Atomic Physics at GSI: Current and Future Research

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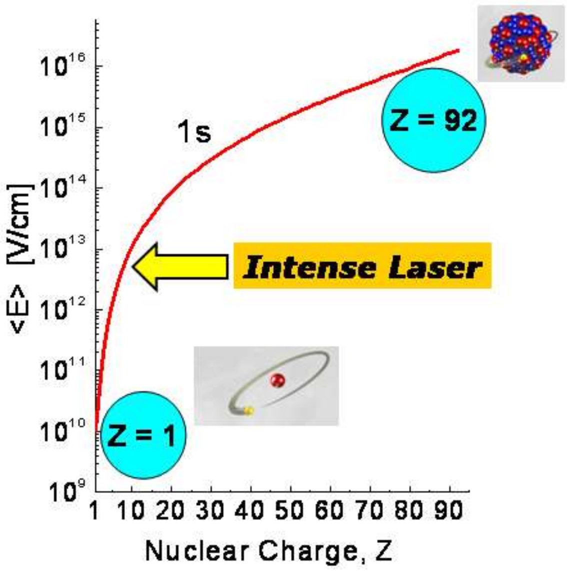
GSI summer student program 2012
Friday, 10 August 2012, 11:10 – 12:30

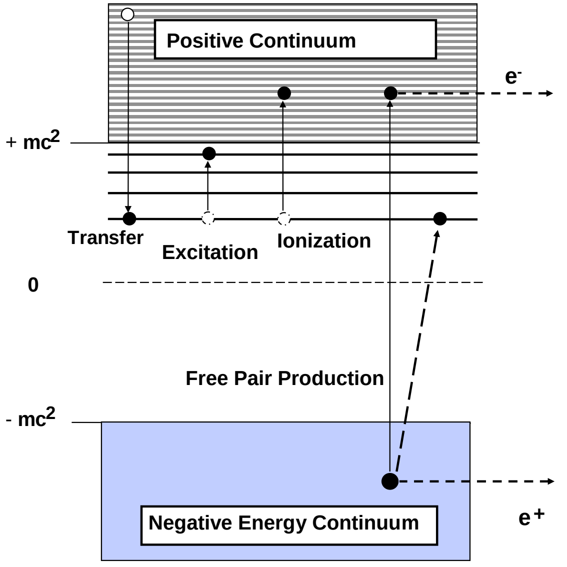
Atomic Physics Group

Contents of my talk

- atomic physics at GSI
- strong electromagnetic fields → QED, relativity, correlation
- the hydrogen atom
- the creation of ions and charge exchange processes
- storing and cooling of ions
- the experimental storage ring ESR
- mass spectrometry, laser and x-ray spectroscopy
- the HITRAP facility
- the future facility FAIR

Atomic Physics at GSI





Atomic Structure at High-Z

- bound state quantum electrodynamics (QED)
- effects of relativity on the atomic structure
- electron correlation in the presence of strong fields
- borderline of atomic & nuclear physics

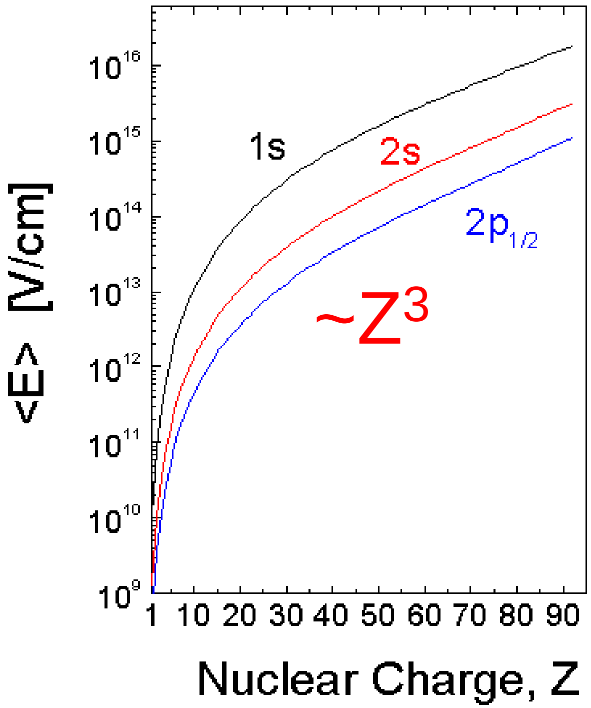
Atomic Collision at High-Z

- time reversal of elementary atomic processes
- photon-matter interaction
- dynamically induced strong field effects

the interest in highly-charged ions

Simple (few electron) systems:
from hydrogen to H-like uranium.

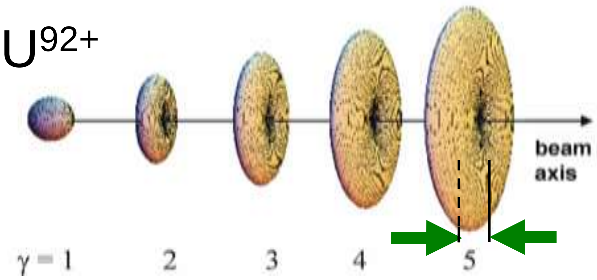
Tests of QED in extreme electromagnetic fields.
New access to fundamental constants and to nuclear ground state properties.



$E_B \sim 10^5$ eV
$Z\alpha \sim 1$

$E_B \sim 10$ eV
$Z\alpha \sim 10^{-2}$

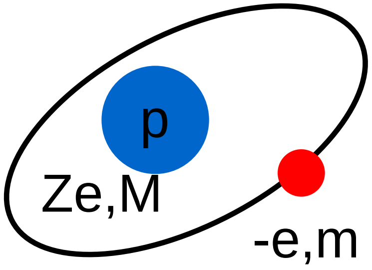
Extremely short and extremely intensive electromagnetic pulses at relativistic energies of highly-charged ions.



$t \leq 0.1$ as
$I \approx 10^{21}$ W/cm²

The best place to start off with is…

hydrogen



no relativity, no reduced mass, no QED, etc. !

Derivation of the Bohr (hydrogen) atom groundstate energy.
Force balance:

$$m\ddot{\vec{r}} = \vec{F_C} + \vec{F_{cf}} = -\frac{Ze^2}{4\pi\epsilon_0 r^2}\hat{r} + \frac{mv^2}{r}\hat{r} = 0 \tag{1}$$

Quantization of angular momentum:

$$\boxed{mvr = n\hbar} \tag{2}$$

Energy balance:

$$E_{tot} = E_{kin} + E_{pot} = \frac{mv^2}{2} - \frac{Ze^2}{4\pi\epsilon_0 r} \tag{3}$$

Rewrite eq. (1) as:

$$\frac{Ze^2}{4\pi\epsilon_0 r} = mv^2 \tag{4}$$

Use (4) in (3) and obtain for the total energy of the system:

$$E_{tot} = \frac{mv^2}{2} - mv^2 = -\frac{mv^2}{2} \tag{5}$$

Bound states!

Multiply both right- and left-hand side of (1) by r^2, and insert (2):

$$mv^2 r = v(mvr) = vn\hbar = \frac{Ze^2}{4\pi\epsilon_0} \tag{6}$$

For the velocity v we thus obtain:

$$v = \frac{Ze^2}{4\pi\epsilon_0 n\hbar} \qquad \boxed{v = \frac{Z\alpha c}{n}} \tag{7}$$

Combining (5) and (7) gives the *quantised* energies:

$$E_n = -\frac{mv^2}{2} = -\frac{m}{2}\left(\frac{Ze^2}{4\pi\epsilon_0 n\hbar}\right)^2 \tag{8}$$

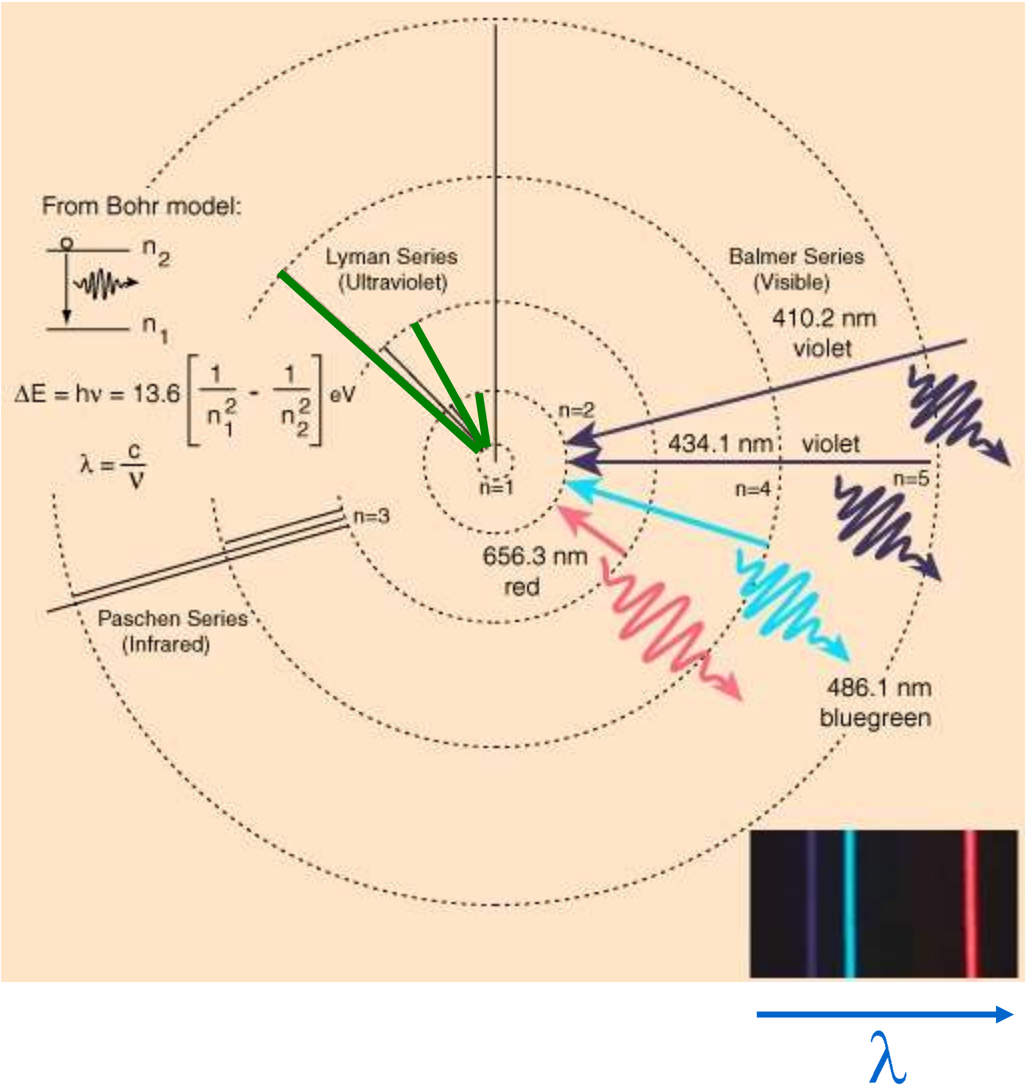
Using the fine structure coefficient $\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} \approx 1/137$, we finally obtain

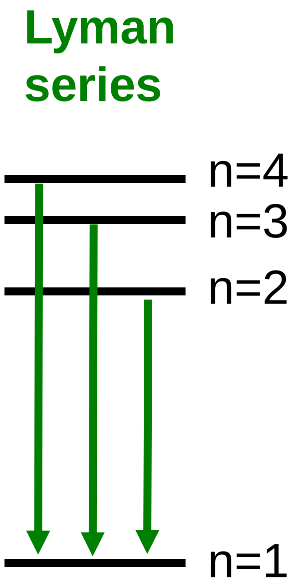
$$\boxed{E_n = -\frac{1}{2}mc^2\frac{(Z\alpha)^2}{n^2}} \tag{9}$$

Using $m = 9.11 \times 10^{-31}$ kg, $c = 3 \times 10^8$ m/s, $e = 1.6 \times 10^{-19}$ C, and $Z = 1$ and $n = 1$, the groundstate energy is $E_1 = -13.6$ eV.

the simple Bohr model

These are important lines for highly-charged ions!

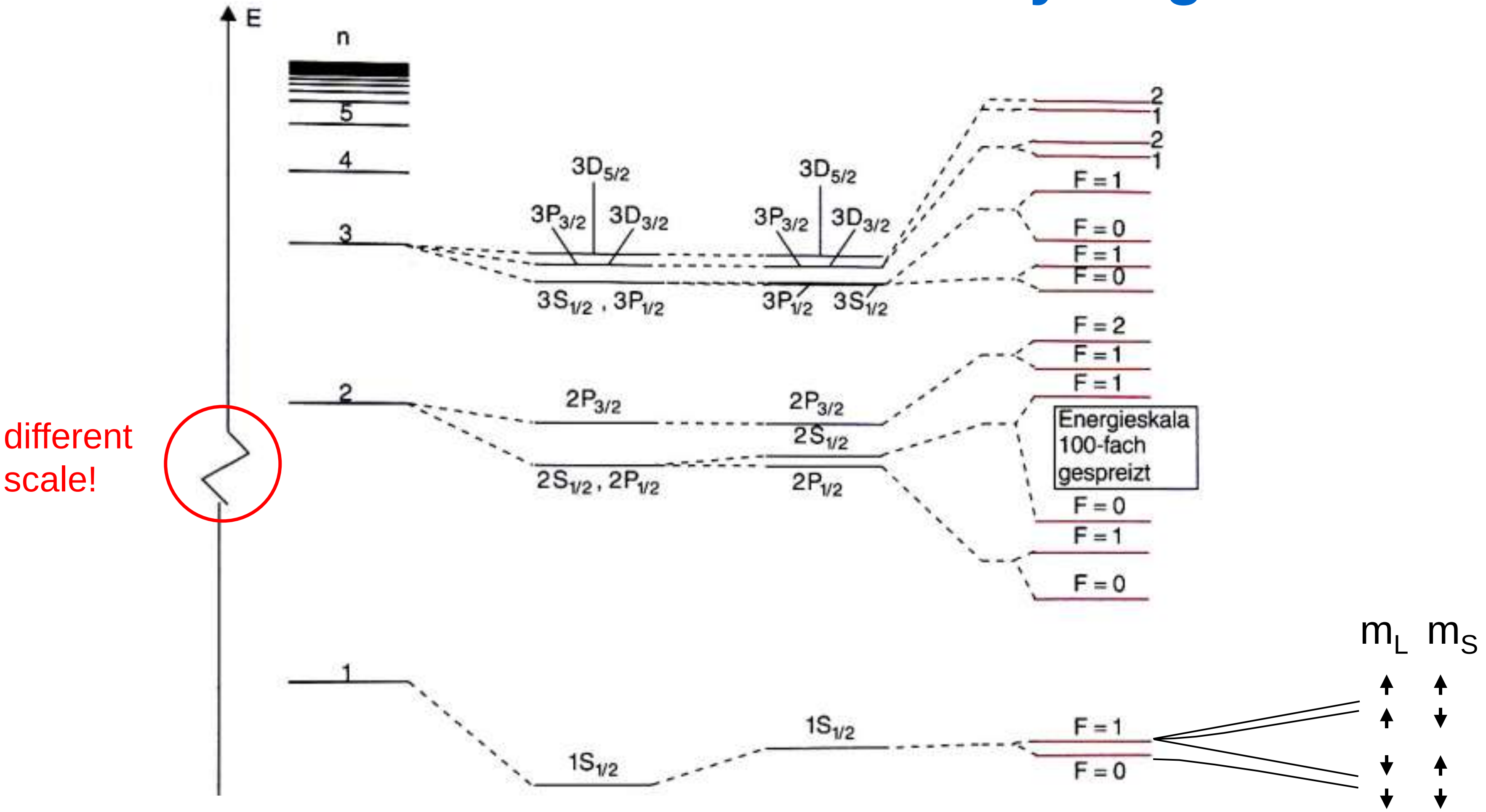




"size"

"energy"

the real structure of hydrogen



Bohr energy levels = Schrödinger equation (no spin)

fine structure by Dirac = electron spin (LS-coupling and reduced mass)

Lamb shift = QED correction (vacuum polarisation)

hyperfine structure = nuclear spin

Zeeman splitting (magnetic field)

the scale of things:

To remove the 1^{st} electron in hydrogen,
an energy of the order of ~10 eV is needed.
(Z=1)

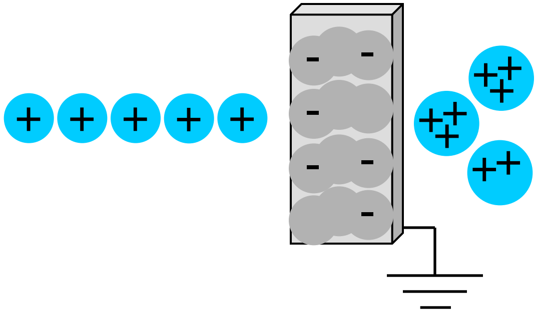
To remove the 92^{nd} electron in uranium,
requires an energy of the order of ~100 keV.
(Z=92 → $\sim Z^2$)

→ One needs a lot of energy for
complete ionisation of heavy elements!

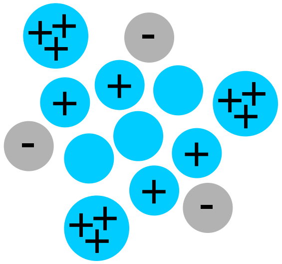
→ Experimentally, photons can't really do the trick,
but fast electrons & ions can!

three methods to create multi-charged ions:

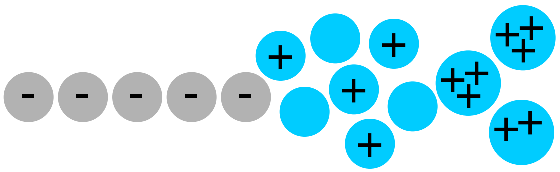
stripper foil



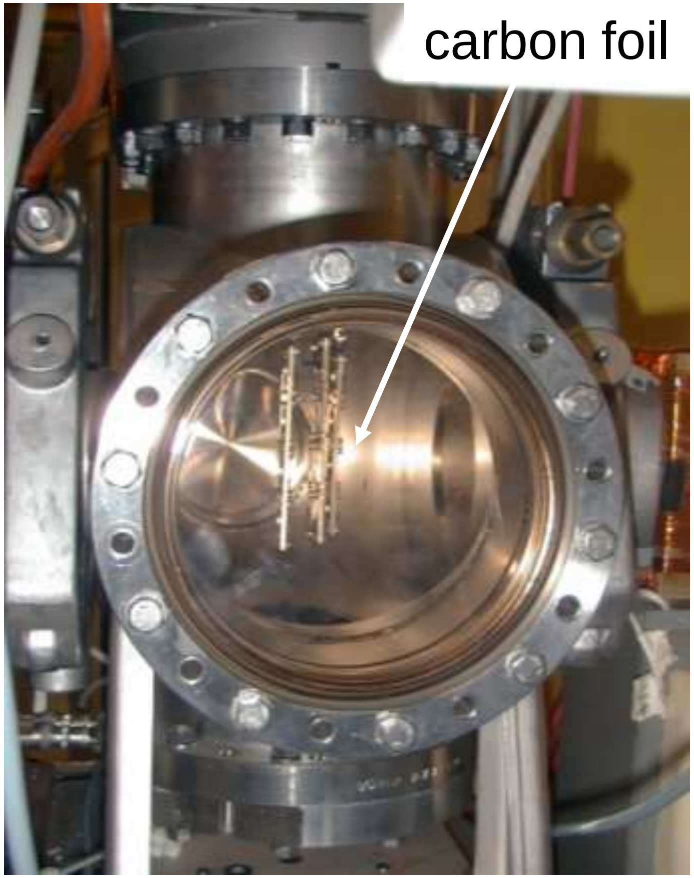
electron cyclotron resonance ion source
(**ECRIS**)



electron beam ion source
(**EBIS**)



the stripper target



☺ simple method and fast

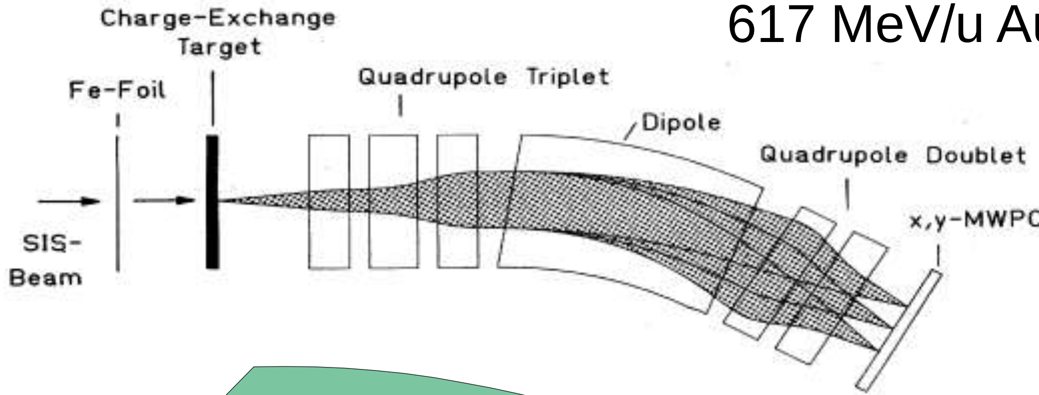
☹ needs pre-acceleration

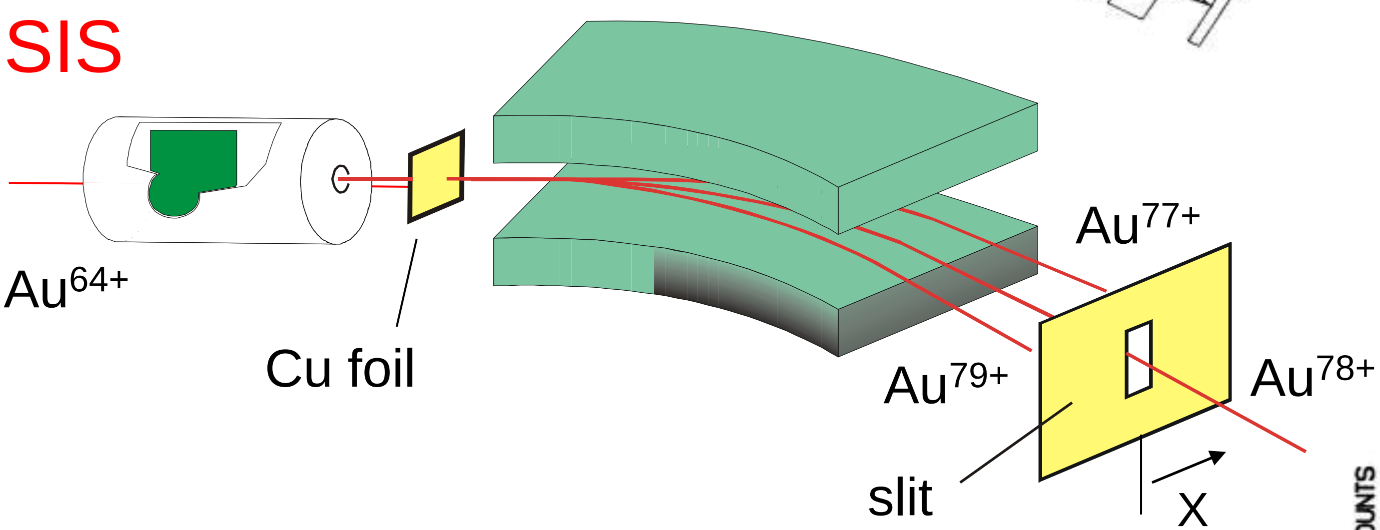
☹ emittance growth

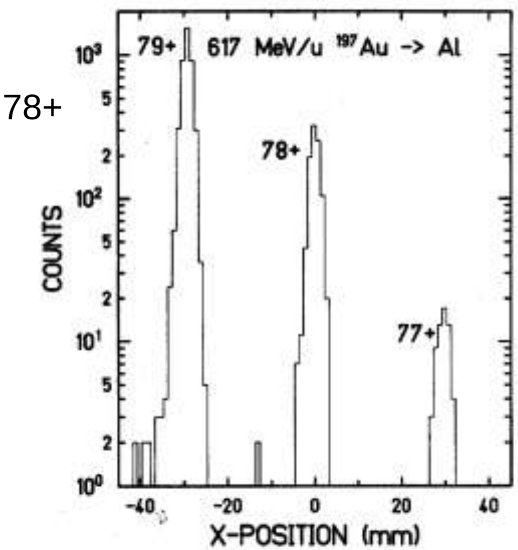
this method yields large numbers of ions in high charge states

charge state distributions

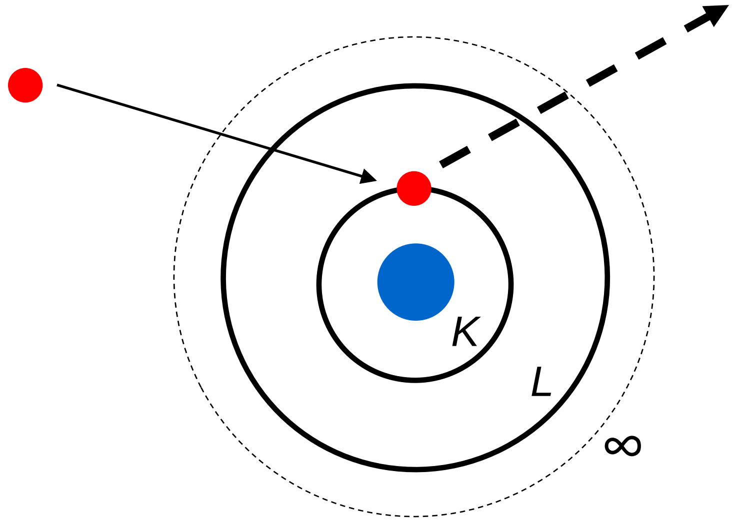
617 MeV/u Au beam







charge exchange processes



electron impact ionisation

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

For the generation of (highly-charged) ions,
this process is also frequently used.

(since it is easier to create keV electrons
than it is to produce keV photons)

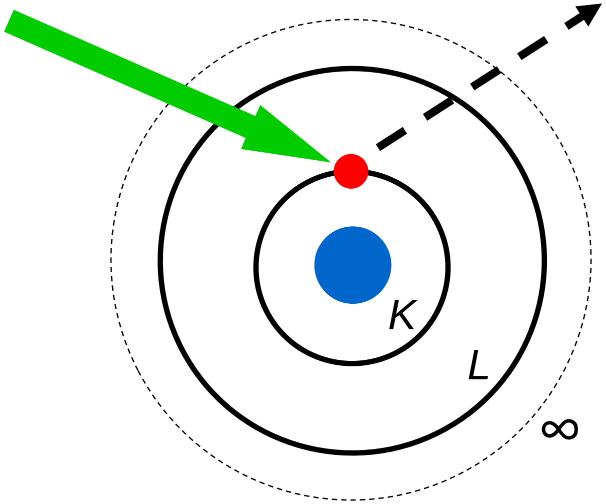
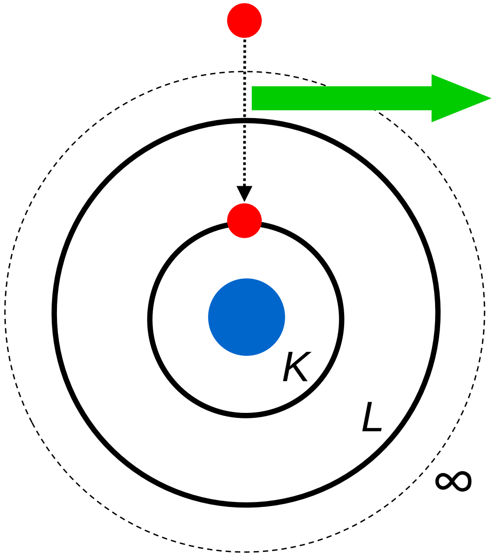


photo ionisation

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

Excitation is, of course, also a possibility !
We also study such effects at GSI:
(electron excitation, proton excitation, etc.)



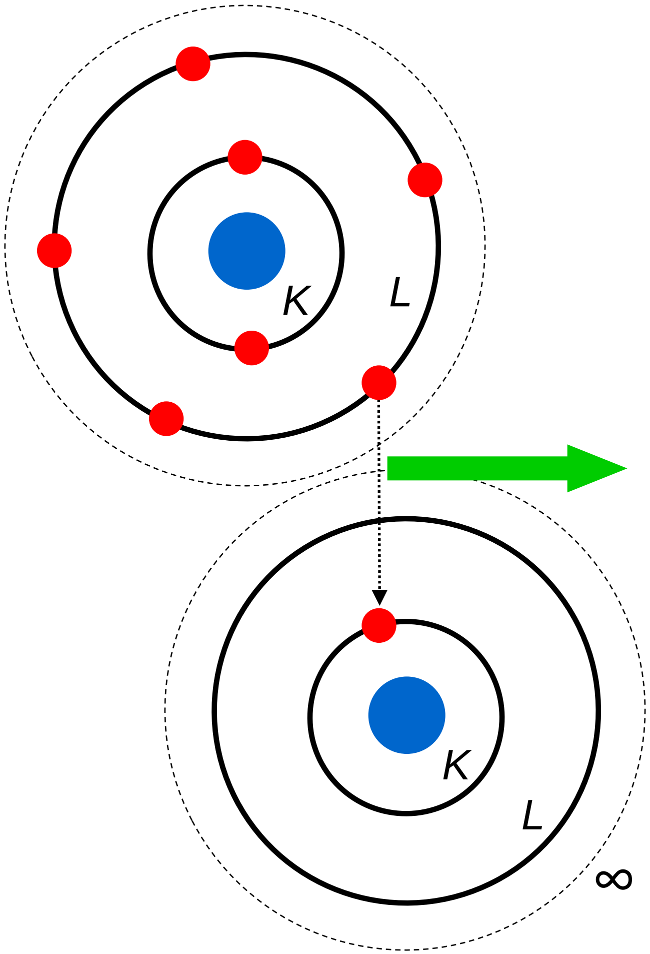
radiative recombination (*RR*)

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

neutralisation !

time-reversed photo ionisation process !

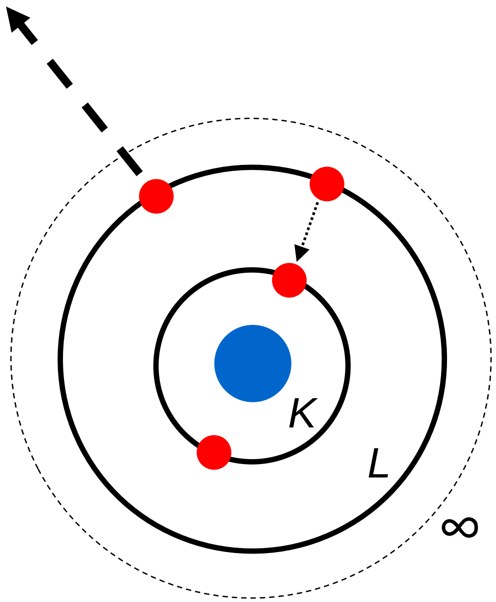
But the captured electron can also be bound to an atom (quasi-free):



radiative electron capture (*REC*)

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

neutralisation !



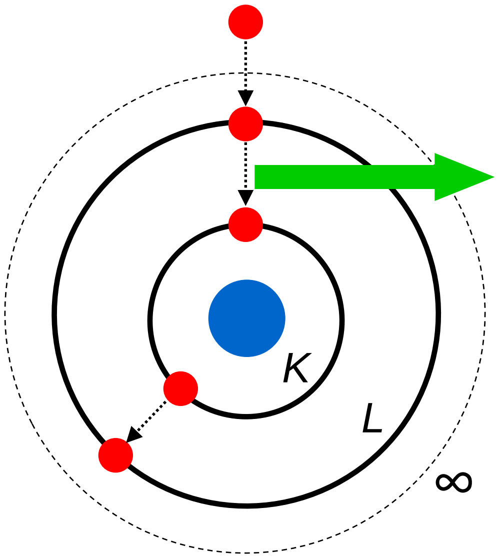
Auger process (*KLL*)

$$A^{*q+} \rightarrow A^{(q+1)+}$$

ionisation !

For example, *KLL* Auger electrons from ${}^{14}_{7}N^{4+}$ or ${}^{16}_{8}O^{5+}$ $1s(2l)^2$ configurations typically have energies of several hundred eV.

Note: the ejected electron is called the `Auger electron'



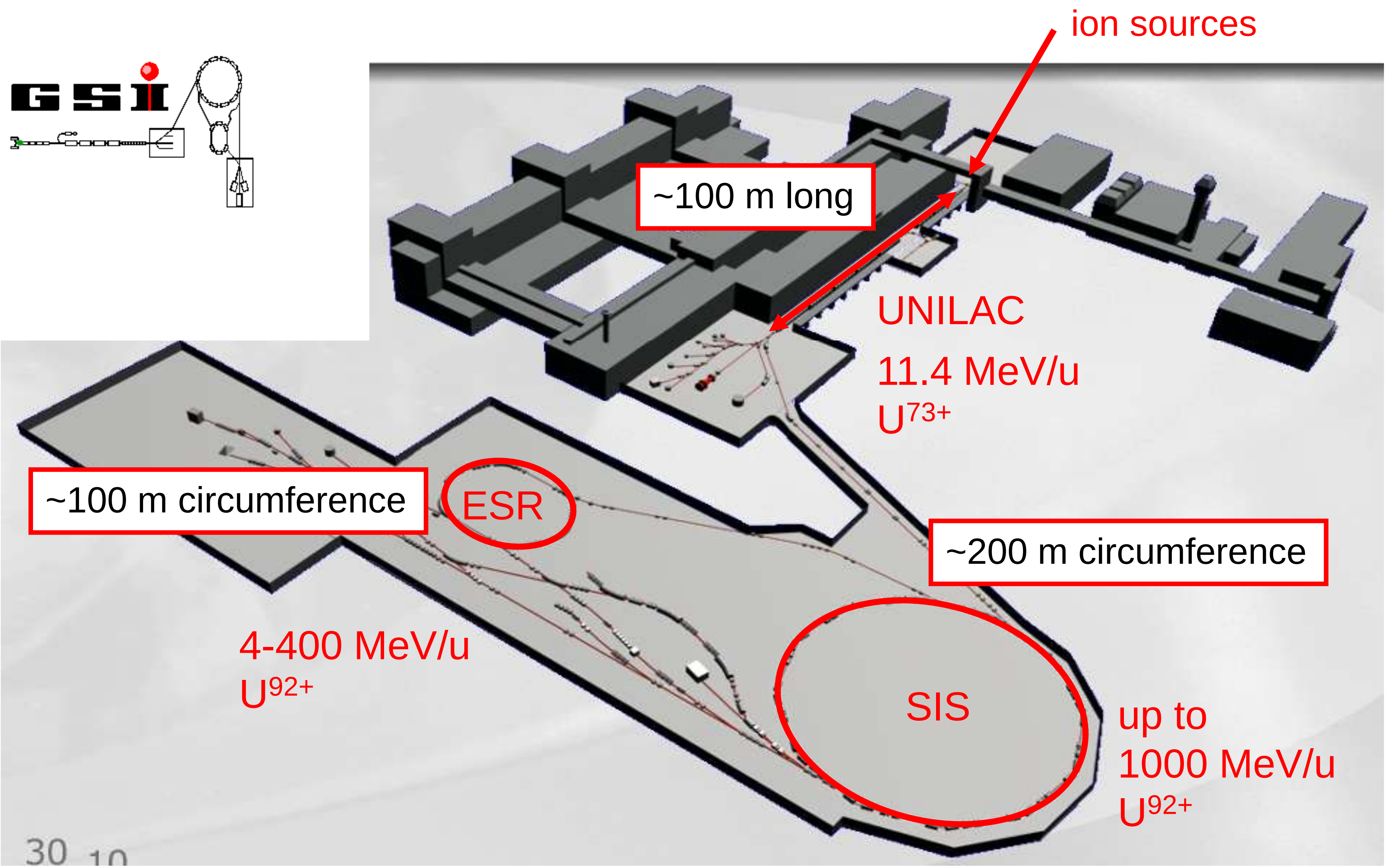
dielectronic recombination (*DR*)

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

neutralisation !

time-reversed Auger process !

the current GSI facility



pioneers of storing and cooling

Principle of Penning Traps

Frans Michel Penning

Storage and Cooling of Antiprotons

Nobel Prize 1984

J. van der Meer
C. Rubbia

Storage and Cooling of Ions

Nobel Prize 1989

H. Dehmelt
W. Paul

Storage and Cooling of Atoms

Nobel Prize 1997

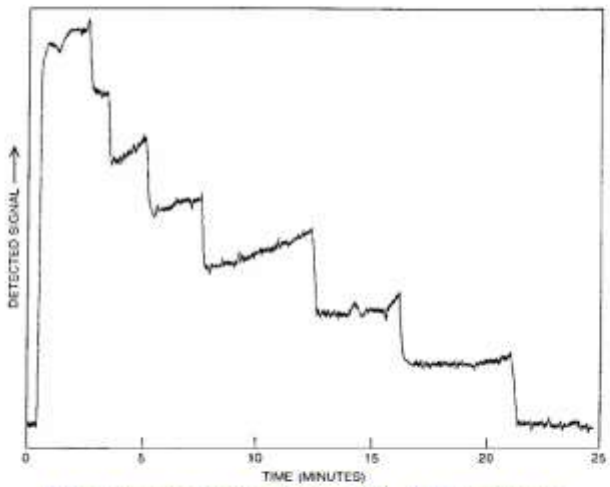
S. Chu C. Cohen-Tannoudji W. D. Phillips

Bose-Einstein Condensation

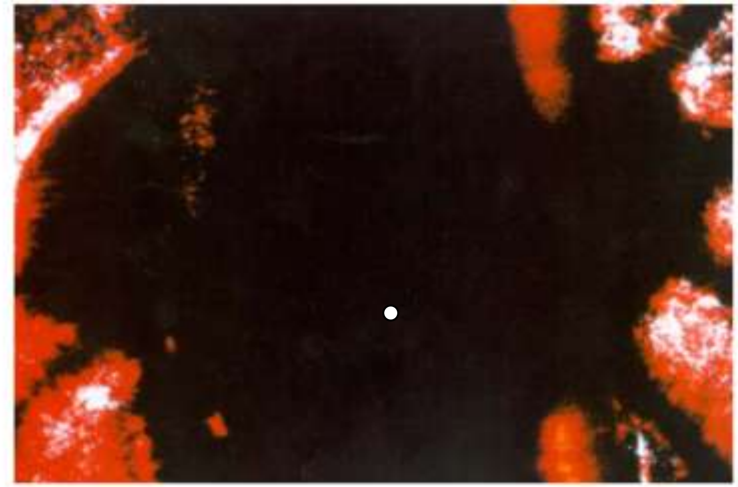
Nobel Prize 2001

E. Cornell W. Ketterle C. Wieman

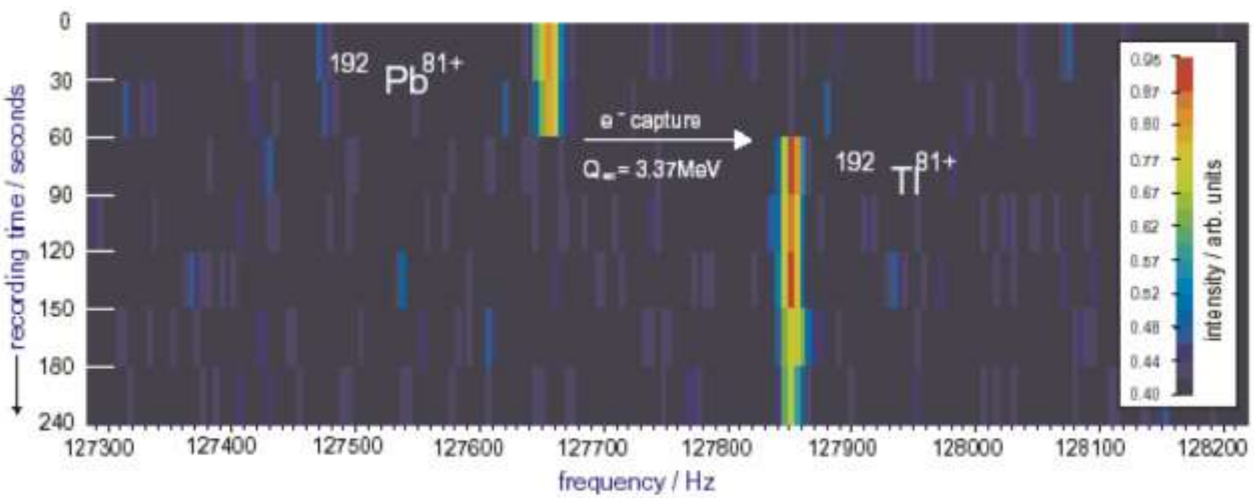
impressive results with confined ions



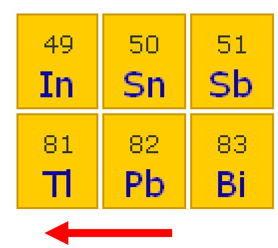
Electronic Detection of 1–7 Electrons in a Penning Trap Dehmelt et al.



Optical Detection of a Single Barium Ion in a Paul Trap
Dehmelt, Toscheck et al.

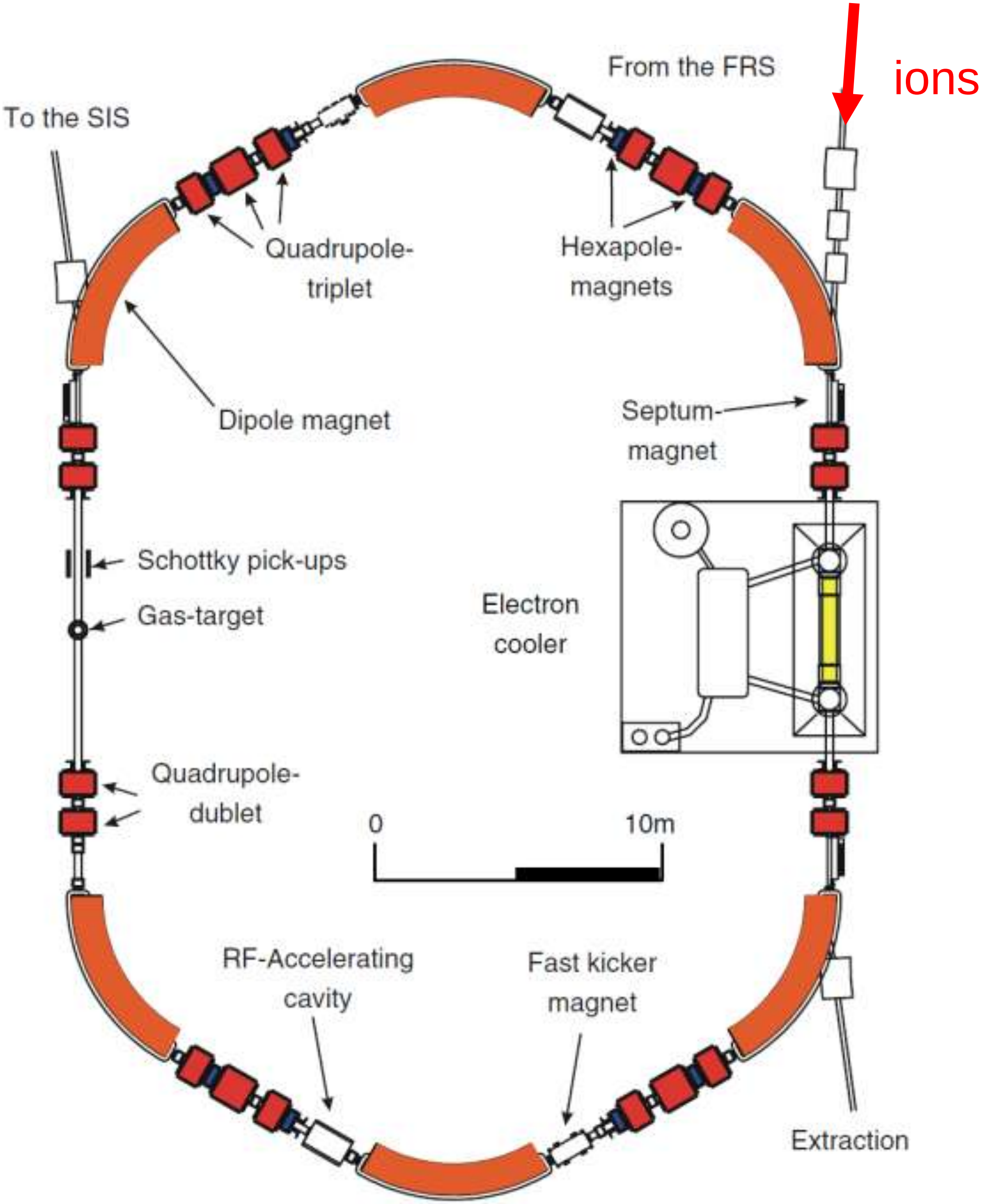


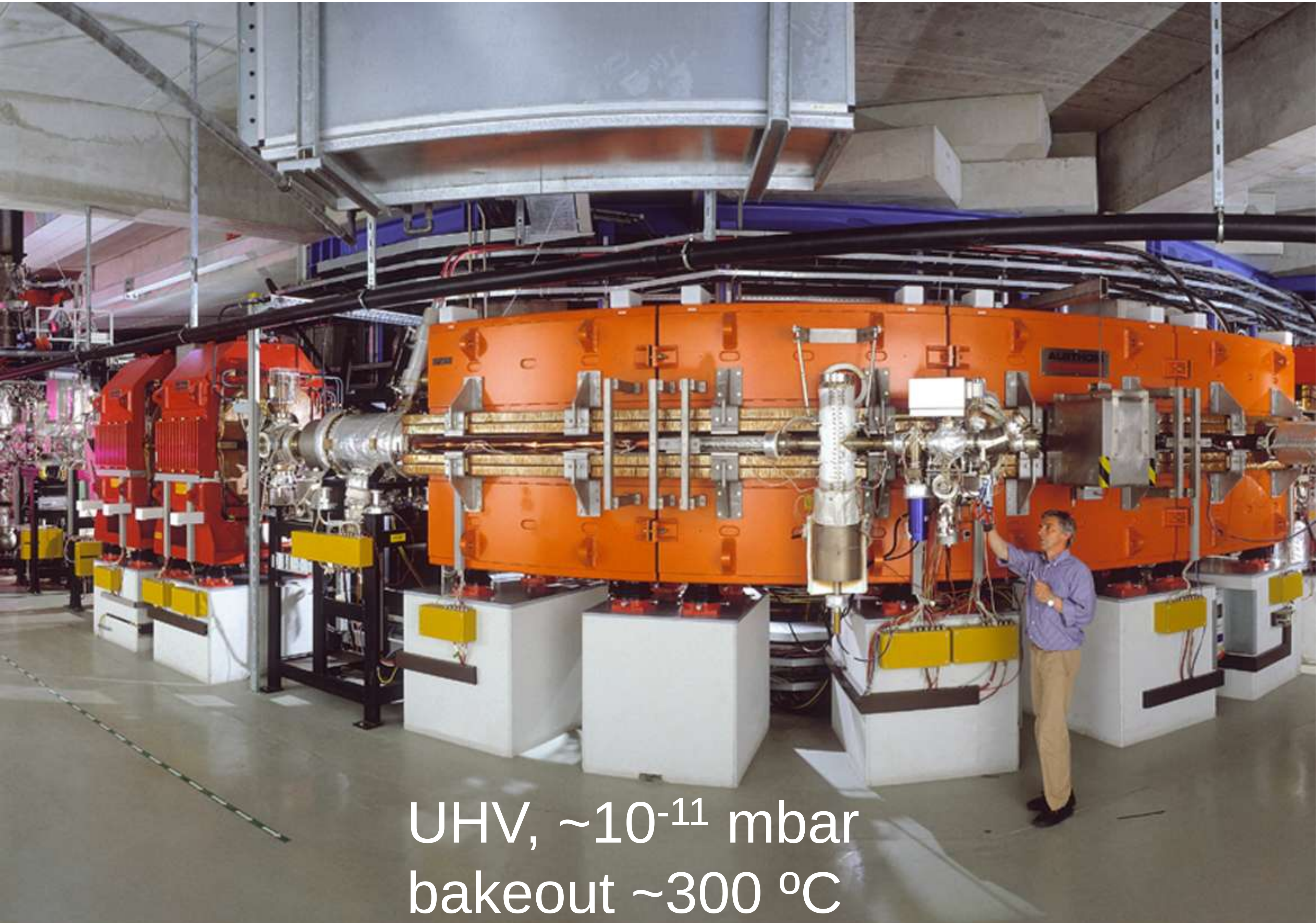
Electron capture in a single Pb ion in the ESR. Bosch *et al*.

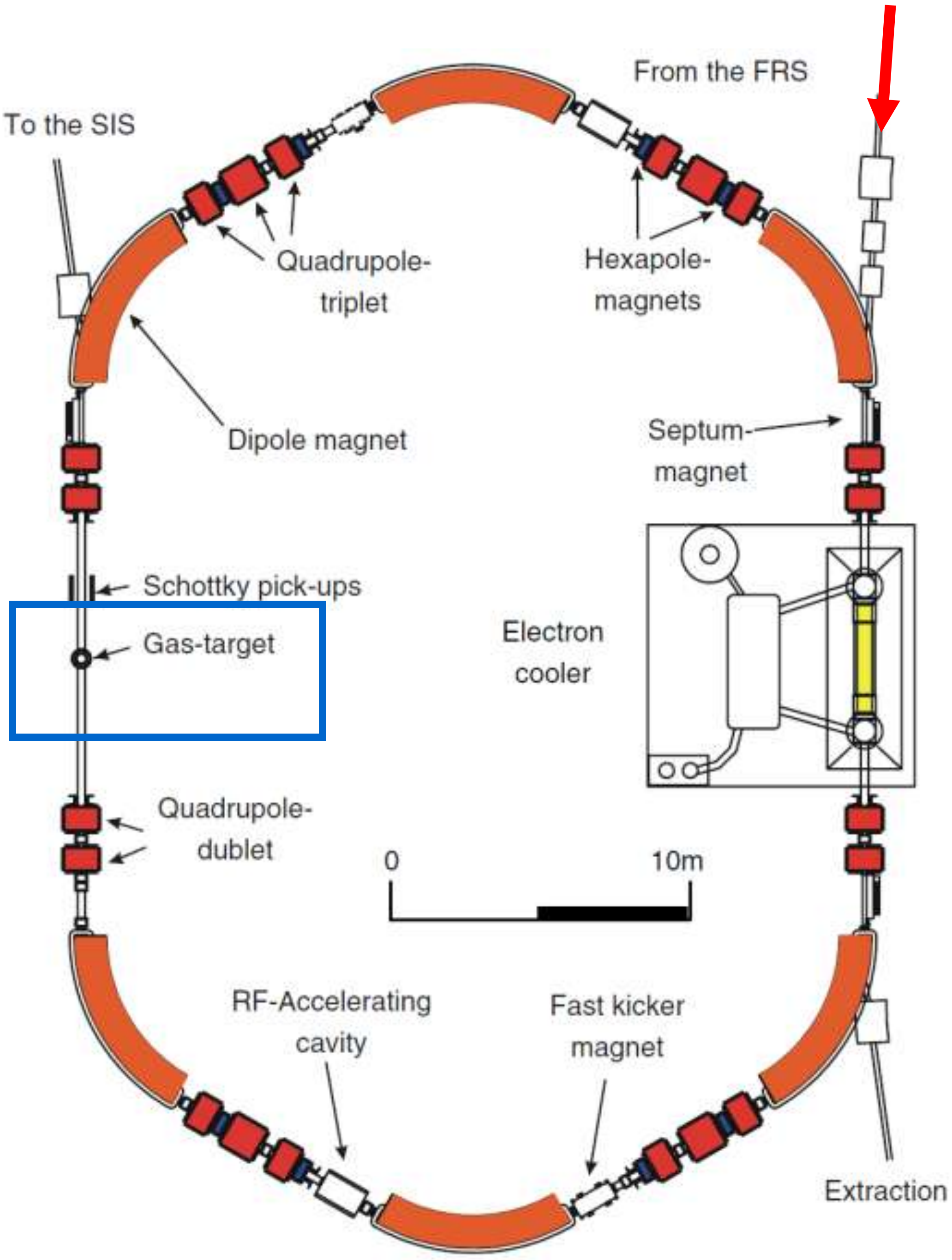


thallium ← lead

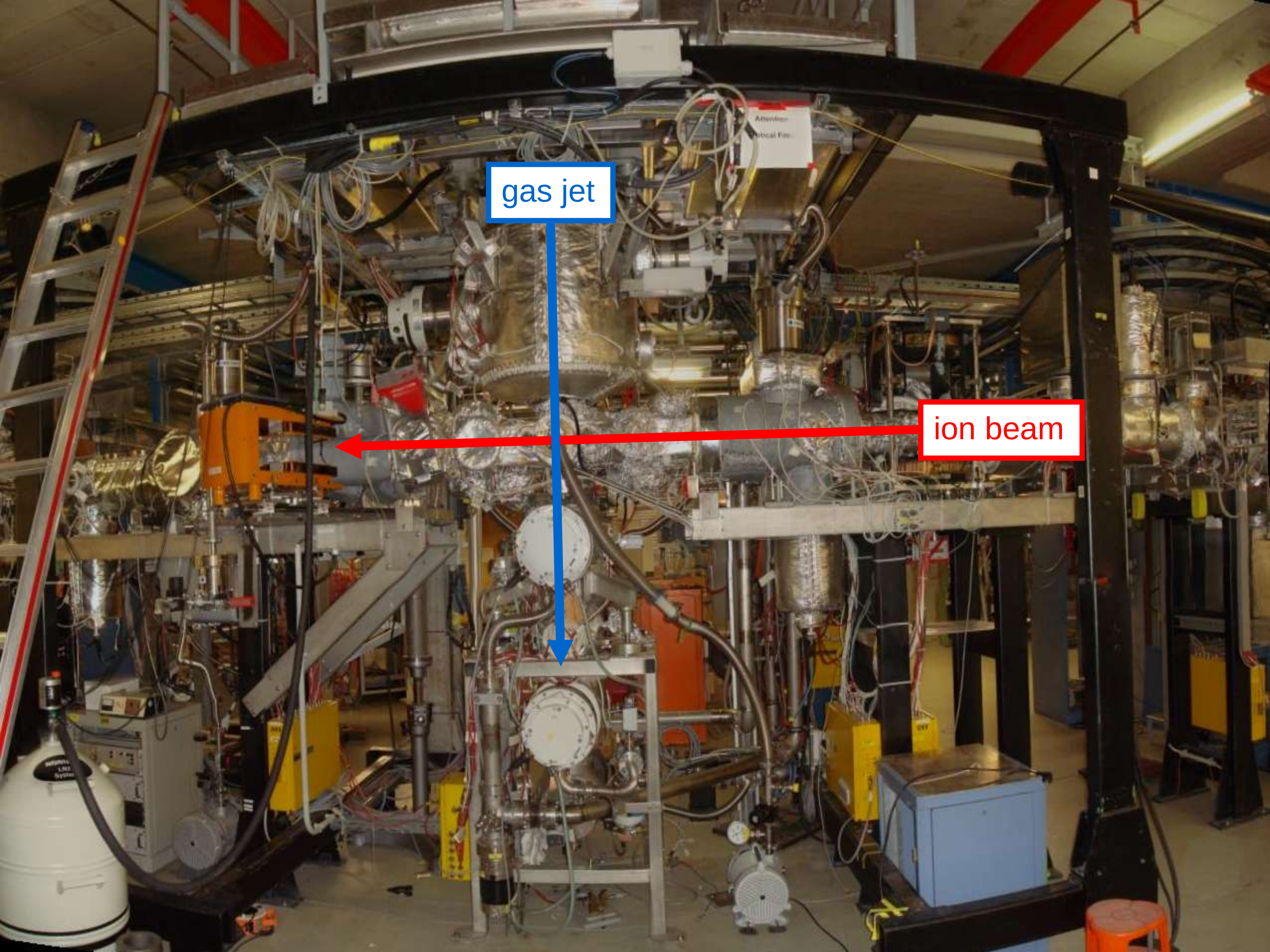
Experimental Storage Ring




UHV, ~10^{-11} mbar
bakeout ~300 ºC

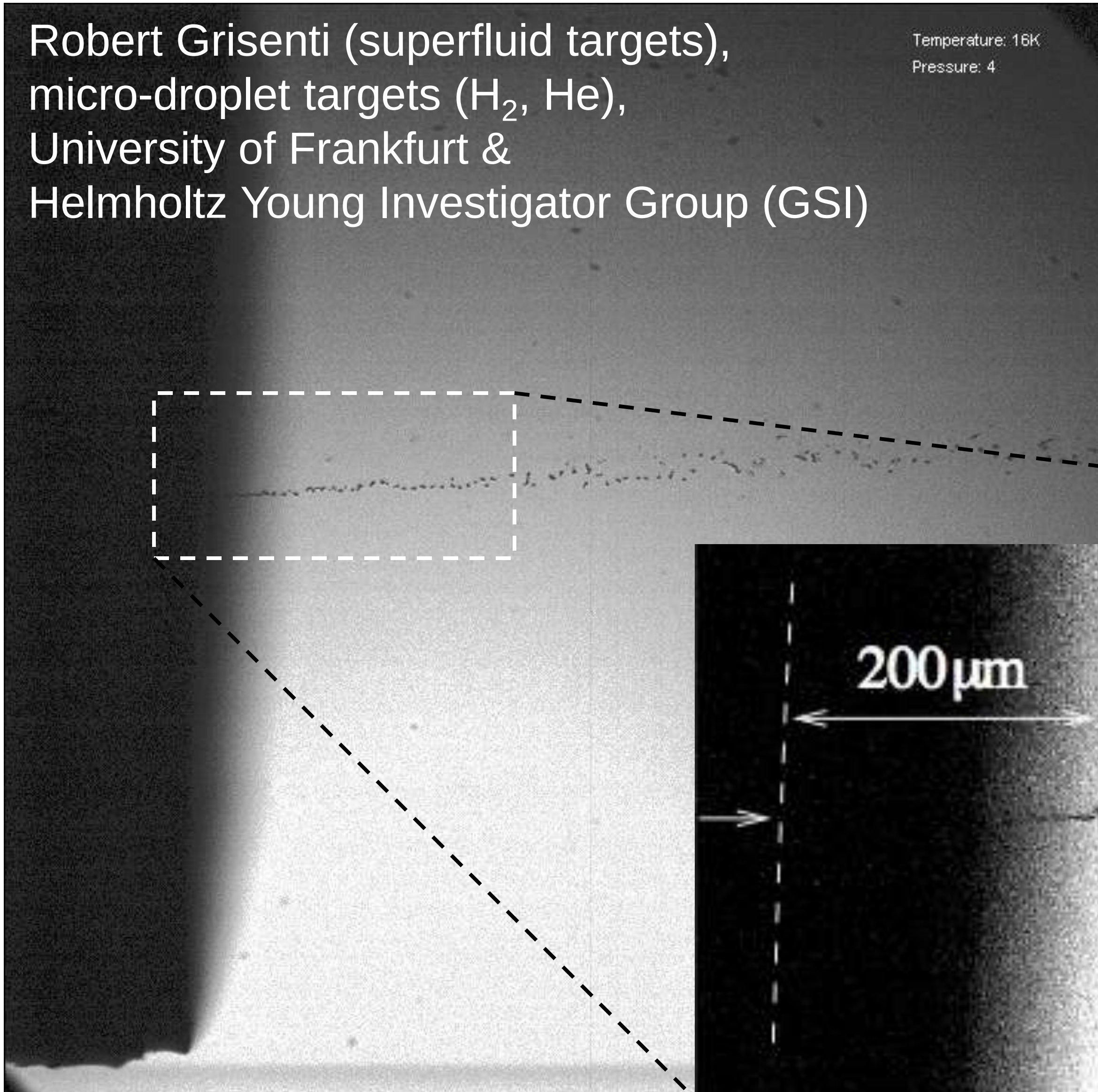


internal target
(gas jet H_2, He, N_2...)

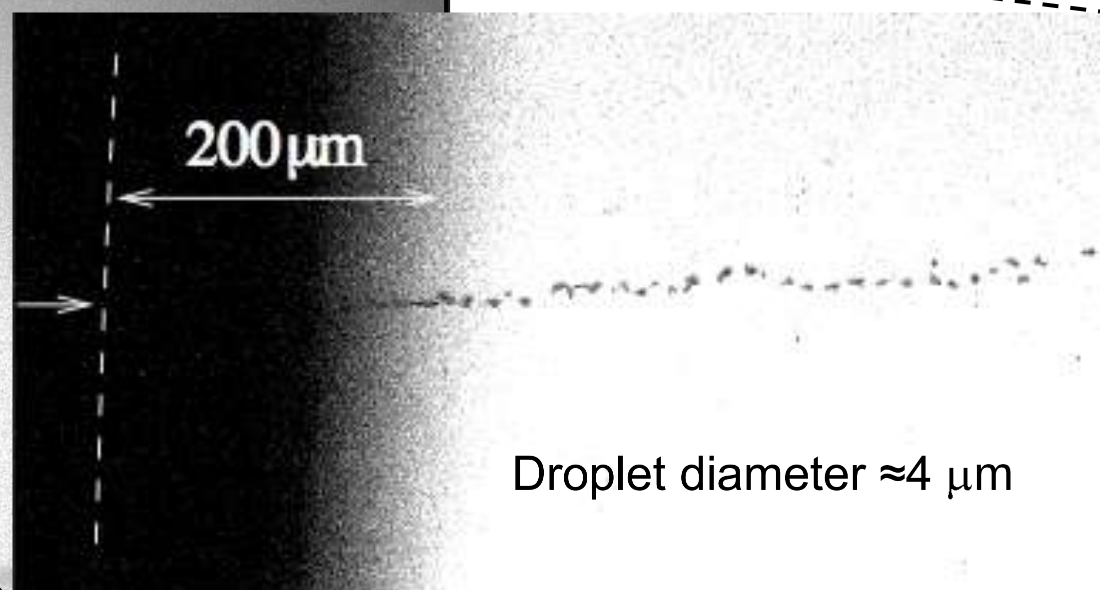

gas jet
ion beam

new liquid targets with high densities

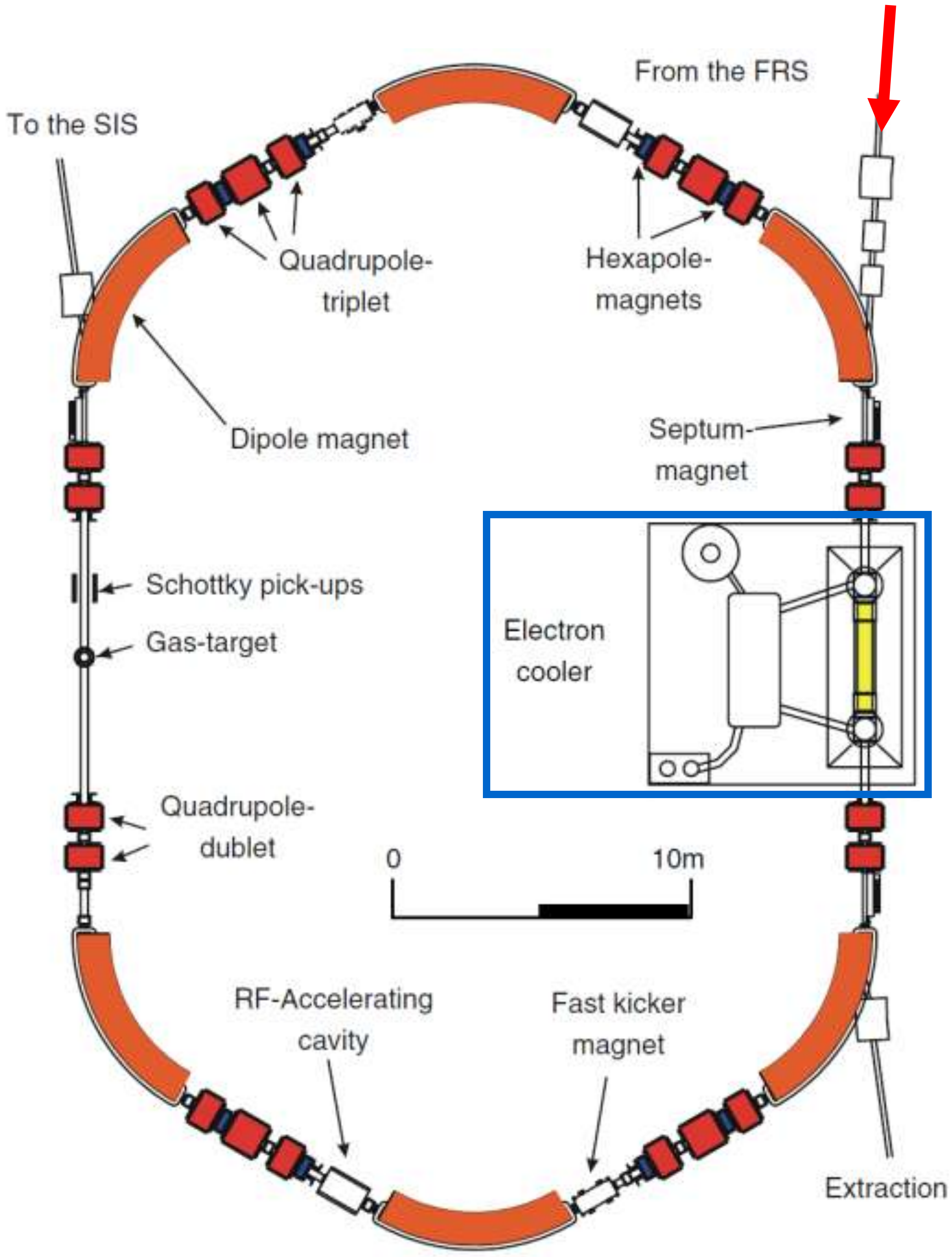
Robert Grisenti (superfluid targets),
micro-droplet targets (H_2, He),
University of Frankfurt &
Helmholtz Young Investigator Group (GSI)



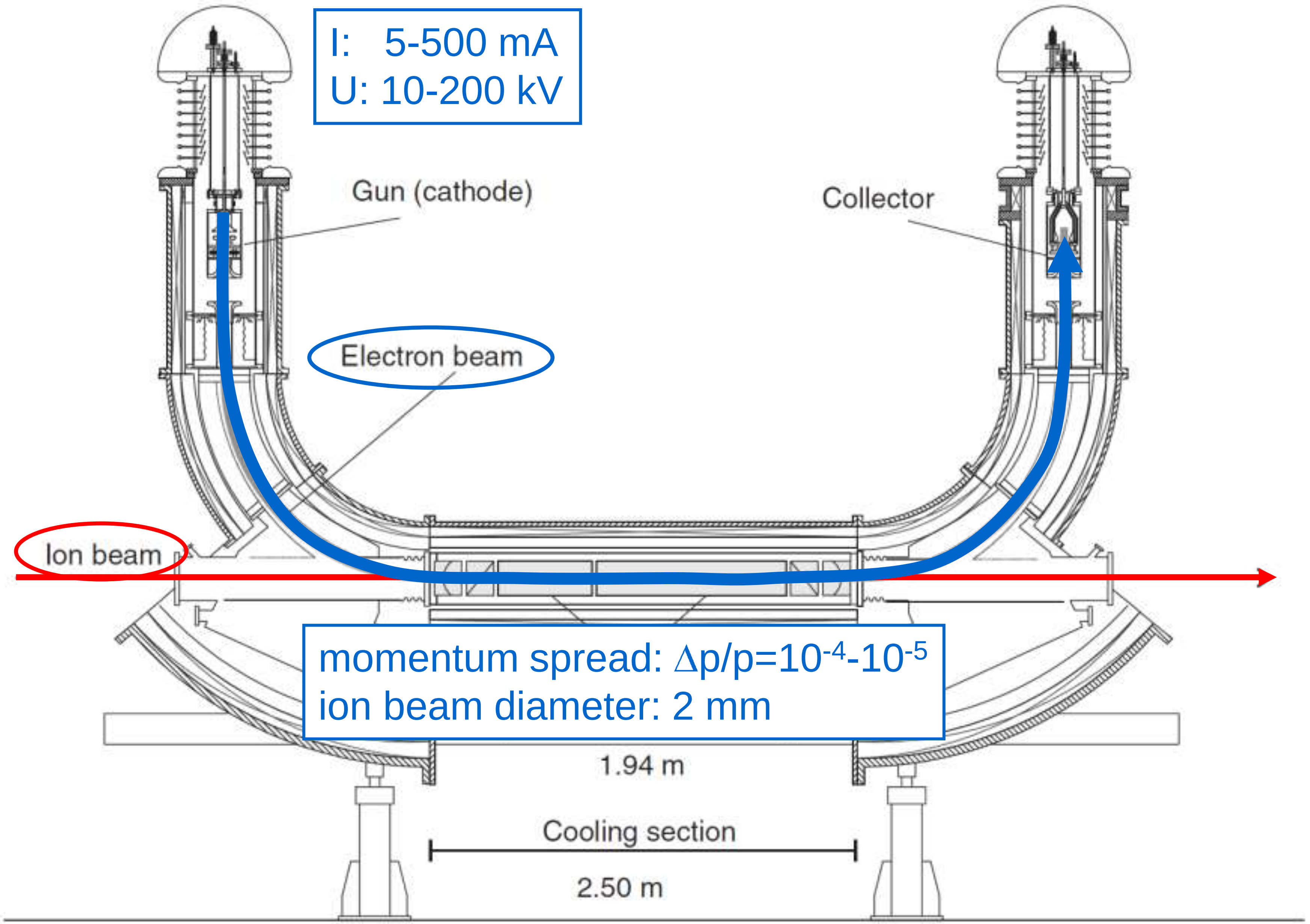
Design goal for NESR:
jet-diameter below 1 mm;
densities 10^{11} - 10^{16} 1/cm^3



the electron cooler

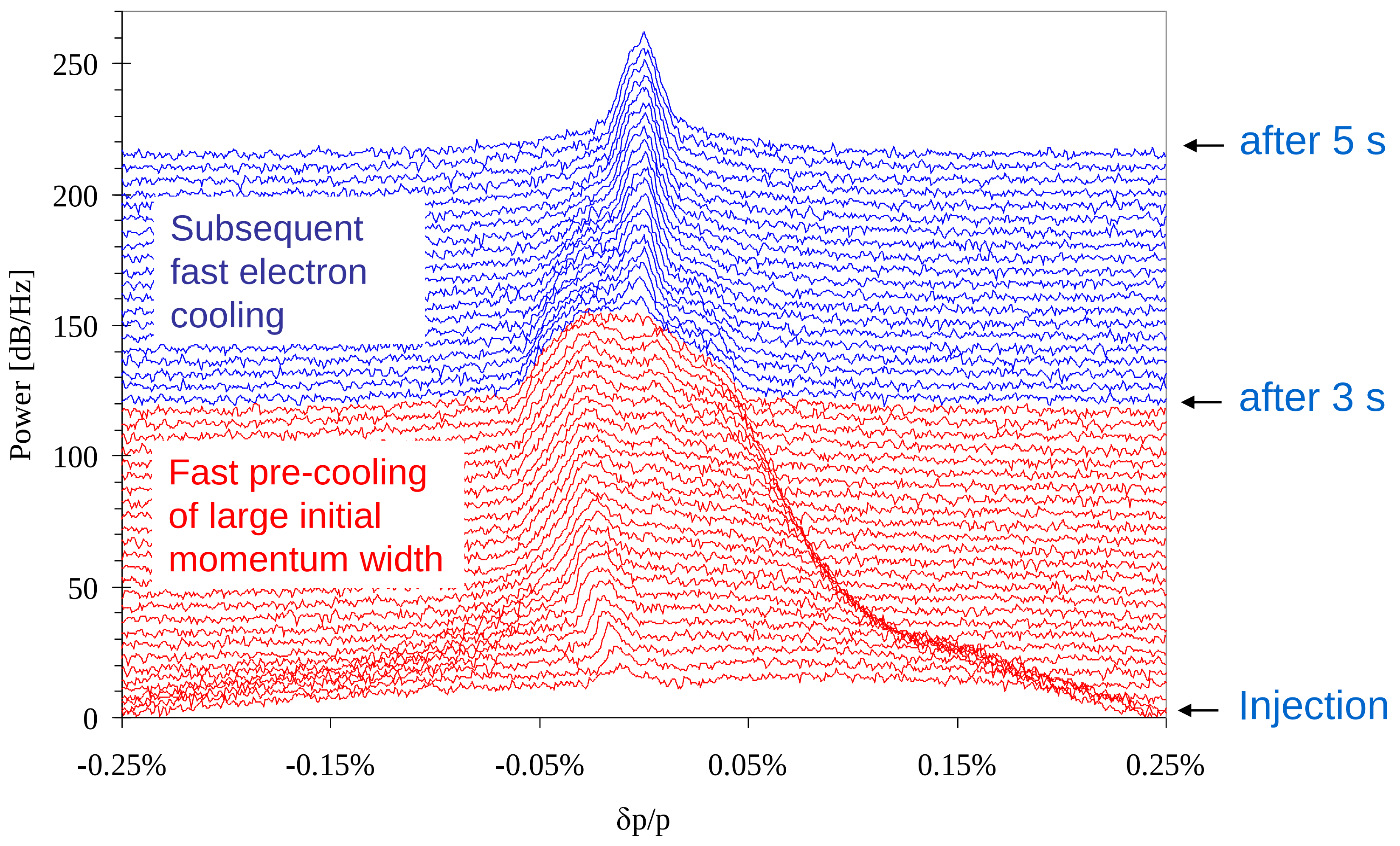


the electron cooler at the ESR



cooling: narrowing velocity, size and divergence

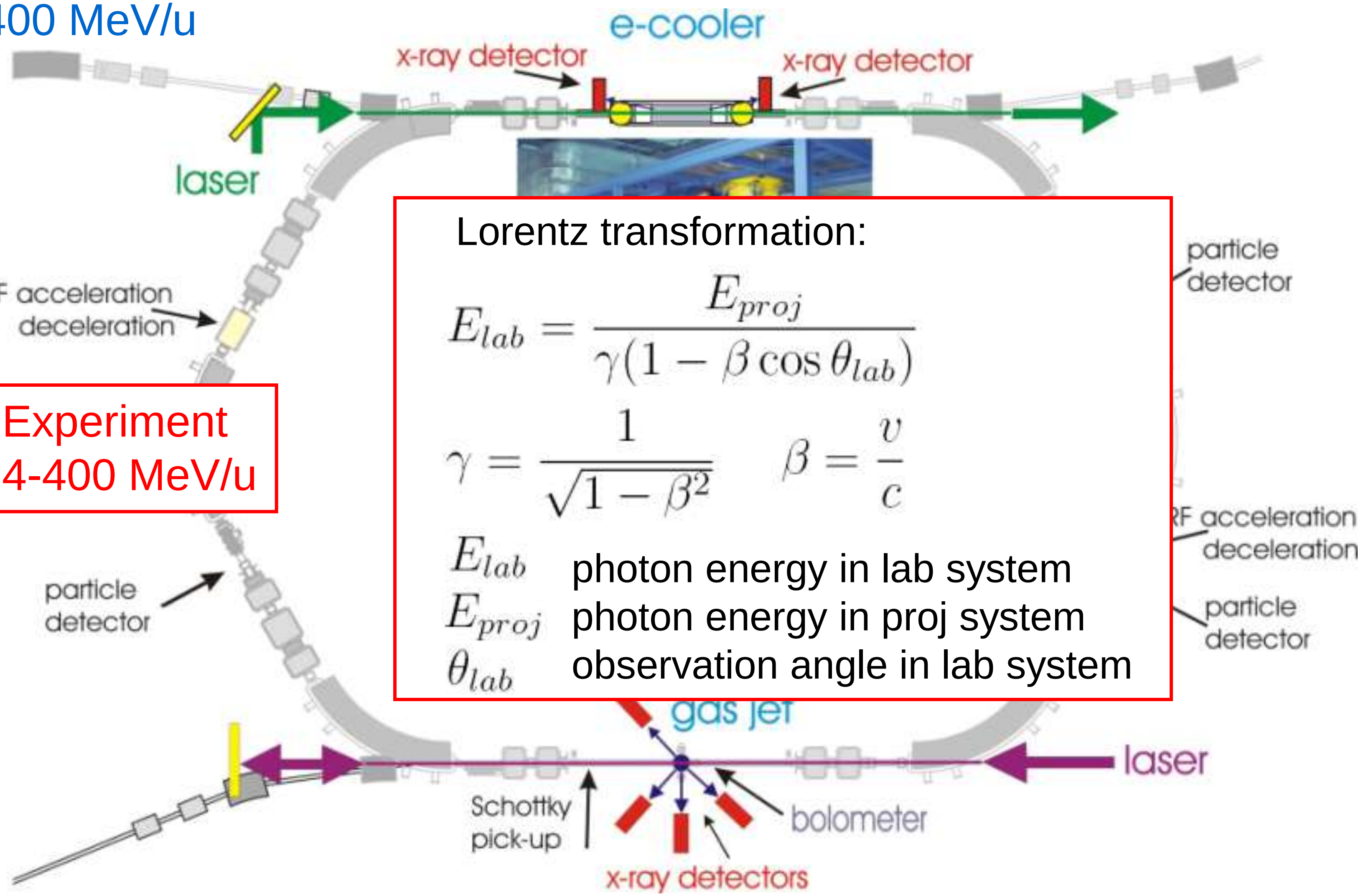
Primary uranium beam



momentum distribution

Spectroscopy at the ESR

Injection Energy
400 MeV/u



Experiment
4-400 MeV/u

Lorentz transformation:

$$E_{lab} = \frac{E_{proj}}{\gamma(1-\beta\cos\theta_{lab})}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c}$$

E_{lab} photon energy in lab system
E_{proj} photon energy in proj system
θ_{lab} observation angle in lab system

Topics:

Dielectronic recombination (DR)

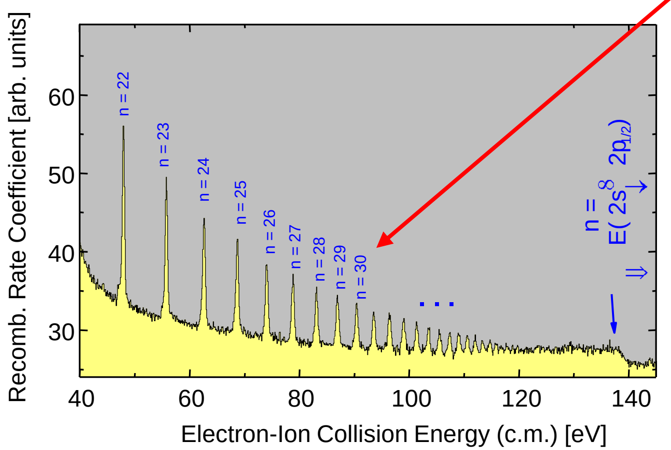
Mass spectrometry

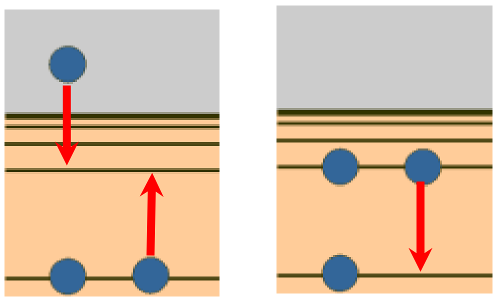
Laser spectroscopy and laser cooling

X-ray spectroscopy

Electron target → Dielectronic recombination

$e + Nd^{57+}(1s^2 2s_{1/2}) \rightarrow Nd^{56+}(1s^2 2s_{1/2} nl_j)$



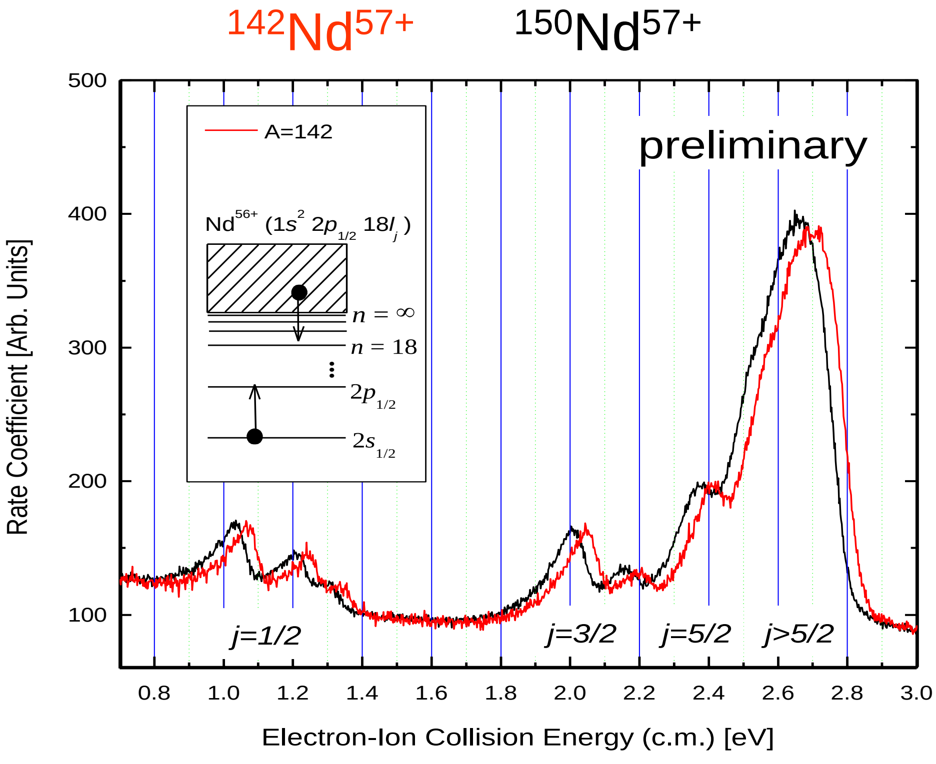


$e + A^{q+}$ $A^{(q-1)+}$

DR experiments of Li-like heavy ions at the ESR: the achieved accuracy is comparable with that of x-ray experiments

Isotopic shift of Li-like $^{142}Nd^{57+}$ vs. $^{150}Nd^{57+}$

DR → measure charge radii (stable and exotic ions)



C. Brandau, C. Kozhuharov, *et al*. PRL 2008

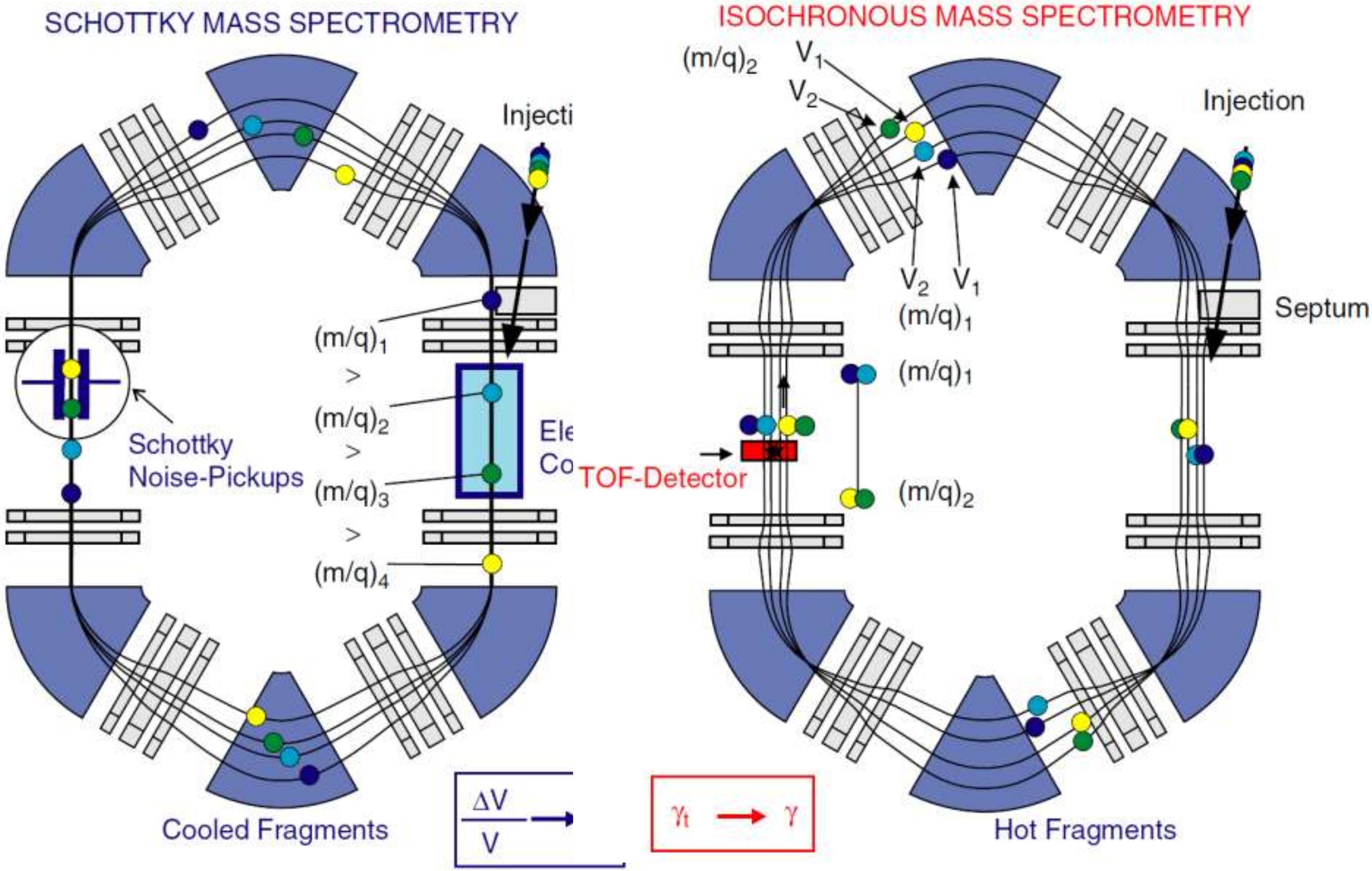
Topics:

Dielectronic recombination (DR)

Mass spectrometry

Laser spectroscopy and laser cooling

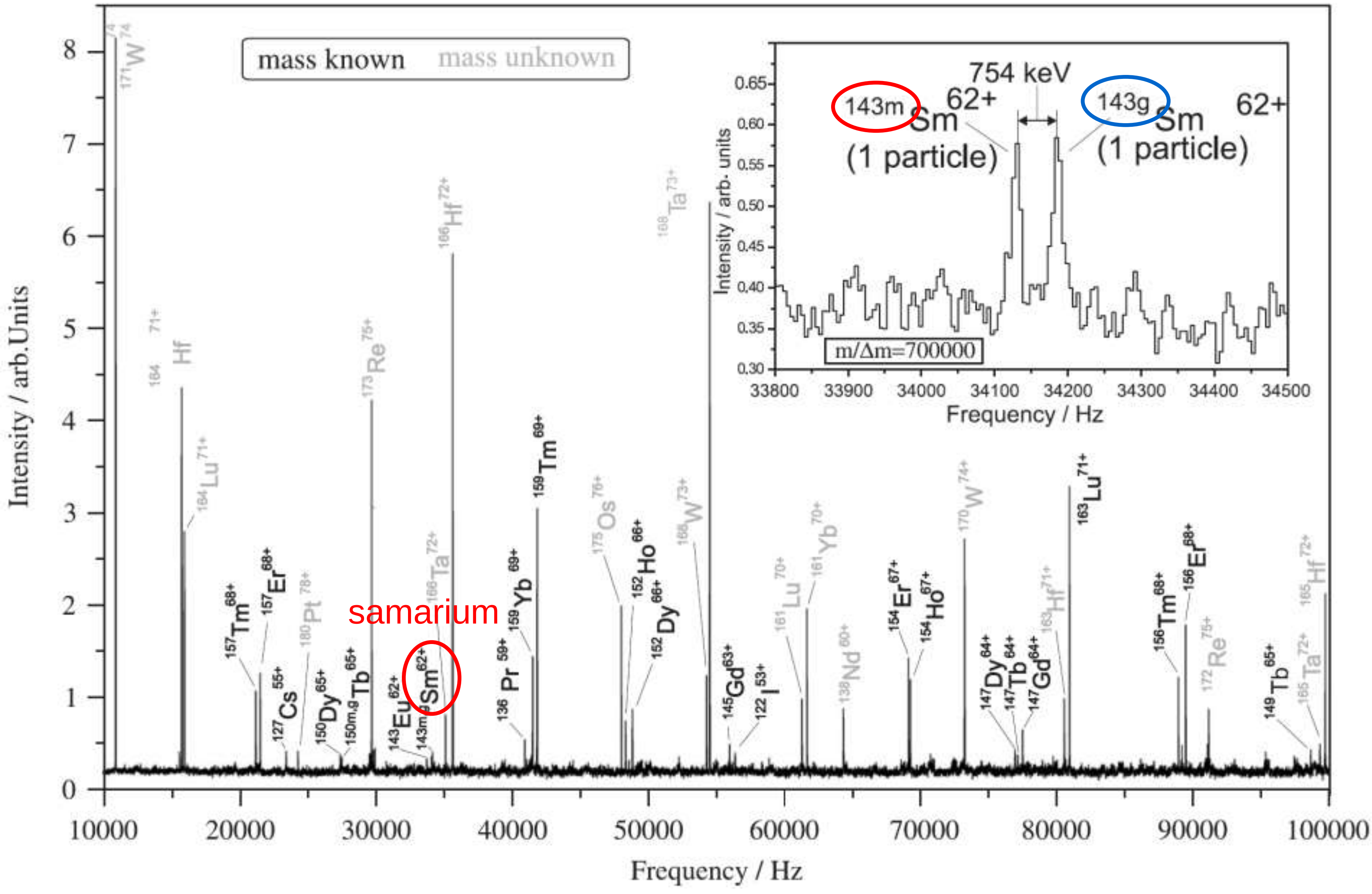
X-ray spectroscopy



frequency ↔ mass

$$\frac{\Delta v}{v} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1 - \frac{\gamma^2}{\gamma_t^2}\right)$$

(single particle) mass measurements



Topics:

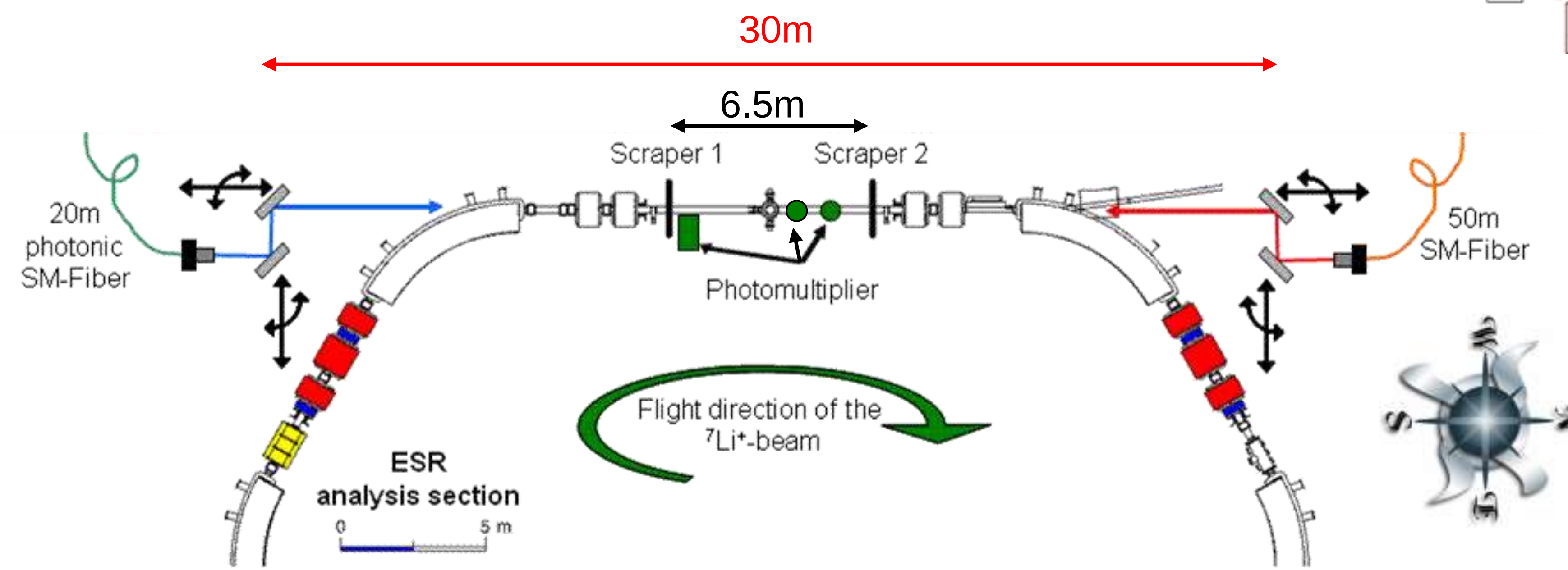
Dielectronic recombination (DR)

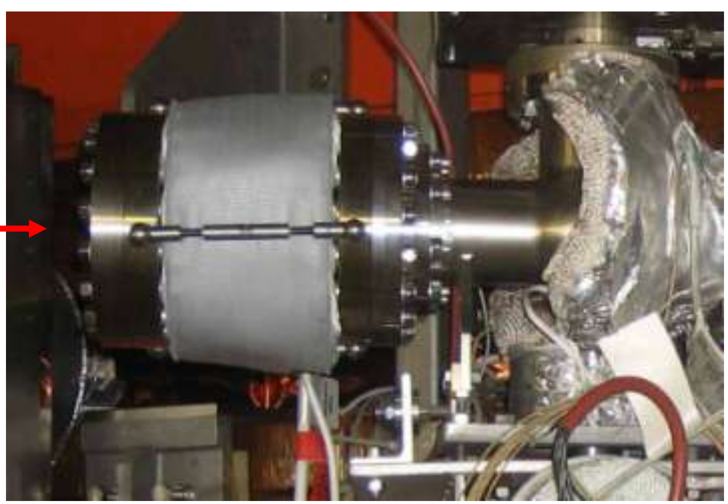
Mass spectrometry

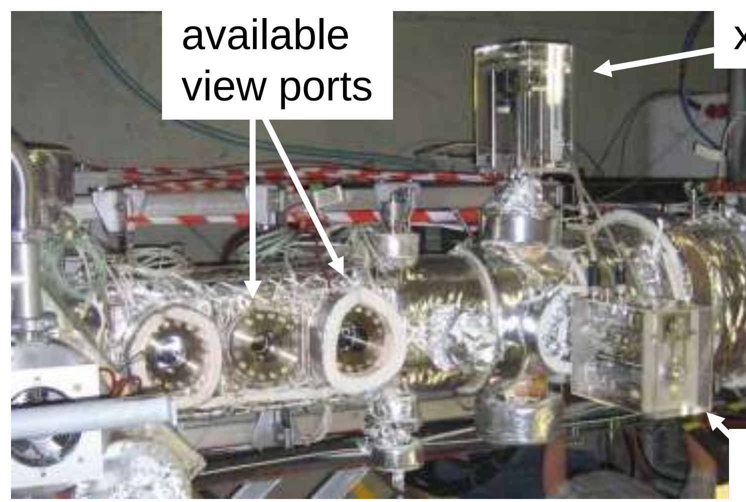
Laser spectroscopy and laser cooling

X-ray spectroscopy

lasers at the ESR



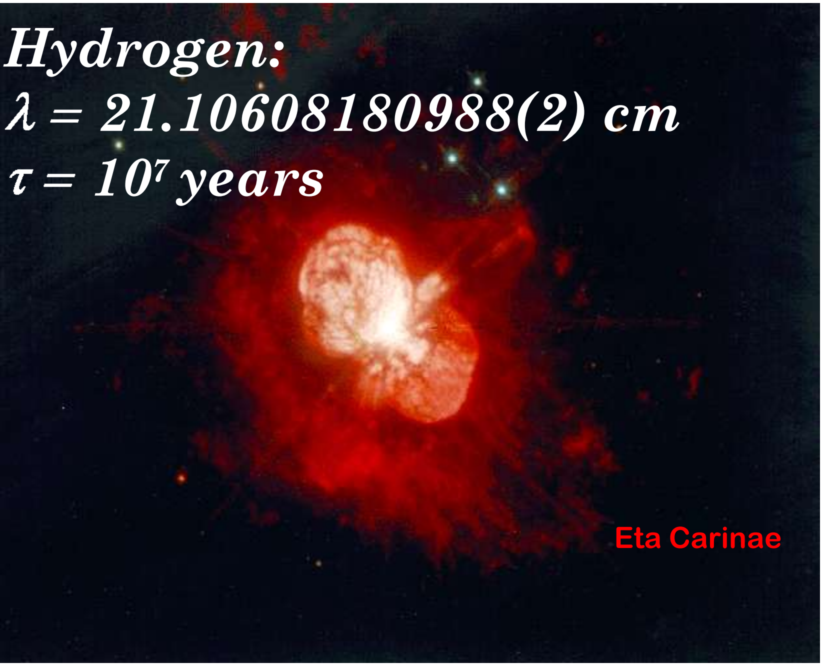


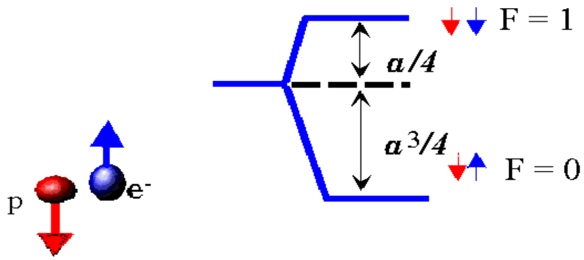


Measurement of the ground state HFS in $^{209}Bi^{80+}$

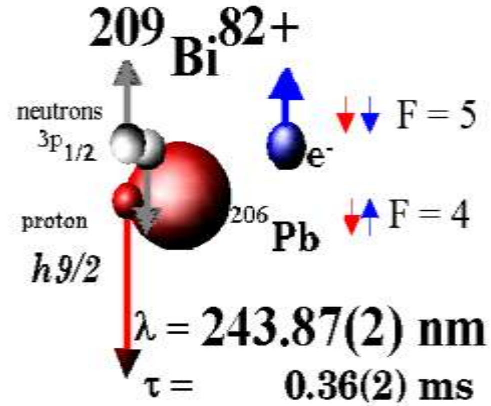
M. Lochmann, R. Sanchez, C. Geppert, W. Nörtershäuser...
Th. Kühl, D. Winters, Th. Stöhlker...
Ch. Weinheimer, V. Hannen, R. Jöhren,...
G. Birkl, Th. Walther...

GS hyperfine structure in highly-charged ions

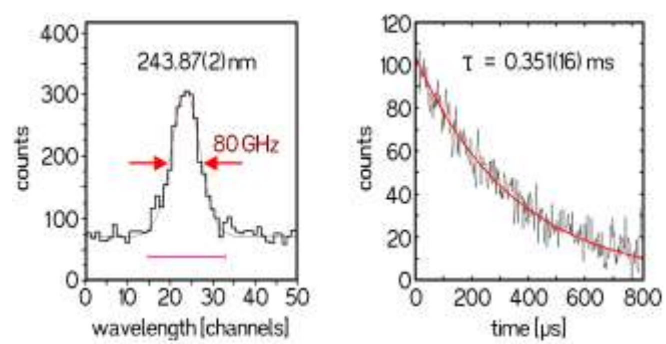




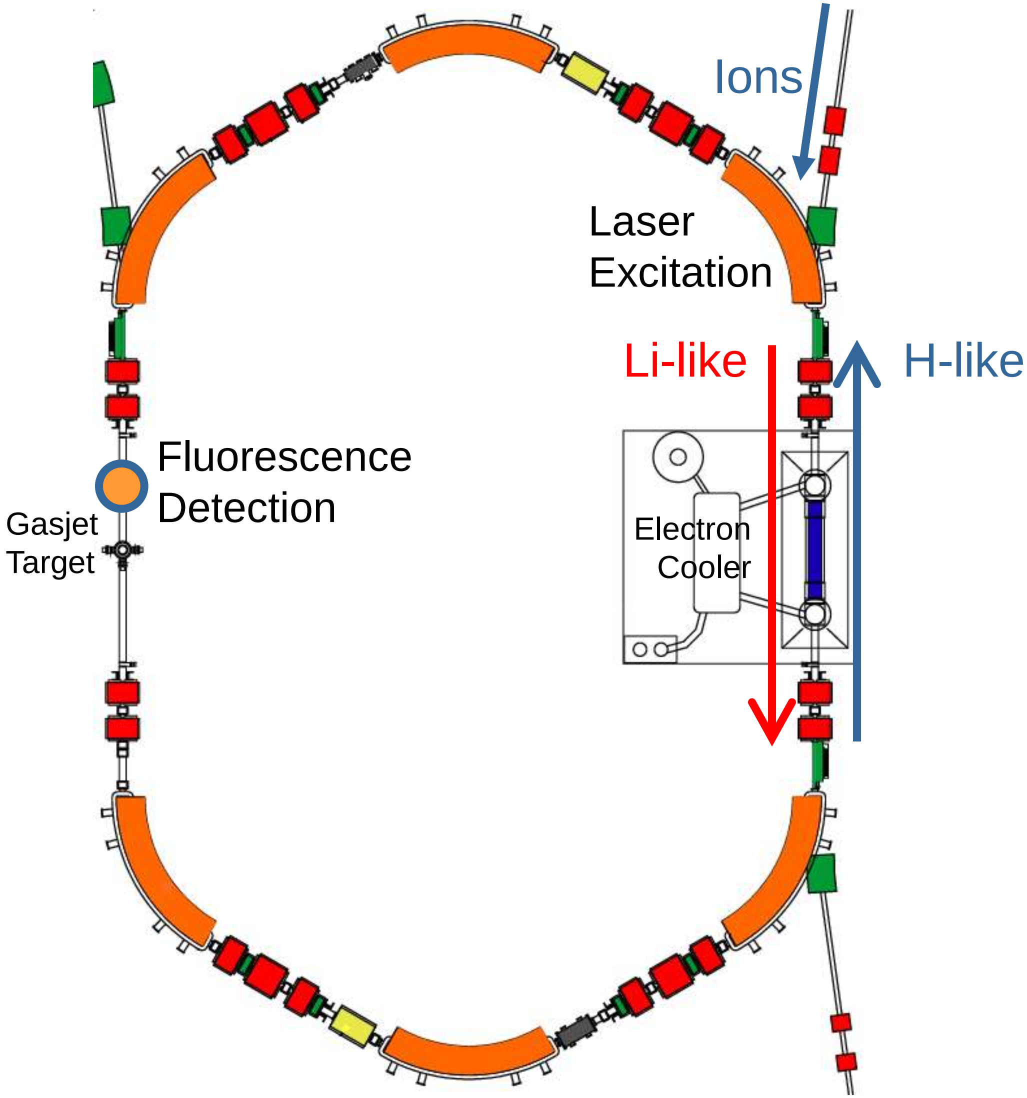
J=1/2 & I=1/2, → F=0,1



J=1/2 & I=9/2, → F=4,5



laser spectroscopy of the HFS in ^{209}Bi



With the same laser
~615 nm @ 428 MeV/u

$^{209}Bi^{82+}$ (H-like)

$^{209}Bi^{80+}$ (Li-like)

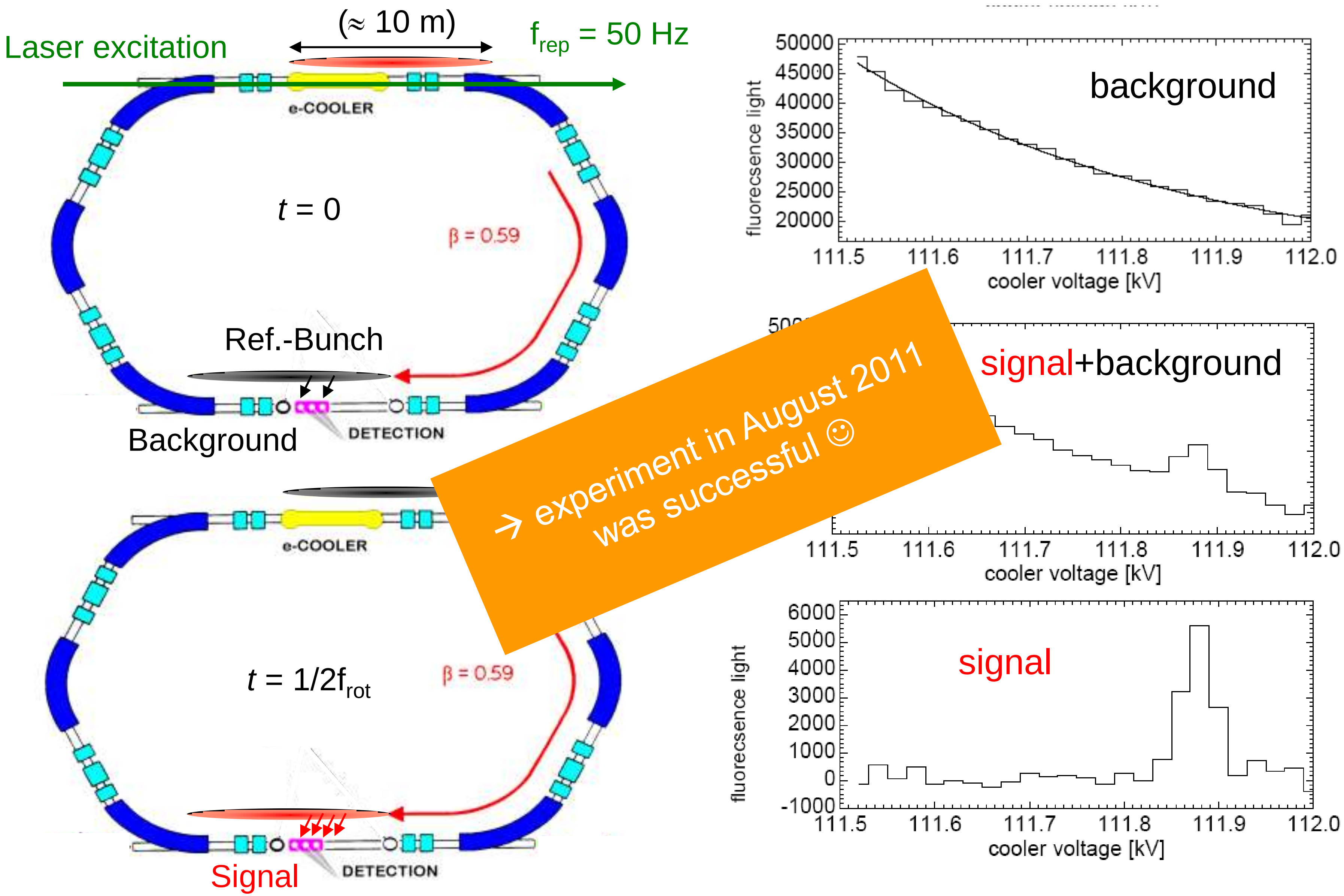
J=1/2 and I=9/2 give F=4,5

F=4 → F=5 transition

Especially the Li-like transition
is of great interest, since there is
quite some debate about its value.

In the 3 previous attempts the
1550 nm line was not found...

P. Beiersdorfer *et al*. Phys. Rev. Lett. **80** (1998) 3022
V.M. Shabaev *et al.*, Phys. Rev. Lett. **86** (2001) 3959



Th. Kühl, W. Nörtershäuser, D. Winters, M. Lochmann *et al.*

Test of Special Relativity with $^7Li^+$

(a modern Ives & Stilwell experiment)

C. Novotny, S. Reinhardt, G. Saathoff, S. Karpuk...
B. Botermann, W. Nörtershäuser, C. Geppert...
Th. Kühl, Th. Stöhlker...

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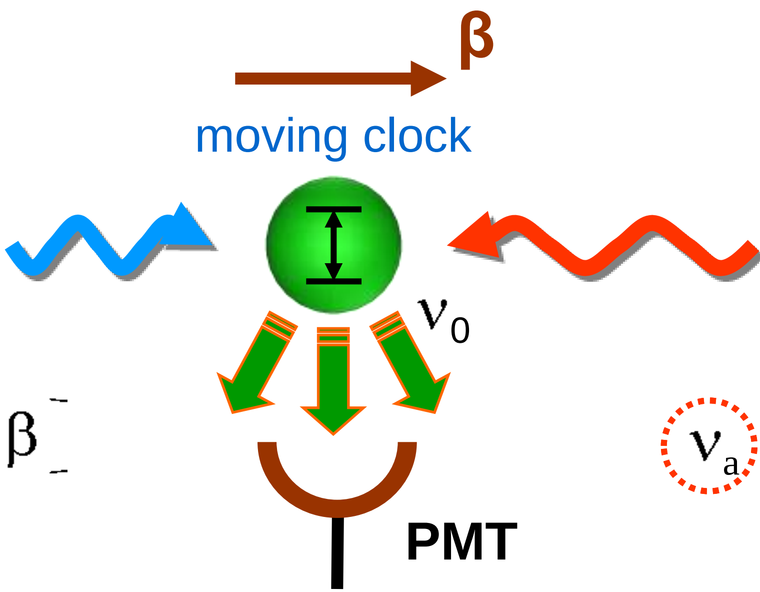
Testing Lorentz transformation via optical frequency measurements



$$\nu_p = \nu_0 \cdot \gamma \cdot (1+\beta) \qquad \nu_a = \nu_0 \cdot \gamma \cdot (1-\beta)$$

Testing Time Dilation via three optical frequencies
(Doppler-free laser saturation spectroscopy)

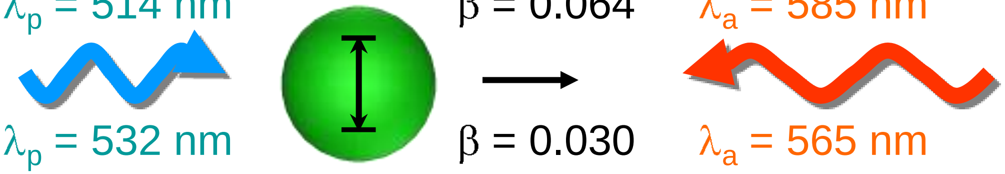
$$\frac{\nu_a \cdot \nu_p}{\nu_0^2} = \gamma^2 \cdot (1-\beta^2) \overset{?}{\equiv} 1 \longrightarrow \frac{\nu_a \cdot \nu_p}{\nu_0^2} = 1 + 2 \cdot \delta\alpha \cdot \beta^2$$

experiments at the TSR

measured at the TSR

$^7Li^+$

λ_p = 514 nm β = 0.064 λ_a = 585 nm



λ_p = 532 nm β = 0.030 λ_a = 565 nm

λ_0 = 548 nm

(1s2p) $^3P_2$ - (1s2s) $^3S_1$

ν_0 =	546 466 918 790	400 kHz
ν_p =	582 490 603 430	3 kHz
ν_a =	512 671 028 075	73 kHz

the error in the rest frequency dominates

➔ measurement at two different velocities

$$\frac{\nu_a \cdot \nu_p}{\nu_0^2} = 1 + 2 \cdot \delta\alpha \cdot \beta^2 \longrightarrow \frac{\nu_{a2} \cdot \nu_{p2}}{\nu_{a1} \cdot \nu_{p1}} = \frac{1 + 2 \cdot \delta\alpha \cdot \beta_2^2}{1 + 2 \cdot \delta\alpha \cdot \beta_1^2} \approx 1 + 2 \cdot \delta\alpha \cdot \left(\beta_2^2 - \beta_1^2\right)$$

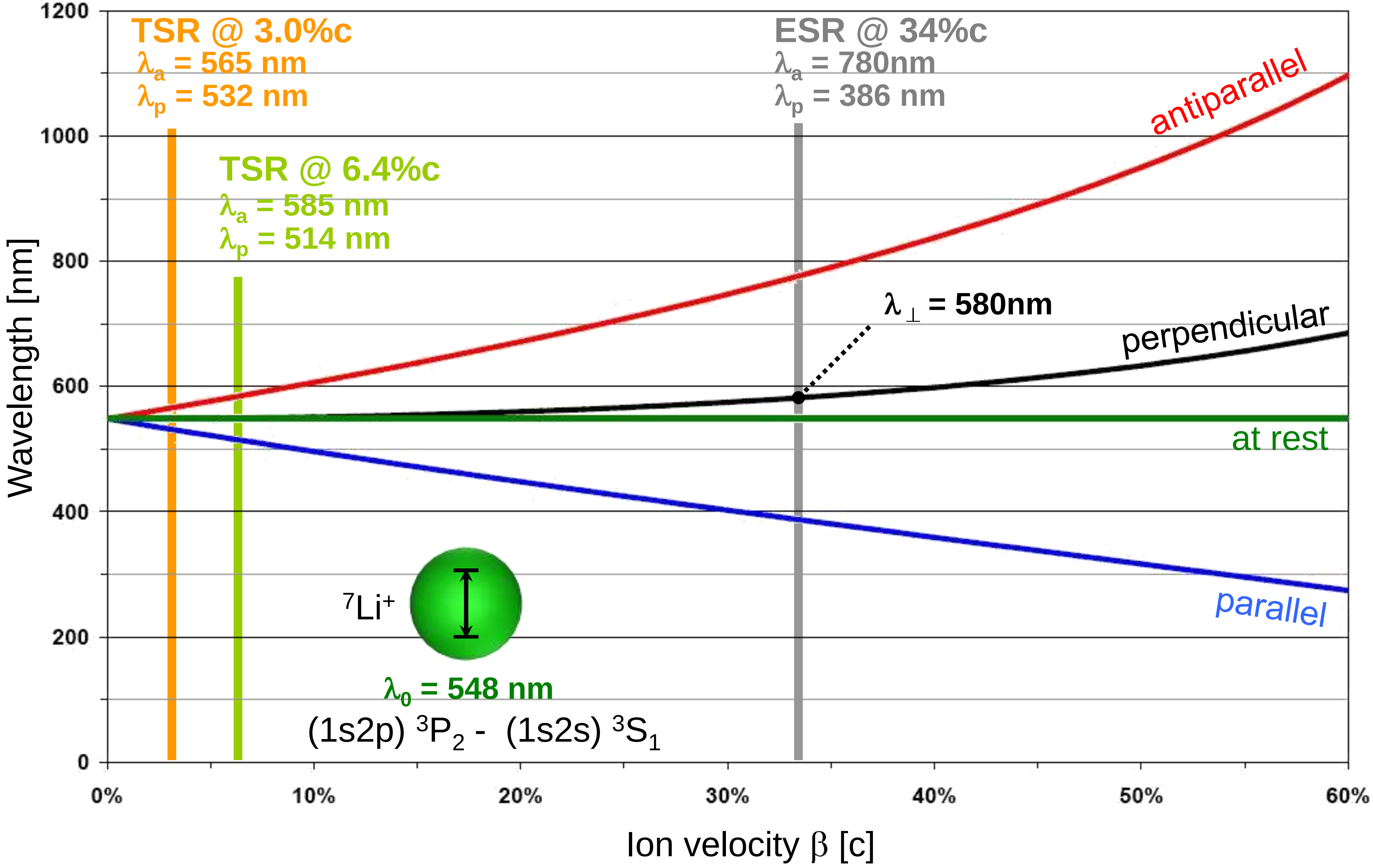
cancels out the uncertainty of the rest frequency

best upper bound for $\delta\alpha$: $\delta\alpha < 8.4 \times 10^{-8}$

[G. Saathoff, et al.
PRL *91 (2003) 190403*]

[S. Reinhardt, et al.
Nature Physics *3 (2007) 861*]

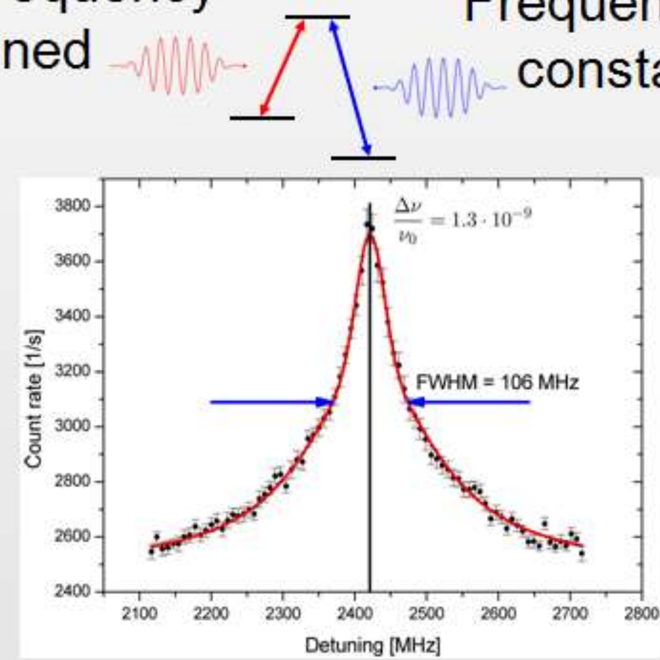
Why go to the ESR?



Spectroscopy signals

Frequency tuned

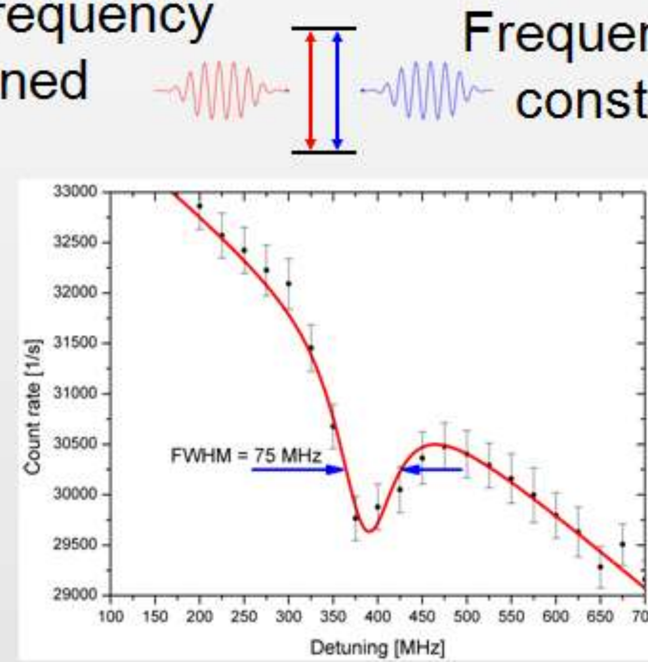
Frequency constant



Doppler-free signal
(Λ-spectroscopy)

Frequency tuned

Frequency constant



Doppler-free signal
(saturation spectroscopy)

from Benjamin Botermann (2011)

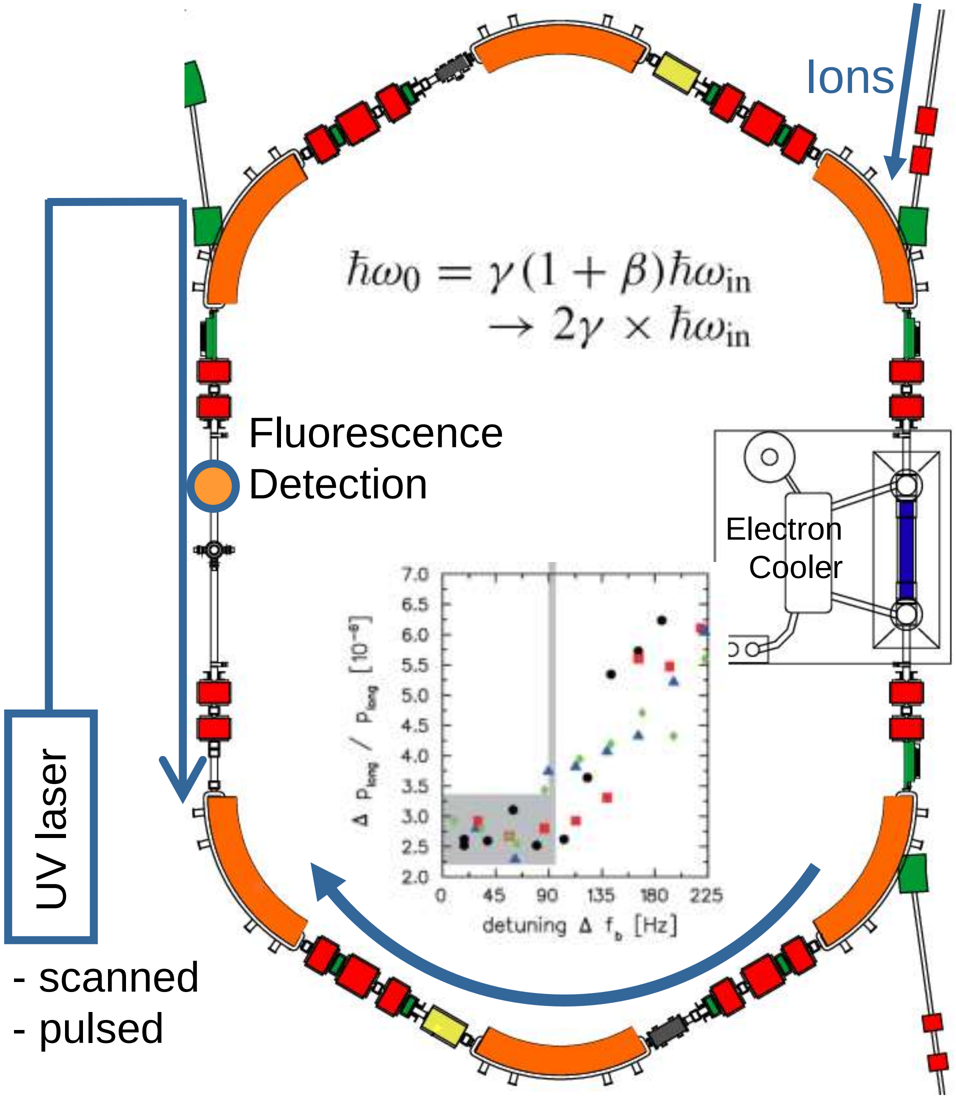
Laser Cooling of C^{3+}

M. Bussmann, U. Schramm...
W. Wen, X. Ma...
G. Birkl, Th. Walther...
D. Winters, Th. Stöhlker...
M. Steck, F. Nolden, C. Dimopoulou…

Motivation

- only cooling method available at SIS300 (also spectroscopy of high-Z Li-like ions)
- applicable to all stable and unstable (Li-like) ions
- study laser cooling without pre-electron cooling
- use broadband pulsed laser cooling for fast cooling of many ions
- set up fluorescence detection to determine the lower limit for longitudinal cooling $\Delta p/p<10^{-7}$

laser cooling of relativistic ion beams



Laser cooling of Li-like ions:
- fastest cooling method
- smallest momentum spread

$\Delta p/p \approx 10^{-8}$

Only cooling method for SIS300, since electron cooling would require too high voltages.

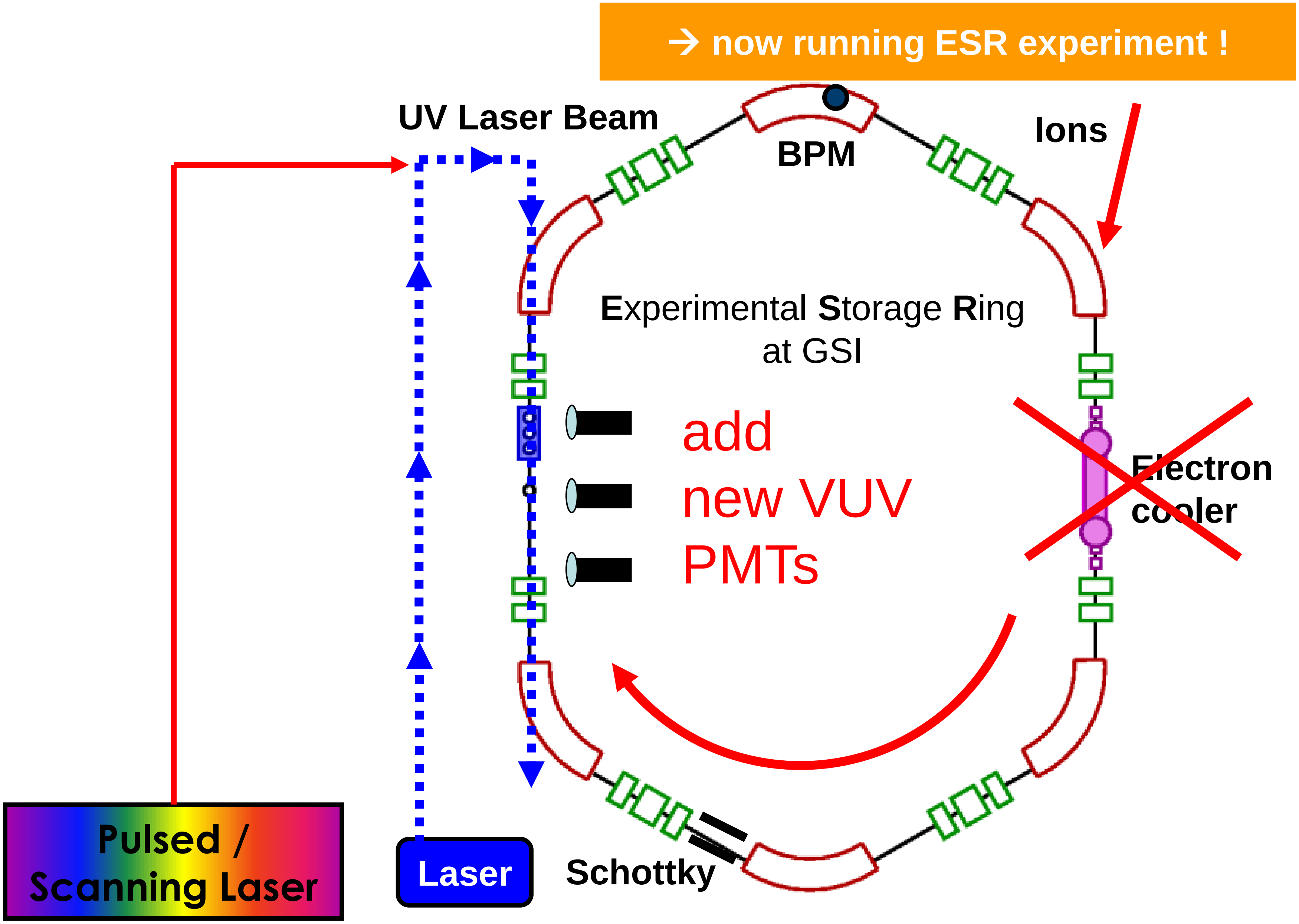
ESR experiments:

(257 nm @ 122 MeV/u)

$^{12}C^{3+}$ (Li-like) @ 155 nm

$(1s^2 2s)\ ^1S_{1/2} \rightarrow (1s^2 2p)\ ^1P_{1/2,3/2}$

Experiment improvements



Laser spectroscopy of the $(1s^2 2s2p)\ ^3P_0 - {}^3P_1$ level splitting in Be-like krypton

Danyal Winters

Thomas Kühl, Dieter Schneider, Paul Indelicato, Regina Reuschl, Reinhold Schuch, Eva Lindroth and Thomas Stöhlker

Scientific motivation and measurement goal

• Heavy few-electron ions (*e.g.* Be-like ions), are ideal atomic systems to study effects of correlation, relativity and quantum electrodynamics.

• Recent theoretical and experimental studies of these species achieved a considerable improvement in accuracy.

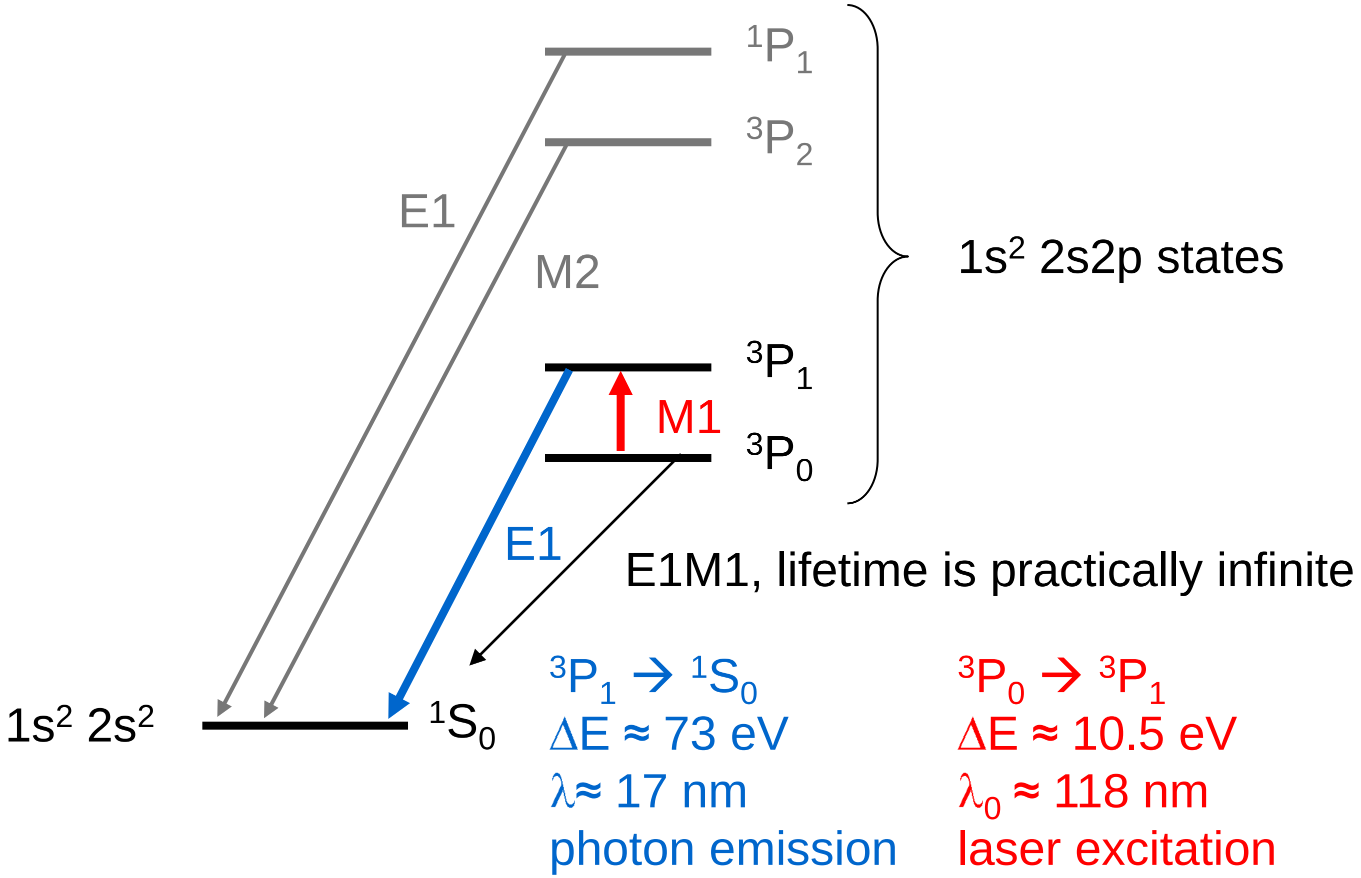
•The Be-like ions are interesting because their first excited state $(1s^2 2s2p)\ ^3P_0$ has an almost infinite lifetime in the absence of nuclear spin, as it can only decay by a two-photon $E1M1$ transition to the $(1s^2 2s2)\ ^1S_0$ ground state.

• In addition, the energy difference between the $^3P_0$ and the $^3P_1$ states is expected to be almost completely unaffected by QED effects, and is therefore dominated by the effects of correlation and relativity.

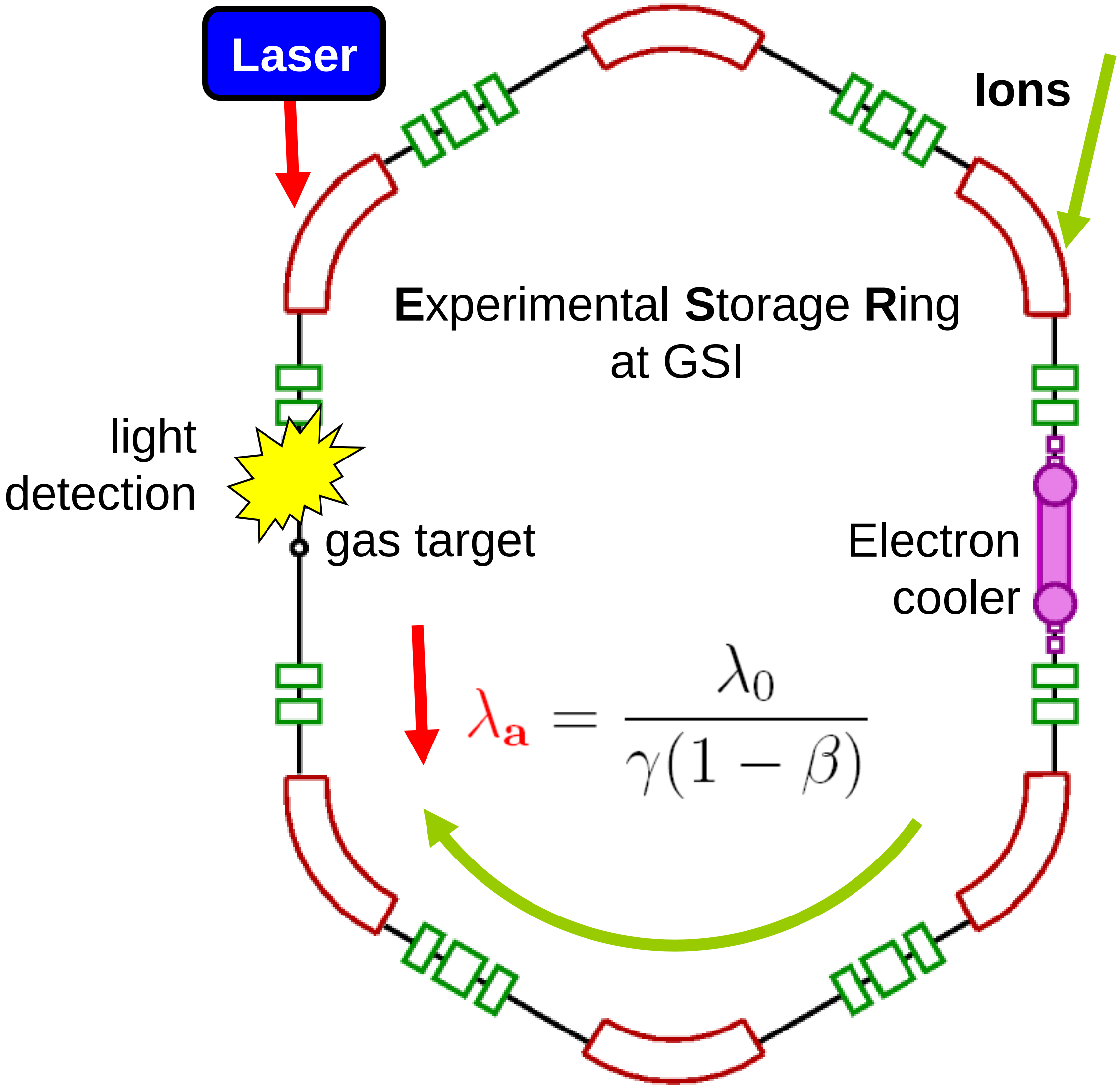
• We would like to determine the $(1s^2 2s2p)\ ^3P_0$ - $^3P_1$ level splitting in Be-like ^{84}Kr by means of laser spectroscopy at the ESR.

→ The accurate result ($\sim 10^{-5}$) tests correlation and relativity in medium-Z ions.

Level scheme of Be-like krypton



Laser spectroscopy of $^{84}Kr^{32+}$ at the ESR



~10^8 ions, ~10% in $^3P_0$
Be-like $^{84}Kr^{32+}$
Ion energy ≈ 360 MeV/u
($\beta \approx 0.69$, $\gamma \approx 1.38$)
$f_{rev} \approx 1.92$ MHz

$^3P_0 \rightarrow {}^3P_1$
$\Delta E \approx 10.5$ eV
$\lambda_0 \approx 118$ nm

Topics:

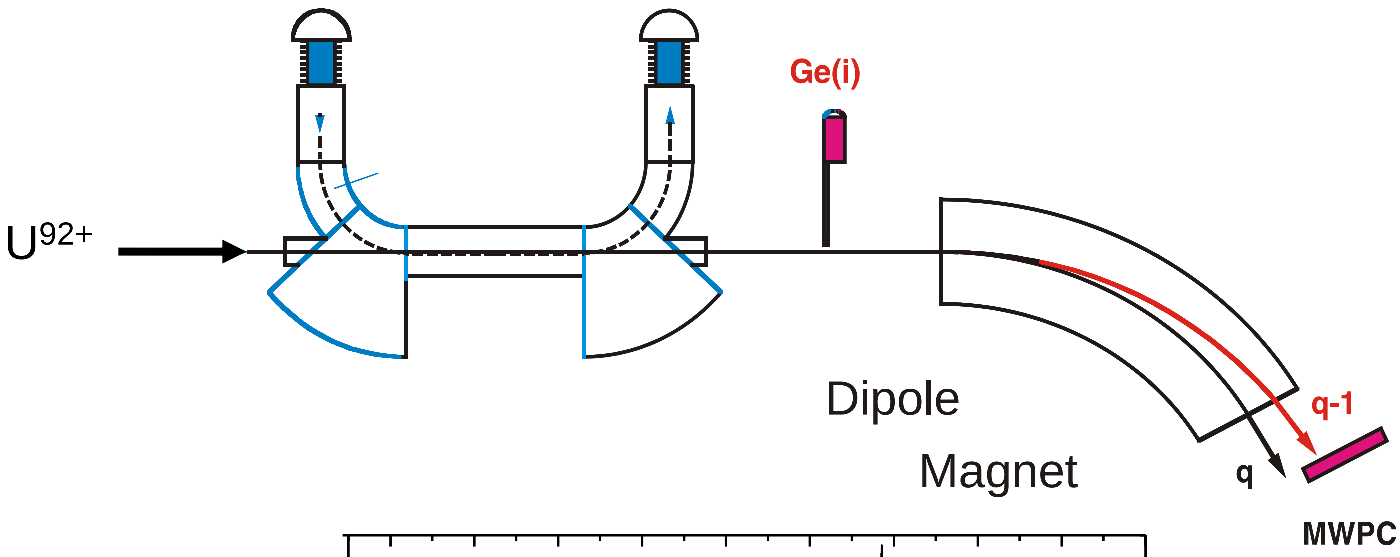
Dielectronic recombination (DR)

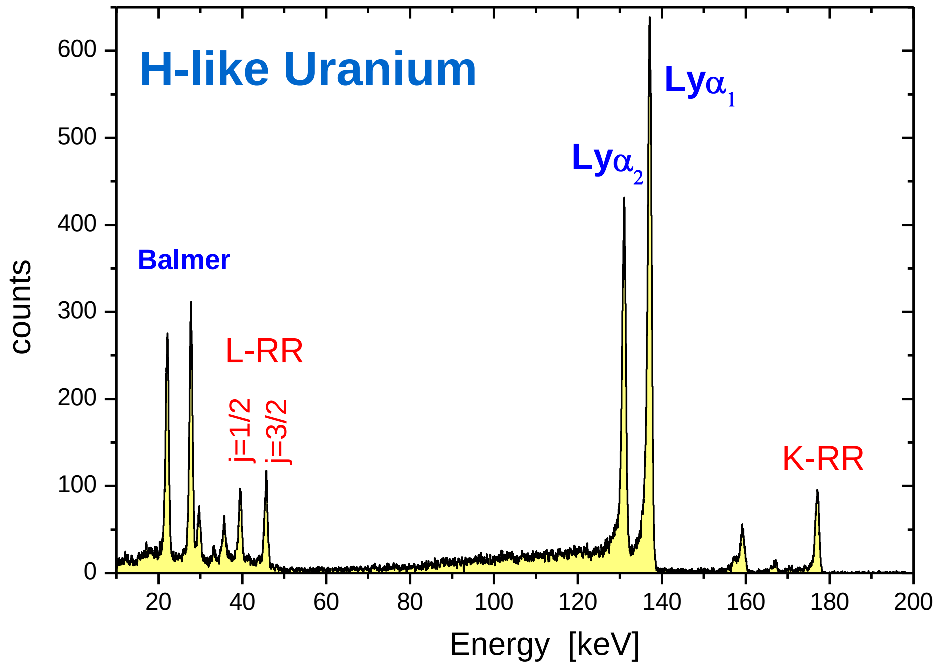
Mass spectrometry

Laser spectroscopy and laser cooling

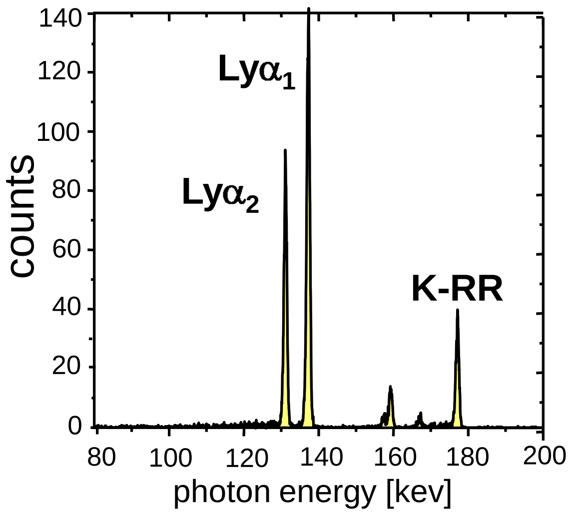
X-ray spectroscopy

0º x-ray spectroscopy at the electron cooler





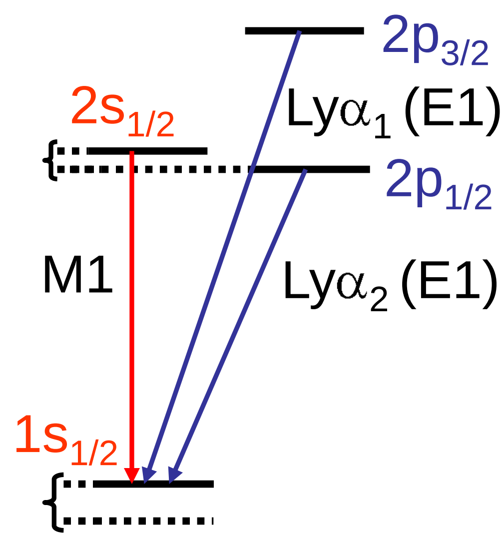
the 1s-Lamb shift in He-like U → a test of QED



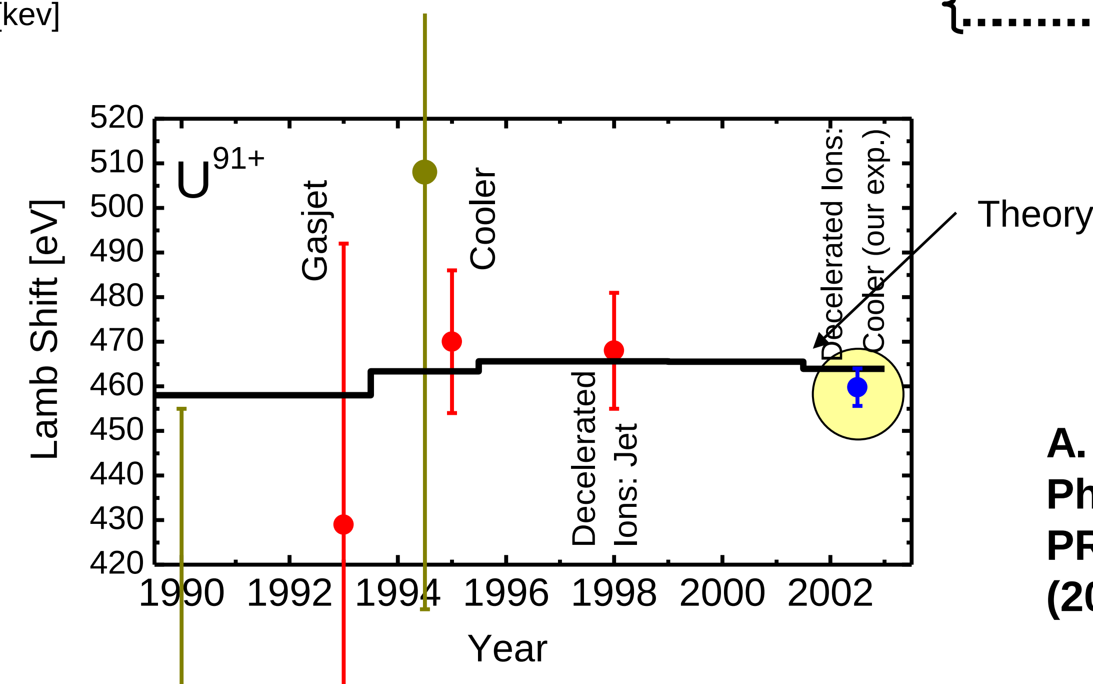
1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV



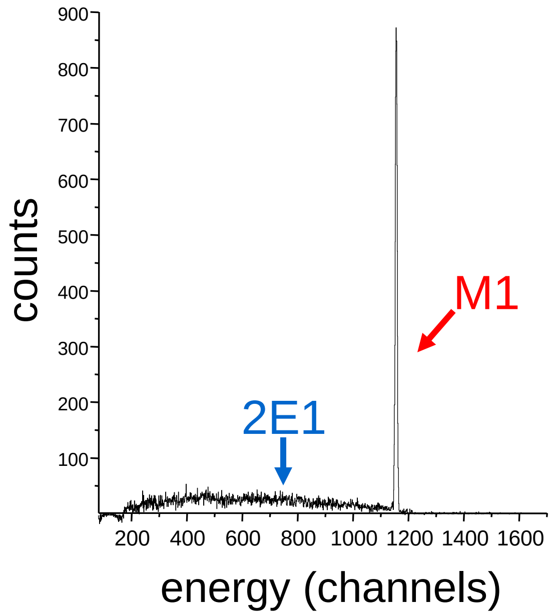
459.8 2.3±3.5 eV

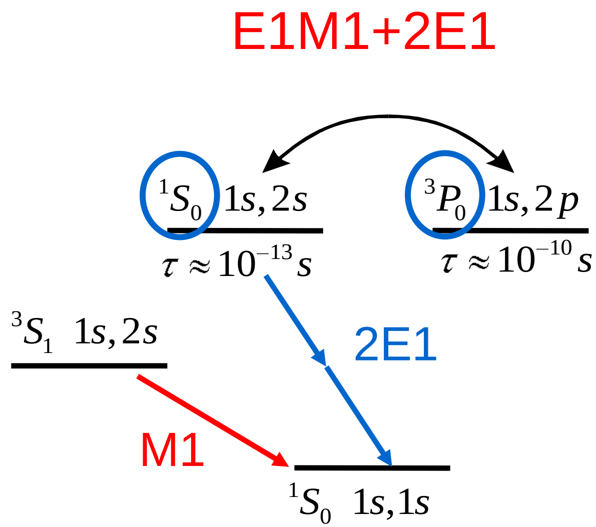


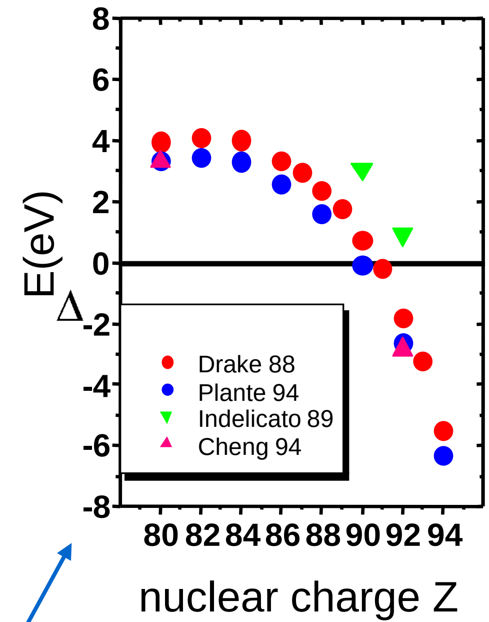
Research Highlights
Nature **435**, 858-859
(16 **June 2005**)

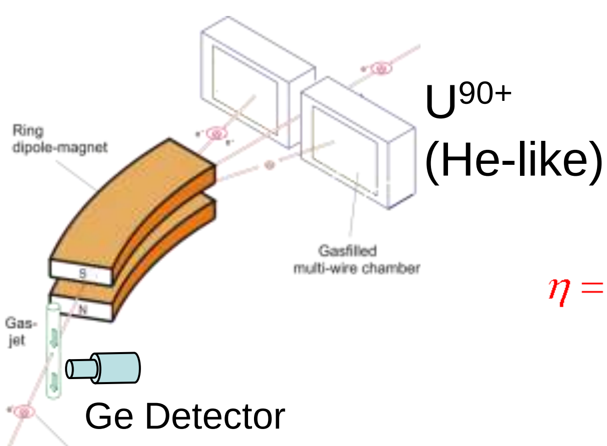
A. Gumberidze
PhD thesis 2003,
PRL 94, 223001
(2005)

parity violation in He-like uranium









U89+ (Li-like)

Parity admixture

$$\eta = \frac{\left\langle 2\ {}^3P_0 \right| \frac{G_F}{2\sqrt{2}} \left(1 - 4\sin^2\Theta_w - \frac{N}{Z}\right) \rho_{el}\gamma_5 \left| 2\ {}^1S_0 \right\rangle}{E\left(2\ {}^3P_0\right) - E\left(2\ {}^1S_0\right)}$$

$$|\eta| = 5 \cdot 10^{-6}$$

G_F: Fermi constant,

N: neutron number,

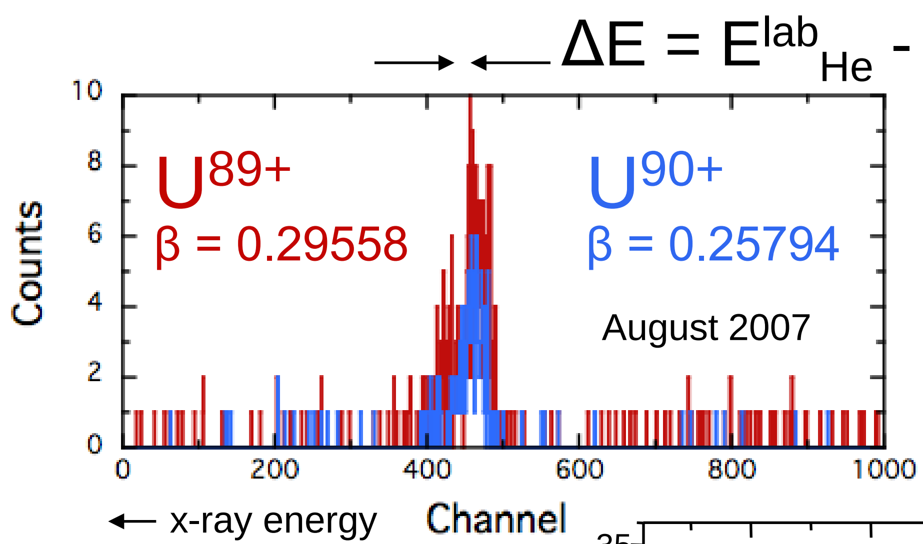
Θ_w: Weinberg angle

Z: proton number

ρ_{el}: electric charge density

first observation of the $\Delta n=0$ $^3P_2 \rightarrow {}^3S_1$ at high-Z

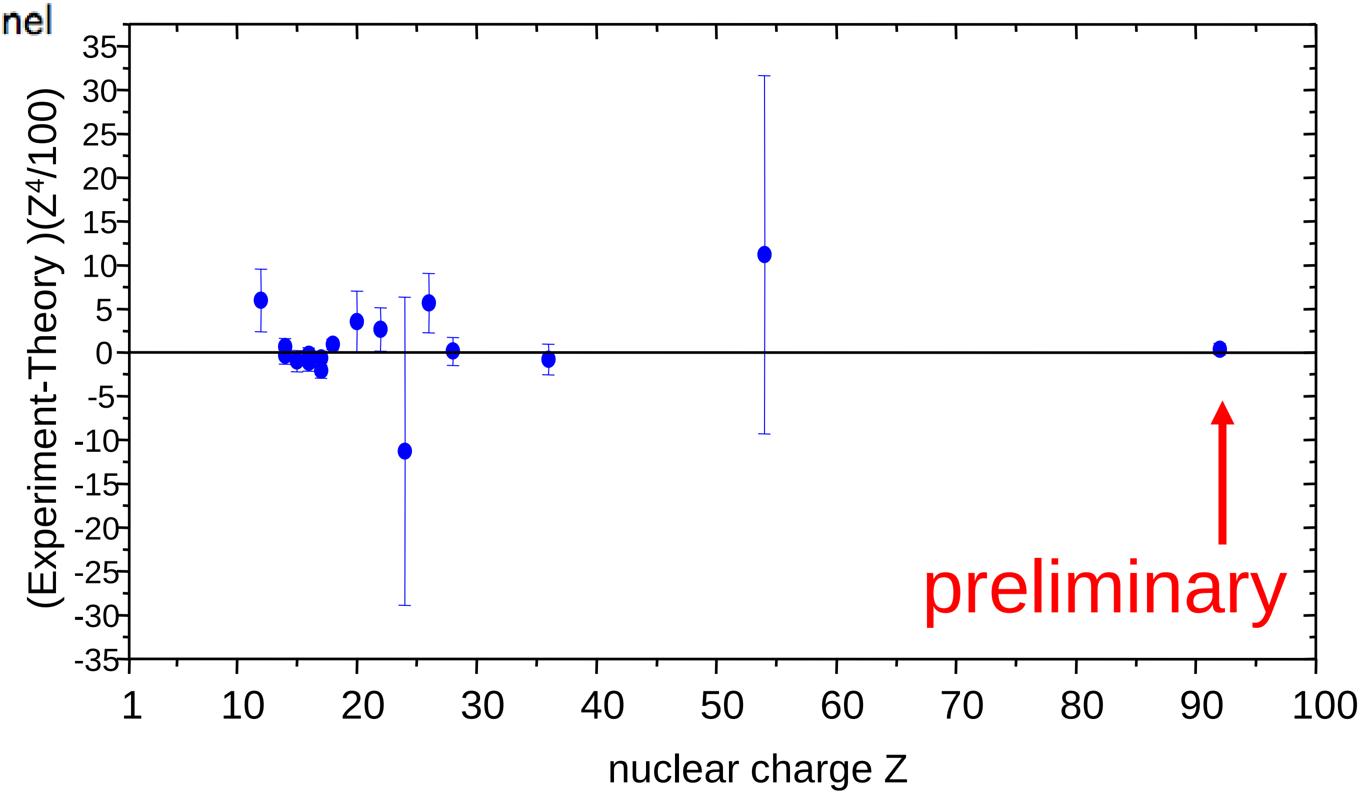
$\Delta E = E^{lab}_{He} - E^{lab}_{Li}$



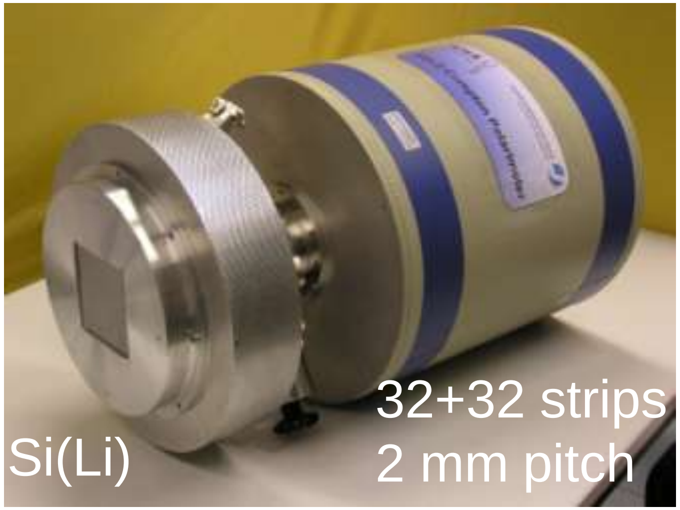
Relative measurement

He-like ⬄ Li-like (well-known)

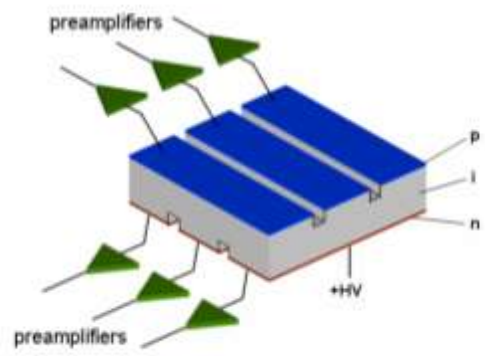
M. Trassinelli *et al.*, Europhysics Letters 2010

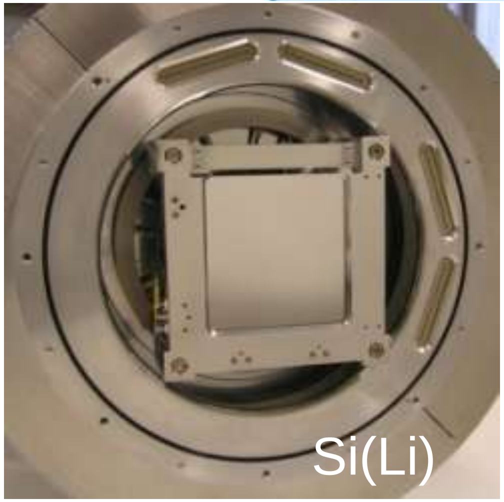


2D Si(Li)-detector for Compton polarimetry



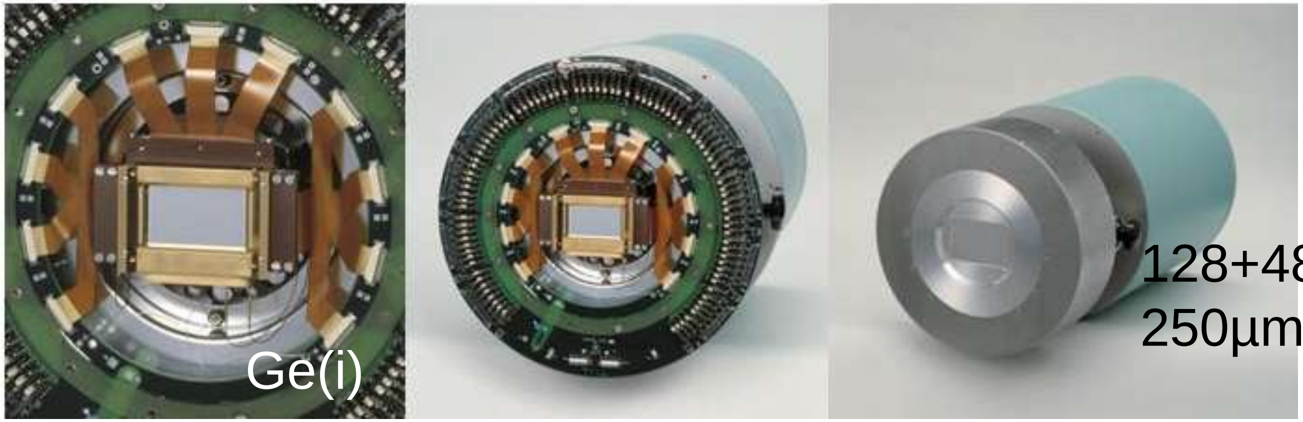
Si(Li) and Ge(i) based Compton polarimeter





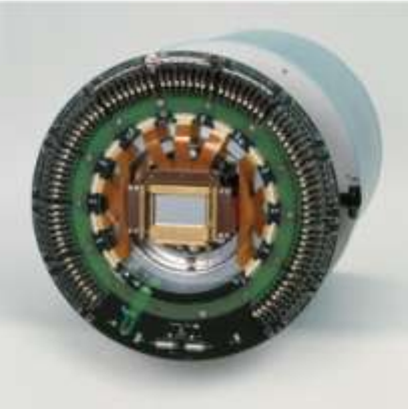
crystall size: 4" x 4"

energy resolution – timing - 2D position sensitiviy

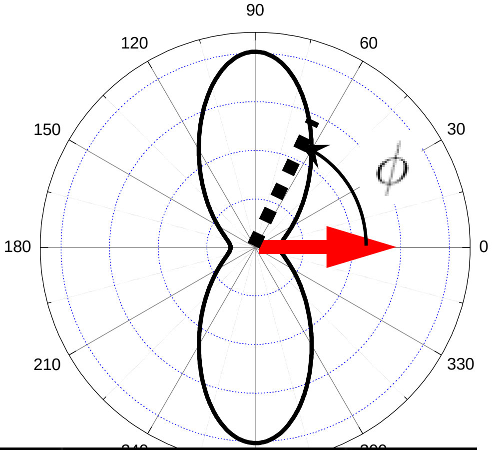


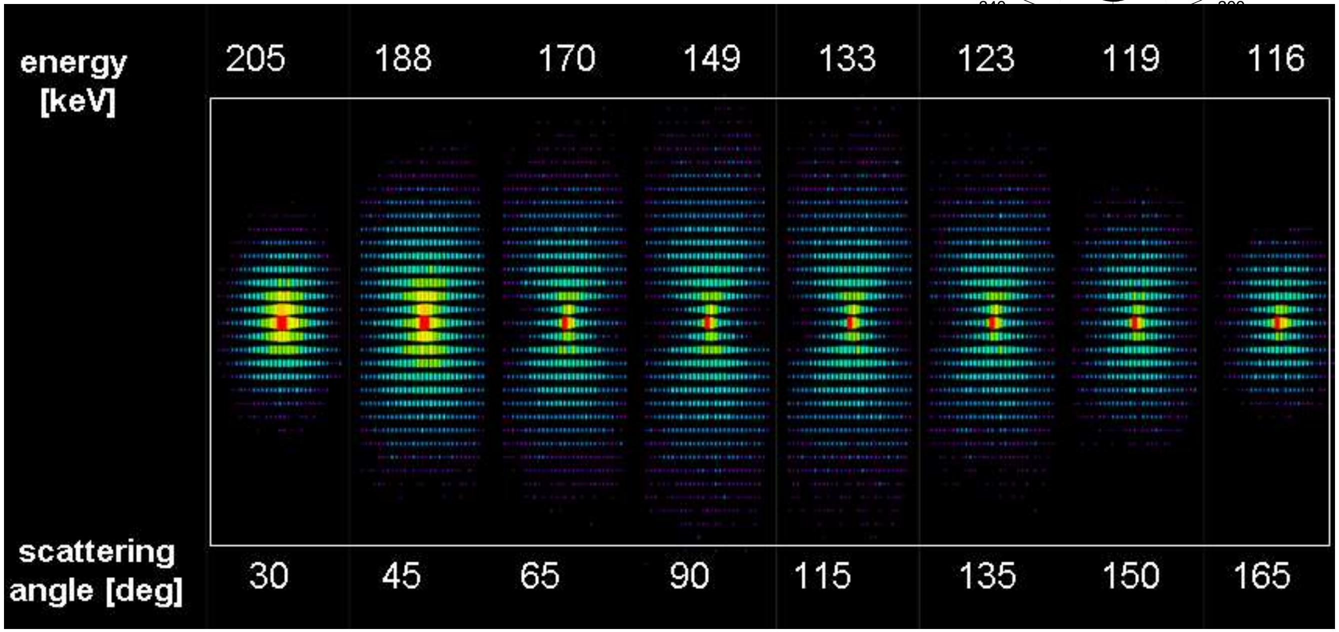
exploiting position and energy resolution

polarisation measurement via Compton scattering



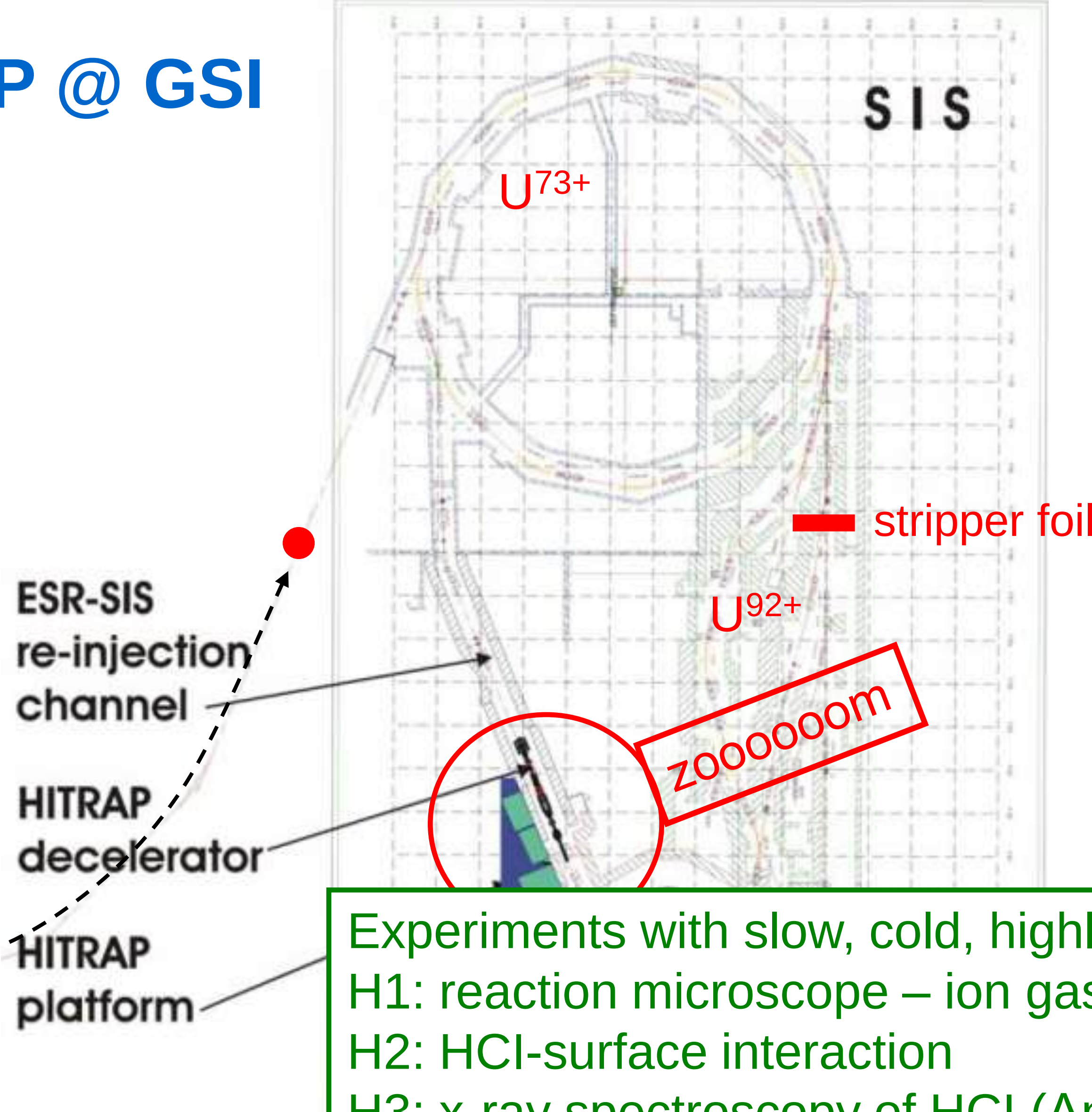
$$\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{m_e c^2}(1 - \cos\theta_C)}$$





x-ray images for Compton scattering as a function of the scattering angle

HITRAP @ GSI



Experiments with slow, cold, highly-charged ions:

H1: reaction microscope – ion gas collisions

H2: HCI-surface interaction

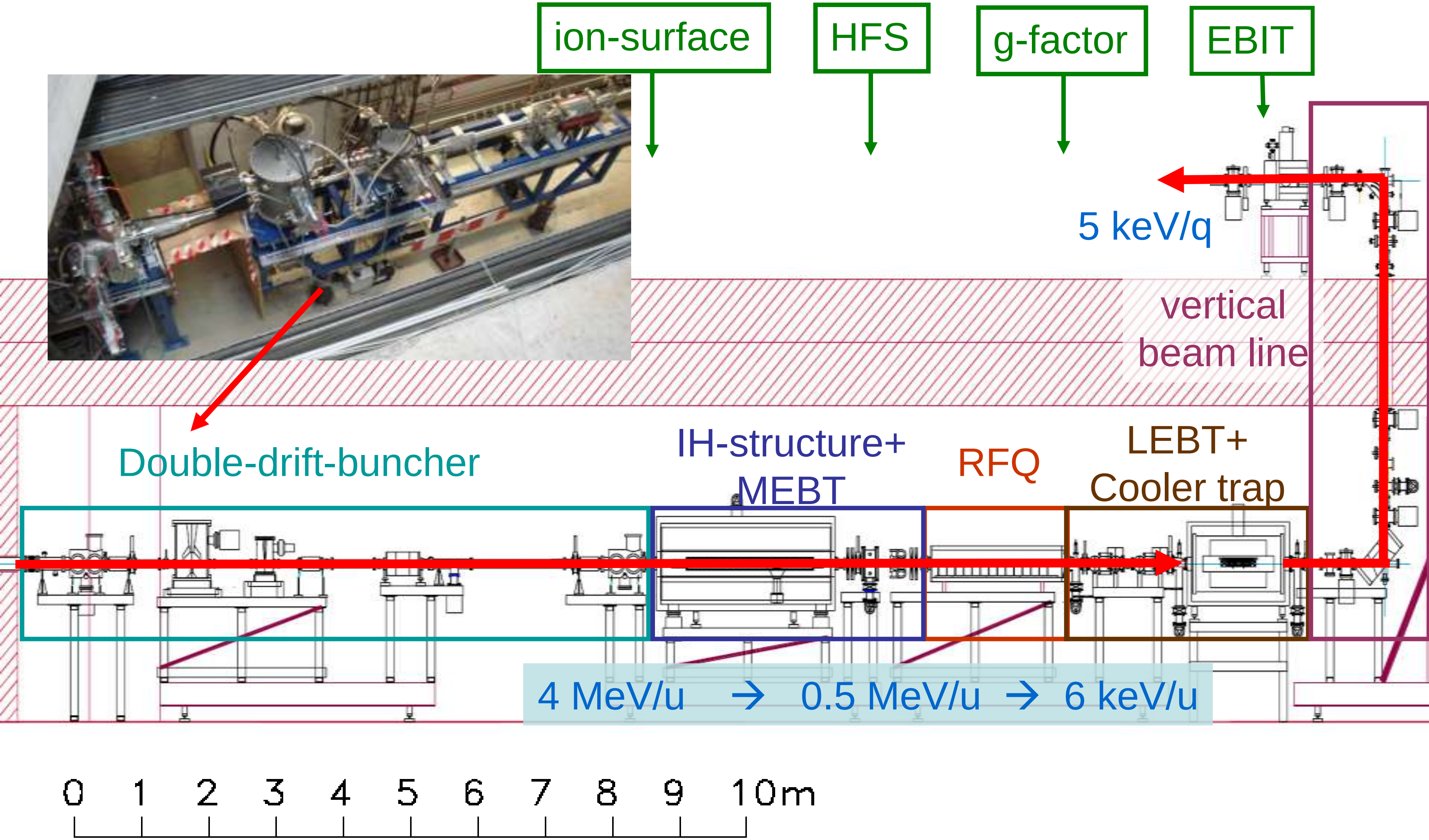
H3: x-ray spectroscopy of HCI ($\Delta n=0$)

H4: g-factor measurements of the bound electron

H5: mass measurements of extreme accuracy

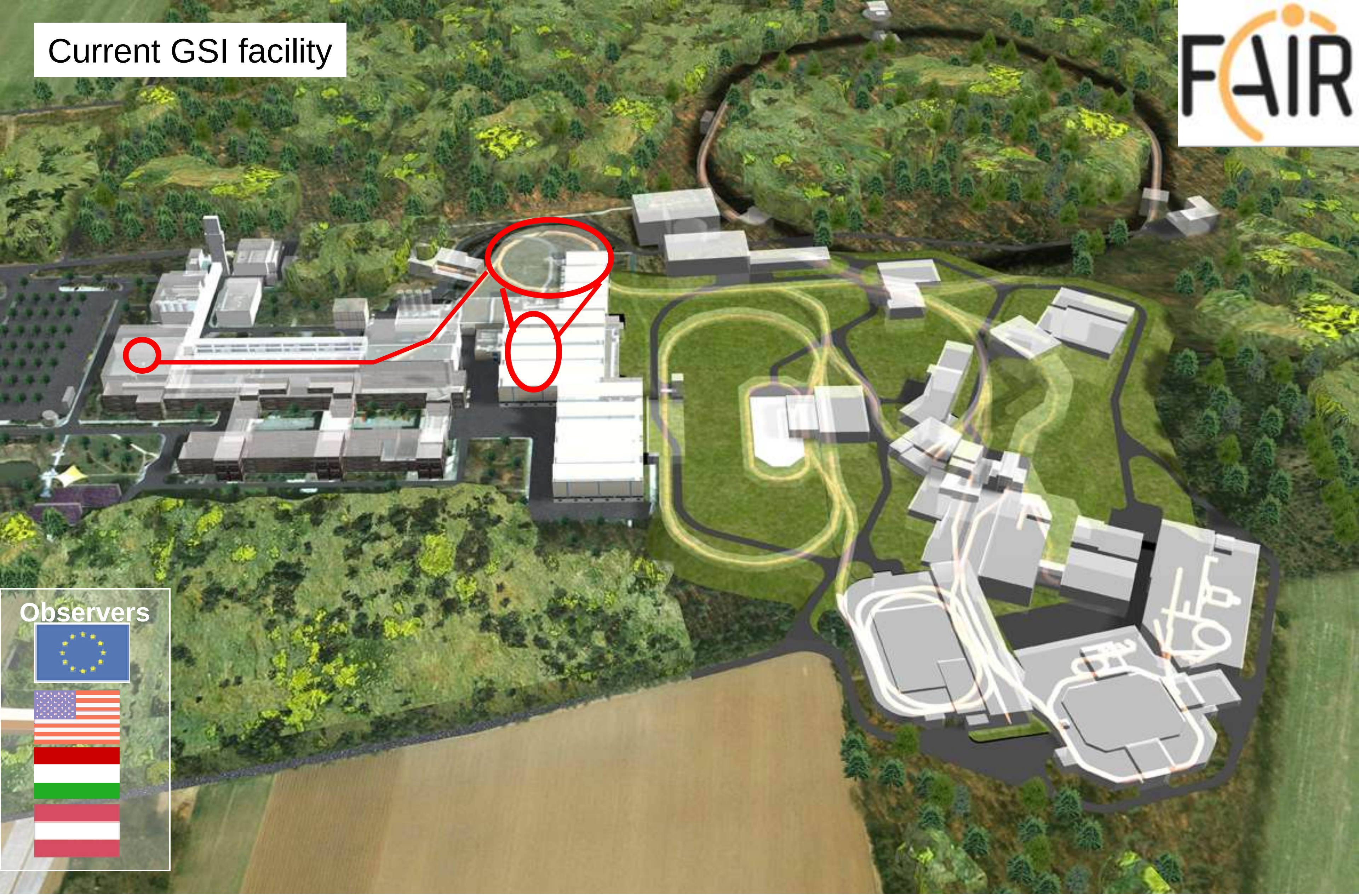
H6: laser spectroscopy of HFS

overview of the HITRAP facility



Facility for Antiproton an Ion Research

(FAIR)

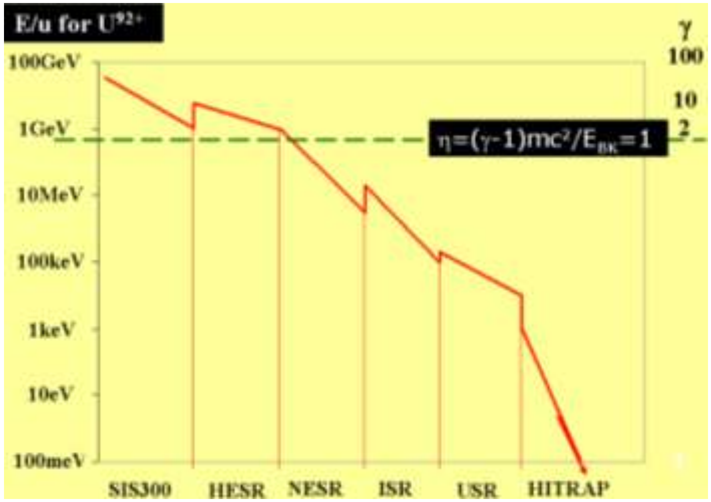


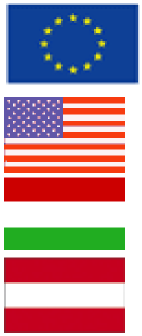
CN DE ES FI FR GB GR IN IT PL RO RU SE

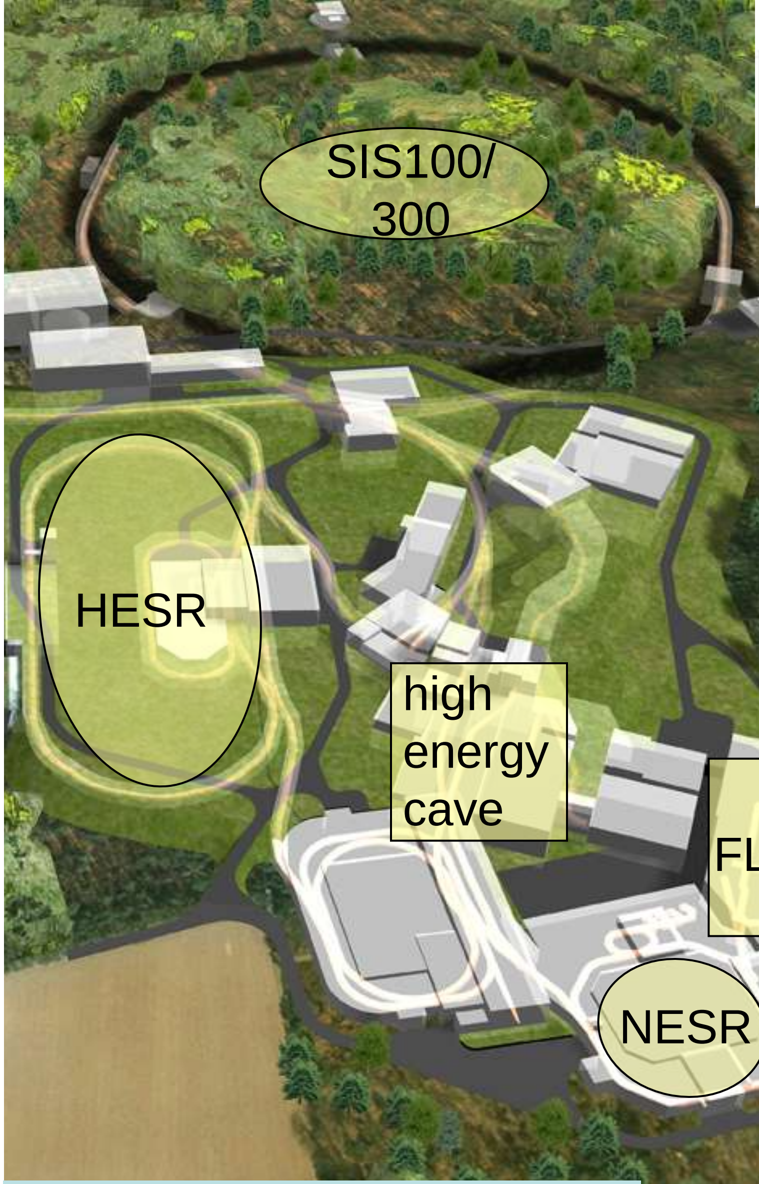
the **SPARC** collaboration:

- heavy HCI
- relativistic heavy ions
- radioactive nuclei
- extreme static EM fields
- extreme dynamic fields

the **FLAIR building**







→ novel instrumentation

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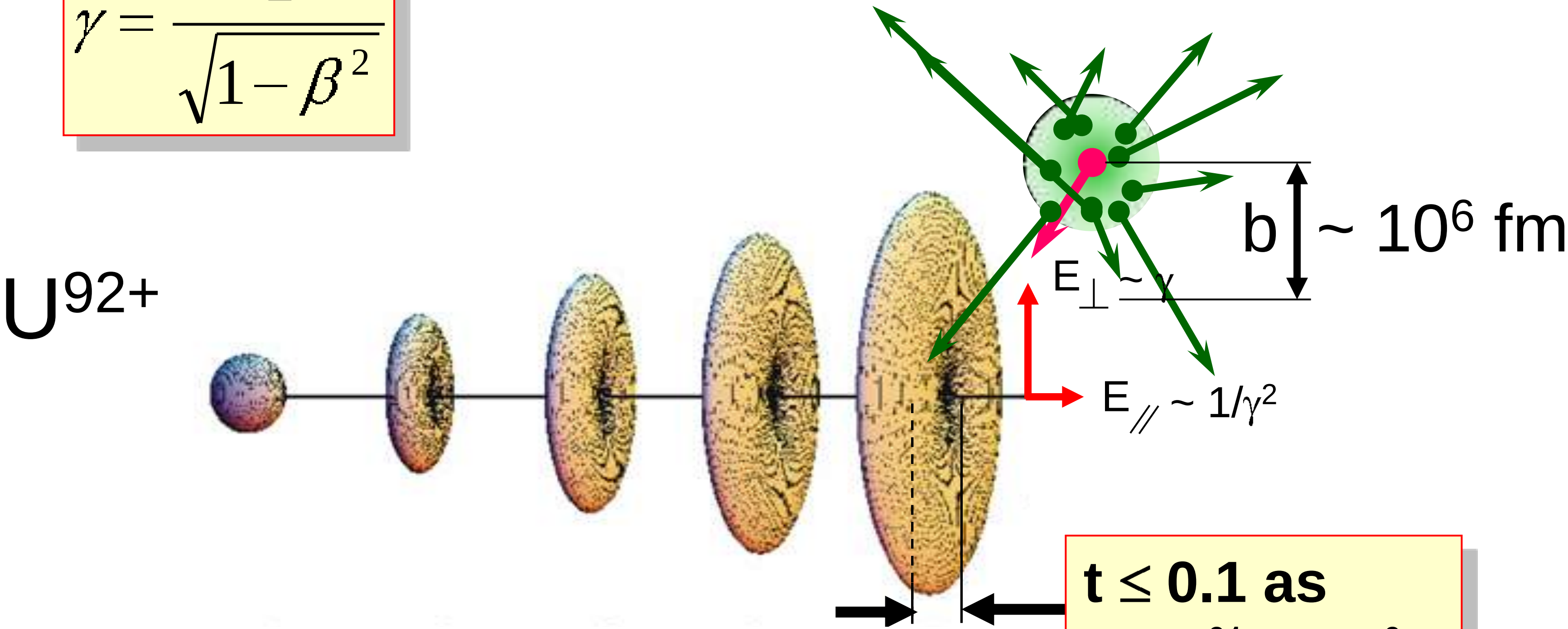
relativistic projectiles in extreme dynamic fields

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$



$\gamma =$ 1 2 3 4 5

0 87 94 97 98

percent of the velocity of light

$t \leq 0.1$ as

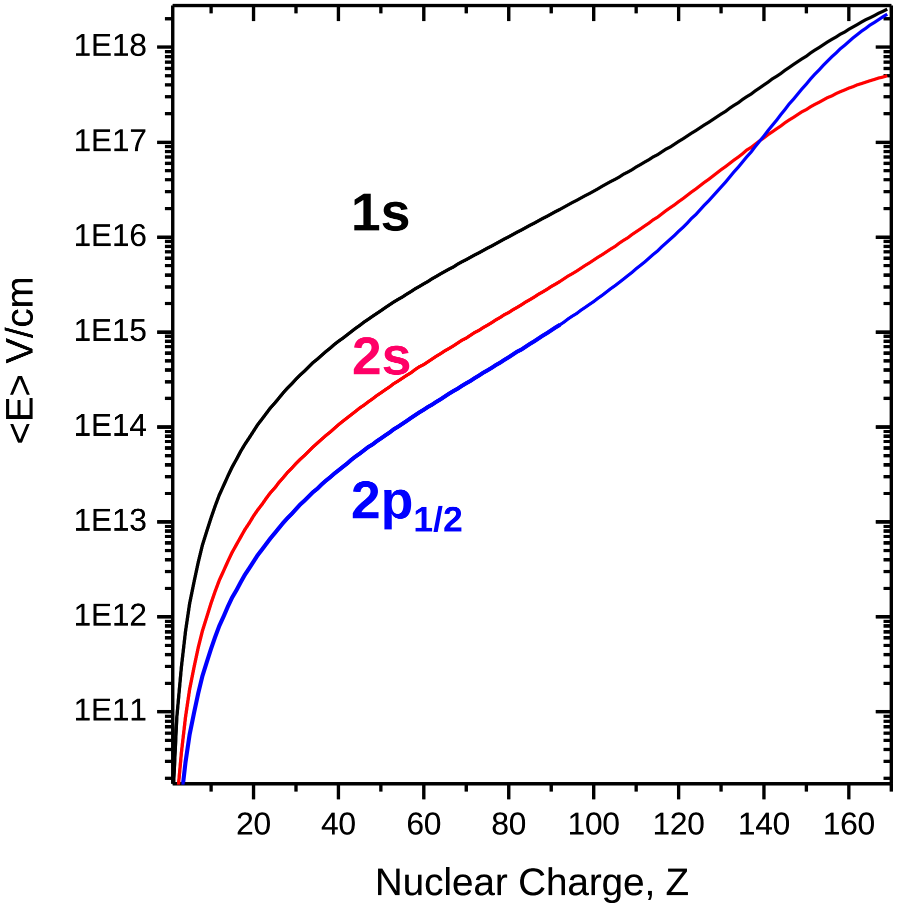
$I \approx 10^{21}$ W/cm^2

intense fields

ultra-short electromagnetic pulses

pair production

critical and super-critical fields



$U^{92+} \rightarrow U$ =>

U^{91+} + MO x-ray...

as a function of impact parameter


Thank you for your attention ☺
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