This document describes the CRY-RIMS experiment. It presents the methods and apparatus for coincidence momentum imaging (also called Reaction Microscope) of electrons and ions. This instrument allows investigating the dynamic of ion-atom collisions and the response of an atomic, molecular or cluster target, which is induced by the impact of a highly charged ion to highest detail.
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1. Introduction and overview

This project aims to develop and build a versatile COLTRIMS Reaction Microscope [1,2] (CRY-RIMS), which is to be integrated in the CRYRING@ESR storage ring. The CRY-RIMS allows measuring the vector momenta of all charged particles (electrons and ions) in coincidence, which are produced in a reaction of the highly charged projectile ions with the atoms, molecules or clusters provided by the internal gas target. The charged particles/fragments are projected onto large position and time sensitive multi-channel plate (MCP) detectors, using specially optimized electric and magnetic fields. Therefore the solid angle for the particle detection reaches $4\pi$. The MCP-detectors with delay line anodes are combined with fast electronics and state of the data acquisition. From the particle’s impact positions and their time-of-flights, the 3d momentum vector of all created charged particles can be derived. In figure 1, such a COLTRIMS Reaction Microscope is sketched. The operation within a storage ring demands a vacuum of low $10^{-10}$ mbar or better. Ideally, the reaction microscope is combined with a gas target of variable density. This variability becomes important when used with a bunched beam to make sure that less than one ionization event per pulse occurs. The internal gas target, delivering target densities for single atoms/molecules of $10^9 - 10^{10}$ atoms/cm$^2$ will be available at CRYRING@ESR and is not part of this TDR. The possible experiments range from the investigation of single atoms, small and larger molecules (some of them are liquid at room temperature) as well as clusters of different kinds and size (for example doped helium nano droplets).

![Fig. 1: Sketch of a COLTRIMS Reaction microscope in the so-called transversal extraction geometry.](image)

Scientifically the envisaged CRY-RIMS, enables the investigation of fundamental atomic collision processes as well as the study of complex systems. Some examples for the fundamental atomic collisions are described in the “CRYRING@ESR Physics Book” [3]: single and multiple electron transfer, target and/or projectile ionization, excitation or combinations of all processes, for various

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1 The gas-jet TDR is being submitted.
perturbations. The rather “low” energy of the CRYRING@ESR enables the study of adiabatic ionizing collisions [4,5], where the electron is dominantly found in the target or projectile continuum (CUSP) or at small transversal momenta around the quasi molecular axis. Also the Thomas-capture [6] is of interest, which was studied for proton-helium collisions already with the CRYRING and the precursor COLTRIMS in Stockholm [7,8]. However especially the multiple Thomas-capture as well as the influence of other projectile/target combinations is still open. Additionally the capture process can be used as a tool to do spectroscopy of the highly charged ion [9,10]. About a decade ago, a discussion on how the coherence properties of the projectile [11,12] might influence the collision process, was started and is still heavily debated [13]. Here the huge variety of projectiles (atomic number, charge state, velocity) combined with a dedicated and optimized tool will contribute with tremendous improved data to solve this riddle.

![Diagram](image)

Fig. 2: Typically momentum phase space, covered by electrons (top) and ions (bottom) for various reactions, like target impact ionization, projectile ionization (loss), saddle point ionization (adiabatic collision), electron transfer and Coulomb explosion in a longitudinal ($p_\parallel$) vs. transversal ($p_\perp$) representation (assuming a non-relativistic collision, as valid for CRYRING energies).
Furthermore the CRY-RIMS will pave the way towards the study of more complex systems such as molecules and clusters. The very short interaction time between projectile and each target atom of a few atto seconds, allows studying the frozen molecular geometry and investigating electron dynamics in the molecular frame with unprecedented completeness. This will also take studies on the handedness of chiral molecules [14-18] to a new level and enable the study of dynamical changes of their handedness. Additionally, the short interaction combined with multiple ionization of the target allows a novel type of “pump-probe” experiments on ultra-short time scales, which can’t be reached by any other technique. The time delay scales with R/v_P, where R is the molecular size and v_P the projectile velocity. Therefore the time delay is varied by changing the projectile’s velocity. The rather low projectile velocity regime covered by CRYRING@ESR allows the investigation of chemical nuclear dynamics (structural changes of molecules) as well as the dynamics of the electrons (for example charge migration) [19]. Instead of pre-orienting the molecule by laser alignment, the molecular orientation at the instance of interaction can be reconstructed from the ion’s momentum vectors (post-orientation). Moreover, experiments on nuclear dynamics within clusters [20-22] are highly interesting and will provide crucial new input to simulations for ion beam therapy [23-24].

This breadth of different experiments, covering a diverse range of targets and a large variety of reaction dynamics comes for a price: In figure 2 the typically covered electron and ion momentum phase space is depicted for various reactions. This requires very different electric field geometries for the spectrometer. We give two examples for these requirements and the spectrometer geometries it calls for:

- **“Atomic collision”:** When the projectile with a large perturbation slowly approaches the target atom, they form a quasi-molecule, in which the internuclear separation adiabatically decreases (until the point of closest approach) and increases (until infinity). This nuclear dynamics drives the electrons such that upon ejection they are found either on one or the other nucleus (termed as target / projectile cusp) or in-between (saddle point ionization). The electron momentum distribution, as shown in figure 2 is very narrow in transverse direction, but rather extended in the longitudinal direction. For a projectile with an incident energy of 2 MeV/u, the electrons form the projectile cusp (moving frame) having 9 au momentum in the laboratory frame (=1100 eV), while their transverse momentum is rather small (1 au). In contrast the ion has a small longitudinal momentum and transverse momentum is mainly balanced with the projectile’s nucleus with its strength depending on the impact parameter. For this case a spectrometer with “longitudinal extraction” is best suited, as the large momentum component is along the time-of-flight axis. Therefore a rather low electric field (a few V/cm) is applied, combined with a low magnetic guiding field and the detectors placed far away (0.5 m or even more), such that the recoiling ion can illuminate the whole detector. All together this results in a drastically increased momentum resolution.

- **“Coulomb explosion imaging”:** If a molecule/cluster is multiply-ionized, several positive charges are spatially close to each other, resulting in an explosion, due to the strong Coulomb repulsion. Here ion momenta of several hundred atomic units are not uncommon.
Keeping the electric field rather low (instead of increasing by a factor 100), the ion detector needs to be placed much closer to the interaction point. This is best done in a “transversal extraction”.

Considering the High Energy Storage Ring at FAIR, the HESR, which will provide projectile ions at much higher energies (up to \( \gamma = 6 \)), the kinetic energy of forward emitted electrons will increase further, demanding a longitudinal spectrometer even more. However such collisions are scientifically exceptionally interesting since the higher velocities enable the investigation of even faster dynamical processes down to the zepto second time scale.

2. Physics requirements

The CRY-RIMS, as all Reaction Microscopes, is an extremely versatile instrument. It allows for a high flexibility in choosing the perfect balance of particle momentum resolution and solid angle (up to \( 4\pi \)) addressing a wide range of physics questions. This results in a breadth of possible application from which we list a few highlights here:

**CRY-RIMS as a spectroscopic tool**

To investigate atomic and ionic ground and excited energy levels across all charge states numerous methods have been developed. Most of them are based on photon detection. The key advantage of this type of photon-out spectroscopy is often superior energy resolution. There are however two severe disadvantage to any photon-out spectroscopy. The first one is the rather small solid angle of the photon detector (percent or less of \( 4\pi \)), which is prohibitive for studying very rare events. The second disadvantage is that it is blind for optically forbidden transitions. An alternative to photon-out spectroscopy is projectile energy loss or translational spectroscopy. Here e.g. the energy change of the projectile ion upon capturing one or more electrons into the levels of interest is measured. The energy resolution of this technique is however usually limited to \( 10^{-5} \) of the projectile’s kinetic energy. For a typical highly charged (Ne\( ^{8+} \)) ion with 100 keV/u impact energy, a resolution of 20 eV is already challenging.

The key problem is that a small change on top of an already large quantity has to be measured. This is solved elegantly by going to inverse kinematics and instead of measuring the energy/momentum change of the fast, high energy projectile one measures its counterpart on the target from which the electron has been captured. For any electron capture reaction the energy change of the projectile is related to the longitudinal (along the ion beam) momentum transfer to the recoiling ion \( p_i \). Thus the Q-value of the reaction which entails the energy levels of interest can be derived with high resolution from the measurement of the longitudinal momentum of the ion:
The CRY-RIMS collaboration has demonstrated the superior energy resolution achievable by this technique in many single path ion-atom collision experiments; in Fig 3 we show two examples. Note that the advantage of using this technique in CRYRING@ESR is twofold: first, rare and also short-lived ionic species can be studied and second in the ring the projectile velocity, \( v_p \), is very well defined which increases the resolution. CRY-RIMS will be specially optimized to achieve the maximum resolution on the ion momentum and has implemented all the technical refinements which have been developed by the consortium over the years.

\[
p_{||} = -\frac{Q}{v_p} - \frac{v_p}{2}
\]

Fig. 3: Single electron transfer in collisions with a helium gas target. (a-c) ion momentum distribution of \( p^+\text{He} \) at 1.2 MeV impact energy [9] measured with a transversal extraction spectrometer. (c) The longitudinal ion momentum \( p_{||} \) encodes the \( Q \)-value, which corresponds to the total energy difference of the reaction. A momentum resolution 0.04 au (FWHM) was achieved. (b) The transversal momentum \( p_{\perp} \) encodes the scattering angle distribution, which can be investigated state selective! (d) \( Q \)-value for slow Ne\(^{8+} \) ions, resolving the sublevels of \( n=4 \) with an energy resolution of 0.72 eV and a momentum resolution of 0.07 au [10].
**CRY-RIMS as a Reaction Microscope**

Spectroscopy as outlined above studies the properties of stationary systems. This is already theoretically challenging for multi electron systems. Even more challenging and potentially even of broader impact is the dynamics, i.e. the question which electronic processes occur and why. Electronic multi-electron dynamics is what drives chemistry and ultimately biology. Electron transfer and electron emission from target or projectile in ion-atom and ion-molecule collisions are among the prime prototype processes available today to study this dynamics. Ion impact driven dynamics as it can be studied with CRY-RIMS is a complementary approach to photon driven processes studied with laser and synchrotron radiation and FELs today. The particular strength of this approach is the ultrashort time scales ranging from femtoseconds at slow collisions to zeptoseconds at GeV collisions at HESR in the future. This spans exactly the relevant time scale for electron dynamics from the regime where the perturbation is so short that electrons can be considered frozen to the regime where the electrons can follow almost adiabatically the potentials determined by the nuclei of projectile and target.

This large range of accessible time scales and perturbation strength is complemented by a large number of possible reaction channels which each allows highlighting different aspects of the ultrafast dynamics. In figure 4 we show four examples. Panel (a) shows the momentum distribution of an electron promoted in a rather slow (projectile’s kinetic energy = 15 keV) collision of alpha particles with Helium atoms. Here slow refers to the fact that the projectile velocity is of the order or smaller than the relevant velocities in the driven electronic wave function. Consequently, the electrons follow quasi-adiabatically the time evolution of the two-center potential, which finally drives a part of the wave function into the continuum where it can be imaged. In panel (a) the target is at the origin (0/0) while (1/0) is the momentum space position of electrons which are travelling with the projectile. As the figure shows, the electron distribution features a distinct nodal line and spread in between the target and projectile. Such amazing details can only be seen since these data have been taken with a COLTRIMS Reaction Microscope where in addition to the three-dimensional image of the electron wave function in the continuum the deflection of the recoiling ion has been measured. From these quantities the orientation of the collision plane and the impact parameter can be inferred: Only this allows for a complete control of the potentials driving the electrons. In Panel (b) the integrated (non-coincident) electron emission from $\text{F}^{8+}/\text{He}$ collisions is shown. Clearly visible are the different contributions from target electron emission (Slow Electron Emission, SEE = target CUSP) and electron emitted from the moving projectile frame (electron capture to the continuum, ECC = projectile CUSP).
Fig. 4: (a) Electron momentum distribution in a quasi-molecular collision of He$^{2+}$/He at 15 keV [25]. (b) Non-coincident electron emission from F$^{8+}$/He collisions at 0.53 MeV/u, clearly showing the target and the projectile CUSP [26] (c) Ion momentum distribution for the simultaneous target and projectile ionization (loss) induced by a 1 MeV He$^{+}$ beam colliding with He. The two emitted electrons are located around the target and the projectile in velocity space (0 / 3.2 au) [27]. (d) Electron momentum distribution for 400 eV photoionization of H$_2$. The sharp ring nicely shows the achieved momentum resolution for such large momenta.

Panel (c) shows another facet of great interest, the interplay between electron-electron interaction and the influence of the nuclei on the electrons. The figure shows the momentum distribution of the ions in a collision where the projectile and the target loose one electron. The two island result from two distinct processes, one in which the ionization occurred due to interaction between the electrons and the other where the nuclei drove the electrons [27]. Similarly the simultaneous ionization of C$^{2+}$ projectiles with 3.6 MeV/u and a He target at 3.6 MeV/u was investigated using a reaction microscope in single pass geometry at GSI. The two processes described before could also be distinguished clearly [28]. Panel (d) shows that the consortium has solved a major technical challenge of reaction microscopes. For a long time the technique was thought to be restricted to the detection of low electron energies. This would have excluded the study of many interesting effects.
in ion atom and ion-molecule collisions, in particular electrons emitted from fast moving projectiles and Auger electrons. Panel (b) shows the successful imaging of an electron of 380 eV, while panel (a) show electrons below 5 eV. The CRY-RIMS design will be such that it can be used as a zoom lens, which allows focusing and magnifying the respective regions of electron phase space, which are of relevance for the process under study, where the extreme cases are the electron loss from a fast projectile and the target ionization.

**CRY-RIMS as a tool for Coulomb explosion imaging**

For complex systems like molecules and clusters not only the electronic but in particular the geometrical structure is of paramount interest. CRY-RIMS offers a unique approach to image this structure with many possible applications. If one removes the binding electrons the remaining ions in a molecule or cluster drive the system apart and from the direction and energy of the fragments ions one can infer the structure of the system at the instant of ionization. This technique, termed Coulomb explosion imaging, was pioneered at Argon National Lab and later at MPI-K Heidelberg to study molecular ion beams from which the electrons have been stripped off transition through a thin foil. By definition this approach is limited to molecular ions and usually done in a single path experiment. Alternatively CRY-RIMS will allow pursuing the same route of Coulomb explosion imaging but for neutral species. The highly charged ion beam serves as a tool for ultrafast electron removal. Compared to other drivers of coulomb explosion like laser induced multiple ionization the major advantage of ion collision is the ultrashort timescale.

**Figure 5:** Three examples for Coulomb Explosion Imaging using a COLTRIMS Reaction Microscope. (a) square of the $H_2^+$ wave function showing also the nodal structure of the vibrational wave functions [29], (b) Helium dimer, note the scale extending to 300 Å [30] and (c) Efimov state of He3, similar scale as middle panel [31].

Figure 5 (b) and (c) show two examples of images of cluster wave function obtained by FEL or femtosecond laser driven coulomb explosion imaging. A further interesting aspect which is special for the use at CRYRING@ESR is that also loss or capture processes in stored molecular ions can be studied. Figure 5 (a) shows one beautiful example of such a study where the full vibrational wave function of the $H_2^+$ was imaged. This image has reached the limits imposed by the Heisenberg uncertainty principle on a position/momentum imaging. Technically the use of CRY-RIMS for Coulomb explosion imaging requires that extremely large ion momenta can be collected by the field geometries. The range of energies which needs to be covered by CRY-RIMS spans from 10 meV
with a resolution of $\mu$eV up to 20 eV. The spectrometer is modular in a way that allows changing the extraction geometry and applied fields tailor the acceptance range of momenta to the problem under study.

3. Summary of prototype results

Currently no COLTRIMS reaction microscope is installed in a storage ring. Sole exception is a reaction microscope, planned to operate in the cryogenic electrostatic storage ring at MPIK in Heidelberg. This ring stores projectiles with very low kinetic energies (<300 keV*q). Experiments, which aim at investigating the electron/nuclear dynamics of reactions, are today done in single-pass experiments. This usually limits to reactions with rather large total cross section. The planned setup follows the know-how gained by reaction microscopes, which were built in the CRYRING (Stockholm), the TSR (Heidelberg) and tentatively at the ESR (Darmstadt). These systems have proven that the technique of reaction microscopes in storage rings works. During the past 20 years the detection technique as well as electron/ion optic improved dramatically. Nowadays time-to-digital-converter with 25 ps resolution are not uncommon and increase the ion/electron momentum resolution dramatically.

The consortium has extensive experience in the design and construction of COLTRIMS Reaction Microscopes. The original COLTRIMS spectrometer installed in the Stockholm-CRYRING was also designed in collaboration with the Frankfurt team. Recently a COLTRIMS Reaction Microscope was built for the XFEL in Hamburg, which has many specs in common similar with the one proposed for CRYRING@ESR. For this previous setup the specially shaped hexagonal delay line detectors have been tested for resolution and multihit capability. Also the experimental
apparatus as a whole successfully met the vacuum requirements and has already achieved $2 \cdot 10^{-11}$ mbar. The most challenging part at the heart of the setup is the spectrometer, which projects the electrons and ions towards the detectors.

We aim for two different spectrometers, with one being very versatile (transversal) and the other rather fixed (longitudinal) in its dimensions. Either one of these two can be inserted and used separately. This allows tailoring the acceptance and resolution to the respective physics requirements.

**Fig. 7:** (a) Spectrometer simulation, optimized for the investigation of molecular break-up in multiple fragments. (b) Electric potential, which is applied on each plate of the spectrometer. (c) Picture of the built spectrometer, which has a total length of 70 cm.

In figure 6 a spectrometer, optimized for ion-atom-collision experiments in transversal geometry is shown. The ion-arm is built in a time- and space-focusing geometry (length 1.9 m) to achieve a maximum resolution (see figure 3 for obtained results) and references [9,13,32-37]. The electron arm is 600 mm long and therefore suitable also in a longitudinal spectrometer. This is just one example of a prototype spectrometer, which was used successfully in many experiments.

Figure 7 shows a simulation of a meshless spectrometer, which was built also in a time- and space-focusing geometry, but optimized for large ion kinetic energies (50 eV) in order to measure Coulomb explosion of molecules. This meshless version increased the 5-particle detection efficiency by a factor 5. In figure 8 (left), the time-of-flight-coincidence spectrum of Coulomb exploding methyl-oxirane ($C_3H_6O$) is shown. Sharp diagonal lines correspond in this representation to momentum-conservation between the plotted ions, while broader distributions indicate that the total momentum is not conserved, due to a third – not shown – particles momentum. The revised spectrometer, shown in figure 7 (right), clearly resolves the various break-up lines, indicating the loss of several hydrogen atoms or the different mass distribution among the created fragment (for example $\text{CH}_m^+$/C$_2$OH$_n^+$ and OH$_m^+$/C$_3$H$_n^+$).
\[
\gamma (550 \text{ eV}) + \text{methylxirane (C}_3\text{H}_4\text{O)}
\]

Fig. 8: Ion-Ion time-of-flight coincidence spectrum for O(1s) photo ionized methylxirane, breaking up in two charged molecular ions. Left: regular spectrometer design; right: for molecular break-up optimized spectrometer geometry. This improved spectrometer (see simulation in figure 7) resolves the various losses of single hydrogens, as can be seen from the numerous parallel diagonal lines.

To guide the electrons towards the detector, a magnetic field of typically 5 – 25 Gauss is applied. This has to be homogenous over the whole length of the electron arm of the spectrometer. Assuming 600 mm between target and detector, the coils would need to have a diameter of 2.4 m, if build in a Helmholtz configuration. This size can be reduced by adding smaller correction coils in a certain distance. The simulated magnetic field of such multiple coil geometry is shown in the next chapter (figure 11). A similar version of this 4-coil geometry is successfully used for many years in Frankfurt (see figure 10 for a simulation). The main coils are made of insulated copper pipe (10 mm inner diameter, 12 mm outer diameter) and water cooled.

4. Summary of physics simulations

As discussed in the previous section, various spectrometers with different combinations of electric and magnetic fields, field free drift areas and electrostatic lenses have been tested and successfully applied in the past. However, this high variability to optimize the spectrometer for the respecting experiment can only be used in the transversal extraction. Besides the prototypes, which were shown in figures 6 and 7, some more examples of simulated spectrometer geometries are given in figure 9. In the longitudinal geometry, the minimum distance between target and detector is given by the tilt angle and the maximum is limited to the available space at the YR09 experimental section of the CRYRING@ESR.
Fig. 9: Various types of electric field geometries for imaging the emitted electrons (blue) and ions (black). These are just a few examples of spectrometers, which have been built and used for different purposes. Top: 3D time- and space-focussing ion arm for maximum momentum resolution on particles with small momenta. Middle: Double time- and space-focussing spectrometer for electrons and ions with the same kinetic energy. Bottom: “molecule” spectrometer for the detection of ions (usually originating from a Coulomb explosion) with and electrons with large kinetic energies.

To generate an extended homogenous magnetic field for up to 40 Gauss along the spectrometer axis for at least 60 cm, a geometry with 4 coils was simulated, assuming 2 large main coils and 2 smaller one. The results of this simulation are presented in figure 10 and show that over a length of more than 60 cm (measured from the centre) the magnetic field strength varies by less than 1 %. The inner coils have a radius of r=76 cm, are placed at x=±38 cm with respect to the centre (=target position) and have a total current of 2090 A; the outer coils have a radius of r=25 cm, are placed at x=±69 cm with respect to the centre. Also geometries with other combinations in diameter and relative distance are possible.

Finally, one exemplary experiment is discussed in terms of rates and data acquisition. Therefore the following assumptions are made: projectile energy 1 MeV/u, which corresponds to a velocity of 6.3 au (=250 kHz circulation frequency in CRYRING). Furthermore 1·10⁶ particles circulating in the ring, in total 2.6·10¹¹ projectiles pass by the target per second (=4·10⁻⁵ mA). For a typical cross section of 1·10⁻¹⁷ cm² and a target density of 1·10¹⁰ atoms/cm², the reaction rate will be about 25 kHz. Taking into account the detection efficiency in a 2 particle coincidence (60 % on the MCP and 80 % transmission per mesh, which has to be passed), about 5800 kinematically complete events can be recorded. All assumptions made here, strongly depend on the particular reaction and can vary over a few orders of magnitude.
Fig. 10: Simulation of the on-axis magnetic field for a 4 coils configuration. The position of the coils is depicted by the vertical lines. The inner coils have a radius of $r=76$ cm, are placed at $x=\pm38$ cm with respect to the centre and have a total current of 2090 A; the outer coils have a radius of $r=25$ cm, are placed at $x=\pm69$ cm with respect to the centre.

The influence of the spectrometer’s electric and the guiding magnetic field on the stability of the stored ion beam have been simulated for both geometries:

- transversal geometry ($\alpha=90^\circ$): electric field of 100 V/cm (15 cm) magnetic field of 20 Gauss over 2 m
- longitudinal geometry ($\alpha=20^\circ$): electric field of 20 V/cm (1.2 m) magnetic field of 20 Gauss over 2 m

In these rather extreme examples (for most experiments, the fields are much lower), the imposed shift of the projectile beam could be compensated by the CRYRING’s ion optic. Also it has to be mentioned that in the Stockholm CRYRING many experiments with the reaction microscope were performed with stored beams as low energetic as 300 keV/u.

5. Technical specification and design details – main subject

As discussed the ideal spectrometer geometry (orientation, length, field strength etc.) strongly depends on the exact requirements of the planned experiment. Therefore CRY-RIMS will adopt transversal and longitudinal geometry.
In figure 11 the geometry of the spectrometer and the HCI beam are sketched. As can be seen the minimum angle between those two depends on the position of the spectrometer and its diameter. For $x=600$ mm and the minimum distance of the detector $d_{det}=92$ mm, the minimum angle $\alpha=11^\circ$. The maximum of 600 mm is given by the available space in the experimental section of the CRYRING@ESR. Ions and electrons are detected by micro channel plates detectors, which are equipped with delay line anodes for multihit position read-out. For increased multihit capability and to compensate for nonlinearity effects in the reconstruction of the impact position, anodes with three wire layers are used. For an active detection diameter of 125 mm, the minimum detector diameter is 250 mm. However to get $\alpha$ as small as possible we developed a three layer detector, where the inner most layer is shorter. A sketch of the detector with an active diameter of 125 mm is shown in figure 12. The red shaded area indicates the “saved” space and in green the position of the coasting HCI beam is shown. Without the reduction of the inner most layer, the minimum angle would be $\alpha=17^\circ$. However the exact angle is to be determined.

The main experimental chamber is composed of two stainless steel pipes (CF300) with connections for the CRYRING gas target (CF40) and its Jet dump (CF100) (see figure 13). To meet the
requirements (vacuum, low magnetic permeability), the chamber is built of 316LN-ESR stainless steel. In Figure 13 the vacuum vessel, inserted in the CRYRING@ESR experimental section, is shown including the spectrometer in longitudinal configuration. Here an angle of $25^\circ$ between spectrometer axis and HCI beam are assumed, which allows for a minimum spectrometer length of 24 cm. The spectrometer including the detectors is mounted on 4 stainless steel rods, which is mounted on the CF300 flange. On the other two CF300 ports, a turbo molecular pump (700 l/s), combined with NEG (non-evaporable getter pump) with 3000 l/s ($H_2$) are mounted. The CF100 pipe for the HCI beam measures in total 1.2 m, while the long side of the CF300 cross measures 1.4 m and the short side, which is used for the transversal extraction, 1 m. The CF300 sides can be extended to improve the momentum resolution.

![Image](image_url)

**Fig. 13:** Sketch of the CRY-RIMS, positioned in the CRYRING's experimental section YR09 (gas target). The angle between HCI beam and spectrometer axis is $25^\circ$, allowing a minimum spectrometer length of 24 cm. At the corresponding, not for the spectrometer used, two open ports (CF300) a turbo pump (700 l/s and a non-evaporable getter pump with 3000 l/s for $H_2$ are mounted).

For the transversal geometry the spectrometer itself can be adapted easily, as it is composed of an assembly kit. Several simulations and prototypes for various experiments have been presented in the previous sections. A sketch of the spectrometer assembled in the transversal geometry is shown in the cover picture. In this case the spectrometer mounted on the CF300 flanges will be inserted in the port perpendicular to the beam direction and therefore swapped with the pumps (NEG and turbo molecular). The spectrometer kit contains the field defining spectrometer plates made of copper (see figure 14), ceramic rods and ceramic spacers to hold them in place. The spectrometer in both geometries is build such that the beam can enter/leave the spectrometer without colliding with the spectrometer. Therefore an uncooled beam diameter of 50 mm is assumed. Additionally aluminium is used, first to hold the stainless steel mesh, and second to mount the detectors on the stainless steel rods.
The operating voltages of the spectrometers and detectors vary, depending on the chosen geometry and requirements. Usually 4 kV are not exceeded as well as the maximum drawn current is below 1 mA. Inside the vacuum cables, insulated with kapton are used and outside standard SHV connectors. All used materials are bakeable and XUHV compatible. The limitation in terms of temperature is given by the delay line anode and should not exceed 140°C. Otherwise the strain during heating might break the thin wires.

**Magnetic field:**

In table 1 a set of typical design parameter for the coils used to generate an extended homogenous magnetic field, is shown. With these design parameters a magnetic field of 25 Gauss (as shown in the simulation, figure 10) can be achieved.

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<td>4</td>
<td>25</td>
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</table>

*Table 1: Typical parameters set for the coils, generating the magnetic field, with $R_C$ the radius of the coil and $x$ the position of the coil relative to the center (interaction point).*

The coils are made from insulated copper pipe, which has an inner diameter of 10 mm and an outer diameter of 12 mm, resulting in 34.5 mm² of copper. Operating the coils in series, thus they have the same current (139 A), the total power consumption is estimated to be 1.5 kW. Assuming a cooling water flow (parallel) of 2 l/min, the water temperature increases by 5 °C (difference of in-flow and
out-flow). For the outer, smaller coils, which are made of copper wire with 2 mm diameter, the total power consumption is estimated to be 20 W.

**Fast electronics and data acquisition:**

The signals, coming out of the detector are typical 5 mV in height and have a pulse width of 5 - 20 ns. Therefore fast amplifiers (100 and 400 MHz bandwidth) will be used to amplify the detector signals. Afterwards these analogue signals are converted into standard NIM-signals using constant fraction discriminators. To keep up with high ionization rates and good time resolution, also new data acquisition is required. The time-to-digital-converters (TDC) has 25 ps time resolution and 8 channels [39]. Pulse durations as short as 5 ns can be handled. The double pulse resolution is typically <5 ns and there are no limitations in terms of multiple signals (multihit capability). Also the maximum data acquisition range per event is up to 420 µs. The TDC can be run in dead-time free mode, where the complete data streamed is recorded and events are extracted later on. In order to record the full information of an experiment, 15 signals (each detector generates 1 MCP and up to 6 anode signals plus one reference signal from a charge exchange/projectile detector) have to be recorded. Therefore two TDC's have to be used in parallel. Synchronization is achieved by an external clock card. The TDC cards (PCI express) can directly be used in any standard PC or in case of insufficient space on the motherboard used with an external crate. The time-of-flight is usually determined with respect to a reference signal. For most of the experiments, the charge exchange/projectile detector delivers this reference. However also a bunched beam (projectile packages as short as possible and spaced >100 ns) or the electron can provide in some cases the reference signal.

**Fig 15: Time-to-digital-converter (Roentdek) with 8 channels and 25 ps resolution [39].**
6. Radiation environment, safety issue

The spectrometer and the detectors operate at high voltages (<6 kV, <1 mA) and standard high-voltage cables/connectors will be used. The coils, which generate a homogenous magnetic field, can operate at high currents (<300 A, <40 V) and are water cooled. This requires supply of cooling water and insulation/enclosures of all open metallic contacts of the coils to prevent accidental short cuts.

7. Production, Quality Assurance and Acceptance Tests

The design and production of the spectrometer will be performed in the laboratories of the Institut für Kernphysik (Goethe-University, Frankfurt). Several tests regarding the achievable vacuum, the detector and spectrometer performance will be done, using also the Van-de-Graaff-Accelerator (see also chapter 8).

8. Calibration with test beams

The Spectrometer including the two detectors will first be tested in Frankfurt using the Van-de-Graaff-Accelerator of the Institut für Kernphysik. For this purpose we will study two benchmark reactions in He⁺ₚ-He⁺ᵣ₂ collisions: electron transfer (He⁺ₚ + He⁺ᵣ ←→ He⁺₀ₚ + He⁺ᵣ) and the simultaneous projectile/target ionization (He⁺ₚ + He⁺ᵣ ←→ He⁺₂⁺ₚ + He⁺⁺ᵣ + 2e⁻). These tests will show the functionality and imaging quality of the spectrometer and the detectors. Following commissioning at the CRYRING is necessary, especially to test for negative effects of the spatially extended uncooled beam size. For calibration purposes the same reactions of electron transfer and projectile/target ionization will be studied, but using a heavy, highly charged ion as projectile. In order to perform these tests the gas-jet target is needed. As the spectrometer has two modes of operation (e.g. two orientations), two separate commissioning times are planned. As described above, in order to study reaction dynamics, using the CRY-RIMS, the internal gas-jet target is a prerequisite.

9. Civil engineering, cave, cooling, cranes etc.

The CRY-RIMS is mainly comprised of a vacuum chamber (CF300) with the shape of a cross. With pumps etc. its weight is approx. 150 kg. The setup rests on its own stand, thus it can be easily mounted within the storage ring. An area of about 2 m² is therefore necessary. The separable coils, which generate a homogenous magnetic field, are 1.8 m in diameter and weigh each 30 kg. After insertion of the vacuum vessel in the ring, the coils will be mounted around the vessel and the

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2 The subscript letter highlights which particle is meant (projectile=Heₚ and target=Heᵣ)
existing beamline. The power supplies (two in parallel) for these coils each require a three-phase 16 A standard power connector. All other electronics uses standard single phase connectors. Power supplies, also for the coils, data acquisition electronics etc. are mounted within a 19” rack (100 kg), which should be positioned close to the experiment. A distance of less than 4 m is favourable. The electric power consumption is typically less than 15 kW, dominated by the coils. The coils needs to be water cooled and we estimated a water flow of 5 litres per minute to be sufficient. Getting the experimental chamber to the desired vacuum of 10^{-11} mbar, the chamber has to be baked for 1-2 weeks at <150 °C (limited by the detectors). During this period approx. 2–3 kW electrical energy are required. As the power supply for the coils and the baking are not used in parallel, the electric power plug from the coils could be used for this short baking period.

10. Installation procedure, its time sequence, necessary logistics from A to Z including transportation

Due to the space constraints at CRYRING@ESR and to the incompatibility with other experimental setup in section YR09 (the gas-jet-target section), the CRY-RIMS setup will be installed on a movable stand and will be moved in and out the experimental area, depending on the experimental campaigns. Before an experimental campaign it has to be decided in which mode of operation (transversal or quasi-longitudinal) the spectrometer of the CRY-RIMS will be inserted as well as its ideal dimensions (lengths, field strength, focussing geometry etc.). Due to the modular construction the assembly is rather easy and may take one or two days. The CRY-RIMS will operate within the storage ring (YR09) and is combined with the internal gas-jet target. In order to meet the high vacuum requirements (10^{-11} mbar) a baking of the whole setup at 120 °C is necessary. This varies from a few days (when being baked-out before and transported under Argon atmosphere) up to two weeks, in case that the spectrometer was taken out, modified and re-installed. For example at the SQS-instrument of the XFEL it is planned that the dedicated Reaction Microscope will be baked-out in a different lab and with turbo pumps spinning on stand by the whole setup will be moved on an air cushion. However this approach will require more space for the installation of differential pumping on both sides of the setup.

11. Organization and distribution of responsibilities

Within the applied funding, 1 Postdoc was requested for the full project duration of 3 years. Currently it is anticipated that Gregor Kastirke will be employed on this position and is responsible for the technical coordination. It is anticipated that 2 master and 2 bachelor students support him in the numerous tasks and performance tests, which have to be done during the 3 years. As he has already built 2 COLTRIMS reaction microscopes (also the one for European XFEL), he has all necessary knowledge. He will also receive full support of the rest of the collaboration, where most of the people have either worked with reaction microscopes and ion-beams (or in storage-rings integrated reaction microscopes) and/or built them for this purpose.
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