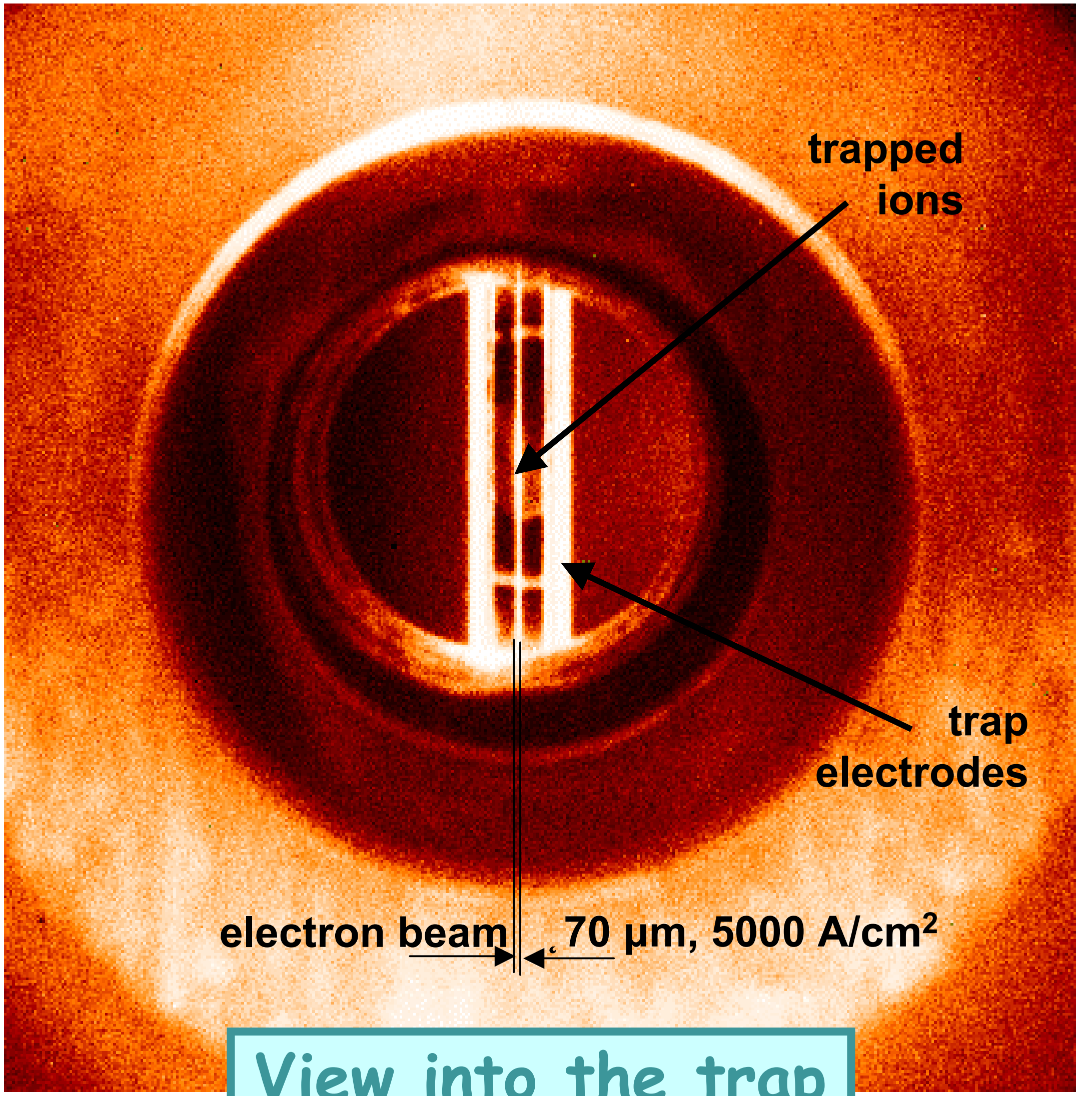
The Stockholm EBIT (Electron Beam Ion Trap)

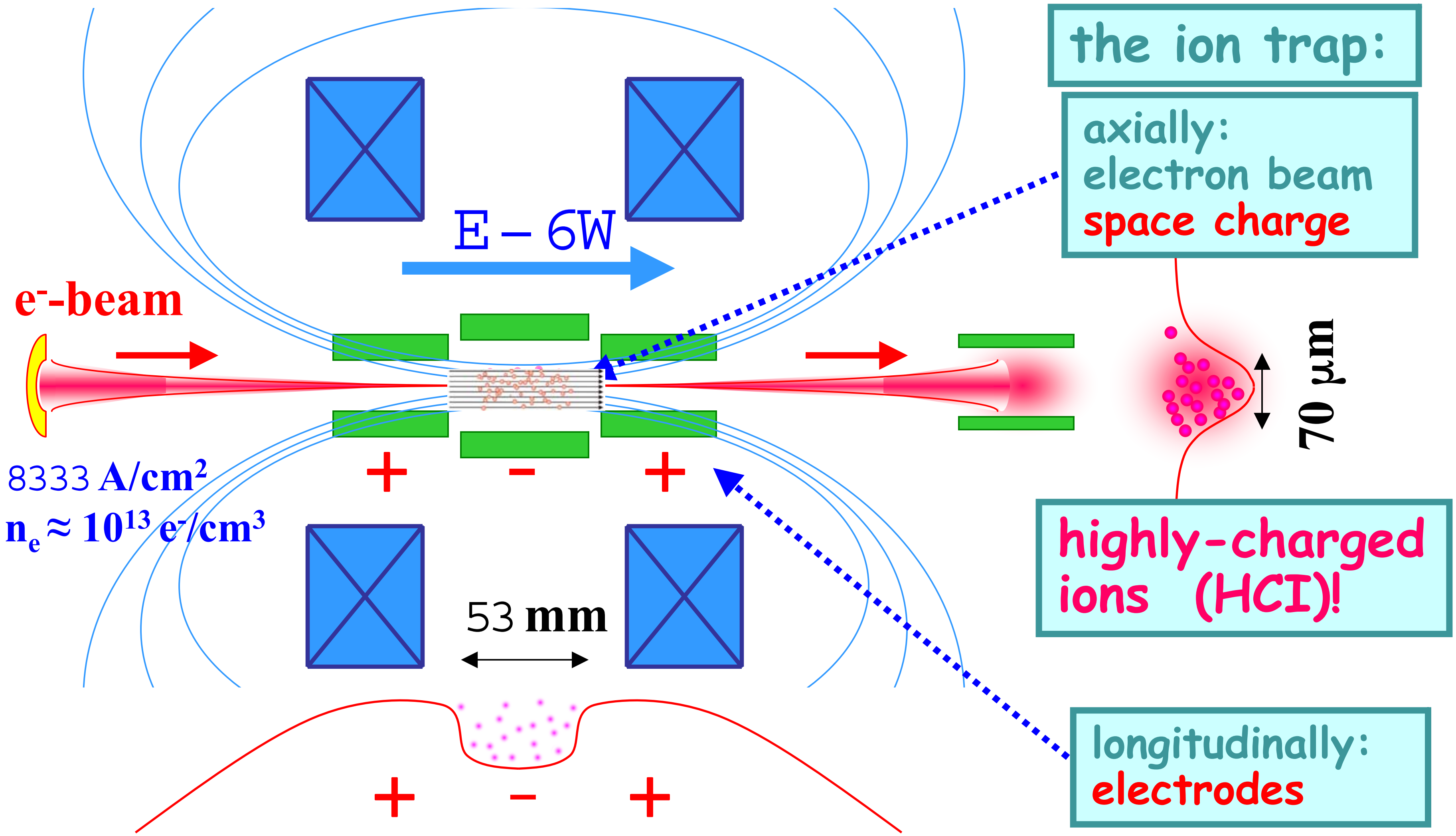


View into the trap

The Stockholm Electron Beam Ion Trap

- **1.** Basic principles of R-EBIT
- **2.** Optimizing Trap and Electron Beam
- **3.** Recombination with Electrons
- **4.** Photon Experiments in the Trap
- **5.** Extracting an Ion beam for experiments with nano-capillaries, precision mass determination
- **6.** Upgrade to a super-EBIT (250 kV)

principle of an EBIT (electron beam ion trap)



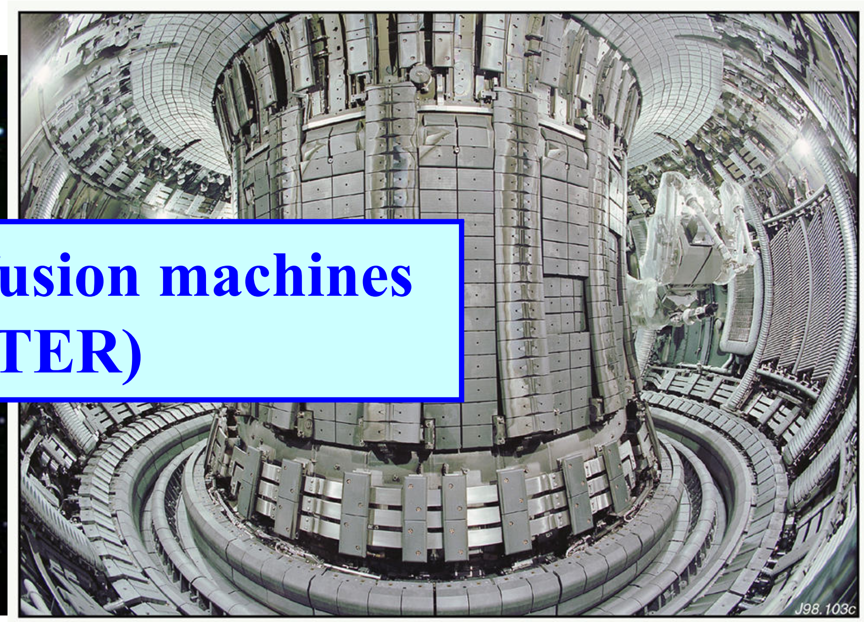
trap potential $U_t \approx$ 100 V
(q ion charge) $qU_t \approx$ 5000 eV

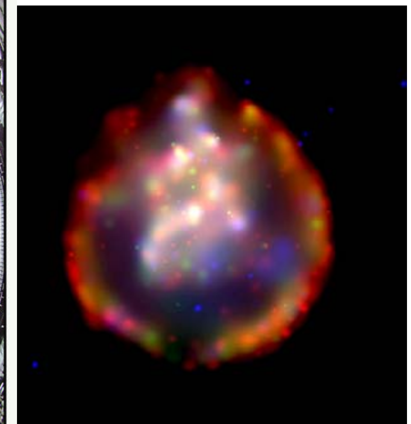
Highly Charged Ions(HCI): where, why, how?

- They are everywhere in our (galactic) neighbourhood and beyond: Tokamak, laser produced plasmas, Solar wind, Solar corona (and nucleus), Supernova remnants, shocks, active galactic nuclei, ...

- They interact proportional (square) with their charge with external world (accel. fields, electrodes,...)

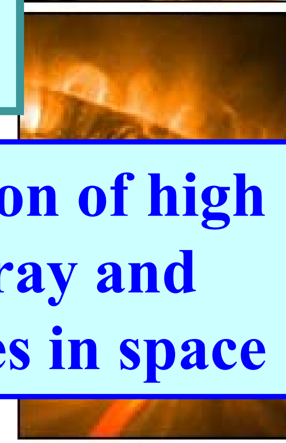
- Atomic structure can be selected, strong relativistic and QED effects

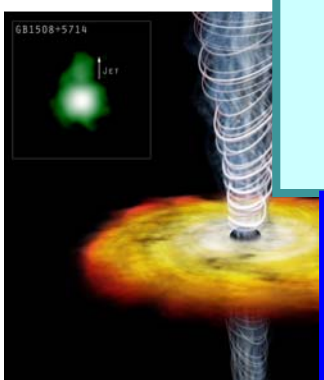


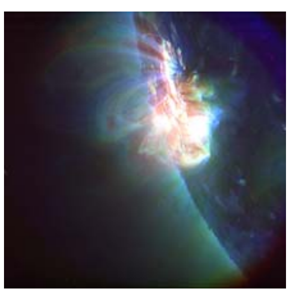


new fusion machines
(...., ITER)

There are plenty of good reasons for making HCI...



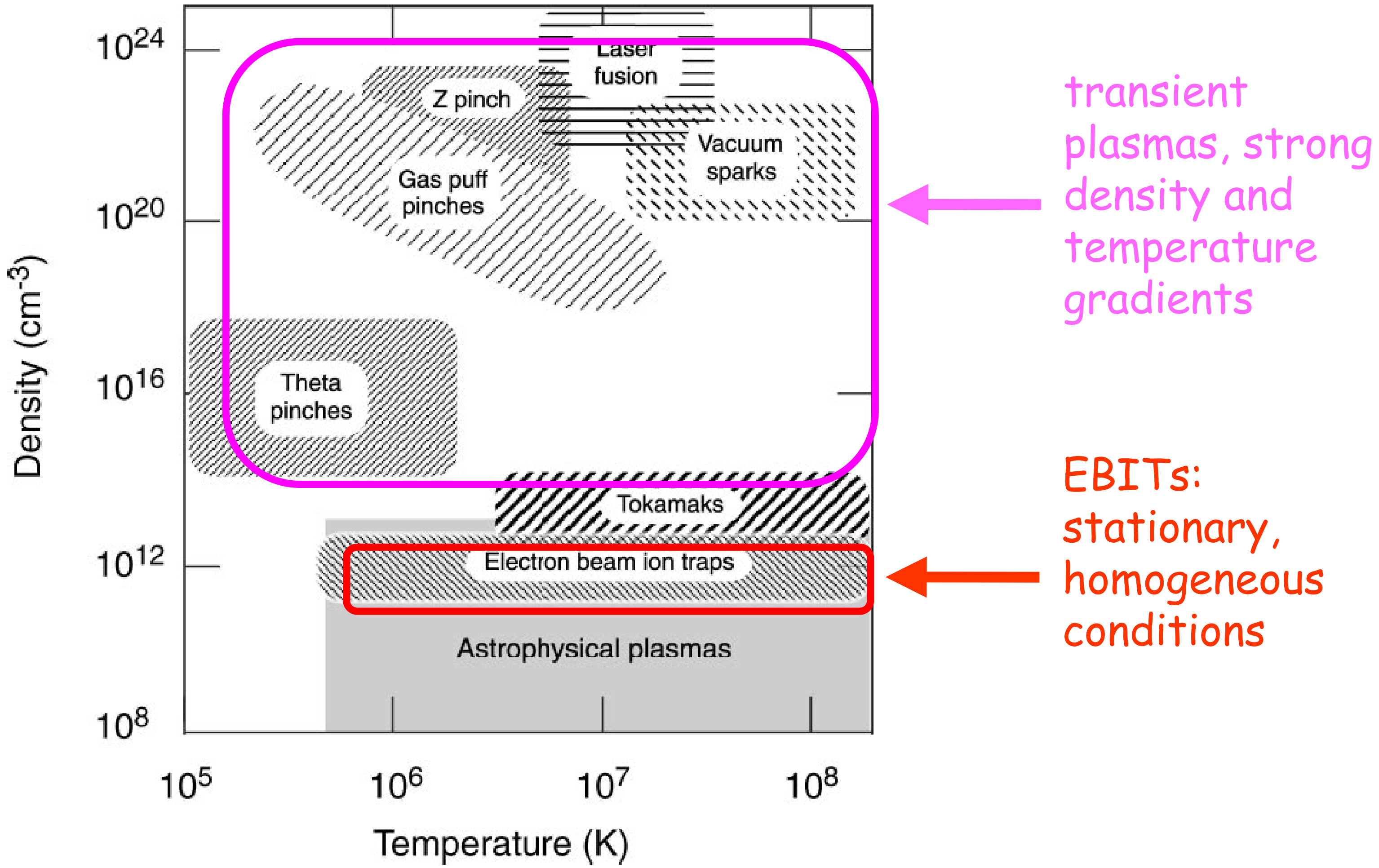




observed: wavelength, line ratios
and
line widths...
inferred: identification of species, temperature, magnetic field, plasma density...

eration of high
n x-ray and
ellites in space

EBITs are good to reproduce the conditions prevailing in astrophysical & fusion plasmas



Density and temperature space sampled by different spectroscopic light sources

P. Beiersdorfer, Annu. Rev. Astron. Astrophys. 41 (2003) 343-390

Electron Beam Ion Traps (EBITs) around the World

Place

- **Livermore LLNL (US)**
- **Berkeley LBL (US)**
- **Washingt NIST (US)**
- **OXFORD Uni (UK)**
- **BERLIN MPI (D)**
- **SHANGHAI Fudan (C)**
- **HEIDELBERG MPI (D)**
- **TOKYO Univ (J)**
- **STOCKHOLM U (S)**
- **Vancover TRIUMPF (CD)**
- **Harvard U(ordered) (US)**
- **Belfast U(construct) (UK)**
- **Darmstadt GSI (planned) (D)**

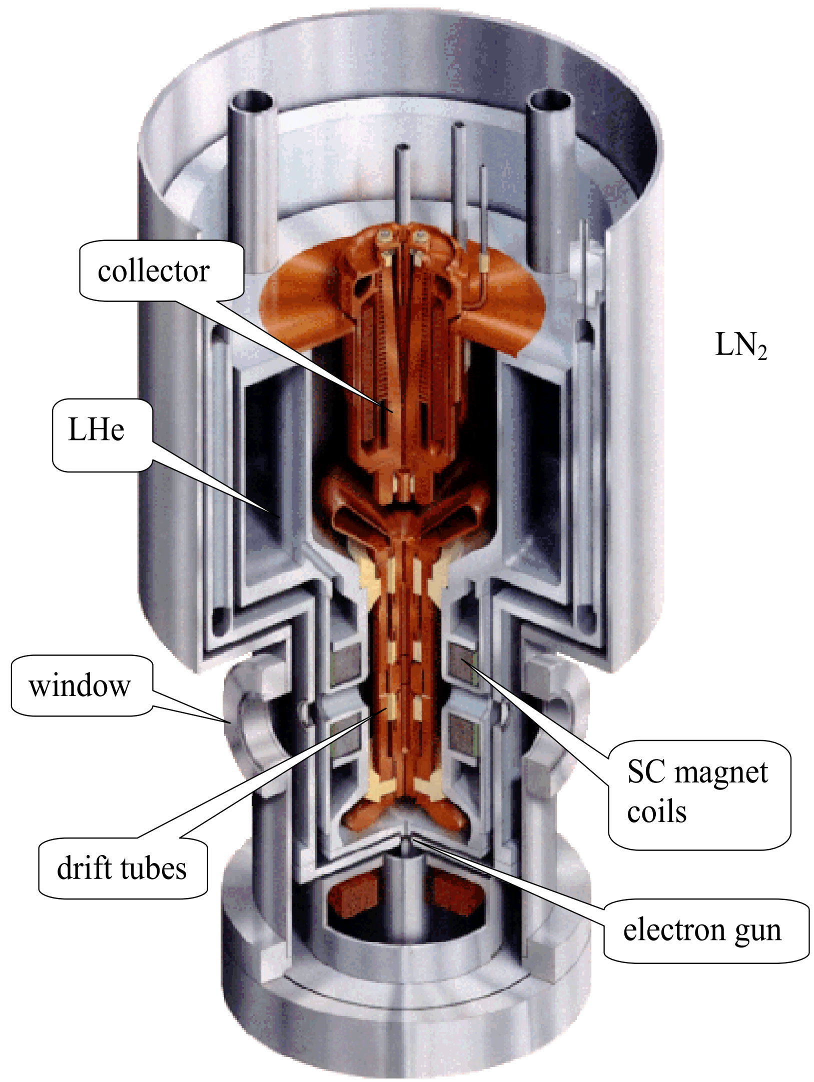
- USES
  - Spectroscopy
  - Quantum computer
  - HCI surface studies
  - Spectroscopy
  - Recombination studies
  - Spectroscopy
  - Collisions, Spectroscopy
  - X-ray microscope
  - Spectroscopy, masses
  - Radioactive Ions, masses
  - Recombination studies
  - Collisions, Spectroscopy
  - Radioactive Ions, masses

A little bit of history...

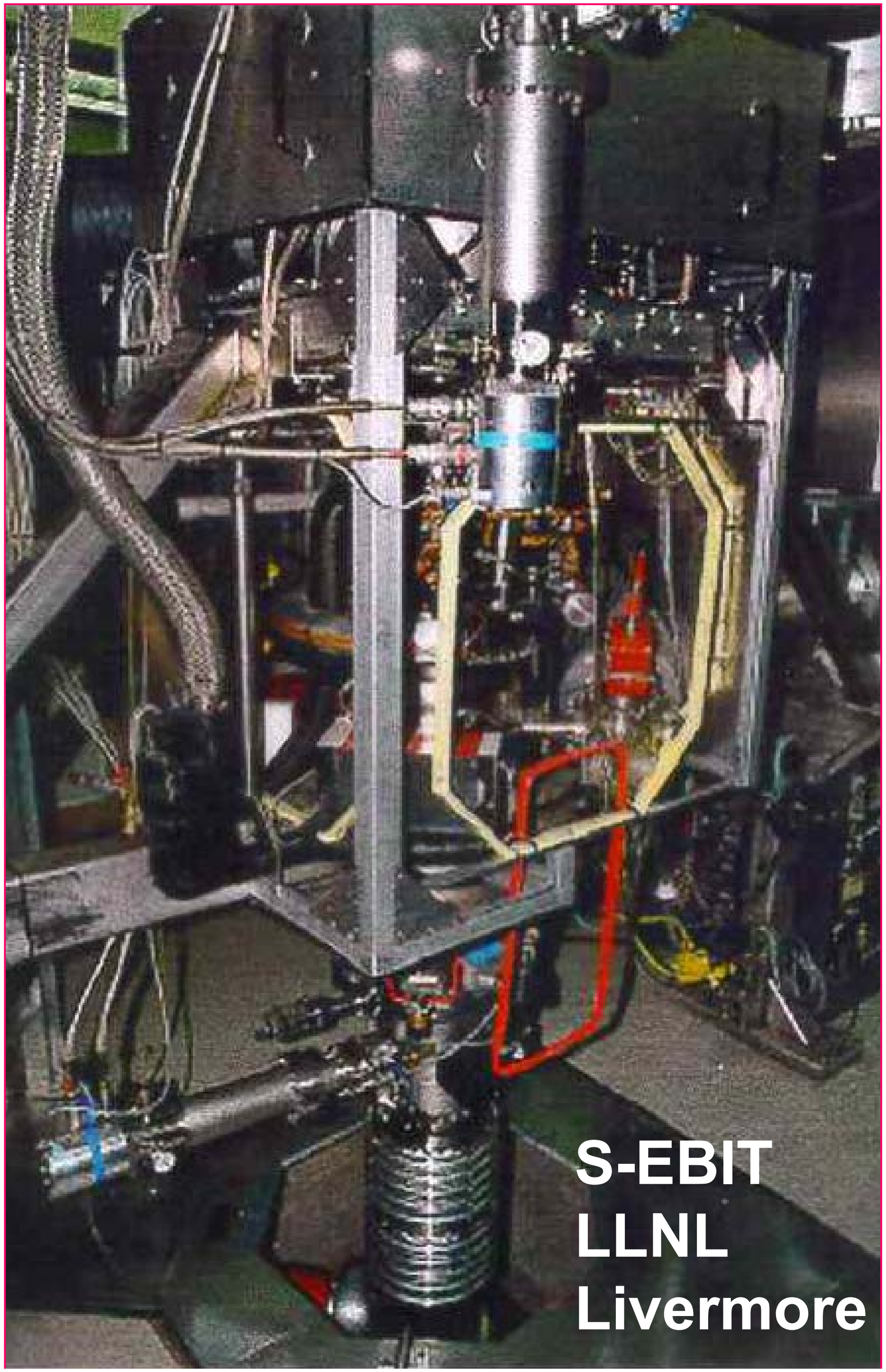
The original EBIT development at Livermore Lab. (Levine&Marrs), based on EBIS principle by Donets(Dubna), changing an already smart design of an EBIS to an even better one with S-conducting Helmholtz magnet

First SuperEBIT was similarly built (R.Marrs) around ´95 to produce bare U^{92+} with a electron beam energy of up to 200 keV.

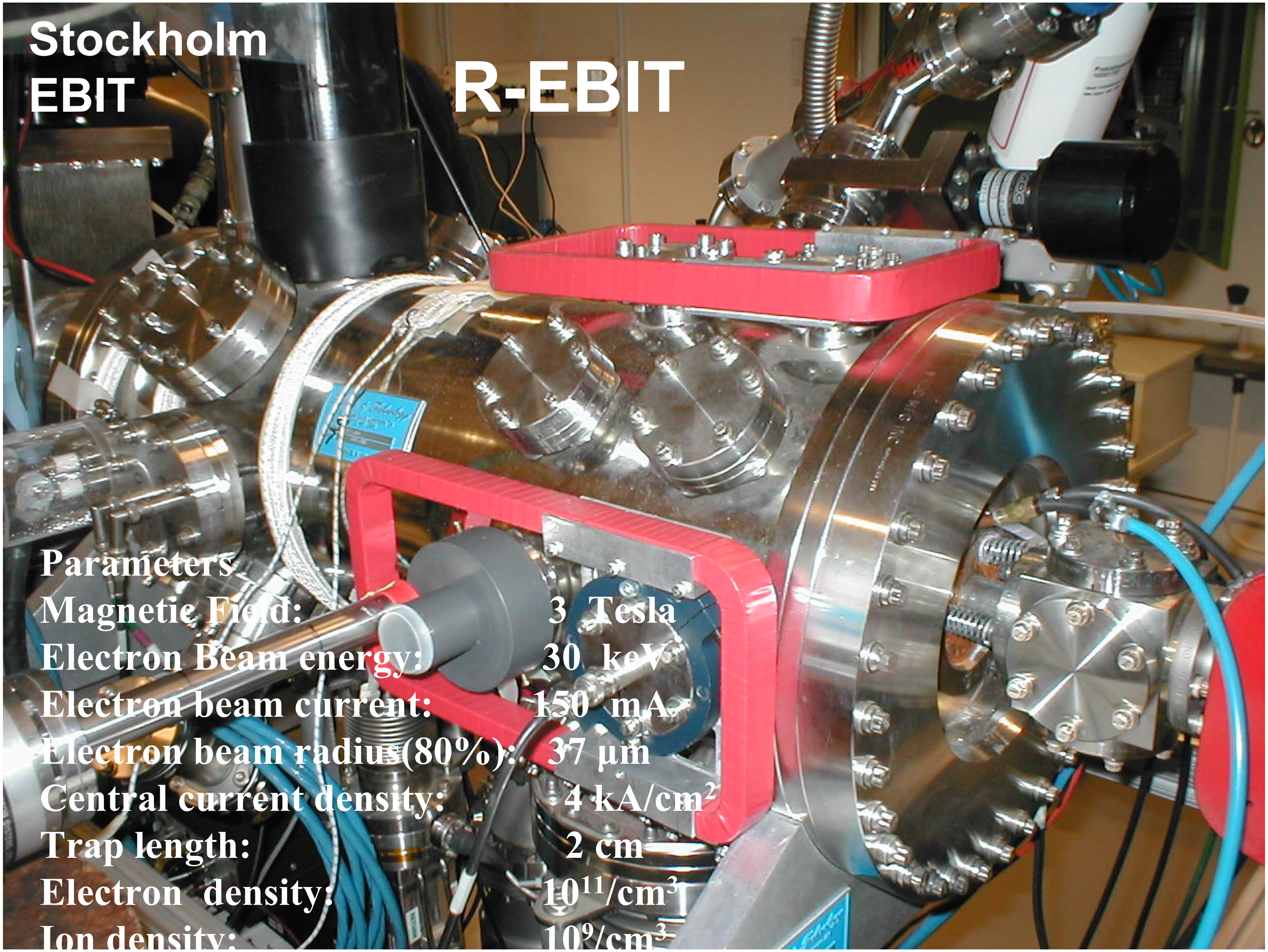
Electron Current 280 mA, densities around 6000 A/cm^2



EBIT II

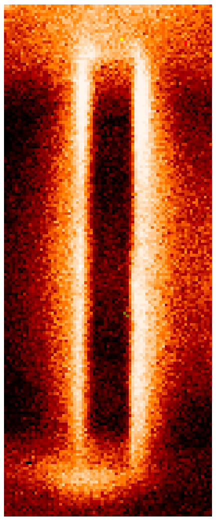

S-EBIT
LLNL
Livermore


Tokyo
EBIT
Lqu. N2 + He 6 Ltr/h 5000 Kr/day

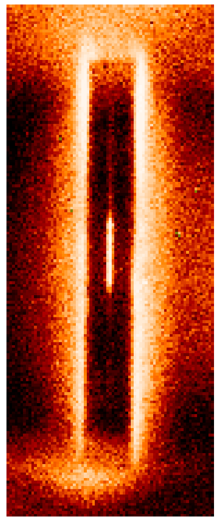


S-conduct. magnet, fully Refrigerated ⇒Lqu. N_2 + He 0 Ltr/h,

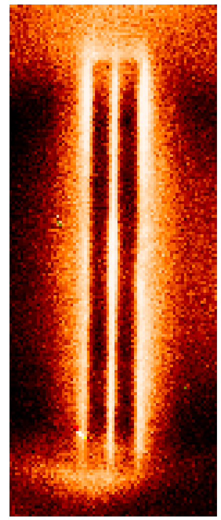
filling the trap by an atomic beam injector:



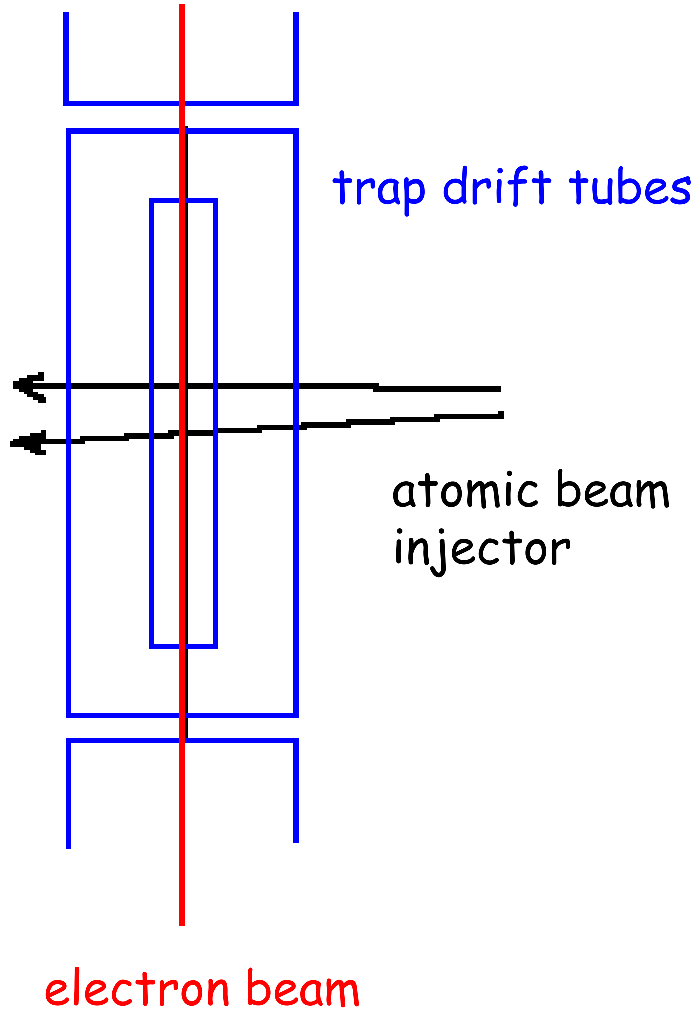
injection off,
trap off;
EBIT empty



injection on,
trap off;
only neutrals
passing through

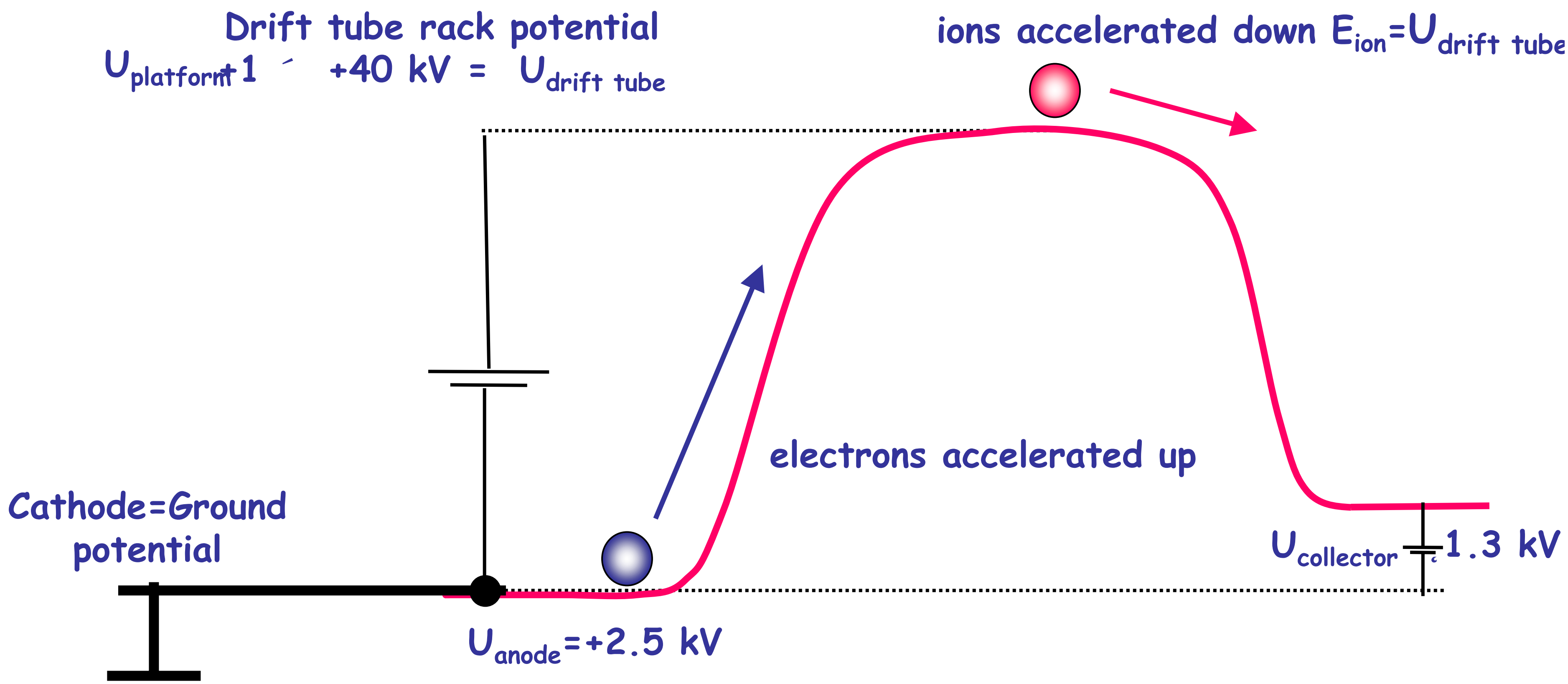


injection on,
trap on;
ions fill the
whole trap



...and viewing the trapped ions and electron beam

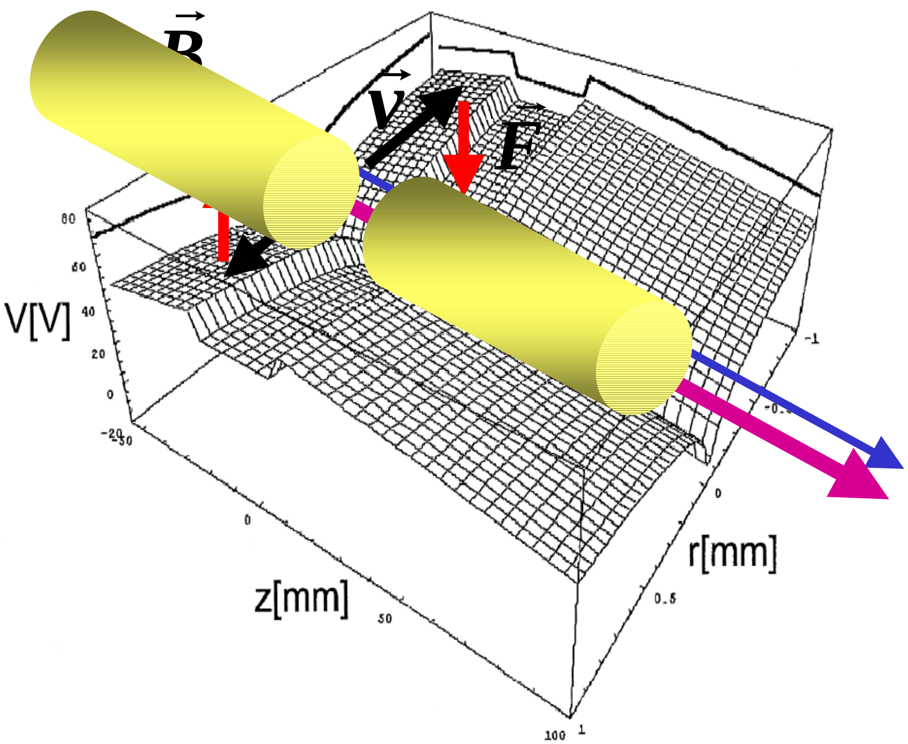
Potential rollercoaster for electrons



Electron beam energy = platform potential $U_{platform}$ = 1 ´ +40 keV

El.-Magnetic trapping modes

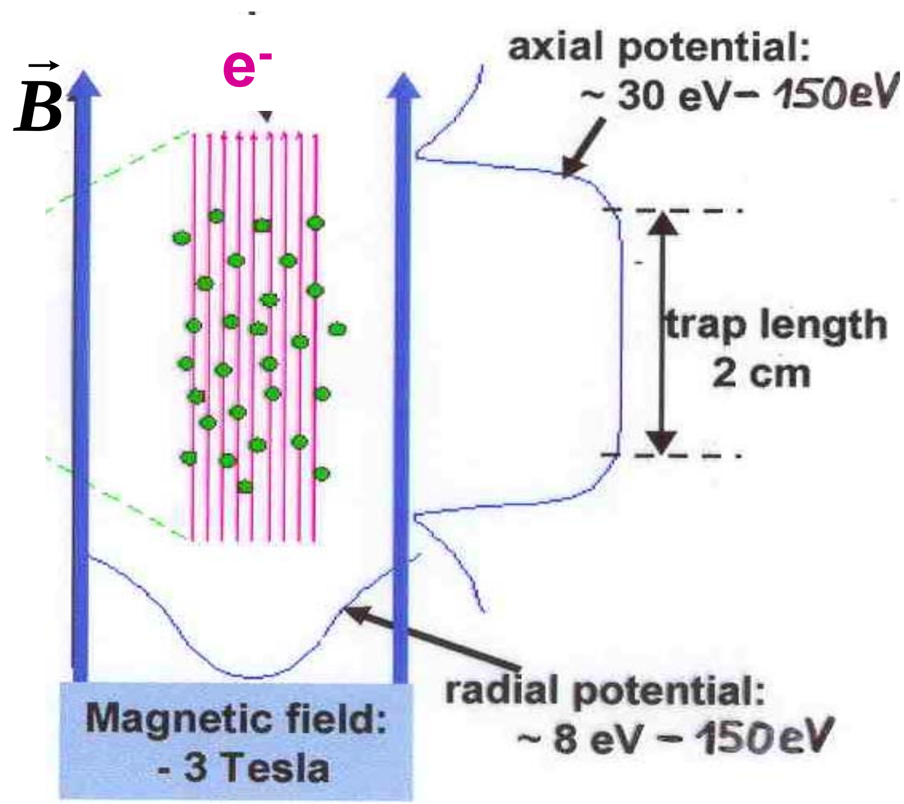
Electrostatic potential from e^- experienced by ions



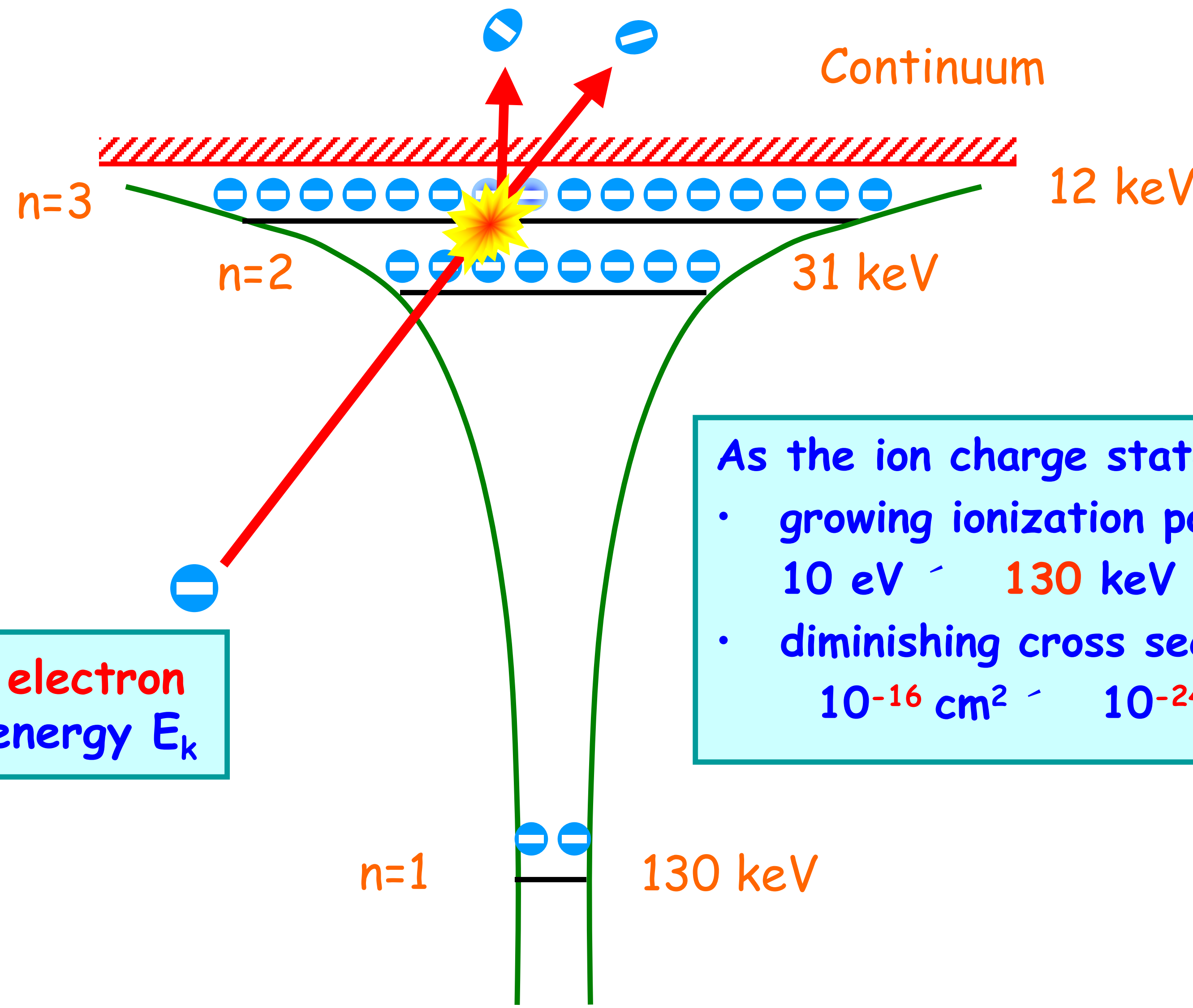
+Lorentz force: $\vec{F} = q\vec{v} \times \vec{B}$

Ions are trapped...

- Radially+Axially by the e-beam space charge.
- Axially by electrostatic potential applied to drift tubes.
- Radially by the magnetic field (Penning trap).



Sequential electron impact ionization of U

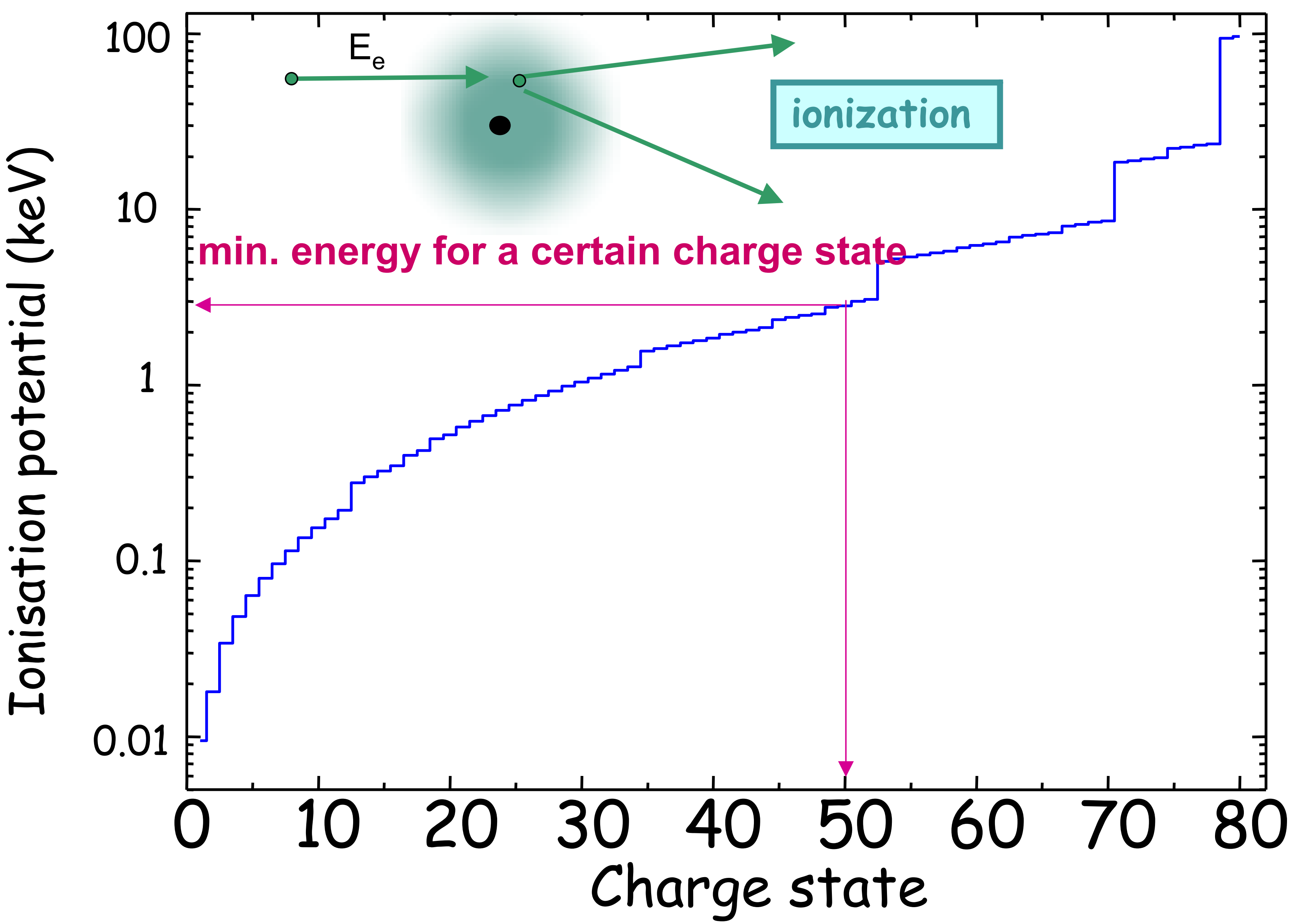


beam electron
with energy E_k

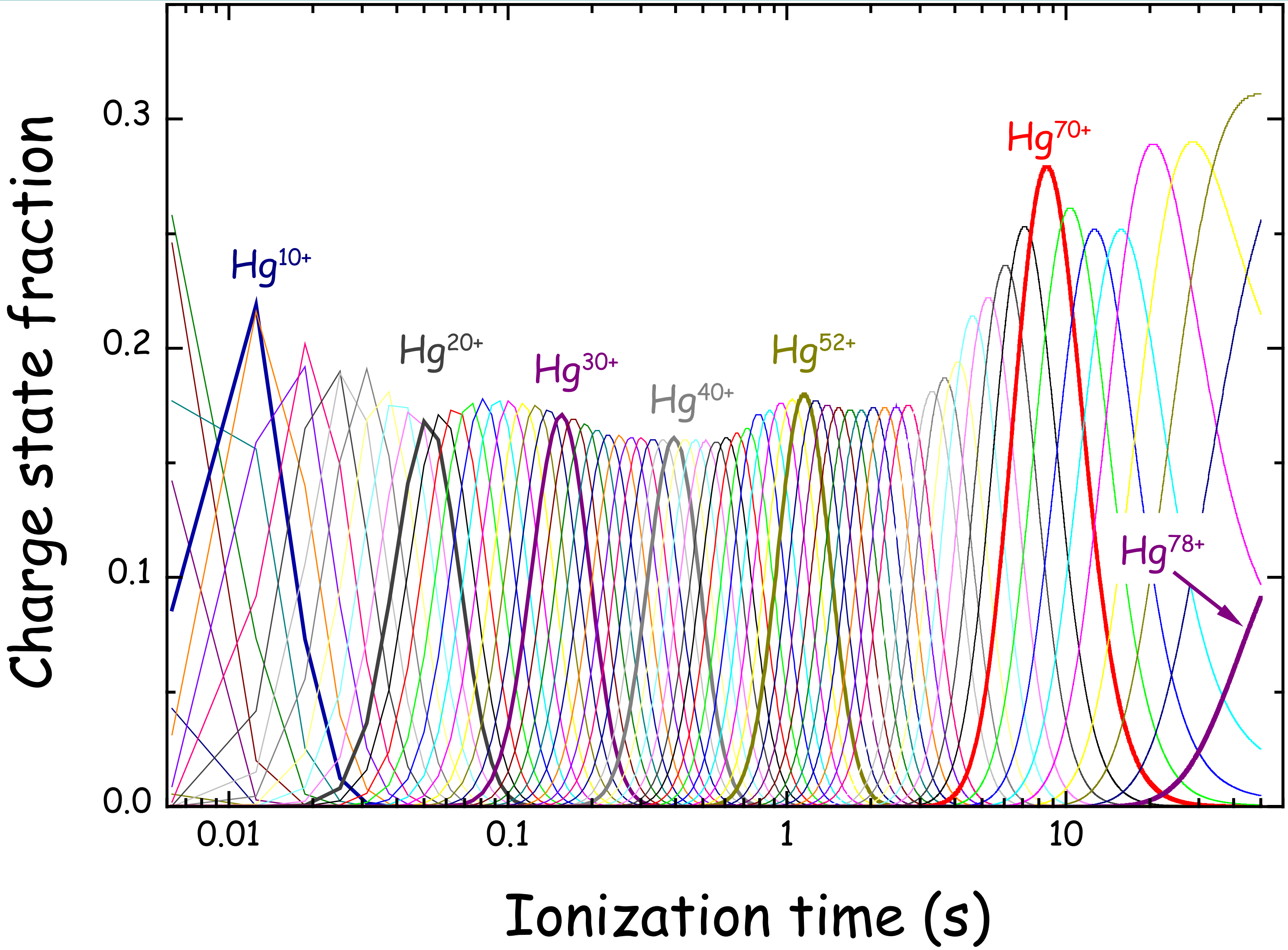
As the ion charge state goes up:

- growing ionization potential:
  10 eV - 130 keV
- diminishing cross section:
  10^{-16} cm^2 - 10^{-24} cm^2

Rise of Hg ionization potential with ion charge state

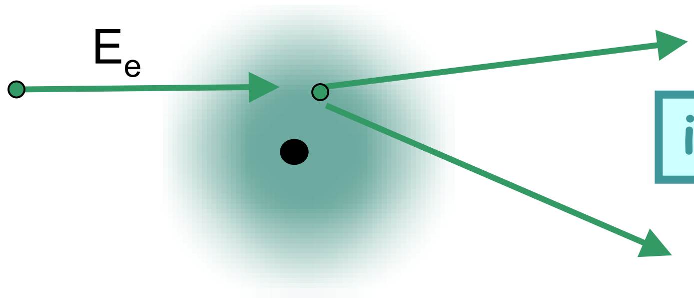


Time evolution of the ion population in the different charge states for a 70 keV, 150 mA beam with 5% overlap HD-EBIT

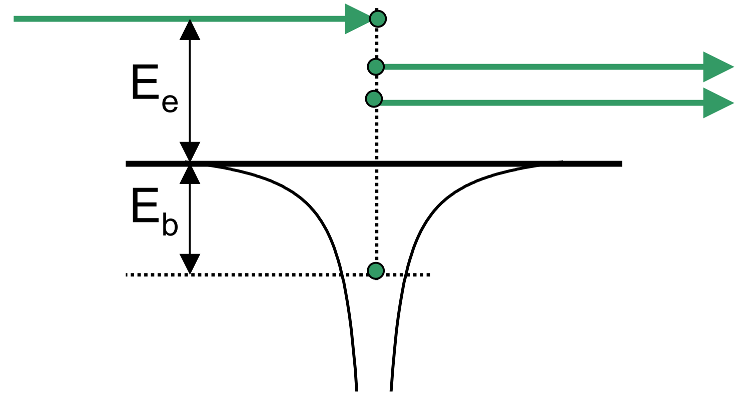


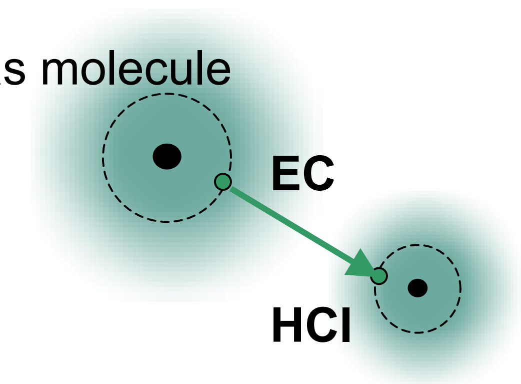
depends on e- current and capture rate

Charge balance in an EBIT



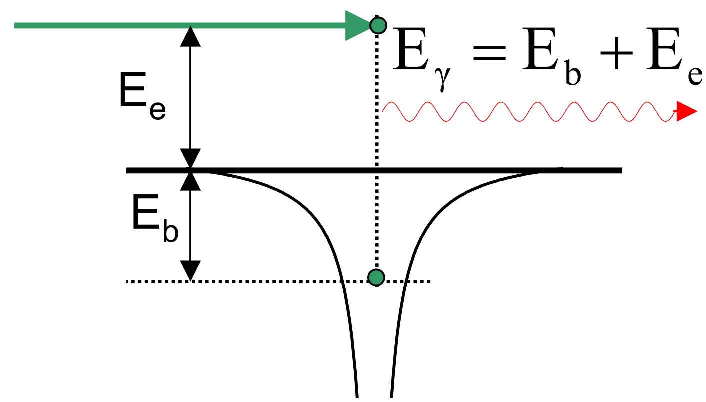
ionization





electron capture

Radiative recombination RR



relative abundance of charge states:

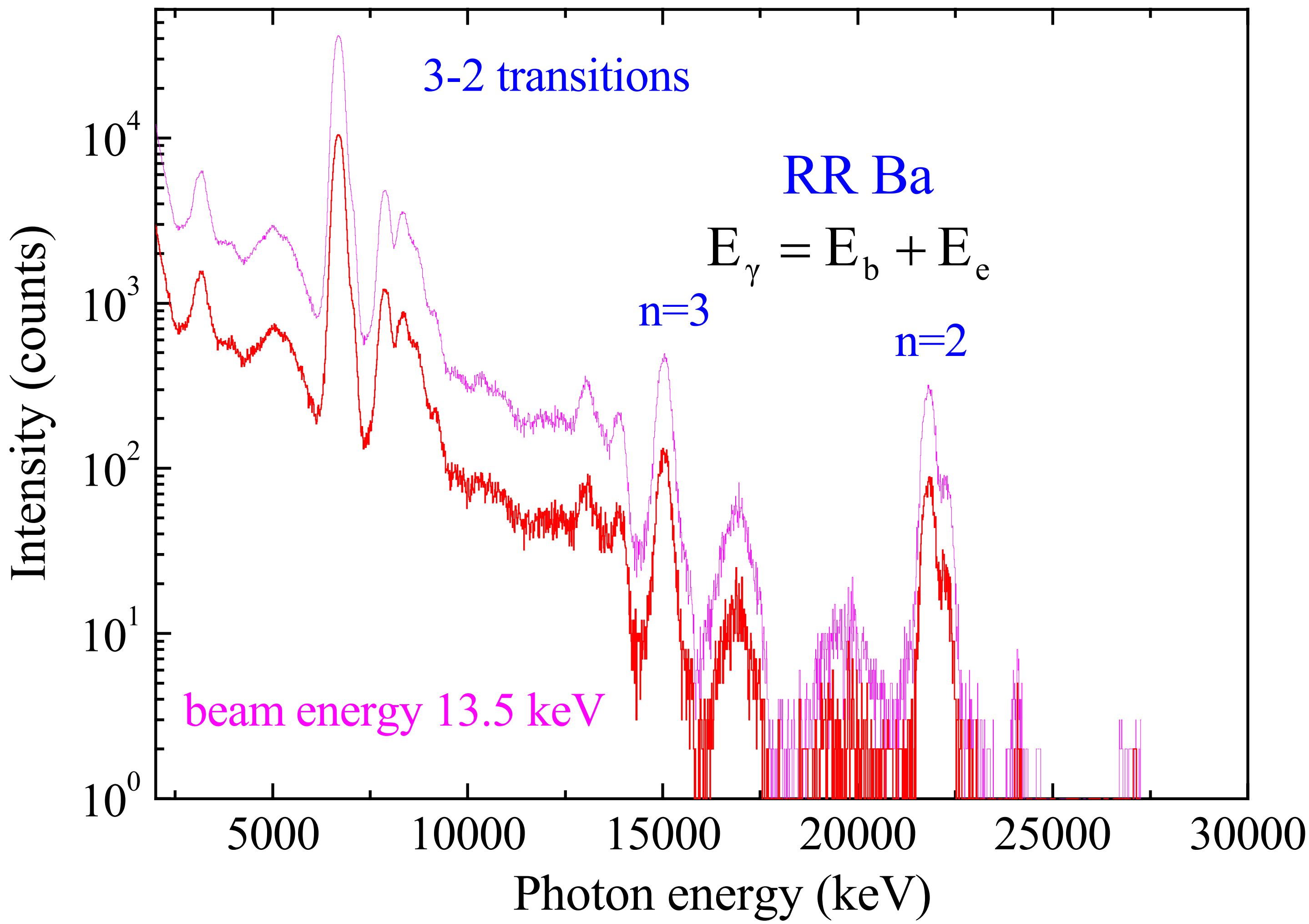
$$\boxed{\frac{N_q}{N_{q+1}} = \frac{\sigma^{RR}_{q+1} + \langle \sigma^{EC}_{q+1} \rangle}{\sigma^{ion}_q}}$$ if small

σ^{RR}_{q+1} decrease with $\uparrow E_{e-}$

σ^{ion}_q max: $E_e \approx 2E_b$

ion intensity and q

Radiative recombination X-rays of $Ba^{46+...54+}$ at 13.5 keV electron beam energy MPI-EBIT



Parameters determining the charge balance

- Electron Beam energy (ratio ionization rate to radiative recombination rate)
- Ionization time (saturation of ionization state - steady state)
- Residual gas pressure (10^{-12} Torr or better!)
- Trap potential depth
- Pulsed or continuous neutral gas injection into the trap
- Evaporative cooling: ion temperature, improved trapping and tuning of high charges!

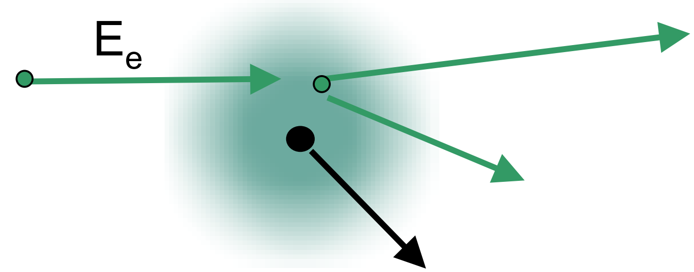
EBIT: evaporative cooling with light ions

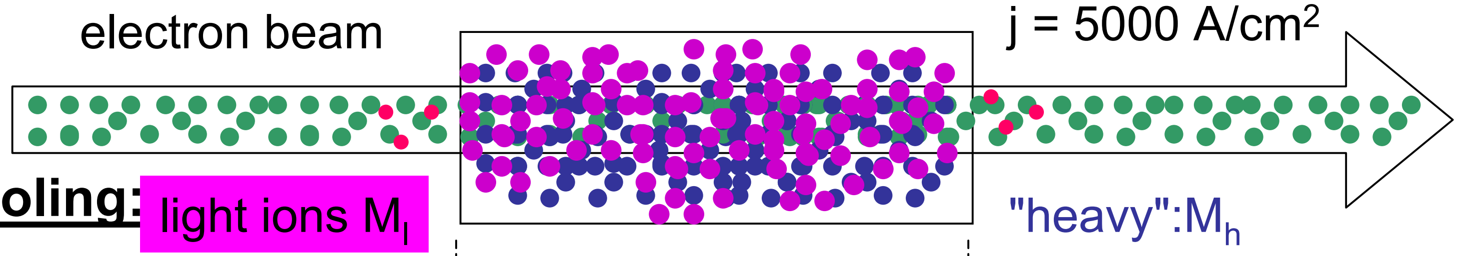
Heating:

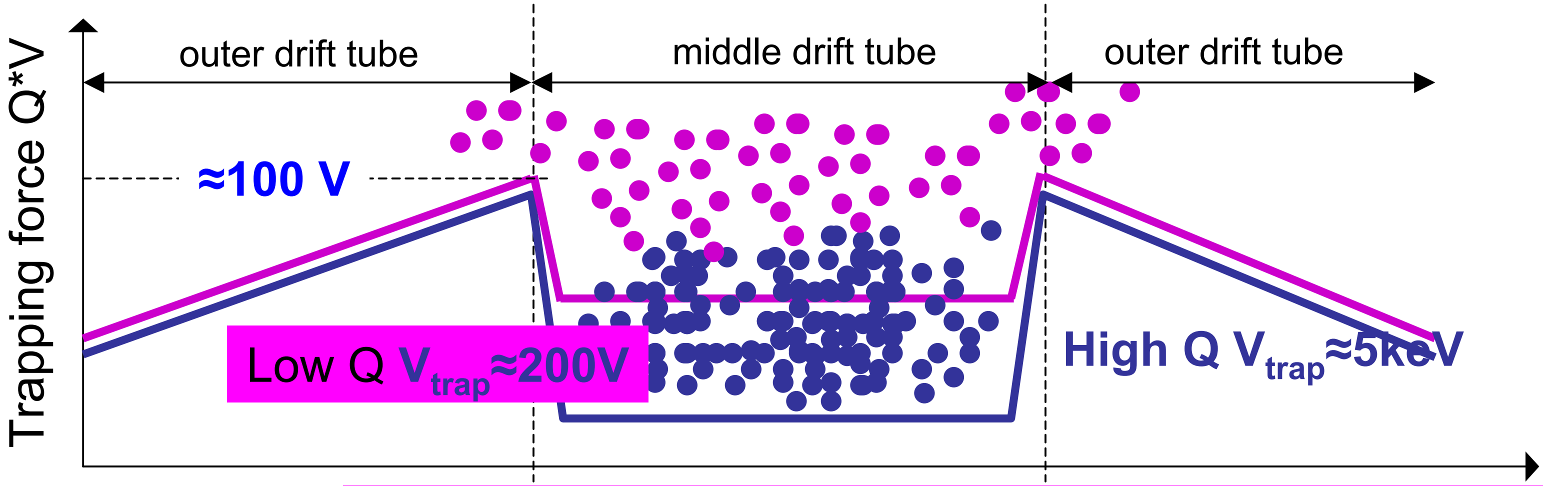
$$\frac{dE_{ion}}{dt} \propto \frac{Q_{ion}^2 \cdot j \cdot m}{E_e \cdot M} \approx 300 \mathrm{eV/s}$$

by collisions

(20keV, 100mA)







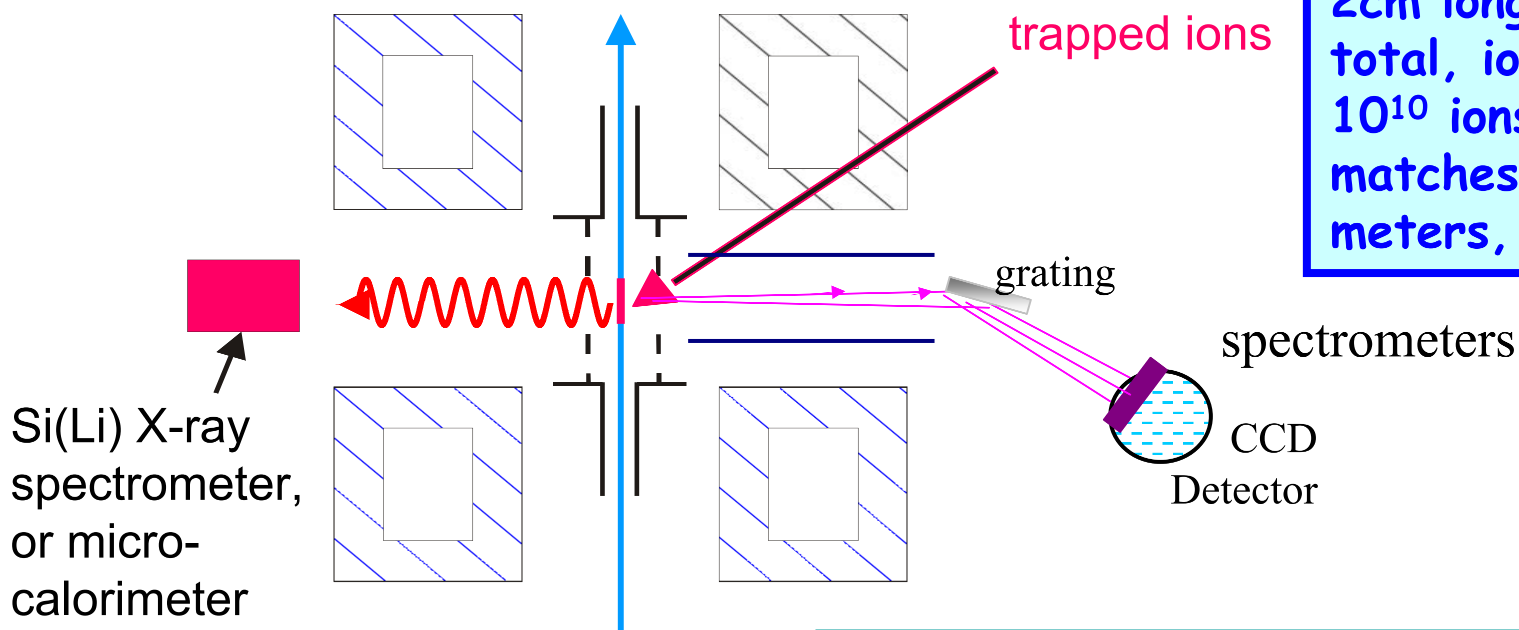
Loss of all low charged ions in msec, He^{2+} takes away 200 eV

highly charged ions remain trapped

Cold Ions: Advantages of EBIT for Spectroscopy

Ions at rest⇒no Dopplercorrection and width

narrow trapping volume (70 μm diam. 2cm long, 10^6 ions total, ion density 10^{10} ions/cm^3) matches spectro-meters, lasers,…



Ion temperatures down to eV

⬇

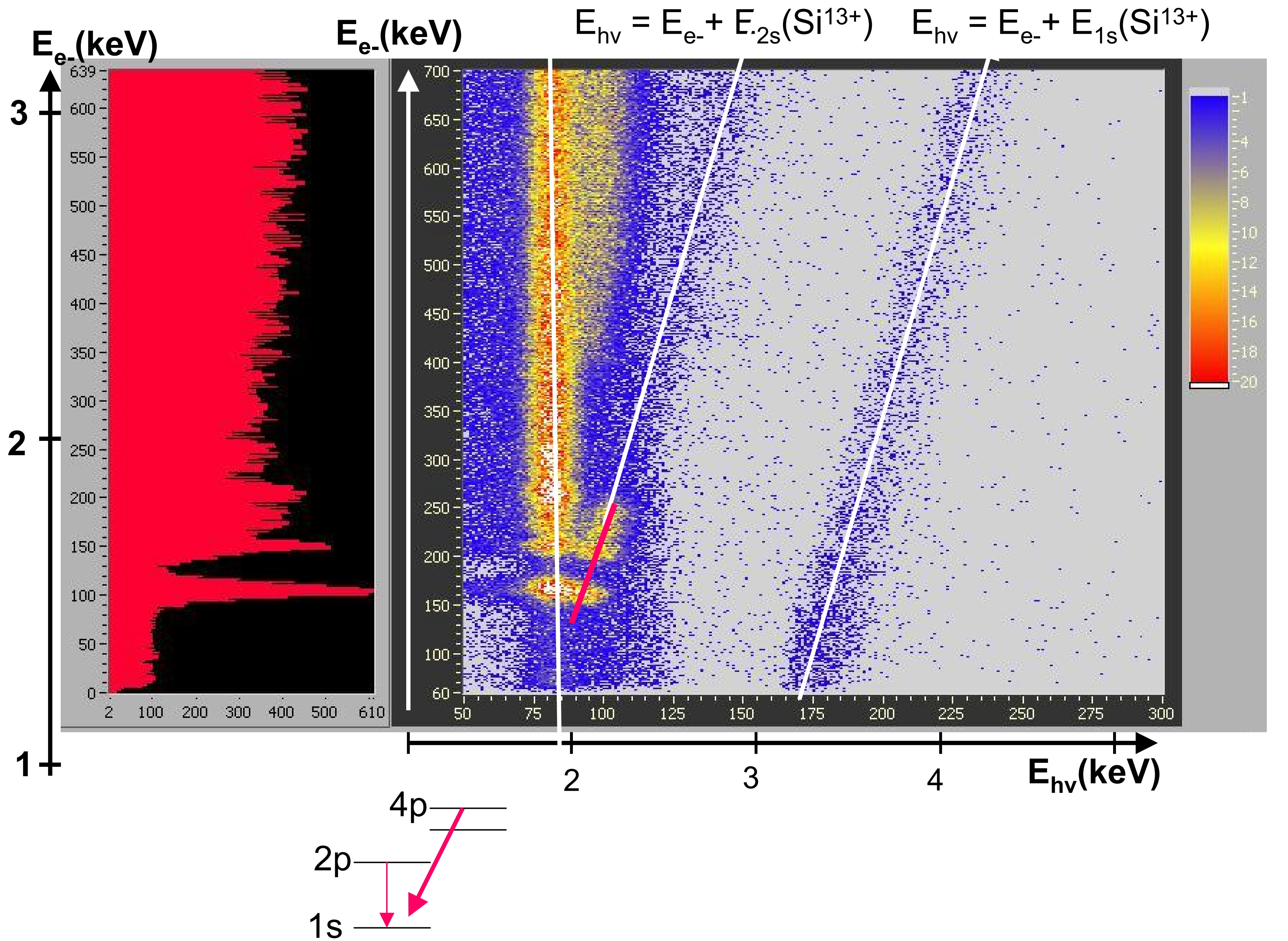
Doppler width $\Delta q/q \approx 510^{-6}$

⬇

High resolution spectroscopy

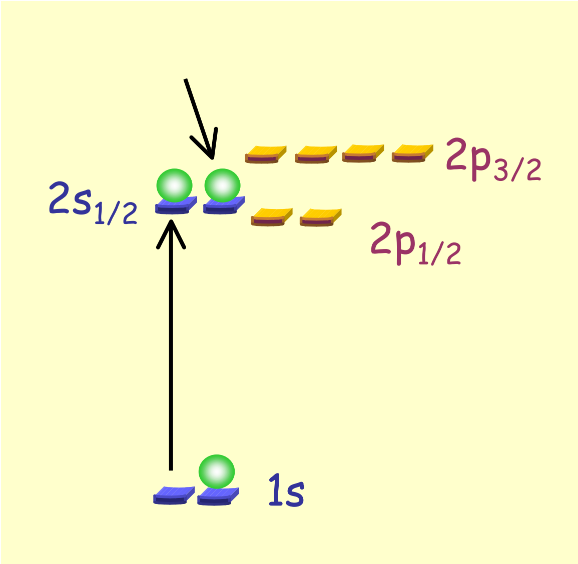
Variable energy electrons in combination with photon detection

First Results from Stockholm EBIT: $Si^{12+-14+} + e^{-} \rightarrow Si^{q+} + h\nu$

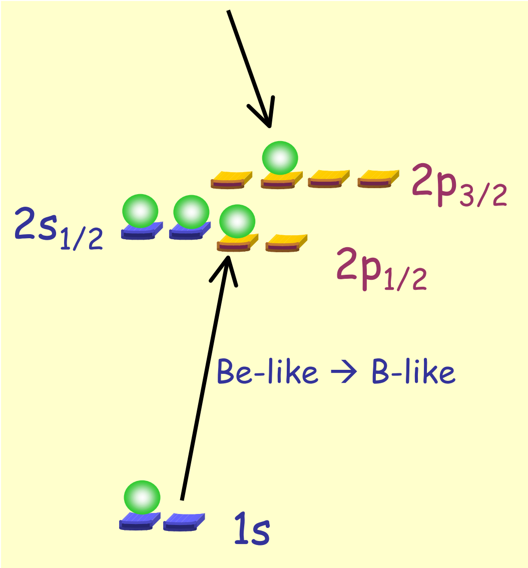


The KLL resonances

$KL_{1/2}L_{1/2}$



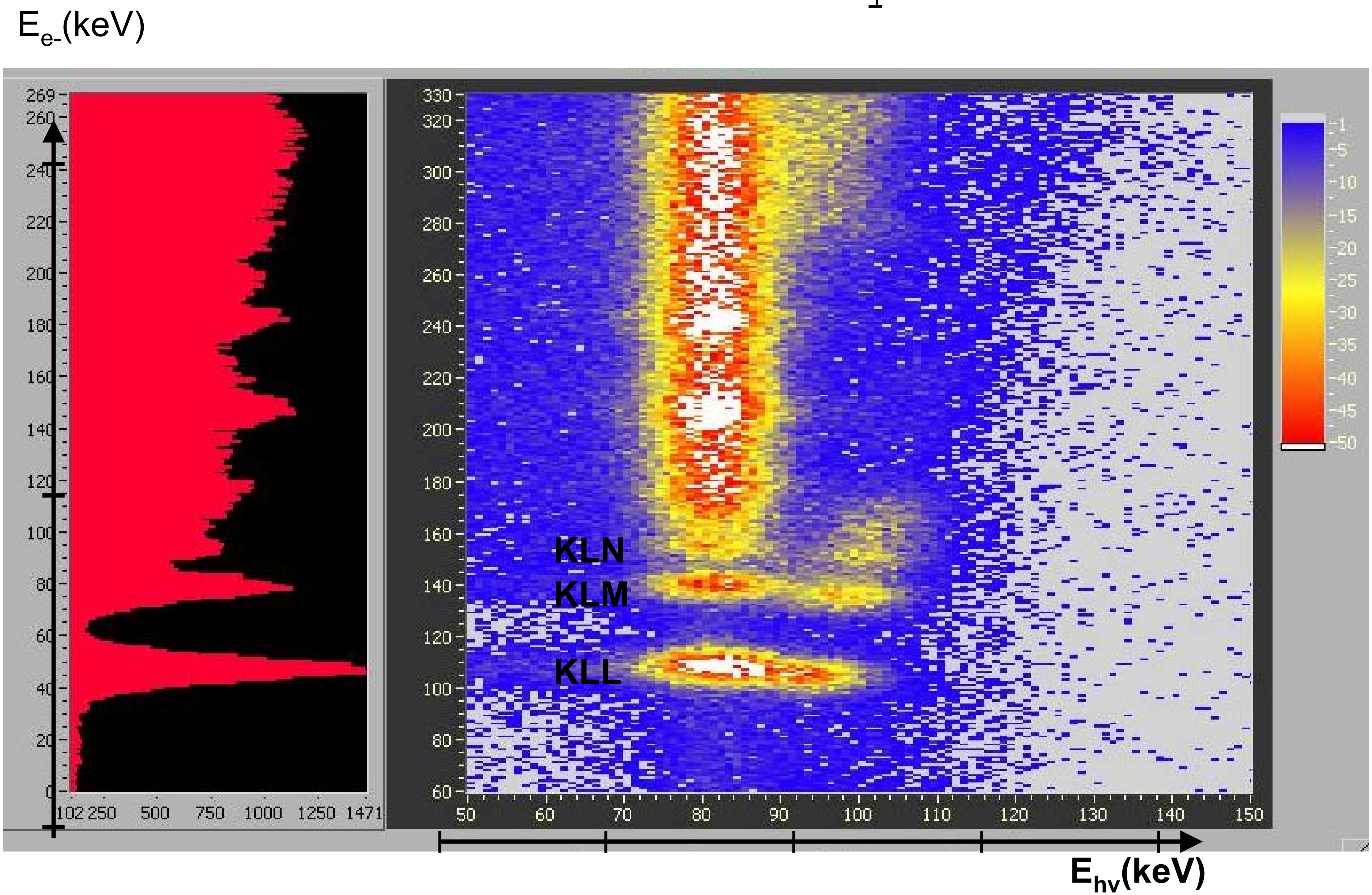
$KL_{1/2}L_{3/2}$

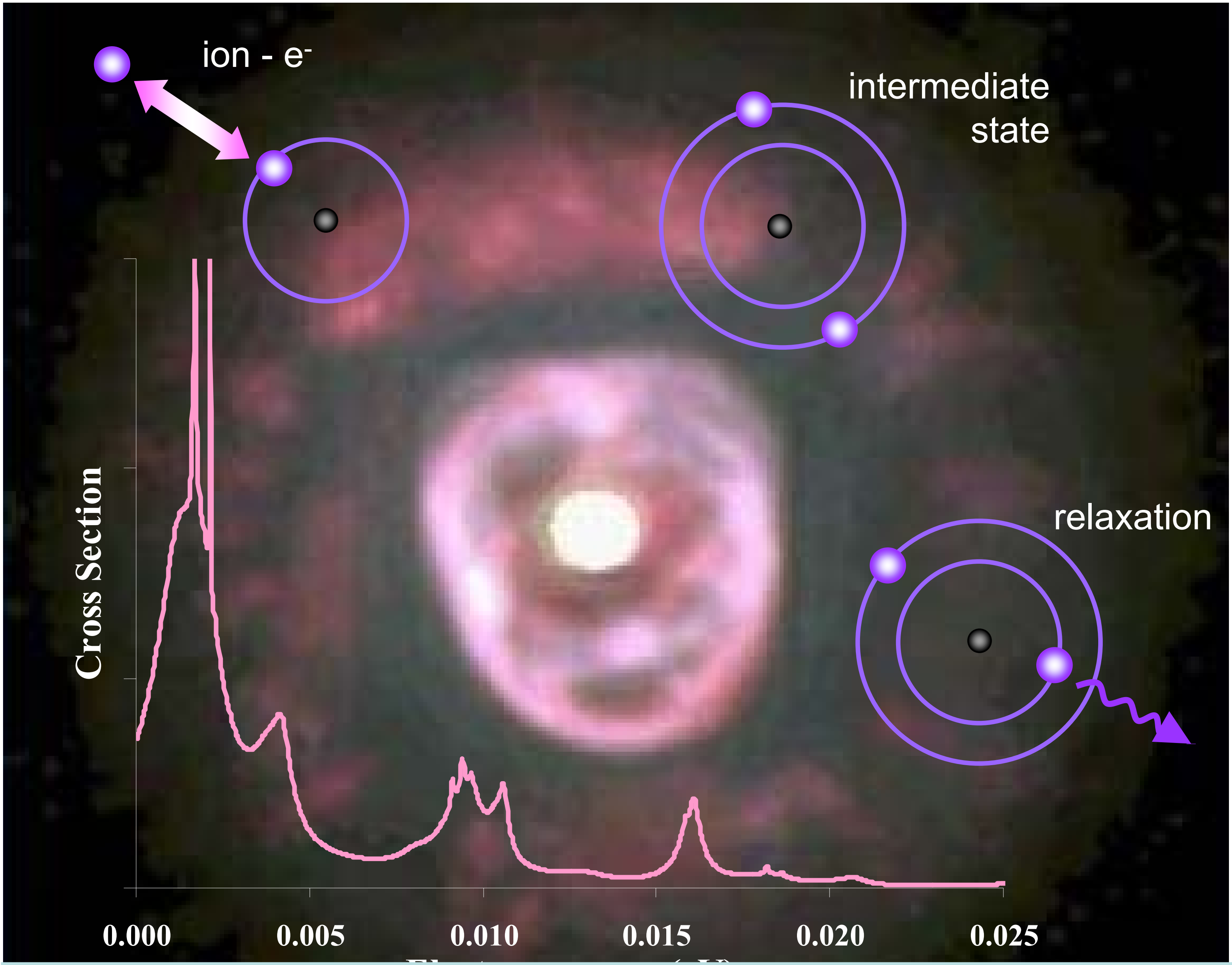


and analogously the $KL_{3/2}L_{3/2}$

Use the dielectronic recombination resonances to study the electronic structure with high accuracy

$Si^{12+-14+} + e^- \rightarrow Si^{q+} + h\nu$





The spectra of ionized planetary nebulae are dominated by strong H, He, O, Ne, Mg,... recombination lines, emitted during recombination

R-EBIT provides a Localized Cold Cloud of Highly-Charged Ions for Interaction Studies with Intense Photon Fields

From GDR of MAX IV on Atoms, Molecules, Ions and Free Clusters:
In order to conduct an experimental program to study the interaction of gas phase ions at MAX IV we propose… to conduct experiments using an Electron Beam Ion Trap (EBIT) ion source (Fig 14).
An EBIT is a very advanced trap/source allowing for front line research....

Design Report X-FEL DESY, Hamburg: Small Quantum Systems

1. Inner shell ionization in atomic ions (using R-EBIT)

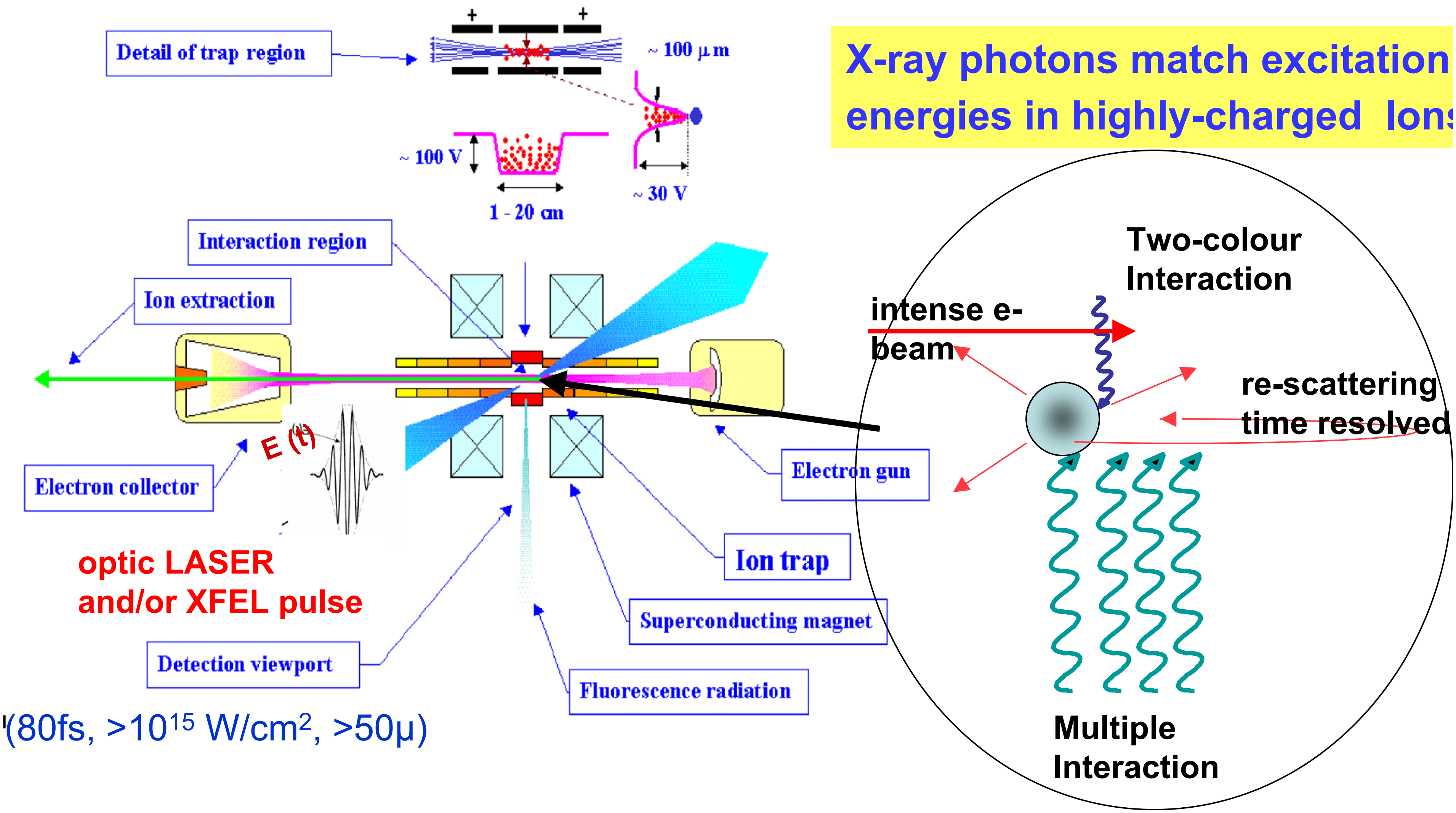
5. QED spectroscopy and nuclear polarization by hyperfine optical pumping of highly charged ions in traps (using R-EBIT)

6. X-ray diffraction on trapped ion crystals (using R-EBIT)

R-EBIT is moveable, and can be brought to advanced light source facilities.

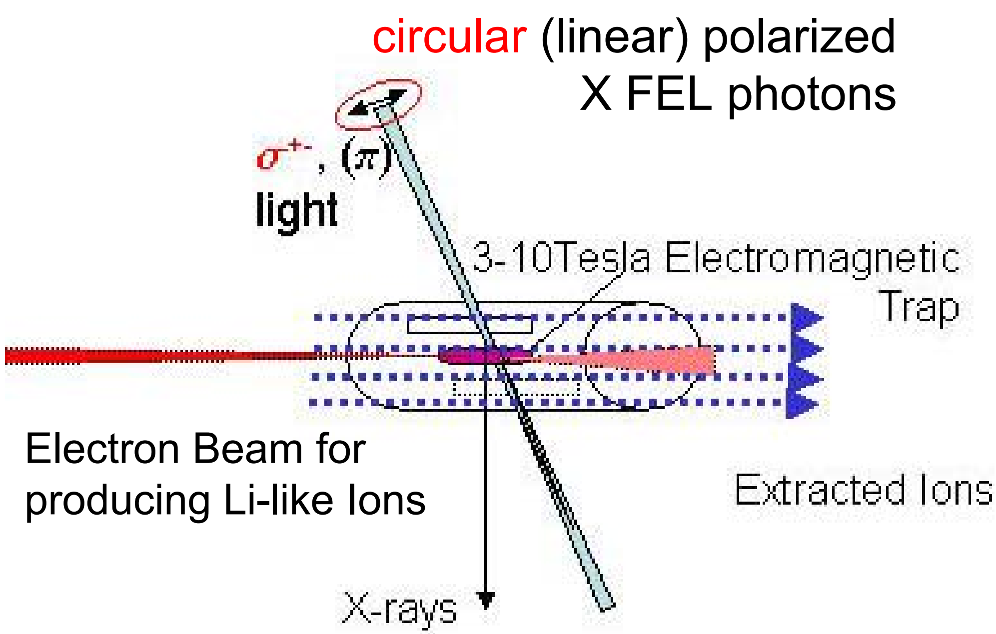
EBIT: Trapped Highly-Charged Ions and Intense FEL & Laser Photons

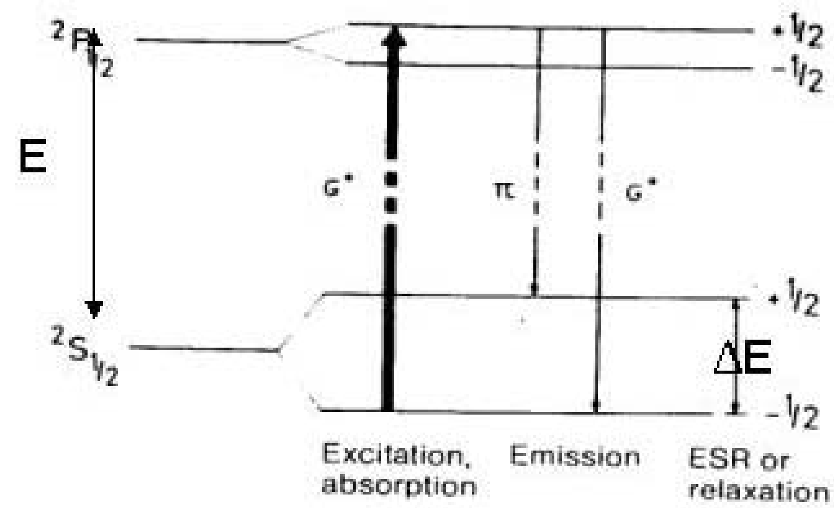
X-ray photons match excitation energies in highly-charged Ions



Optical pumping of highly-charged ions

Zeeman splitting of the $2s_{1/2}$-$2p_{1/2}$ levels in lithium-like krypton or uranium in strong B-field of an EBIT

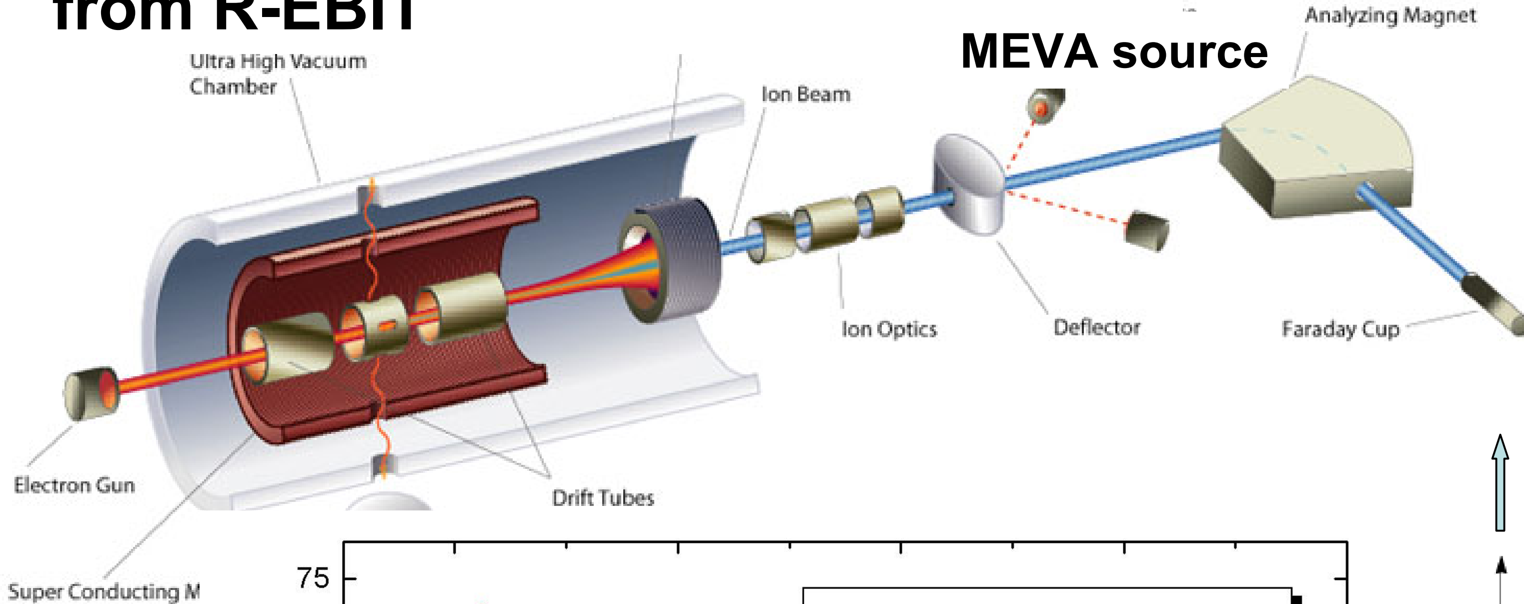




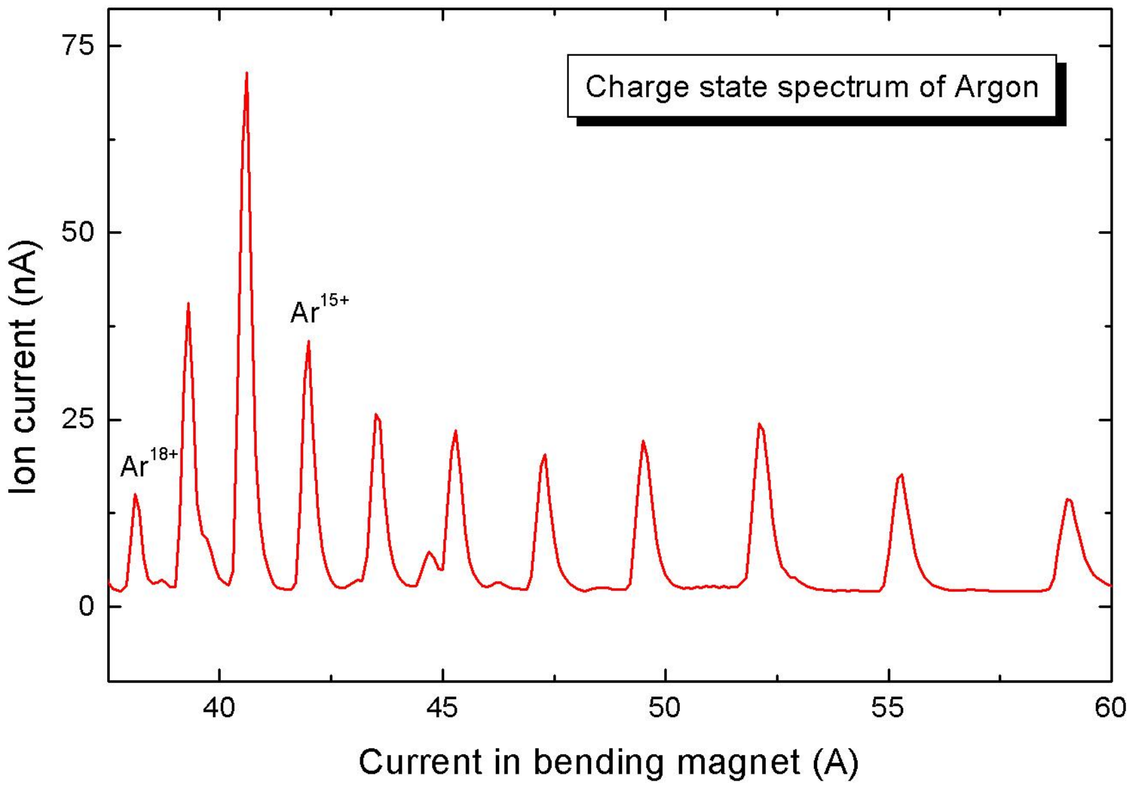
selecting v^+ or v^- circular polarized X FEL photons ⇒ population of +1/2 or -1/2 spin states

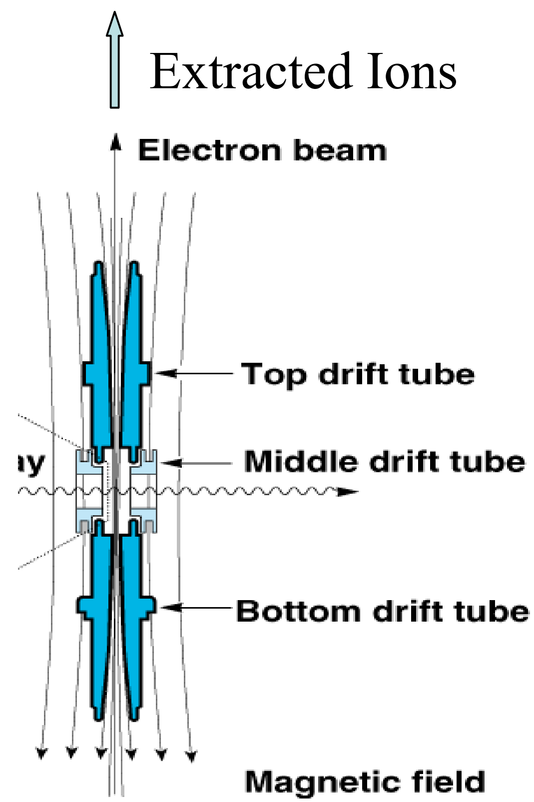
⇒Hyperfine Inter. produces nuclear spin pol.

Highly-charged Ions are extracted from R-EBIT



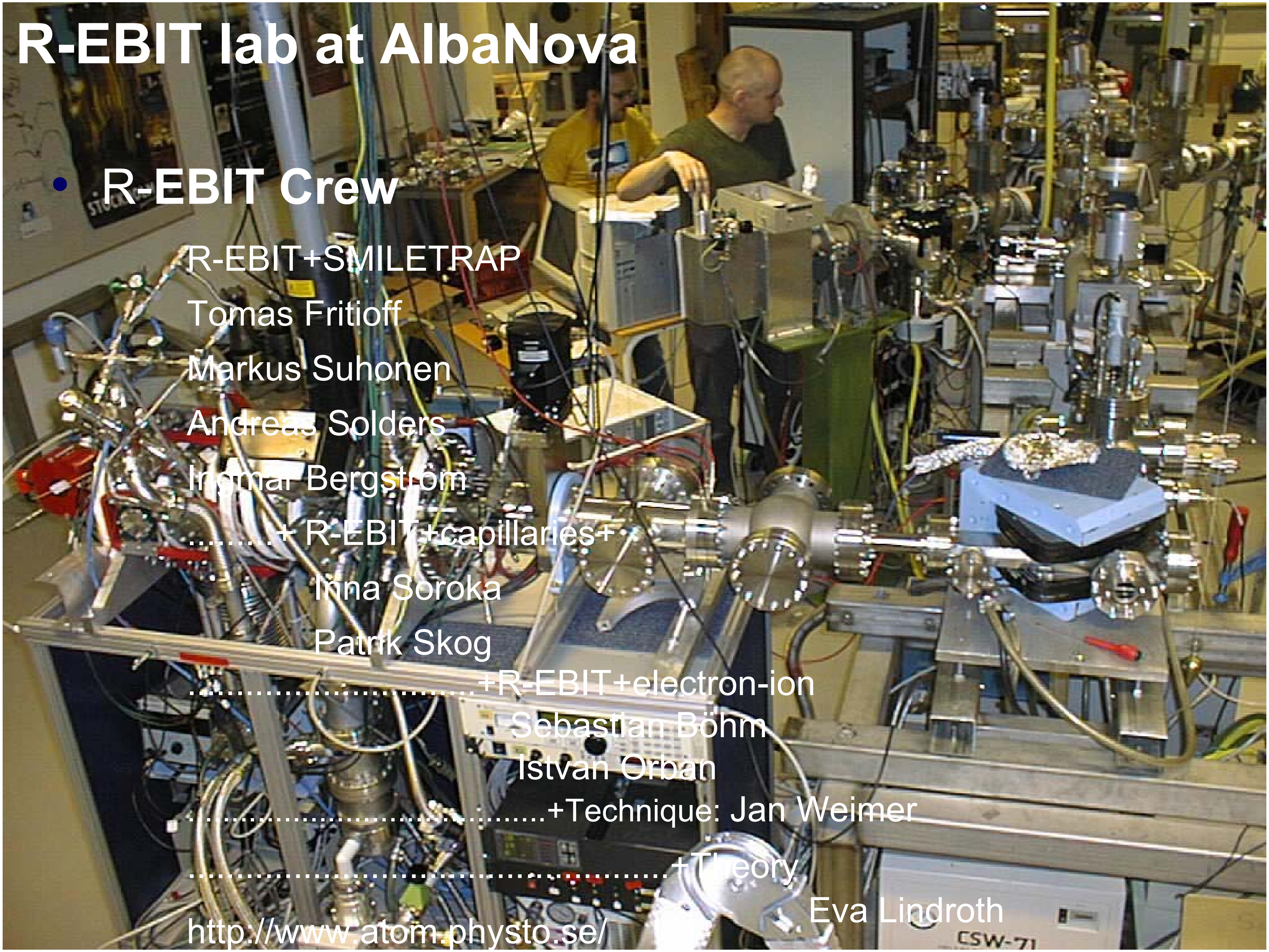
Crystate for S-cond. Magnet
big Cryopump
⇒ Vacuum:
¸ 10^{-11} mbar





100 µsec

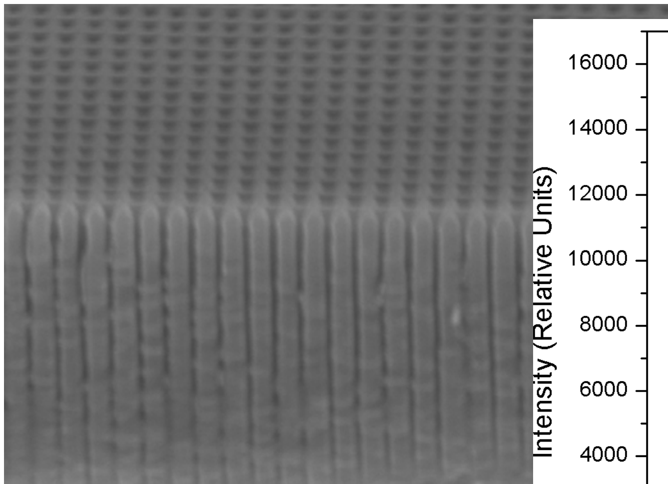
2 Hz

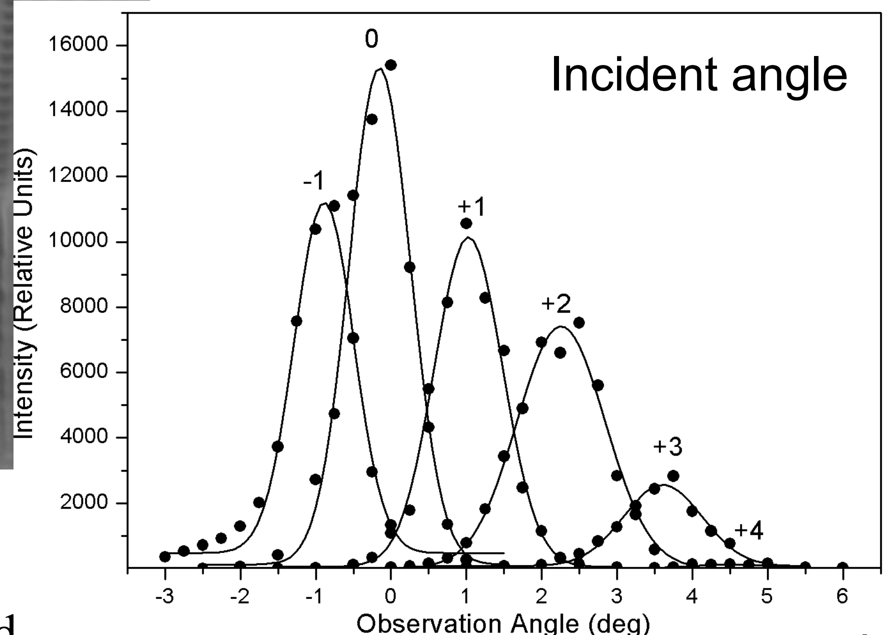

R-EBIT lab at AlbaNova
• R-EBIT Crew
R-EBIT+SMILETRAP
Tomas Fritioff
Markus Suhonen
Andreas Solders
Ingmar Bergström
.........+ R-EBIT+capillaries+
Irina Soroka
Patrik Skog
..............................+R-EBIT+electron-ion
Sebastian Böhm
Istvan Orban
....+Technique: Jan Weimer
....+Theory
Eva Lindroth
http://www.atom.physto.se/
CSW-71

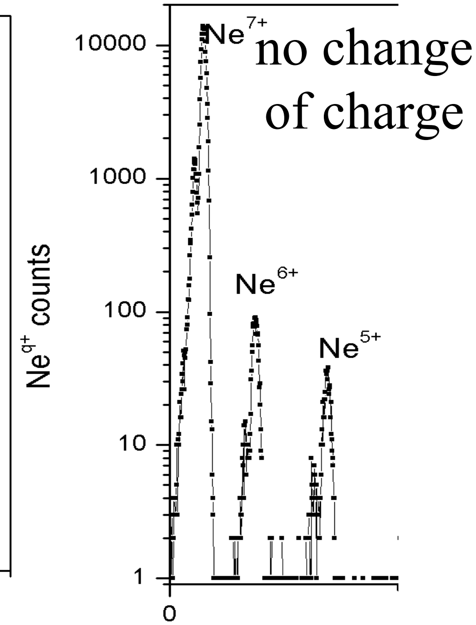
Highly-Charged Ions for Electric Properties in Nano - capillaries

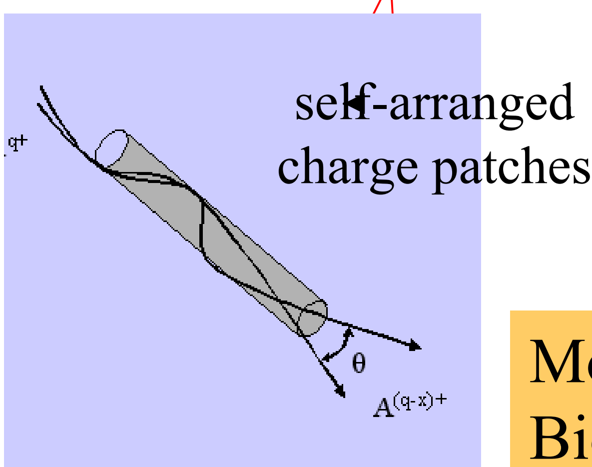
Ne^{7+} ions

100 nm capillary in 10-25 µm thin Si, SiO_2, Al_2O_3 membrans (varying conductivity)

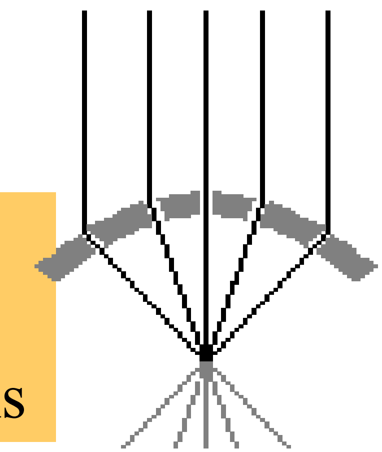






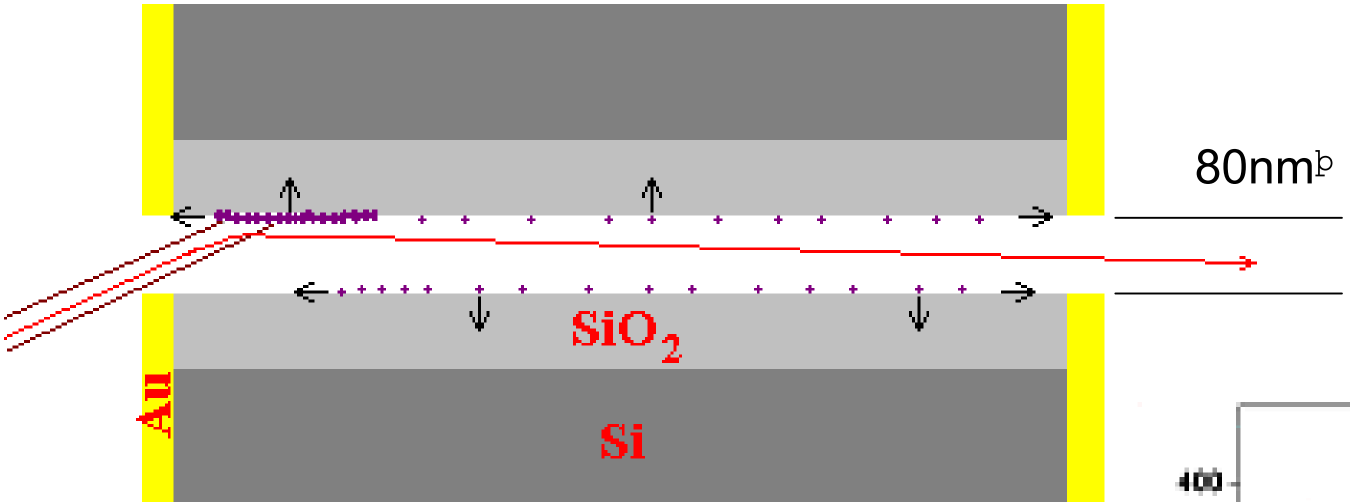


Motivation:
Biological membrans elektrical properties, nano-size lenses for ions

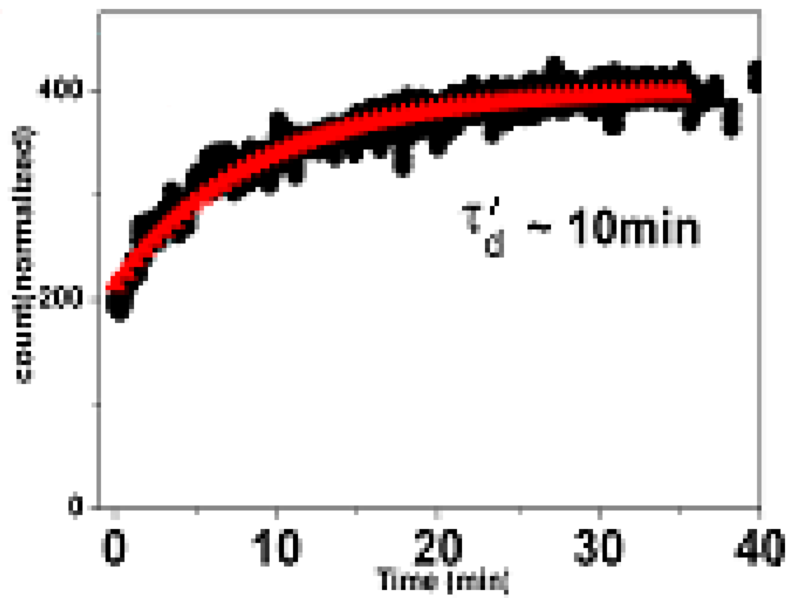


Guiding of HC Ions through Nano-capillaries

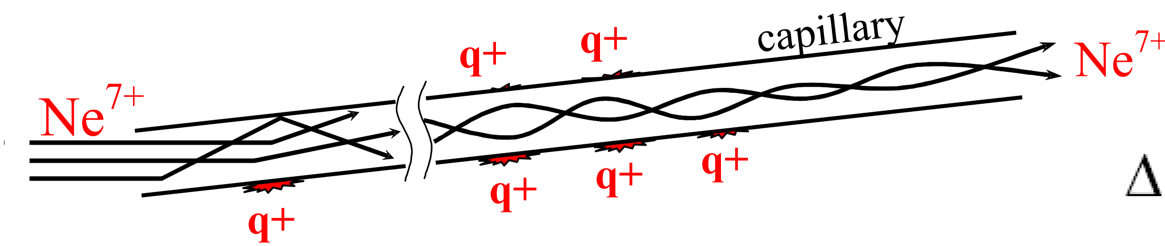
HCI make in insulating nano-capillary (SiO_2 in Si membranes) localized positive charge patches which deflect ions, entering at a later stage, through the capillary



Time Dendence: Full Ion Transmission after ≈ 10 min



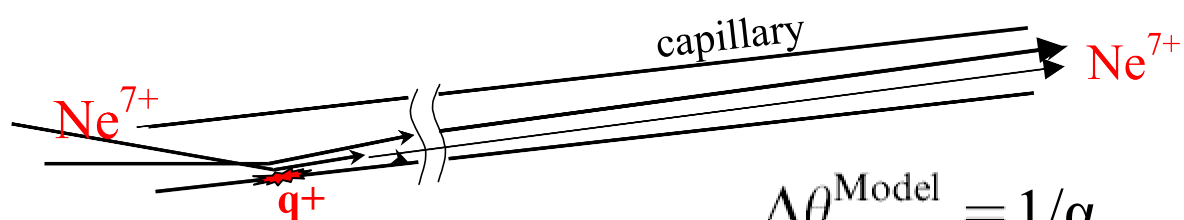
Model descriptions of observed angular distributions



$$\Delta\theta^{\mathrm{Model}} = 2\sqrt{\ln 2\frac{q_{\mathrm{f}} U_{\mathrm{g}}}{E_{\mathrm{p}}}}.$$

Trajectory simulations by Burgdörfer&Lemell show,
this configuration is unstable!!

but this configuration with 1 patch is stable!!

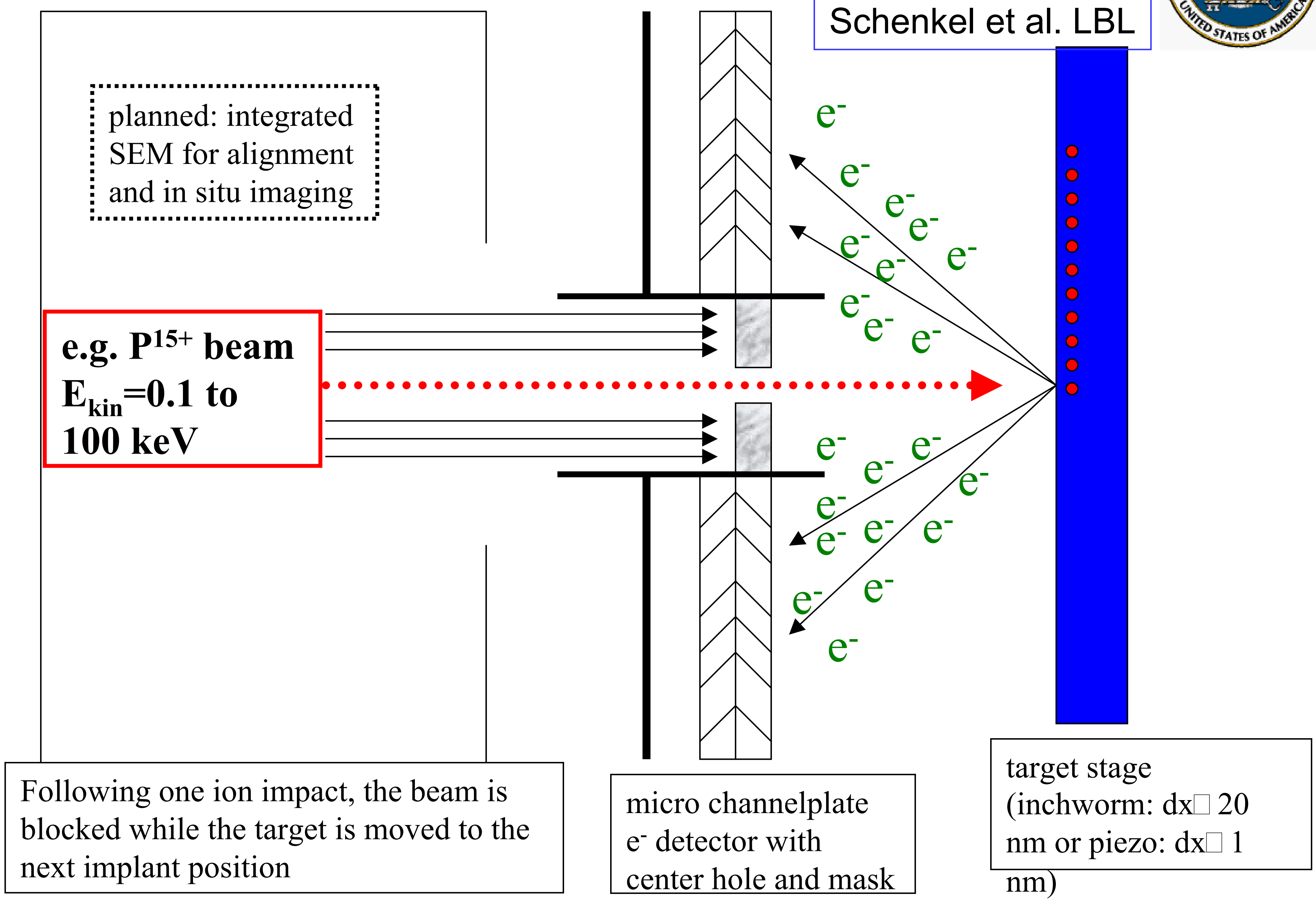


$$\Delta\theta^{\mathrm{Model}} = 1/\alpha$$

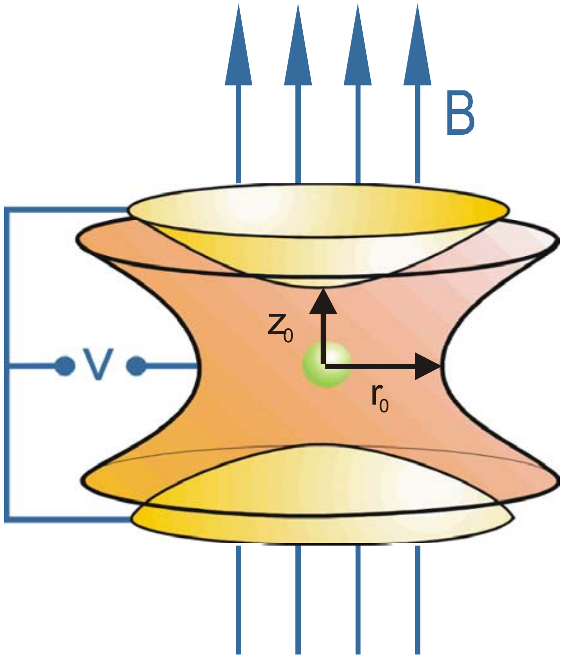
However, angular distr. wider ¬ 2/α ⇒ explanation by diffusion of charge into the bulk material, and charge transport on the surface ⇒ test different material

Schematic of Single Ion Implantation Setup

Schenkel et al. LBL



Ultra-Precise Mass Measurements



PENNING trap

SMILETRAP

Stockholm **M**ainz **I**on **LE**vitation **TRAP**

Principle for high accuracy: Use highly-charged ions!

$$\frac{m}{\Delta m} = \frac{\nu_c}{\Delta \nu_c} = \frac{1}{2\pi \Delta \nu_c} \cdot \frac{q}{m} \cdot B$$

unique in the world

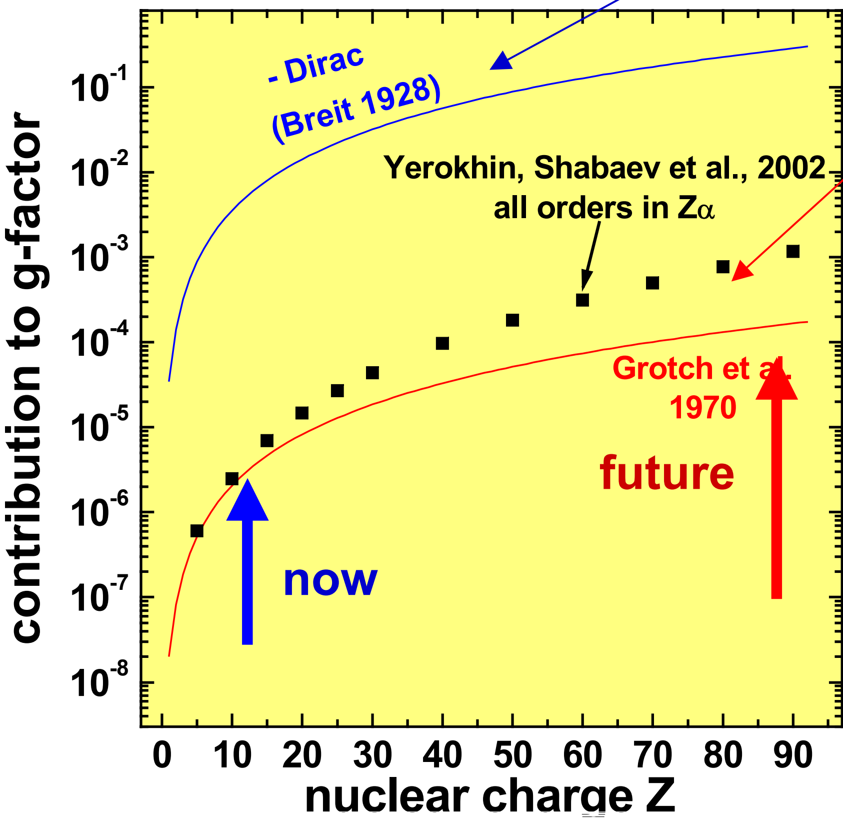
- ***Almost any stable mass can be measured with an accuracy <1 ppb***
  - accuracy close to 10^{-10} reached at SMILETRAP
  - *to day at* MSL, maybe soon to AlbaNova, EBIT lab

(Flaggship)Test av QED: Bound electron g-factor

$$g_{bound}/g_{free} \approx 1 - 1/3(Z\alpha)^2 + \alpha/4\pi(Z\alpha)^2$$

relativistic effect (Dirac)

bound-state QED



Precise g-Factor measurements @ HITRAP(GSI) & SMILETRAP

Larmor precesion

$$h\nu_L = g_J \mu_B B$$

Cyclotron motion

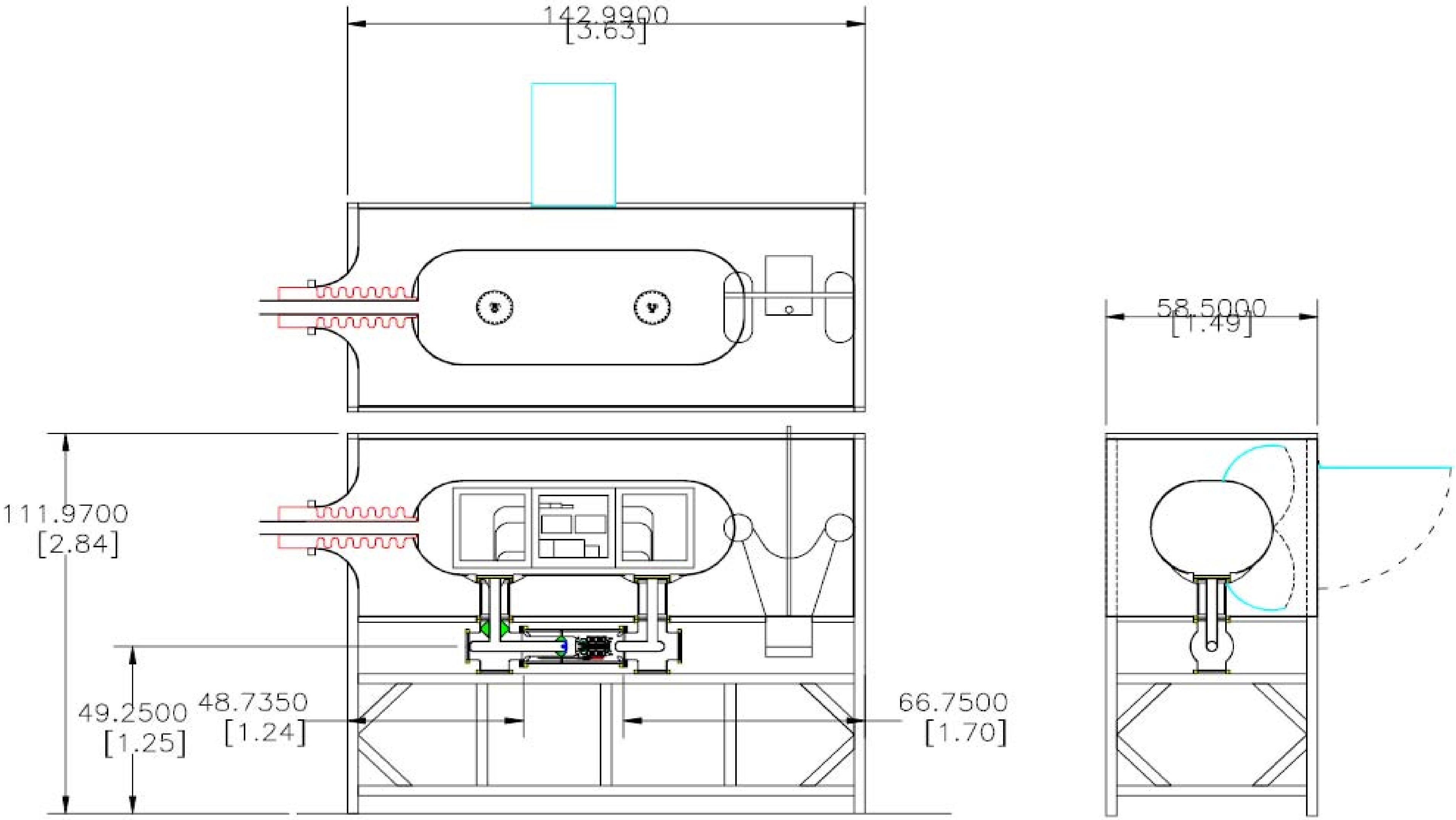
$$\nu_c = \frac{q}{2\pi M_{ion}} B$$

$$\Rightarrow \quad g_J = \frac{2\omega_L}{\omega_c^{ion}} \frac{q m_e}{M^{ion}}$$

So far results for C^{5+}, O^{7+}, $^{40}Ca^{19+}$

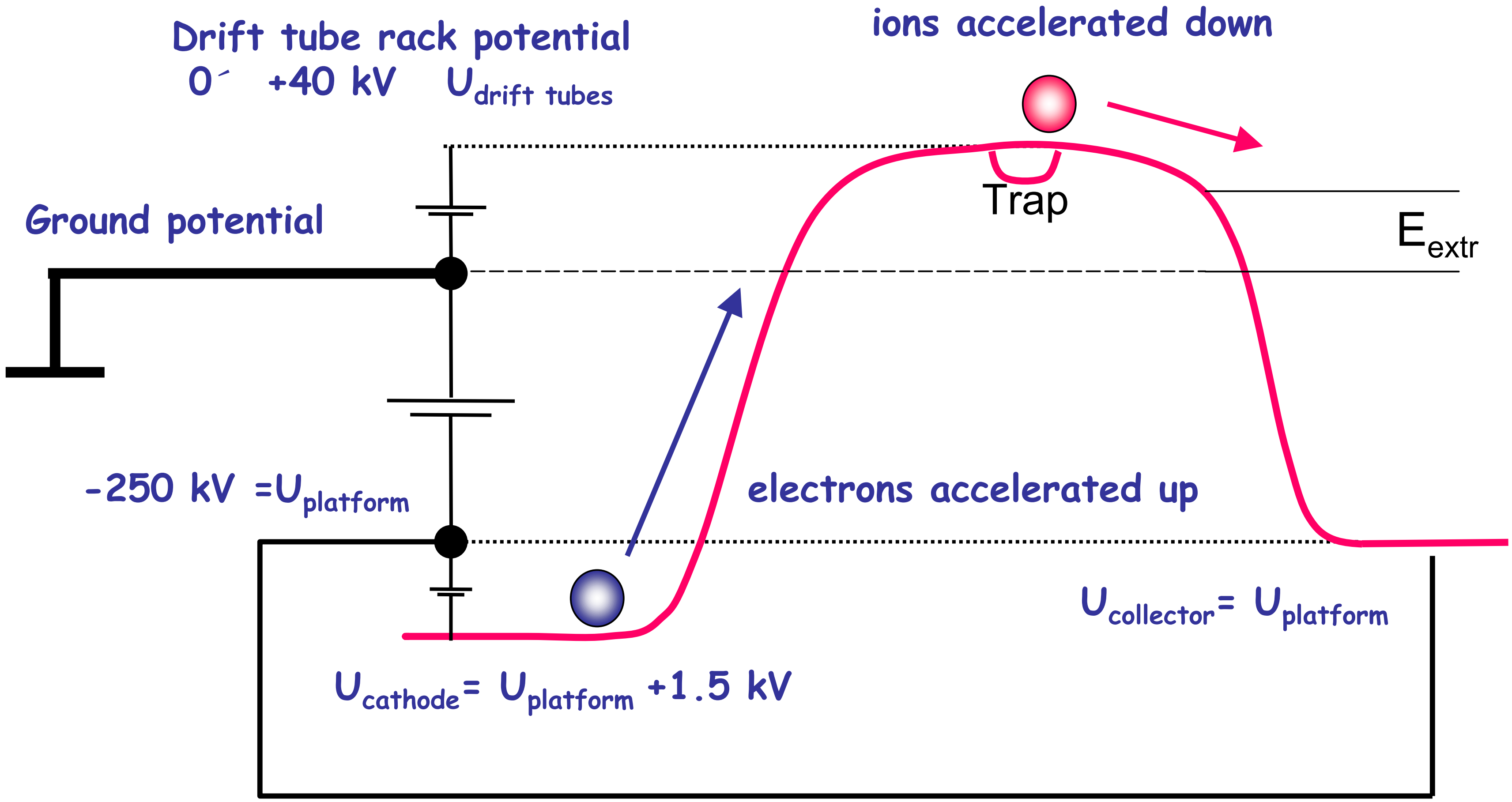
Future: need mass of U^{91+} with <0.5 ppb from SMILETRAP& S-EBIT

Future: Design of Stockholm Super-EBIT



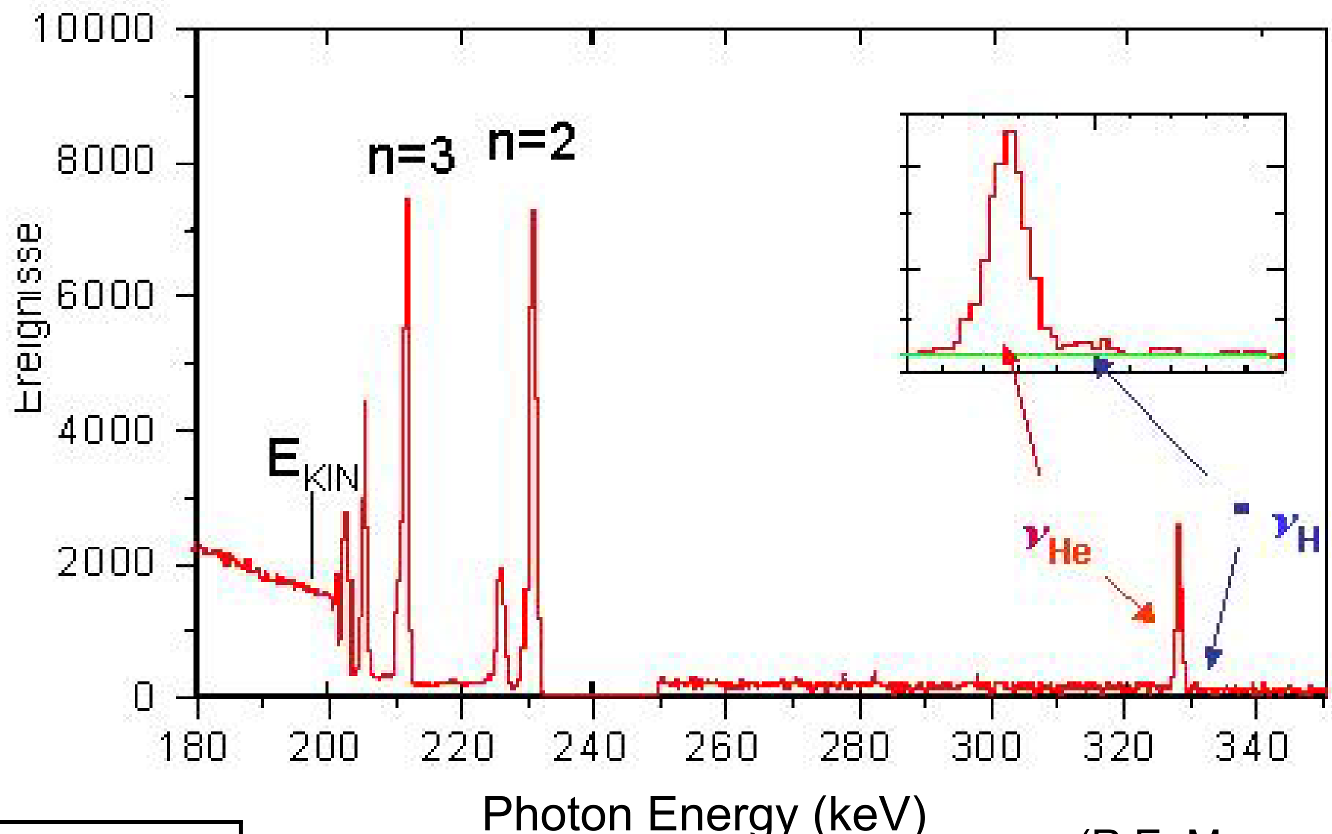
250 keV electron beam ´ U^{92+}

Potential rollercoaster for a Super-EBIT



Electron energy = $U_{cathode} + U_{drift\ tubes}$

First Production of bare Uranium at rest in an EBIT:



(R.E. Marrs et al., 1998)

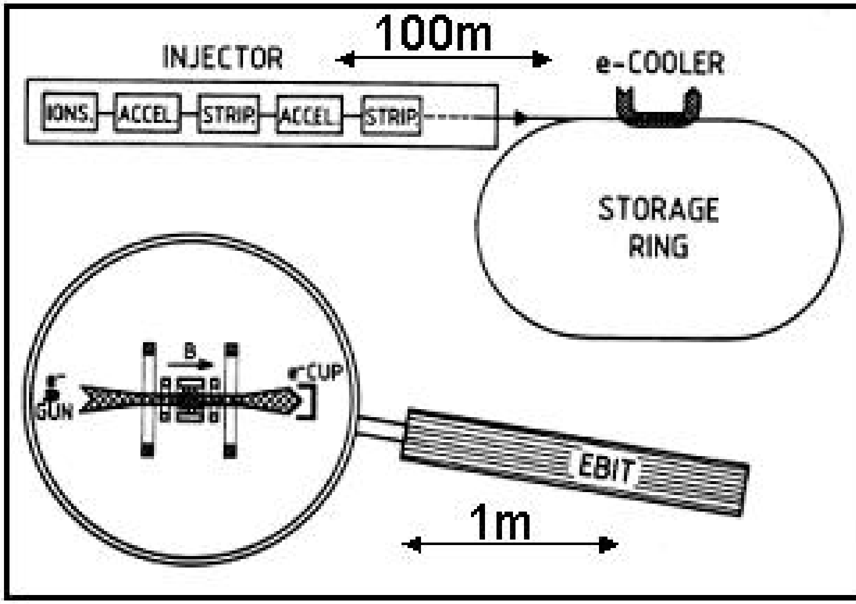
EBIT values:	
Voltage	**198 kV**
Current	**200 mA**

q_{He}: Capture in groundstate of H-like Ions

q_{H}: Capture in groundstate of bare **Ions**

Schemes for Production of Highly Charged Heavy Ions

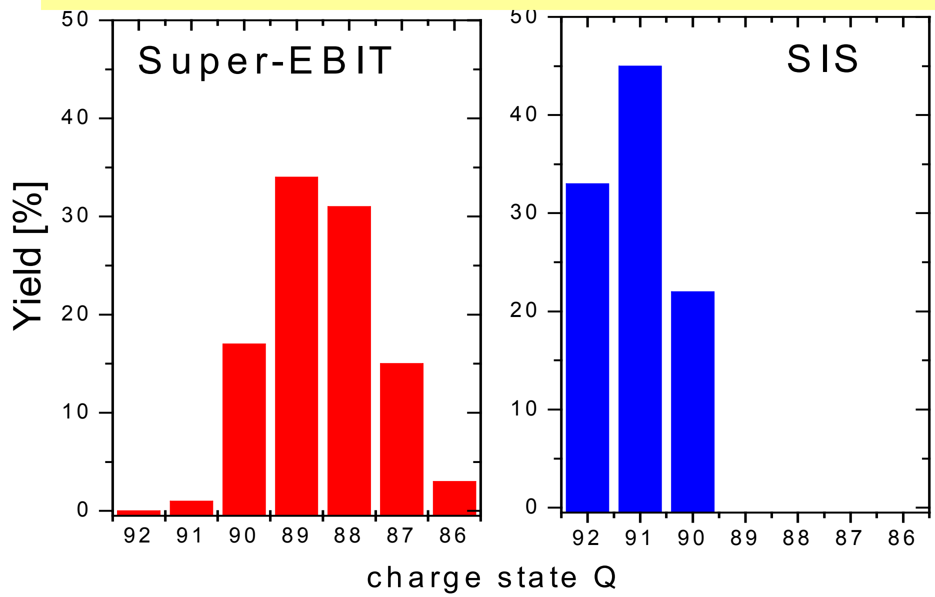
EBIT: Trapped, stationary ions; charge state production by electron bombardment



Accelerator: Fast moving ions, charge state production by penetration through stripper targets (HITRAP,GSI)

Charge State Distributions for Uranium

200 keV electron energy (ion at rest)



Ions at E=500 MeV/u ($\gamma \approx 0.65$)

summary R-EBIT features:

• highly charged ions, trapped in small volume $\Rightarrow$ high brightness ions (10^6 ions total, ion density 10^{10} ions/cm^3) of any element H^+ - U^{74+}.

- cloud size matches spectrometer, laser, FEL,..
- Ions nearly at rest, negligible Doppler spread

• energy variation of electron beam allows spectroscopic access to doubly excited states, can be combined with photon detection.

• intense pulses of ions with low emittance can be extracted for

- retrapping in Penning trap precision mass spectrometer
- g-factor of bound electron
- guiding in nano-capillaries

• R-EBIT is UHV compatible, transportable, and has

- inexpensive operation