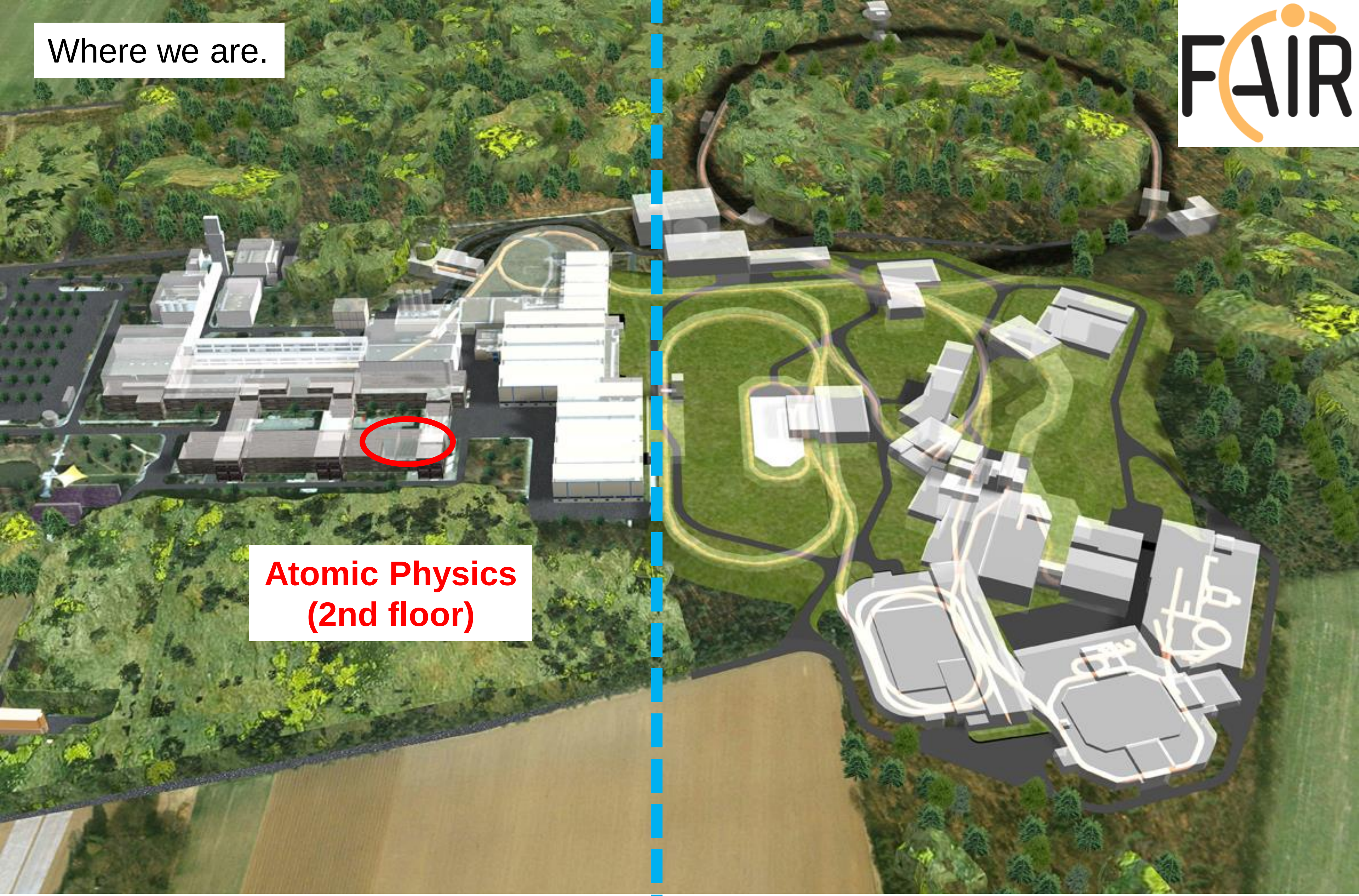
Atomic Physics at GSI: Current and Future Research

Danyal Winters

GSI summer student programme 2013
Friday, 16 August 2013, 14:00 – 15:30


Where we are.
FAIR
Atomic Physics
(2nd floor)

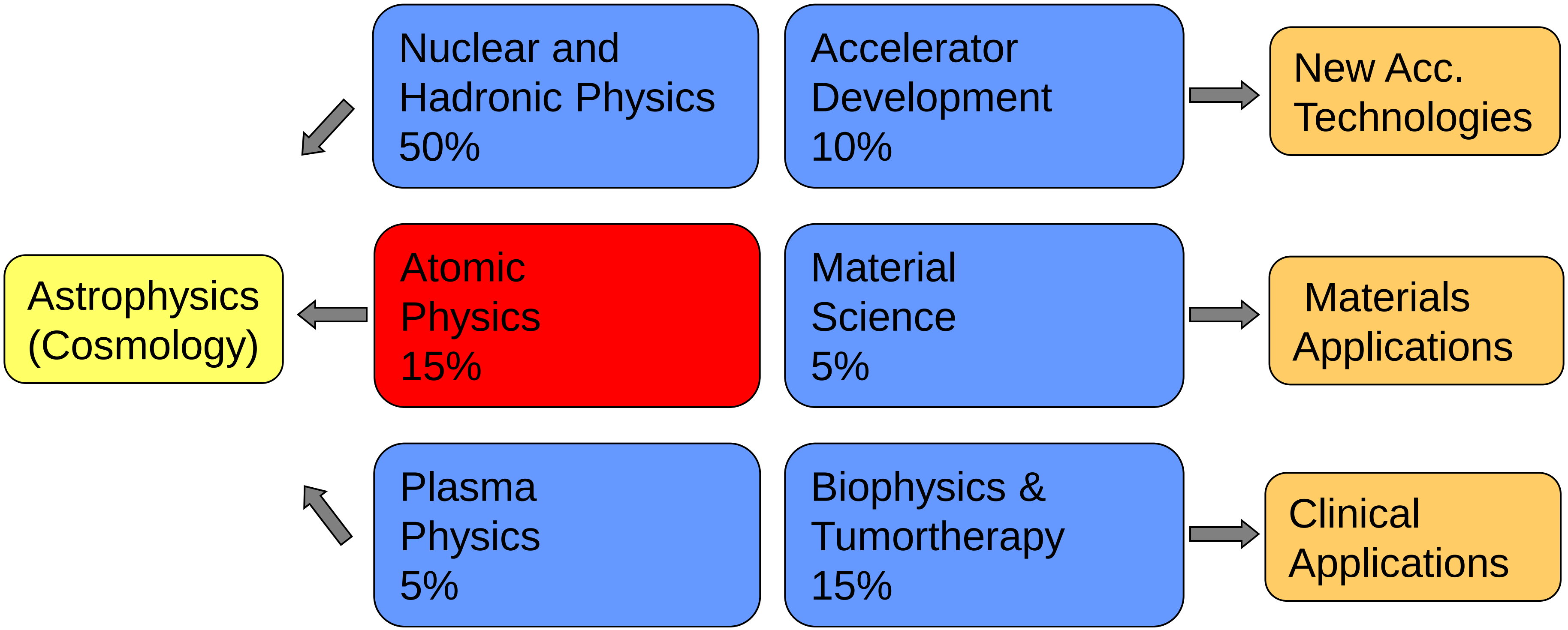
Who we are.

Prof. Thomas Stöhlker
„AP Boss“

Prof. Horst Stöcker
„GSI Boss“

Due to the project „FAIR@GSI“, many AP people now belong to „stored beams“. Others are affiliated with EMMI, HI-Jena, or the surrounding universities of Frankfurt, Darmstadt, Mainz, Heidelberg, Jena,Giessen (or have left).

Research Programme at GSI

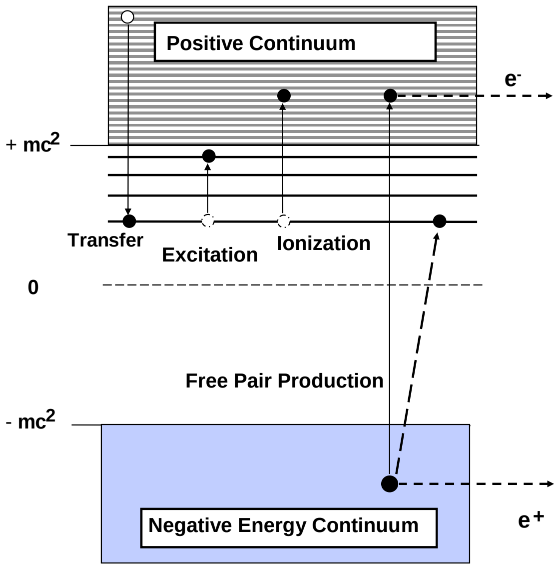


Research in all areas is performed in international collaborations between GSI, universities, and other research centres.

Contents of my talk

- atomic physics at GSI
- the hydrogen atom
- storing and cooling of ions (ESR)
- ESR experiments (recent and future)
- the HITRAP facility
- SPARC @ 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

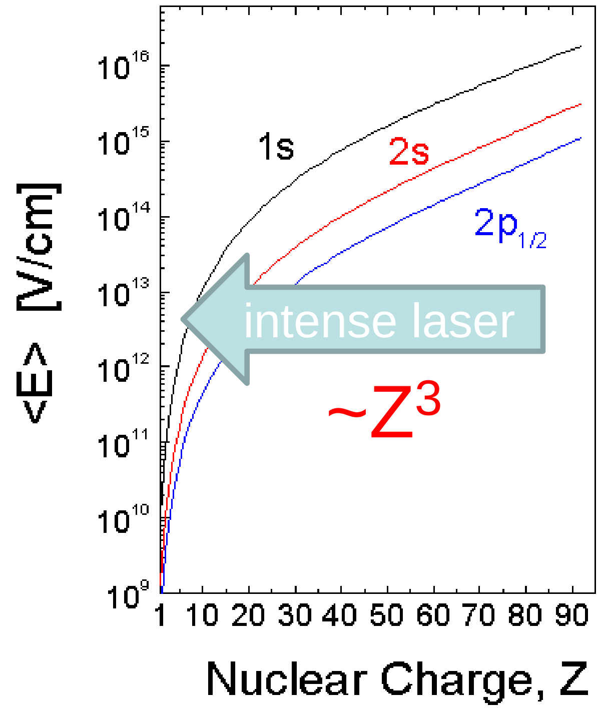
Atomic Collision at High-Z

- 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.

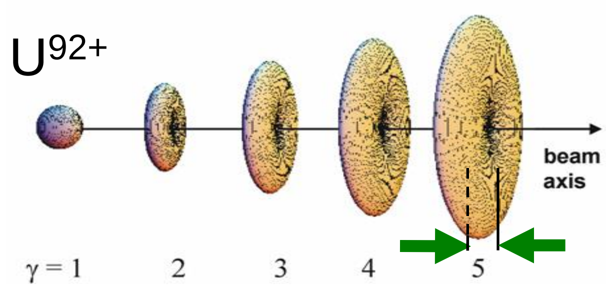
Tests of QED in extreme electromagnetic fields.
New access to fundamental constants and to nuclear ground state properties.



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

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

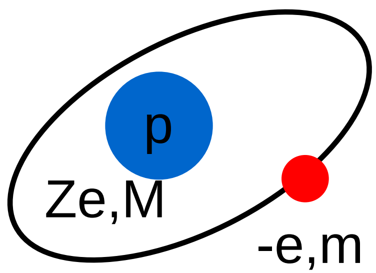
Extremely short and extremely intensive electromagnetic pulses at relativistic energies of highly-charged ions.



$t \leq 0.1$ 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. !

The best place to start off with is…

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):

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

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:

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

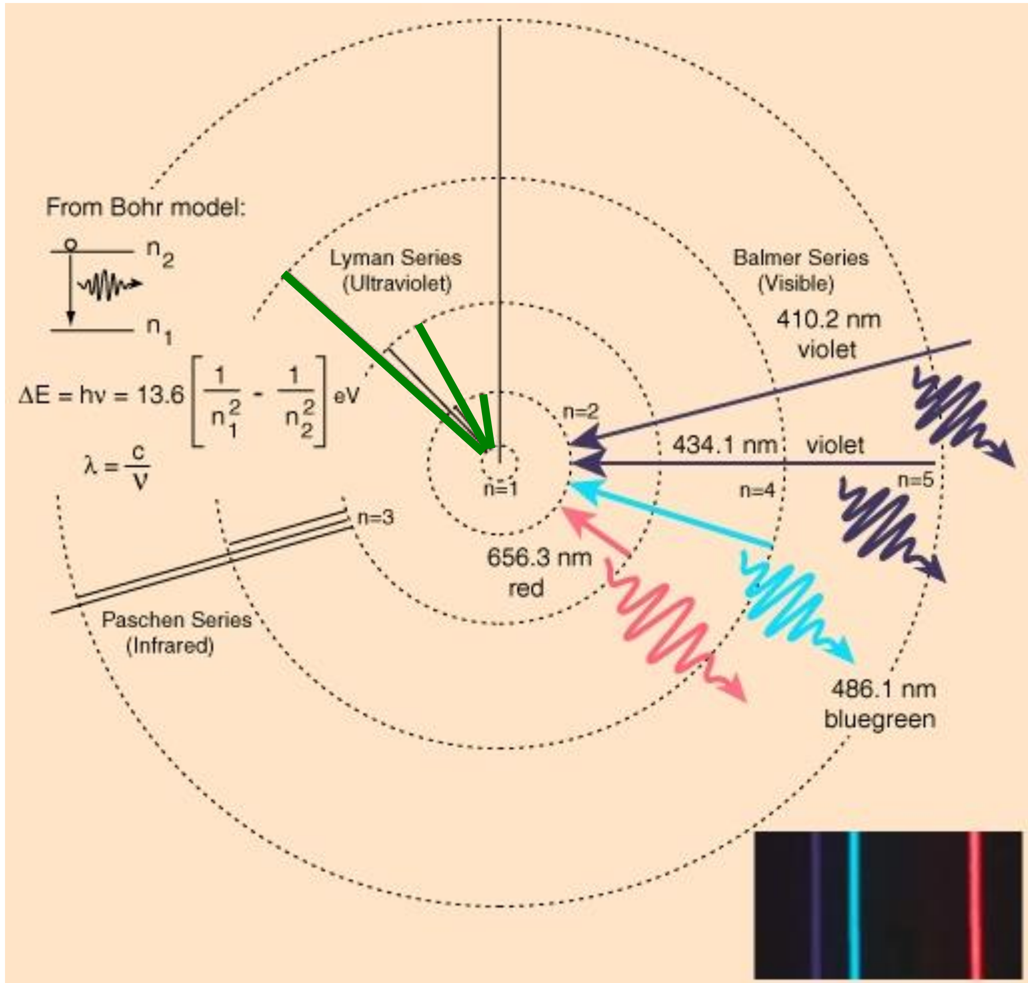
Using the fine structure coefficient $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \approx 1/137$, we finally obtain

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

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

the simple Bohr model

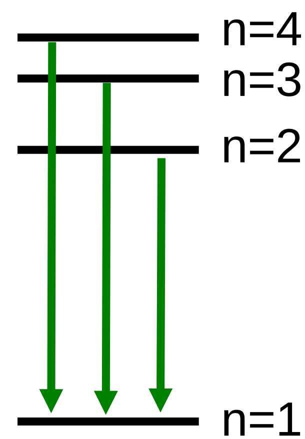
These are important lines for highly-charged ions!



λ

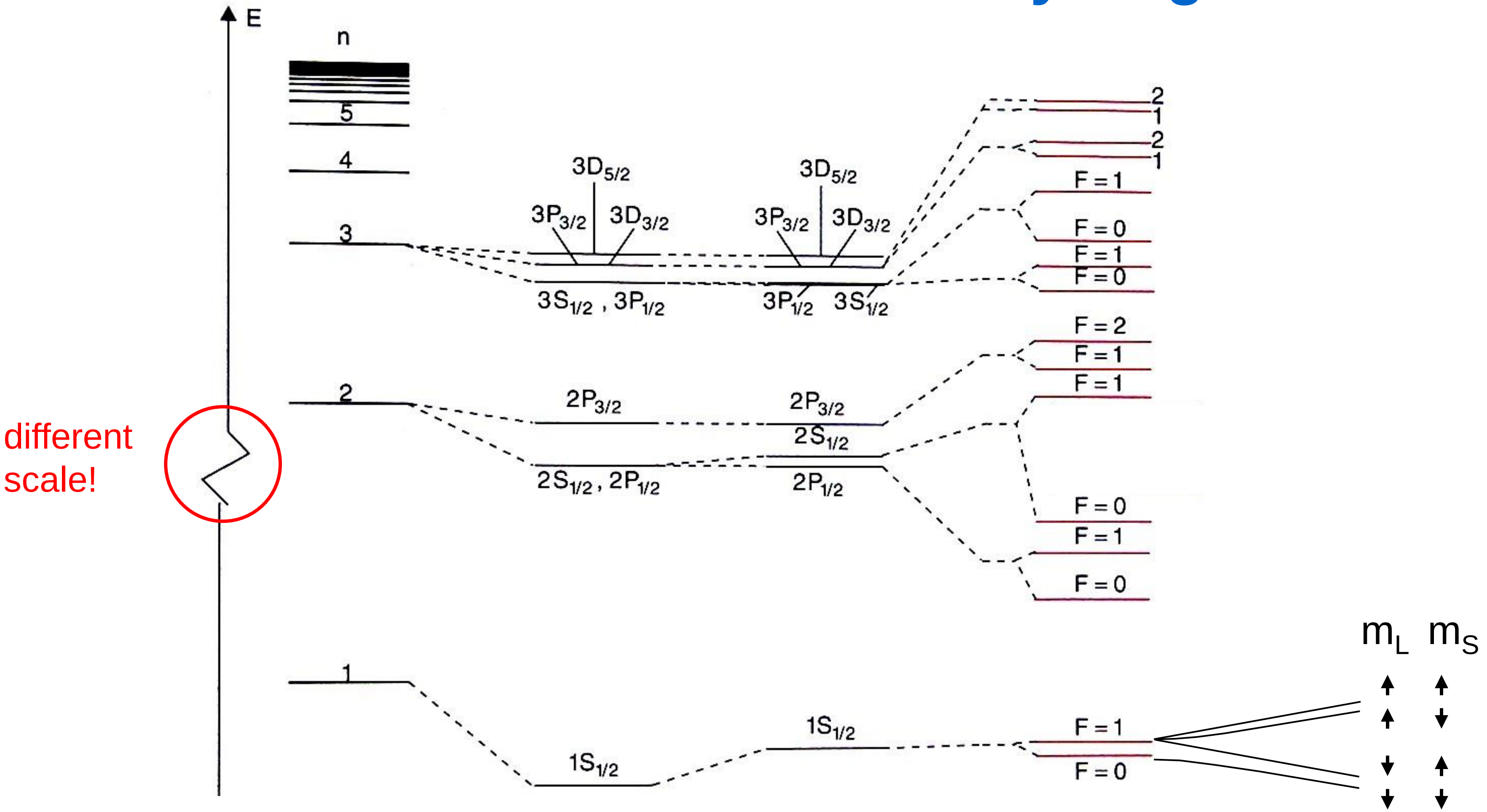
"size"

Lyman series



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

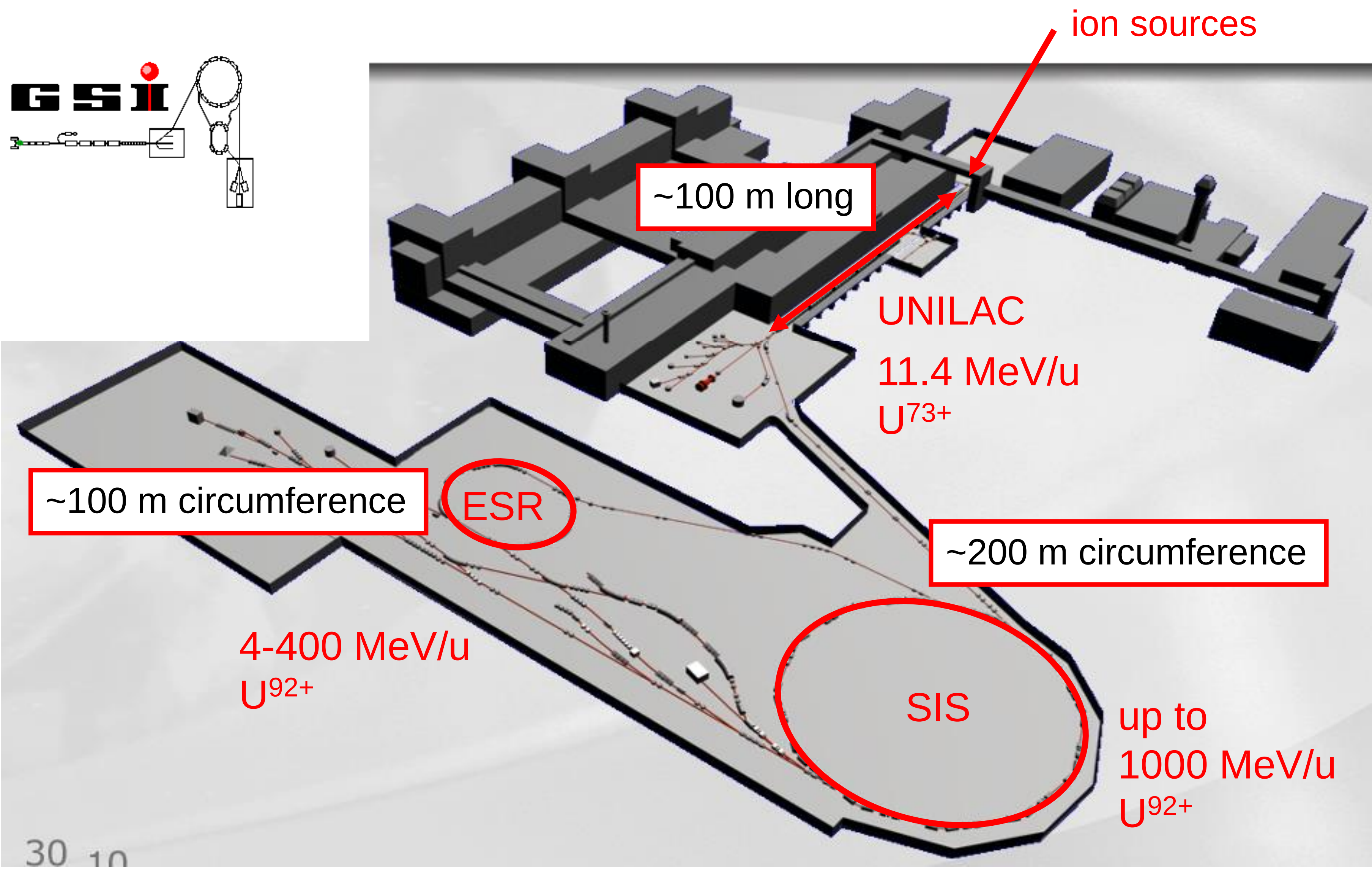
To remove the 92nd electron in uranium,
requires an energy of the order of ~100 keV.
(Z=92 → ~Z^2)

→ 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!

@ GSI we use the "stripper-foil" method and produce:
bare, hydrogen-, helium-, lithium-, or beryllium-like ions
0 e^- 1 e^- 2 e^- 3 e^- 4 e^-

the current GSI facility



pioneers of storing and cooling

Principle of Penning Traps

Frans Michel
Penning

Storage and Cooling of Atoms

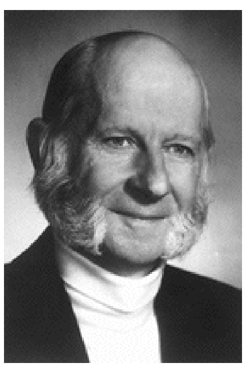
Nobel Prize 1997

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

Storage and Cooling of Antiprotons

Nobel Prize 1984

J. van der Meer
C. Rubbia



Storage and Cooling of Ions

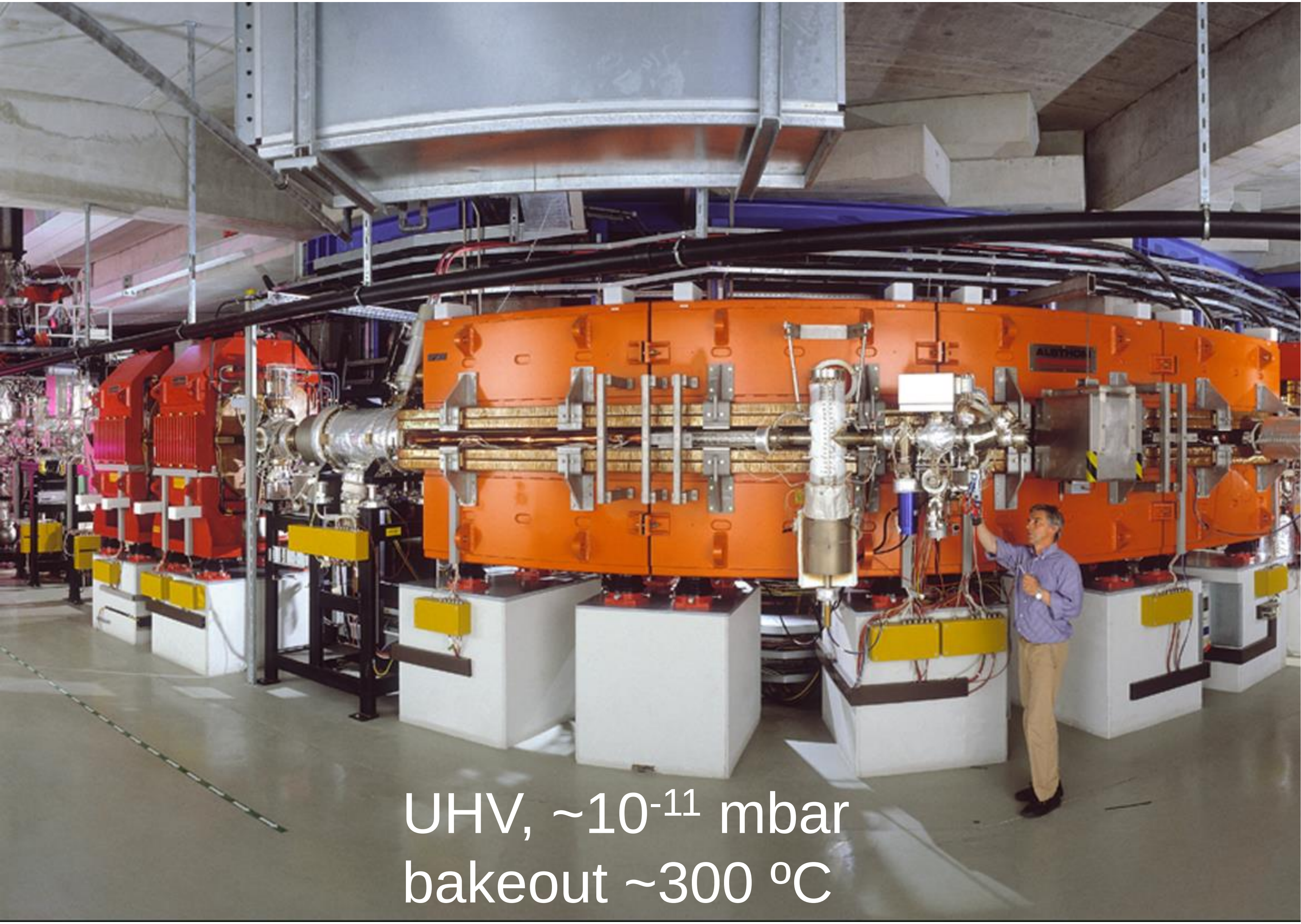
Nobel Prize 1989

H. Dehmelt
W. Paul

Bose-Einstein Condensation

Nobel Prize 2001

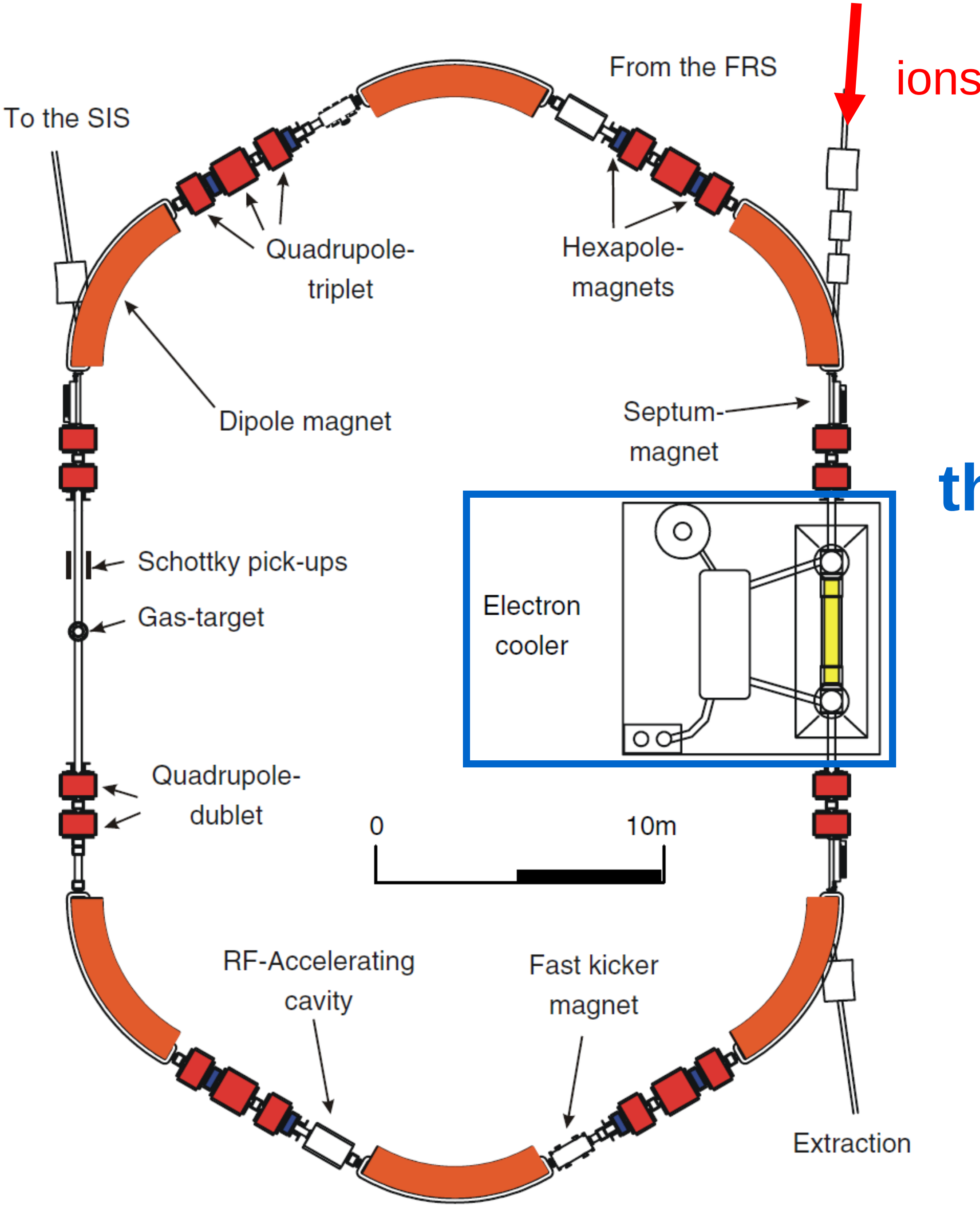
E. Cornell   W. Ketterle   C. Wieman



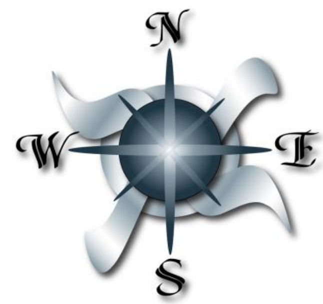
UHV, ~10^{-11} mbar

bakeout ~300 ºC

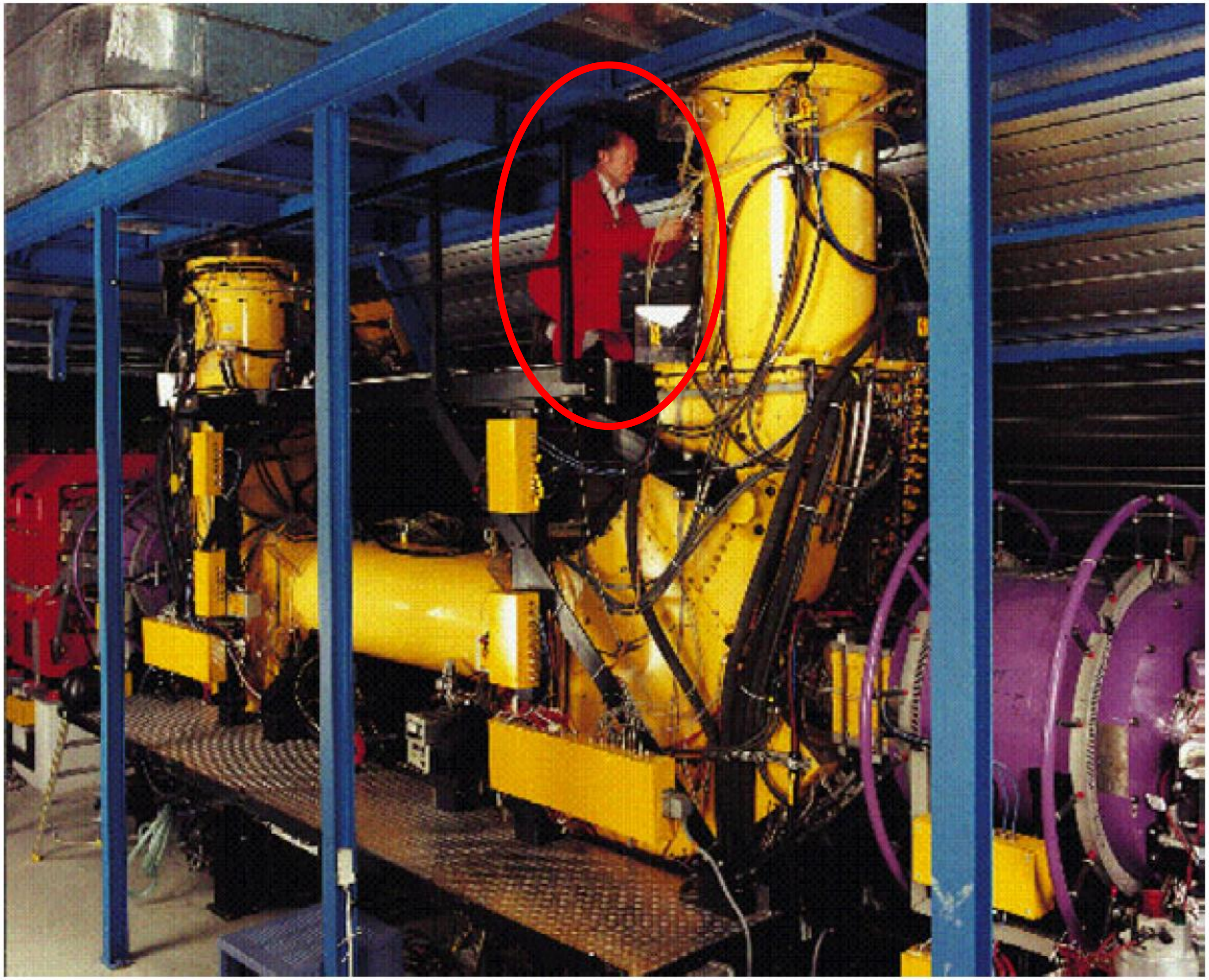
Experimental Storage Ring



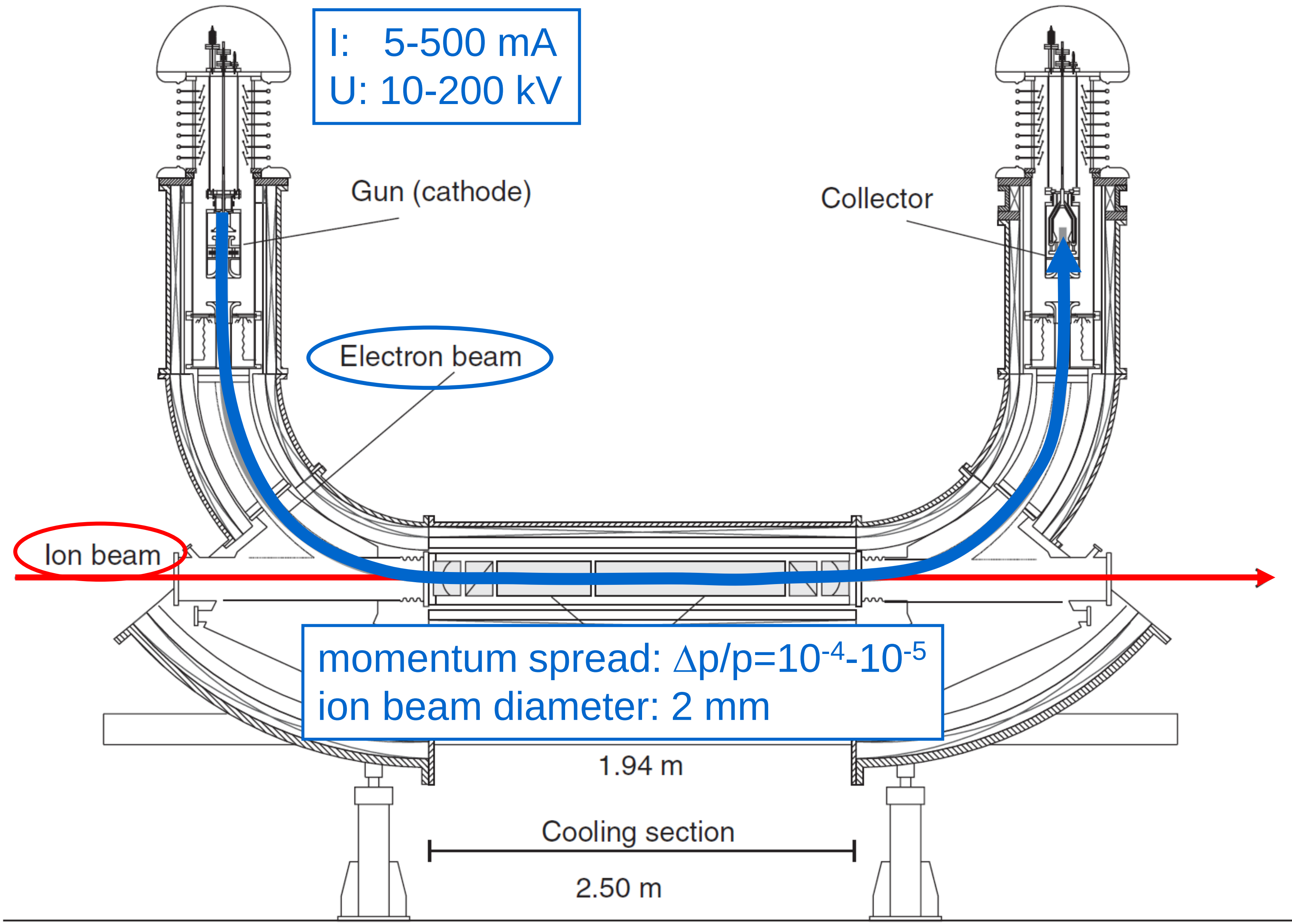
the electron cooler



photograph of the electron cooler

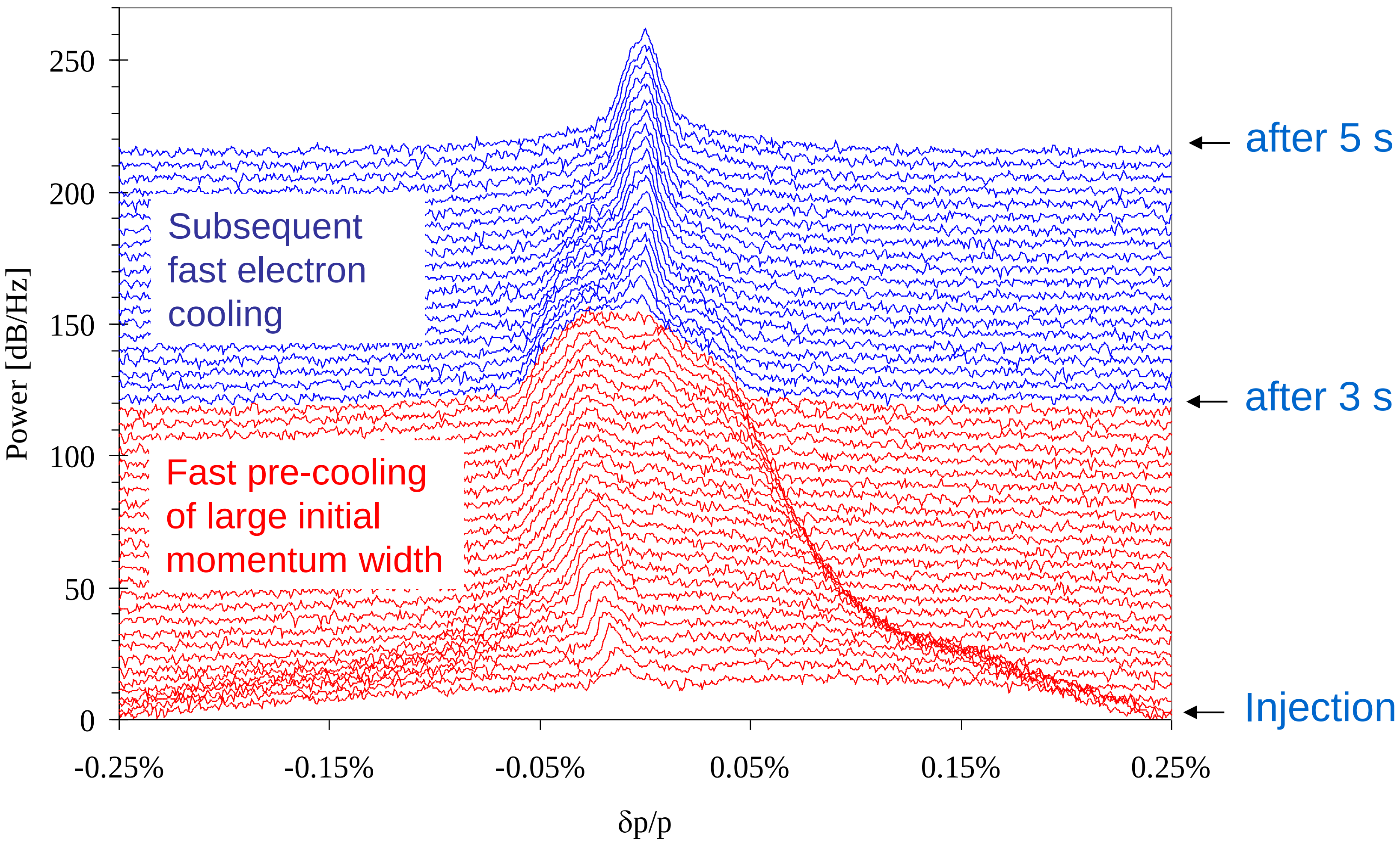


the electron cooler at the ESR

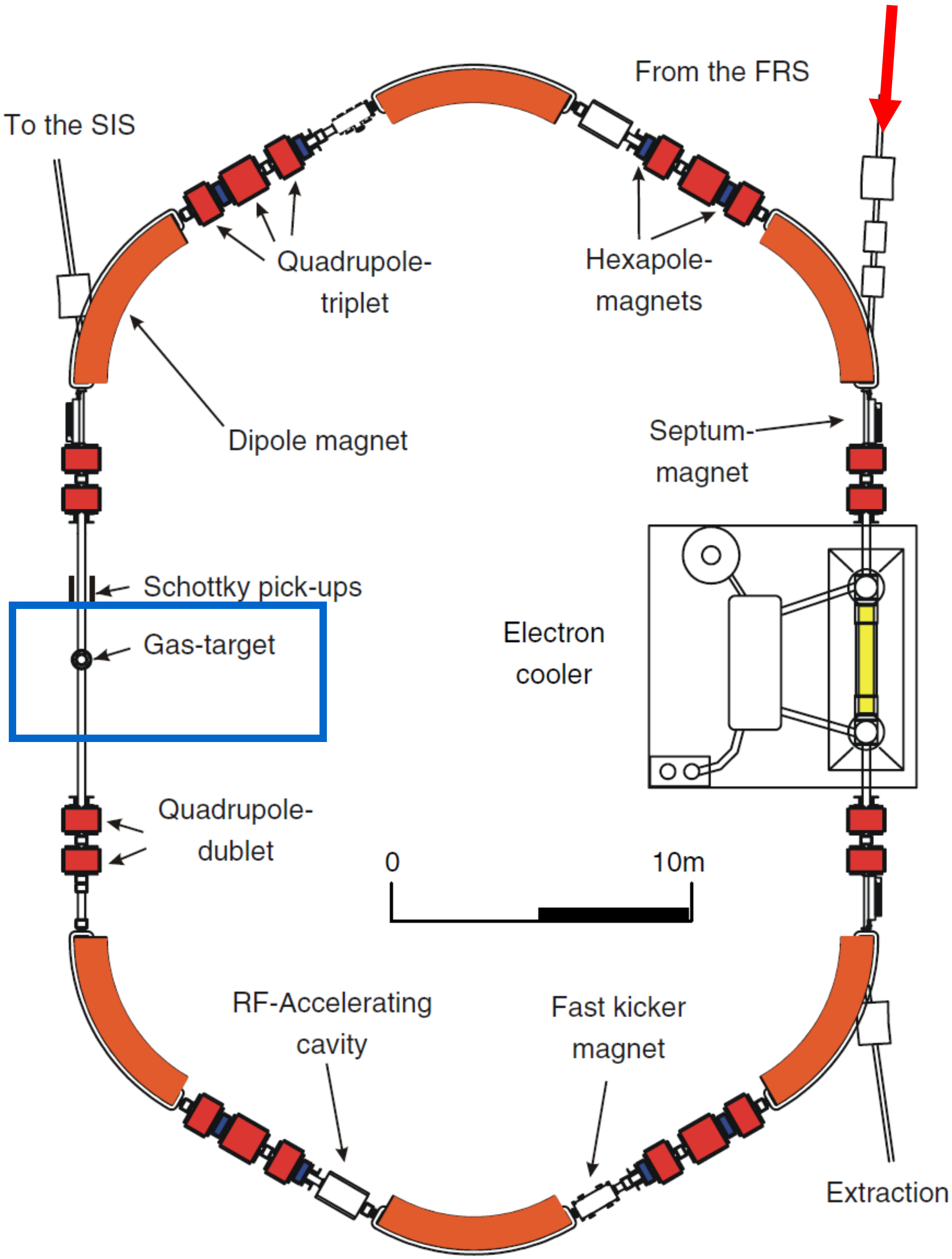


cooling: narrowing velocity, size and divergence

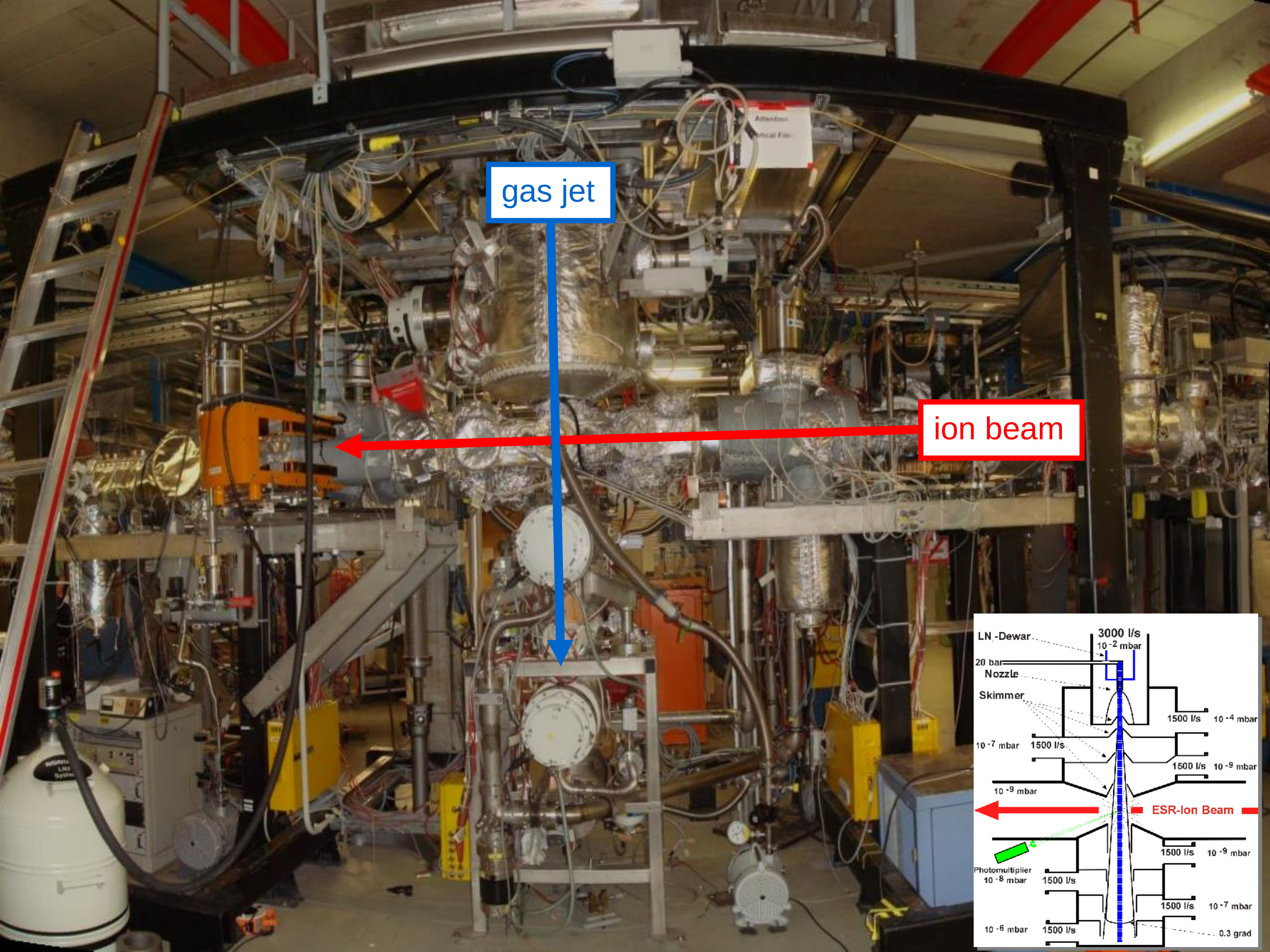
Primary uranium beam



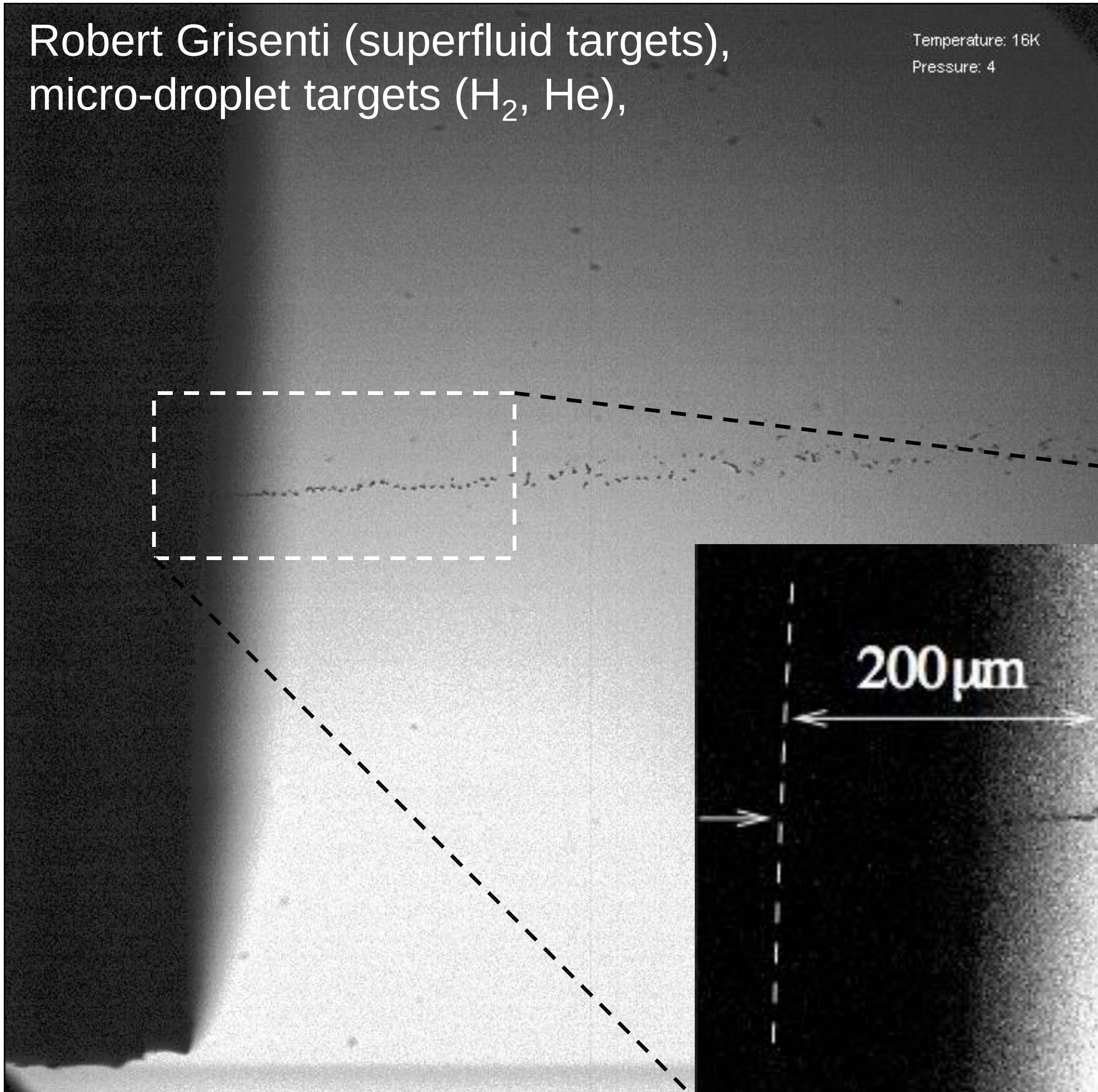
momentum distribution

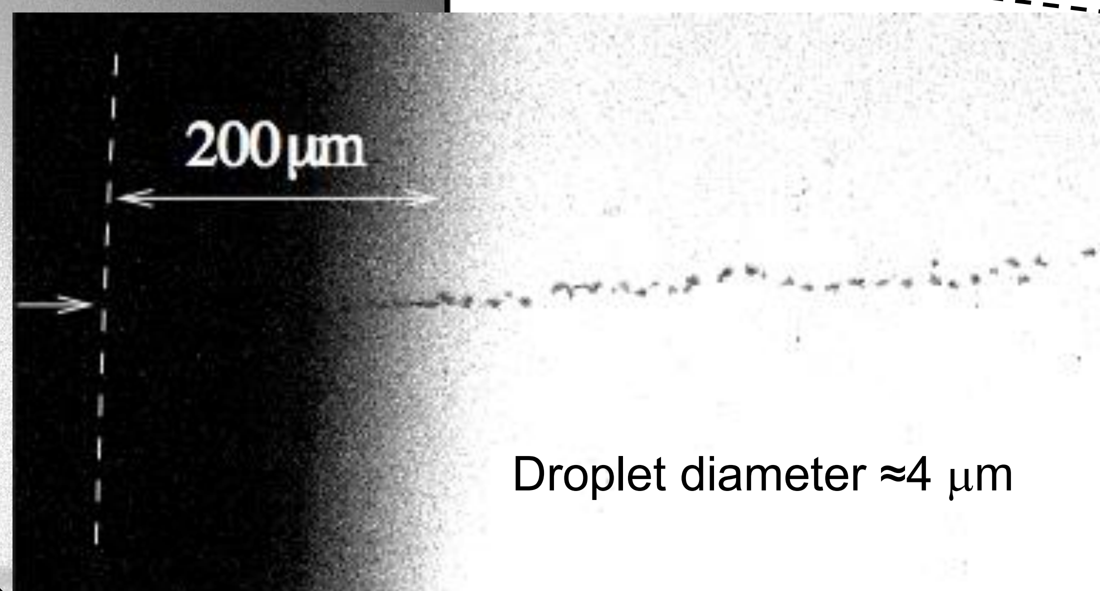


internal target
(gas jet H_2, He, N_2...)


gas jet
ion beam
LN -Dewar
3000 l/s
10 -2 mbar
20 bar
Nozzle
Skimmer
1500 l/s
10 -4 mbar
10 -7 mbar
1500 l/s
1500 l/s
10 -9 mbar
10 -9 mbar
ESR-Ion Beam
1500 l/s
10 -9 mbar
Photomultiplier
10 -8 mbar
1500 l/s
1500 l/s
10 -7 mbar
10 -6 mbar
1500 l/s
0.3 grad

new liquid targets with high densities



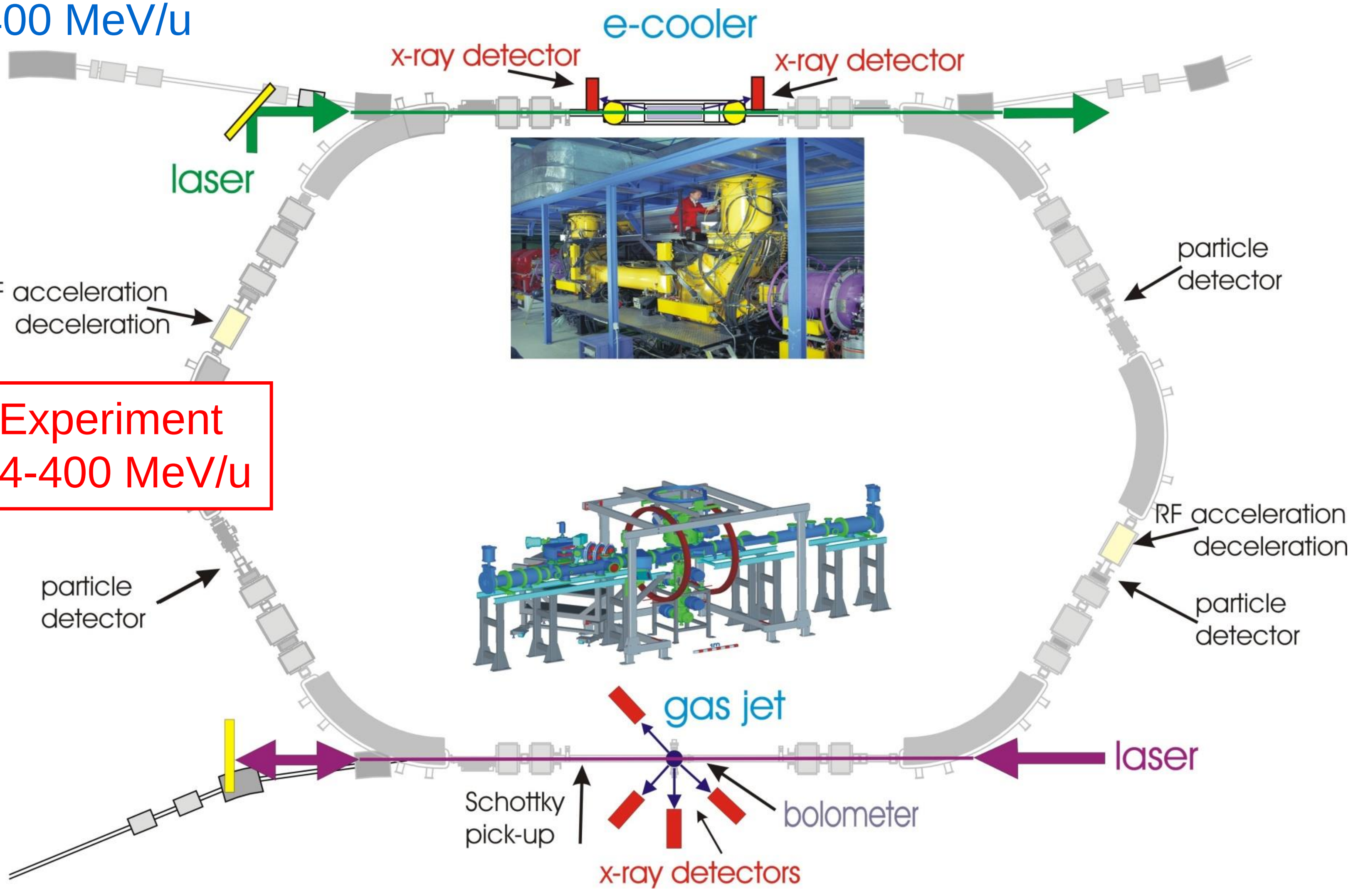


Design goal for HESR:
jet-diameter below 1 mm;
densities 10^{11} - 10^{16} 1/cm^3

Spectroscopy at the ESR

Injection Energy
400 MeV/u

Experiment
4-400 MeV/u



Beamtime @ GSI („Strahlzeit)“

<table>
<tr><th colspan="10">Block 2 / 2011</th><th colspan="11">August 2011</th><th colspan="10">Schedule as of 17-Aug-2011</th></tr>
<tr><th colspan="7">Week 31</th><th colspan="7">Week 32</th><th colspan="7">Week 33</th><th colspan="7">Week 34</th><th colspan="3">Week 35</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th>31</th></tr>
<tr><td></td><td colspan="13">UMAT, Severin/Trautmann, Au (PIG), 50 Hz, 4.8 MeV/u, 3 ms, M</td><td></td><td></td><td></td><td></td><td colspan="13">U258, Düllmann/Düllmann, 50Ti, 4.5-5.5 MeV/u, >500 pnA in X8, 50 Hz, 5 ms, X8 TASCA</td></tr>
<tr><td></td><td colspan="13">UMAT, Severin/Trautmann, Au (PIG), 11,4 MeV/u, 50 Hz, 3 ms, X0</td><td colspan="2">UBIO, Au, 11,4 MeV/u, 5 Hz, 3 ms, X6</td><td colspan="2">UMAT Au, 4,8 MeV/u, 5 Hz, M3</td><td colspan="5"></td><td colspan="3">U224, O. Rosmej, 50Ti, 4.7 MeV/u, 1-5 umA, 5Hz, Z6</td><td></td><td></td><td colspan="3">U266, O. Rosmej, 50Ti, 4.7 MeV/u, maximal, Z6</td></tr>
<tr><td colspan="31"></td></tr>
<tr><td colspan="3">a) SMAT Bi, 200 MeV/u, HTA</td><td colspan="11">S371, Cuttone/Pleskac, 12C (EZR), 200, 400 and 1000 MeV/u, 1E4-1E5/spill, slow extr., 1-10 s spill, flat spill, HTC</td><td colspan="4">b) S407, Au, 1E7/spill, HAD</td><td colspan="13"></td></tr>
<tr><td colspan="3">c) S371, 12C, HTC</td><td colspan="5">S402, Bozyk/Spiller, Bi (MEVVA), 50 MeV - 900 MeV, 1E9/spill, fast extr., HHT</td><td colspan="4">d) S407, Au, 1E6/spill, HAD</td><td colspan="3">e) S323, Bi, FRS</td><td colspan="3">S390, Liu/ Gerl, 600 MeV/u, 1e8/spill, nights only, HTC</td><td colspan="13"></td></tr>
<tr><td colspan="31"></td></tr>
<tr><td colspan="8">E083/E101, Nörtershäuser/Winters, 209Bi80+, 209Bi82+ (MEVVA), 400 MeV/u, 1E8 ions in ESR, ESR</td><td colspan="10">E103/E090, Gumberidze/Hagmann, Bi (MEVVA), 50 MeV/u, highest intens., ESR</td><td colspan="8"></td><td colspan="3">ESR</td><td></td><td></td></tr>
</table>

Allocated beam time blocks include the accelerator tuning time - each Tuesday 8:00 to 16:00 is reserved for accelerator service

a) SMAT, Schuster/Trautmann, Bi, 200 MeV/u, 1E9/spill, 1s extr., HTA

b) S407, Salabura/Pietraszko, Au(PIG), 1,25GeV/u, 1E7/spill, fast ramping, HAD

c) S371, Cuttone/Pleskac, 12C (EZR), 200, 400 and 1000 MeV/u, 1E4-1E5/spill, slow extr., 1-10 s spill, flat spill, HTC

d) S407, Salabura/Pietraszko, Au(PIG), 1,25GeV/u, 1E6/spill, fast ramping, HAD

e) S323, Montes/Nociforo, Bi (MEVVA), 1GeV/u, 1E9/spill, FRS

Topics:

Electron spectroscopy

Dielectronic recombination

Mass spectrometry

X-ray spectroscopy

Laser spectroscopy and laser cooling

Electron spectroscopy at the high-energy endpoint of electron-nucleus bremsstrahlung

Pierre-Michel Hillenbrand[1,2]

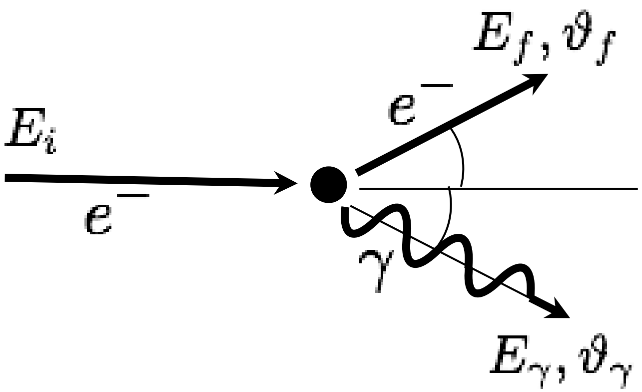
S. Hagmann[1,3], D. Atanasov[1], D. Banas[4], C. Brandau[2,5], K.-H. Blumenhagen[6], W. Chen[1],
E. DeFilippo[7], A. Gumberidze[1,5], D. Guo[8], C. Kozhuharov[1], M. Lestinsky[1], Y. A. Litvinov[1], A. Müller[2], H. Rothard[10],
S. Schippers[2], U. Spillmann[1], M. Schöffler[3], S. Trotsenko[1,6], N. Winckler[1], X. Yan[8], X. Zhu[8], Th. Stöhlker[1,6]

with Theory support from
D. Jakubaßa-Amundsen[11], A. Surzhykov[6] & V. A. Yerokhin[9], A. Voitkiv[12] & B. Najjari[12]

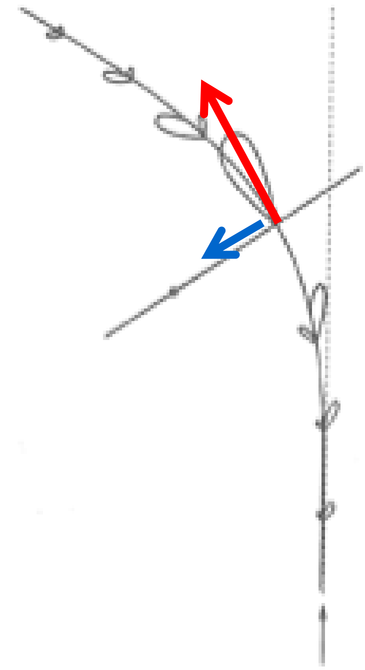
[1]GSI Darmstadt, [2]Universität Giessen, [3]Universität Frankfurt, [4]Jan Kochanowski University, Poland,
[5]ExtreMe Matter Institute, [6]Helmholtz-Institut Jena, [7]INFN Catania, Italy, [8]IMP Lanzhou, China,
[9]Universität Heidelberg, [10]CIRIL-GANIL, Caen, France, [11]LMU München, [12]MPI-K Heidelberg

Motivation

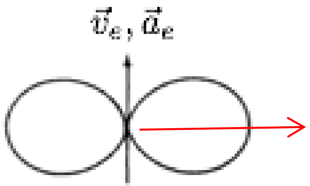
- Fundamental process of electron-nucleus bremsstrahlung („breaking radiation“)



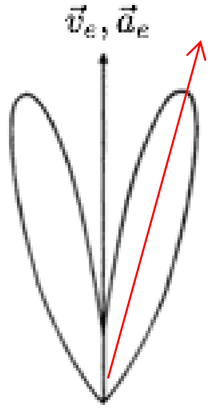
$$E_\gamma = E_f - E_i$$



photon emission perpendicular to electron acceleration



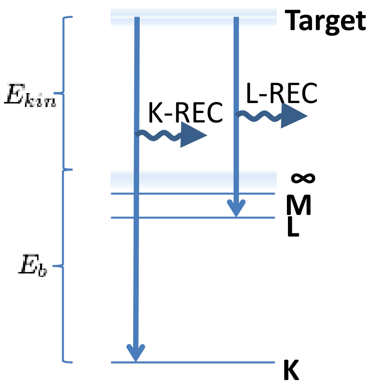
low energy
$\sim sin^2\vartheta_\gamma$



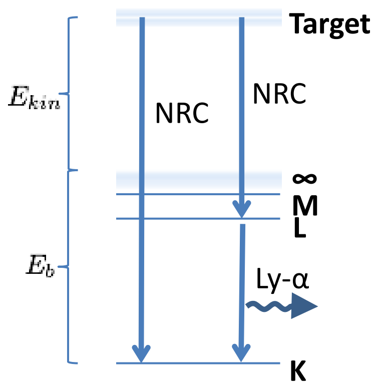
high energy
forward emission

(Radiative) electron capture to continuum

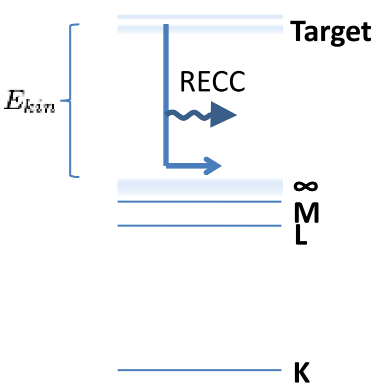
- electron capture processes in ion-atom collisions



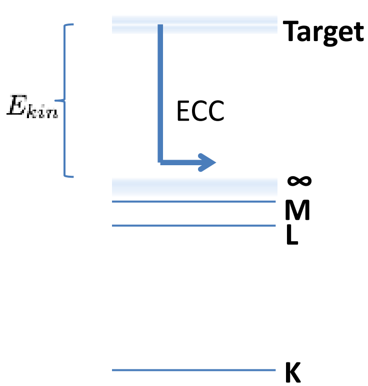
Radiative electron capture



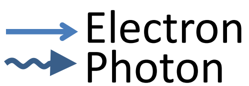
Nonradiative electron capture

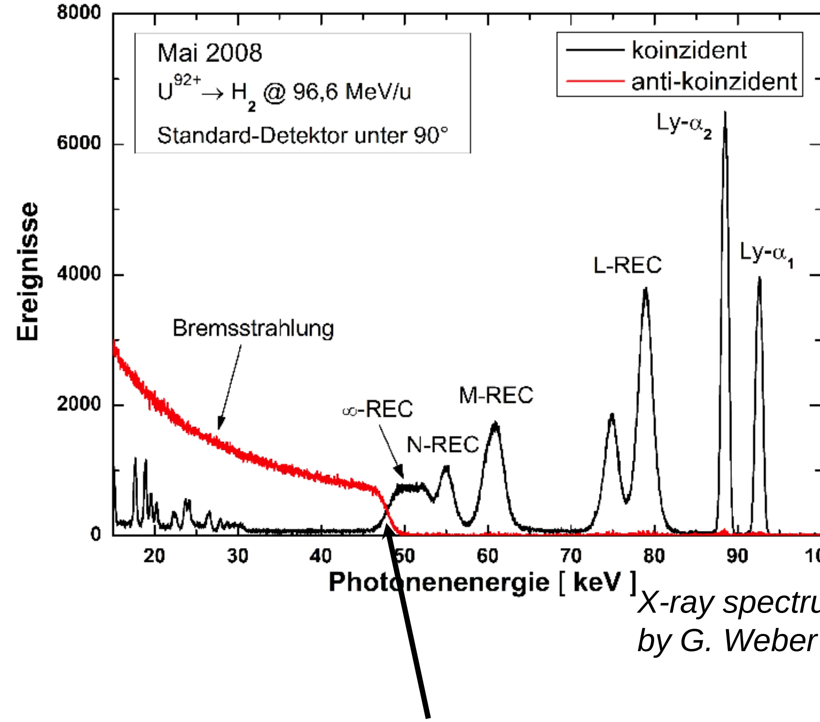


Radiative electron capture into continuum



Nonradiative electron capture into continuum

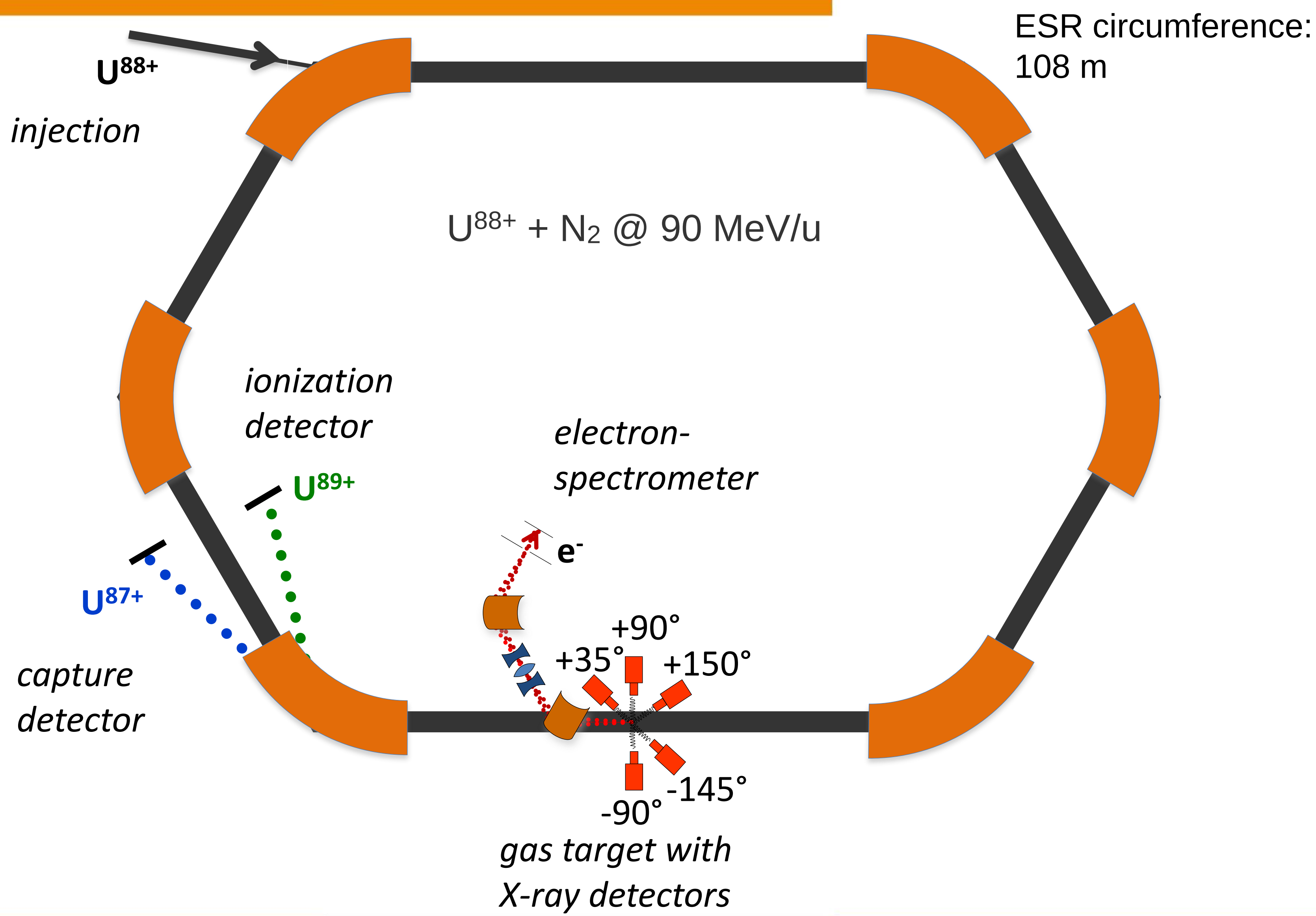


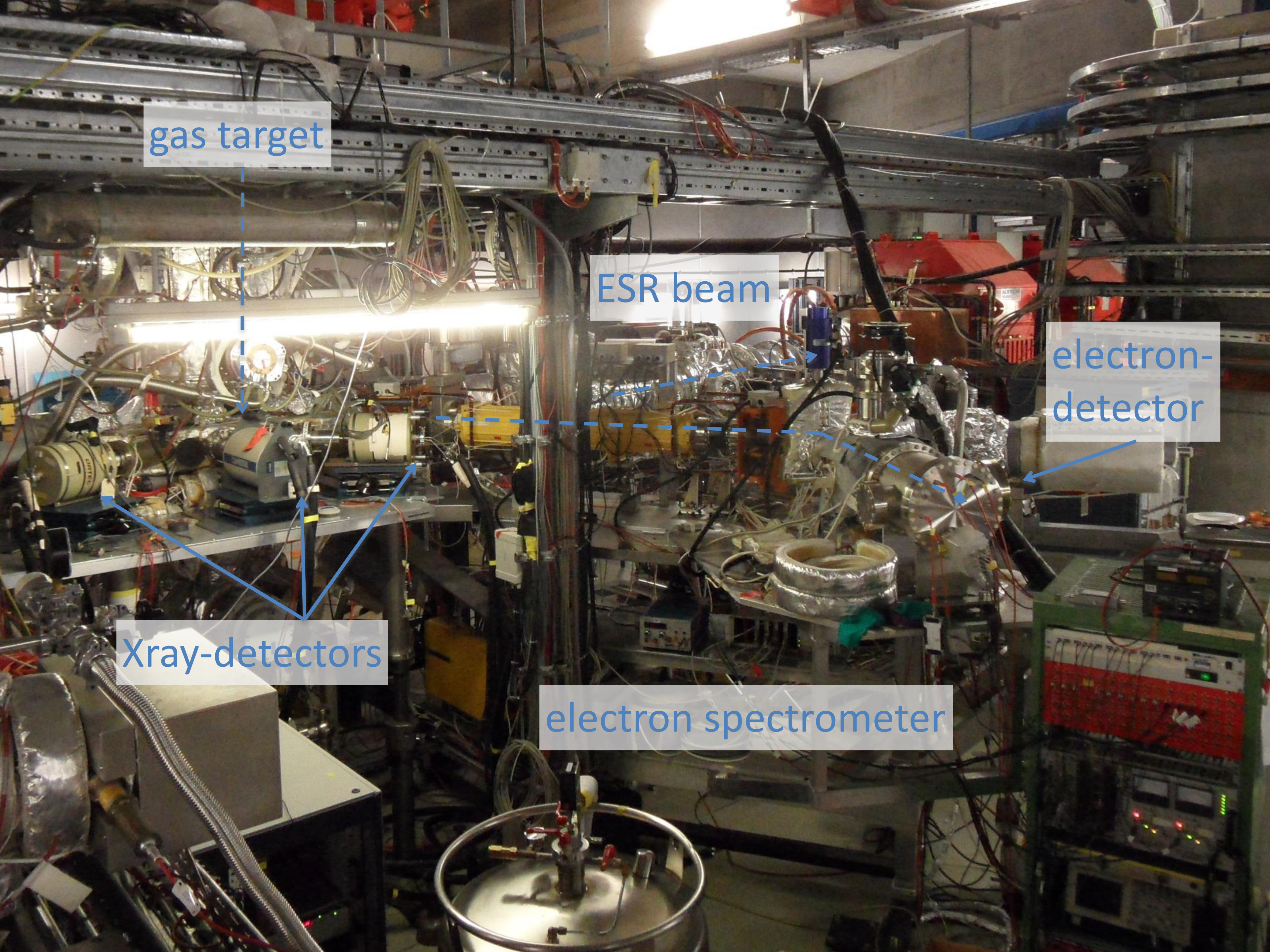


X-ray spectrum by G. Weber et a

Radiative electron capture into continuum

Experimental setup at the ESR

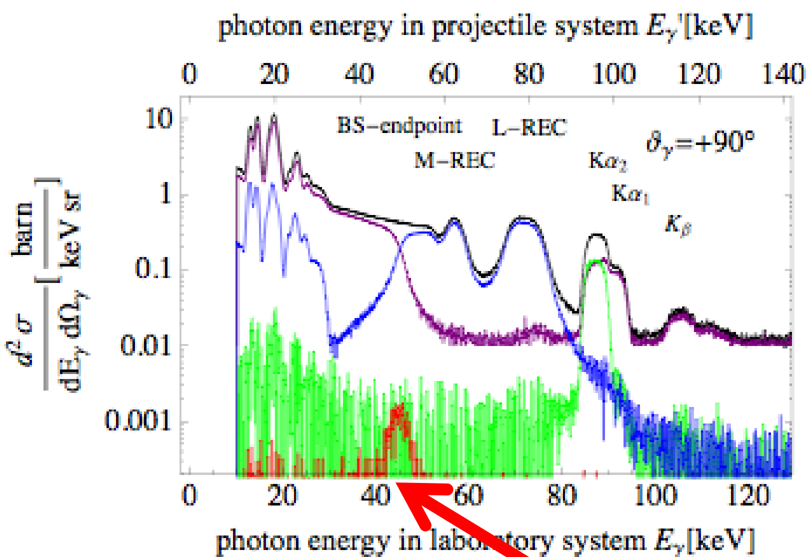


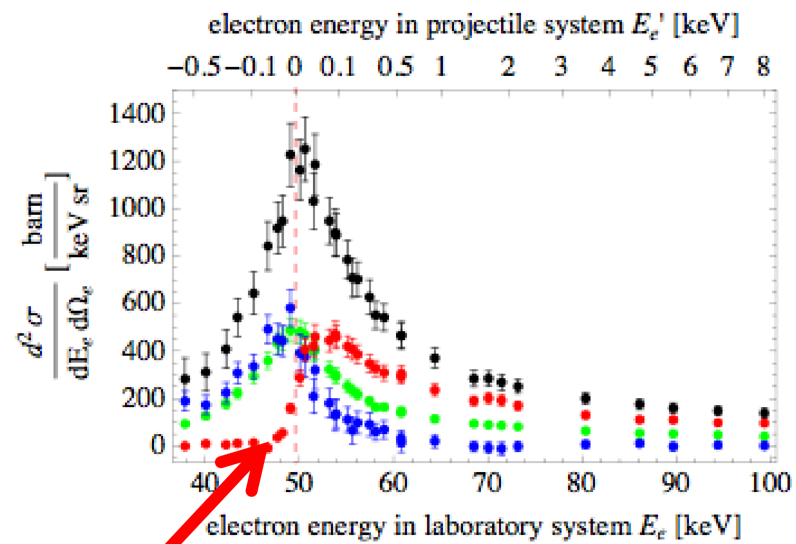

gas target
ESR beam
electron-
detector
Xray-detectors
electron spectrometer

Summary & Outlook

x-ray spectra

electron spectra





RECC

Topics:

Electron spectroscopy

Dielectronic recombination

Mass spectrometry

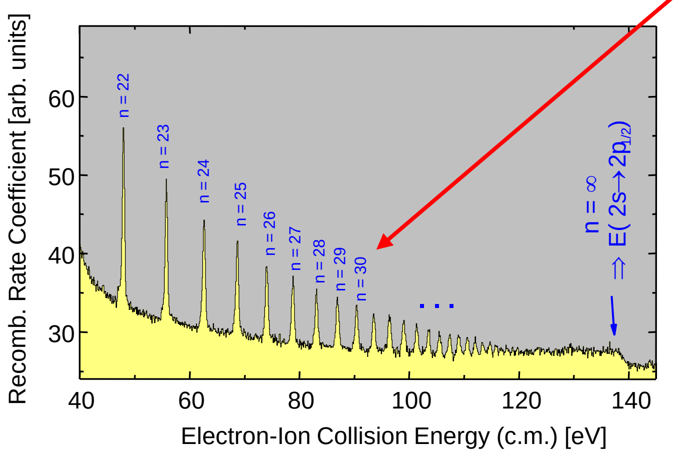
X-ray spectroscopy

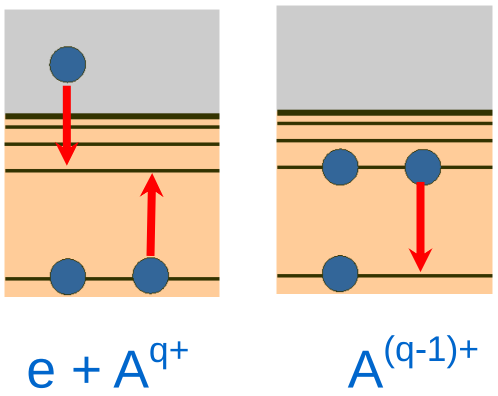
Laser spectroscopy and laser cooling

Electron target → Dielectronic Recombination

The heavy highly-charged ions capture electrons from the electron cooler.

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

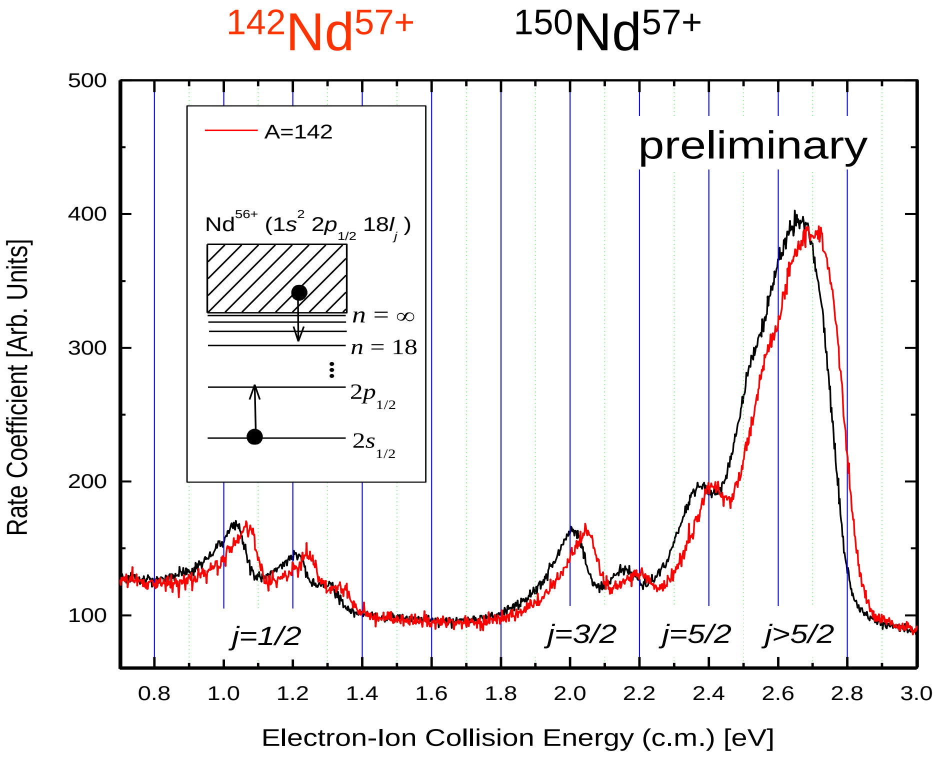




DR experiments of Li-like heavy ions at the ESR: the achieved accuracy is comparable with that of x-ray experiments

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:

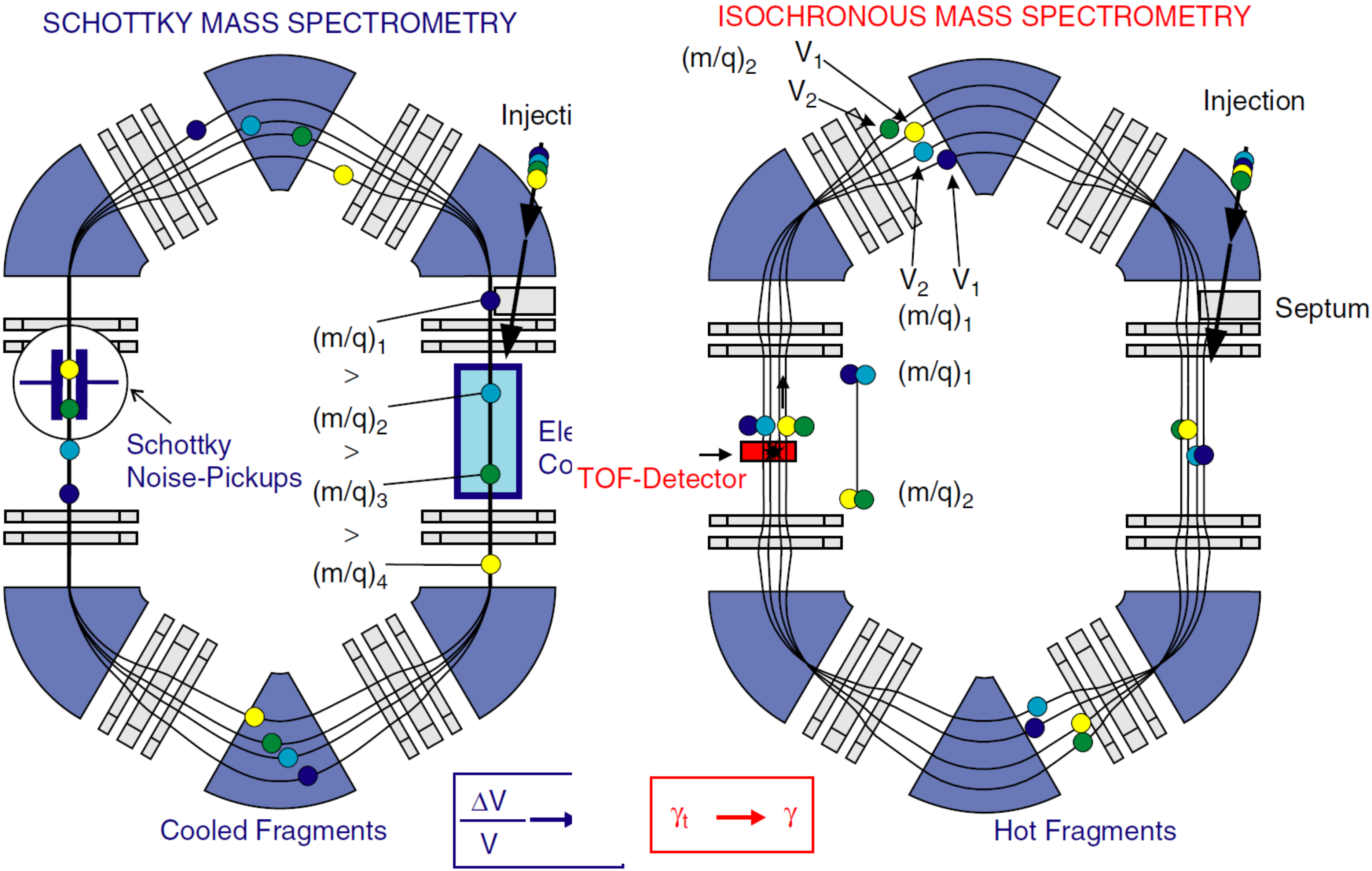
Electron spectroscopy

Dielectronic recombination

Mass spectrometry

X-ray spectroscopy

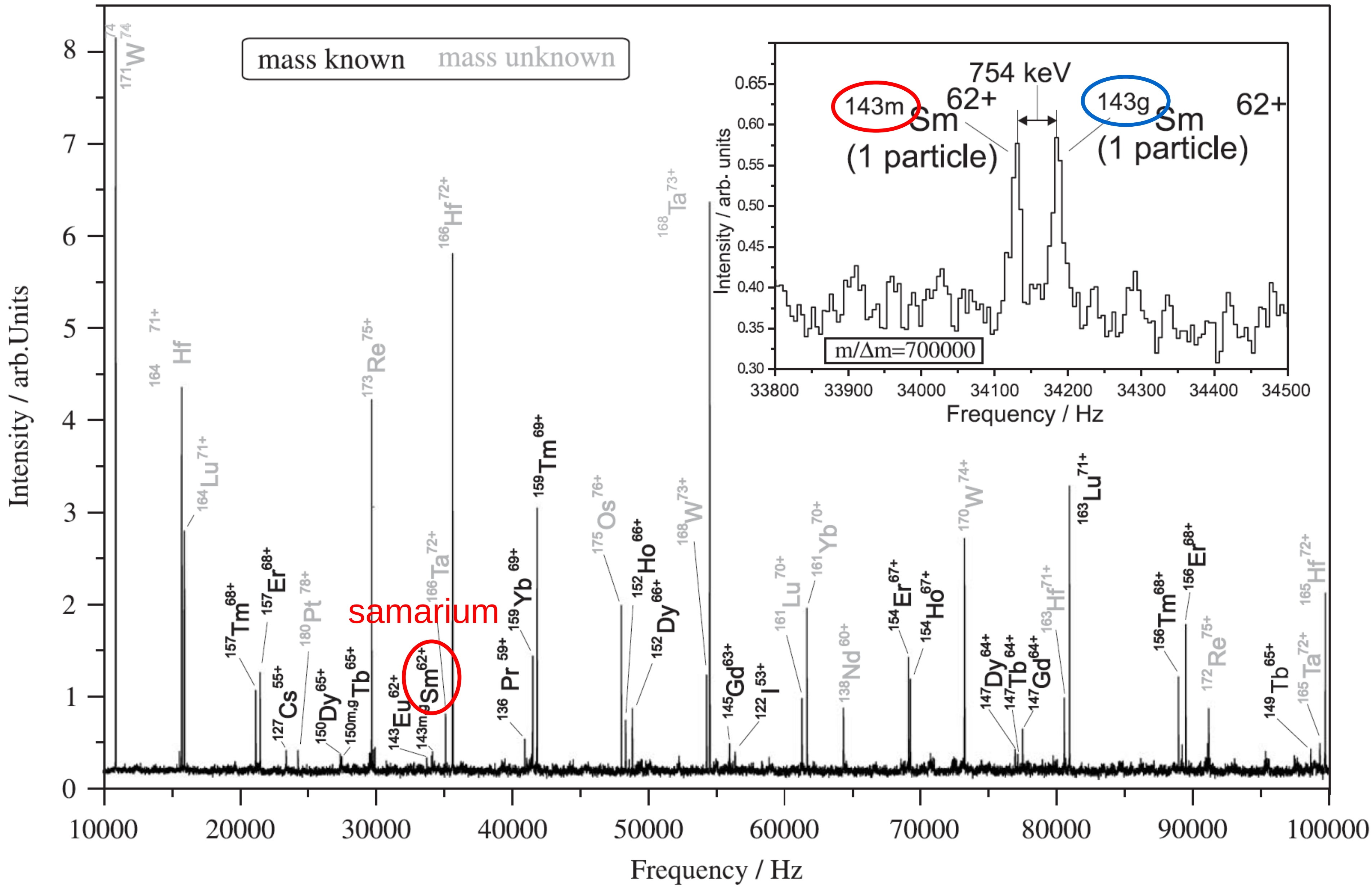
Laser spectroscopy and laser cooling



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:

Electron spectroscopy

Dielectronic recombination

Mass spectrometry

X-ray spectroscopy

Laser spectroscopy and laser cooling

The 1s-Lamb Shift in heavy H-like ions

H. Beyer, T. Gassner, R. Heß,

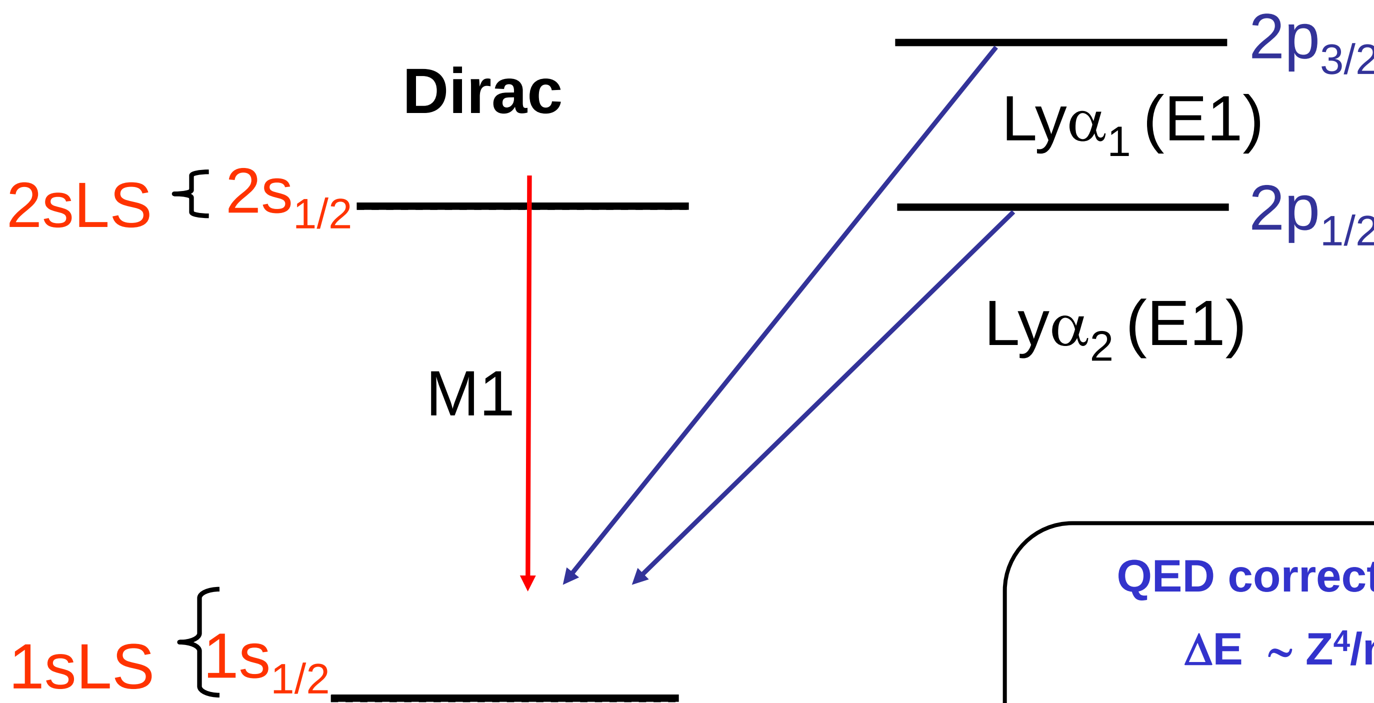
A. Gumberidze, U. Spillmann, Th. Stöhlker et al.

Helmholtz Institut Jena

GSI Darmstadt, Atomic Physics

Motivation: QED Test in Strong Fields

Term scheme of a hydrogen like system according to Dirac



$$(E_{2p_{3/2}}^{\text{theory}} - E_{\text{Ly-}\alpha_1}^{\text{experiment}}) - E_{1s_{1/2}}^{Dirac} = \Delta E_{LS}$$

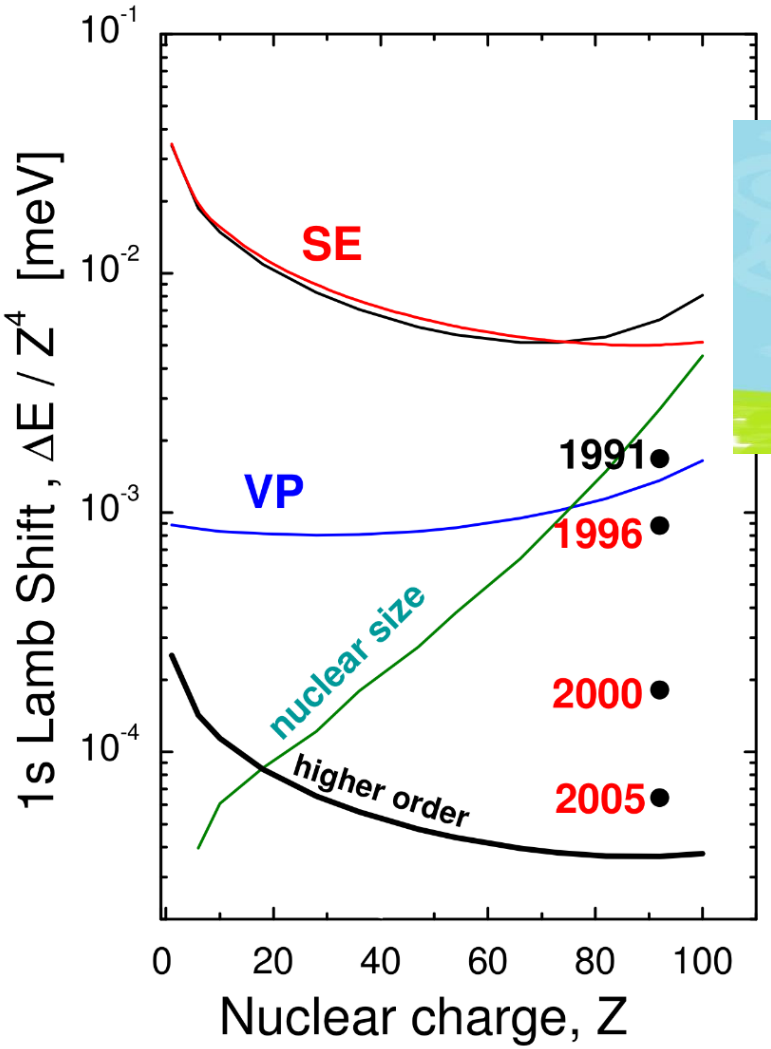
QED corrections

$\Delta E \sim Z^4/n^3$

Z: nuclear charge
n: principal quantum number

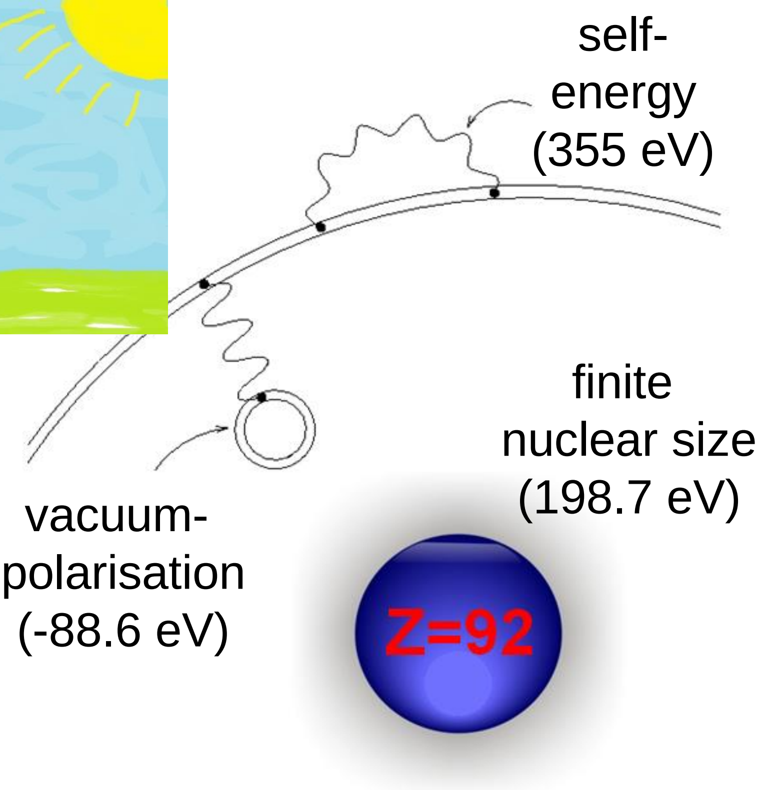
important for s-states

Motivation: QED Test in Strong Fields



U^{91+} K-shell binding energy:

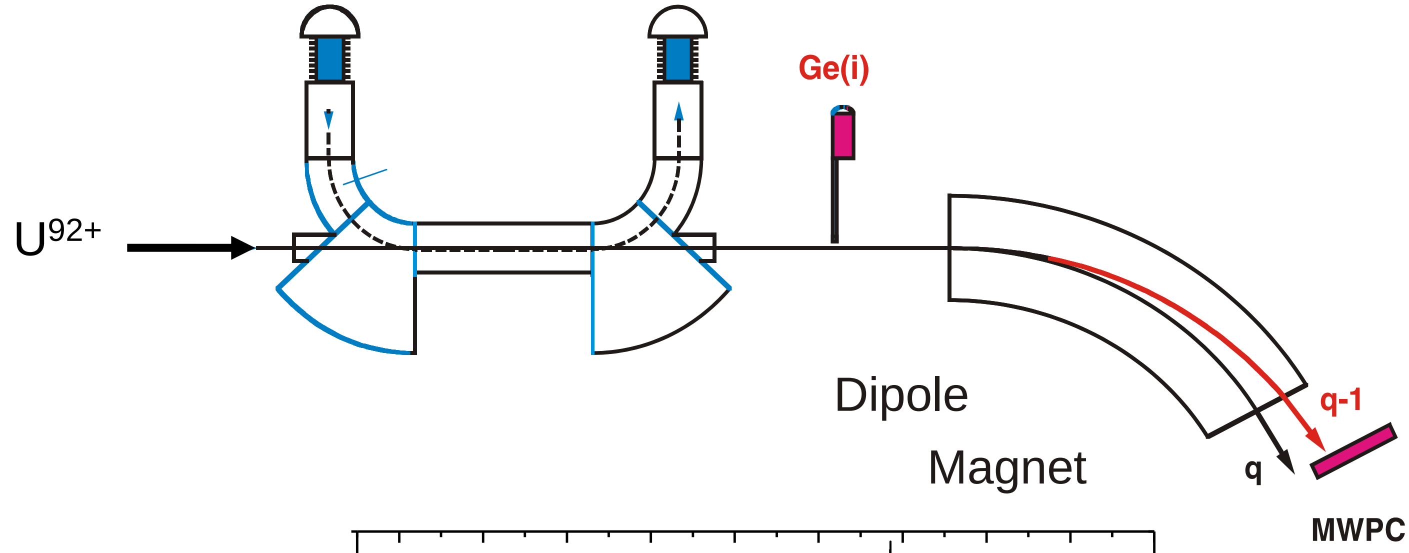
E_K = 132 keV

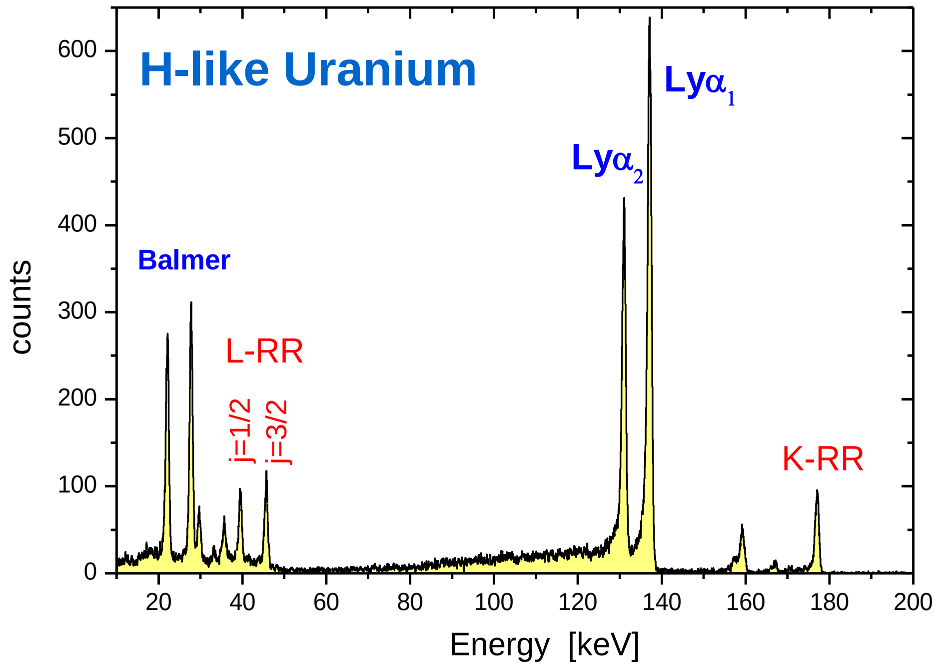


Higher order contribution:

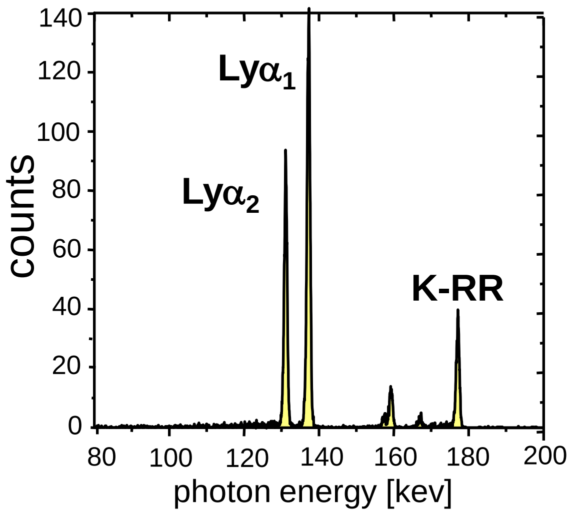
E_{HO}< 1 eV

0º x-ray spectroscopy at the electron cooler





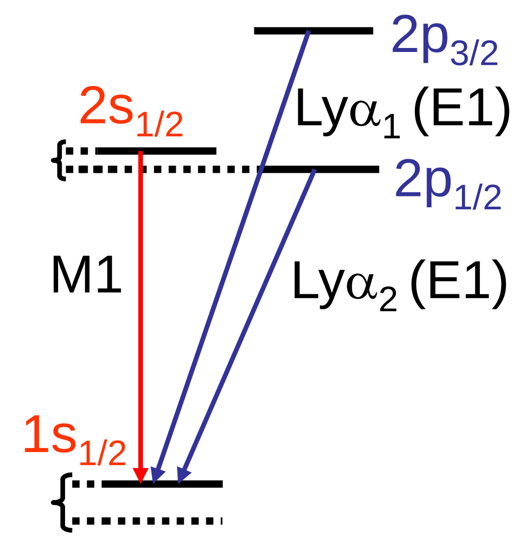
the 1s-Lamb shift in He-like U → a test of QED



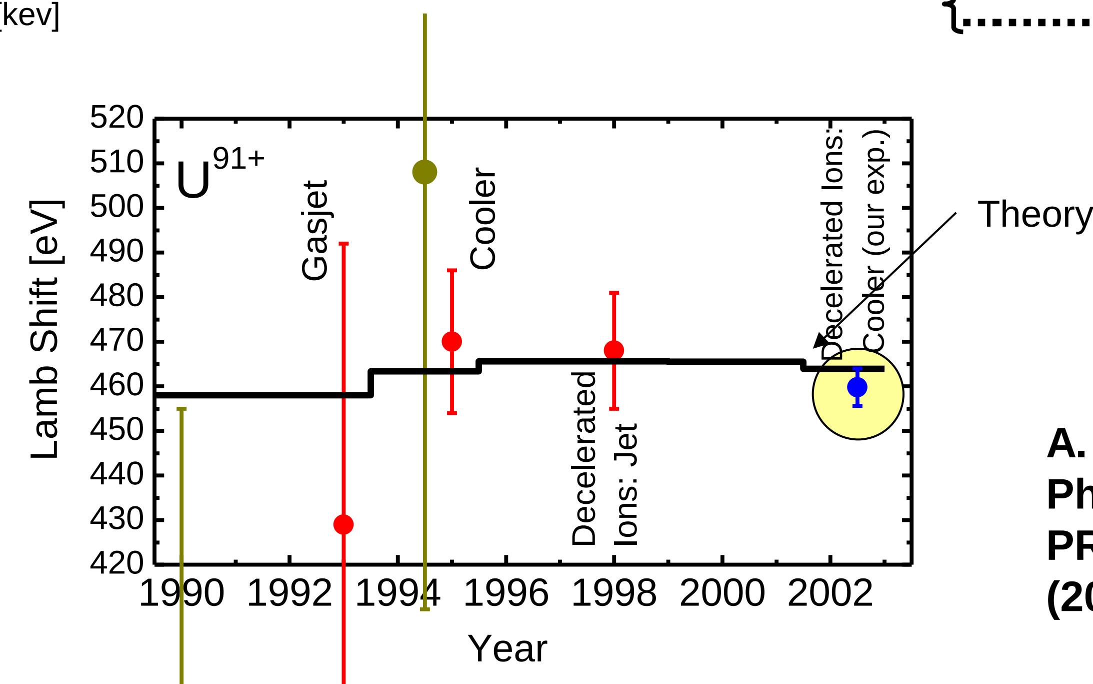
1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV



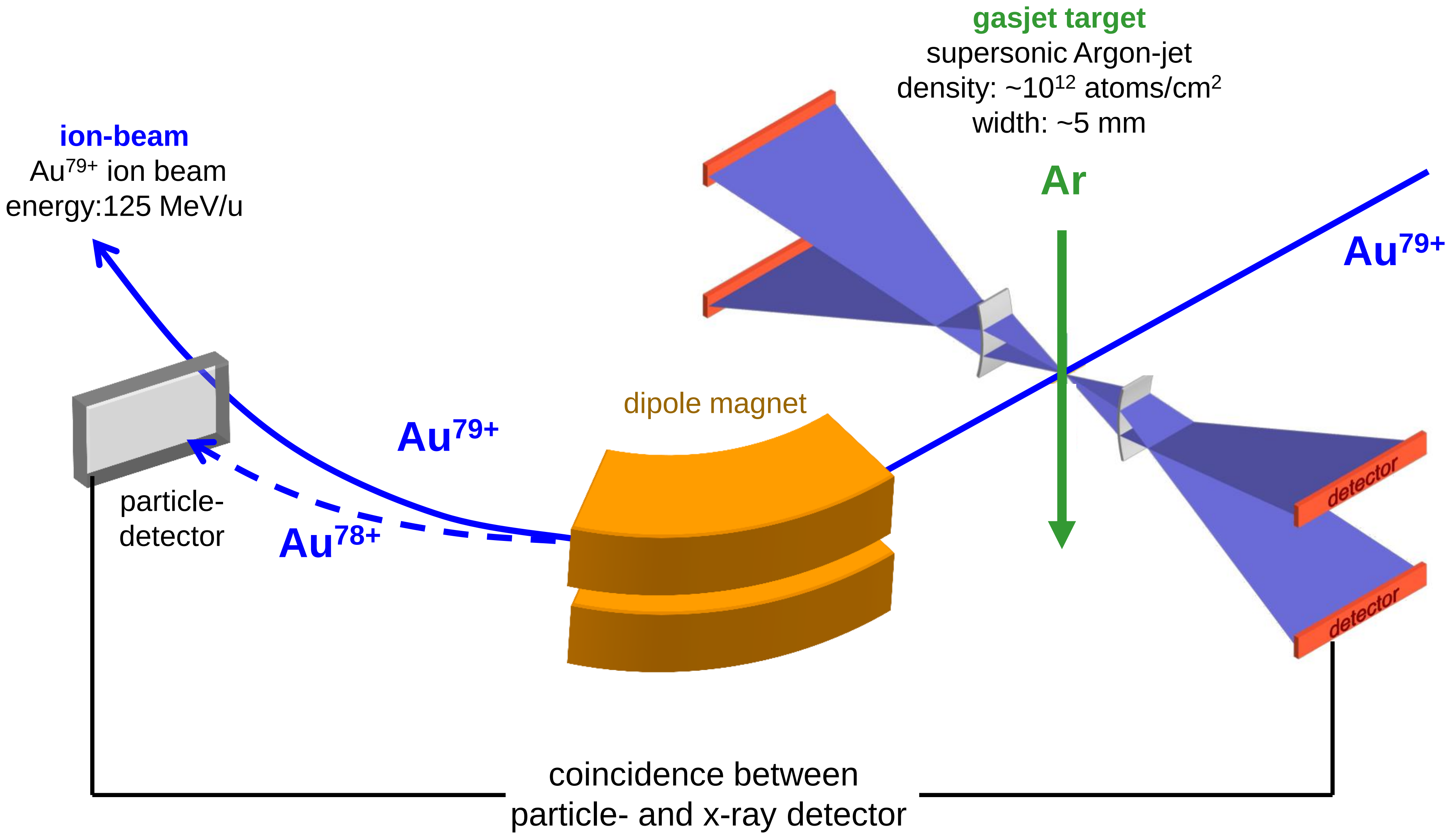
459.8±2.3±3.5 eV



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

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

Tests in 2003 and 2006
FOCAL experiment in April / May 2012

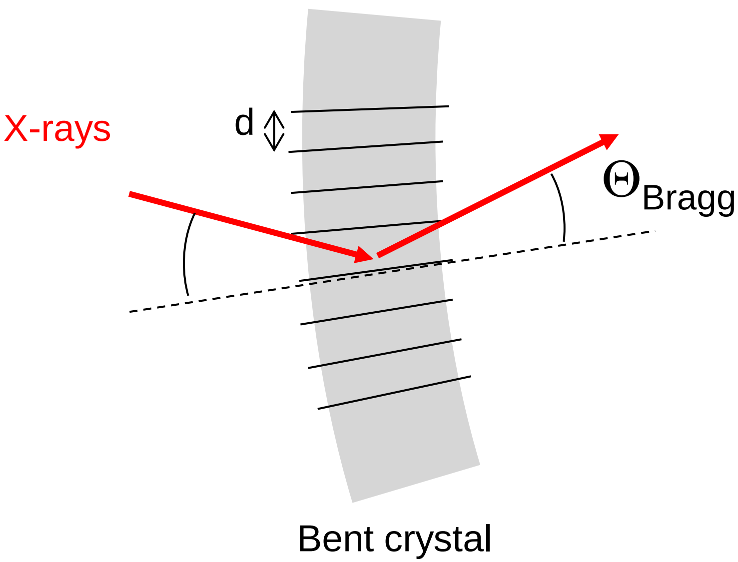


3 – 5 counts/h

Laue-Crystal-Spectrometer

Bragg-Laue Relation

$$\lambda = 2 \cdot d \cdot \sin\Theta$$



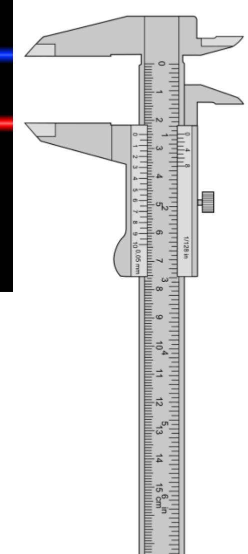
crystal-spectrometer

measurement of the reflection angle

➔determination of the wave-length

resolution: ~ 75 eV @ 60 keV

Δy ➔ ΔE : 1mm ≈ 750 eV



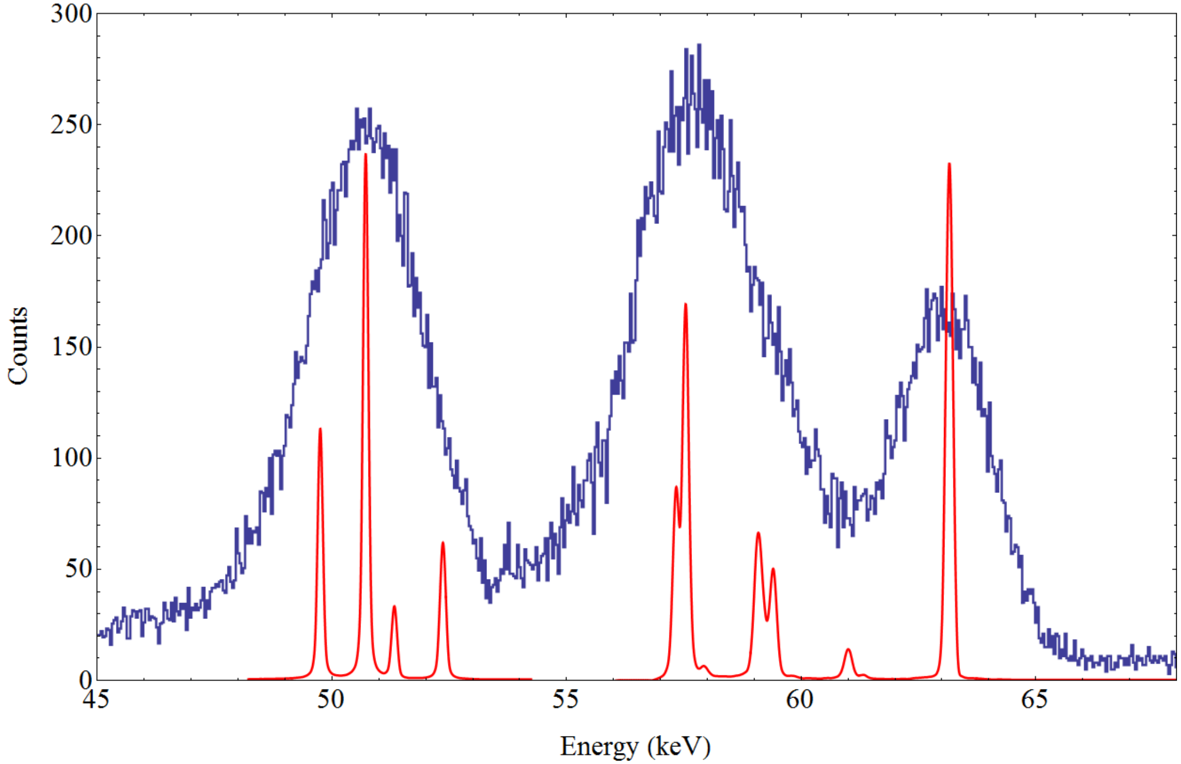
the „trick“: energy → angle → position

Ge(i) detector vs. FOCAL

Spectrum of a ^{169}Yb Source recorded with a single strip of the Ge-detector

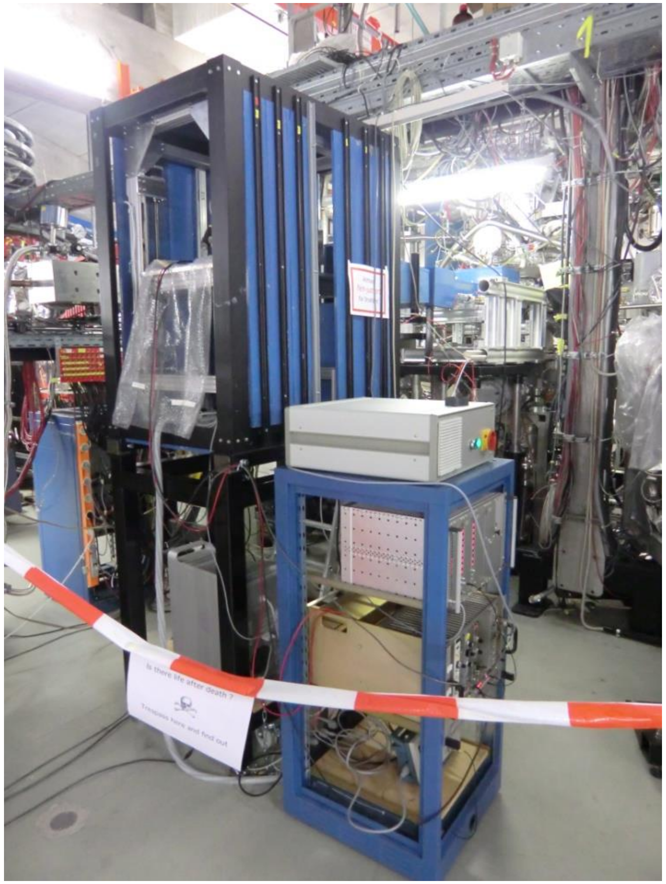
resolution ≈ 100 eV / 100 keV ≈ 10^{-3}
efficiency ≈ 10^{-4}

Same spectrum obtained with the combination crystal spectrometer – Ge-detector
$\Delta E/E$ ≈ 1 eV / 100 keV ≈ 10^{-5}
$\varepsilon \approx 10^{-8}$

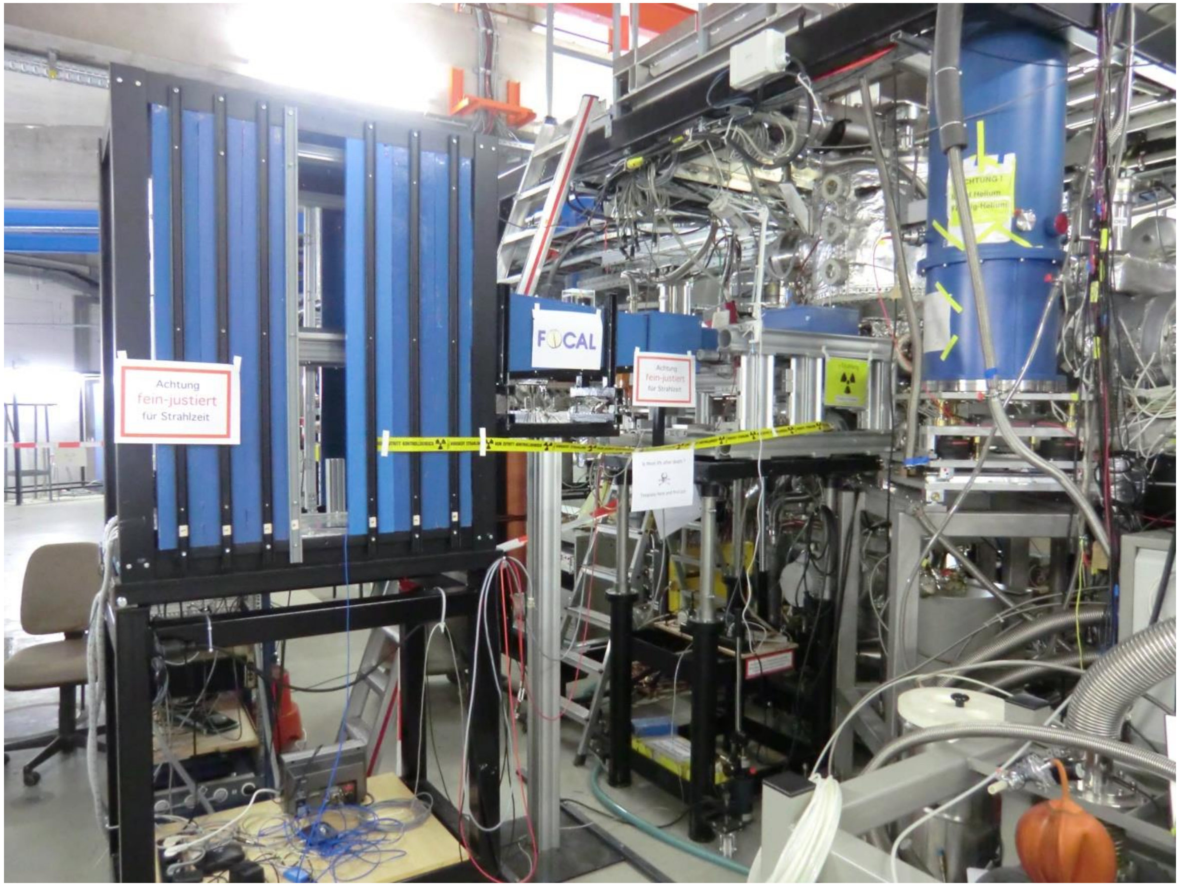


Experiment Impressions

FOCAL 1

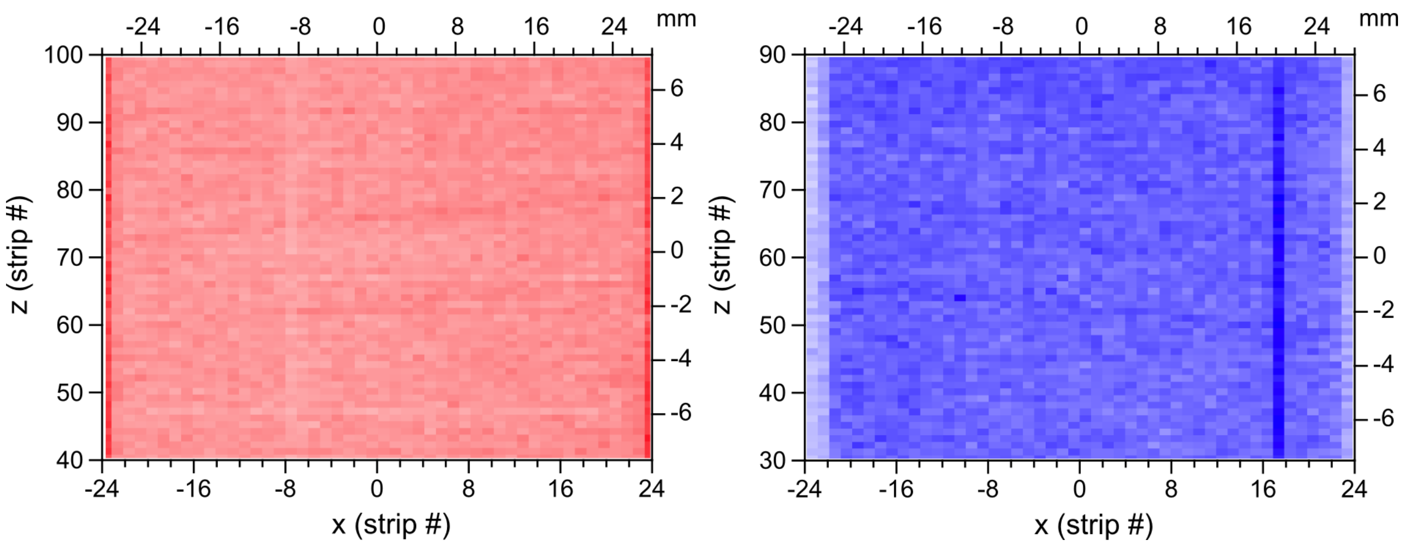


FOCAL 2

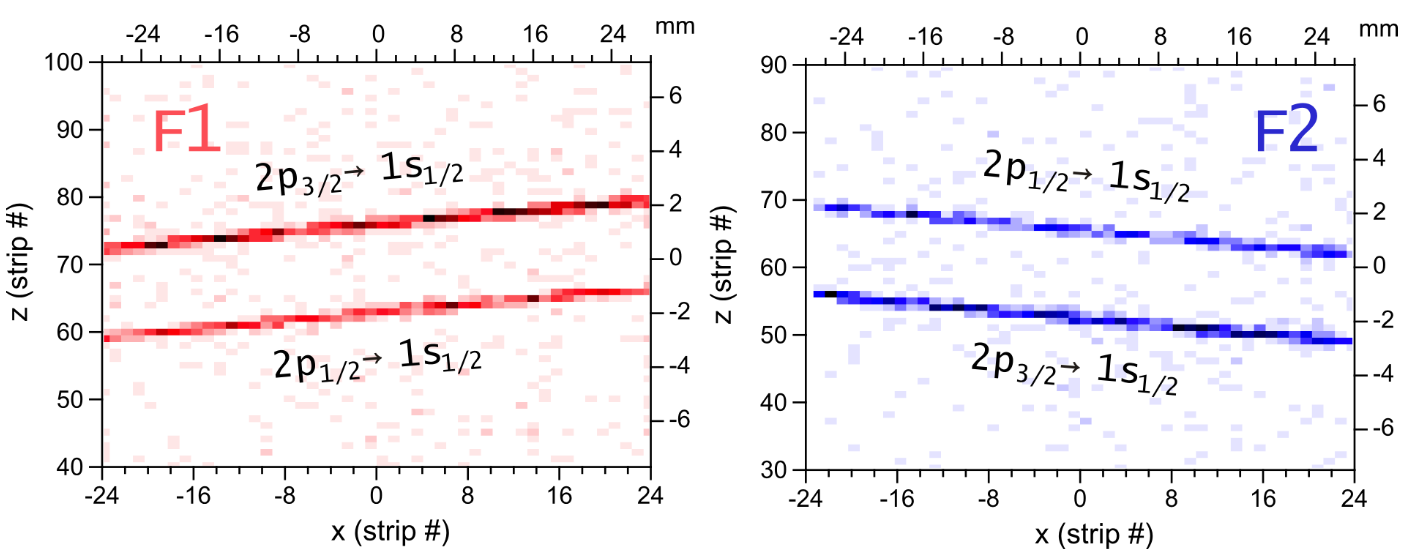


Preliminary results

Raw 2D spectrum



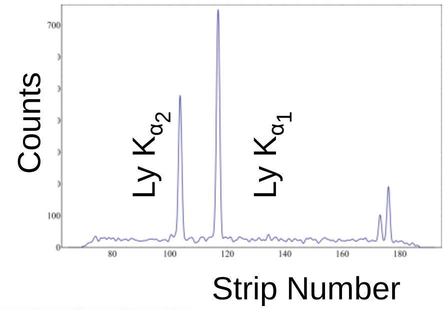
2D spectrum with energy and time condition

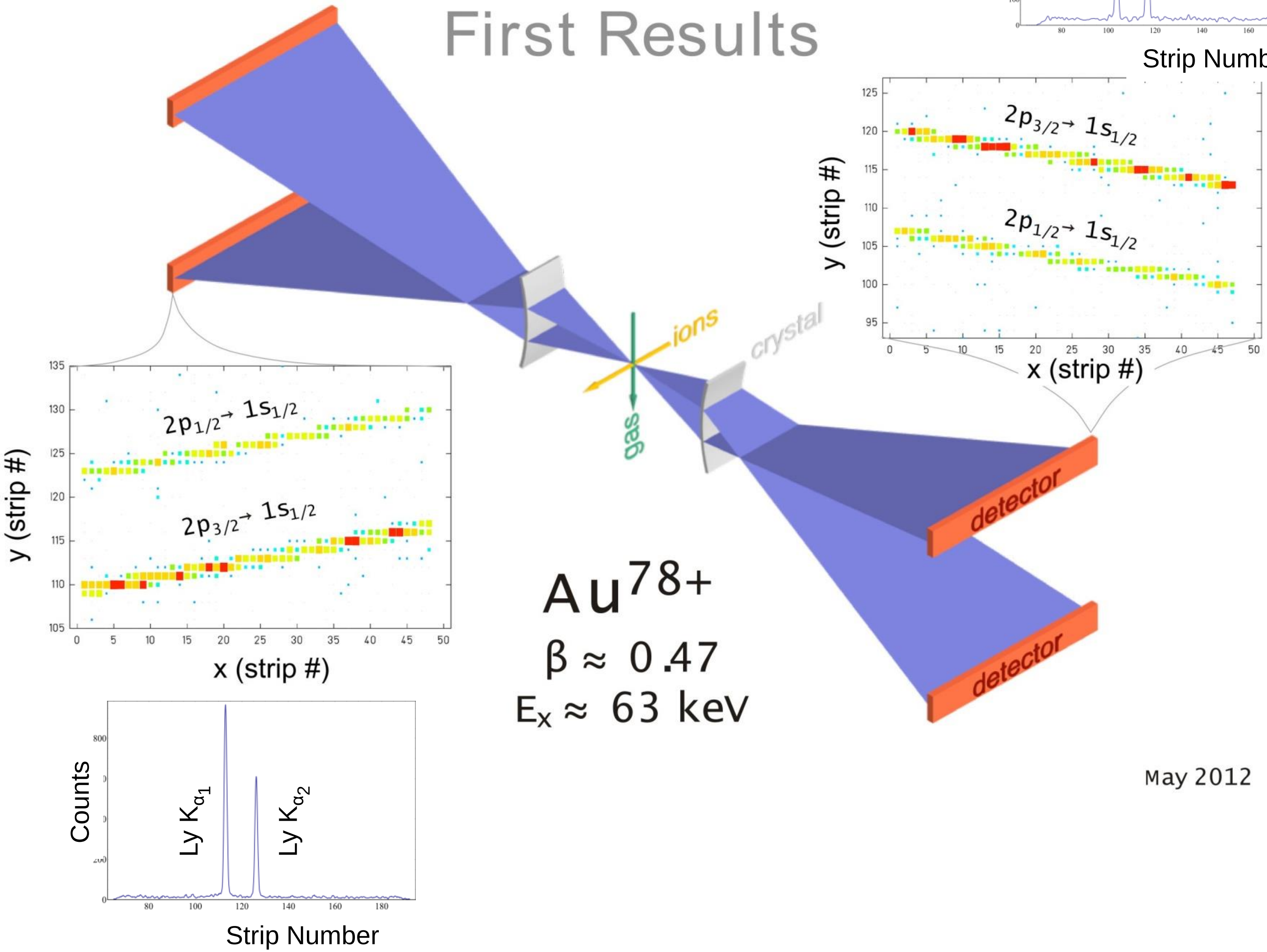


Beamtime April 2012

Bi-FOCAL

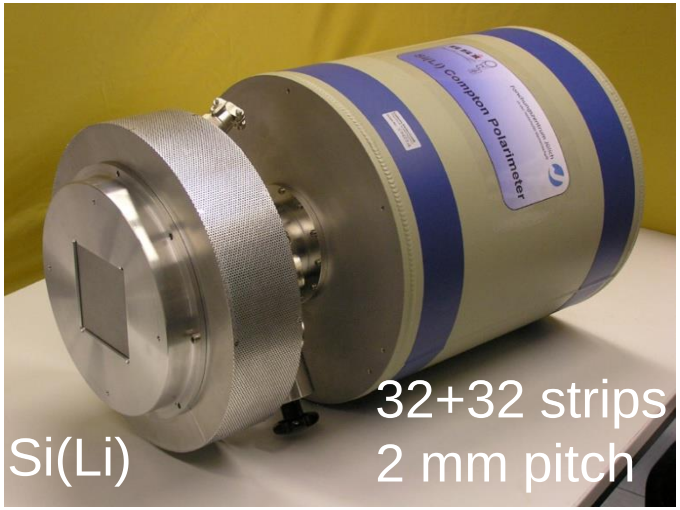
First Results



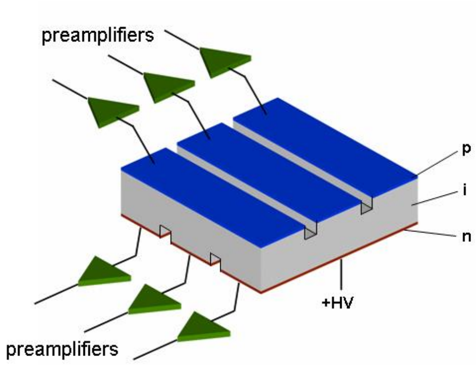


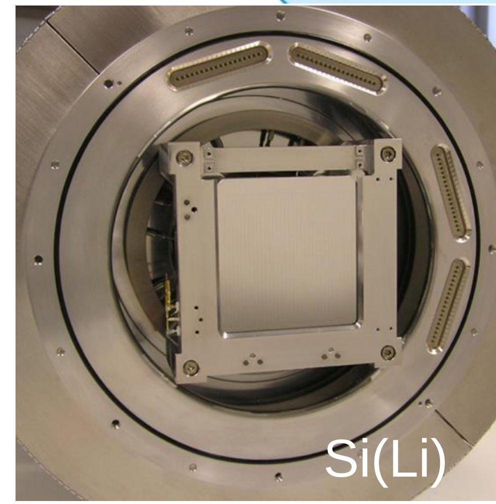
May 2012

2D Si(Li)-detector for Compton polarimetry



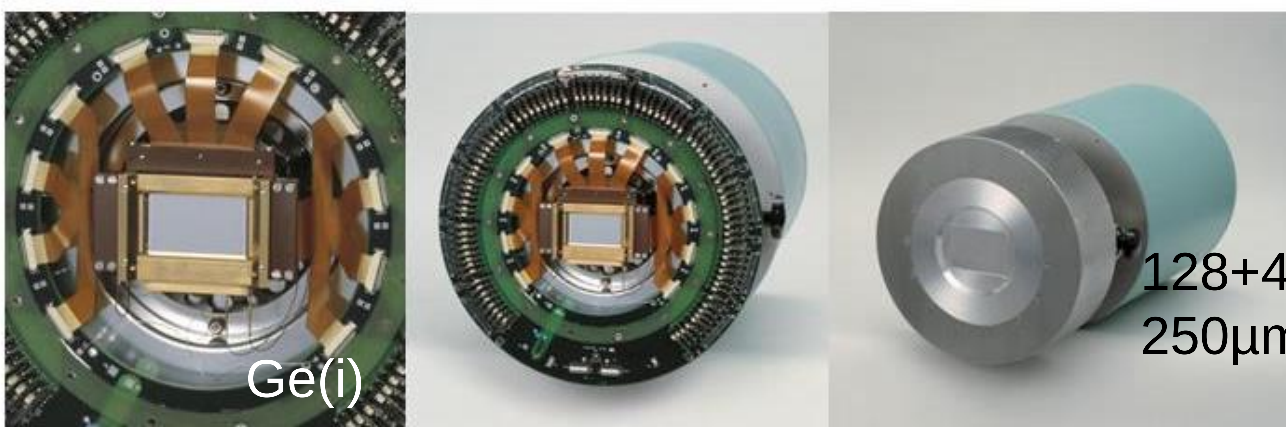
Si(Li) and Ge(i) based Compton polarimeter





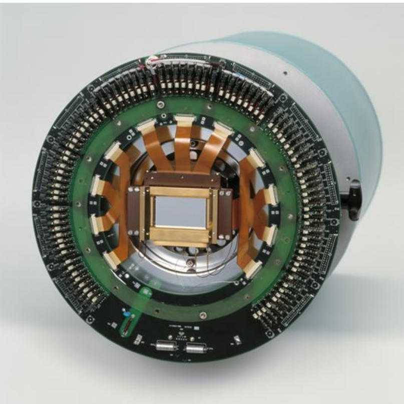
crystall size: 4" x 4"

energy resolution – timing - 2D position sensitiviy



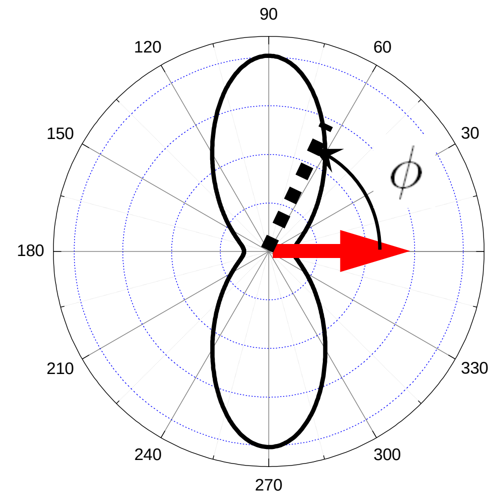
exploiding position and energy resolution

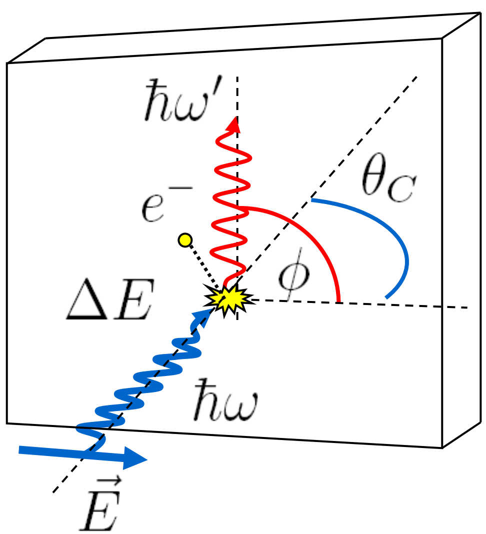
polarisation measurement via Compton scattering

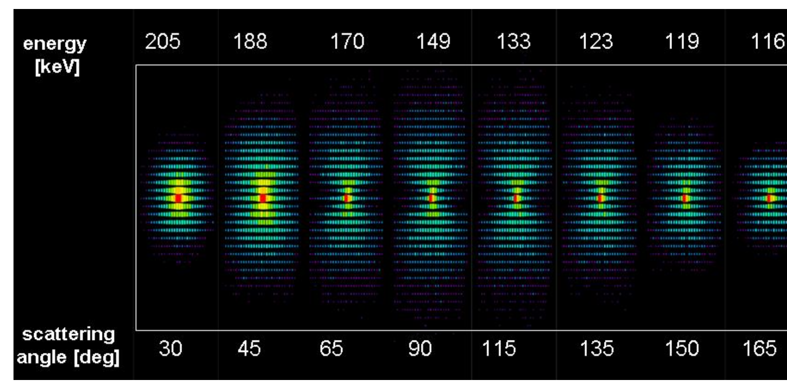


2D µSTRIP germanium detector

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



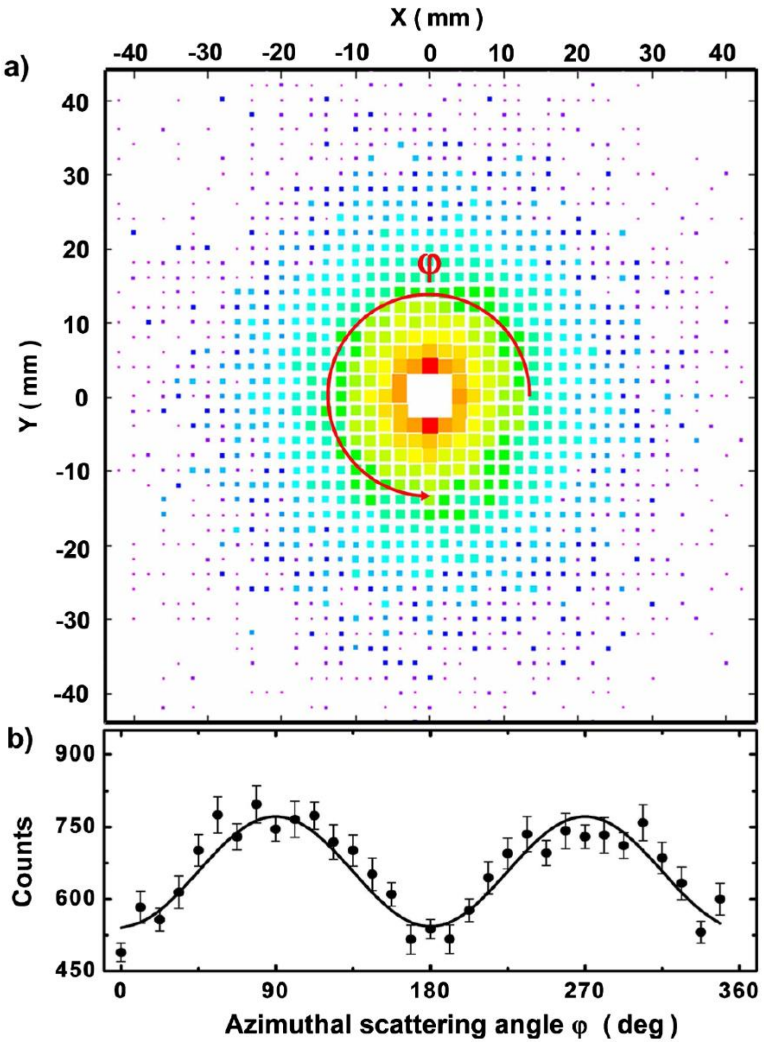




x-ray images for Compton scattering as a function of the scattering angle

Direct Determination of the Magnetic Quadrupole Contribution to the Lyman-α_1 Transition in a Hydrogenlike Ion

G. Weber,[1,2,3] H. Bräuning,[1] A. Surzhykov,[1,2] C. Brandau,[1,4] S. Fritzsche,[1,5,6] S. Geyer,[7] S. Hagmann,[1,8] S. Hess,[1] C. Kozhuharov,[1] R. Märtin,[1,2] N. Petridis,[8] R. Reuschl,[1,5,9] U. Spillmann,[1] S. Trotsenko,[1,3] D. F. A. Winters,[1,2] and Th. Stöhlker[1,2,3]



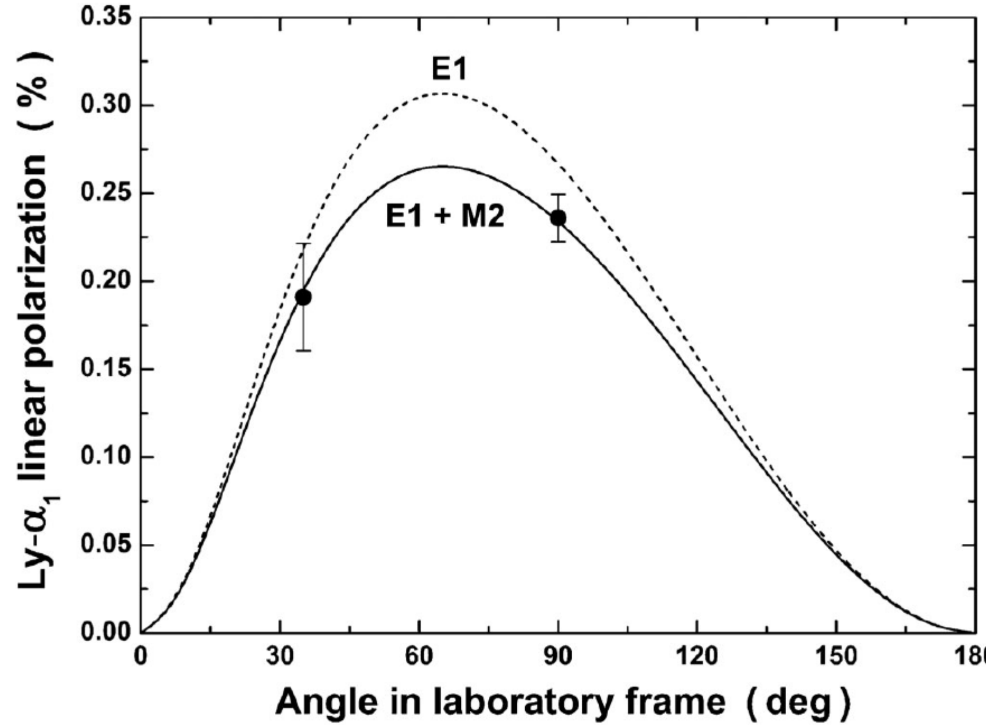


FIG. 3. Measured linear polarization of the Ly-α_1 line following the REC into initially bare uranium projectiles with energy 96.6 MeV/u in comparison to theory with (solid curve) and without (dashed curve) taking into account the $E1$-$M2$ interference.

Topics:

Electron spectroscopy

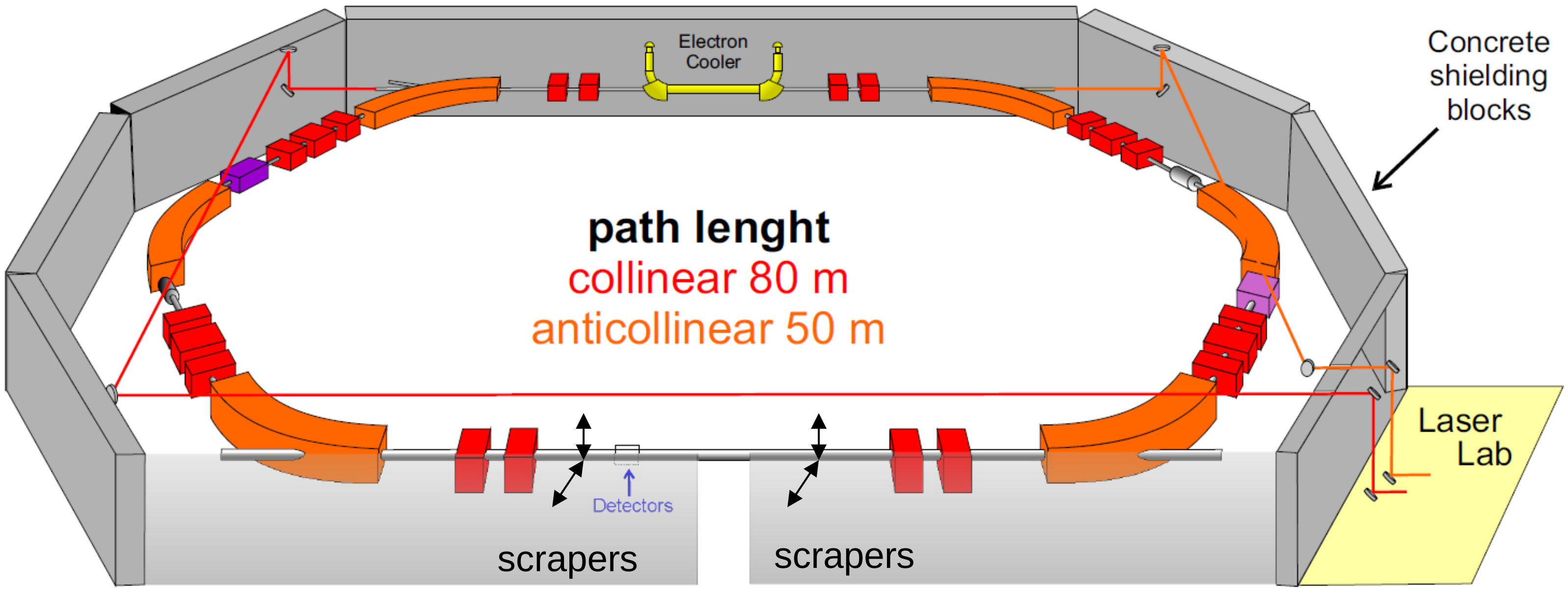
Dielectronic recombination

Mass spectrometry

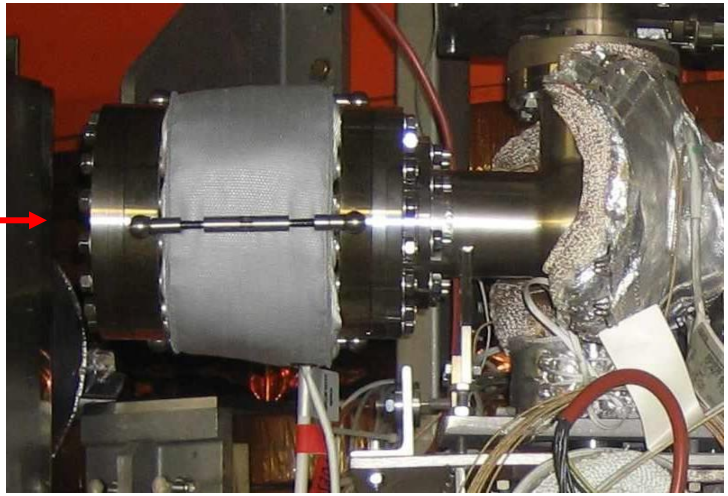
X-ray spectroscopy

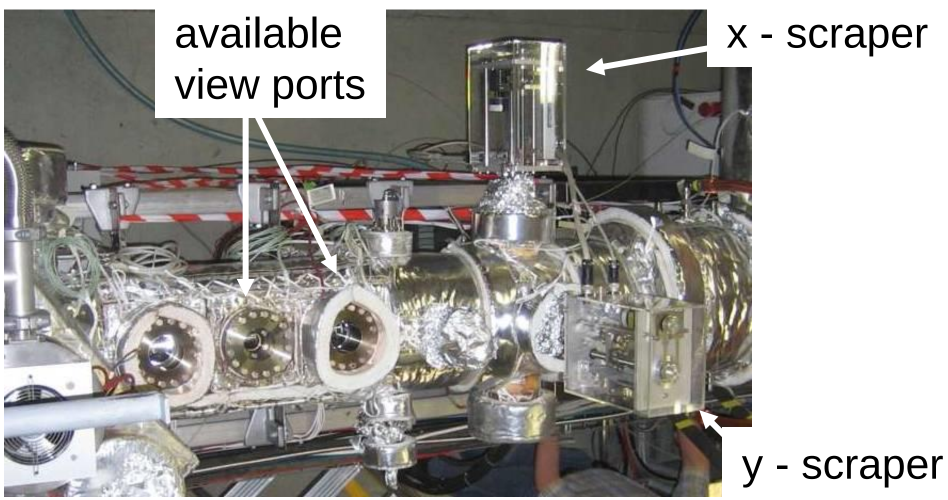
Laser spectroscopy and laser cooling

lasers at the ESR



Laser light





Laser spectroscopy and laser cooling:

Recent results

(@ GSI)

August 2011

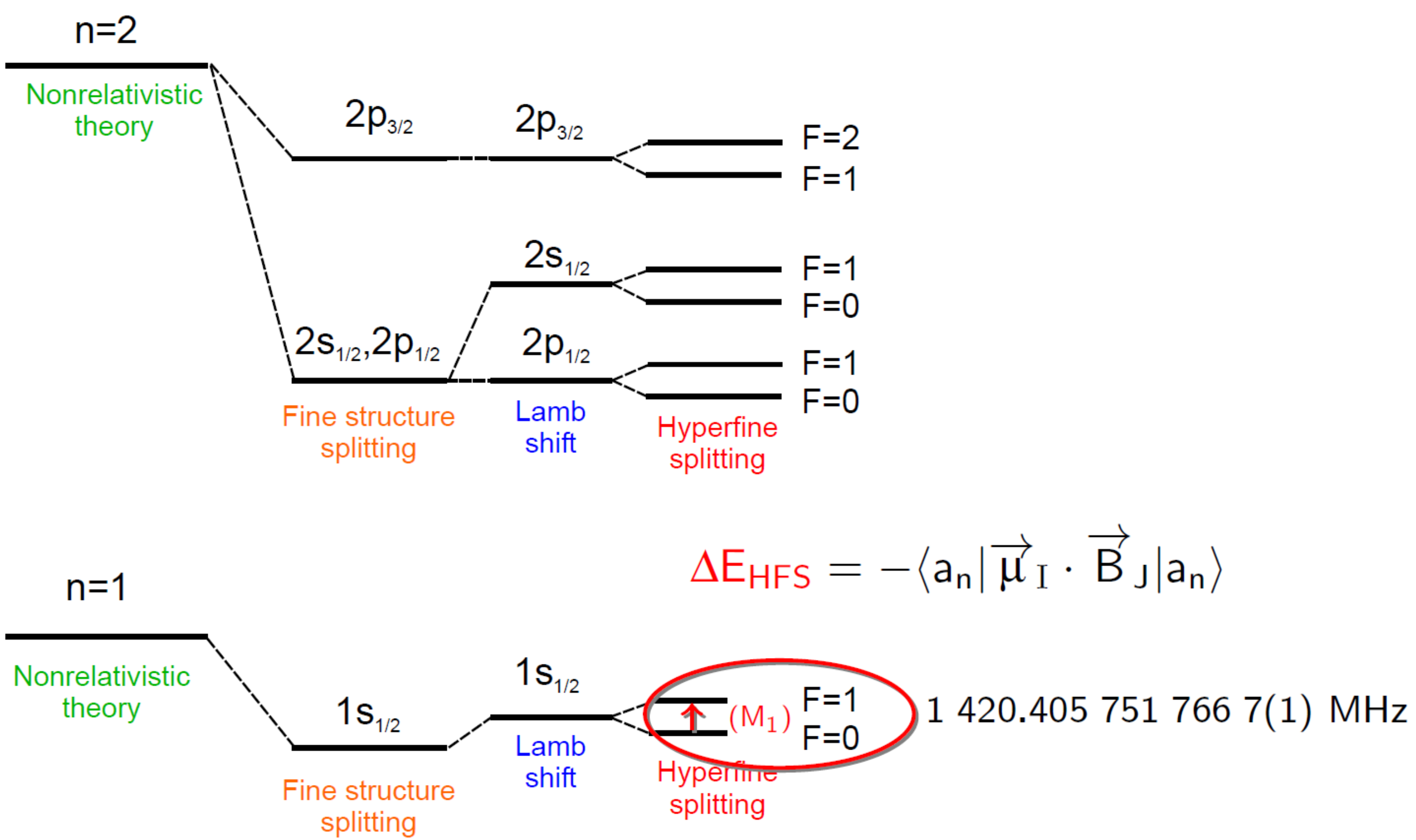
Hyperfine Splitting in Lithium-like Bismuth

Rodolfo Sánchez
GSI Helmholtzzentrum für Schwerionenforschung GmbH

Matthias Lochmann, Zoran Andjelkovic, Benjamin Botermann, Michael Bussmann, Andreas Dax, Nadja Frömmgen, Christopher Geppert, Michael Hammen, Volker Hannen, Raphael Jöhren, Thomas Kühl, Yuri Litvinov, Jonas Mader, Wilfried Nörtershäuser, Thomas Stöhlker, Richard Thomson, Andrey Volotka, Christian Weinheimer, Weiqiang Wen, Elisa Will and Danyal Winters

GSI; Johannes Gutenberg Universität Mainz; Westfälische Wilhelms-Universität Münster; Technische Universität Darmstadt; CERN; Imperial College London; Technische Universität Dresden; HZDR Helmholtz Zentrum Dresden Rossendorf

Hyperfine Splitting - Hydrogen



$$\Delta E_{HFS} = -\langle a_n | \vec{\mu}_I \cdot \vec{B}_J | a_n \rangle$$

So far ...

Theory

$$\Delta E^{(2s)} = \Delta' E + \xi \; \Delta E^{(1s)}$$

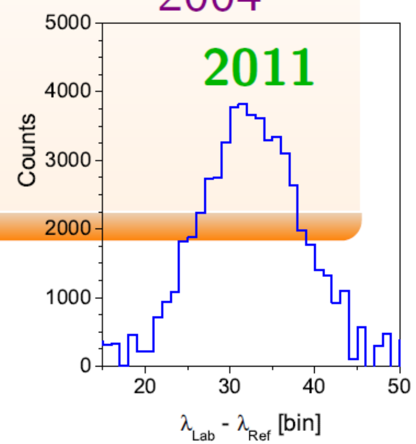
Li-like Bismuth

$\lambda_0 \approx 1555$ nm

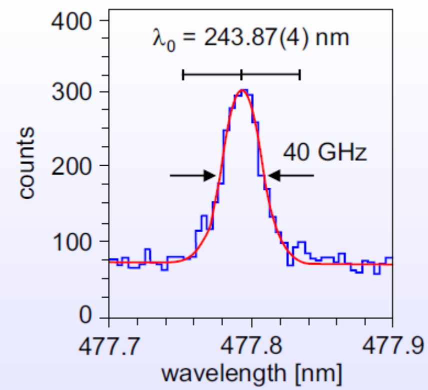
$\Delta E = 797.16(14)$ meV

$\tau \approx 80$ ms

~1998
2001
2004
2011



H-like Bismuth



$\lambda_0 = 243.87(4)$ nm

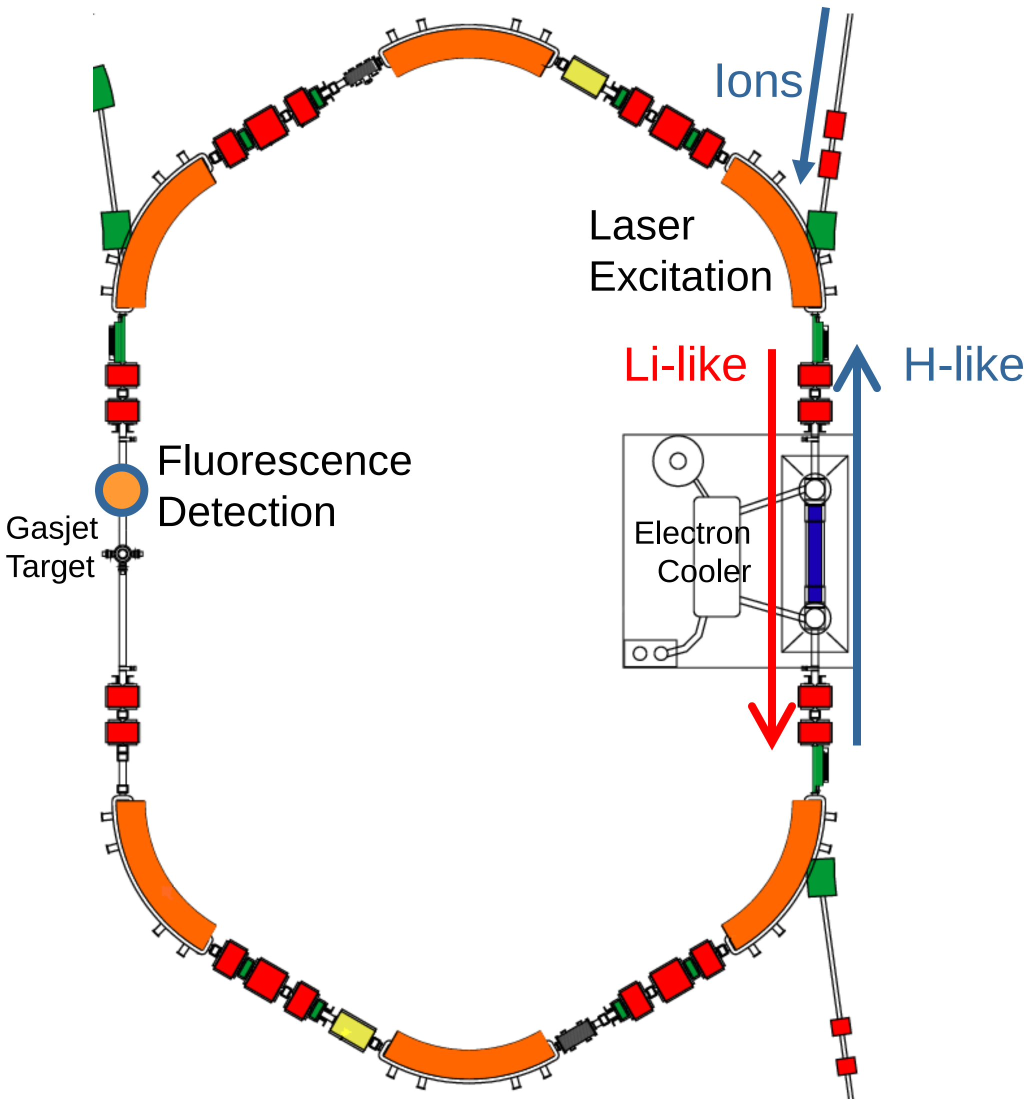
$\Delta E = 5.0840(8)$ eV

$\tau = 351(16)$ µs

Klaft I *et al* 1994

Phys. Rev. Lett. **73** 2425

laser spectroscopy of the HFS in ^{209}Bi



Concept: with the same laser ~615 nm @ 428 MeV/u reach:

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

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

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

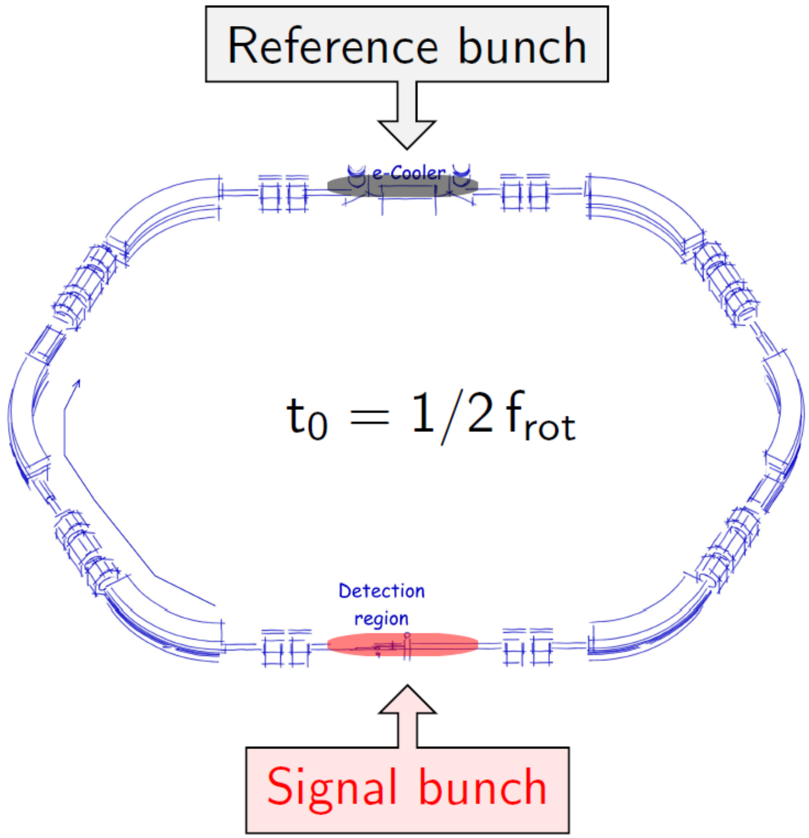
F=4 → F=5 transition

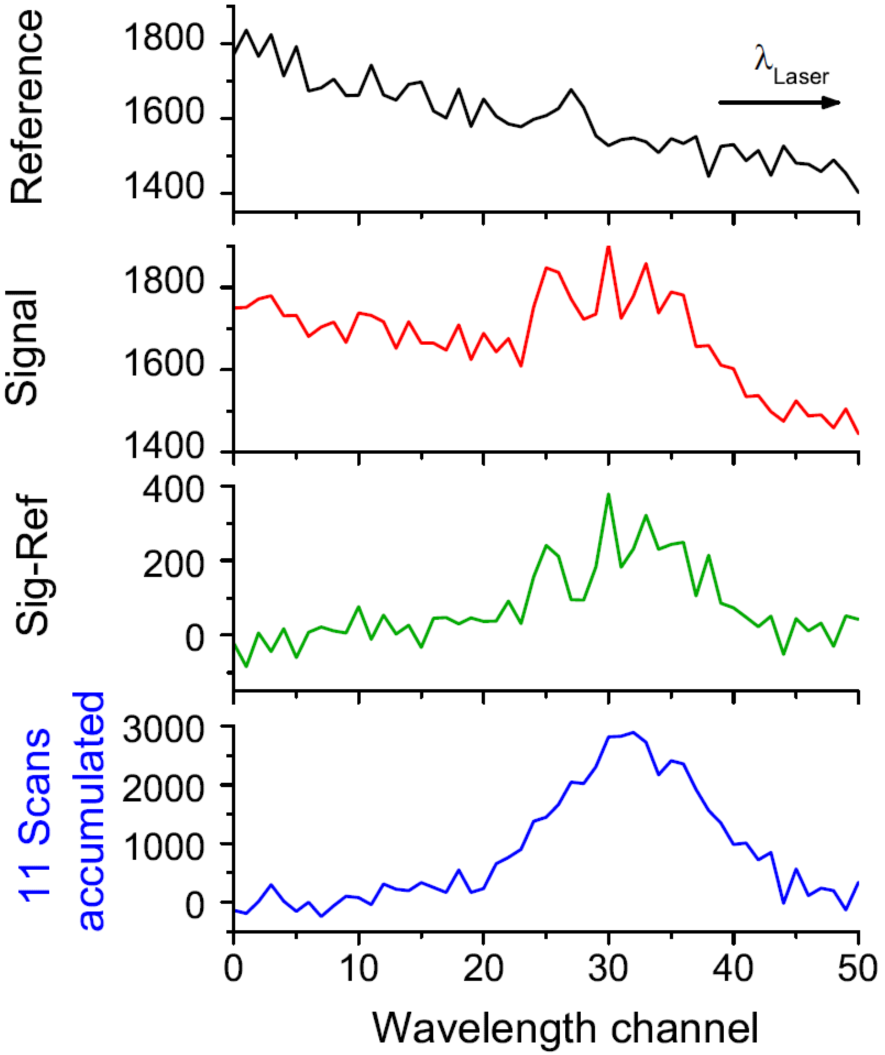
Especially the Li-like transition is of great interest, since there is quite some debate about its value.

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

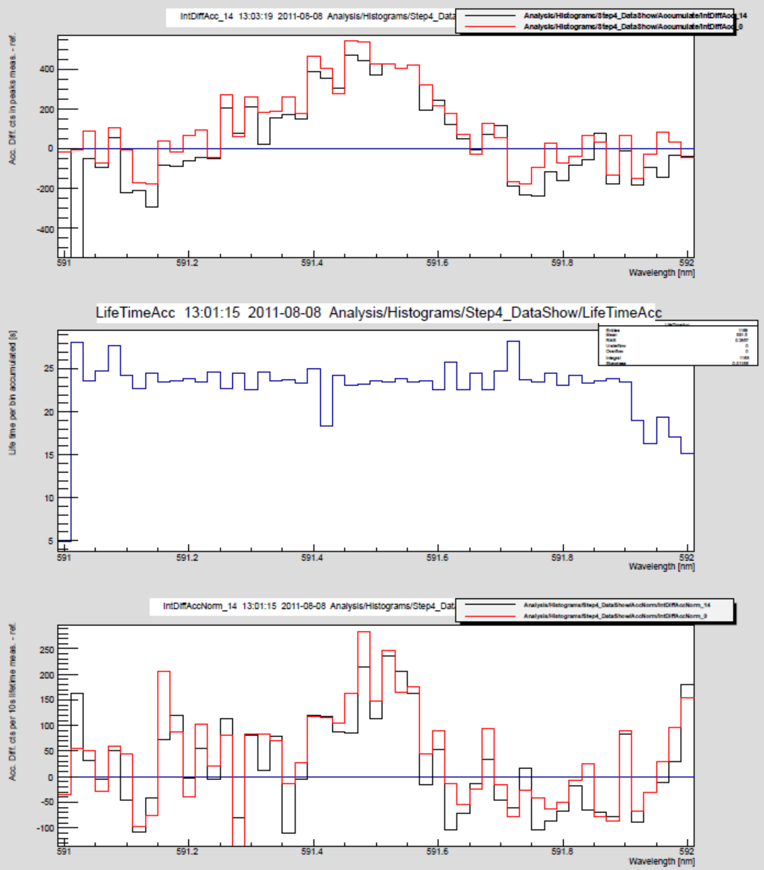
Laser Spectroscopic Technique





Results

Raw data



Scan469-471+473-475, **Mo. 8.8.**, 13:03

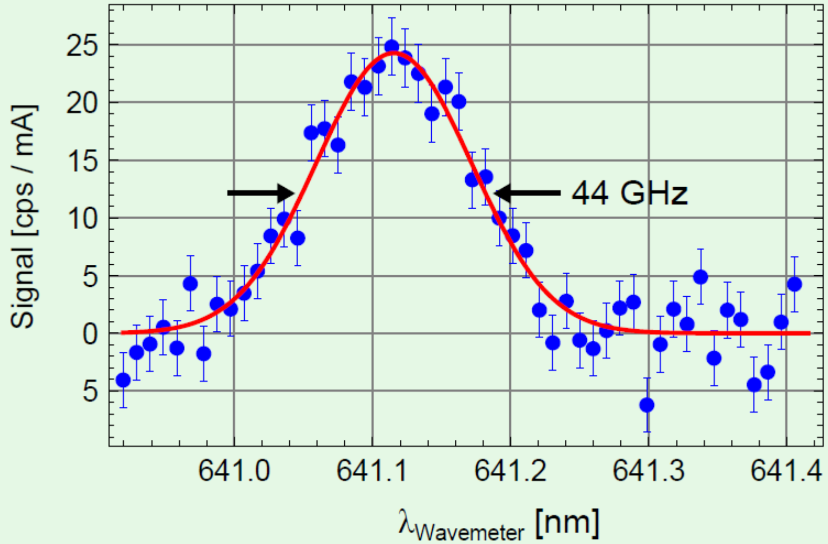
Summing up ca. 2 hours of scanning

Hardware gated (red line)

Software gated (black line)

Preliminary

$$\lambda_{lab} = 641.112(24)\ \text{nm}$$



Total number of accumulated scans: 100

Total efficiency: $\frac{\text{1 fluorescence photon}}{\text{30 000 revolutions}}$

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

(a modern Ives & Stilwell experiment)

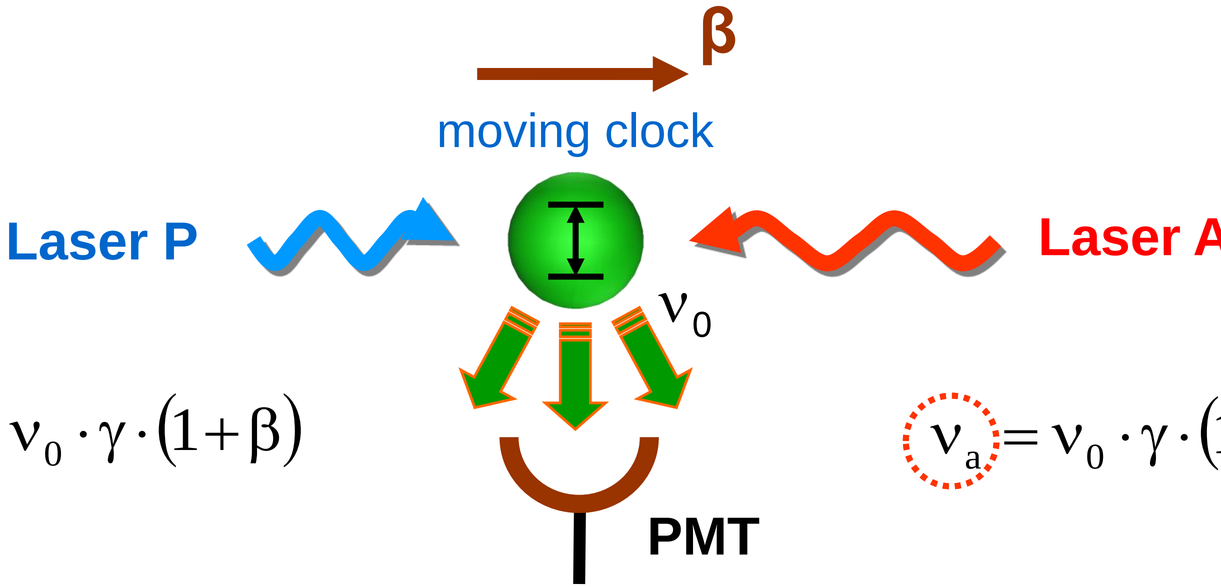
C. Novotny, S. Reinhardt, G. Saathoff, S. Karpuk...
B. Botermann, W. Nörtershäuser, C. Geppert...
Th. Kühl, Th. Stöhlker...

Johannes Gutenberg Universität Mainz

Max-Planck-Institut für Kernphysik

Ruprecht-Karls-Universität Heidelberg Physikalisches Institut

Testing Lorentz transformation via optical frequency measurements



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

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

Testing Time Dilation via three optical frequencies

(Doppler-free laser saturation spectroscopy)

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

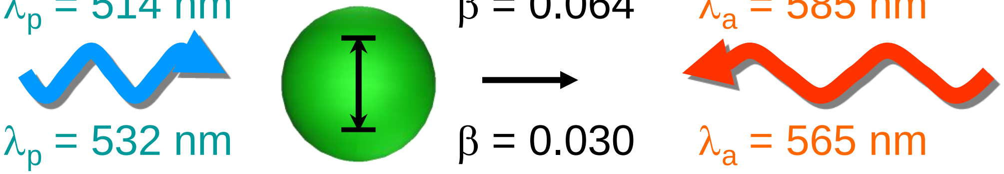
experiments at the TSR

measured at the TSR

Max-Planck-Institut für Kernphysik

$^7Li^+$

$\lambda_p = 514$ nm $\qquad \beta = 0.064 \qquad \lambda_a = 585$ nm



$\lambda_p = 532$ nm $\qquad \beta = 0.030 \qquad \lambda_a = 565$ nm

$\lambda_0 = 548$ nm

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

$\nu_0 = 546\,466\,918\,790 \pm 400$ kHz

$\nu_p = 582\,490\,603\,430 \pm 3$ kHz

$\nu_a = 512\,671\,028\,075 \pm 73$ kHz

the error in the rest frequency dominates

➔ measurement at two different velocities

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

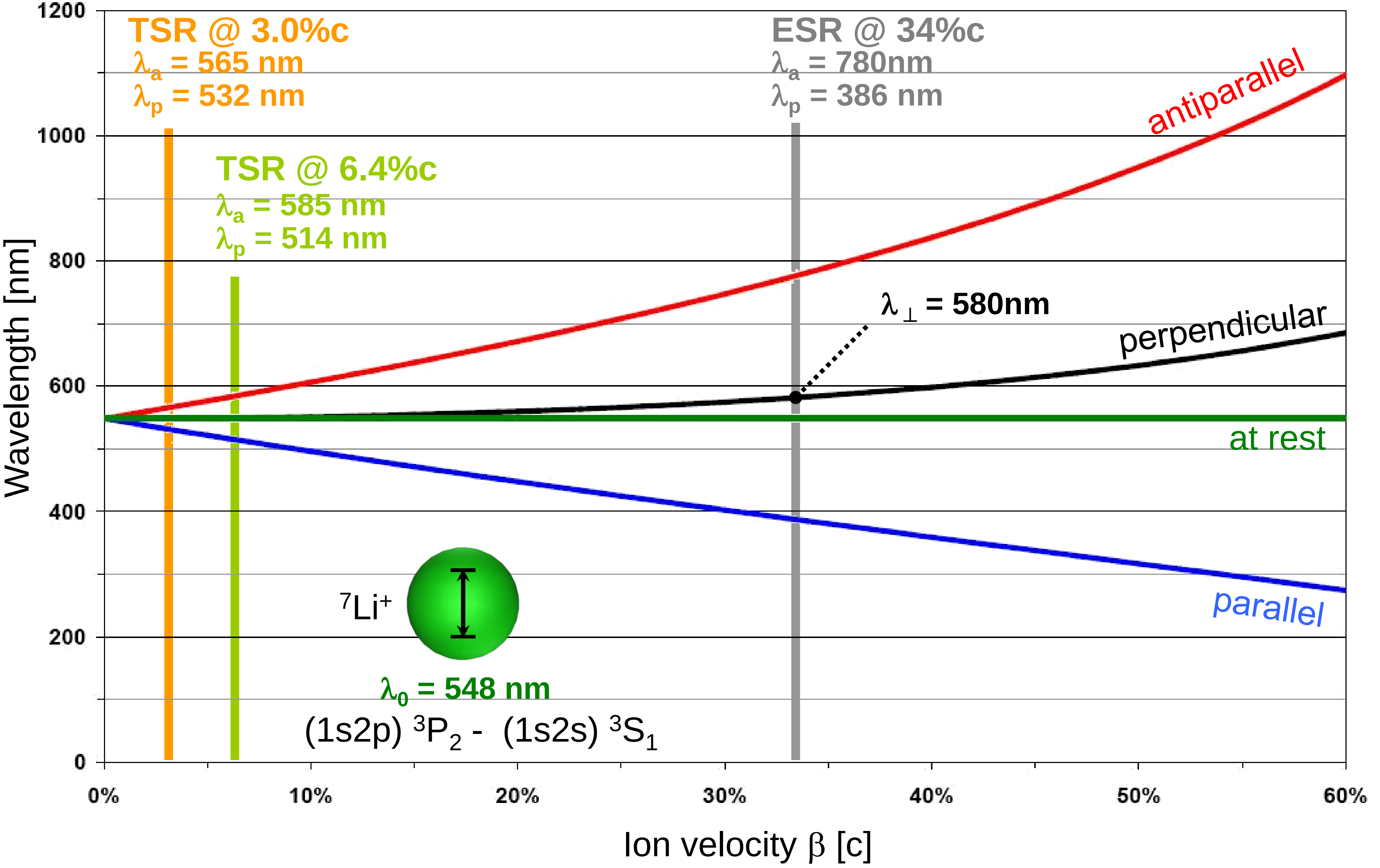
cancels out the uncertainty of the rest frequency

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

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

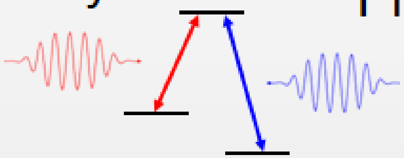
[S. Reinhardt, et al.
Nature Physics *3 (2007) 861*]

Why go to the ESR?

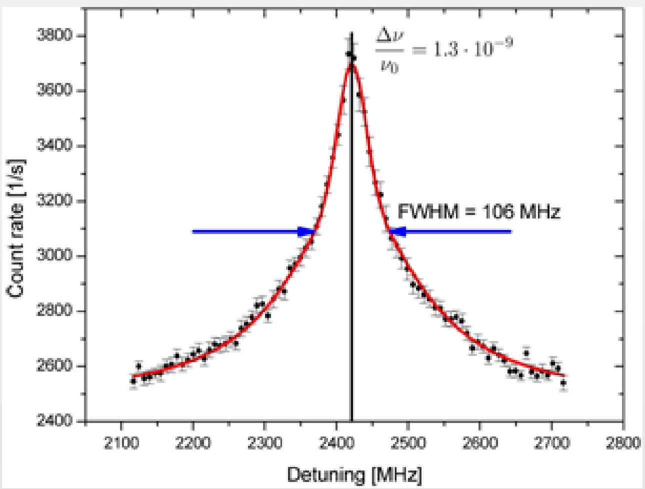


Spectroscopy signals

Frequency tuned

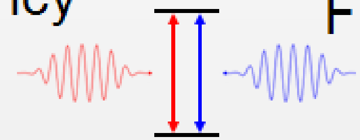


Frequency constant

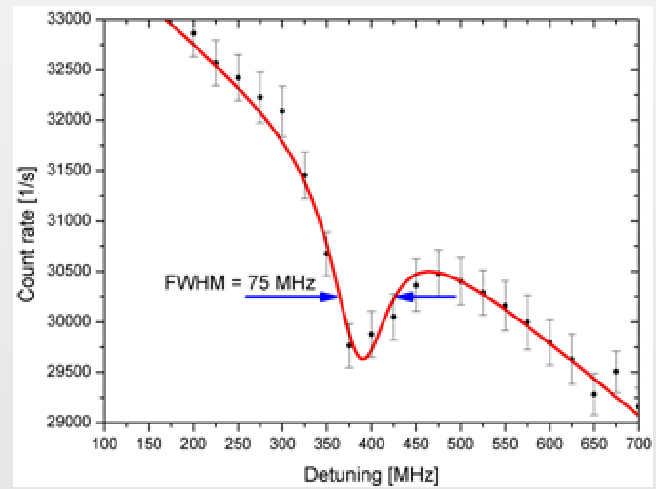


Doppler-free signal
(Λ-spectroscopy)

Frequency tuned



Frequency constant



Doppler-free signal
(saturation spectroscopy)

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 SIS100/300 (also spectroscopy of high-Z Li-like ions)

- applicable to many stable and unstable (Li-like) ions

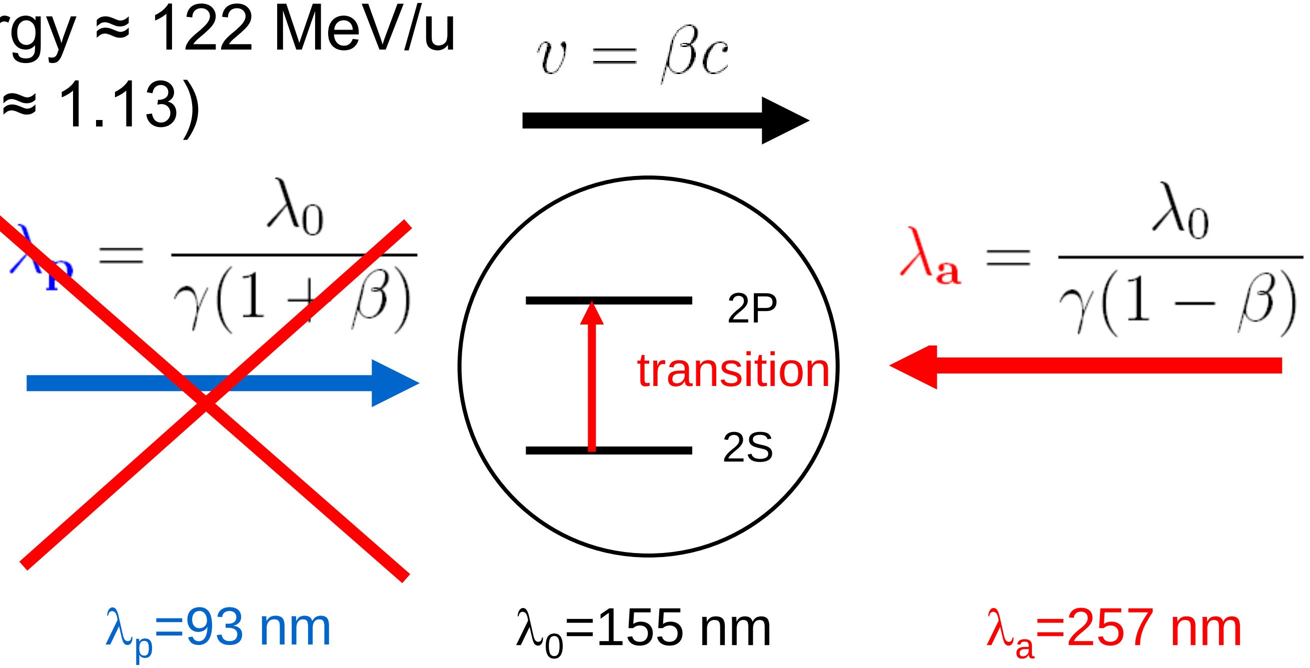
- study laser cooling without pre-electron cooling

- use broadband (pulsed) laser cooling for fast cooling of many ions

- set up fluorescence detection to determine the lower limit for longitudinal cooling $\Delta p/p<10^{-7}$

The principle: laser cooling of stored relativistic ions

C^{3+} ion energy ≈ 122 MeV/u
($\beta \approx 0.47$, $\gamma \approx 1.13$)



In our case, the cooling laser force is counteracted by the restoring force of the `*bucket*´ when **the ion beam is bunched**.

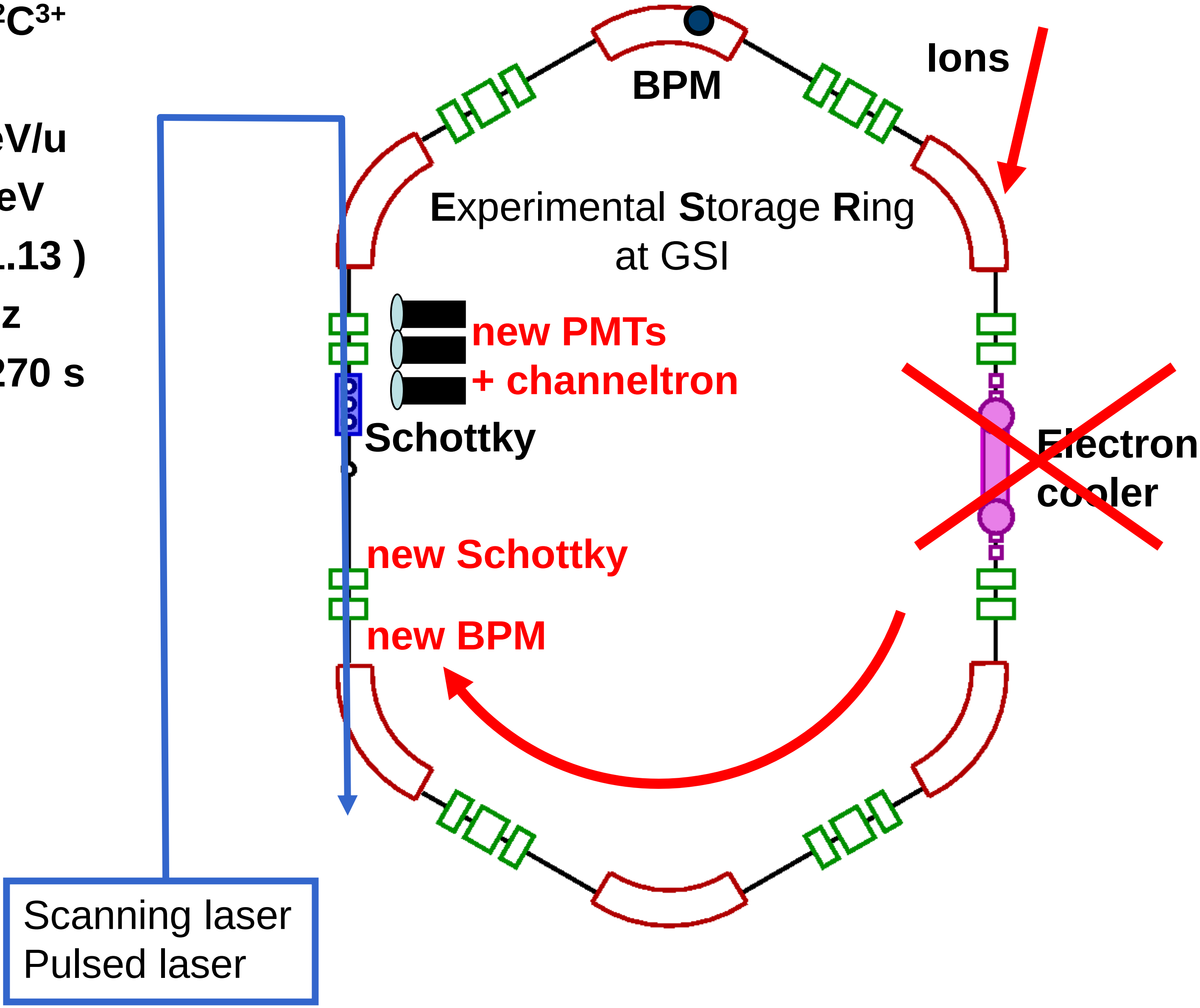
Experiment improvements

Ion Species: $^{12}C^{3+}$

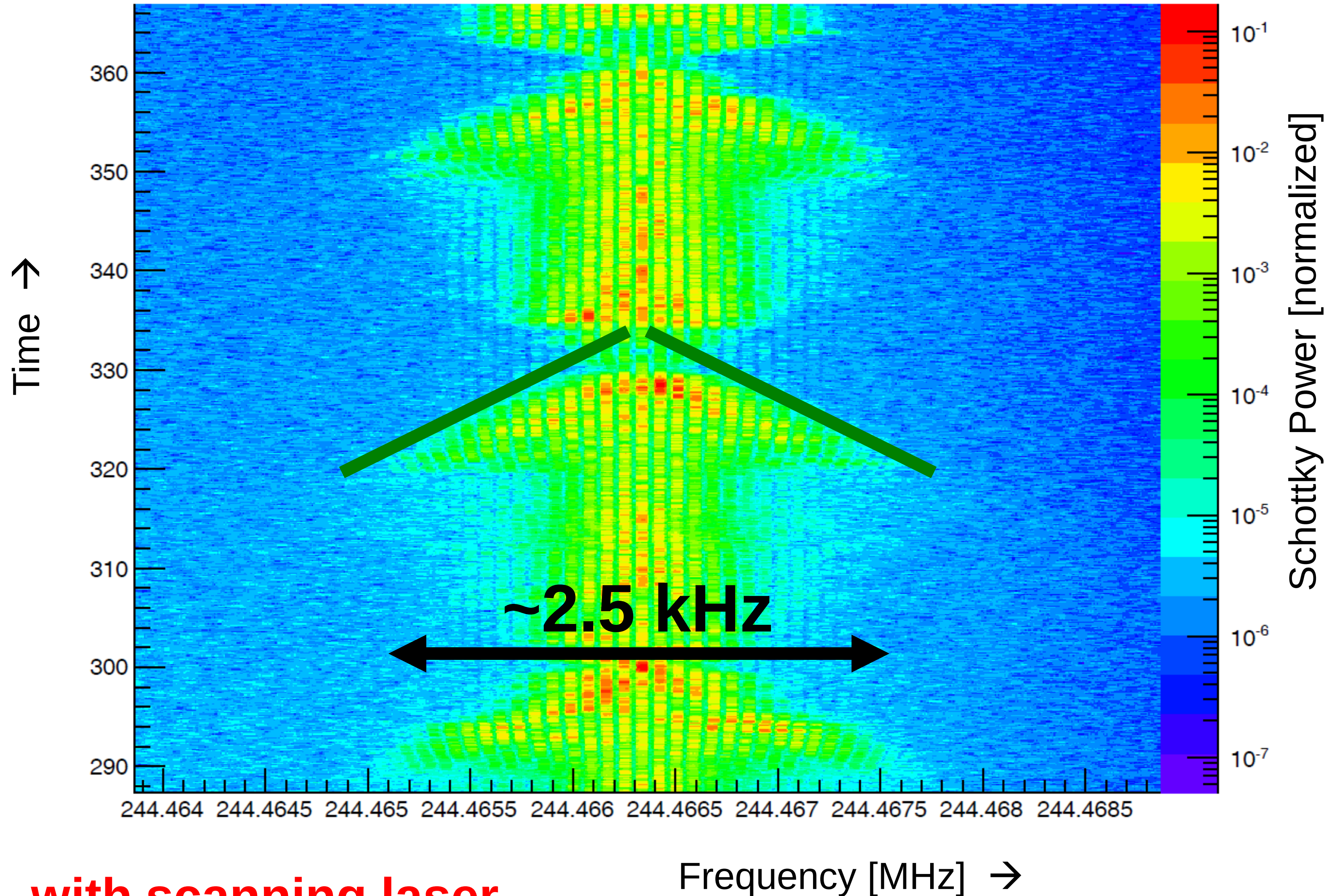
E_{beam} = 122 MeV/u
= 1.47 GeV
(β = 0.47, γ = 1.13)
f_{rev} = 1.295 MHz
τ_{beam} ~ 450 s, 270 s
(no cooling)

λ_{laser} = 257 nm

$2S_{1/2} \rightarrow 2P_{1/2}$
λ_{rest} = 155 nm
τ_{rest} = 3.8 ns



Very preliminary experimental results:



with scanning laser
bunched ion beam

Laser spectroscopy and laser cooling:

What comes next?

(@ GSI and FAIR)

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

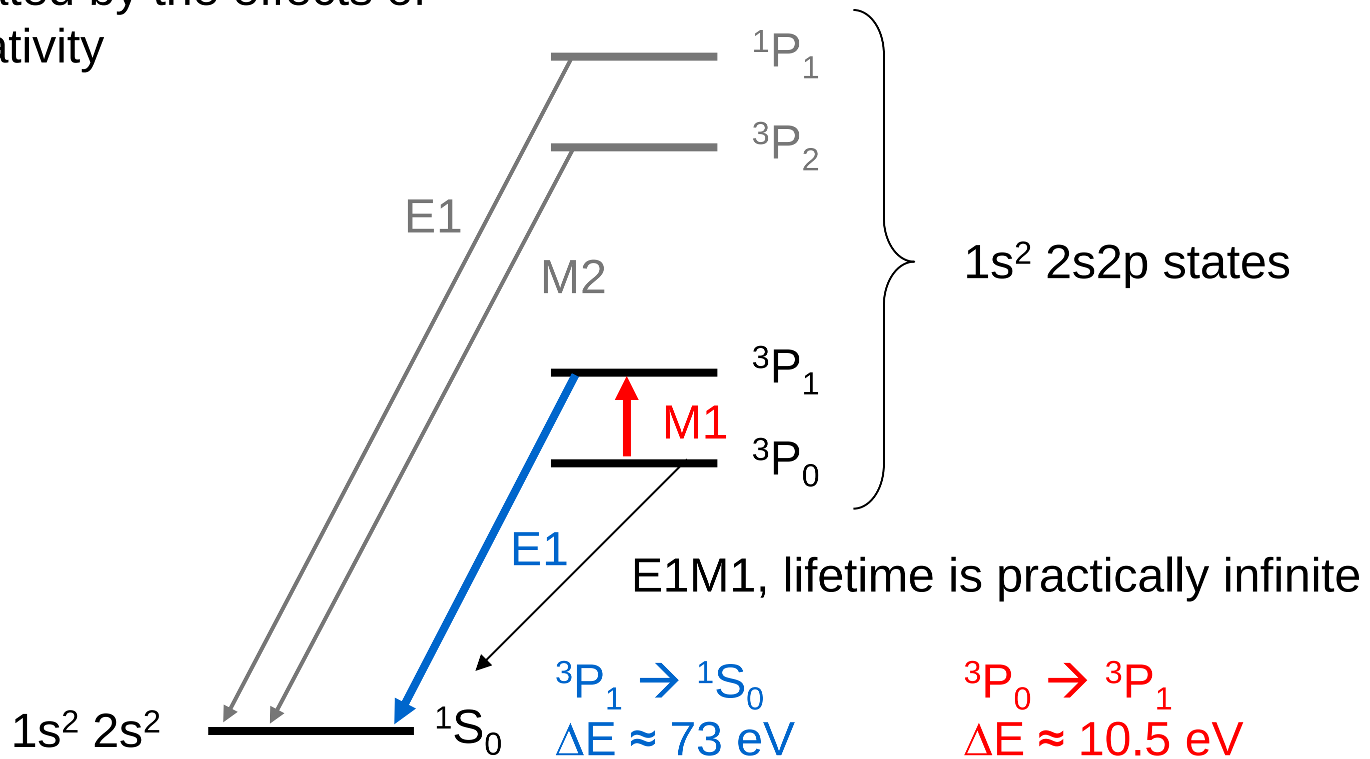
Danyal Winters

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

Level scheme of Be-like krypton

ideal atomic systems

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



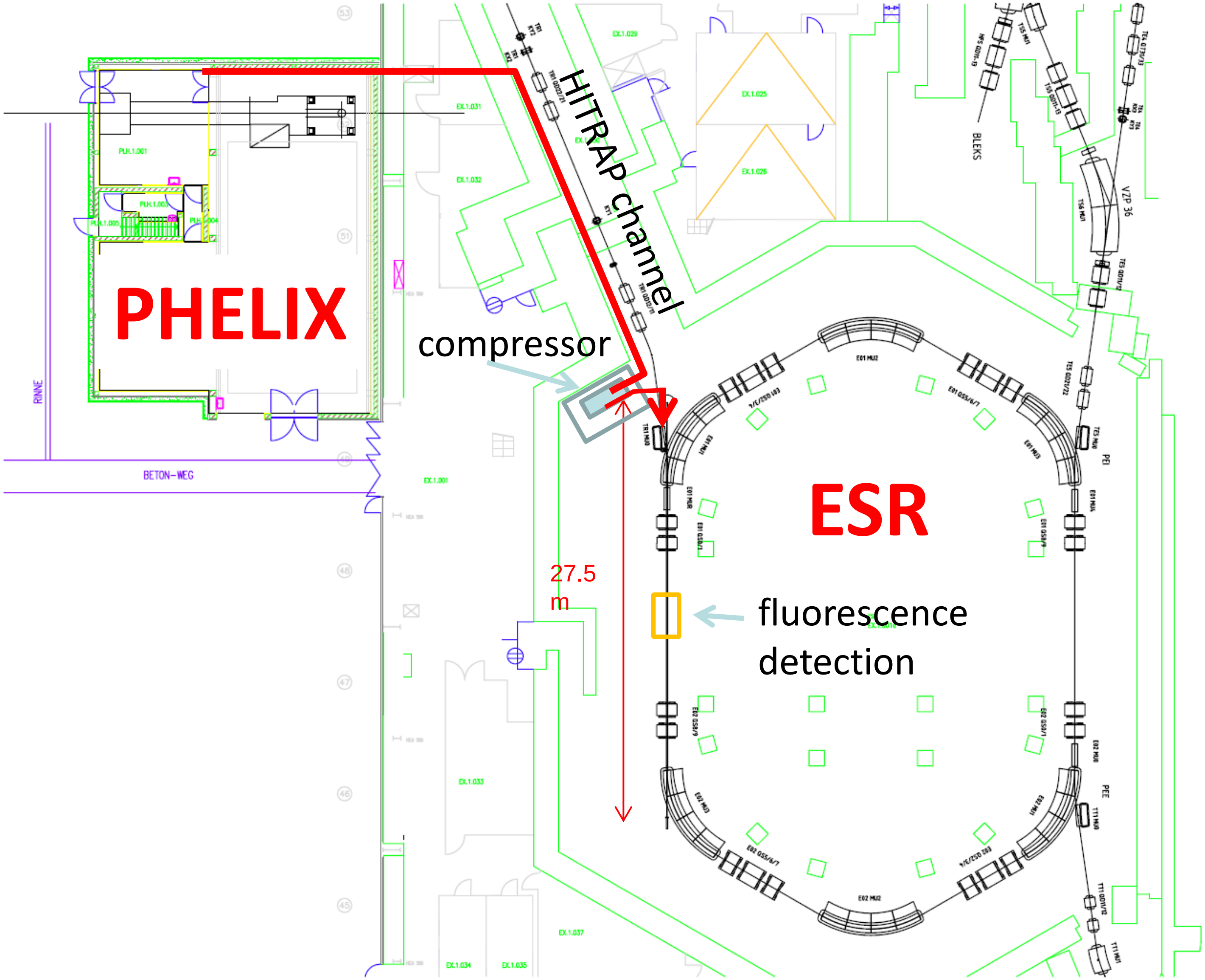
$^3P_1 \rightarrow {}^1S_0$
$\Delta E \approx 73$ eV
$\lambda \approx 17$ nm
photon emission

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

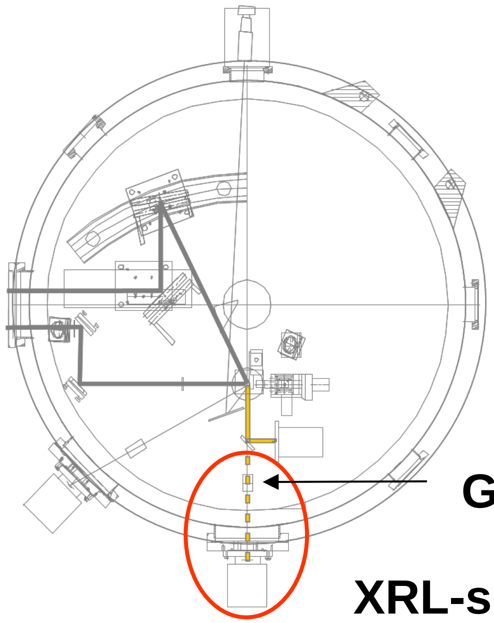
X-ray laser spectroscopy of relativistic heavy ions

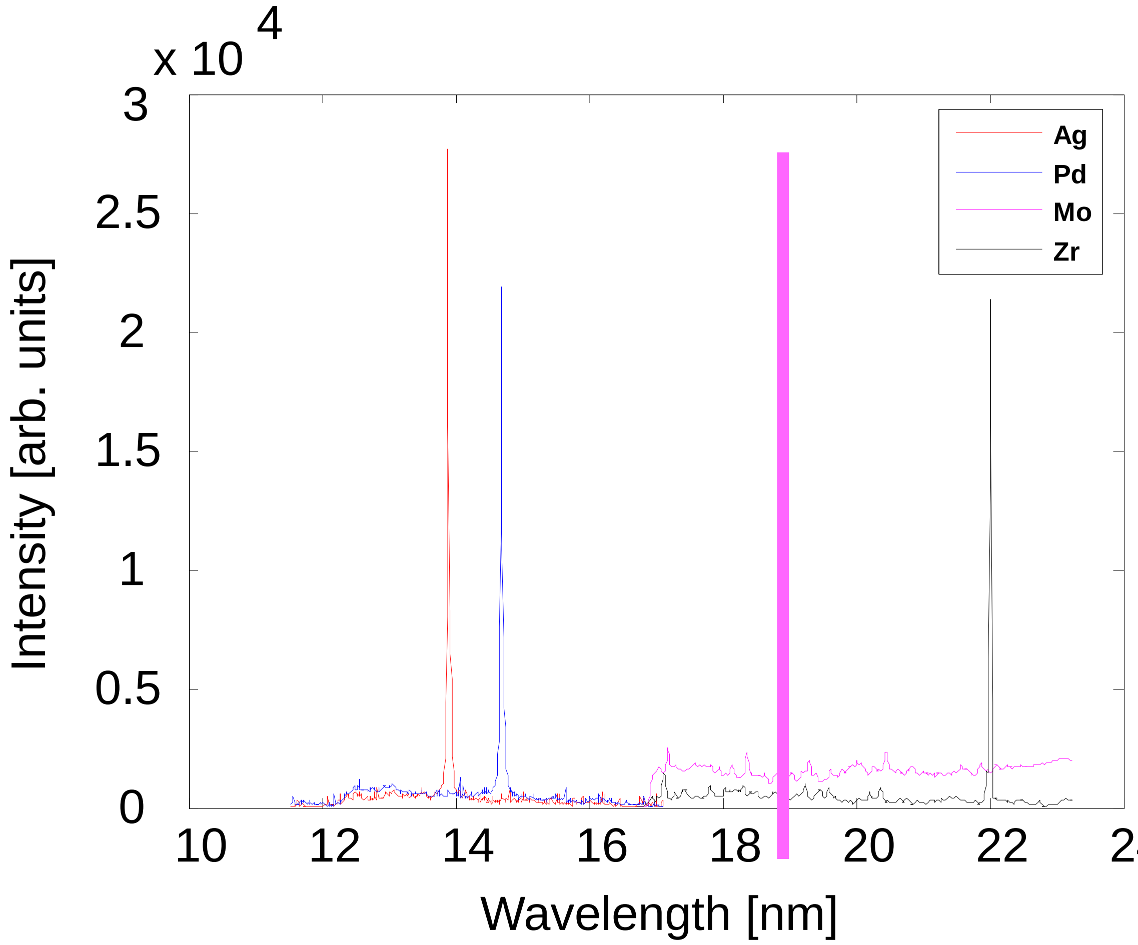
Th. Kühl, Th. Stöhlker, Y. Litvinov, B. Aurand, V. Bagnoud, B. Ecker, D. Winters, B. Zielbauer – GSI
D. Hochhaus, P. Neumayer – EMMI
J. Seres, E. Seres, B. Landgraf, M. Schnell, C. Spielmann – HI Jena
H.Y. Zhao - IMP CAS Lanzhou
S. Namba – Hiroshima University
D. Ros, K. Cassou, B. Cros, S. Daboussi, O. Guilbaud, S. Kazamias – Laserix, Paris-Sud
Ph. Zeitoun, T. Le, E. Oliva, L. Li – LOA Paris
R. Maier, D. Prasuhn – FZ Jülich

Scientific infrastructure at GSI: PHELIX, ESR



Experimental data: different x-ray wavelengths



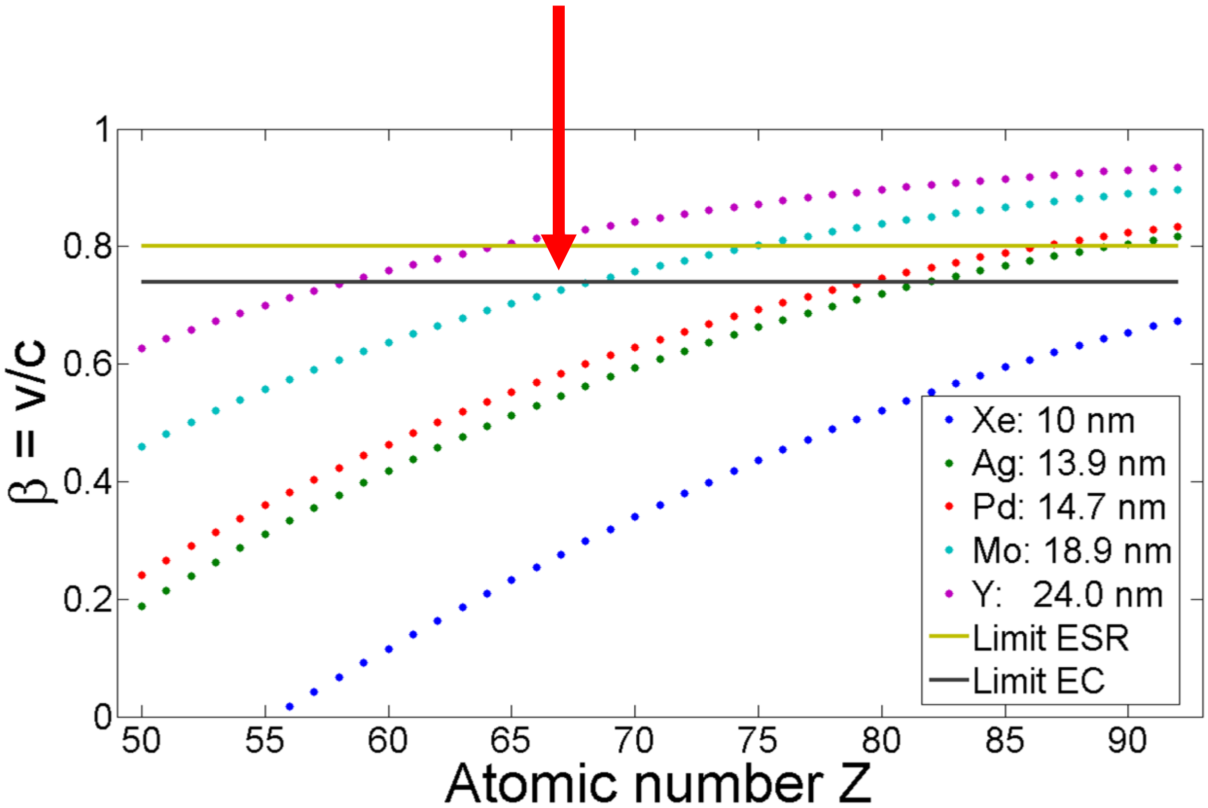


Bandwidth: $\Delta\lambda/\lambda = 4 \times 10^{-5}$

19 nm = 65 eV

Method: laser spectroscopy at a storage ring

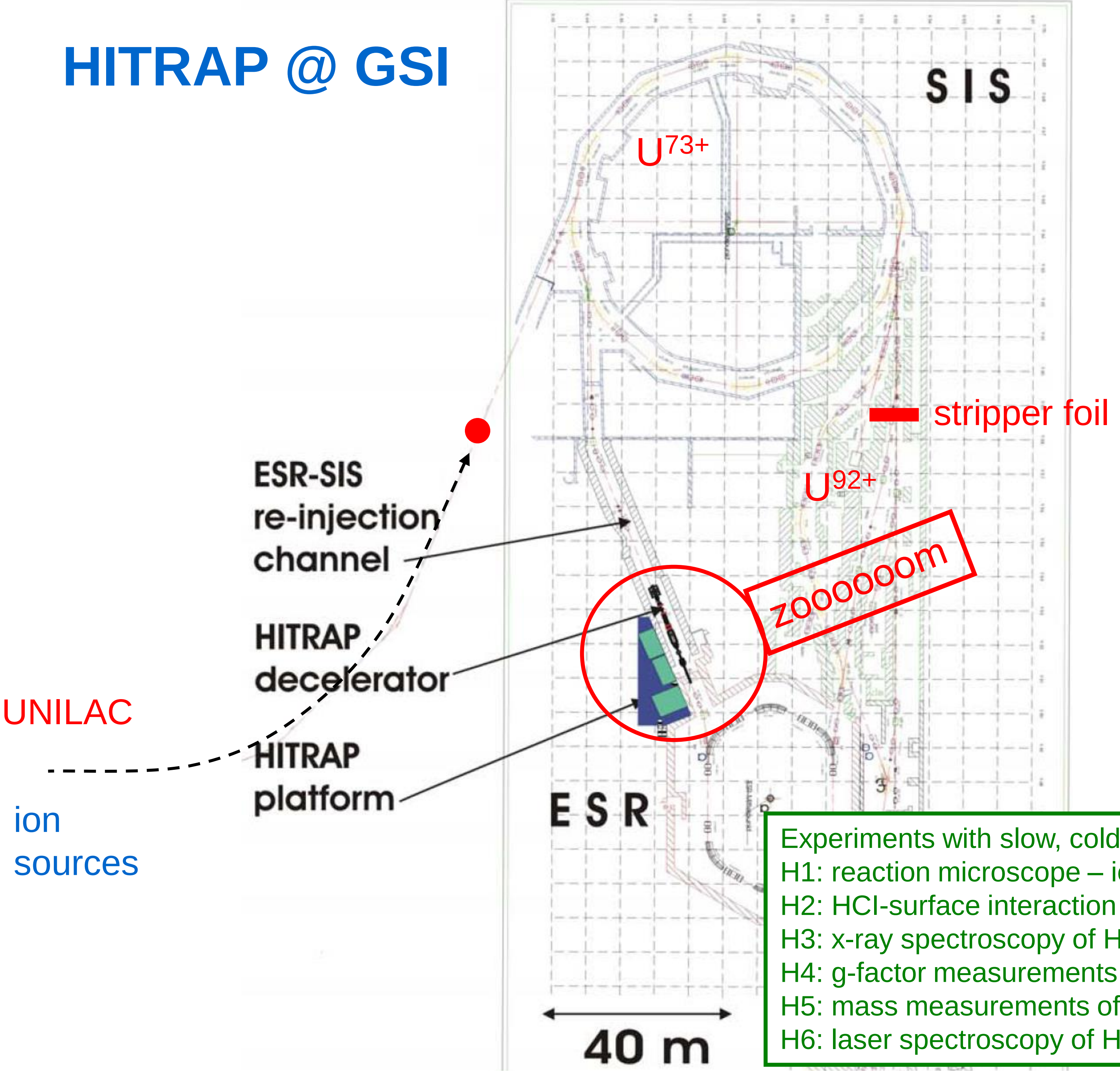
Mo XRL (66 eV) supports the transition up to Li-like $_{67}$Ho (165 eV)
@ESR: Doppler “boost” of 100 eV!



$$\lambda_T(Z) = \lambda_{SXRL} \cdot \sqrt{\frac{1-\beta}{1+\beta}}$$

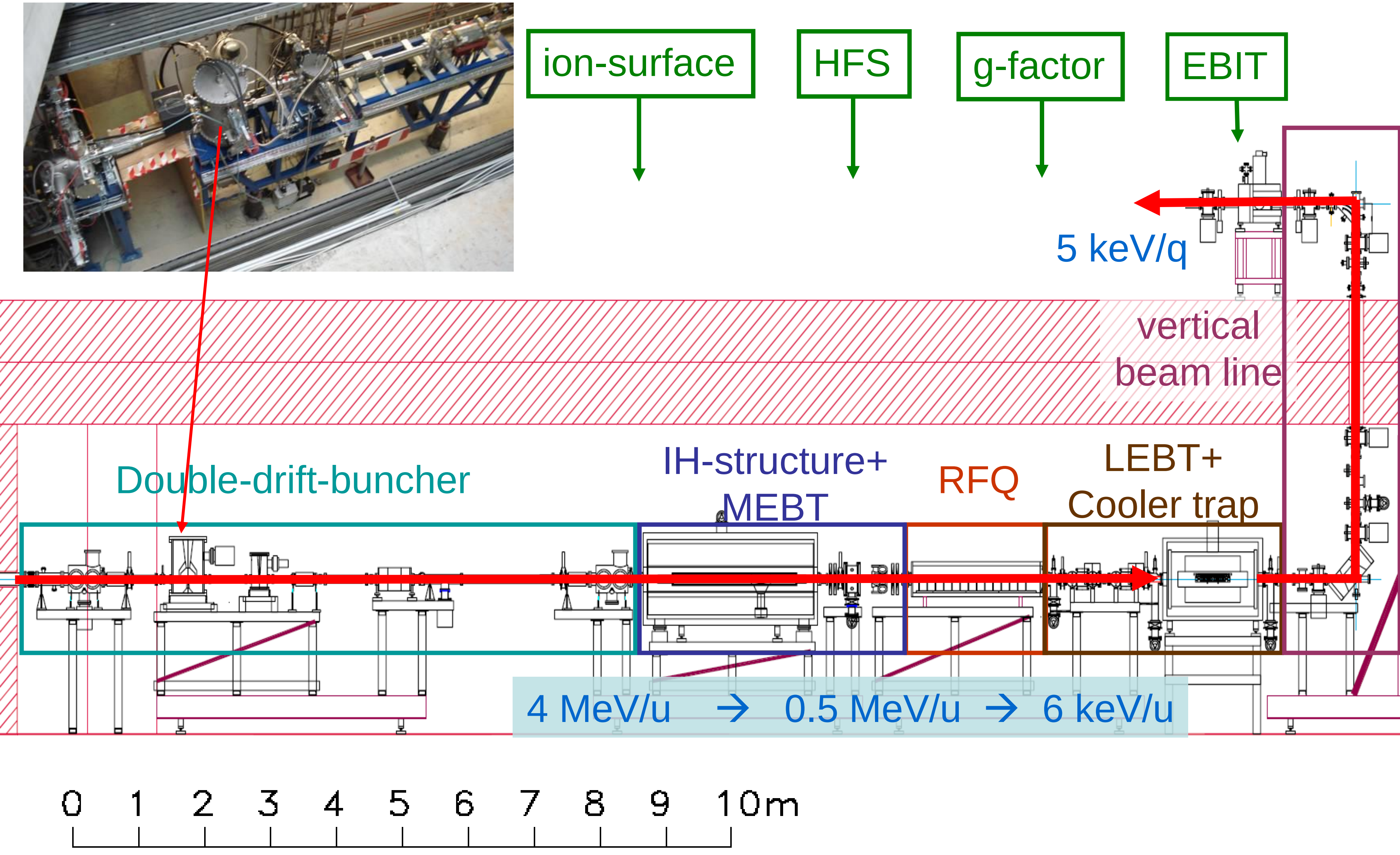
$$\beta(Z) = \frac{\lambda_{SXRL}^2 - \lambda_T^2}{\lambda_{SXRL}^2 + \lambda_T^2}$$

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 (Δn=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



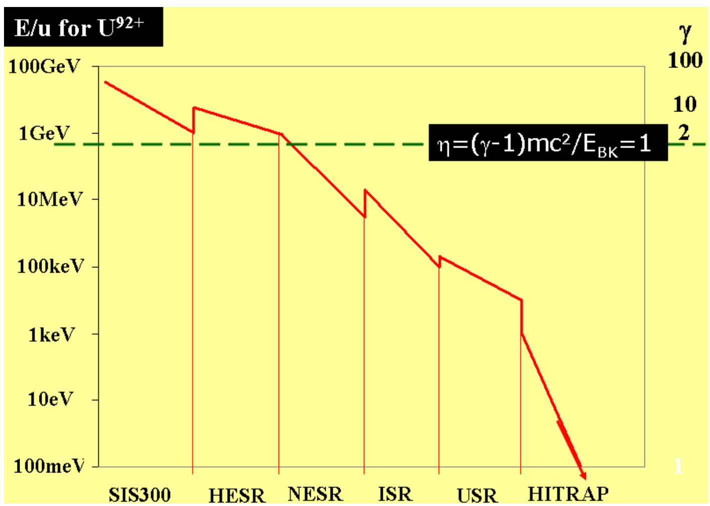
Facility for Antiproton an Ion Research

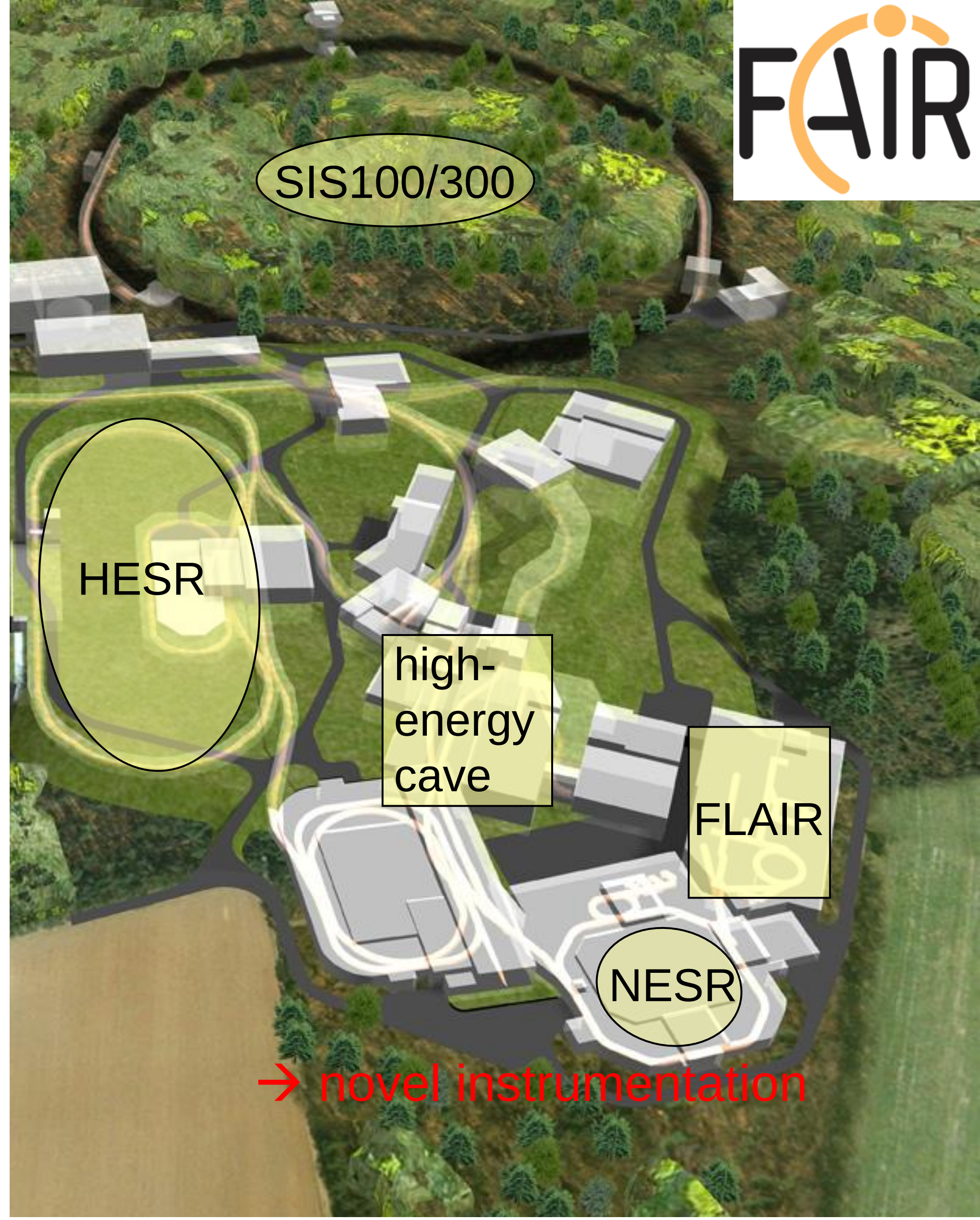
(FAIR)

the **SPARC** collaboration:

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

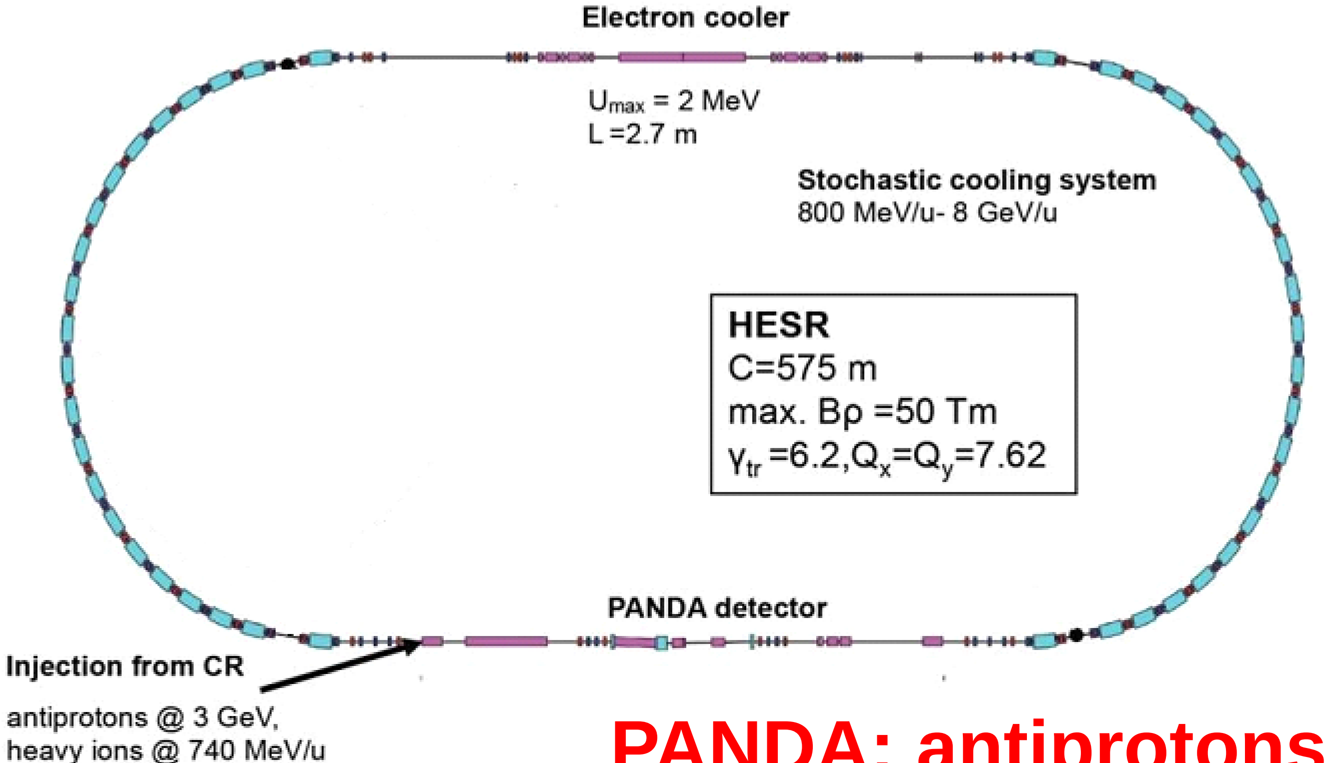
the **FLAIR building**





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

Properties of the High Energy Storage Ring (HESR)



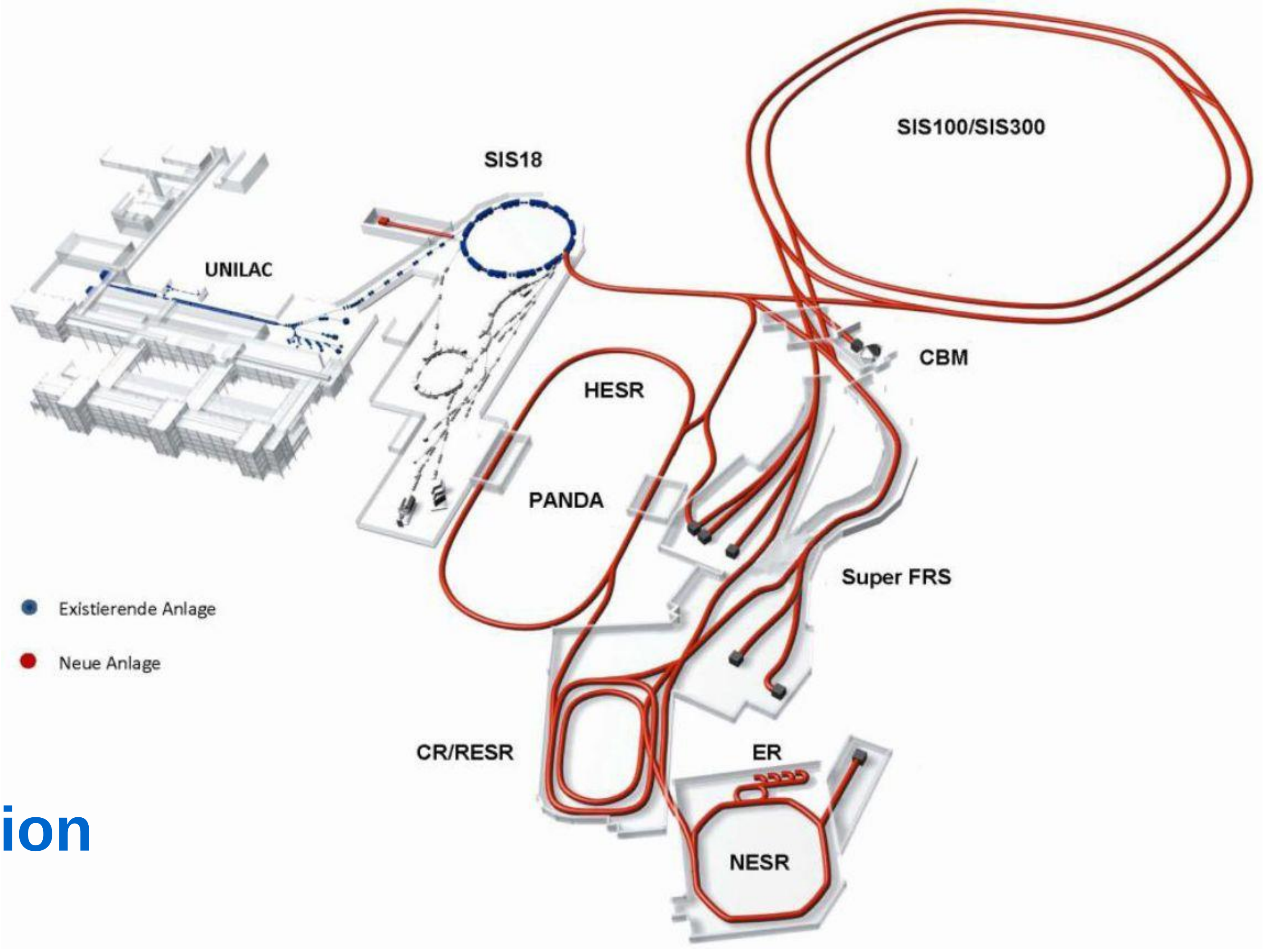
PANDA: antiprotons

SPARC: heavy HCI

x-ray laser spectroscopy (HESR up to γ=6): $2s_{1/2}$ → $2p_{3/2}$

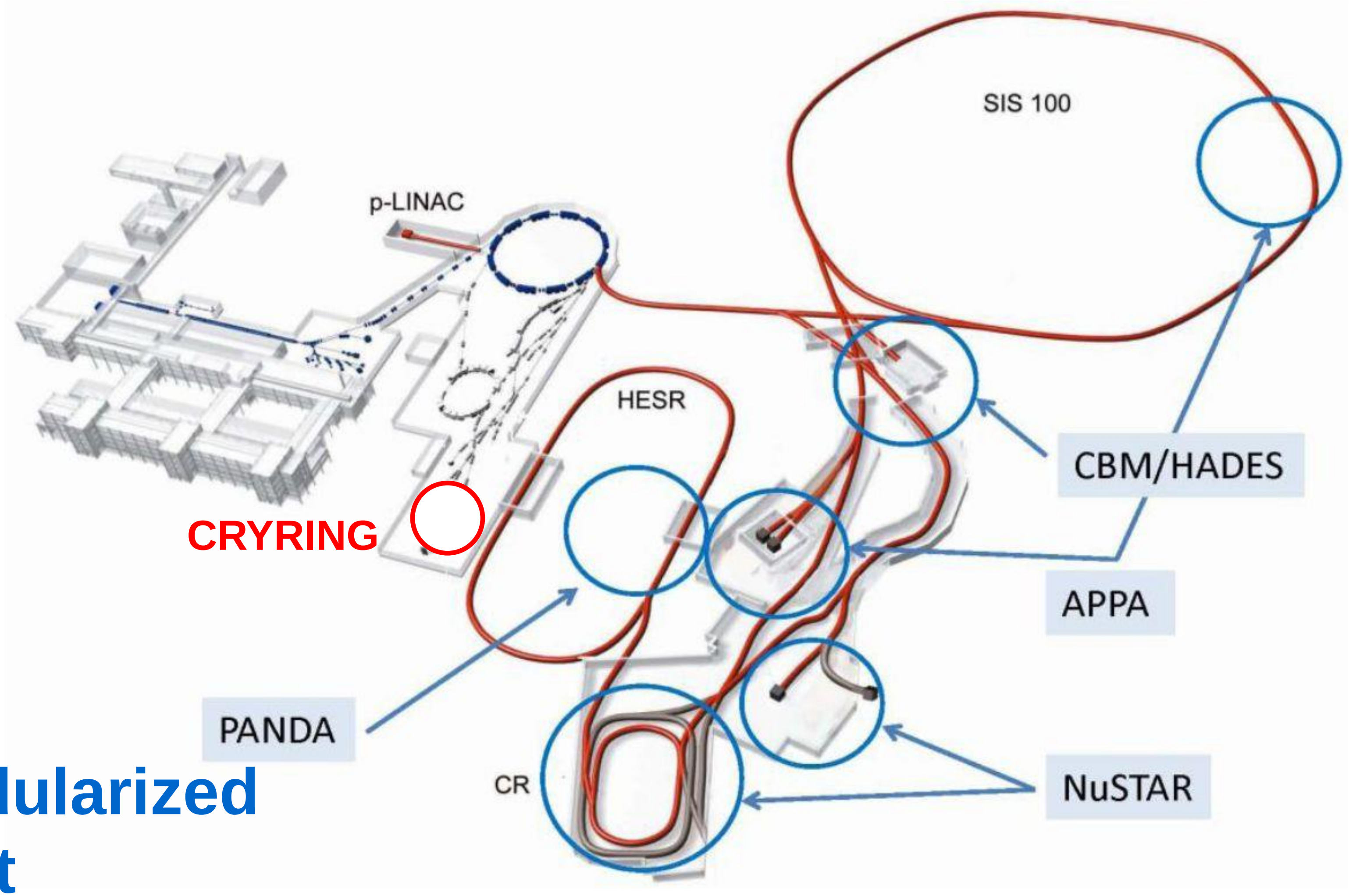
“OPERATION OF THE HESR STORAGE RING OF THE FAIR PROJECT WITH IONS AND RARE ISOTOPES”, M. Steck, C.Dimopoulou, A. Dolinskii, T. Katayama, Y. Litvinov, Th. Stöhlker, R. Maier, D. Prasuhn, H. Stockhorst Proceedings of IPAC2012, New Orleans, Louisiana, USA

Facility for Antiproton and Ion Research (FAIR)



full version

Facility for Antiproton and Ion Research (FAIR)



modularized start version

Luftbild des Baufeldes vom 05.05.2013 (Foto: Jan Schäfer für FAIR)

✕


Thank you for your attention ☺