Atomic Physics at GSI: Current and Future Research

Danyal Winters

RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG
PHYSIKALISCHES
INSTITUT

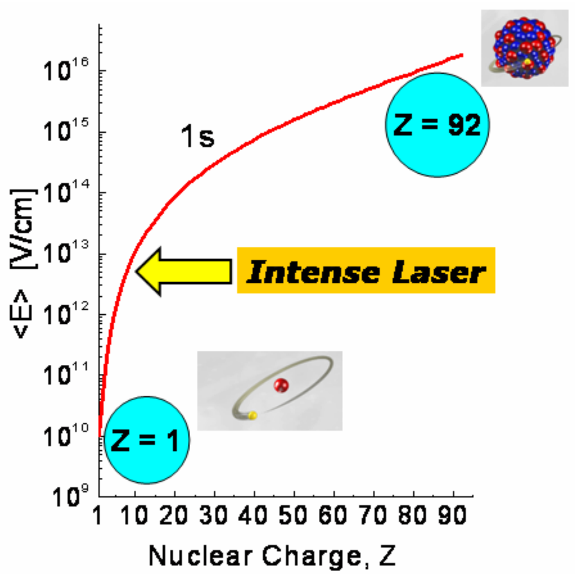
GSI summer student programme 2011
Tuesday, 16 August 2011, 11:10 – 12:30

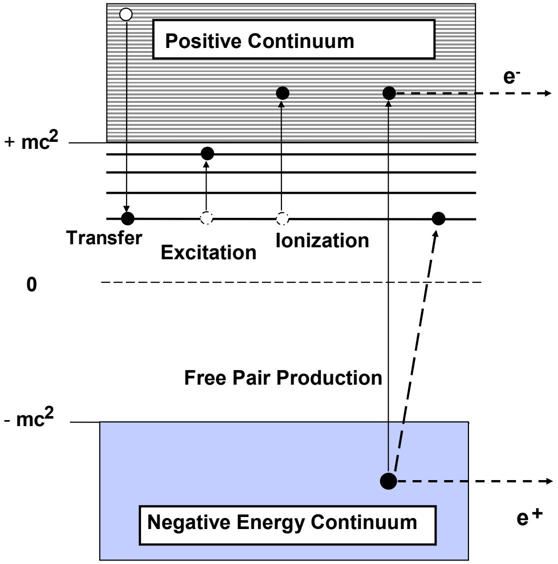
Atomic Physics Group

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

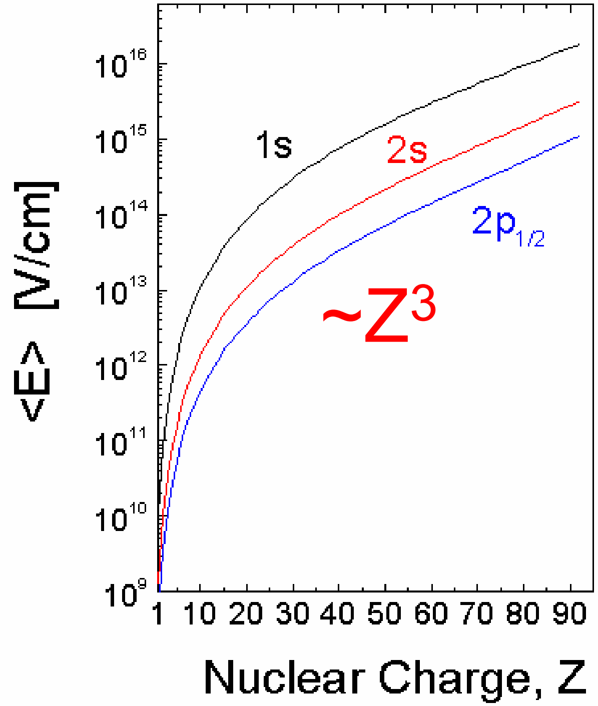
Atomic Collision at High-Z

- 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.

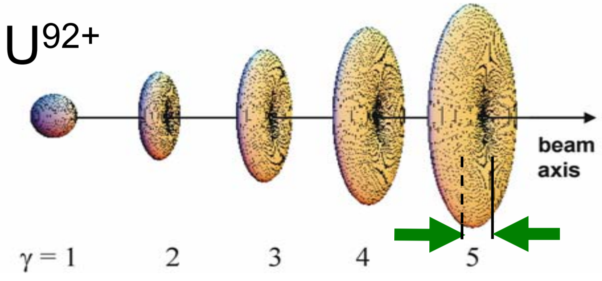
Tests of QED in extreme electromagnetic fields.
New access to fundamental constants and to nuclear ground state properties.



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

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

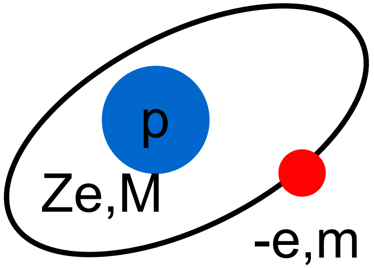
Extremely short and extremely intensive electromagnetic pulses at relativistic energies of highly-charged ions.



$t \leq 0.1$ as
$I \approx 10^{21}$ W/cm^2

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:

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

Bound states!

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

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

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:

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

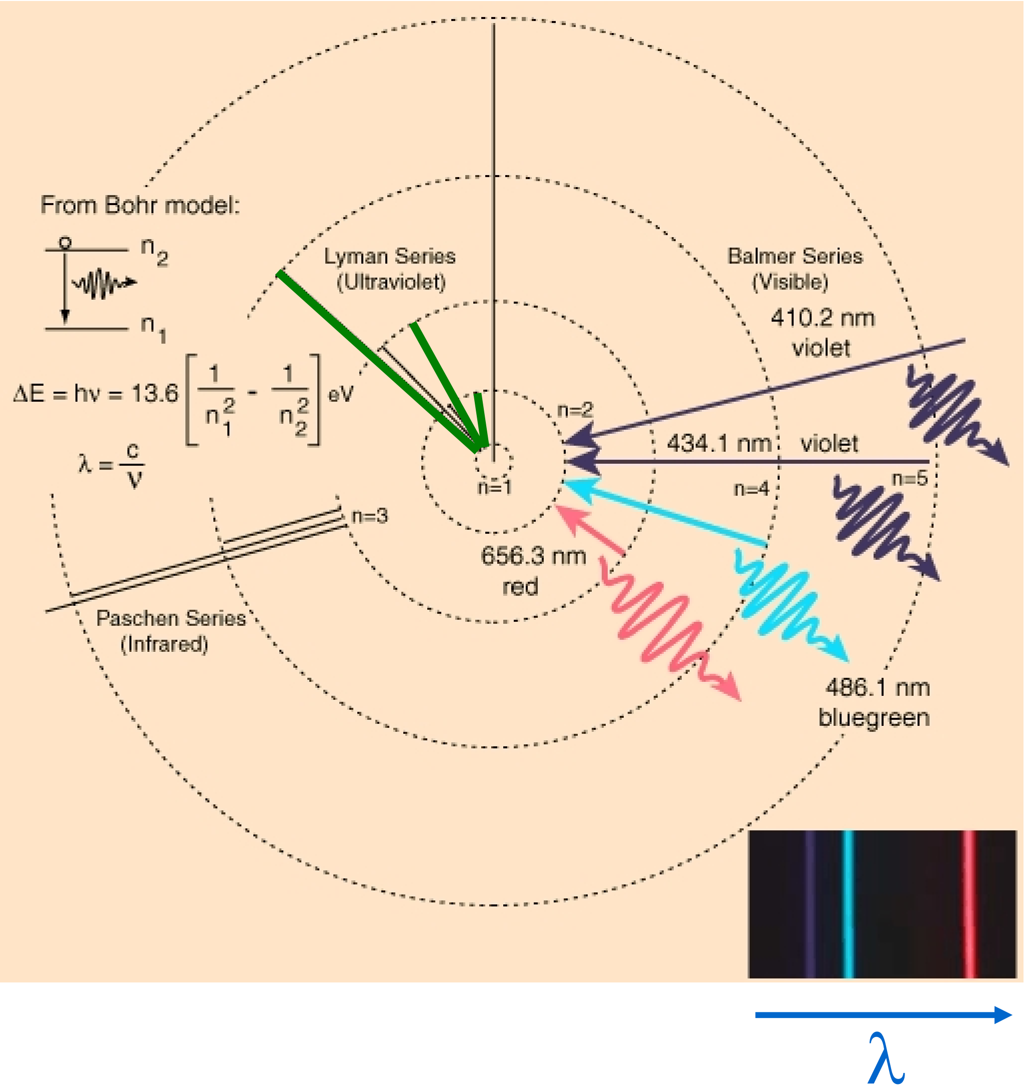
Using the fine structure coefficient $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \approx 1/137$, we finally obtain

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

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

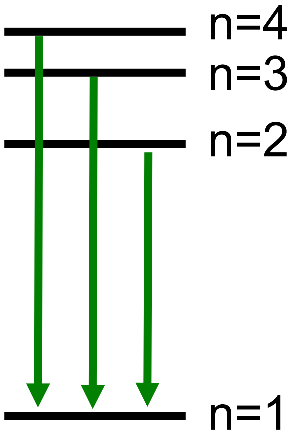
the simple Bohr model

These are important lines for highly-charged ions!



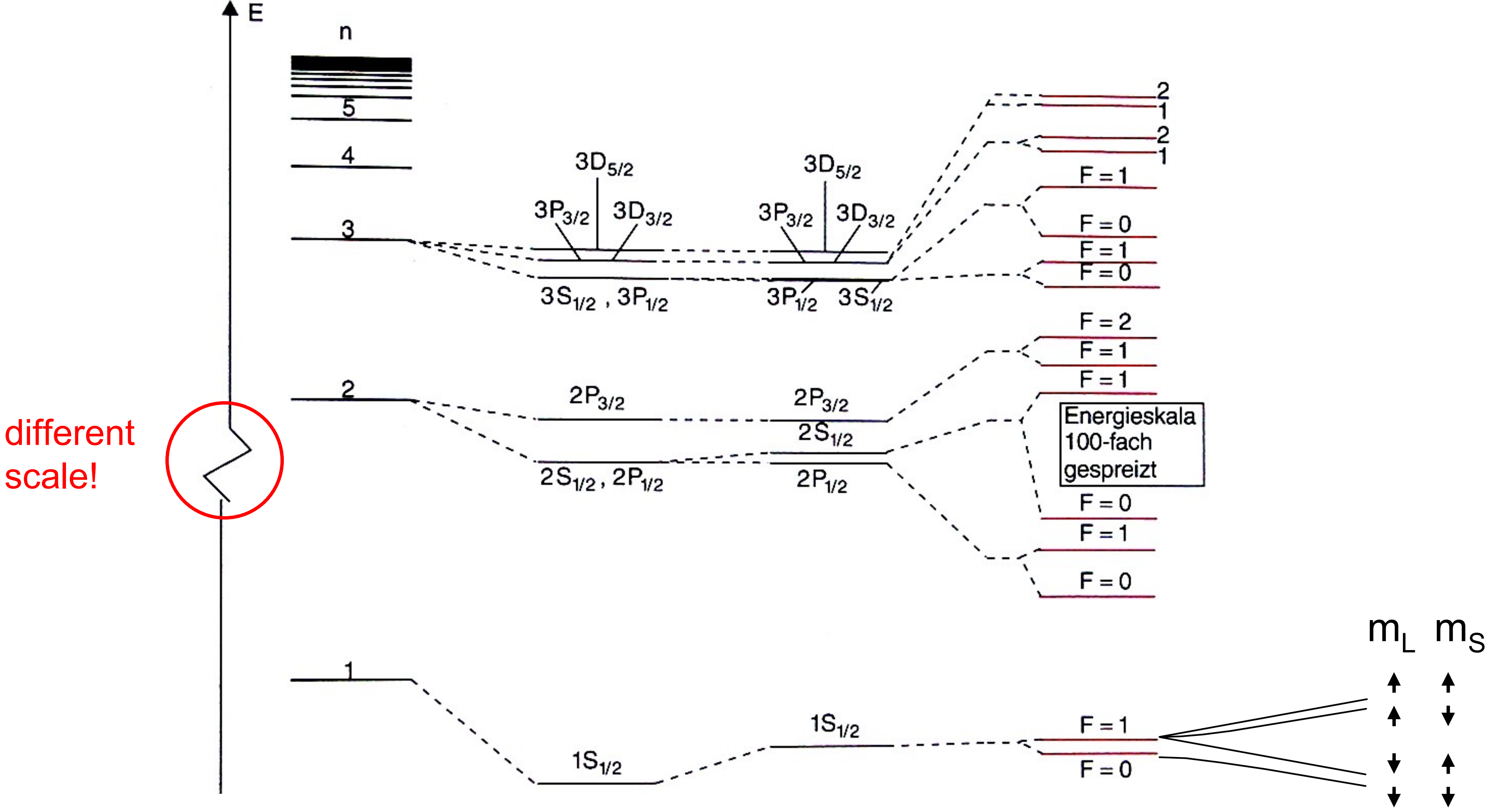
"size"

Lyman series



"energy"

the real structure of hydrogen



different
scale!

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

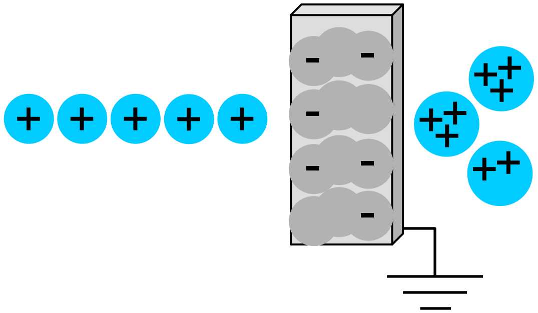
To remove the 92nd electron in uranium,
requires an energy of the order of ~100 keV.
(Z=92 → ~Z^2)

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

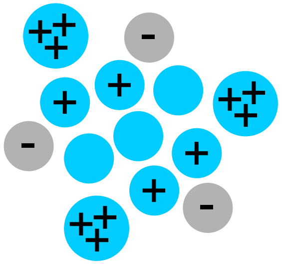
→ Experimentally, photons can't really do the trick,
but fast electrons & ions can!

three methods to create multi-charged ions:

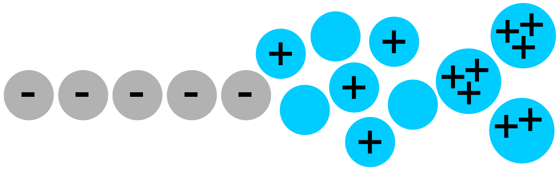
stripper foil



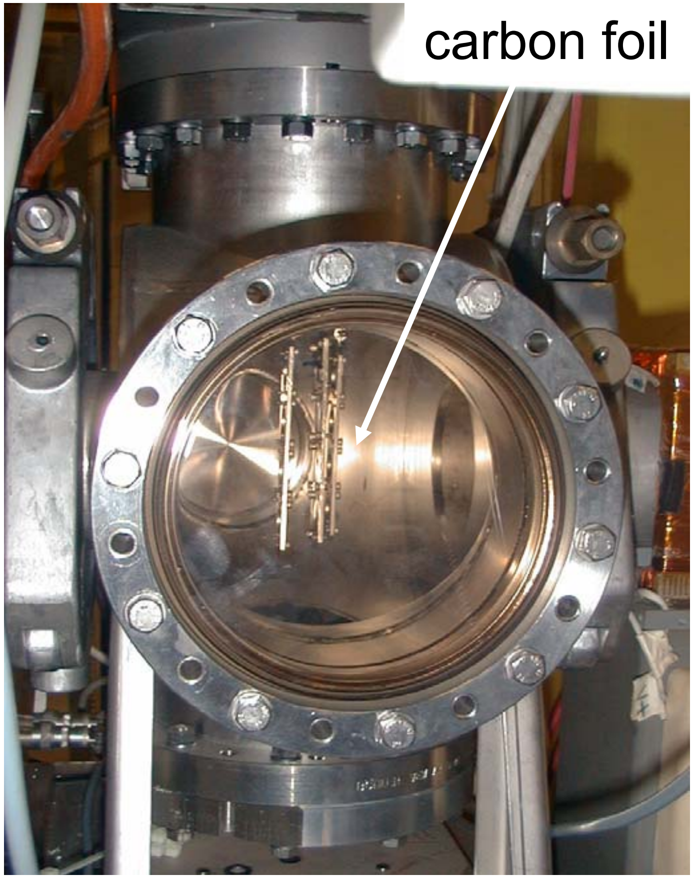
electron cyclotron resonance ion source (**ECRIS**)



electron beam ion source (**EBIS**)



the stripper target

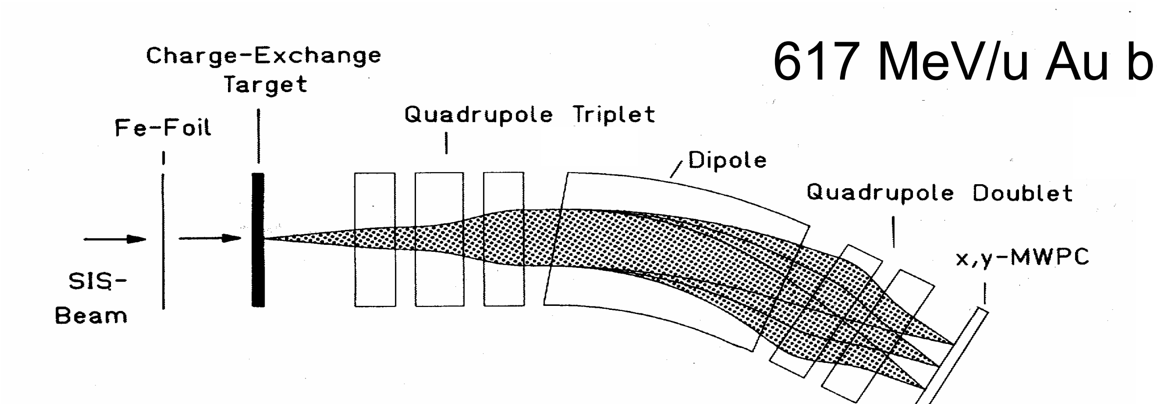


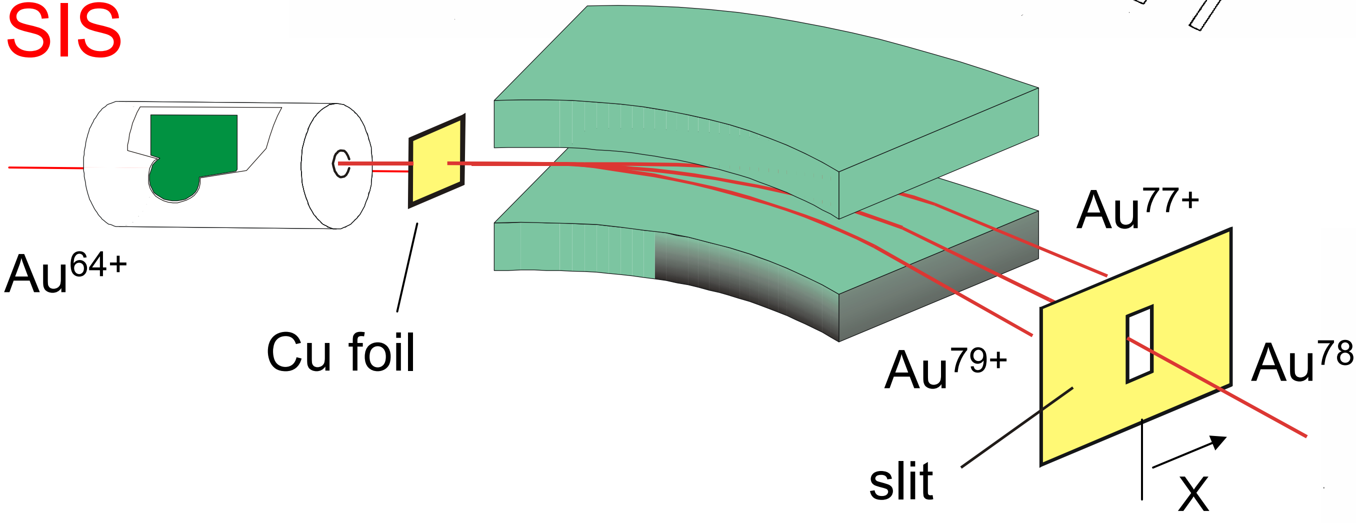
- ☺ simple method and fast
- ☹ needs pre-acceleration
- ☹ emittance growth

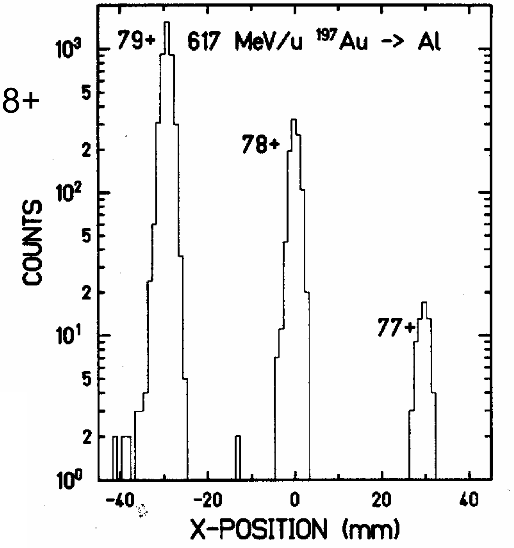
this method yields large numbers of ions in high charge states

charge state distributions

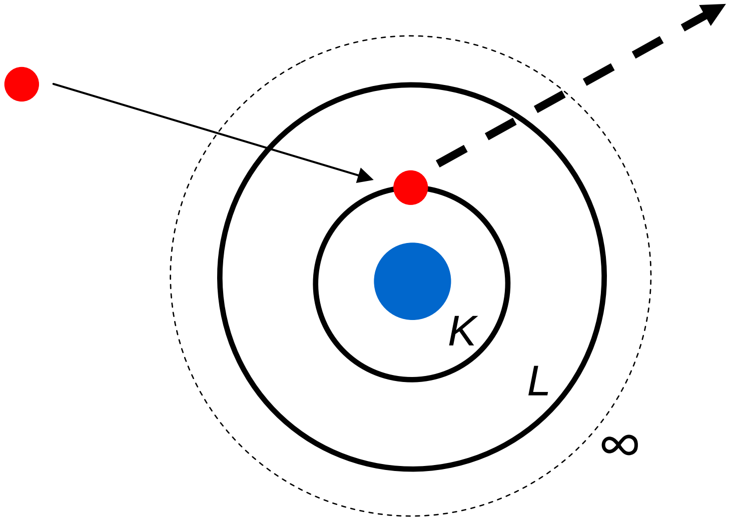
617 MeV/u Au beam







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)

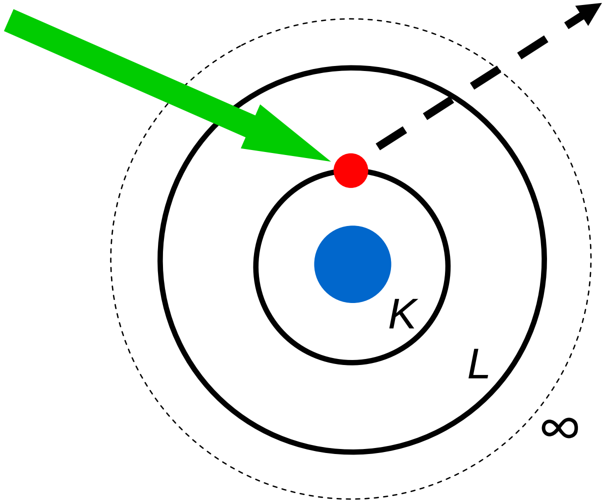
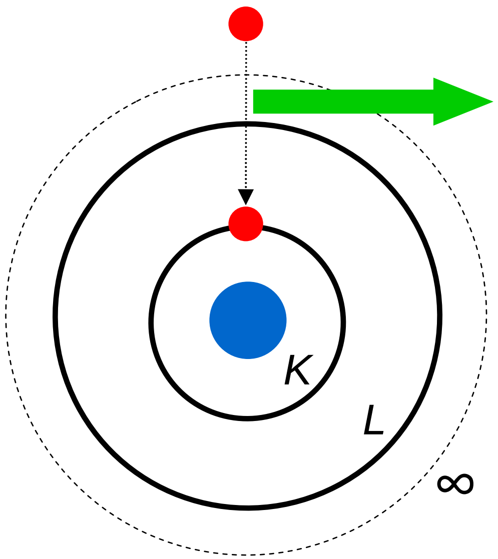


photo ionisation

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

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



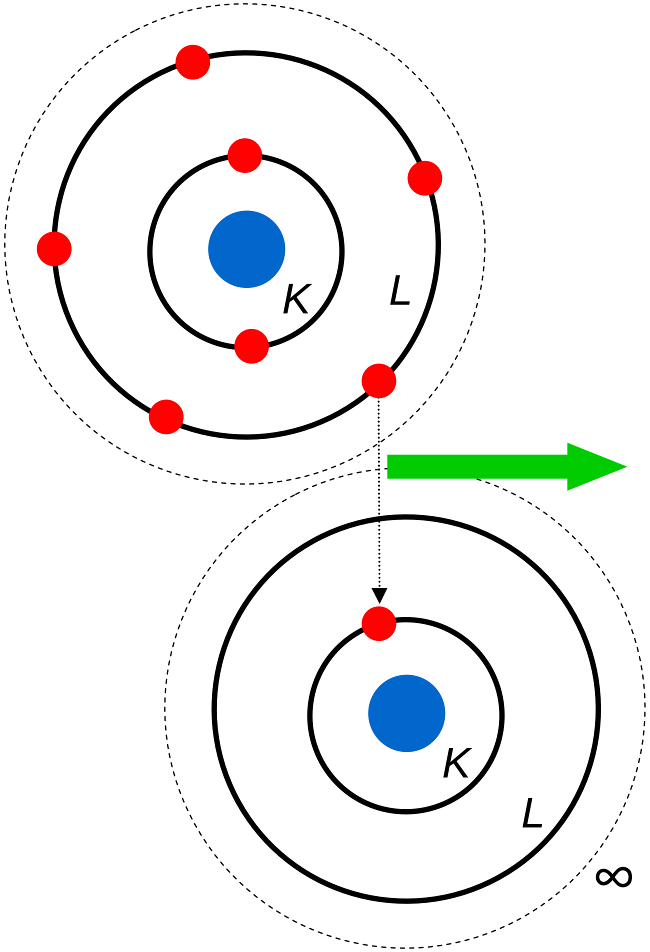
radiative recombination (*RR*)

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

neutralisation !

time-reversed photo ionisation process !

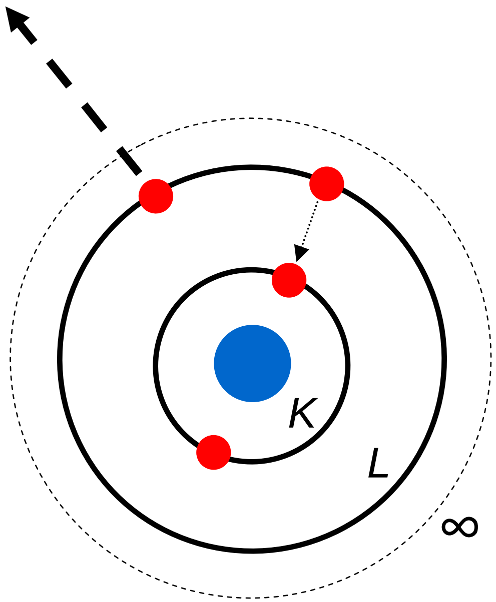
But the captured electron can also be bound to an atom (quasi-free):



radiative electron capture (*REC*)

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

neutralisation !



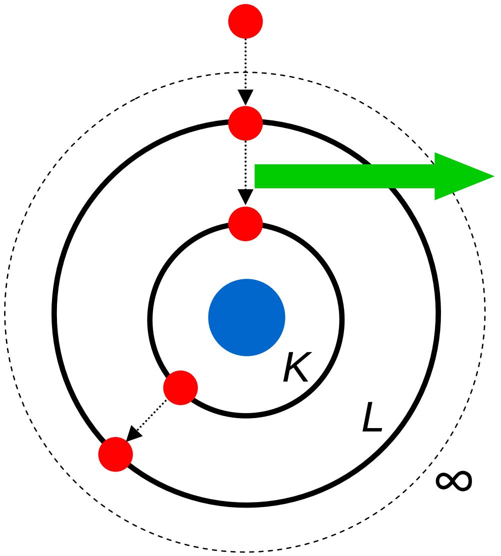
Auger process (*KLL*)

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

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'



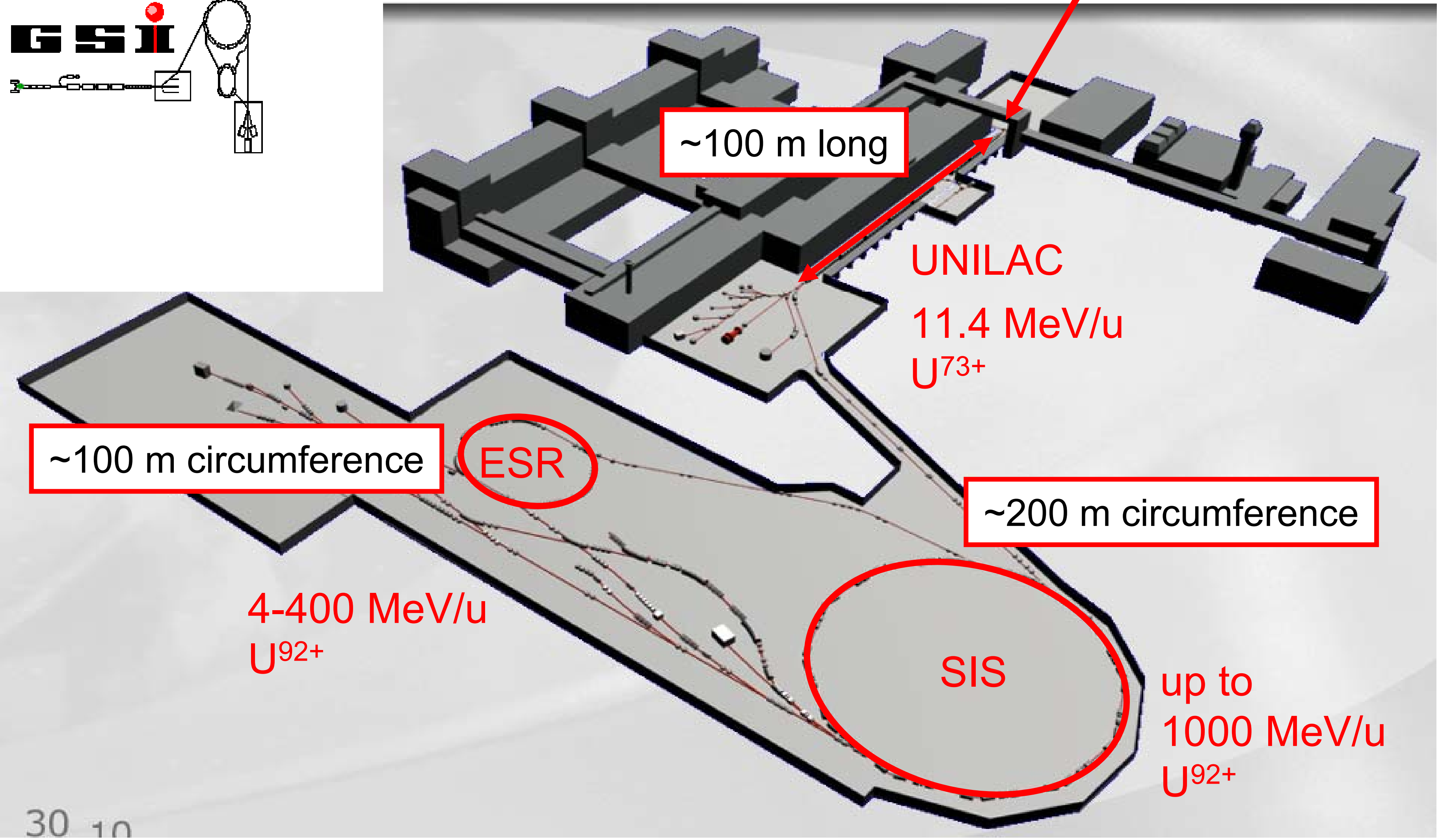
dielectronic recombination (*DR*)

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

neutralisation !

time-reversed Auger process !

the current GSI facility



ion sources

~100 m long

UNILAC

11.4 MeV/u

U^{73+}

~100 m circumference

ESR

~200 m circumference

4-400 MeV/u

U^{92+}

SIS

up to

1000 MeV/u

U^{92+}

pioneers of storing and cooling

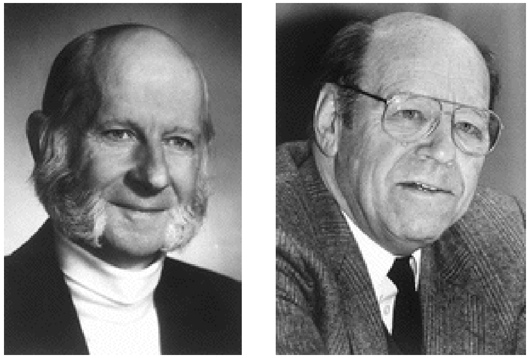
Principle of Penning Traps

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

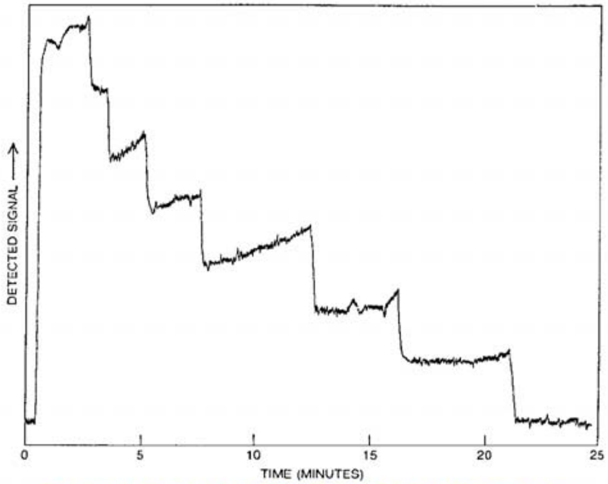
S. Chu C. Cohen-Tannoudji W. D. Phillips

Bose-Einstein Condensation

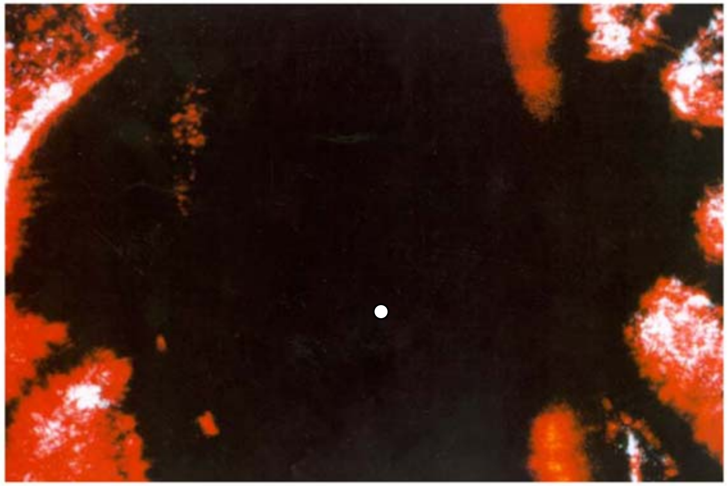
Nobel Prize 2001

E. Cornell W. Ketterle C. Wieman

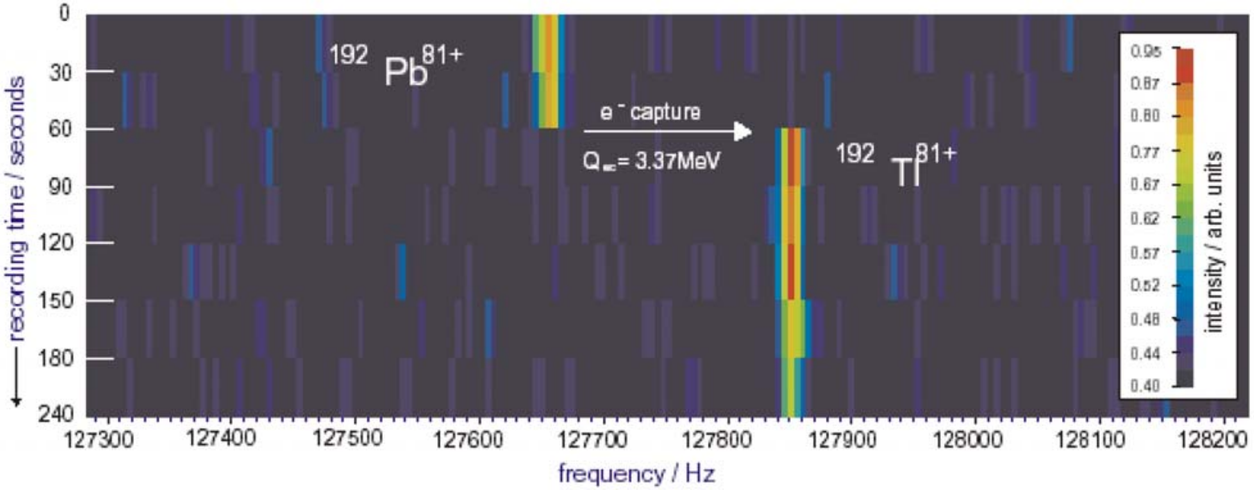
impressive results with confined ions



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.

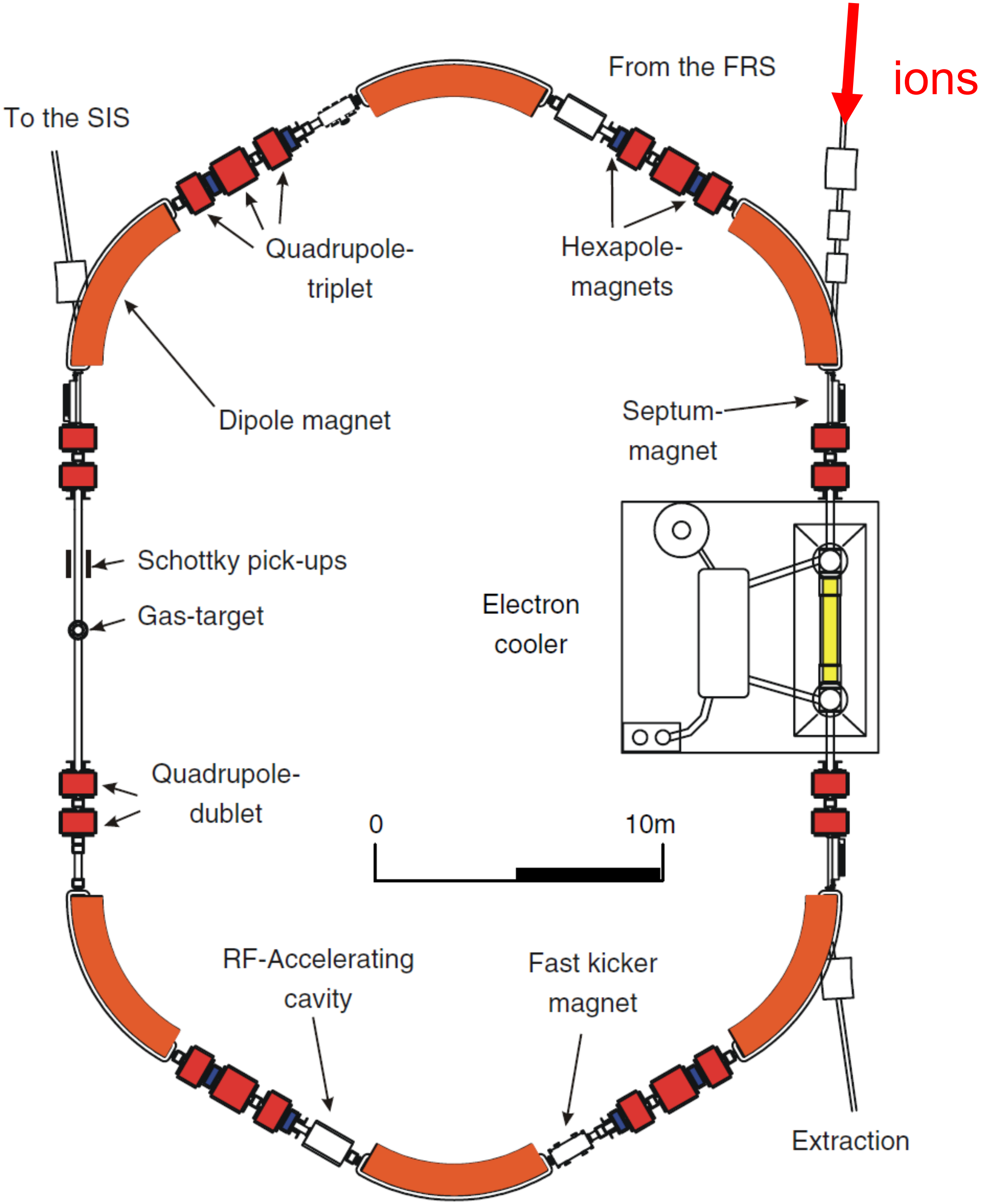


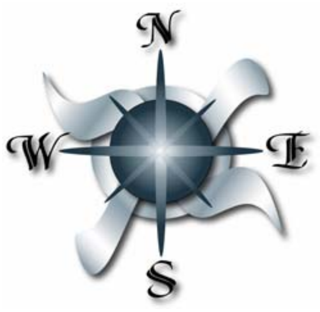
Electron capture in a single Pb ion in the ESR. Bosch *et al.*

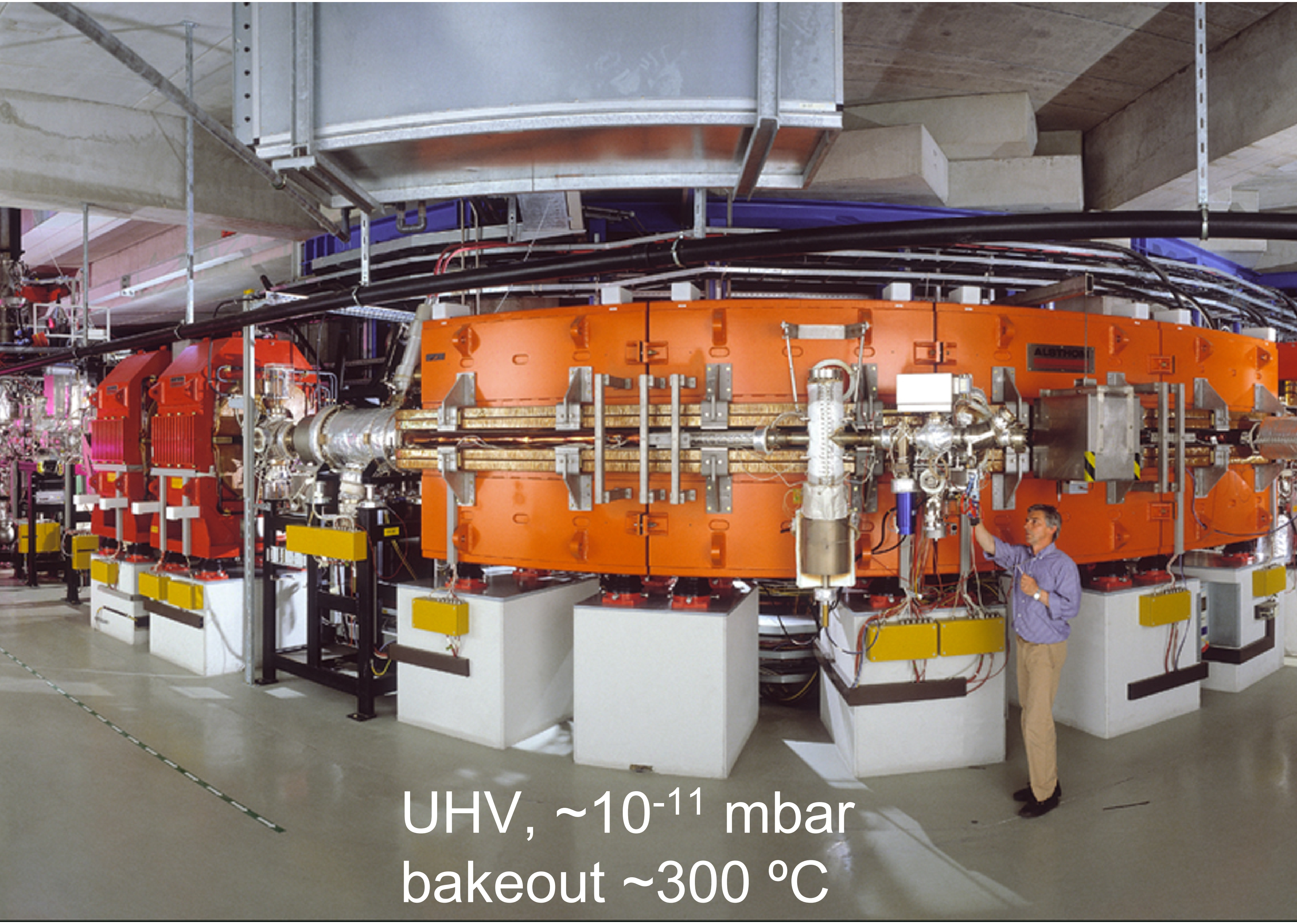
49 In	50 Sn	51 Sb
81 Tl	82 Pb	83 Bi

thallium ← lead

Experimental Storage Ring

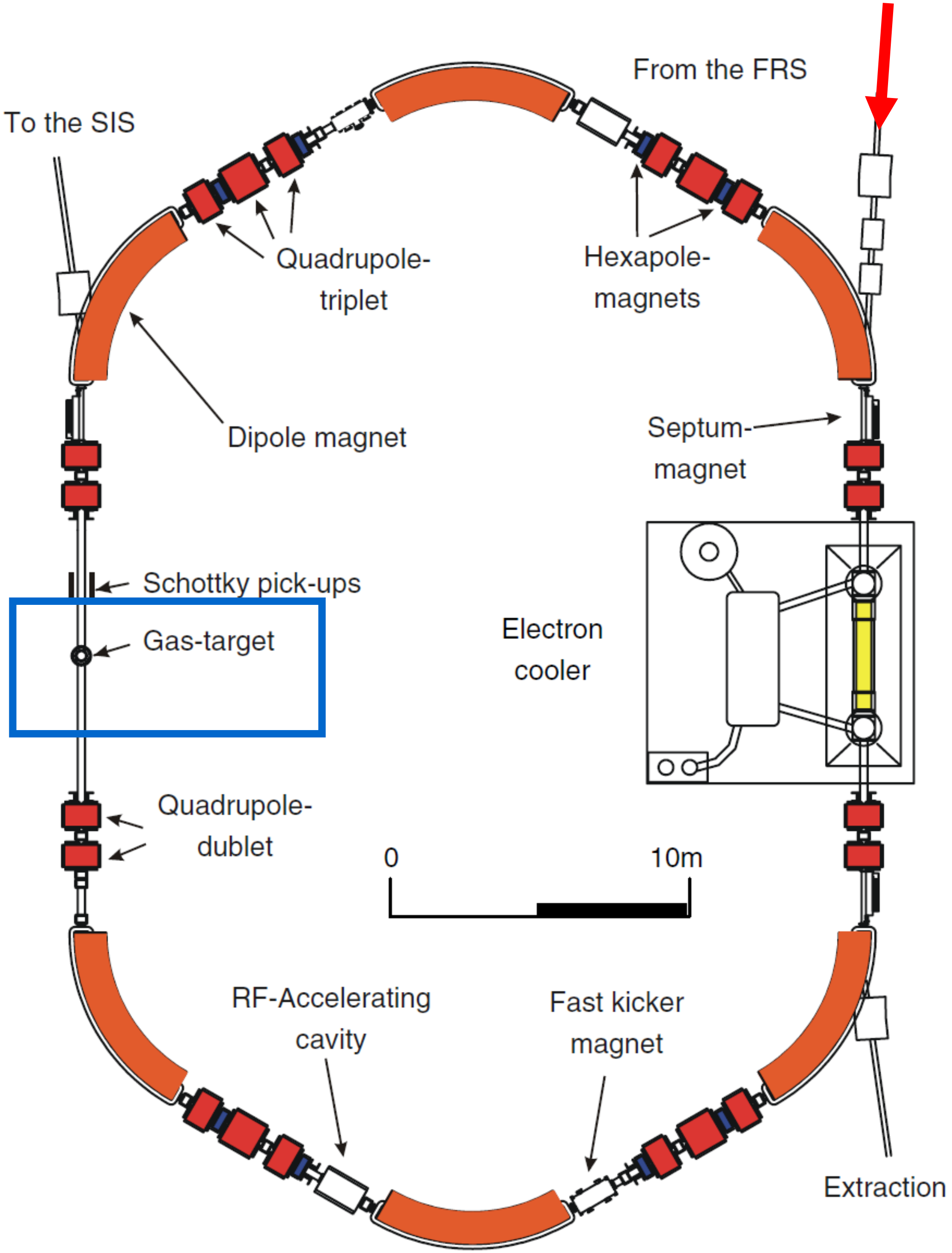




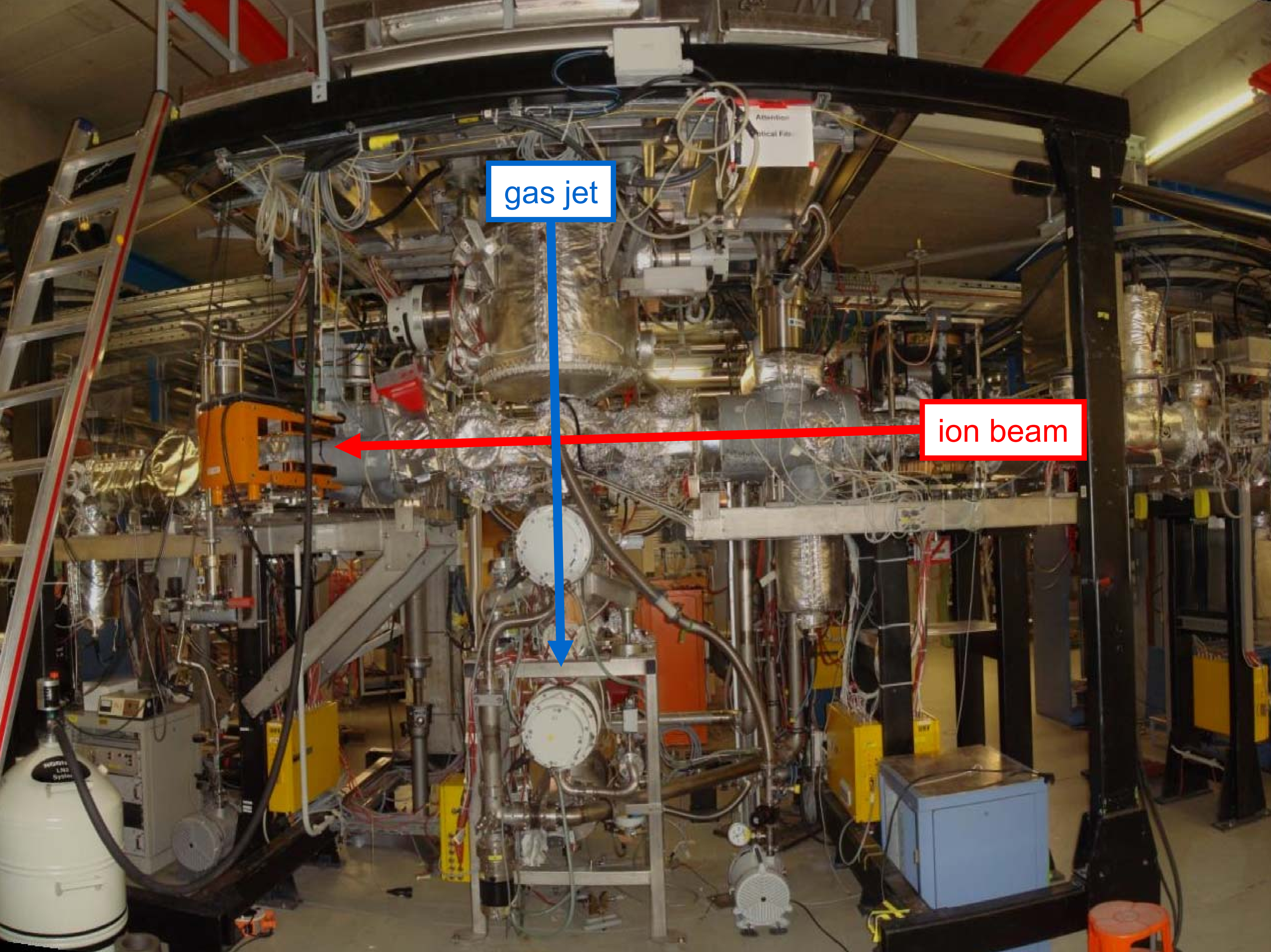


UHV, ~10^{-11} mbar

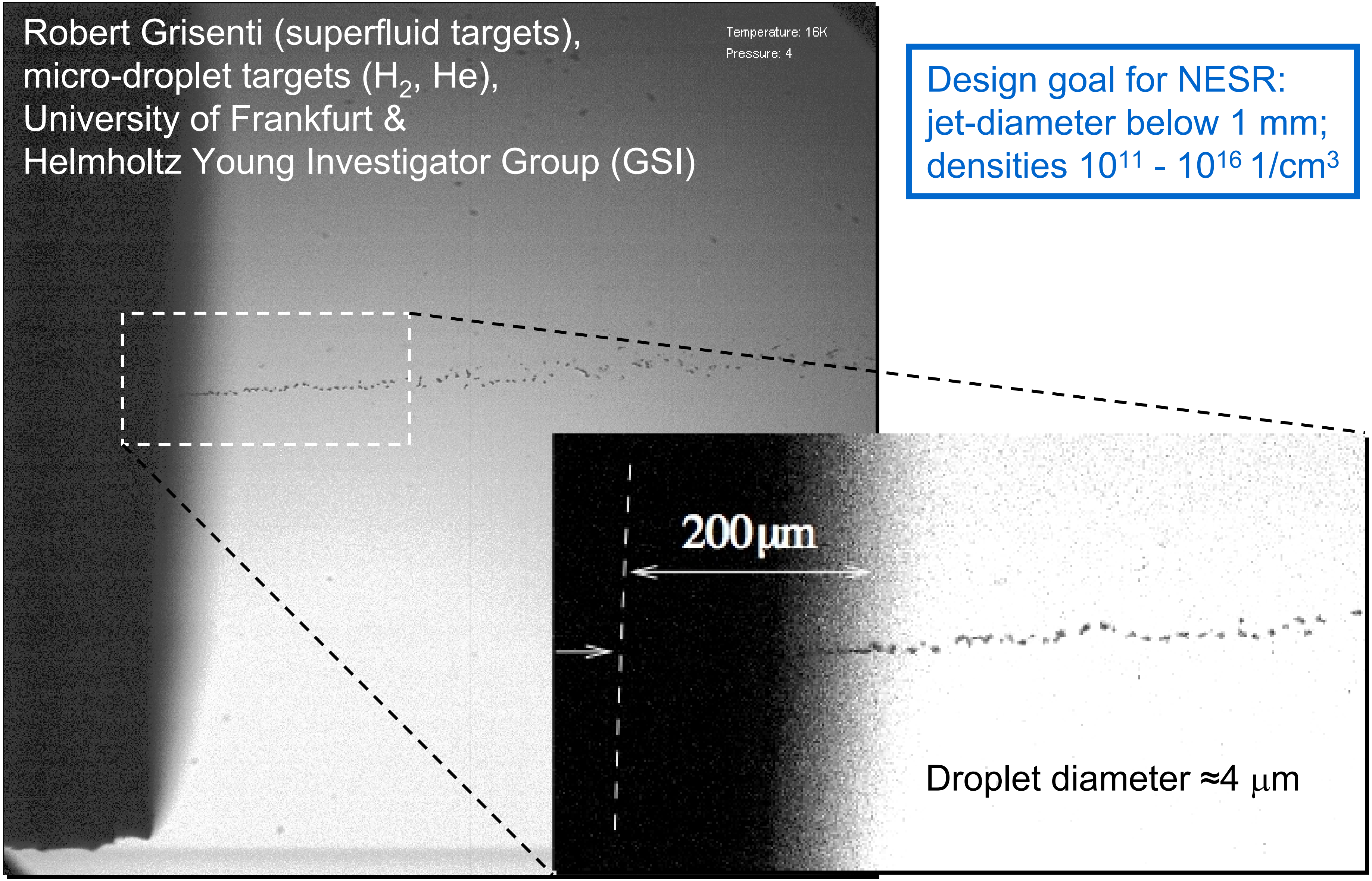
bakeout ~300 ºC



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


gas jet
ion beam
Attention

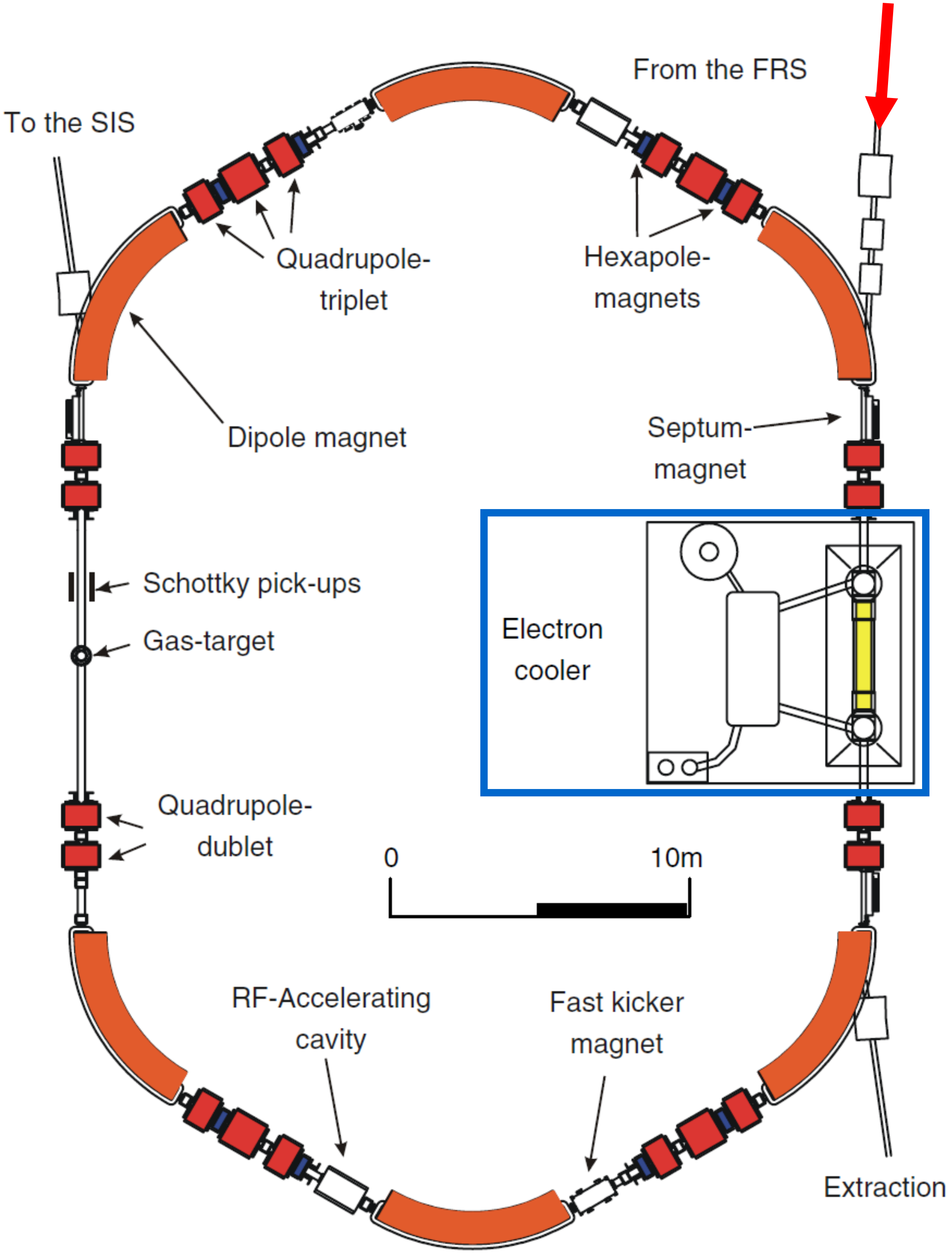
new liquid targets with high densities



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

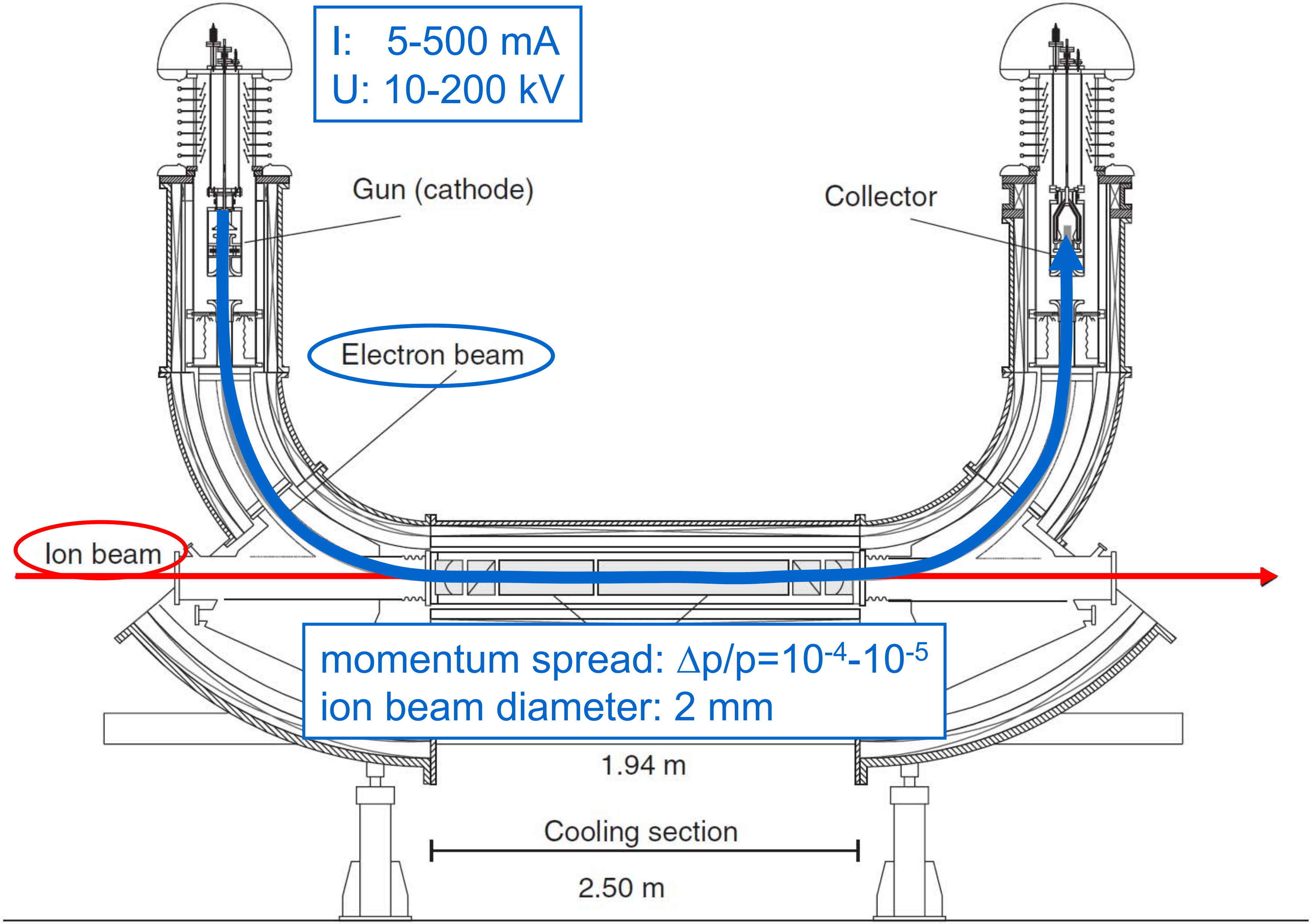
Design goal for NESR:
jet-diameter below 1 mm;
densities 10^{11} - 10^{16} 1/cm^3

Droplet diameter ≈4 µm



the electron cooler

the electron cooler at the ESR

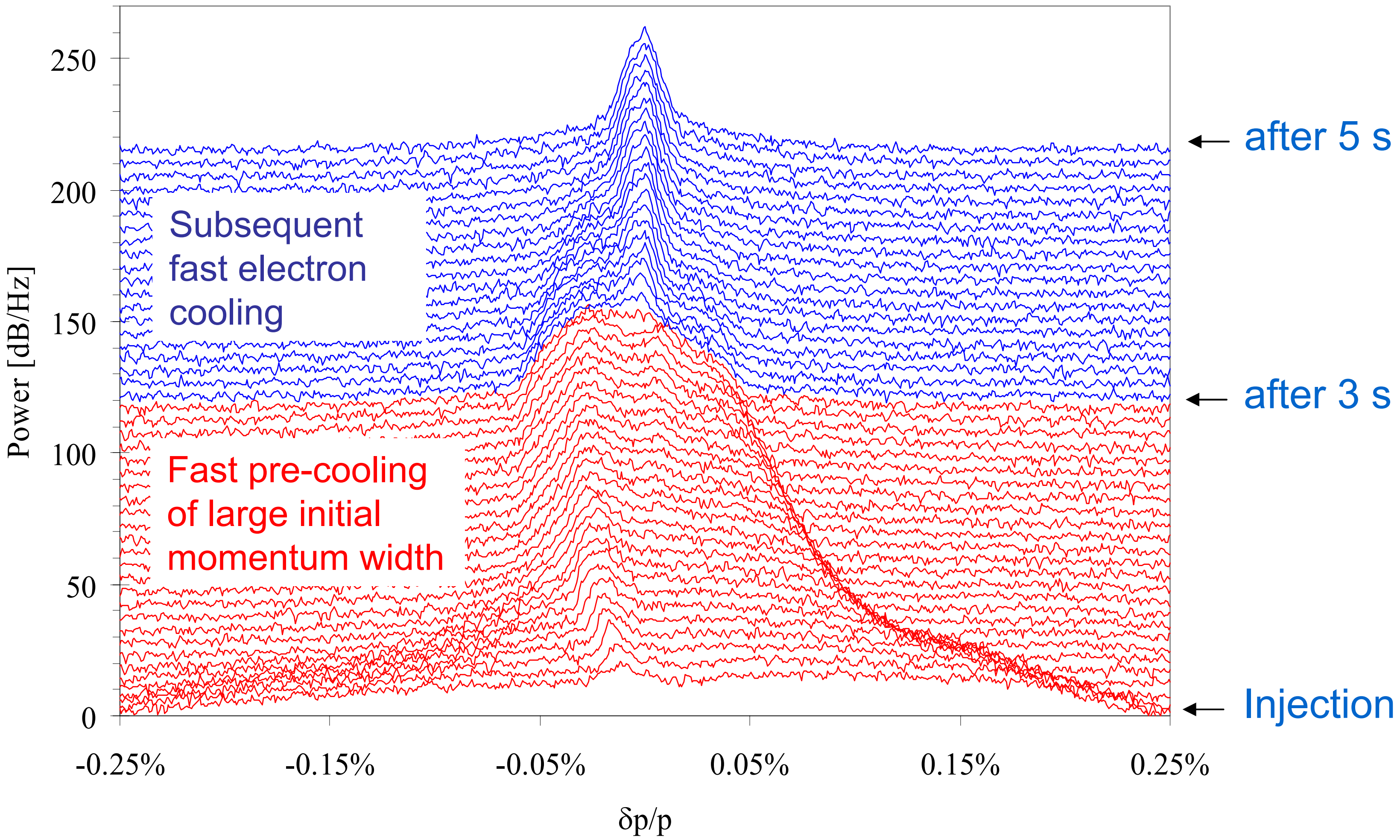


I: 5-500 mA
U: 10-200 kV

momentum spread: $\Delta p/p=10^{-4}-10^{-5}$
ion beam diameter: 2 mm

cooling: narrowing velocity, size and divergence

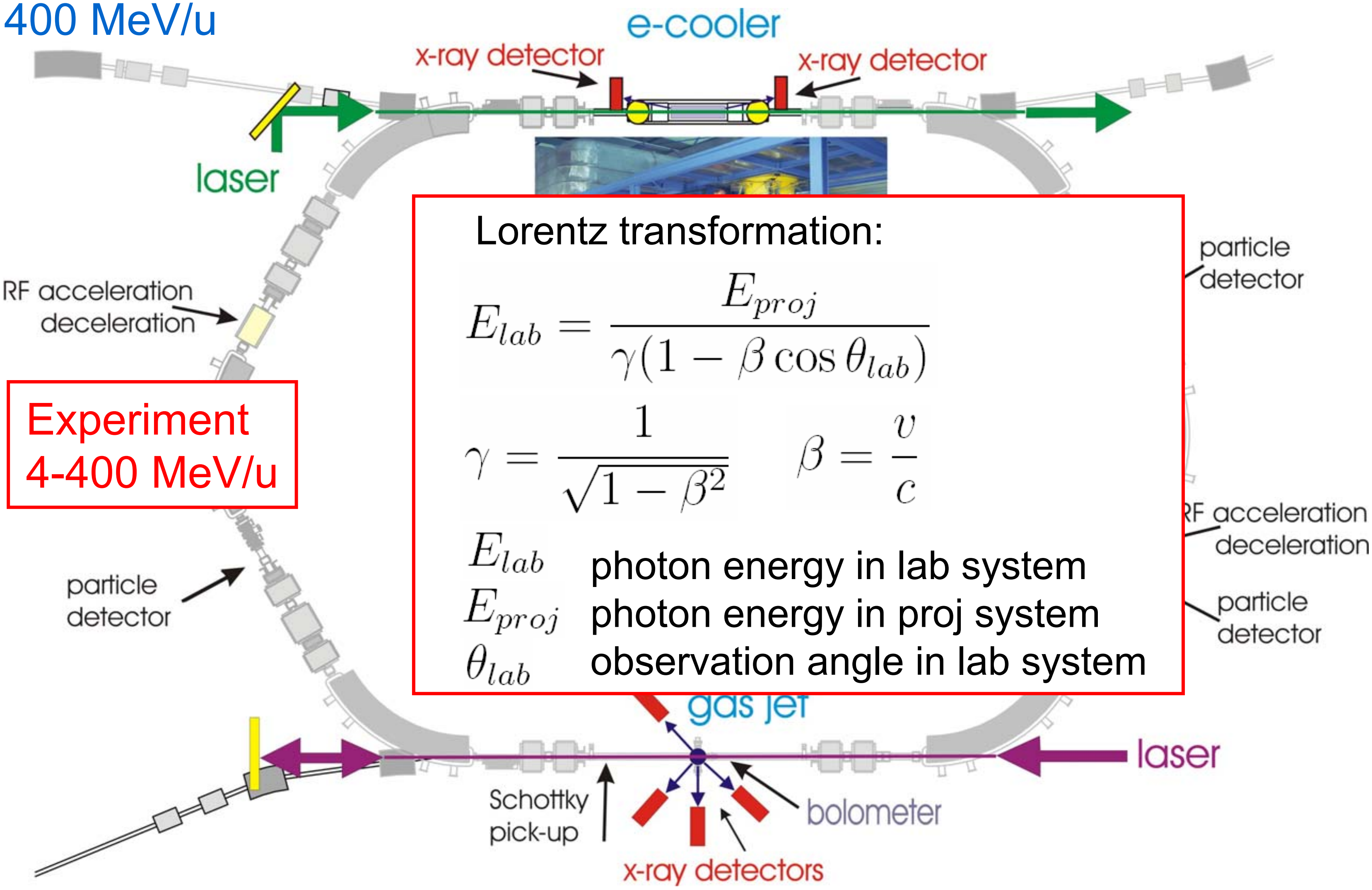
Primary uranium beam



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:

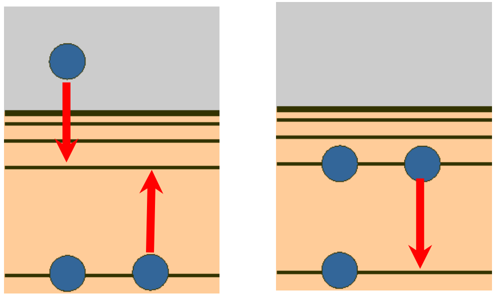
Dielectronic recombination (DR)

Mass spectrometry

Laser spectroscopy and laser cooling

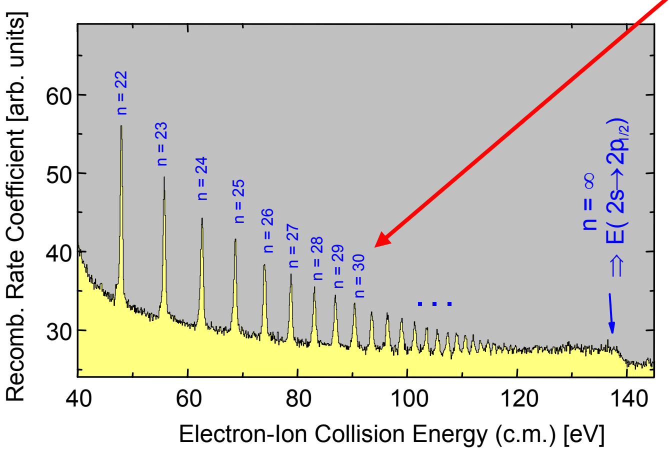
X-ray spectroscopy

Electron target → Dielectronic recombination



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

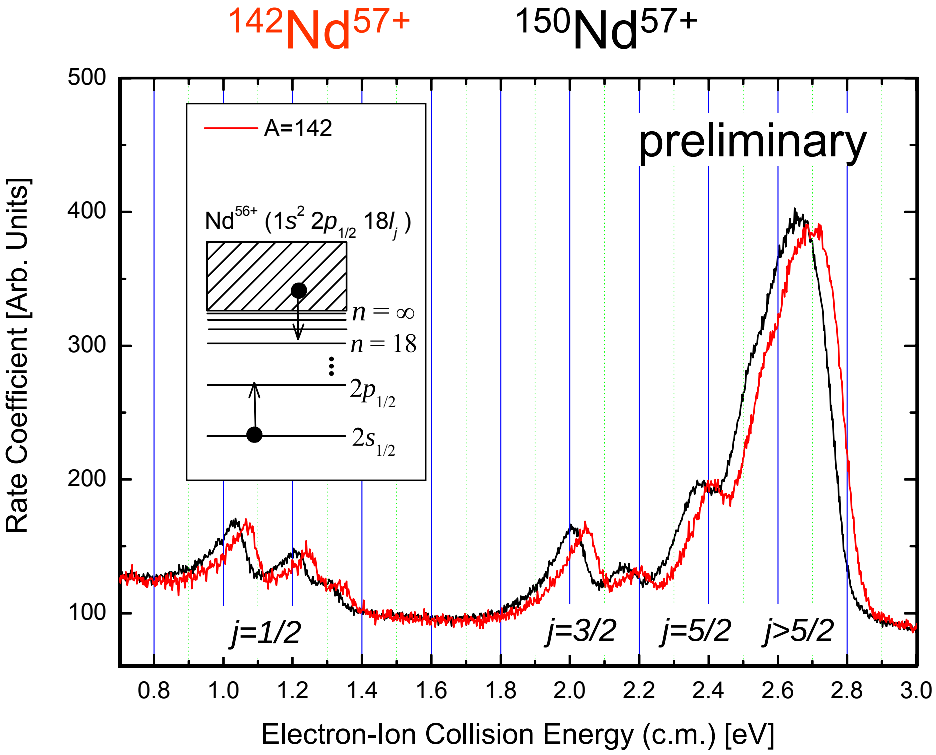
$e + Nd^{57+}(1s^2 2s_{1/2}) \rightarrow Nd^{56+}(1s^2 2s_{1/2} nl_j)$



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:

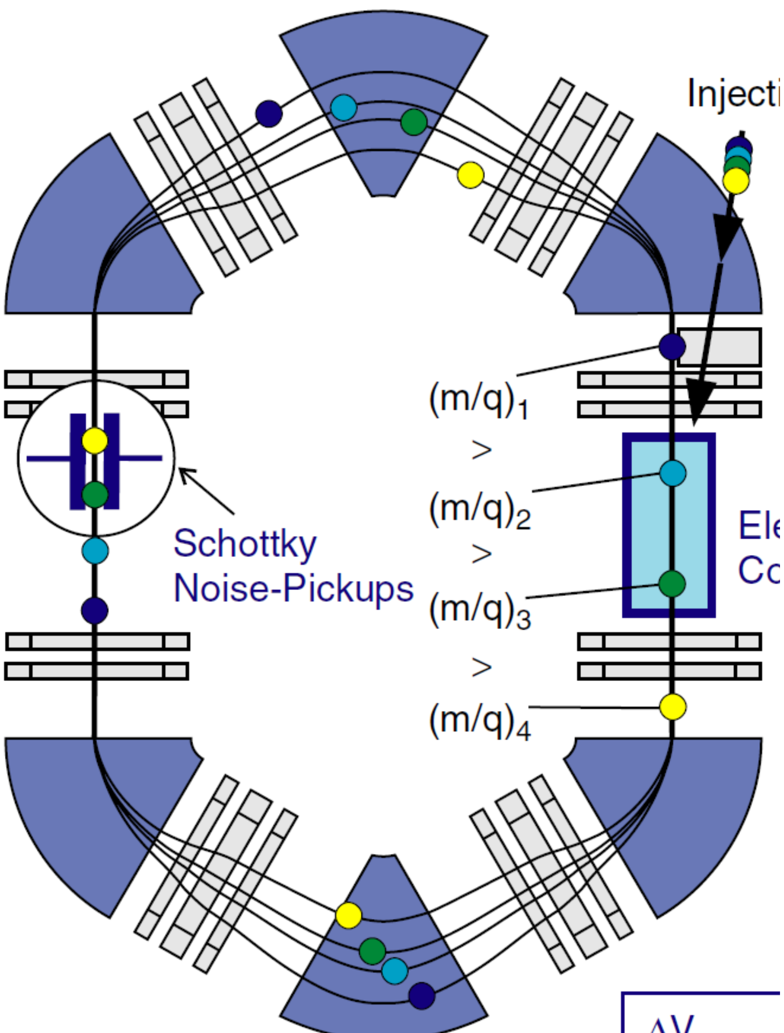
Dielectronic recombination (DR)

Mass spectrometry

Laser spectroscopy and laser cooling

X-ray spectroscopy

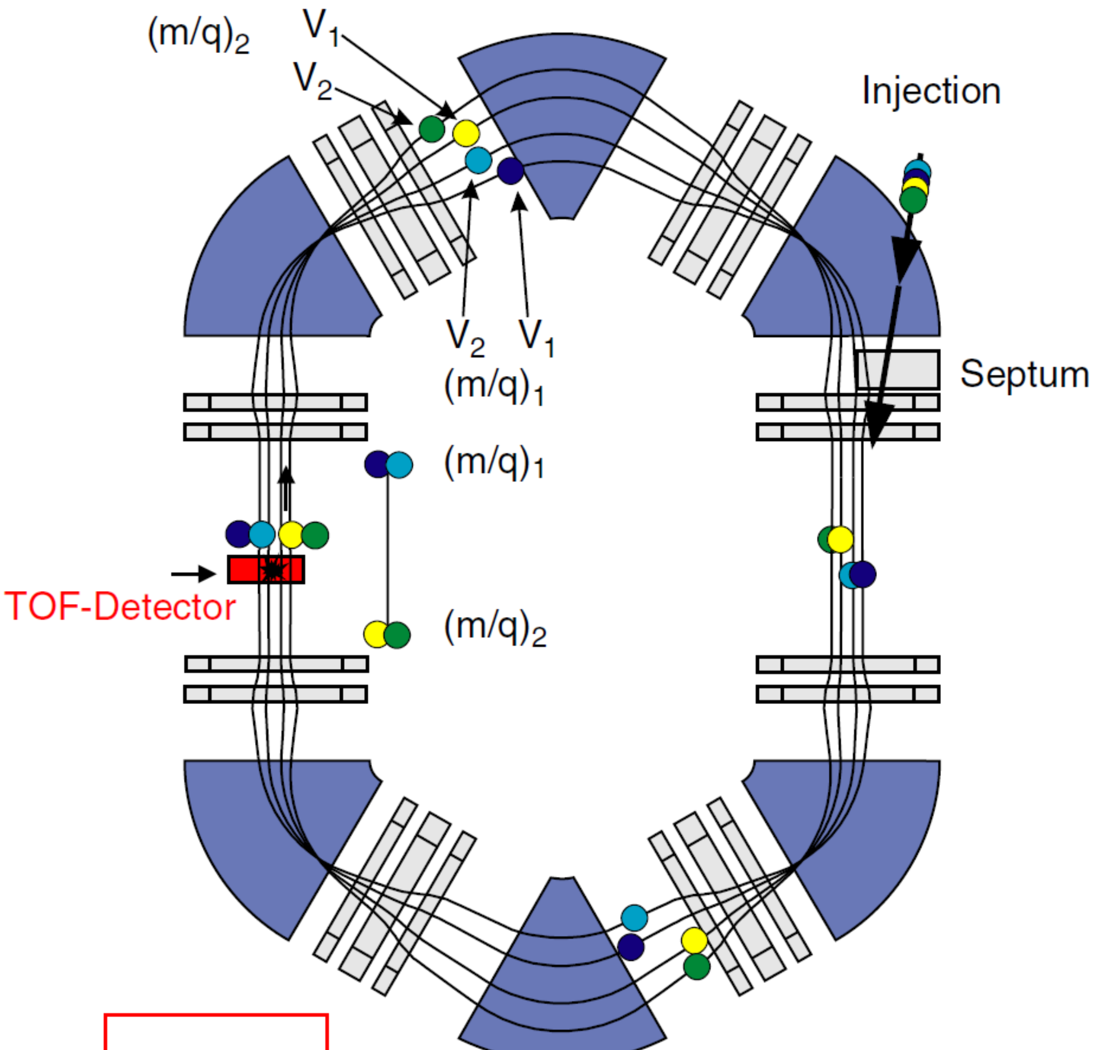
SCHOTTKY MASS SPECTROMETRY



Cooled Fragments

$\frac{\Delta V}{V} \rightarrow$

ISOCHRONOUS MASS SPECTROMETRY



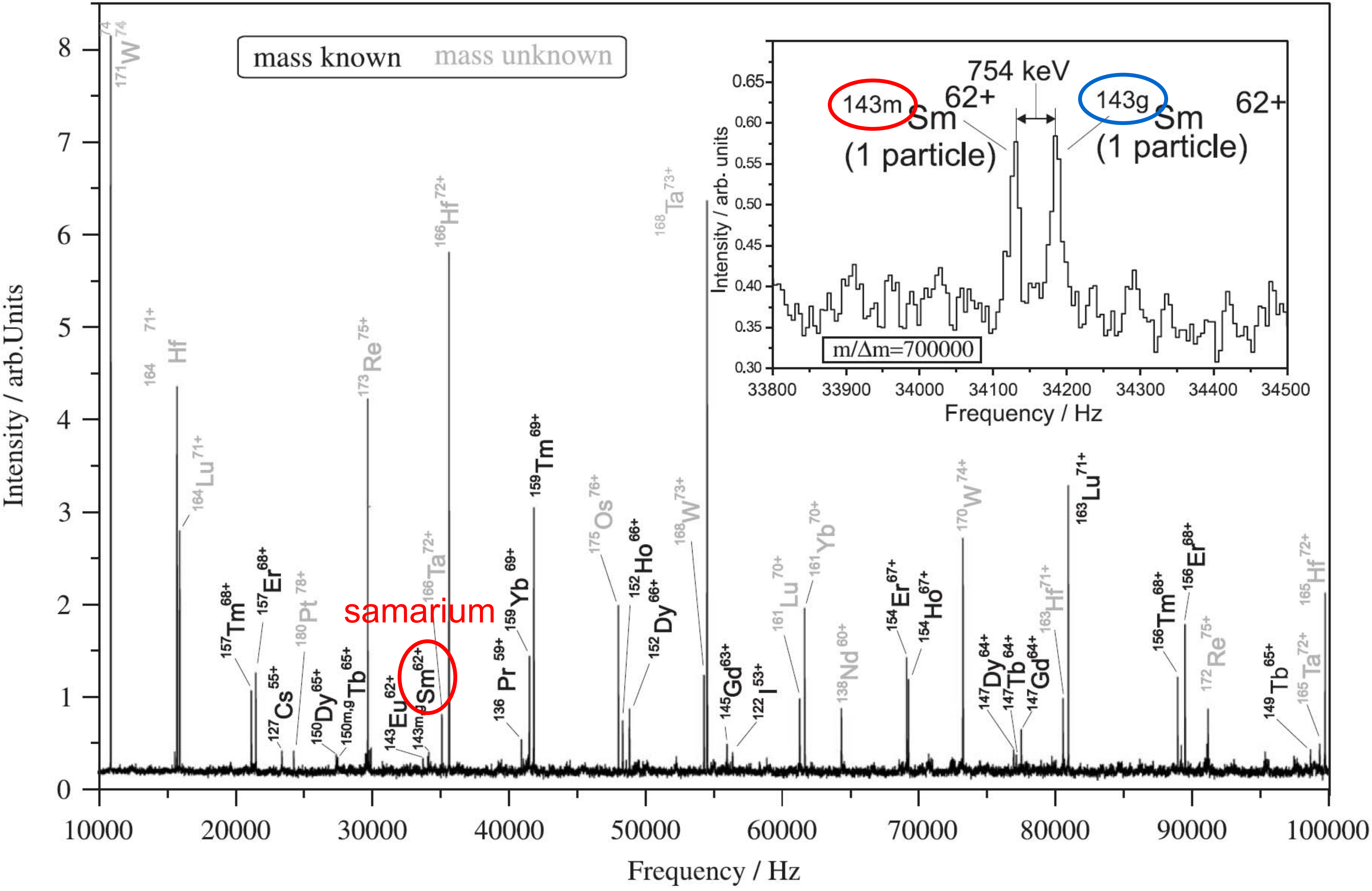
Hot Fragments

$\gamma_t \rightarrow \gamma$

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:

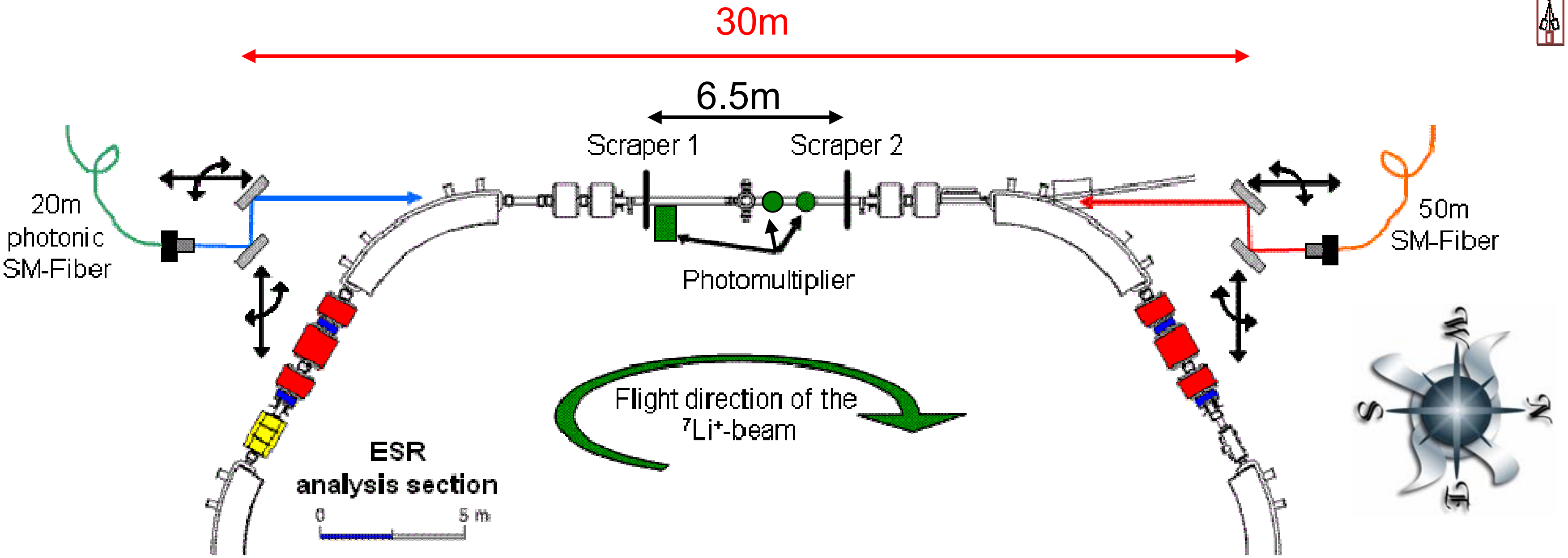
Dielectronic recombination (DR)

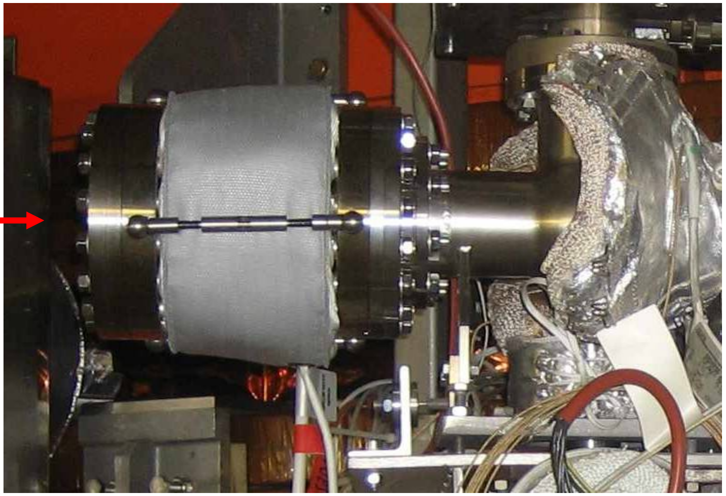
Mass spectrometry

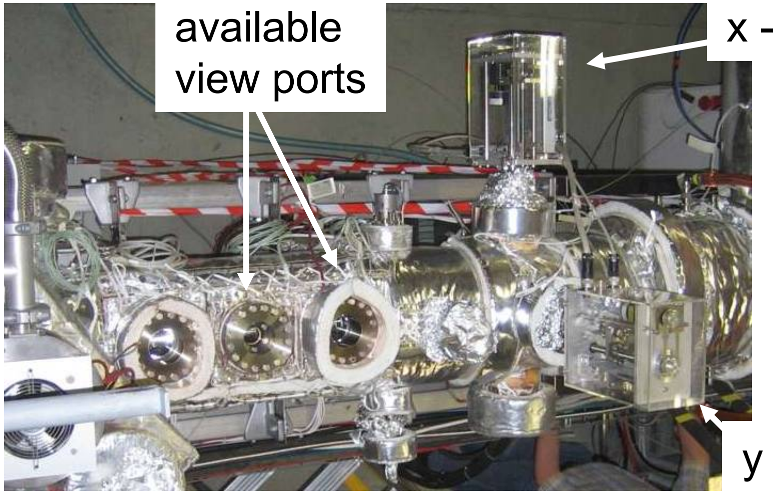
Laser spectroscopy and laser cooling

X-ray spectroscopy

lasers at the ESR





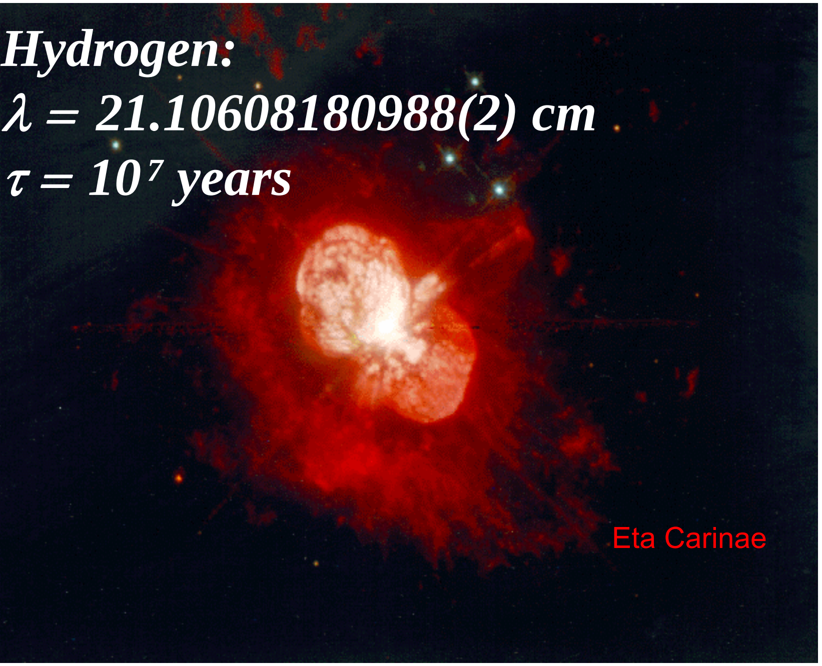


Measurement of the ground state HFS in $^{209}Bi^{80+}$

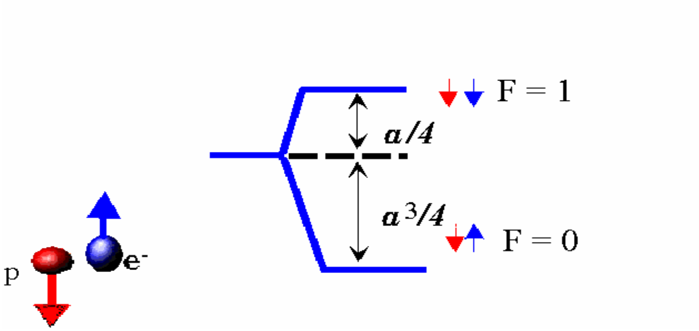
M. Lochmann, R. Sanchez, C. Geppert, W. Nörtershäuser...
Th. Kühl, D. Winters, Th. Stöhlker...
Ch. Weinheimer, V. Hannen, R. Jöhren,...
G. Birkl, Th. Walther...

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
FZD Forschungszentrum Dresden Rossendorf
TECHNISCHE UNIVERSITÄT DARMSTADT
Westfälische Wilhelms-Universität Münster
RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG PHYSIKALISCHES INSTITUT

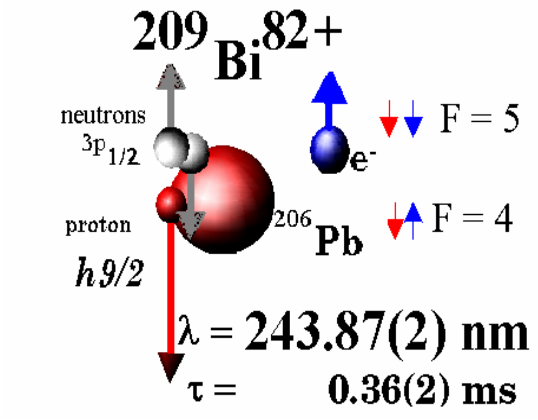
GS hyperfine structure in highly-charged ions



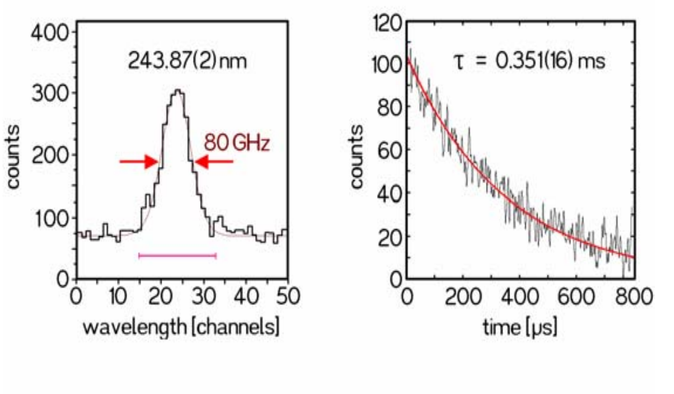
Hydrogen:
$\lambda = 21.10608180988(2)$ cm
$\tau = 10^7$ years



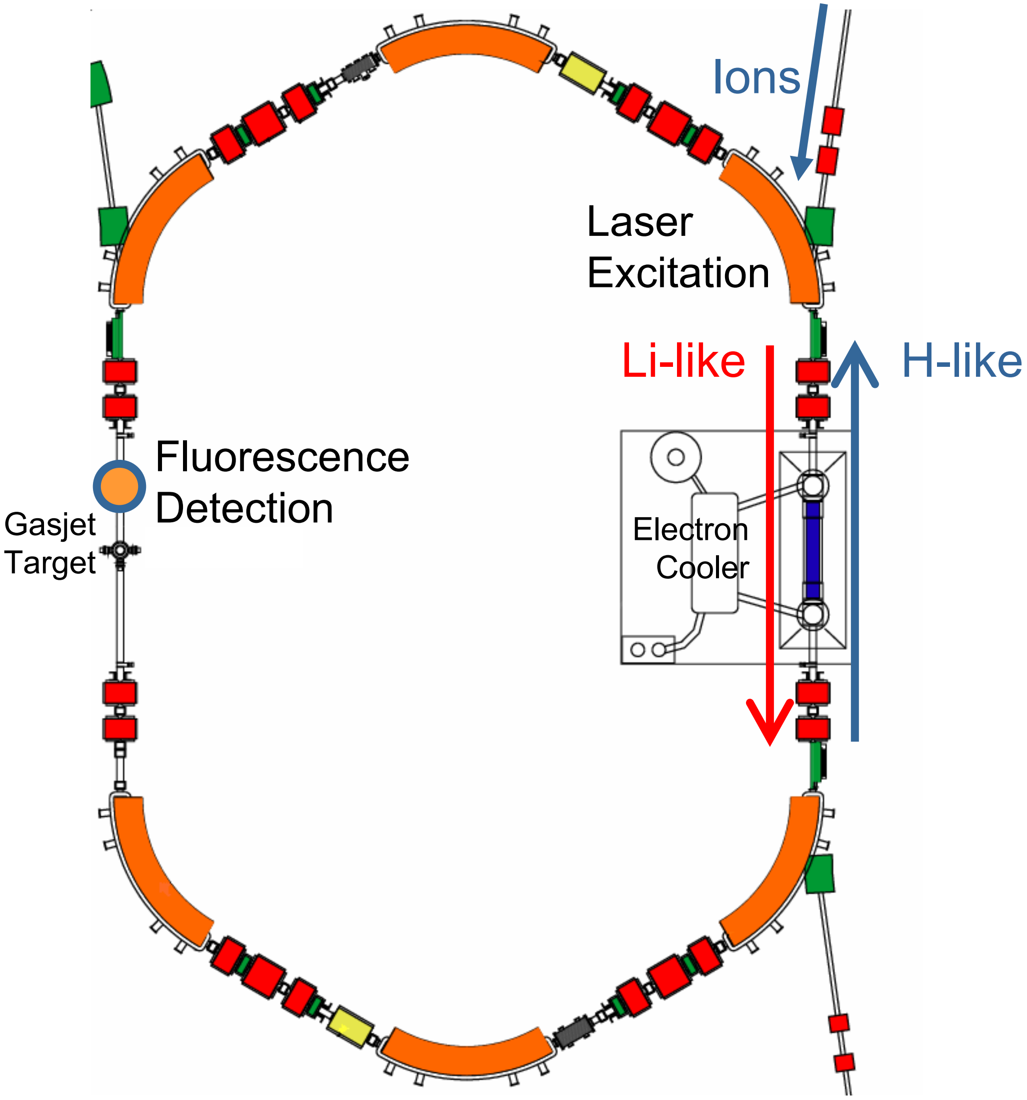
J=1/2 & I=1/2, → F=0,1



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)

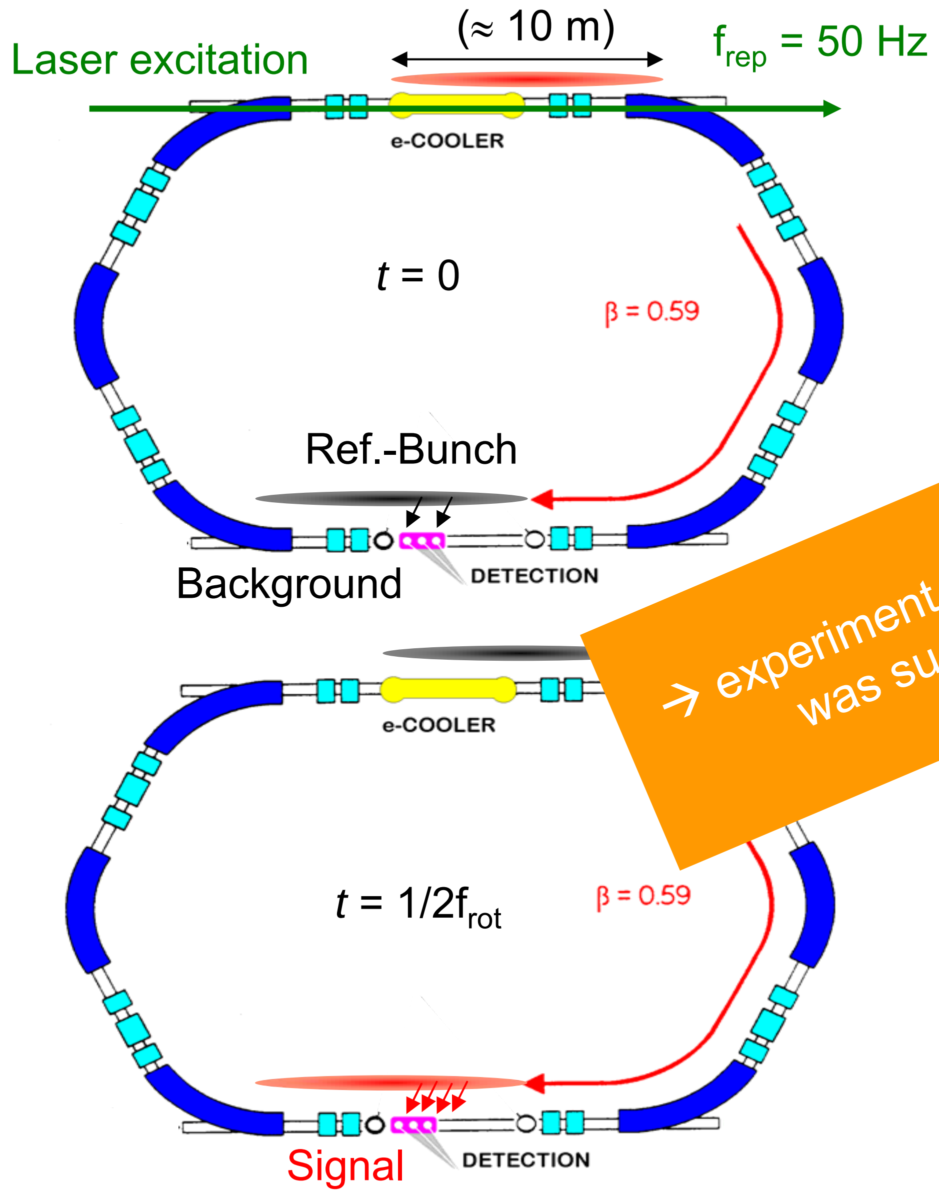
J=1/2 and I=9/2 give F=4,5

F=4 → F=5 transition

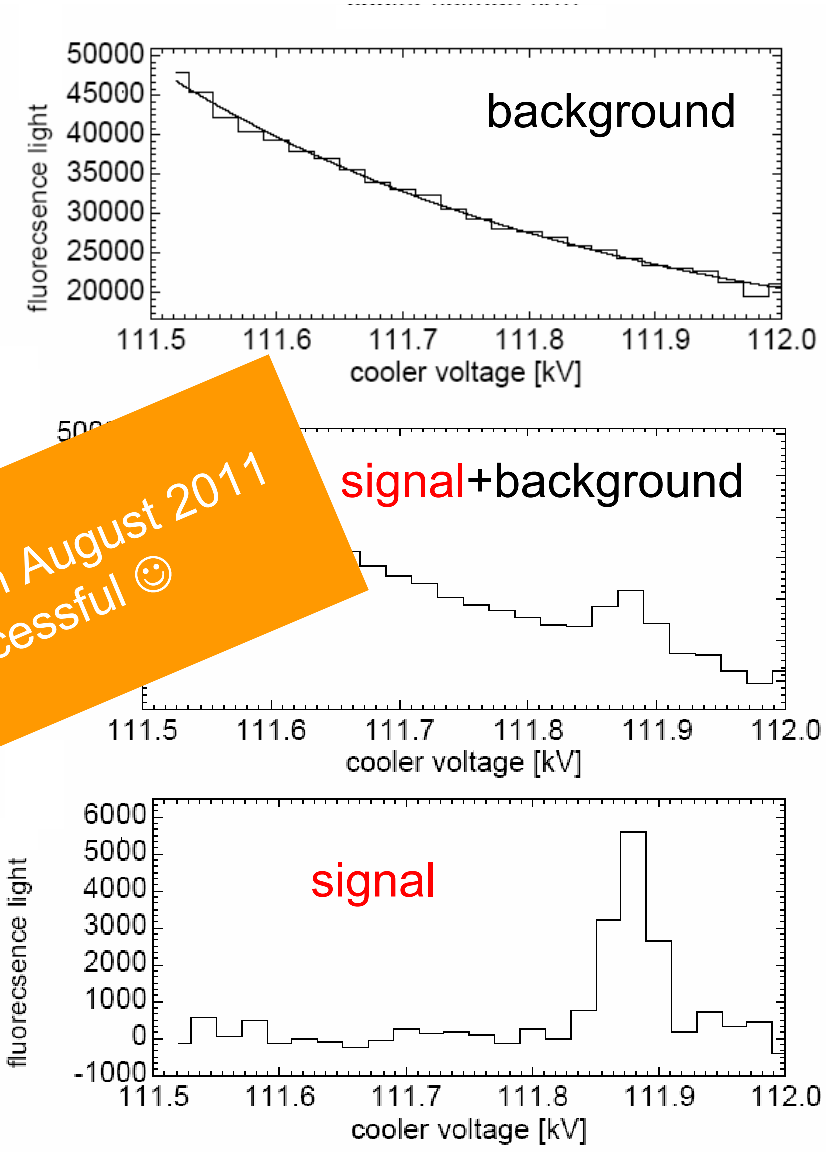
Especially the Li-like transition is of great interest, since there is quite some debate about its value.

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



→ experiment in August 2011 was successful ☺



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

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

(a modern Ives & Stilwell experiment)

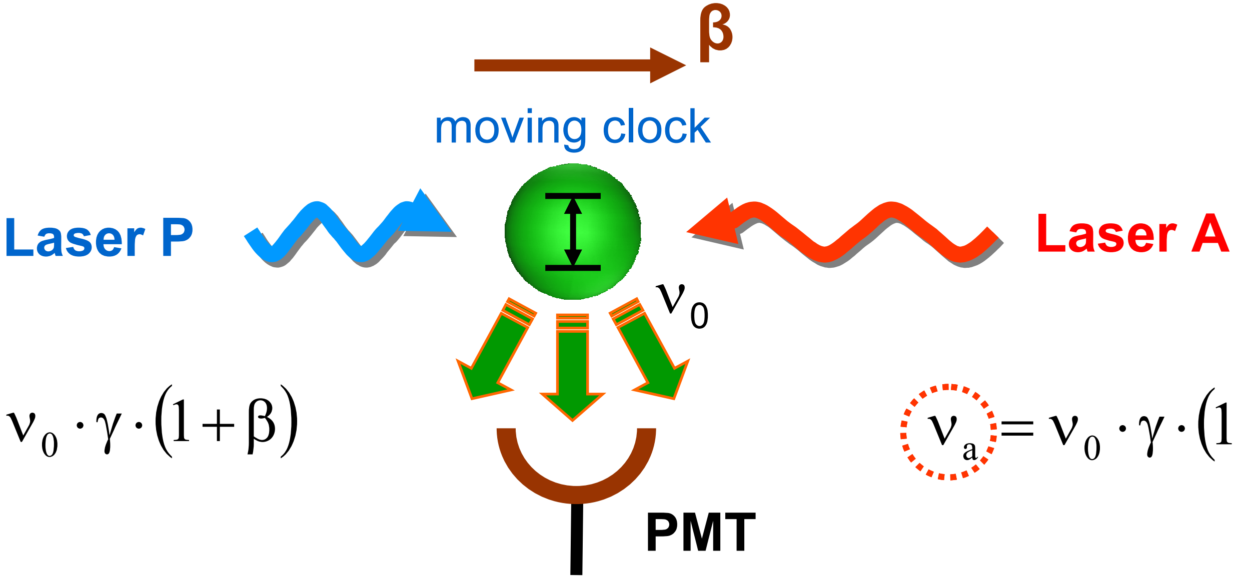
C. Novotny, S. Reinhardt, G. Saathoff, S. Karpuk...
B. Botermann, W. Nörtershäuser, C. Geppert...
Th. Kühl, Th. Stöhlker...

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Max–Planck–Institut für Kernphysik

RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG
PHYSIKALISCHES INSTITUT

Testing Lorentz transformation via optical frequency measurements



$$\boxed{\nu_p} = \nu_0 \cdot \gamma \cdot (1 + \beta)$$

$$\boxed{\nu_a} = \nu_0 \cdot \gamma \cdot (1 - \beta)$$

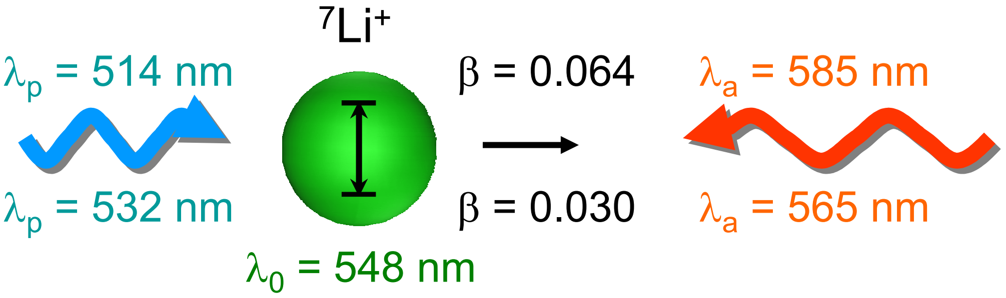
Testing Time Dilation via three optical frequencies
(Doppler-free laser saturation spectroscopy)

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

experiments at the TSR

measured at the TSR

Max-Planck-Institut
für Kernphysik



$^7\mathrm{Li}^+$

λ_p = 514 nm

λ_p = 532 nm

β = 0.064

β = 0.030

λ_a = 585 nm

λ_a = 565 nm

λ_0 = 548 nm

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

$$\left.\begin{aligned} \nu_0 &= 546\,466\,918\,790 \pm 400\ \mathrm{kHz} \\ \nu_p &= 582\,490\,603\,430 \pm 3\ \mathrm{kHz} \\ \nu_a &= 512\,671\,028\,075 \pm 73\ \mathrm{kHz} \end{aligned}\right\}$$

the error in the rest frequency dominates

➔ measurement at two different velocities

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

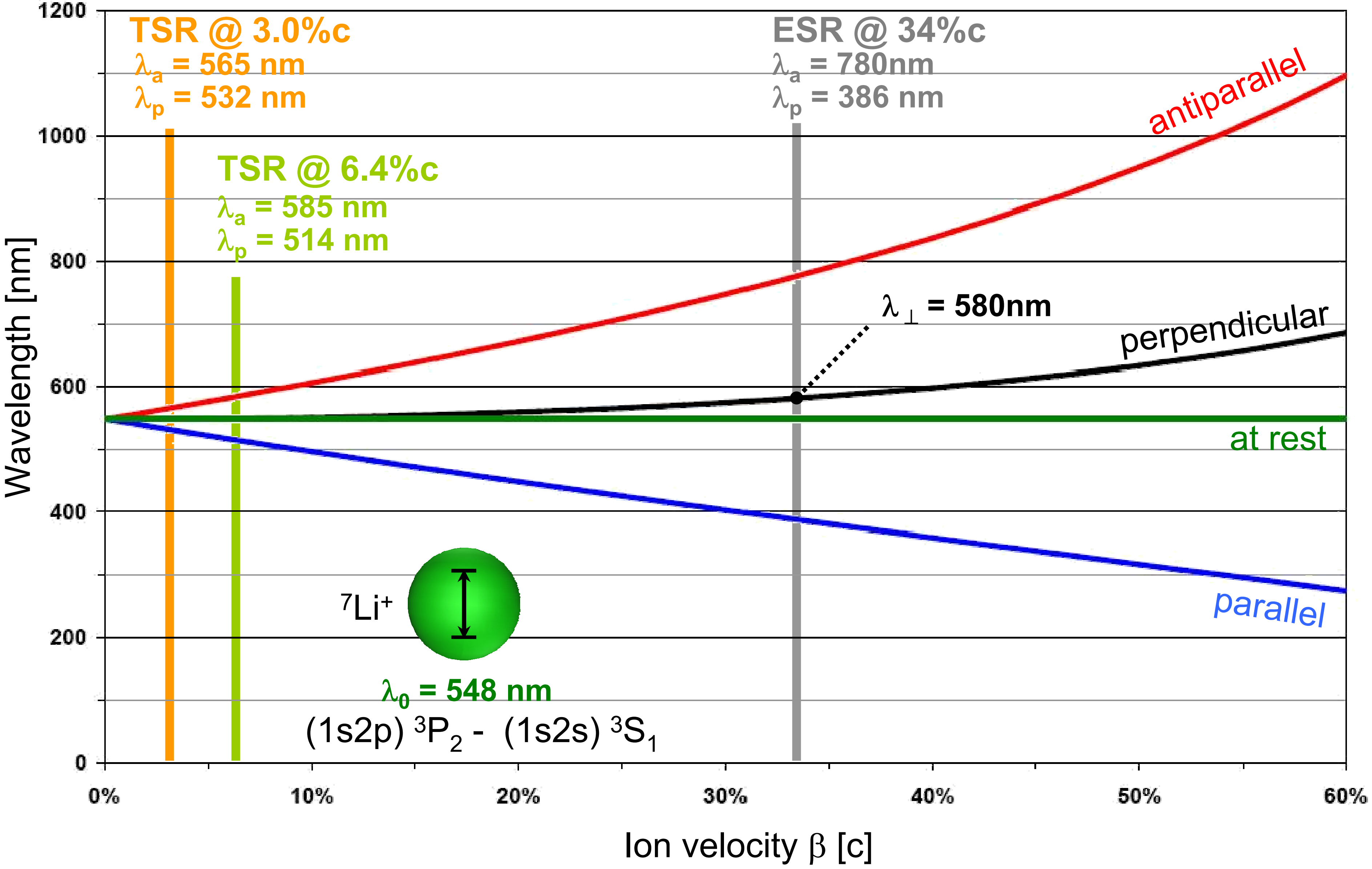
cancels out the uncertainty of the rest frequency

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

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

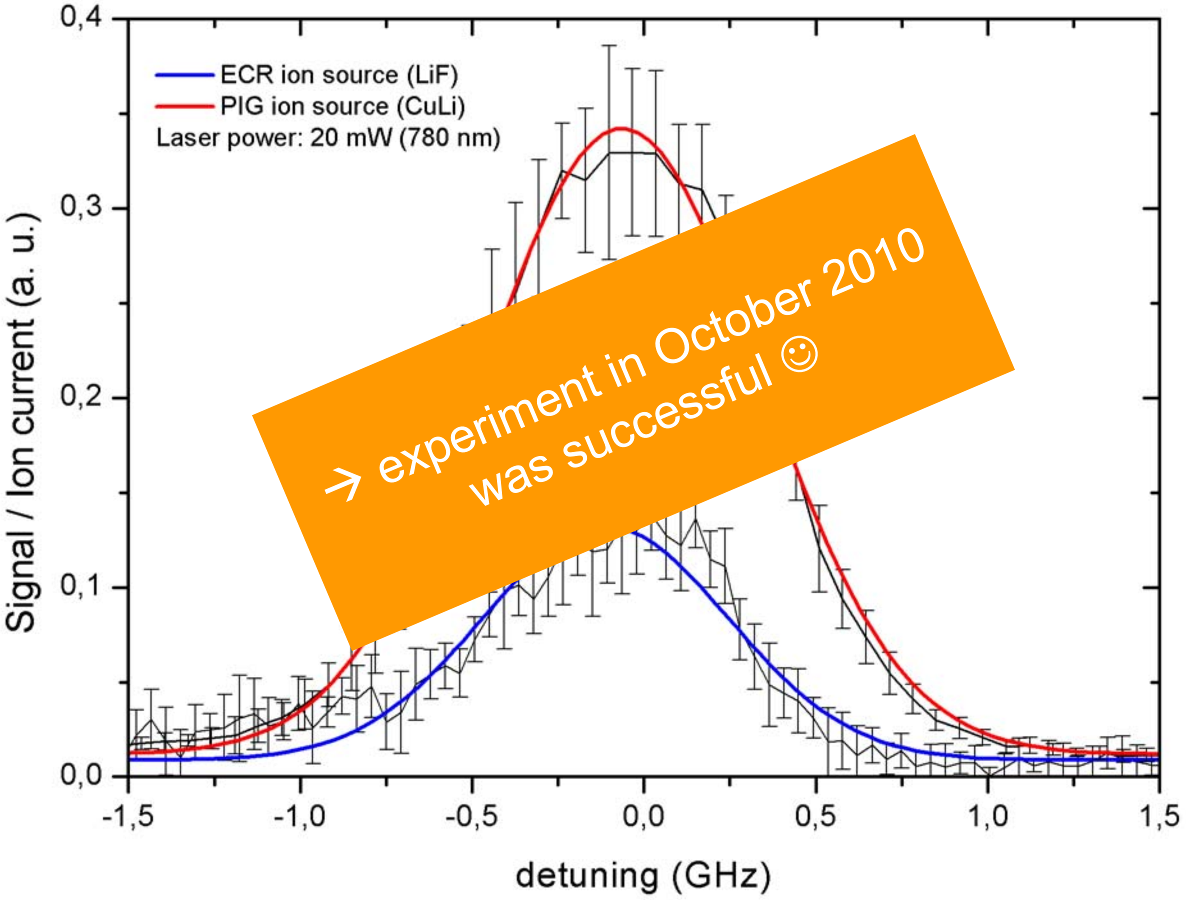
[S. Reinhardt, et al.
Nature Physics *3 (2007) 861*]

Why go to the ESR?



Production of excited Li^+ ions

Old recipe: LiF in an Electron Cyclotron Resonance Ion Source (ECRIS)
New recipe: Penning Ionisation Gauge (PIG) with source material LiCu
→ **ESR ion current x5, fraction of excited Li^+ in ESR x2 !!**
this recipe will be used for the coming beamtime



→ experiment in October 2010 was successful ☺

C. Novotny
Mainz University

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…

Forschungszentrum Dresden Rossendorf

Technische Universität Darmstadt

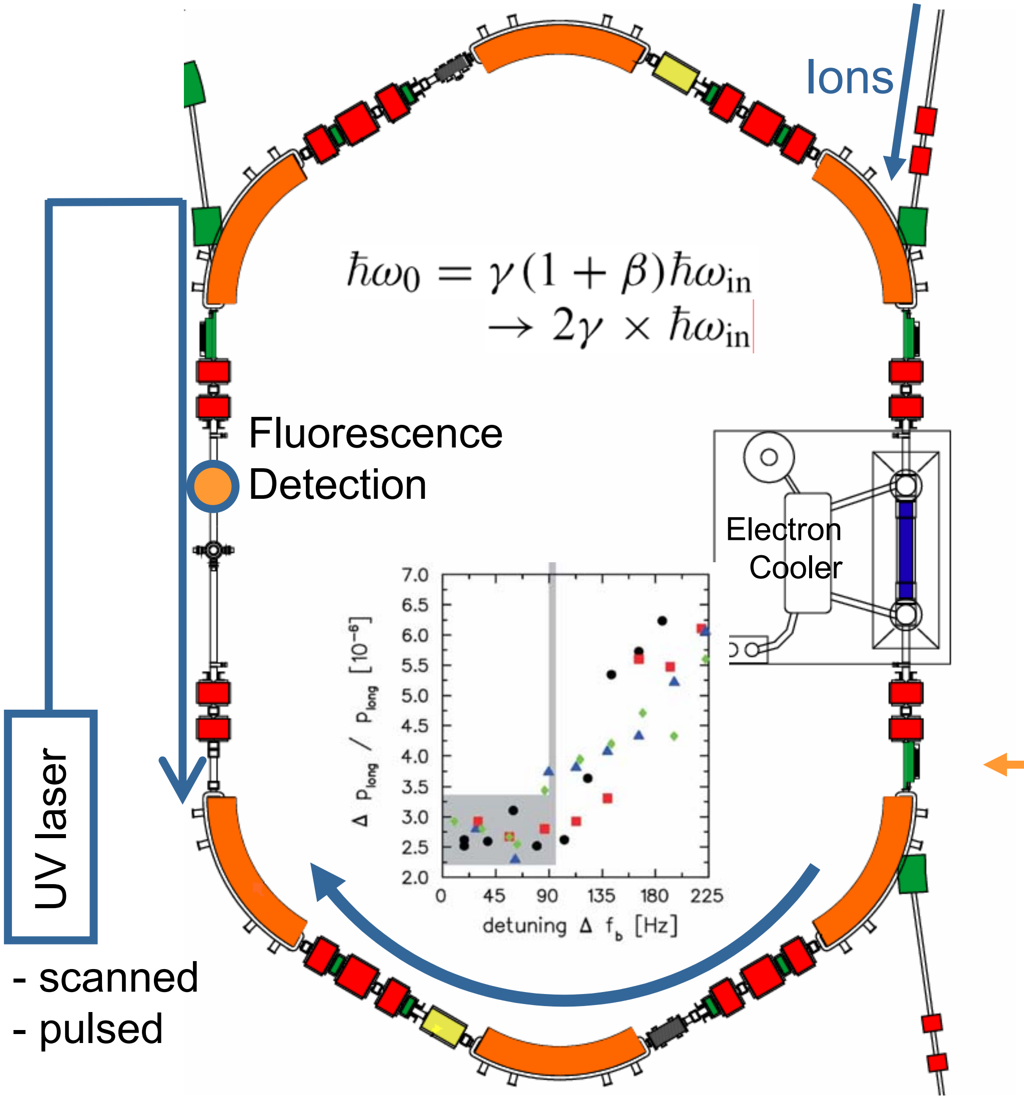
Westfälische Wilhelms-Universität Münster

Ruprecht-Karls-Universität Heidelberg
Physikalisches Institut

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



$$\hbar\omega_0 = \gamma(1+\beta)\hbar\omega_{\rm in} \rightarrow 2\gamma \times \hbar\omega_{\rm in}$$

- scanned
- pulsed

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.

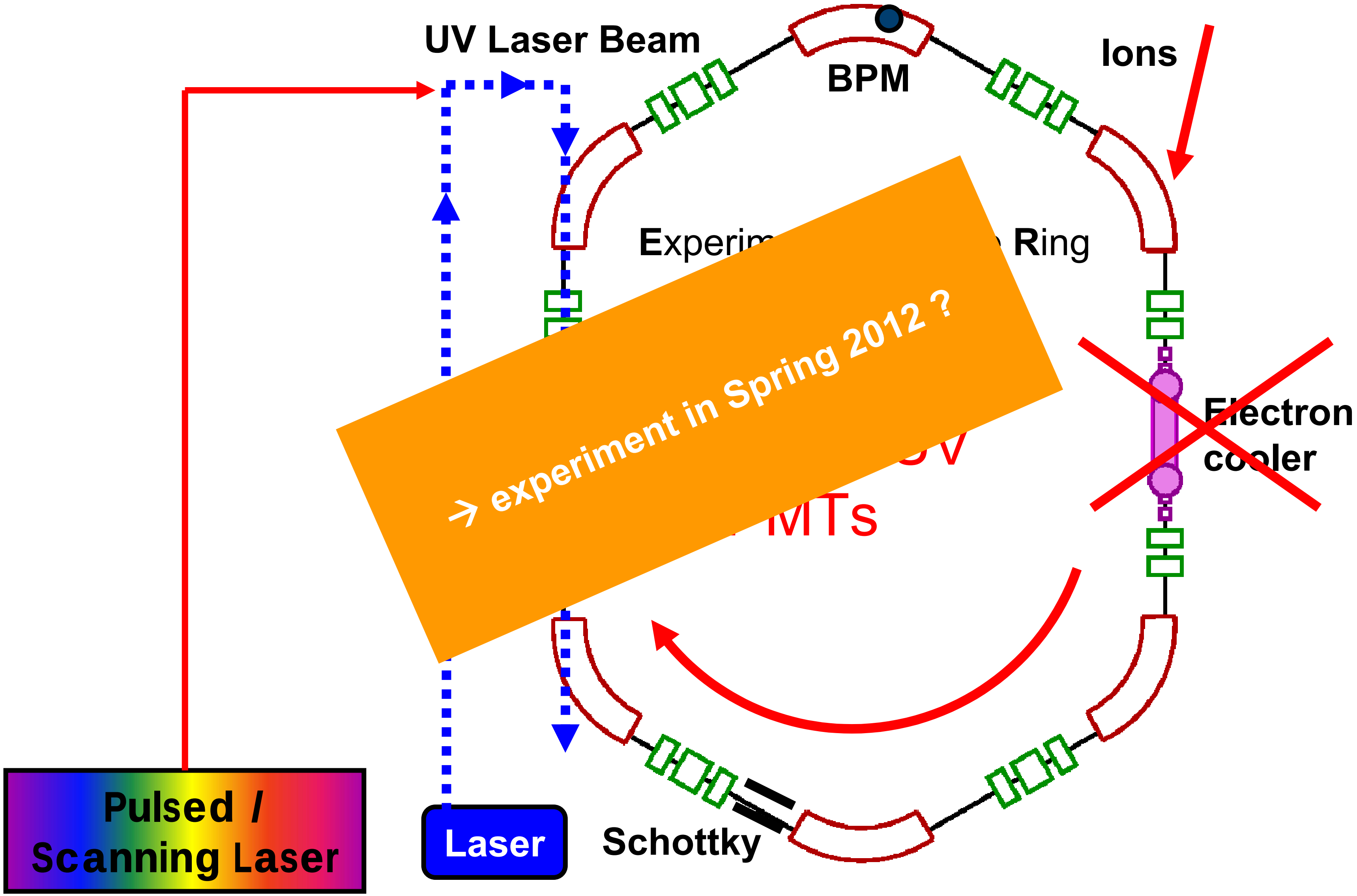
ESR experiments:

(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



→ experiment in Spring 2012 ?

Topics:

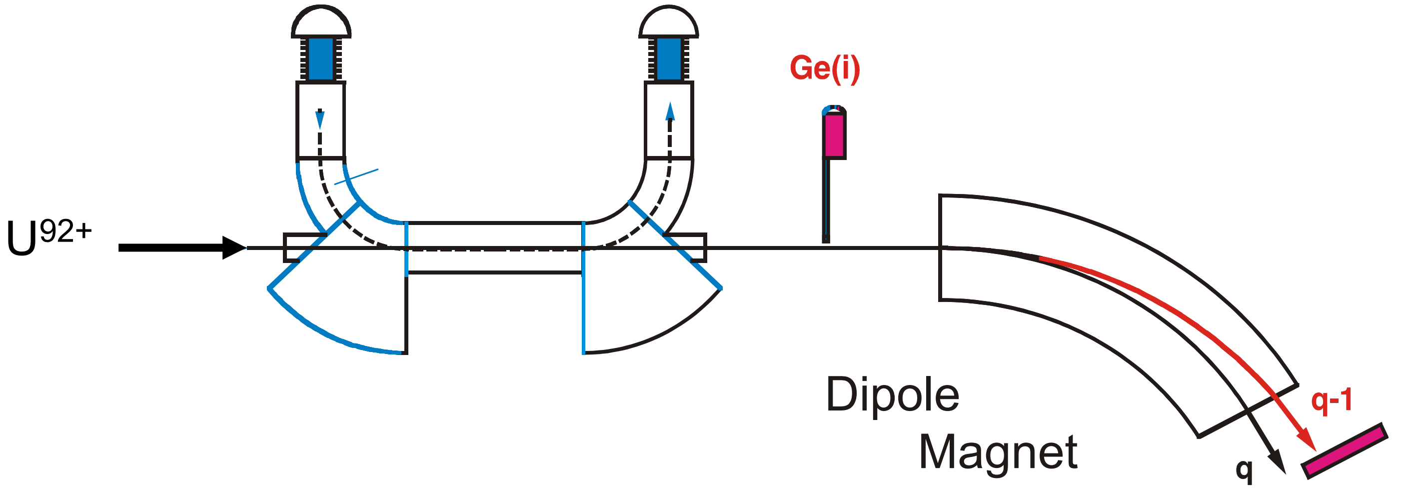
Dielectronic recombination (DR)

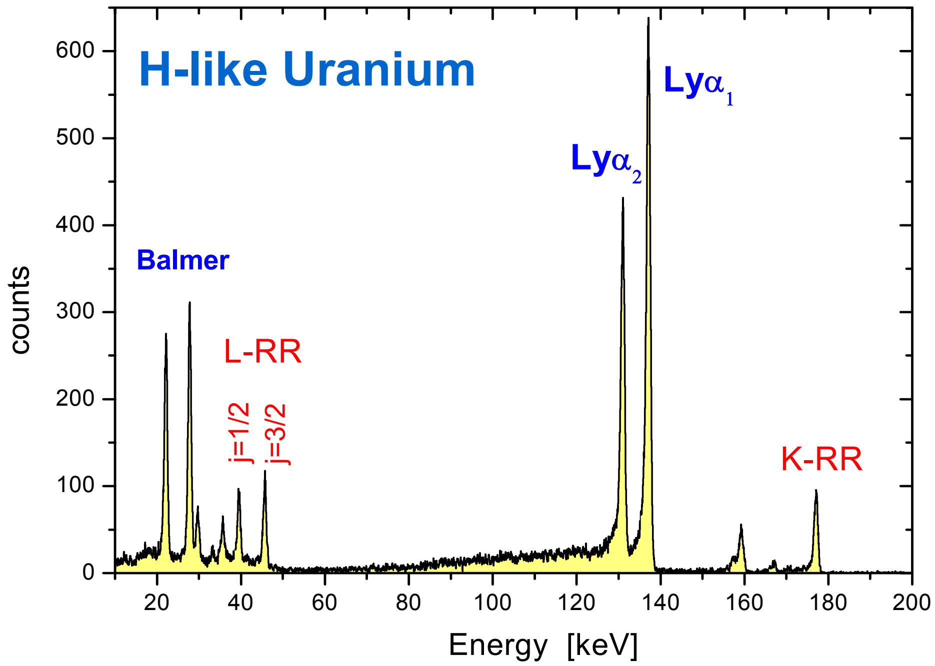
Mass spectrometry

Laser spectroscopy and laser cooling

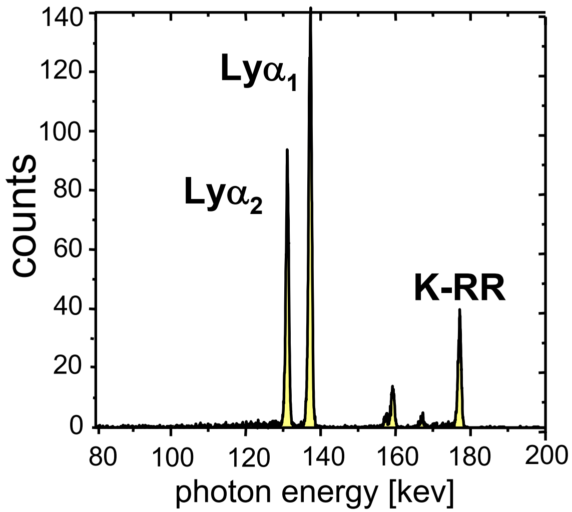
X-ray spectroscopy

0° x-ray spectroscopy at the electron cooler





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

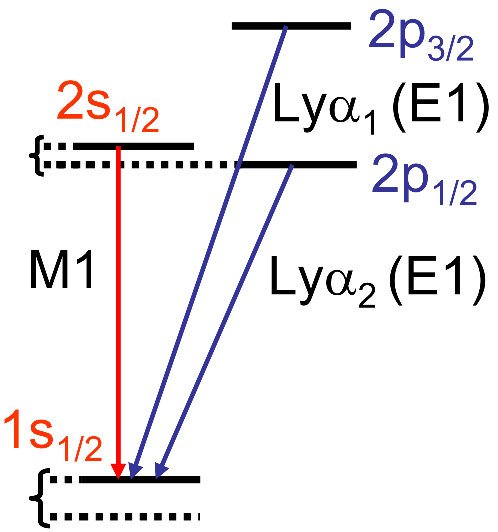


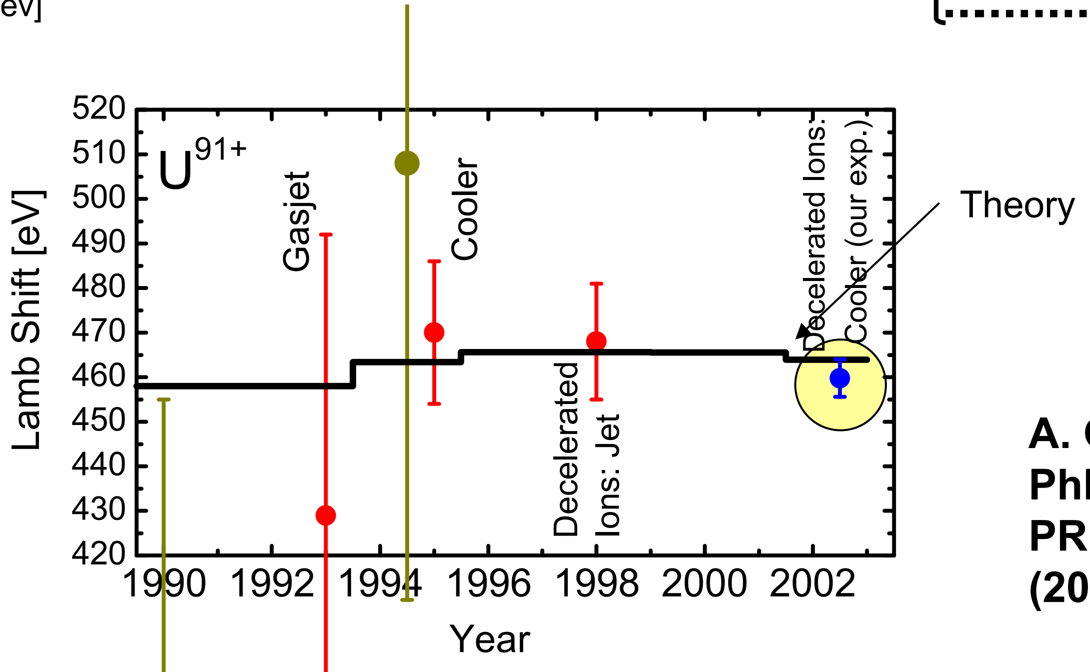
1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV

459.8±2.3±3.5 eV

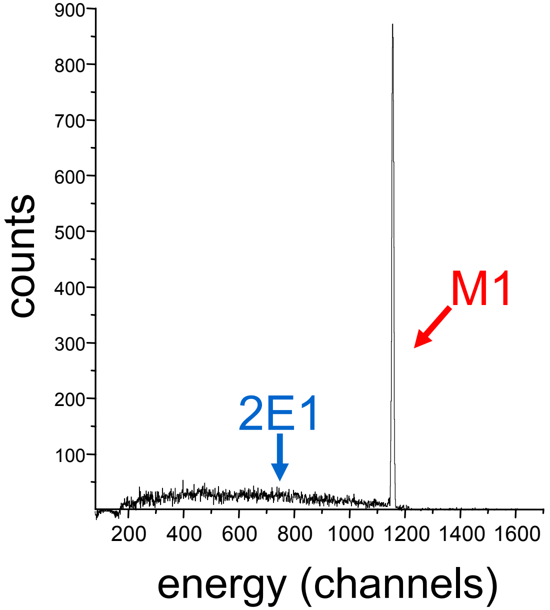


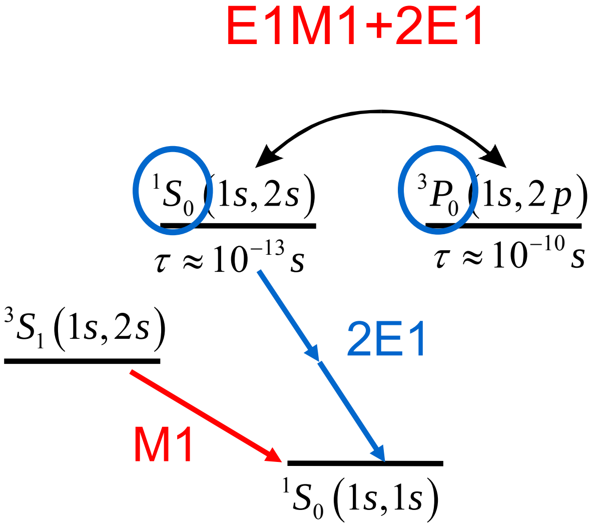


Research Highlights
Nature **435**, 858-859
(16 June 2005)

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

parity violation in He-like uranium





E1M1+2E1

$^1S_0(1s,2s)$ $\tau \approx 10^{-13}s$

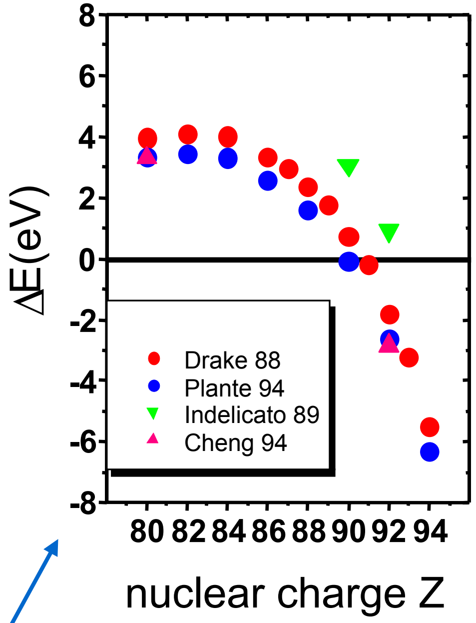
$^3P_0(1s,2p)$ $\tau \approx 10^{-10}s$

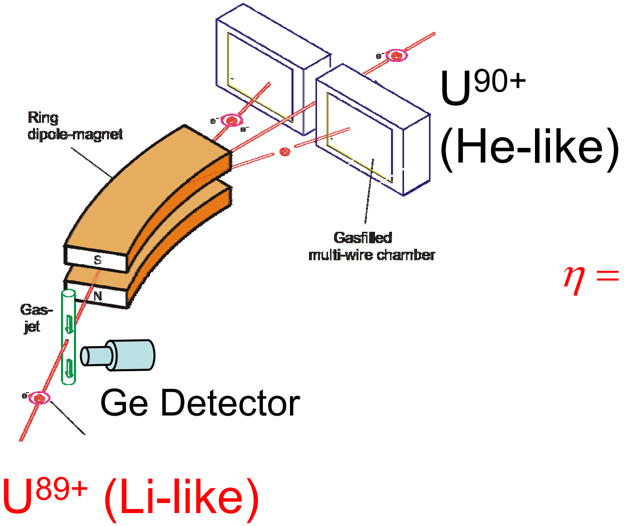
$^3S_1(1s,2s)$

2E1

M1

$^1S_0(1s,1s)$





Parity admixture

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

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

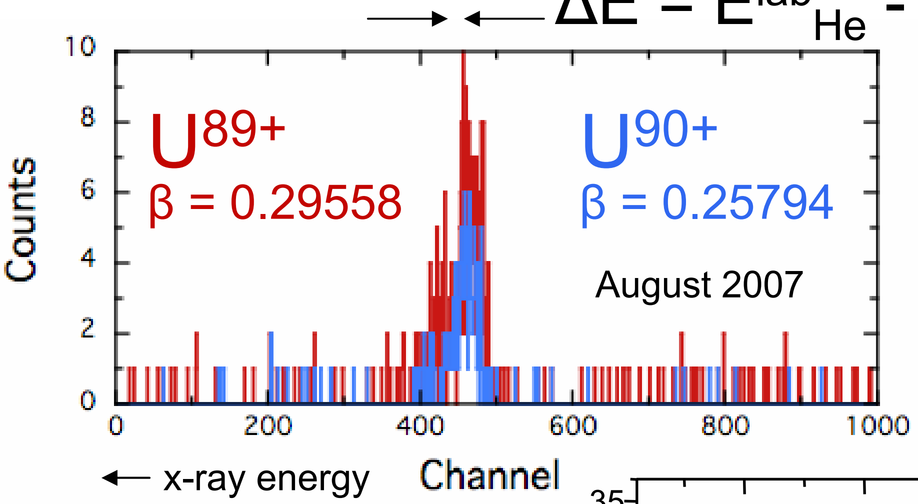
G_F: Fermi constant,

N: neutron number,

Θ_w: Weinberg angle
Z: proton number
ρ_{el}: electric charge density

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

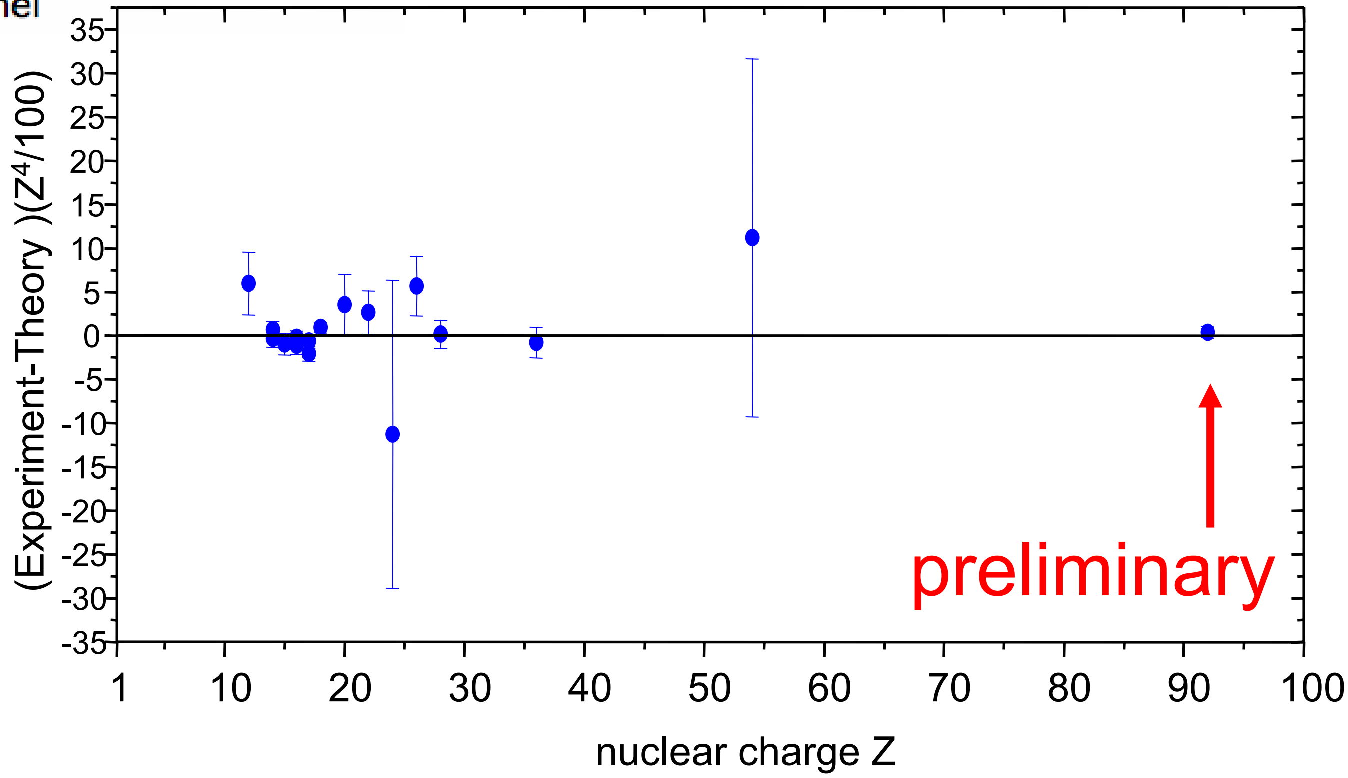
$\Delta E = E^{lab}_{He} - E^{lab}_{Li}$



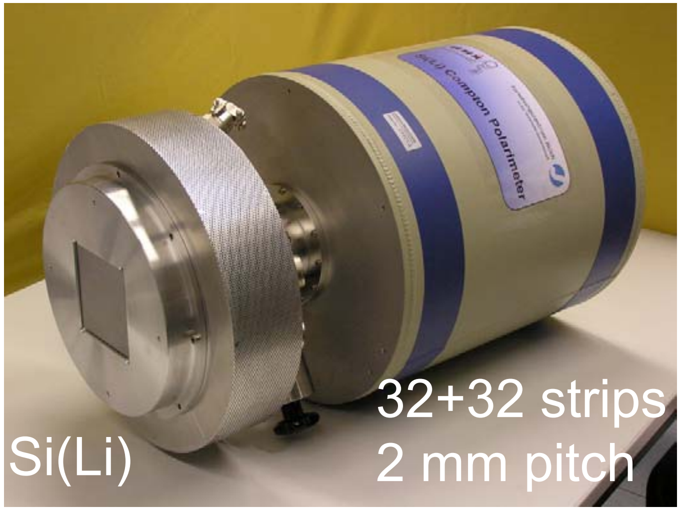
Relative measurement

He-like ⇔ Li-like (well-known)

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

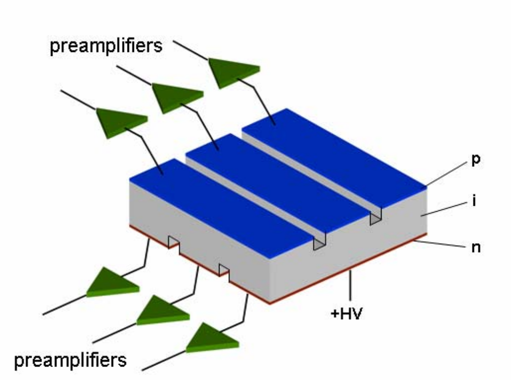


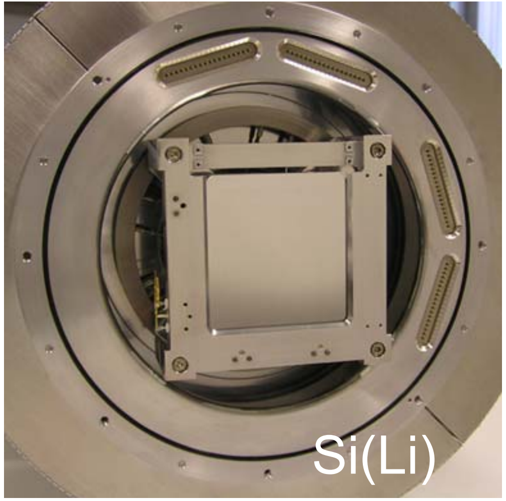
2D Si(Li)-detector for Compton polarimetry


Si(Li)

32+32 strips
2 mm pitch

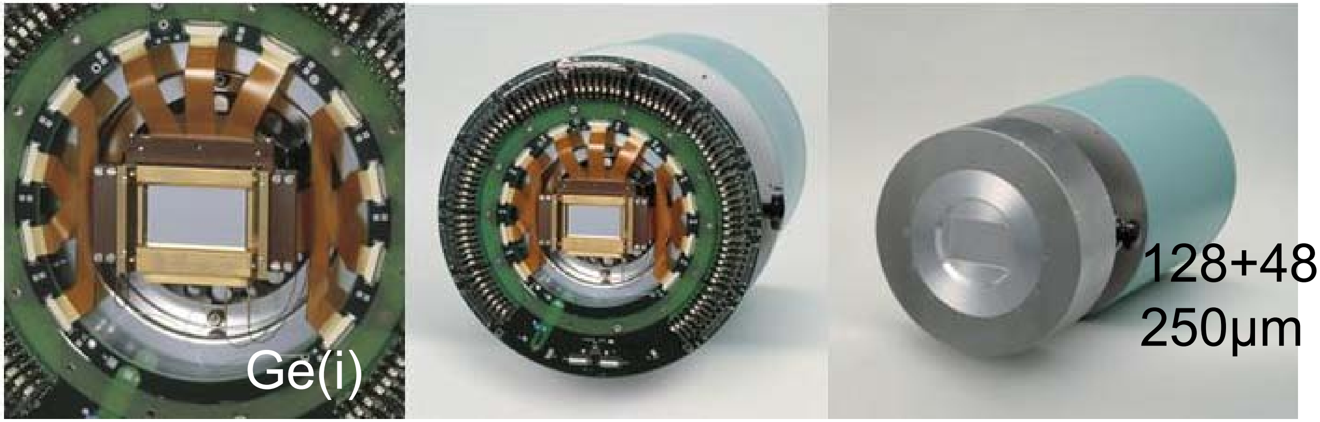
Si(Li) and Ge(i)
based Compton
polarimeter




Si(Li)

crystall size: 4" x 4"

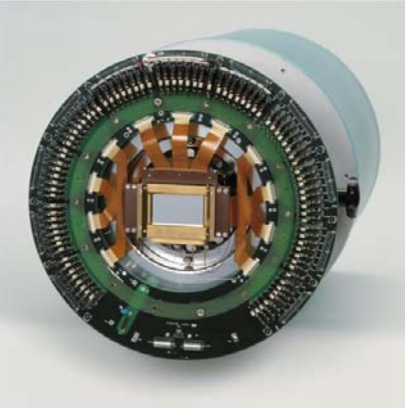
energy resolution – timing - 2D position sensitiviy


Ge(i)

128+48 strips
250µm and 1167µm

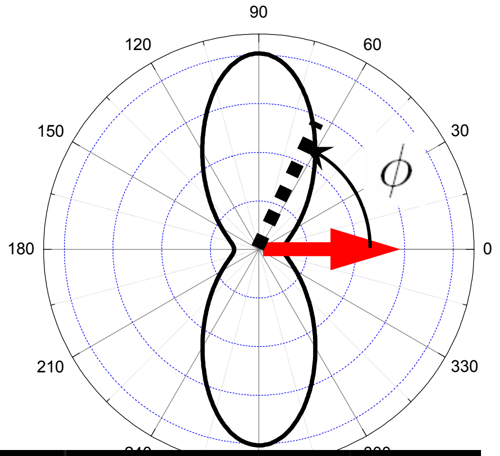
exploiding position and energy resolution

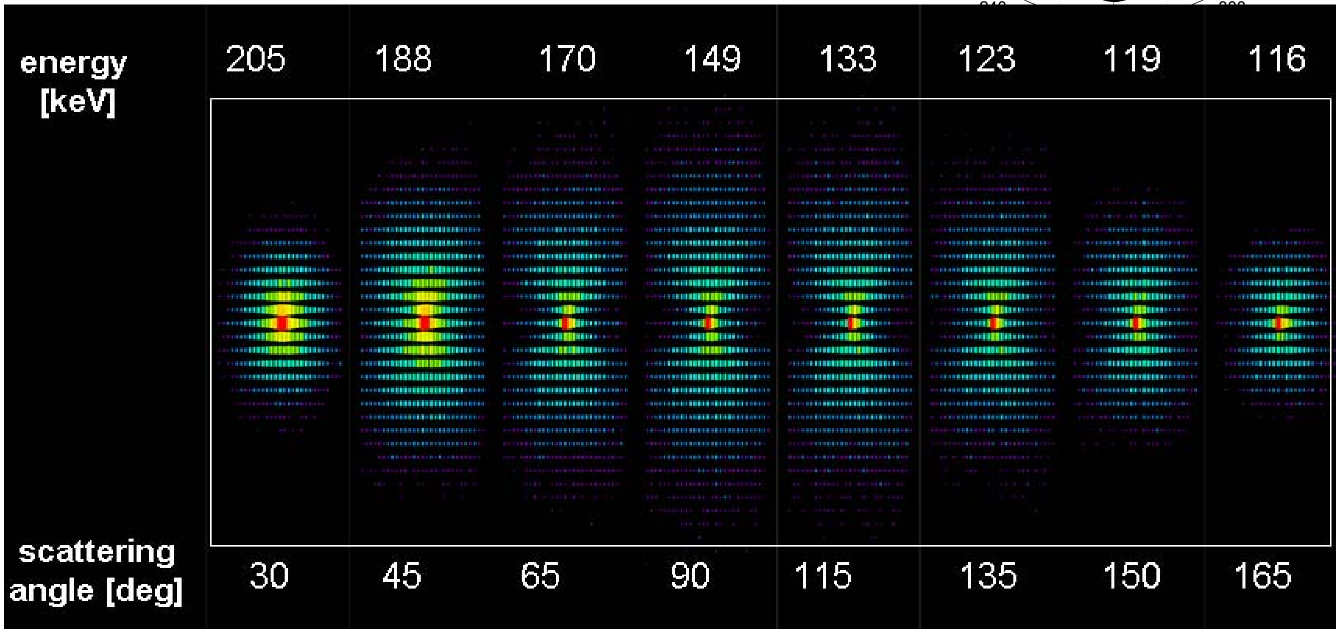
polarisation measurement via Compton scattering



2D µSTRIP
germanium detector
-GSI

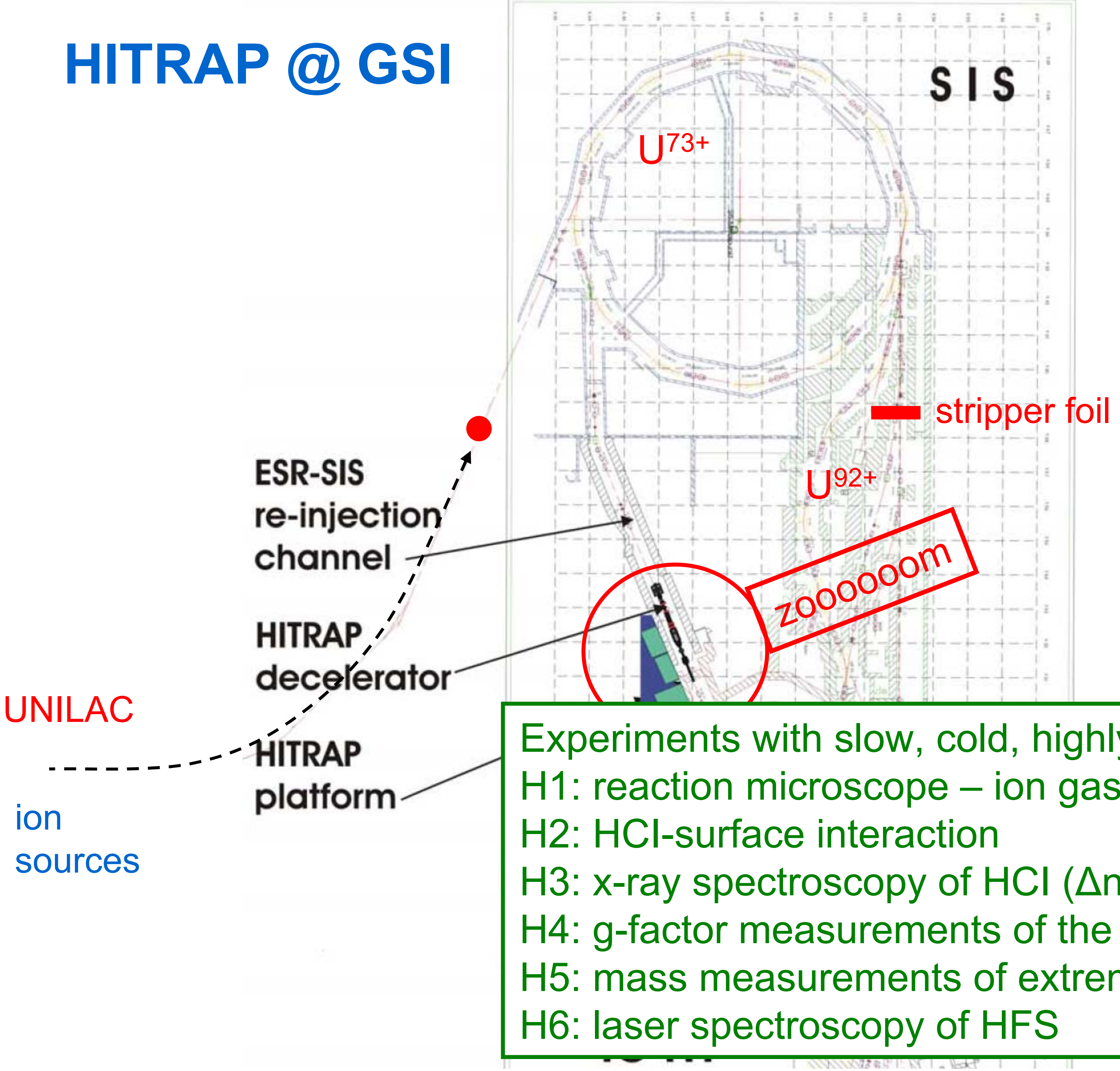
$$\hbar\omega' = \frac{\hbar\omega}{1 + \frac{\hbar\omega}{m_e c^2}(1 - \cos\theta_C)}$$





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

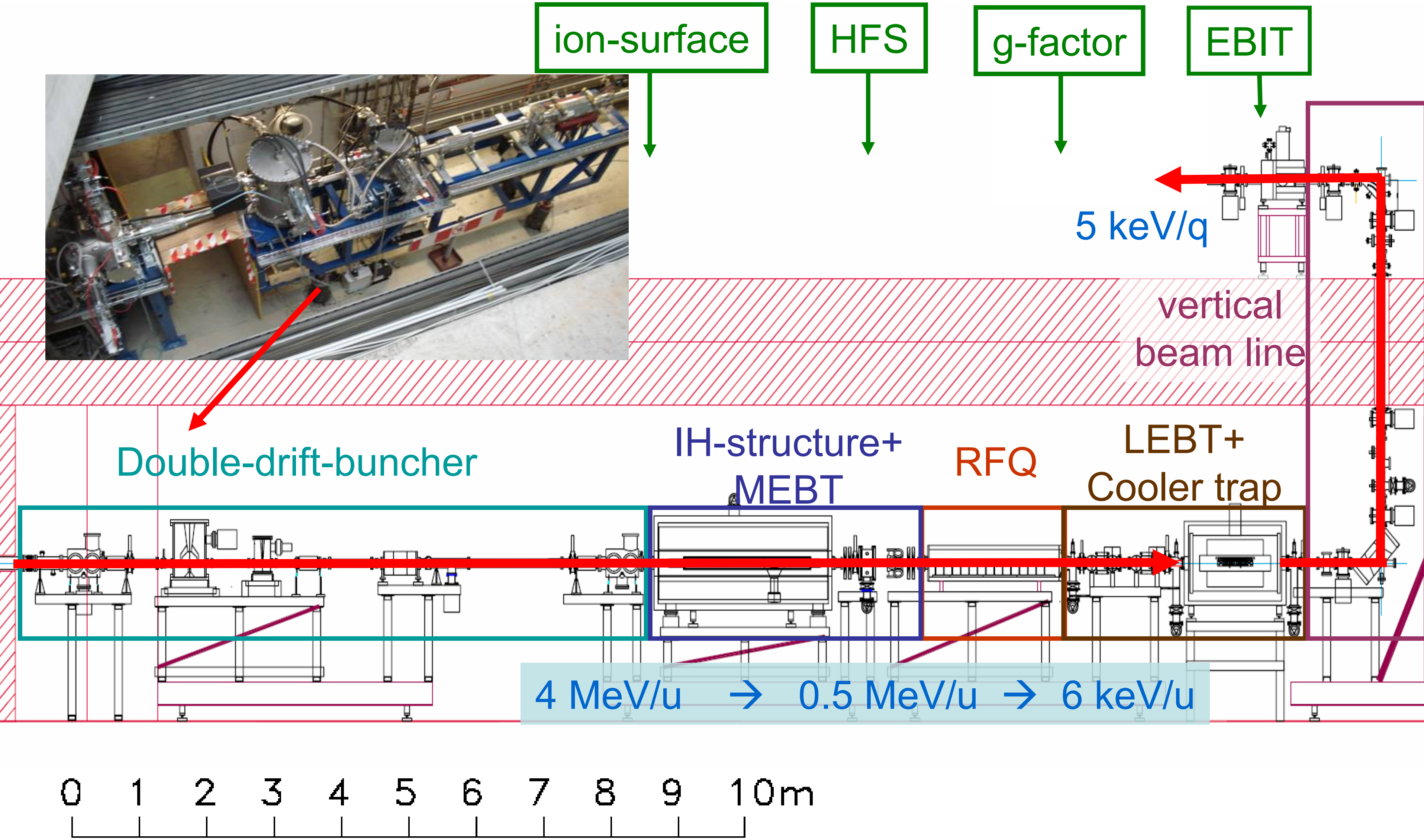
H3: x-ray spectroscopy of HCI ($\Delta n=0$)

H4: g-factor measurements of the bound electron

H5: mass measurements of extreme accuracy

H6: laser spectroscopy of HFS

overview of the HITRAP facility



ion-surface

HFS

g-factor

EBIT

5 keV/q

vertical beam line

Double-drift-buncher

IH-structure+ MEBT

RFQ

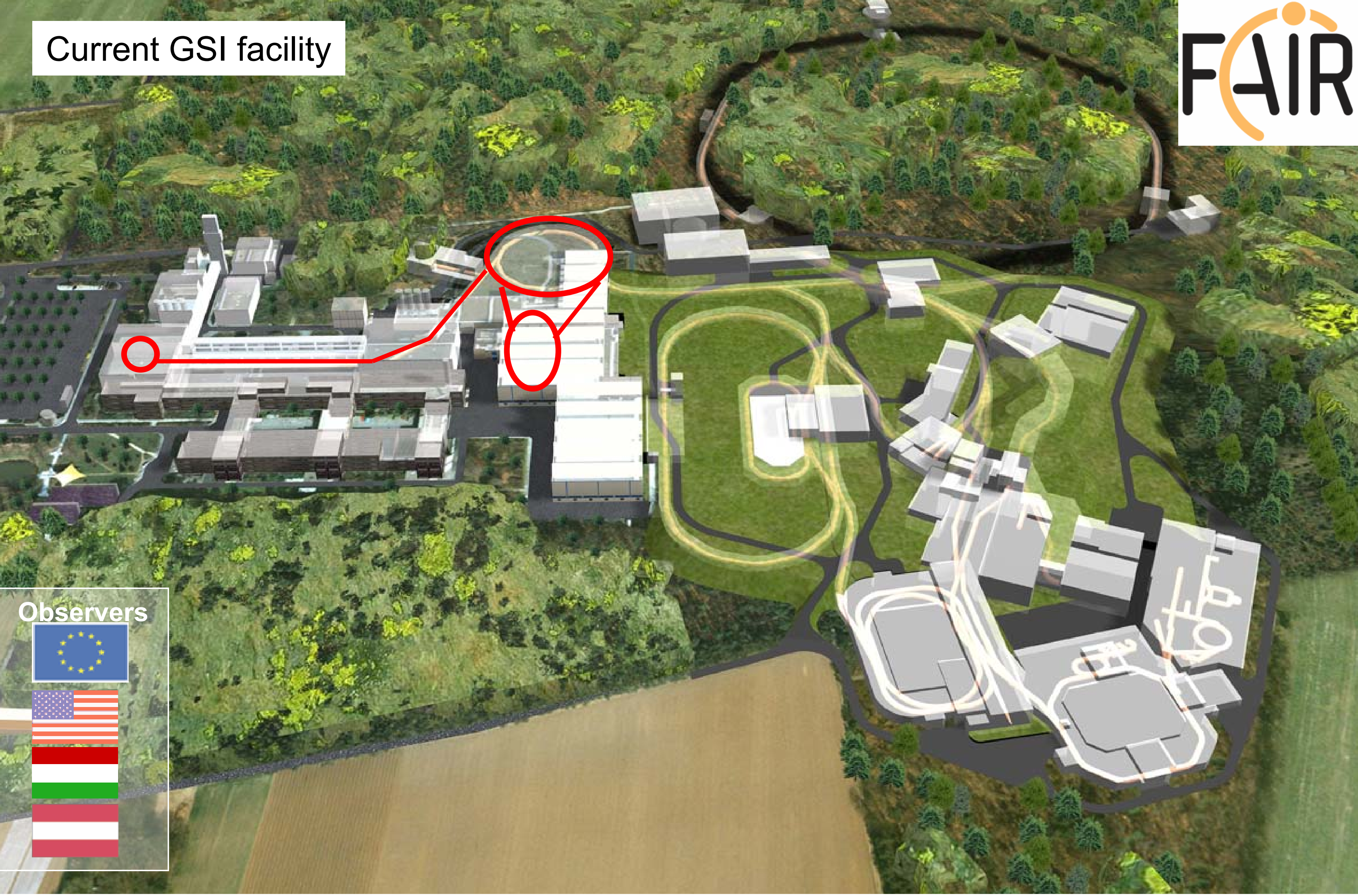
LEBT+ Cooler trap

4 MeV/u → 0.5 MeV/u → 6 keV/u

Facility for Antiproton an Ion Research

(FAIR)

Current GSI facility



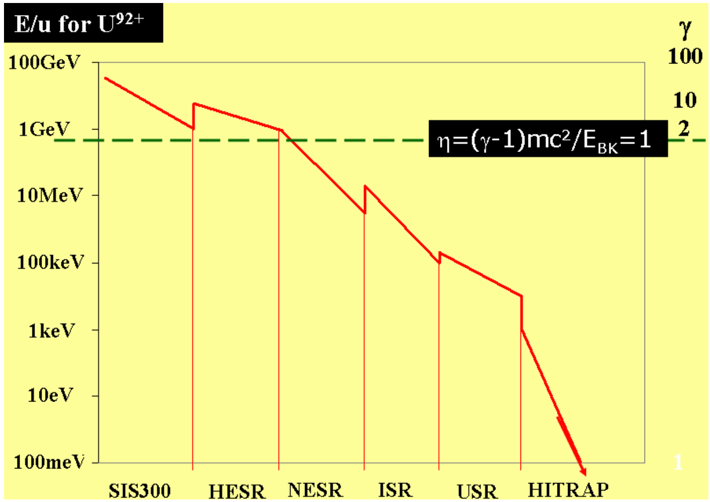
Observers

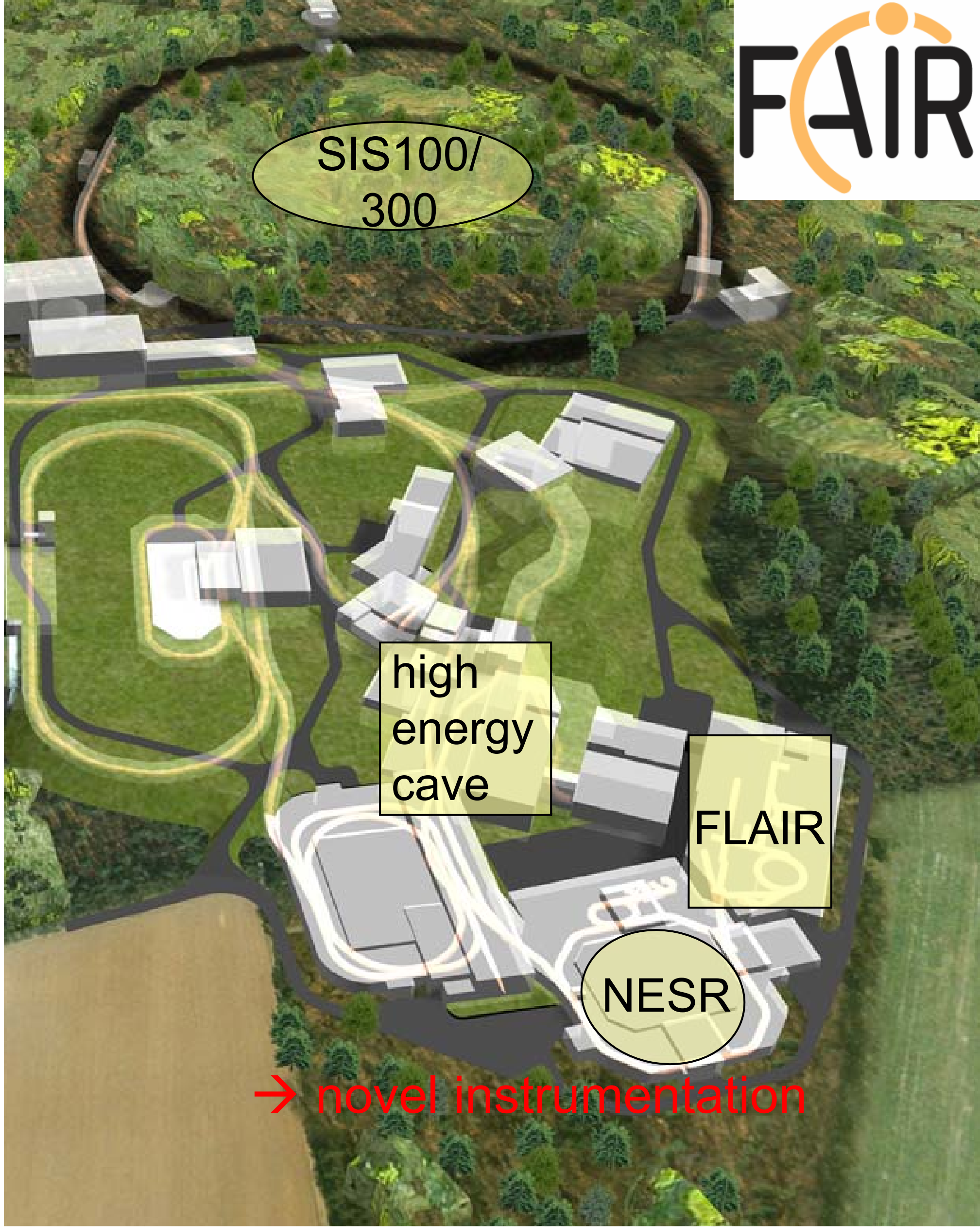
🇪🇺
🇺🇸
🇭🇺
🇦🇹

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**



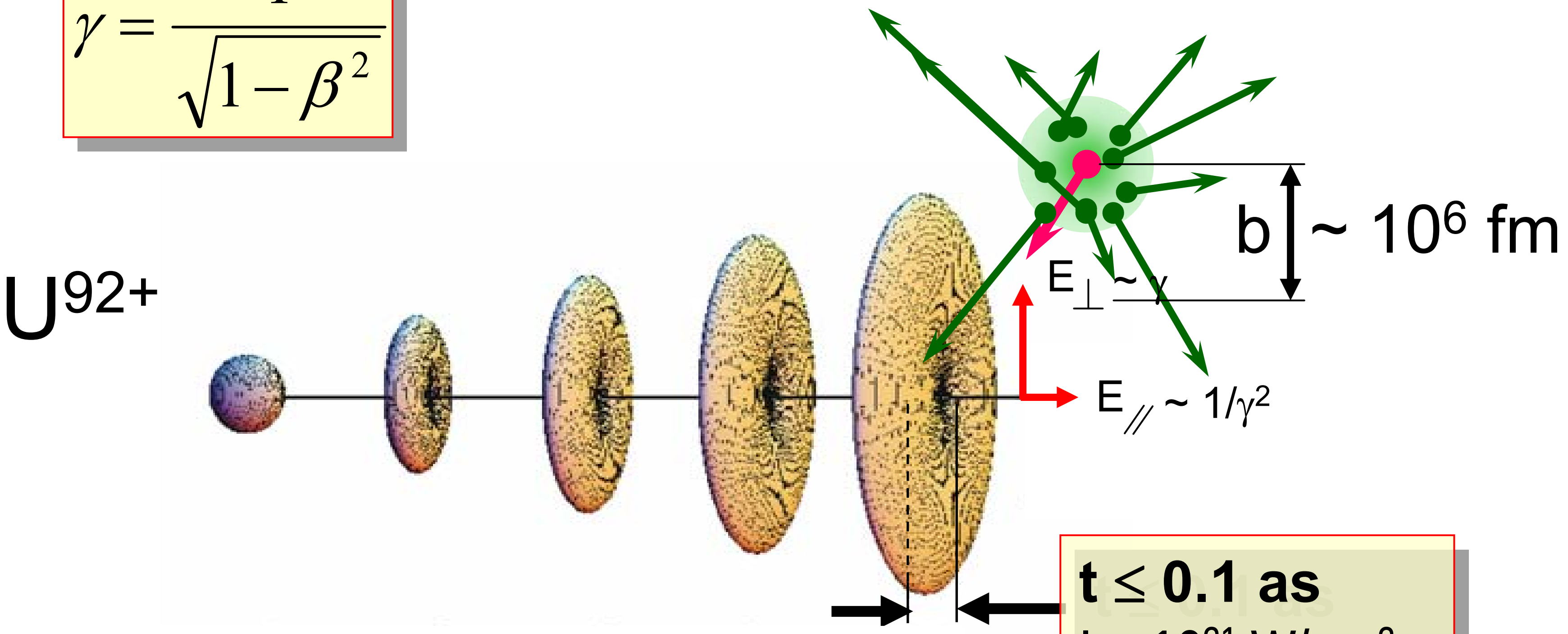


→ novel instrumentation

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

relativistic projectiles in extreme dynamic fields

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



γ = 1 2 3 4 5

0 87 94 97 98

percent of the velocity of light

t ≤ 0.1 as

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

intense fields

ultra-short electromagnetic pulses

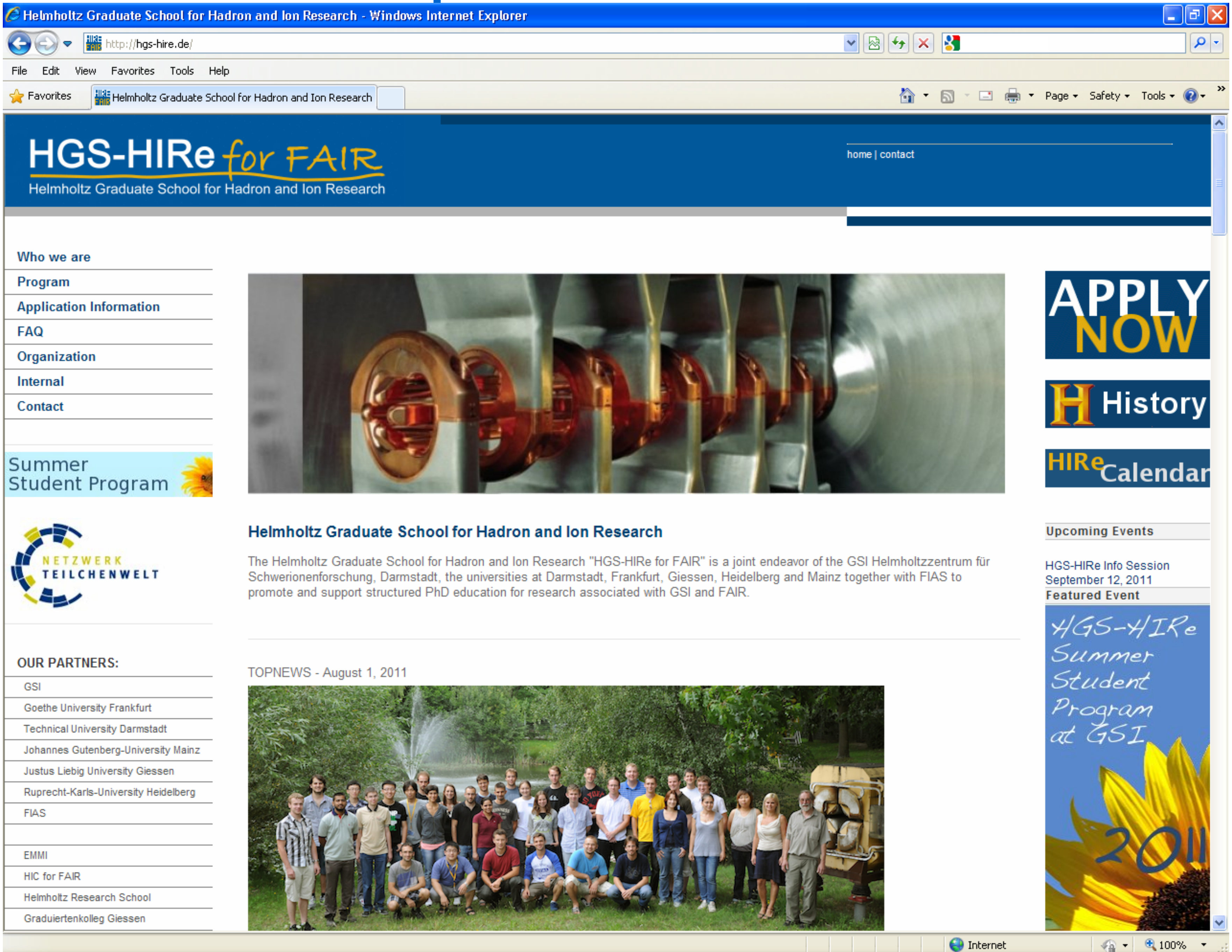
pair production

Thank you for your attention ☺

Observers:

FAIR Partner Countries

PhD possibilities at GSI



Helmholtz Graduate School for Hadron and Ion Research

The Helmholtz Graduate School for Hadron and Ion Research "HGS-HIRe for FAIR" is a joint endeavor of the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, the universities at Darmstadt, Frankfurt, Giessen, Heidelberg and Mainz together with FIAS to promote and support structured PhD education for research associated with GSI and FAIR.

TOPNEWS - August 1, 2011

OUR PARTNERS:

- GSI
- Goethe University Frankfurt
- Technical University Darmstadt
- Johannes Gutenberg-University Mainz
- Justus Liebig University Giessen
- Ruprecht-Karls-University Heidelberg
- FIAS

- EMMI
- HIC for FAIR
- Helmholtz Research School
- Graduiertenkolleg Giessen

Upcoming Events

HGS-HIRe Info Session
September 12, 2011

Featured Event

HGS-HIRe Summer Student Program at GSI 2011