FACILITY FOR ANTIPROTON AND ION RESEARCH

SPARC Collaboration

Technical Design Report:
Experimental Instrumentation
of CRYRING®ESR

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Chapter 1

Executive summary

CRYRING@ESR [1, 2] is the first new storage ring installation of the FAIR facility. The installations are ongoing [3] and commissioning with the local injector for light ions is expected to begin as soon as second half of 2015. Full operation with highly charged ions (HCI) transferred from ESR into CRYRING is planned in 2018, depending on the restart of the GSI facility operation.

The CRYRING@ESR storage ring is dedicated to low-energy experiments on highly-charged heavy ions. Ions are being produced in the upstream accelerator chain of the existing GSI installations. For a future extension, a possible connection beamline of the FAIR rings back to the GSI rings is presently under discussion. This transfer beamline would further extend the available species by high-intensity radioactive ion beams and antiprotons thus covering the entire landscape of rare isotopes, highly-charged ions, and antiprotons. A detailed discussion of the physics case for CRYRING@ESR is presently being prepared [4].

The important features of CRYRING are long storage times at low ion energies, a fast ramping capability for ion energies $300\text{keV/u} \lesssim E/m \lesssim 15\text{MeV/u}$, an electron cooler with ultra-cold electrons for high-resolution collision spectroscopy, a dedicated straight section for experiments, and slow/fast ion extraction for downstream experiments. Key experimental techniques in atomic physics will allow for the investigation of processes at the electron cooler, at a dedicated electron target, a gas-jet target, and using laser spectroscopy.

This document bundles the required experimental instrumentation for CRYRING@ESR in order to realize a first generation of storage ring experiments motivated by atomic physics research. The majority of the installations described in this TDR will be constructed and set up by German university groups. The individual responsibilities are given in the according chapters of present document.

This work is organized in packages and comprizes:

- installations at the CRYRING electron cooler that facilitate high-precision dielectronic collision spectroscopy (chapter 3),
- a dedicated intense free-electron target that operates in crossed-beams collision geometry (chapter 4),
- a new type of detector drives for beam-like atomic and nuclear reaction products (chapter 5),
• a VUV-VIS spectrometer (chapter 6) for the observation of target radiation in the vacuum ultraviolet to visible regime,
• a new type of position- and energy-resolving multi-wire/multi-tube proportional counters for x-rays (chapter 7),
• a dedicated setup for laser spectroscopy (chapter 8),
• a new precision high-voltage divider for the electron cooler which allows for the determining the absolute ion energy on a level better than $10^{-5}$ (chapter 9).

It should be noted, that the original gas-jet target of CRYRING [5] was shipped to Darmstadt along with the ring components will be installed in the ring after an needed upgrade. A dedicated TDR will follow at a later date. Alternatively, the HESR gas-jet target [6] may in principle also be used at CRYRING temporarily or copied over.

According to the present status, CRYRING@ESR will become fully operational around 2018 including the availability of highly-charged ions (HCI) using the ESR as primary injector. The timelines of the present installations for first generation experiments are aligned to this schedule.

In the following chapters we first give a brief scientific overview for planned experiments. The technical details of the proposed installations, are given in individual chapters for the respective work packages.
Chapter 2

Science case

The scientific motivation for the installation of CRYRING@ESR was presented in a study group report [2] which was evaluated and approved by the ECE in 2012. A full description of the science case is presently being prepared for publication [4]. Here we highlight selected scenarios which will be available with the realization of the installations presented in the following chapters.

Despite more than a century of atomic spectroscopy, the research on bound electrons still has many challenges to a complete understanding. For example, even for the most fundamental atom — hydrogen — an exact description of the electronic structure suffers from uncertainties in the proton charge radius [7]. When stepping up the complexity of the system under consideration, next to nuclear size many other nuclear effects, such as the hyperfine interaction, leave their imprints on the electronic shell. In addition, radioactive species change the nuclear magnetic moment through the decay process and the shape of the nucleus. Moreover, the non-perturbative regime of high-Z is one of the frontiers of strong-field quantum electrodynamics.

Highly charged ions are an ideal probe for precision studies on such systems. First, the reduction of the complexity in the atomic shell allows to unambiguously derive products from such systems. Second and more important, the wavefunctions of deeply bound atomic levels overlap more strongly with the nucleus, thus signatures of nuclear effects become more evident.

These contributions can be measured in detail utilizing modern spectroscopic methods on HCI beams in storage rings. Storage rings for heavy ions provide high luminosity with clean, almost background free conditions. At FAIR/GSI, two heavy ion storage rings operating combined and adjacent energy regimes is world-unique and offers a long list of opportunities. While ESR accepts, prepares and purifies a broad cocktail of isotopes and charge states originating from upstream nuclear reactions, even down to the level of atomic and nuclear quantum levels, CRYRING is utilized for precision analysis of a well-formed beam on even rare species. The experimental toolbox contains various probes to induce sensitive transitions: resonant electron-ion collisions, atomic collisions and successive characteristic photonic emissions in the x-ray to visible regime, and laser spectroscopy. They are elaborated on in detail below.
2.1 Collision spectroscopy at the CRYRING@ESR electron cooler

Electron-ion collision spectroscopy at storage rings, and in particular the utilization of resonant process of dielectronic recombination (DR) is a highly sensitive precision tool to address a broad range of physics topics from the fields of atomic, astro-, plasma- and nuclear physics [8, 9]. Owing to its versatility electron-ion collision spectroscopy plays an important role in the experimental programme of the SPARC collaboration at FAIR [10–12].

The knowledge about the DR process itself nowadays is very advanced. This holds true for the DR theory, in particular for few-electron ions, as well as for the experimental techniques. Over the years, research on resonant electron-ion collisions has focussed with increasing emphasis on its application for precision spectroscopy. High sensitivity, clean experimental conditions, and repeated interaction of ions circulating in a storage ring facilitate the investigation of processes with low resonance strengths and/or with low intensity beams such as rare isotopes. Experiments with as low as few hundred ions produced and injected every 10 minutes into the storage ring were successfully conducted.

The list of physics questions studied with electron-ion collision spectroscopy at storage rings is long and it is covered by more than hundred publications. Some of the hitherto addressed topics are:

- Precision studies of fundamental interactions, in particular on QED in strong fields [13–15] or on time-reversal symmetry [16].
- Atomic structure and dynamics investigations in the relativistic domain, e.g. [17–19],
- Correlated multiple-electron excitation processes [20].
- Influence of external fields on photorecombination [21, 22].
- Absolute rate coefficients for application in plasma physics [23–25] and astrophysics [26–32].
- Investigations of metastable ions [33–36] including excitations from the metastable state, life time studies, and the hyperfine induced quenching of metastable states [37, 38].
- Usage as an atomic physics method for the investigation of nuclear properties [39–41], that more recently has been extended to studies of radioisotopes and of nuclear isomers [42–45].

Summaries about recent achievements can be found in the reviews [9, 46] and [47], whereas the latter focusses more strongly on results from the CRYRING.

With the relocation of CRYRING from Stockholm to the ESR at GSI/FAIR two outstanding facilities are presently being joint in the past each by its own delivered spectacular results in the field of resonance spectroscopy. The setup at the CRYRING in Stockholm was one of the pioneering installations used for DR measurements with a transversally cold electron beam and thus highest experimental resolving power, [13, 39, 47] and references therein. GSI/ESR is world leading in storage ring DR measurements of the heaviest few-electron ions such as U$^{89+}$ [14, 41, 48] or, very recently, of DR experiments with exotic ions [42–45]. In contrast to ESR, CRYRING is equipped with an electron cooler with a very small electron energy-spread, in particular in transverse direction. Experiments in Stockholm demonstrated...
Figure 2.1. Simulation of DR spectra of Li-like $^{142}$Nd$^{57+}$ convolved with the electron temperatures of the ESR cooler (black curve, $k_B T_\parallel = 175\mu$eV, $k_B T_\perp = 120$ meV) and for the CRYRING electron cooler (red curve, $k_B T_\parallel = 50\mu$eV, $k_B T_\perp = 1.5$ meV). The underlying model DR cross section was inferred from experimental data measured at ESR [41].

the capability of the CRYRING cooler to provide electron beams with temperatures $k_B T_\perp < 1.5$ meV and $k_B T_\parallel \approx 0.05$ meV [1]. The longitudinal temperatures obtained with the CRYRING cooler are about a factor of 2-4 lower than those for the ESR cooler. However, through the implementation of adiabatic transverse expansion with expansion factors of up to 100, the transverse electron temperature of the CRYRING cooler is a hundred times lower than the one of the ESR cooler.

The low temperatures of the electron beam yield an energy-sharp experimental response function (section 3.1), that in turn leads to a vastly improved experimental resolution and a higher precision for the determination of resonance energies (section 3.1 and Figures 2.1 and 3.1). At GSI/FAIR these outstanding capabilities can now be applied to very highly charged heavy ions and exotic ions and boost precision and sensitivity of spectroscopic studies, e.g., in the field of quantum electrodynamics (QED) in strong fields [9, 14, 36, 49] (compare also Figure 2.1).

A new field of application that will significantly benefit from the spectroscopic potential of the CRYRING cooler is the investigation of in-flight synthesized radioisotopes or of nuclear isomers through high-resolution DR resonance spectroscopy. Such measurements can be performed without the fragment separator FRS. As demonstrated recently, the storage ring ESR can serve as an isotope separator [42–45]: in an international collaboration under the lead of the Institute for Atomic and Molecular Physics, Gießen and the FAIR storage ring group (M. Steck and coworkers) a procedure was developed at the ESR to produce intense beams (typically $10^4$–$10^6$ per injection) of long-lived radioisotopes ($>10$ s) in a thick target foil in the transfer beamline between the heavy ion synchrotron SIS and the ESR, and to perform the isotope separation solely in the ESR. After the separation, successful atomic collision experiments on radioisotopes (e.g. uranium isotopes with $A = 235...238$) and even on isomers ($^{234m}$Pa$^{88+}$, $^{235m}$U$^{89+}$) were conducted [42–45]. For the investigation of isomers a further advantage of
storage rings was utilized that at first glance appears to be trivial. By waiting and performing recombination measurements at different times after injection signatures from nuclear ground and isomeric state uniquely identified in the hyperfine structure of the atomic resonance spectra. In addition, the intensity of a resonance that is attributed to ground or isomeric state could be monitored over time and thus be used for the determination of according lifetimes (similar to [37]).

As an example for DR storage-ring experiments with isomers [44], Figure 2.2 depicts the case of the radioisotope $^{234}$Pa that possesses an isomeric state 73.92+x keV above the nuclear ground state. Li-like $^{234}$Pa$^{88+}$ was produced from a $^{238}$U primary beam impinging on a 1.85 g/cm$^2$ Be-plate in the transfer beamline between synchrotron SIS and ESR. The in-flight produced $^{234}$Pa$^{88+}$ is subsequently separated in the ESR from the primary beam and from further reaction products. The isomer decayed by $\beta^-$-emission with a lifetime of 1.17 min. The decay was much faster than the $\beta^-$-decay of the nuclear ground state and was monitored by means of particle detectors in the ESR (Figure 2.2, left panel). Different relative populations of ground and isomeric state and furthermore of the atomic hyperfine states belonging to the $I^{\pi} = 4^+$ nuclear ground state were obtained in dependence on the waiting time after injection [44]. With the beam prepared in this way, electron-ion collision experiments were be performed (C. Brandau et al., unpublished).

A detailed compilation of the possibilities of merged-beams collision spectroscopy at the CRYRING@ESR electron cooler is given in the Physics book: CRYRING@ESR [4]. In the following we provide an itemized list and short comments on collision spectroscopy experiments at the CRYRING@ESR cooler from the field of atomic and nuclear physics.
2.1. Collision spectroscopy at the CRYRING@ESR electron cooler

2.1.1 Selected atomic physics experiments at the CRYRING e-cooler

**Precision spectroscopy with emphasis on strong-field QED:** Determination of level energies of the first excited states in very highly charged few-electron systems such as the $2s - 2p_j$ splittings in Li-like uranium with ultra-high accuracy for testing QED in strong fields.

**Spin-flip transitions in strong fields:** Electron-induced spin-flip transitions for example of fluorine-like uranium ions in DR processes $U^{83+}(1s^2 2s^2 2p^5 2P_{1/2}) + e \rightarrow U^{82+}(1s^2 2s^2 2p^5 2P_{3/2} \text{nl}) \rightarrow U^{82+}(1s^2 2s^2 2p^6 1S_0) + h\nu$.

**DR with electron excitation between hyperfine states:** Due to the high resolution at low energies, DR between the hyperfine levels of H-like ions becomes observable, e.g. $^{209}\text{Bi}^{82+}(1s \text{F}=4) + e \rightarrow ^{209}\text{Bi}^{81+}(1s \text{F}=5 \text{ nl})$.

**Lifetime studies of atomic metastable states:** In Be-like ions the first excited state above the ground state is the metastable $3P_0$ state that for ions with nuclear spin $I = 0$ can only decay via emission of two photons (E1M1) or even three photons (3E1). For light ions, the lifetimes are of the order of years, but, for heavy ions with $Z > 50$, the lifetimes become comparable to storage times at heavy ion storage rings. Theoretical predictions differ by orders of magnitude, and no experimental benchmark data is yet available.

2.1.2 Selected cooler experiments that utilize DR as a tool for nuclear physics

**Probing nuclear properties by means of electron-ion collision spectroscopy:** Isotope shift and hyperfine splitting studies will be carried out by means of DR of few-electron ions, typically in Li-like configuration. With the DR technique nuclear charge radii, magnetic moments, and nuclear spins of stable isotopes, of radioisotopes with a lifetime $> 10\text{ s}$, and of nuclear isomers can be measured. Due to its high sensitivity the approach can be used down to a few hundred ions. In this context it is worth to emphasize three important benefits of the setup at CRYRING:

- The dual ring operation that allows for a dedicated preparation and control of the ions in the ESR before they are transferred to CRYRING for measurement,
- the vastly improved experimental resolution at the CRYRING cooler,
- and the possibility of a full QED treatment (three-electron ions) in the analysis of the candidates of interest [15, 41, 50, 51].

**DR resonances for intensity monitoring and control of beam admixtures:** The energy-sharp resonance features of DR are ideally suited to monitor the relative intensity of beam admixtures. This comprises among others cocktail beams of different isobars, atomic metastable states, hyperfine excited states or nuclear isomers. The unique signatures of DR resonances can be utilized for
Exploration of the unique properties of nuclear isomers: A central topic that has been already started at the ESR electron cooler is the investigation of the many facets of nuclear isomers with low excitation energy. As an example, Figure 2.3 shows a simulation of DR spectra of the ground state and the isomeric state of the astrophysically important nucleus $^{176}$Lu$^{68+}$. Resonances of the ground and the isomeric state are well separated because of different hyperfine splittings and nuclear size effects. Of particular interest are the energetically lowest known isomeric states, e.g., in $^{229m}$Th ($E^\ast = 7.8$ eV, $T_{1/2} = 79$ h [52, 53]), $^{235m}$U ($E^\ast = 76.5$ eV, $T_{1/2} = 26$ min). The excitation energies of these isomers are suitably low that they can be accessed with lasers or x-ray lasers, respectively. The “nuclear clock” isomer $^{229m}$Th is in the focus of current research worldwide due to the overwhelming opportunities that arise once a handle to its dedicated investigation is found. More than 100 publications about $^{229m}$Th can be found in the literature highlighting its importance. Among others, the isomeric transition in $^{229}$Th is a candidate for a “nuclear clock” with a precision of $10^{-19}$ [54]. A major breakthrough is still pending: the transition has not yet been observed directly. Even more fundamentally, all experiments that claimed to provide definitive evidence of the existence of the isomer have been questioned [55–58]. The combination of CRYRING and ESR provides ideal conditions for DR spectroscopy studies within this outstanding physics topic. An according LOI for the ESR has been positively evaluated by the GSI GPAC. Moreover, the experimental conditions to investigate $^{229m}$Th utilizing DR spectroscopy at the CRYRING significantly improve the experimental boundary.

Figure 2.3. Simulation of the DR spectrum of $^{176}$Lu$^{68+}$ (3 electrons) in the ground state (red line; $I = 7, \mu = 3.169$) and in the isomeric state (black line; $I = 1, \mu = 0.318$). The simulated experimental conditions ($k_B T_\parallel = 50 \mu$eV and $k_B T_\perp = 1.5$ meV) correspond to the conditions that are expected at the CRYRING electron cooler.

- lifetime measurements of the beam admixtures, i.e., of the long-lived atomic and nuclear states but also of otherwise unresolved isobars,
- the detection of reaction products, e.g., in supplement of laser spectroscopy,
- the enrichment or separation of isobars, isomers or atomic metastable ions (based on the charge-changing nature of DR).
conditions compared to the ones at the ESR cooler.

**Related work packages**
- Collision spectroscopy at the electron cooler (chapter 3),
- Fast particle detection (chapter 5),
- Precision HV divider for the electron cooler (chapter 9).

### 2.2 A dedicated electron target in crossed-beams collision geometry

In contrast to the electron cooler of CRYRING that — beyond its cooling tasks — can be used as cold free-electron target for high-resolution collision spectroscopy (chapter 3), a dedicated electron target that operates in transversal collision geometry, i.e., with a (laboratory frame) collision angle of $90^\circ$ with respect to the ion beam, is envisaged (Figure 2.4). Such “crossed beams” electron-ion collision experiments have been successfully operated for more than 35 years at low-energy single-pass setups, for instance at the University of Gießen [8, 59]. Yet, at heavy-ion storage rings such a transverse electron target has never been implemented until now.

A transverse electron target provides an interaction region between the ion beam and a ribbon-shaped electron beam that is spatially well localized and not surrounded by a guiding solenoidal B-field. The collision volume can be easily viewed from many directions and enables photon and electron spectroscopy with large solid angles. The utilization of a transversal free-electron target at the CRYRING@ESR benefits from synergies with other projects of the SPARC collaboration such as the development of x-ray optics, VUV spectrometers, electron spectrometers and large area x-ray polarimeters, that can be used to cover a large solid angle for photon detection.

A transverse electron target will provide access to a whole new class of experiments that are not feasible with the established longitudinal setup. In addition, in a separate dedicated target higher electron-ion collision energies and an improved duty cycle can be achieved since

![Figure 2.4. Schematic drawing of an electron target that operates in “crossed-beams” collision geometry. The ribbon-shaped electron beam (blue) with a width of several cm crosses the ion beam at an interaction angle of $90^\circ$.](image-url)
the target can operate independently of any cooling tasks. A fully electrostatic electron target using a thermal cathode that is optimized for experimental usage can deliver electron densities of several $10^9 \text{ cm}^{-3}$ at a target length of the order of 10 cm [60–62]. In combination with the high revolution frequencies of ions in a storage ring (typically 0.5-1 MHz) and the according repeated interaction of ions and target electrons, a very high luminosity is achieved.

By contrast with a gas-jet target, the “kinematic” energy resolution [8, 63–65] from the collision is substantially improved, since the energy spread of the electrons within the beam is of the order of a few tenths of an eV instead of 13.6 eV of a hydrogen target and the corresponding Compton momentum profile of the “quasi-free” electrons [66, 67].

With an electron gun the collision energy can be changed over a wide energy range (section 4.2.1) without altering the ion energy. The capability to easily change the collision energy combined with the high kinematic energy resolution (Figure 4.5), the luminosity and the well-defined experimental conditions at a storage ring provide an ideal scenario for the investigation of threshold and resonance phenomena. In addition, an electron beam might be operated in a pulsed mode with fast switching times, thus offering new opportunities with respect to timing and background suppression. Similarly, the whole interaction region can be put on a potential leading to reaction products with different kinetic energy in order to the interaction zone. The latter approach is only useful for low ion energies.

A further asset of a free-electron target with regard to the low ion energies envisaged at CRYRING@ESR, is the complete absence of the so-called kinematic or non-radiative electron capture (NRC) mechanism [66, 68] that occurs for the “quasi-free” electrons of a gas-jet target. NRC is mediated by the presence of the target nucleus. At very low energies, in particular for heavy highly charged ions, NRC is the determining beam loss and/or background process even for a hydrogen target.

Below a brief summary of new experimental perspectives for a transverse free-electron target at the CRYRING@ESR is given. More details and elaborated examples are given in the CRYRING physics book [4].

1. Compared to a gas-jet target kinematic capture (NRC) is absent. NRC is the dominating recombination process and beam loss process of very highly charged ions at low energies. A free electron target facilitates the investigation of highly charged ions such as bare uranium (U$^{92+}$) at the lowest energies available at CRYRING. Here, Doppler broadening is practically absent, thus, allowing for high precision spectroscopic studies, e.g., for QED in the strongest electromagnetic fields.

2. In contrast to a gas-jet target, the relative collision energy can be chosen in a wide range independently of the ion energy. In combination with the high resolution this facilitates the investigation of threshold and resonant processes.

3. High-resolution photon-ion coincidence experiments of electron-ion excitation or recombination with large solid angle and determination of the polarization of the emitted x-ray photons.

2.3. Laser-spectroscopy

5. Experiments of electron-impact ionization of highly charged ions, in particular of the indirect contributions due to excitation-autoionization (EA) and resonant ionization mechanisms [8] in the relativistic domain.

6. First observation of the process of nuclear excitation by (resonant) electron capture (NEEC), the time-inverse process of internal conversion.

7. In perspective, the transversal target may be also equipped with alternative electron emitters (field emission photo cathode) in order to create colder electron beams or to further reduce the heat- and gas-load for the vacuum. In particular, the use of a cooled photocathode is very attractive since it enables also a beam of polarized electrons. A similarly constructed setup might also be used to produce an intensive target beam of singly charged alkali ions, thus, facilitating novel in-ring ion-ion collision studies.

**Related work packages**
- Transverse electron target (chapter 4),
- Fast-particle detection (chapter 5).

### 2.3 Laser-spectroscopy

#### 2.3.1 Laser-induced polarization of ions in storage rings

Although polarized beams of particles like electrons, protons, and muons are nowadays routinely produced and have found many applications in basic research, beams of polarized light or heavy ions are not yet available in storage rings even though proposals have been discussed already at the end of the last century [69]. However, optical pumping of ion beams with a few keV beam energy in collinear geometry is applied [70], e.g. at the COLLAPS setup at ISOLDE and the TRIUMF β-NMR beamline [71] in order to polarize nuclei that are afterwards implanted into crystals or other surfaces. The problem at storage rings is the conservation of polarization during the round-trip through the magnetic fields of the quadrupole and dipole magnets. It is not known whether the ion polarization will survive the fast and repetitive transition through the strong magnetic fields and gradients [72, 73].

The interest in polarized beams is largely motivated by the possibility to observe parity non-conservation (PNC) effects [73–76]. These effects can be especially pronounced in highly charged helium-like ions. The information on the standard model that can be extracted from such investigations is complementary to information obtained by the investigation of neutral systems or singly charged ions, due to the contribution of radiative corrections that are negligible in neutral atoms. For a polarization of lithium-like ions, optical pumping of hydrogen-like ions with subsequent electron capture that maintains the nuclear polarization was proposed [73].

Recently, an indication for optical polarization of an ion beam has been observed at the ESR. For a test of time dilation within special relativity, spectroscopy was performed in the $1s2s^3S_1 \rightarrow 1s2p^3P_2$ transition on Li$^+$ ions stored in the ESR [77, 78]. Two lasers were used to apply Doppler-reduced $\Lambda$-spectroscopy employing the $1s2s^3S_1 F = \frac{5}{2} \rightarrow 1s2p^3P_2 F = \frac{5}{2}$
Figure 2.5. Indication for optical pumping was observed in experiments on a $\Lambda$-scheme of Li$^+$ ions (left part, red arrows) with $\beta \approx 0.34$ at the ESR. The centre frame shows the fluorescence signal observed for different polarizations. Using circular polarizations leads to a disappearance of the signal as shown in the lower trace in the centre. It is assumed that the optical pumping into the $m_F = 5/2$ state (right) is maintained within a round trip of the ions in the ESR.

and the $1s2s\,^3S_1 \rightarrow 1s2p\,^3P_2$ hyperfine transitions as shown in the left part of Figure 2.5. In the middle of the figure the resonance signal obtained with linear polarization is shown (top) and its disappearance as soon as one circularly polarized light is used. This can be understood by taking into account optical pumping as depicted in the right hand part of the figure, where it is illustrated for the $1s2s\,^3S_1 \rightarrow 1s2p\,^3P_2$ transition. By applying $\sigma^+$-light, the population is transferred into the $m_F$ substate with the maximum projection along the quantization axis $m_F = +F$. From here, further excitation with $\sigma^+$-light is not possible any more and the resonance disappears. For $\sigma^-$-light the population is correspondingly transferred into the $m_F = -F$ state. However, this is only true, if the polarization induced by the laser survives the revolution in the ring. To our knowledge, this would be the first time that such an optically polarized ion beam has been established in a storage ring at relativistic energies. However, we have so far only indirect signs of polarization and many more tests have to be carried out to understand the dynamics of the polarization. Moreover, only a tiny part of the ions stored in the ring is interacting with the laser and could have been polarized since only approximately 1% of the ions were prepared in the metastable $^3S_1$ state and the narrowband single-mode laser addresses only a tiny fraction of those due to the Doppler width of about 1 GHz.

It might be that the polarization is largely produced during the excitation in front of the optical detection region. But due to the relatively long lifetime of the upper state (30 ns) and the limited interaction length, a full polarization that completely destroys the resonance signal is not likely if not at least a part of the polarization is maintained during the round trip. Since a
clear conclusion about the polarization cannot be drawn from the data currently available, this
topic deserves further investigation and more detailed studies. Since a clear conclusion about
the polarization cannot be drawn from the data currently available, this topic deserves further
investigation and more detailed studies. CRYRING is an ideal place for such investigations,
especially during the shutdown phase of the GSI accelerator facility, since it is equipped with
an off-line ion source and does therefore not require the full GSI accelerator facilities for such
studies.

2.3.2 Combining laser spectroscopy with dielectronic recombination

Laser spectroscopy on the M1 transition in hydrogen-like [79, 80], and lithium-like ions [81, 82]
is often hampered by the long wavelength of the transition and the very low detection efficiency
for the emitted fluorescence photons and the strong background that is inherent in the detection
of low-energy photons [83]. Partially this can be improved by the Doppler shift of relativistic
ions but a more versatile technique could be based on low-background ion detection. Here,
CRYRING offers the opportunity to test and develop a resonance detection using dielectronic
recombination (DR).

The principal idea is to look for a DR signal with the bound electron being excited in the DR
process from the upper hyperfine level, as illustrated in Figure 2.6. No prior knowledge of the
exact hyperfine splitting energy is needed, however, in order to be able to resolve the different
DR resonance structures originating from hyperfine ground and upper states the energy splitting
should be larger than 50 meV for stable ions and larger than 100 meV for radioisotopes corre-
spending to transition wavelengths of approximately 24 µm and 12 µm, respectively. These
values apply for the energy resolution of the present DR set-up at the ESR. At CRYRING these
limits can still be considerably lower due to the higher energy resolution that can be achieved
at its cooler. The higher DR resolution at CRYRING adds a further decisive benefit to the ap-
proach: in DR measurements the area of a resonance is preserved with increasing resolution,
which in consequence leads to a significantly improved signal-to-background ratio of the DR
detection process and thus precision and sensitivity. Using DR as a detector for the population
of the upper hyperfine state, only a small DR detection background signal will be observed as
long as the laser is not in resonance, because the initial population of the upper state is negli-
gible after a considerably long waiting for the initial decay of the upper hyperfine level after
injection. As soon as the laser is in resonance and transfers a considerable part of the lower
state population into the upper state, a DR signal will appear. Fast switching of the DR voltage
between the DR energy for a signal and a second voltage in the smooth RR background region
will allow for a sensitive detection. Recording the time dependence of this signal would also
give access to the lifetime of the upper hyperfine state and even allow the determination of the
$g$-factor of the bound electron, which also serves as a test of strong-field QED.
Figure 2.6. The principle of dielectronic recombination, shown on the left hand side, is based on the matching of the energy gain of an electron from an external target falling into a doubly-excited resonance state of an ion with a charge \( N \) and the energy loss of a bound electron during its excitation to the double-resonant state. The resulting ion with a charge of \( N - 1 \) can then de-excite by an emission of a photon. In the case of a laser induced dielectronic recombination, the bound electron reaches the state where the excitation energy is matched only after pre-excitation with a laser (right hand side of the figure). The rising recombination rate of the ions stored in a ring is in that case a sign of the successful laser excitation.

2.3.3 Laser-based velocimetry and high voltage measurements

Laser spectroscopy as a tool for very precise velocity determination of ions. It has been mentioned before that the velocity determination of the ion beam is limiting the accuracy of many experiments. Precision voltage dividers, as they are available at the University of Münster [84] and have previously been used to measure beam energies in collinear laser spectroscopy experiments [85] will provide means of a voltage determination at the \( 10^{-5} - 10^{-6} \) level at the electron cooler (see 9). Investigation of the ions’ transition frequencies by means of laser spectroscopy can inside the ring be used to compare the measured electron cooler voltages with the real ion velocity and to study the influence of experimental parameters like electron-beam ion-beam overlap in great detail. This was proven to be very important for the analysis of the laser spectroscopy results on Bi\(^{80+}, 82+\). It was shown that the influence of the space charge of the electron cooler on the ion beam can be measured to higher accuracy by using the optical resonance position combined with precision voltage measurement, than by using the conventional Schottky signal. The additional absolute frequency measurement can be realized at different levels of accuracies, e.g. by using a high-precision wavemeter [82], by laser stabilization to known atomic or molecular transition frequencies [86, 87] or to a frequency comb [88, 89]. All these techniques have already been used at the ESR or other on-line facilities.
2.4 Target radiation

Literature describes only a few experiments employing the observation of highly dispersed fluorescence in the VUV-VIS spectral range (35 nm to 650 nm) for the investigation of collision processes between heavily charged/heavy ions and a gas target or with electrons. Examples of the use of dispersed fluorescence emitted after such collision processes are experiments performed at GANIL [90, and references therein] and the experiment of Ali et al. [91], proving the feasibility and applicability of fluorescence detection in such investigations. In the latter experiment the formation probability of atomic and ionic carbon fragments after collisionally induced fragmentation of Buckminster fullerenes, methane or iso-butane was investigated. Through the dispersed detection of VUV fluorescence the colleagues proved that no excited carbon dimers emerge as fragments from the fullerenes. Moreover, they proved that the fluorescence emission has a large time delay between the fragmentation event and the fluorescence emission, an effect which could not be explained at that time.

For the grazing-incidence VUV spectral range below 35 nm there is a series of investigations on relativistic and QED-effects by comparing very accurately measured emission wave-lengths of $2s^2S_{1/2} \rightarrow 2p^2P_{1/2,3/2}$ transitions in Lithium-like ions and level-energy differences from detailed calculations [92–96]. The corresponding measurements have been carried out by a grazing incidence spectrometer and determined wavelengths were in the range between 10 nm and 30 nm. For Li-like ions the above transitions split due to the large spin-orbit interaction for large nuclear charge number $Z$ (or small average distance between electron and nucleus). Additionally they possess different natural lifetimes due to their largely different emission wavelengths. Here ions were beam-foil excited and the fluorescence of the ions transmitted through the foil was observed under $90^\circ$ with respect to the ion trajectories. This angle had been chosen to minimize uncertainties due to the Doppler shift caused by the swift ions. The grazing incidence of the emitted fluorescence photons on the spectrometer grating implied a very difficult mechanical motion of the grating (rotation along with a transversal motion along the Rowland circle keeping the grating centre always on the Rowland circle; the Rowland circle represents the focus line of the used spherical reflection grating and rotates together with the grating rotation; therefore a transversal grating motion is necessary if a detector is fixed at a defined position). Additionally a large and expensive grating for moderate fluorescence photon flux on the detector is necessary. Alternatively the detector has to undergo a complicated motion. In any case this setup requires very complicated mechanics under ultra-high vacuum conditions. Notwithstanding the challenging mechanical set up further experiments with the same instrument [e.g. 97] showed the possibility to quantify the charge state distribution after beam foil excitation, an important prerequisite for further experiments. The spectrometer to be installed at CRYRING shall be much simpler in its mechanical set-up for mechanical rigidity and for largely failsafe operation.

Related work packages

- Laser setup (chapter 8)
- Precision HV divider for the electron cooler (chapter 9)
- Collision spectroscopy at the CRYRING@ESR electron cooler (chapter 3)
from CRYRING user groups. Nevertheless it is designed to be very versatile in its possible applications and represents a very good compromise between high resolution, high transmission and mechanical stability. It shall consist of a Seya-Namioka-type spectrometer, the reasons on this set up will be given below. The spectrometer is designed to record fluorescence in the wavelength range between 35 nm and 650 nm with different detector/grating combinations and it can be used with gratings of different focal lengths as the spectrometer arms can be modularly extended or shortened according to the required focusing conditions. The use of this spectrometer is complementary to experiments using x-ray [98–100] and particle spectrometry [14] for the study of collisions between heavily charged/ heavy ions and gas targets or electrons. A spectrometer for this spectral range is not available at GSI currently. The scientific motivation is manifold. Therefore only a few examples of scientific questions to be addressed with this instrument are briefly mentioned:

1. In a recent theoretical study Tolstikhina et al. [101] calculated a dramatic influence of relativistic effects on the electron loss cross section in the reaction

\[ X^{q^+} + A \rightarrow X^{(q+1)^+} + \sum_i A_i + e^- \]  

(2.1)

between a heavily charged many-electron ion \( X^{q^+} \) and a neutral atom \( A \). The sum on the right hand side of eq. 2.1 indicates that the originally neutral atom may be ionized or excited or any combination of both. This averaged theory can be compared with experiments where the resulting ions \( X^{(q+1)^+} \) are detected, where over all possible channels via different states \( A_i \) leading to the same charge state \( X^{(q+1)^+} \) is averaged. For a specific physics process, however, it is of utmost importance to investigate individual channels for electron loss or a certain class of channels. With the current spectrometer it is possible to measure excited-state fluorescence of an excited neutral species \( A^* \) as a result of the electron loss or the excited-state fluorescence of inner-shell ionized species \( A^{++*} \). The fluorescence wavelength is characteristic for the excited state \( i \) of the atom and is therefore specific for a certain electron loss channel or a class of electron loss channels. As the detectors foreseen for this spectrometer are single-photon counting and fast, coincidence measurements between the resulting ion \( X^{(q+1)^+} \) (or the x-ray fluorescence emitted from an excited \( X^{(q+1)^{++}} \) ion) and the fluorescence photon characteristic for the resulting atomic (or \( A^{+}\)-ionic) state will enable a channel-specific investigation of these processes.

2. In further theoretical work Litsarev and Shevelko [102] pointed out that multiple electron loss in such collisions account for up to 65% (in their specific example) of the total electron loss cross section. Also here, dispersed fluorescence is able to selectively detect excited states \( A^* \) or \( A^{n+*} \) in specific charge states of the formerly neutral atom after the collision in coincidence with the ions \( X^{(q+m)^+} \) for a specific channel of an \( m \)-fold electron loss process. With the known fluorescence emission wavelengths it is possible to identify both, the excited state and the charge state of the formerly neutral atom.

3. A discrepancy between the experimentally determined probabilities for radiative electron capture and the results of advanced calculations [103, 104] has been pointed out. In all
experiments known to us the ions have been detected without sensitivity to a potentially excited state, and in all calculations there has been averaging over all possible states into which the electron might have been captured.

A second motivation arises from the possibility to characterize the gas target for ion beam experiments and to characterize the longitudinal ion bunch profile in case of bunched ion beams by time dependent measurements of the fluorescence emission from a diluted gas target when the ion bunch is passing through the target. The possibility of such a characterization method has been demonstrated recently by Wen et al. [105] where the diluted gas was indeed the background gas of the experimental chamber. These authors showed that such kind of measurements were even superior to those performed with a dedicated ion beam profile monitor for the longitudinal shape of the beam. Measurements have been performed using a photomultiplier detecting fluorescence in the UV spectral range and a channeltron detecting VUV fluorescence (both measurements did not disperse the fluorescence, but recorded fluorescence intensity as a function of time). They could show that fluorescence transitions with longer lifetimes have large uncertainties when trying to quantify the longitudinal beam profile. Therefore it would be extremely advantageous to be able to select specifically a single transition with a very short lifetime, which could be carried out with this spectrometer. This instrument provides therefore many possibilities for experiments of a variety of user groups as well as for machine studies and routine characterization measurements.

Related work packages

- Seya-Namioka fluorescence spectrometer for wavelengths between 35–650 nm (chapter 6),
- the electron cooler setup (chapter 3), the transverse electron target (chapter 4), or a gas-jet target [5, 6] as collision zone.
Chapter 3

Collision spectroscopy at the CRYRING@ESR electron cooler

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PSP code: 1.3.1.5.9

The work package described here addresses the scientific goals expressed in section 2.1.

3.1 Electron-Ion Merged-Beams Experiments at Cooler Storage Rings

The tool of electron-ion collision spectroscopy at storage-ring electron coolers or merged-beams free-electron targets is a well-established spectroscopic technique [8, 9, 47, 106]. The setup at the CRYRING benefits from the world-unique combination of a high-resolution electron cooler/target at the CRYRING and a very capable injector that can deliver intense beams of heavy highly charged ions and few-electron radioisotopes. The dual-storage ring assembly provides further unprecedented options for measurements. The experimental methods and techniques are well-known, thus, we only briefly summarize some key aspects relevant for the installation of a merged-beams electron-ion collision spectroscopy setup at the CRYRING:

Dielectronic recombination – the primary spectroscopic tool: Electron-ion collision spectroscopy comprises the measurement of the energy-dependence of a cross section with high resolution, and utilizes resonances or cross section thresholds in order to obtain spectroscopic information. Such sharp spectroscopic features can be found in the ionization, excitation and
the recombination channels [8, 107] of electron-ion collisions. In merged-beams experiments at cooler storage rings dielectronic recombination (DR) is the primary atomic process that is applied for spectroscopy [8, 9, 47, 107, 108]. DR is a two-step process:

\[ X^{q+} + e^- \rightarrow X^{(q-1)+*} \rightarrow X^{(q-1)+}\text{+} + \text{photons}. \]  

(3.1)

In the first step, a free electron is resonantly captured, thereby exciting an already bound electron, thus forming a doubly excited intermediate state. This initial dielectronic capture (DC) is time-inverse to autoionization and leads to sharp resonance structures in the recombination cross section. In DR collision spectroscopy, the electron-ion collision energy is scanned in fine steps. For center-of-mass (CM) collision energies that match the resonance energies, a higher count rate of recombined \( X^{(q-1)+}\) ions, is recorded. DR collision spectroscopy can be regarded as Auger spectroscopy in inverse kinematics. In Auger spectroscopy the kinetic energy of an emitted electron is precisely determined, whereas in DR the kinetic energy of the captured electron that forms a doubly excited state yields the relevant structure information. Usually the photons that are emitted in the second step of DR, i.e., during the radiative stabilization to below the autoionization threshold, are not observed at cooler-type DR setups.

At CRYRING the electron cooler will be used as a target for free electrons. The experiment is performed by detuning the electron-energy from cooling conditions for a series of short time-intervals of the order of a few ten ms, thereby realizing a sequence of relative electron-ion collision energies (see below). Using the measured values for count rate \( R \), ion current \( I_i \) and electron density \( n_e \), the recombination rate coefficient \( \alpha \) is determined on an absolute scale as [9]

\[ \alpha = \frac{1}{1 - \beta_i c R} \frac{q e \beta_i c R}{I_i n_e L}. \]  

(3.2)

In this equation, the ion and electron velocities \( \beta_{i,e} = (1 - 1/\gamma_{i,e}^2)^{1/2} \) are given in units of speed-of-light \( c \), \( q \) is the initial ion charge state, \( e \) is the electron charge, \( L \) is the length of the overlap of electron and ion beam, and \( R \) is the ring circumference.

**Experimental response function:** The rate coefficient \( \alpha(v_{\text{CM}}) \) that is measured in the electron-ion merged-beams setup is a convolution of \( v \sigma(v) \) with the distribution of relative velocities between electrons and ions \( f(v_{\text{CM}}, \vec{v}) \):

\[ \alpha(v_{\text{CM}}) = \langle v \cdot \sigma(v) \rangle = \int \sigma(v) \cdot v \cdot f(v_{\text{CM}}, \vec{v}) d^3v. \]  

(3.3)

For a well-cooled ion beam, the experimental resolution and the experimental line shape are predominantly determined by the temperatures [9, 109] \( k_b T_{\perp} \) and \( k_b T_{\parallel} \) of the electron beam, that are transversal or respectively parallel to the direction of the beam (for an exception, refer to [19]). The according distribution of electron energies is approximated by a flattened Maxwellian distribution \( (k_b T_{\parallel} \ll k_b T_{\perp}) \) around \( v_{\text{CM}} \) [109]:

\[ f(v_0, \vec{v}) = \sqrt{\frac{m_{e0}}{2\pi k_b T_{\parallel}}} \exp \left[ -\frac{m_{e0}(v_{\parallel} - v_{\text{CM}})^2}{2k_b T_{\parallel}} \right] \times \frac{m_{e0}}{2\pi k_b T_{\perp}} \exp \left[ -\frac{m_{e0}v_{\perp}^2}{2k_b T_{\perp}} \right]. \]

The influence of the two temperatures on the linewidth and shape is visualized in Figure 3.1. The transversal temperature \( T_{\perp} \) introduces an energy-independent asymmetry and a shift of the
3.1. Electron-Ion Merged-Beams Experiments at Cooler Storage Rings

Figure 3.1. Influence of the electron beam temperatures \(k_B T_\parallel\) and \(k_B T_\perp\) on DR resonance line shapes. Left panel: influence of different values for \(k_B T_\perp\) on a \(\delta\)-resonance with resonance energy \(E_{\text{Res}} = 10\) eV. Right panel: Broadening of a DR resonance with increasing \(E_{\text{Res}}\) for fixed values of \(k_B T_\parallel\) and \(k_B T_\perp\). The energy-dependent symmetric broadening stems from \(k_B T_\parallel\). Please note the persistent shift of the center-of-gravity of the resonance due to \(k_B T_\perp\).

The center-of-gravity by about \(k_B T_\perp\) towards lower collision energies. The parallel temperature \(T_\parallel\) broadens the line symmetrically with a width that increases with increasing relative collision energy. At higher energies, the symmetric broadening overrules the asymmetry from \(T_\perp\) resulting in a symmetric but still shifted resonance. The experimental energy spread \(\Delta E\) (FWHM) can be described by [8]

\[
\Delta E_{\text{cm}}(E_{\text{cm}}) = \sqrt{[k_B T_\perp \ln(2)]^2 + 16\ln(2) k_B T_\parallel E_{\text{cm}}}.
\]

The electron beam of the CRYRING is expanded adiabatically in the transversal direction by an expansion factor of 100. Due to this adiabatic expansion of the beam by a factor of 100 the temperature of the electrons in the transversal direction is lowered to \(k_B T_\perp = 1.0 - 1.5\) meV, compared with the initial value from thermionic electron emission of about 100 – 150 meV [110–112]. Typical values that are measured in experiments at CRYRING are \(k_B T_\perp = 1.0 - 3.5\) meV and \(k_B T_\parallel = 0.05 - 0.2\) meV [1]. An example for the determination of the electron beam temperatures at CRYRING using DR resonance shapes is depicted in Figure 3.2.

At the CRYRING electron cooler, the temperature in the transversal direction is more than two orders of magnitude lower than the one from the ESR cooler, which is \(k_B T_\perp^{\text{ESR}} = 120^{+40}_{-20}\) meV. The typical parallel temperature at the ESR cooler is \(k_B T_\parallel^{\text{ESR}} \approx 0.2\) meV. Also the longitudinal temperature of the CRYRING cooler is still a factor of 2-4 lower than \(T_\parallel\) at the ESR. According to Equation (3.4) this leads to a significant improvement of the energy resolution (Figure 3.3) in particular at low electron-ion collision energies. In addition, the higher resolution leads to a considerably improved signal-to-background ratio since the area of the peak is conserved.
In the present example, the electron beam temperatures were determined by fitting Equations (3.3) and (3.4) to the measured line shapes to be $k_B T_\perp = 1.5$ meV and $k_B T_\parallel = 0.1$ meV.

A further benefit of the low transversal temperature is that it leads to lower associated uncertainty of DR resonance position. At the ESR cooler, the imperfect knowledge of the transversal temperatures ultimately limits the precision for the determination of excitation energies to about 40 meV, i.e., to the level of the uncertainty of the temperatures [14, 36, 49]. This limit is mainly caused by the according uncertainty in the shift of the center-of-gravity of the resonance introduced by $T_\perp$ (Figure 3.3). For CRYRING the total value for the transversal temperature is more than one order of magnitude lower than the uncertainty of $T_\perp$ at the ESR, thus almost completely eliminating one of largest sources of uncertainties in the determination of resonance positions.

Variation of collision energies – scanning: The energy variation in a DR experiment is typically performed by repeated swift and precise switching of the cooler between cooling and measurement potentials, cf. [113, 114] and Figure 3.4. An energy scan consists of a sequence of several hundreds or thousands of measurement steps of a few 10 ms duration that are interlaced by cooling steps of about the same duration (Figure 3.4). The intermittent cooling steps are used to maintain the ion energy by minimizing and/or leveling the effect of the cooling force on the ion beam that tends to drag the ion velocity towards the velocity of the electrons at the measurement potential. In addition, the intermittent cooling steps preserve the quality of the stored and cooled ion beam.

The relevant potentials for the determination of the collision energy $E_{\text{lab}}$ in the laboratory frame are the cathode potential at cooling $U_{\text{cool}}$, a detuning voltage $U_{\text{det}}$ that is applied on
top of $U_{\text{cool}}$ to realize the energy scanning, and the space-charge potential $U_{\text{sc}}$ of the electron beam. With the electron rest mass $m_{e0}$, the relativistic Lorentz factor for the electrons $\gamma_e$ can be determined as

$$\gamma_e = 1 + \frac{E_{\text{lab}}}{m_{e0}c^2} = 1 + \frac{e(U_{\text{cool}} + U_{\text{det}} + U_{\text{sc}})}{m_{e0}c^2}. \quad (3.5)$$

At electron cooling, $U_{\text{det}} = 0$, and, by definition, electron beam ($e$) and the cooled ion beam ($i$) have the same relativistic $\gamma$-factor, $\gamma_e \equiv \gamma_i$. For a measurement energy $U_{\text{det}} \neq 0$, $\gamma$ stays constant and $\gamma_e$ is varied thus introducing a relative energy between electrons and ions.

Once $\gamma_i$ and $\gamma_e$ are known, the relative collision energy $E_{\text{CM}}$ in the center-of-mass (CM) frame is readily calculated [8]. As a consequence of the merged-beams kinematics, the transformation from the laboratory system to the CM-frame follows roughly a slightly asymmetric parabola (Figure 3.5). Hence, the experiments at the cooler possess very high sensitivity at low collision energies where the dependence between laboratory and CM-energy is very shallow.
For an ion beam with an energy of 14 MeV/u, in order to introduce $E_{CM} = 1$ eV, in the laboratory system an offset voltage from cooling of about $U_{det} \approx 175$ V is required, for $E_{CM} = 10$ eV slightly more than 545 V, and roughly 1660 V for $E_{CM} = 100$ eV.

### 3.2 The merged-beams collision spectroscopy setup at CRYRING@ESR

The CRYRING electron cooler (Figure 3.6) was already used in Stockholm for collision
spectroscopy. Therefore, only a few modifications are necessary for an adaption to the conditions at GSI/FAIR.

**Ion energy:** For collision spectroscopy a high ion energy is favorable in order to achieve the longest possible beam lifetime in the CRYRING and to minimize background from collisions in the residual gas of the ring. It is therefore foreseen to perform collision experiments at the CRYRING cooler predominantly at or close to the maximum rigidity $B\rho = 1.44$ Tm of the CRYRING, i.e., at an ion energy of 14 MeV/u. This corresponds to an cooling voltage of $U_{\text{cool}} = 6582$ V in the laboratory system.

**Energy scanning:** In order to be able to swiftly and precisely ramp the energy of the electron cooler and thus to introduce relative electron ion energies, a fast HV amplifier with a voltage range of $\pm 2$ kV will be used. The fast voltage ramps will sit on top of the potential of the electron cooler. Consequently, the HV amplifier will be isolated from to ground potential using an isolating transformer. The HV amplifier will be controlled via a DAC and a corresponding data acquisition program [40].

**Determination of experimental parameters:** Specialized equipment for the measurement of two main experimental parameters will be needed:

- For the precise determination of the cooler high voltage, two different procedures to measure the voltage will be implemented:
  - One is a comparatively slow HV divider with very high precision for static voltage measurements and an precision voltage divider with fast voltage-to-frequency converter (VFC). The slow type was recently implemented and tested at the ESR storage ring by a collaboration of groups of the universities in Münster (group Prof. Dr. C. Weinheimer) and Darmstadt (group Prof. Dr. W. Nörthershäuser) and the PTB (see also chapter 9).
  - A fast VFC/voltage divider will be used during the energy scanning where the cooler HV needs to be precisely measured in time slices of 1 ms. Similar devices that operate up to 10 kV were developed at the University of Gießen and are in operation at the TSR storage ring in Heidelberg and at the ESR. A new device based on this existing layout will be built. It will be calibrated at the PTB.
- For a precise and fast determination of the cooler electron current a dedicated current measurement will be installed. Similar to the HV measurements, a suitable unit was developed in Gießen and was used at the TSR and in a electron target setup at the university in Gießen.

**Data acquisition system:** A data acquisition system will be needed that operates according to the present standards at GSI/FAIR, i.e., a VME based CPU with Lynx operating system and GSI MBS capabilities. Where possible, FPGA programmable GSI modules (VULOM/VUPROM etc.) will be used. The FPGA will flexibly be adapted to the particular needs of the individual setup. Template FPGA code that covers the basic requirements is available at GSI.
Experiment controls/accelerator slow control: Signals from accelerator slow controls, ion current, counts and profiles from beam profile monitors and the main cooler parameters need to made available by the CRYRING control system. An according interface (software/hardware pulse remote control) between accelerator and experiment needs to be defined and implemented.

Particle detectors: Fast standard particle detectors with low noise and high dynamic range (sub 1 Hz to a few hundred kHZ) will be needed. Since predominantly high ion energies (14 MeV/u) will be used it is foreseen to use detector pockets. However, for lower energies in-vacuum detectors such as YAP:Ce [40, 115, 116] and channeltron boxes [117] can also be used.

Further requirements: The user/experimentalist needs the possibility to remotely control as many cooler parameters as possible in order to be able to fine tune settings during the experiment. The control over such parameters as cooler voltage, electron current, expansion factor of the electron beam, solenoidal B-field, tilt of electron beam with respect to the ion beam, fast pulsing (on/off) of electron beam shall be made available. An according interface (software/hardware pulse remote control) between accelerator and experiment needs to be defined and implemented.

3.3 Organization

3.3.1 Work packages and responsibilities

Within this workpackage the infrastructure to conduct high-resolution precision resonance spectroscopy at the CRYRING electron cooler will be built up and installed. The work is based on year-long expertise of members of the SPARC workgroup “Electron Targets / Cooler” (work package coordinators: Dr. C. Brandau, Uni Gießen, and Prof. Dr. S. Schippers, Uni Gießen) at the storage rings TSR in Heidelberg, CRYRING in Stockholm and at GSI’s ESR. Besides S. Schippers and C. Brandau and the group in Gießen, main tasks will be carried out by M Lestinsky (GSI, physics coordinator CRYRING) in collaboration with the AP group at GSI. The setup of the control software and the DAQ will be carried out in collaboration with the GSI division “Experiment Electronics” and with the group of Prof. Dr. H. Simon (“Nuclear reactions”, GSI) with respect to the FPGA programming of electronic modules.

In addition, the whole work will be arranged with the accelerator and storage ring division of GSI, in particular with respect to the provision of slow control signals and the integration of the experimental logic in the accelerator control system.
3.3. Organization

3.3.2 Timeline and milestones

The timeline is shown in Table 3.1.

Table 3.1. Timeline and milestones: collision spectroscopy at the CRYRING electron cooler.

<table>
<thead>
<tr>
<th>Task</th>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tbody>
<tr>
<td>1 Purchase, test and commissioning of fast HV amplifier and control electronics</td>
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<tr>
<td>2 Implementation of control electronics for HV amplifier (hardware, software, programming of voltage ramps)</td>
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<td>3 Integration of HV amplifier into CRYRING©-ESR cooler voltage system (slow controls, voltage ramping cycle control)</td>
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<td>4 Working fast HV ramping of CRYRING©ESR electron cooler (without ion beam)</td>
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<td>5 Setup of electronics for precision voltage measurement of CRYRING© electron cooler</td>
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<td>6 Test of particle detectors for recombination experiments behind e-cooler</td>
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<td>7 Development, manufacturing, and test of electronics for precision electron current measurement</td>
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<td>8 Purchase, test and commissioning of collision spectroscopy data acquisition (DAQ)</td>
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<td>9 Adaption and test of FPGA programming of DAQ</td>
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<td>10 Working collision spectroscopy electronics and DAQ</td>
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<td>11 Fully working collision spectroscopy setup at CRYRING©ESR e-cooler</td>
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<td>12 Tests and first experiments at CRYRING (if applicable with local ion injector)</td>
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<tr>
<td>13 Integration of ESR collision spectroscopy DAQ, ESR slow controls and Schottky signal data acquisition (for dual ring operation)</td>
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<td>14 Ready for dual ring experiments ESR©CRYRING</td>
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— time of development    ⋆— milestone.
Chapter 4

Transverse electron target

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4.1 Electron target developments and single-pass crossed beams experiments

The present transversal electron target for CRYRING will be based on more than 35-year expertise of groups at the universities in Frankfurt (IAP, Prof. Dr. O. Kester) and Gießen (IAMP, Prof. Dr. S. Schippers). In a long-standing collaboration of the two groups several electron guns that operate in crossed beams collision geometry [59, 118] were developed. These guns were successfully implemented and used in low-energy electron-ion collision experiments at the University of Gießen since the early 1980s [59, 64, 118, 119]. Advances of the “crossed-beams” method, of the electron targets and in particular the realization of a fast energy-scan scheme lead to world-unique results in the field of electron-impact ionization, e.g. [64, 65, 119–123]. A review and further references are given in [8]. A decisive improvement in terms of a dense electron target was achieved with the design of a flexible new high-current electron gun [60, 62] (Figure 4.1). In contrast to earlier designs, the new electron optical layout (section 4.2.3; Figs. 4.6 and 4.7; Table 4.1) features additional control electrodes that allow for an independent control of extraction voltage and of beam formation, focussing, and transport. Such a high intensity electron target (Figure 4.1) is presently being commissioned for use in the Gießen low-energy electron-ion collision setup [62]. First successful tests were performed up to electron energies of 3.5 keV (limited by the available power supplies) and electron currents and densities of 1 A
Figure 4.1. High-perveance high-energy electron gun used as a target in a single-pass electron-ion collision setup at the Institute for Atomic and Molecular Physics in Gießen. The electron-optical and mechanical layout of the target (section 4.2.3) will serve as the basis for the transversal CRYRING electron target. The assembly of the Gießen target is compact with closed electrode structure and optimized for the single-pass experiment in Gießen. The gun assembly and layout needs to be slightly revised for CRYRING. The according details are discussed in section 4.2.4.

and about $3 \times 10^9$ cm$^{-3}$, respectively.

4.2 Specifications and operation modes

4.2.1 Energy range

For the transverse electron target we envisage a ribbon shaped electron beam with an electron energy up to $T_{el} = 10$ keV in the collision region. In order to reach this electron energy, power supplies with 12.5 kV will be needed [60] (section 4.2.3). With 10-keV electrons and the maximum ion energy of CRYRING of close to $T_{ion} = 15$ MeV/u (limited by the maximum magnetic rigidity $B \rho = 1.44$ Tm of the ring [1]) a center-of-mass collision energy of about $E_{cm} = 18$ keV can be accessed (Figure 4.3).

With this energy, ionization of the L-shell ions up to molybdenum (e.g. Li-like Mo$^{39+}$ [124]) and M-shell ions up to uranium (e.g. Na-like U$^{81+}$ [125]) become accessible in the most interesting regions of indirect ionization processes such as excitation-autoionization (EA) and resonant ionization mechanisms. Similarly, resonant electron scattering can be studied roughly up to $Z = 40$. In the same energy region the resonances of the most promising candidate for a first experimental observation of NEEC (U$^{90+}$ to U$^{92+}$) can be found [126, 127].

In this high-energy mode the target density is about a factor of 10 lower than for a high density mode (section 4.2.3). For a high electron current the first anode needs to have a potential difference to the cathode as big as possible, thus, limiting the maximum energy in the collision
4.2. Specifications and operation modes

Figure 4.2. Electron target setup at the ‘crossed-beams’ experiment of the Institute for Atomic and Molecular Physics in Gießen. The actual target including all supply lines can be moved with step motors in several directions. The vacuum requirements for the single-pass experiment in Gießen are moderate but during routine operation pressures below $10^{-9}$ mbar are obtained (limited by the pumps and the recipient). A new UHV-capable vacuum system aligned to the environment at the CRYRING that operates at the required vacuum pressure of $\sim 10^{-11}$ mbar with according pumps, manipulators and interaction chamber will be needed. For details, please refer to section 4.2.4.

region to about 2.5 keV. Several other combinations of maximum electron energy and density can be set (cf. section 4.2.3). In Figure 4.3 the accessible center-of-mass energy ranges for a given ion energy are displayed.

4.2.2 Modes of operation

According to a given use case the transverse electron target will be operated in three different ways:

**Static mode:** In the “static mode” the electron beam will be optimized with respect to loss current and background for a fixed electron energy and brought to full overlap with the ion beam. The “static mode” is ideally suited for photon or electron spectroscopy where it is necessary to keep constant experimental conditions for a long time in order to collect sufficient statics for a setting.

**Animated crossed beams:** The “animated beams” technique or “dynamic measurement mode” aims at a precise determination of cross sections on an absolute scale. In colliding-beams experiments one important factor that enters the determination of absolute cross sections
Figure 4.3. Electron-ion collision energy range in the center-of-mass (cm) frame for a transverse electron target at the CRYRING that operates in “crossed-beams” (90°) collision geometry. The cm-energies are given for 7 different ion energies. 300 keV/u is the ion energy of CRYRING’s own injector.

is the overlap of the two beams. An elegant way to address this question is to move one of the beams across the other beam and hence get a measure for the mutual overlap [118, 129]. The relative positioning of the two beams can be achieved by deflecting/sweeping one beam across the other [129] or by mechanically changing the beam overlap [118]. The latter approach in which the whole electron target is moved in position in very small steps in a short time is envisaged for the CRYRING electron target. The method is successfully used at the single-pass setup in Gießen. Figure 4.4 shows the typical example of such an electron-impact ionization cross section measurement at the Gießen setup [128]. The position of the gun/electron beam is changed relative to the one of the ion beam from no-overlap at channel 0 to maximum overlap roughly at channel 256 to no-overlap at channel 512. For every position, the detector signal, electron and ion current and measurement time are recorded. Please note, the velocity per step and hence the retention period per step is much smaller at the low and the high channel numbers (turning points of the gun movement) leading to higher rates for all four measured parameters. The normalized signal contains the full information for a determination of the cross section on an absolute scale. For details about the electronics and the formulae to calculate the cross section, cf. e.g. [118, 128]. The mechanics to position the electron gun can also be seen in Figure 4.2.

Energy scan mode: In order to resolve fine structures in the cross section such as excitation steps or resonant contributions, the relevant energy region needs to be scanned in energy with very fine energy steps. In contrast to classical spectroscopy, in this collision spectroscopy approach, the structure information is obtained from the relative collision energies (compare also chapter 3). A very important asset for the CRYRING electron
4.2. Specifications and operation modes

Figure 4.4. Example of a cross section measurement using the “animated beams” approach. The gun is mechanically repositioned in 512 small (1/30th mm) fast steps. At every step the detector signal, electron and ion current and measurement time are recorded yielding a normalized reaction signal [118]. The spectra are taken from [128].

The target will thus be an “energy scan mode” for the transverse target. In the “energy scan mode” fast voltage amplifiers are used to change all electrode potentials of the target synchronously, swiftly and precisely [64, 120]. The typical duration for a measurement step is about $3 - 10$ ms although longer measurement steps might be used in combination with photon or electron spectroscopy. A sequence of measurement steps is called energy ramp and can consist of several hundreds or even several thousand small energy steps. The ramps are repeated many times until the statistics is sufficient. An illustrative example on the capability of this method is given in Figure 4.5 for the electron impact ionization of metastable two-electron $\text{N}^{3+}(1s^2s^3S_1)$. The excitation-autoionization (EA) and resonant contributions sit on top of the smooth, 20 times stronger direct ionization cross section. For details about the physics, please refer to [65]. The measurement is a nice example about the progress that is achieved with the crossed beams “energy scan mode” and emphasizes the stability, reliability and high resolution (here: about 1.7 eV at a cm-energy of 550 eV) of the method.

Further examples of electron-ion collision measurements in crossed-beams geometry employing the “animated beams” or the “energy scan” method can be found in the review [8].

4.2.3 Electron optical layout

The general electron optical layout of the gun will be based on the work of [60–62] and needs to be slightly adopted to the environment at CRYRING@ESR. In the following we will discuss the gross features of the gun along the original work presented in [60]. The gun is realized in an optimized version with a high break-down voltage limit (Figure 4.9) that is designed...
Figure 4.5. Example for the “energy scan technique” at a transverse electron target. The experiments were performed at the Gießen electron-ion collision facility. Shown is the electron impact ionization of metastable two-electron N$_5^+$ ($1s^2 2s^3 S^1$) in the collision energy region from 440 eV to 650 eV [65]. The contribution from ground state ions is already subtracted. The cross section shows nicely resolved step and resonance features (resolution $\sim$ 1.7 eV at 550 eV in the cm-system). For details, cf. [65].

to sustain voltages of more than 12 kV [62]. Many developments that are important for an operation of a transverse target in a storage ring are also presented in [61]. Figure 4.6 shows the general layout of the multi-electrode gun [60]. Electrons are emitted from a cylinder-shaped barium impregnated tungsten cathode. The electron current is mainly determined by the voltage difference between the cathode and the first anode (labeled “electrode 1” in Figure 4.6). The “control electrode 2” serves several purposes:

1. It can be used for an independent adjustment of electron current and electron energy,
2. it focusses or defocusses the electron beam and hence determines height and density in the interaction zone,
3. and it can be used to fine-tune the potential in the interaction region (Figure 4.7) in order to compensate the space-charge potential or to provide a well or ridge that traps or respectively removes slow positive ions in the interaction region.

The interaction region is defined by two electrodes that will be set to ground potential, hence the electron energy is defined by the potential difference between cathode and the interaction region. Down-beam the interaction region the electrodes are arranged mirrored to the cathode side in order to decelerate the beam before dumping it in a water-cooled collector.

As a guidance, a non-comprehensive list of eight different electron optical modes is given in Table 4.1 that illustrate the flexibility of the given electron-gun design. Please note, that the numbers for the effective perveance in the table are provided for a width of the interaction region of 6 mm and a length of the cathode of 6 cm. Slightly different numbers will apply for
Figure 4.6. Electron-optical calculations of a high-perveance high-energy electron gun with a ribbon-shaped electron beam used as a target in a single-pass electron-ion collision setup at the Institute for Atomic and Molecular Physics in Gießen [60, 62]. Electrons are extracted from the cathode (left) with electrode 1, accelerated and shaped towards the interaction region (green). After the interaction region the electrons are decelerated again and dumped in a water cooled collector. The electron-optical and mechanical layout of the target and the one of a similarly constructed target in Frankfurt will serve as the basis for the transversal CRYRING electron target. Both assemblies need to be slightly revised for CRYRING. The details are discussed in section 4.2.4.

The CRYRING electron target. Depending on the voltage ratios the effective electron current and density in the interaction region differ by about an order of magnitude. Restrictions for the combinations apply as a consequence of break down voltages and the maximum voltage of the power supplies. These limits restrict the maximum energy of a modes with high perveance. For instance, for mode m1, already for 2 keV electron energy, the first electrode needs to be set to a voltage of 10 kV and in turn, 10 keV electron energy would require 50 kV on electrode 1. In opposition, in the electron optical modes m5 and m6 electron energies up to 10 keV will be reached but at a lower electron current.

The column “Lower limit” indicates the lowest electron energy that can be used with a given mode. The lower limit is determined from the voltages below which the thermal motion of the electrons leads to uncontrolled behavior of the electron beam.

The last column indicates whether the applied voltage setting of the mode leads to a trapping of positive ions in the interaction region (Figure 4.7). The fine-control about the shape of the potential in the interaction region can be used to provide a further flattening and enhanced control of the potential distribution in the interaction region and thus to achieve well-defined electron energies in direction of the ion beam, which is important for a high energy-resolution. In contrast to a pencil-shaped beam the space-charge potential of a ribbon-shaped beam is shal-
Table 4.1. Non-comprehensive list of optical modes of the electron gun according to the design of Shi et al. [60]. The second column lists the electrode potential with respect to the potential difference between the cathode and the electrodes that define the interaction region (compare Figure 4.6). The lowest electron energy for which acceptable beam quality and stable operation is achieved is given in column “Lower limit”. An effective perveance is given that is defined with respect to voltage and electron current in the interaction zone $I_{\text{int}}/U_{\text{int}}^{3/2}$. The last column “Trap” indicates whether space charge and electrode potentials lead to a trapping of slow positively charged ions (see Figure 4.7 and text).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Electrode voltage ratio</th>
<th>Lower limit</th>
<th>Effect. perveance $10^{-6} \text{AV}^{3/2}$</th>
<th>Trap</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>5.00 : 1.25 : 1 : 1.25 : 5.00</td>
<td>$\gtrsim$ 10 eV</td>
<td>31.1</td>
<td>Yes</td>
</tr>
<tr>
<td>m2</td>
<td>4.00 : 1.25 : 1 : 1.25 : 4.00</td>
<td>$\gtrsim$ 30 eV</td>
<td>22.3</td>
<td>Yes</td>
</tr>
<tr>
<td>m3</td>
<td>3.00 : 1.25 : 1 : 1.25 : 3.00</td>
<td>$\gtrsim$ 50 eV</td>
<td>14.5</td>
<td>Yes</td>
</tr>
<tr>
<td>m4</td>
<td>2.00 : 1.25 : 1 : 1.25 : 2.00</td>
<td>$\gtrsim$ 70 eV</td>
<td>7.9</td>
<td>Yes</td>
</tr>
<tr>
<td>m5</td>
<td>1.25 : 1.25 : 1 : 1.25 : 1.25</td>
<td>$\gtrsim$ 100 eV</td>
<td>3.9</td>
<td>Yes</td>
</tr>
<tr>
<td>m6</td>
<td>1.25 : 0.85 : 1 : 0.85 : 1.25</td>
<td>$\gtrsim$ 100 eV</td>
<td>3.9</td>
<td>No</td>
</tr>
<tr>
<td>m7</td>
<td>2.00 : 0.65 : 1 : 0.65 : 2.00</td>
<td>$\gtrsim$ 100 eV</td>
<td>7.9</td>
<td>No</td>
</tr>
<tr>
<td>m8</td>
<td>2.50 : 0.45 : 1 : 0.45 : 2.50</td>
<td>$\gtrsim$ 50 eV</td>
<td>11.0</td>
<td>No</td>
</tr>
</tbody>
</table>

low in the long-direction, i.e., in the crossing direction of the ion beam and can furthermore be controlled by several measures such as a fine-control by means of the electrodes, by additional potentials or by a controlled trapping of positive charges in the interaction region.

4.2.4 Technical details for the CRYRING electron target

Transverse electron targets denote technically mature experimental equipment that is successfully used in single-pass experiments and that is continuously advanced over more than three decades. Likewise, the experimental techniques and protocols are well-established. For the installation of a transverse electron target at the CRYRING@ESR several additional aspects have to be considered. The existing designs [60–62] need to be optimized for an installation at CRYRING. The relevant factors are summarized and discussed in the following list.

Adaptation of the target to the UHV of CRYRING: Essentially, the existing targets are designed for operation under UHV conditions but due to the lack of corresponding vacuum equipment the targets were tested only down to a pressure of slightly better than $10^{-9}$ mbar, limited mainly by the available pumps. This vacuum level is sufficient for the hitherto existing single-pass experiments. For CRYRING a final pressure in the $10^{-11}$ mbar region is required. The techniques for further optimization of the vacuum conditions are well known. The required low residual gas level can be reached by implementation of the following measures: Installation of suitable types of vacuum pumps with sufficient pumping speed, the usage of special materials for gun cables and vacuum chambers, reduction of gas-load by efficient cooling of electrodes...
4.2. Specifications and operation modes

Figure 4.7. The two-dimensional potential distributions around the interaction region. In the left panel, the distribution is shown for the same ratios of electrode potentials as indicated in Figure 4.6 (mode m5) and leads to a potential that traps positive ions. On the right side the potential distribution is calculated for ratios of the potentials on the control electrodes 2 and 3 of 85% (mode m6) instead of 125%. For mode m6 positive ions are removed from the interaction region. The details are discussed in the text.

(Figure 4.8) and by minimization of leakage currents on electrodes using a feedback control system. The whole setup needs to have baking capabilities for temperatures of 200 – 250°Celsius. Standard vacuum components for CRYRING are made from 316 LN steel and are H2-poor vacuum-fired at 950°Celsius in order to remove hydrogen [1]. Despite all efforts to minimize the gas-load, high-performance operation of the target will lead to some gas-load during operation. Therefore, in addition to the obligatory getter and ionization pumps up to two turbo pumps with high compaction, i.e., with low final pressure capability will be used.

**High voltage stability:** In order to reach potential differences of up to 12.5 kV special measures needs to be taken to increase the flash-over voltage. A solution to increase the high-voltage stability was developed and tested in Gießen: Typically, the electrodes are aligned with four isolated rods in the corners of the electrodes. This concept is revised using eight rods that are arranged in two groups of four rods. The electrodes are retained alternatingly by the two sets of rods (Figure 4.9). For alignment special ceramic spacer were constructed.

**Sufficient clearance during ion beam injection:** During initial injection of the ion beam into the storage ring the electron target needs to provide sufficient clearance. The situation is more severe when the target is used with CRYRINGs own injector that delivers an initially uncooled beam.

The conditions ease substantially if a precooled ion beam is injected from the ESR. For ions from the ESR only a single injection is foreseen, and the beam will be injected into CRYRING on an orbit that leads to a beam that it will be already in the first turn at its final position in the ring section of the jet target.
For injection from the CRYRING injector a multi-turn scheme with 10 subsequent injections will be used that will occupy a large part of the phase space of the ring for ion accumulation [1]. Thus, a comparatively large aperture needs to be kept clear for the ion beam. This implies that the target needs to be removed during injection and/or that the interaction zone needs to wider than the 6 mm as used in the design of Shi et al. [60, section 4.2.3], even for an electron-cooled ion beam.

Since in the horizontal direction more clearance is needed than in the vertical direction it is planned to orient the electron beam of the CRYRING target vertically (compare Figure 4.10, in contrast to Figures 2.4 to 4.2). The electrodes that define the interaction zone need to be opened up to 10-12 mm [61] for injection of a cooled beam from ESR. For an uncooled beam from the CRYRING injector, the gap of the interaction needs to be still wider. At present we plan for an opening of 20 mm but even this is a compromise that will limit the injection acceptance and finally the ion beam intensity in case the experiment is run with the CRYRING injector [1, 2]. Please note that experiments with the CRYRING injector will be primarily used for commissioning and that the electrode assembly can be changed relatively easily.

A short distance of the electrodes of the interaction box is advantageous and desired for three reasons: The potential in the interaction zone is better defined and more flat. The distance of the control electrodes likewise needs to be moved further away from the interaction zone leading to a lower electron density and less control of the actual potential distribution (e.g. trapping of ions, cf. section 4.2.3).

Presently, effort is spent to develop position-adjustable electrodes by means of precision UHV actuators in order to be able to open and close the interaction region online. Alternatively, it is investigated whether the target can be opened to one side and thus moved during beam injection. These features are optional but would further improve the flexibility beyond the standard fixed-electrode target setup.
Figure 4.9. Detail of electrode assembly showing the HV voltage optimized support of electrodes. The electrodes are alternatingly fixated by two series of ceramic supports thus significantly increasing the breakdown voltage [62, 128].

Optimization of the electrode structure for spectroscopy: In the earlier electron target designs no particular care was taken to provide an open view to the interaction region and thereby enable photon spectroscopy. Yet, a closer look at the presented photos of the guns reveals that free access to the interaction region perpendicular to electron and ion beam can be easily achieved if the pipes for water, cables and according supports are rearranged. In addition, the size and shape of the electrodes can be further optimized to provide a maximum sight field. Substantial progress in this direction is obtained in the latest design of the Frankfurt group (Figure 4.10; cite[61]).

Position of the target in the CRYRING experimental section: The transverse electron target needs to share the experimental section of the CRYRING with the internal gas-jet target [1, 2]. Transverse electron target and jet-target will be exchanged for dedicated campaigns with either of the two setups. Thereby, the electron target experiments can use the same particle detector stations (chapter 5) than the jet target.

Vacuum system: The mobility and interchangeability requires that the electron target can be removed from the experimental site while still being kept permanently under vacuum in order to guarantee the excellent vacuum conditions of CRYRING. This procedure will also ensure that a change of the setup can be performed without extended pumping and baking cycles and will avoid an early deterioration of the getter pumps as a consequence of too frequent activation
cycles.

Accordingly, the target including its scattering chamber needs own gate valves that stay attached to the target chamber and beam pipes to fit the target into its position in the ring. For the target combined getter and ionization pumps are envisaged that will be combined with high-compaction turbo pumps for baking and for operation of the target in high-performance mode that will lead to some gas-load. Correspondingly, also the connecting beam pipes need own getter pumps and angle valves for pumping down. It should be noted that the layout of the vacuum system does not depend on mechanical design and the electrode structure of the electron gun.

**Further requirements:**

- **Electrical power:** Sufficient electrical power for the heating of the target is available in the cave. For the operation of the power supplies, of the vacuum pumps and of the electronics a electrical power of max. 40 kVA need to be installed.
- **Cooling water:** Demineralized water for cooling with a cooling power of 20 kW is needed.
- **Remote control:** Remote control of the power supplies and of the target control need to
be implemented. If possible, the target shall be integrated into control system of the CRYRING.

- **Data acquisition:** A data acquisition system needs to be implemented that is based on existing types of GSI FPGA VME-modules. The VME crate has to fulfill the according GSI/CERN specifications and shall be operated under the GSI multi branch system (MBS) using Lynx as the operating system.
- **Experiment controls/accelerator slow control:** signals from accelerator slow controls, ion current, counts and profiles from beam profile monitors and the main cooler parameters need to made available by the CRYRING control system. An according interface (software/hardware pulse remote control) between accelerator and experiment needs to be defined and implemented.
- **Particle detectors:** fast standard particle detectors with low noise and high dynamic range (sub 1 Hz to a few hundred kHZ) will be needed. Since predominantly high ion energies (14 MeV/u) will be used it is foreseen to use detector pockets. However, for lower energies in-vacuum detectors such as YAP:Ce [40, 115, 116] and channeltron boxes [117] can also be used.

## 4.3 Organization

### 4.3.1 Work packages and responsibilities

The central task of the present work package involves the construction, setup and test of a high-performance transversal electron target that is integrated into CRYRING and optimized for operation under beam storage conditions.

The principal concept of a very flexible electron gun as outlined above was worked-out, improved and applied over many years and can be considered as mature. Working electron targets albeit not yet fully adapted to the experimental surrounding at the CRYRING are likewise in operation since many years. Within the scope of recent developments in Frankfurt and Gießen, the missing details for the necessary modifications have been elaborated. The transverse electron target anticipated for CRYRING will use this groundwork as a well-defined starting point for a dedicated setup at CRYRING.

Based on the long-standing fruitful collaboration on the field of electron targets, the main tasks will be shared between the Institute for Applied Physics, Uni Frankfurt (Prof. Dr. O. Kester) and the Institute for Atomic and Molecular Physics, Uni Gießen (Prof. Dr. A. Müller and Prof. Dr. S. Schippers). Also the Atomic Physics department at GSI/FAIR and technical support groups (construction, UHV, electronics, major assembly etc.) at GSI/FAIR will participate in the realization of the project.

The coordination of the project will be performed by the official SPARC work package co-ordinators “Electron Targets / Cooler”, Dr. C. Brändau, Uni Gießen, and Prof. Dr. S. Schippers, Uni Gießen.

Since expertise regarding many aspects of the electron target exists in both groups, in Frankfurt as well as in Gießen, the work load will be shared according to free resources. This parallel
workflow comprises in particular available workshop capacity and shall ensure a timely availability of the transverse electron target at CRYRING@ESR. The Gießen group is well-known for their pioneering work and their competence in electron-ion collisions at storage rings. In practice, the emphasis of the Frankfurt group will be placed on the construction of the electron gun whereas the Gießen group will be responsible for the design, implementation and the installation of the electron-ion scattering setup (mechanical and electronic control of gun, operation control, data acquisition, vacuum layout, scattering chamber, slow control integration) at the CRYRING.

The construction of the full setup at CRYRING will be prepared by the Gießen and the Frankfurt groups in cooperation with the mechanical design office and the vacuum group at GSI. This approach will guarantee the fulfillment of the GSI/FAIR specifications and the integration into the technical design of CRYRING.

Solutions for the control units for the “energy scan system”, i.e., the fast and precise parallel voltage ramping by means of fast voltage amplifiers, and for the electron density measurements are existing at the University of Gießen and will be adapted.

### 4.3.2 Timeline and milestones

The time for construction and preliminary tests stretches over three years from the start of funding. An timeline overview is given in Table 4.2.
### Table 4.2. Timeline and milestones: transverse electron target.

<table>
<thead>
<tr>
<th>Task</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2015</td>
</tr>
<tr>
<td>1 Processing of latest requests for design changes</td>
<td>I</td>
</tr>
<tr>
<td>2 Definition of target parameters</td>
<td></td>
</tr>
<tr>
<td>3 Mechanical design of target</td>
<td>E</td>
</tr>
<tr>
<td>4 Details of vacuum technical design</td>
<td>E</td>
</tr>
<tr>
<td>5 Completion of mechanical design drawings</td>
<td>E</td>
</tr>
<tr>
<td>6 Electronic design of control units for power supplies, electron current measurement</td>
<td>E</td>
</tr>
<tr>
<td>7 Machining and assembly of target</td>
<td>E</td>
</tr>
<tr>
<td>8 Purchase and offline tests of vacuum components</td>
<td></td>
</tr>
<tr>
<td>9 Offline installation of main vacuum parts (target, chamber, manipulator); optimization of vacuum</td>
<td></td>
</tr>
<tr>
<td>10 Setup and test of target under vacuum conditions, vacuum without beam better 10(^{-10}) mbar</td>
<td></td>
</tr>
<tr>
<td>11 Purchase, commissioning of power supplies</td>
<td>E</td>
</tr>
<tr>
<td>12 Commissioning of power supplies completed</td>
<td></td>
</tr>
<tr>
<td>13 Installation and commissioning of joint setup of control units, power supplies with target</td>
<td></td>
</tr>
<tr>
<td>14 Offline function and vacuum tests with electron beam</td>
<td></td>
</tr>
<tr>
<td>15 Functioning remote controls, vacuum with electron beam better 10(^{-10}) mbar</td>
<td></td>
</tr>
<tr>
<td>16 Characterization of target (at test beamline)*</td>
<td></td>
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<tr>
<td>17 Setup of data acquisition system</td>
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</tr>
<tr>
<td>18 Integration into CRYRING@ESR control system</td>
<td></td>
</tr>
<tr>
<td>19 Installation at CRYRING@ESR</td>
<td></td>
</tr>
<tr>
<td>20 Completed installation at CRYRING@ESR</td>
<td></td>
</tr>
<tr>
<td>21 Commissioning and tests at CRYRING@ESR</td>
<td>⋆</td>
</tr>
<tr>
<td>22 Start of experiments at CRYRING@ESR</td>
<td>⋆</td>
</tr>
</tbody>
</table>

- — time of development
- ⋆ — milestone
- *: optional, if time permits.
In this work package installations for detection of fast particles in the storage ring will be realized. The detection of fast reaction products is needed basically for all collision experiments in atomic and nuclear physics as outlined in chapter 2. The most important unit is a flexible detector drive system as ring infrastructure for housing a variety of different detector heads. The particle detector heads are specific to each particular experiment and are beyond the scope of the present TDR.

5.1 Introduction

The registration of fast ions that have changed charge state and/or momentum in a collision or after a decay is one of the most important tasks in storage ring experiments and is thus essential to virtually all experiments. The storage ring itself serves as a high-resolution spectrometer that separates the circulating fast ions according to their momentum-over-charge ratio. The detectors have to be moved into positions that intercept the path of reaction and/or decay products but at the same time must not disturb the circulating primary beam.

At CRYRING a large variety of different experimental scenarios is envisaged with setups from the areas of atomic and nuclear physics [4]. Accordingly, the requirement profiles for fast-ion detectors of individual experiments are manifold and vary largely:

The CRYRING will be operated with ion energies from 0.3 MeV/u to about 15 MeV/u, i.e., from the energy of CRYRING’s own injector [1, 2] up to an energy corresponding to the maximum rigidity of the ring. For ion energies below 6 – 10 MeV/u, the ESR standard detector
pockets with 25 µm steel entrance windows [130] cannot be used. For these energies alternative pocket designs that foresee a thinner window and that are vacuum pumped [131] are called for. Ultimately, at even lower energy, the detectors have to be placed directly into the main vacuum of the storage ring.

Moreover, in many cases the registered ion is fully stopped in the detector material and thus may lead to enhanced radiation damage or degradation of the detector performance. Beyond the mere counting of the particles several experiments need position resolution or even the determination of the total energy of the reaction product. In addition, the very low residual gas level in the CRYRING with pressures of $10^{-11}$ mbar imposes further restrictions with respect to detector materials, cables and types of detectors.

In order to cope with the broad and partially conflicting range of requirements for the particle detectors, we envisage the installation of flexible detector drive systems (section 5.3) that are equipped with vacuum gate valves and vacuum pumps. Thus, the detectors can be retracted from the ring vacuum and, by closing the valve, separated completely from the main vacuum system of the storage ring [132, 133].

In 2013/2014, prototypes of such detector actuators were successfully implemented and tested at the storage ring ESR. Due to the design, a high degree of maintainability and flexibility is achieved, since the actual detector installations can be accessed rather easily. Only the volume of the bellows and of the pump recipient has to be vacuum baked and not the whole ring sector. The short turn-around time for setup changes facilitates the development and continuous improvement of the detector installations. In addition, this new type of detector drive system is ideally suited for the high vacuum constraints ($\sim 10^{-11}$ mbar) of the CRYRING since it guarantees minimal interference with the ring vacuum itself.

5.2 Particle detector positions at CRYRING

For a full instrumentation of the CRYRING with fast-particle detectors 12 different positions in the storage ring need to be covered. In CRYRING, collision experiments are envisaged in two experimental sections, i.e., the cooler section for high-resolution electron-ion collision spectroscopy (cf. chapter 3) and a dedicated target section on the opposite side of the ring. The target section will host several individual experimental installations such as an internal gas-jet target [1, 2, 4] or a free-electron target in “crossed-beams” collision geometry [4, and chapter 4]. The setups will be interchanged and used in different dedicated measurement campaigns.

The circulating primary beam ions with charge state $q$ needs to be sufficiently separated in space from ions that have captured or lost electrons to be able to register the reaction products without destruction of the primary beam. Depending on the initial $q$ after some travel path the separation of the charge states becomes too large and the charge-changed ions leave the ring acceptance. As an example, in Figure 5.1 the corresponding ion optics in first order of the first two dipoles and the intermediate straight section after the cooler experimental section are depicted for initial charge states $q = 28^+$ and $q = 82^+$. The situation is analogous for the main experimental target section on the opposite side of the ring [1, 2]. In order to cover the full
Figure 5.1. Ion trajectories for primary beams with charge state \( q = 28^+ \) (top) and \( q = 82^+ \) (bottom) and trajectories of reaction products that changed the charge state by \( \pm 1 \) and \( \pm 2 \) units. Shown is a segment of the ring from the experimental sections to beyond the second downstream main ring dipole chamber (here, starting from the cooler section, yet, the ion optics at the experiment section on the opposite side of the ring is similar). Dipoles are indicated in cyan, quadrupoles in red and blue, hexapoles in purple. A scheme of the CRYRING’s vacuum vessels is given for guidance (middle). Detector positions for electron loss and electron capture of ions with low \( (q \lesssim 20) \), medium \( (20 \lesssim q \lesssim 50) \), and high \( (q \gtrsim 50) \) charge state are indicated by orange arrows.

range of charge states from the lightest to the heaviest ions, each experimental section requires \( 2 \times 3 \) different detector positions, i.e., for \( q \lesssim 20 \), for \( 20 \lesssim q \lesssim 50 \) and for \( q \gtrsim 50 \), respectively.

5.3 Detector drive system

5.3.1 Prototype setup of a new detector drive system at the ESR

The present concept of a detector actuator for CRYRING is based on recent R&D and two prototype setups at the storage ring ESR [132, 133]. The specifications for such a new detector drive systems were jointly discussed, planned and implemented by nuclear physics groups and atomic physics groups at the Universities Frankfurt (IAP Frankfurt, Prof. Dr. R. Reifarth),
Chapter 5. Fast-Particle Detection

Figure 5.2. Prototype setup of a new detector actuator in the dipole magnet of storage ring ESR. The detector is moved by a combination of a step-motor with long travel path for retraction and exact positioning and a pneumatic cylinder with fixed 20 cm travel path for fast out/in movements during injection. The detector/pocket can be fully retracted behind a gate valve, isolated from the ring vacuum and maintained without breaking of the ESR ring vacuum.

Edinburgh (School of Physics & Astronomy, Prof. Dr. P. Woods), Gießen (IAMP Gießen, Dr. C. Brandau) and the departments “Nuclear Reactions” and “Atomic Physics” at GSI. The two prototype systems (cf. Figure 5.2 and [132, 133]) were installed in the north and in the south arc of the storage ring ESR, respectively, and were successfully tested. In the north arc setup a special detector mount combined with two 32-bit feedthroughs for detector signals enabled the placement of a Si-detector in the UHV of the ESR. The south arc setup features a detector pocket with a thin 25 $\mu$m steel entrance window. All detector installations and pockets can be completely retracted and can be separated from the ring vacuum using suitable translational motion devices and gate valves. For the movement of the detector, both, a step motor for slow, fine-tunable movement of the full travel distance, and an additional pneumatic drive for fast short-distance travels (e.g. out/in during injection) were implemented.

5.4 Detector drive systems for CRYRING

Figure 5.3 shows the result of a design study for a detector drive system for CRYRING. For CRYRING two different lengths for the travel path needs to be taken into account. The translational motion of the actuators for the dipole chambers need to cover a longer distance than for the other 8 positions. The design is very close to the one developed for ESR:

Own vacuum system and gate valve: The detector drive system has an own closed vacuum system and gate valve. In case of detector maintenance only the small volume of the bellow and the pumping recipient need to be baked. The main vacuum system remains unaffected from any tests or changes in the setup. The preparation of the detector setups can be performed independently from venting of large parts of the ring thus ensuring ideal vacuum conditions in the ring.
Positioning with step motor and pneumatic drive: The detector will be positioned, moved in and retracted by a comparatively slow step motor. The use of a step motor allows for a fine-tuning of the position to below 0.1 mm. For fast in and out motion the whole step motor part can be moved between fixed positions using a pneumatic drive with fixed travel path of 5 cm, 8 cm or 10 cm (exchangeable). This fast positioning will be mainly used during injection and subsequent quick repositioning for data taking. With the pneumatic drive, positioning times are achieved that are ten times faster than with a step motor, i.e., of the order of one second [130]. This fast positioning is important with regard to the rather short beam lifetimes at low ion energies or for beams with otherwise short lifetimes such as radioisotopes or nuclear isomers or atomic metastable states. Please note, that a fully-positionable pneumatic drive system [130] as is partially used at the ESR is not available any more and can furthermore not be used for the rather long travel distance that is required for a system with own gate valve/pumping station.

Pumping recipient and diagnostics: A separate double cross hosts a SAES NexTorr pump (combined NEG + ion pump) for low final pressure, and an angle-valve for installation of a pump-station with rough pump and turbo pump for the initial pumping and during vacuum baking. In addition, the recipient features a UHV vacuum gauge for vacuum control and windows that facilitate adjustment and monitoring of the position of the detector mount/pocket.

The flexible detector drive system facilitates experiment-specific setups by using different detectors or other similar modules. Such an optional installation of different modules offers a wide range of applications such as:

1. In-vacuum window-less detectors for atomic and nuclear collision studies at low ion energies. For example, such a low ion energy is favorable for precision x-ray spectroscopy (low Doppler shift) but also for nuclear reactions around the Coulomb barrier or around the Gamow window.

2. Although the CRYRING will be primarily operated at low ion energies, for experiments that favor higher energies of \( \gtrsim 12 \text{ MeV/u} \) the use of GSI standard detector pockets with thin-metal-foil windows (25 \( \mu \text{m} \)) are still foreseen. Alternative pockets with thinner entrance window [131] that are evacuated in order to minimize energy loss and straggling the pocket volume may be considered for even lower energy. Detector pockets enable the use of detectors that cannot operate under the extreme ultra-high vacuum conditions of CRYRING such as gas counters or plastic scintillators.

3. Arbitrarily positionable scrapers or positionable slit systems.

4. Thin-foil in-vacuum detectors for time-of-flight, particle tracking or even in-ring channeling experiments.

In general it will be the task of the experimental groups to provide their own detector system that is ideally adapted to their needs. These experiment-specific exchange of particle detector is supported by the new detector drive system.

For many applications, the task of the fast-particle detectors is restricted to particle counting and timing for coincidence setups, only. Further options that will be frequently needed are
Figure 5.3. Design study of a detector actuator for the CRYRING dipole chamber. For details, please refer to the text. The double cross on the left provides ports for a vacuum gauge, SAES NexTorr 500 combined NEG + ion pump, an angle-valve for the initial pumping down a with turbo pump, and windows to view the movement and to allow for the adjustment of the horizontal and vertical position of the detector mount/pocket. The whole detector drive unit is separated from the main ring vacuum by a gate valve (not shown here).

position-sensitivity and, in particular for nuclear physics studies, energy resolution of the detectors. Therefore, a set of standard equipment that comprises detector pockets, generic vacuum detector mounts with feedthroughs for voltages and signals and standard detector systems will be foreseen at CRYRING.

At ion energies above 10-14 MeV/u detector pockets with thin metal windows [130] can still be used, e.g., for most merged-beams electron-ion collision spectroscopy experiments at the cooler (chapter 3).

The general operation scenario at CRYRING will focus on significantly lower ion energies for which the particle detector needs to be placed directly into the vacuum. Further demands such as the stringent vacuum conditions of the CRYRING and a high radiation resistivity were already discussed previously. Detector systems for low energy ions that fulfill the given boundary conditions were routinely operated at the storage rings TSR [40, 116, 134] in Heidelberg, at the CRYRING during its time in Stockholm [115], at the CSRm/CSRe storage rings in Lanzhou [135, 136], at the UNILAC [137], but also at low ion-energy collision facilities, e.g. at the University of Gießen [117]. In most cases the detectors were primarily targeted at single particle counting, yet in UNILAC recombination experiment a micro channelplate with position sensitive resistive anode was used [137].
5.5 Organization

5.5.1 Work packages and responsibilities

The main task of this work package involves the construction, machining, setup and test of 12 detector drive systems for fast-particle detection including 12 generic detector mounts with feedthroughs for signals and voltages as well as 4 detector pockets. The new detector drives are based on the positive experience that is obtained with similar drives at the ESR. The main tasks will be shared between the Institute for Applied Physics, Uni Frankfurt (Prof. Dr. R. Reifarth), the Institute for Atomic and Molecular Physics, Uni Gießen (Dr. C. Brandau and Prof. Dr. S. Schippers) and the Atomic Physics Division at GSI (Dr. M. Lestinsky, Dr. A. Bräuning-Demian). The work of both groups will be supported by expert groups at the host lab (construction, UHV, electronics, major assembly etc.). The coordination of the project will be performed by Prof. Dr. R. Reifarth, Uni Frankfurt and Dr. M. Lestinsky, GSI and the official SPARC work package coordinator “SPARC Infrastructure”, Dr. A. Bräuning-Demian, GSI. The construction of the setup at CRYRING will be prepared in cooperation with the construction office and the vacuum group at GSI. This approach will guarantee the fulfillment of the GSI/FAIR specifications and the integration into the technical drawings of CRYRING. In order to guarantee a timely availability of the detector drive units is envisaged to share the load for machining of parts between the mechanical workshops at GSI and at the IAP, Uni Frankfurt according to free capacities.”

5.5.2 Timeline and milestones

The timeline and milestones are given in Table 5.1.
Table 5.1. Timeline and milestones: fast-ion detection. Two batches of 6 drive systems each are planned, whereby batch 1 comprises the installations of a stripped-down start version and batch 2 the additional units for the full equipment.

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— time of development  ★— milestone.
Chapter 6

Seya-Namioka fluorescence spectrometer for wavelengths between 35 nm and 650 nm

Ph. Reiss, A. Ehresmann

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PSP code: 1.3.1.3.12 / 1.3.4.2.11

The work package described here implements a VUV-VIS spectrometer, which addresses the scientific questions given in section 2.4.

6.1 Technical design

The setup will consist of a Seya-Namioka type fluorescence spectrometer meeting the ultra-high vacuum conditions necessary for the operation in a heavy-ion storage ring (Figure 6.1). Although the Seya-Namioka design is a little inferior to standard normal-incidence spectrometers in terms of resolving power, it possesses several other advantages which lead to the choice of this design. The first advantage is its mechanical simplicity: the grating must only be rotated for changing the dispersed wavelength and still being in focus at the fixed detector position. This is the case when the detector arm has an angle of 70.15° with respect to the entrance arm and when the detector is placed at 0.818 times the nominal focal length of the grating. This special design originally developed by Seya and Namioka [138–141] reduces largely focusing errors when the grating is rotated. A drawback is the large astigmatism of this design, which can be compensated by apertures to reduce the effective length of the grating grooves (on the expense of transmission) or by an advanced data analysis of the recorded two-dimensional fluorescence spectra. The angle of 70.15° has an additional mechanical advantage as the single-photon counting detectors can be mounted at the detector arm of the spectrometer essentially
without interfering with the storage ring, or characterization or vacuum assemblies of the ring. As this spectrometer will be combined with position-sensitive detectors the requirement for the angle between entrance and exit arm of the spectrometer is not too strict. The accuracy for the mechanical fabrication for the angle between the mid points of the connecting flanges of the grating chamber is $0.1^\circ$. The accuracy for the radial position is $\pm 0.5 \text{ mm}$ and easily achievable by standard positioning devices. The spectrometer will consist of a reflection grating holder, where the grating position can be adjusted in three dimensions and where the grating can be pitched, yawed, and tilted around three perpendicular axes. This ensures the adjustment of the grating with respect to its rotation axis for dispersion. The spectrometer will be equipped with interchangeable diffraction gratings for the dispersion of the fluorescence radiation, each optimized for a different spectral range (typically there will be gratings optimized for the wavelength ranges between 35 nm and 120 nm, between 115 nm and 190 nm, 160 nm and 350 nm, and between 300 nm and 650 nm). It is foreseen that the grating chamber houses three interchangeable gratings on individual holders with a mechanical grating exchange. In the first stage a grating exchange will be by manual operation (and therefore access to the spectrometer is required for about 15 min) and in the second stage it is planned for the gratings can be changed remotely. The number of optical components in this arrangement is as low as possible since for the VUV range, no transparent materials exist and the reflectivity of mirrors and gratings drops dramatically. For large transmittance and medium resolution gratings with 1 m focal length will be used ($\Delta \lambda \approx 0.3 \text{ nm}$), for higher resolution ($\Delta \lambda \approx 0.1 \text{ nm}$) gratings with 3 m focal length will be used, as the arms of the spectrometer can be modularly extended or shortened, fitting to the focal length of the grating and the experiment. As there is no transmissive material for this wavelength range, the connection to the ring has to be also UHV-compatible.
The detection of the photons is performed by two-dimensional position- and time-resolving single-photon counting detectors consisting of a combination of a (sensitized) stack of multi-channel-plates and a position-sensitive anode allowing the simultaneous measurement of several fluorescence lines within a certain fluorescence wavelength range. In test experiments a similar spectrometer with a 1 m optical reflection grating and 600 lines/mm achieved a resolution of $\lambda/\Delta\lambda \approx 1000$ using an adjustable entrance slit. The position sensitive anode shall be a Hex-Delay-line anode [142], facilitating multi-hit detection and with very small dead time [143]. The time resolution for photon detection is aimed to about 10 ps offering the possibility for lifetime and coincidence measurements. Two detectors sensitive for wavelength ranges of 115 nm to 650 nm for wavelengths between 160 nm to 300 nm are already available. A third detector for the wavelength range between 35 nm and 120 nm will be assembled at Kassel University and tested after completion. The detectors can not be changed remotely. When different detectors are to be used, they have to be disconnected/connected with the spectrometer assembly. A separate valve will prevent the spectrometer from being vented when the detector is changed.

Feasible event rates that can be detected by these detectors lie between a few events per second and about 10 kHz. The dark noise of these detectors is in the range of 5 counts per second over the whole detector area (2048 x 2048 pixel) for the VUV-detector and about 30 counts per second over the whole detector area for the VIS-detector. These detectors are superior to the also used CCD-based detectors due to their low dark noise. The sensitive surfaces of the detectors will be placed tangentially to the Rowland circle of the reflection grating in a UHV-compatible assembly.

The entrance slit assembly of the spectrometer includes a remotely controlled positioning for best focusing during beam times. As the entrance slit shall be as close as possible to the source volume during measurements, it must be retractable during ion beam injection. The entrance slit shall be illuminated in its width homogeneously by the fluorescence from the source volume (distance between centre of ion beam and entrance slit about 5 mm, slit width typically 100 $\mu$m, slit length 3 cm). In experiments where the transversal electron target (chapter 4) of the University of Giessen is used (width of the electron beam: 6 cm, depth of the electron beam 5 mm) this requirement is fulfilled. A first test experiment [144] at a gas target with a provisional set up proved that fluorescence intensities are sufficient and the illumination of the entrance slit assembly appears to be homogeneous over its width, although the slit position has not been optimized in these tentative experiments. The whole spectrometer will also include a remotely controlled adjustment unit for spectrometer adjustment at the beginning of the beamtimes.

6.2 Timeline and work packages

The timeline for the VUV-VIS spectrometer subproject is given in Table 6.1. This in-kind contribution will be realized by the group of A. Ehresmann at Kassel university.
### Table 6.1. Timeline and work packages.

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<th>Task</th>
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<td>3 Setup of vacuum system and remote control</td>
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<td>4 Detector tests and characterization at CRYRING</td>
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<td>5 Ready for Experiments at CRYRING@ESR and data analysis</td>
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</table>

- Time of development
- Milestone

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Chapter 7

Position-sensitive multiwire proportional counters (MWPC) and multitube proportional counters (MTPC) for X-Ray spectroscopy

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PSP code: 1.3.1.5.2

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7.1 Introduction

The purpose of this work package is development, construction and use of two-dimensional multitube proportional counters (MTPC) with time resolution around 50 ns and spatial resolution around 100 µm for the detection of soft x-rays (3–10 keV). Each two such detectors are used at the double-crystal spectrometers for x-ray spectroscopy. One may note, that compared to conventional CCD detectors, the timing capability of MWPC detectors in combination with crystal spectrometers will allow the study of x-ray transitions in coincidence with the charge state of the ions (in case electron capture processes are used to populate the excited states). This enables to suppress unwanted background and in particular line-blends caused by x-ray transitions associated with projectiles in neighboring charge states. The associated data acquisition system is developed and used. As a first step, four position-sensitive multiwire proportional counter (MWPC) were designed, constructed and preliminary tested. Requirements are met
partially. The precise measurements of the energies within the L-shell of highly charged ions which are typically around $\sim 5$ keV are to be done.

For testing QED with high precision x-ray spectroscopy of the low energetic transitions in highly charged heavy ions investigations two crystal spectrometers in a symmetrical setup (to compensate the Doppler shift) have been already demonstrated at the ESR for QED investigations on He and Li-like high-Z ions and investigations has been started [145–147]. For the identification of the x-ray lines in the focal plane used position sensitive x-ray detectors: microstrip germanium detectors for high energy x-rays and cooled back-illuminated CCD-cameras for the soft x-rays. Both detector setups provide good spatial and energy resolution but insufficient time resolution which is serious issue concerning background reduction [148]. According to this and new requirements of the position resolution of 0.1 mm and timing resolution $<100$ ns, multiwire backgammon position-sensitive proportional gaseous detectors (MWPC) are built. The newly developed CMOS-based gas detectors are not the best match for the mentioned experiment while it has low time resolution and small active area (14 mm $\times$ 14 mm) [149]. Also, since multistripes detectors are not the most suitable for this purpose, we here pursue the concept of multiwire proportional counters and, specifically, multitube proportional counters as possible solution.

7.2 Technical design

7.2.1 Design choices

As a first step, four identical detectors (multiwire backgammon cathode based counters, MWPC) with window of 12 mm x 40 mm are designed to match the spectrometer (Figure 7.1). Requirements for the time and energy resolution are met. The lab tests show an energy resolution of 12.05% at 5899 eV (Figure 7.4) with 50 ns time resolution. The spatial resolution would be measured experimentally but it will not be sufficient for all sorts of experiments due to the backgammon geometry. As a second step, we want to construct and develop new type of miniaturized multitube proportional counter (Multitube Proportional Counter, MTPC). We assume to primarily improve the spatial and time resolution. Four identical in design position-sensitive proportional detectors were designed to study the concept of multiwire detectors. Each detector consists of anode frame of 5 to 8 wires (diameter 20 $\mu$m, gold-plated tungsten), backgammon type cathode as a printed circuit board. Spatial resolution is better than 100 um regarding to the work of Beyer and Deslattes [150]. It will be examined under tests in the next steps. In parallel, simulation of the detector performance using Garfield is done to optimize the spatial resolution by variation of the spacing between electrodes(anodes itself; anodes and cathodes), arrangement of the electrodes and quantity of the anodes. The gas volume of the detectors is separated from the vacuum by the beryllium foil of 0.1 um thick. There are different views of the test setup, backgammon cathode and anode frame in Figure 7.1. The housing of the detector is made of a stainless steel (1.4301, nonmagnetic). The connection is flange CF-63 to match the connection to the Bragg spectrometer. The gas used is Ar-CO2 9:1 mixture, pressure 1 bar. For the calibration used $^{55}$Fe radiation source (37 kBq), calibrated by the PTB. The detectors
has been tested and are operational. The associated electronics is only partially available (NIM modules, Figure 7.1, bottom left) and consists of old partially screened components borrowed from the GSI and it is partially functional so that the detectors are not in the beam and the Bragg spectrometer can not be currently used. The outer dimensions of the multiwire detector are: 128 mm × 128 mm × 128 mm.

Figure 7.1. Overview of the multiwire position-sensitive proportional gaseous counter (MWPC) during first tests, backgammon cathode and anode frame.

The dimensions of the coated area of the cathode are 64 mm × 24 mm. Its thickness is about 2 mm with a 5 μm Cu metallized layer electroplated with 2 μm Au. The spacing line thickness is 50 μm and the length 41 mm. The anode frame is made of a 2 mm thick board with a window inside of size 64 mm × 24 mm. The anode wires are of 20 μm gold plated tungsten and stretched on the frame along the long side using a 50-g load. The spacer is also an 2 mm thick bare board that is used for the space setting between anode and cathode. It has a window of the same size as the anode, i.e., 64 mm × 24 mm. To enclose these 3 plates (anode frame, cathode, spacer) O-rings are used and a pressure plate on top of it with vacuum flange screws. O-rings between the components ensure the sealing of the 64 mm × 24 mm × 4 mm detector volume.
7.2.2 Development, simulation, design and use of a Multitube Proportional Counters, MTPC

As a part of the main project, novel position-sensitive gas detectors with many parallel tubes (Multitube Proportional Counter, MTPC; shown schematically at Figure 7.3) are designed. The anode wires, gas supply and electronics connections (as well as further details of construction) are not shown in this picture. Such concept allows us to get the three-dimensional position. The material used for the housing surrounding the tubes is planned to be kapton or mylar. The mass absorption coefficients of the materials limit the resolution in the third axis and the thickness of the tube layers. Each tube has a window of 1/3 of the tube length. For the production of the housing a 3D-printer with a spatial resolution of 0.25 mm will be used. The holes for tubes will be drilled in the housing and than metallized or composed through the material deposition system. The anode will be fixed by using a dielectric holder produced by a 3D-printer. The active area is the area which is not drilled. There are gas connections to each tube from the sides of the detector which are attached to the plug-in connector. The detailed construction of the detector is the essential part of the project. Parallel to the development of the hardware proceeds the simulation of the detector using the Garfield software package for scaling and optimization purposes. Compensation of side effects are explored by using simulation software. New software for the detector calibration and for signal processing has been developed and tested. Another results will be an integrated electronics for power supplying, signal preamplification and processing.

Figure 7.3. Schematic overview of the MTPC (Multitube Proportional Counter)
7.2.3 Advantages with respect to other designs

The main advantages of the MTPC and MWPC are a good spatial resolution, high probability of detecting low energy x-ray photons with low background, low manufacturing costs, and durability. Moreover, the MTPC design has additional advantages: homogeneous field, miniature scales, low voltage operation, and possibility of having three dimensional position information through the multi-layered structure. In the multiwire concept the risk of broken wires may disable the operation of the whole detector. In contrast, in an MTPC only the tube with the broken wire is affected. Such a concept of detectors (multiple layer tubes) gives simultaneously sufficient energy resolution, good time resolution, and spatial resolution which is the main advantage in comparison with microstrip germanium detectors for high energy x-rays and cooled back-illuminated CCD-cameras for the soft x-rays. Both detector setups provide good spatial resolution and energy resolution but insufficient time resolution which is a serious issue concerning background reduction. Straw chambers which are frequently used as vertex detectors in storage-rings experiments are usually made from thin aluminised mylar foils and are operated under high pressures. Thus, aluminised mylar foils can bend in some cases and cause the field distortions. This is not the case for the MTPC: To make the tubes we drill the holes in the housing and then aluminize from inside. Because of its small size MTPC are good candidates for high-rate experiments and due to the short electron drift distance they can also be operated in high magnetic fields without significant deterioration of the spatial resolution. The suggested technical developments can contribute significantly to the successful implementation of the planned experiments at FAIR and to x-ray spectroscopy of HITRAP, CRYRING, ESR, HESR. Thus, the scientific objectives are the study of relativistic and QED effects of heavy ions with one or few electrons.

7.2.4 Results and Simulation

In the same time of the counter establishment, the simulation of the proposed concept of the detector has been started using the Garfield software package. In Figure 7.4 below, simulated spectrum of the $^{55}$Fe for a cylindrical proportional counter with diameter 2 mm and 20 $\mu$m anode wire can be seen (gas Ar-CO$_2$ 9:1, $^{55}$Fe source represented as gamma particle of 5899 eV energy) and on top of it is energy spectrum obtained via MWPC that correlates well with spectrum obtained by Siemens proportional counter (used as a reference) and also in agree with reference [151]. The right side of Figure 7.4 shows the simulated time spectrum for the MTPC, time resolution is $\sim$11 ns. The MTPC will consist of 64 similar tubes in two staggered layers.

7.3 Project organization

A timeline for this sub-project is given in Table 7.1.
Figure 7.4. Energy spectrum of the $^{55}$Fe source obtained via multiwire position-sensitive proportional gaseous counter (MWPC), gas Ar-CO$_2$-9:1 (left, top). Simulated spectrum of the $^{55}$Fe source obtained with Multitube proportional counter (MTPC) using the Garfield software package, Ar-CO$_2$-9:1 (left, bottom). Simulated time spectrum of the Multitube proportional counter (MTPC) using the Garfield, ArCo2-9:1, $^{55}$Fe source represented as gamma particles of 5899 eV energy.

Table 7.1. Development steps of the Multitube Proportional Counters (MTPC) for 2015-2018.

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<thead>
<tr>
<th>Task</th>
<th>Year Quarter</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tbody>
<tr>
<td>1 Modelling and Simulation of the MTPC counter</td>
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<tr>
<td>1.1 Development of electronics: test preamps, biasing electronics</td>
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<tr>
<td>2 Production of MTPC detector prototypes: a) 3D printer for the detector chamber and b) material deposition system for electrodes</td>
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<td>3 Verification and optimization of the MTPC</td>
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<tr>
<td>4 Development of final version of the detector and some part of the electronics setup for the DAQ</td>
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<tr>
<td>5 Implementation of MTPCs to FAIR experiments. Optimization.</td>
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<tr>
<td>6 Use of MTPC, MWPC in the FAIR experiment and x-ray spectroscopy at HITRAP, CRYRING, ESR, HESR.</td>
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--- time of development, ★— milestone; one of the PhD students will finish during Q3/2015.
In the following we describe the experimental and technical requirements for approaching the questions defined in the science case (section 2.3.1, 2.3.2, and 2.3.3). They include the preparation of suitable ion species, detection of ion fluorescence, the construction of a dedicated laser laboratory and the methods for laser beam coupling into CRYRING.

### 8.1 Experimental Requirements

#### 8.1.1 Measurement candidates

Singly charged magnesium or beryllium ions are favourable candidates for these investigations since they provide closed two-level schemes. The most abundant magnesium isotope $^{24}\text{Mg}$ will be used to investigate polarization of the atomic shell, i.e. pumping in the $^2S_{1/2} \rightarrow ^2P_{1/2}$ state with circularly polarized light is expected to lead to dark pumping into the $m_J = +1/2$ state for $\sigma^+$-light and $m_J = -1/2$ state for $\sigma^-$-light. Optical polarization can clearly be proven, e.g. by applying another laser on the same transition and using $\pi$-light or the opposite circular polarization in another arm of the ring. If the signal that was pumped away previously, reappears as soon as the second laser is applied, this manifests a clear indication for optical pumping. Additionally, a high-repetition rate laser with e.g. ps-pulses, adapted in the linewidth to the Doppler width of the electron-cooled ions could be applied to address all velocity classes simultaneously.

Once this has been successfully demonstrated, further tests including isotopes with a nuclear
spin can be performed. The isotopes $^9\text{Be}$ and $^{25}\text{Mg}$ provide a hyperfine structure and can be used for hyperfine pumping, but this time two lasers are already required to avoid dark pumping in the hyperfine structure of the ground state. The next step would then be to address the hyperfine structure of a highly charged ion.

A particular interesting application would be optical pumping in the hyperfine transition of highly charged heavy ions, like, e.g. $^{209}\text{Bi}^{82+}$, $^{207}\text{Pb}^{81+}$ or $^{140}\text{Pr}^{58+}$. This is much more sophisticated since the slow transitions require a long durability of the produced polarization. It is of course important to measure the obtained degree of polarization. For $^{140}\text{Pr}^{58+}$, the electron capture decay could be an indicator of the optical polarization: it has been demonstrated at the ESR that the new, high-resolution Schottky system is capable of determining the emission direction of the electron neutrino from the recoil of the daughter ion [152]. An unpolarized beam shows the daughter ion appearing statistically with a higher or lower momentum than that expected from the electron cooler voltage. Once the beam is polarized, the daughter ion should appear always on the same side. The direction can be switched by changing the laser polarization from $\sigma^+$ to $\sigma^-$ or vice versa. This experiment provides information about the neutrino helicity as it was measured in the Goldhaber experiment [153].

### 8.1.2 Optical detection

A multi-purpose fluorescence detection system for the range from optical to near UV wavelength has been planned for the first laser-assisted experiments at CRYRING. This sensitive wavelength range follows on one hand from the discussed measurements investigating the possibility of storing polarized ion beams that will be performed using singly charged magnesium ions (transition at 280 nm) and beryllium ions (transition at 313 nm) and on the other hand from experiments regarding dielectronic recombination using Ca$^{+}$ ions, where transition wavelengths of 393 / 397 nm and 854 / 866 nm have to be detected.

A detector constructed for this purpose, shown in Figure 8.1, will consist of a mirror system arranged in a diagnostics chamber around the ion beam to efficiently collect fluorescence.
photons and guide them via UV transparent viewports onto cooled photomultipliers (PMTs) outside the vacuum. To reduce background the system should ideally image photons only from the path of the ion beam onto the viewport. A system with a similar design has already been developed for the collinear laser spectroscopy at the TRIGA reactor in Mainz [154]. In one of the possible designs the geometry of a so called Compound Parabolic Concentrator was used to construct a mirror system imaging a line geometry onto a PMT. The design could be used as a starting point for computer simulations of the detection system envisaged for CRYRING. A suitable GEANT4 based simulation code has already been developed at the University of Münster during the design of the parabolic mirror system for the ESR and will be adapted and re-used for this purpose. Besides the geometric shape, another focus in the development of the CRYRING fluorescence detection will be on suitable mirror materials that have to be UHV compatible and exhibit a high reflectivity over the complete wavelength range of interest. The material used for the segmented mirror section at the ESR (MIRO2 from company Alanod) is in this case not suitable, as its reflectivity breaks down too early when moving to the UV region. When the mechanical design is finished, the individual components will be manufactured in the mechanical workshop of the Institute for Nuclear Physics in Münster.

The photons transported through the viewports will be detected, depending on their wavelength, using UV sensitive (for wavelengths down to 200 nm) or red-enhanced PMTs (for wavelength up to 900 nm). For the latter a cooling system is required to reduce the thermally induced dark count rate. Readout of the signals will proceed via a fast amplifier and a constant fraction discriminator to a time-to-digital converter (TDC) that can be read out via VMEbus.

## 8.2 Technical requirements

### 8.2.1 Laser laboratory

A laser laboratory is needed for stable and safe implementation of laser-based experiments. It shall reduce the mechanical and thermal instabilities, typically present in the general accelerator experimental area, which hamper precision laser experiments or even render them impossible. At the same time, it shall provide a safe environment for work with various laser systems, accessible only for trained personnel. Ideally, in order to keep the transport distance of the laser beams at a manageable length, the laboratory shall be located as close as possible to the ring, but outside the concrete shielding. At the moment such a laboratory does not exist around the CRYRING cave and the area outside the south-east corner of the cave is preliminary foreseen for the purpose. The technical requirements for the laser laboratory are listed below:

- Minimum of 22 m², with a minimal 3.5 m wall-to-wall width.
- Vibration-free solid ground, no double floor, ideally the ground level, wet-cleanable.
- Temperature stability better than 1°C with air conditioning. Water cooling with a total cooling power not less than 30 kW.
- Sound proofing better than 20 dBA.
Figure 8.2. Simplified sketch of the laser setup at CRYRING (not to scale). The laser beam can be transported with the help of mirrors to either the electron cooler section or to the experimental section. The laser beams have to be isolated all the way to the interaction region with tubes. One of the experimental sections is zoomed in to indicate to positions of the optical detection chamber and the XY-scrapers. The latter are needed at the electron cooler side as well.

- Infrastructure such as network, electricity (single and three-phase), cable connections with the ring, ports for laser beam coupling towards the ring.

- Illuminated laser warning light, located at the exterior of the entrance door, as well as inside the CRYRING-cave, with the corresponding interlocks.

8.2.2 Laser beam transport and coupling

Coupling of laser beams into CRYRING has to be carried out both at the electron cooler and at another section of the ring where also the optical detection chamber needs to be installed, as indicated in Figure 8.2. Because of the relatively long lifetime of the excited states, the precise location of the second beam coupling ring section is not of critical importance. High-quality bakeable vacuum windows with large transmittance in the optical and near-optical part of the spectrum will be used for the purpose. For ensuring a good laser beam — ion beam overlap, two sets of XY scrapers are needed at both locations.

Laser beam transport from the laser laboratory to CRYRING will be carried out with re-
motely controlled motorized 2-3 inch optical mounts, Piezo actuators, and high-reflectivity optical elements. They will ensure the smallest possible losses and high stability for transport of continuous and pulsed laser beams over a length of several tens of meters. Beam-guiding tubes will be used for safety purposes inside the CRYRING cave. In case the tubes cannot be fixed permanently inside the cave, a removable system has to be designed and installed during the beamtimes with the use of lasers.

Several laser systems from the previous experiments at the ESR are readily available for the planned experiments at CRYRING. They include a continuous wave Ti:Sa laser with a frequency doubling stage and a pulsed dye laser with a corresponding pump laser. An additional continuous wave dye laser system is needed for the optical pumping and dielectronic recombination experiments, as depicted in section 2.3.1 and section 2.3.2.

### 8.3 Project organization

The most important work packages for the experiments described in section 2.3.1 and section 2.3.2 are the preparation of the necessary laser systems, their frequency stabilization and the development of the optical detection. After the successful completion of laser spectroscopy experiments at the ESR in the previous years [78, 81], the expertise is readily available at GSI and through the fruitful collaboration with the Technical University Darmstadt and the group of Prof. Dr. W. Nötershäuser, as well as with the University Münster and the group of Prof. Dr. Ch. Weinheimer and Dr. V. Hannen.

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<tr>
<th>Task</th>
<th>Year</th>
<th>2015</th>
<th>2016</th>
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<td>Design and construction of the laser laboratory, preparations of infrastructure</td>
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<td>Procurement and installation of the laser systems</td>
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<td>Laser frequency stabilization and absolute frequency determination</td>
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<td>Development and implementation of the optical detection system</td>
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<td>Development and implementation of the data acquisition system</td>
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<td>Cave closed, electron cooler running</td>
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<td>Laser beam transport, coupling and stabilization</td>
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<td>Deployment of precision HV divider (chapter 9)</td>
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<td>Cooled beam available, singly charged ions</td>
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<td>Optical pumping experiments with singly charged ions</td>
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<td>GSI accelerators running, heavy HCl beams injected from ESR to CRYRING</td>
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<td>Optical pumping experiments with HCl</td>
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<td>Dielectronic recombination experiments with highly charged ions</td>
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Table 8.1. Project timeline for the laser spectroscopy experiments at CRYRING.

- | time of development
- | milestone.
Chapter 9

Precision high-voltage divider for the electron cooler at CRYRING

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PSP code: 1.3.1.5.8.2

This work package is essential for the measurements described in section 2.3.3. Moreover, it provides an excellent calibration tool for spectroscopy with the electron cooler as described in section 2.1.

9.1 Introduction

The low energy storage ring CRYRING is currently being set up as the first storage ring of the upcoming accelerator facility FAIR at GSI, Darmstadt. In the initial phase, the ring will be operated with a local ion source and will enable to store ions at energies between 0.3 MeV/u and 15 MeV/u. Like the existing storage ring ESR also CRYRING features an electron cooler, where the ion beam is superimposed with a monoenergetic electron beam in order to cool the ions and thus achieve a low momentum spread of the stored beam. To determine the velocity of the ions a precise knowledge of the acceleration voltage of the electron cooler is essential. This became obvious in measurements of the ground-state hyperfine transition in lithium-like bismuth during the LIBELLE experiment at the ESR in 2011. This experiment was able for the first time to observe the transition in a laser spectroscopy measurement. In this first beamtime, the accuracy of the transition energy in the ions rest frame was limited by the insufficient knowledge of the electron cooler voltage and thus the velocity of the ions [82]. Therefore a second beamtime was undertaken beginning of 2014 where the electron cooler voltage of ca. 214 kV was monitored continous by a dedicated high precision voltage divider provided temporarily.
by the Physikalisch Technische Bundesanstalt (PTB). According to the first analysis of the experiment data, this will allow for a much improved accuracy of the determined transition energy with a relative uncertainty below $10^{-4}$. Since commercially available high-voltage dividers do not offer the desired precision and stability for use at CRYRING and also for the low energetic range at ESR, we therefore plan to construct a high-precision divider for voltages up to 35 kV which will be similar to the ultrahigh-precision voltage dividers which have been constructed in Münster in cooperation with PTB for use at the KATRIN experiment [84, 155]. The precision of the divider will be in the low ppm range and will, if other sources of systematic uncertainties like e.g. space charge effects are under control, allow for measurement uncertainties in the $<10^{-5}$ region. At the ESR, this divider will complement a commercial one that is currently under commissioning and will provide an accuracy of only $10^{-4}$ but up to voltages of 250 kV.

9.2 Divider concept

The simplest version of a voltage divider consists of two resistors connected in series. For high-voltage dividers the upper resistance $R_{HV}$ usually consists of many resistors $R_i$ connected in series in order to allow for the requested maximum voltage. The output voltage $U_{out}$ is measured using a high-precision digital voltmeter over the low voltage resistor $R_{LV}$. Voltage dividers are characterized by their scale factor

$$M = \frac{U_{in}}{U_{out}} = \frac{\sum_i R_i + R_{LV}}{R_{LV}}. \quad (9.1)$$

This scale factor describes the factor between input and output voltage and has to be matched to the high-voltage range of interest and the most sensitive range of the applied digital voltmeter. Because the most common reference voltage sources have an output voltage of 10 V (e.g. Fluke 732A) and also suitable multimeters have the best performance in the 10 V (Agilent 3458A) to 20 V range (Fluke 8508A), scale factors for measurement ranges up to 10 kV and up to 35 kV would be around $M = 1000 : 1$ and $M = 3000 : 1$, respectively.

The total resistance of a high-voltage divider is a compromise between different properties and has to be optimized for the particular application. In order to reduce the dissipated power of the divider and hence the influence of a temperature dependence of the resistors, the total resistance has to be as high as possible. On the other hand $R_{LV}$ will also increase for higher total resistance in order to meet the desired scale factor and hence the thermal voltage noise over a frequency band $\Delta f$ will also increase. Secondly, the current which flows through the voltage divider must be significantly higher than the leakage currents being transported across the utilized insulators. High-precision high-voltage dividers typically use currents passing through the divider of about 100 $\mu$A. Therefore one has to find a suitable balance between high total resistance and a low $R_{LV}$.

To achieve the desired accuracy and stability, there are different effects to be considered. One point is the thermal behaviour of the resistors, characterized by the temperature coefficient of resistance (TCR). The TCR is expressed as absolute change of resistance with temperature $\delta R/\delta T$ or as relative change $(\delta R/\delta T)/R$. An unbalanced change of all resistors will directly
lead to a change in the scale factor of the voltage divider. In order to counteract this thermal behaviour the resistors have to be selected according to their thermal characteristics and combined in a way that the overall thermal behaviour sums up to nearly zero temperature dependence. This can be further improved by an additional thermal stabilization of the voltage divider. The compensation of the TCRs is only possible if the resistors are available with positive and negative temperature dependence.

Disturbances caused by the high voltage, such as corona discharges or leakage currents, can change the scale factor of a high-voltage divider as well. In order to reduce leakage currents, insulators with high volume and surface resistance have to be used for the mounting structure of the resistors. A very suitable material for that purpose is PTFE. To prevent corona discharges, high field gradients must be avoided and the electric field inside the divider has to be homogeneous, with low field strengths. The resistors are arranged in a helix which is divided into several sections that are separated by copper electrodes to shape the field inside the divider. The copper electrodes obtain their potential from an independent secondary control divider in parallel to the high precision divider. This secondary divider also contains capacitances to protect the high precision divider against transient overload, when the voltage is switched on or off. The overall assembly is enclosed in a steel vessel filled with dry nitrogen. Besides enabling a temperature regulation of the system, this Faraday cage additionally screens the divider from external disturbances like RF noise.

Figure 9.1 displays the inner workings of the K35 divider assembly together with its equivalent circuit. The divider has been developed in cooperation with the PTB at the University of Münster for the KATRIN experiment. It is suitable for voltages up to 35 kV and features a stability of better than 1 ppm/month [84]. Together with the later developed K65 divider (suitable for voltages up to 65 kV, see [155]) these dividers will precisely measure the retarding potential (-18.6 kV) of the main spectrometer of the KATRIN experiment over the projected measurement time of five years. The K35 and K65 were also used to calibrate two high-voltage supplies providing the acceleration voltage for collinear laser spectroscopy measurements at the
The planned divider for the electron cooler at CRYRING will make use of high-voltage resistors of type VHA-518/11, manufactured by Vishay (see Figure 9.2, right). These resistors come from a batch of 200 resistors purchased in 2003 of which 100 were installed in the K35 divider. The remaining resistors are still of very high quality and it can be expected that the aging should benefit their long term stability. The expected precision of the divider is in the few ppm region.

9.3 Technical realization

The construction of the CRYRING precision voltage divider will largely follow the design of the KATRIN K35 divider with some modifications taking into account knowledge gained in the operation of the KATRIN dividers over the past years and taking into account the environment at CRYRING (e.g. integration into the slow control system).

The aimed for measurement precision in the ppm range translates into requirements on the individual divider components:

- The temperature and voltage dependence of the precision resistors has to be in the low ppm range.
- The warm-up behaviour of the resistors needs to be uniform and reproducible.
- To prevent corona discharges all HV parts need to have smooth edges and the overall setup should be operated with a dry nitrogen filling only.
- Leakage currents need to be negligible compared to the measurement current through the divider chain.
- To minimize external disturbances, the setup needs proper electrical shielding and has to be temperature stabilized on the 0.5% level.
- Voltage spikes, e.g. during power-on, have to be avoided in order not to damage resistors or other electronic components.
- Thermally induced voltages at the measurement points (thermocouples) result in measurement errors and have to be avoided.
- Electrical disturbances due to heaters and computer control installed in the divider have to be properly shielded from the measurement chain.

These requirements have already been successfully addressed in the KATRIN dividers and will be transferred to the planned CRYRING HV divider.

Photographs or technical drawing shown in the following sections are taken from the K35 divider and will be adapted wherever necessary in the technical design of the CRYRING divider.
9.3.1 Characterization of resistors

VISHAY’s “Hermetically Sealed High Precision Bulk Metal Foil Technology Resistors” consist of several resistor chips mounted inside a tinned brass cylinder, which is filled with oil for a better heat transport from the chips to the cylinder (see Figure 9.2, right).

![Figure 9.2](image) Left: compensation of the positive and negative temperature coefficients of two selected precision resistors. Right: inside view of the Vishay VHA-518/11 resistors.

Each chip is made out of a ceramic substrate with a meander-type metal film on it. Since both materials have different thermal expansion coefficients, the metal film reacts to the mechanical stress during temperature changes by a mechanical deformation designed to counteract the temperature dependence of the electrical resistance of the metal. The remaining temperature dependence characterized by the temperature coefficient of resistance (TCR) can have both negative and positive signs. To further improve on the temperature dependence, the TCR of each resistor needs to be measured with the aim to select resistor pairs of similar positive and negative TCRs compensating each other, such that the overall TCR of the resistor pair comes close to zero (see Figure 9.2, left). It should be mentioned that this compensation holds for a given operation temperature, which in the case of the KATRIN dividers is 25 °C.

An overview of the specifications of the VISHAY resistors is given in Table 9.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>resistance</td>
<td>1840 kΩ</td>
<td></td>
</tr>
<tr>
<td>tolerance of resistance</td>
<td>0.1 %</td>
<td></td>
</tr>
<tr>
<td>max. Voltage</td>
<td>600 V</td>
<td></td>
</tr>
<tr>
<td>TCR</td>
<td>±0.2 ppm/K</td>
<td>from 24 °C to 26 °C (T_{ref} = 25 °C)</td>
</tr>
<tr>
<td>voltage coefficient</td>
<td>&lt; 0.1 ppm/V</td>
<td></td>
</tr>
<tr>
<td>inductance</td>
<td>0.08 µH</td>
<td></td>
</tr>
<tr>
<td>capacitance</td>
<td>0.5 s pF</td>
<td></td>
</tr>
</tbody>
</table>

The characterization will be performed at the university of Münster by measuring the warm-up drift (WUD) of the resistors using the test setup displayed in Figure 9.3. Here the change of
resistance over time is measured after applying a defined voltage while the ambient temperature is kept constant.

For this purpose the resistor under test $R_{UT}$ is connected in series with a reference resistor $R_{ref}$ to form a simple divider circuit. The chosen reference resistor has a resistance of $R_{ref} = 36.8 \, \text{k}\Omega$, thus the thermal load of this resistor is negligible. In order not to compromise the measurement precision, the reference resistor is also a high-precision Bulk Metal Foil resistor from VISHAY. The warm-up drift has been shown to have a strong correlation with the TCR, but is much simpler to measure and has the further advantage that the resistors are tested under conditions of operation.

### 9.3.2 Mechanical setup

The primary resistor chain of the divider is subdivided into several storeys separated by copper electrodes to provide a uniform electrical field across the resistors of each level (see Figure 9.1, left). A technical view of one of these storeys is shown in Figure 9.4. The resistors of the primary divider chain are arranged in a helix structure which is isolated from the copper electrodes that enclose the individual levels, while the electrodes themselves are connected by HV resistors and HV capacitors of the control divider to provide a uniform electrical field within a level. The complete resistor tower is mounted on a stainless steel bottom plate and enclosed in a stainless steel vessel (see Figure 9.5) that allows to operate the divider with a temperature stabilized dry nitrogen atmosphere and shields the setup from electrical disturbances.

High voltages are coupled to the divider via an S150 HV connector on the top lid of the enclosure. On the bottom side feedthroughs in the CF100 blind flange provide connections for measurement signals, temperature sensors and the heat exchanger. KF 40 flanges on both top and bottom lids serve to exchange the nitrogen gas in the vessel. The electrodes are supported...
Figure 9.4. Setup of the resistor helix in one of the divider levels: 1. copper electrode, 9. POM rod, 11. and 12. isolated feedthrough, 13. connection for control divider, 16. precision resistor.

by Polyoxymethylene (POM) rods for stability and feature 9 PTFE rods per level to which the resistor helix is attached. The large central openings in each of the electrodes are connected by an acrylic pipe distributing the temperature stabilized gas flow over the individual divider stages. Below the lowest copper electrode we find the low voltage measurement points, the heat exchanger, fan and filter and the temperature sensors. The divider vessel is mounted in a support frame made of KANYA elements that houses in its bottom part a 19" rack for installation of the temperature stabilization and slow control system.

9.3.3 Measurement circuit

Primary resistor chain

For the primary resistor chain that serves as measurement divider about 80 precision resistors will be selected from the available 100 VISHAY VHA518-11 resistors. Given the maximum voltage rating of 600 V per resistor (see table 1), this would allow for a maximum voltage of the divider of 48 kV. The resistors are arranged in a helix structure mounted on PTFE rods and spanning over several storeys in the divider tower. The rotational direction of the helix changes from level to level, to reduce the overall inductance. The connections between the resistors are realized with rounded screw joints. This has the advantage that no soldering takes place on the selected resistors, which might otherwise slightly alter their characteristics and would thus affect the low TCR achieved by pairing resistors with opposite TCR values of nearly equal magnitude.

Secondary resistor chain

The secondary divider chain consists of HV resistors connecting the copper electrodes of the divider levels. Per level we have one resistor in the chain, whose resistance is chosen close to the summed resistance of the resistors of the primary divider chain on that level (44 MΩ resistors from Caddock type MX480 in the K35 divider). The purpose of the secondary divider chain is to supply a uniform electric field across the precision dividers installed in the individual storeys.
of the divider. Two parallel resistors with a lower resistance (90 kΩ from Caddock type MS260 in the K35 divider) are used to connect the lowest copper electrode to the grounded base plate of the divider.

**Capacitive divider chain**

The capacitive divider chain is formed by HV capacitors installed parallel to the secondary resistor chain and has the task to protect the divider from overcurrents induced by fast voltage fluctuations or voltage spikes occurring during switch-on. In the K35 divider VISHAY MKT 1816-225/117-2 capacitors were used with a voltage rating of 10 kV and a capacitance of 2.5 nF.

**Low voltage probe circuit**

The scaling factor of the HV divider is defined by the resistors installed in the low voltage part of the device. It is designed to match the full scale range of the attached precision DVM at the maximum operation voltage of the divider or, if several probe points are realized, at the most important input voltages occurring during the actual operation of the device. In case of the K35 divider two probe points were realized, one with a scaling factor of 3944 : 1 to bring the maximum operation voltage of 35 kV into the range of a 10 V precision voltmeter, a second one with a scale factor of 1972 : 1 for operation during tritium measurements of the KATRIN spectrometer at voltages around 18.6 kV. Figure 9.6 shows the equivalent circuit of the low voltage probe.
Figure 9.6. Setup of the low voltage probe points. The input voltage $U_{in}$ is connected to the output of the primary resistor chain. Two blocks of three 140 kΩ resistors each allow for divider ratios of 3972 : 1 and 1972 : 1.

The parallel arrangement of several resistors protects the input of the attached precision DVM in case of a failure of a single resistor. The resistors of the low voltage part are only charged with voltages in the several 10 V range and therefore do not exhibit significant warm-up induced changes of resistance. Nevertheless the TCRs of the resistors used will also be measured arranged such that remaining warm-up effects are minimized.

**Precision DVM**

The measurement of the output voltage at one of the probe points provided in the low voltage part of the precision divider is achieved using commercial precision digital voltmeters like the Agilent 3458A DVM (10 V range) or the Fluke 8508A DVM (20 V range). Possible voltage offsets or measurement gains of the DVM used have to be determined using a 10 V DC reference source like the Fluke 732A.

The DVM also determines the readout speed of the divider. In case of the Fluke 8508A DVM a measurement interval of 5 s (in fast mode) is required to obtain the highest precision of 8.5 digits. If lower accuracy is tolerable the readout time can be shortened, e.g. to 3.3 ms for 5.5 digits precision. The time constant of the resistor chain is negligible compared to the given readout times.

To investigate a possible voltage ripple at high frequencies, the capacitive divider chain will be equipped with a measurement tap that acts as a high pass filter. While high frequency signals are attenuated with a capacitive divider ratio of 6, the low frequencies are suppressed by a factor 2000. The cut-off frequency of the filter can be adjusted e.g. to 60 Hz. This allows to monitor noise or small voltage fluctuations on top of the high voltage applied to the divider using an oscilloscope.

Table 9.2 summarizes the preliminary specifications of the planned HV divider setup and the expected performance. The actual numbers may deviate slightly, depending on the final circuit layout.
Table 9.2. Preliminary specifications of the planned HV divider setup.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. voltage</td>
<td>35 kV</td>
<td>in primary divider chain</td>
</tr>
<tr>
<td>number of resistors</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>total resistance</td>
<td>147.2 M</td>
<td>in primary divider chain</td>
</tr>
<tr>
<td>load per resistor</td>
<td>8.5 mW</td>
<td>at 10 kV</td>
</tr>
<tr>
<td>divider ratios</td>
<td>∼ 2000 : 1</td>
<td>for voltages up to 35 kV</td>
</tr>
<tr>
<td></td>
<td>∼ 500 : 1</td>
<td>for voltages up to 10 kV</td>
</tr>
<tr>
<td></td>
<td>∼ 100 : 1</td>
<td>for low voltage calibration</td>
</tr>
<tr>
<td>calibration uncertainty</td>
<td>&lt; 5 ppm</td>
<td>of the scale factors</td>
</tr>
<tr>
<td>warm-up deviation at 35 kV</td>
<td>&lt; 2 ppm</td>
<td></td>
</tr>
<tr>
<td>stability</td>
<td>&lt; 1 ppm/month</td>
<td></td>
</tr>
</tbody>
</table>

9.3.4 Slow control

Power supplies and front end electronics for slow control are installed in a 19” rack below the divider vessel in a common support frame. Figure 9.7 shows the setup as it was present in the initial support frame of the K35 divider.

Figure 9.7. Slow control rack of the K35 divider. Left: front panel, right: back side.

The main task of the slow control system is the temperature stabilization of the divider and readout of the installed sensors.

Temperature control

The temperature control has the task to provide stable environmental conditions for the precision resistors. The warm-up due to electrical load on the resistors cannot be avoided, but is minimized by the pairing of resistors as described in section 9.3.1. However, a temperature change of the complete divider chain due to an unstable environmental temperature will change the overall resistance of the chain. In order to achieve ppm stability it is therefore necessary to stabilize the temperature inside the divider vessel on the ±0.1 °C level. In order to decouple the electrically powered parts of the heating / cooling system of the temperature control from the measurement points of the divider, the heat transfer to the vessel is realized using a cooling liquid. Inside the vessel the liquid flows through a heat exchanger and a gas flow along the
exchanger and through the resistor tower is driven by a 6 cm diameter, 24 V fan. Outside of the vessel, the temperature of the cooling liquid is regulated using a resistive heater and a Peltier cooler. These are controlled by a PID circuit that evaluates a PT100 temperature sensor located in the gas flow near the heat exchanger inside the vessel.

**Readout and computer control**

For computer readout of the sensors and operational control of the temperature stabilization a compact Field Point unit from National Instruments (cFP-2020) is used in the K35 divider. As National Instruments is no longer selling these modules, we will need to change to a more modern type of controller for the CRYRING divider. One possibility is to step over to the CompactRIO product line that is the successor of the compact Field Point from NI. Depending on the slow control environment at CRYRING one could also consider other types of real-time controllers in order to stay compatible.

The control unit continuously monitors and logs the operating parameters of the divider like temperatures, heating / cooling cycles and the voltage drop over the low voltage part of the secondary divider chain as a less precise measure of the applied high voltage. Furthermore it activates or deactivates the operation of the PID controller, the heating / cooling units, the cooling liquid pump and the fan unit inside the vessel. Communication with the controller proceeds via an optical - ethernet converter, preventing electronic noise via standard ethernet connections.

**9.3.5 Calibration**

The calibration of the newly build CRYRING HV divider will be performed against the existing K35 and K65 KATRIN dividers. These dividers have themselves undergone several calibration campaigns at the Physikalisch Technische Bundesanstalt Braunschweig and have thus not only scaling factors known on the ppm level, but also well known voltage dependencies and a well documented long term behaviour over a time span of many years (the first calibration campaign for the K35 divider took place in 2005). For details on the calibration procedure please see reference [157].

Moreover, a high-precision voltage measurement setup based on collinear laser spectroscopy is currently being developed in close proximity to GSI in the Institute for Nuclear Physics at TU Darmstadt. This will provide another opportunity for an independent calibration.

**9.4 Timeline**

Table 9.3 provides an overview of the expected schedule for characterization, design, manufacture and calibration of the precision divider ending with the commissioning at CRYRING.
Table 9.3. Project timeline for the divider development

<table>
<thead>
<tr>
<th>Task</th>
<th>Year Quarter</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tr>
<td></td>
<td></td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
</tr>
<tr>
<td>1 Characterization of precision resistors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2 Thermal design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Manufacture of electrodes and divider components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Assembly and test of the voltage divider in Münster</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Calibration using the KATRIN precision divider</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Integration and test at CRYRING</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
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</table>

— time of development  ⭐ — milestone.
## Appendix A

### SPARC Organization

<table>
<thead>
<tr>
<th>Working group</th>
<th>Coordinators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron / Positron Spectrometers</td>
<td>Xinwen Ma, Siegbert Hagmann</td>
</tr>
<tr>
<td>Electron Targets / Cooler</td>
<td>Carsten Brandau, Stefan Schippers</td>
</tr>
<tr>
<td>High Energy Single Pass Experiments</td>
<td>Alexandre Gumberidze, Angela Bräuning-Demian</td>
</tr>
<tr>
<td>HITRAP / Traps</td>
<td>Frank Herfurth, Wolfgang quint</td>
</tr>
<tr>
<td>Intense Laser / Ion Interaction (intense laser)</td>
<td>Vincent Bagnoud, Thomas Kühl</td>
</tr>
<tr>
<td>Laser Cooling</td>
<td>Michael Bussmann, Danyal Winters</td>
</tr>
<tr>
<td>Laser Spectroscopy</td>
<td>Wilfried Nörtershäuser, Rodolfo Sanchez</td>
</tr>
<tr>
<td>Photon and X-Ray Spectrometers</td>
<td>Martino Trassinelli, Heinrich Beyer</td>
</tr>
<tr>
<td>Photon Detector Development</td>
<td>Günter Weber, Andreas Fleischmann</td>
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<tr>
<td>Reaction Microscope</td>
<td>Daniel Fischer, Siegbert Hagmann</td>
</tr>
<tr>
<td>Ring Physics and Performance</td>
<td>Michael Lestinsky, Yuri Litvinov</td>
</tr>
<tr>
<td>Slow Ion / Surface Experiments</td>
<td>Angela Bräuning-Demian</td>
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<tr>
<td>Target Developments</td>
<td>Robert Grisenti, Alfons Khoukaz</td>
</tr>
<tr>
<td>Theory: Atomic Structure / Collision Dynamics</td>
<td>Stephan Fritzche, Andrey Surzhykov</td>
</tr>
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</table>

**Technical Support**

<table>
<thead>
<tr>
<th>Working group</th>
<th>Coordinators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Analysis and Simulations</td>
<td>Harald Bräuning</td>
</tr>
<tr>
<td>SPARC DAQ / Slow Controls</td>
<td>Harald Bräuning, Uwe Spillmann</td>
</tr>
<tr>
<td>SPARC Infrastructure</td>
<td>Angela Bräuning-Demian</td>
</tr>
</tbody>
</table>
Table A.2. APPA-SPARC collaboration board

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Representing</th>
</tr>
</thead>
<tbody>
<tr>
<td>F. Currell</td>
<td>Queens University of Belfast</td>
<td>UK</td>
</tr>
<tr>
<td>D. Fluerasu</td>
<td>NIPNE, Romania</td>
<td>Romania</td>
</tr>
<tr>
<td>M. Fogle</td>
<td>Auburn University</td>
<td>USA</td>
</tr>
<tr>
<td>G. Garcia</td>
<td>CSIC, Madrid</td>
<td>Spain</td>
</tr>
<tr>
<td>J. Gillaspy</td>
<td>NIST</td>
<td>USA</td>
</tr>
<tr>
<td>R. Hoekstra</td>
<td>KVI</td>
<td>The Netherlands</td>
</tr>
<tr>
<td>T. Kirchner</td>
<td>York University, Toronto</td>
<td>Canada</td>
</tr>
<tr>
<td>X. Ma</td>
<td>Institute of Modern Physics, Lanzhou</td>
<td>China</td>
</tr>
<tr>
<td>M. Pajek</td>
<td>Swietokrzyska Academy, Kielce</td>
<td>Poland</td>
</tr>
<tr>
<td>J. Rangana</td>
<td>CIMAP</td>
<td>France</td>
</tr>
<tr>
<td>J. P. Santos (deputy spokesperson)</td>
<td>Faculdade Ciencias Tecnologia / Univ. Nova Lisboa</td>
<td>Portugal</td>
</tr>
<tr>
<td>S. Schippers</td>
<td>University Giessen</td>
<td>Germany</td>
</tr>
<tr>
<td>R. Schuch (spokesperson)</td>
<td>Stockholm University</td>
<td>Sweden</td>
</tr>
<tr>
<td>V. Shabaev</td>
<td>St. Petersburg State University</td>
<td>Russia</td>
</tr>
<tr>
<td>Th. Stöhlker (local contact)</td>
<td>Helmholtz Institut Jena; GSI, Darmstadt; University Jena</td>
<td>Germany</td>
</tr>
<tr>
<td>A. Surzhykov</td>
<td>Helmholtz Institut Jena, University Jena</td>
<td>Germany</td>
</tr>
<tr>
<td>M. Trassinelli</td>
<td>Université VI (Pierre et Marie Curie), Paris</td>
<td>France</td>
</tr>
<tr>
<td>L. Tribedi</td>
<td>Tata Institute of Fundamental Research</td>
<td>India</td>
</tr>
<tr>
<td>A. Wolf</td>
<td>MPI-K, Heidelberg</td>
<td>Germany</td>
</tr>
<tr>
<td>T. Azuma</td>
<td>AMO Physics Lab, RIKEN</td>
<td>Japan</td>
</tr>
<tr>
<td>T. Zouros</td>
<td>University of Crete</td>
<td>Croatia, Greece, Hungary, Italy</td>
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</tbody>
</table>
Bibliography


<table>
<thead>
<tr>
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<th>Details</th>
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