Exploring QED in strong fields at FAIR & NICA

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QED

Richard Feynman
1918-1988

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

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

R. Feynman, 1985

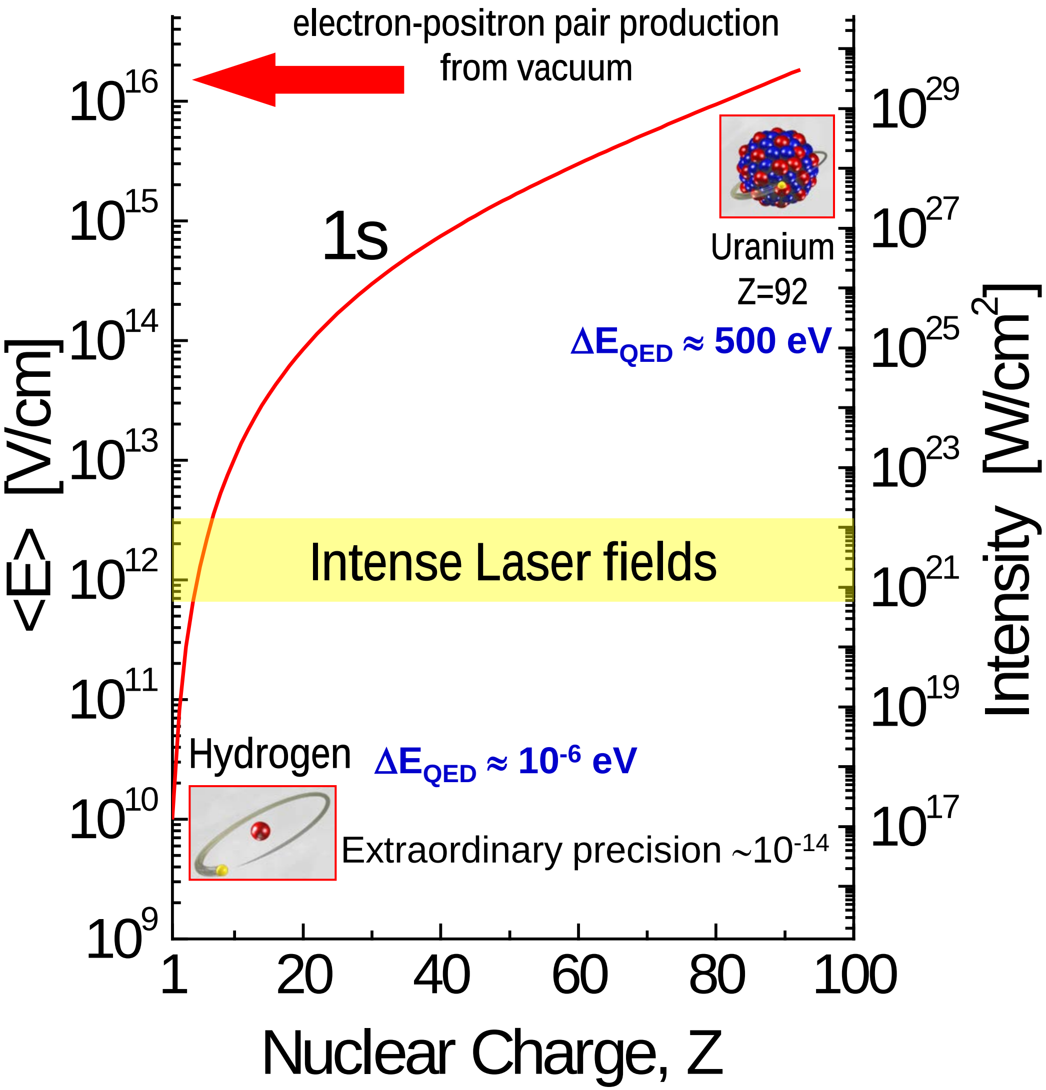
The theory of quantum electrodynamics is, I would say, the jewel of physics – our proudest possession.

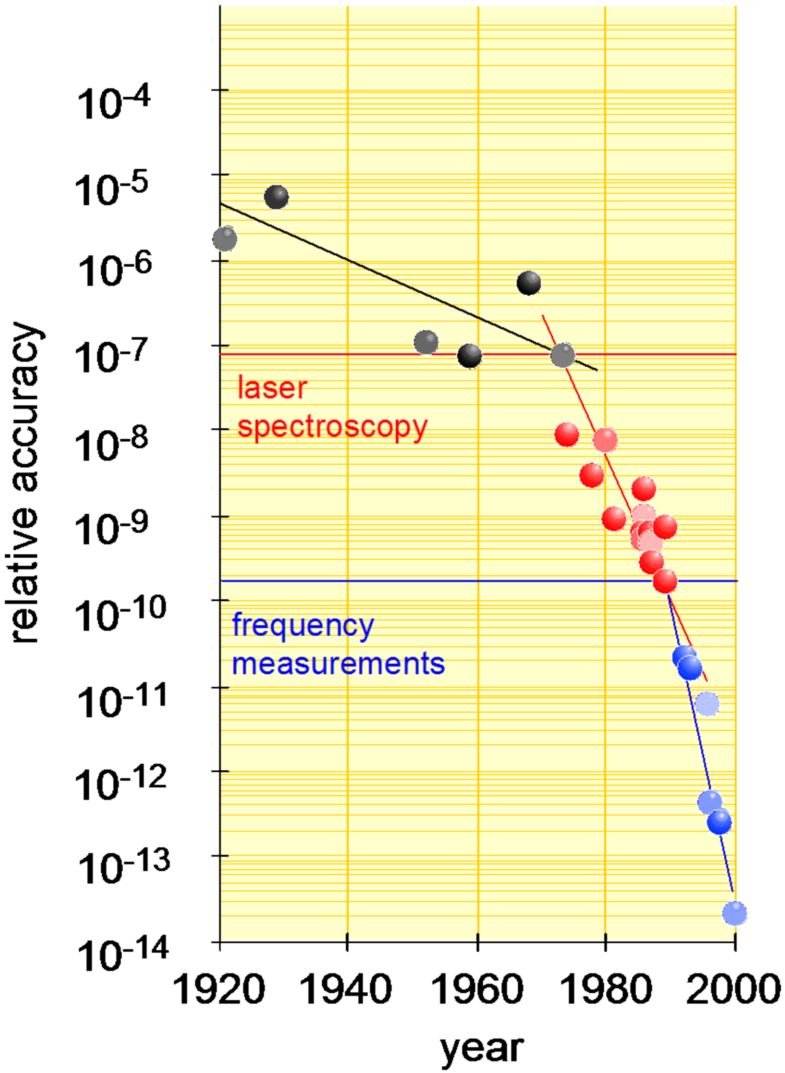
R. Feynman, 1983

Quantum electrodynamics (QED) is a theory of EM interactions or light-matter interaction.
It is a basis of the Standard Model and of other field theories.

FAIR

Physics of extremely strong fields





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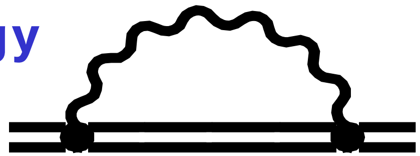
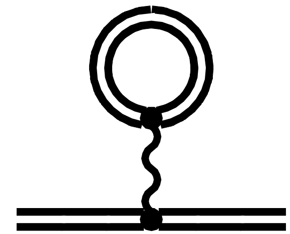
Bound-State QED in Strong Fields: effects of the quantum vacuum

Self-energy



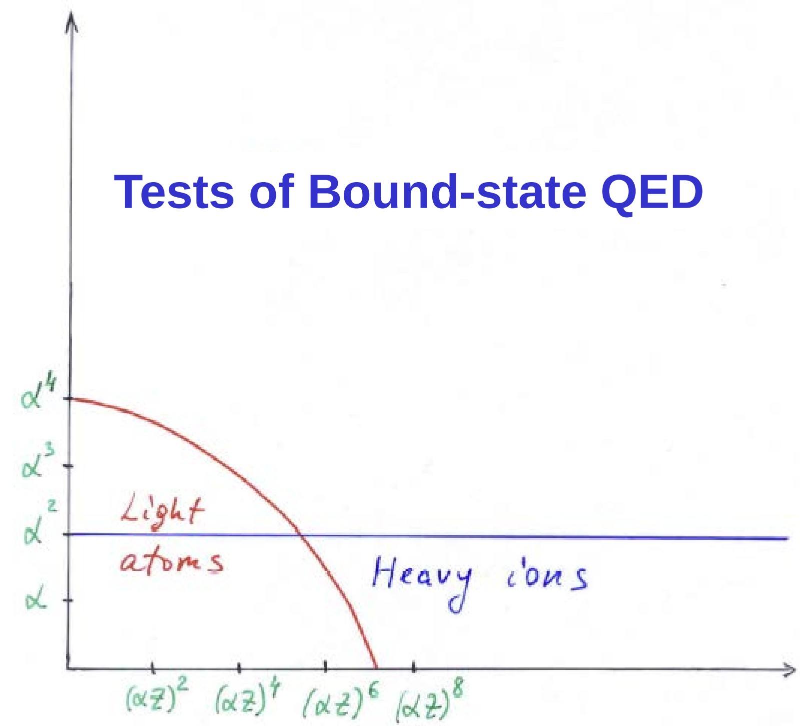


Vacuum-polarization

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

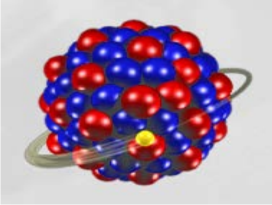
Low Z-regime: $\alpha Z << 1$
$F(\alpha Z)$: expansion in αZ

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



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

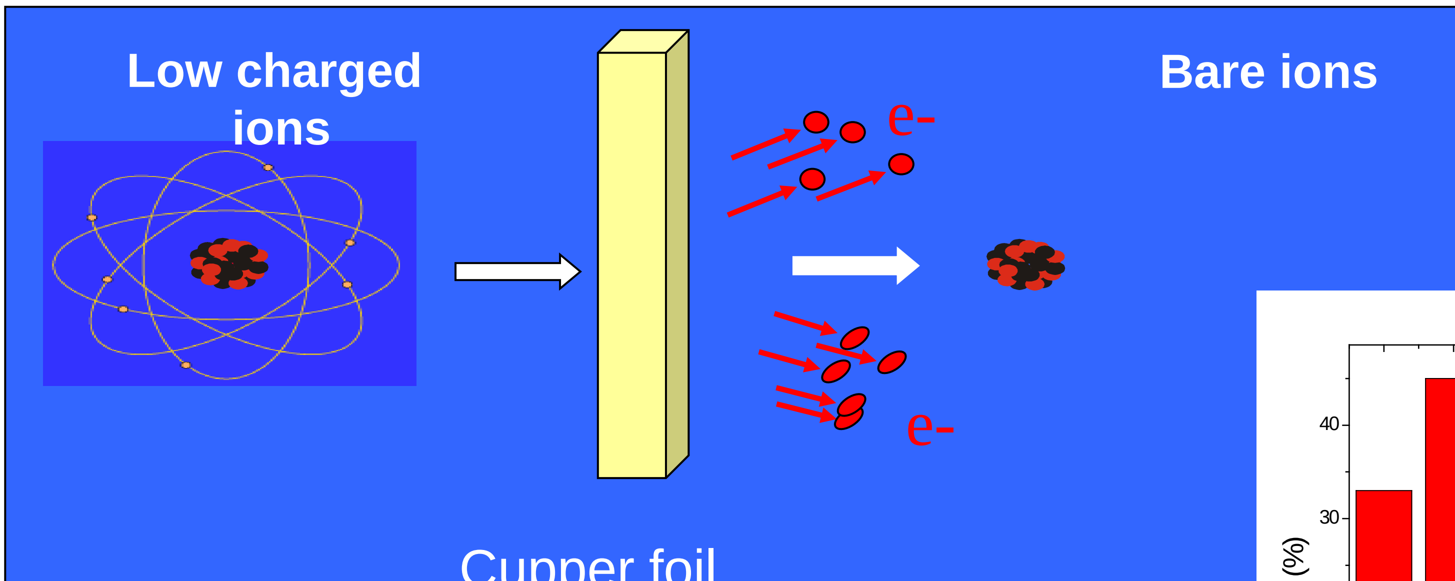
Fundamental constants:
Rydberg, α, electron mass

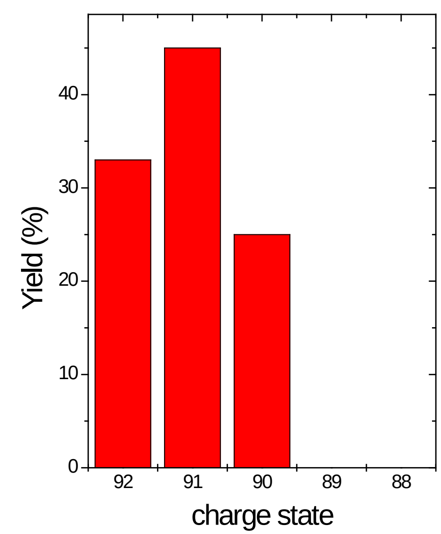
Why do we need accelerators?

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

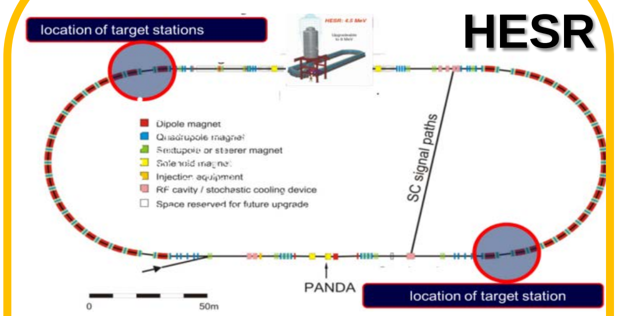
Uranium

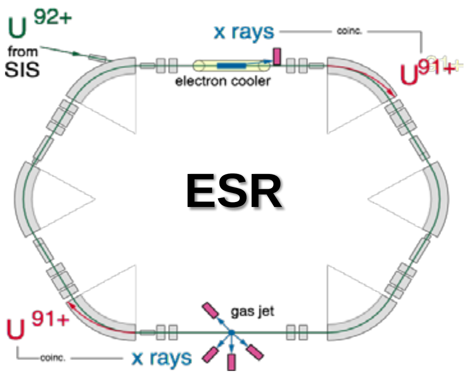
$v_K / c \approx 0.67$ → $\mathbf{E_{KIN} \approx 330\ MeV/u}$

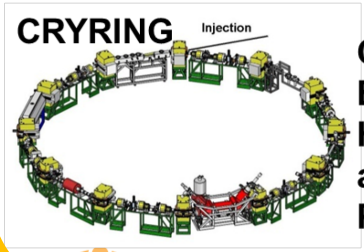




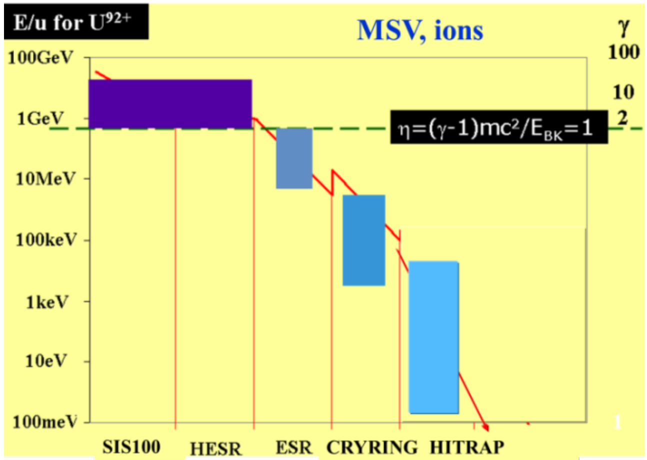
Storage Ring Facilities at FAIR



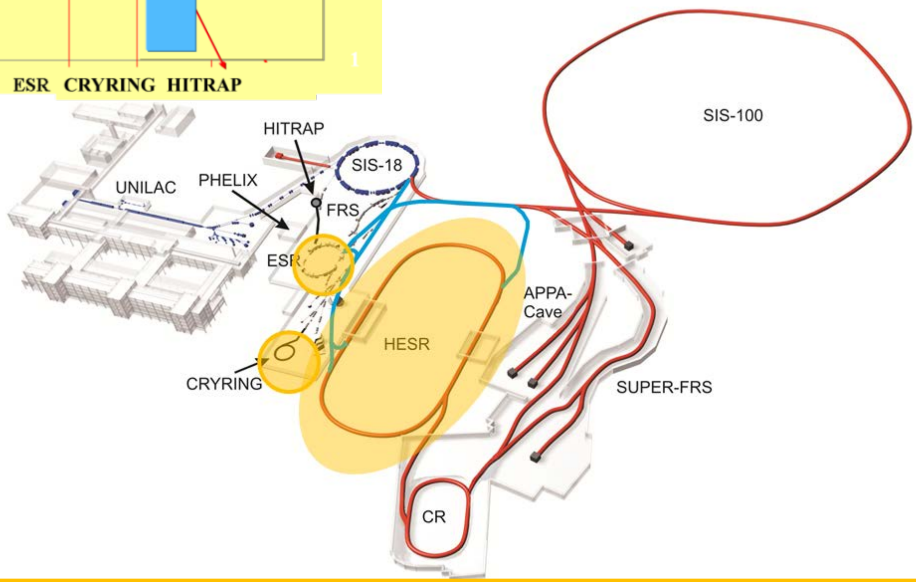




Cold Low-Energy Heavy Ions and Anti-Protons

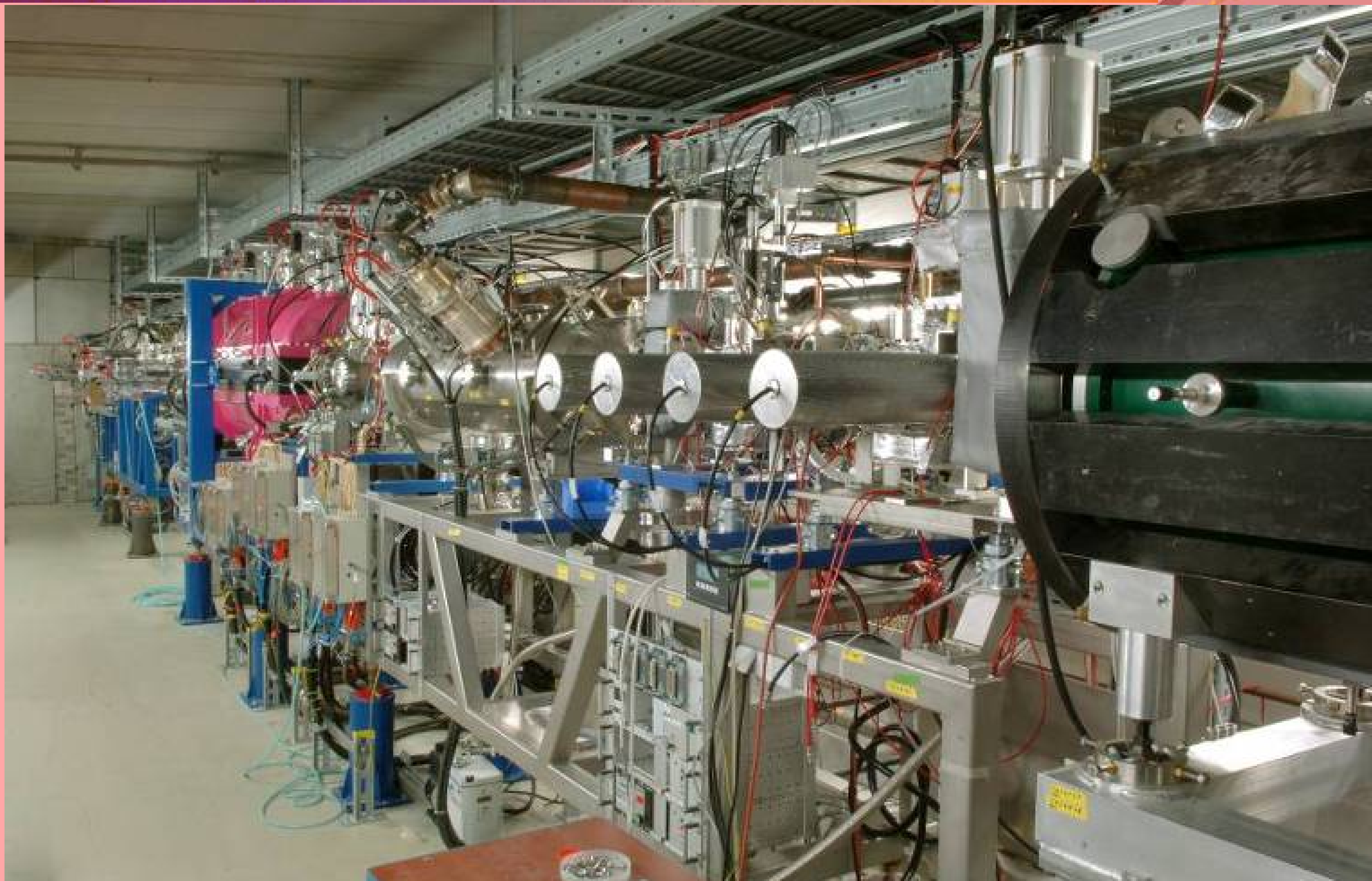


Storage ring physics is a unique feature of FAIR for experiments with stable ions and exotic nuclei !



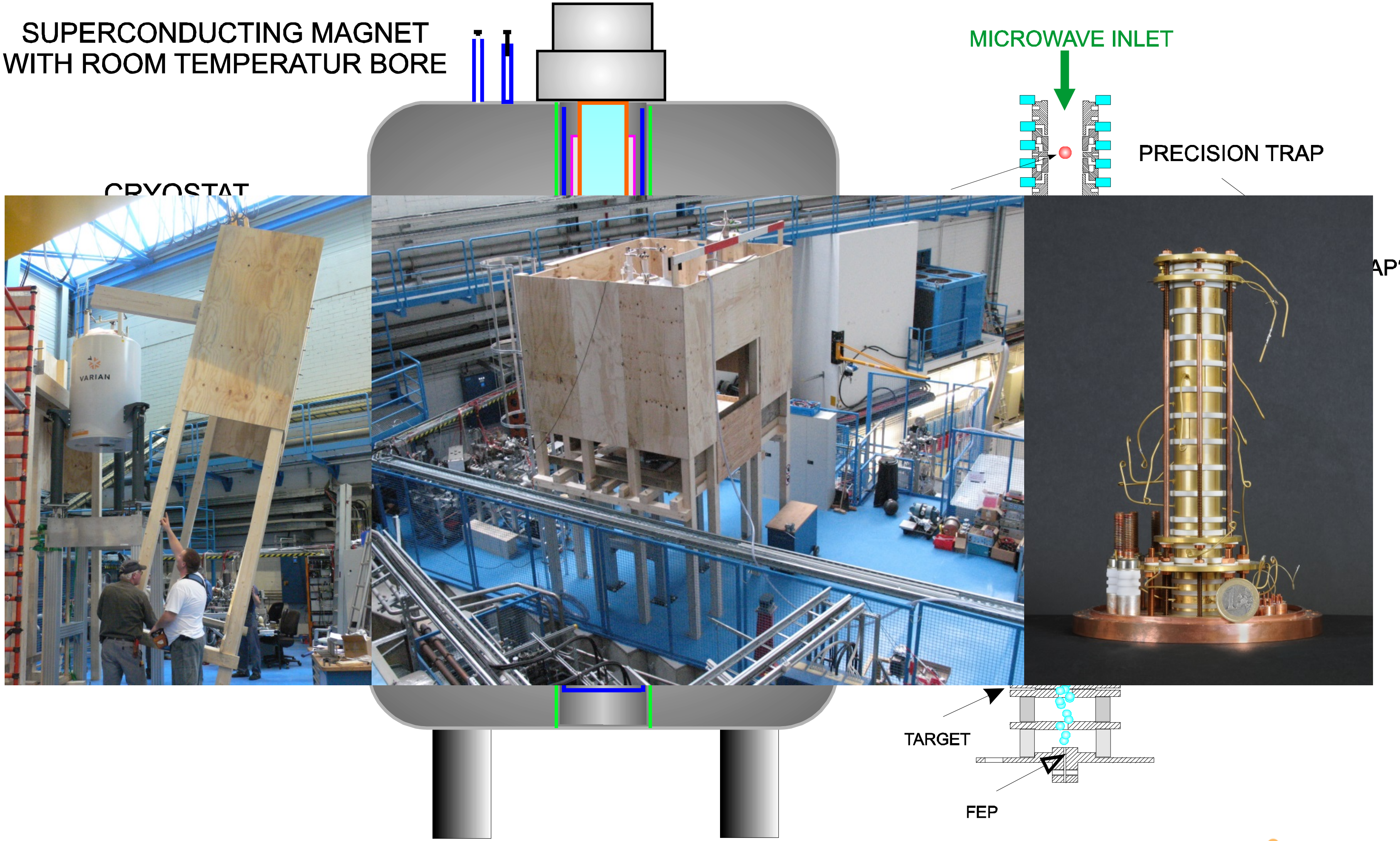
HESR: Worldwide premiere – novel energy regime for precision experiments using cooled relativistic ion beams

HITRAP



GeV/u

HITRAP: g-factor apparatus

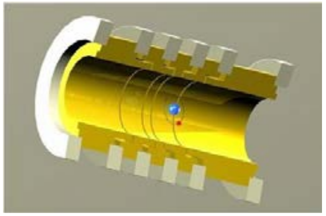


Experimental techniques

different observables – different experimental techniques

g-factor of the bound electrons

Penning traps, microwave and laser spectroscopy

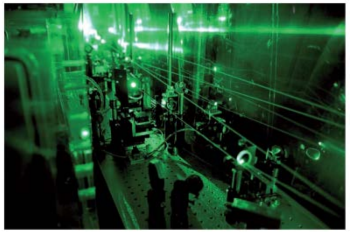


Binding energies, transitions energies

Storage rings, X-ray spectroscopy, DR spectroscopy

Hyperfine structure

Storage rings, traps, Laser spectroscopy

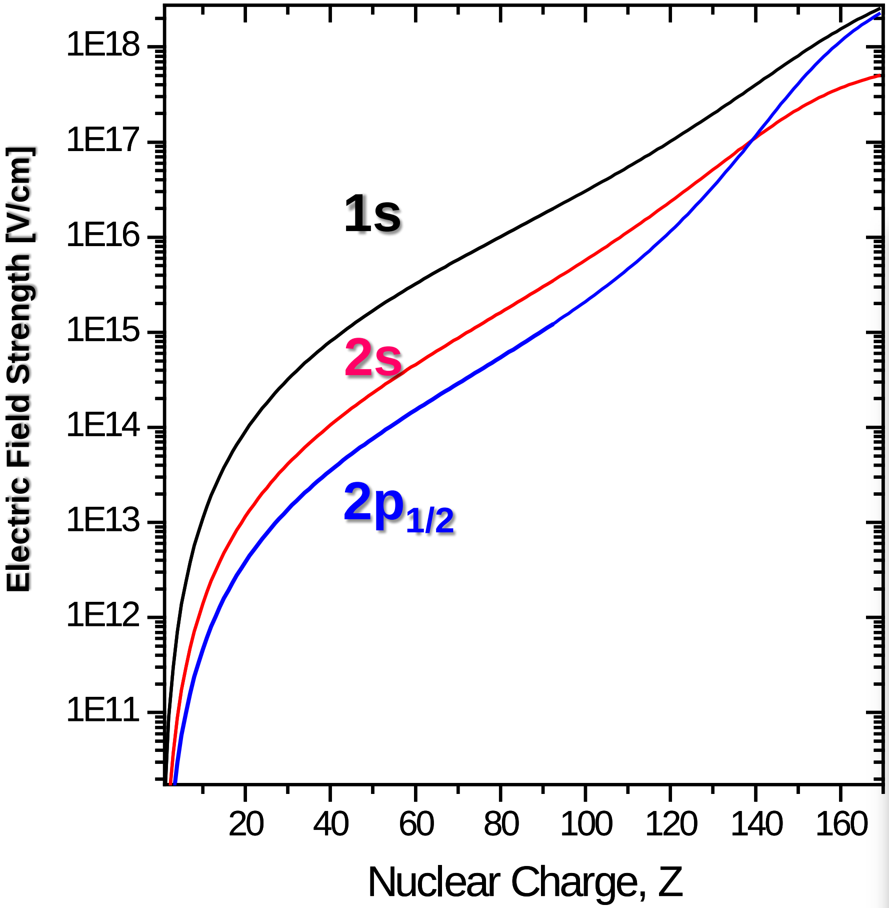


- STORING
- COOLING

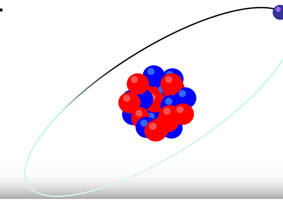
→ **PRECISION**

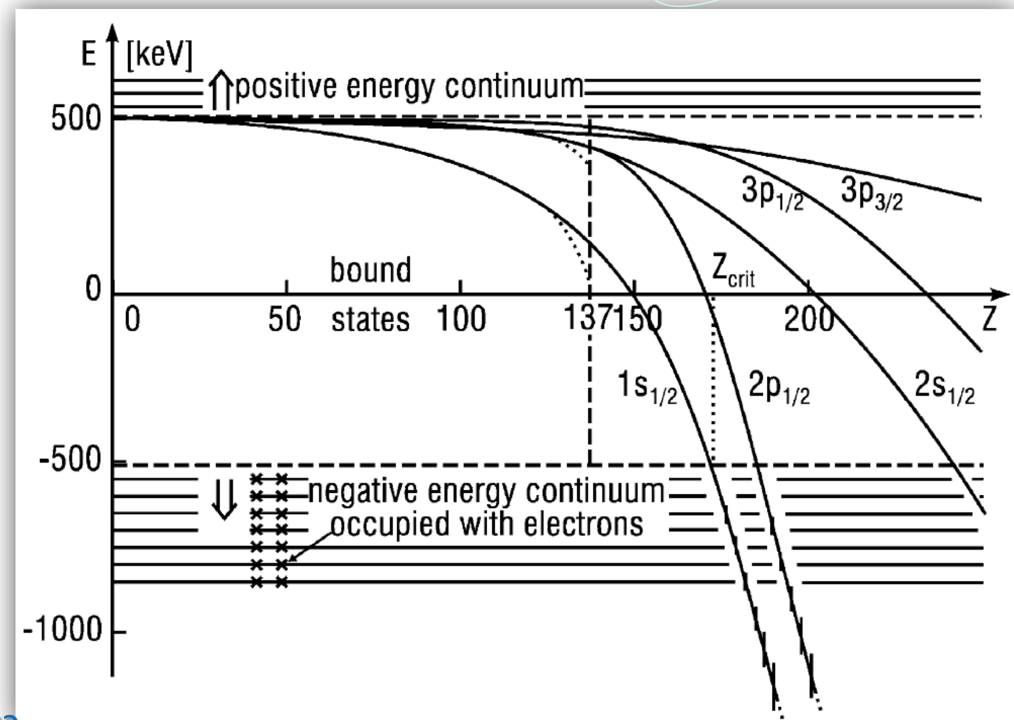
FAIR

Critical- and Super-Critical Fields



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





- 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!

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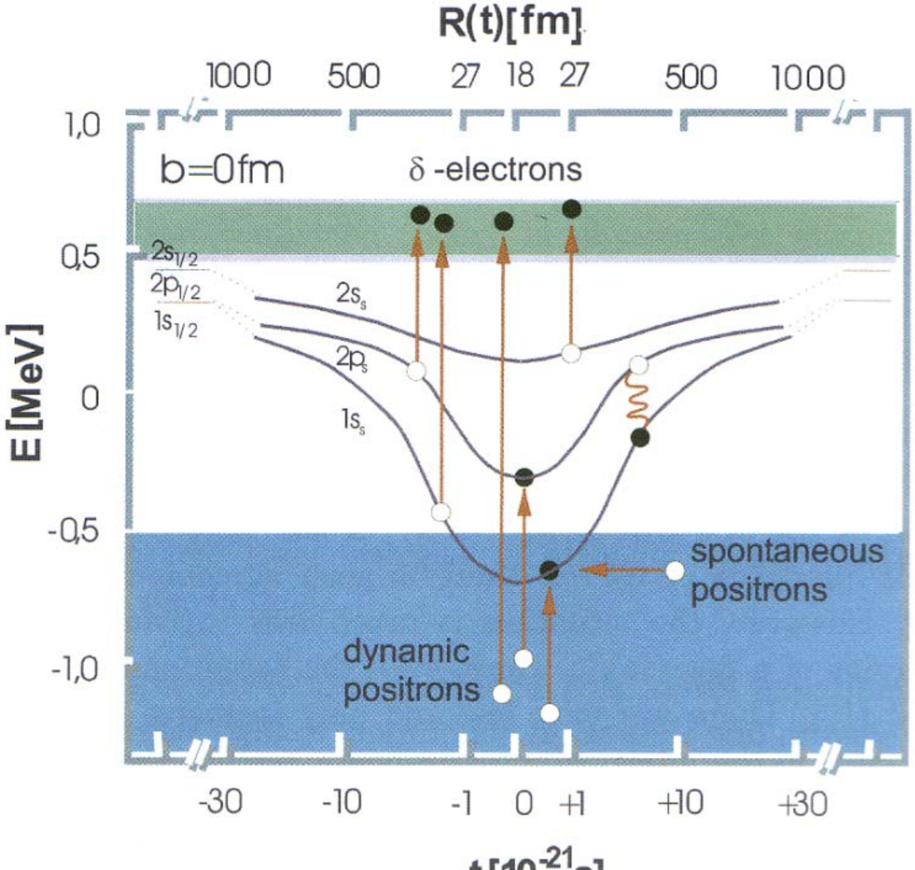
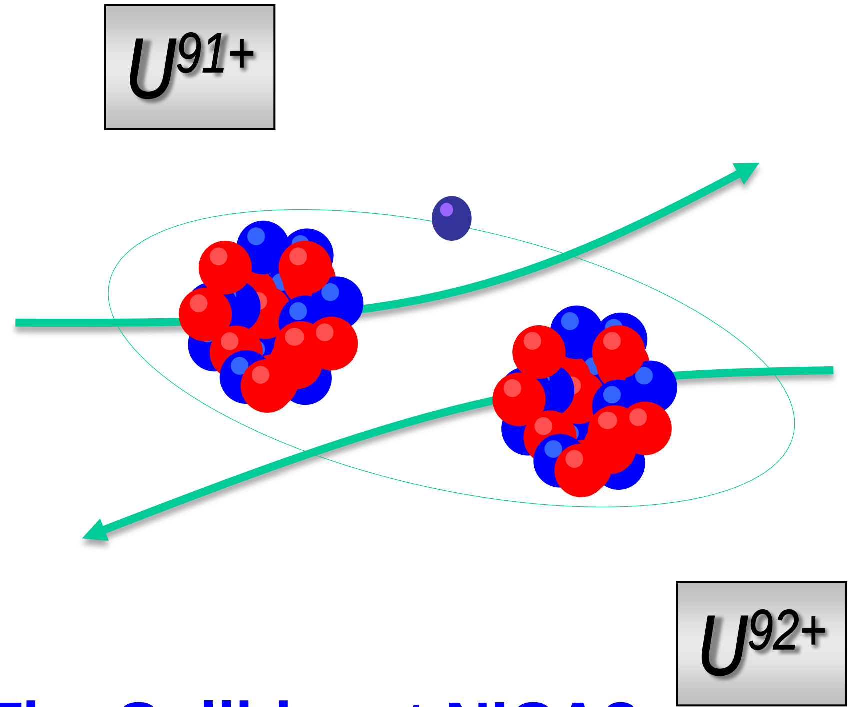
Supercritical fields: Formation of Quasi-Molecules

Merged Beams



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



The Collider at NICA?

~ 5 MeV/u -> co-propagating beams

Summary

- There are few large scale heavy-ion accelerator projects planned or already in construction

- Those accelerators when/if combined with storage rings, traps and different detection techniques offer many interesting opportunities for **atomic physics with heavy HCI, i.e. exploring physics of extremely strong EM fields**

- At **FAIR** there is an extensive atomic physics research program planned within the **SPARC** and **FLAIR** collaborations

- The collider at **NICA** (and possibly **HIAF** in China) could offer world-wide unique facility for exploring **adiabatic heavy ion-ion collisions and thus for the challenging search of the spontaneous vacuum decay**

Wordwide Unique Research Opportunities
. . . & Challenges for Atomic Physics

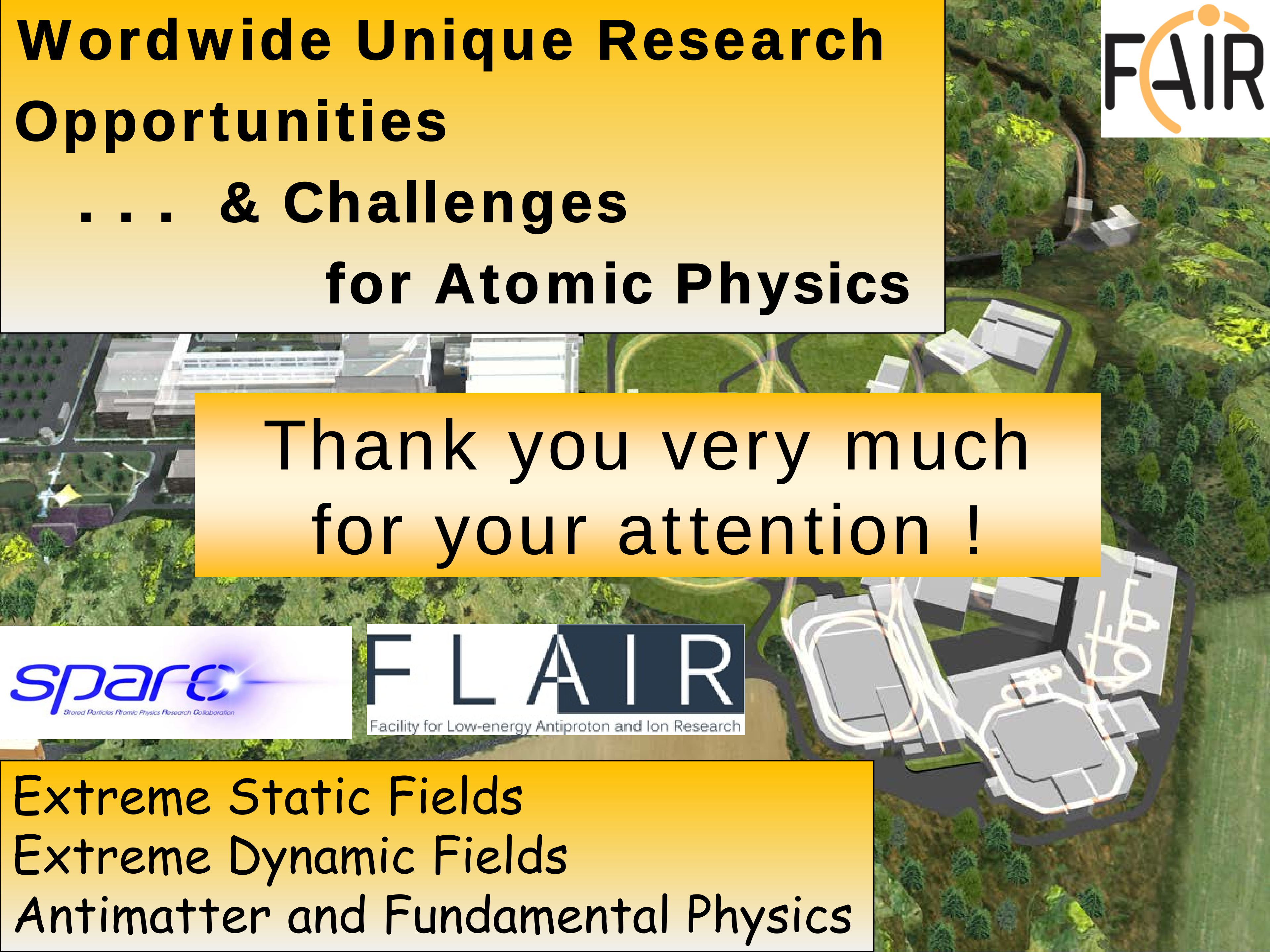
FAIR

Thank you very much for your attention !

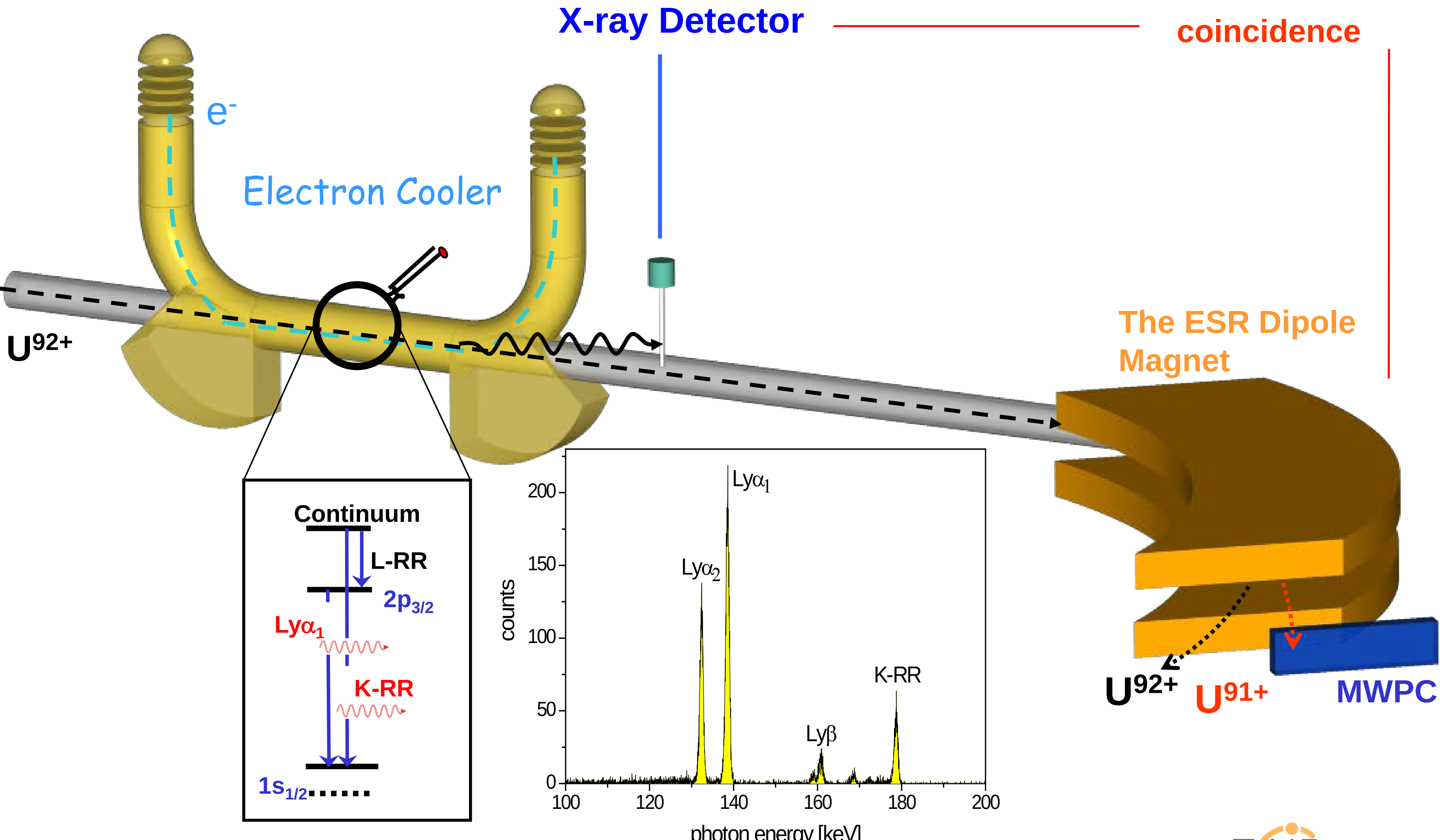
sparc
Stored Particles Atomic Physics Research Collaboration

FLAIR
Facility for Low-energy Antiproton and Ion Research

Extreme Static Fields
Extreme Dynamic Fields
Antimatter and Fundamental Physics



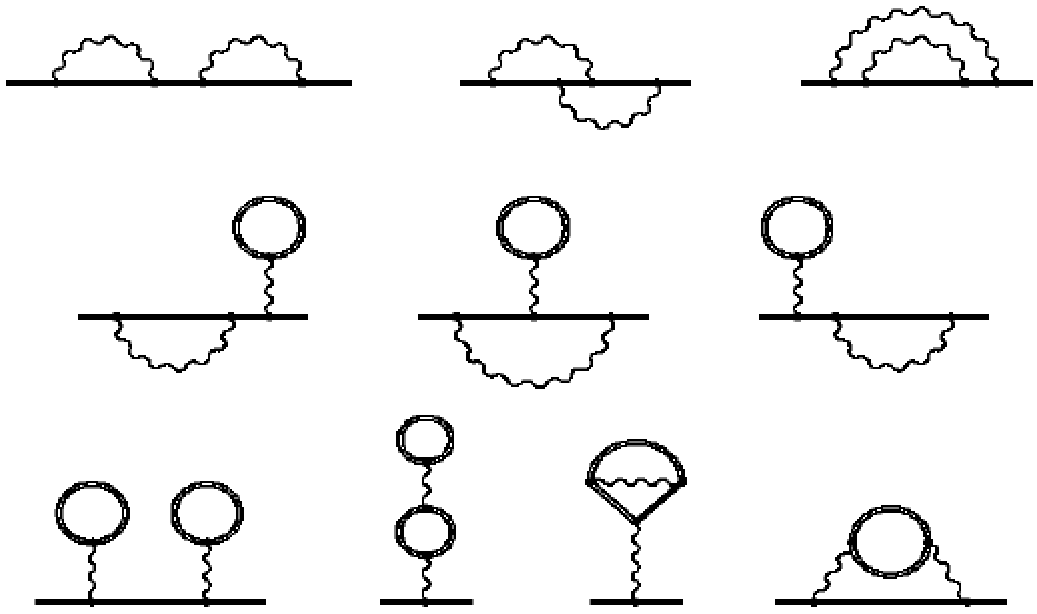
PRECISION TESTS OF BOUND-STATE QED IN EXTREME FIELDS:
Ground state Lamb shift in H-like uranium



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

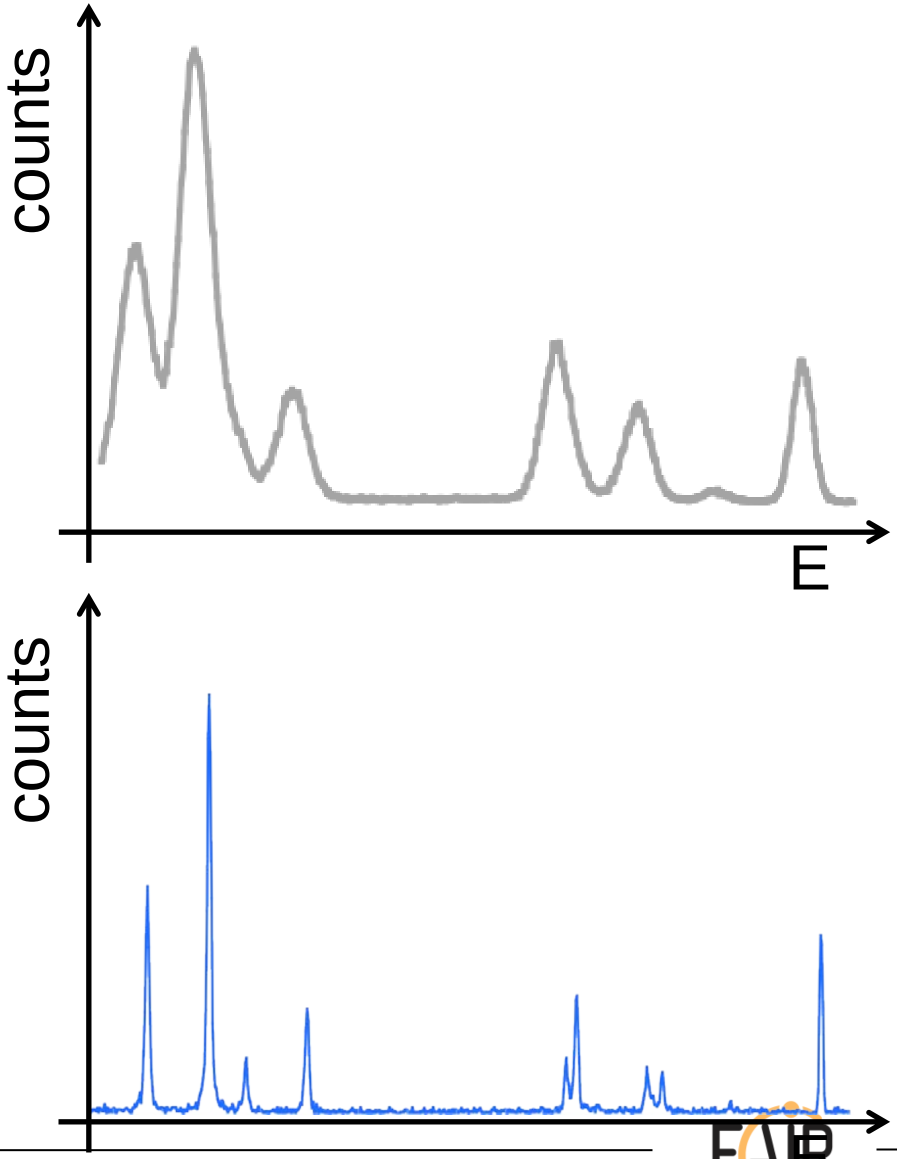
FWHM ≈ 500 eV

$\varepsilon = 10^{-4}$

crystal spectrometer
and/or microcalorimeter

FWHM ≈ 50 eV

$\varepsilon = 10^{-8}$



A Laue Crystal Spectrometer

Bragg-Laue Relation

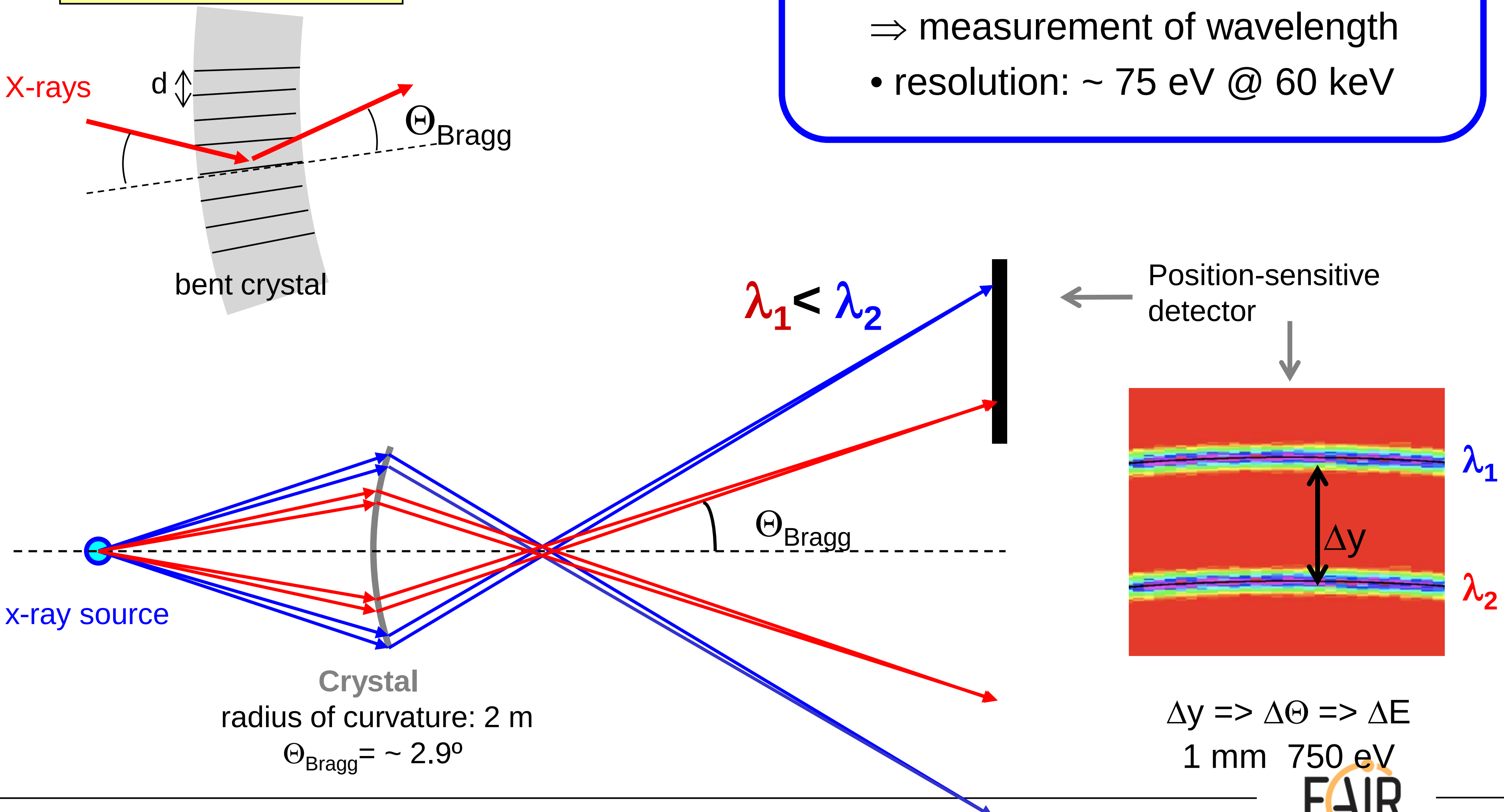
$$\lambda = 2 \cdot d \cdot \sin\Theta$$

Crystal Spectroscopy

- measurement of angles

$\Rightarrow$ measurement of wavelength

- resolution: ~ 75 eV @ 60 keV



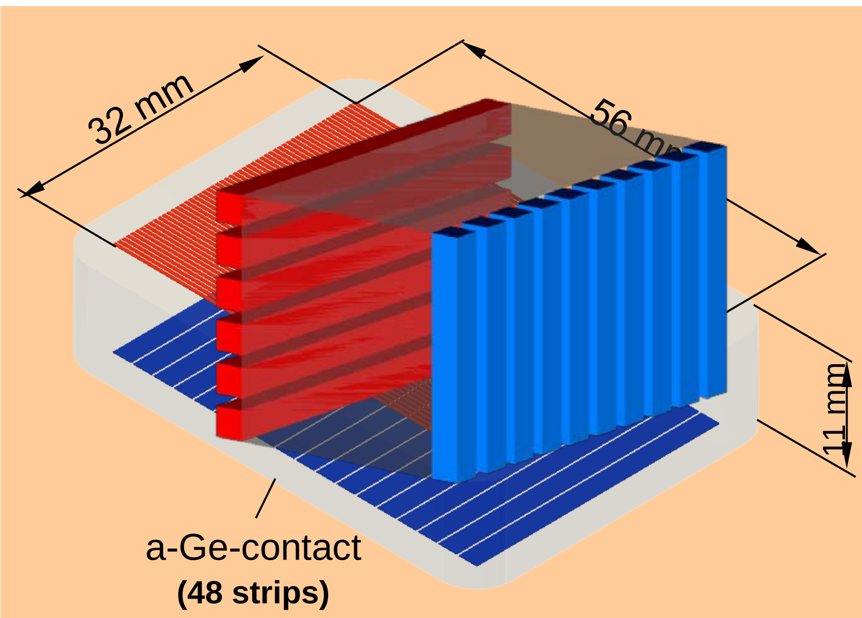
$\Delta y \Rightarrow \Delta\Theta \Rightarrow \Delta E$

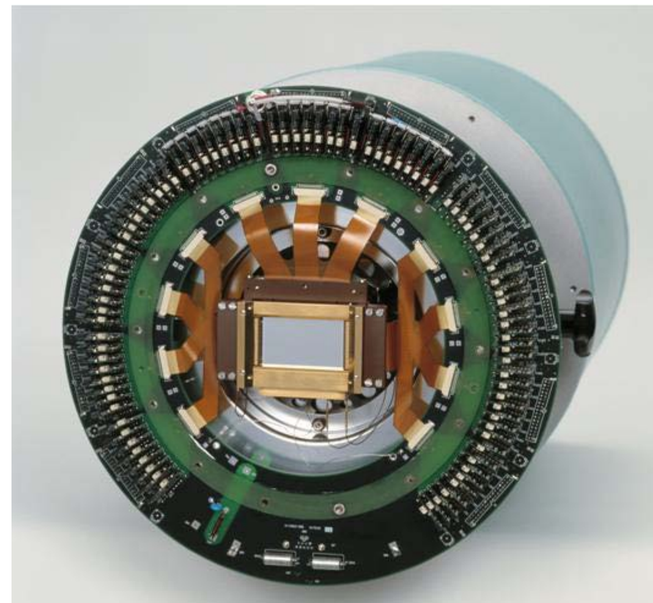
1 mm 750 eV

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**

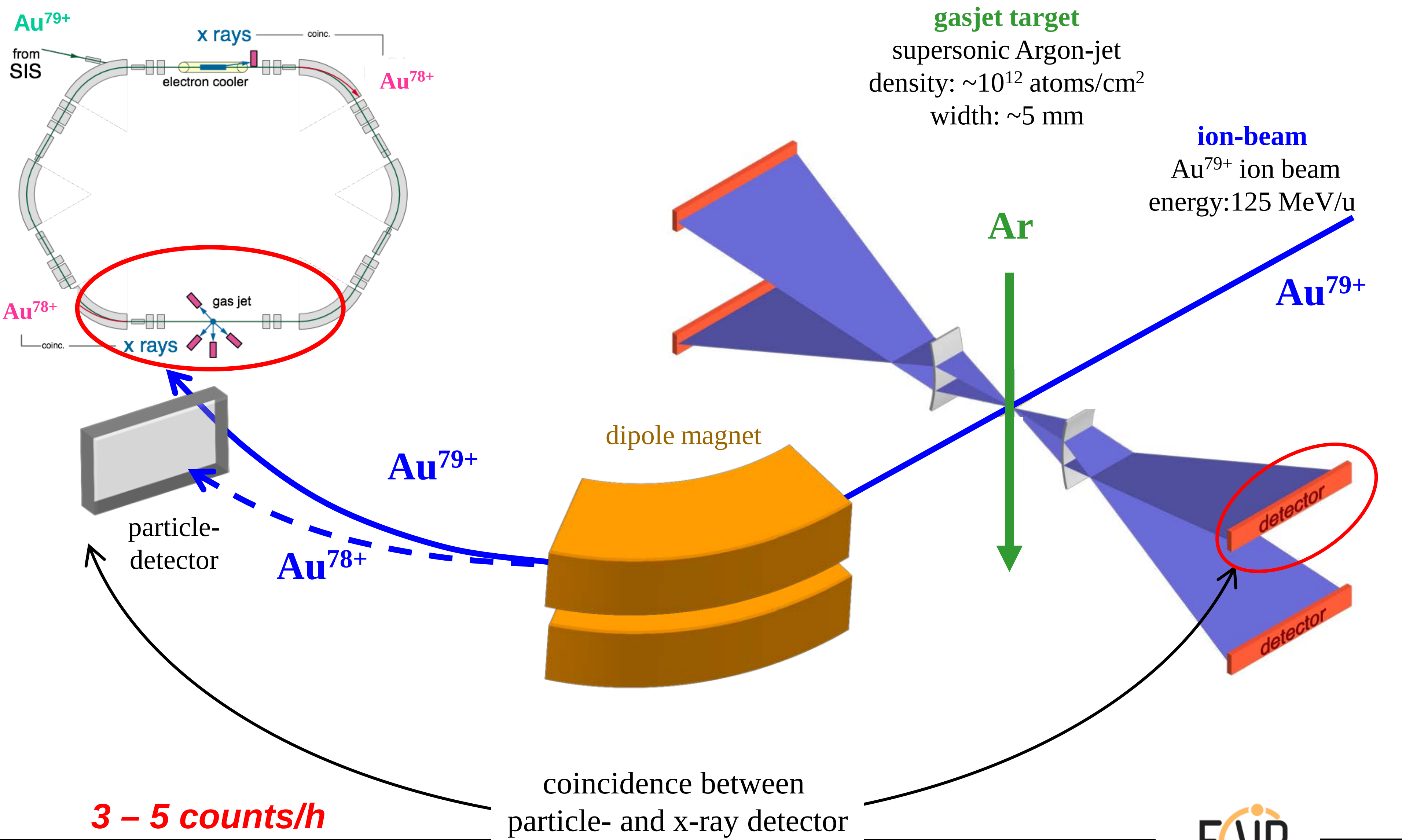
front: 128 strips pitch ~250μm

back: 48 strips pitch ~1167μm

equivalent to 6144 pixel

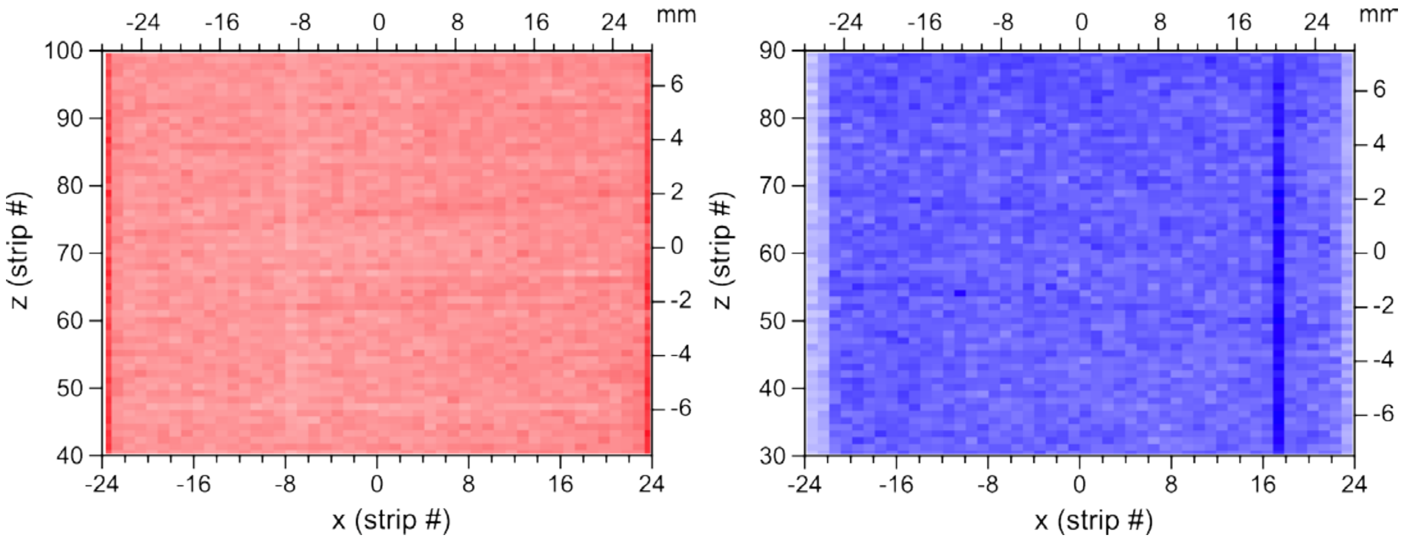
2D μSTRIP germanium detector

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

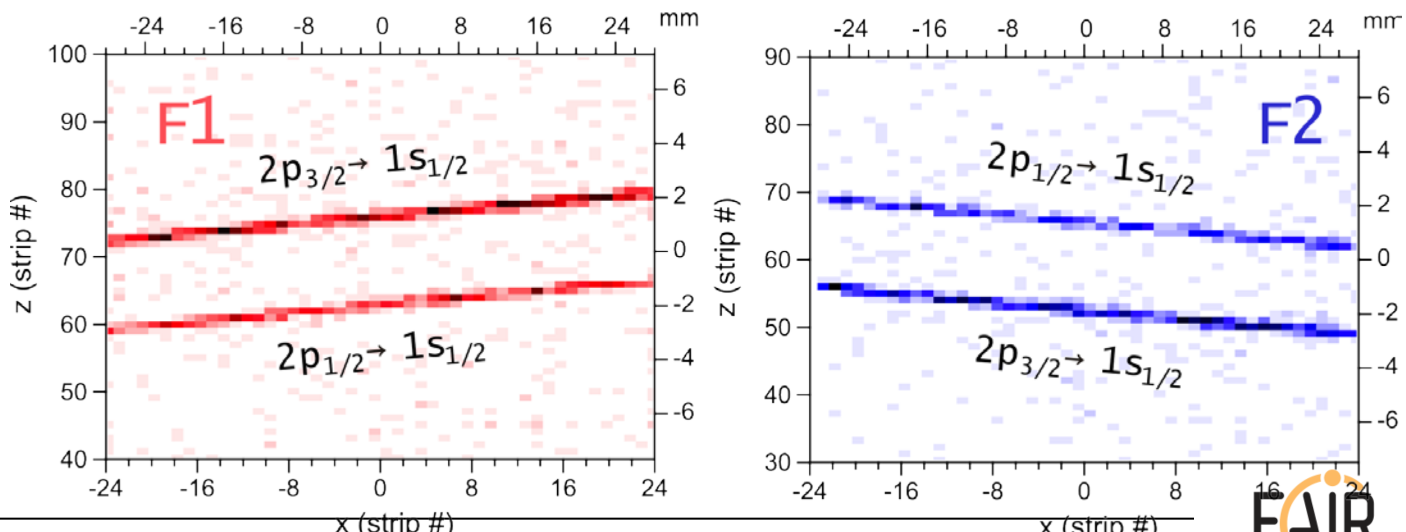


3 – 5 counts/h

Raw 2D spectrum



2D spectrum with energy and time condition



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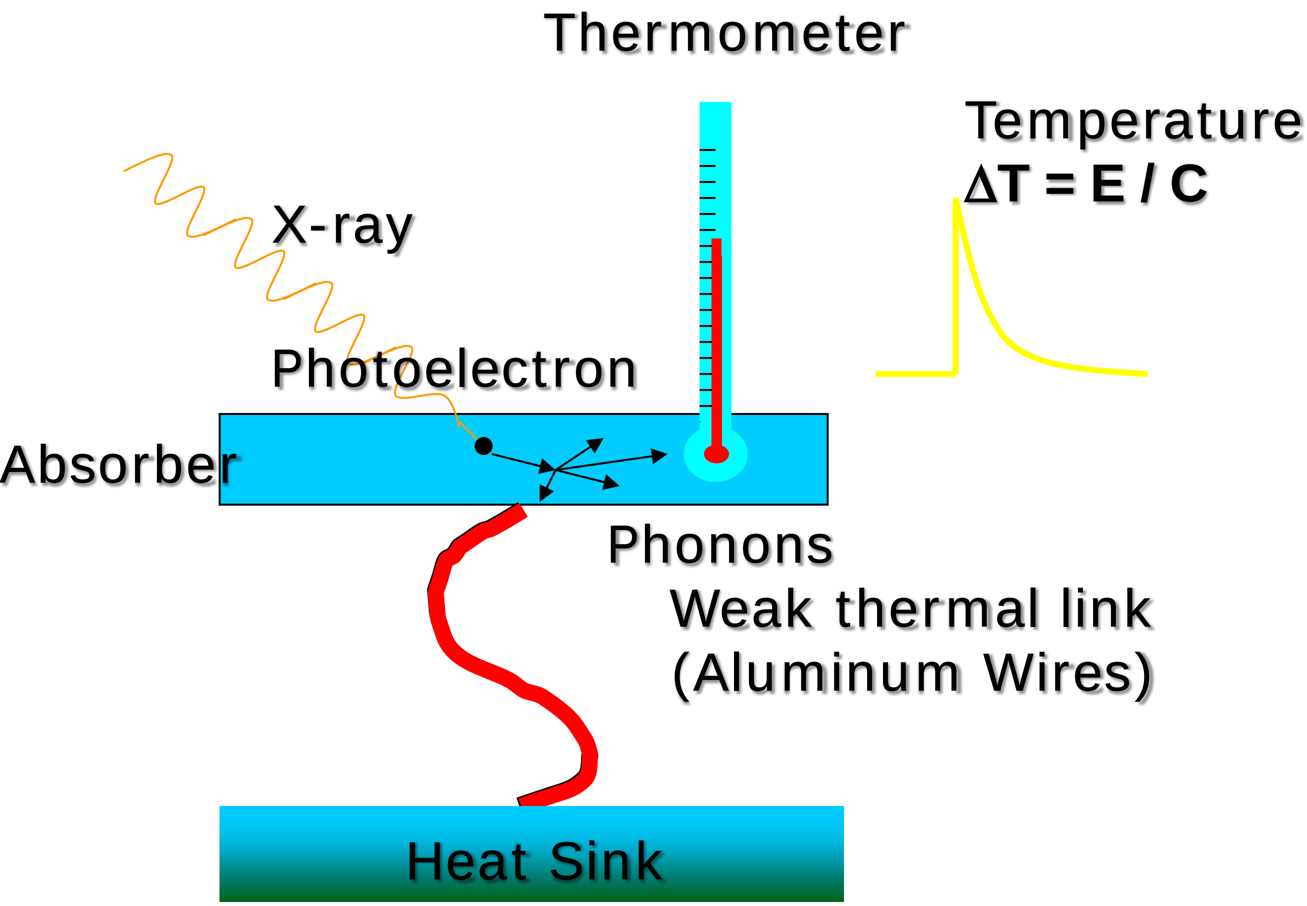
Novel x-ray detectors: Micro-Calorimeter



Heat capacity: $C = c \cdot m$

$C \sim T^3$

Spezific heat capacity : c

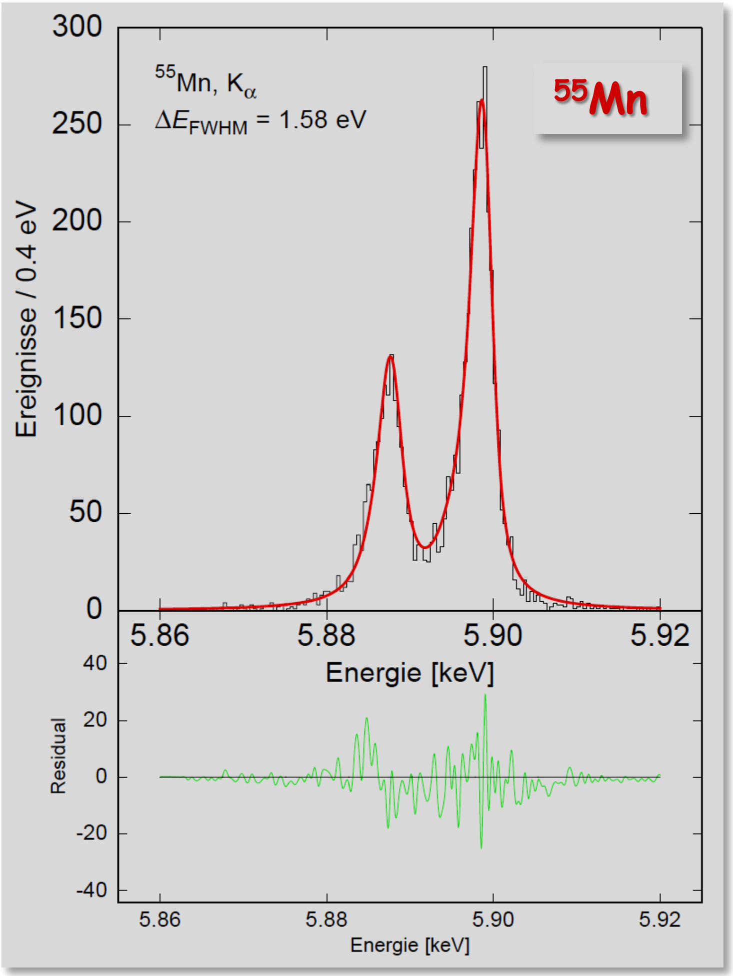
Detector mass: m

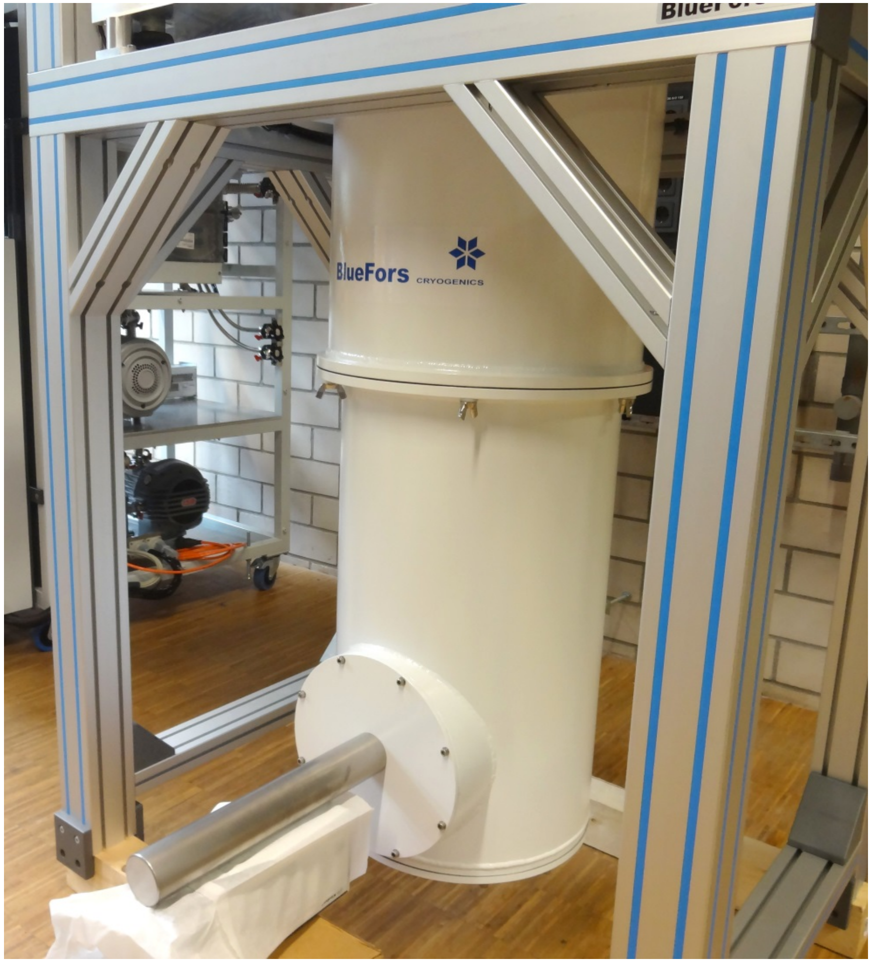
Detector operates at about 50 mK

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



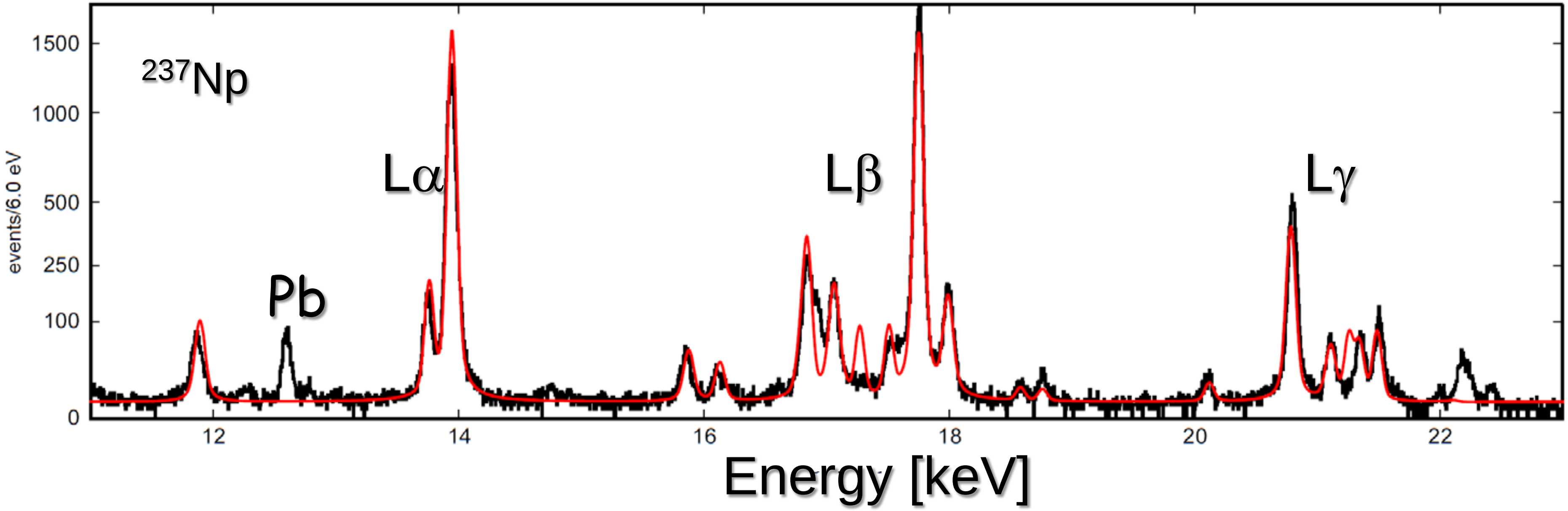


ΔE_{FWHM} = 1.6 eV @ 6 keV

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