Electron beam ion traps at and from MPIK

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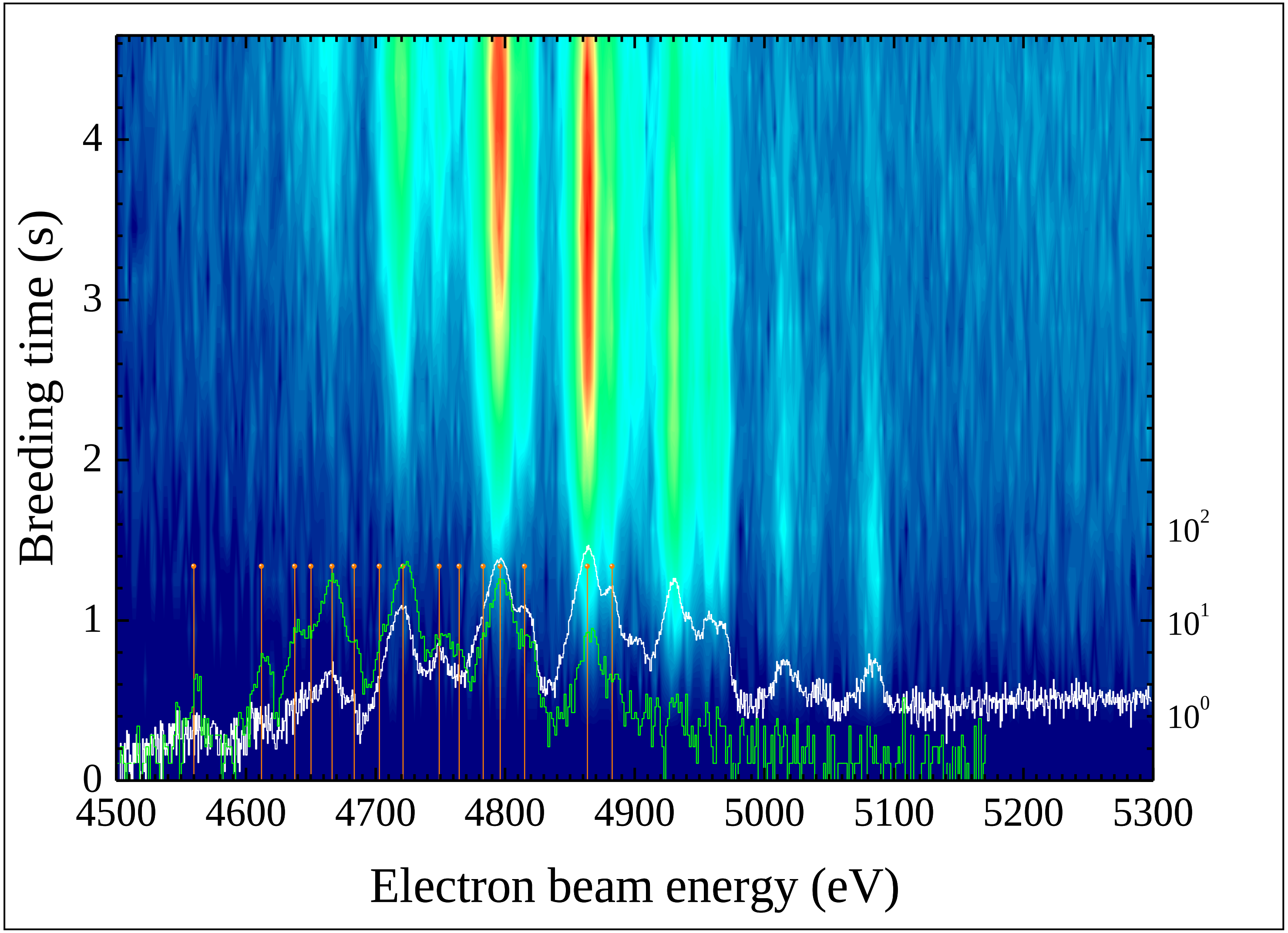
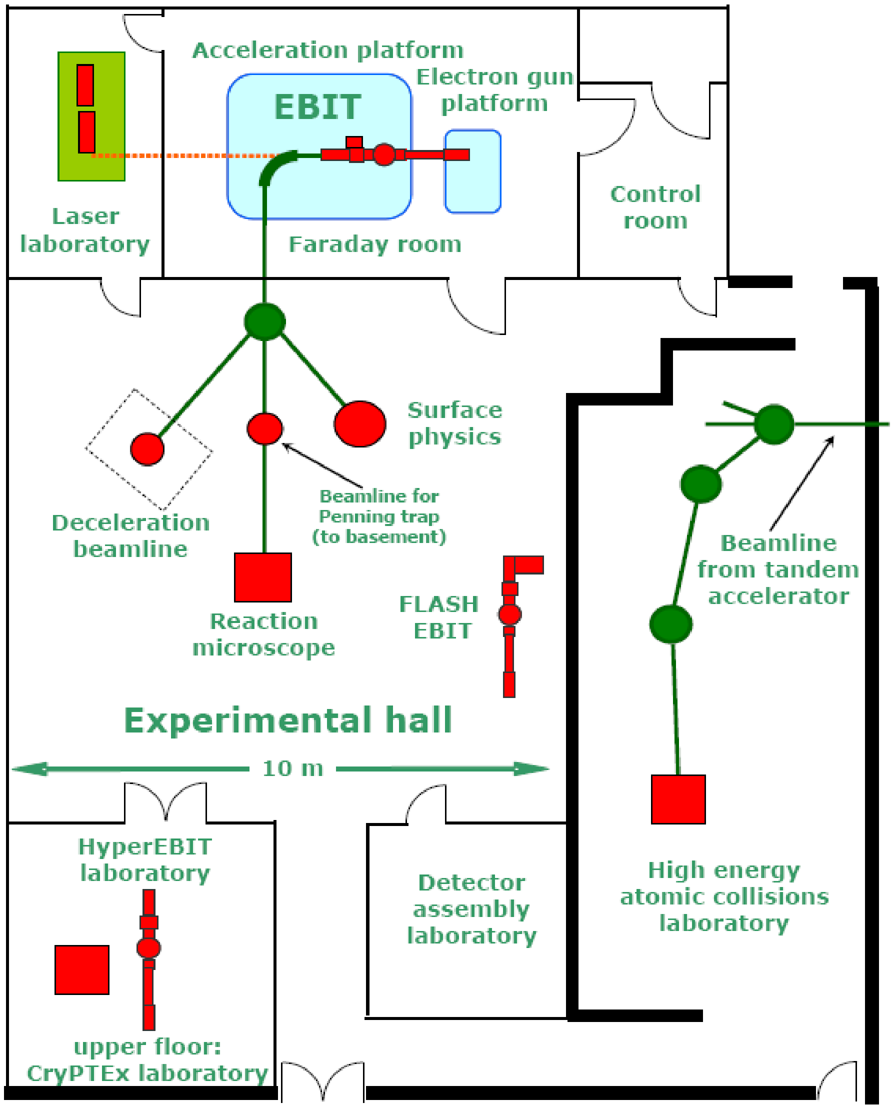
Max Planck Institute for Nuclear Physics
Heidelberg

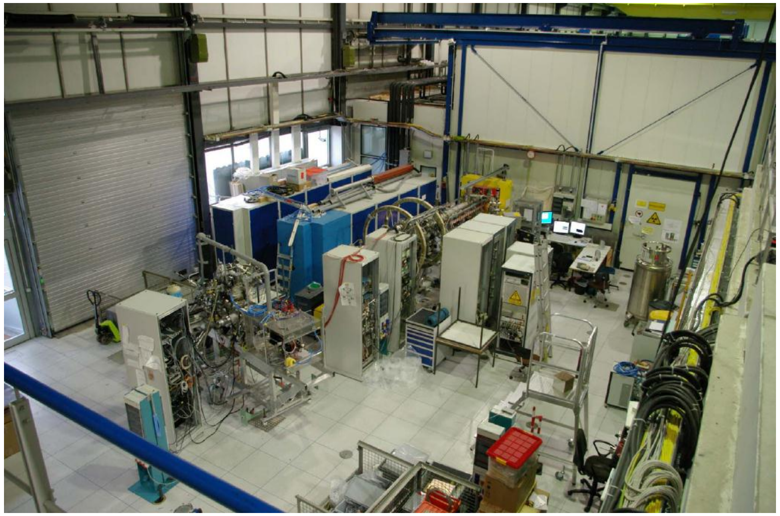
EBITs are versatile sources



Ions in any desired charge state can be prepared, stored and studied

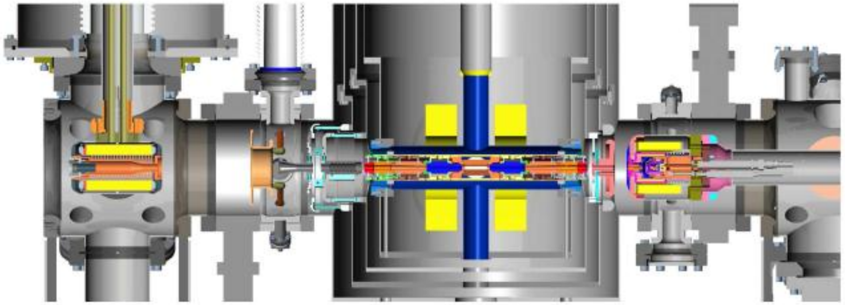
EBIT facility in Heidelberg



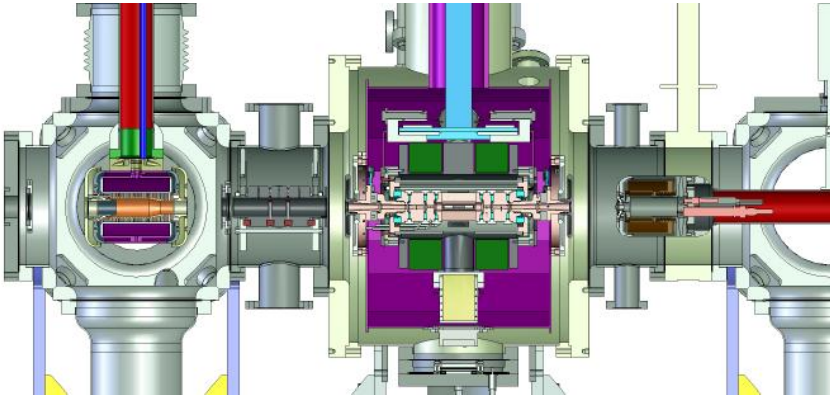


Electron beam ion traps at MPIK

- HD EBIT: stationary machine built in 1999 (former FreEBIT)



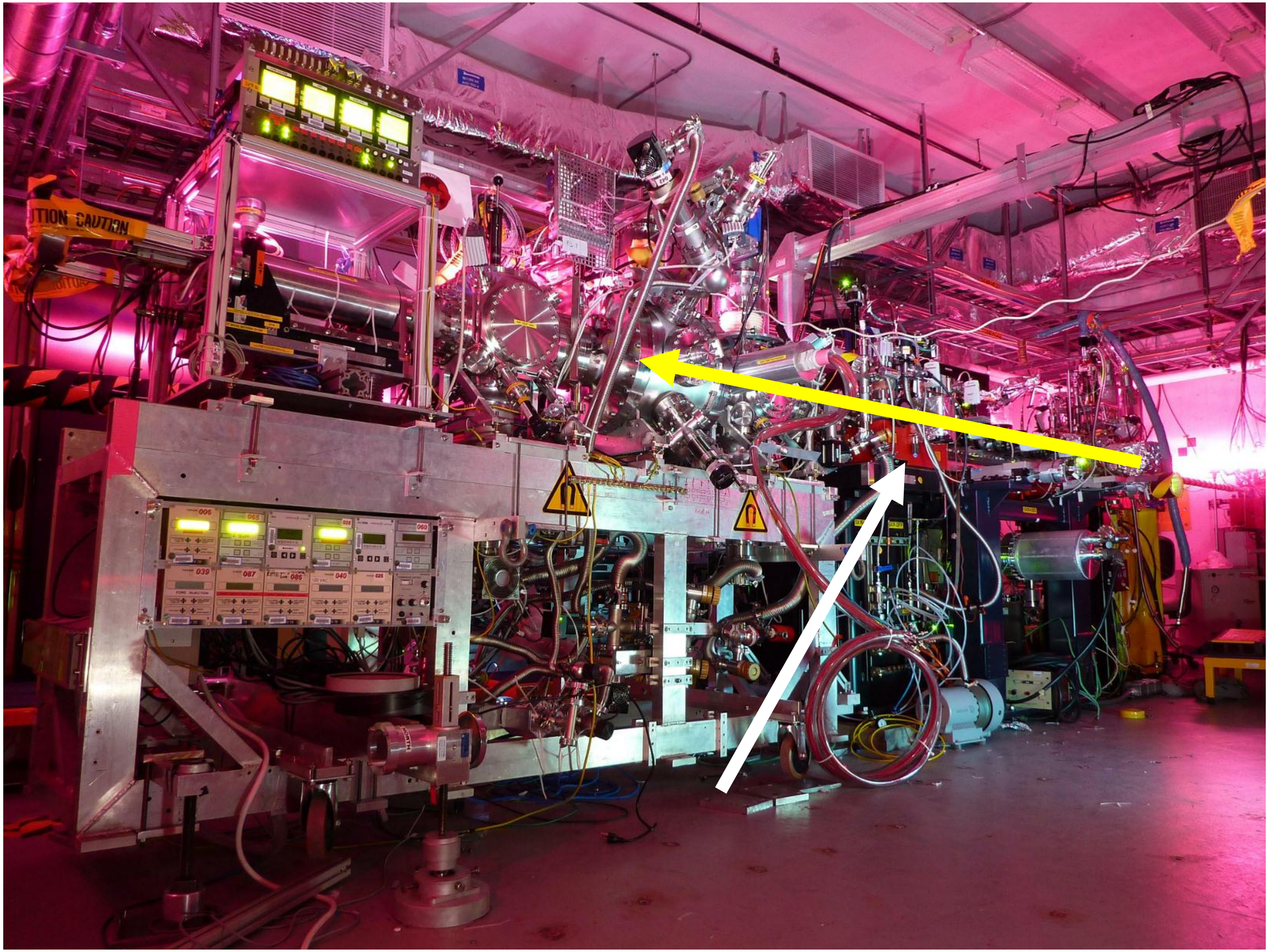
- FLASH EBIT: transportable machine built in 2005 for external beamtimes at facilities like FLASH, BESSY or LCLS



- Hyper EBIT: upgraded FLASH EBIT

- Mini EBIT (not yet operational)

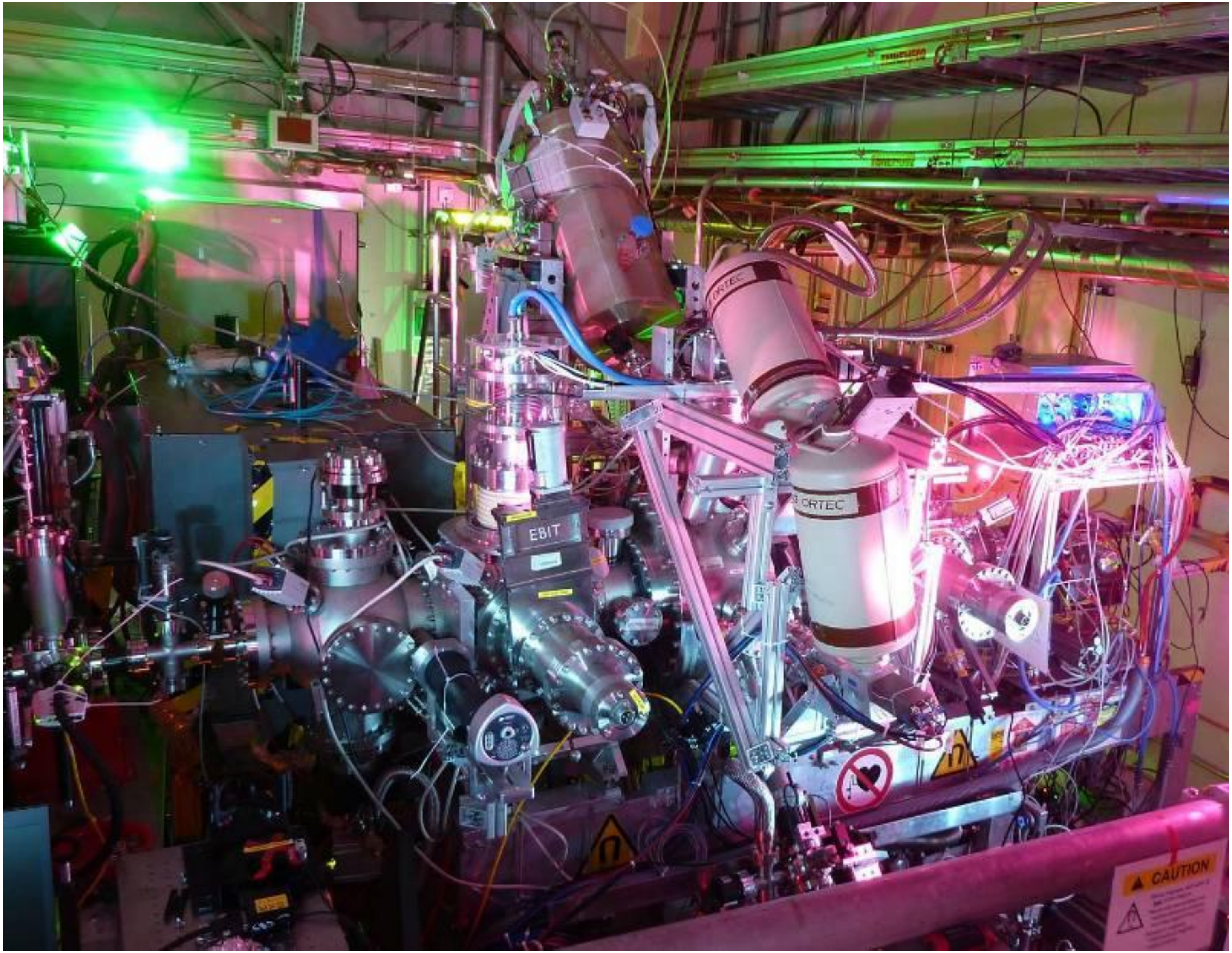
FLASH EBIT at SLAC (LCLS)



Soft X-ray monochromatic photon beam at SXR

Max-Planck-Institut für Kernphysik

FLASH EBIT at SLAC (LCLS)



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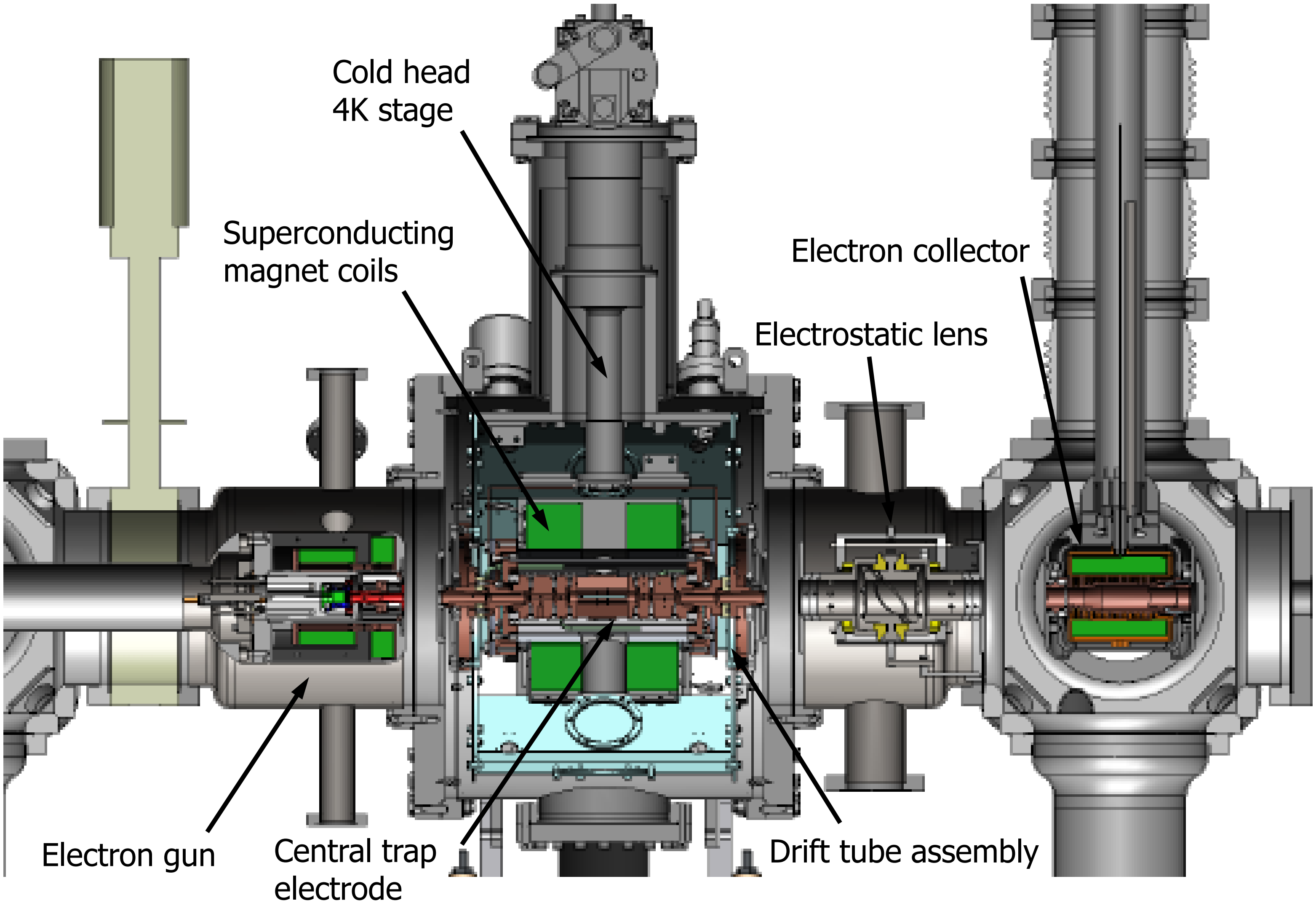
Hyper EBIT



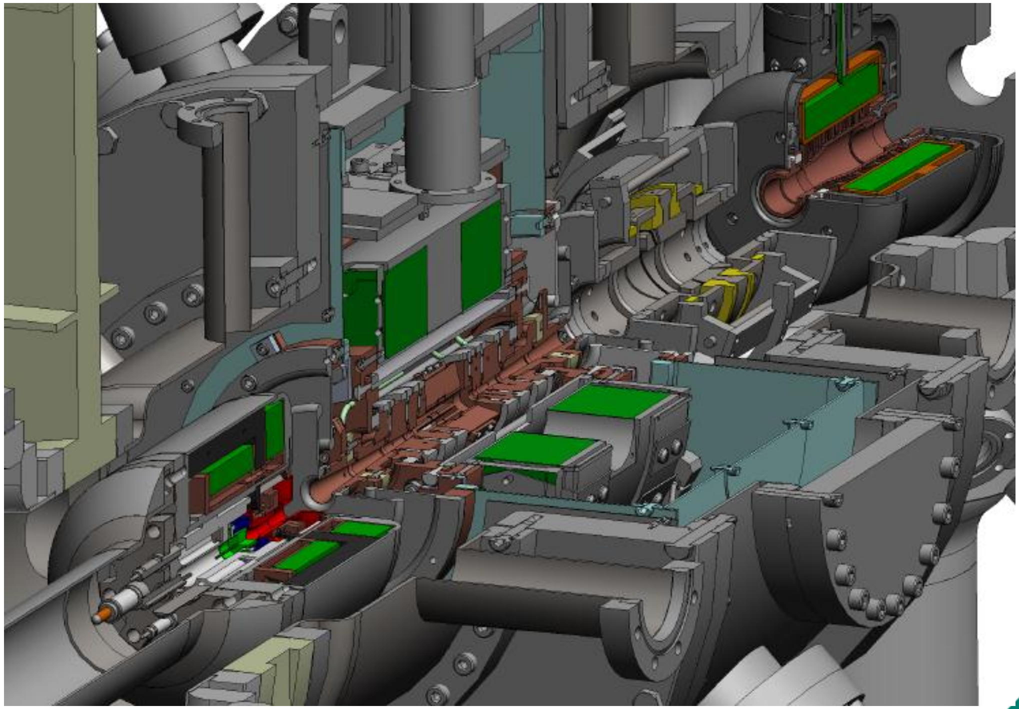
Cold head
4K stage
Superconducting
magnet coils
Electron collector
Electrostatic lens
Electron gun
Central trap
electrode
Drift tube assembly

Design values of Hyper EBIT

- Design based on the FLASH EBIT
- Magnet cooled to 4 K by cold head (1W @ 4 K stage)
- Magnetic coils up to 7.3 Tesla, cold bore
- Trap electrodes similar to those of FLASH EBIT

- Segmented central trap electrode (cyclotron resonance excitation)

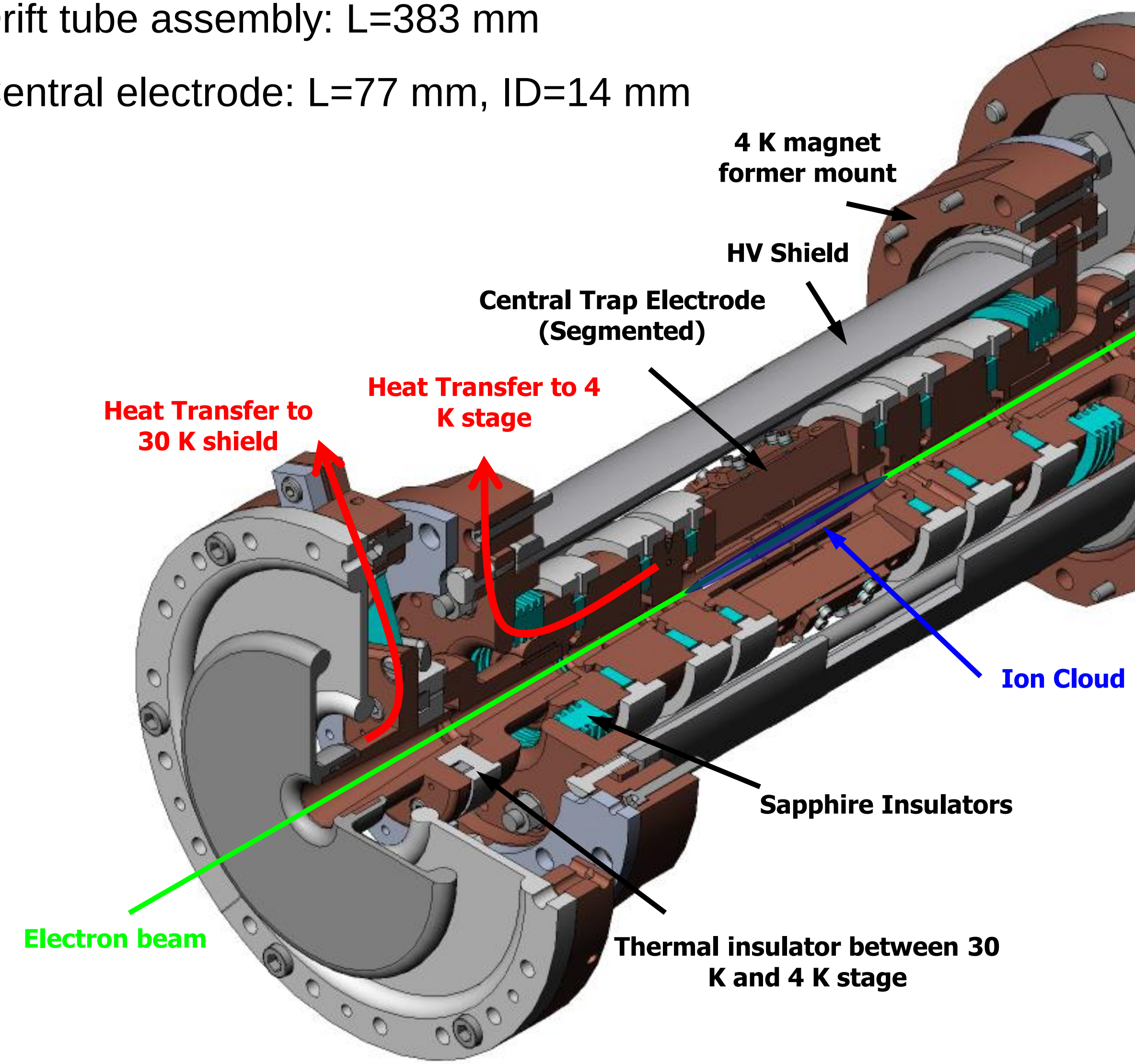
- Electron gun equipped with larger cathode (for 2~5 A beam current)

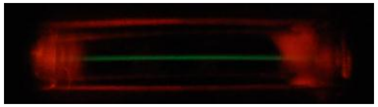


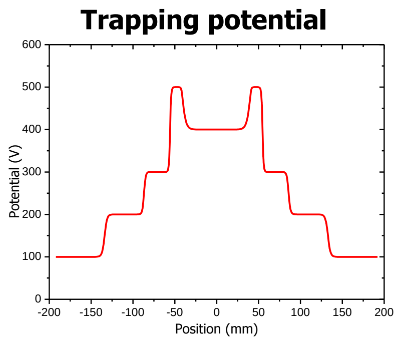
Design of the new EBIT

Drift tube assembly: L=383 mm

Central electrode: L=77 mm, ID=14 mm

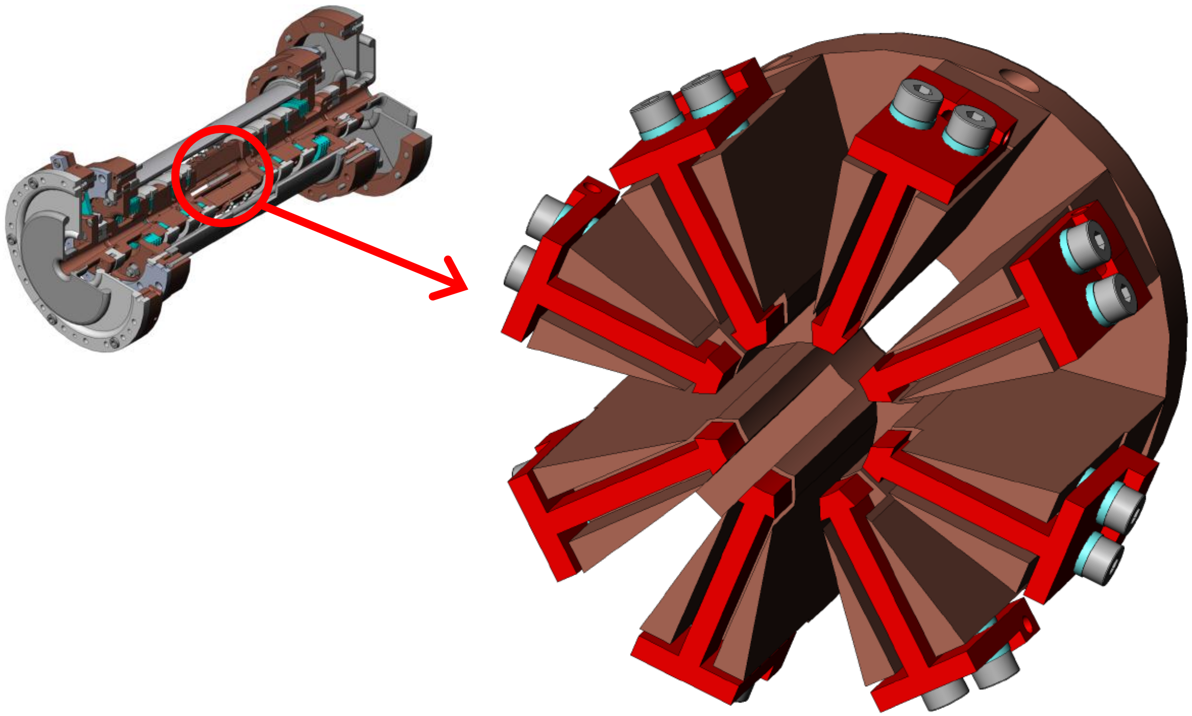


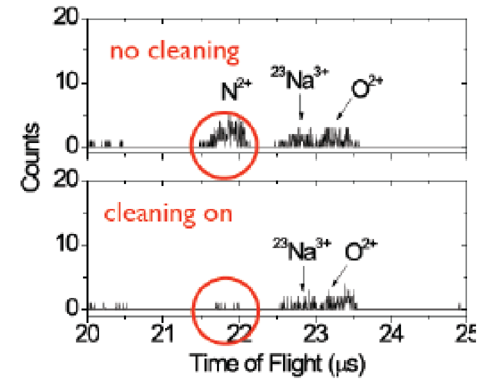




Design of the new EBIT

Ion cyclotron resonance excitation





TITAN EBIT data on contamination cleaning

$$\omega_C = \frac{q}{m} B$$

Segmented trap electrode:

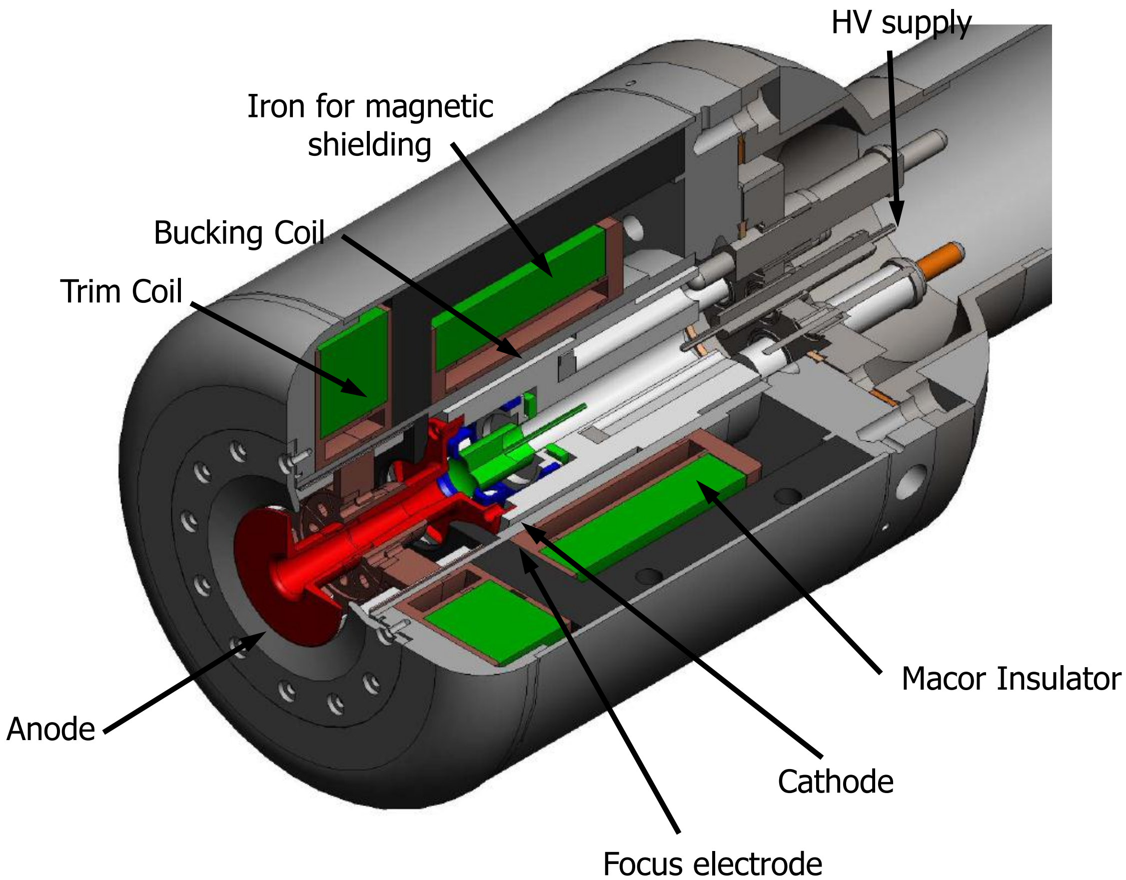
- Modification of the ion population with RF field
- Diagnose trap content by ion cyclotron resonance excitation
- Magnetic trapping mode without electron beam (Penning trap)

Design of the new EBIT

The 5 Ampere electron gun (MSU, Stefan Schwarz)

EBIT Cathodes:

- *Ba impregnated W matrix*
- *spherical concave shape (Pierce geometry)*
- *heated to about 1100 °C*
- *diameters*
  - *3 mm -> 0.5 A*
  - *6 mm -> 2 A*
  - *12 mm -> 5 A*



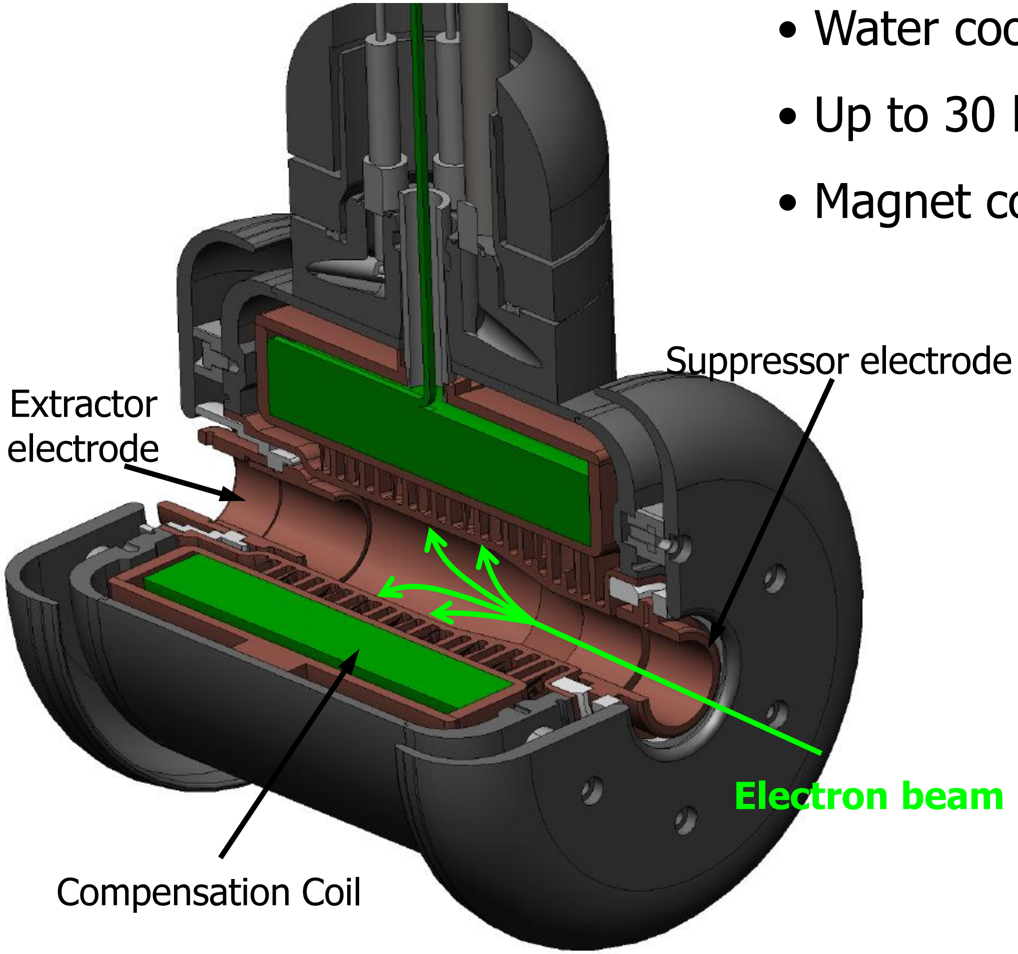
Length: 190 mm, Diameter: 150 mm

Gun designed in cooperation with Michigan State University (MSU)

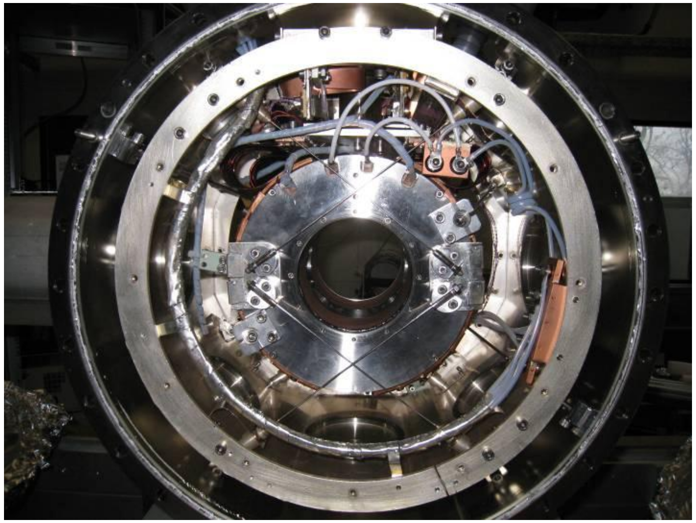
Design of the new EBIT

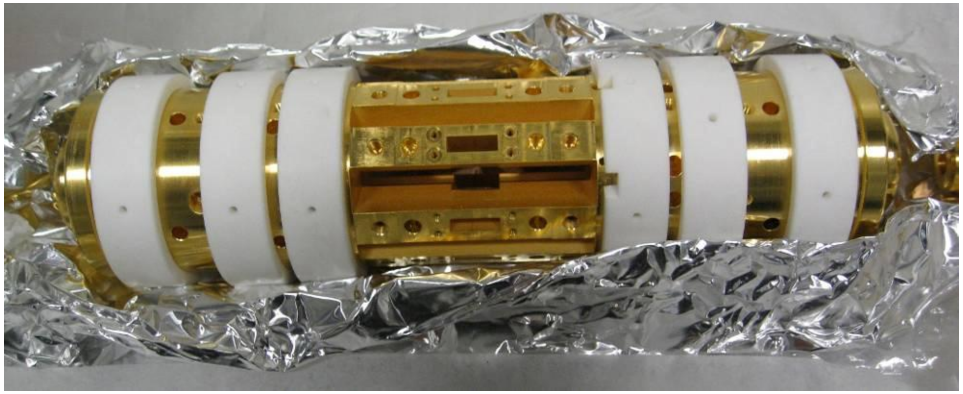
The collector

- Water cooled electron collector
- Up to 30 kW (design value)
- Magnet coil to compensate EBIT B field

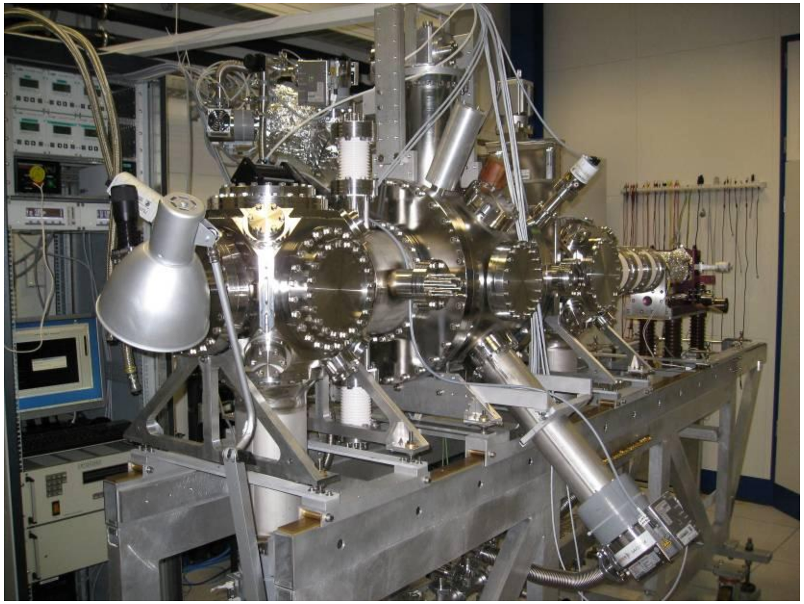


Assembly of the new EBIT

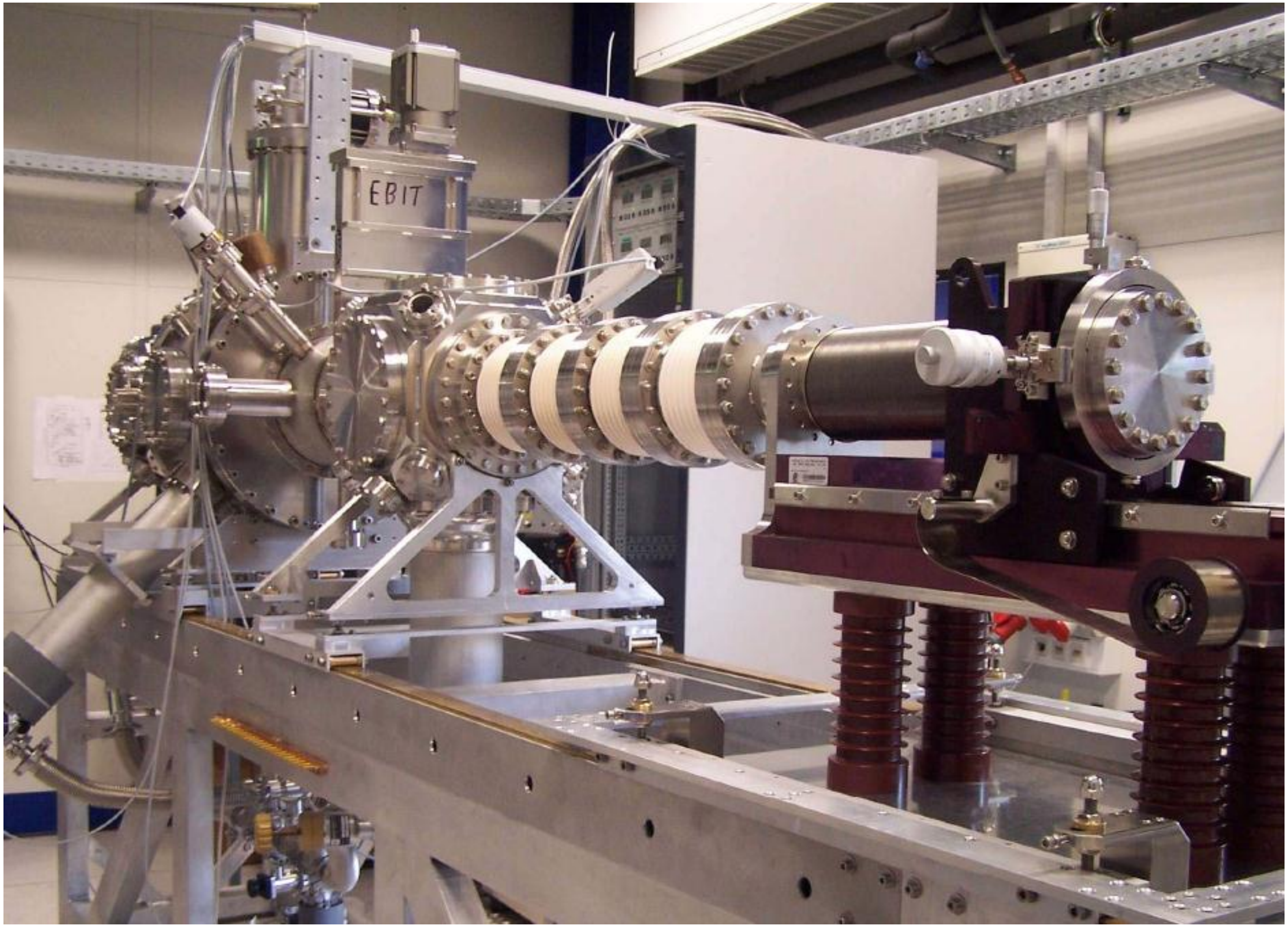

Magnet


Trap

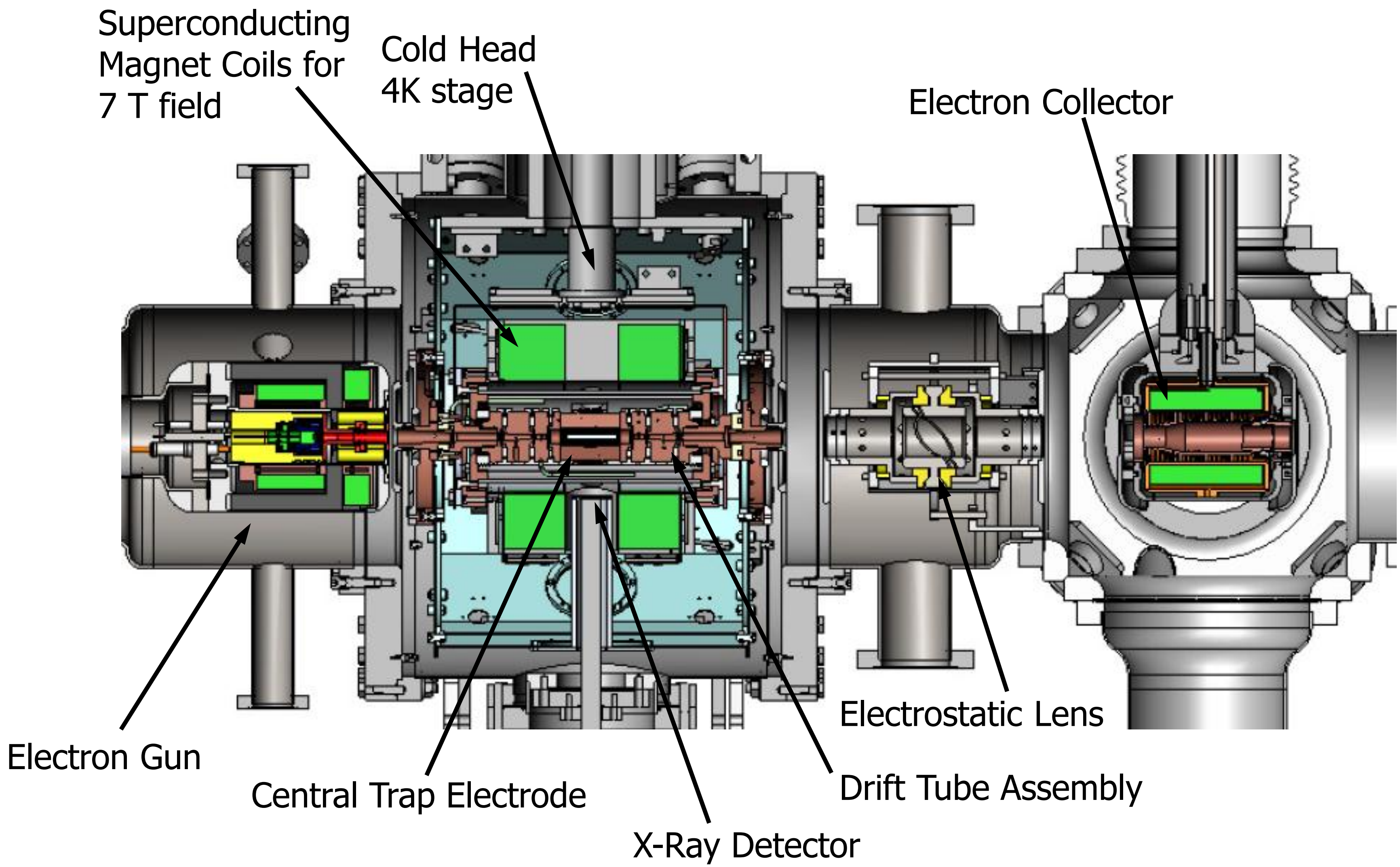

Sikler lens


Assembly

EBIT facility in Heidelberg



Experimental Setup



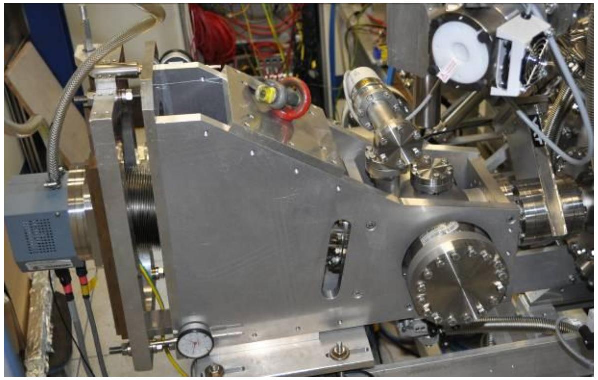
Experimental Setup

Detectors for charge breeding diagnostics

- X-Ray (1 keV to 30 keV):
  Silicon Drift Detector
  25 mm², 70 mm from the trap center
  Resolution: 130 eV at 6 keV

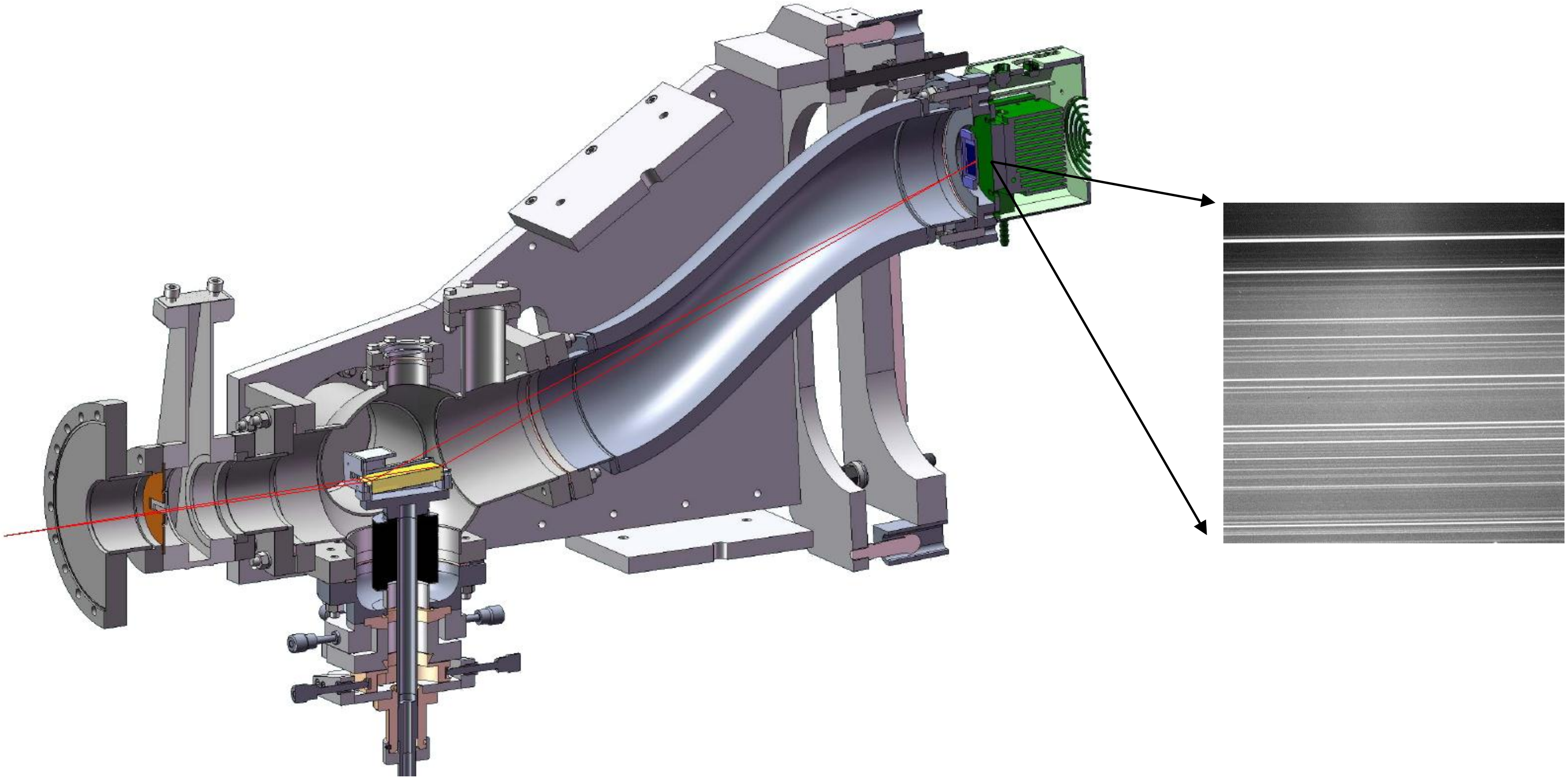
- Soft X-Ray (250 eV to 1000 eV; 5 nm to 1 nm): Grating spectrometer

- Extreme ultraviolet region (40 eV to 250 eV; 30 nm to 5 nm): Grating spectrometer



* amptek.com

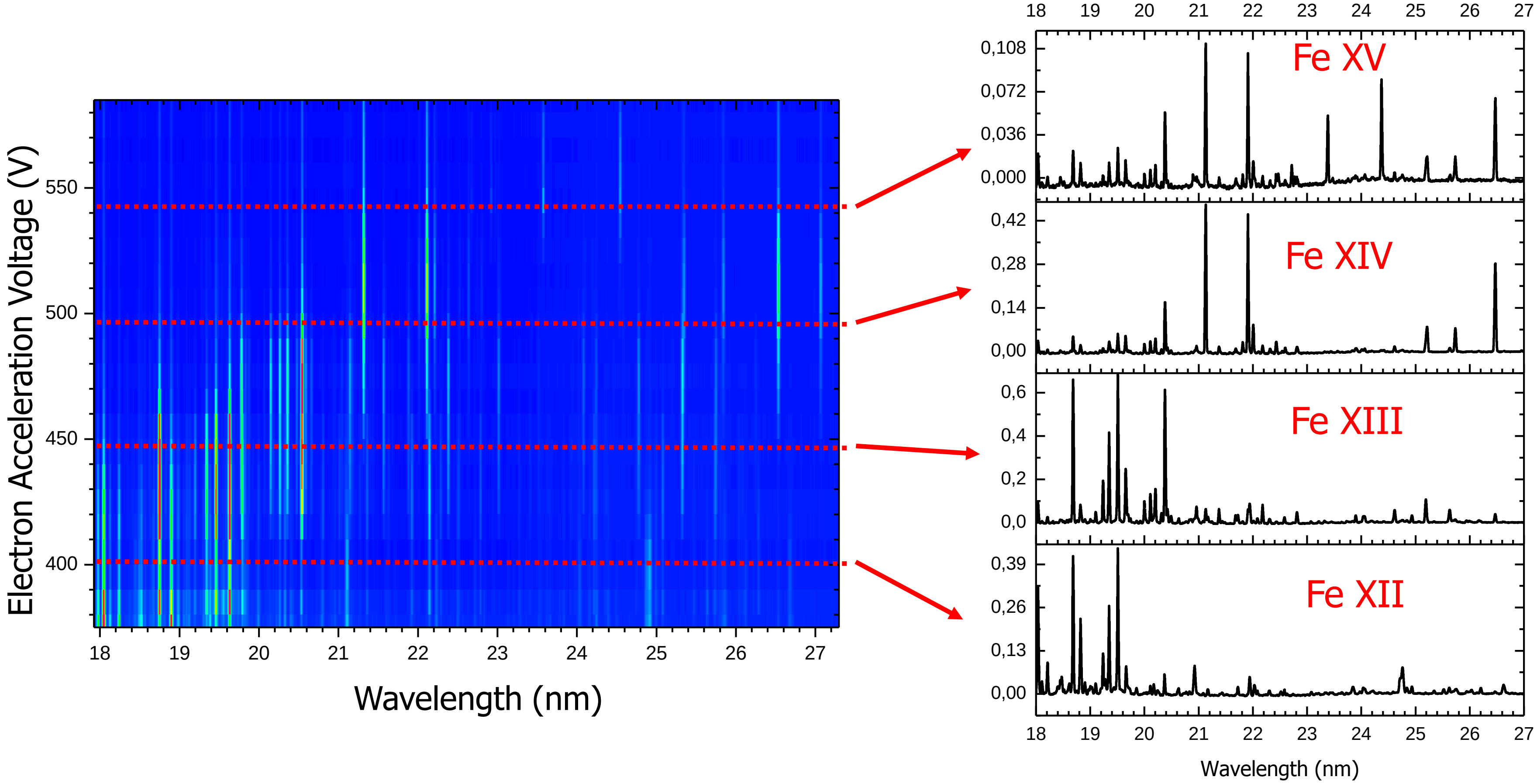
EUV flat-field grating spectrometer



Grating spectrometer for EUV region (40 eV to 250 eV; 30 nm to 5 nm):

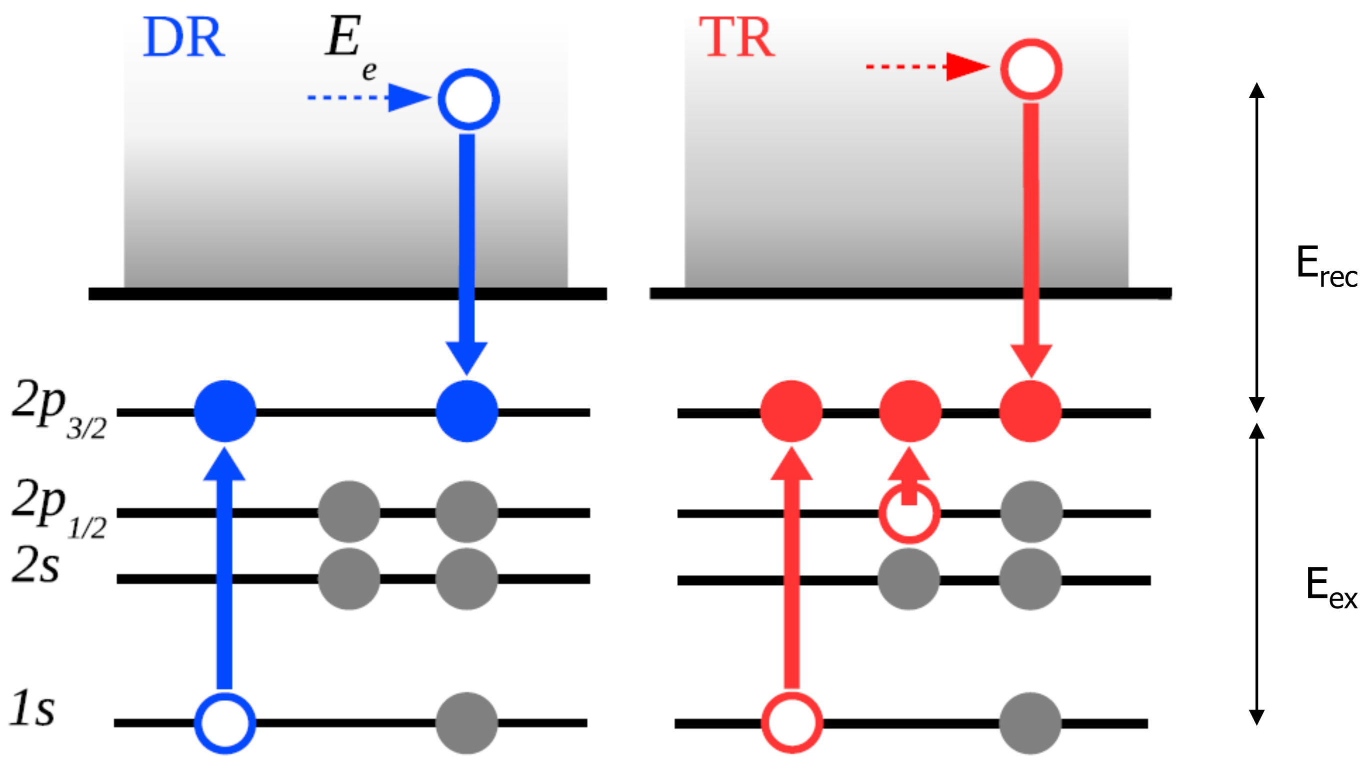
Plasma diagnostics using EUV spectra

- Electron beam energy is ramped up in discrete steps
- EUV spectrum (15 ~30 min) taken at each



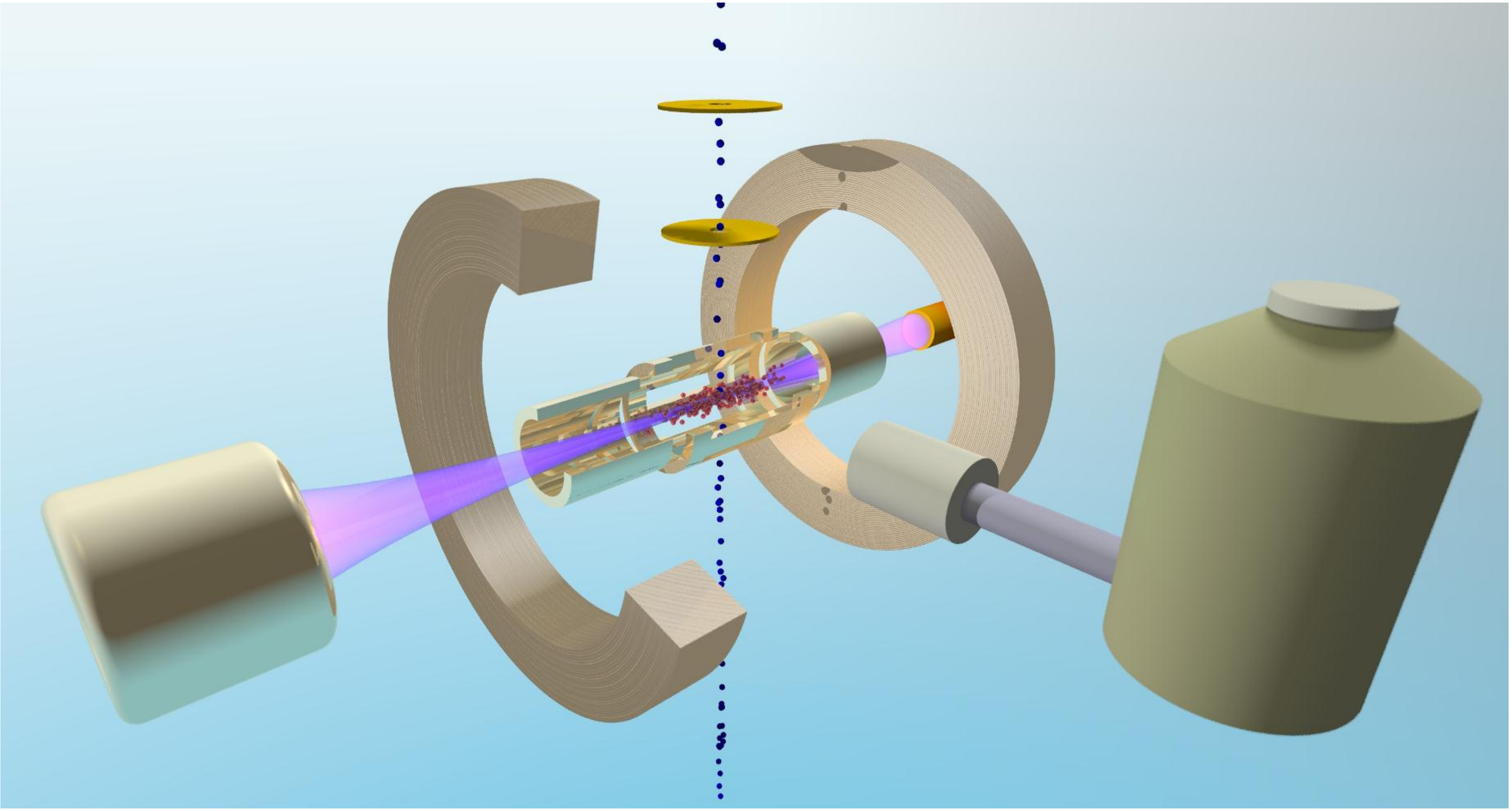
Resonant recombination in silicon

KLL resonant recombination



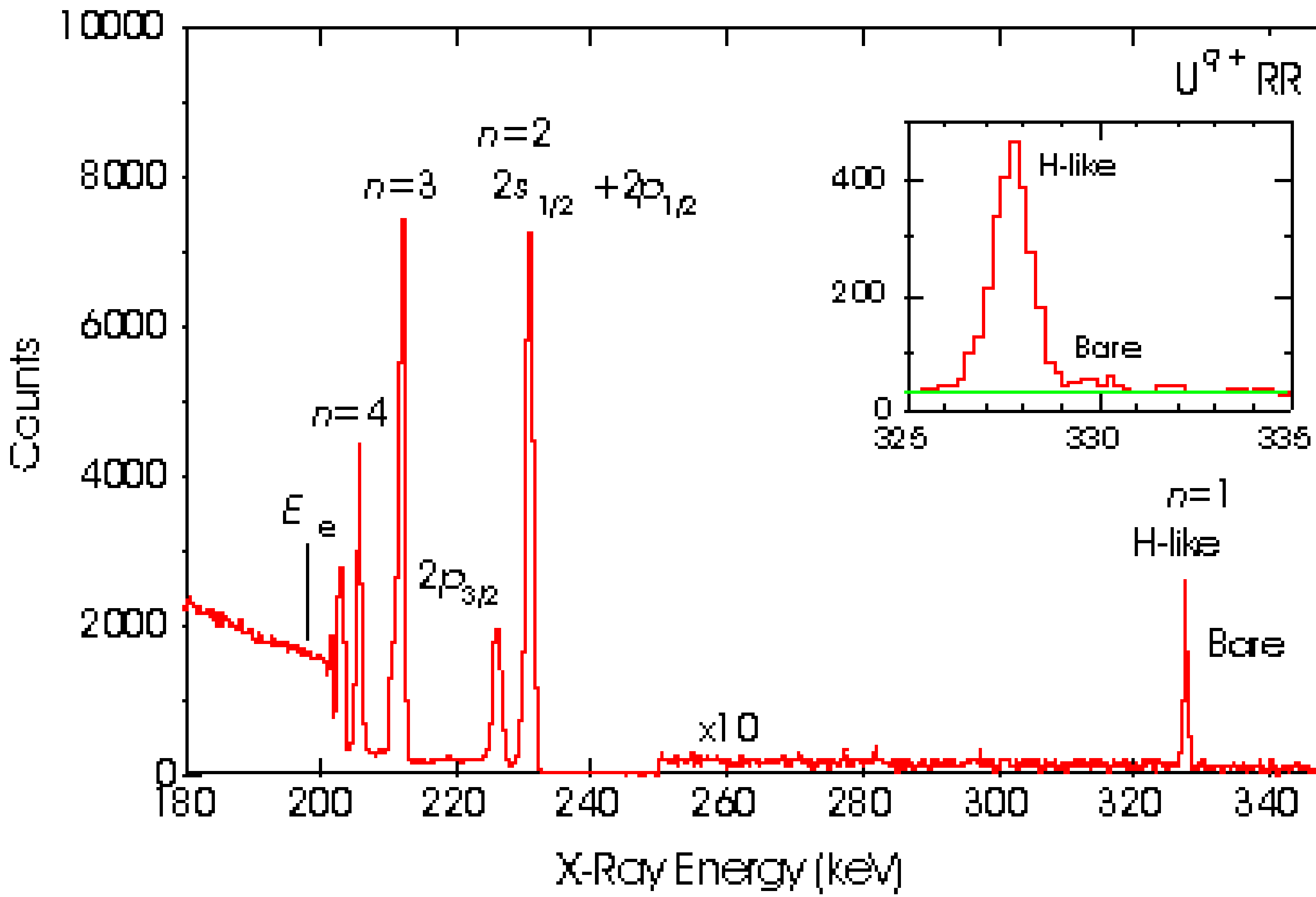
Resonant process: $E_{ex} = E_e + E_{rec}$

Resonant photorecombination



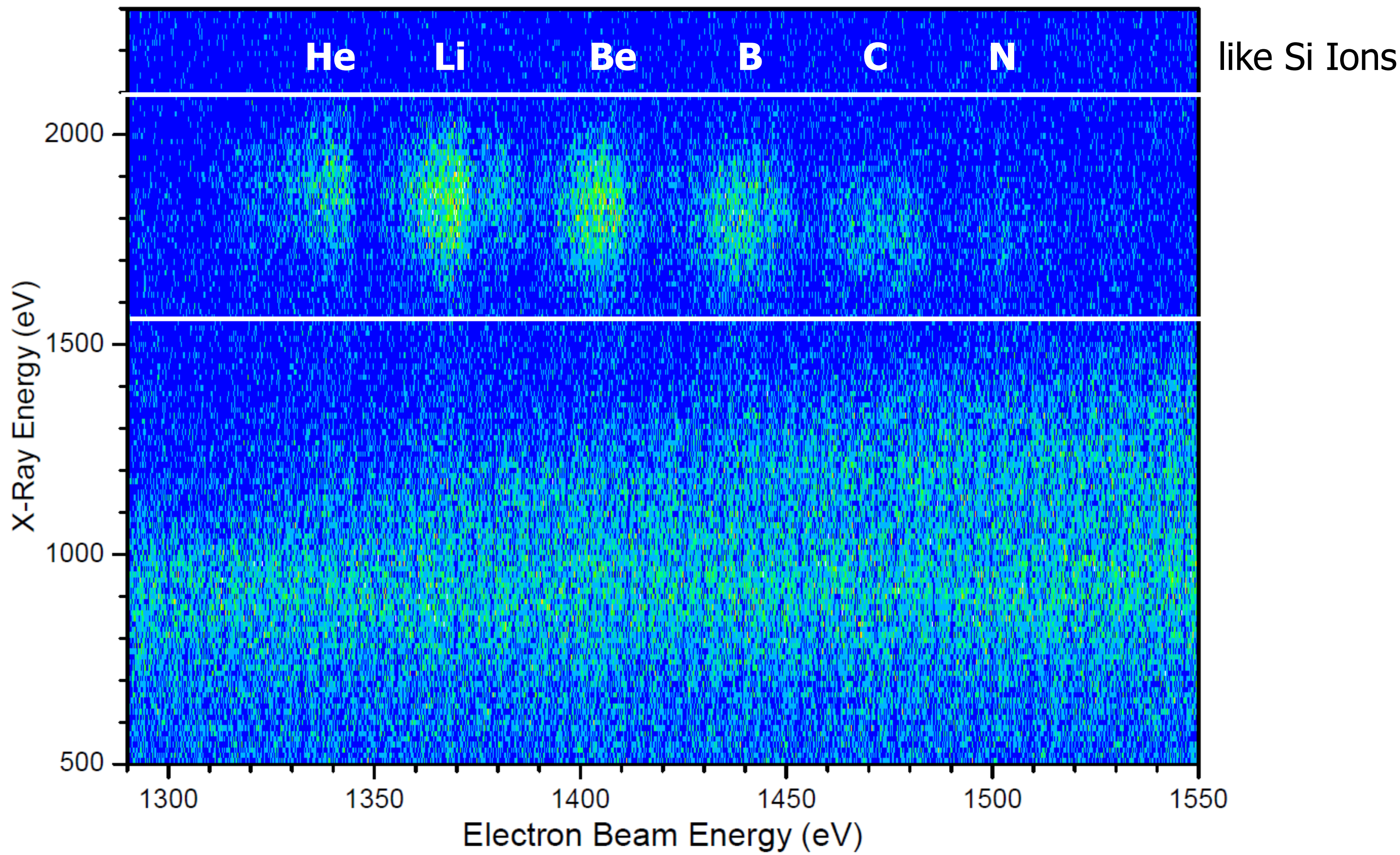
Germanium detectors for X-ray diagnostics

The famous U^{92+} signal from LLNL



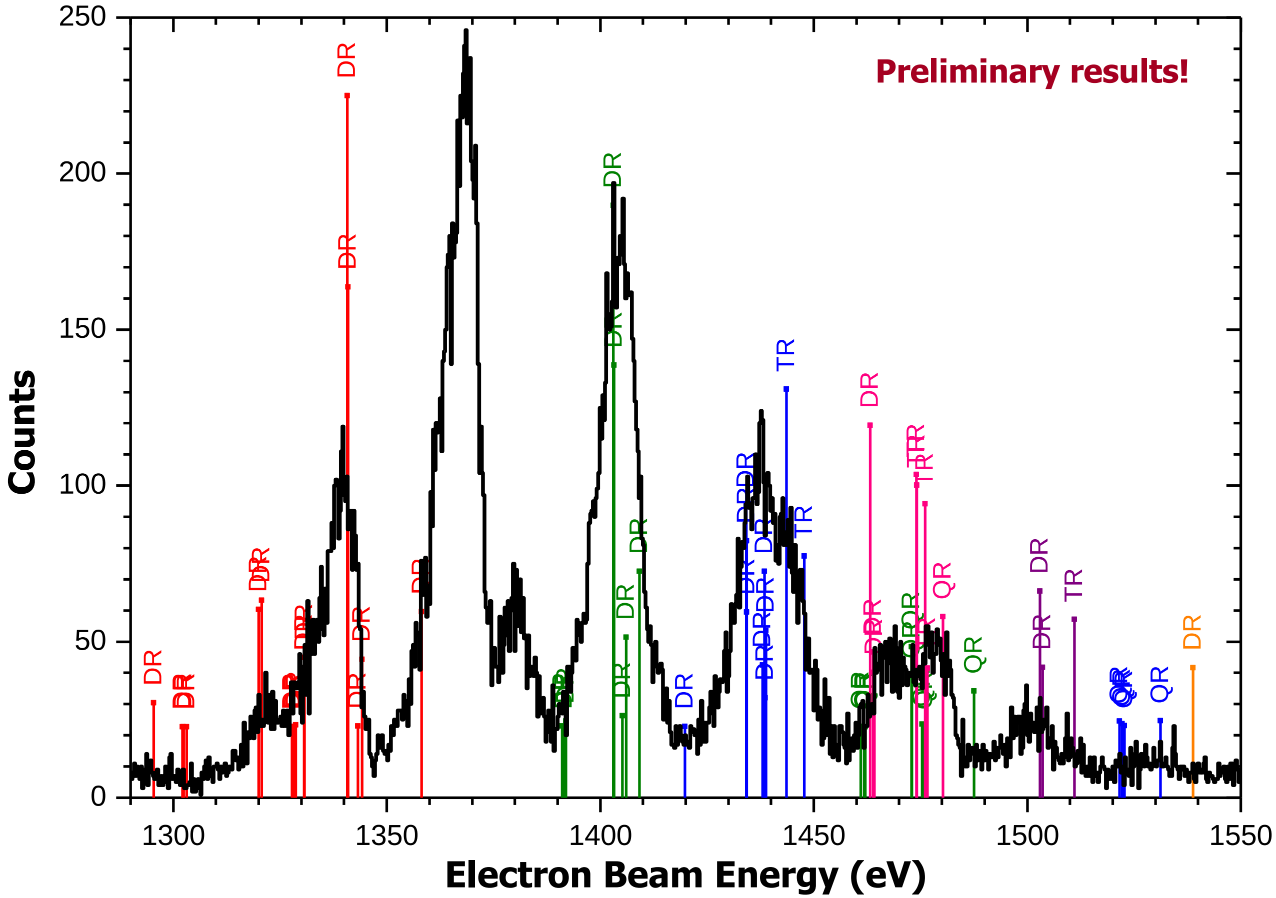
→Talk to the inventor, Ross Marrs... PRL1994

Resonant recombination in silicon



X-Ray Spectrum dependent on the electron beam energy

Resonant recombination in silicon



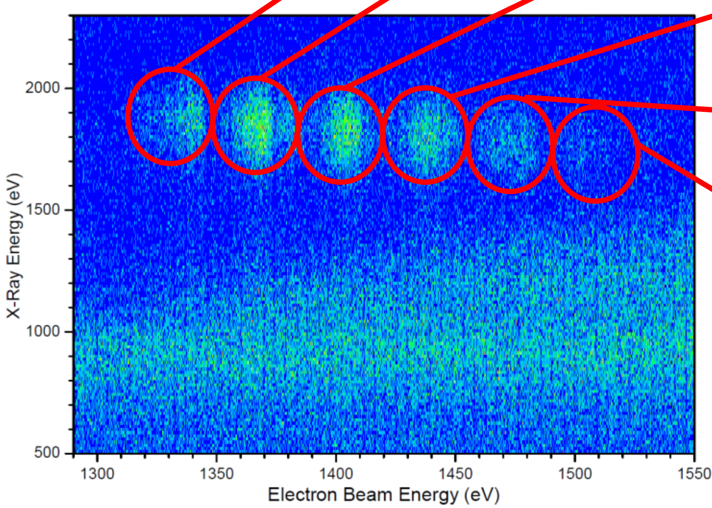
Projection of the DR region of interest on the electron beam energy scale.

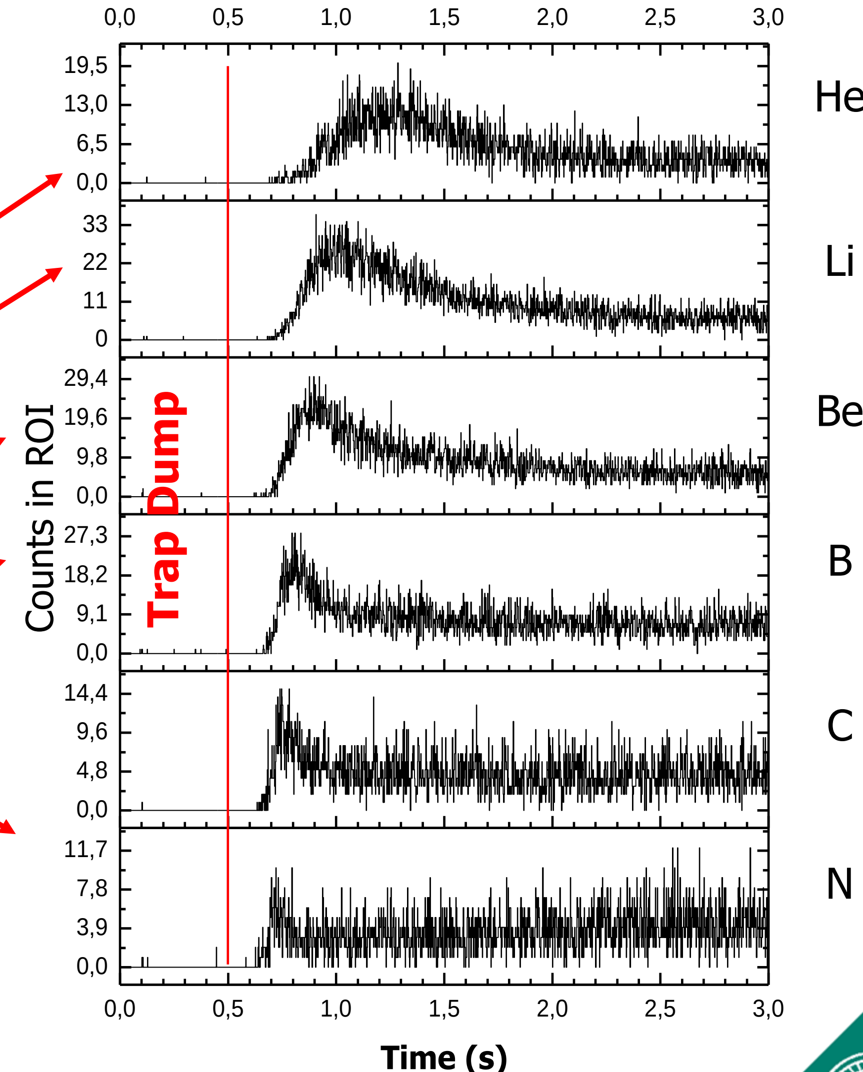
Resonant recombination in silicon

Time evolution

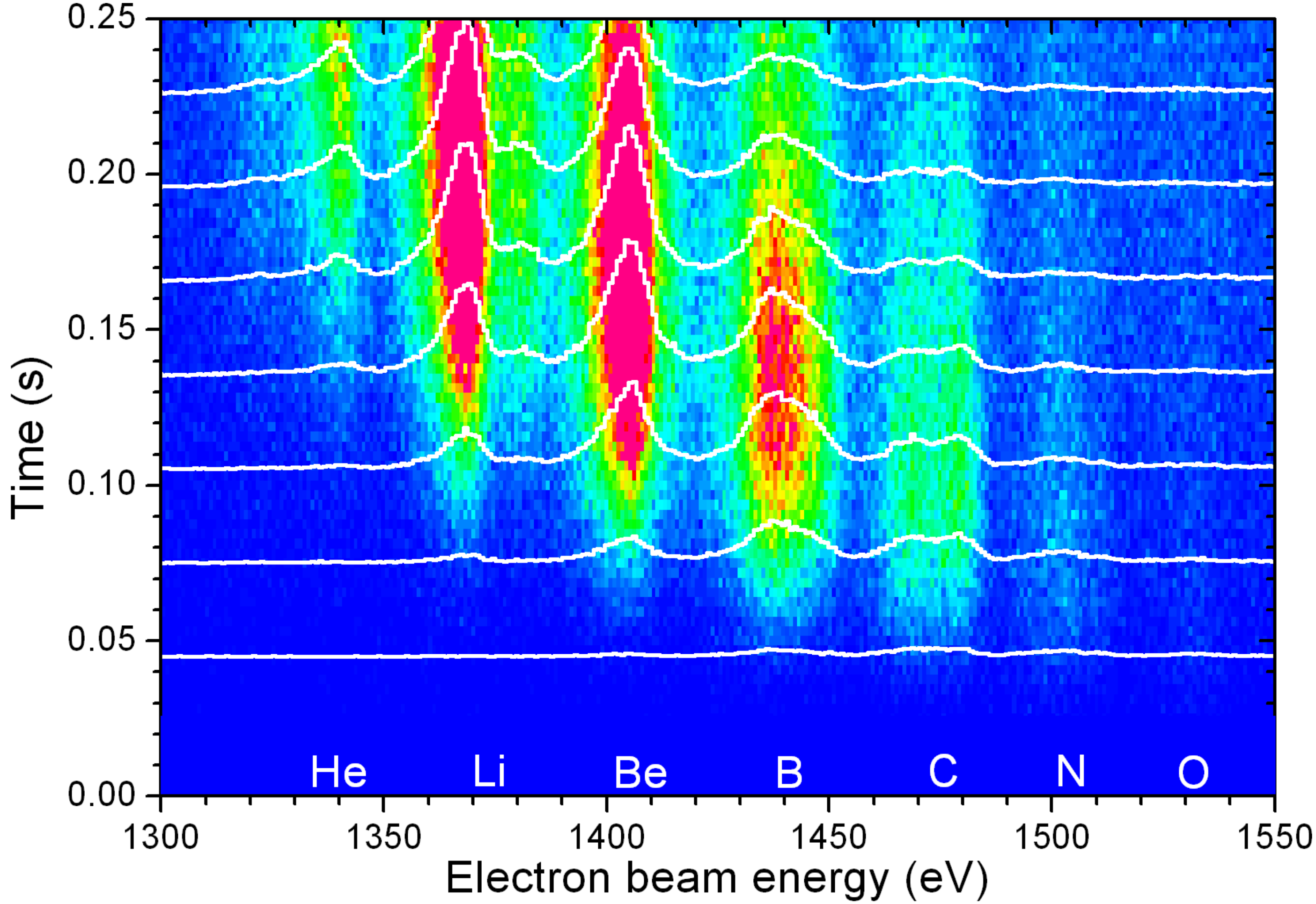
Extract time information:

- Eliminate background contributions of higher charge states
- Measure charge state distribution and breeding times



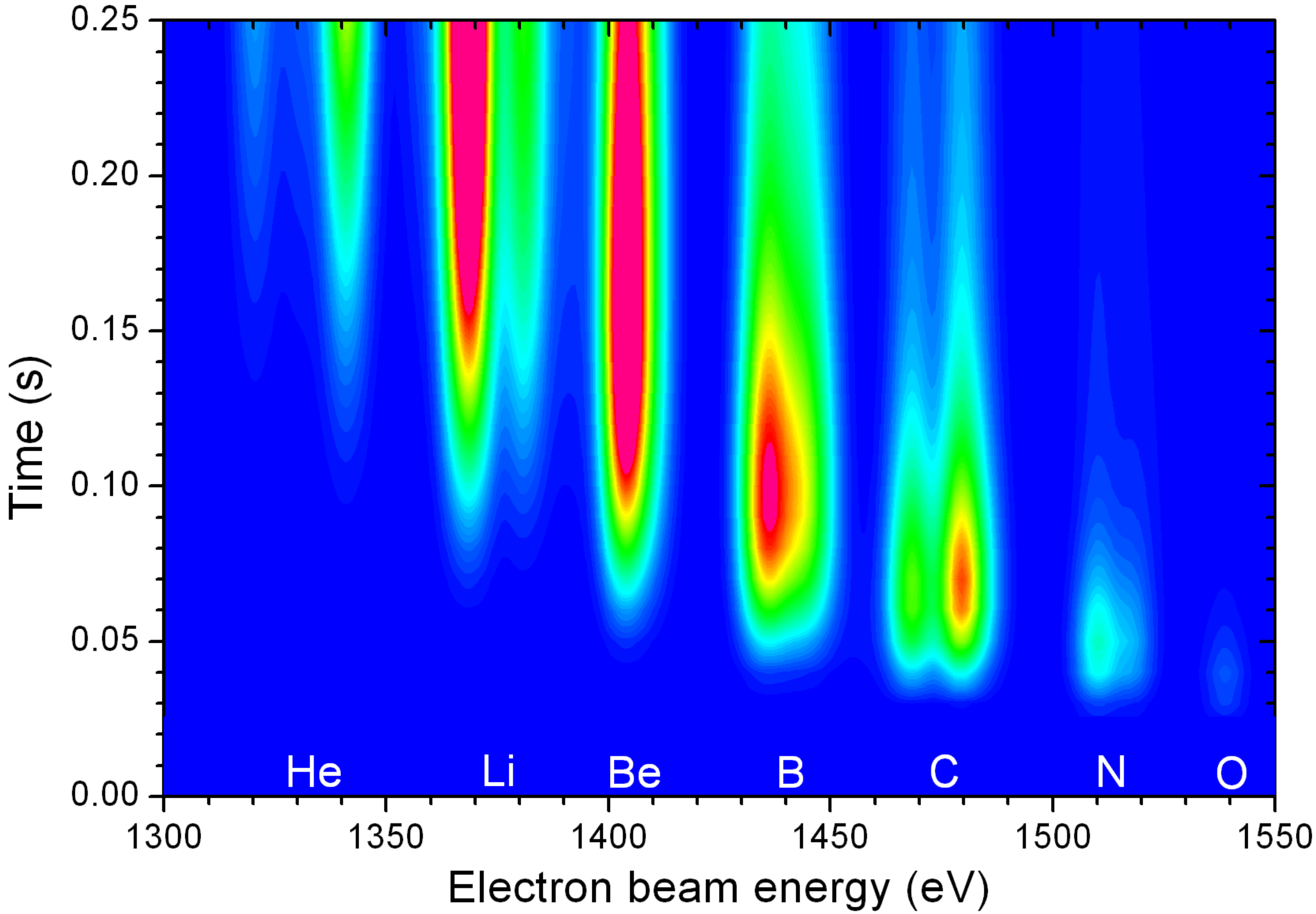


Resonant recombination in silicon



Time-resolved X-ray spectrum dependent on the electron beam energy (measurement)

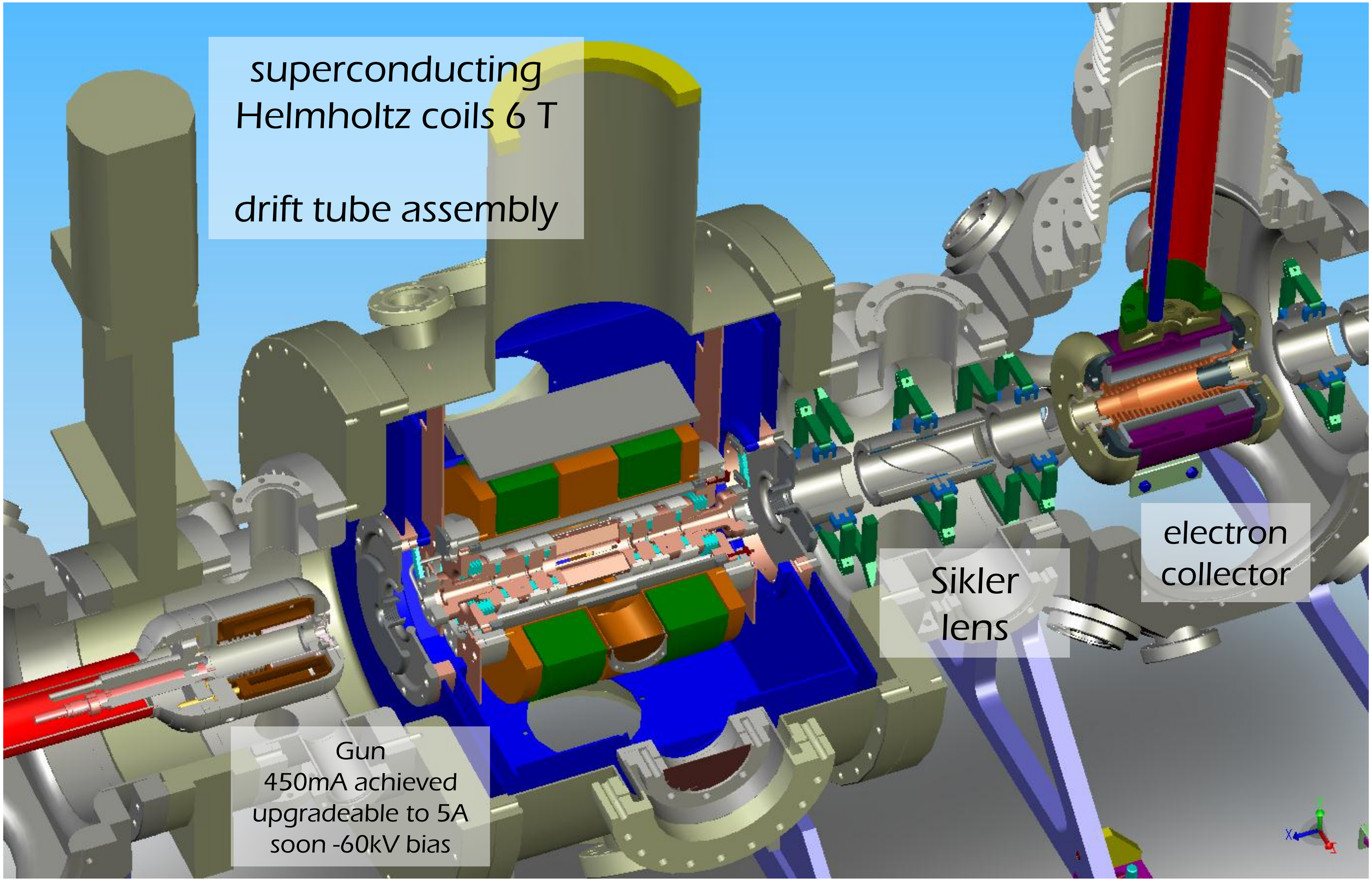
Resonant recombination in silicon



Time-resolved X-ray spectrum dependent on the electron beam energy (Simulation with rate model and FAC atomic physics)

The TITAN-EBIT

Max-Planck-Institut für Kernphysik



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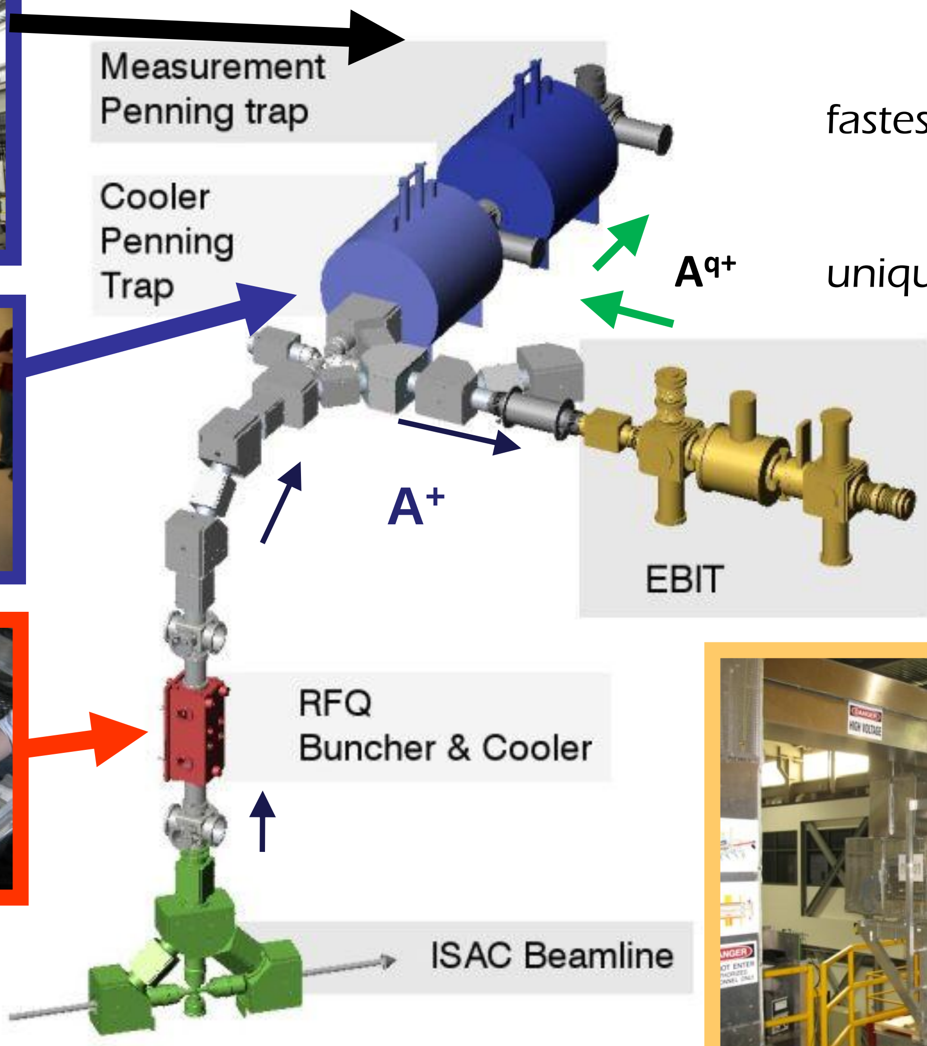


fastest system:

$t_{1/2}$ = 8.8ms

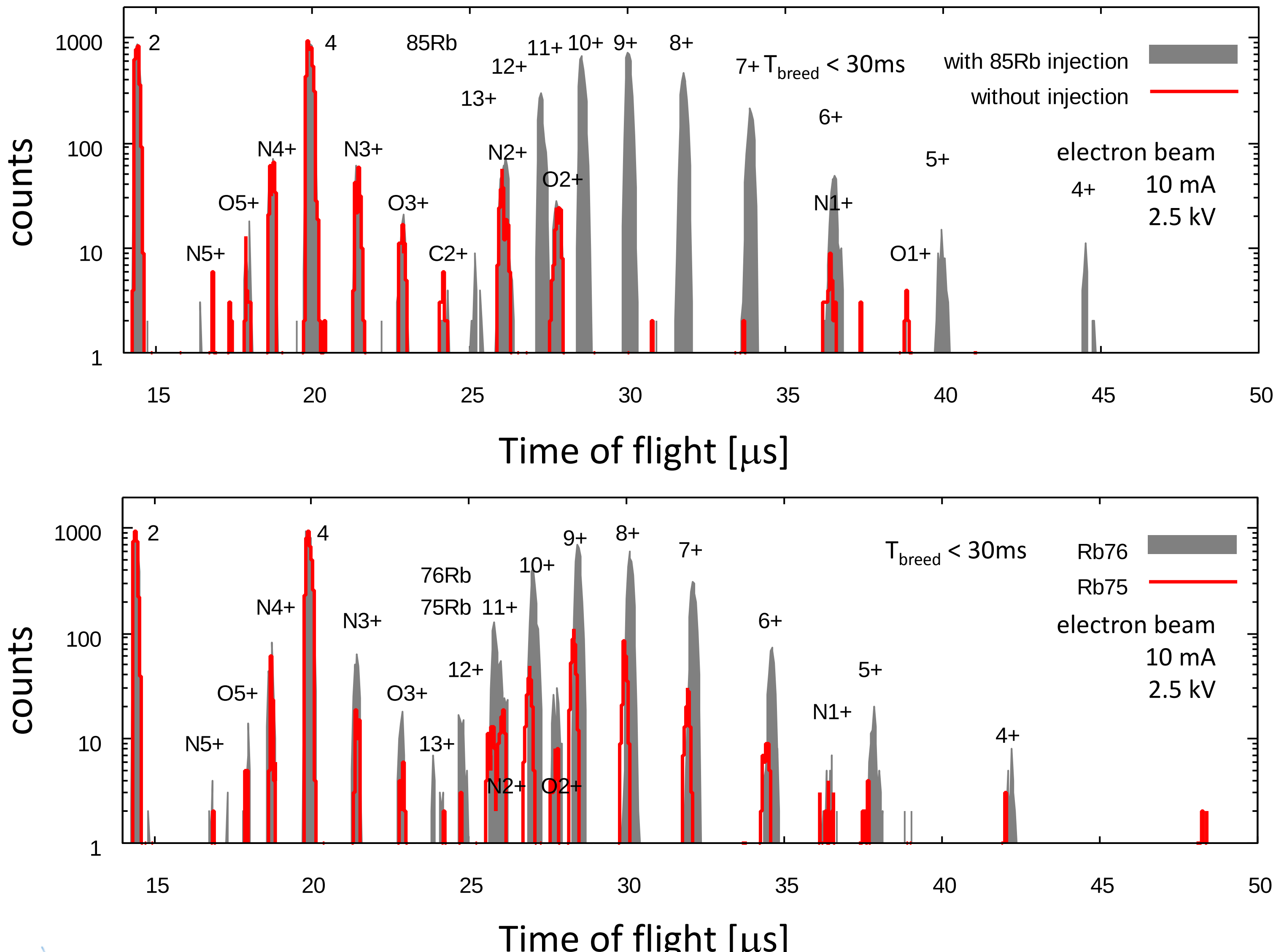
unique access to
short lived isotopes
in high charge states

A^{q+}

ISAC beam:
A^{+}

continuous,
radioactive beam

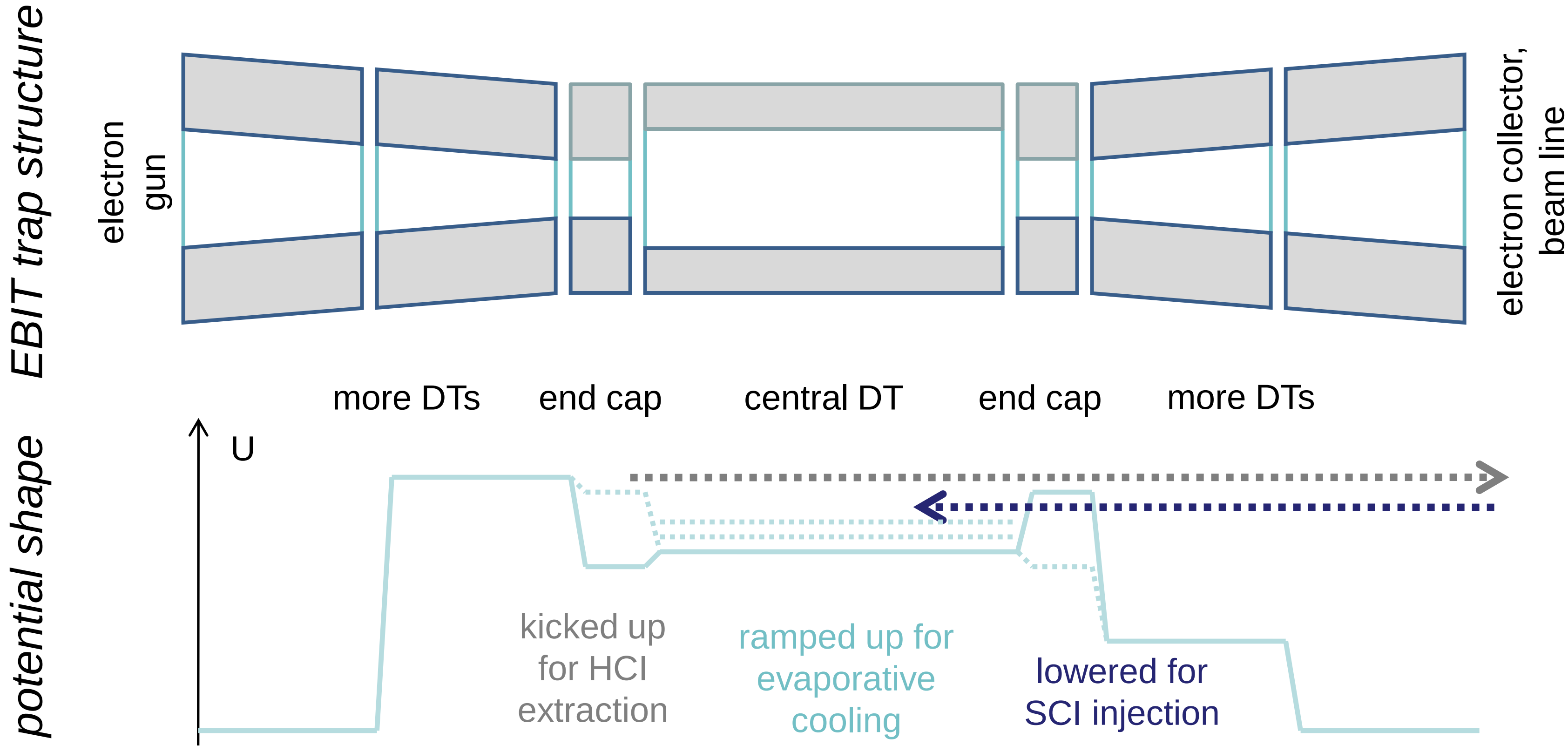
Charge breeding Rb: stable & radioactive



Martin Simon et al., Rev. Sci. Instrum. **83**, 02A912 (2012)

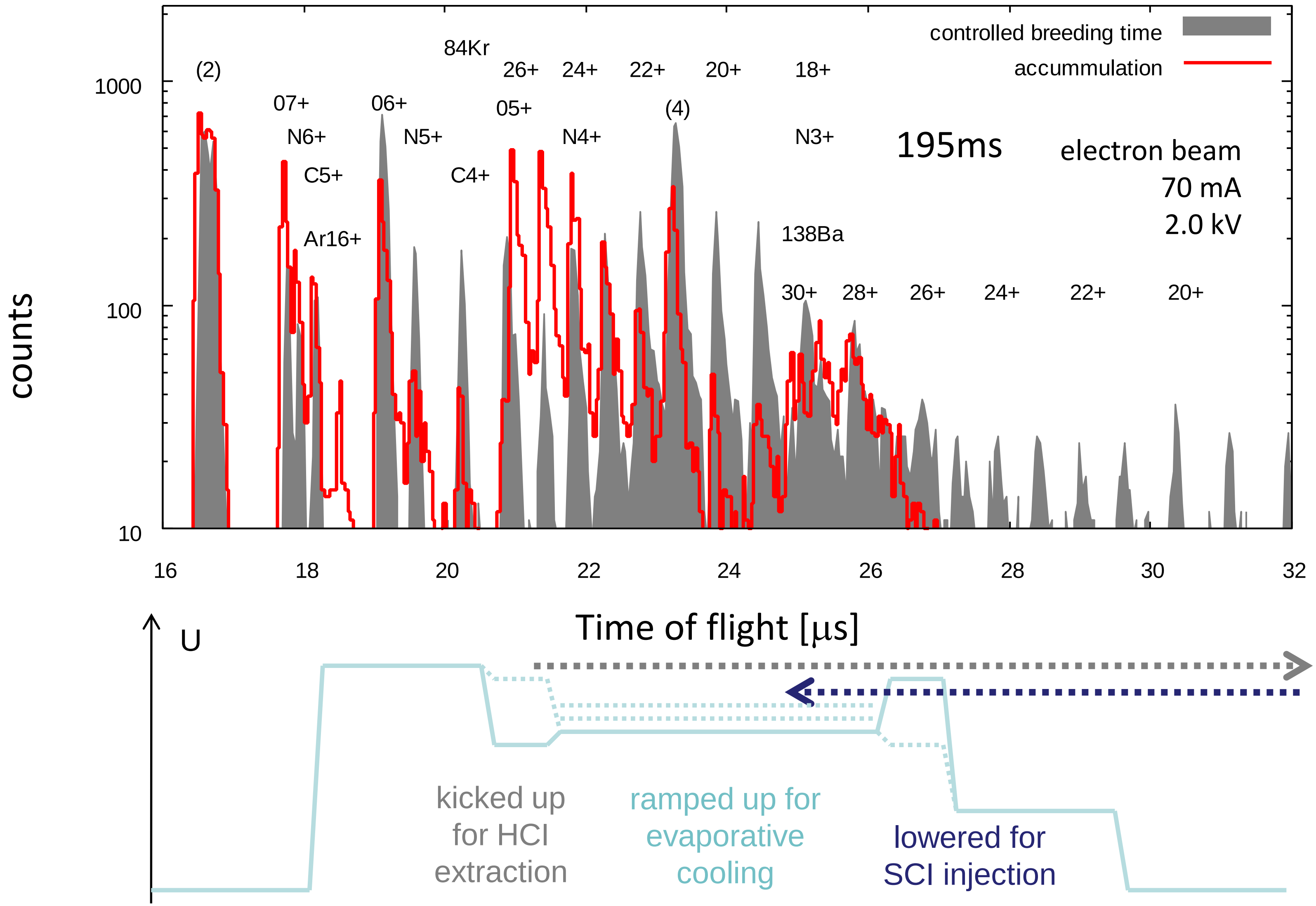
Ion accumulation in EBIT

- breeding time < measurement time
- breeding time + measurement time ~ few half lives



Martin Simon et al., Rev. Sci. Instrum. **83**, 02A912 (2012)

Accumulation in the EBIT



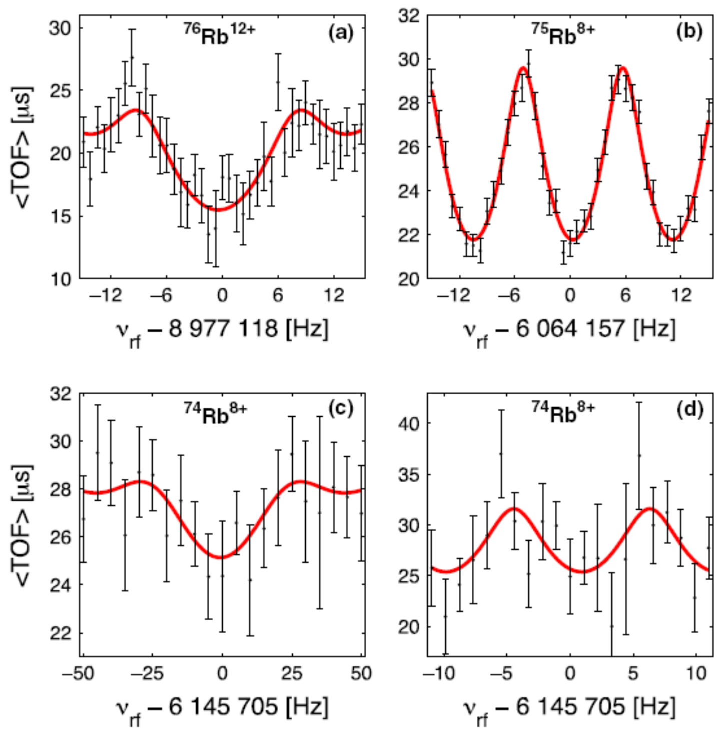
Martin Simon et al., Rev. Sci. Instrum. **83**, 02A912 (2012)

Superallowed beta decay: ^{74}Rb

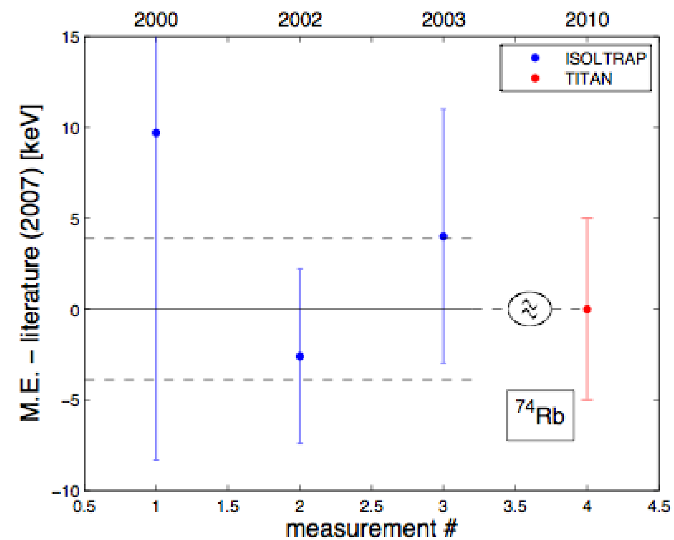
determination of the element V_{ud} of the CKM-matrix

- ISAC Yield: around 2000 ions/s
- Contamination from ^{74}Ga

$\tau_{1/2}$: 65ms ***$^{74}Rb^{8+,12+}$***



SCI measurement **HCI**



$\sigma_{stat} \approx$ **4.1 keV**

TITAN
ISAC-TRIUMF

TRIUMF ISAC

S. Ettenauer, M. C. Simon et al. PRL **107**, 272501 (2011)

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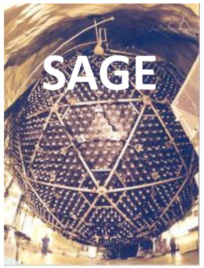
^{71}Ge-^{71}Ga Q-value

Solar neutrinos: detector calibration discrepancy



	source	event ratio exp / theory
GALLEX	51Cr	0.882±0.078
SAGE	51Cr	0.95± 0.12
SAGE	37Ar	0.79±0.10
average	37Ar, 51Cr	0.87±0.05

Detector calibration with terrestrial sources

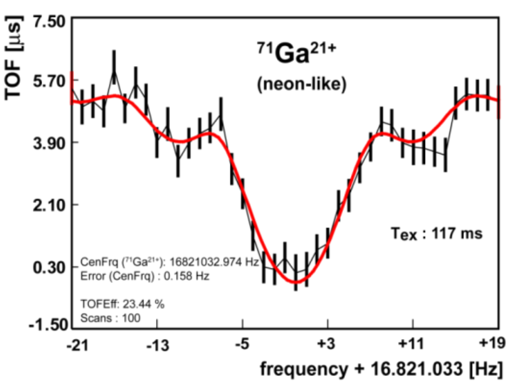
Q-value enters neutrino cross section in 2nd order

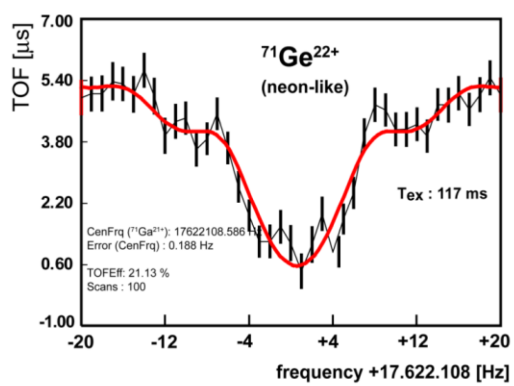
If literature value was only 5% off the 10% discrepancy could be explained; not the case!

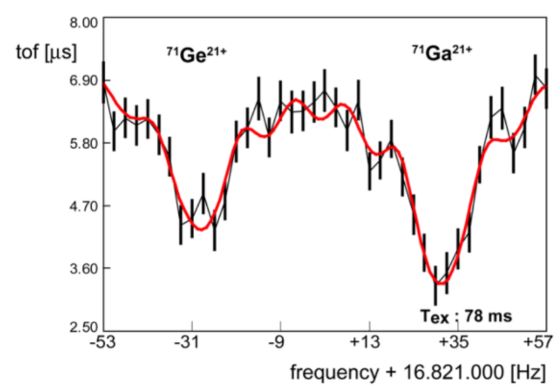
pure Ga:
TRILIS Lasers are off
→ only Ga delivered

pure Ge:
electron energy <2keV
→ no ions beyond Ne-like Ga^{21+}/Ge^{22+}

mixed Ga/Ge:
measurement with ions in same charge state: q=21+



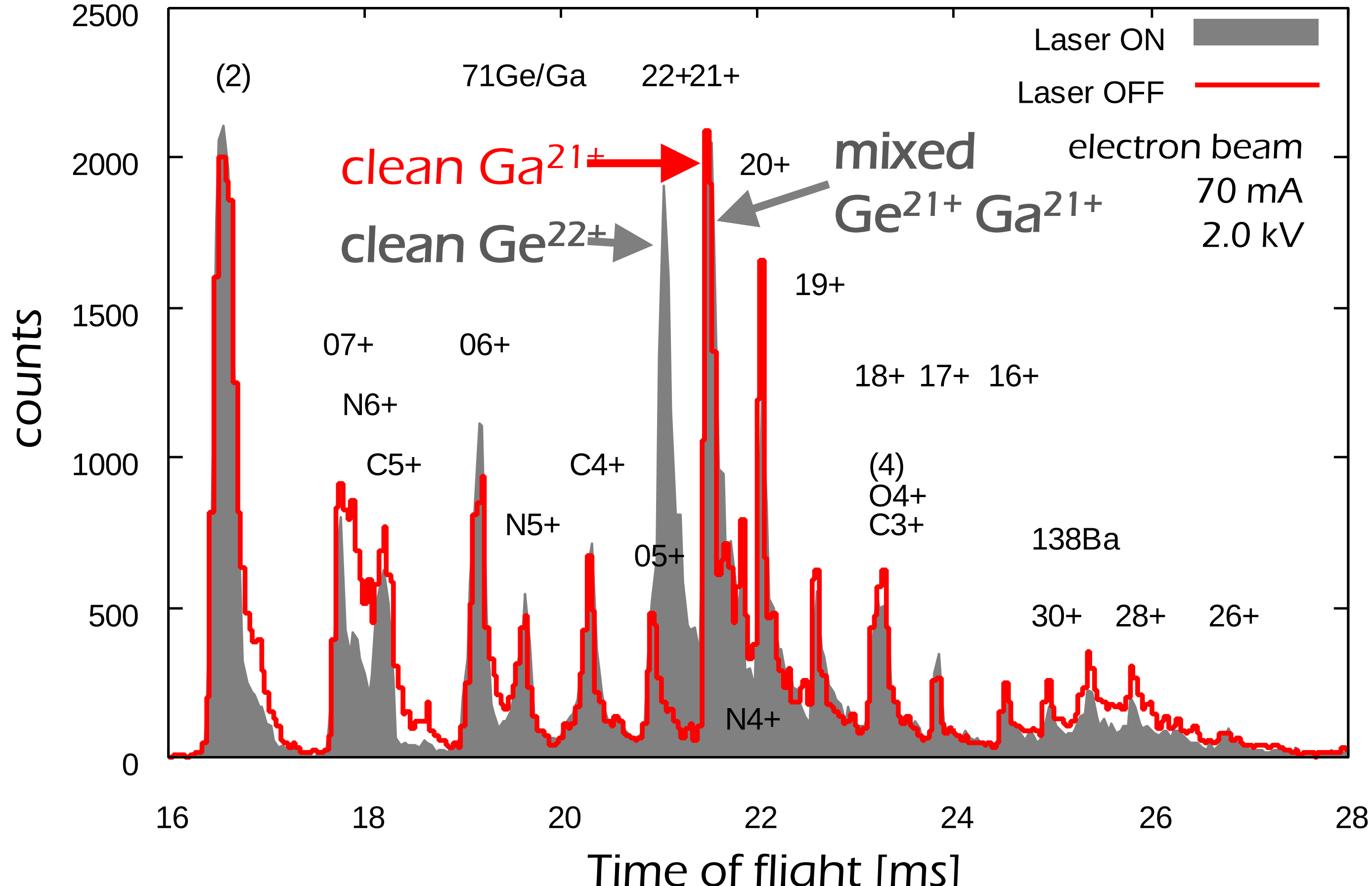




D. Frekers, M. C. Simon et al., submitted to PRL

^{71}Ge-^{71}Ga Q-value

Isobaric separation by charge breeding to atomic shell closures



TITAN
ISAC-TRIUMF

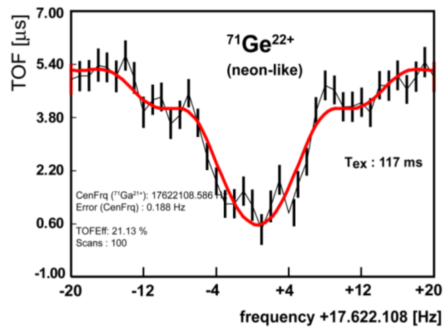
Ge delivery from ISAC requires laser Ionization

- clean $^{71}Ga^{21}$ if Laser OFF (Ga produced through surface ionization)
- clean $^{71}Ge^{22}$ if Laser ON (Ga not breeded to q=22+)

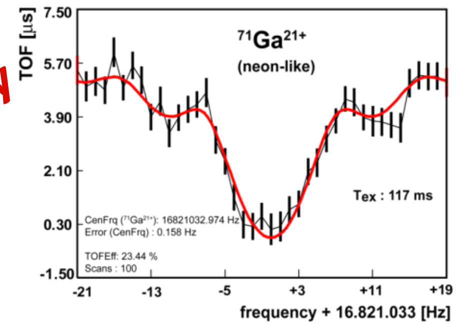
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

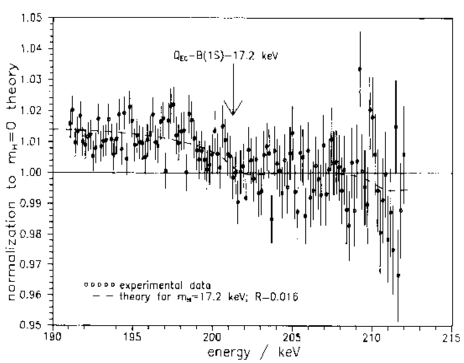
Ne-like ^{71}Ge and ^{71}Ga

- Separation of isobars by ionization potential threshold
- Charge breeding: Z of Ge and Ga is different
- and e-binding is Z-dependent (both Ne-like)



preliminary



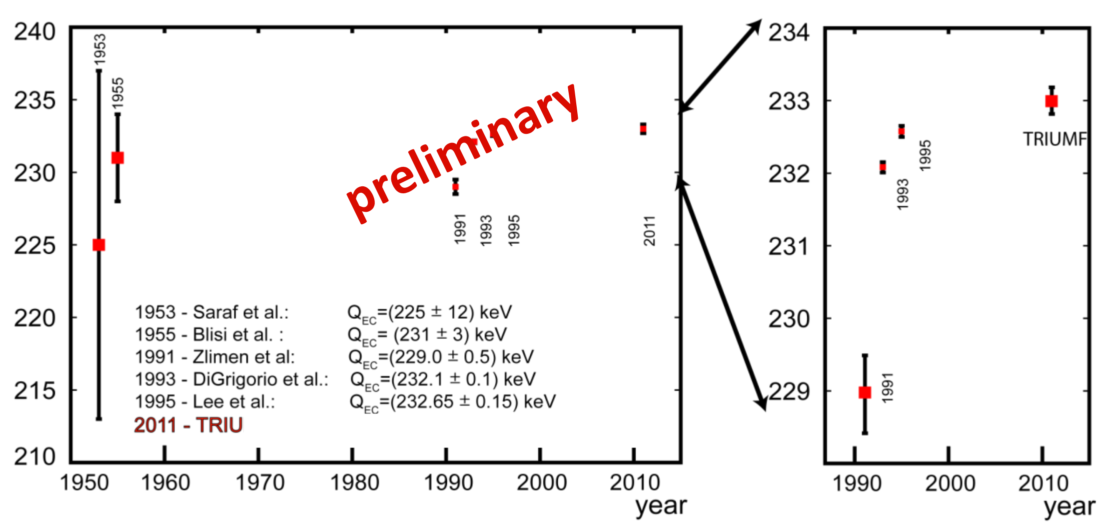


Previous data:

Žlimen et al., PRL **67**, 560 (1991)

Q_{EC}=229.0 ± 0.5 keV

^{71}Ge Q_{EC}-value [keV]



TRIUMF ISAC

D. Frekers, M. C. Simon et al., submitted to PRL

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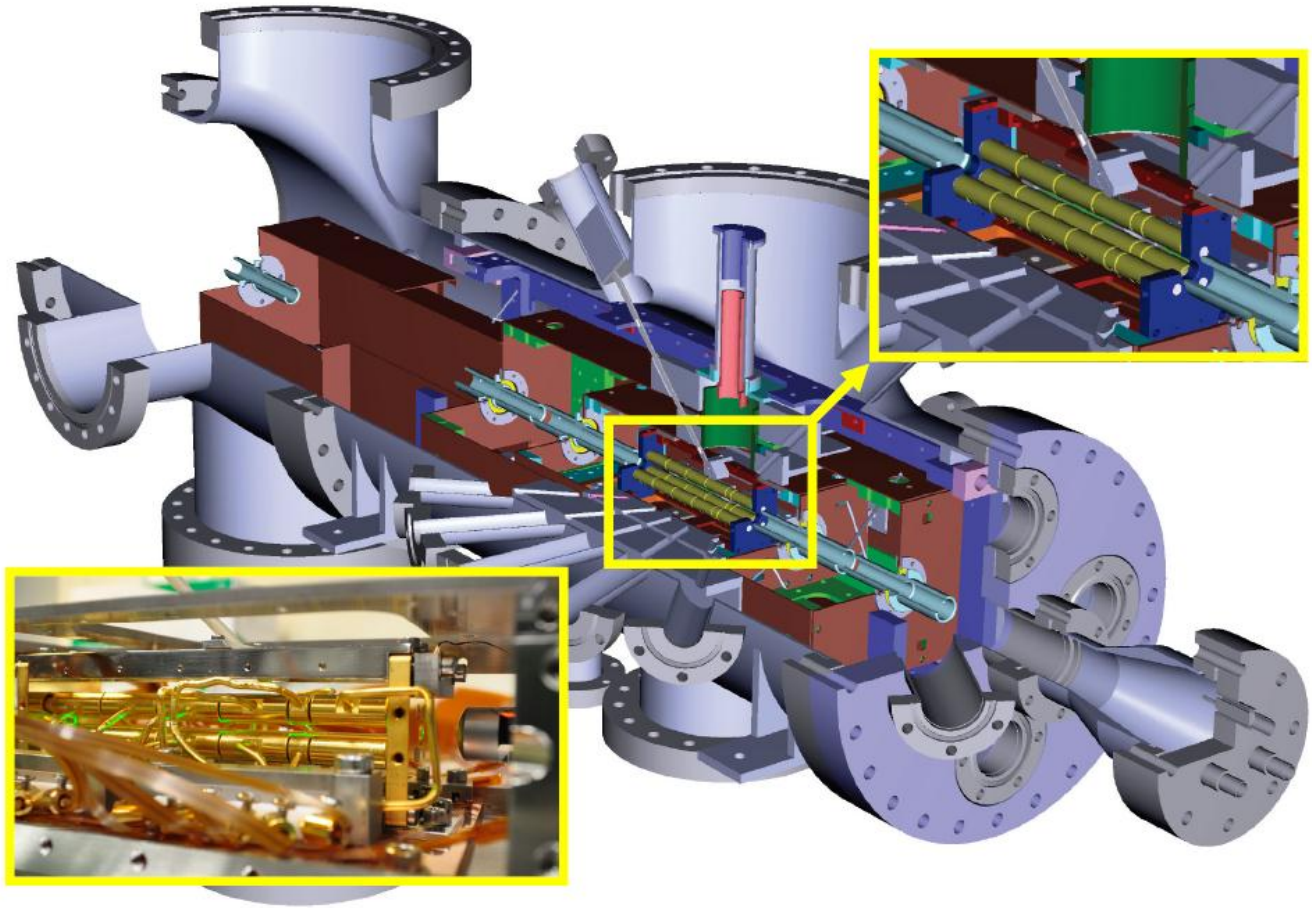
EBIT facility in Heidelberg

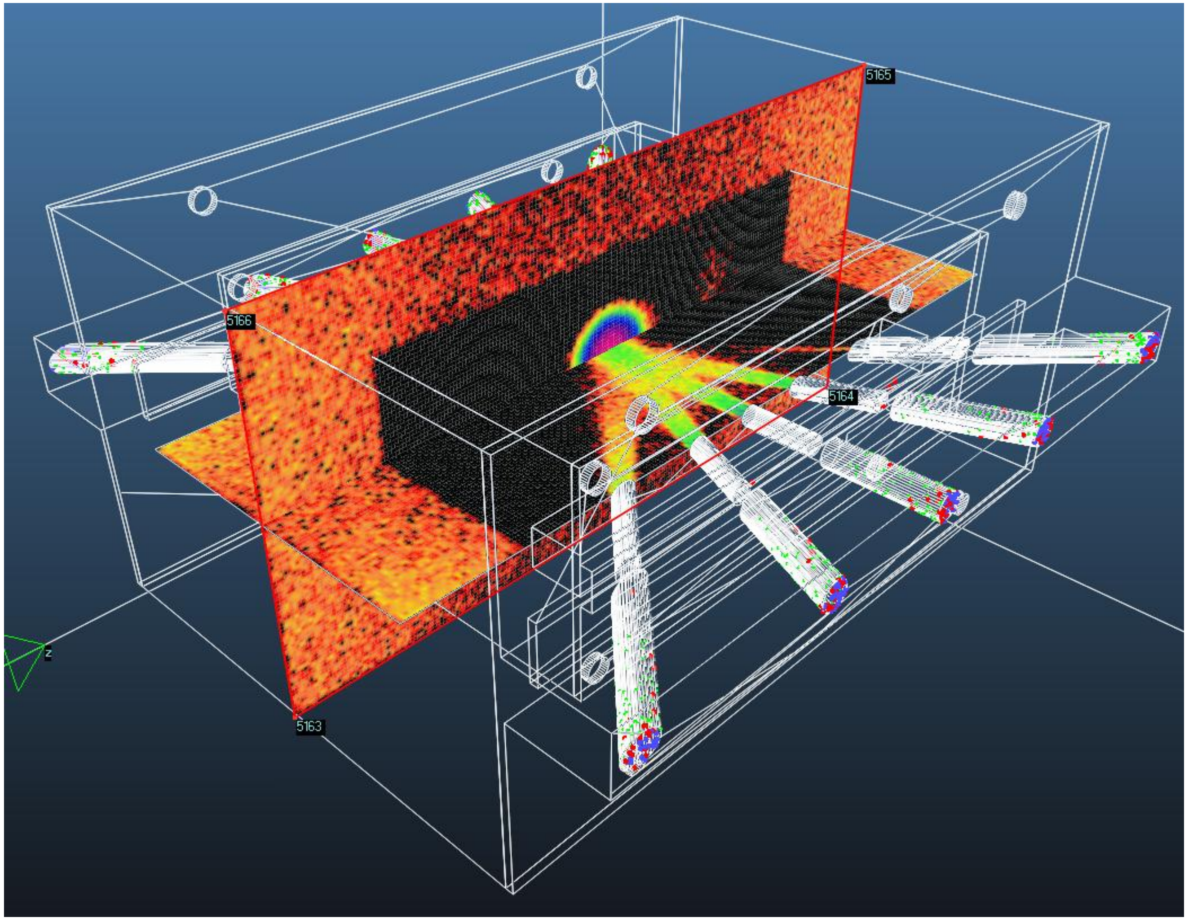


Cryogenic Paul trap CryPTEx (M.Schwarz et al., RSI 2012)

- pulse tube cooler, 40 K and 4 K heat shields
- staged turbo pumps
- Measured pressure 10^{15} mbar

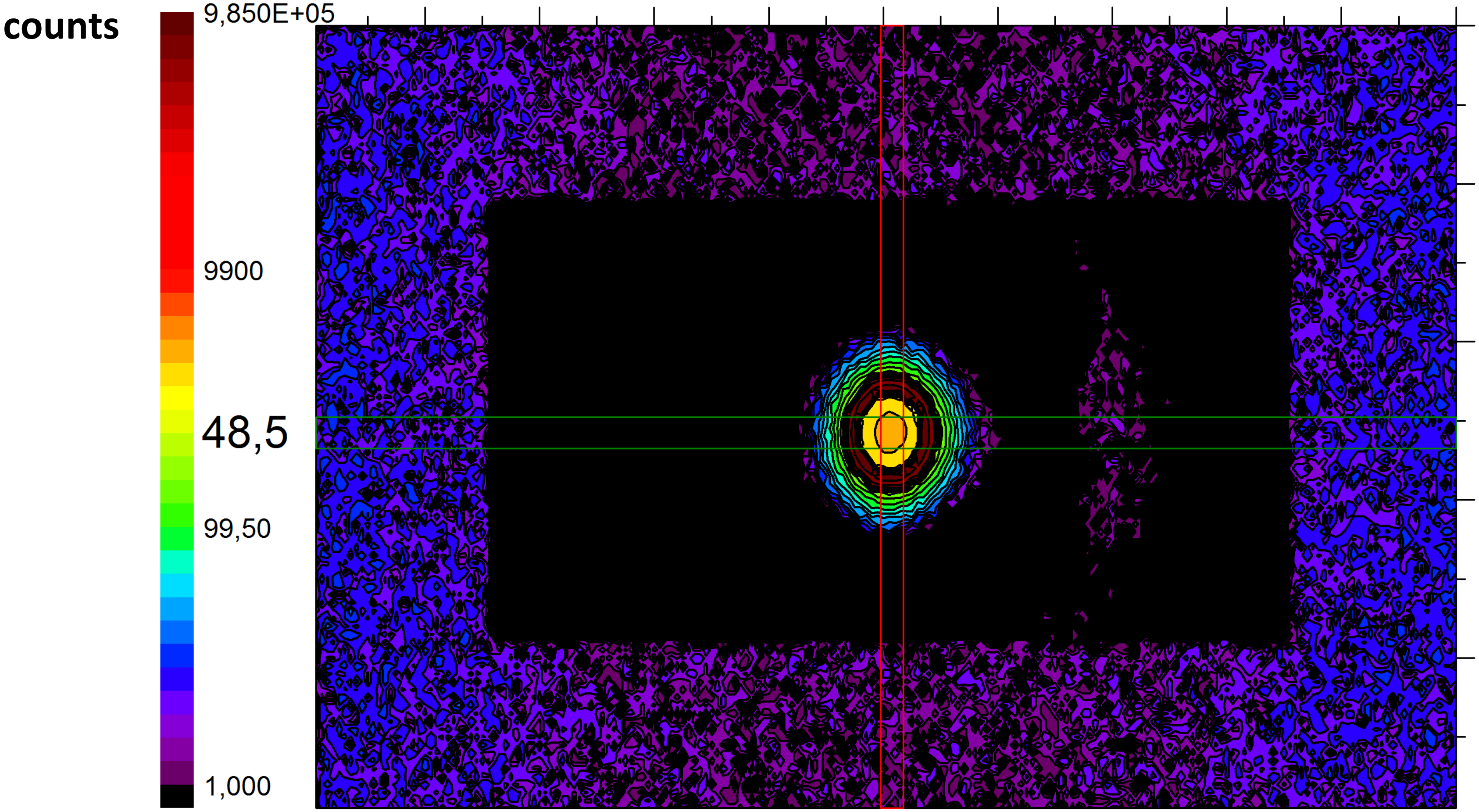
Vacuum simulations

- Monte Carlo simulation by Sören Bieling
- Ballistic gas flow through ports
- horizontal + vertical plane particle number flow

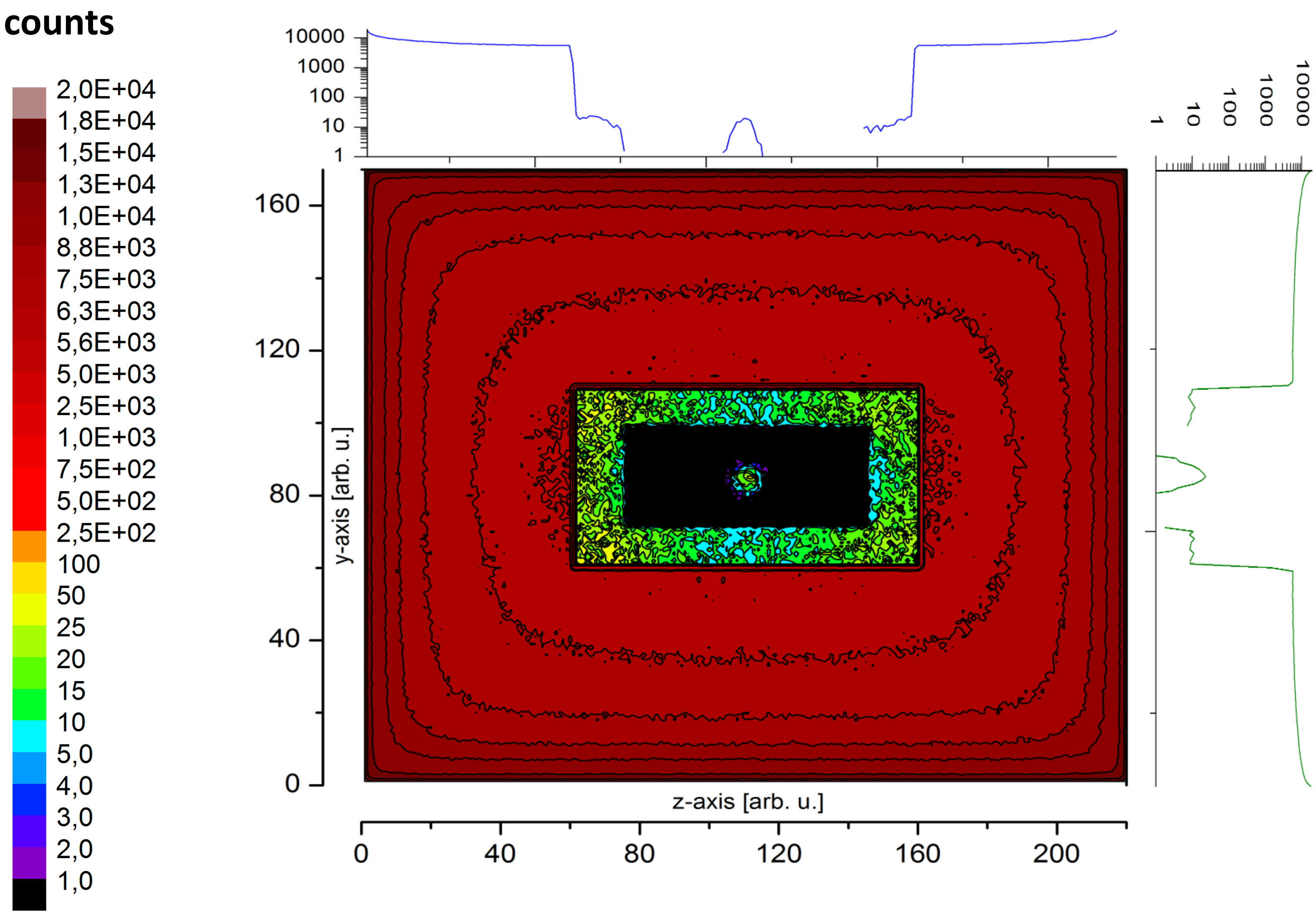


using MOLFLOW+ by R. Kersevan *et al.*, J. of Vac. Sc. & Tec. A **27**, 1017+ (2009)

Close-up 40K & 4K boxes



Section through 297K, 40K & 4K boxes



Continuous neutral injection degrades mean charge state but improves total yield

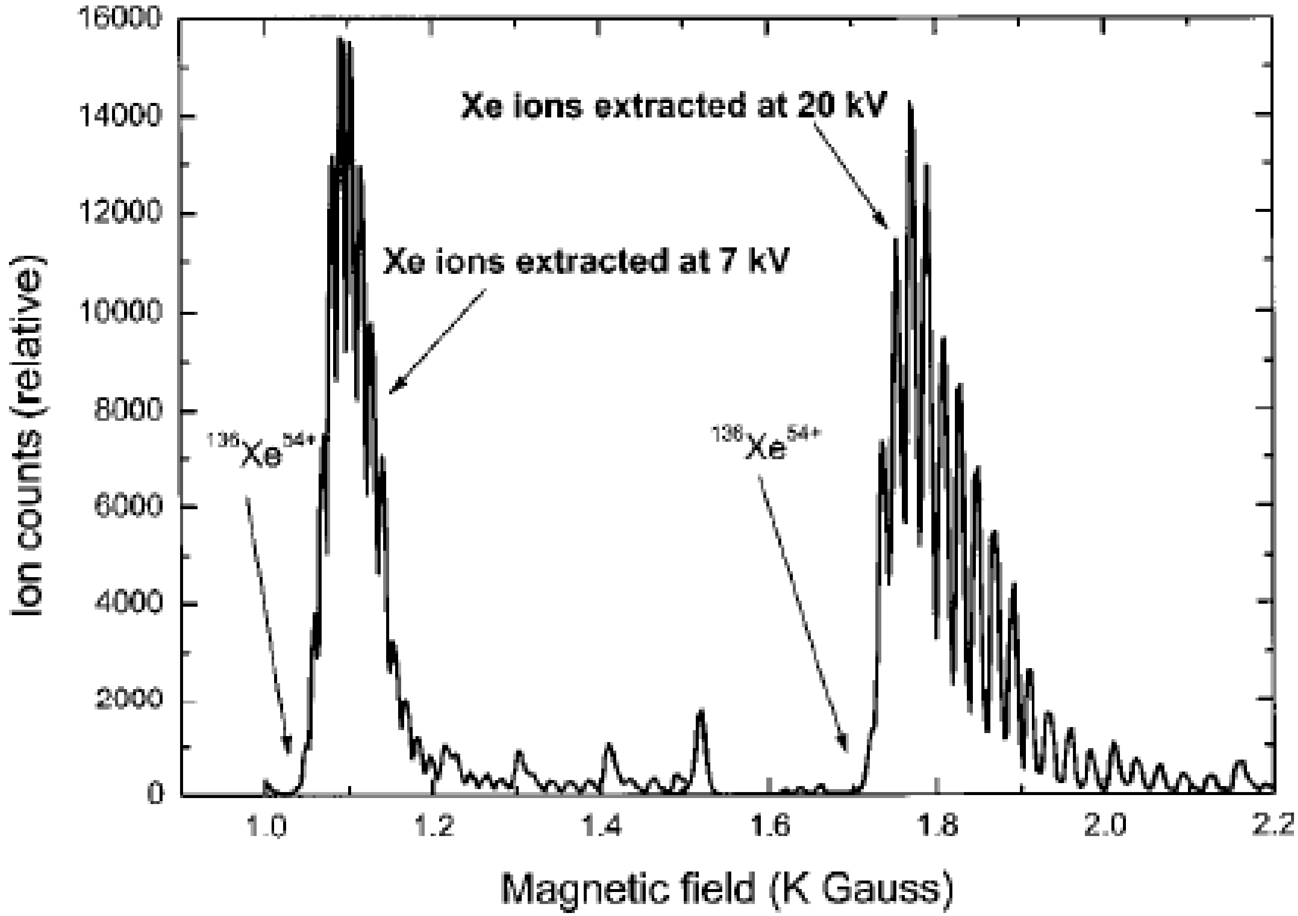


FIG. 3. Charge state analyzed extracted Xe spectra at 7 and 20 keV.

Charge state distribution

even with continuous injection of neutral Xe, the charge state distribution can be very sharp for closed shell ions as He-like or Ne-like systems

Xe^{44+}

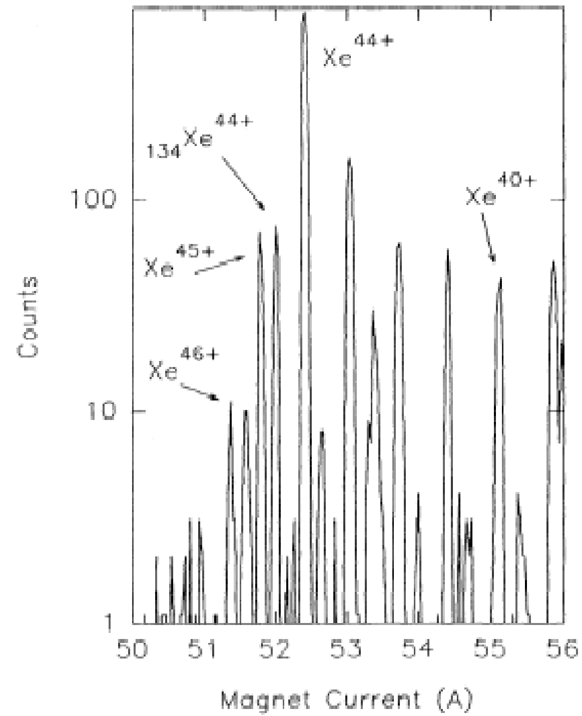
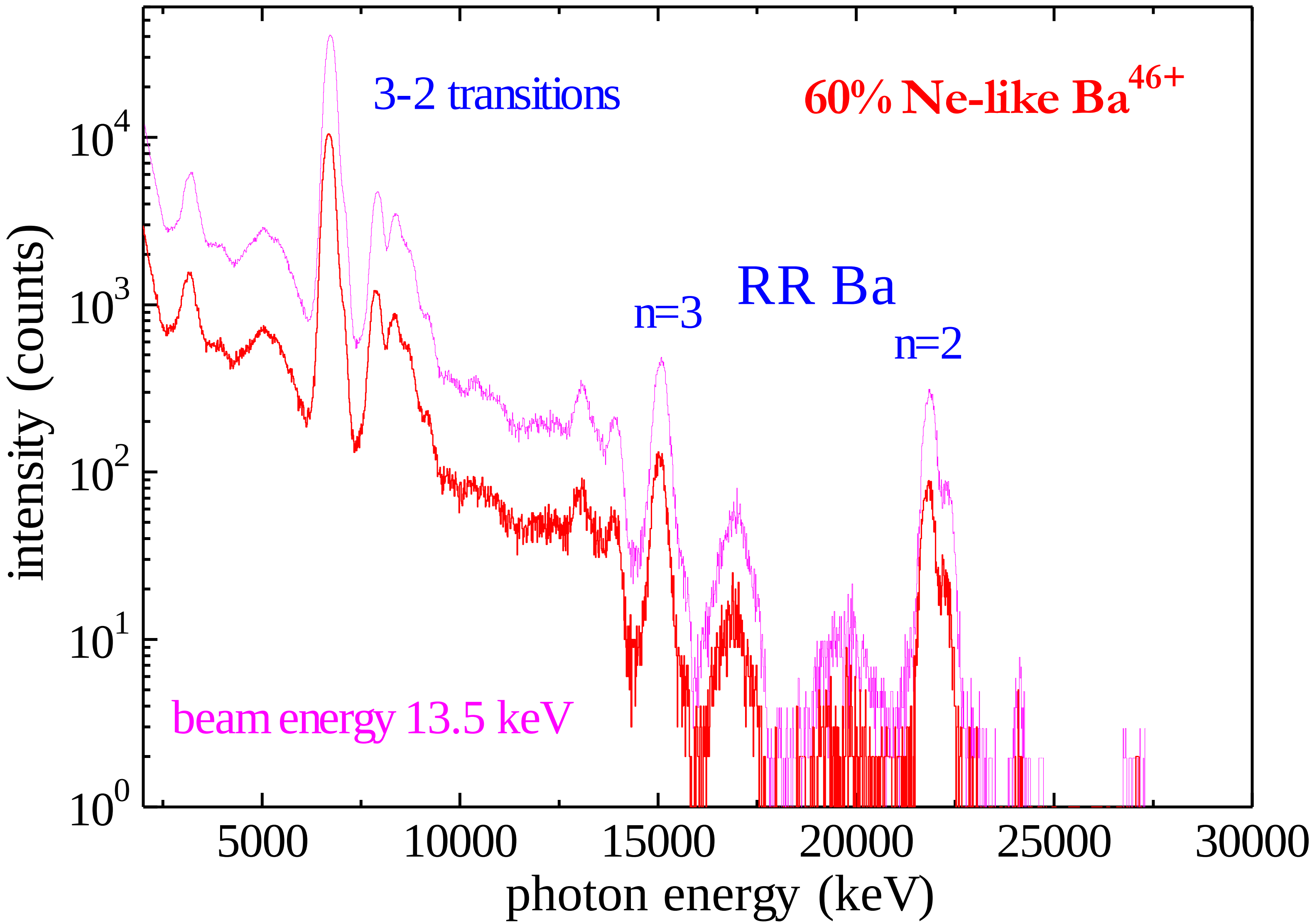


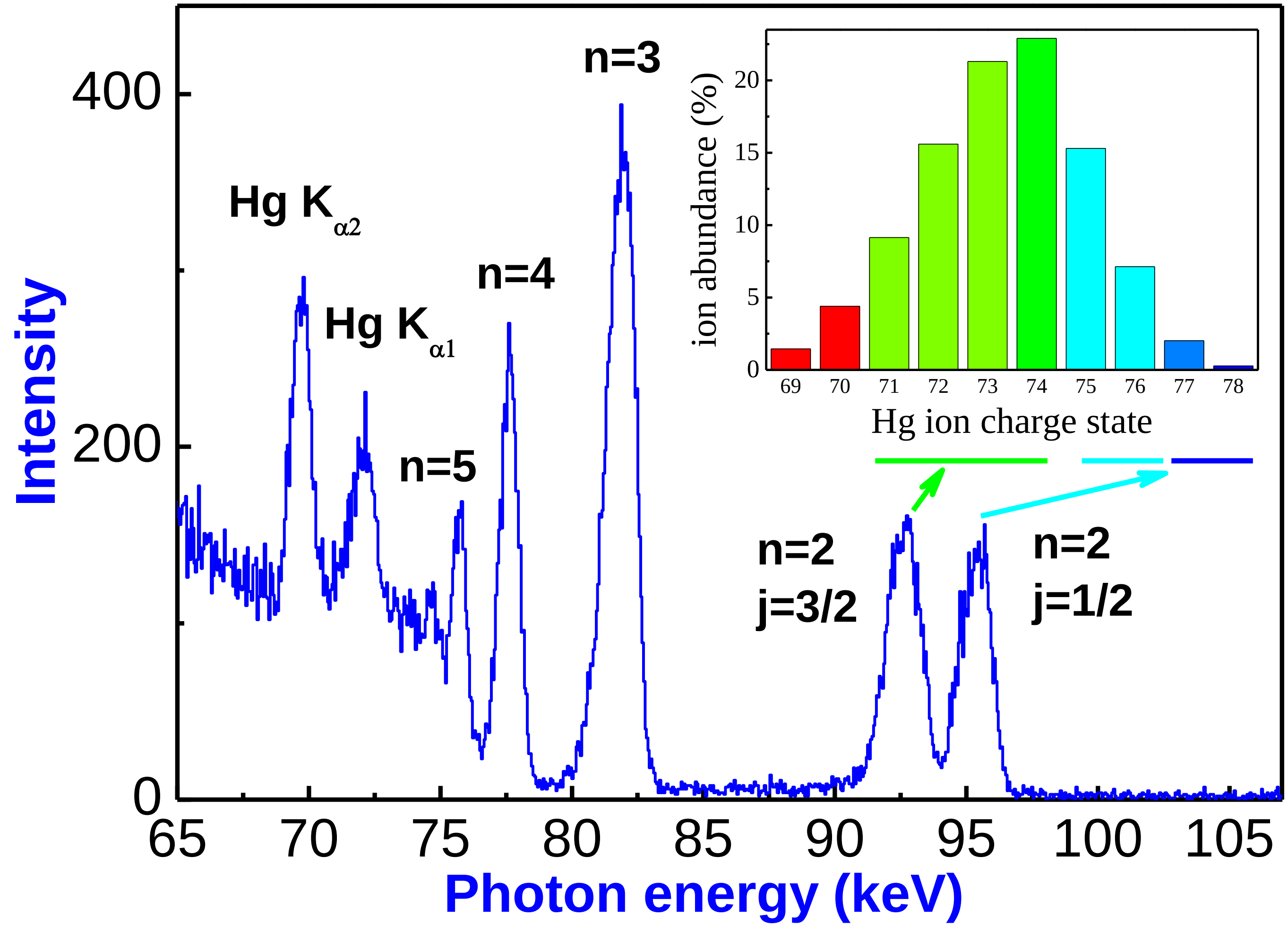
FIG. 1. Xenon charge-state distribution. The distribution peaks at neonlike xenon (Xe^{44+}). The yields of fluorinelike and oxygenlike ions are one and two orders of magnitude lower, respectively. Isotopically enriched xenon, with 90% $_{136}Xe$ and 10% $_{134}Xe$, is used in order to reduce the overlap of the ion peaks. The ions were produced in 800 msec, using a 31-mA electron beam at 7.9 keV.

from: DeWitt *et al*., PRA **47** (1993)

Charge state distribution

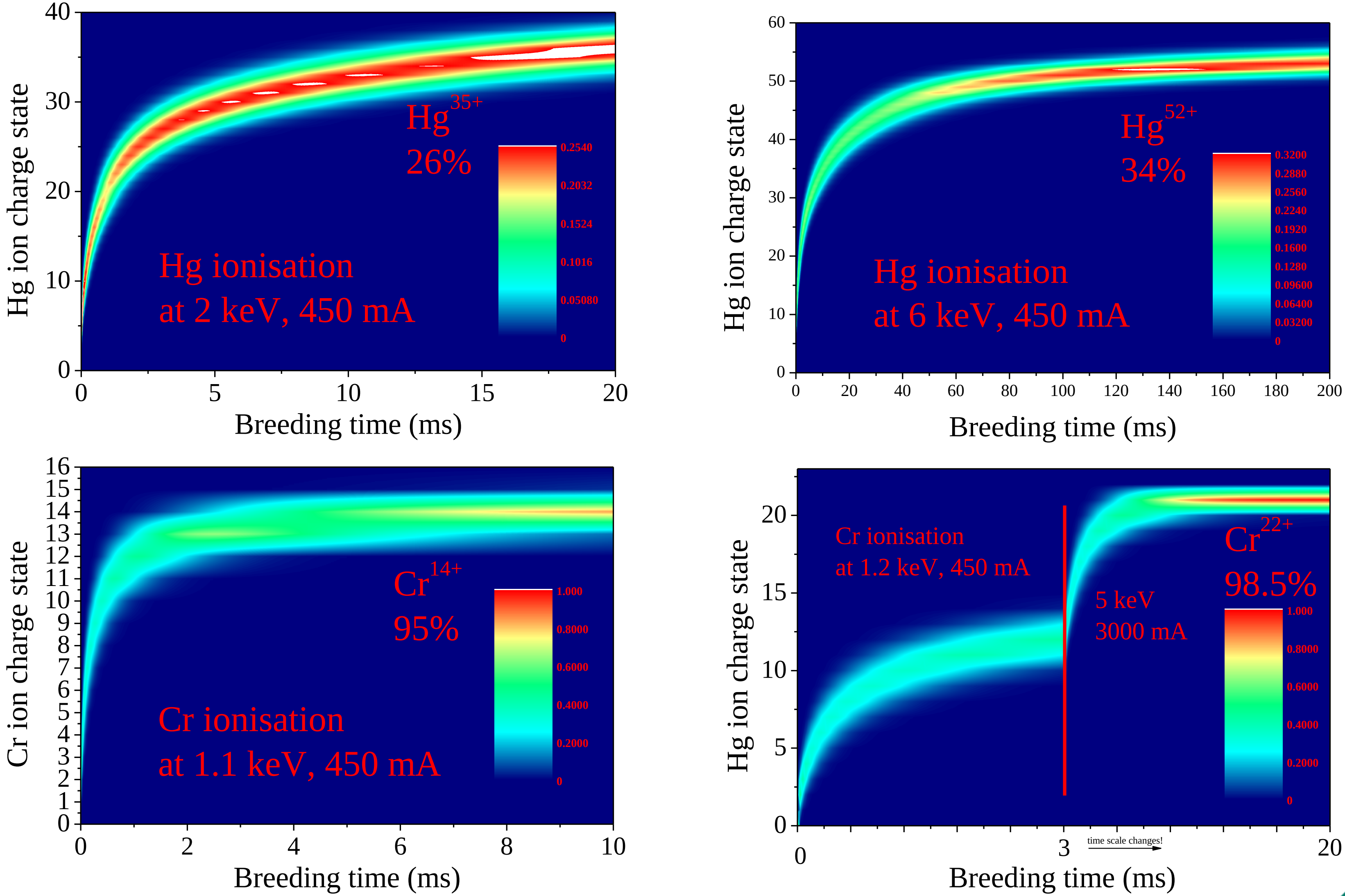


Photorecombination of $Hg^{72+...78+}$

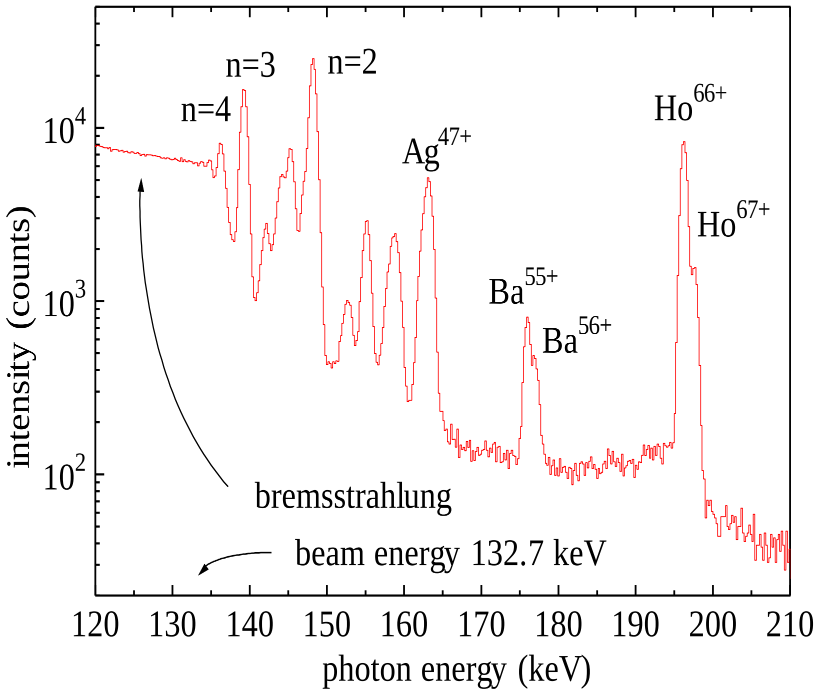


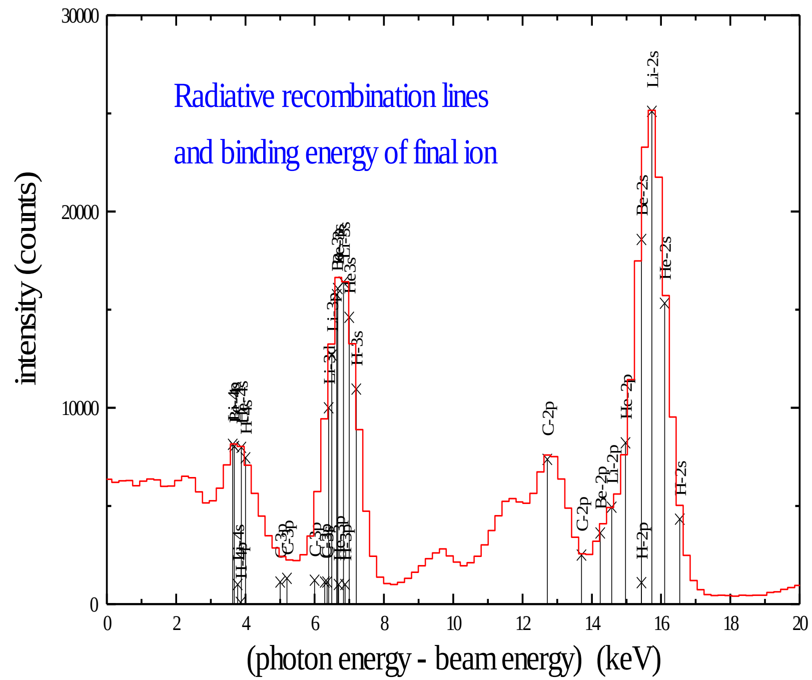
72.5 keV electron beam energy

Charge breeding strategies



Charge state distribution observed through radiative recombination: Ho^{65+} and Ho^{64+} dominate at 132 keV

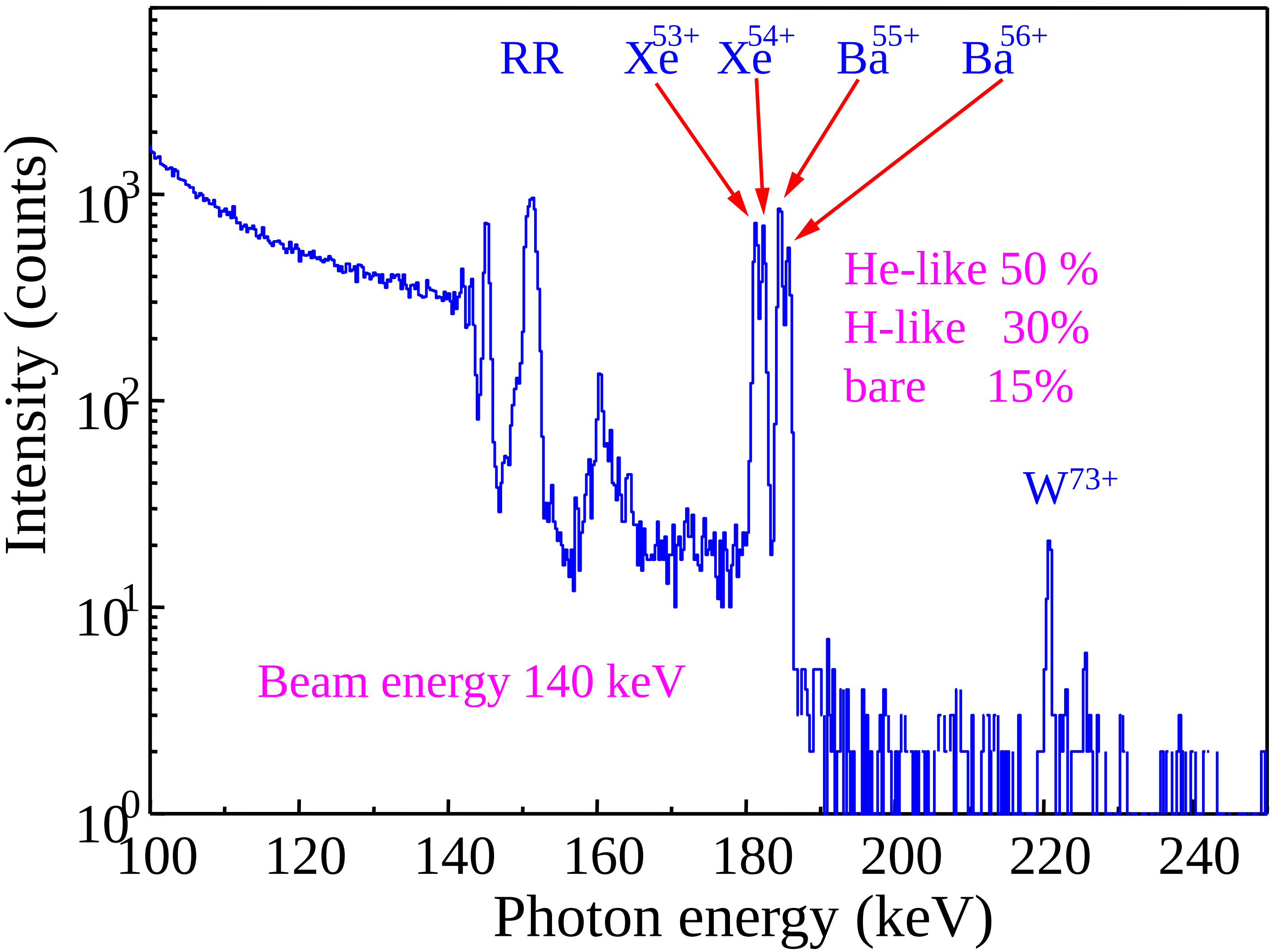




40% Ho^{65+} 25% Ho^{64+}

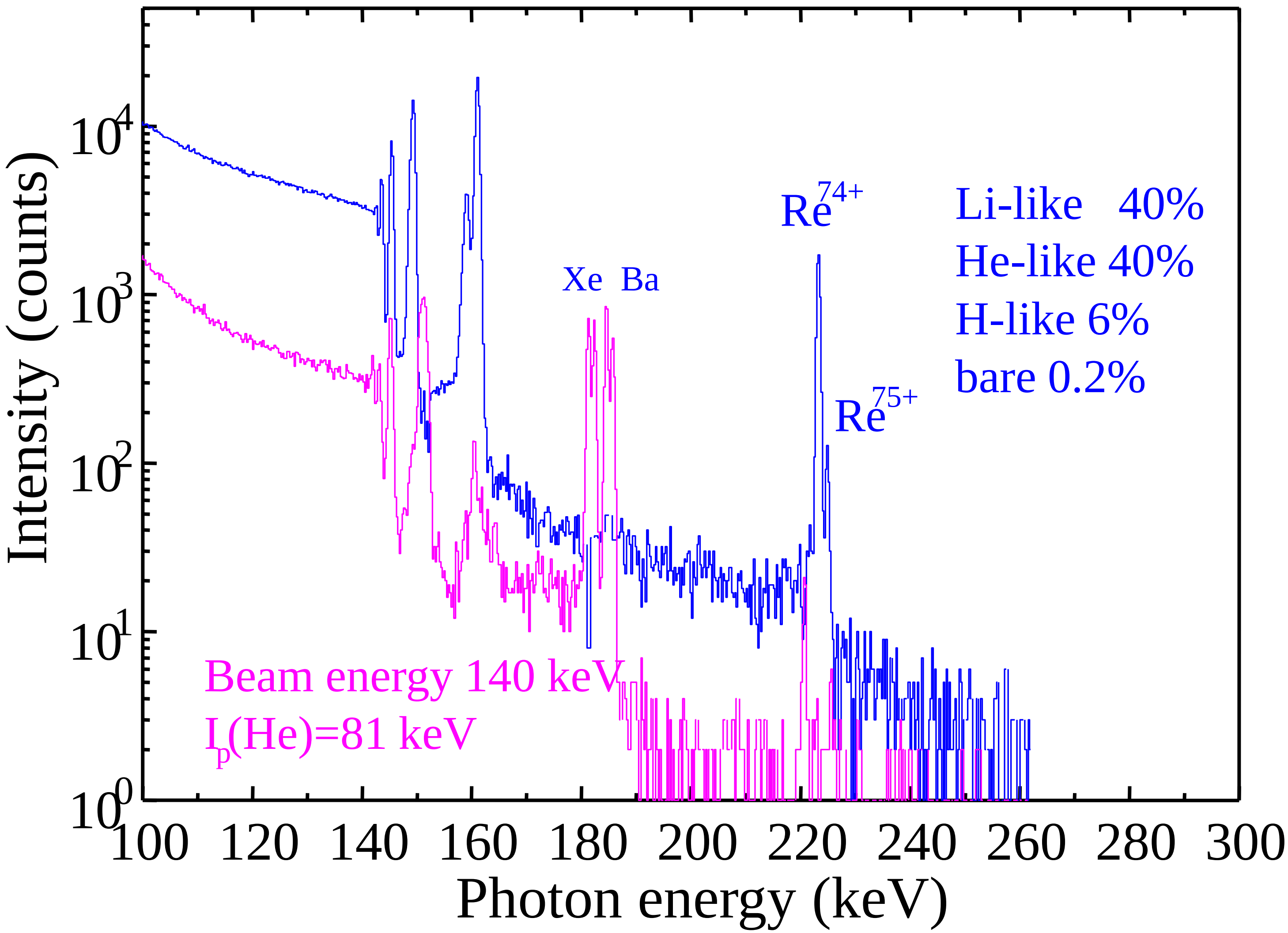
Data from LLNL EBIT, e.g., JRCLU et al., PRL 1996
R. Marrs et al., PRL 1994

Charge state distribution



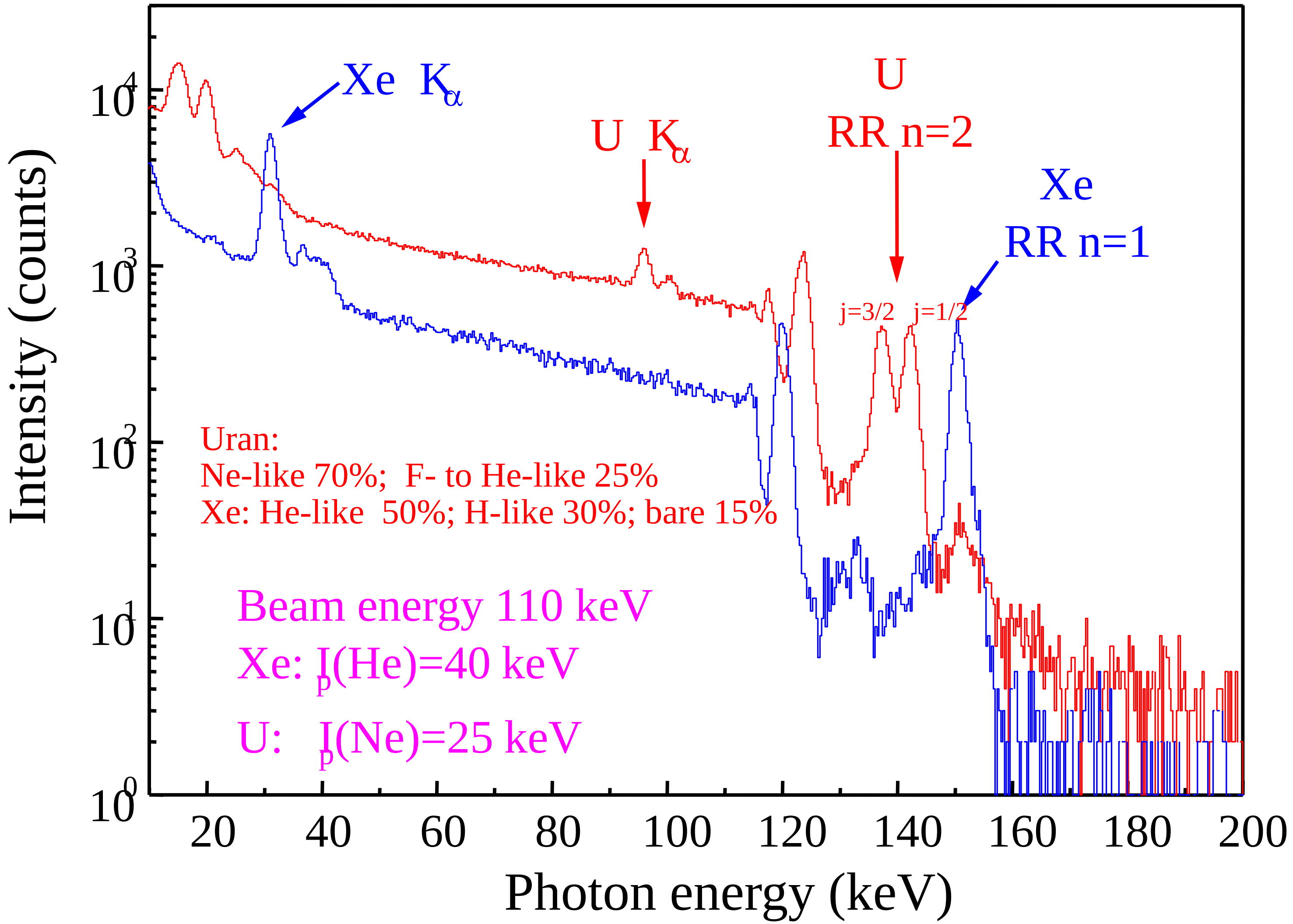
Data from LLNL EBIT, e.g., JRCLU et al., PRL 1996
R. Marrs et al., PRL 1994

Charge state distribution



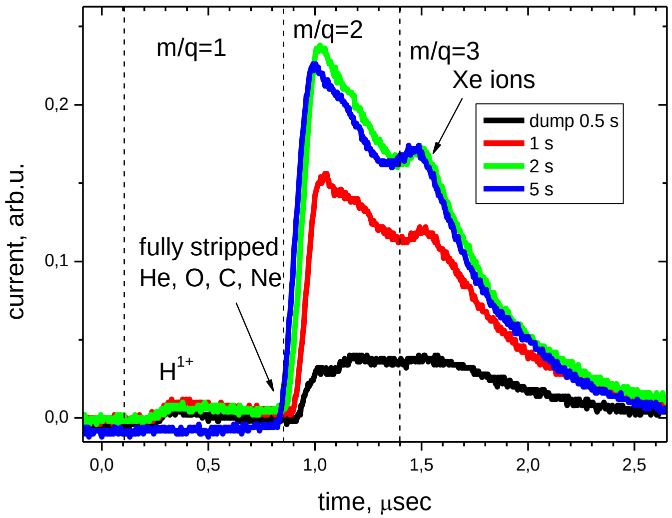
Data from LLNL EBIT, e.g., JRCLU et al., PRL 1996
R. Marrs et al., PRL 1994

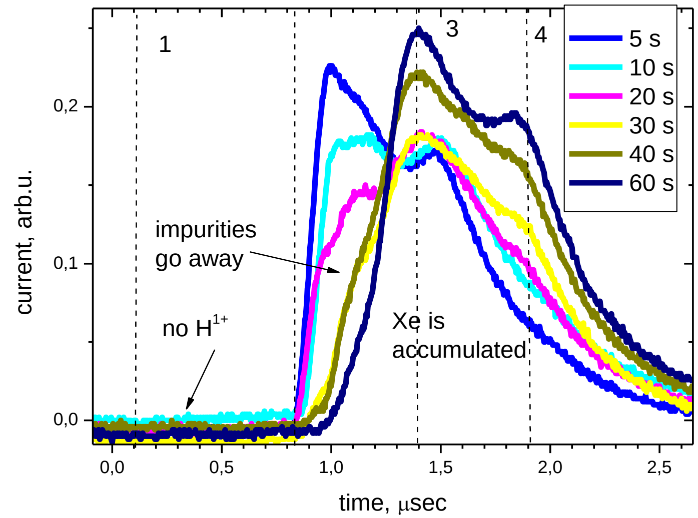
Charge state distribution

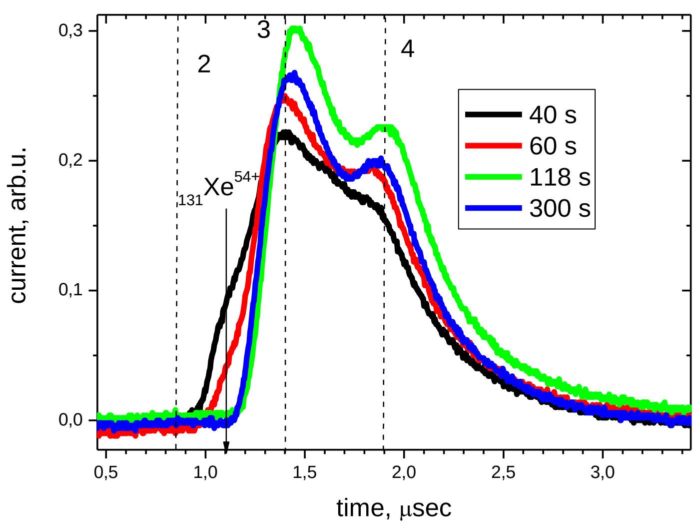


Data from LLNL EBIT, e.g., JRCLU et al., PRL 1996
R. Marrs et al., PRL 1994

Xe dump pulses







Ions extracted in pulsed mode

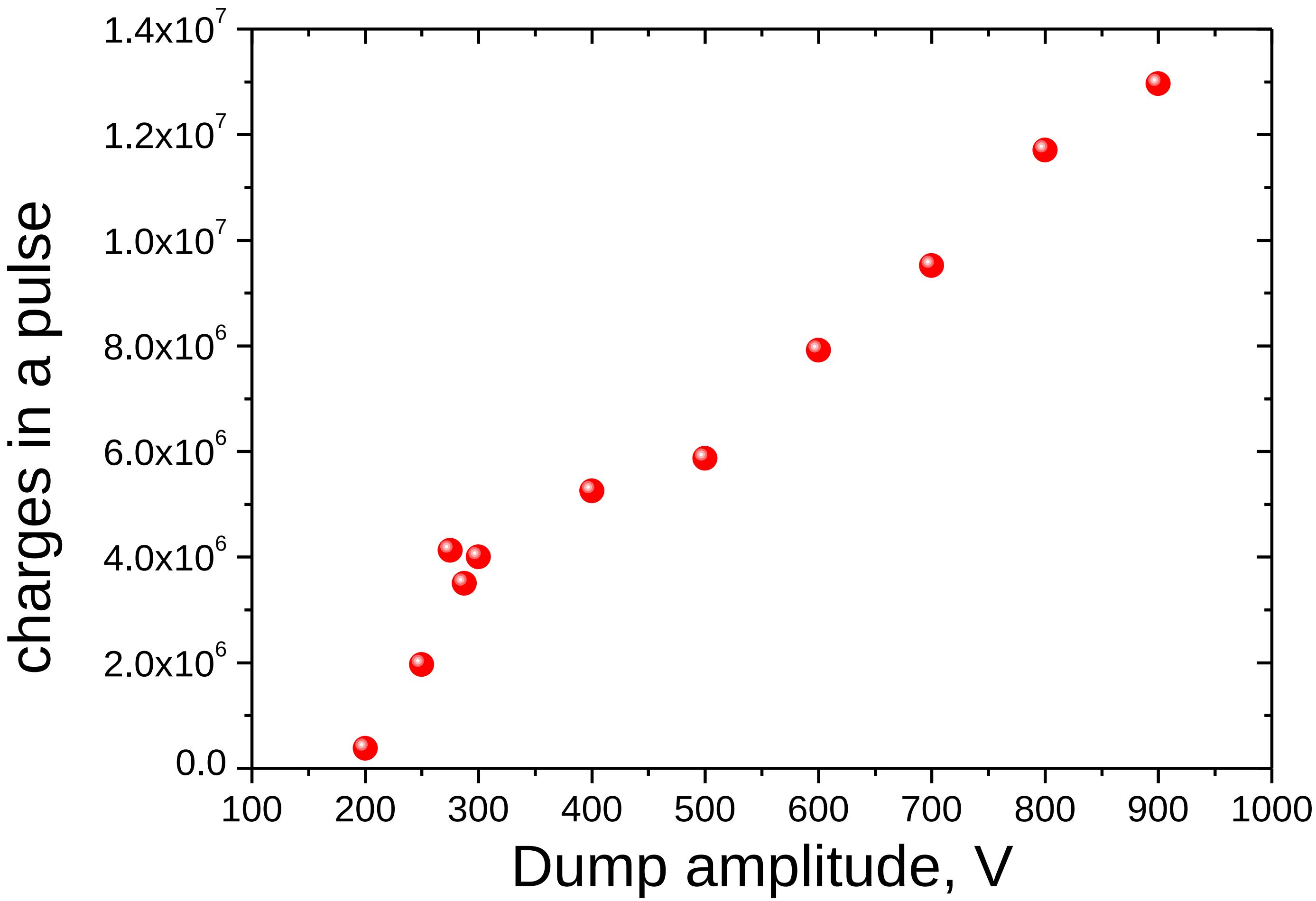
Injection of Xe

I_e=240 mA, U_{DT}=10 kV

U_{GUN}=30 kV

Currents are measured by the Faraday cupper for each dump

Total number of elementary charges



Integrated charge of ions extracted in pulsed mode depends on dump voltage pulse amplitude: no saturation yet

Summary

- The Heidelberg EBITs operate between 40 eV~120 keV, with currents from 1 mA~450 mA
- Both liquid He and cold head operation, 6~8 T magnets
- Vacuum levels between 10^{-12} and 10^{-15} mbar
- Cryogenic vacuum system extremely convenient
- Alignment problems less severe than in simulations

- X-ray and VUV diagnostics imperative for performance
- Radioactive isotopes down to 10 ms have been bred (TRIUM EBIT)
- Dense ion target for ion-photon beam interaction studies
- Ions extracted in continuous and pulsed modes
- Isobar separation improved through electronic shell as well as state selective charge breeding (shell closures and dielectronic resonances)