Electron Beam Ion Sources

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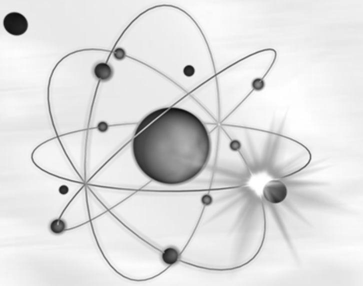
Why Highly Charged Ions ?

Exciting properties of

highly charged ions



Properties of Highly Charged Ions

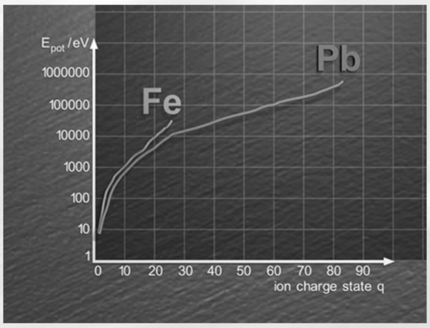
Potential Energy

The potential energy of an ion increases with the degree of ionization.

Example:

Xe^{44+} has a potential energy that is **4200 times higher** than that of Xe^{1+}

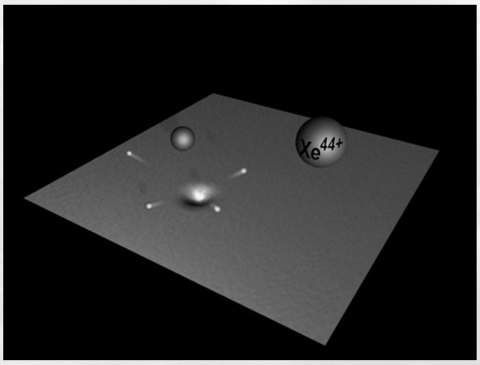
Xe^{54+} has a potential energy that is **16700 times higher** than that of Xe^{1+}



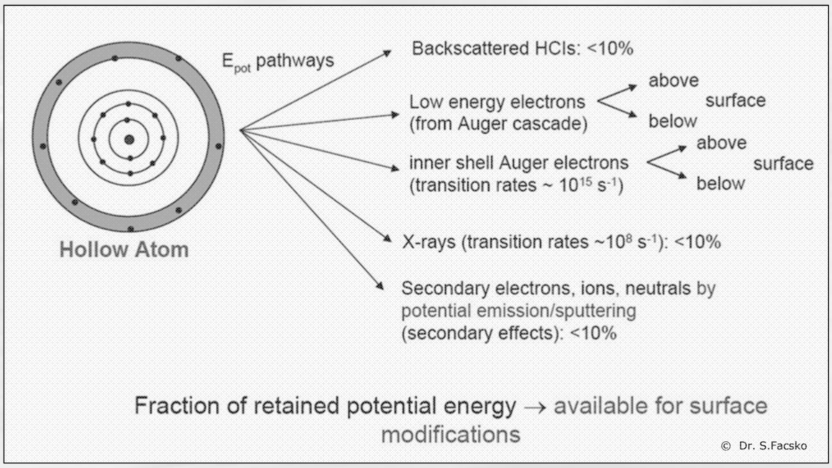
Properties of Highly Charged Ions

High power Deposition into the Surface

The deposition of potential energy leads to ultrafast intense electronic excitations up to: **10^{12} … 10^{14} W/cm²**



Pathways of Potential Energy



E_{pot} pathways

- Backscattered HCIs: <10%
- Low energy electrons (from Auger cascade)
  - above surface
  - below surface
- inner shell Auger electrons (transition rates ~ 10^{15} s^{-1})
  - above surface
  - below surface
- X-rays (transition rates ~10^{8} s^{-1}): <10%
- Secondary electrons, ions, neutrals by potential emission/sputtering (secondary effects): <10%

Fraction of retained potential energy → available for surface modifications

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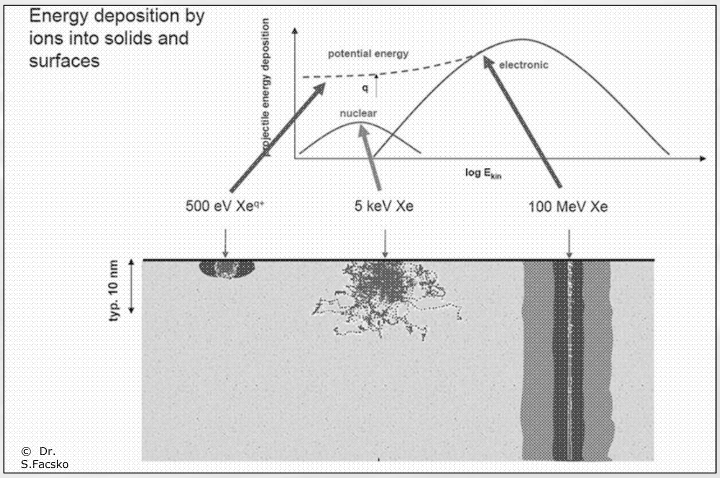
Engery Deposition into Surface

Energy deposition by ions into solids and surfaces



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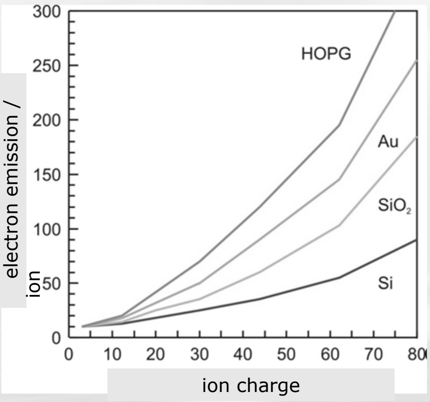
Highly Charged Ions give higher Yields of Secondary Ions and Secondary Electrons

J.W.McDonald et al: NIM B 240, 829 (2005)

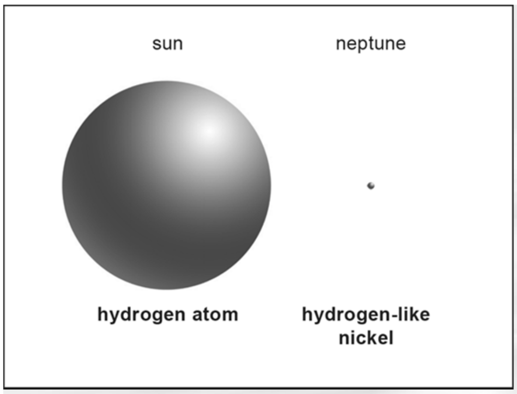


Total electron yields

vs ion charge state q

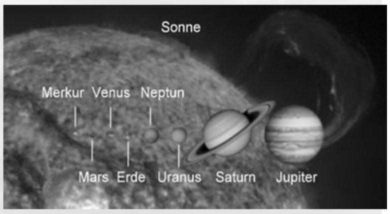
Properties of Highly Charged Ions

Small Spatial Extent of the Projectiles



(Idea by J.Gillaspy, NIST)

The size ratio of a hydrogen-like nickel ion to a neutral hydrogen atom is approximately equal to the size ratio of the planet neptune to the sun.

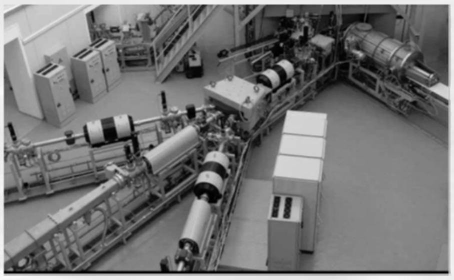


Properties of Highly Charged Ions

Extremely Compact Accelerator Structures are possible

Due to their high charge q ions can be accelerated very effectively

~ q for linear accelerators
~ q² for ring accelerators



Example:

Xe^{1+} and Xe^{44+} acceleration at ΔU = 20 kV

ΔU = 20 kV	**linear accelerator**	**ring accelerator**
Xe^{1+}	20 keV	20 keV
Xe^{44+}	880 keV	38720 keV = 38,72 MeV
		(energy gain about factor 2000!)

Applications of HCI

Highly Charged Ions in Basic Research and Industry

highly charged ions

Plasma physics

Materials science

X-Ray astrophysics

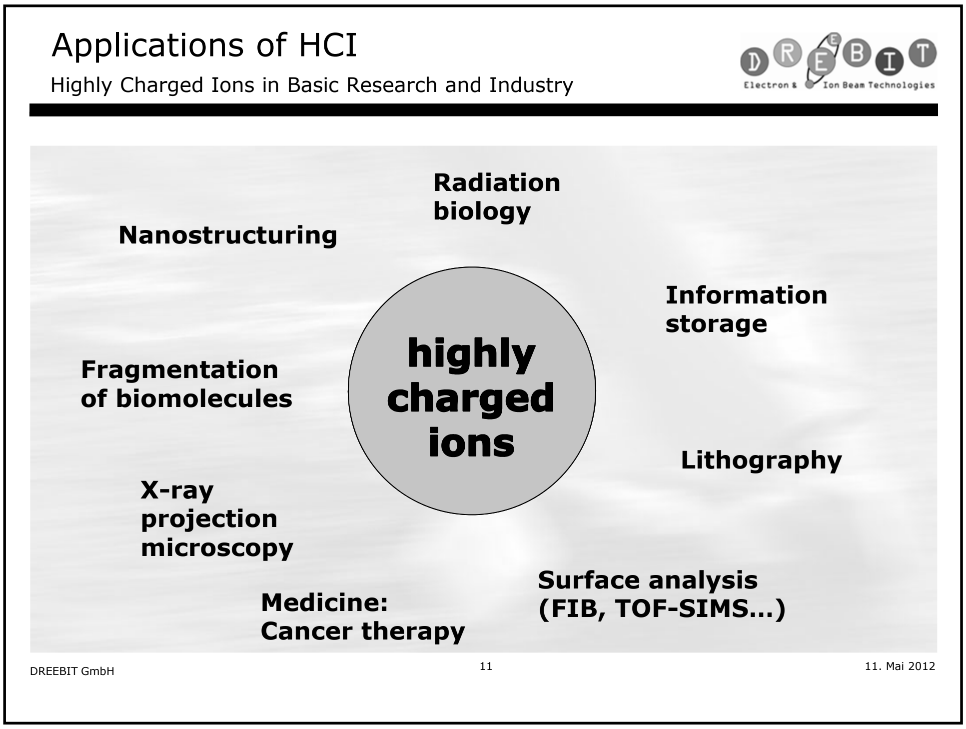
Atomic physics

Ion source physics

Solar physics

Molecule and cluster physics

Biophysics



Applications of HCI

Highly Charged Ions in Basic Research and Industry

highly charged ions

Radiation biology

Nanostructuring

Information storage

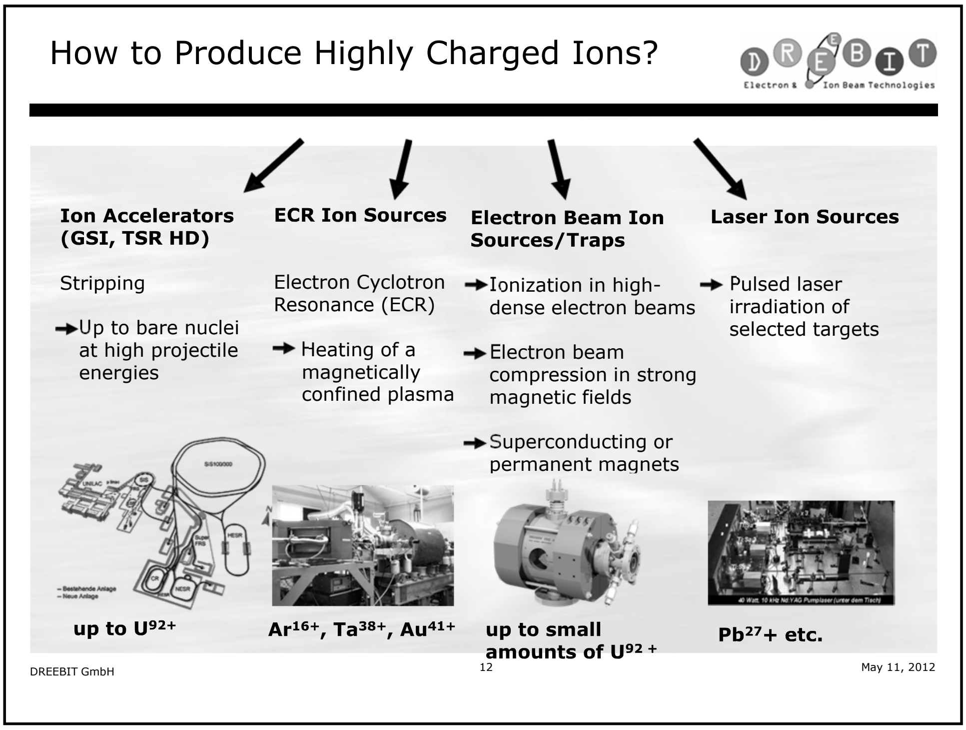
Fragmentation of biomolecules

Lithography

X-ray projection microscopy

Surface analysis (FIB, TOF-SIMS…)

Medicine: Cancer therapy



How to Produce Highly Charged Ions?

Ion Accelerators (GSI, TSR HD)

Stripping

➔Up to bare nuclei at high projectile energies

ECR Ion Sources

Electron Cyclotron Resonance (ECR)

➔ Heating of a magnetically confined plasma

Electron Beam Ion Sources/Traps

➔Ionization in high-dense electron beams

➔Electron beam compression in strong magnetic fields

➔Superconducting or permanent magnets

Laser Ion Sources

➔ Pulsed laser irradiation of selected targets

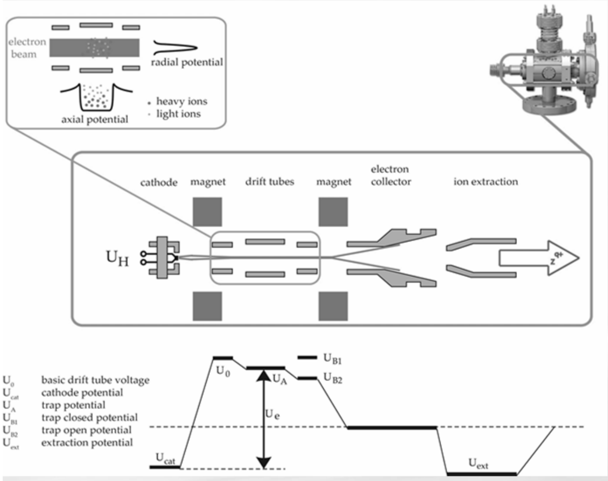
up to U^{92+}

Ar^{16+}, Ta^{38+}, Au^{41+}

up to small amounts of U^{92+}

Pb^{27}+ etc.

Electron Beam Ion Trap – Basic Idea



quantity	**range**
Electron beam energy	up to 200 keV
Electron beam current	up to A (typically up to some hundreds of mA)
Source vacuum	10^{-8} mbar up to 10^{-12} mbar

EBIS/T – Short History

Selected Milestones

Year	**Place/ Name**	**Device**	**Ions**	**Source type** (B, trap length)
1968	Dubna (USSR) Donets	IEL I, IEL II	Au^{19+}	warm EBIS 0.4 T, 16 cm
1971	Dubna (USSR) Donets/Pikin	KRION I	C^{6+}, N^{7+}, O^{8+}, Ne^{10+}	SC 1.2 T, 1.2 m
1974	Dubna (USSR) Ovsyannikov /Donets	KRION 2	Ar^{18+}, Kr^{36+}, Xe^{54+}	SC 2.2 T, 1.2 m
1981 1986	Orsay (France) Arianer	CRYEBIS 1 CRYEBIS 2	C^{6+}, N^{7+}, Ne^{10+}, Ar^{18+}	SC, 3 T, 1.66 m SC, 5 T, 1.66 m
1984	Saclay (France) Faure	DIONE	Ar^{16+}, Kr^{30+}, I^{41+}	SC, 6 T, 1.2 m

EBIS/T – Short History

Selected Milestones

Year	Place/Name	Device	Ions	Source type (B, trap length)
1988 1990	LLNL (USA) Levine Marrs/Knapp	EBIT-I EBIT-II	Xe^{54+}, U^{88+}	SC, 3 T, 2 cm ($E_{(e,max)}$ = 29 keV)
1990	LLNL (USA) Marrs/ Schneider	S-EBIT	U^{92+}, Cf^{96+}	SC, 3 T, 2 cm ($E_{(e,max)}$ = 215 keV)
1999	Freiburg (Germany) Crespo	F/HD-EBIT	Xe^{54+}	SC, 9 T, 4-30 cm
2009	Brookhaven (USA) Beebe/Pikin	RHIC-EBIS	Xe^{36+} high current EBIS	SC 6 T, 1.5 m

EBIS/T – Short History

Selected Milestones

Year	Place/ Name	Device	Ions	Source type (B, trap length)
1999	TU Dresden (Germany) Ovsyannikov/ Zschornack	Dresden EBIT	Ar^{18+}, Xe^{44+}, Ir^{67+}	warm EBIT 0.25 T, 2 cm ($E_{(e,max)}$ = 15 keV)
2005 2008	Dreebit GmbH (Germany) Ovsyannikov/ Zschornack	Dresden EBIS Dresden EBIS-A	Ar^{18+}, Xe^{48+}, Ir^{67+}	warm EBIS, 0.4/0.6 T, 6 cm ($E_{(e,max)}$ = 25 keV)
2009	Dreebit GmbH (Germany) Ovsyannikov/ Zschornack	Dresden EBIS-SC (medical applications and R&D)	C^{6+}, Ar^{18+}, Xe^{48+}	SC, 6 T, 4-30 cm ($E_{(e,max)}$ = 20 keV)

EBIS/T – Short History

Selected Milestones

There are actually about 60 EBIS/EBIT around the world.
(For a list see R.Becker, O.Kester; RSI 81(2010) 02A513)

Most of them are special laboratory constructions.

Worlwide there are only two commercial offerers:

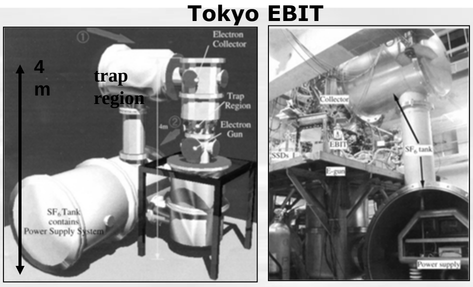
1. **Physics and Technology Livermore (USA)**
   REBIT (Refrigerated Electron Beam Ion Trap)
2. **DREEBIT GmbH Dresden (Germany)**
   Dresden EBIT
   Dresden EBIS
   Dresden EBIS-A
   Dresden EBIS-SC
   (Refrigerated Electron Beam Ion Trap)

Dresden EBIT, Dresden EBIS, Dresden EBIS-A: Room-Temperature EBIS/T

EBIS/T

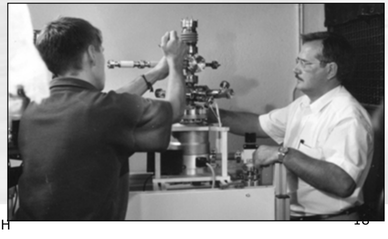
Different solutions

Tokyo EBIT

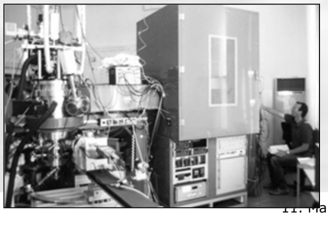


Shanghai EBIT

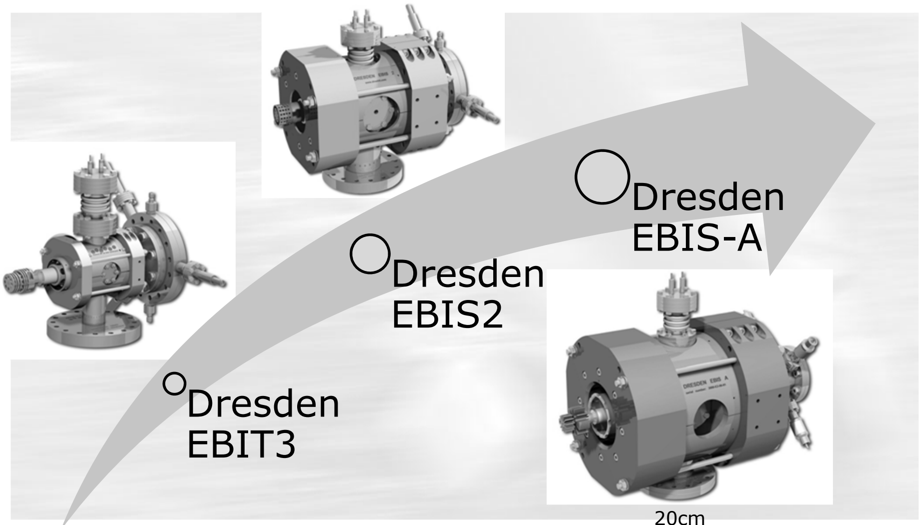
Dresden EBIT



LLNL EBIT
(at the MPI for Plasma Physics Berlin)



Room-Temperature EBIS

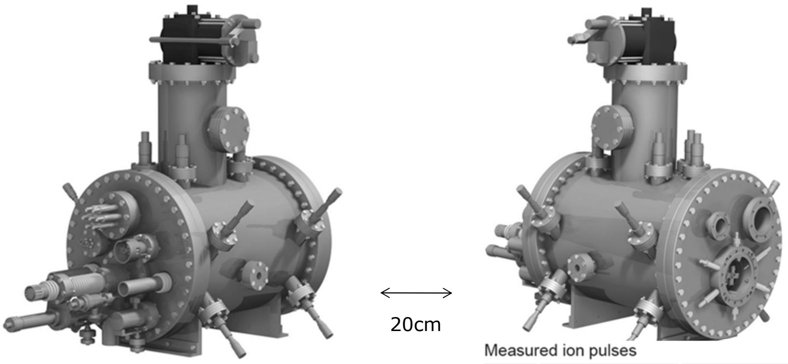


Dresden EBIT3

Dresden EBIS2

Dresden EBIS-A

Dresden EBIS-SC – A superconducting EBIS



Measured ion pulses

Ion	Max. Ions/pulse	Max. pulse rate/Hz
H^+	$3 \cdot 10^9$	500
H_2^+	$3 \cdot 10^9$	1000
C^{4+}	$8 \cdot 10^8$	10
C^{6+}	$4 \cdot 10^8$	10
Ar^{16+}	$2 \cdot 10^7$	2
I^{43+}	$1 \cdot 10^6$	1

- L-He free at 4.2K
- electron beam energy up to 30 keV
- electron beam current up to 700 mA
- magnetic field on-axis 6T

Basic Physics of EBIS

The intended purpose of an EBIS is to produce highly charged ions. For a certain ionisation stage q two opposite processes take place in the electron beam:

Charge-generating processes

- Ionisation (ion)
- Charge Exchange (ce)
- Radiative Recombination (RR)

Charge destructive processes

- Ionisation
- Charge Exchange
- Radiative Recombination
- Ion loses from the trap

Charge Balance of Ions with the Charge State q

Rate equations

$$\frac{dn_q}{dt} = n_e v_e \left[\sigma^{ion}_{q-1\to q}\, n_{q-1} - \left(\sigma^{ion}_{q\to q+1} + \sigma^{RR}_{q\to q-1}\right) n_q + \sigma^{RR}_{q+1\to q}\, n_{q+1}\right]$$
$$- n_0 v_{ion} \left[\sigma^{ce}_{q\to q-1}\, n_q - \sigma^{ce}_{q+1\to q}\, n_{q+1}\right] - f^{col}_q \, \frac{e^{-\frac{qeU_t}{kT_{ion}}}}{\frac{qeU_t}{kT_{ion}}}\, n_q$$

Charge-generating processes (sources for A^{q+})

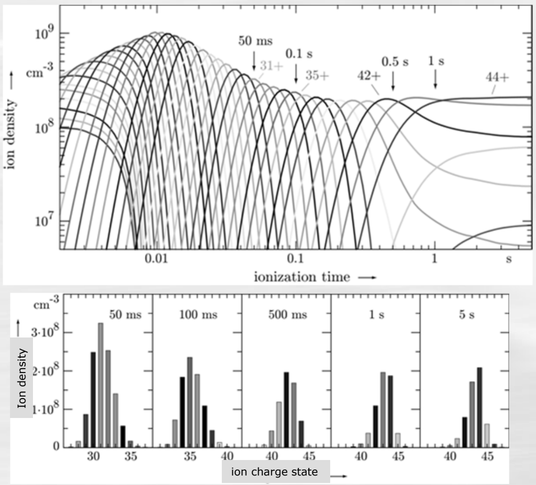
Charge destructive processes (sinks for A^{q+})

U_t - depth of the potential wall (radial and axial) trap potential
kT_{ion} - ion energy

→ We should consider

- the electron beam energies
- the vacuum in the ionization region
- the excitation functions of individual processes

Example:
Ionization of Xenon in a Dresden EBIS-A



Pressure: 2×10^{-9} mbar

Electron beam energy: 14 keV

Production of HCI - Ionization Factor

The basic process in the electron beam of an EBIS is **successive electron impact ionization** with an average ionization time for the ionization of ions with the charge state q of

$$\tau_{q\to q+1} = \frac{n_q}{f_{q\to q+1}} = \frac{1}{n_e v_e \sigma_{q\to q+1}} = \frac{e}{j_e \sigma_{q\to q+1}}$$

with the collision frequency

$$f_{q\to q+1} = n_e n_q v_e \sigma_{q\to q+1}$$

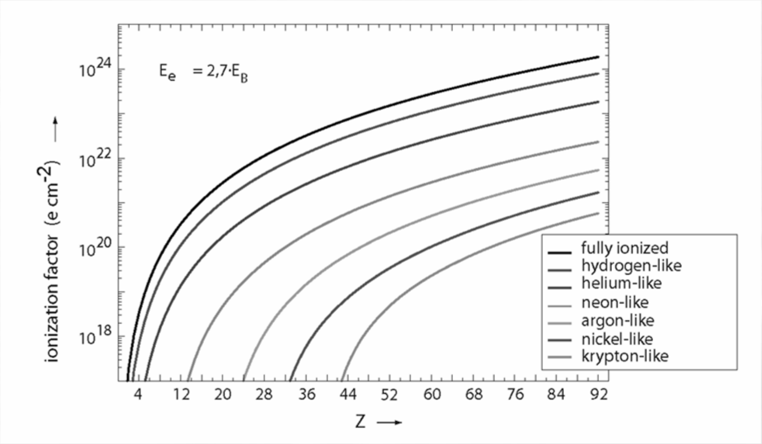
This expressions lead to the **ionization factor**

$$j_e \tau_{q\to q+1} = \frac{e}{\sigma_{q\to q+1}}$$

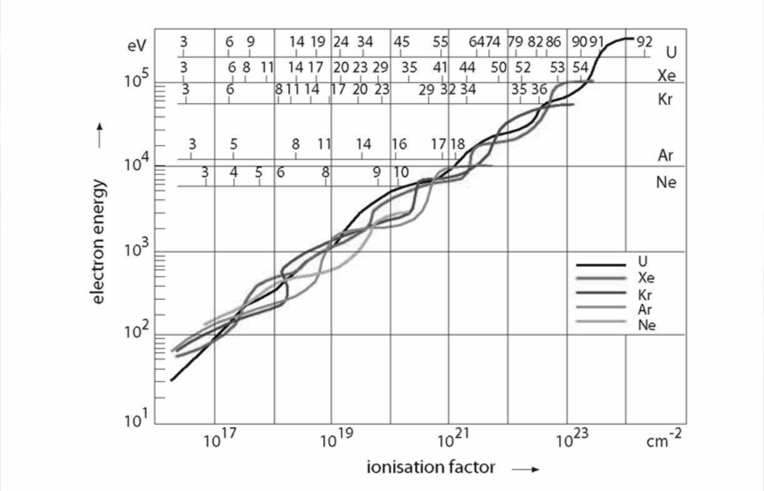
i.e. ionization is possible if we have

$$j_e \tau_{q\to q+1} \geq \frac{e}{\sigma_{q\to q+1}}$$

Ionization Factor vs. Atomic Number and Degree of Ionisation



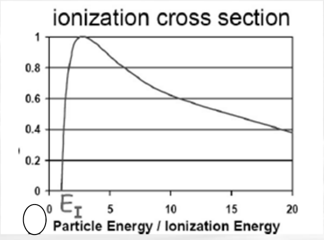
Ionization Factor vs. Atomic Number, Degree of Ionization and Electron Energy

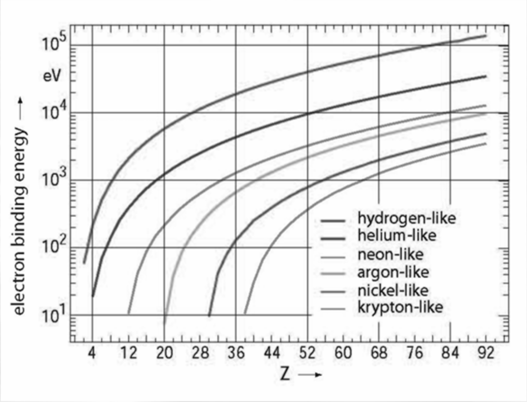


According to an idea from Prof. E.D.Donets [Dubna])

Electron Binding Energies

Threshold values for ionization



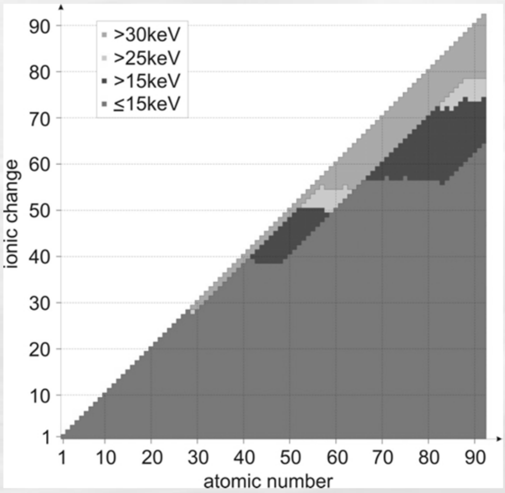


The optimal energy for ionizing an ion from the charge state q to to q+1 is nearly e-times the ionization energy of the weakest bound electron.

Ionization starts at the ionization threshold E_I.

Electron Binding Energies

Threshold values for ionization



Basic Physics

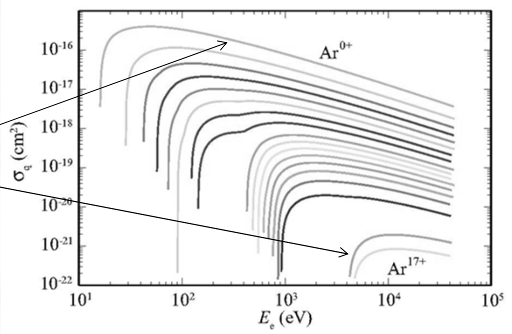
Let's have a look onto the most important physical processes in the electron beam:

- Single ionization
- Double ionization
- Single charge exchange
- Double charge exchange
- Radiative recombination

Basic Physics

Single Electron Impact Ionization

$$A^{q+} + e^- \rightarrow A^{(q+1)+} + 2e^-$$



The higher the ion charge state, the smaller is the ionization cross section

$$\sigma_{q\rightarrow q+1} = 4.5 \cdot 10^{-14} \sum_{i=1}^{N} \frac{ln \frac{E_e}{E_{nl}}}{E_e \cdot E_{nl}} \; [cm^2]$$

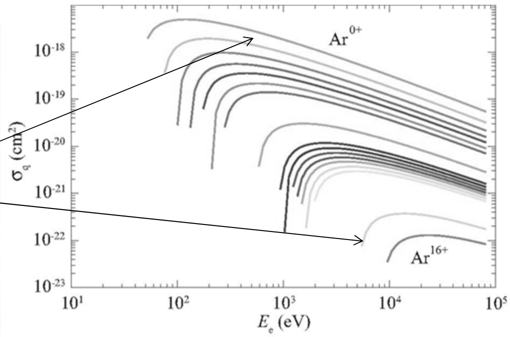
Lotz formula for $E_e >> E_{nl}$ (estimated error: up to 10%; N: number of subshells)

Basic Physics

Double Electron Impact Ionization

$A^{q+} + e^- \rightarrow A^{(q+2)+} + 3e^-$

The higher the ion charge state, the smaller is the ionization cross section



Shevelko formula

$$\sigma_{q\rightarrow q+2} = 1.4 \cdot 10^{-19} \frac{N^{1.08}}{\left(\frac{E_q[eV]}{13.6\, eV}\right)^2} \left(\frac{U}{U+1}\right)^c \frac{\ln(U+1)}{U+1}\ [cm^2]$$

with

$$U = \frac{E_e}{E_q} - 1$$

c=1 for neutrals and c=0.75 for ions
E_q – sum of the ionization potentials of both weakest bound electrons
N - number of electrons in the atom/ion

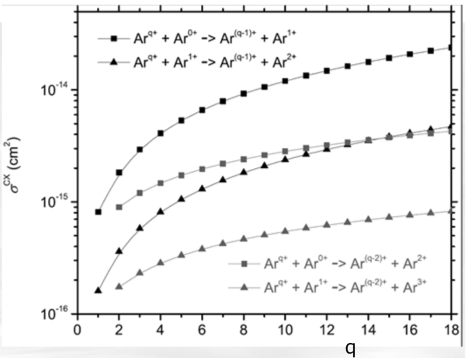
Basic Physics

Charge Exchange

$A^{q+} + A^{p+} \rightarrow A^{i+} + A^{(q+p-i)+}$

Cross sections are independent on the electron energy.

Charge exchange with neutrals is dominant and the main loss process for highly charged ions.



$$\sigma_{q\rightarrow q-1} \approx (1.43 \pm 0.76) \cdot 10^{-12} q^{1.17} \left(E_q[eV]\right)^{-2.76} [cm^2]$$

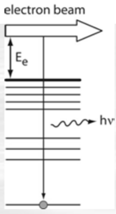
Single charge exchange
(Müller and Salzborn)

$$\sigma_{q\rightarrow q-2} \approx 1.08 \cdot 10^{-12} q^{0.71} \left(E_q[eV]\right)^{-2.8} [cm^2]$$

Double charge exchange

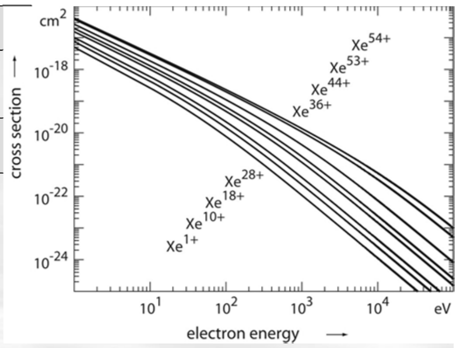
Basic Physics

Radiative Recombination (RR)



$$A^{q+} + e^- \to A^{(q-1)+} + \hbar\omega$$

Charge exchange is strong at low electron energies.



Due to RR processes ionization in an EBIS is more efficient at higher electron energies.

$$\sigma_{q\to q-1}^{RR} = 2.10 \cdot 10^{-22} \frac{E_0^2}{nE_{cm}(E_0 + n^2E_{cm})}\ [cm^2]$$

Theory from Stobbe (for fully ionized atoms)

Eo – binding energy of the hydrogen-like ground-state ion
n - main quantum number of the shell where the electron is captured
E_{cm} – CM collision energy between electrons and ions

$$\sigma_{q\to q-1}^{RR} = \frac{8\pi}{3\sqrt{2}}\alpha\,\lambda_e^2\,\chi_q(E_e) ln\left(1 + \frac{\chi_q(E_e)}{2(n + (1 - W_n) - 0.3)}\right)$$

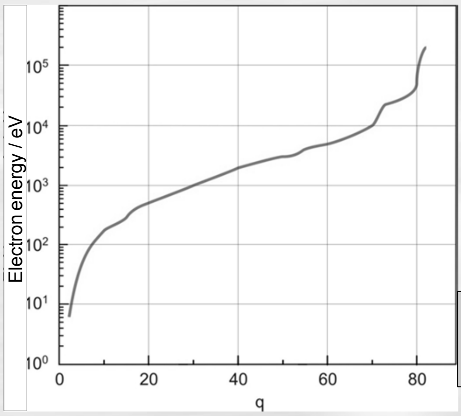
Theory from Kim and Pratt (for all ions)

W_n – ratio of the number of unoccupied states to the total number of states in the subshell
λ_e - Compton-wavelength

with $\chi_q(E_e) = (Z+q)^2 \frac{13.6\ eV}{4E_e}$

Basic Physics

Radiative Recombination (RR)



Balance between ionization and radiative recombination for lead ions
(after: R.Becker; ICIS 2009, Gatlinburg)

Ion loss ratio:

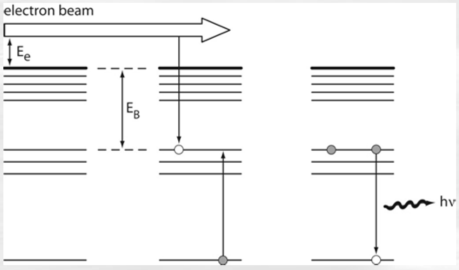
$$R = 2 \cdot 10^{-13}\ n_e[cm]^{-3}\ \frac{q^2}{\sqrt{E_e\ [eV]}}\ \left[\frac{cm^3}{s}\right]$$

Basic Physics

Dielectronic Recombination (DR)

$$A^{q+} + e^- \rightarrow \left[A^{(q-1)+}\right]^* \rightarrow A^{(q-1)+} + \hbar\omega$$

Capture of an electron from the continuum at simultaneous excitation of a second electron and following deexcitation (photon emission).



$$R_{DR} = 6 \cdot 10^{-10}\, N \left(\frac{q}{E_e}\right)^{\frac{3}{2}} \sqrt{E_q}\, e^{-\frac{E_q}{E_e}} \quad \left[\frac{cm^3}{s}\right]$$

N – number of electrons in the outermost occupied shell

E_q – ionization energy of the ion with the charge q

Ion loss ratio

EBIS: Basic Properties

Electrical trap capacity

The total number of ions stored in an EBIs is determined by the electrical trap capacity C_{el}.

Assumption:

Homogeneous electron beam passing an ion trap of the **length L** with an **electron beam current I_e**. The **electron energy** is **E_e**.

With

$$I_e = \frac{dQ}{dt},\ v_e = \frac{dx}{dt},\ v_e = \sqrt{\frac{2E_e}{m_e}} \quad \Longrightarrow \quad \Delta Q = \frac{I_e\, \Delta x}{v_e} = \frac{I_e\, L}{\sqrt{\frac{2E_e}{m_e}}}$$

folllows

$$C_{el} = 1.05 \cdot 10^{13}\ \frac{I_e[A]\ L[m]}{\sqrt{E_e[eV]}}$$

EBIS: Basic Properties

Electrical trap capacity

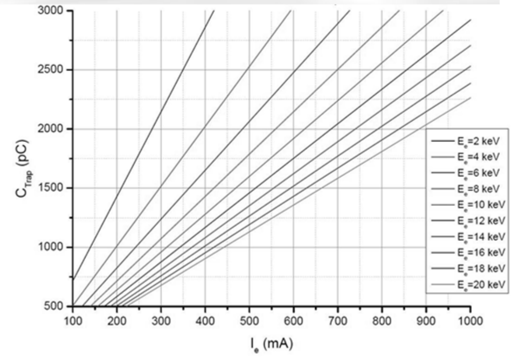
$$C_{el} = 1.05 \cdot 10^{13} \, \frac{I_e[A] \, L[m]}{\sqrt{E_e[eV]}} \cdot f \cdot \alpha$$

For practical purposes we must consider

- the charge compensation f (f<1) of the electron beam,
- the fraction α of ions with a certain ion charge state in the ion charge state spectrum of the produced ions.

<u>Example:</u>

Trap capacity of the Dresden EBIS-SC at different electron beam currents and different electron beam energies.



EBIS: Basic Properties

Electron beam: space charge potential

Radial trap potential

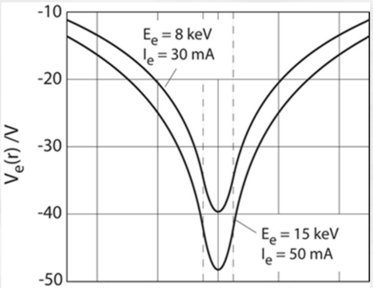
$$V_e(r) = \begin{cases} U_e \left(\dfrac{r}{r_e}\right)^2 & f\ddot{u}r \;\; r < r_e \\ U_e \left(2 \ln \dfrac{r}{r_e} + 1\right) & f\ddot{u}r \;\; r > r_e \end{cases}$$

with

$$U_e = \frac{I_e}{4\pi\varepsilon_0 \, v_e} = \frac{1}{4\pi\varepsilon_0} \cdot \sqrt{\frac{m_e}{2}} \frac{I_e}{\sqrt{E_e}}$$

For estimations we get:

$$U_e = \frac{30 \, I \, [A]}{\sqrt{1 - \left(\dfrac{E_e[keV]}{511} + 1\right)^{-2}}} \; [V]$$



<u>Example:</u>

Radial trap potentials in a Dresden EBIT.

The potential of the drift tubes is superimposed by U_e in the center of the electron beam.

EBIS: Basic Properties

Electron beam: equation of motion and beam radius

Equation of motion for r

$$\frac{d^2r}{dt^2} = \frac{eI_e}{2\pi\varepsilon_0 v_z r m_e} + \frac{e^2}{4m_e^2}\left(\frac{B_c^2 r_c^4}{r^3} - B_z^2 r\right)$$

B_C – B-field at the cathode

r_C – cathode radius

Assuming $B_C = 0$ exists a stationary solution of the above equation.
The solution corresponds to an equilibrium flow of the elctrons with constant radius, the so- called Brillouin-Flow.

We obtain:

$$B = B_B = \frac{1}{r}\left(\frac{2I_e m_e}{\pi\varepsilon_0 v_z |e|}\right)^{1/2} \quad and \quad r_B = \frac{1}{B_B}\left(\frac{2I_e m_e}{\pi\varepsilon_0 v_z |e|}\right)^{1/2}$$

For a Brillouin flow all electrons have a constant distance to the beam center. Thereby the Lorentz force caused by the magnetic field is compensated by the space charge and the centrifugal force of the rotating electrons.

EBIS: Basic Properties

Electron beam: beam radius and Herrmann theory *

Electron beam dynamics, considering

- a magnetic field at the cathode,
- thermal effects at the cathode due to filament heating up to the temperature T_C,
- interactions between the electrons

lead to a corrected electron beam radius (smaller than r_B)

→ Herrmann Theory

* (G.Herrmann; J.Appl.Phys., 29 (1958) 127)

EBIS: Basic Properties

Electron beam: beam radius and Herrmann theory*

Electron beam radius, enclosing 80% of the beam

$$r_e = r(0) \cdot \sqrt{\left(1 - \frac{r_0}{r(0)}\right)^2 + \frac{2}{1 + \frac{B_C^2\ r_C^4}{B_z^2\ r_0^4}} \left(\frac{v_e\ \tan\gamma}{\frac{e}{m_e}\ B_z}\ \gamma\right)}$$

and

$$r_0 = r_B \left(\frac{1}{2} + \frac{1}{2}\left[1 + 4\left(\frac{8kT_C r_C^2 m_e}{e^2 B_z^2 r_B^4} + \frac{B_C^2 r_C^4}{B_z^2 r_B^4}\right)\right]^{1/2}\right)^{1/2}$$

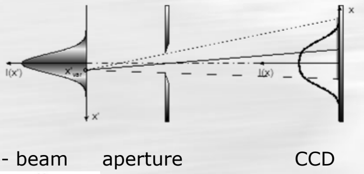
with
r(0) – beam radius at the cathode
γ - angle deviation from the source axis

* (G.Herrmann; J.Appl.Phys., 29 (1958) 127)

EBIS: Basic Properties

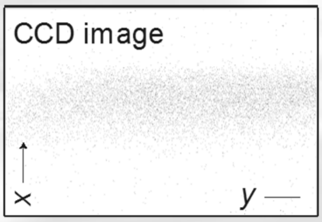
Electron beam: experimental results

- Electron beam density determines the ionization rate → investigation necessary for understanding the ionization process
- Dresden EBIT:
  $r_{80\%}$ = **89±4 µm**; j_e = 96±9 A/cm²
  @ Ee = 7.8 keV; Ie = 30 mA



Generally:
electron beam diameter

(40…200) µm

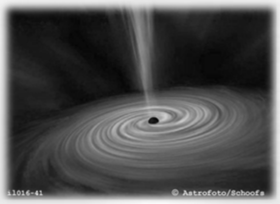


Electron Beam Ion Sources

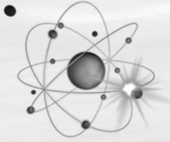
Production of HCI

Electron-impact ionization:
It is hot in the ion trap

> 100.000.000 K



Conditions as at the border of a black hole …

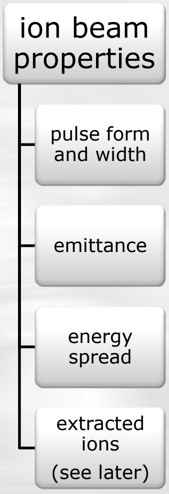


The electron beam energy of an EBIS can be adjusted with a precision of eV

→ Selective excitation and preparation of atomic states and ion charge states

Electron beam scalpel

EBIS: Basic Properties



ion beam properties
- pulse form and width
- emittance
- energy spread
- extracted ions (see later)

EBIS/T – Operation Modes

Three operation modes:

1. Permanently opened trap – transmission mode

The trap is permanently open and ions are produced in the electron beam without axial trapping.

This mode delivers high currents of the lowest charged ions (nA … µA).

2. Partially closed trap – leaky mode

Selecting a low axial potential wall a certain amount of ions with adequate kinetic energy can surpass the potential wall and are extracted continously.

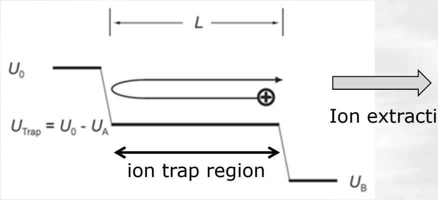
This mode delivers ions with preferently low up to intermediate ion charge states (up to nA) and a low fraction of higher ion charge states.

3. Periodically opened and closed trap – pulsed mode

The potential wall is high enough to trap all ions axially. Periodical opening of the trap releases pulses of ions extracted with typical pulse lengths in the order of some microseconds and allow to produce highest currents of highly charged ions (up to µA per pulse).

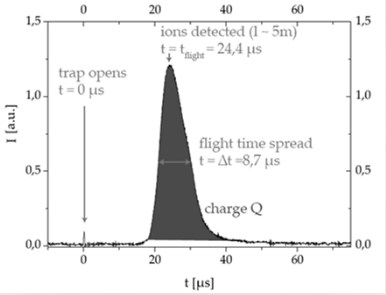
Particularities of EBIT/EBIS puls form – classical extraction

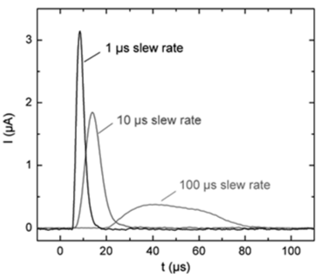
FWHM is in the order of µs



Ion extraction

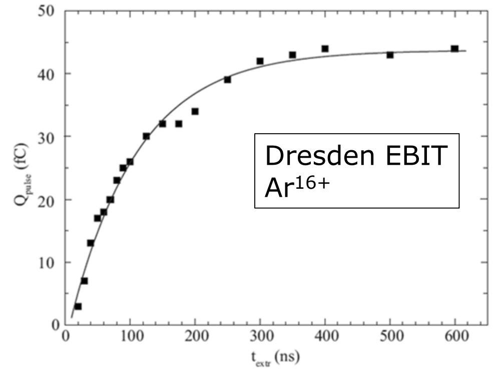
Ion paths in the moment of ion extraction





Ion pulses from the Dresden EBIS-A Trap length – 6 cm

Particularities of EBIT/EBIS puls form – ns ion extraction



Dresden EBIT
Ar^{16+}

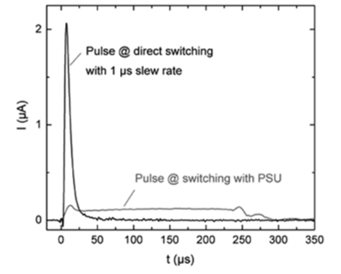
FIG. 3. Extracted ionic charges per Ar^{16+} pulse in dependence on the extraction time t_{extr} (U_0=4.0 kV, I_e=24 mA, t_{cyc}=100 μs, t_{wait}=1 s, p=3.1×10^{-9} mbar). The solid line is a guide to the eye.

REVIEW OF SCIENTIFIC INSTRUMENTS **81**, 02A507 (2010)

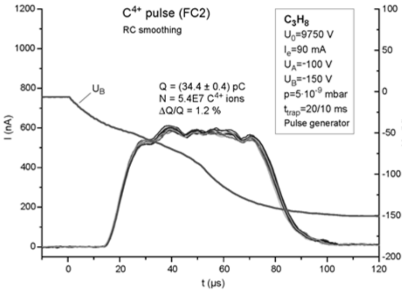
Short time ion pulse extraction from the Dresden electron beam ion trap[a)]

U. Kentsch,[1] G. Zschornack,[2,b)] A. Schwan,[1] and F. Ullmann[1]
[1]*Dreebit GmbH, D-01109 Dresden, Germany*
[2]*Institute of Applied Physics, Dresden University of Technology, D-01062 Dresden, Germany*

Particularities of EBIT/EBIS puls form – flat top pulses



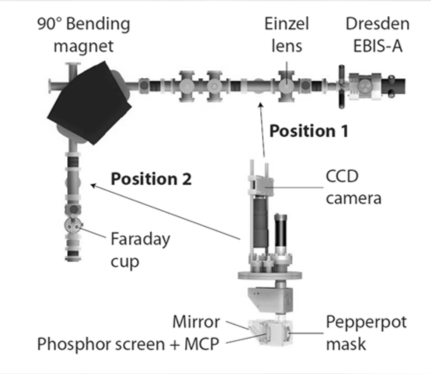
Proton pulse from the Dresden EBIS-A after direct trap opening and after switching with the PSU forming a flat-top pulse shape



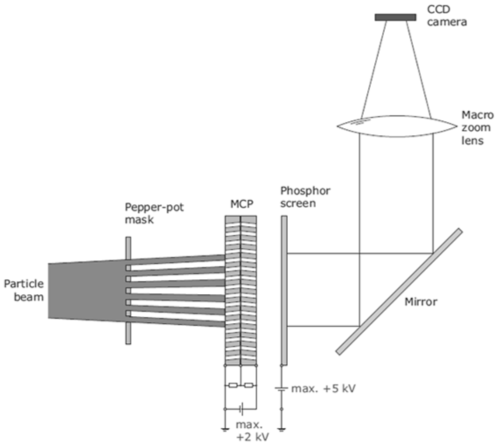
One of the requirements for the applications of EBIS with synchrotrons are flat-top pulses.

Controlling properly U_B flat-top pulses with FWHM to at least 100 μs can be formed.

Particularities of EBIT/EBIS Emittance

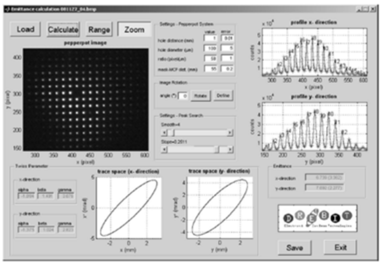


Particularities of EBIT/EBIS Emittance



The scheme of the Pepper-Pot Emittance Meter is pictured in figure 2. The incoming particle beam passes the Pepper-Pot mask and is separated into several beam spots. The particles hitting the MCP create an electron current which is amplified passing the two micro channel plates. The electrons are than accelerated towards the phosphor screen. The visible light spots created at the phosphor screen are detected after 90° deflection by a CCD camera.

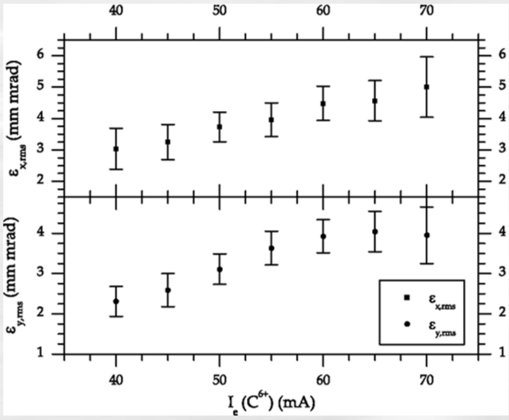
The emittance of the beam can be determined from the position, the size, and the shape of the light spots.



hole distance (mm) 1 0.01
hole diameter (µm) 100 5
ratio (pixel/µm) 50 1
mask-MCP dist. (mm) 55 0.2
angle (°) 0
Smooth=4
Slope=0.2611

Display of the results after calculation

Particularities of EBIT/EBIS Emittance

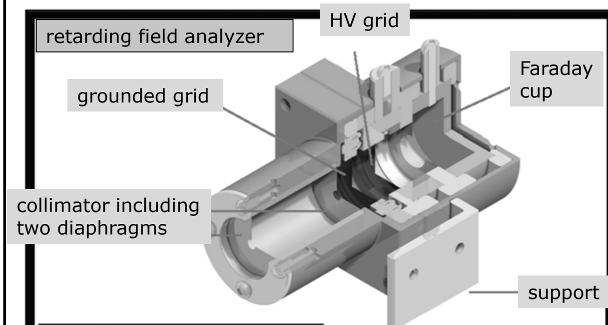


Dresden EBIS-A

For comparison:

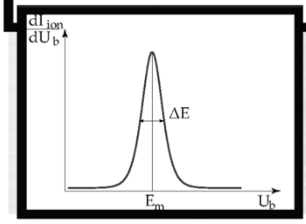
Dresden EBIS-SC
about 30 mm mrad
for I_e = 300 mA

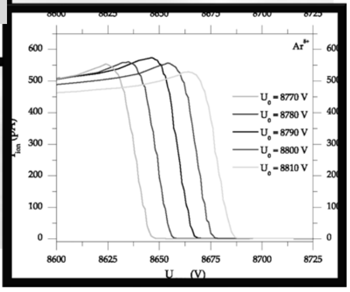
Particularities of EBIT/EBIS Energy spread



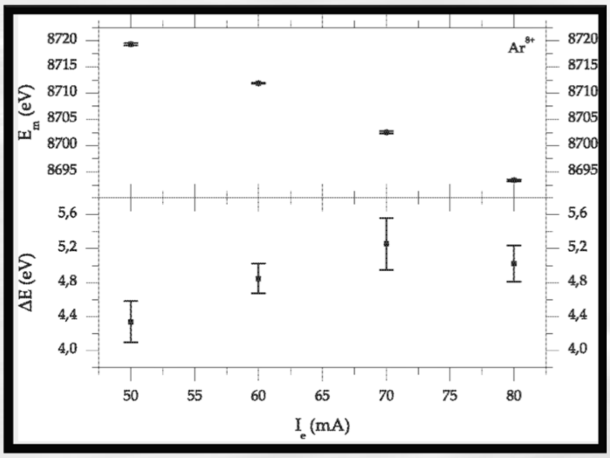
The differentation of the measured curves gives

- The energy spread
- The total beam energy of the analyzed ion beam.





Particularities of EBIT/EBIS
Energy spread



Dresden EBIS-A Ar^{8+}

Total ion beam energy (shifts due to different depths of the beam Coulomb potential)

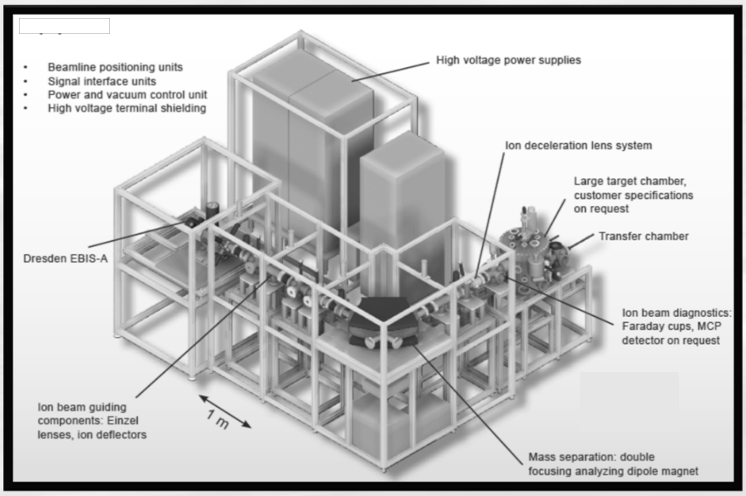
Energy spread of Ar^{8+} (the energy spread is below 1 eV/u in any case)

EBIS: Diagnostics
Processes in the ion source

- q/A analysis
  - Dipole magnet
  - Wien filter
- X-rays (UV, EUV, visible light)
  - energy dispersive spectroscopy
  - wavelength dispersive spectroscopy
  - time-resolved spectroscopy

EBIS: Diagnostics

q/A Analysis



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q/A analysis: dipole magnet

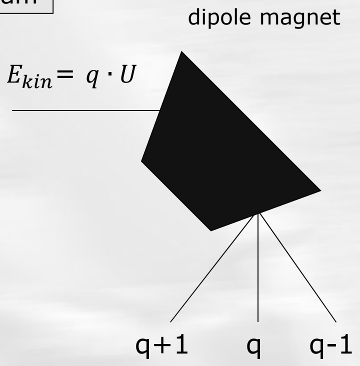
Objective: charge state separated ion beam

Lorentz force = centripetal force

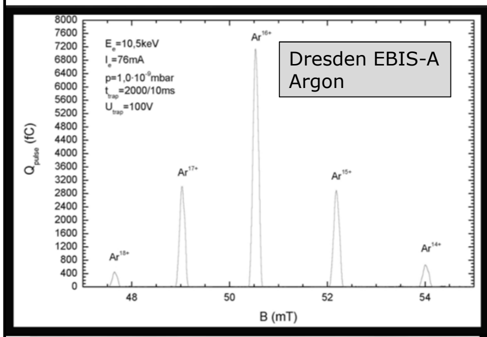
$$q \cdot v \cdot B = \frac{mv^2}{r}$$

- Ion charge state separation

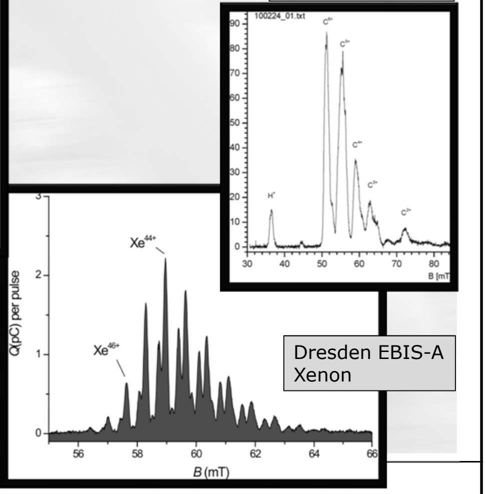
$$\boxed{\frac{q}{A} = \frac{2 \cdot U}{r^2 B^2}}$$



q/A analysis: dipole magnet Examples for ion charge state spectra



Dresden EBIS-A
Argon



Dresden EBIS-SC
Carbon

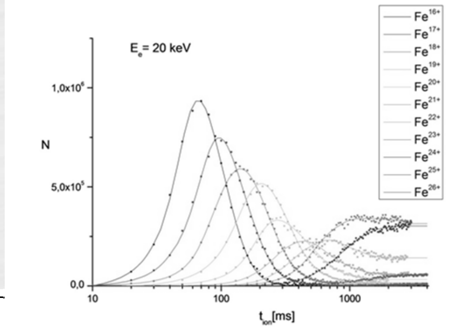
Dresden EBIS-A
Xenon

Ion extraction spectra measured with a Faraday cup after ion charge state separation.

q/A analysis: dipole magnet time-resolved ion charge state spectra

Signal intensity of individual ion charge states measured at different ionization times → reveals the evolution of charge states in the trap

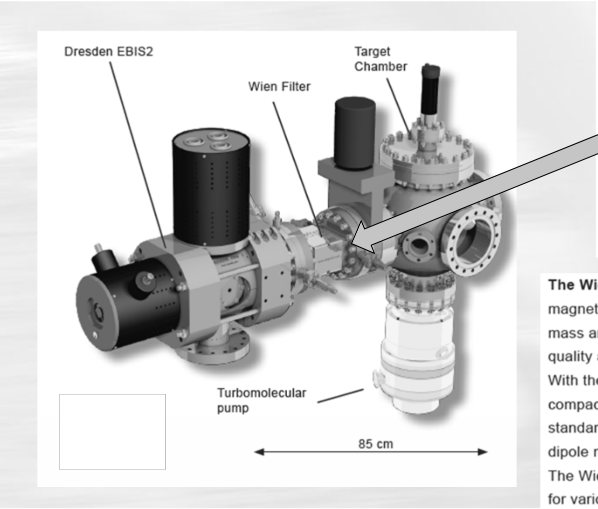
Further analysis allows for
- characterizing the charge balance inside the trap
- estimating the ionisation factor of the source
- determining electron impact ionisation cross sections.



Dresden EBIT Fe^{q+}

EBIS: Diagnostics

q/A Analysis with a Wien filter

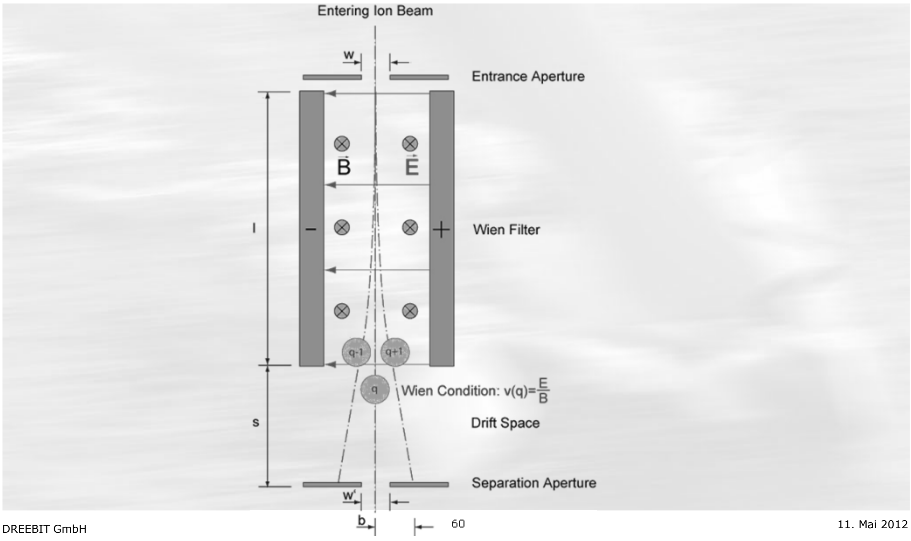


The Wien Filter is a particle separator with a crossed magnetic and electric field configuration providing mass and charge state separated beams of excellent quality at small spatial dimensions (15cmx20cmx20cm) With the Wien filter as an ion source add-on an very compact device is available substituting a complete standard beamline setup with a space consuming dipole magnet and other necessary equipment.

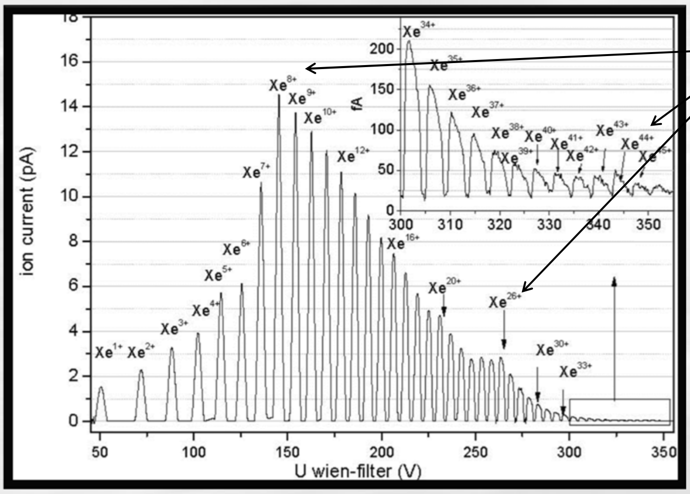
The Wien filter can be used as stand-alone solution for various beam line setups. In dependence on the installed mass- and charge state-separating aperture a resolution of better than 80 is available.

EBIS: Diagnostics

q/A Analysis with a Wien filter



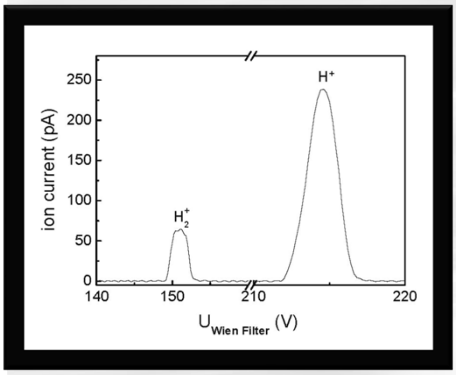
q/A analysis: Wien filter
Examples for ion charge state spectra

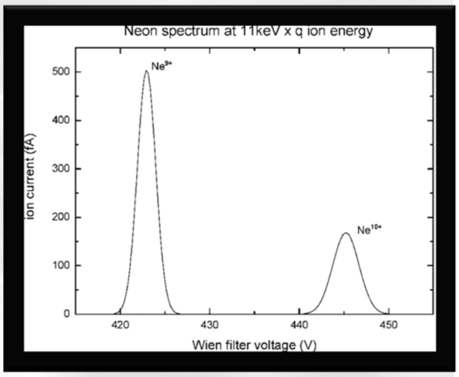


Closed atomic shells

Dresden EBIT
Xenon

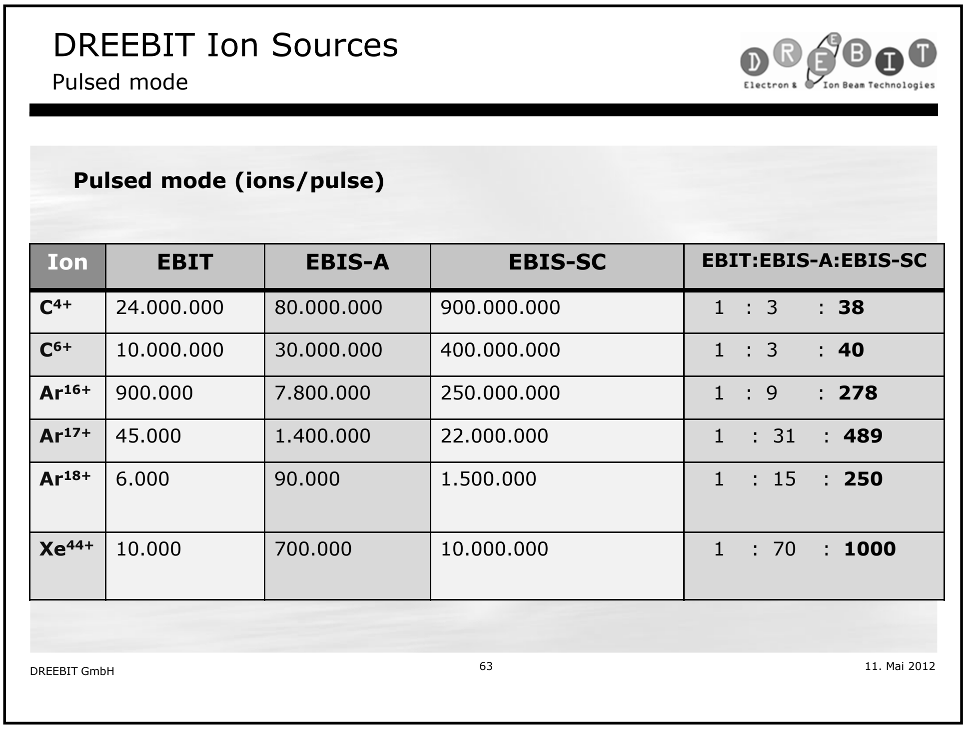
q/A analysis: Wien filter
Examples for ion charge state spectra





Dresden EBIT
Hydrogen

Dresden EBIT
Neon

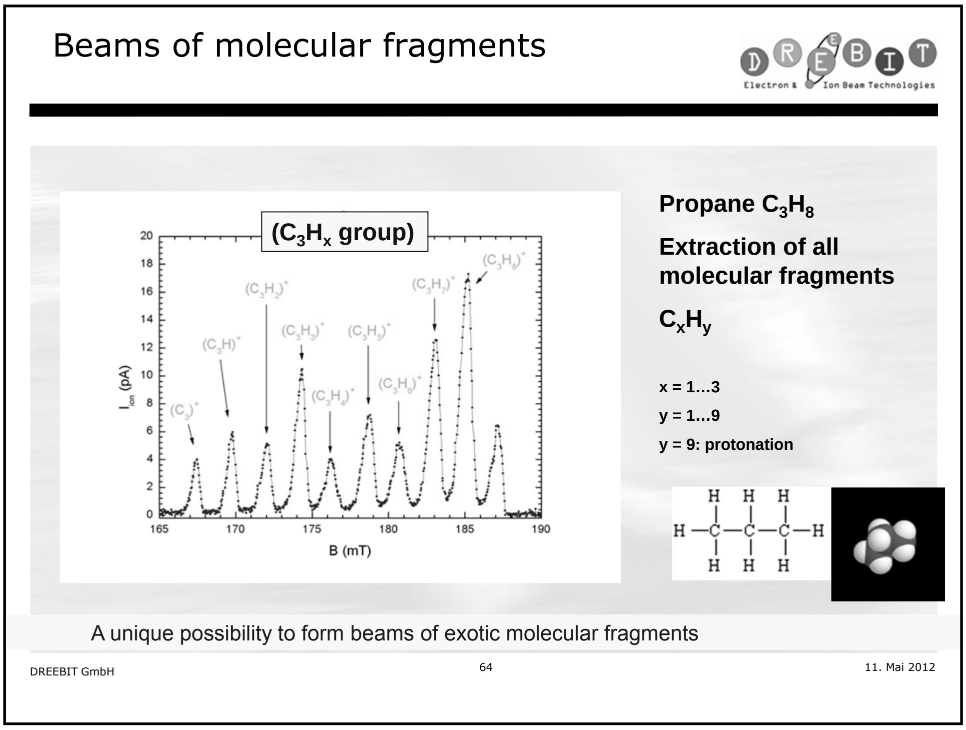


DREEBIT Ion Sources

Pulsed mode

Pulsed mode (ions/pulse)

Ion	EBIT	EBIS-A	EBIS-SC	EBIT:EBIS-A:EBIS-SC
C^{4+}	24.000.000	80.000.000	900.000.000	1 : 3 : **38**
C^{6+}	10.000.000	30.000.000	400.000.000	1 : 3 : **40**
Ar^{16+}	900.000	7.800.000	250.000.000	1 : 9 : **278**
Ar^{17+}	45.000	1.400.000	22.000.000	1 : 31 : **489**
Ar^{18+}	6.000	90.000	1.500.000	1 : 15 : **250**
Xe^{44+}	10.000	700.000	10.000.000	1 : 70 : **1000**



Beams of molecular fragments

Propane C_3H_8

Extraction of all molecular fragments

C_xH_y

x = 1…3
y = 1…9
y = 9: protonation

A unique possibility to form beams of exotic molecular fragments

EBIS: X-Ray Diagnostics
X-ray output from EBIS

For an x-ray detector the following count rate can be expected

$$\dot{N}_q = \varepsilon \frac{\Omega}{4\pi} V j_e \omega_q n_q \sigma_q^{exc}$$

$$\dot{N}_q = \varepsilon \frac{\Omega}{4\pi} l I_e \omega_q n_q \sigma_q^{exc}$$

with
ε – detector efficiency
$\Omega/4\pi$ – solid angle
V – apparent beam volume
L - apparent beam length
ω_q – x-ray fluorescence yield
n_q – number of ions with the charge q
E_{if} - transition energy
Σ_q^{exc} - excitation cross section

The emitted radiation power can be estimated as

$$P = \dot{N}_q E_{if} e$$

For individual dipole lines radiation power on the order of nW was recorded

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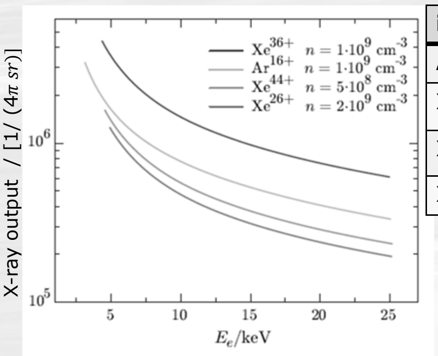
EBIS: X-Ray Diagnostics
X-ray output

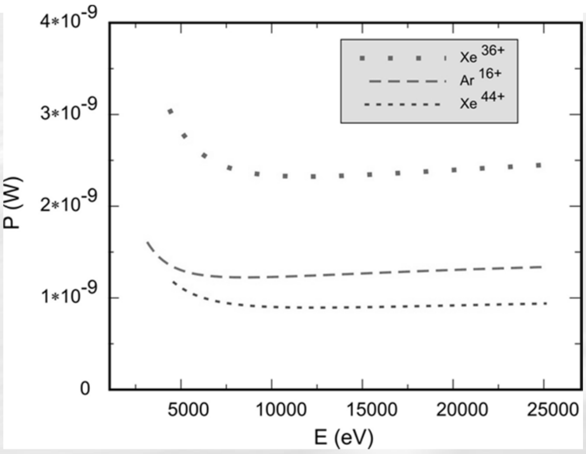
EBIS are excellent sources of X-rays from highly charged ions.



X-ray output from the Dresden EBIT

ion	**transition $i \rightarrow f$**	**E_{if}/eV**	**A_{if}/eV/ħ**
Ar^{16+}	$2p(^1P_1) \rightarrow 1s(^1S_0)$	3138,8	0,073
Xe^{26+}	$3d(^1P_1) \rightarrow 2p(^1D_2)$	4159.6	0.208
Xe^{36+}	$3d(^1P_1) \rightarrow 2p(^1S_0)$	4366.8	0.372
Xe^{44+}	$3d(^1P_1) \rightarrow 2p(^1S_0)$	4558.0	0.321

X-rays from highly charged ions radiation power of the Dresden EBIT



The graph shows the most dominant dipole transitions for DE in case of 3 different ion species

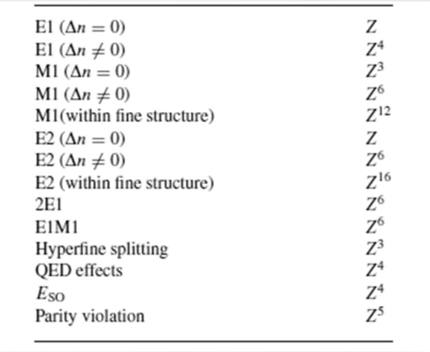
EBIS-A: x 10

EBIS-SC: x 200

→ higher transition power

$$\mathrm{P}[W] = \frac{photons}{s}\,E[eV]\,e[As]$$

Z-dependence allowed and forbidden transitions HFS, QED, parity violation



E1 ($\Delta n = 0$)	Z
E1 ($\Delta n \neq 0$)	Z^4
M1 ($\Delta n = 0$)	Z^3
M1 ($\Delta n \neq 0$)	Z^6
M1(within fine structure)	Z^{12}
E2 ($\Delta n = 0$)	Z
E2 ($\Delta n \neq 0$)	Z^6
E2 (within fine structure)	Z^{16}
2E1	Z^6
E1M1	Z^6
Hyperfine splitting	Z^3
QED effects	Z^4
E_{SO}	Z^4
Parity violation	Z^5

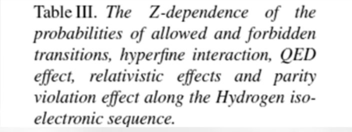
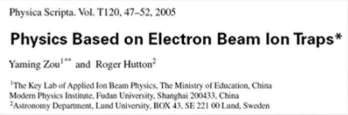


Table III. *The Z-dependence of the probabilities of allowed and forbidden transitions, hyperfine interaction, QED effect, relativistic effects and parity violation effect along the Hydrogen iso-electronic sequence.*

With higher atomic number the intensity of otherwise weak transitions increases.

For highly charged ions otherwise forbidden transitions can become dominant.



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Physics Based on Electron Beam Ion Traps*

Yaming Zou[1**] and Roger Hutton[2]

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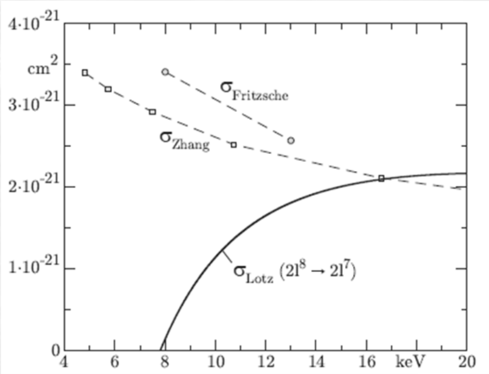
[2]Astronomy Department, Lund University, BOX 43, SE 221 00 Lund, Sweden

X-rays: excitation vs. ionisation



excitation cross-section for

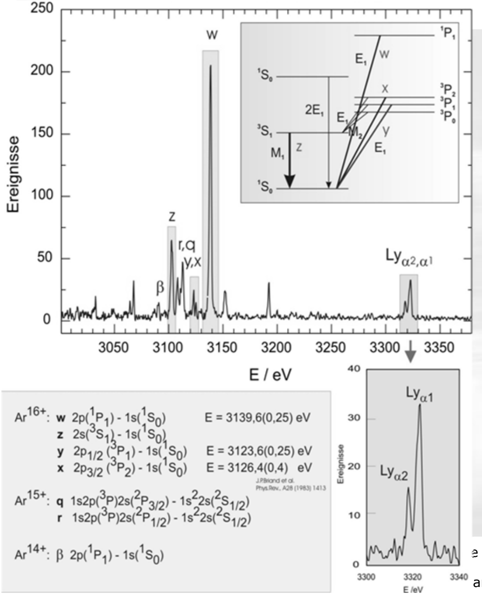
2p($^1S_0$) → 3d($^1P_1$)

vs.

L-shell ionisation cross-section

in Xe^{44+}

Wavelength X-ray spectroscopy: Argon



Ar^{16+}: **w** 2p($^1P_1$) - 1s($^1S_0$) E = 3139,6(0,25) eV
z 2s($^3S_1$) - 1s($^1S_0$)
y $2p_{1/2}$ ($^3P_1$) - 1s($^1S_0$) E = 3123,6(0,25) eV
x $2p_{3/2}$ ($^3P_2$) - 1s($^1S_0$) E = 3126,4(0,4) eV

J.P.Briand et al. Phys.Rev., A28 (1983) 1413

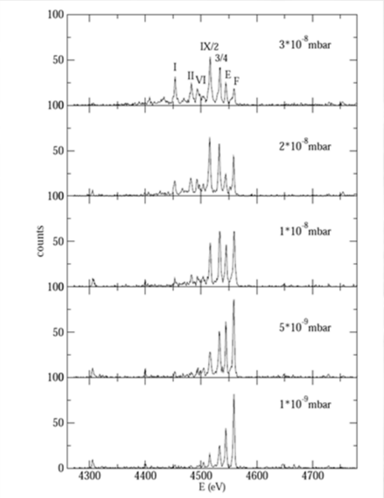
Ar^{15+}: **q** 1s2p(^{3}P)2s($^2P_{3/2}$) - 1s^{2}2s($^2S_{1/2}$)
r 1s2p(^{3}P)2s($^2P_{1/2}$) - 1s^{2}2s($^2S_{1/2}$)

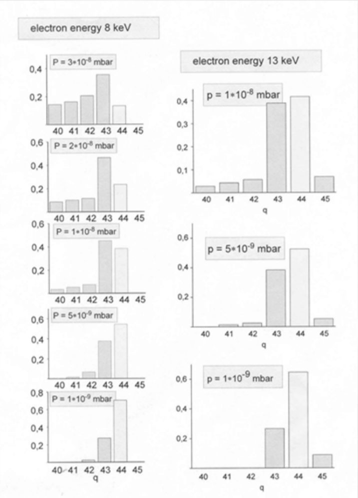
Ar^{14+}: β 2p($^1P_1$) - 1s($^1S_0$)

Transition energies in one- and two-electron systems can be calculated very precisely.

Therefore hydrogengen-like ions are excellent sources for well known x-ray transitions: **Lyman lines**

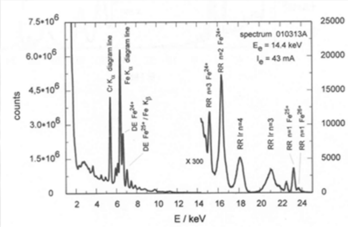
Wavelength X-ray spectroscopy: Xenon

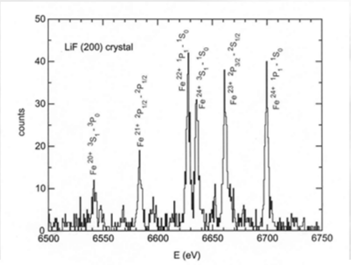


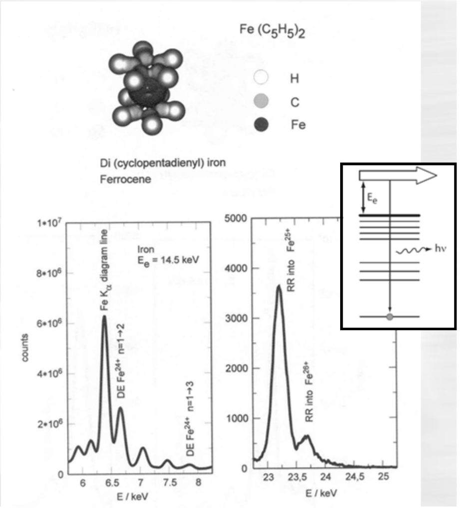


E: 3s – 2p
F: 3d – 2p

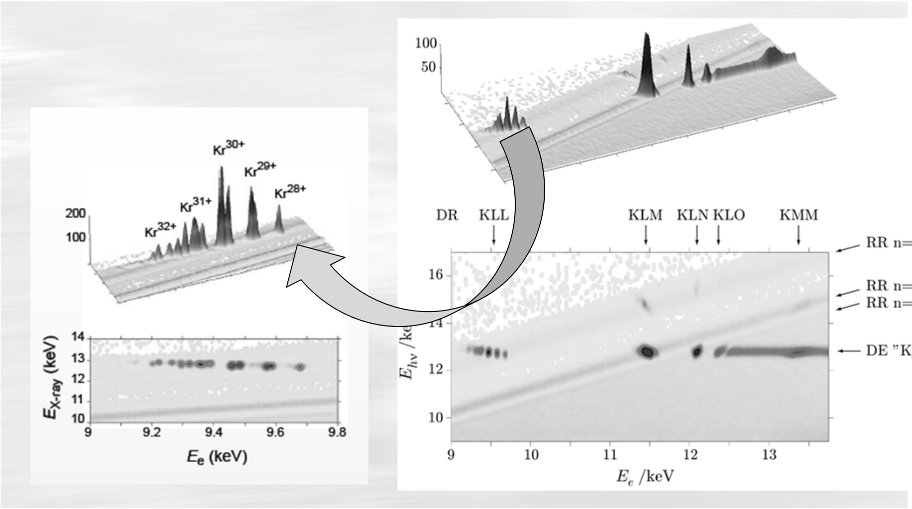
Energy and Wavelength X-ray spectroscopy: Iron



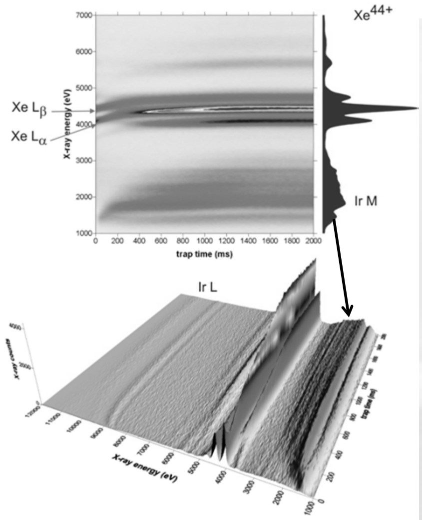




X-Ray Spectroscopy: Scatterplot

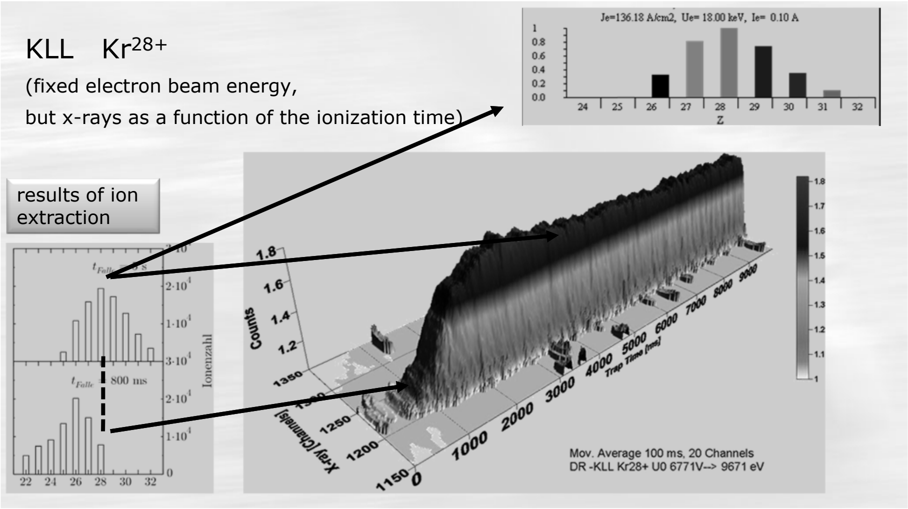


Time-resolved x-ray spectroscopy



Time-resolved energy dispersive x-ray spectroscopy on xenon ions

Time-resolved KKL-DE x-ray spectroscopy



KLL   Kr^{28+}

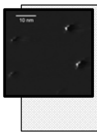
(fixed electron beam energy,
but x-rays as a function of the ionization time)

results of ion extraction

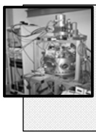
Applications of highly chargeds ions (examples)

Applications of HCI

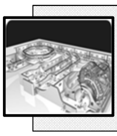
Applications of highly chargeds ions (examples)



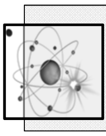
Nanostructuring



FIB, Surface analysis

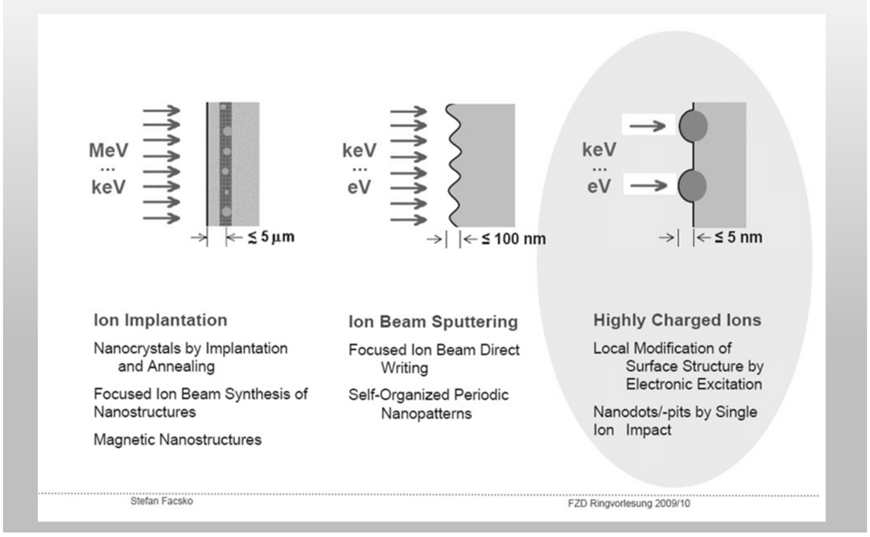


Particle Therapy



Charge Breeding

Nanostructuring with highly charged ions



Ion Implantation

Nanocrystals by Implantation and Annealing

Focused Ion Beam Synthesis of Nanostructures

Magnetic Nanostructures

Ion Beam Sputtering

Focused Ion Beam Direct Writing

Self-Organized Periodic Nanopatterns

Highly Charged Ions

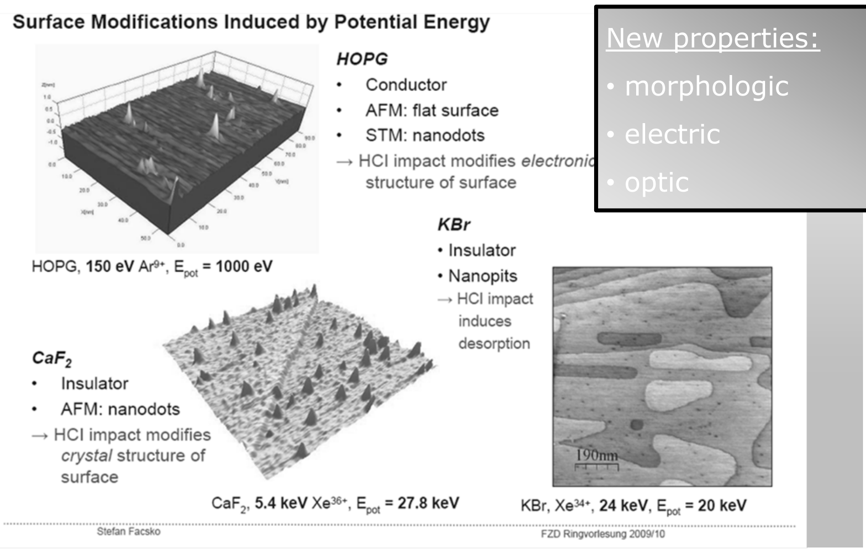
Local Modification of Surface Structure by Electronic Excitation

Nanodots/-pits by Single Ion Impact

Stefan Facsko

FZD Ringvorlesung 2009/10

Nanostructuring with HCI



Surface Modifications Induced by Potential Energy

HOPG
- Conductor
- AFM: flat surface
- STM: nanodots

→ HCI impact modifies *electronic* structure of surface

HOPG, **150 eV** Ar^{9+}, E_{pot} **= 1000 eV**

KBr
- Insulator
- Nanopits

→ HCI impact induces desorption

CaF_2
- Insulator
- AFM: nanodots

→ HCI impact modifies *crystal* structure of surface

CaF_2, **5.4 keV** Xe^{36+}, E_{pot} **= 27.8 keV**

KBr, Xe^{34+}, **24 keV**, E_{pot} **= 20 keV**

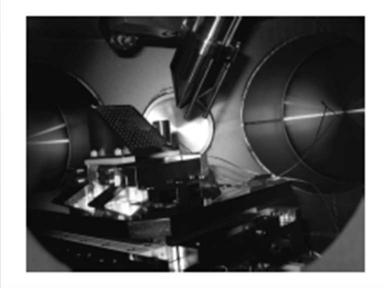
Stefan Facsko

FZD Ringvorlesung 2009/10

New properties:
- morphologic
- electric
- optic

Focussed Ion Beams

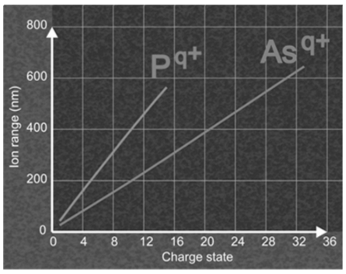
FIB
(Focused Ion Beam)



A new class of FIB

Feature	New Advantage
Projectiles	Almost all elements of the periodic table, in particular noble gases
Charge State	Free choice of projectile charge state
Sputter Yield	Variable, according to the kinetic and potential energy
Implantation	Variable implantation depth, according to the kinetic projectile energy

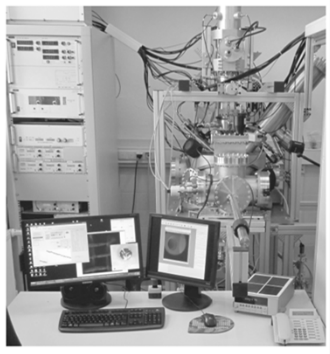
Implantation in Si:
Realization of different implantation depths due to different ion charge states at a fixed ion acceleration potential



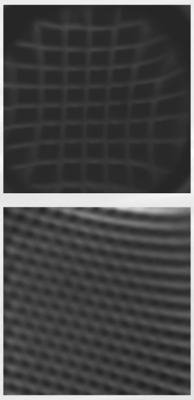
A new class of FIB
By using DREEBIT ion sources

Production of ion beams with different ion charge states with diameters in the micrometre up to nanometre region.

Applications
Lithography
Nano Engineering
Photonic Structures
Materials Characterization
Micro-Machining
Quantum Dots
Radiation Biology
Surface Analytics



Xe - FIB

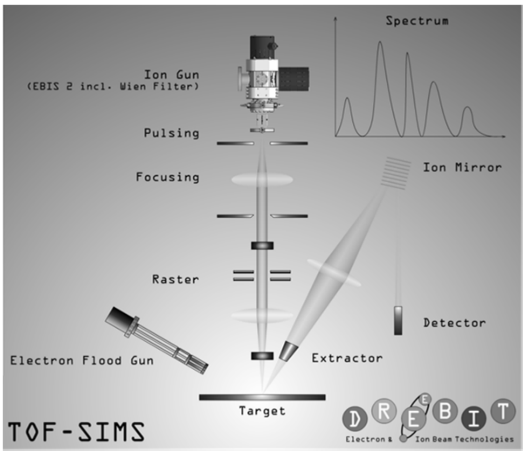


lattice width 2 μm

Worldwide first SEM-figures produced with a Xe ion beam!

Time-of-Flight
Secondary Ion mass Spectrometry

TOF-SIMS



Applications of HCI

Time of Flight
Secondary Ion Mass Spectroscopy

Anwendungen
Semiconductor industry
Surface analysis
"Soft matter“ applications (bio materials, polymers, …)
Materials science
Basic research
Classical industry (glass, paper, metal, ceramics, …)
Analysis of contaminations, adhesion, friction, corrosion, diffusion, cell chemistry, bio compatibility

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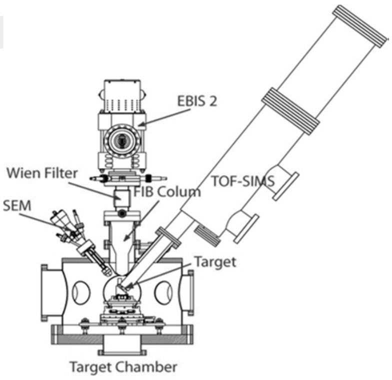
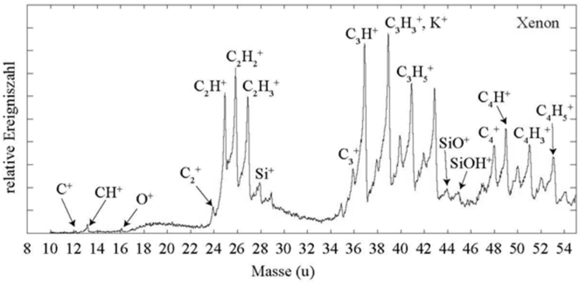
Applications of HCI



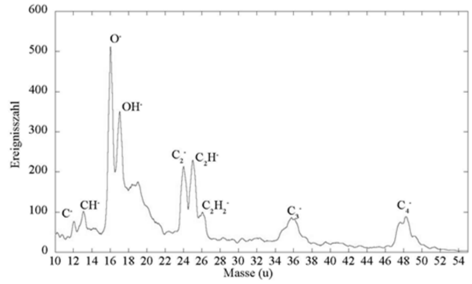
Applications of HCI TOF-SIMS



Non-cleaned Si-surface

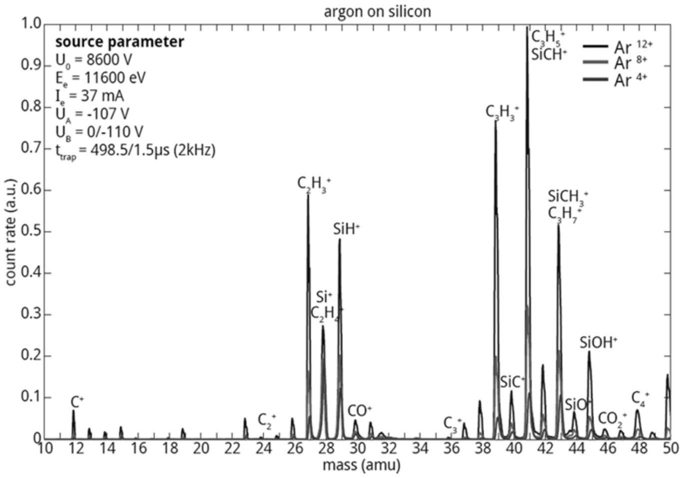
Excitation with xenon ions

Positive ions



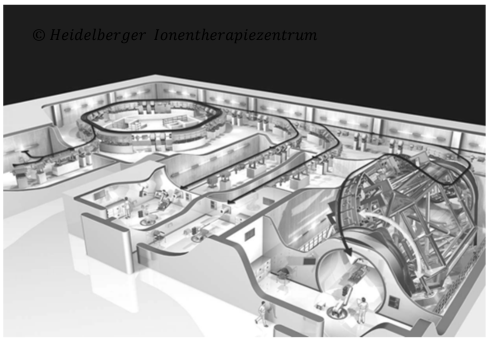
negative ions

Applications of HCI: TOF-SIMS



Medical Particle Therapy

Hadron Therapy


© Heidelberger Ionentherapiezentrum

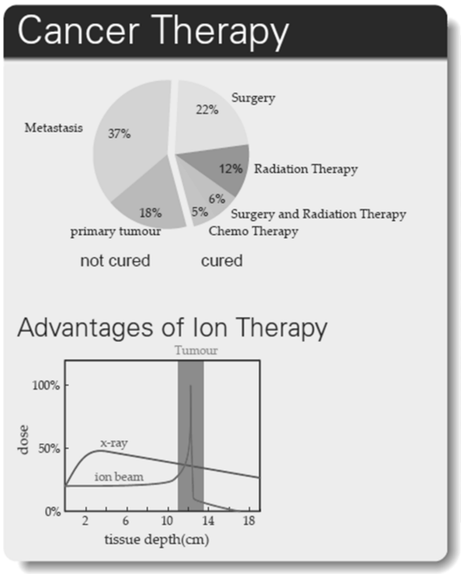
Cancer - a Worldwide Problem

- **Cancer is the the second most common cause of death and about 33% of all inhabitants of the EU will confront some kind of cancer in their life**
- **About 45% of cancer patients can be treated, mainly by surgery and / or radiation therapy [S.Peggs, PAC07, June 25'07]**
- **Hadron therapy with protons and carbon ions is - taken its success rate - the second most successful technique in cancer treatment, outmatched only by surgery**
- **Until 2005 about 40.000 patients worldwide were treated by particle therapy at 22 PT centers (Europe, USA, Japan, China, South Africa). The number of treated patients is constantly increasing.**

Advantages of Therapy with Ion Beams

It is possible to focus carbon ions with great precision directly onto the tumor. Therefore, only the tumor is damaged irreversibly but the healthy tissue remains intact.

Another advantage is the high biological efficiency of carbon ions, causing more damage in the tumor cells than other kinds of irradiation.

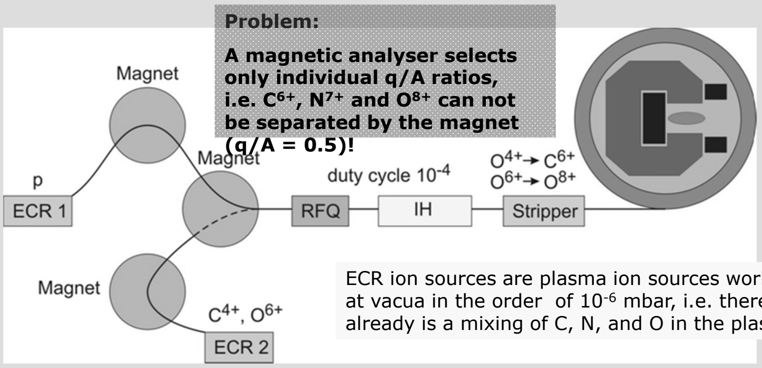


Basic Structure of a Synchrotron-based Irradiation Facility

Heidelberg Hadron Therapy Facility HIT:

Problem:

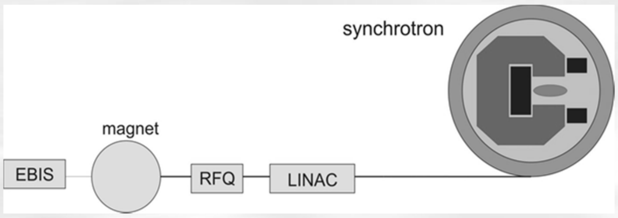
A magnetic analyser selects only individual q/A ratios, i.e. C^{6+}, N^{7+} and O^{8+} can not be separated by the magnet (q/A = 0.5)!



ECR ion sources are plasma ion sources working at vacua in the order of 10^{-6} mbar, i.e. there already is a mixing of C, N, and O in the plasma.

R.Becker, ICIS-05 PA9/RSI MS # C05005

Simplification of Therapy Facilities by using a New Kind of Ion Source



Advantages:

only one ion source
only one separation magnet
shorter LINAC
no stripper
lower injection energy
single-turn injection (at 4 MeV/u)
smaller synchrotron magnets
lower power consumption

the complexity of the irradition facility decreases,

the beam quality is improved,

costs can be reduced

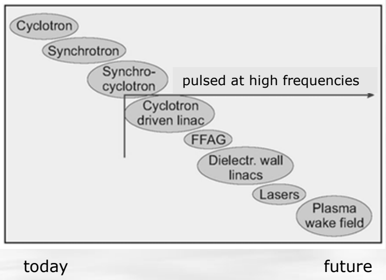
Particle therapy

Cyclotrons
- IBA (Belgium)
- SIEMENS (Germany)
- HITACHI (Japan)
- MITSUBISHI (Japan) a.o.

Synchrotrons
- SIEMENS (Germany)
- HITACHI (Japan)
- MITSUBISHI (Japan) u.a.

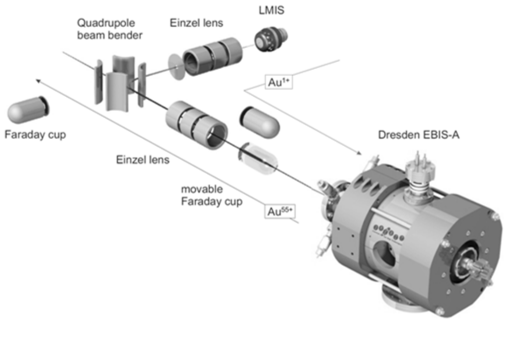
CYCLINACs
- ADAM (Switzerland; CERN)

DDA, DWA
- SIEMENS (Germany)
- some instituts (USA. Japan)

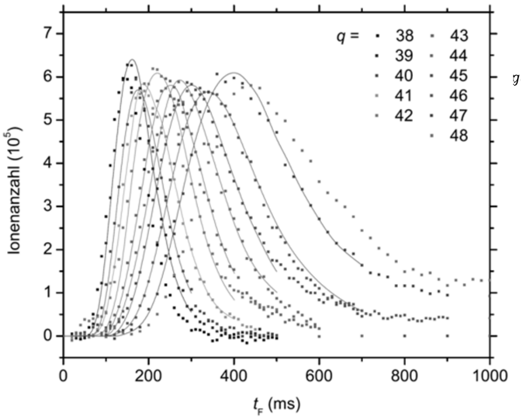


Charge Breeding

Charge Breeding



Charge Breeding



q/A analysis

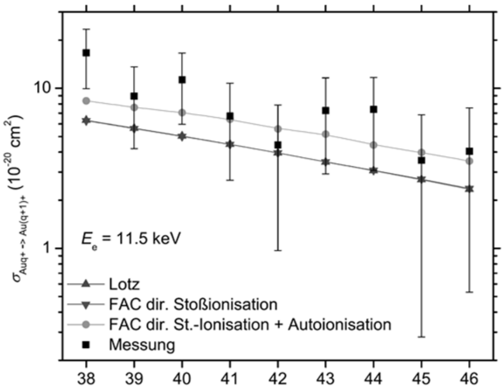
→ Evolution of the ion charge states Au^{38+} to Au^{48+}

Description:

$$dN_{q+}/dt = \lambda_{q-1} \cdot N_{q-1} - \lambda_q \cdot N_q + \lambda_{q+1} \cdot N_{q+1}$$

Charge Breeding

Electron & Ion Beam Technologies



Electron impact ionisation cross-sections for charge bred gold ions

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Thank you … and thanks to the team!

Electron & Ion Beam Technologies

Dr. G.Zschornack R.Mertzig U.Kentsch E.Ritter

Dr.V.P.Ovsyannikov Dr. F.Grossmann Dr. R.Heller Dr. A.Thorn M.Schmidt M.Hartig

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http://www.tu-dresden.de

Electron & Ion Beam Technologies

http://www.dreebit.com

Founding and cooperation

ZIM für wachstum

Europa fördert Sachsen.
EFRE
Europäischer Fonds für regionale Entwicklung

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ZENTRUM DRESDEN
ROSSENDORF