Atomic physics at FAIR:
Precision experiments with highly-charged ions

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ExtreMe Matter Institute

Collaborations

APPA Physics (Atomic, Plasma Physics and Applications)

- **BIOMAT** (**Bio**logy and **Mat**erial Science)
- **FLAIR** (**F**acility for **L**ow-Energy **A**ntiproton and Heavy **I**on**R**esearch)
- **HEDgeHOB** (**H**igh **E**nergy **D**ensity Matter **ge**nerated by **H**eavy I**o**n **B**eams)
- **SPARC** (**S**tored **P**articles **A**tomic **R**esearch **C**ollaboration)
- **WDM** (**W**arm **D**ense **M**atter) collaboration

sparc
Stored Particles Atomic Physics Research Collaboration

FLAIR
Facility for Low-energy Antiproton and Ion Research

Physics at Extreme Fields with Highly ChargedvHeavy Ions

Atomic structure
QED, many body effects

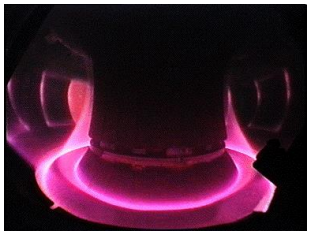
Atomic reactions and dynamics
photon-matter interaction

Nuclear Physics:
masses, nuclear moments, charge radii

two body decay etc.

Physics with highly-charged heavy ions

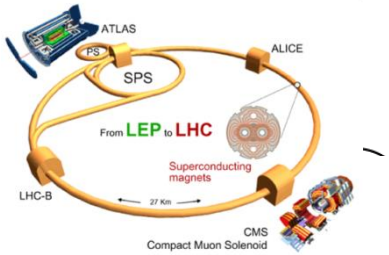
Plasma physics



Astrophysics

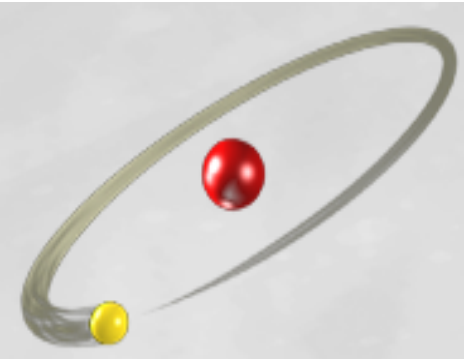
Accelerator physics

Physics beyond the standard model

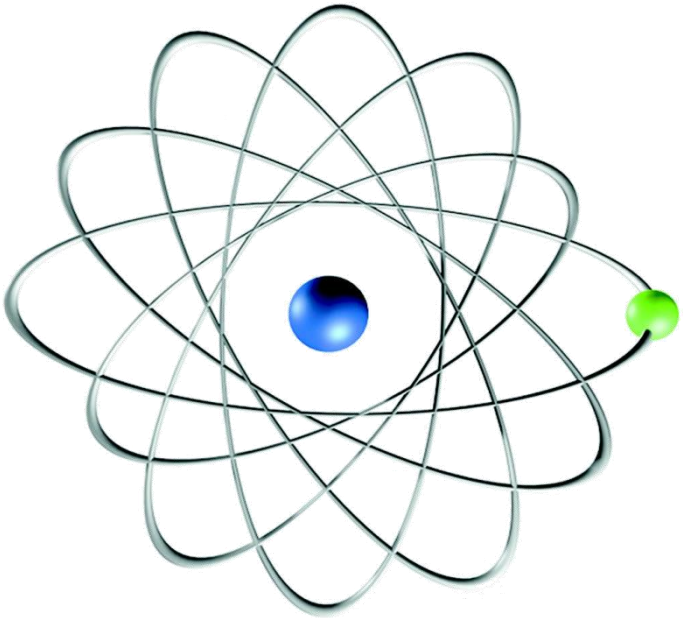


Highly-charged ions (HCI)

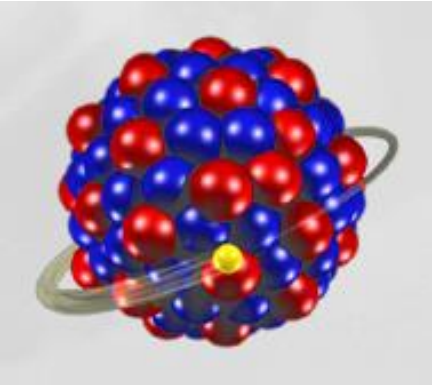
Hydrogen



Neutral Atom



Hydrogen-like uranium:
92 Protons in the nucleus and only one electron

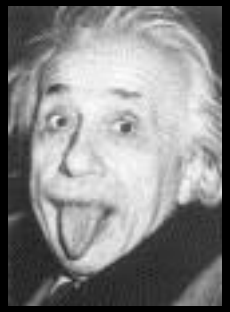


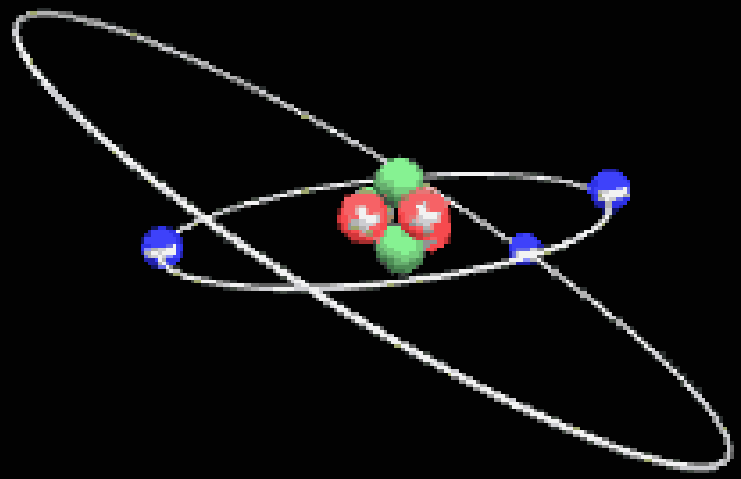
Smaller distance between electron and nucleus
*(for uranium: electron is **about 100 times closer to the nucleus** than in hydrogen)*

Electrons move very fastly; they are relativistic
(for uranium: K-shell electron moves with about 70% of the speend of light)

Heavy Ions with Few Electrons

Theory of relativity





Quantum mechanics

When in heavy ions with more than one electron relativistic effects become important on the top of quantum phenomena then it becomes really complicated:

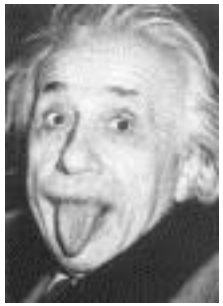
the electrons move very fastly, i.e. relativistically
each electron has its own time (own clock)

?

HELMHOLTZ ASSOCIATION

Quantum mechanics (non-relativistic)

Theory of relativity



Relativistic Quantum mechanics
Dirac‘s theory

Quantum Electrodynamics (QED)

QED

Richard Feynman
1918-1988

... having to resort to such hocus-pocus [renormalization] has prevented us from proving that the theory of QED is mathematically self-consistent.

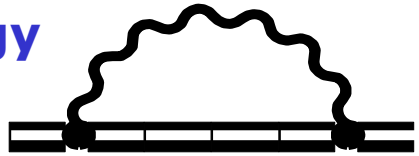
R. Feynman, 1985

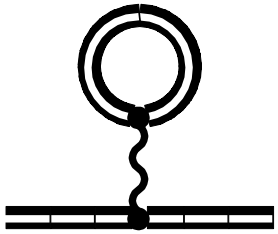
"The theory of quantum electrodynamics is, I would say, the jewel of physics – our proudest possession.

... [renormalization] is what I would call a dippy process.

R. Feynman, 1985

Self-energy





Vacuum-polarization

Extremely strong EM fields

STRONG EM FIELDS [V/cm]

Electron-Positron Pair production our of vacuum

$eEd=2mc^2$

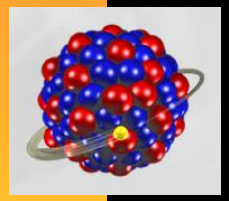
10^{20}

10^{15}

10^{10}

10^{5}

K-shell Uranium



H-like Uranium
E_K = -132 • 10^3 eV

Laser, z.B. PHELIX

Hydrogen atom

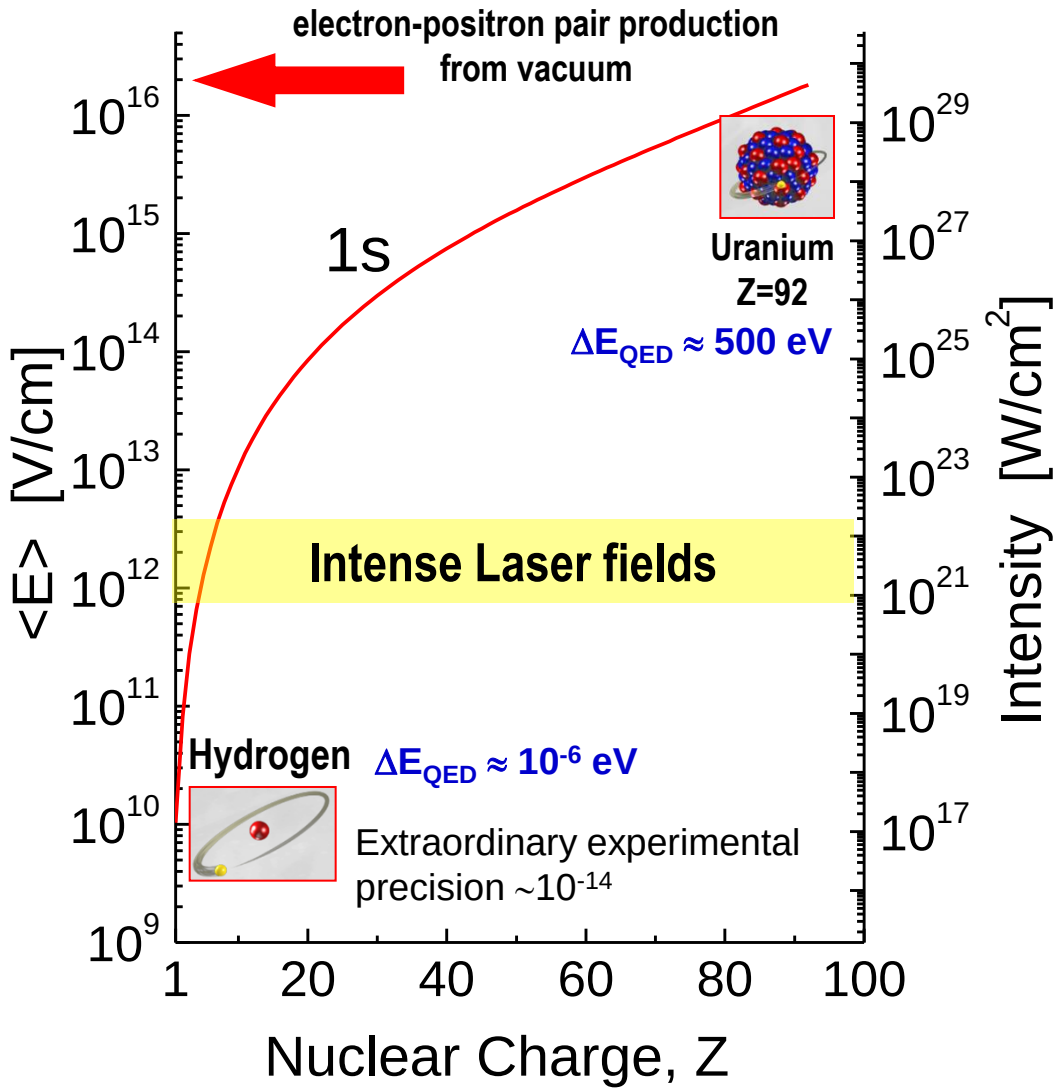
Hydrogen
E_K = -13.6 eV

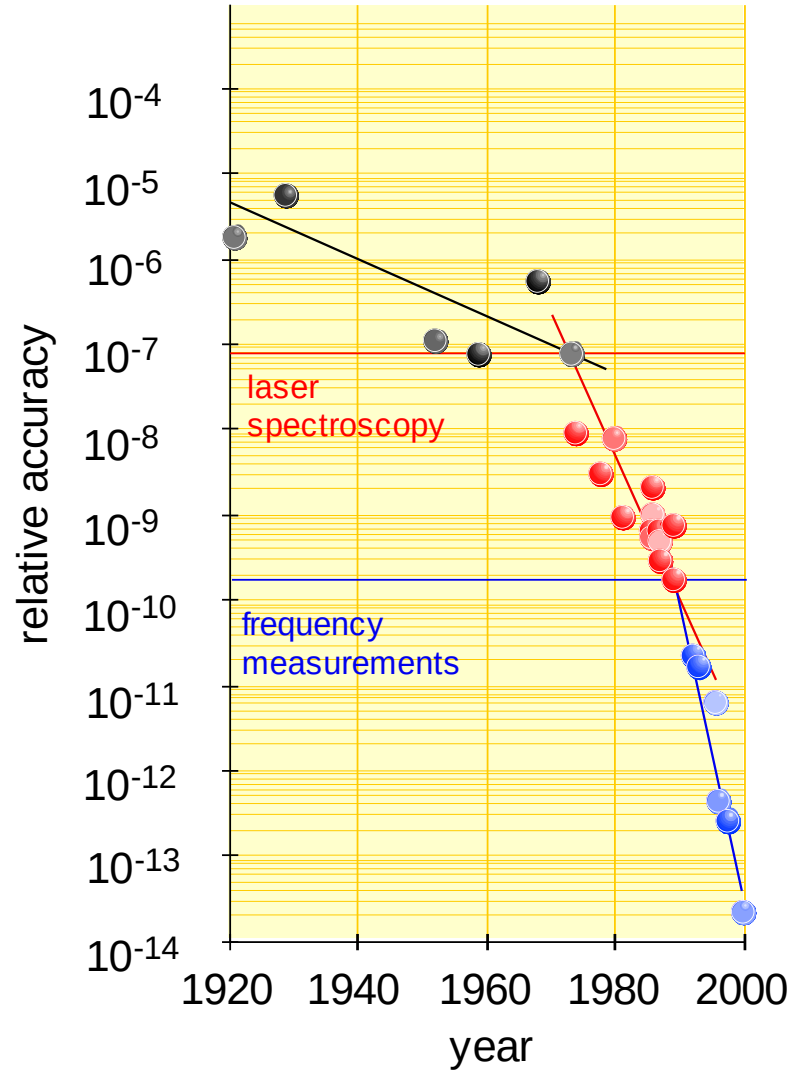
Accelerator

Spark Plug

HELMHOLTZ ASSOCIATION

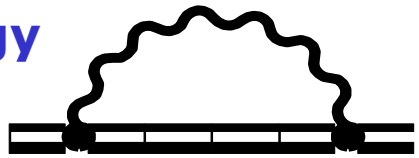
Physics of extremely strong fields

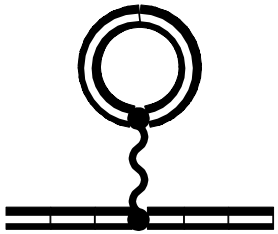




Bound-State QED in Strong Fields: effects of the quantum vacuum

Self-energy





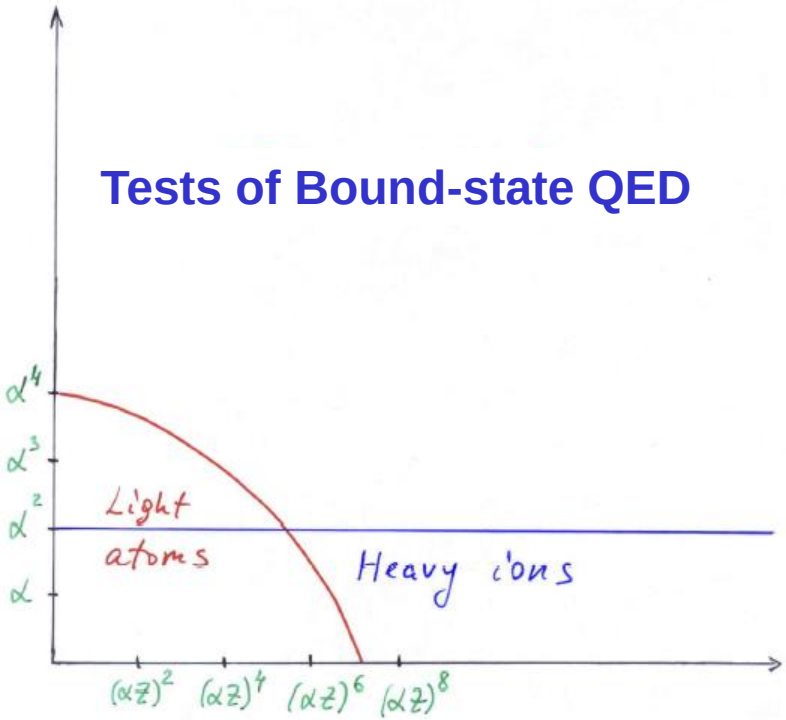
Vacuum-polarization

$$\Delta E = \alpha/\pi\ (\alpha Z)^4\ F(\alpha Z)\ m_e c^2$$

Low Z-regime: $\alpha Z << 1$
$F(\alpha Z)$: expansion in αZ

High Z-regime: $\alpha Z \approx 1$
$F(\alpha Z)$: expansion in αZ not applicable (calculation to all orders)

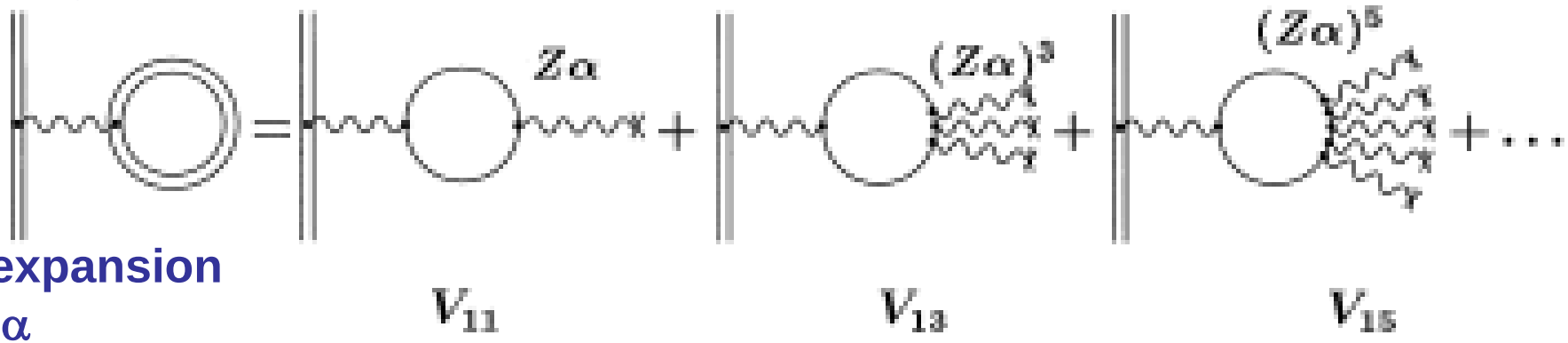
Tests of Bound-state QED



Bound-state QED: treatment non-perturbative in Zα

non-perturbative treatment

perturbative treatment: expansion in Zα



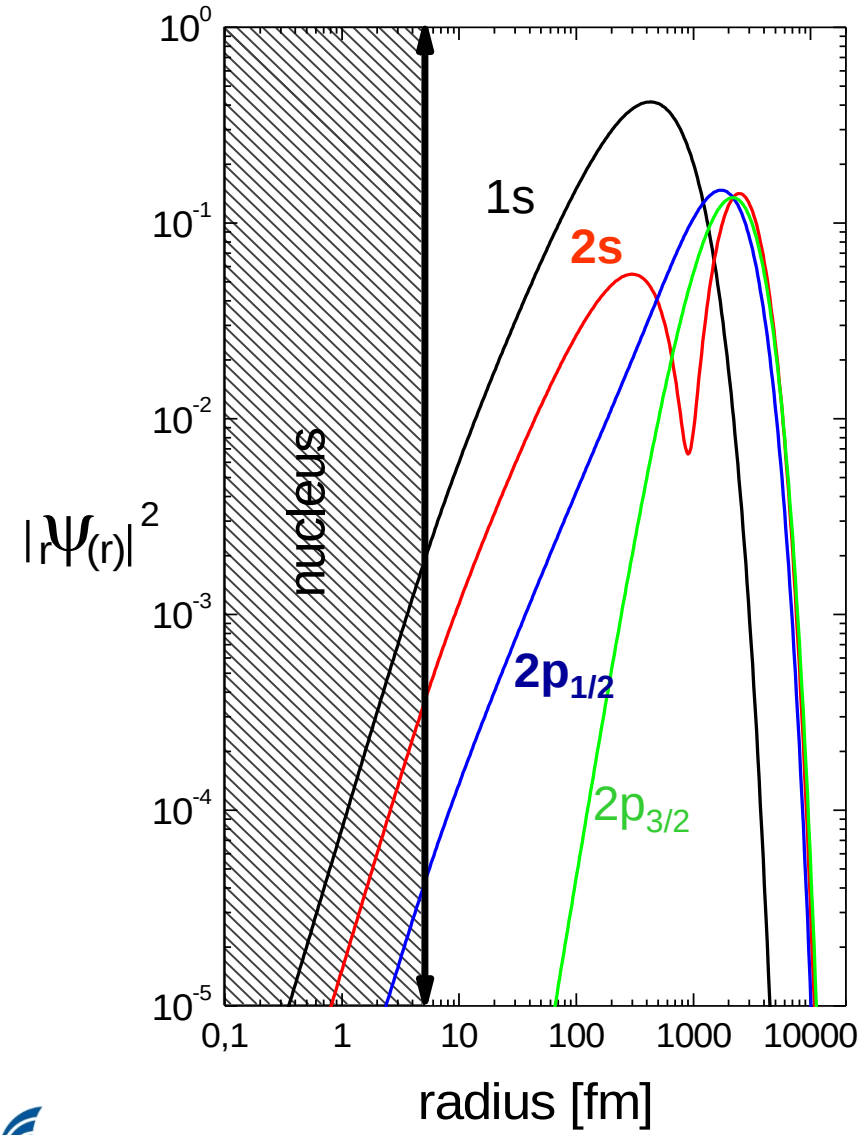
no expansion in Zα

Non-perturbative bound-state QED was developed in the last 20 years by excellent theoreticians like:

Beier, Blundell, Breit, Czarnecki, Glazov, Jentschura, Johnson, Karshenboim, Lindgren, Lee, Milstein, Mohr, Pachucki, Persson, Plunien, Salomonson, Sapirstein, Shabaev, Soff, Sunnergreen, Terekhov, Tupitsyn, Volotka, Yerokhin, and others.

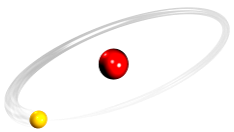
Ref.: U.D. Jentschura, P.J. Mohr, G. Soff, PRL 82, 53 (1999); T. Beier, Physics Reports 339, 79 (2000)

Lamb Shift: nuclear effects



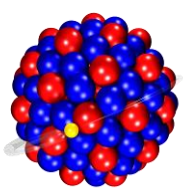
Level Scheme of Hydrogen

hydrogen

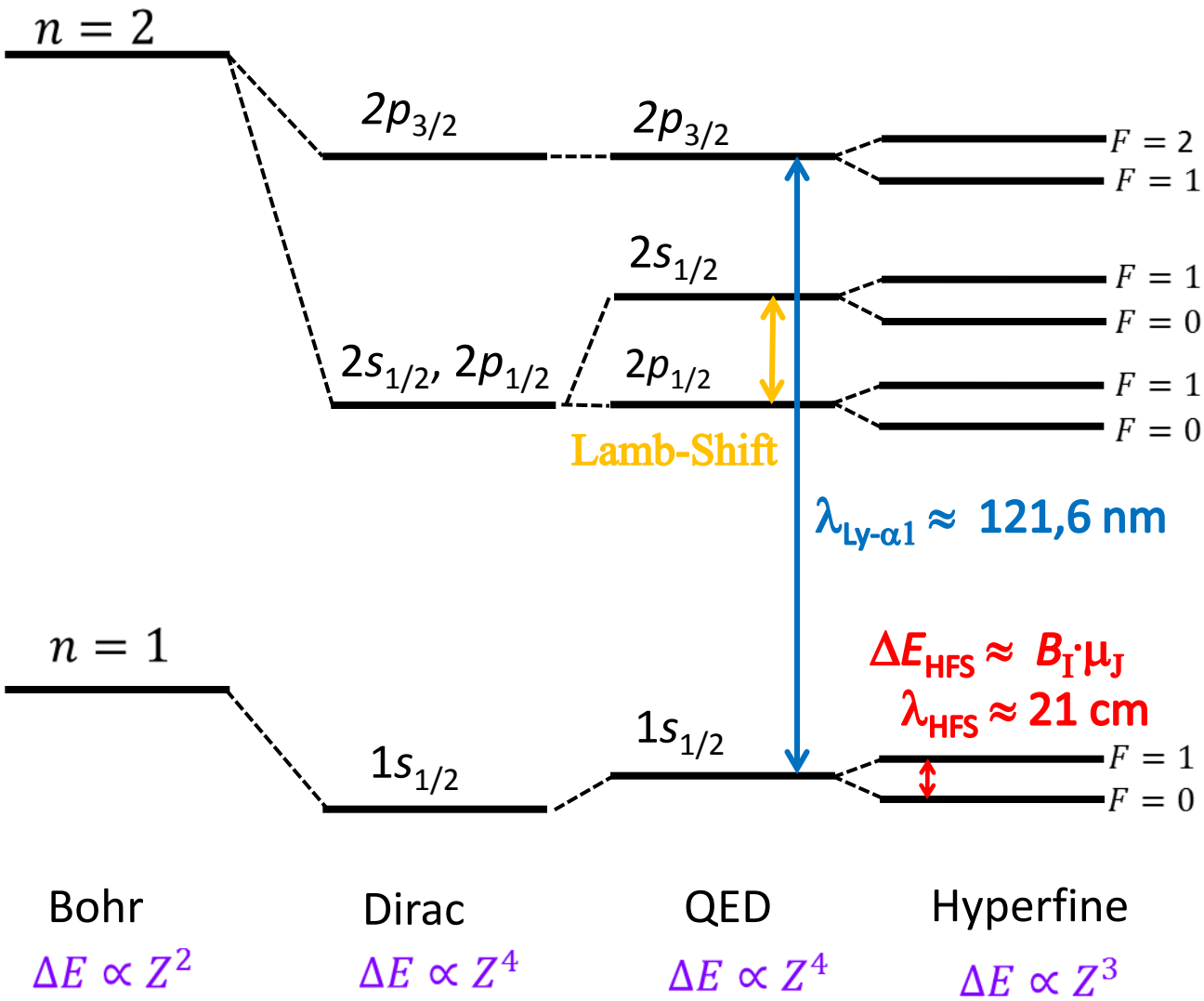


Z=1
E_b = 13.6 eV
$Z \cdot \alpha \ll 1$

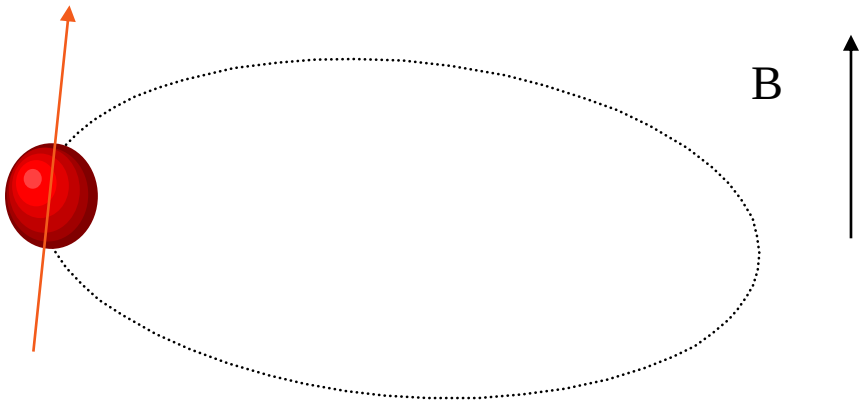
uranium ion



Z=92
E_b = 132 keV
$Z \cdot \alpha \approx 1$



g-factor of an electron



$$\mu = g \cdot \frac{e}{2m} J$$

m: magnetic moment
g: g-factor
e: charge
m: mass
J: angular momentum

g-factor of an electron

mass **m**
(*no theoretical prediction*)

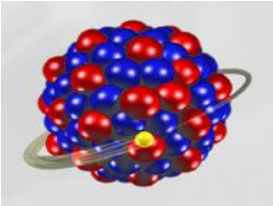
charge **e**
(*no theoretical prediction*)

Electron

magnetic moment **μ**
(**QED**, *most successful theory in physics*)

Precision Experiments in Atomic Physics

Testing our current understanding of EM interactions (QED) in different regimes with fundamental atomic systems



H-like Uranium
<E>~ 10^{16} V/cm

Precision calculations
QED, many body effects, extreme fields

Obervables

(B.E., g-factor, HF-structure, etc.)

Measured with high precision

NUCLEAR GROUND STATE PROPERTIES
masses, nuclear moments, charge radii

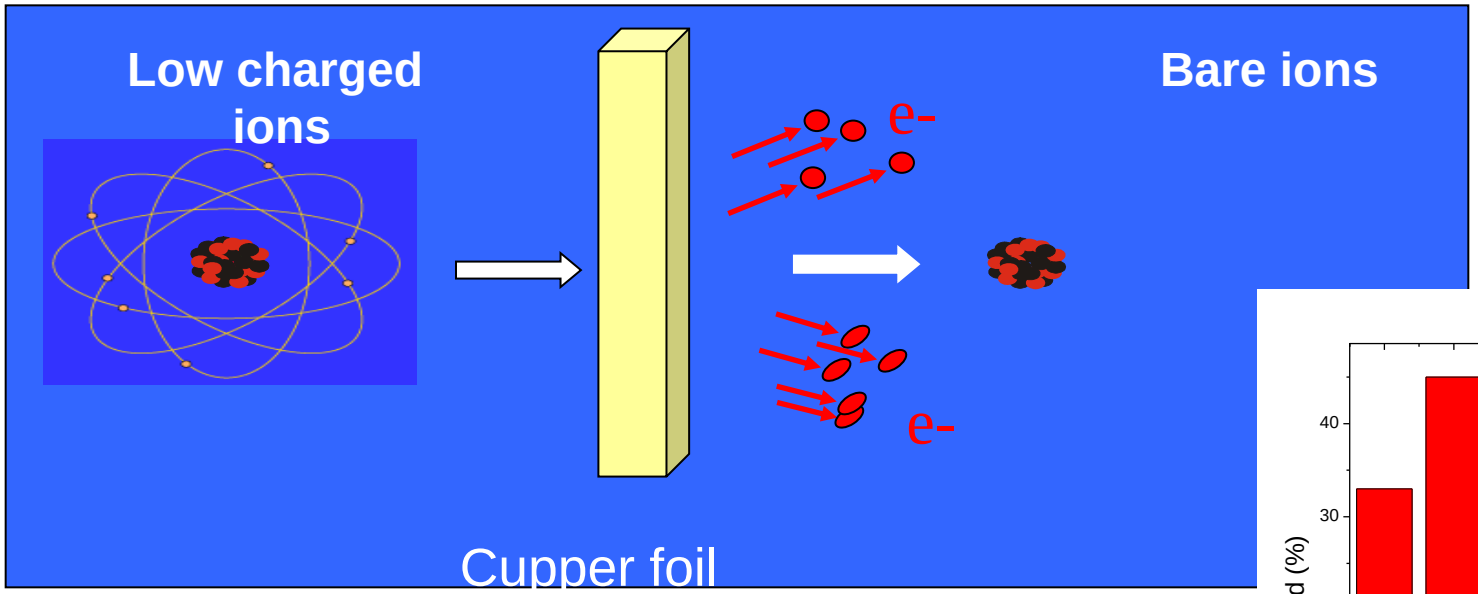
Fundamental constants:
Rydberg, α, electron mass

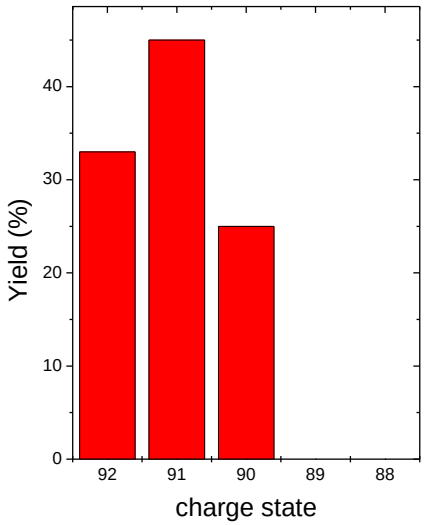
Why relativistic velocities?

Bohr criteria: *Largest ionization cross section at* $V \approx V_K$

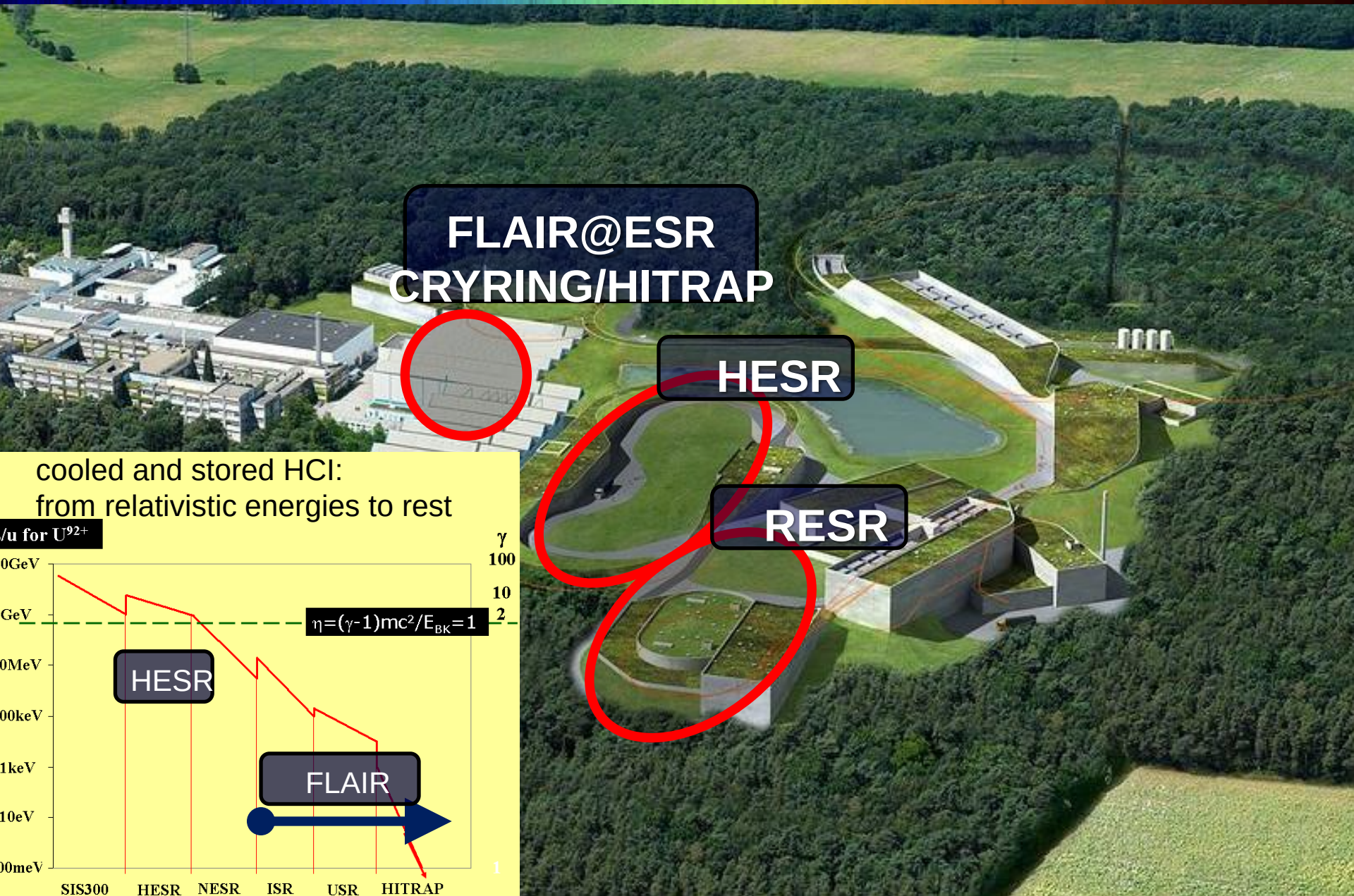
Uranium

$v_K / c \approx 0.67$ → $E_{KIN} \approx$ **?**





Facilities for Atomic Physics at FAIR MSV



cooled and stored HCI:
from relativistic energies to rest

Experimental Conditions at the HESR

location of target stations

Worldwide premiere: Precision experiments using cooled relativistic ion beams

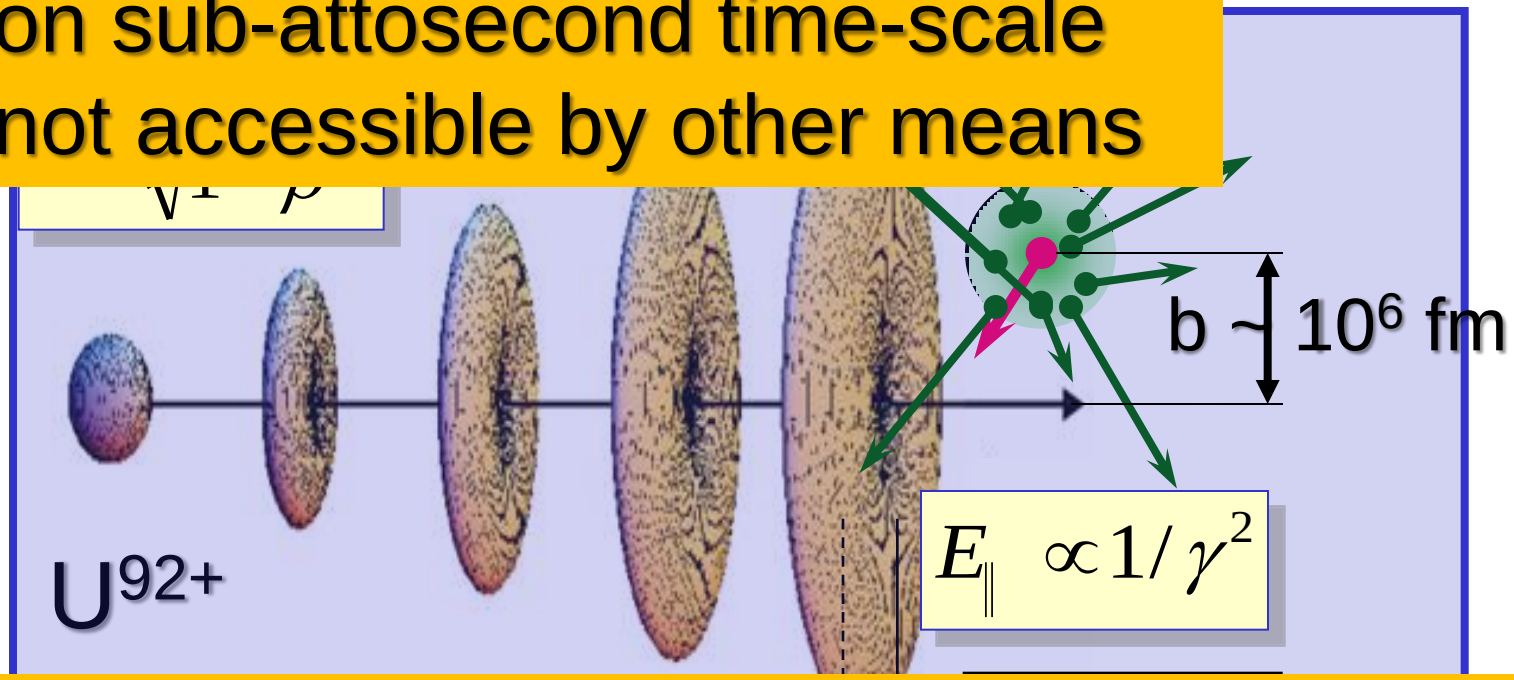
- species: p, pbar, HCl, RIB
- circumference 574 m
- injection energy 740 MeV
- $B\rho$ = 50 Tm
- for U^{92+}: 4.937 GeV/u
- γ_{MAX}=6.30; β_{MAX}=0.987
- momentum (energy) rang
- c (0.8-14.
- ng / e-coo

the
SR

- **Stochastic cooling & electron cooling**
- **electron-, gasjet-, fiber-targets (!)**
- **Particle detectors**
- **Ion stacking**
- **Luminosity (number of stored ions)**
- **Beam diameter/charge separation**
- **Acceleration and deceleration**
- **Coupling of laser to the ion beam line**
- **Building / Space for setups**

Extreme Dynamic Fields

Explore correlated electron dynamics
- on sub-attosecond time-scale
- not accessible by other means



Explore relativistic quantum dynamics
- particle production
- non-perturbative regime
- coupling to the radiation field

Physics program at high energies (HESR)

pair-production phenomena

- non-perturbation regime ($\alpha Z_1 \approx \alpha Z_2 \approx 1$)
- multiple pairs (???)
- negative continuum dielectronic recombination

radiative processes

- recombination (polarization phenomena etc.)
- Photon-photon angular correlations (2E1-decay)

target ionization

- correlated electron motion – exploring the ultrafast, extremely strong transient fields of relativistic ions

electron impact phenomena

- electron impact excitation and ionization

bound state QED and nuclear parameters

- laser excitation in Li-like ions ($\Delta n = 0$)

Laser-ion Interaction at high γ

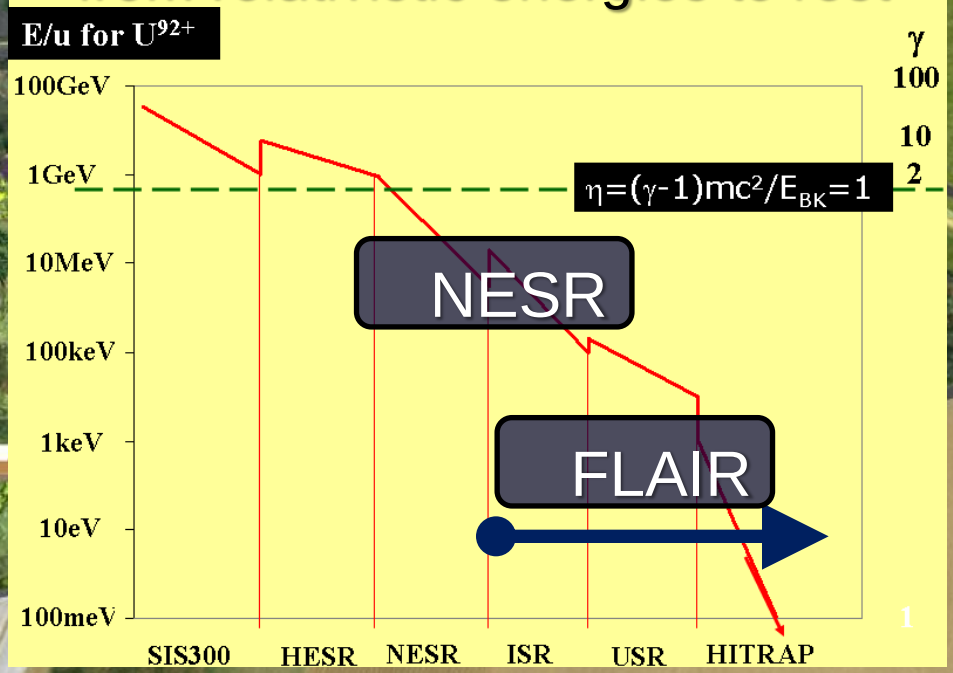
- test of special relativity
- laser cooling

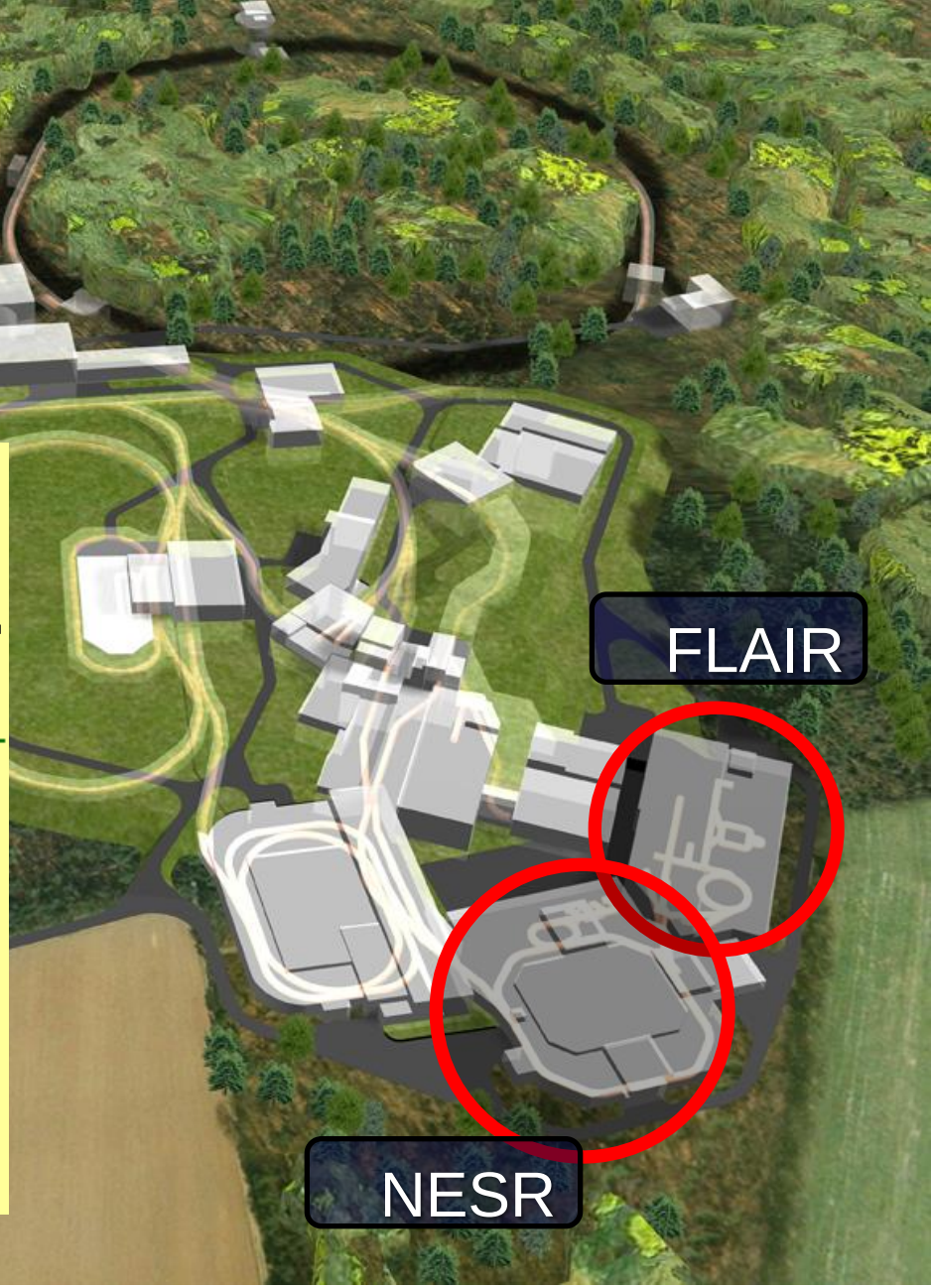
Tests of the standard model

- PNC effects in high-Z ions

sparc @ FAIR

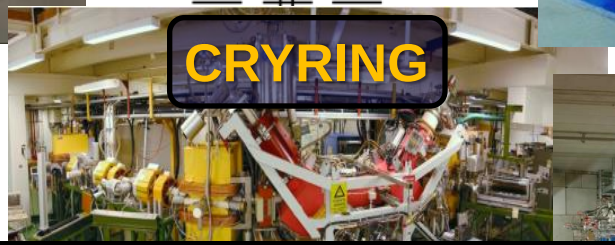
cooled and stored HCI:
from relativistic energies to rest

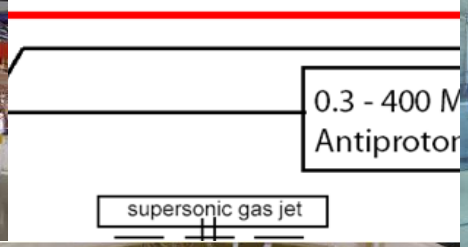


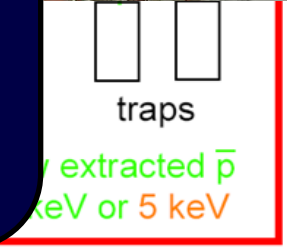


Low-energy branch

FLAIR-Facility @ ESR & SIS18







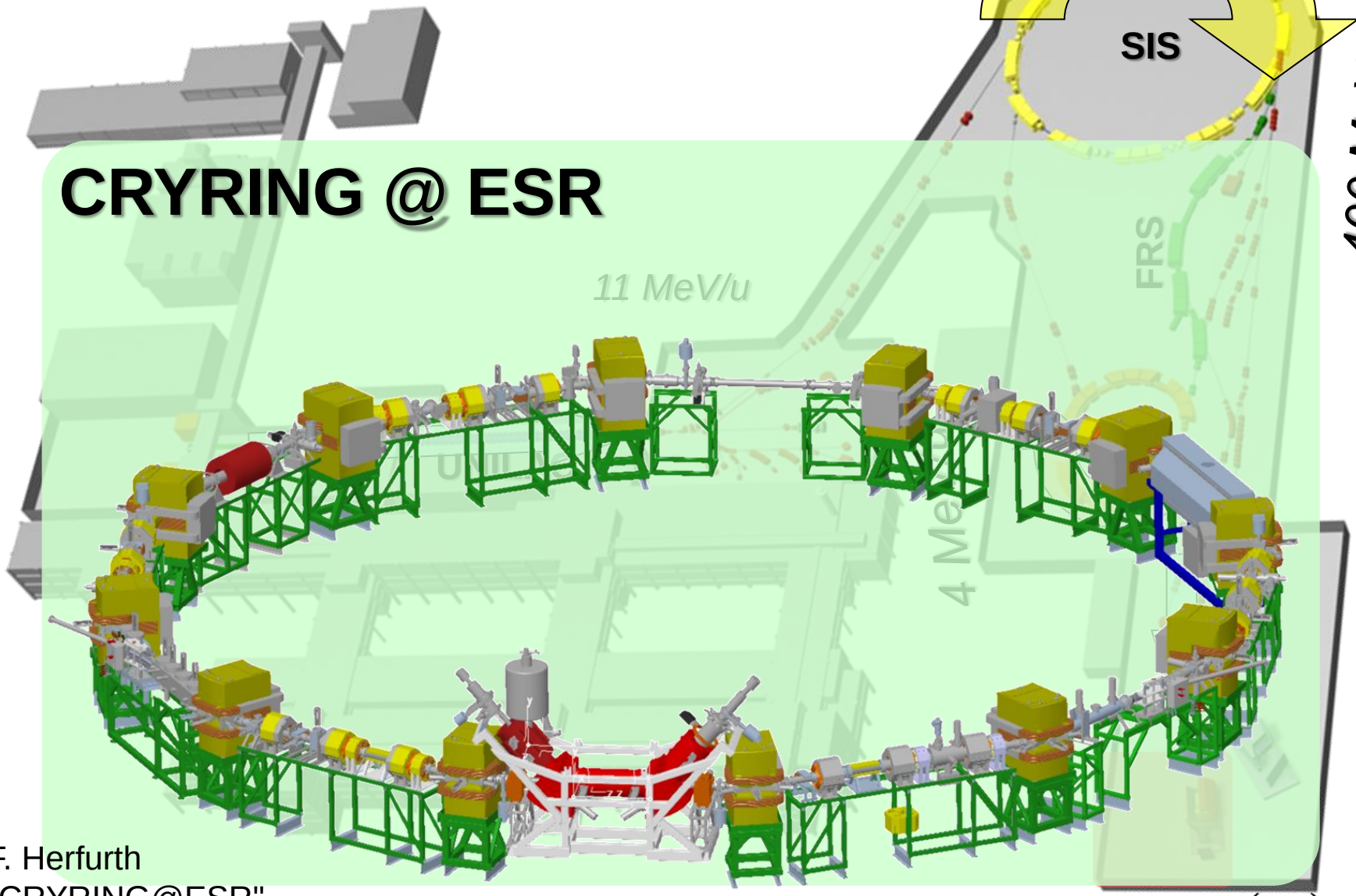
already at SIS18/ESR:

unique physics opportunities !!!

with RESR:

e-cooled low-energy pbars

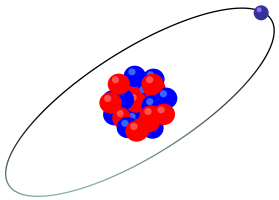
CRYRING @ ESR



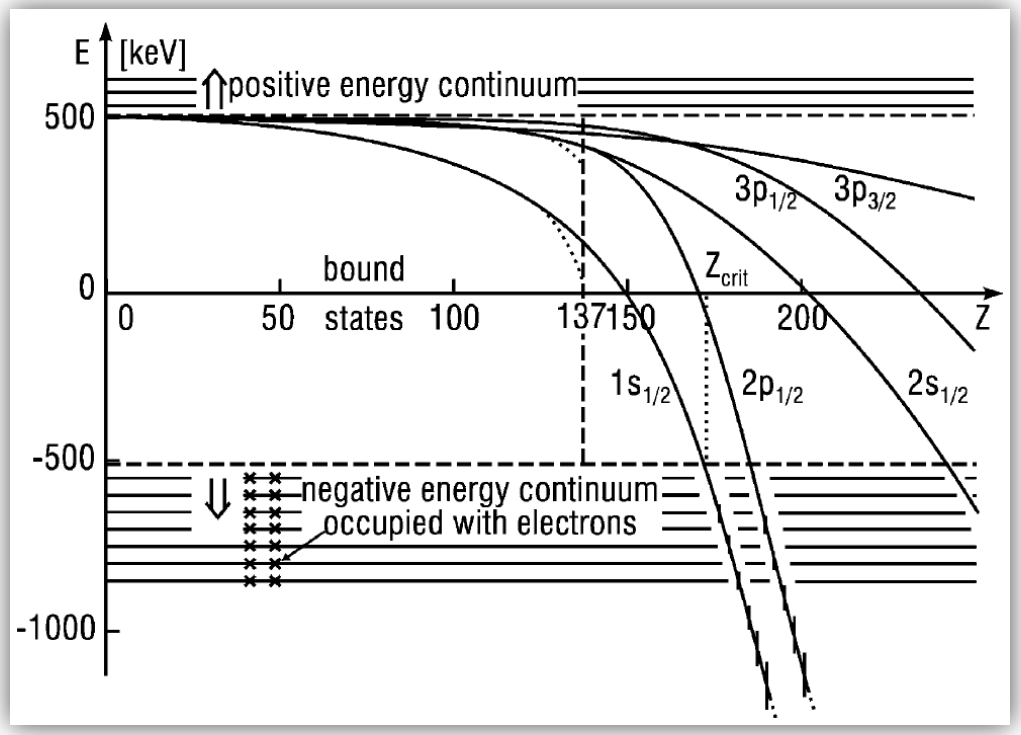
(Super)-critical electromagnetic fields

- Let us come back to Dirac energy of a *single* hydrogen-like ion:

$$E_{1s} = mc^2\sqrt{1-(Z\alpha)^2}$$

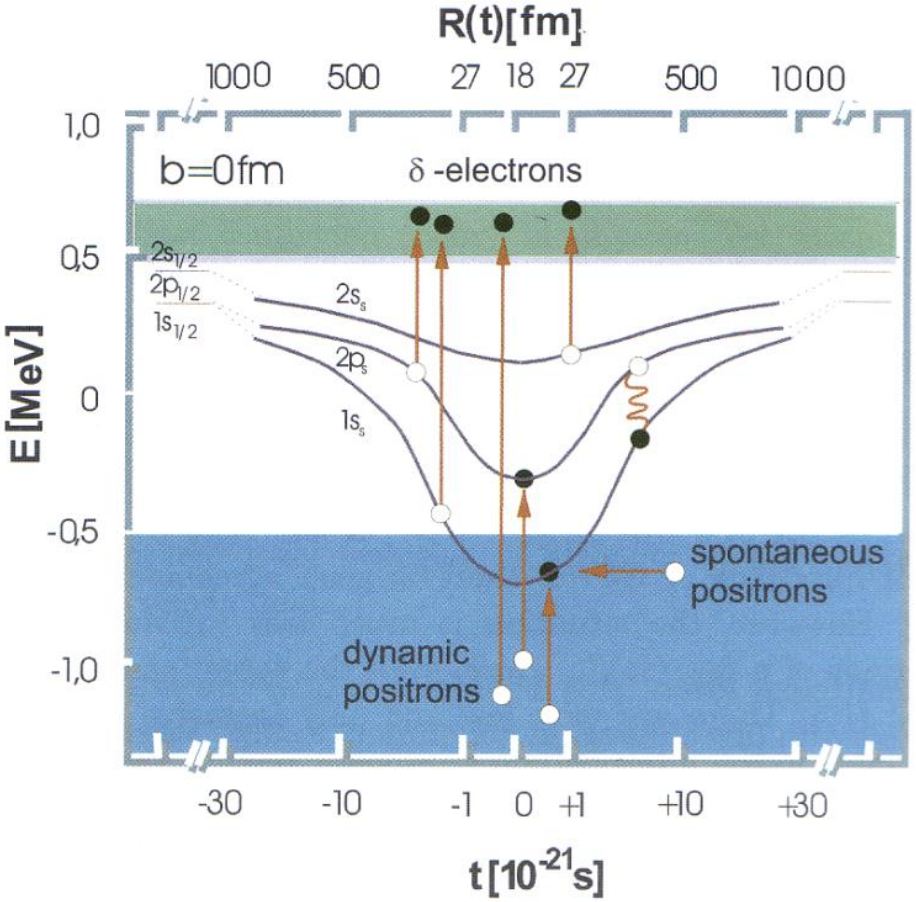


- What happens if we increase the nuclear charge Z?
- If nuclear charge of the ion is greater than Z_{crit} the ionic levels can "dive" into Dirac's negative continuum.
- Physical vacuum becomes unstable: creation of pairs may take place!

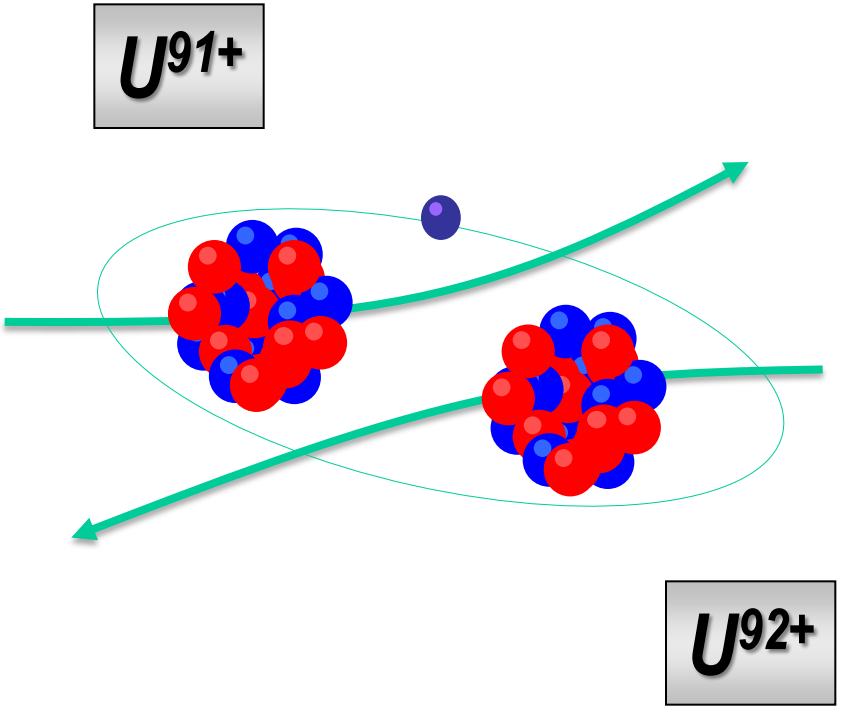


Supercritical fields: Formation of Quasi-Molecules

Merged Beams

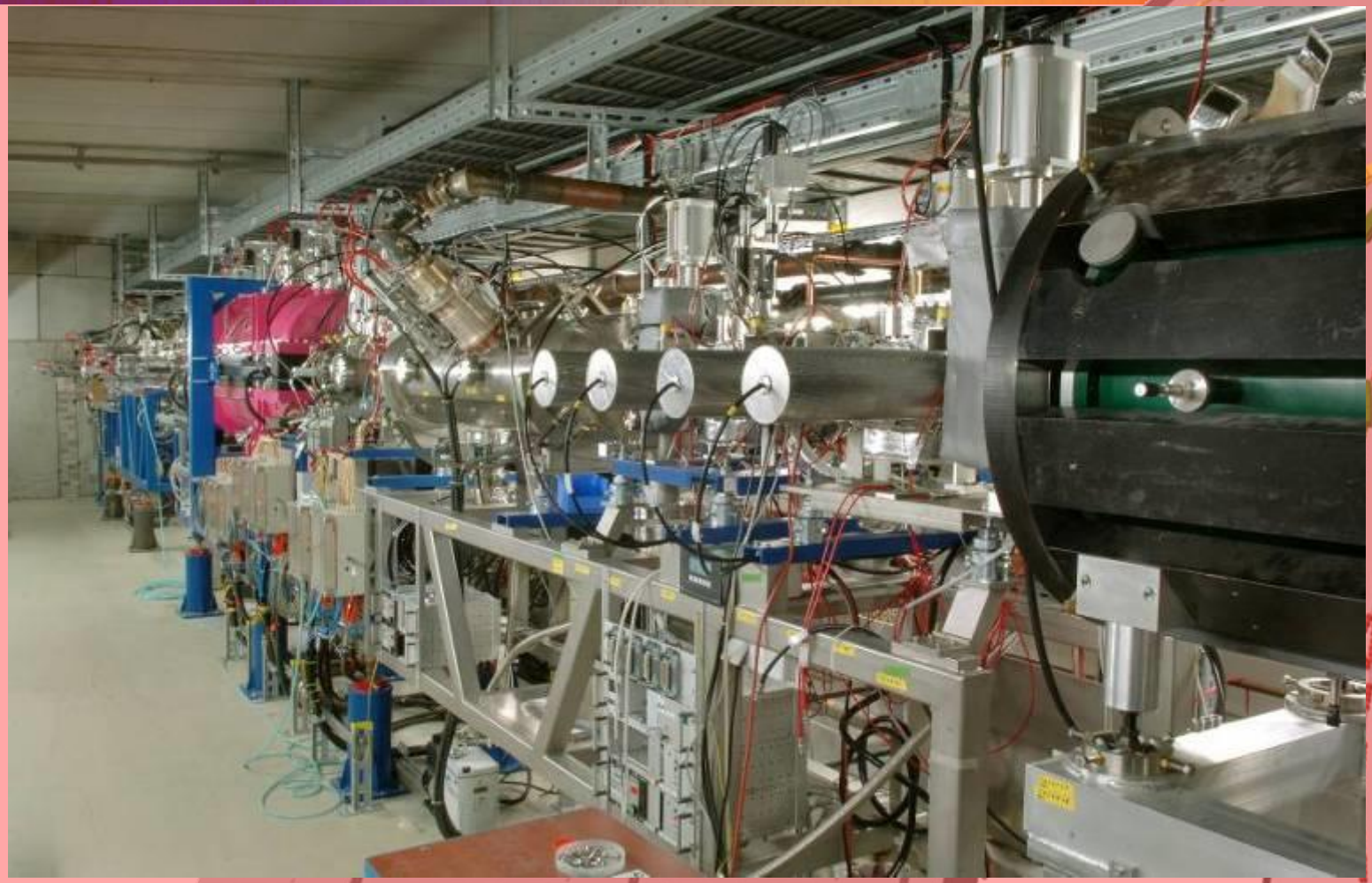


A. Artemyev, et al. J. Phys. B **43** (2010) 235207



HITRAP

GSI

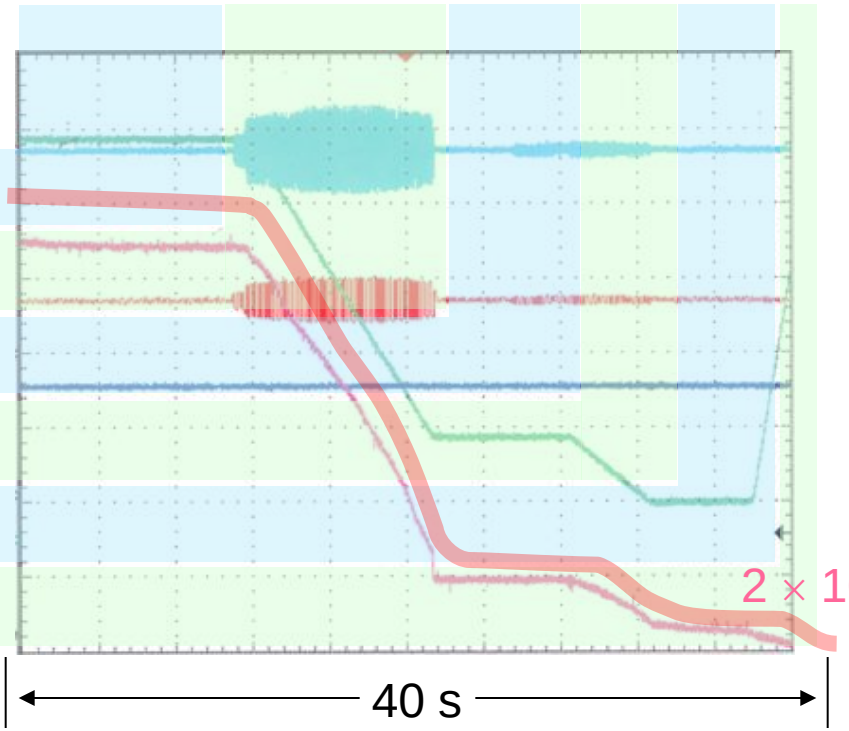


ESR - From 400 to 4 MeV/u

ESR – Experimental Storage Ring at GSI with stochastic and electron cooling

Ni^{28+} 400 → 30 → 4 MeV/u

time (s)	**ESR cycle during recent experiment**
5..20	injection, **stoch. cooling**
3..10	deceleration 400 – 30 MeV/u
2..6	e^- cooling, rebunching
2..5	deceleration 30 – 4 MeV/u
2..5	e^- cooling, ejection
3	reset magnets



signal:

RF amplitude

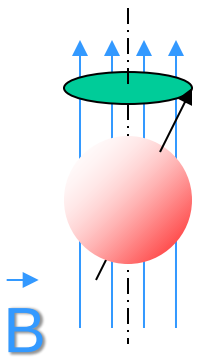
magn.dipole field

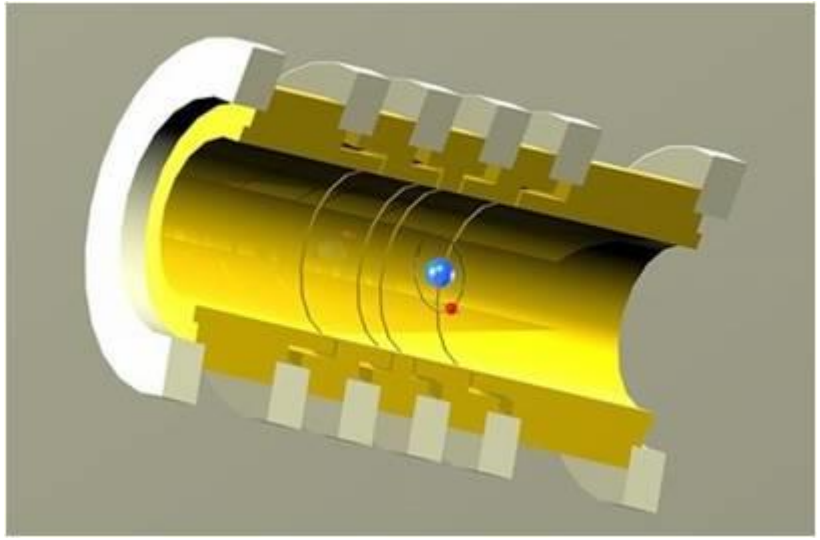
2×10^7 ion current

1100 μA → 180 μA → 25 μA

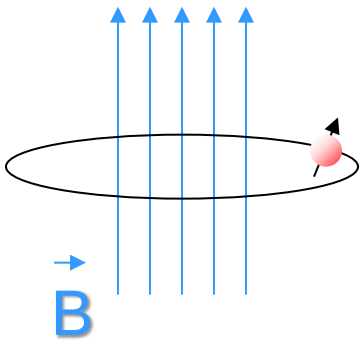
g-factor of the bound electron in a HCI

Lamor frequency





cyclotron frequency



$$\omega_L = g_S \frac{e}{2m_e} B$$

$$\omega_c = \frac{e}{m_e} B$$

$$g = 2\left(\frac{q}{e}\right)\frac{m_e}{M_i}\left(\frac{\omega_L^e}{\omega_c^i}\right)$$

'experimental g-factor' comparison with theory

external input parameter

measurement

nature International weekly journal of science

High-precision measurement of the atomic mass of the electron

S. Sturm, F. Köhler, J. Zatorski, A. Wagner, Z. Harman, G. Werth, W. Quint, C. H. Keitel & K. Blaum

Affiliations | Contributions | Corresponding author

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The quest for the value of the electron's atomic mass has been the subject of continuing efforts over the past few decades[1, 2, 3, 4]. Among the seemingly fundamental constants that parameterize the Standard Model of physics[5] and which are thus responsible for its predictive power, the electron mass m_e is prominent, being responsible for the structure and properties of atoms and molecules. It is closely linked to other fundamental constants, such as the Rydberg constant R_∞ and the fine-structure constant α (ref. 6). However, the low mass of the electron considerably complicates its precise determination. Here we combine a very precise measurement of the magnetic moment of a single electron bound to a carbon nucleus with a state-of-the-art calculation in the framework of bound-state quantum electrodynamics. The precision of the resulting value for the atomic mass of the electron surpasses the current literature value of the Committee on Data for Science and Technology (CODATA[6]) by a factor of 13. This result lays the foundation for future fundamental physics experiments[7, 8] and precision tests of the Standard Model[9, 10, 11].

Quantum Dynamics in Extreme Fields: The Program of the SPARC Collaboration

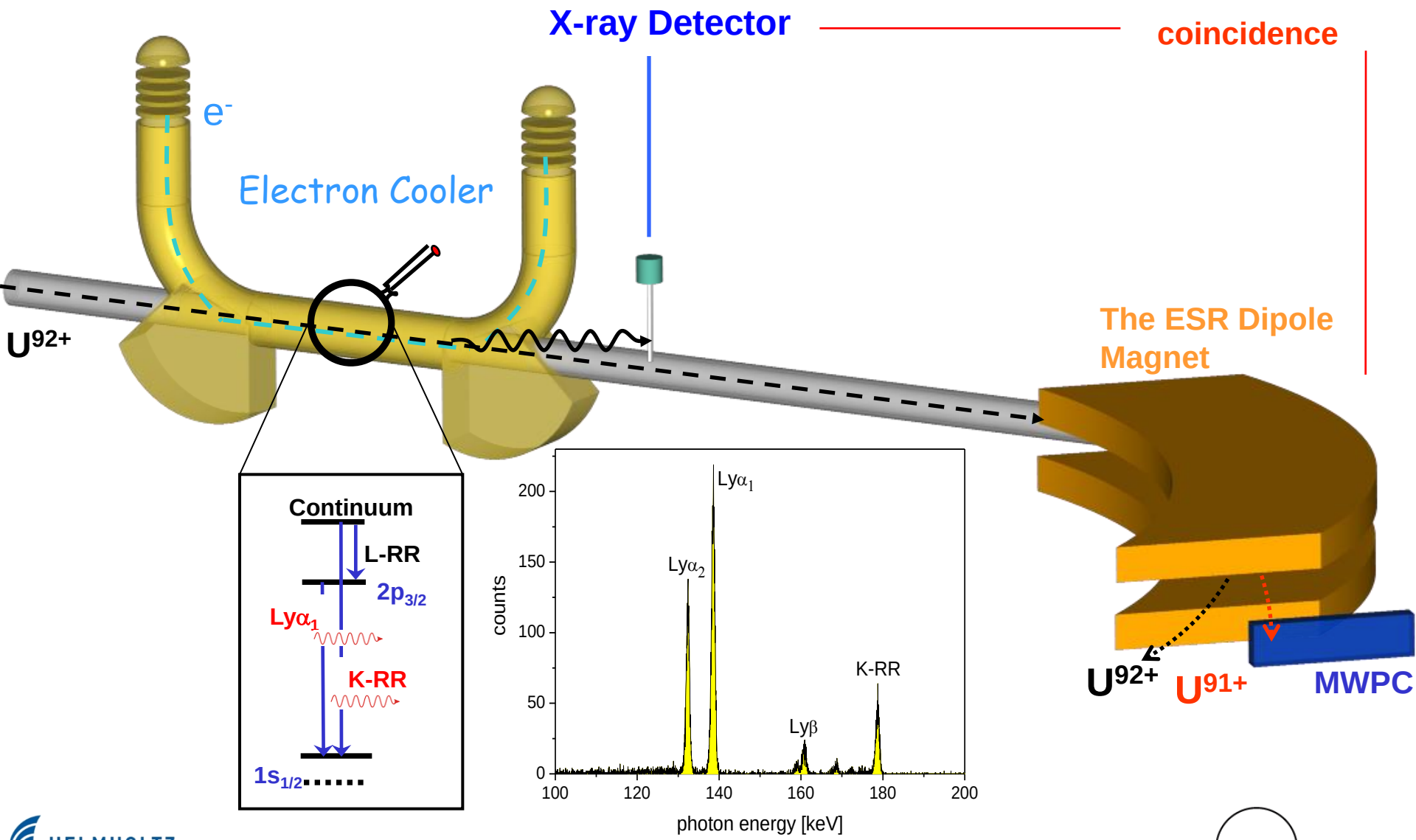
Scientific Goal: **Precision Studies of the Quantum Dynamics of Atomic Systems in Critical and Super-Critical Fields**

Discovery Potential:

- new concepts for QED in extreme fields
- inside into the correlated many-body dynamics via ultrashort and super intense field pulses ($<10^{-18}$ s)
- precision determination of fundamental constantes (α, m_e)
- proof of fundamental symmetries
- discovery and understanding of new decay modes of nuclei
- determination of fundamental nuclear properties via atomic data

Observables: x-rays, electrons, positrons, ions (projectiles, recoil)

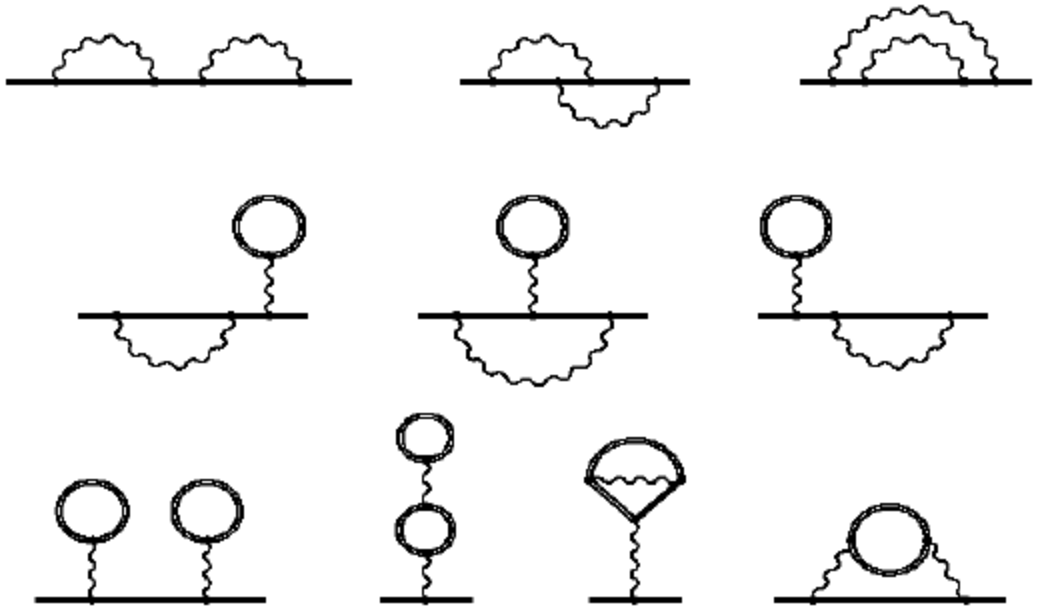
PRECISION TESTS OF BOUND-STATE QED IN EXTREME FIELDS:
Ground state Lamb shift in H-like uranium



QED effects on the energy levels of high-Z few-electron systems

One-electron QED corrections of second order in α

Non-perturbative calculations (in $Z\alpha$)



Goal

~1 eV

Recent progress: Evaluation of the two-loop self-energy diagrams

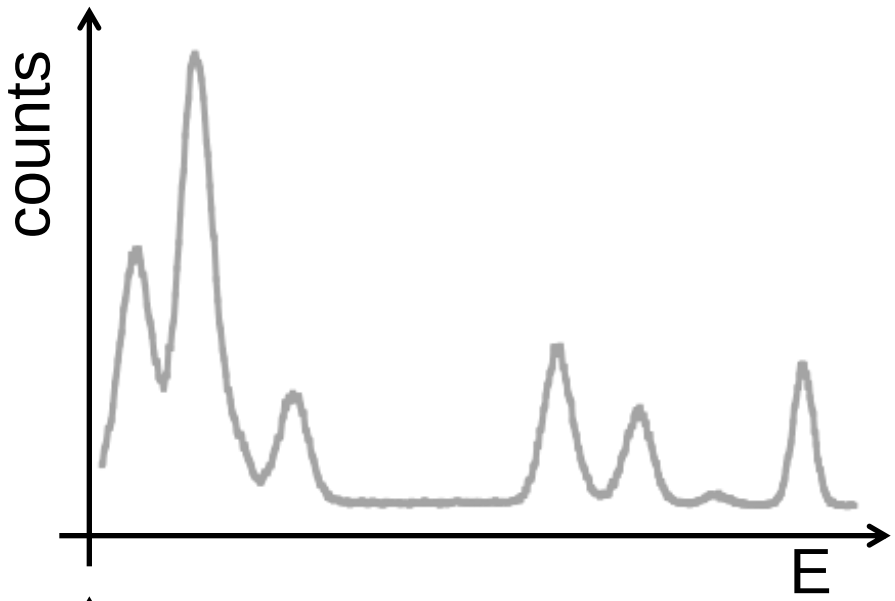
(V.A. Yerokhin, P. Indelicato, and V.M. Shabaev, JETP, 2005; PRL, 2006).

Towards an accuracy of 1 eV

Ge(i)-detector

FWHM ≈ 500 eV

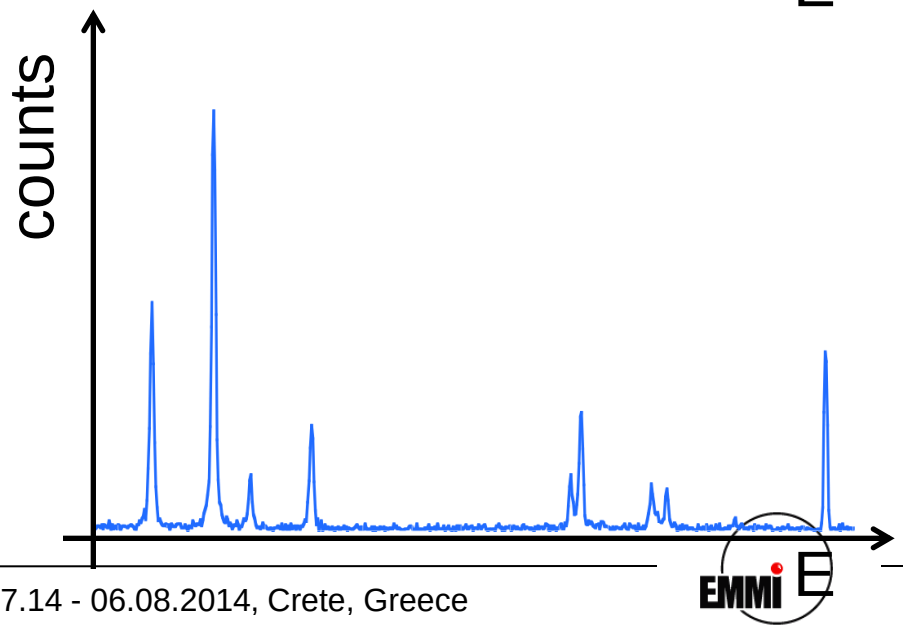
$\varepsilon = 10^{-4}$



crystal spectrometer
and/or microcalorimeter

FWHM ≈ 50 eV

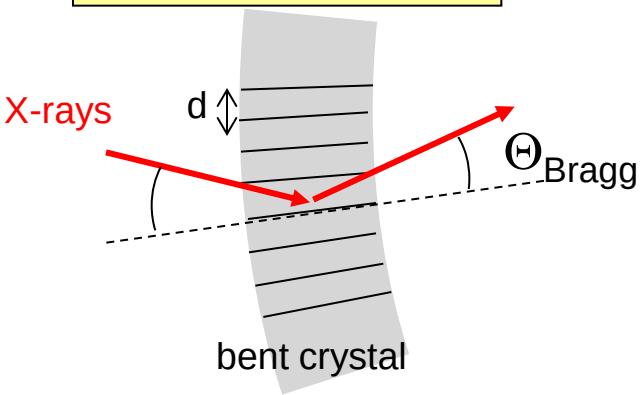
$\varepsilon = 10^{-8}$



A Laue Crystal Spectrometer

Bragg-Laue Relation

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

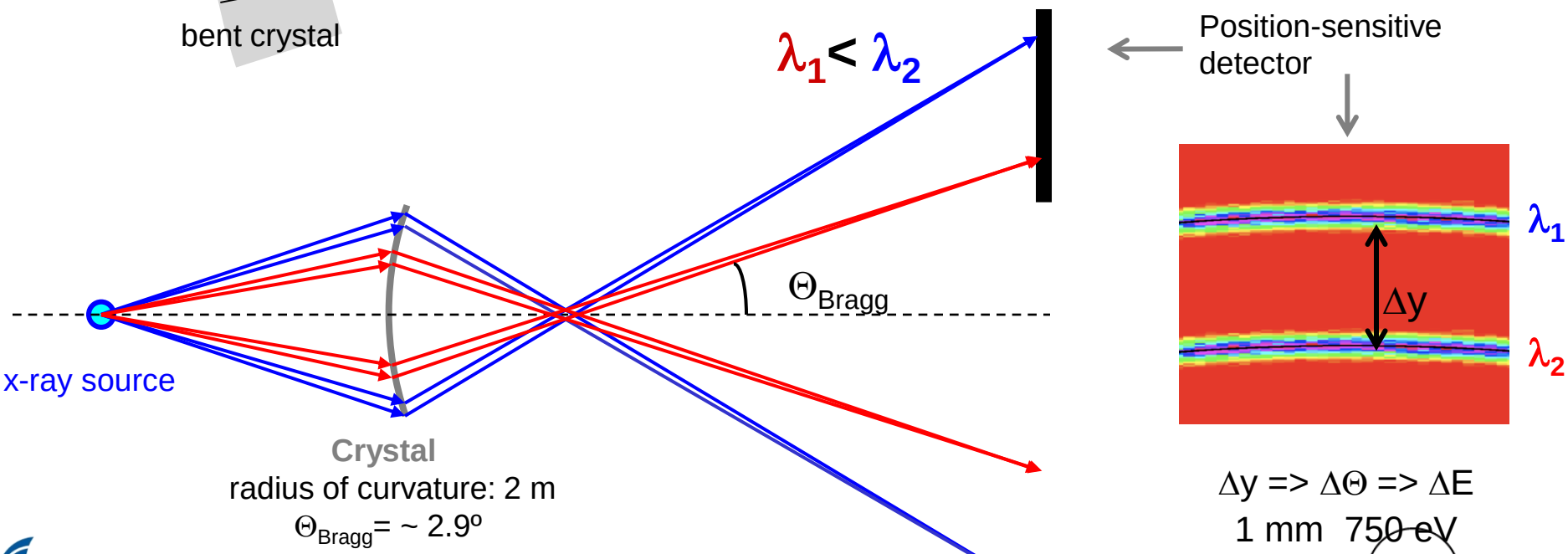


Crystal Spectroscopy

- measurement of angles

$\Rightarrow$ measurement of wavelength

- resolution: ~ 75 eV @ 60 keV



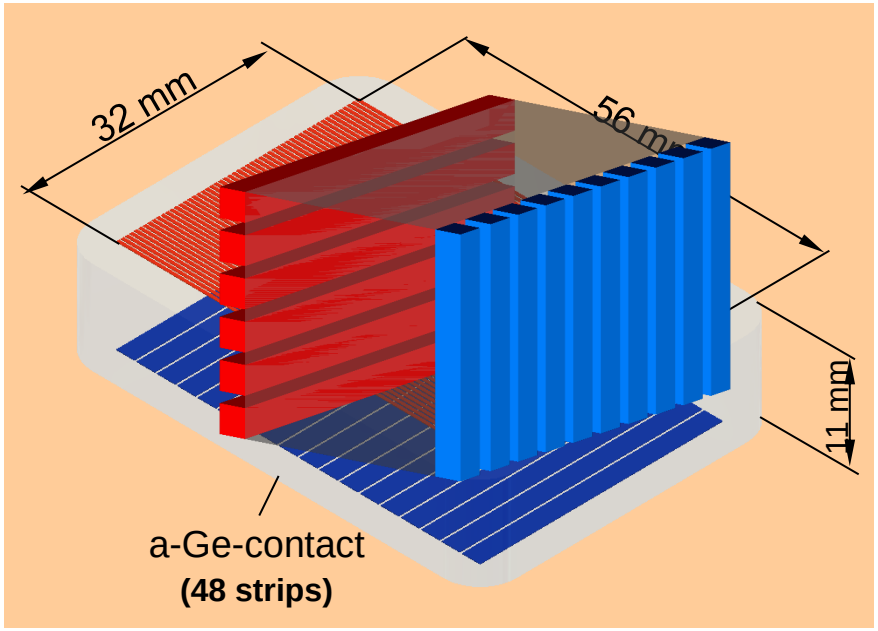
Crystal
radius of curvature: 2 m
Θ_{Bragg}= ~ 2.9º

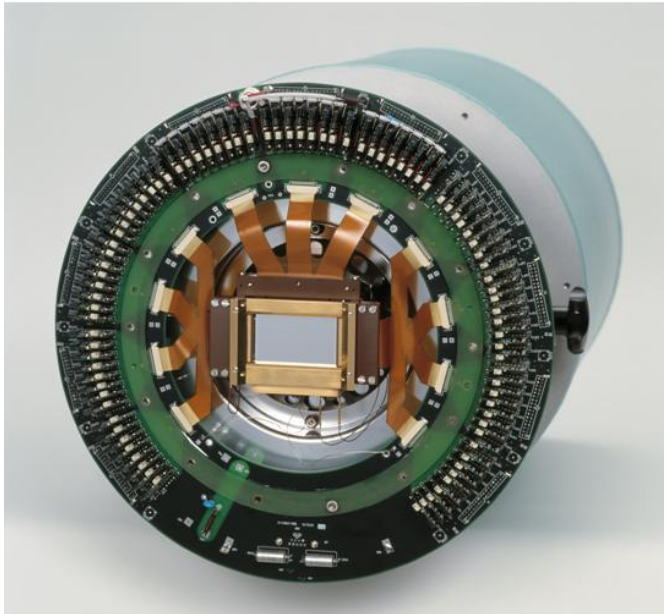
$\Delta y \Rightarrow \Delta\Theta \Rightarrow \Delta E$
1 mm 750 eV

Prototype 2D *μSTRIP* X-Ray Detector

2D μSTRIP planar detector systems for precision x-ray spectroscopy experiments (FOCAL)

energy resolution – timing - 2D position sensitiviy





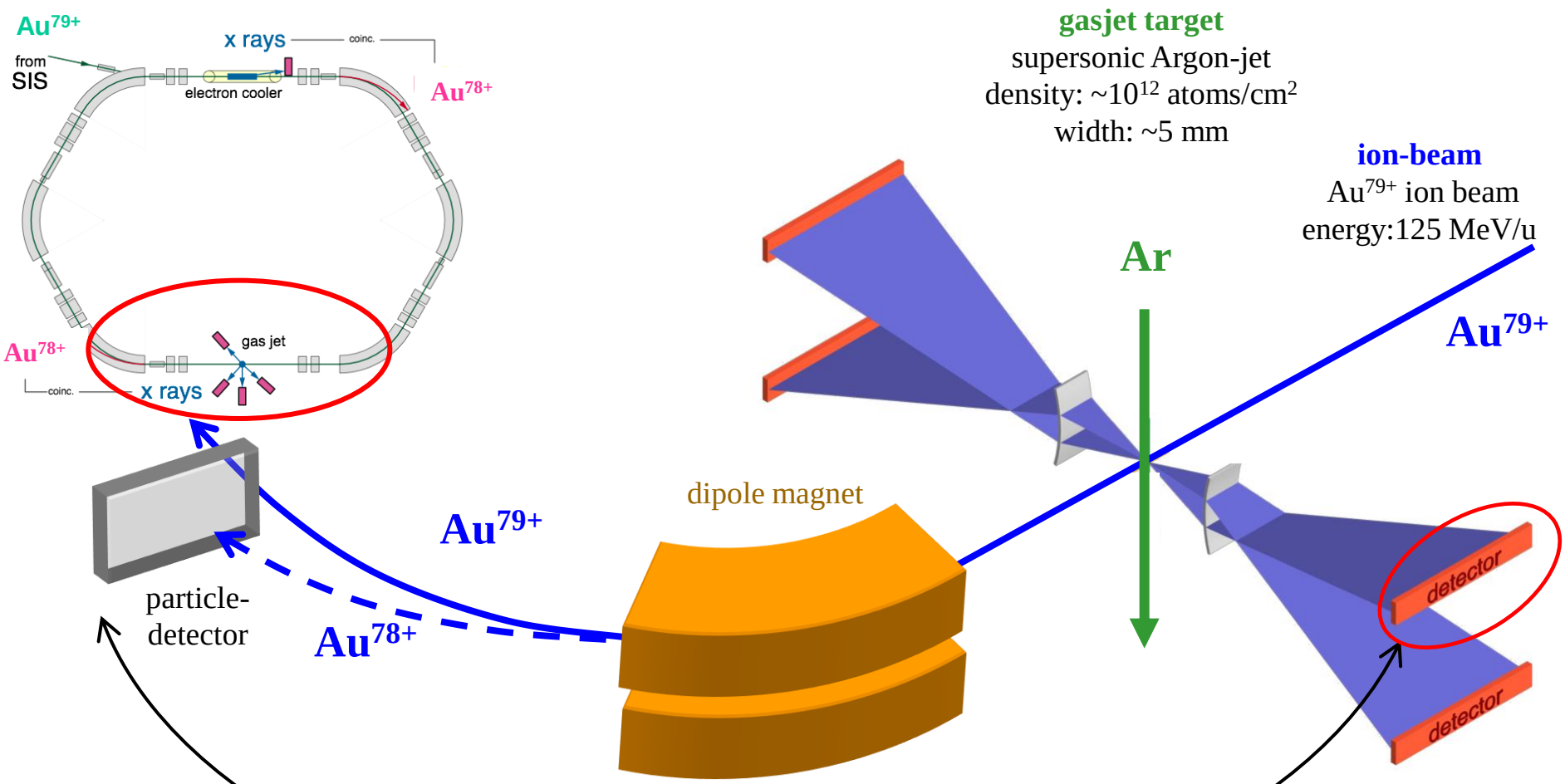
***μSTRIP* detector developed by**

front: 128 strips pitch ~250μm

back: 48 strips pitch ~1167μm

equivalent to 6144 pixel

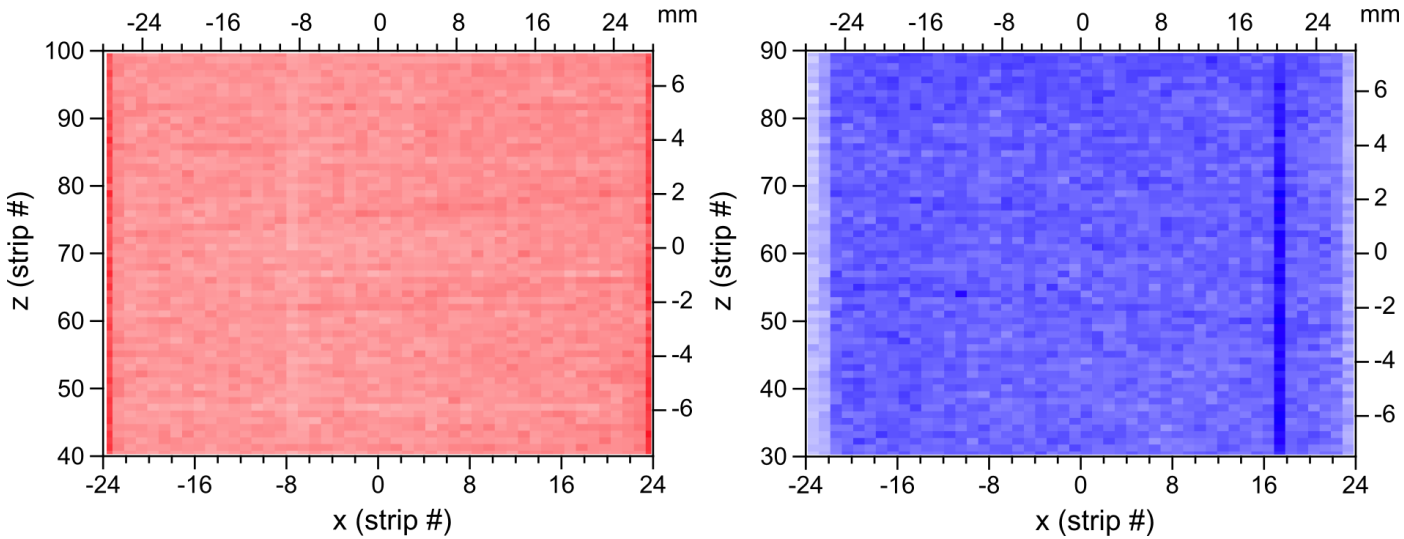
The FOCAL setup:
dedicated transmission spectrometers + 2D *μSTRIP* x-ray detectors



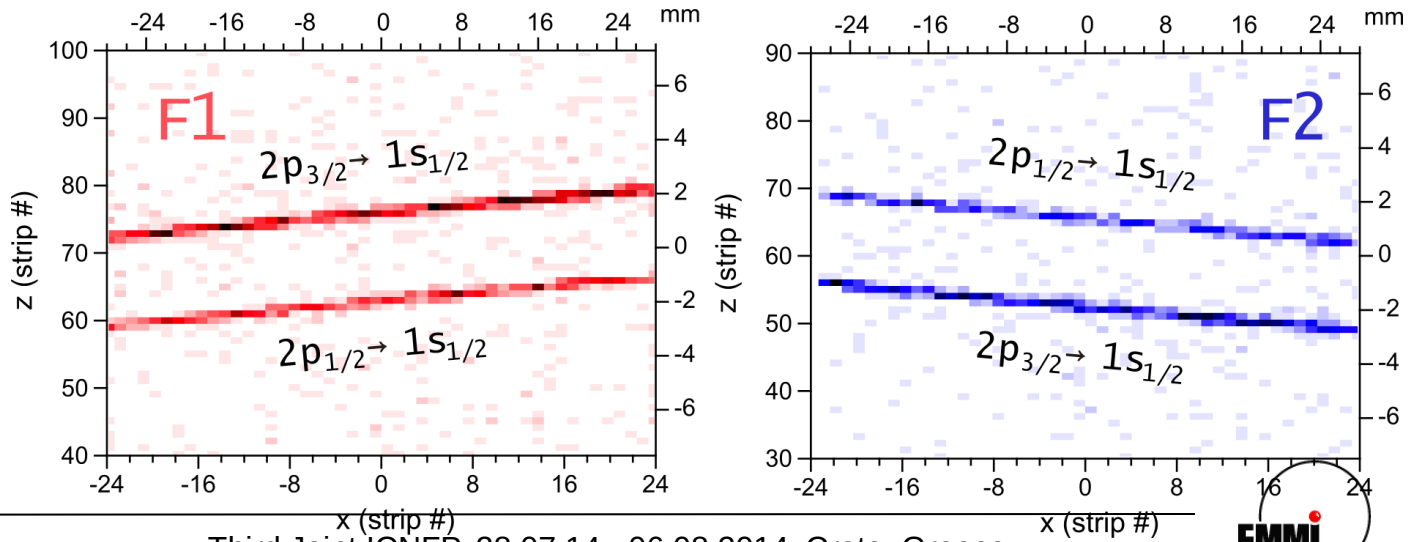
coincidence between
particle- and x-ray detector

3 – 5 counts/h

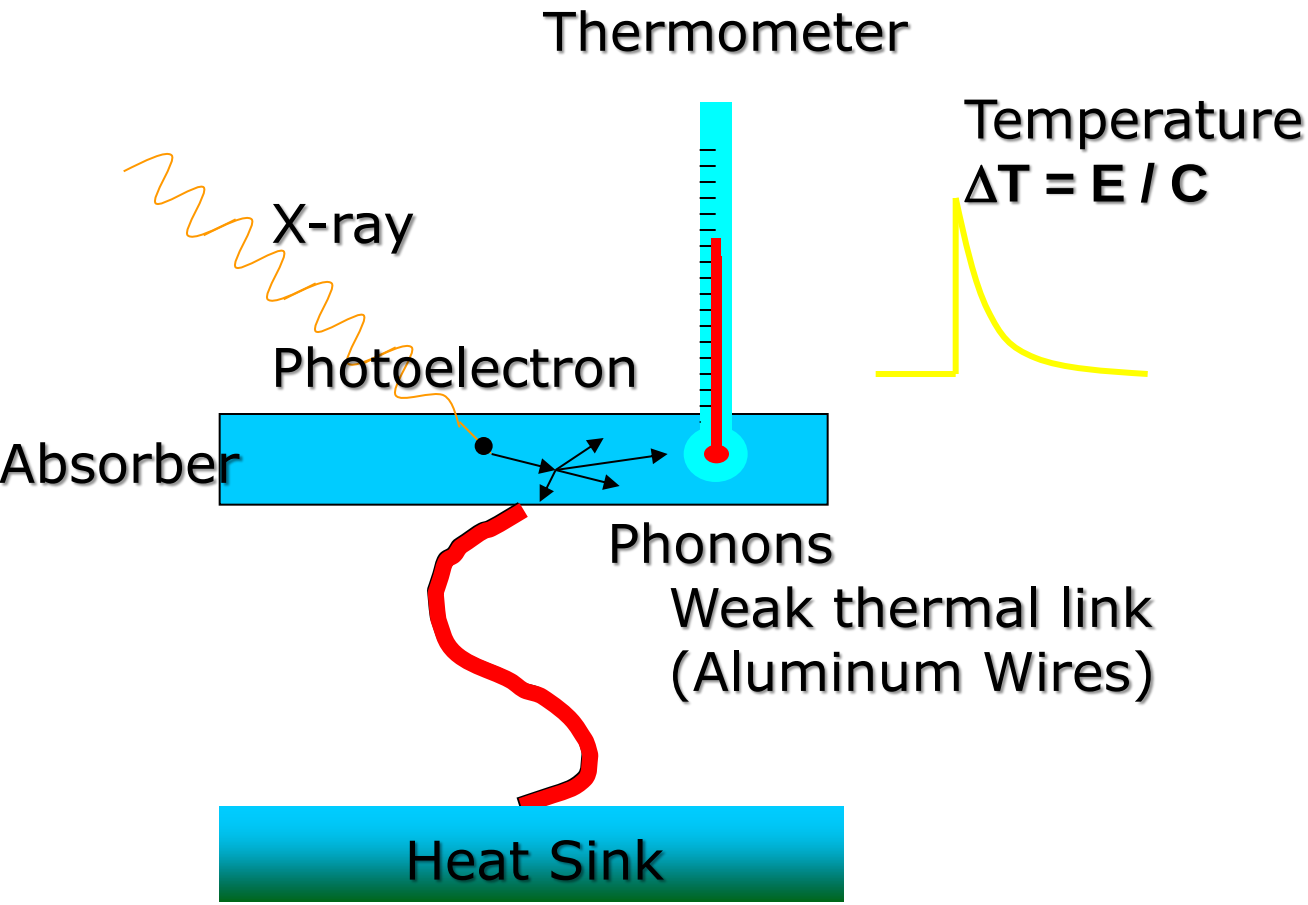
Raw 2D spectrum



2D spectrum with energy and time condition



Novel x-ray detectors: Micro-Calorimeter



Heat capacity: $C = c \cdot m$

$C \sim T^3$

Spezific heat capacity : c

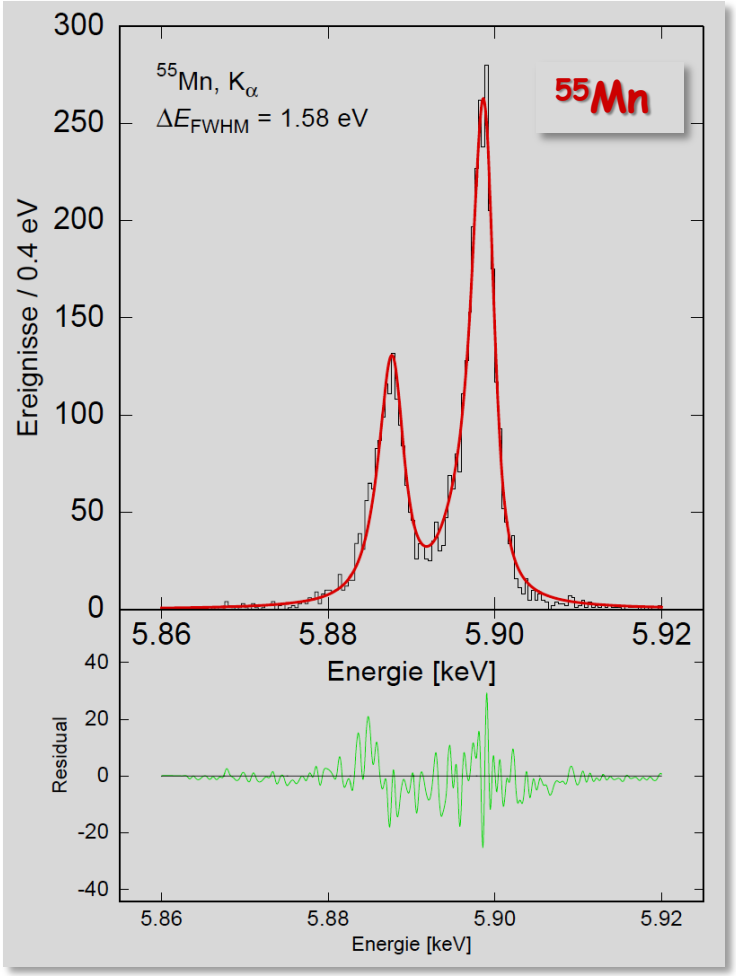
Detector mass: m

Detector operates at about 50 mK

Micro-calorimeter detector: large wavelength acceptance, large quantum efficiency, and excellent energy resolution (4 keV@5eV => 35 keV@30 eV).

maXs-20 Prototyp Spectrum

A. Fleischmann, C. Enss, University of Heidelberg

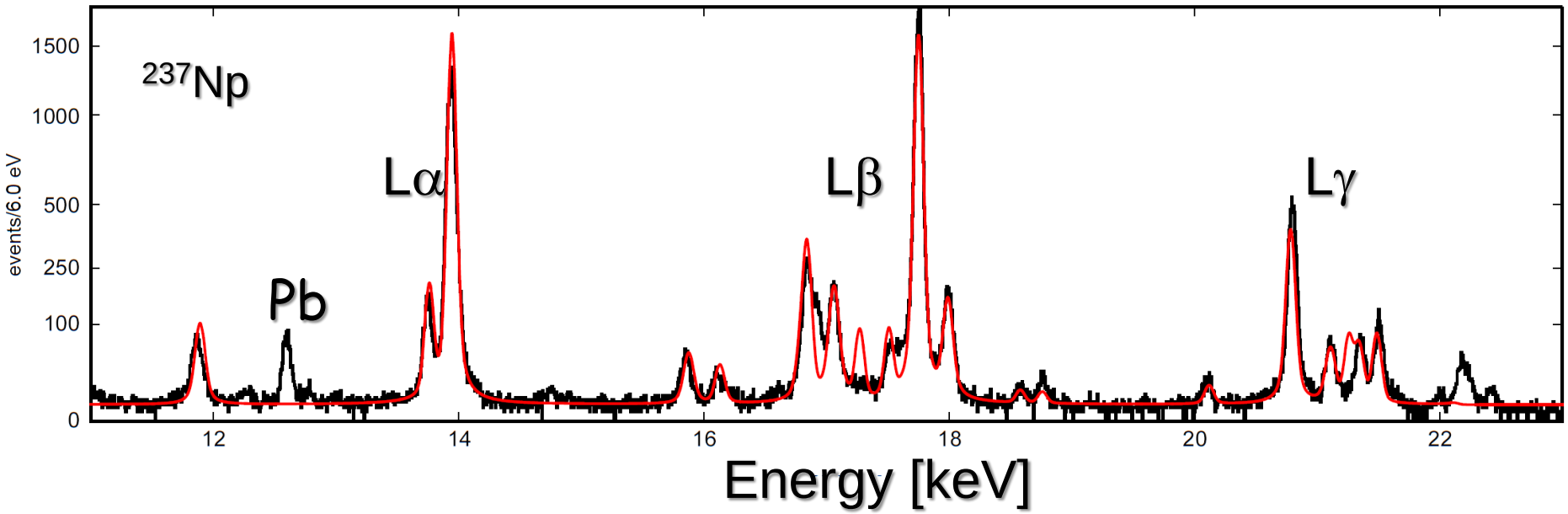


ΔE_{FWHM} = 1.6 eV @ 6 keV

World record together with TES-sensors of NASA-GSFC!

maXs-200: detector arrays for hard x-rays

First characterization with an ^{241}Am-source



ΔE_{FWHM} = 40 eV @ 0-10 keV

ΔE_{FWHM} = 60 eV @ 60 keV

Slight degradation towards higher energies due to

- **Poor temperature stability** in this first experiment
- **Possible marginal position dependence**,
  to be fixed by stems between absorber and sensor

Novel instumentation:
other ongoing developments

- X-ray lasers
- Trapping/measurement techniques
- DR spectroscopy
- non-destructive in-ring ion detection systems
- particle detectors in UHV (in-ring)
- RCE spectroscopy
- ...

Wordwide Unique Research Opportunities

. . . & Challenges for Atomic Physics

Thank you very much for your attention !

sparc
Stored Particles Atomic Physics Research Collaboration

FLAIR
Facility for Low-energy Antiproton and Ion Research

Extreme Static Fields
Extreme Dynamic Fields
Antimatter and Fundamental Physics