Abstract

The design of an internal target station suitable for the operation at the CRYRING storage ring at GSI is presented in this document.

Proposed is a combination between the existing CRYJET target station and the SPARC target inlet chamber, enabling an internal target operation at certain parameters and with a flexibility that exceeds the possibilities of the former CRYJET setup. A broader range of variable area densities and target species allows for novel experimental approaches at CRYRING. In particular, the installation of the SPARC target inlet chamber at CRYRING would open up synergistic effects since this setup, destined as the main design for the future FAIR storage ring internal target stations, is designed and tested with remarkable results.
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1 Physics Case

The exploration of the unique properties of stored and cooled beams of highly-charged ions as provided by heavy-ion storage rings has opened novel and fascinating research opportunities in the realm of atomic and nuclear physics research. In the present chapter, the scientific program which is planned at the CRYRING internal target section will be briefly outlined. A more detailed overview can be found in the CRYRING physics book [1].

The study of transient superheavy quasi-molecules with \( Z_{UA} \geq 173 \), where \( Z_{UA} = Z_{\text{proj}} + Z_{\text{target}} \), in adiabatic collisions of very heavy projectiles like Pb and U with heavy targets has been a key field of investigation at GSI since its beginning [2]. In very heavy quasi-molecular collision systems the \( 1s\sigma \) molecular orbital (MO) and the evolution of its energy have been in the focus of experimental and theoretical endeavours since the prediction of its diving into the Dirac sea for transient supercritical systems. The predicted very strong dependence of MO-energies on various relativistic and QED effects already for \( Z \geq 137 \) (effects, whose individual \( Z \)-dependencies follow \( Z^n \) with mostly \( n \geq 4 \)) have given rise to new questions about the character of the actual diving of molecular orbitals into the Dirac sea. CRYRING in combination with the existing ESR storage ring will open unprecedented possibilities for investigation of this kind of phenomena. Experiments will begin with symmetric systems where Xe\(^{54+}\)-Xe is most favorable, as this system can be directly investigated with the internal target and existing in-ring electron and photon spectrometers and reaction microscopes. Collision dynamics and molecular orbital structure of transient quasi-molecules can be studied via the emission of electrons, positrons or x-rays in coincidence with outgoing recoil ions. The measurement of the projectile scattering angle will provide the impact parameter, and hence, the internuclear distance during the collision event. Recently, a pilot experiment devoted to impact parameter sensitive studies of inner shell atomic processes for low-energy ion-atom collisions was performed at the ESR, demonstrating the feasibility of such studies at storage rings [3].

In the research field of atomic collision physics, \((e, 2e)\)-spectroscopy has established itself as one gold standard and the most significant test of theory for determination of atomic structure, e.g. state specific momentum wave functions, and for the quantitative description of collision dynamics on the atomic scale. In this context, in-ring experiments designed for CRYRING in combination with the ESR will allow for the measurement of kinematically complete triple differential cross sections \( \frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_2} \) for \((e, 2e)\) electron impact ionization of H-, He-, Li-like and other few-electron ions over a wide Z range and for selected ions of astrophysical relevance [4]. However, such investigations necessarily require a cold, dense He-target serving as a source of quasi-free electrons. The internal target at CRYRING will in this regard offer much higher densities compared to former achieved values, thus offering favorable experimental conditions.

Another interesting investigation concerns two-center interference in charge transfer at MeV ion-molecule collisions studied previously at CRYRING while operated at Stockholm University [5]. There, a surprising observation using a \( \text{N}_2 \) target colliding with protons was made of the observed angular distribution of the dissociated nitrogen atoms [6]. Further investigations at higher projectile energies would expectedly yield more dramatic
and characteristic effects as foreseen by the interference model which was believed to be valid only in case of H\textsubscript{2} targets. At GSI, N\textsubscript{2} or even O\textsubscript{2} internal targets could be applied for further investigations at the CRYRING facility.

In the field of nuclear astrophysics, photodissociation reaction processes (\textit{p}-process) taking place in the energy range of the so called Gamow window between 2 and 5 MeV/u of the projectile are of special interest, because the number of measured reaction rates for the (\gamma,p) and (\gamma,\alpha) reactions is scarce. Due to this, the calculated rates are uncertain by factors of two to three even for the stable nuclides [7]. As a consequence, the element abundances obtained from \textit{p}-process models are reproduced within a factor of about three [8]. No \textit{p}-process models can presently explain the relatively large abundances of \textsuperscript{92,94}Mo and \textsuperscript{96,98}Ru, the so-called Mo-Ru anomaly. Addressing (\textit{p},\gamma) and (\alpha,\gamma) reactions in the astrophysically interesting energy range, Gamow window, is a challenge. It is difficult already for the stable nuclei. However, the majority of the nuclei involved in the \textit{p}-process are radioactive. The investigation of these reactions is probably the best to be done in inverse kinematics where the produced radioactive beam collides with the hydrogen or helium target. At many facilities in the world such experiments are performed/planned using an external target. A storage ring offers the possibility to reuse the produced exotic nuclei by storing them at a defined energy and to measure the reaction rates of interest by intersecting the beam with the thin and pure internal gas-jet target of hydrogen and helium. The bending magnets of the storage ring are used as a magnetic spectrometer to analyze the reaction products, which can be detected with high efficiency. The CRYRING turns out to be a versatile tool for such measurements. Proof-of-principle experiments have been performed at the ESR at higher energies (5.5-10 MeV/u), where the cross sections of the proton capture for stable \textsuperscript{96}Ru and \textsuperscript{124}Xe nuclei (\textsuperscript{96}Ru(\textit{p},\gamma)\textsuperscript{97}Rh and \textsuperscript{124}Xe(\textit{p},\gamma)\textsuperscript{125}Cs) were measured [9–11]. Furthermore, the thin gas-jet target together with the electron cooled beams of interest will enable the investigations of resonant reaction channels.
2. The target station for CRYRING

For the field of atomic physics as well as for nuclear reactions and nuclear astrophysics experiments in a storage ring the use of an internal target is mandatory in order to investigate collision processes with tiny reaction cross sections down to the mbarn region. In particular, internal targets produced by means of molecular beam techniques [12–18] offer unique advantages, such as the possibility to study the interaction of brilliant, cooled ion beams with matter under single-collision conditions using different types of target materials. Accordingly, the use of an internal gas-jet target will be of great importance for future collision experiments at CRYRING.

![Figure 1: 3D model of the CRYRING setup at GSI in Darmstadt with the straight experimental section ("YR09") where the internal target station will be installed.](image)

The straight section of CRYRING, labeled as "YR09", will be used for the installation of the internal target station (see Fig. 1). Generally, experimentalists may devise any kind of setup to be installed in this section, provided the proposed setup meets the requirements of the experimental environment. The geometrical restrictions are given by the nominal height of the beam axis of about two meters, the maximum length of the experimental section of $\approx 3.43 \text{ m}$ and the total height of the setup, which is limited to $2.8 \text{ m}$. The ring vacuum is separated from the experimental section by two CF100 gate valves, on the entrance and the exit of the experimental section, and are part of the ring vacuum control system. The setup which is installed at the straight section must be bakeable and equipped with sufficient pumping capabilities in order to reach vacuum levels of below $10^{-11} \text{ mbar}$ [1].

2.1 The original CRYJet target

For the experiments performed at the Manne Siegbahn Laboratory, Stockholm University, the CRYRING was equipped with a high-performance gas-jet target (CRYJet). A detailed description of the original target can be found in the respective technical design report [19] and a picture of the CRYJet target station setup is shown in Fig. 2. The CRYJet was built up of a vacuum inlet chamber, consisting of four differential pumping stages, an interaction chamber and a dump system. It was devised to provide target area densities of up to $10^{12} \text{ cm}^{-2}$ for the light target gases hydrogen and helium while meeting the extremely stringent requirements for the CRYRING high-vacuum environment of about $10^{-11} \text{ mbar}$. The gas jet was produced by expanding the target gas through a $30 \mu \text{m}$
pinhole orifice nozzle. In order to achieve the above target densities a cooling of the gas-jet source was required. This was provided by a closed-cycle cryostat, which reached source temperatures as low as 30 K during operation. The longitudinal size of the target beam in the intersection region with respect to the circulating ion beam was 1.02 mm, which was invariably determined by the orifice diameters of three skimmers mounted inside the inlet chamber and separating the four differential pumping stages. The dump chamber consisted of three differential pumping stages separated by conductance-limiting tubes. Their respective diameters were optimized relative to the opening angle of the target beam in order to reduce as much as possible the number of particles that might hit the inner tube walls and eventually fly back to the interaction region thereby deteriorating the ring vacuum. A schematic overview of the old target setup is shown in Fig. 3

The target components that have been shipped to GSI together with the CRYRING as an in-kind contribution for FAIR are listed below:

- All the inlet, interaction, and dump vacuum chambers;
- The closed-cycle cryostat for nozzle cooling and the associated compressor;
- An xyz-translational stage for positioning of the gas-jet source;
- The 30 µm pinhole orifice nozzle;
- A 1600 ℓ/s turbo molecular pump for the last stage of the dump chamber.

However, a number of major components of the original CRYJet target were not part of the delivery. The following necessary components were not included in the Stockholm in-kind contribution:

- All the turbo-molecular pumps required to evacuate the four inlet differential pumping stages and three differential pumping stages of the dump system;
2. THE TARGET STATION FOR CRYRING

Figure 3: Drawing of the CRYJet target station as it was installed at the Manne Siegbahn Laboratory.

- All the pumps for the corresponding fore-pumping system;
- Some single components such as the control unit for the delivered 1600 ℓ/s turbo molecular pump and the temperature controller (including a temperature calibration sensor) for the closed-cycle cryostat;
- All the required elements for vacuum monitoring such as vacuum gauges and the related control units;
- The gas supply system, including major typical elements such as pressure regulators, purifying filters, and manometers.

Owing to the lack of all the above crucial components a recommissioning of the original CRYJet target is not possible. Only after replacing the missing elements can a full setup of the target station be realized. As far as the expected costs are concerned, the required turbo-molecular pumps represent the most costly components. For a full costs estimation see Table ?? reported in Sec. 3.1.

In its original configuration at CRYRING, the overall geometry of the inlet and interaction chambers was especially designed to carry out mostly atomic physics experiments based on the use of the Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS) technique [20–23]. This technique in combination with the unique CRYJet target features has enabled to provide deep insights into fundamental atomic physics processes [24]. However, as briefly discussed in the physics case section above and exhaustively described in the CRYRING physics book [1], within CRYRING@FAIR it is planned to carry out atomic and nuclear physics experiments that go well beyond the former experiments performed at CRYRING. This implies, on the one side, that the interaction chamber should be able to accommodate a large variety of specific instrumentations. On the other side, it is a challenging task to design a single interaction chamber that would allow performing conceptually different experiments as those planned by the nuclear and atomic physics communities. The inlet chamber should thus necessarily provide some degree of flexibility in order to permit the exchange between completely different setups as fast as possible, thereby reducing the intervention time in the ring and saving valuable beamtime. For
example, depending on the design of the applied experimental interaction chamber, significant differences might be expected in the distance between the nozzle orifice and interaction region, yet requiring at the same time similar target beam features in terms of areal density and size. It is clear that without a substantial modification of the inlet system such requirements can only hardly be met with the currently available vacuum chambers [19], therefore a substantial modification of the inlet system is absolutely necessary.

Accordingly, it is proposed here to realize an internal target for the CRYRING@FAIR based on a different inlet chamber, while keeping the original dump system. The new inlet vacuum system, hereafter SPARC target [25], would then allow accommodating the different interaction chambers specifically designed for the variety of atomic and nuclear physics experiments planned at the CRYRING [26, 27]. A general overview of the proposed target station is shown in Fig. 4, in which the three major components can be readily identified: the target source, represented by the cryostat and the translational stage, the inlet chamber, and the target dump. The SPARC target will be briefly presented in the next section, emphasizing its main features that make it ideally suited as target for the CRYRING@FAIR. We point out here that, except for the components already discussed above and reported in Table ??, no additional, substantial costs will be required for the SPARC inlet chamber: this latter has recently been set up at GSI and is presently being tested within a program for prototype target development for future storage ring experiments at FAIR [28].
2. THE TARGET STATION FOR CRYRING

2.2 SPARC Target@CRYRING

The target beam source consists of two basic elements, i.e., the cryostat and the nozzle, which are mounted on a three axis manipulator. The motor-driven manipulator would allow the remote, precise alignment of the target beam. A significant difference with respect to the original target is here the use of the trumpet-shaped nozzles, which were originally introduced at CERN [29]. Such nozzles with orifices in the range of 10-15 \( \mu m \) diameter allow to achieve target densities comparable to those provided by a the original 30 \( \mu m \)-diameter pinhole orifice at a much reduced gas throughput. The nozzle geometry is shown in Fig. 5. The closed-cycle cryostat is the Sumitomo (SHI) 4 K Refrigerator - RDK-415D from Janis Research, a more modern version of the original cryostat employed at CRYRING, which provides, in particular, a nominal cooling power of 1.5 W@4.2 K. This high cooling power allows reaching lower temperatures especially for the light gases hydrogen and helium. This feature combined with the use of a CERN-type nozzle ultimately allows reaching significantly higher target area densities than those achieved with the original CRYJet target. We note that though the production of trumpet-shaped nozzles has been suspended a few years ago, different options are presently being considered in order to restore the production of CERN-type nozzles. One major option concerns new methods to fabricate CERN-like nozzles by a combination of electro-erosion and laser techniques as being investigated in the group of A. Khoukaz at the Münster University. A particularly important aspect of this second approach is represented by the expected low nozzle production costs, of the order of 500 – 1000 Euro per piece. A first nozzle with a diameter of 25 \( \mu m \) produced in this fashion has been successfully tested at the prototype internal target station in Münster [30].

The SPARC inlet vacuum system is characterized by four differential pumping stages, and in this respect it is similar to the original CRYJet inlet chamber. However, there are also significant differences. First, the chamber has a modular structure in which the turbo pumps will be mounted headfirst on the lateral “wings” visible in Figs. 4 and 6. This configuration allows for an overall distance between the first skimmer and

![Figure 5: 3D model of the trumpet-shaped CERN nozzle with its cryostat adapter (left) and the respective technical drawing depicting the geometrical dimensions of the nozzle (right).](image)
2. THE TARGET STATION FOR CRYRING

Figure 6: Picture of the existing SPARC inlet chamber at GSI mounted onto a preliminary support frame. The four differentially pumped stages are equipped with turbomolecular pumps and pressure gauges are installed at the chamber.

the interaction point of \( \approx 40 \) cm. The differential pumping stages are separated by circular metal plates, which are fixed to the inlet chamber by means of clamps and thus can be easily removed. Each plate has in its center a commercially available skimmer (collimator) that can be physically separated from the plate and adjusted with a sub-mm precision. The skimmer diameter are of the order of 1 mm. It is necessary to be able to switch the target beam on and off as fast as possible during the experimental runs and during the ion cooling procedure in order to optimize the duty cycle time. This will be accomplished by the interchangeable skimmer setup in the second inlet differential pumping stage and controlled by a pneumatically-driven linear feedthrough.

The unique combination of nozzle geometry and lower source temperatures allows to reduce the overall gas throughput while, at the same time, reach considerably higher target densities than those previously achieved by the original CRYJet target, even at a slightly larger distance from the nozzle to the interaction region. Simply achieving higher target densities is not necessarily a major goal at CRYRING due to the consequently dramatically reduced lifetime of the ion beam. However, the extended range of possible target densities offered by the SPARC target would enable to considerably reduce the interaction length while maintaining the target density at the level achieved previously at CRYRING. Reducing the longitudinal target size is an important aspect at storage rings in general, but even more fundamental at CRYRING because of low ion energies. In the present case the angular divergence of the target beam is determined by the opening diameter of the first two skimmers of the inlet chamber. The third and fourth skimmers have only a conductance limiting function and do not affect the overall shape of the beam. For example, the skimmer diameter configuration (from the top to the bottom) of 0.2, 0.4, 1.5, and 2 mm leads to an interaction length of 1.8 mm. A reduction of the second skimmer diameter to, e.g., 0.3 mm would narrow the target beam spread to about 1 mm at the interaction point, slightly smaller compared to the original CRYJet target. Here the change of the skimmer is accomplished by the use of a panel on which three skimmers
2. THE TARGET STATION FOR CRYRING

with different opening diameters are mounted at well defined distances from each other. The panel is allowed to slide along an especially designed guide rail contained in the circular plate that separates the second from the third pumping stage. The panel can be driven remotely with micrometer precision by means of a commercial linear feedthrough manipulator mounted on a CF-35 flange. A model of the device is shown in Fig. 7. Circular skimmers are available, but eventually skimmers with different geometries can also be considered in order to meet specific experimental boundary conditions. In this regard, the Münster group has fabricated and successfully tested a collimator with a $70 \mu m \times 700 \mu m$ slit opening in order to better define the ion-target interaction geometry while optimizing the achievable effective target area density [31].

As mentioned in Sec. 2 there are several geometrical boundary conditions that have to be met for the installation of the target station. These also greatly affect the design of a possible support frame for the target station. In particular, the internal target requires a mobile, stand-alone setup which allows for a fast integration and removal between beamtimes. In addition, the inlet chamber has to be adjustable in three axes relative...
3. ORGANISATION AND COSTS

3. Organisation and Costs

3.1 Costs

3.2 Timeline

An overview of the expected setup process of the target station is shown in Fig. 9. It includes the procurement of components, the installation and assembly of the target station and the testing and commissioning of the target at the CRYRING. The assembly and commissioning of the target station can be done before the installation into the CRYRING environment. After the completion of the performance tests the target station will be moved to the experimental area of the CRYRING by means of its mobile support frame.

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Figure 9: Overview of the timeline for the setup of the SPARC target@CRYRING.

3.3 Work packages

The design and testing of the SPARC inlet chamber is being performed within the Atomic Physics Department at GSI. As already pointed out, the dump chamber was shipped to GSI and is readily available for installation and the interaction chamber(s) will be designed and provided by the respective experiment. The assembly of the complete target station and the commissioning process will be performed by the CRYRING target working group at GSI.
References


