

Asymmetric von Hamos spectrometer for low-energy X-ray spectroscopy at the CRYRING@ESR electron cooler



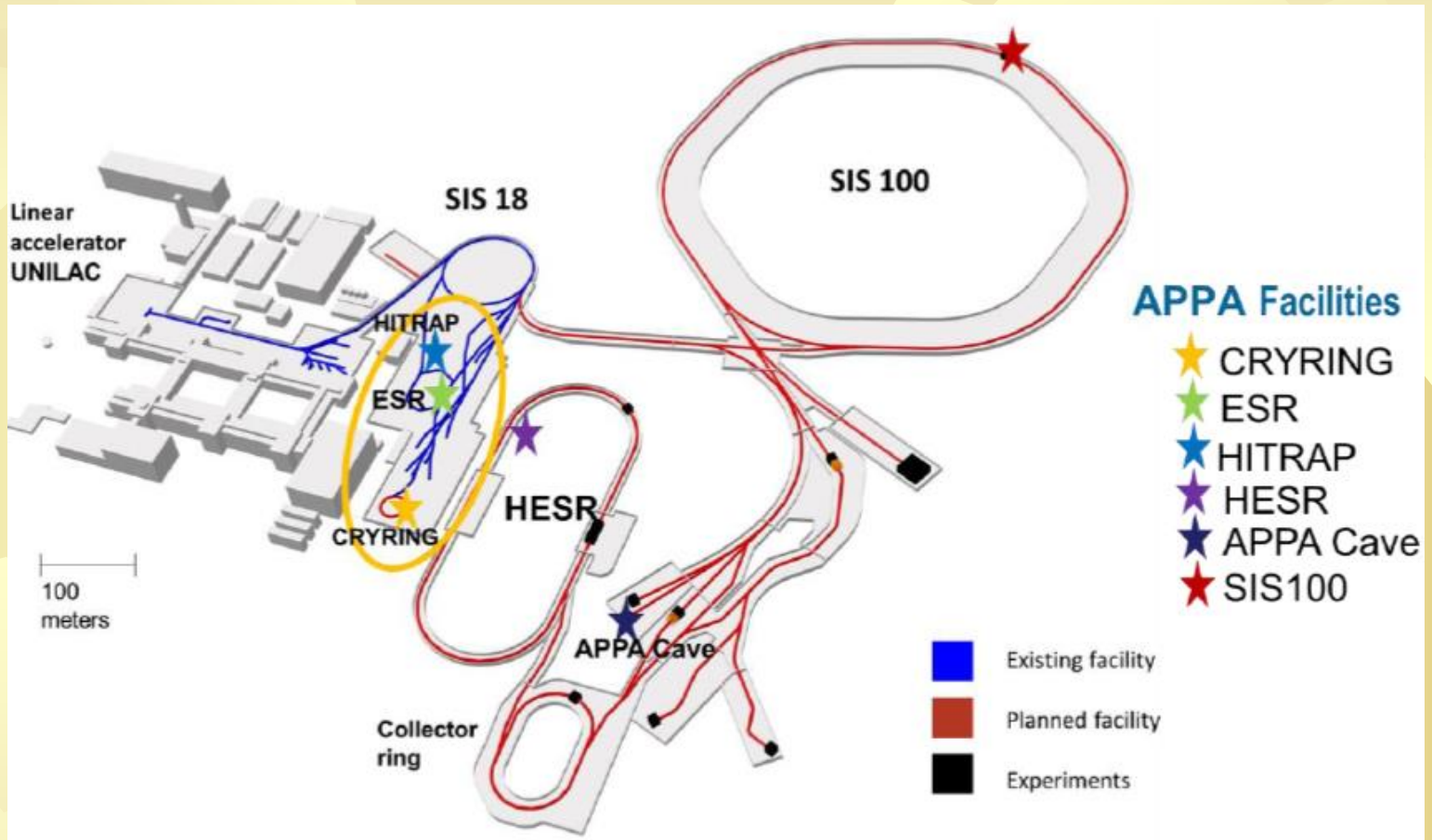
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for 



Outline

- Precision x-ray spectroscopy of QED effects
- CRYRING@ESR electron cooler
- Concept of asymmetric von Hamos (AvH) spectrometer for low-energy x-rays (5-10 keV)
- Technical design of AvH spectrometer
- Simulations of x-ray spectra for mid-Z H-like ions
- Energy resolution of AvH spectrometer
- Towards measurements of two-loop QED effects in few-electron ions

FAIR accelerator facilities



SPARC X-ray experiments at CRYRING@ESR electron cooler

CRYRING@ESR



CRYRING@ESR and electron cooler

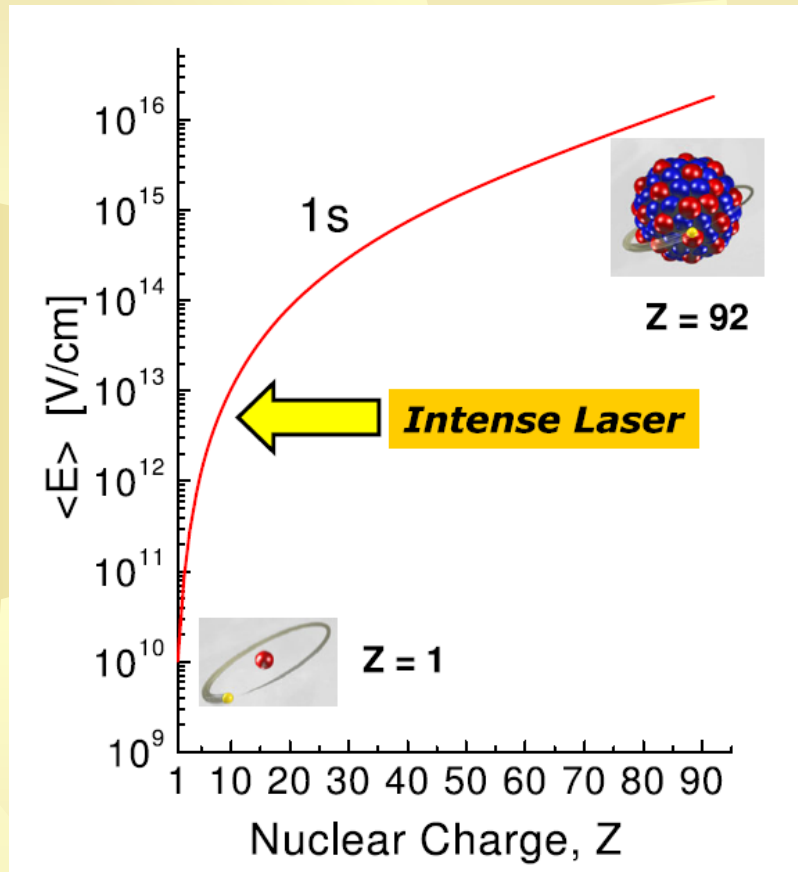
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Electron coolers in ion storage rings, in which ion beam is merged with cold electron beam, allow to study **interaction of electrons with ions at very low relative energies**, down to **meV** range, limited only by transverse electron beam temperature

Dense and cold electron beams give access to study electron-ion **radiative (RR)** and **dielectronic (DR) recombination** processes

CRYRING@ESR offers presently the best worldwide access to study the QED effects in H- and He-like ions by measuring precisely the X-rays emitted from RR

Why high-Z H-like ions ?



- simple two-body system
- no electron-electron interaction
- $\alpha Z \sim 1$ implies a use of a nonperturbative treatment which can be tested
- importance of QED corrections which scales with high powers of Z
- H-like ions are available at ion storage rings

Extremely strong electric fields act on electron in high-Z H-like ions !

Radiative recombination (RR)

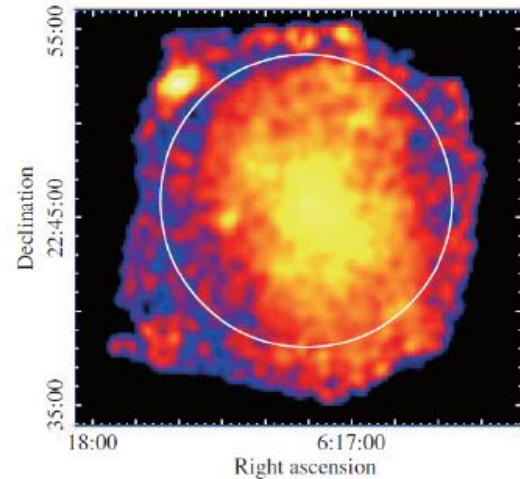
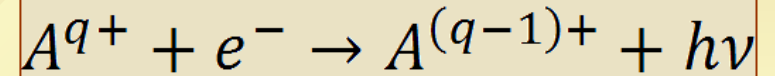
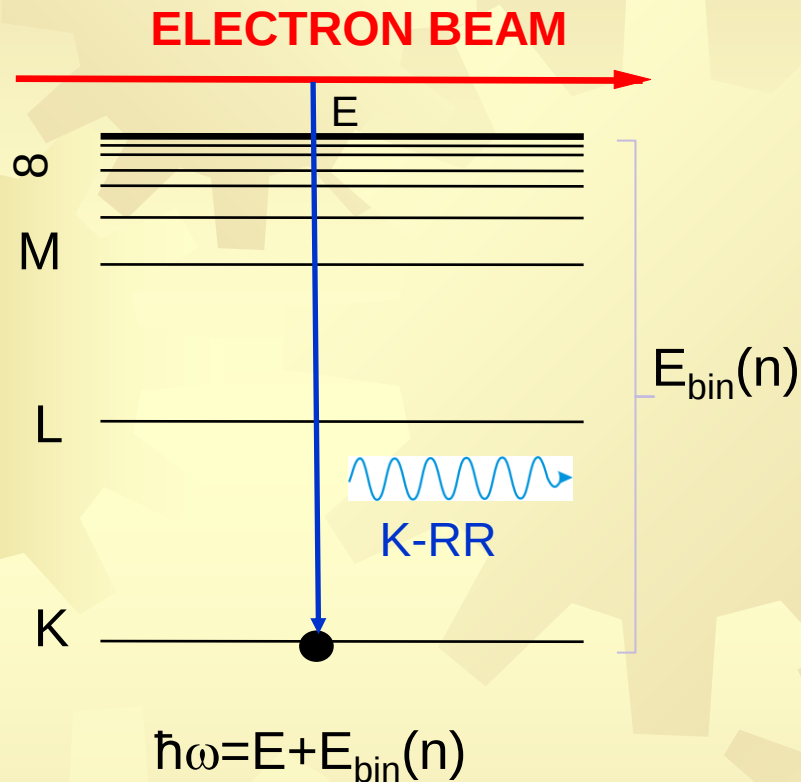
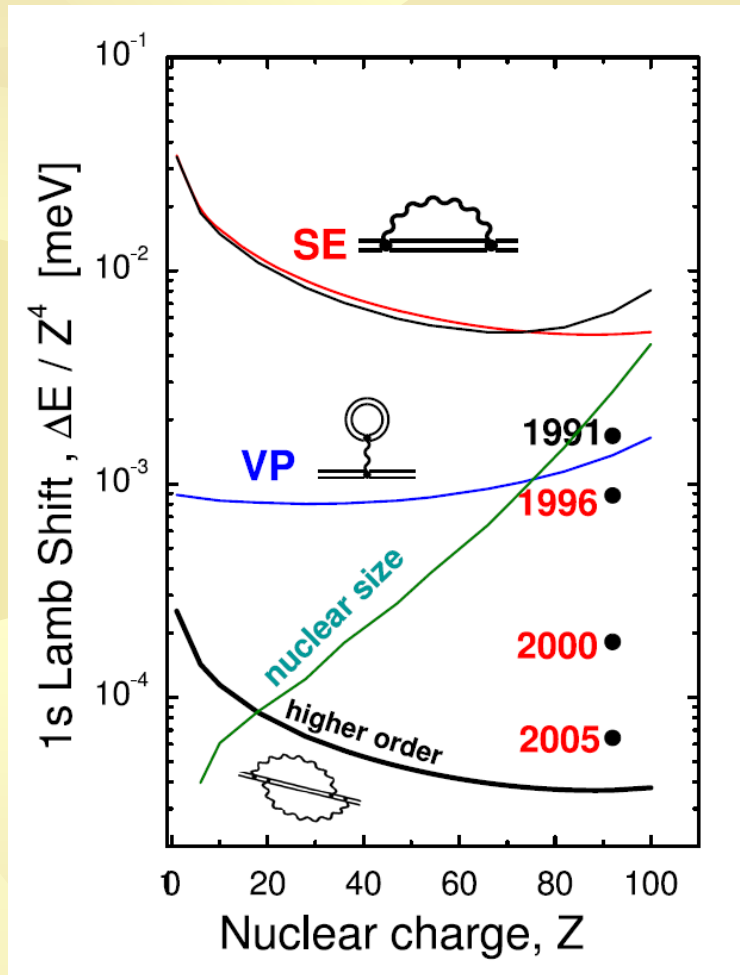


Figure 1: X-ray image of the Galactic supernova remnant IC 443 in the 3.7-10 keV photon energy band recorded by the *Suzaku* X-ray satellite observatory [6]. The image is dominated by the RR emission from H-like and He-like Ca, Fe and Ni ions.

Radiative recombination is a fundamental process of interaction of radiation with matter being time-reversed photoionization

Z- scaling of QED effects



The QED effects (Lamb shift), such as one-loop self-energy (SE) or vacuum-polarization (VP) and higher order corrections, including the nuclear size effect, are generally small, but they increase strongly with nuclear atomic number Z . Consequently, their relative importance increases in high- Z H-like ions.

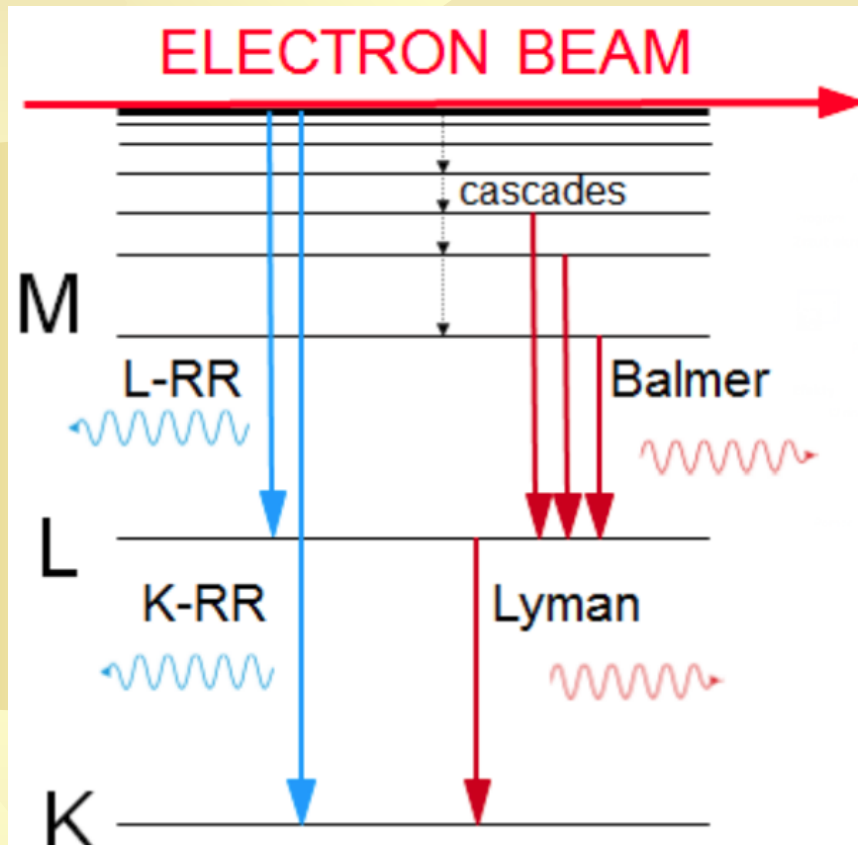
For the heaviest ions, like H-like Uranium, a contribution of nuclear size can limit a precision of determination of smaller QED effects

For mid- Z ions, in the range of $Z=20-30$, the nuclear size effect becomes smaller than higher-order two-loop QED corrections

Scaling of 1s Lamb shift in H-like ions with atomic number Z

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X-ray emission from electron cooler



X-rays emitted in/after RR of bare ions with cold electrons in electron cooler

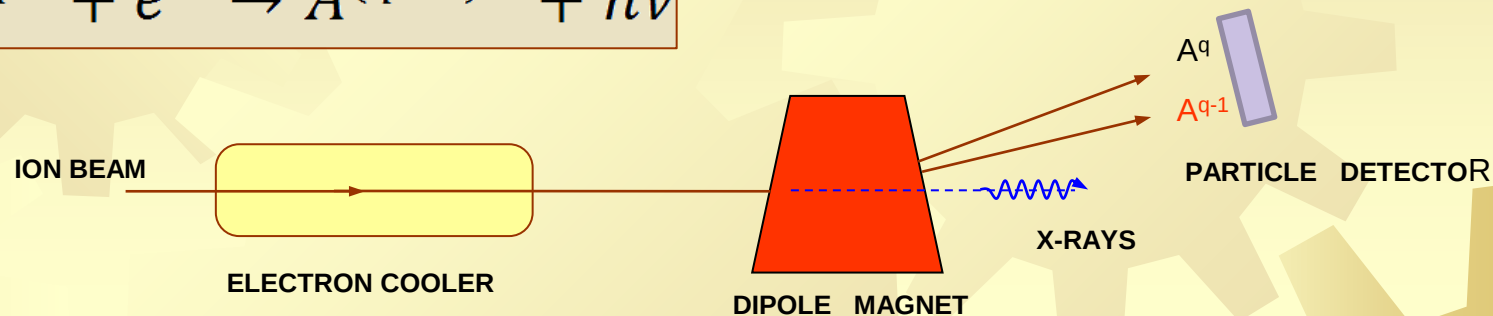
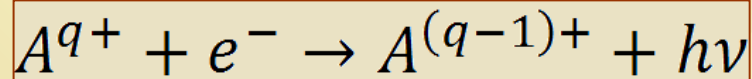
Two types of X-rays are emitted in interaction of bare ions with electrons in an electron cooler:

RR photons from free-bound transitions (e.g. K-RR, L-RR, M-RR X-rays)

Photons from bound-bound transitions in deexcitation cascade forming in H-like ions the X-ray series (e.g. Lyman, Balmer, Paschen)

The **natural widths** of K-RR transitions in H-like ions are given by the **transverse electron beam temperature (meV !)** while for Lyman transitions the widths are determined by the **radiative decay rates $\sim Z^4$** (e.g. 60 meV for Vanadium $Z=23$)

Radiative recombination experiments

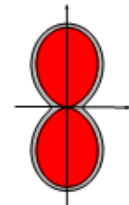


- radiative recombination of ions with cooling electrons
- electron cooling: $\langle \underline{v}_e \rangle = \langle \underline{v}_{ion} \rangle$ (detuning: $\langle \underline{v}_e \rangle \neq \langle \underline{v}_{ion} \rangle$)
- flattened electron velocity distribution: $T_{||} \ll T_{\perp}$
- recombination rate coefficient: $\alpha(n) = \langle v \sigma_n(v) \rangle$
- recombined ions detected $\rightarrow$ total rates measured $\alpha_{tot} = \sum \alpha(n)$
- x-rays detected $\rightarrow$ state selective angle-differential rates measured $d\alpha/d\Omega(n, \theta)$

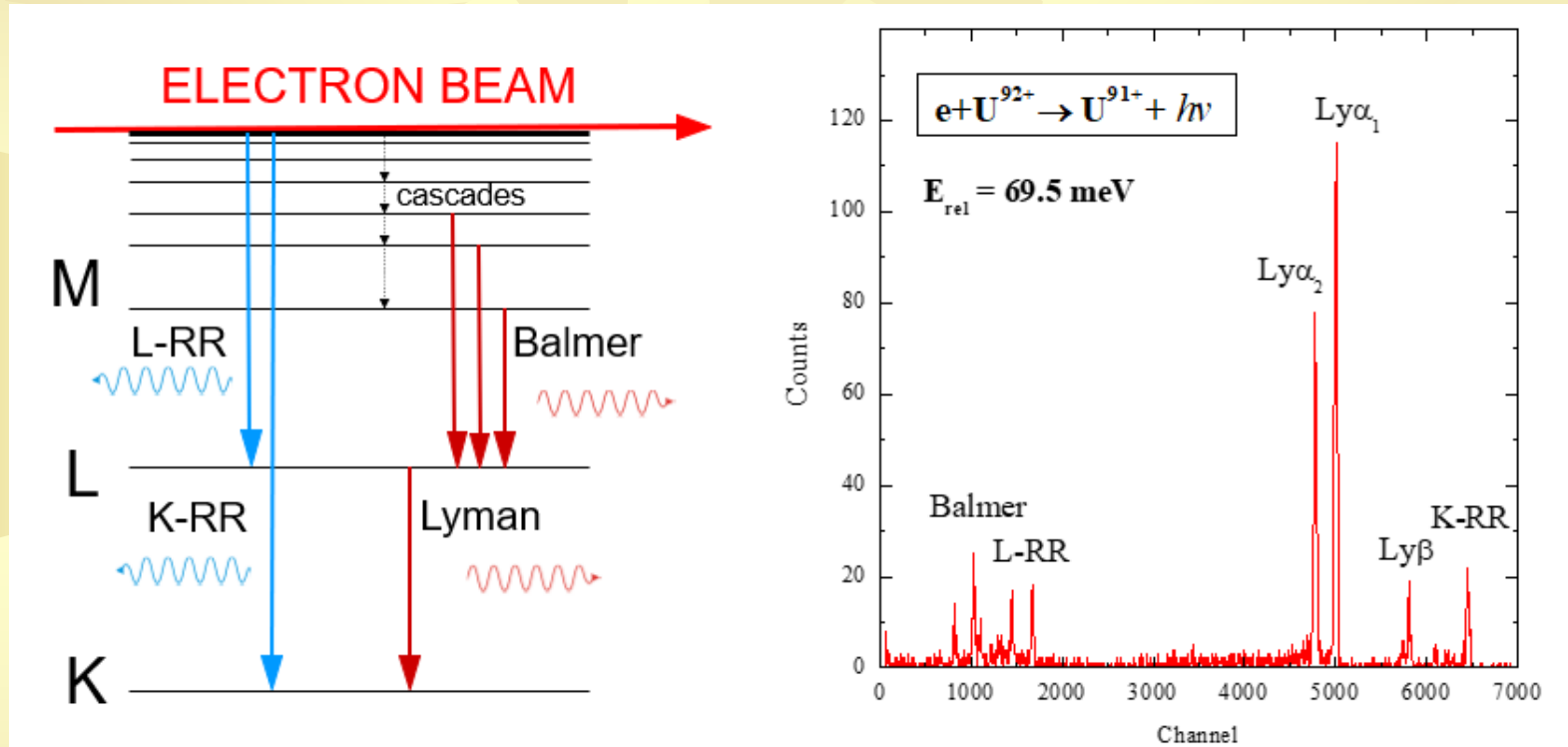
RR in low-energy approximation

Radiative recombination of bare ions with low-energy electrons ($E \ll E_{\text{binding}}(n)$) electrons can be treated within the **nonrelativistic dipole approximation**:

- recombination cross sections: $\sigma_{nl} \sim Z^2 / E$
- recombination rate coefficient ($T_{\parallel} \ll T_{\perp}$): $\alpha_{nl} \sim Z^2 / \sqrt{T_{\perp}}$
- angular distribution: $w(\vartheta) \sim 1 - \frac{\beta_{nl}}{2} + \frac{3}{4} \beta_{nl} \sin^2(\vartheta)$
- asymmetry parameter for K-RR $\beta_{10} = 2$ and
 $w(\vartheta) \sim \sin^2(\vartheta)$ (dipole term)

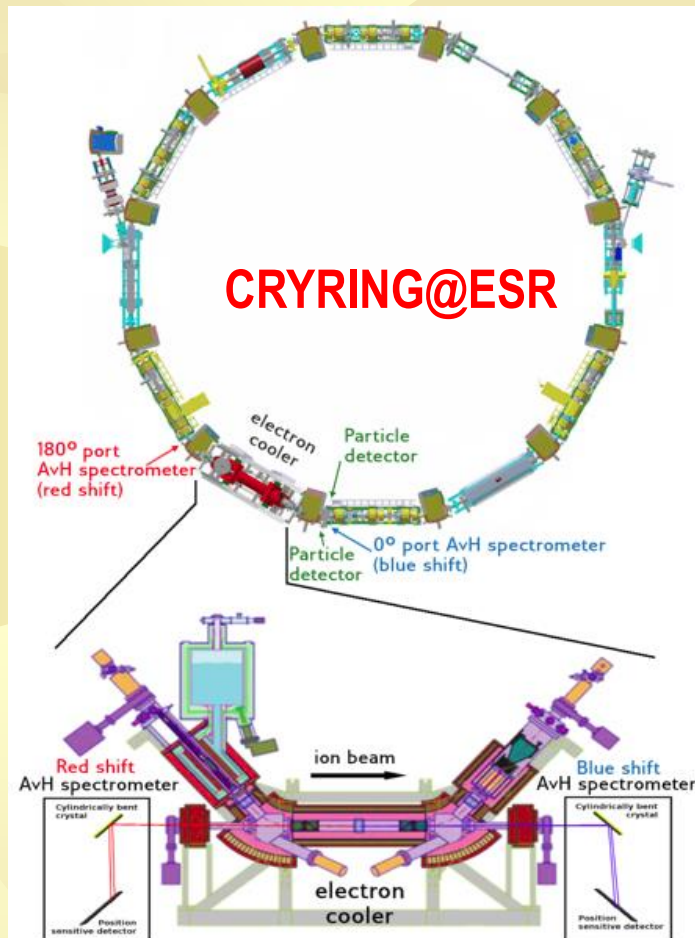


Measured K-shell RR X-rays



X-ray spectrum from RR of bare Uranium ions with electrons measured at the ESR electron cooler for detuning electron energy 69.5 meV

CRYRING@ESR electron cooler



CRYRING@ESR, electron cooler
and location of X-ray spectrometers

In CRYRING@ESR the **transverse** electron beam temperature of about $kT_{\perp} \approx 1 \text{ meV}$ can be achieved

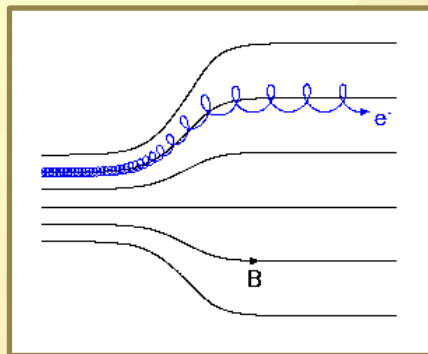
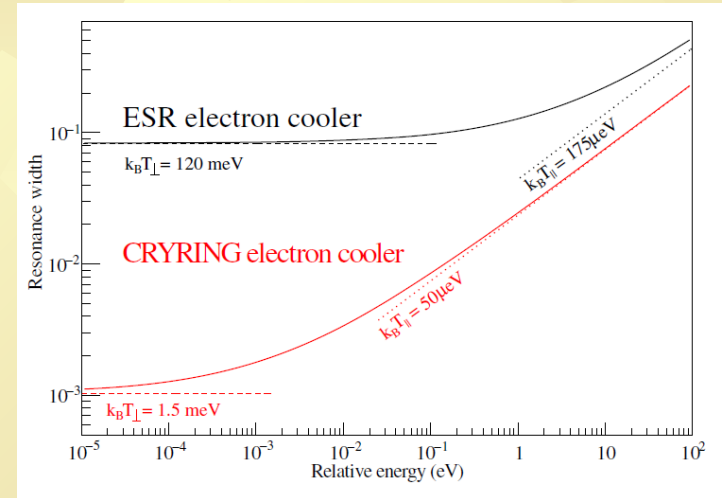
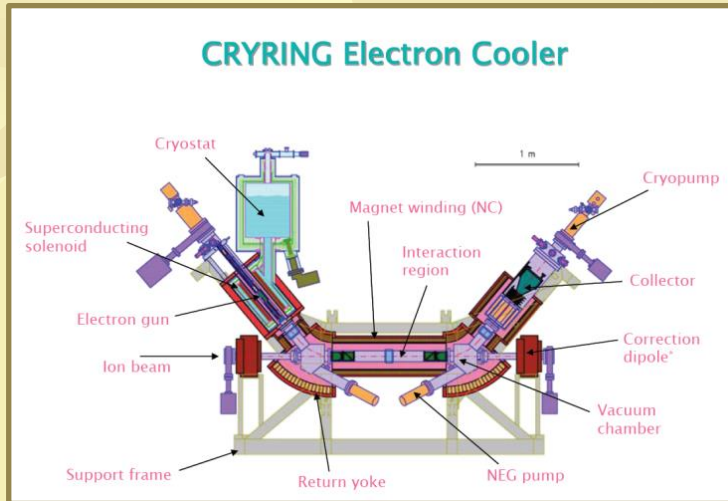
X-rays are emitted from a **long linear X-ray source** ($\sim 1 \text{ m} \times 1 \text{ mm}$) formed by overlapping electron and ion beams in the electron cooler

Available X-ray observation ports are on the **electron cooler axis** $0^\circ / 180^\circ$

Doppler effect causes **blue/red** shifts of observed X-ray energies at $0^\circ / 180^\circ$ in the LAB frame.

In order to eliminate the influence of the Doppler effect **two X-ray spectrometers** will be used to observe both **blue-** and **red-shifted** photons

Adiabatic magnetic expansion



Adiabatic magnetic expansion of the electron beam applied in the CRYRING@ESR electron cooler allows to achieve the transverse electron beam temperature as low as about **1 meV**. This improves drastically (**100 times** !) energy spread of K-RR X-ray lines and recombination rates by **10 times**.

X-ray spectrometers

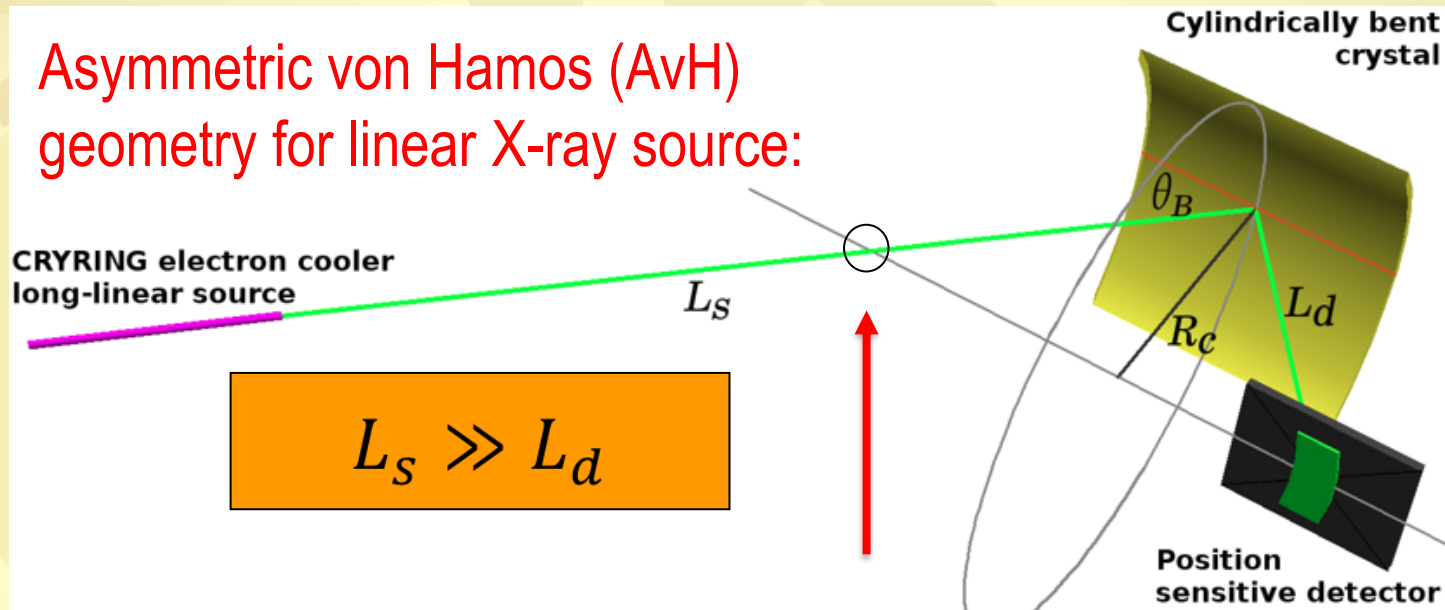
Semiconductor X-ray spectrometers (Si(Li), Ge(Li), SDD) →
energy dispersive, energy resolution: $\sim 100 \text{ eV @ } 5 \text{ keV}$

Microcalorimeters →
energy dispersive (heat), small, energy resolution $\sim 1 \text{ eV}$

Crystal diffraction spectrometers (Johann, Johanson, von
Hamos) → small point-like (collimated) x-ray source
wavelength dispersive, low efficiency, energy resolution: $\sim \text{meV}$

Asymmetric von Hamos spectrometer

Asymmetric von Hamos (AvH)
geometry for linear X-ray source:

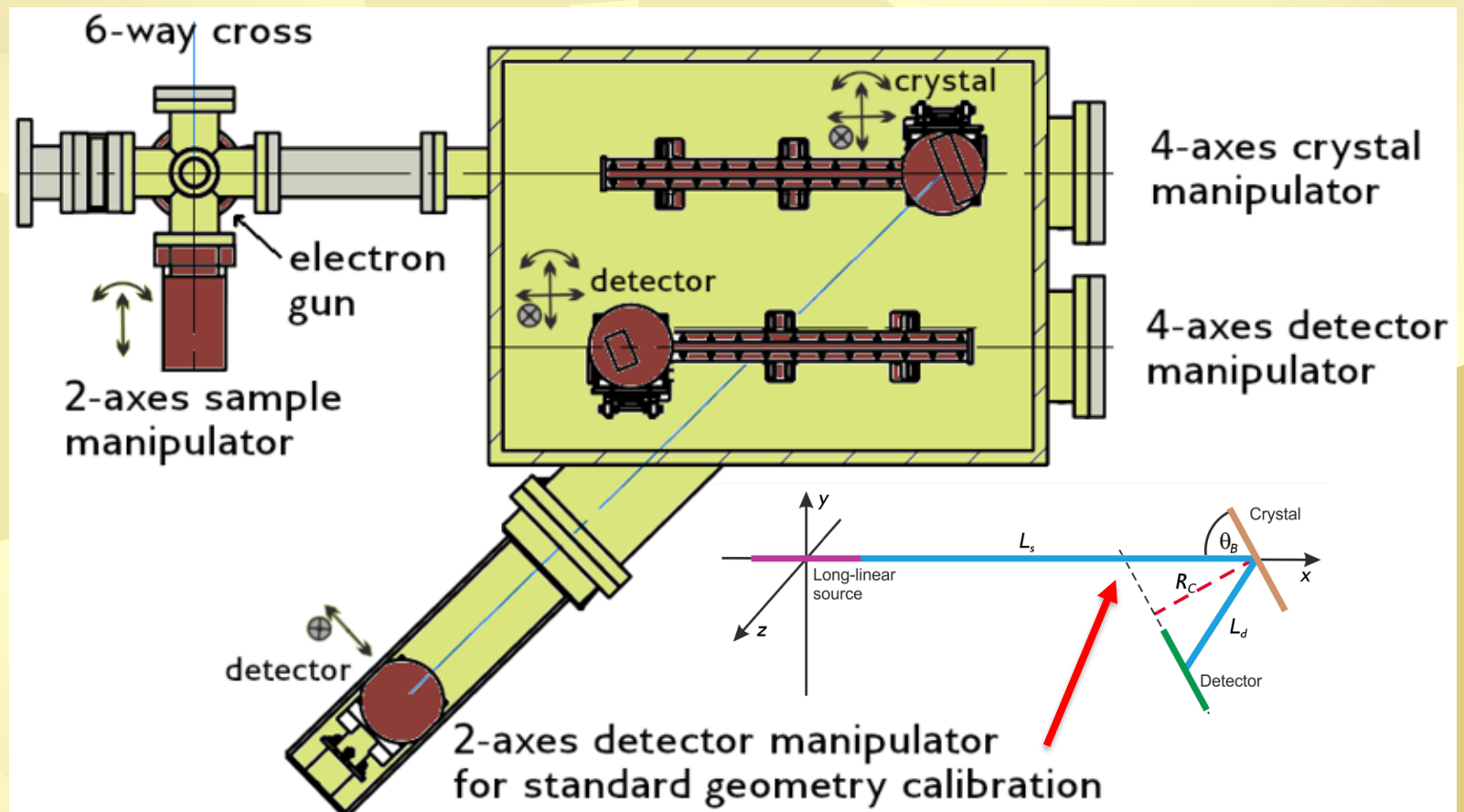


Classical von Hamos geometry for point-like X-ray source:

$$L_s = L_d = R_c / \sin \theta_B$$

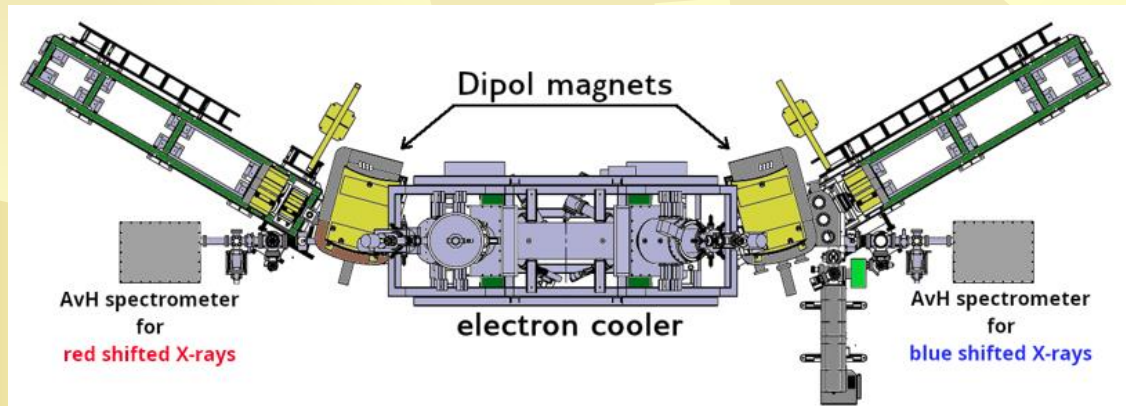
Note: in von Hamos geometry a crystal is **flat in dispersive plane** and **cylindrically bent in focusing plane** → it improves energy resolution for narrow, low-divergence X-rays emitted from the electron cooler on its axis

Desing of AvH X-ray spectrometer



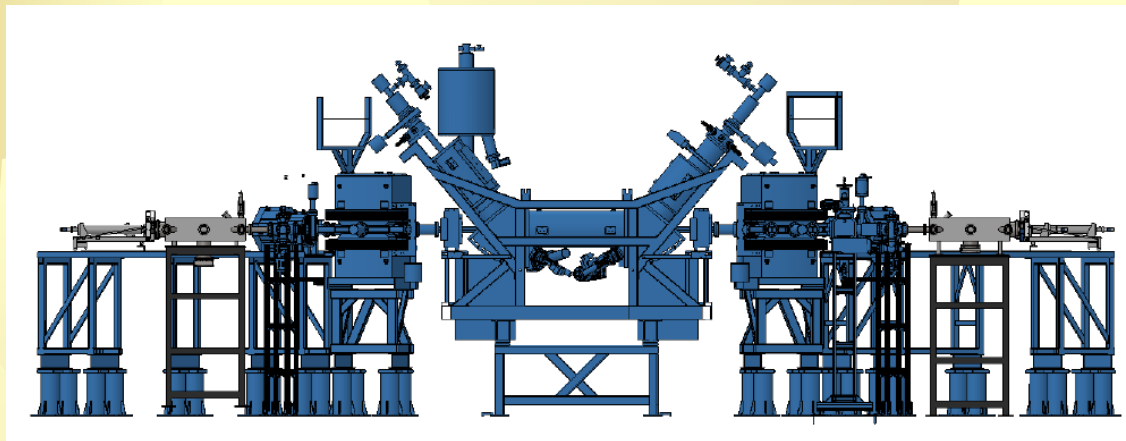
Layout of the AvH spectrometer with electron gun installed for energy calibration in „classical” von Hamos geometry

Observation of blue/red shifted X-rays



X-rays emitted along the electron cooler axis at 0°/180° are blue/red shifted due to the Doppler effect

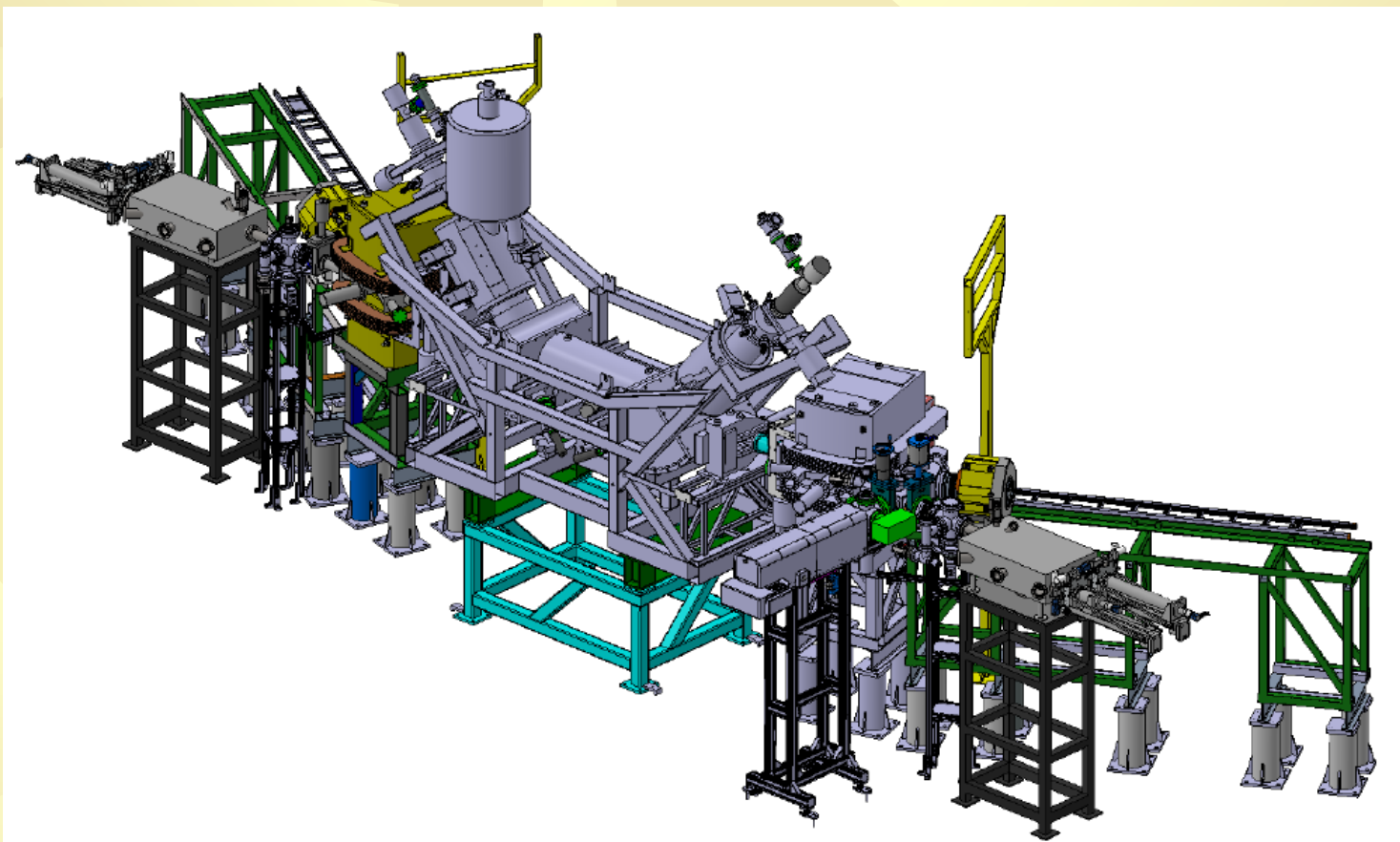
Observation of blue/red shifted photons allows to eliminate the influence of ion velocity $\beta=v/c$ on the studied X-ray energy E_0 in the moving frame



$$E_{b,r} = E_0 [(1 \pm \beta) / (1 \mp \beta)]^{1/2}$$

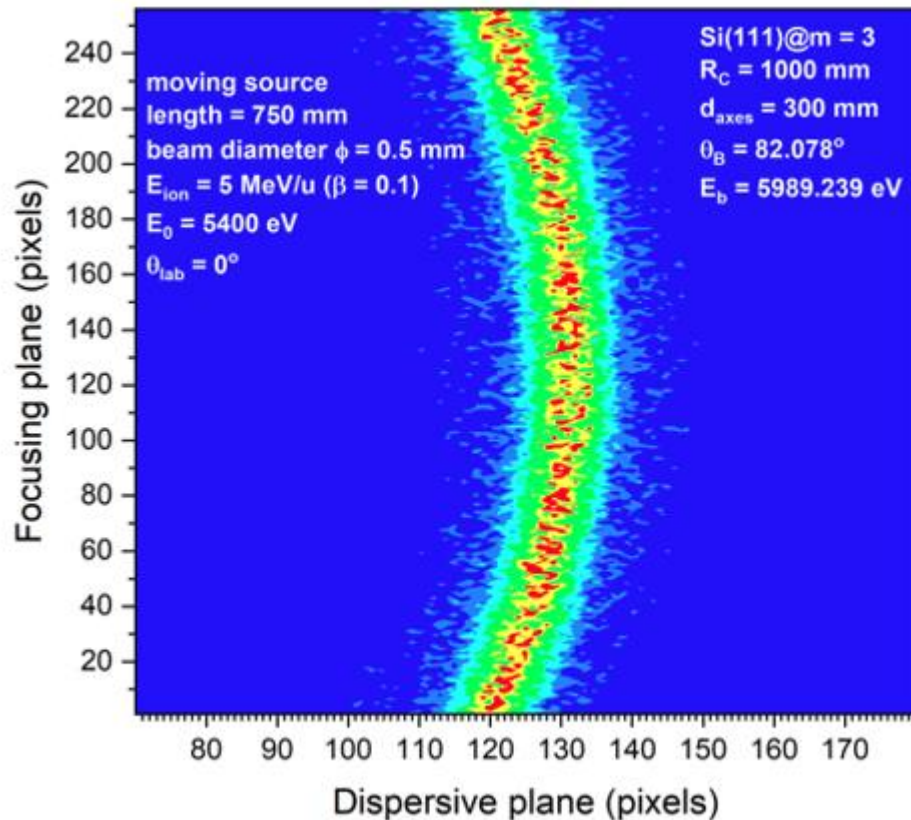
$$E_0 = (E_b E_r)^{1/2}$$

AvH at CRYRING@ESR



Layout of instalation of AvH spectrometer at CRYRING@ESR electron cooler.

Simulations of diffracted X-rays



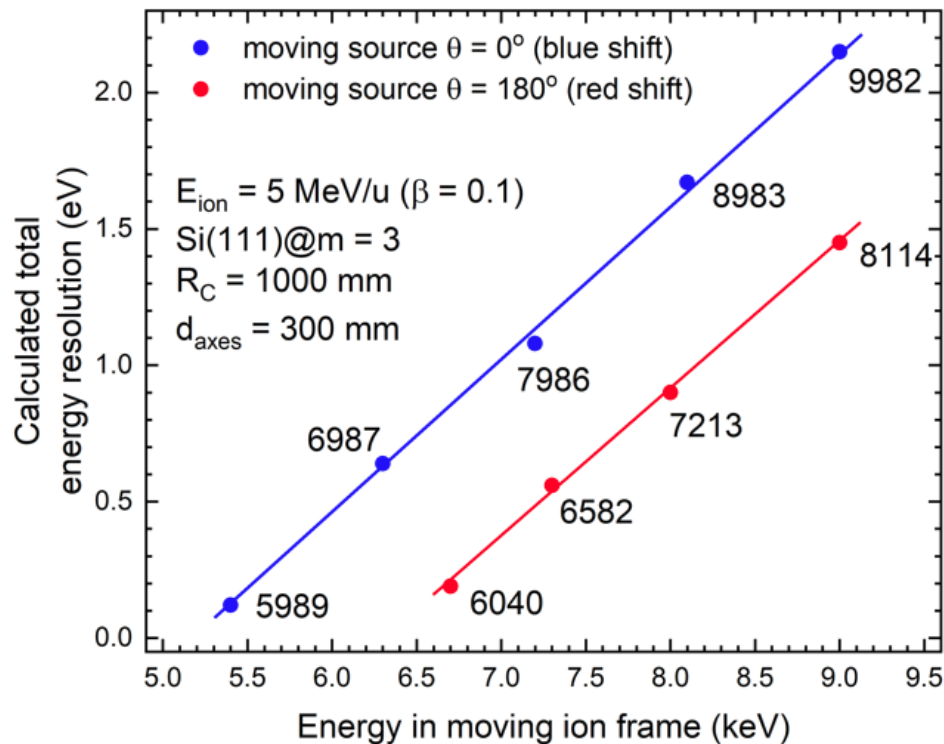
The X-rays diffracted at **Si(111) @ m=3** order will be measured by a pixelated position sensitive X-ray detector positioned at the Bragg angle.

The **Monte Carlo X-ray tracing simulations** were performed using a code developed in our group by P. Jagodziński [NIM A 753 (2014) 121].

X-ray energy profiles are derived from 2D-plots taking into account a bending of the recorded pattern

Simulated 2D-plot of recorded blue-shifted X-rays by the AvH spectrometer

Energy resolution of AvH

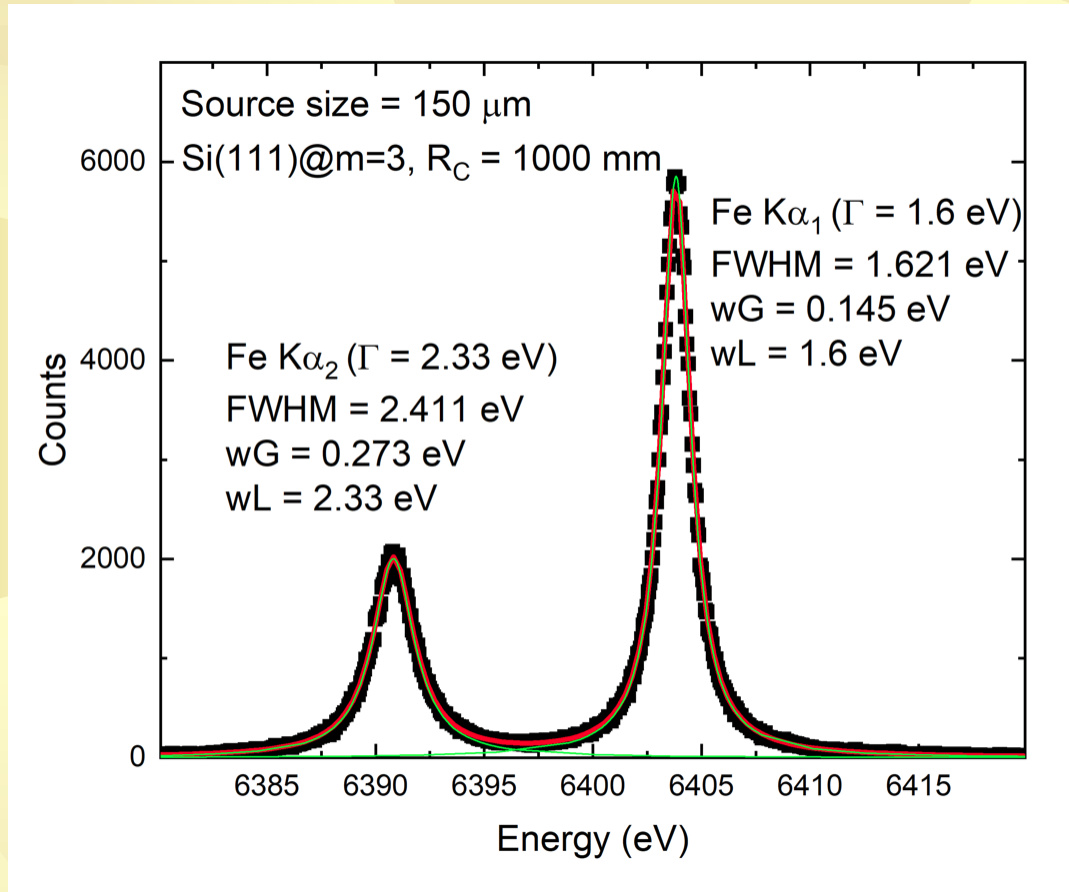


The performer X-ray tracing simulations for **Si(111)** crystal bended at **$R=1000 \text{ mm}$** for diffraction order **$m=3$** show that:

The energy resolution of AvH spectrometer varies between **0.1–2 eV** for photon energies **5–10 keV**.

For the lowest photon energies close to 5 keV the energy resolution of about **100 meV** can be achieved for expected ion beam size **$\phi = 1 \text{ mm}$** .

Tests & calibrations of AvH

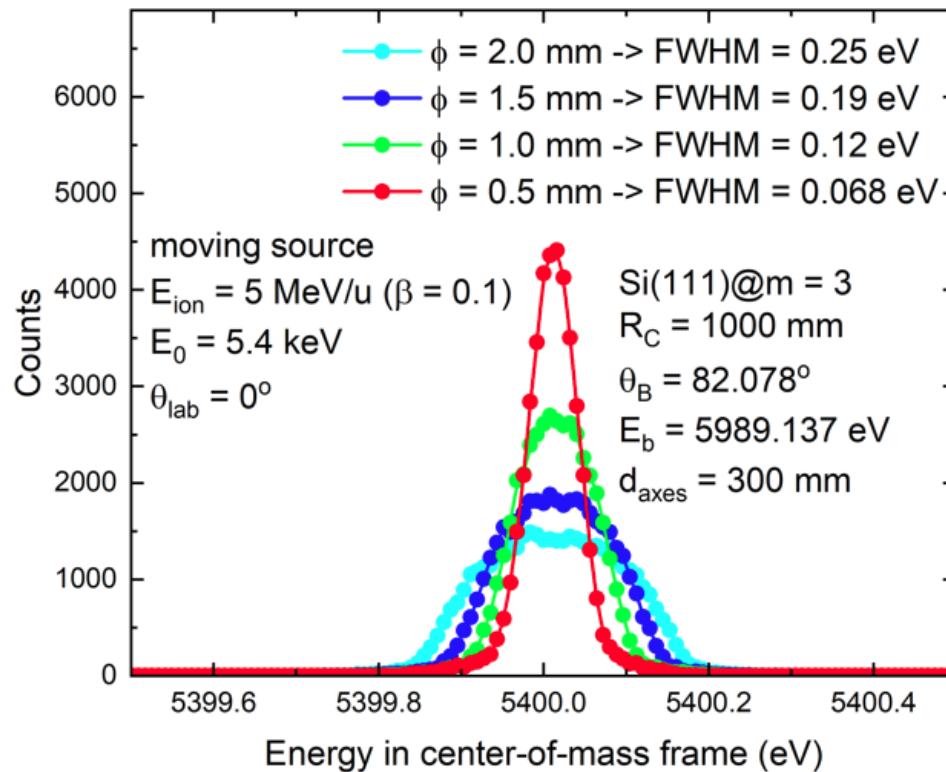


The AvH spectrometer allows to measure X-rays excited by a narrow electron beam in calibrating Fe target in „classical” von Hamos geometry for a fixed Bragg angle.

Measured energy profiles for Fe $K\alpha_{1,2}$ X-ray transitions will give an access to investigate possible imperfections of bent crystal and will be used for precise energy calibration of the AvH spectrometer.

Profiles of K- α X-ray transitions excited by electron impact in Fe calibrating target expected to be measured in „classical” von Hamos geometry

Simulations of X-ray energy profiles



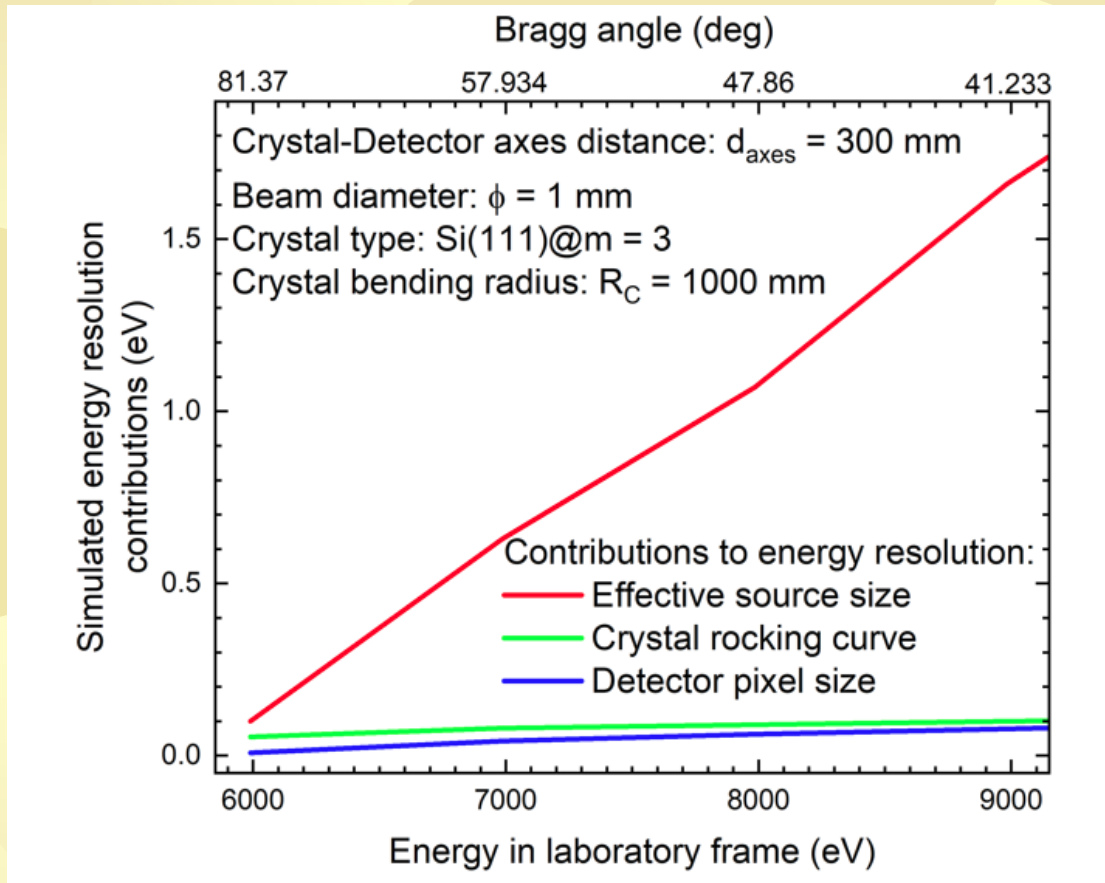
The energy profile X-rays measured by AvH spectrometer depends strongly on a size of ion beam

This is purely geometrical effect, related to an effective size of X-ray source, increases substantially the energy resolution (FWHM) of the spectrometer

However, the measured energy profiles remain symmetric which allows precision determination of the X-ray transition energies (e.e. profile centroids !)

Simulated energy profiles of X-rays measured by AvH spectrometer for different sizes of ion beam

Energy resolution - contributions



Contributions of different effects to the energy resolution of the AvH X-ray spectrometer.

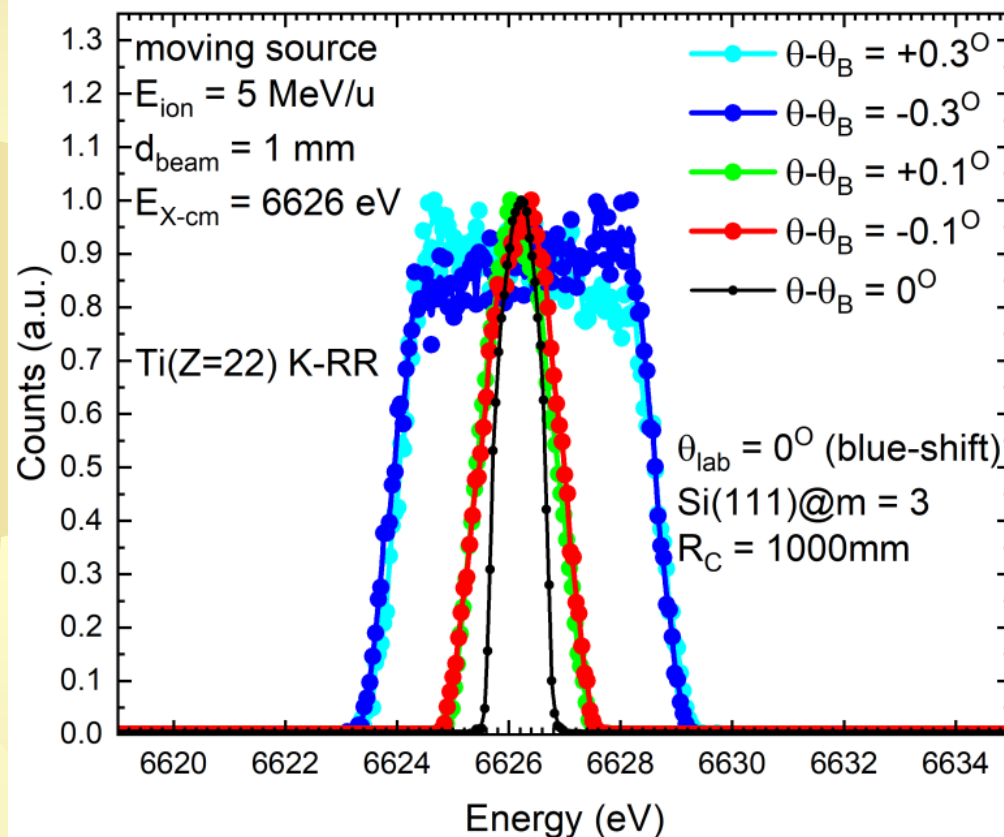
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Energy resolution of X-ray AvH spectrometer is determined by various factors with **dominating contribution of ion beam size**, which fastly decreases from 1.8 eV at 9 keV down to about **100 meV for 5 keV X-rays**

Contributions of **crystal rocking curve** and **pixel size** are smaller and nearly constant at a level a few tens of meV

At low photon energies (~ 5 keV) the AvH will give a new access for a **precision studies of QED effects** in few-electron mid-Z ions ($Z=20-30$)

Misalignment effect

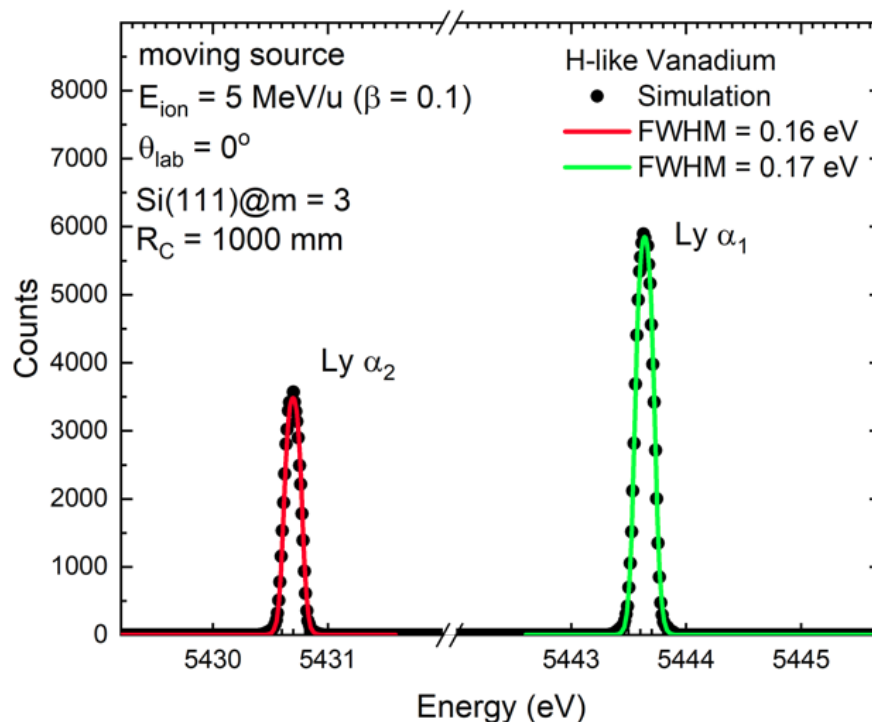


X-ray energy profiles for different settings of Bragg angle

For RR X-ray photons emitted from the electron cooler (line source !) being measured by AvH spectrometer the measured X-ray line profiles are sensitive to possible misalignment of ion beam and spectrometer axis. In this case the Bragg condition is fulfilled for a wider range of diffracted photon observation angles (energies).

This effect gives a new access for precision alignment of the AvH spectrometer with respect of ion beam axis !

Lyman X-ray emission from H-like V



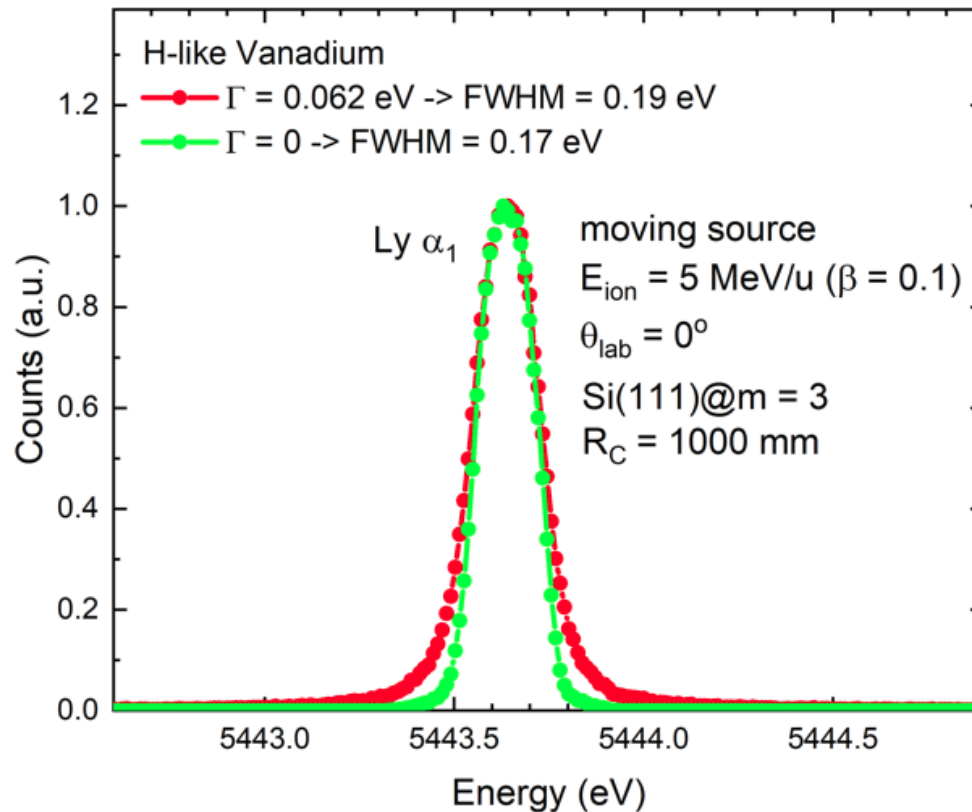
The energy resolution for blue-shifted Lyman X-ray transitions in H-like Vanadium is about **170 meV**

The centroids of Lyman X-ray lines can be determined with much higher precision, being a small fraction of energy resolution (FWHM)

Performed X-ray tracing simulations shows that the X-ray transition energies can be measured with a high precision of about **1 meV** ($\sim 0.1 \text{ ppm}$)

Simulated energy profiles of Lyman transitions in Vanadium ($Z=23$) for AvH spectrometer set at corresponding Bragg angles

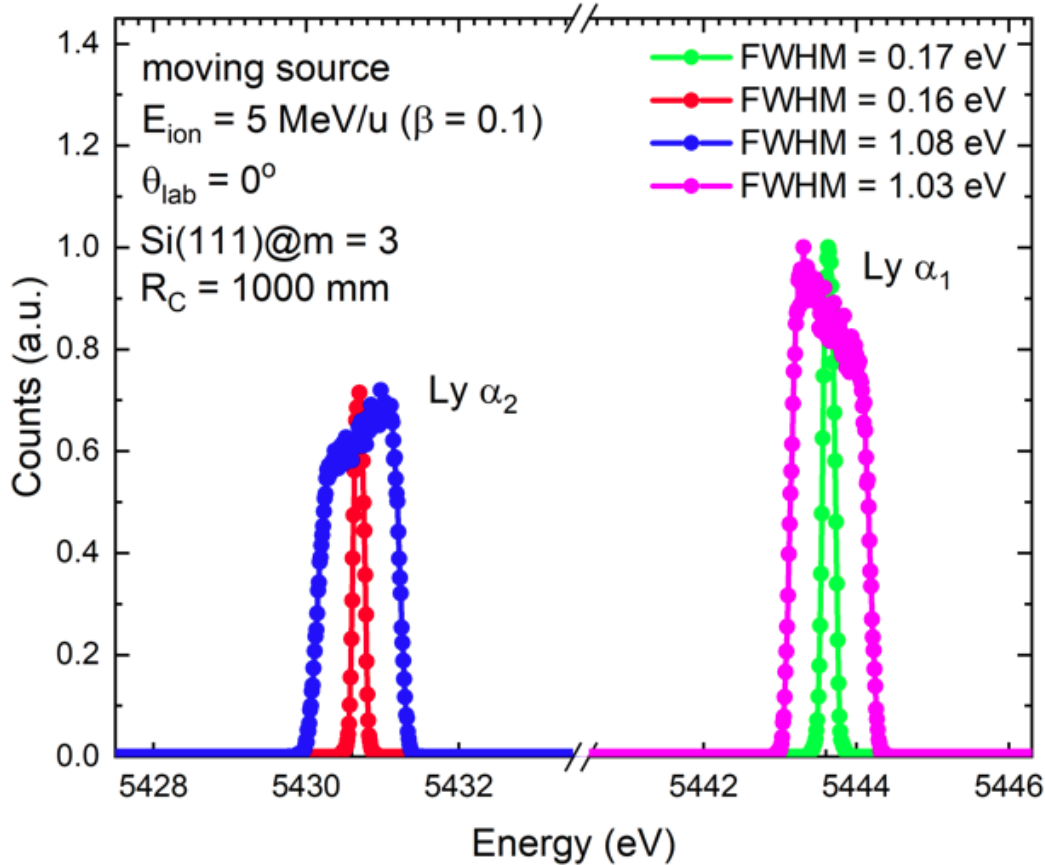
Influence of natural linewidth



The natural widths of Lyman transitions in mid-Z H-like ions have small influence on the FWHM widths of measured energy profiles for discussed experimental conditions

Influence of a natural width of Lyman transition in H-like Vanadium on measured energy profile

Bragg angle setting



For multicomponent X-ray spectra (e.g. for Lyman $\text{Ly}\alpha_{1,2}$ transitions in H-like ions) the energy profiles measured by AvH spectrometer were found to depend on the selected Bragg angle

This effect, which can be expected for a linear X-ray source, gives a new access for precision alignment of the AvH spectrometer with respect of ion beam axis !

X-ray energy profiles for different settings of Bragg angle

Design, construction & commissioning

FACILITY FOR ANTIPROTON AND ION RESEARCH
SPARC COLLABORATION



September 9, 2019

Technical Design Report:

A high-resolution asymmetric von Hamos spectrometer for low-energy X-ray spectroscopy at the CRYRING@ESR electron cooler

Abstract

The design of a high-resolution asymmetric von Hamos spectrometer for low-energy X-ray spectroscopy experiments at the electron cooler of CRYRING@ESR [1] in the International Facility for Antiproton and Ion Research (FAIR) in Darmstadt is presented in this document. The spectrometer will allow to measure, with a high resolution of down to 100 meV, the low-energy X-rays (5-10 keV) from radiative recombination (RR) of stored bare or few-electron heavy ions interacting with cooling electrons. Performed X-ray tracing simulations show that the energies of the X-ray transitions can be measured with relative precision of a few ppm, which gives access to study the QED effects for medium-Z bare ions with a high precision. For these ions the nuclear size effect is much smaller than one-loop QED corrections. The proposed asymmetric von Hamos spectrometer benefits from the unique features of RR X-ray emission in the electron cooler of CRYRING@ESR, namely, the extremely long-linear ($\sim 1 \text{ m} \times 1 \text{ mm}$) X-ray source accepted by von Hamos geometry and very cold electron beam temperature of about meV. This is achieved by application of adiabatic magnetic expansion of the electron beam, which increases substantially the intensities of RR X-rays and, consequently, the precision of determination of X-ray energies. In order to control the Doppler effect, two copies of the asymmetric von Hamos spectrometers will be installed next to the dipole magnets on both sides of the electron cooler to detect blue/red ($0^\circ/180^\circ$) shifted RR X-rays, what allows to eliminate completely the influence of Doppler effect on measured X-ray energies. The X-rays diffracted by the cylindrically bent crystal will be measured by a novel type of position sensitive semiconductor detector having nanoseconds time resolution, what will be crucial to eliminate non-RR X-ray background by counting photon-downcharged-ion coincidences. The spectrometers will be mounted to the dedicated intermediate chambers on the e-cooler axis.

Timeline:

Technical Design Report – 2019

Technical consultations - 2023

Agreements and tender – 2024

Manufacturing – 2024/25

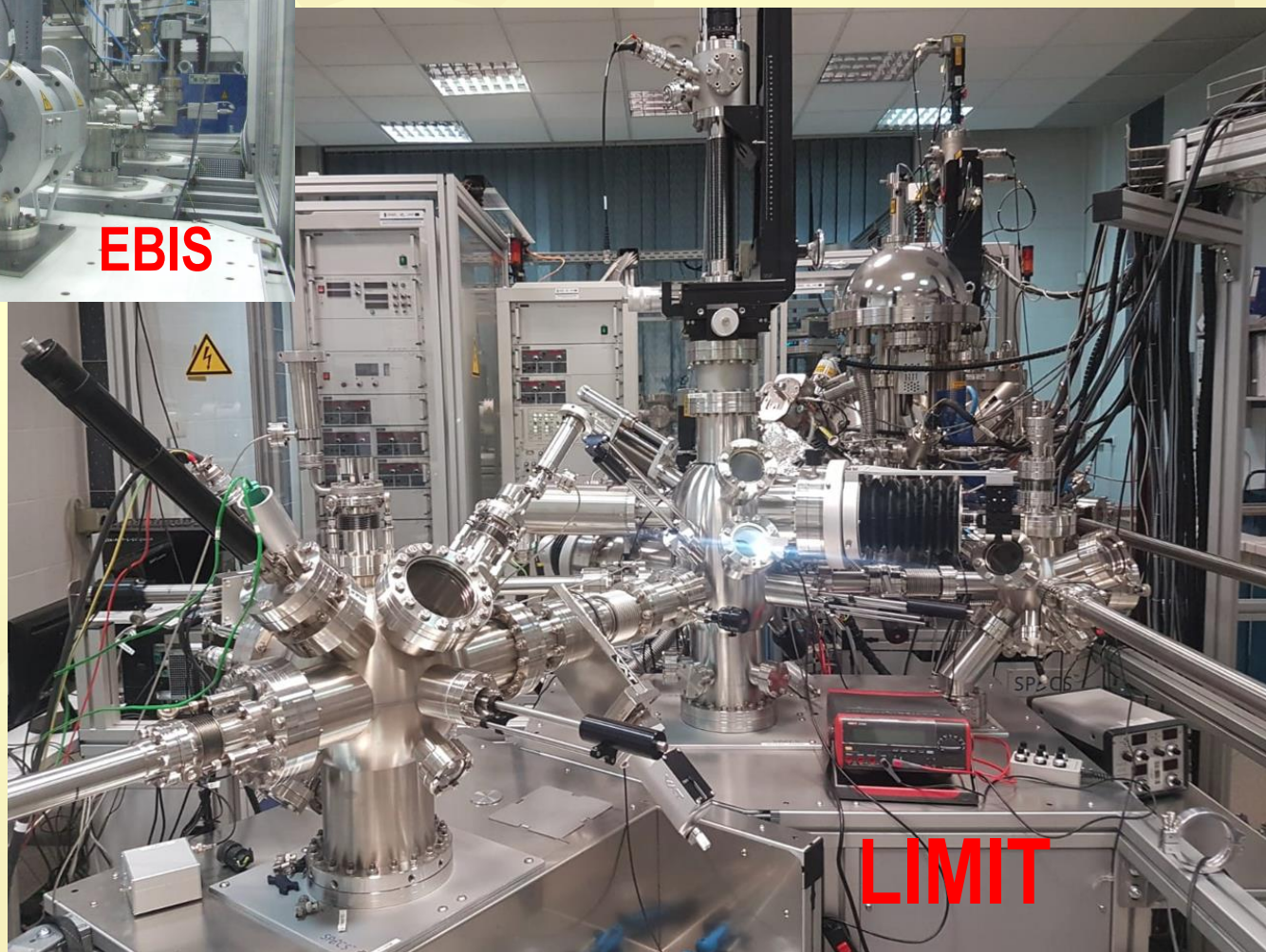
Tests and commissioning - 2025

Experiments – 2025 on

Conclusions

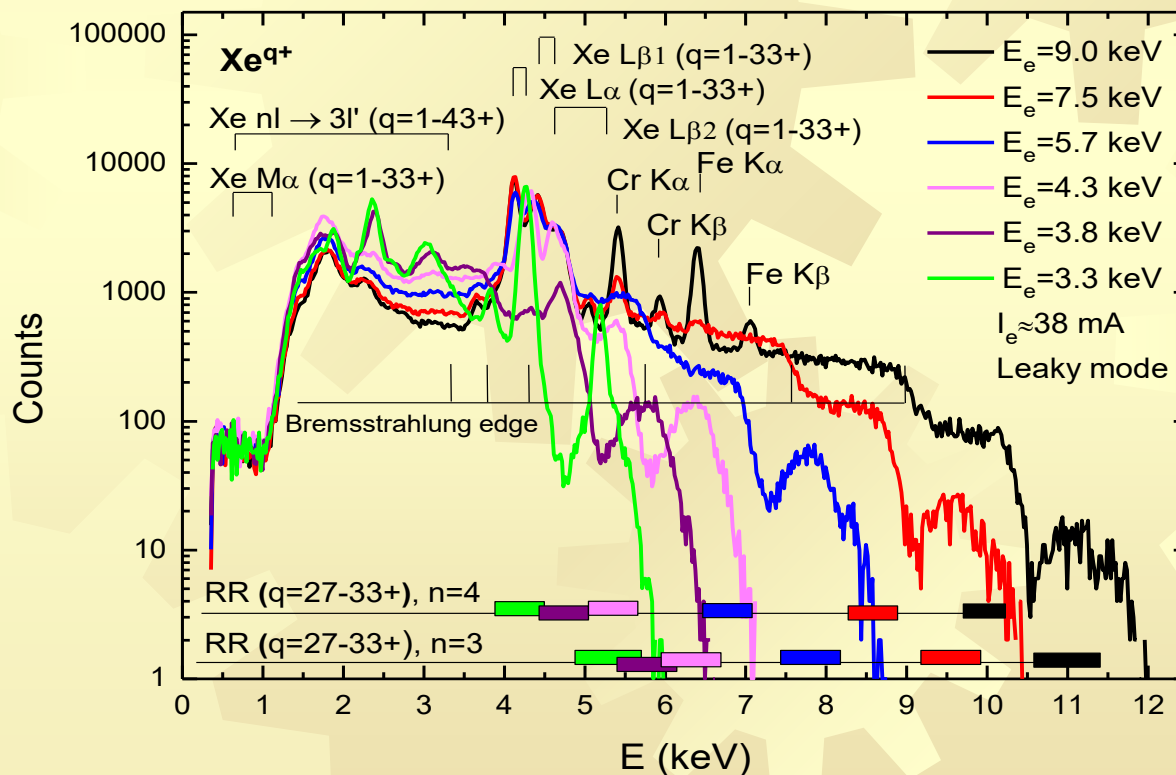
- ✱ Asymmetric von Hamos diffraction spectrometer for precise measurements of low-energy X-rays (5-10 keV) at CRYRING@ESR electron cooler is constructed
- ✱ Simulated energy resolution (FWHM) of AvH is close to 100 meV@5 keV which results in expected 1 meV accuracy of X-ray energy determination
- ✱ Expected high precision of AvH X-ray spectrometer will give access to study the two-loop QED effects in H-like and He-like ions in $Z=20-30$ range

LIMIT@EBIS laboratory



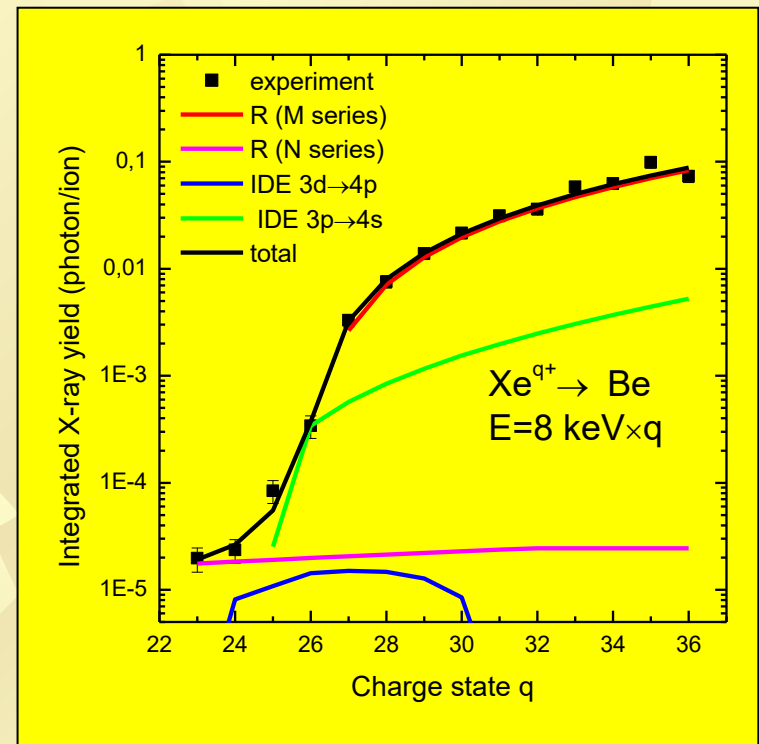
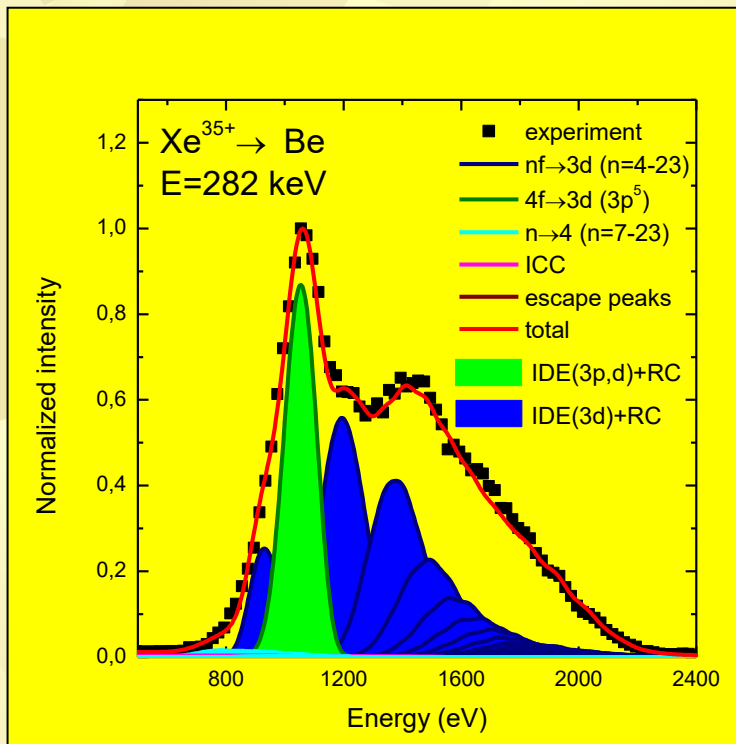
X-rays from EBIT

X-ray emission from EBIT plasma measured by XFLASH SDD detector → collision processes involved: radiative (RR) dielectronic (DR) recombination, electron-impact excitation (EIE) and ionization (EII) → astrophysical implications



X-rays from HCl-surface collisions

X-ray emission from Rydberg hollow atoms (RHA) →
observation of ultrafast relaxation of RHA at surfaces



Exotic Internal dielectronic excitation (IDE), Interatomic Coulombic Decay (ICD) and two-electron one-photon (TEOP) processes were observed.