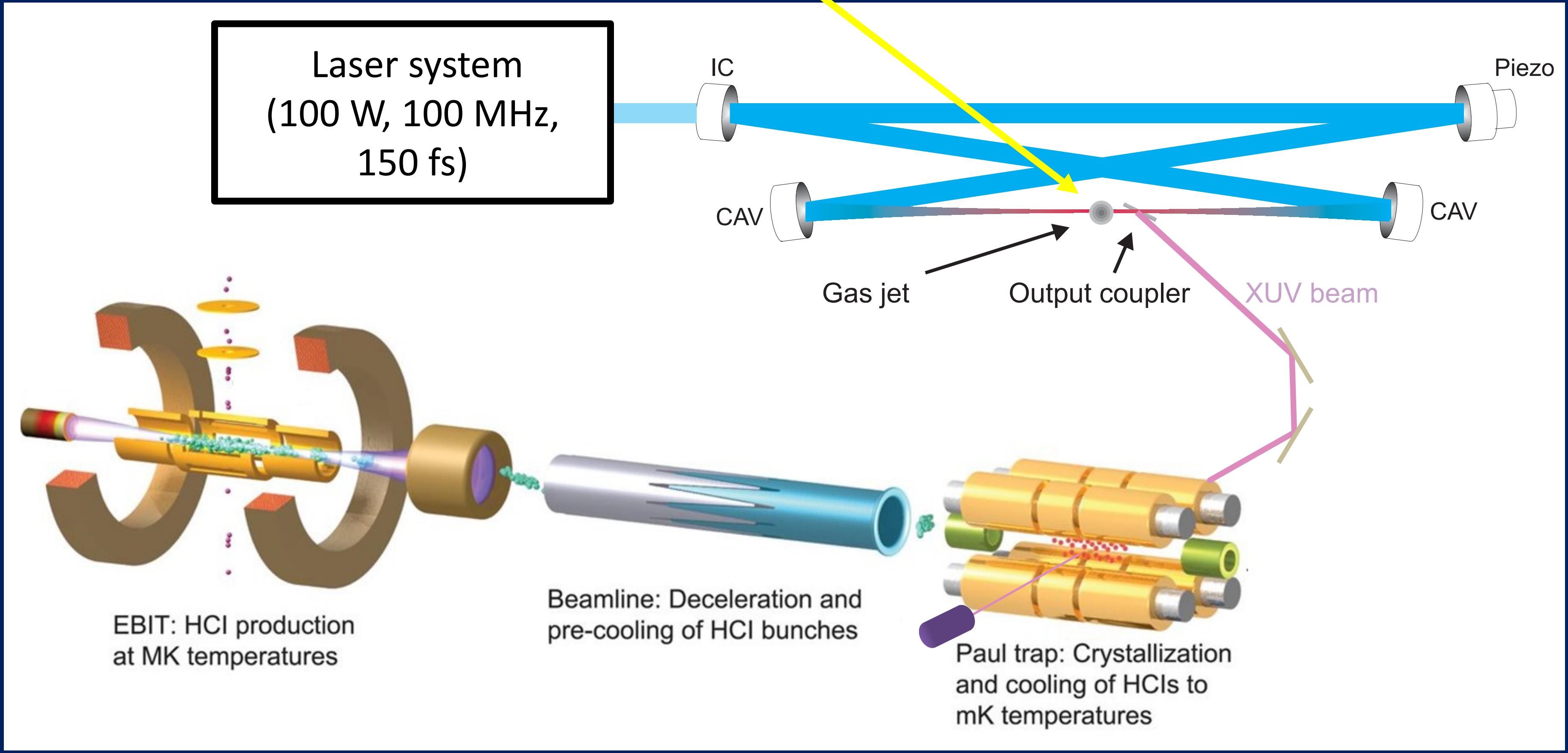
- Highly stable, vibration-free mounting of cavity optics in vacuum
- Frequency comb and Paul trap inside thermally and acoustically isolated container
- 100 Watt amplifier stage for reaching higher intensities



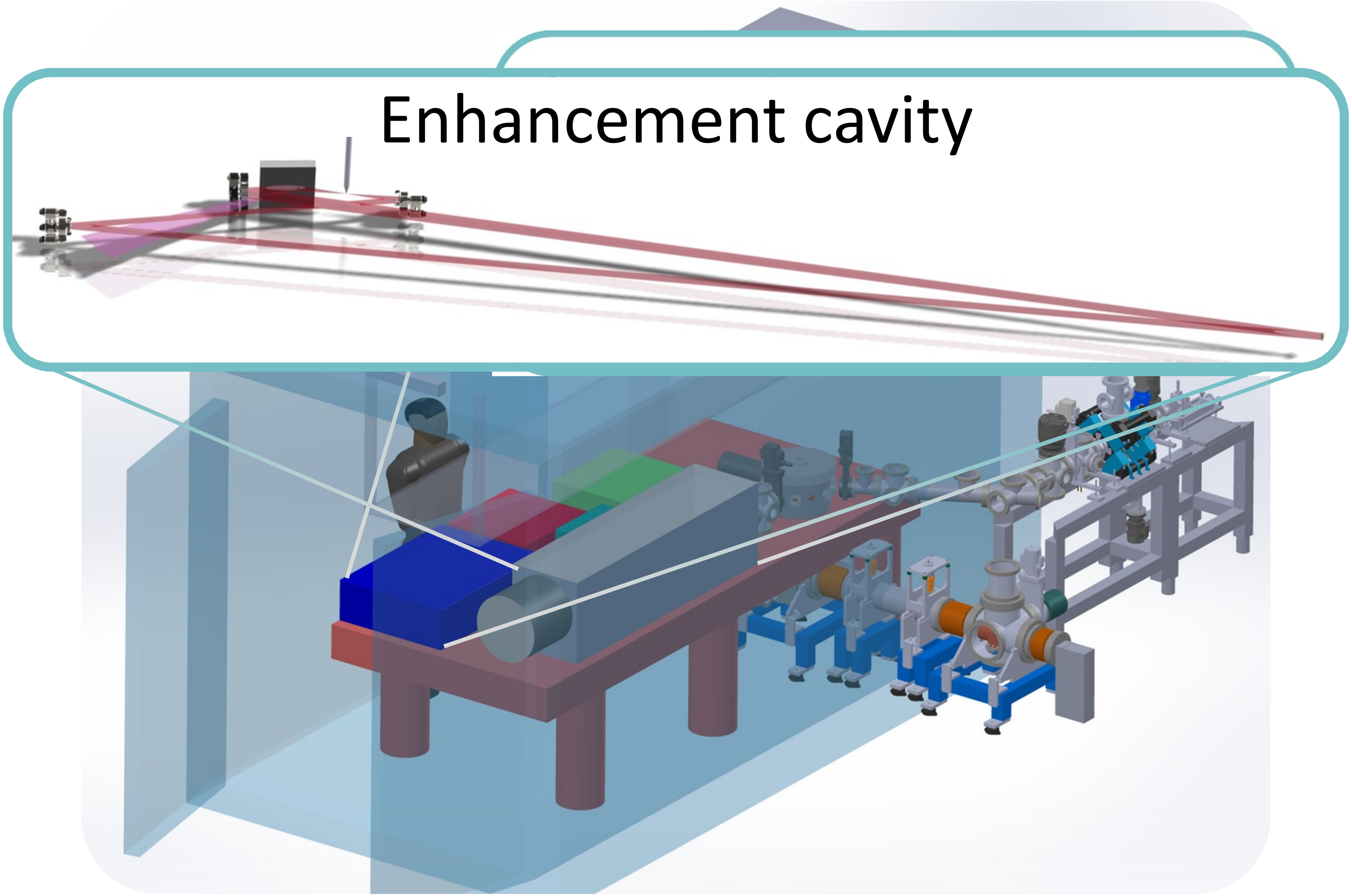
High harmonics and HCI



VUV frequency comb
- in-vacuo enhancement cavity
- in 15 µm focus ≈ 10^{13} W/cm^2
- 100 MHz repetition rate
- Under development

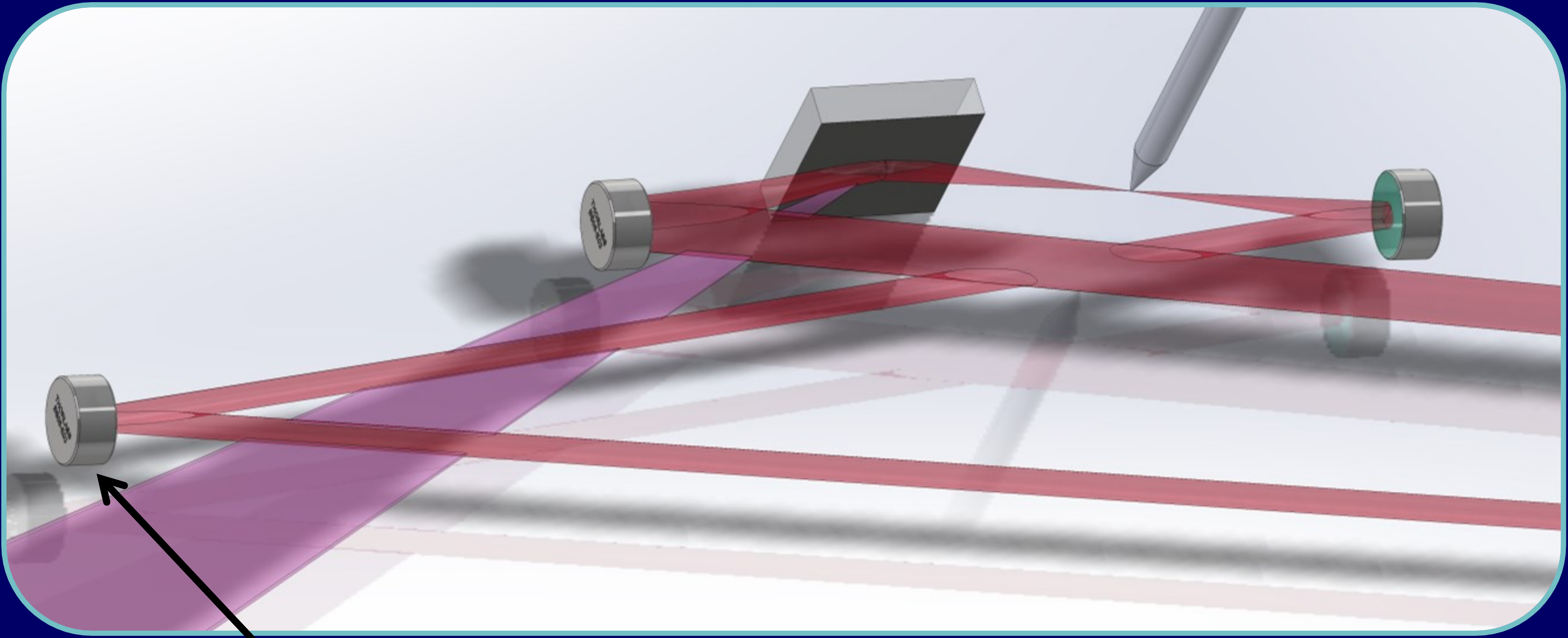


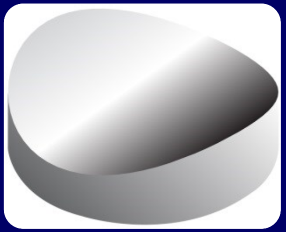
Experimental overview



Enhancement cavity

Design of HHG focus

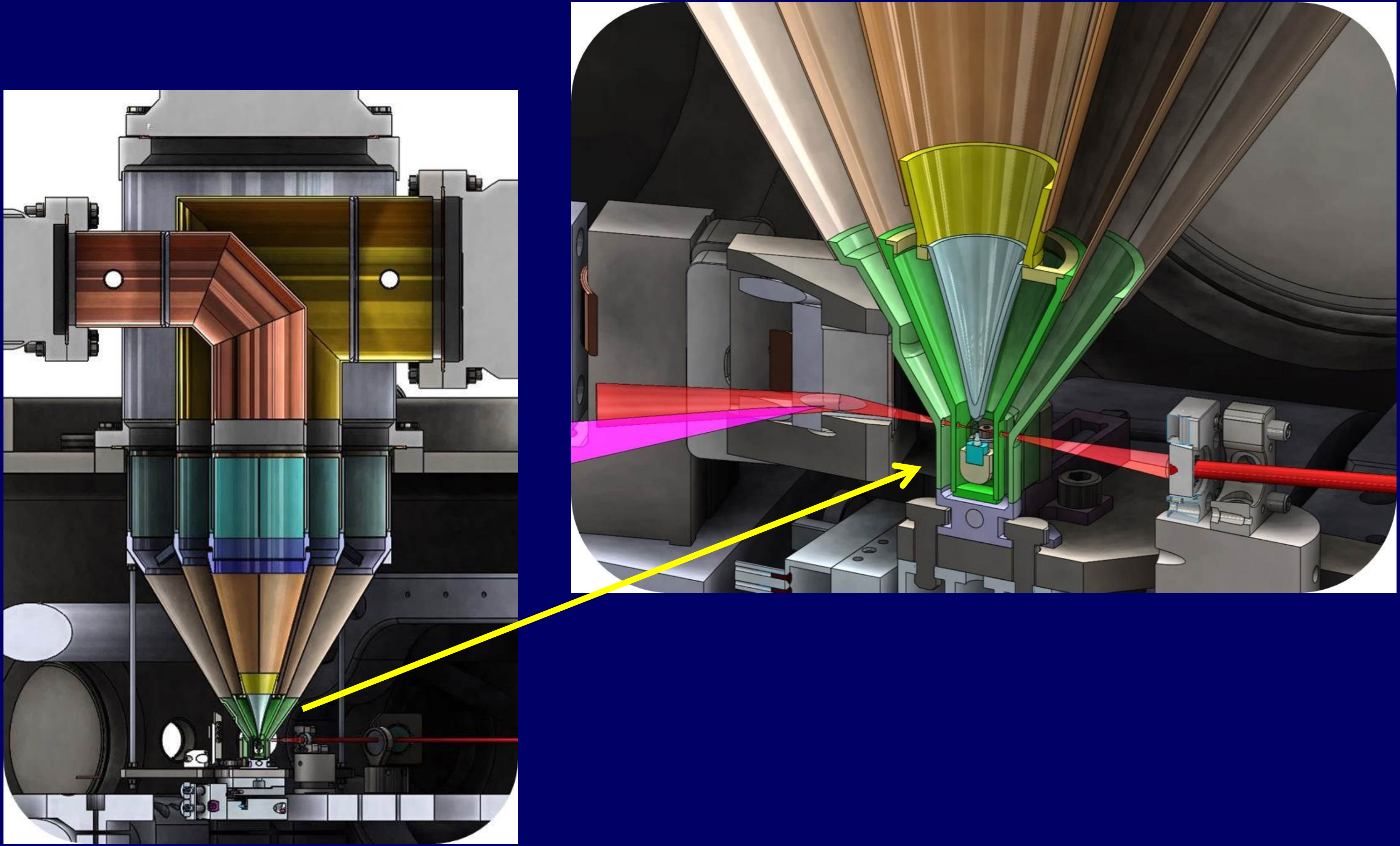




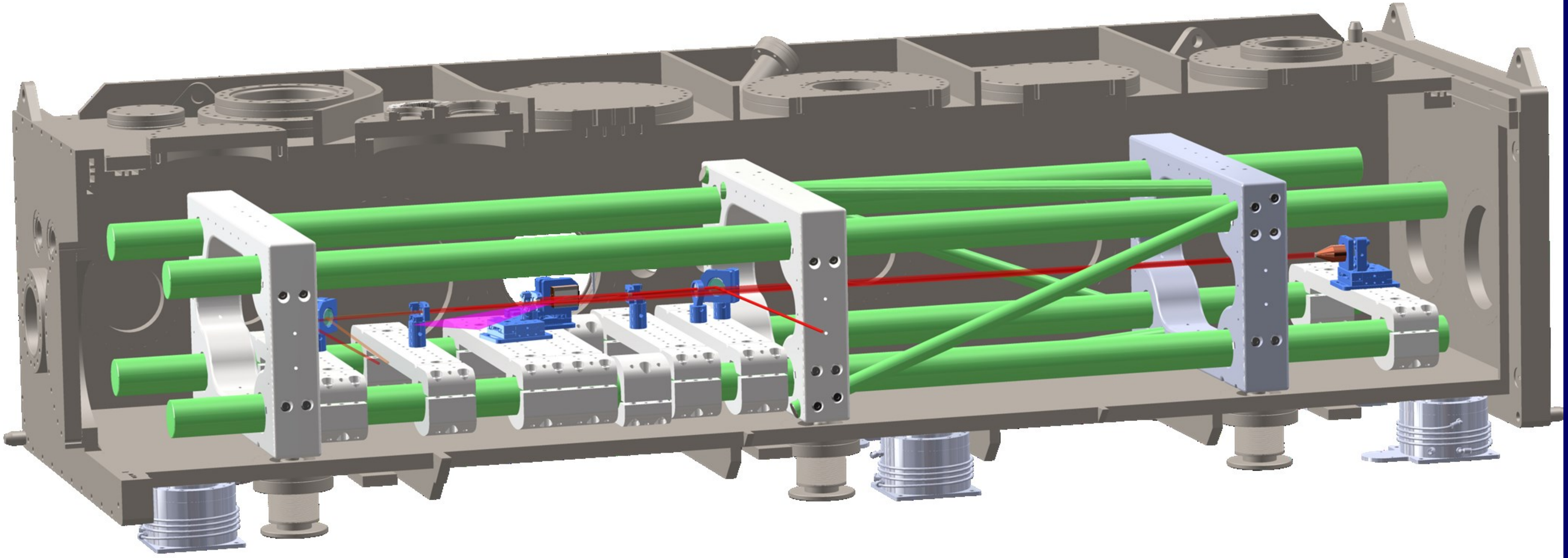
Idea: use cylindrical incoupling mirror to compensate astigmatism around focus region

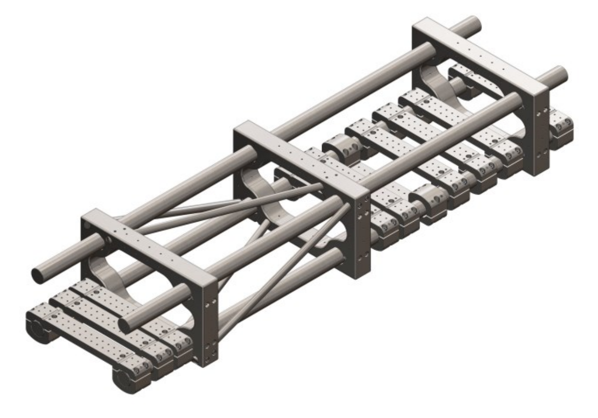
Focus ≈ 15 µm
At 10 W with enhancement ≈ 10^{13} W/cm^2

Design of HHG focus

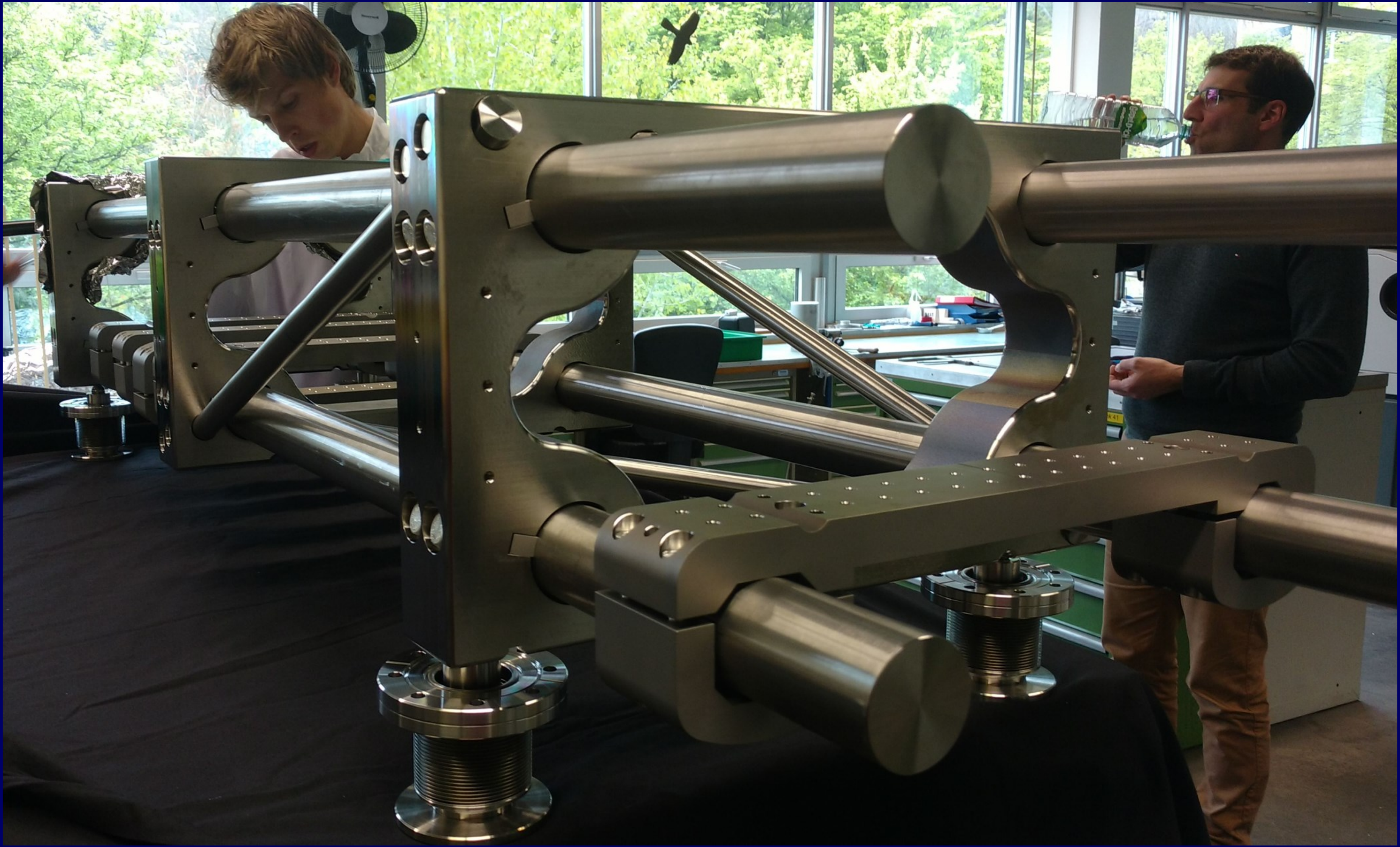


UHV, high-stiffness optical enhancement cavity

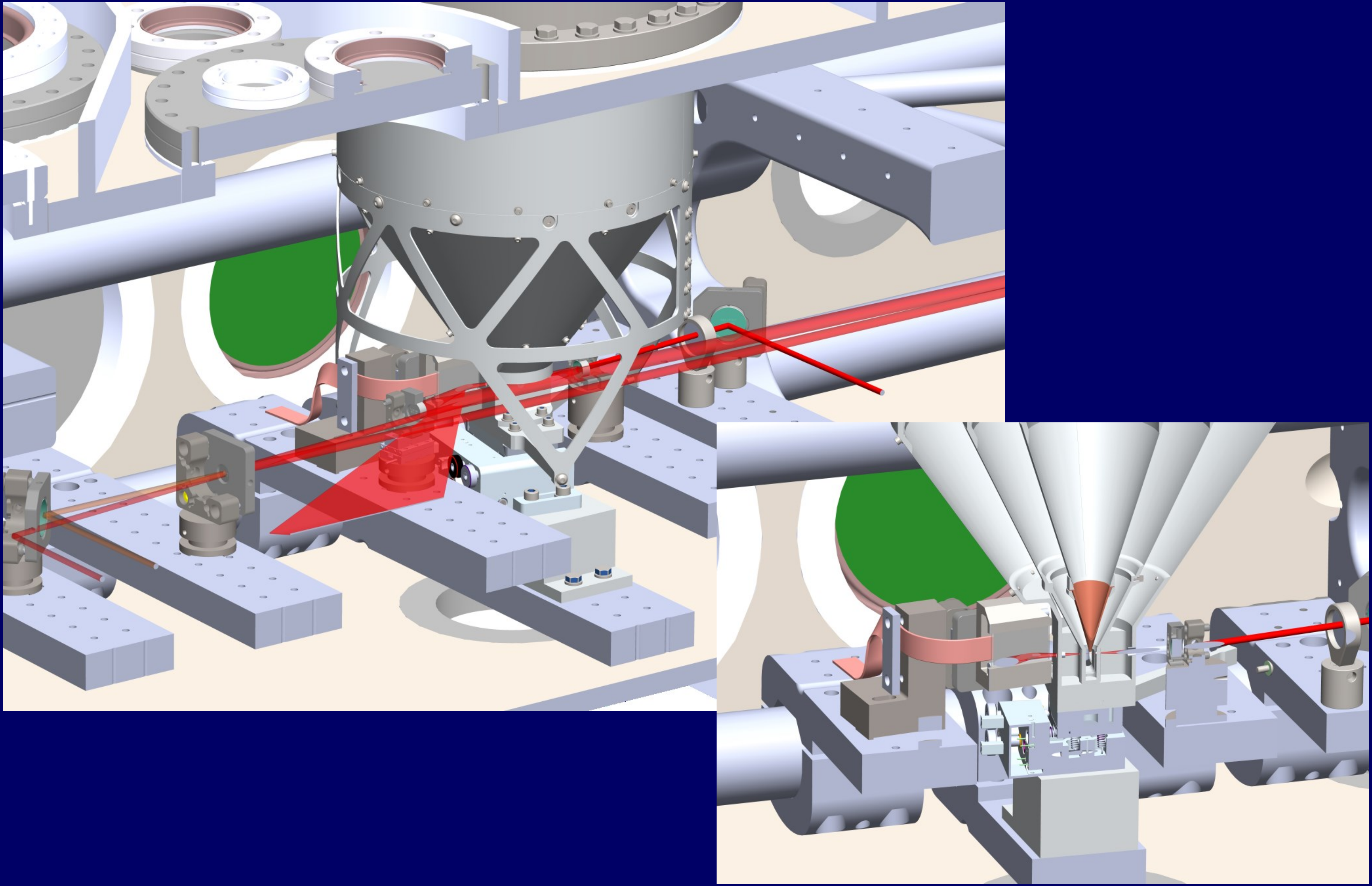




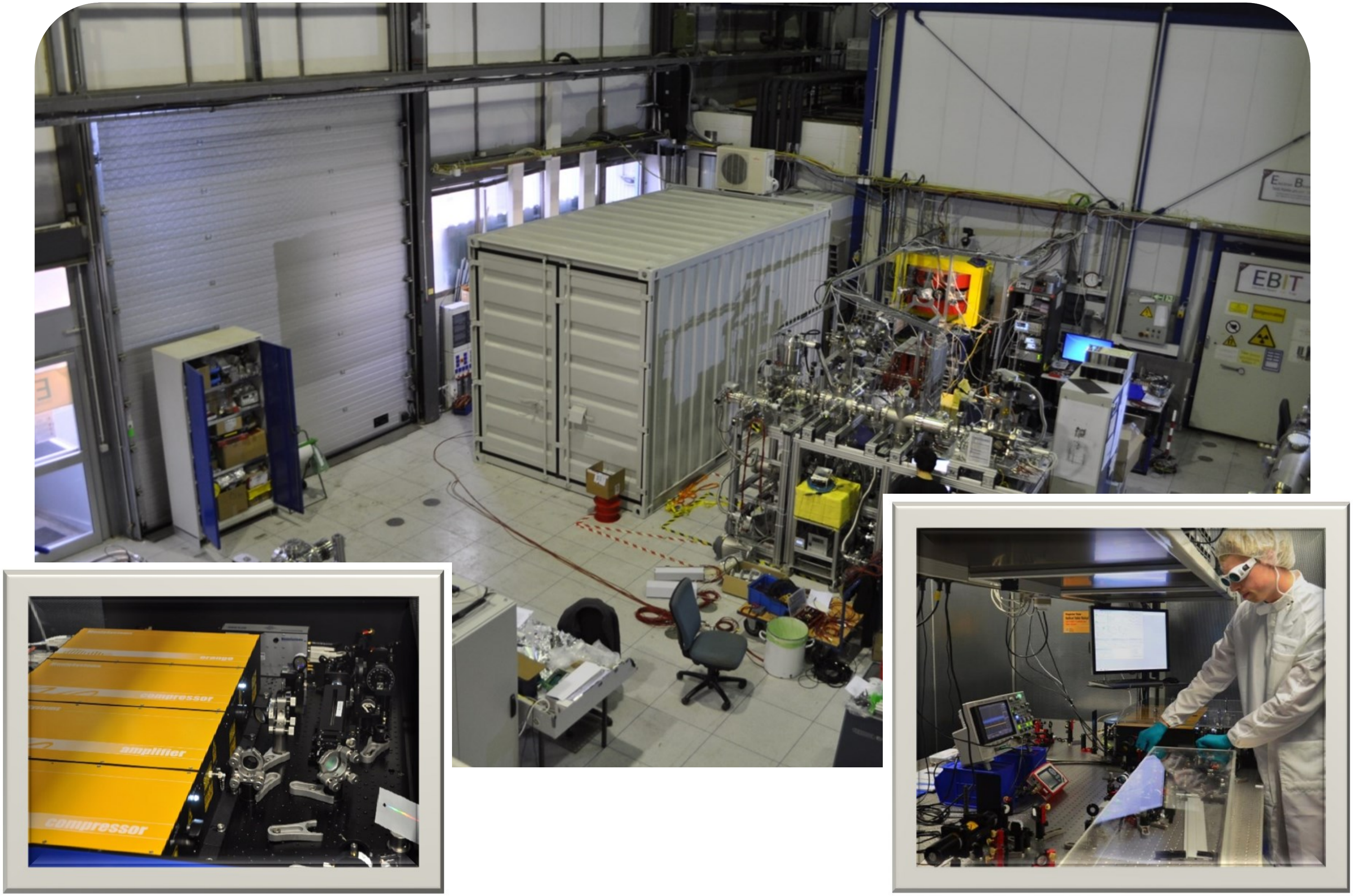
UHV, high-stiffness optical enhancement cavity



Design of HHG focus

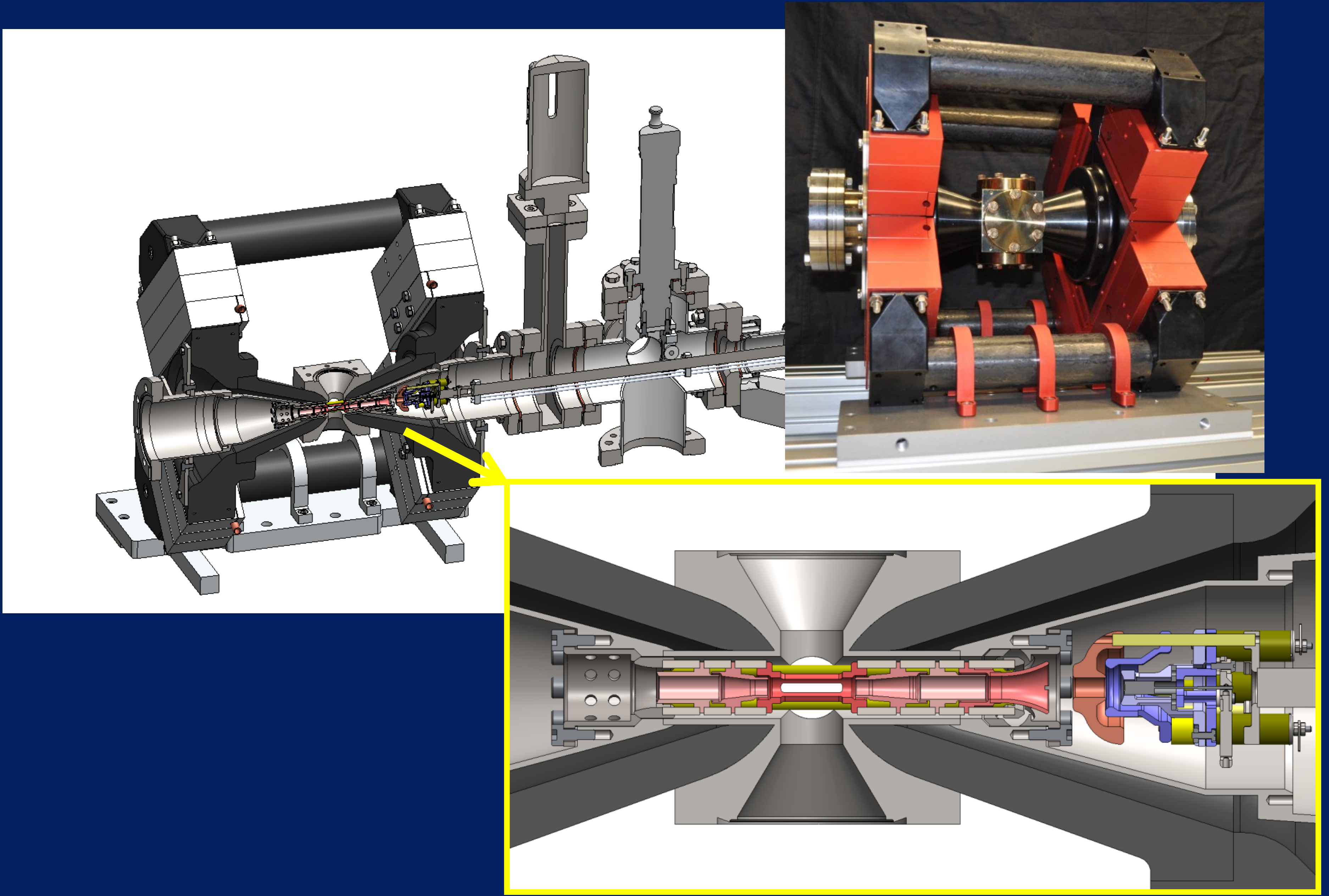


Status & Outlook



Status & Outlook

A table-top EBIT for PTB



Possibilities through frequency metrology

- Whole new class of laser-accessible targets, with *Z* and ionic charge as parameters
- Great variety of optical and EUV lines from fine and hyperfine transitions up to the highest charge states
- Stable up to X-ray region
- Forbidden transitions suitable as frequency standards
- Low sensitivity to DC, AC Stark, Zeeman and blackbody shifts
- Highest sensitivity to fine-structure constant α in atomic systems

Summary

- Spectroscopy of HCI in EBITs has suffered from high ion translational temperatures in the MK range.

- CryPTEx is a linear RF trap to simultaneously confine Be^+ cooling ions and HCI extracted from an EBIT.

- HCI implantation into Coulomb crystal is observed by imaging the crystal and determining the ion-ion separation and the motional excitation frequencies.

- Sympathetic laser cooling already brings HCI from 1 MK to 100 mK temperature, and possibly below.

- New oportunities for optical clocks and fundamental studies due to their insensitivity to perturbations.

Current developments for frequency metrology at MPIK.

- Table-top EBIT for PTB experiments
- CryPTEx-II, a cryogenic Paul trap with vibration suppression for quantum logic at PTB.
- High Q-value (superconducting) RF resonator for a HCI Paul trap.
- High-harmonic frequency comb for the VUV range.

MPIK

Lisa Schmöger, Oscar O. Versolato, Maria Schwarz, Janko Nauta, A. Borodin, Julian Stark, F. Brunner, S. Feuchtenbeiner, B. Piest, Hendrik Bekker, Alexander Windberger, E. Peper, Peter Micke, Steffen Kühn, Sven Bernitt, I. I. Draganic, A. Lapierre, R. Soria Orts, JRCLU, T. Pfeifer

PTB

Piet O. Schmidt, Tobias Leopold, Matthias Kohnen, Joachim Ullrich

UNSW

Julian Berengut

Aarhus University

Michael Drewsen, L.Klosowski, A. Gingell, A. K. Hansen

MAX-PLANCK-GESELLSCHAFT

PTB

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DEPARTMENT OF PHYSICS
AND ASTRONOMY
FACULTY OF SCIENCE
AARHUS UNIVERSITY