Technical Design Report:

A high-resolution asymmetric von Hamos spectrometer for low-energy X-ray spectroscopy at the CRYRING 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 [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. 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 mid-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, namely, the extremely long-linear (\(~1 \text{ m x 1 mm}\)) 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 spectrometer will be installed next to the dipole magnets on both sides of the electron cooler to detect blue/red (0°/180°) 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 vacuum chambers on the e-cooler axis.
AUTHORS:

D. Banaś¹,⋆, P. Jagodziński¹, M. Pajek¹, A. Warczak², H. F. Beyer³, A. Gumberidze³, G. Weber³, Th. Stöhlker³, M. Trassinelli⁴ on behalf of SPARC collaboration

¹ Institute of Physics, Jan Kochanowski University, Kielce, Poland
² Institute of Physics, Jagiellonian University, Cracow, Poland
³ GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
⁴ Institut des NanoSciences de Paris (INSP), CNRS, Paris, France

⋆Contact person: d.banas@ujk.edu.pl
<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation/Institution</th>
<th>Country</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. Azuma</td>
<td>AMO Physics Lab and RIKEN</td>
<td>Wako, Saitama, Japan</td>
<td>represents Japan</td>
</tr>
<tr>
<td>E. Benis</td>
<td>University of Ioannina</td>
<td>Ioannina, Greece</td>
<td>represents Greece, Italy</td>
</tr>
<tr>
<td>D. Dumitriu</td>
<td>National Institute for Physics and Nuclear Eng.</td>
<td>Bucharest, Romania</td>
<td>represents Romania</td>
</tr>
<tr>
<td>M. Fogle</td>
<td>Auburn University</td>
<td>Auburn, Alabama, US</td>
<td>represents USA</td>
</tr>
<tr>
<td>G. Garcia</td>
<td>Spanish National Research Council</td>
<td>Madrid, Spain</td>
<td>represents Spain</td>
</tr>
<tr>
<td>R. Hoekstra</td>
<td>KVI, University of Groningen</td>
<td>Groningen, the Netherlands</td>
<td>represents the Netherlands</td>
</tr>
<tr>
<td>Z. Juhasz</td>
<td>Institute of Nuclear Research (ATOMKI)</td>
<td>Debrecen, Hungary</td>
<td>represents Hungary, Croatia</td>
</tr>
<tr>
<td>T. Kirchner</td>
<td>York University</td>
<td>Toronto, Canada</td>
<td>represents Canada</td>
</tr>
<tr>
<td>X. Ma</td>
<td>Institute of Modern Physics</td>
<td>Lanzhou, China</td>
<td>represents China</td>
</tr>
<tr>
<td>M. Pajek</td>
<td>Jan Kochanowski University</td>
<td>Kielce, Poland</td>
<td>represents Poland</td>
</tr>
<tr>
<td>H. Rangama</td>
<td>CIMAP, University of Caen</td>
<td>Caen, France</td>
<td>represents France</td>
</tr>
<tr>
<td>C. P. Safvan</td>
<td>Inter-University Accelerator Centre</td>
<td>New Delhi, India</td>
<td>represents India</td>
</tr>
<tr>
<td>J. P. Santos</td>
<td>University Nova Lisboa</td>
<td>Lisboa, Portugal</td>
<td>represents Portugal</td>
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<td></td>
<td>(deputy spokesperson)</td>
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<tr>
<td>S. Schippers</td>
<td>Justus Liebig University Giessen</td>
<td>Giessen, Germany</td>
<td>represents Germany</td>
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<tr>
<td>R. Schuch</td>
<td>Stockholm University</td>
<td>Stockholm, Sweden</td>
<td>represents Sweden</td>
</tr>
<tr>
<td>V. Shabaev</td>
<td>St. Petersburg State University</td>
<td>St. Petersburg, Russia</td>
<td>represents Russia</td>
</tr>
<tr>
<td>Th. Stohlker</td>
<td>Helmholtz Institut Jena &amp; GSI &amp; University of Jena</td>
<td>Jena, Darmstadt, Germany</td>
<td>represents Germany</td>
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<td>(local contact)</td>
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<tr>
<td>A. Surzhykov</td>
<td>Technische Universitat Braunschweig</td>
<td>Braunschweig, Germany</td>
<td>represents Germany</td>
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<tr>
<td>R. Thompson</td>
<td>Imperial College London</td>
<td>London, UK</td>
<td>represents UK</td>
</tr>
<tr>
<td>M. Trassinelli</td>
<td>Institut des NanoSciences de Paris (INSP), CNRS</td>
<td>Paris, France</td>
<td>represents France</td>
</tr>
<tr>
<td>L. Tribedi</td>
<td>Tata Institute of Fundamental Research</td>
<td>Mumbai, India</td>
<td>represents India</td>
</tr>
<tr>
<td>A. Wolf</td>
<td>Max Planck Institute for Nuclear Studies</td>
<td>Heidelberg, Germany</td>
<td>represents Germany</td>
</tr>
<tr>
<td>W. Wolff</td>
<td>Universidade Federal do Rio de Janeiro</td>
<td>Rio de Janeiro, Brazil</td>
<td>represents South America</td>
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1 Introduction and motivation

1.1 Radiative recombination of highly charged ions with electrons

Radiative recombination (RR) is one of the most fundamental processes occurring in collisions of highly charged ions with electrons. In this process a free electron is captured into a bound state of an ion with simultaneous photon emission as follows:

\[ A^{q+} + e(E) \rightarrow A^{(q-1)+}(n) + \hbar \omega. \]  

(1)

The emitted photon carries away the energy difference \( \hbar \omega = E - E_n \) between the electron continuum state with the energy \( E \) and the bound electron state \( E_n \) with principal quantum number \( n \). Detailed nonrelativistic quantum mechanical descriptions of RR were developed by Stobbe [2] and Bethe and Salpeter [3]. The RR cross sections generally increase for lower electron energies exhibiting for bare ions \( Z^2/nE \) scaling in the low-energy limit \( (E << E_n) \) [4], where for few electron ions the nuclear charge number \( Z \) (in electron charge units) has to be replaced by an appropriate effective charge \( Z_{eff}(q) \). Consequently, RR is important for low \( n \)-states of highly charged high-Z ions interacting with cold electrons and leads to emission of X-rays. The role of the relativistic and high multipole effects for interpretation of RR X-ray experiments at high electron energies, especially for heavy, highly-charged ions has been demonstrated and discussed in Ref. [5].

The radiative recombination plays an important role in astrophysical and laboratory plasmas as a cooling mechanism taking away energy from the plasma by radiation. As an example, Fig. 1 shows the X-ray image of the Galactic supernova remnant IC443 (called ”Jellyfish Nebula”) recorded by the Japanese-US Suzaku X-ray satellite observatory in the photon energy range 3.7-10 keV [6]. With this image, which was interpreted in terms of the RR emission in recombination of free electrons with H-like and He-like Ca, Fe and Ni ions, it was possible to make important conclusions on the details of IC443 supernova explosion.

The radiative recombination of bare or few-electron ions with cold electrons having very low energies, down to meV as it happens in the electron cooling process in ion storage rings, gives unique possibilities to study the QED effects in mid-Z and high-Z highly charged ions. In this case, the binding energies of electrons in the final bound states can be precisely measured when a high resolution X-ray spectroscopy is applied. Consequently, the emission of X-rays from RR of highly charged ions with cold electrons in ion storage rings gives access to study the QED effects in HCI with very high precision and thus significantly contribute to development of new precise theoretical calculations.

1.2 QED effects in highly charged ions

Despite of the fact that the quantum electrodynamics (QED) has been tested to extremely high precision in hydrogen [7,8], the QED effects [9,10] for large coupling constant, up to \( Z\alpha \approx 0.7 \) in uranium, are of fundamental interest due to the nonperturbative nature of QED corrections in this regime. In high-Z H-like ions, the higher order QED effects, which scale with high powers of \( Z \), become more important. For the Lamb shift the dominating one-loop QED corrections, self-energy and vacuum polarization scale as \( (Z\alpha)^4 \) while the two-loop corrections contain terms scaling as \( (\sim Z\alpha)^5 \). For few-electron ions the QED affects additionally the electron-electron interaction [11]. The finite nuclear size effect,
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.

increasing strongly as $(Zα)^{4+2(1-(Zα)^2)^{1/2}}$ [9, 11], limits the precision of determination of the Lamb shift in high-Z ions by the uncertainties in the knowledge of nuclear charge distribution.

For this reason the studies of QED effects for mid-Z ions, in particular in the $Z = 20 - 30$ range, are of special interest because here the nuclear size effect, which strongly decreases with $Z$, becomes small, while, on the other hand, the relative precision for the determination of the Lamb shift is still acceptable for a given energy resolution of a spectrometer. The precision measurements of X-ray transitions, in the context of investigations of the QED effects in medium $Z$ H- and He-like ions, were reported during the last decade [12–21]. In RR of bare and H-like ions with $Z = 20 - 30$ the K-shell RR and the intense Lyman-α X-ray transitions are in the range 4-12 keV. For these ions the calculated one-loop Lamb shift is about 2-5 eV, being much larger than the nuclear size effect contributing about 15-120 meV, while the two-loop QED contribution [22] is in the range 1-8 meV, respectively. Assuming thus, for instance, about 100 meV energy resolution of a spectrometer for the studied X-ray line and finer (better than 1/10) precision of its energy (centroid) determination the energy of X-ray transition can be determined with an accuracy higher than 10 meV. This would imply a few ppm precision in determination of X-ray transition energy. Consequently, with such a high resolution X-ray spectrometer, the Lamb shift could be measured with precision well below 1% for mid-Z H-like ions, for which a contribution of nuclear size effect is small (below 1%) in contrast to the heaviest U$^{92+}$ ions for which it reaches 43%. Multi-electron mid-Z ions studies could also con-
tribute to investigation of e-e interactions (developed as $1/Z$) making a bridge between perturbative and non-perturbative theoretical approach.

1.3 High resolution RR measurements at storage rings

The ion storage rings equipped with an electron cooler offer unique experimental possibilities to study the RR of bare and few-electron high-Z ions with electrons. An electron cooler provides an intense beam of cold electrons which is merged with the ion beam circulating in the ring. The electrons, whose average velocity matches the average ion velocity $\langle v_e \rangle = \langle v_{\text{ion}} \rangle$ for cooling condition, are used to cool the stored ion beam by elastic electron-ion collisions, but can also be employed as an electron target to study the RR at low relative energies down to the meV range. More precisely, in the electron cooler the electron velocities in the ion frame have the so-called flattened Maxwellian distribution characterized by transverse ($kT_\perp$) and longitudinal ($kT_\parallel$) electron beam temperatures with $kT_\parallel \ll kT_\perp$. At cooling condition the RR rates are determined by the electron transverse temperature, typically $kT_\perp \sim 100$ meV, which is defined by the cathode temperature in the electron gun. Generally, the RR rates for bare ions recombining with free electron having flattened velocity distribution scales as $\alpha_{\text{RR}} \sim Z^2/(kT_\perp)^{1/2}$ (see Ref. [4] for details). In this context it is important to emphasizes that at the CRYRING the adiabatic expansion of the electron beam in the cooler is applied [23, 24]. This results in a reduction of the transverse electron beam temperature by two orders of magnitude, down to $kT_\perp \sim 1$ meV [24] which, taking into account that the electron density can be conserved for expanded electron beam [23,24], increases the RR rates by an order of magnitude. It is important to note that the relative electron-ion velocity in the electron cooler can be detuned from its “cooling” value for a short time, which allows to measure a dependence of both the radiative (RR) and dielectronic (DR) recombination on the electron energy. This is of particular interest for DR studies which can deliver independent information on the electron beam temperatures in the electron cooler. The RR in storage rings can be studied experimentally by detecting the downcharged ions separated by the dipole magnet next to the electron cooler. In this case only the total RR rates, i.e. summed up from $n = 1$ to some $n_{\text{cut}}$ limited by the field ionization effect in the dipole magnet can be accessed. The counting of downcharged ions is also applied in DR studies aimed to observe narrow DR resonances, which also carry information on the electronic structure of the ion. In order to make the RR experiments state-selective, the RR photons, i.e. X-rays in case of mid- or high-Z ions, have to be observed. For bare ions stored in the ring the RR X-ray spectra measured in the electron cooler consist of a series of RR lines from recombination of free electrons to the bound states, e.g. K-RR, L-RR, etc. and secondary X-rays from the Lyman, Balmer and higher series, due to radiative deexcitation cascades following the initial population of higher bound states by RR process. It is important to note that the radiative cascades effectively increase the intensities of characteristic X-rays, by as much as an order of magnitude for Lyman transitions [25].

The X-ray RR experiments at the electron cooler of the ESR storage ring have been performed with bare Au$^{79+}$ and U$^{92+}$ ions [26–30], aiming at testing of QED effects. In these experiments, both the K-RR and Lyman X-rays were measured using energy-dispersive semiconductor detectors. These experiments have demonstrated the importance of the relativistic and QED effects in H-like and He-like high-Z ions. In particular, the ground-state Lamb shift was measured [30] with a high precision setting one of the strongest test of QED for high-Z H-like ions. In other experiment [31] at the electron
cooler a dependence of RR rate upon the relative electron energy was measured in a state-selective manner for $^{92+}$ ions recombining with electrons in the relative energy range of $\pm 1 \text{ eV}$. This experiment showed that even for ultimately-low-energy collisions the relativistic effects are important [31,32] and, additionally, it demonstrated a systematic enhancement of the measured RR rates for low $n$-states with respect to the standard RR calculations [3, 4]. This finding opens new questions for interpretation of the RR enhancement effect [33] and, on the other hand, it demonstrates that the observed RR enhancement is an important factor which can improve statistics and thus the precision of high-resolution X-ray spectroscopy applied to determine accurately the RR X-ray transition energies.

Up to now, the high-resolution wavelength-dispersive X-ray spectroscopy has been applied at the ESR only at the internal gas target. In these experiments the Focusing Compensated Asymmetric Laue (FOCAL) [34, 35] and Johann-type [36] X-ray crystal diffraction spectrometers have been used. At the internal gas target of the ESR, the precision high-resolution measurements of X-ray transition energies and, consequently of the Lamb shift are influenced by the uncertainties in the determination of the observation angle ($\theta$) and relative ion velocity ($\beta = v_{\text{ion}}/c$). As we show in the following section, these drawbacks do not appear for the proposed spectrometer observing the X-rays on the axis of the electron cooler simultaneously at $\theta = 0^\circ$ and $180^\circ$, which are red- and blue-Doppler shifted photons, respectively (see Figure 2).
Figure 3: Sketch of the asymmetric von Hamos spectrometer adopted for long-linear X-ray source in the electron cooler, where: $L_s$ - source-to-crystal distance, $L_d$ - crystal-to-detector distance, $R_c$ - crystal curvature, $\theta_B$ - Bragg angle.

2 Asymmetric von Hamos spectrometer

The RR X-rays emitted from the electron cooler at CRYRING can be measured with a high energy resolution, of the order of 100 meV, by using a wavelength-dispersive X-ray spectrometer exploiting the diffraction of photons on a crystal to spread out the incident radiation with respect to its wavelengths on a position sensitive X-ray detector. Therefore, the measured Bragg angle determines precisely the wavelength, and consequently the photon energy, of the observed X-ray transition. For low-energy X-rays the reflection-type spectrometers based on X-ray diffraction on a flat or curved crystal geometry of Johann [37], Johansson [38] or von Hamos [39,40] can be used.

The flat-crystal solution generally has a very simple construction, but it is characterized by low efficiency due to the non-focusing X-ray optics. The curved crystal geometry results in improvement of the spectrometer efficiency due to focusing of the diffracted X-rays, but frequently causes a loss in energy resolution due to not well controlled deformation and waviness of the curved crystal [41]. Consequently, the von Hamos geometry, which combines a flat crystal properties in the dispersive plane (influencing resolution) with the focusing capabilities of X-rays in the perpendicular plane (influencing intensity) (see Figure 3), seems to be the optimal solution to design a high resolution X-ray crystal diffraction spectrometer to measure the RR photons from the electron cooler.

When designing a crystal spectrometer to be installed at the electron cooler of ion storage ring a special care has to be devoted to the X-ray source, which has a long-linear shape defined by an overlap of the ion and electron beams. Its effective dimensions for the CRYRING electron cooler are about 750 mm x 1 mm. In order for such an extended X-ray source to be accepted by the focusing geometry of the X-ray diffraction spectrometer, which usually favours a small-size X-ray source to achieve high energy resolution, the asymmetric von Hamos spectrometer (AvH) is proposed here. The spectrometer will be mounted on the axis of the CRYRING electron cooler. As it will be discussed below, such an instrument will have a high energy resolution, ultimately down to 70 meV for about 5 keV, which allows to study with high precision the QED effects in mid-Z highly charged ions. The application of this spectrometer will be discussed here mainly in the context of precision measurements of the K-shell X-rays from RR of medium-Z bare ions with electrons, i.e. to study the bound state QED effects in H-like ions. However, it is worth noting here, that the Lyman-α transitions as well as the K-shell X-ray emission from
He-like ions for the discussed atomic number range $Z=20-30$, having 5-10 keV photon energies, are also of interest and can be studied with this instrument.

2.1 Concept of the spectrometer

In order to measure precisely the RR X-rays emitted from the electron cooler of CRYRING a pair of the asymmetric von Hamos (AvH) X-ray spectrometers is proposed to be operated for low-energy X-rays, in the range 5-10 keV. The spectrometers will be installed before and behind the dipole magnets of the electron cooler section (Fig. 4) in order to detect...
the blue- and red-shifted RR X-rays emitted along the e-cooler axis and thus eliminate the Doppler effect modifying the X-ray transition energy $E_0$ of interest (in the ion frame). For AvH spectrometers mounted on the electron cooler axis ($\theta = 0^\circ$ and $180^\circ$) the measured blue- and red Doppler shifted RR photons in the laboratory frame have the energies $E_{b,r} = E_0[(1 \pm \beta)/(1 \mp \beta)]^{1/2}$, respectively. Consequently, one finds that in this case $E_0 = (E_b E_r)^{1/2}$. This means that the X-ray transition energy in the ion frame can be fully determined from the measured energies of blue- and red-shifted photons, i.e. independently of the angle $\theta$ and relative ion velocity $\beta$, which usually introduce sizeable uncertainties to the Doppler effect correction. Consequently, a concept of the "Doppler-free" X-ray spectrometer is an important aspect of the proposed instrument to be built and used for precise X-ray spectroscopy, in particular, for the measurements of the QED effects in mid-Z highly charged ions.

In a standard von Hamos spectrometer the photons emitted from a small (close to point-like) X-ray source are diffracted at the Bragg angle $\theta_B$ on the crystal, which is flat in the dispersive plane and cylindrically bent to the radius $R_c$ in the perpendicular (focusing) plane, and are measured in the focal point by a position-sensitive X-ray detector (see in Fig. 3). In the fully focusing configuration of the von Hamos spectrometer, the source-to-crystal and crystal-to-detector distances are equal, namely $L_s = L_d = R_c/\sin \theta_B$, and both the X-ray source and the detector are located on the axis of the Rowland circle. Since in the electron cooler of CRYRING the RR photons are emitted from a long ($\sim 1$ m) linear X-ray source located about 4 m away from a possible on-axis location of the diffraction crystal, the asymmetric von Hamos geometry $L_s \gg L_d = R_c/\sin \theta_B$ was chosen in the proposed X-ray spectrometer (Fig. 5). It should be emphasized here, that in this non-standard von Hamos geometry, which is forced by the dimensions of the electron cooler and dipole magnet, the high energy resolution of the proposed spectrometer remains unchanged, mainly, due to its "on-axis" location and a small divergence ($\sim 10$ mrad) of the RR photons hitting the crystal.

In order to cover the 5-10 keV X-ray energy range the asymmetric von Hamos spectrometer will be equipped with a set of Si(111) crystals, cylindrically bent to various curvature radii in the range $R_c=0.60-1.0$ m. The crystals dimensions will be $60 \times 60$ mm$^2$. For the foreseen 3$^{rd}$ order diffraction the spectrometer will cover the Bragg angle range $\theta_B=36^\circ - 83^\circ$. Installation of segmented-type crystals will be considered as an option in order to reduced possible imperfections of crystal bending, which could affect the energy resolution of the spectrometer. The crystal and the X-ray detector will be mounted on precision 5-axis goniometers allowing to set the Bragg angle and the crystal/detector positions, including their fine adjustments.

### 2.2 X-ray tracing Monte-Carlo simulations

A straightforward procedure to determine the main characteristics of the proposed X-ray spectrometer, as well as to achieve better understanding of its optical properties is the application of X-ray-tracing simulation approach. The Monte-Carlo method is especially well suited to study the properties of the complex optical instruments for which a fully analytical treatment is impractical. Therefore, the Monte-Carlo X-ray-tracing code [42], which was developed to simulate the intensity distribution of diffracted X-rays on the 2D-detector for various geometries and crystals, in particular for asymmetric von Hamos configuration, was used here. This code tracks the trajectory of each photon emitted randomly from, in this case, long-linear X-ray source and checks whether this photon is
diffracted by the crystal and registered by the position sensitive detector recording the hitting position (x,y). The diffraction of photons on the crystal surface is described by the crystal rocking curve calculated by the XOP2.4 code [43]. In this way the 2D distribution of photons registered by the position-sensitive detector is obtained, which is further used to obtain the energy resolution of the discussed spectrometer.

As an example, the simulated 2D-distribution of the detected photons having $E_{cm} = 5400$ eV energy in the ion (moving) frame is shown in Fig. 6 for Si(111) crystal set to the Bragg angle $\theta_B \approx 82^\circ$ for 3$^{rd}$ order diffraction, which was bent to the radius $R_c = 975$ mm. In this case, the Doppler blue-shifted ($\theta = 0^\circ$) photon energy in the laboratory frame is $E_{lab} = 5989$ eV for assumed 5 MeV/amu ion energy corresponding to the ion velocity $\beta = 0.1$. By projecting the simulated 2D-distribution of detected X-rays (Fig. 6) on the dispersion plane of the detector, the energy profile of measured X-rays can be obtained. In Fig. 7 the simulated X-ray profiles expected for different ion beam diameters in the range 0.5-2.0 mm are presented. The FWHM widths of these profiles, which can be interpreted as the energy resolution of the spectrometer, are in the range 70-220 meV. One should keep in mind that by fitting the centroids of such symmetric profiles, the uncertainties of determination of X-ray transition energies can be further improved by a factor of 10 (see Fig. 7). Consequently, the performed simulations show that the proposed asymmetric von Hamos spectrometer can measure the energies of X-ray transitions with very high precision, down to 7 meV for about 5.4 keV photon energy (in the ion frame) and small ion beam diameter (0.5 mm). The simulated variation of the spectrometer resolution with the of X-ray photon energy is shown in Fig. 8 for the ion beam size of 1 mm. This figure demonstrates that for 5-10 keV X-ray energies the energy resolution of the spectrometer
Figure 7: Simulated energy profiles of 5.4 keV photons (in the ion frame) emitted at forward angle ($\theta = 0^\circ$), diffracted by a cylindrically bent Si(111) crystal and registered by position-sensitive X-ray detector. Fitted energy resolutions (FWHM) are shown in the figure for different ion beam diameters.

Figure 8: Simulated energy resolution of von Hamos spectrometer for Si(111) and Ge(620) crystals for photon energy range 5-10 keV (in the ion frame) for stationary source and 5 MeV/amu ion beam of 1 mm diameter.
Figure 9: Location of the asymmetric von Hamos geometry at the CRYRING. In the drawing, part of the e-cooler, the dipole magnet and the intermediate UHV chambers with sketched geometry of the X-ray AvH spectrometer are shown. In this configuration, a position of the crystal along the e-cooler axis is fixed, while the X-ray position-sensitive detector will move according to the selected Bragg angle and crystal curvature radius.

varies, respectively, in the range 0.12-1.8 eV. This means that the lower X-ray energies, slightly above 5 keV, corresponding to the energies K-RR X-rays for $Z \approx 20$, are best suited to study precisely the QED effects. In this case, the energy of X-ray transition can be measured at 1-2 ppm precision, meaning that the Lamb shift effect can be studied at 0.3% precision level. It is worth noting here that the expected high precision of the order of few meV, approaches the “natural” linewidth of K-RR lines, which for the free-bound electron transitions to the ground state are given solely by the transverse electron beam temperature being in the CRYRING electron cooler of the order of 1 meV. This shows that for the discussed case the anticipated precision of determination of X-ray energies nearly reaches the ultimate “natural” limit set by the transverse temperature of the electron beam.

2.3 Technical specification and design details

The asymmetric von Hamos spectrometer designed for use at the CRYRING electron cooler at FAIR is foreseen to measure with a high-resolution the low-energy X-rays (5-10 keV) emitted in RR of highly charged mid-Z ions with cold electrons. It will also make possible high resolution measurements of the Lyman series (for $Z \approx 20 - 30$), Balmer series (for $Z \approx 57 - 74$) and intershell transitions for high-Z HCI ions. The spectrometer system will consist of a pair of the asymmetric von Hamos spectrometers, each equipped with cylindrically bent Si(111) crystal and a position sensitive Timepix3 [44] detector to detect the diffracted X-rays. The AvH spectrometers will be mounted on the electron cooler axis before and after the dipole magnets (see Fig. 5 and Fig. 9). More precisely, the spectrometers will be connected to the CF63 ports of the intermediate multipurpose UHV chambers designed to give access for different on-cooler-axis ($\theta = 0^\circ/180^\circ$) experiments, in particular, for the laser and X-ray spectroscopy, in the latter case for the X-ray microcalorimeter and crystal spectrometers.

The dispersive plane of the asymmetric von Hamos spectrometer will be oriented
Table 1: K-shell RR rate coefficients for the flattened electron beam of transverse temperature $kT_\perp = 1$ meV calculated for selected bare ions with $Z=20-30$ [4]

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<td>Ca$^{20+}$</td>
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<td>Zn$^{30+}$</td>
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horizontally. Both the diffraction crystal and the X-ray detector will be mounted on the 5-axis motorized goniometers to secure the adjustment of their position for various bending radii of the crystal. The stepping precision of the linear and rotational movements will be 1 $\mu$m and 0.001°, respectively, which enables the necessary fine tuning of the positions and angles of the crystal and X-ray detector. The diffracted X-rays will be measured by the position-sensitive Timepix3 detector [44]. This detector is sensitive to the hitting position $(x,y)$ and time of the registered photon. Its time resolution is 1.6 ns. The detector has a modular matrix structure. The single matrix is a square with pixel number of 256 in both directions and pixel size of 55 $\times$ 55 $\mu$m$^2$. In order to increase the efficiency of the spectrometer three matrices will be used to form a 2D-detector of dimensions 14 mm x 42 mm with longer dimension oriented in the focusing plane. The timing capability of the Timepix3 detector will be important to eliminate the continuous X-ray background from the intense electron beam generating bremsstrahlung. This will be achieved by counting the coincidences between the X-rays and downcharged ions, separated from the costing ion beam in the dipole magnet and detected by the particle detector (see Fig. 2). The separation of the bremsstrahlung photons will be important for ion beam energies higher than 10 MeV/u, for lower in beam energy, the bremsstrahlung endpoint (high energy part of the spectrum with lowest intensity) will be lower than 5 keV and therefore outside of the accessible energy range of the spectrometer. For considered geometry and the Timepix3 X-ray detector dimensions the spectrometer will have for 5-10 keV photon energies and a fixed detector position the X-ray energy bandwidth 2-20 eV or 6-60 eV, depending on the focusing/dispersive-orientation of the matrices of the 2D-detector. Finally, the efficiency of the spectrometer, as obtained from the performed Monte-Carlo X-ray tracing simulations, is about $1.5 \times 10^{-7}$.

In order to estimate the expected count rate of the K-shell RR photons detected by the designed asymmetric von Hamos spectrometer, the needed K-shell RR rate coefficients were calculated following Ref. [4]. Further, $10^8$ of mid-Z bare ions stored in the ring and an electron beam density in the e-cooler of $10^7$ cm$^{-3}$ [24] were assumed. With these numbers, the expected rate of K-shell RR X-rays for bare mid-Z ions, e.g. Ca$^{20+}$ ions is of the order of $10^6$ photons/s (see Table 1). Therefore, taking into account the simulated efficiency of the asymmetric von Hamos spectrometer, the X-ray detection count rate is expected to be about 50 photons/hour.

In order to perform off-line tuning of the asymmetric von Hamos spectrometers they will be equipped with 30 keV electron guns for in situ energy calibration, optimization and tests. The electron gun, delivering intense electron beam of a diameter down to a few micrometer, will be used to excite characteristic X-ray fluorescence to determine the energy resolution of a spectrometers. For this reason, the spectrometer chamber will
be additionally equipped with a movable multi-target holder to fix a set of appropriate calibrating materials. The absolute calibration of measured X-ray transitions is a general problem of a precision ($\sim$ ppm) X-ray spectroscopy which can be addressed by applying standard techniques as the electron of photon excited X-ray fluorescence [45]. Recently, a more complex method exploiting the X-ray emission for selected transitions in few-electron ions was proposed [19], which can be considered to be used in the ion storage ring.

The spectrometer will be mounted in the UHV chamber containing the bent crystal installed on a holder and the position sensitive X-ray detector, each mounted on a 5-axis goniometer enabling positioning and fine adjustments of these elements for fixed Rowland radius in the range 0.60-1.0 m. This chamber will be connected with pipe to multipurpose intermediate UHV chamber designed for coupling the spectrometers (calorimeters and crystal spectrometers) to the e-cooler ports. The spectrometer chamber will be separated from the UHV by a Be X-ray window and it will be evacuated with a turbomolecular pump in order to eliminate the X-ray absorption in air. Finally, the spectrometer will be fixed to a bench-type support made of standard Al-profiles isolated from the environment using table top vibration isolation system.
References


