Technical Design Report

SPARC@HESR: Instrumentation

for the SPARC Collaboration

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Preface

The facility for Antiproton and Ion Research, FAIR, [1, 2] will offer the highest intensities for relativistic beams of stable and unstable heavy nuclei. SPARC stands for “Atomic physics, quantum electrodynamics, ultra-high electro-magnetic field studies with beams of highly-charged heavy ions” and the central tools to address highly-charged heavy ions are inevitably trapping and storage facilities. If one considers the accessible ionic charge states and beam energies, the realization of the full version of FAIR will allow for the extension of atomic-physics research across basically the full range of atomic interactions [3]. SPARC experiments will investigate collision dynamics in strong electro-magnetic fields and fundamental interactions between electrons and heavy nuclei up to bare uranium. The central facility for SPARC experiments in FAIR was the New Experimental Storage Ring, NESR [4]. However, according to the FAIR Green Paper [5], the FAIR project will be realized in stages and the NESR belongs to the 4th module. Thus, its construction will inevitably be delayed. Therefore, the MSV caused a significant impact on the SPARC scheduling. This has triggered substantial efforts to investigate alternatives within the MSV, which would enable unique experiments with stored and cooled ion-beams in the realm of atomic physics. Apart from the MSV program at a dedicated fix-target experimental hall, APPA-Cave and laser-cooling experiments in SIS-100, new plans include the installation of the CRYRING at the presently operating ESR [6, 7] and the realization of an experimental program with relativistic ions beams in the High Energy Storage Ring, HESR [8]. The operation of the HESR with heavy highly charged ions has been investigated within a dedicated feasibility study [9]. The study included the investigation of the injection, cooling, acceleration of the ions in the HESR and the feasibility of performing SPARC experiments in terms of achievable luminosities, resolution, storage time, and background conditions. The FAIR ECE committee treated the study as a TDR, and evaluated and approved it in spring 2014. Furthermore, the TDR on the central instrument for SPARC experiments, the internal gas target, was also approved by the corresponding FAIR committees [10]. The present TDR comprises further installations at the HESR.
Structure of the present TDR

The present document is structured as follows:
- In the introduction chapter the science case is given as a short sketch, due to the fact that it is already endorsed by the FAIR committees;
- Chapter 2 is on the general requirements of the SPARC experiments in the HESR and updated ion-optical properties of the HESR;
- Chapter 3 is on the general purpose detectors;
- Chapter 4 is on the electron-positron spectroscopy;
- Chapter 5 is on the laser spectroscopy;
- Chapter 6 is on the X-ray polarimetry;
- The final chapter provides a summary of the costs and the time line;
- The structure of the SPARC collaboration and SPARC working groups is given in appendices.

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1. Physics case

To perform SPARC experiments in the HESR was first suggested in the FAIR Conceptual Design Report [2]. However, in the course of time, SPARC focused on the physics at the NESR [11]. Due to the MSV, the SPARC collaboration revised and worked the physics case for the HESR in very detail, which can be followed in the peer-reviewed publications [12–14]. Since the physics case of SPARC in the HESR is published and already endorsed by the FAIR ECE (2014), here we provide only a short description.

Collision times in the sub-attosecond regime

\[10^{-22} \text{s} < t < 10^{-18} \text{s}\]

The HESR was primarily designed for experiments with stored and cooled antiprotons [8]. However, it turned out that HESR offers unique features for atomic physics within the MSV of FAIR. A careful investigation of the ring parameters (injection, cooling, stacking, available place for equipment, beam emittance, ion optics, radiation safety, etc.) revealed a promising result that the ring is well-suited for operation with heavy ions without any significant ring modifications [9]. Stored and cooled beams at relativistic energies with \(\gamma\)-values ranging from 2 (injection energy) to 6 will be available. Such experimental conditions do presently not exist anywhere else in the world. Slowing down to energies as small as about 200 MeV/u would be possible as well, though this energy range is covered by the ESR.

The study of the dynamics of highly relativistic ion-atom collisions extends the frontiers of our present knowledge about the interaction of charged particles with extremely strong, rapidly varying electromagnetic fields. The transverse electric and magnetic components of the electromagnetic fields associated with the moving ions
increase proportionally with $\gamma$ and become almost equal in magnitude while the duration of the electromagnetic pulse decreases with $1/\gamma$. This is clearly a relativistic effect. In the relativistic domain, cross sections and impact parameter dependencies of elementary processes such as ionization, excitation, electron capture and pair production (see Figure 1) are dramatically affected by the strong dependence on the transverse electromagnetic field of the projectile [15–18].

As an illustrative example, Figure 2 shows the energy dependence of an electronic transition in a high-Z projectile as produced by Coulomb excitation. The displayed logarithmic increase of the cross section holds true for all other kinds of excitation-like processes such as ionization and $e^-e^+$ pair creation. A precise understanding of the relativistic quantum dynamics offers the key for the advance of our basic knowledge in the physics of strong fields [15, 20, 21]. Utilizing the high luminosity of the HESR facility, differential aspects of atomic processes at high energies that are beyond inclusive cross section studies become accessible, for which the electromagnetic interaction significantly differs from the low-energy regime. For example, by a measurement of the impact parameter dependence for both inner-shell ionization and excitation processes will enable the separation of the longitudinal and the transversal field contributions to the interaction [15, 20, 21]. For such investigations, the spectroscopy of photons as well as electrons and positrons is required. The photon emission gives the details of the specific

Figure 2. Reduced cross sections $\sigma/Z_t^2$ for $1s_{1/2}(\mu = 1/2) \rightarrow 2p_{1/2}(\mu = \pm 1/2)$ transitions ($\mu$ stands for the magnetic quantum number) in a hydrogen-like $\text{Au}^{78+}$ projectile ion as functions of the collision energy (full line). The partial cross section for the $\Delta\mu = 0$ transition (dashed-dotted line) decreases with the collision energy and then saturates. In contrast, the partial cross section describing transitions with $|\Delta\mu| = 1$ (dashed line) increases with the collision energy such that for energies beyond 5 GeV/u the total cross section for the transition to the $2p_{1/2}$-state becomes proportional to $\ln(\gamma)$ [19].
excitation mechanism in those fields. It also offers the special opportunity to study angular-resolved photoionization at very high energies by means of its time-reversed process, the radiative electron capture (REC). The search for recombination followed by \(e^+e^-\) pair production instead of photon emission should be mentioned as well [16, 17, 22–27].

This higher-order process, presumably requiring high collision energies, is similar to di-electronic recombination, but with the electron being excited from the negative to the positive continuum. The momentum transfer associated with the virtual photon field is small and therefore the correlated initial momenta of the bound leptons remain nearly unperturbed. While the field strengths produced in such collisions are orders of magnitude larger than those associated with other excitation techniques (e.g. synchrotron radiation, strong laser pulses, plasma pinch devices etc.), the duration of the interaction mediated by the relativistic ions of high-Z is much shorter \((10^{-22} s < t < 10^{-18} s)\) [15]. One goal of future experiments will be the measurement of the complete momentum balance in relativistic collisions both in transverse and in longitudinal direction by detecting the emitted electrons/positrons in coincidence with the recoiling target ion [2, 15, 18]. From measuring the momenta of the electrons/positrons and the recoil ion with high relative accuracy, direct information on the correlated many-lepton dynamics can be obtained [28]. Also, high-resolution electron spectroscopy will allow a unique isolation of the relativistic and quantum-electrodynamical contributions to the electron-electron interaction in strong fields.

It is feasible to bring laser beams into the HESR and merge them at the “missing-dipole” sections with circulating highly-charged ion beams either in co-propagating or counter-propagating directions, where the latter is obviously of a clear interest due to the high velocities of the ions [29]. This additional dimension of interactions with laser pulses with stored ions in the HESR can be expected to create access to new physics phenomena, both by precision spectroscopy and in the combination of static and dynamic electromagnetic fields. On the one hand, laser spectroscopy will enable studies for selected highly charged ion species and provides access to the properties of stable and unstable nuclei by atomic physics techniques. On the other hand, another class of experiments can be addressed in the HESR by the interaction of ultra-short laser pulses of high energy with highly charged ions in order to supply appropriate field strength. Thus the frequencies of novel laser and laser-driven sources in the visible and the x-ray regime can be boosted in combined experiments with heavy ions. By using soft x-ray lasers, as developed for experiments at ESR and NESR, laser spectroscopy of transitions at much higher transition energies will become possible. This is an exciting feature, since the successful measurements of hyperfine transitions, as the ones done in hydrogen- and lithium-like Bi ions in the ESR [29–32], might be extended to measurements of fine-structure transitions. Even pump/probe laser experiments for the investigations of decay properties of excited states of highly ionized atoms can be anticipated.

Finally, we summarize a selection of physics topics to be addressed at the HESR experimentally by the SPARC collaboration. In parentheses installations and parameters are given which are of special importance for the particular experiment.

- Pair-production phenomena: non-perturbation regime \((\alpha Z T \approx \alpha Z p \approx 1)\); multiple pairs (internal target, recoil spectrometer, electron/positron spectrometer) [16, 17, 22–27].
- Negative continuum di-electronic recombination (electron cooler, internal target,
electron/positron spectrometer) [16, 17, 22–27].

- Relativistic photon-matter interaction: radiative recombination and bremsstrahlung (polarization phenomena etc.; photon-photon angular correlation (electron cooler, internal target, x-ray spectrometer)) [20, 21].

- Target Ionization: correlated electron motion exploiting the ultrafast, extremely strong transient fields of relativistic ions (internal target, recoil spectrometer) [18, 28].

- Electron impact phenomena (electron cooler, electron spectrometer, x-ray spectrometer) [2, 11].

- Bound state QED and nuclear parameters: laser excitation of fine structure transitions in few-electron heavy ions (laser beam, beam lifetime) [2].

- Exotic nuclear decay modes in highly charged ions (electron cooler, x-ray spectrometer) [2, 33].

- Test of special relativity (laser beam, beam lifetime) [34].

- Parity Non-Conservation effects in high-Z ions and extreme electromagnetic fields (electron cooler, internal target, laser beam) [2, 35].
2. SPARC experiments in the HESR

2.1. Location of the SPARC experimental setup in the HESR

2.1.1. Optimization of the HESR ion optics for operation with heavy ions

The schematic illustration of the HESR is given in Figure 3 (see section 2.2).

The ion optical layout was optimized specifically for the HESR operating with heavy ions. In this operation mode the ions, which range up to bare uranium U^{92+}, will be stored, cooled, and accelerated. The optimization was conducted to achieve the following:

- Enhance the transverse acceptance;
- Maximize the dynamic aperture in order to have minimal beam loss during the beam storage;
- Satisfy the requirements of the physics experiments with heavy beams up to U^{92+}.

Two locations for an internal target have been examined in terms of the charge state separation in planned atomic physics experiments. The obtained optical functions are plotted in Figure 4. The calculated transition energy is $\gamma_u = 5.1$. The frequency slip factor for the injection energy 740 MeV equals $\eta = 0.27$. That means that the stochastic cooling studies which were carried out earlier for an optics with $\gamma_u = 6.2$ and the corresponding slip factor $\eta = 0.28$ [36] can still be applied for the current lattice.

The tune working point was found close to the linear difference resonance with a tune difference $|Q_x - Q_y| \approx 0.01$. The tunes $(Q_x, Q_y) = (5.81, 5.82)$ allow to significantly enhance the dynamic aperture. The maximum $\beta$-amplitudes values are around 90 m in both planes, which results in an increased by a factor of 4 transverse acceptance (comparing to the antiproton optics [8]). Table 1 summarizes the main parameters of the ion optical layout.
Table 1. A list of the parameters of the heavy ion mode optics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Injection energy, $E_{\text{inj}}$</td>
<td>0.74 GeV/u</td>
</tr>
<tr>
<td>Magnetic rigidity range, $B_{\rho}$</td>
<td>[5, 50] Tm</td>
</tr>
<tr>
<td>Kinetic energy range $E_k$ for $^{238}\text{U}^{92+}$</td>
<td>[0.17, 5.0] GeV/u</td>
</tr>
<tr>
<td>Transition energy, $\gamma_{tr}$</td>
<td>5.1</td>
</tr>
<tr>
<td>Slip factor at the injection energy, $\eta$</td>
<td>0.27</td>
</tr>
<tr>
<td>Tunes, $Q_{h}/Q_{v}$</td>
<td>5.81/5.82</td>
</tr>
<tr>
<td>Chromaticities, $\xi_{h}/\xi_{v}$</td>
<td>-7.3/-8.4</td>
</tr>
<tr>
<td>Maximum beta functions, $\beta_{x}/\beta_{y}$</td>
<td>91/90 m</td>
</tr>
<tr>
<td>Maximum dispersion, $D_{x}$</td>
<td>8.0 m</td>
</tr>
<tr>
<td>Transverse acceptance hor/ver</td>
<td>21.8/22.0 mm mrad</td>
</tr>
<tr>
<td>Dynamic aperture</td>
<td>15.6 beam $\sigma$</td>
</tr>
</tbody>
</table>

Figure 4. Optical functions of the lattice in heavy ion mode: horizontal amplitude $\beta_{x}$ (black), vertical amplitude $\beta_{y}$ (red), dispersion function $D_{x}$ (green). Path length $s$[m]: 0-156 m - north arc, 156-287 m - electron cooler, 287-443 m - south arc, 444-575 m - PANDA straight.
2.1.2. Location of the gas-jet targets and the resolution

A hydrogen gas-jet target is foreseen as an internal target for the SPARC physics experiments. Two different target positions are discussed.

A bare uranium beam with the applied electron cooling is modelled using MIRKO simulation program [37]. The *rms* values of the horizontal and vertical emittances with the electron cooling turned on are $e_x/e_y = 0.25/0.15$ mm mrad [38] ($e_x/e_y = 0.125/0.125$ mm mrad before cooling [39]) and the relative momentum spread value equals to $\delta p/p = 5 \times 10^{-5}$ ($\delta p/p = 5 \times 10^{-4}$ before cooling).

![Figure 5](image)

Figure 5. In yellow shown the propagation of the bare uranium beam after the electron cooler and its charge exchange reaction products after the interaction with the target. In red one can see the hydrogen-like uranium ions coming as a result of the electron-ion recombination reaction in the E-cooler. Remark: the height of the red peak, which corresponds to the ions coming from the electron cooler is extremely exaggerated. Its purpose is to show the transverse position and the distribution width of the corresponding ions in the detector.

Figure 5 shows the charge separation downstream the target, which is located in the south-west arc. It is clear that the peak resolution is high enough to separate the beams with different charge states. One can also see that the electron cooler, which is installed in the straight section upstream the target, as well as the long straight section might pose a problem because of ion recombination with electrons in the cooler and rest gas, respectively. When created, the hydrogen-like uranium ions coming due to this reaction might interfere the final results as shown in Figure 5.

The recombination rate can be significant since the HESR is not foreseen to be bake-able from the very beginning of its operation. The rest gas pressure of $10^{-9}$ mbar is specified. However, the arcs of the HESR are designed to be bake-able and, if enabled, the rest gas pressure down to $10^{-11}$ mbar can be expected.

Therefore, as an alternative, another location in the drift space in the north-west part of the ring will also be used. The advantage of this position, in comparison to the south-
west arc, is the absence of the electron cooler upstream the target as well as any long straight section. Therefore we do not obtain the "parasitic" ions coming from the electron-ion recombination. This results in much more clean experimental conditions.

Figure 6 shows the uranium beam separation of the three charge states after the target. Although there is only one bending magnet, which is available for the separation, it obviously is still enough to resolve the uranium charge states. As one can see from the picture the helium-like ions are slightly out of the physical aperture. Yet this problem is easily solvable via modulating the $\beta$-amplitudes in this region. That gives us a possibility either to decrease the separation split between ion charge states or to squeeze the beam slightly in the desired position or do both. We emphasize, that the achievable resolving power is minimal for uranium and is higher for lower-Z ions.

As discussed in the laser spectroscopy section, the coupling of lasers to the HESR in the counter-propagating direction is feasible at the northwest target position, while in co-propagating direction this will be done at the south-west position. Therefore, both locations shall be built such that the SPARC target station can be installed there.

2.2. Dedicated laboratory buildings

Since the SPARC experiments were not foreseen at the HESR from the beginning of the HESR building planning, several modifications of the building are necessary to accommodate SPARC infrastructure, which has to be placed outside of the ring tunnel. The latter is needed to access instruments during the running of the HESR, which thus have to be outside of the radiation blocked areas.
A schematic illustration of the HESR is given in Figure 3. The ring consists of two long straight sections and two 180° arcs nearly entirely filled with bending dipole magnets. However, there is a peculiarity in the lattice, that in order to increase dispersion the second and the pre-last dipole magnet in each arc is removed, thus offering about 4.5 m of space. Ion-optical simulations have shown that these “missing-dipole” locations are well suited to accommodate the SPARC internal target stations and the corresponding detector equipment.

In the insert of Figure 3 a SPARC setup, which is presently in operation in the ESR is given to illustrate an approximate view of the setup in the HESR, which will be optimized for the HESR energies and the available space. On both ends, the SPARC setup will be separated from the HESR by vacuum valves and will be replaced by an empty vacuum pipe during the high current antiproton operation of PANDA. The same holds for the detector setups after the bending magnets.

The HESR tunnel will be surrounded by 1 m of concrete and by an additional earth packet of about 3 m in thickness. Figure 7 shows a suggestion for a laboratory building on top of the tunnel in the south-west section of the HESR. The same building is also planned in the north-west section. The corresponding building change request has been submitted to the FAIR management.

The laboratory buildings will accommodate primarily the infrastructure for the gas-jet and laser experiments. However, also experiment electronics of various experiments can be located there. According to the radiation safety calculations, the holes of 20 cm diameter from the laboratory to the tunnel pose no additional restrictions from the radiation protection.

2.2.1. Requirements for the laser laboratory

The basic requirements for the laser laboratory are given in Laser Spectroscopy Chapter.

2.2.2. Requirements for the gas-jet infrastructure laboratory
The basic requirements for the gas-jet infrastructure laboratory are given below:

- **Size**: about 7×9 m, room height min 3 m;
- **Holes**: 3 holes into the tunnel, each 20 cm diameter (infrastructure from tunnel to lab, gas target pump controls and gases, experiment control and acquisition): preferably near the (outer) tunnel wall, depending on radiation safety. Since the tunnel is under low air pressure, the holes will be sealed after cabling;
- **Temperature**: stabilized to about 21°C, a variation of less than 1°C is desirable, filtered fresh air has to be provided continuously;
- **Electrical power**: switchboard 63 A 3 phase current, compressor 7.5 kW 3 phase current, and plugs 30×230 V/16 A, 8×400 V/16 A, and 4×400 V/32 A;
- **Network**: 20×LAN
- **Cooling water**: 20 kW, 15°C inlet, no purity requirements needed;
- **Gases**: target gases (Helium, Nitrogen, Argon, Krypton, Xenon) and Hydrogen;
- **Safety**: safety for hydrogen gas operation (security valve, alarm system in gas cabinet);
- **Cabinets**: gas cabinet for non-flammable gases inside the room. Space for 3 bottles. Security gas cabinet required for flammable gases, e.g. hydrogen, (if inside the room) or standard gas cabinet (if located outside the building);
- **Exhaust pump**: must be located at the wall or roof (area requirement 1 m²), required for the safe operation of flammable gases.
3. General purpose detectors

3.1. Intensity and revolution frequency measurement

Resonant Schottky pick-ups have proven to be indefensible tools in ion storage rings both for diagnostics and as experimental detectors. They can be used to determine beam parameters relevant to maintenance and commissioning of the storage rings as well as measuring masses and lifetimes of particles. As an example, the ESR resonant pick-up [40] has been successfully used in many in-ring experiments as a diagnostics tool for measuring beam lifetime [41], as a detector for measuring lifetime of short-lived nuclear species [42] and in experiments related to the borderline of the atomic and nuclear physics [43].

Longitudinal Schottky signals can be used to determine mean revolution frequency, frequency distribution, momentum spread and number of particles in a beam circulating in storage rings [44,45]. Due to their characteristic impedance R/Q at any given mode, resonant cavities can be used to pick up Schottky signals at their corresponding resonant frequency [46].

The design of the pick-up is based on a shallow circular cavity with beam pipes as shown in Figure 8. Its dimensions are as follows: diameter = 70 cm, depth = 10 cm and pipe radius = 5 cm. Simulations using Microwave Studio® show characteristic modes as shown in Table 2, with their R/Q maps [47] shown in Figure 9. It can be seen from the table that the Q value is very high. Of course this value is for an absolutely ideal case, no plungers, no couplers and perfectly conducting walls. After construction, the Q values and field distributions can be measured on the bench top. With a proper coupling, e.g. the so-called critical coupling the actual loaded Q value will be half of that. Further heavy loading can be applied to even further reduce the Q value if needed.

The cavity is made of stainless steel and is fully evacuated and contains no ceramic gaps. There is no need for copper coating. Plungers have vacuum tight bellows. An automatic shorting mechanism may be needed for very high current operations, which needs further investigations. Another – trivial and cost effective – solution, would be to...
remove the Schottky detectors together with the entire SPARC setup prior to the antiproton operation of the HESR for PANDA. Preferably, two resonant cavities will be placed in the HESR in the opposite corners to each other in order to allow for measurement of signals with different phase. For the purpose of frequency tuning, two plungers will be placed symmetrically 180 degrees from each other, allowing for 2 coupling loops to be place at the remaining quadrants. Tuning is possible in the range of 2 to 3 MHz at the fundamental frequency without deforming the shape of the magnetic field.

The characteristic impedance R/Q is directly proportional to the amount of energy particles loose to every mode. The full voltage drop across the cavity gap can be achieved theoretically only when the gap is infinitely small and the particle travels at the speed of light. The R/Q values of the above figures and table are for such a theoretical case. To account for the shortcomings related to non-relativistic particles and non-zero gap lengths, the transit time factor needs to be calculated. Transit time factor of the simulated cavity is shown in Figure 10(a). The square of this value is multiplied with the above values for R/Q to result in the actual R/Q for a given particle energy (velocity).

HESR utilizes the CF100 standard for the beam pipe in the region reserved for the SPARC detectors. With a radius of 5 cm the cut-off frequency for this pipe is calculated to be about 1.75 GHz. This is much higher than the fundamental and several higher order modes so that these preferably stay within the resonator region and do not propagate along the storage ring. In order to avoid unwanted transversal kicks to the beam during the operation, these higher order modes need to be damped. To this end, special HOM couplers should be planned. Also due to the small pipe radius, the region of extension of the electric field (see Figure 10(b)) into the pipes is comparatively lower compared to other designs such as the ESR resonator [46].
**Table 2. Fundamental and 2 higher order modes of the simulated cavity.**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Freq. [MHz]</th>
<th>$Q_{\text{unloaded}}$</th>
<th>R/Q at center [$\Omega$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>330</td>
<td>21465</td>
<td>104</td>
</tr>
<tr>
<td>2</td>
<td>518</td>
<td>26504</td>
<td>~0</td>
</tr>
<tr>
<td>3</td>
<td>700</td>
<td>31283</td>
<td>~0</td>
</tr>
</tbody>
</table>

A typical beam inside HESR is bare $^{238}$U$^{92+}$ with energies between 740 MeV/u and 6 GeV/u. These correspond to the beta range of 0.83 to 0.99. Comparing with Figure 10(a) one can see that there are no problems concerning the transit time factor. The single component cooled beam has a size of just a few millimeters with a momentum spread $\Delta p/p$ of $10^{-4}$ to $10^{-5}$ and number of particles from $10^9$ down to $10^3$. To use the device to measure the momentum spread of the beam both before and after cooling, proper measures should be taken into account to reduce the Q value as described above. For special physics cases sensitivities down to single particles are desirable.

### 3.2. Detectors for charge-exchanged ions

In the high energy storage ring (HESR) the ions will circulate at relativistic energies (from 0.74 GeV/u up to 5 GeV/u). Based on the experience gained by us during the design, construction, and the operation of the ESR [49,50] [147], as well as on the expert knowledge with Roman pots at CERN [148] we will design and manufacture movable Roman pots/pockets for the particle detectors. The Roman pots/pockets and the bellows will be separated by valves from the HESR beam tube, so that it will be very easy (if necessary) to modify or to replace the whole Roman pot/pocket with more sophisticated and/or versatile ones without breaking the HESR vacuum. The Roman pots/pockets for the first generation experiments will be furnished with thin 25 $\mu$m stainless steel windows to separate the inner volume from the HESR vacuum. This way, particle detectors, suitable for the given experiment, can be mounted and exchanged easily, depending on the need of the experiments. The first generation of experiments will be furnished with MWPCs (multi-wire proportional counters) and plastic scintillator counters. Based on the
ESR experience [49,50] the Ar-CO$_2$ MWPCs under atmospheric pressure ensure a very robust and reliable operation with no particular servicing required. The counters usually are used to detect ions that have changed their charge-state and, thus, their magnetic rigidity in experiments at the SPARC multiphase target in the HESR [10] (or – in the electron cooler [21]). These ions can be separated from the primary beam in the bending magnets downstream of the target and guided onto the particle detectors. Spatial resolution is needed, for instance, to distinguish between two different charges states; it will be provided in the case of the MWPCs by means of consecutive delay-line readout of the wires, which will be placed both in the vertical and in the horizontal planes. The minimal spatial resolution needed amounts to approximately 2 mm. If only timing information is required, fast scintillators have also been successfully used, especially for the experiments where a low background is of high importance.

The planned positions of the SPARC target at the HESR are shown in Figures 3, 5 and 6. Also shown is the calculation of the ion beam propagation through the magnets downstream of the target [48]. The calculations are done for the primary beam of bare uranium ($^{238}$U$_{92}^+$) and the charge-exchanged products ($^{238}$U$_{91}^+$ and $^{238}$U$_{90}^+$) due to interaction with the target. The calculations show the optimal position(s) where the particle detectors can be placed to detect the singly or doubly down-charged projectiles. The profile of the primary and the charged-exchanged beam at this position is shown in Figure 11.

![Figure 11. The profile of the primary and the charged-exchanged beam at the detector position shown in Figure 5.](image-url)

It is important to note that in case of a helium-like primary beam ($^{238}$U$_{90}^+$), the singly or doubly ionized reaction products ($^{238}$U$_{91}^+$ and $^{238}$U$_{92}^+$) can be detected symmetrically on the other side of the primary beam trajectory, due to the basically identical dispersion.

Figure 12 shows typical pockets and MWPC detectors used for the detection of charge-exchanged ions in the ESR.

In the high-Z region, the total cross section is still dominated by the atomic ones, even at ion velocities higher than the ones at ESR. We, thus, calculated the count rates for
several typical atomic collision scenarios, in order to check whether the detectors will be capable of sustaining the rates and the fluences.

Estimates for the expected count rates in the detectors for charge-changed projectiles:

**Example 1:**
Electron Capture in collisions of U$^{92+}$ ions with hydrogen gas target at 5 GeV/u:
H$_2$ target density ~ 3×10$^{13}$ particles/cm$^2$
expected number of ions: ~10$^8$
revolution frequency: ~500 kHz
cross section: ~1 barn

**The number of charge-exchanged ions (U$^{91+}$) in the detector:** ~1.5×10$^3$ / s

**Example 2:**
Electron Capture in collisions of U$^{92+}$ ions with xenon gas target at 1 GeV/u:
Xe gas target density ~ 6×10$^{12}$ particles/cm$^2$
expected number of ions: ~10$^8$
revolution frequency: ~460 kHz
cross section: ~1000 barn

**The number of charge-exchanged ions (U$^{91+}$) in the detector:** ~2.8×10$^5$ / s

**Example 3:**
Electron loss in collisions of Pb$^{81+}$ ions in collisions with N$_2$ target at 2 GeV/u:
N$_2$ gas target density ~ 8×10$^{12}$ particles/cm$^2$
expected number of ions: ~10$^8$
revolution frequency: ~500 kHz
cross section: ~140 barn

**The number of ionized ions (Pb$^{82+}$) in the detector:** ~5.6×10$^4$ / s

The Ar-CO$_2$-MWPCs can easily sustain count rates up to a MHz; above 100 kHz, however, the detection efficiency starts decreasing, especially for a high rate of highly localized particle hits. For experiments with count rates above 100 kHz we will use diamond detectors [51-55] metalized with 2 mm vertical stripes in order to have the necessary spatial resolution along. The stripes will be read out individually, in order to sustain the high count rates. (Since the signals of the diamond detectors are narrower than 100 psec, the count rate capability is defined by the bandwidth of the used electronic devices.)

Various types of diamond detectors (see Figure 13) have already been applied in experiments by the atomic physics group [56-58]. A polycrystalline CVD diamond based detector with a needed size of 5 x 1.6 cm can be relatively easily realized with a desirable position-resolution obtained either by segmentation (strips) or a resistive readout.

Other candidates for such experiments are RPCs, for which elaborated know-how is readily available in the GSI detector lab as well. Compared to the operation of the
diamond detectors, they will require more maintenance and servicing, so that the diamond detectors will be our primary choice.

Depending on the need of the future experiments, special detectors, as for instance stacks of PIN-diodes, Si-Strip, etc. will be used as well, e.c. for the Z-identification of the detected particles. A dedicated prototype of such detector is developed within the NuSTAR/ILIMA in-ring research program and is described in Ref. [149].

**Figure 12.** Detector pockets with 25 μm stainless-steel entrance windows and matching detector boards with multiwire chambers. Taken from [50].

**Figure 13.** Polycrystalline CVD diamond detectors used by our group for detection of relativistic heavy highly-charged ions. Left panel: four strip detector with 10×10 mm² stripes. Middle panel: 1D strip detector with 60×40 mm² active area, 32 strips with 1.8 mm width each. Right panel: a 30×30 mm² detector with concentric strips, developed for detection of scattered projectile ions in the ESR, bonded on a modified PADI chip.
We will use the standard DAQ of the GSI, which is based on VME. The number of channels will be rather modest – below one hundred for the particle detectors as a separate experiment. Similarly to the ESR-experiments, the signals of the particle detectors will be integrated in the DAQs of the particular experiments, which will need them for better definition of the processes studied (ionization, electron capture, etc.)
4. Forward electron/positron spectrometer

4.1. Science case

4.1.1. Positron spectroscopy

The origin of atomic electron-positron pairs in heavy-ion collisions at relativistic collision energies has been recognized as one central topic of quantum electrodynamics in extreme electromagnetic fields. For this reason kinematically complete collision experiments at relativistic energies in the HESR will focus on the determination of longitudinal and transverse momentum components of emitted electrons and positrons in coincidence with the recoil ion momentum in order to provide the most stringent tests of \textit{ab initio} theories.

In the first stage of this project, which is covered in the current project, we will focus on spectroscopic investigations of forward emitted electrons and positrons. For pair spectroscopy we shall distinguish two mechanisms in accordance with current most advanced theories:

a) In the first case the electron-positron pair is generated via collisional excitation of an electron from the negative continuum into a bound state of a collision partner.

b) In the second case the energy for generating an electron-positron pair is contributed by the recombination energy of a quasifree electron into a bound state of a collisions partner (see Figure 1).

4.1.1.a. Electron-positron-pair creation as excitation process

In collision processes,

\[ X^{q^+} + A \rightarrow X^{q^+} + A^* + e^+ + e^-, \]

free electron-positron pairs (free pair production, FPP) appear as a significant reaction product channel for collision energies above 1 AGeV. A closely related process, where the electron of the generated pair is captured into a bound state of the projectile (capture pair production, CPP),

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

is appearing at the same collision energy.

In a somewhat simplified picture these processes may be understood as follows: The Coulomb potential of the target perturbs the projectile at relativistic collision energies such that an electron from the negative continuum of the projectile is excited into the positive continuum or a bound state. The CPP is then identified by coincident detection of the emitted positron with the charge exchanged projectile.

It is thus possible to investigate in high resolution the energy distribution of CPP-positrons emitted at an angle of 0° using the proposed positron spectrometer. The investigation of the free-free pair production FPP via coincident electron and positron momentum- and angular distributions, however, is experimentally significantly more demanding, as it requires simultaneously very high angular acceptances and high momentum- and angular resolution of the spectrometers. For this reason a simultaneous
electron-positron coincidence measurement of the total differential cross section has never been accomplished even though it has been regarded as an important topic of very high theoretical interest. Since the experimentally achievable accuracy is increased for CPP as to FPP, the focus of the current project will be on this process.

In relativistic collisions of heavy ions dynamical pair creation was never studied in a storage ring, but was studied in „single pass“ configuration only, however, in two series of experiments: Belkacem et al. [59-62] used a solenoid spectrometer to investigate for projectile energies 0.4 AGeV – 10 AGeV cross sections for FPP and CPP. Vane et al. [63-65] studied FPP and CPP at projectile energies at 160 AGeV and 200 AGeV with a magnetic dipole-like spectrometer. Both series of experiments focused on analyzing scaling properties of the total cross section with projectile nuclear charge Z_p and target nuclear charge Z_t. Some energy- and angular distributions of emitted electrons and positrons were studied in low resolution.

The theoretical description of pair creation using 1st order perturbation theory was initiated by Landau et al. [66], Racah [67], Fano et al. [68], and Jabbur and Pratt [69]. First theoretical differential cross sections were reported by Becker et al. [70-72] and Ionescu and Eichler [73]. An independent theoretical method is based on the Weizsäcker-Williams-method of equivalent photons and was applied by Soff [74] to derive pair-production in U-U collisions, as well as by Baur et al. [75,76] to derive CPP cross sections at ultrarelativistic collisions energies in the ATeV range. CPP may contribute in this collision energy range significantly to beam losses in the heavy-ion colliders LHC and RHIC. For these ultrarelativistic collision energies, multiple pair creation cross sections were calculated by Baur [77] and Artemyev et al. [78]. Rumrich et al. [79] pointed to the non-perturbative character of pair creation.

Experimental data, in particular for high-Z targets, were interpreted by Eichler [80] and Ionescu and Eichler [81] as a pair creation process taking place either in the negative projectile continuum or on the negative target continuum, presumably resulting in distinguishing excitation-type and transfer-type pair creation. This assumption of strict separation of origin was later criticized by Lee et al. [82,83], and Condren et al. [84], who showed that pair creation in collisions of very heavy collision partners can only be consistently described by a two-center approach.

As reliable experimental data was only provided for total pair production cross sections, a comparison with theoretical calculations implied integration over all positron energies and emission angles. The new positron spectrometer in the HESR now for the first time opens the path to high-resolution energy-differential production cross sections for CPP, from threshold up to collision energies corresponding to γ=6. In the HESR highly charged projectile up to U^{92+} can be studied colliding with gaseous target atoms ranging from H to Xe. The advantage of storage rings over „single pass“ experiments derives from the revolution frequency of the coasting ions resulting in significantly enhanced luminosities and a background-free detection of charge-changed projectiles. The supersonic gas-jet target assures single collision conditions. A much more detailed insight into the dynamics of electron-positron pair creation is thus in reach. With high-resolution energy spectra of the positrons for the first time significant benchmarks for non-perturbation theoretical two-center approaches can be provided. Furthermore, the population of final ionic states can be determined for the first time.
4.1.1.b Electron-positron-pair creation as recombination process

It takes \(2m_e c^2 = 1022 \text{ keV}\) to create an electron-positron pair. In ion-atom collisions this energy can be acquired from recombination of a target electron into a bound state \(nl\) of the ionized projectile

\[ X^{q^+} + A \rightarrow X^{(q+2)^+}(nln'l') + A^+ + e^+ . \]

The electron of the electron-positron pair generated in this process is then captured as well into a bound projectile state \(n'l'\), the positron is emitted into the continuum. This process has been postulated by Artemyev et al. [85,86]. They derived the characteristic differential emission cross sections for this new channel called dielectronic recombination from the negative continuum NCDR. The corresponding positron spectra were calculated by Yerokhin et al. [150]. It was, however, not yet experimentally identified up to this date. The NCDR process is understood as an analogue to the radiative electron capture of a target electron into the projectile REC, where the free energy is converted into a photon [21]. For the NCDR the energy balance yields the kinetic energy of the emitted positron,

\[ E_{e^+} = \frac{m_e}{M_p} E_p + E_1^b + E_2^b - 2m_e c^2 + \gamma v_p q_z , \]

for a projectile energy \(E_p\) and final state binding energies \(E_1^b\) and \(E_2^b\). For the dominant process KK-NCDR, where both electrons are captured into the K-shell of the projectile, the respective binding energies for Uranium are \(E_1^b = 131.82 \text{ keV}\) [118] and \(E_2^b = 129.57 \text{ keV}\) [87]. From this a threshold for KK-NCDR of \(1.4 \text{ AGeV}\) is derived. The width of the positron peak is determined by the target Compton profile \(J(q_z)\). A unique signature of the process is the coincidence of a positron with a doubly charge-exchanged projectile.
The NCDR has not been observed up to this date, it thus may qualify for a „1st Day Experiment” at the HESR. The NCDR is of fundamental interest for two reasons: Firstly, the excitation out of the negative continuum may be studied in its dependence on the collision energy \( E_p \), which directly determines the energy available for producing the electron-positron pair. Secondly, the final 2-electron ionic state exhibits a particularly high sensitivity to study various contributions to the electron-electron interaction in He-like systems.

The collision energy range covered by the HESR is ideally suited to follow the collision energy dependence of the NCDR from threshold at 1.4 AGeV via its expected maximum at 2.2 AGeV up to approximately 5 AGeV. As the cross section for NCDR is significantly smaller than that for competing processes like REC, some extended considerations are in order on the experimental methods used. The main concern is the unambiguous attribution of doubly charge-exchanged projectiles and the positron detected in coincidence while background signals are kept at a rate small compared to the true signal. To achieve this goal it appears that the experimental setup has to meet the following conditions:

The cross section of NCDR scales linearly with the number of target electrons \( Z_t \). Najjari et al. [88] showed that for targets with \( Z_t \geq 54 \) the probability of a projectile to undergo simultaneously bound state pair creation CPP and a non-radiative electron capture into a bound projectile state NRC is larger than the probability for NCDR. The simultaneous CPP and NRC exhibit the same signature of a positron in coincidence with a doubly charge-exchanged projectile, the two competing processes would not be experimentally distinguishable. For this reason experiments studying NCDR need to restrict the use of gaseous targets to atoms with \( Z_t \leq 18 \).

The highest usable target area density is defined by the condition \( n_t \times \sigma_{NCDR} \gg (n_t \times \sigma_{REC})^2 \). The reason is that beyond a certain area density \( n_t \), the probability for a projectile to capture in two independent collision events an electron via REC while traversing the target zone, is larger than the probability for NCDR. For the system under consideration, \( U^{92+} + \text{Ar} \), this means \( n_t \ll 10^{-16} \text{cm}^{-2} \). Otherwise the double REC would produce an undesirable number of doubly charge-exchanged projectiles. This condition can only be met with gas targets, but not with solid targets. These strict conditions for luminosity can only be encountered in storage rings.

A necessary condition for unambiguous identification of low cross section reaction channels like NCDR is that the number of recombined projectiles hitting the charge exchange detector be minimized. Extensive ion-optical calculations show that the northwest arc of the HESR, where ions follow the entire northern dipole section before traversing the jet target zone, is the only suitable location for a setup investigating the NCDR (Figure 15). In the south-west arc, however, calculations show that ions, which recombine in the western straight section with the rest gas or in the electron cooler, cannot be separated sufficiently from the primary beam while traversing the dipole magnet which precedes the supersonic jet target. These charge-exchanged ions will also be observed by the charge exchange detector following the target zone. The north-west corner of the HESR thus offers the best background-free detection of doubly charge-exchanged projectile ions.

Once these three conditions are met, the cross section for NCDR and its projectile energy dependence can be studied by detecting singly and doubly charge-exchanged projectiles and determine the ratio. The single charge exchange is dominantly attributed to
the REC, which is theoretically well understood and can be applied in the normalization [21]. The technique to detect charge exchanged ions with near 100% efficiency has been well established at the ESR and can be applied at the HESR storage ring as well.

The estimate for achievable luminosity in the HESR is based on the following assumptions: number of coasting ions $10^8$, area target density of $2 \times 10^{13} \text{cm}^{-2}$ revolution frequency of the beam 500 kHz. From these numbers a luminosity of 1 m barn $^{-1}$s $^{-1}$ is estimated. For the collision system under consideration, $^{92+} \text{U} + \text{Ar}$, the total production cross section for KK-NCDR in its maximum at 2.2 AGeV is 0.5 m barn [85]. When summing over all final states which can be populated in the collision we find 0.8 m barn [86]. For comparison, the total cross section for K-REC at this collision energy is 56 barn.

Background processes to the signature of NCDR, i.e., doubly charge-exchanged projectiles, cannot be totally eliminated, as shown above. Therefore, a unique and indisputable proof for positive identification of the NCDR process can only be provided by coincident detection of the doubly charge-exchanged projectile with the emitted positron. The respective differential production cross section in the laboratory frame at 0° amounts to 2 m barn sr $^{-1}$ [150]. For the 0°-lepton spectrometer currently under development the solid angle is $1.2 \times 10^{-2}$ sr ($\theta_{\text{max}} = 3.6^\circ$), which yields a count rate of 1.4 min $^{-1}$.

The momentum distribution of the positron spectrum produced in the NCDR process is determined by the Compton profile $f(q_e)$ of the respective targets used. For Ar 90% of the Compton profile lies within $q_e^{\text{max}} < 6$ a. u., such that the relative energy width of the positron distribution will be $\gamma v_p q_e^{\text{max}}/E_{e^+} \approx \pm 0.05$. This determines the required minimum momentum acceptance of the spectrometer, i.e., the optimal compromise of high detection efficiency and high momentum resolution. A target with lower nuclear charge $Z_t$ results in a smaller Compton profile, however, on the expense of a reduced cross section and coincident count rate. As the NCDR (similar to the REC) does not exhibit any resonance features, the width of the Compton profile is not an essential parameter.

The new NCDR process was postulated by Artemyev et al. [85,86] several years after the single pass experiments on pair creation were performed by Belkacem et al. [59-62] and Vane et al. [63-65]. The experimental sensitivity of the spectrometers used at that time would not have been sufficient to detect NCDR in the single pass technique. Only storage-ring experiments with in-ring spectrometers will have the necessary luminosity and background suppression necessary. We conclude that a positron spectrometer implemented into the HESR will offer a unique opportunity to positively identify and study in detail the recently postulated NCDR process for the first time. The parameters of the spectrometer are determined by the theoretically predicted differential NCDR cross sections.

29
4.1.2. Electron spectroscopy

4.1.2.a. Quasiphotoionisation

For a detailed understanding of the ionization of atoms or ions in the relativistic regime via photons or charged particles (like electrons or highly charged ions) it is highly instructive to compare the resulting emission characteristics of emitted electrons and positrons, since corresponding ab initio theories for ionization/excitation predict characteristic correspondences and differences in the continua for emitted electrons and positrons and their collision energy dependence. The underlying reason is revealed when one considers that the theoretical treatment of these processes takes into consideration the fact that particularly in very fast collisions and at large impact parameters the electromagnetic field of a relativistic charged projectile resembles that one created by a photon pulse (Weizsäcker-Williams, equivalent photon approach). This equivalence is not given in slow collisions, nor at very small impact parameters, for that matter.

For low-Z ions or atoms this analogy of the charged particle impact ionization in the dipole limit (i.e., in the non-relativistic Bethe-Born approximation [89,90]) with ionization resulting from photoabsorption emerges in close correspondences in total ionization cross sections and can even be traced to the parameters of the angular distribution of the emitted “quasi-photo-electrons”. This has been successfully exploited.
in atomic and molecular spectroscopy [91]. This elementary, yet highly significant relation is not applicable in the relativistic domain for high-Z and the innermost orbitals. Here, new phenomena are expected. For low-Z ions a state of the art theoretical calculation [92] for ionization cross sections and angular distributions for low energy electron emission is compared for γ=2 and the highly relativistic γ=100 in Figure 16.

In this context our present project at the HESR will focus on experiments in the domain of high-Z ions and relativistic collision velocities of a profound theoretical interest. We will embark on an experimental study of the generalized oscillator strength (GOS) via the differential ionization cross sections in the limit of small momentum transfers Δk, i.e., at the „optical limit“ Δk→0. This GOS will be compared with the theoretical optical oscillator strength (OOS) and experiments for relativistic photoelectron emission. Experiments on the angular distribution of K-REC for H-like U^{91+} [21] have exploited similarly a far reaching relation between photoionization and REC. For the deep and interesting relation between GOS and OOS see [93]. The HESR will offer unique experimental conditions for experimental studies of differential ionization cross sections in the relativistic domain and for high-Z projectiles. Experimental differential cross sections in this collision energy range are significant as stringent benchmarks and reference data for new ab initio theories, in particular when the momentum transfer Δk dependence of the differential cross section permits to derive from the generalized oscillator strength in the limit Δk→0 the optical oscillator strength.

In ion-atom collisions, e.g.

U^{91+}(1s') + He → U^{92+} + e_{fast}(0°, Cusp) + e_{slow}(θ_{slow})

one may derive in inverse kinematics differential ionization cross sections for electron impact ionization of U^{91+}.

Kinematical calculations for this collision system at γ=5, as intended at the HESR storage ring, show that for Δk→0 in the laboratory reference frame, both electrons, measured in a kinematic coincidence can conveniently be detected using a combination of reaction microscope and imaging forward electron spectrometer (see Figure 17).
4.1.2.b. (e,2e) for 1s-momentum spectroscopy

Electron impact ionization

\[ e_0 + A \rightarrow [A^+(1s^-)]^* + e_1(E_1, \theta_1, \phi_1) + e_2(E_2, \theta_2, \phi_2) \]

with coincident detection of momentum-selected outgoing electrons has as kinematically complete (e,2e) spectroscopy transformed the field of atomic and molecular spectroscopy of electronic states due to its state selectivity for ionic final states and has exceeded in many applications Compton-spectroscopy, which does not permit to distinguish ionic final states. It is apparent that only (e,2e) spectroscopy can investigate state selectively QED- and relativistic contributions in momentum profiles, e.g. of 1s-, 2s-, or 2p- states of high-Z ions or atoms. This technique is illustrated most clearly in the symmetric non-coplanar configuration of the collision with \(|\theta_1|=|\theta_2|=45^\circ\), \(E_1=E_2\), \(\phi_1=0^\circ\), and \(0^\circ<\phi_2<90^\circ\). In this configuration the momentum density profile of the 1s wave function is detected via measuring the coincidence between outgoing electrons \(e_1\) and \(e_2\) as a function of the azimuthal angle \(\phi_2\). This is the geometric configuration generally applied in momentum spectroscopy, as here for fixed polar angle \(\theta\) the 1s-momentum density profile as function of momentum \(p\) may be derive directly from the differential cross sections as function of azimuthal angle \(\phi\) [94]. Frequently the sum angle \(\theta_1+\theta_2<90^\circ\) is used for independent determination of the inelasticity, i.e., the binding energy of the ionized electron under consideration.

For experiments in the HESR storage ring this configuration will not be used, as the symmetric non-coplanar geometry demands different kind of spectrometers, which is not compatible with the boundary conditions given at the HESR. We will consider the coplanar asymmetric configuration (see Figure 18), which has the advantage to also cover the biggest share of the total ionization cross section. This configuration offers at large collision velocities the efficient detection of state resolved momentum density profiles. The momentum profile of the ionized electron in the initial bound state can be measured in the coplanar asymmetric configuration exactly then, when for an angle \(\theta_b\) the „Bethe-ridge“-condition \(|k_b|=|K|\) is fulfilled [94], i.e., a negligible momentum transfer onto the recoil ion during the collision:

\[ A^{(Z-1)+}(1s) + He \rightarrow A^{Z+} + e_a(\theta_a) + e_b(\theta_b) + [He^+]^* \]
Here, $\theta_a$ und $\theta_b$ designate laboratory detection angles, and the He atom serves as source of quasifree electrons. From this collision one derives in inverse kinematics the electron impact ionization of an electron $e_b$ originally bound in the projectile by an electron $e_a$ originally bound to the target. The electron $e_a$ (see Figure 18) is emitted at an angle $\theta_a$ with very small kinetic energy out of the projectile into the projectile continuum and appears in the laboratory reference frame as electron cusp with very small angle with respect to the projectile.

Obviously, a momentum analysis of the projectile electron $e_a$ using a forward electron spectrometer is very attractive, as nearly the entire solid angle $4\pi$ (in the projectile frame) is covered. The ionizing target electron $e_a$ appears in the final state of the collision in the laboratory reference frame with low kinetic energy, as this collision corresponds to a collision of comparatively low inelasticity in the projectile frame. For this reason a reaction microscope identifying the vector momentum of this electron $e_a$ lends itself in combination with the forward electron spectrometer to an efficient coincident detection of electrons $e_a$ and $e_b$.

![Momentum diagram for (e, 2e) collision experiments: $k_0$, $k_a$, and $k_b$ are the momenta of the incoming, the scattered and the ionized electrons. $K$ is the momentum transfer, $p$ the initial momentum of the emitted (ionized) electron.](image)

Figure 18. Momentum diagram for (e, 2e) collision experiments: $k_0$, $k_a$, and $k_b$ are the momenta of the incoming, the scattered and the ionized electrons. $K$ is the momentum transfer, $p$ the initial momentum of the emitted (ionized) electron [95].

The momentum diagram of Figure 18 shows how the relationship between measured coincident angular distributions of the ionizing and the ionized electron, i.e., the differential ionization cross section, and the initial state one-electron momentum density profile of electron $e_b$ may be established. In Bethe-ridge kinematics the ionized electron has an emitter frame momentum $|k_b| = |K|$. In the scattering plane the vector $k_b$ thus describes a circle around the foot point of $k_0$ (of a sphere instead of a plane, if one wants to also consider scattering outside the plane). In a binary collision one has the vector relation $k_b = p + K$ for every emission angle $\theta_b$. It follows that each angle $\theta_b$ is attributed to a well-defined initial state momentum $p$ of the electron. This means that the probability measured for an electron at angle $\theta_b$ is proportional to the probability of an electron in the initial bound state to have momentum $p$. The measured triply differential ionization cross section is thus proportional to the one-electron momentum density $|\psi(p)|^2$. This opens a sensitive technique to identify for the first time momentum dependent relativistic and QED contributions in the 1s momentum density profile.
4.2. Technical details

The technical parameters of the positron/electron spectrometer are determined by the signature of the respective collision processes under investigation, which are intended for experimental study at the HESR. The immediate goal is the detection of positrons emanating in forward direction from the interaction volume in collisions of highly charged projectiles with atoms from the supersonic gas target. These electrons are first focused vertically by an iron-free quadrupole singlet lens, then deflected out of the projectile direction and momentum selected by a 60° magnetic dipole. With a further identical magnetic dipole and a subsequent vertically defocussing quadrupole singlet positrons are separated from background of electrons and focused onto a position sensitive positron detector. The dipole configuration (+60°/+60°-deflection or +60°/-60°-deflection) determines whether an achromatic or a dispersive optics is applied. This technique permits to focus all positrons within the momentum acceptance $\frac{\Delta p}{p} = \frac{\gamma+1}{\gamma} \frac{\Delta E}{E} \approx \pm 4\%$ either onto a point or as momentum dispersed strip onto the position sensitive detector. The geometric parameters of the spectrometer are listed in Table 4, the trajectories resulting from electron-optical calculations using MIRKO are shown in Figure 19.
These two geometric configurations of the spectrometer will permit to focus either on processes characterized by low cross sections or on high momentum resolution studies for higher event rate reactions. In both cases the horizontal acceptance for positrons emitted in the interaction zone under 0° with respect to the projectile amounts to 40 mrad, the vertical acceptance to 100 mrad. The angle- and momentum acceptance is defined by slits along the trajectory of the positrons within the spectrometer. Positrons with an energy up to 35 MeV can be momentum analyzed in the spectrometer, for an effective radius of curvature $r=240$ mm the maximum magnetic field strength is 0.5 T. Quadrupoles with a focusing strength $k=3.68$ m$^{-1}$ and a maximum field gradient of 1.6 T/m will be implemented. Iron-free quadrupoles will not exhibit a hysteresis and thus have a unique and reproducible dependence of the field gradient from the applied current in the coils. The magnetic field in both dipole magnets will be monitored and controlled by Hall probes.

In the first dipole of the spectrometer positrons are deflected $+60^\circ$ with respect to the primary beam, correspondingly electrons are deflected in the same field in the

Figure 19. (a) horizontal electron optics in the achromatic $+60^\circ/+60^\circ$-configuration, (b) horizontal electron optics in the dispersive $+60^\circ/-60^\circ$-configuration, (c) vertical electron optics.
opposite direction with respect to the beam. Even without optimizing electron optics the location at -60° following the first dipole can be used to implement an electron detector for diagnostic purposes. For experiments where high momentum resolution for electrons is desired the polarity of the B-field can be inverted and the positron detector can be replaced by a suitable position sensitive electron detector.

For minimal ionizing positrons within the intended kinetic energy range plastic scintillation detectors are detectors of first choice, as they exhibit a low detection probability for photons. An additional advantage of plastic scintillators is the very straightforward adaption to any given geometric configuration. A welcome further reduction of the background is obtained by using a ∆E-E telescope. The desired position resolution of the detector system, i.e. 1 mm, is accomplished by a design where the ∆E detector is configured using two wedge-shaped scintillation detectors (see Figure 20).

![Figure 20. Layout of the positron detector as ∆E-E telescope configured from plastic scintillators (cut through horizontal median plane). The rectangular area outlined by the dash-dotted line indicates the location of NaI-detectors for detection of annihilation radiation. They are positioned above and below the plastic detectors. The detection array for electron detection will be analogue to the positron detection system, however, without the NaI detectors.](image)

In the E-detector following the ∆E-detector all positrons must be stopped, in order to facilitate detection of photons from annihilation radiation in the NaI detectors situated above and below the scintillation detector system. For electron detection an identical system without the NaI detectors is foreseen. The thickness of the plastic detectors has of course always to be chosen in accordance with the kinetic energy of the leptons under investigation.

Particular attention has to be paid to the fringe fields of the magnetic dipoles which have a vertical gap of 120 mm (due to consideration of storage ring boundary conditions). These fringe field are not only relevant for optical considerations, but may also have an influence on the detection system. Since the there is no pole face rotation angle with respect to the reference orbit, the influence of the fringe fields on the trajectory is significantly reduced. Aberrations due to these fringe fields can be partially compensated by proper dimensioning the pole shoes and shaping the pole faces. In order to perform extensive Finite Elements (FE) calculations and using the OPERA and CST software packages, a preliminary 3D-version of the spectrometer was designed. Figure 21 shows an isometric representation of the construction.
Figure 21. Isometric representation of the 3D construction of the lepton spectrometer. Above: the complete spectrometer, however, without the quadrupole singlet on the entrance side of the first dipole and the exit side of the second dipole (see also Figure 19). Below: the spectrometer with the top half of the magnet iron yoke removed for a better view of the vacuum chambers. The CF-160 double-cross serves as location for slit systems, pumping ports and further diagnostics.
4.3. Work packages (WP) / Investments

The following work packages (WP) can be defined and are discussed in this section:

1) Definition of basic experiments (in close connection with theoretical experts)
   a. "First day experiment" NCDR
   b. Quasiphotoionisation / Momentum Spectroscopy

2) The final ion optical design (3-D FE Simulations with OPERA or CST)
   a. Magnetic 60°-sectors
   b. Quadrupoles
   c. Particle tracking
   d. Energy resolution

3) Specifications of the magnetic components (at the manufacturer)
   a. Magnetic 60°-sectors
   b. Quadrupoles

4) Verification of the design parameters by the GSI/FAIR Magnet division

5) Vacuum design
   a. Vacuum chamber
   b. Vacuum pumps
   c. Vacuum measurement

6) Development of detector systems
   a. Positron detectors
   b. Electron detectors
   c. Detectors for annihilation radiation

7) Determination of the Spectrometer Function
   a. Source measurements
   b. On-Line Program

8) Implementation at HESR
4.3.1. Rationale and general design considerations

4.3.1.a. “First day experiment” NCDR

This proposal is based on work by our colleagues from theoretical physics A. Surzhhykov (Helmholtz Institute Jena) and A. Voitkiv (Univ. Düsseldorf) on the NCDR process, which has not been verified by experiment so far.

HESR offer the unique possibility to prove this theoretical prediction, which is a milestone in the understanding of atomic physics under extreme conditions. The lepton spectrometer, proposed here, is therefore based on the energy- and angular dependent differential emission cross sections for positron emissions as predicted by the above theoretical work.

4.3.1.b. Quasiphotoionisation / momentum spectroscopy

The forward spectrometer described here, serves to measure fast leptons emitted from projectiles with velocities up to $\gamma \approx 6$. This focuses the emission of leptons from the projectile into a small forward cone. Hence, a large amount of leptons from atomic processes will be detectable in the spectrometer described here, which therefore is also appropriate as a more universal device for the investigation of atomic physics in extreme fields. It is intended to expand these calculations significantly in the first stage of the project in order to cover as many conditions, inherent to interesting atomic observation channels, as possible in the spectrometer design.

4.3.2. The final ion optical design with 3-D FE Simulations (OPERA or CST)

The spectrometer delineated in section 4.2 has been especially designed for the detection of leptons from the NCDR process. It is a combination of two quadrupole singlets with two 60°-sector dipole magnets (Q1-D-D-Q1), in close relation to the existing “imaging forward spectrometer” at ESR, which is a D-Q3-D-instrument. Like this one, the new instrument will also be suitable for the investigation of the other processes discussed above. In the frame of the present Grant by the German Federal Government (BMBF Verbundforschung), we have started a full 3-D finite-element calculation with particle tracking to verify the parameters of the spectrometer design, as described in section 4.2 and as depicted in Figure 21.

4.3.2.a. Magnetic 60°-sectors

A sketch of the magnetic dipole design is shown in Figure 22. In order to allow for the transport of a sufficiently large forward angular range, the gap of the magnetic sectors has an opening of about 120-140 mm (depending also on the final mechanical design of the vacuum chambers), to guarantee a free opening of 100 mm in vacuum as anticipated in the study in section 4.2. At a pole face size of only 268 mm the influence of fringing fields, which is not considered in the model calculations in section 4.2, will have a significant influence. We have therefore already started a study of the transport properties of the dipole magnets using the 3D-FE code CST®. Parts of the results will be discussed in this TDR. These studies will be continued to characterize the different modes of operation of the spectrometer and to form a basis for the experimental determination of the spectrometer function.
4.3.2. b. Quadrupoles

For the D-Q3-D-Spectrometer at ESR a special design of iron free quadrupoles with a vacuum pipe aperture of 150 mm diameter has been verified. The principal coil design of this system has been implemented into the 3-D FE-simulations. It is shown in Figure 23 together with pictures from the existing Q3 system. This model sufficiently resembles the properties of the technical structure of the real quadrupole singlet, which consists of a stack of 5 layers (printed on flexible PCB, which are separated by insulating layers). This structure is assembled around the CF-150 vacuum pipe of the spectrometer and cooled by a water piping.

For the purpose of the simulation discussed in this TDR, only one board is used, and the current is adjusted to meet the design values from the model calculations in section 4.2.
4.3.2.c. Particle tracking

Particle tracking is used to determine the spectrometer functions. In Figures 24 and 24 a first preliminary result is shown for the transport of leptons through the full spectrometer in the dispersive +60°/-60°-configuration (see section 4.2). In order to meet the conditions for an NCDR experiment, electrons with three fixed kinetic energies (4.7 MeV, 4.9 MeV, and 5.1 MeV, i.e. 4.9 MeV ± 4%), with a spread of the emission angle of Δθ = 2.5°) have been chosen for these simulations.

It is obvious, that the basic optical transport features are verified. One clearly sees a separation of the energies at the detector position (right scatter plot in Figure 24). Although the influence of horizontal fringe fields is reduced, because there is no inclination of the pole face with respect to the reference orbit (as e.g. for doubly focusing
sector magnets), the influence of the vertical fringe fields cannot be neglected and has to be taken into account for further refinement of the geometry of the pole faces. For the present simulations, no special geometric corrections of the pole faces have been applied. However, the basic reproduction of the transport properties by this study gives confidence, that the more or less classical design of the sector magnets will be a good basis for the design of the final systems (WP3). Hence, the estimates of costs are predicated on this design.

Figure 24. Typical simulation result of the transport of electrons with three fixed kinetic energies (4.7 MeV, 4.9 MeV, and 5.1 MeV, i.e., center energy ± 4%), with a spread of the emission angle of Δθ = 2.5°
4.3.2.d. Energy resolution

The energy resolution is determined by the position resolution of the scintillation detectors. Typical scatter plots as recorded for the position of the detector are displayed as inserts in Figure 24. The simulations show that the scintillation-detector-stack has to span an area of 12 cm by 25 cm for full detection of all particles. The parameters of the spectrometer have been set to the transport of leptons with energies 4.7 MeV, 4.9 MeV, and 5.1 MeV (which resembles the design transport band of ±4%). The opening angle of the lepton emission from a source at the position of the HESR-target has been chosen as 2.5°.

In Figure 26 the projection onto the horizontal axis is given. From the simulations the energy-resolution is derived as $\Delta E/E \approx 0.1\%$ for a two-dimensional position resolution of 1 mm. Taking the line-shape in Figure 26 into account, which is due to the fringing fields, a resolution of $\Delta E/E \approx 0.8\%$ (i.e., for a one-dimensional read out) is estimated, which may be improved by further refinement of the magnetic configuration (WP2).
Independently, the plastic scintillation detectors (E-detectors) provide an energy resolution for electrons/positrons of $\Delta E/E \approx 8\text{-}10\%$ at 8 MeV, which can be to suppress background. Despite the optical length of the spectrometer, which enables a clean energy selection already by the magnets, energy sensitive detectors will suppress background signal caused by particles scattered on the spectrometer pipe.

In a later stage of the project, more sophisticated detector systems like Si strip detectors, liquid Xe detectors, or detectors based on new solid-state materials may be considered. However, depending on the results of the proof-of-principle experiments, these systems will have to fulfill the requirements of a good time resolution for coincidence measurements with the down-charged projectiles.

4.3.3. Specifications of the electro-mechanical design of the magnetic components

4.3.3.a. Magnetic 60°-sectors

The mechanical design of the dipole magnets is standard, the fields are comparatively low compared to ion optics, and they do not have extraordinary demand on the quality of the material of the yoke. (In the simulations, pure iron (nonlinear) with a permeability of $1 \times 10^3$ has been used.)

4.3.3.b. Quadrupoles

Iron-free quadrupoles have been designed and constructed for the quadrupole triplet in the ESR spectrometer. The quadrupoles for the lepton spectrometer at HESR are simpler in the sense that they are only singlets; however, the fields have to be higher.

4.3.3.c. Power supplies

The first dipole has to be integrated into the control system of the HESR-ring magnets. It therefore has to be designed according to the specifications of the HESR magnets. It is meaningful to adopt this system also for the other power supplies.
4.3.4. Verifications of the design by the GSI/FAIR Magnet division

After delivery, the systems will be inspected by the magnet division of FAIR/GSI and field maps will be established as a basis of the online control and analysis program for the lepton spectrometer.

4.3.5. Vacuum chambers/pumps

The first part (Q1-D) of the spectrometer will be integrated into the HESR vacuum system. The design of the vacuum chambers, pumps and vacuum control therefore will be designed according to the HESR specifications with a basic UHV vacuum of $1 \times 10^{-10}$ mbar. An isometric sketch of the vacuum system is displayed in Figure 27. As the leptons of interest are minimum ionizing, the detector systems for the leptons will be positioned outside the vacuum. For this purpose the end flange of the Vacuum system will be equipped with a thin stainless steel window of, e.g., 50 µm.
4.3.6. Lepton detector systems

4.3.6.a. Positron detectors

For the exemplary collision system shown in Figure 14, the positrons from NCDR are predicted to have kinetic energies in the range of 6-7 MeV. Positrons of this energy ($\gamma_e \approx 13$) are minimum ionizing particles. Therefore, they can appropriately be detected in plastic scintillation detectors positioned outside the vacuum, after traversing a thin foil that separates the vacuum of the spectrometer from the detection area.

As was shown in Section 4.1.1.b, we expect for the NCDR an event rate in the order of 1.4 min$^{-1}$. Therefore, a good background suppression and a good time resolution for coincidence measurement with the down charged projectile is mandatory. The full detector will be set up as stack of $\Delta E/E$ detectors (see Figure 20), which are operated in fast coincidence to provide good suppression of the background by gamma radiation. As the kinetic energies of the positrons are high enough, the stack can consist of two or even more $\Delta E$-detectors followed by an $E$-detector. In this way, two layers of $\Delta E$-detectors can be used to verify two-dimensional resolution. The $E$-detector has to be thick enough to ensure full stopping of the positrons for detection of the annihilation radiation (see Figure 19(c)).

For minimum ionizing particles the energy loss (and hence the light output) depends only on the detector thickness. A combination of two wedge-shaped scintillation detectors, as it is shown in Figure 20, is therefore well suited, to determine the position of the lepton, by division of the integrated light output of both wedges. Since the signals from plastic scintillation detectors are very fast, also an analysis of the time of flight of
the light response on two sides of one scintillation plate can be considered for read out of the position. This method has the advantage that it is also suitable for very thin detectors. The appropriate technique will be determined in dedicated experiments.

4.3.6.b. Electron detectors

The forward spectrometer serves to measure fast electrons, emitted from the projectile. At a projectile velocity of $\gamma \approx 6$ the corresponding electron energies are $E_e = E_{\text{cm}} \pm E_{\text{electron}} \approx 3 \text{ MeV} \pm E_{\text{electron}}$. Here $E_{\text{cm}}$ is the kinetic energy of the electrons, which is due to the emitter movement; $E_{\text{electron}}$ is the electron energy in the projectile frame. This is still in the range of minimum ionization. Hence, also for the electron experiments the same strategy can be applied by detecting the electrons outside the vacuum in the stack of scintillation detectors as designed for the positron detection. Consequently the energy resolution for electrons will be comparable to that of positrons. However, since the production rate of cusp electrons is significantly higher than for positrons, the energy resolution of the measured spectra can be increased by narrowing the slits in the central dispersive plane of the spectrometer.

4.3.6.c. Annihilation radiation detector

The identification of positrons by their annihilation radiation, emitted upon stopping in the E-detectors is inevitable to suppress the ample background of secondary electrons. For this purpose two arrays of NaI gamma-ray detectors are positioned above and below the scintillation-detector-stack, spanning an area sufficiently larger than the scintillation stack in order to cover as much of solid angle as possible (see Figure 20). As the annihilation quanta are emitted back to back this geometry provides a high probability for the detection of both annihilation photons for optimal background subtraction. Appropriate NaI gamma-detectors are commercially available.

4.3.7. Determination of the spectrometer function

After specification and verification of the magnetic properties (see items 4.3.3. and 4.3.4.), and set up of the spectrometer, the spectrometer function (as already determined by the simulations) has to be verified by measurements with sources and at accelerators. Minimum ionizing electrons are available by, e.g., the $^{89}\text{Sr}$ –radioactive source. Alternatively the 2.5 MV van de Graaff accelerator at IKF can be operated in e-mode delivering beams of monoenergetic electrons up to an energy of about 2.5 MeV.

4.3.8. Computer control and implementation into the HESR infrastructure
The first quadrupole and dipole of the spectrometer plus the corresponding ion-optical correction elements are integral parts of the ion-optical ring structure hardware of the HESR. For this reason they are required to be at all times part of the control program of the HESR. The experiment control for the positron/electron spectrometer has to take this into account in implementation of its specifications for field scan cycles in experiments.

As the experiment is positioned in a radiation area, the spectrometer has to be operated and controlled by remote control from the experimental control room situated several 100 m away from the experiment. For this purpose a remote control program has to be set up in accordance to the standards at FAIR. It must also be ensured that parts of the equipment (first dipole and quadrupole) can alternatively be operated and controlled from the HESR control room, as they are integral part of the ring infrastructure.

4.3.9. Setup of the spectrometer at HESR or CRYRING

This step has to be coordinated with the time schedule of the FAIR Civil Construction and Accelerator timeline. The time given in the timelines graph is therefore the time, when the spectrometer will be ready for installation. Before its installation at the HESR, the spectrometer can be commissioned in CRYRING.
4.4.2 Timeline

As the Timeline for the construction of the HESR has been delayed, the funding of this project by BMBF has been postponed to the next funding period. Therefore the timeline for the construction of this spectrometer is shifted, however its design phase will be continued as soon as the project is approved. The timeline follows the FAIR timeline for experiments. Results of a study supported by BMBF during the present period (2012-2015) have entered into this TDR. In the table below we assume 0 as the time of the commissioning of the HESR. The numbers -4 to -1 are in years.

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<td>b</td>
<td>Quadrupoles</td>
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<tr>
<td>c</td>
<td>Particle tracking</td>
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<tr>
<td>5</td>
<td>Design and building of vacuum system</td>
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Milestones
5. Infrastructure for laser experiments

5.1. Introduction

Laser spectroscopy experiments have been successfully performed at the heavy ion experimental storage ring ESR since the early times of its operation. The first observation of the hyperfine transition in hydrogen-like $^{209}$Bi$^{82+}$ in 1994 [96] initiated the field of hyperfine transition measurements in heavy highly charged ions in order to test quantum electrodynamics (QED) effects in strong electromagnetic fields and was later followed by an analog experiment on hydrogen-like $^{207}$Pb$^{81+}$ [97]. Then, just recently, in 2011 and 2014 these kind of measurements were extended to measure the M1 transition in the ground state of lithium-like $^{209}$Bi$^{80+}$ [98-100] and to improve the measurements on hydrogen-like $^{209}$Bi$^{82+}$.

Other laser spectroscopy experiments that have been actively and successfully performed at the ESR during the last decade are an Ives-Stilwell-type test of Special Relativity (SR) performed on Li$^+$ ions at about 34% of the speed of light [100-103] and laser cooling experiments [104,105]. Furthermore, a measurement of the $1s^22s^22p\,^3P_0-^3P_1$ level splitting in beryllium-like $^{84}$Kr$^{32+}$ is under preparation [106].

Precision experiments such as laser spectroscopy at high energy storage rings profit from small ion beam phase space, for which beam cooling is of great importance. Laser cooling [107] has come into focus, because the laser cooling force increases with increasing beam energy and unprecedented low momentum spreads can be reached with this technique. Its experimental requirements in terms of laser beam transport, laser characteristics and optical detection are often similar to the requirements of pure laser spectroscopy experiments.

The measurement principle of all laser experiments performed so far is as follows: The ions of interest are stored at relativistic energies in the ESR. Therefore, thanks to the relativistic Doppler shift, the transition in the reference frame of the ions is shifted to the visible regime in the laboratory frame if the ions are excited by the laser in either the parallel or antiparallel geometry. This light is typically produced using conventional laser systems. The transition is then observed by monitoring the fluorescence emitted by the ions.

Table 9 Atomic systems investigated by laser spectroscopy at the ESR.

<table>
<thead>
<tr>
<th>Year</th>
<th>System</th>
<th>Transition</th>
<th>$\lambda_0$ (nm)</th>
<th>Ion-beam energy (MeV/u)</th>
<th>$\beta$</th>
<th>Spectroscopy</th>
<th>$\lambda_{lab}$ (nm)</th>
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<tr>
<td>1994</td>
<td>$^{209}$Bi$^{82+}$</td>
<td>Hyperfine, M1</td>
<td>243</td>
<td>200</td>
<td>0.57</td>
<td>Antiparallel</td>
<td>478</td>
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<td>1998</td>
<td>$^{207}$Pb$^{81+}$</td>
<td>Hyperfine, M1</td>
<td>1020</td>
<td>238</td>
<td>0.60</td>
<td>Parallel</td>
<td>532</td>
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<tr>
<td>2004/2012</td>
<td>$^{12}$C$^{3+}$</td>
<td>Electronic, E1</td>
<td>155</td>
<td>122</td>
<td>0.47</td>
<td>Antiparallel</td>
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<tr>
<td>2006/2010</td>
<td>$^7$Li$^+$</td>
<td>Electronic, E1</td>
<td>548</td>
<td>59</td>
<td>0.34</td>
<td>Antiparallel</td>
<td>386</td>
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<td>2011/2014</td>
<td>$^{209}$Bi$^{82+}$</td>
<td>Hyperfine, M1</td>
<td>243</td>
<td>400</td>
<td>0.71</td>
<td>Antiparallel</td>
<td>591</td>
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<td>2011/2014</td>
<td>$^{209}$Bi$^{80+}$</td>
<td>Hyperfine, M1</td>
<td>1555</td>
<td>400</td>
<td>0.71</td>
<td>Parallel</td>
<td>650</td>
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</table>
For each of these experiments dedicated laser systems had to be developed. This is strongly correlated with the transition type under investigation. For example, high energy pulsed laser systems that are able to produce about 100 mJ output energy are required to drive M1 hyperfine transitions in highly charged ions. For high-precision spectroscopy on allowed transitions, like e.g., in the Special Relativity test, only a few mW of laser power are needed but stabilization of the laser frequency is a critical issue. Therefore complex arrangements to stabilize the laser frequency are sometimes required. In addition, the relativistic Doppler Effect only allows for antiparallel scattering of laser light off the ions when considering laser systems with wavelengths longer than 200 nm. Thus, for laser cooling moderate bunching of the beam must be foreseen to counteract the laser.

With laser cooling, it is possible to bring all ions in a beam in resonance with a single frequency laser, thus reducing Doppler broadening and allowing for special experiments such as polarizing the stored ions by polarized laser light or reducing the reaction phase space when creating an internal target with high energy density by interaction of the ion beam with a droplet target.

Most laser experiments at the ESR have used fluorescence detection. Monitoring the fluorescence emitted by the ions is not straightforward. The fluorescence is expected to be isotropic in the reference frame of the ions, but in the laboratory frame the fluorescence is neither isotropic nor monochromatic. Due to the Doppler shift and the relativistic aberration, the fluorescence intensity and wavelength depend strongly on the observation angle.

The Facility for Antiproton and heavy Ion Research FAIR will enhance the possibilities for laser experiments offering in principle a much wider spectrum where laser spectroscopy on stored ions can be applied. Here, the kinetic energy of the ions will be available up to some GeV/u. Therefore the laser experiments can be extended from testing fundamental symmetries (like the test of special relativity) and fundamental interactions (like the test of QED), going across the extraction of fundamental nuclear properties (like nuclear magnetic dipole and electric quadrupole moments), to the application of lasers for cooling and ion preparation.

5.2. Physics Case

Heavy Highly Charged Ions (HCI) allow for a unique access into the physics of extreme atomic systems. True ‘few electron systems’ (1-4 electrons) with a highly charged nucleus are ideal candidates for a direct comparison between state-of-the-art atomic structure calculations and precision measurements. By far the most successful and efficient method to create these species, is the ‘stripper-foil method’ applied by the GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt, Germany. Here, ions, boosted to relativistic velocities (up to 90% of c) in the heavy-ion accelerator, pass through a thin foil target and exit as bare, hydrogen-like, helium-like, or lithium-like ions. Since its first operation in 1990, the combination of the heavy-ion synchrotron (SIS) with the experimental cooler-storage ring (ESR) has proven to be very versatile, productive, reliable, and has enabled many world-wide unique high-precision experiments, both in the fields of atomic and nuclear the simple electronic structure of such heavy few-electron ions provides ideal conditions for investigating the structure and dynamics of simple atomic systems in the widely unexplored domain of high nuclear charges and large electromagnetic fields. These conditions unveil relativistic, correlation and quantum electro-dynamical (QED) effects as well as detailed information on the nuclear properties. In this regard hydrogen-like, helium-like or lithium-like ions represent the simplest atomic systems of which the electronic structure can be calculated with high precision. As
such they represent an ideal test bed for state-of-the-art calculations. Because of the steep scaling of energies and field strengths with the atomic number Z, a precision measurement with high-Z ions provides unparalleled sensitivity to QED contributions and unprecedented deep insight into the physics of bound systems at the strong field limit.

During the last decade, also great progress was achieved in the field of high-power high-intensity lasers. As soon as the shot-to-shot reproducibility was sufficient for experiments, and the lasers could be operated for long periods of time, a whole new field of physics opened up. This makes X-Ray Laser (XRL), and XUV sources by High Harmonic Generation available for these experiments.

In combination with the Doppler shift of the stored ions as an example most Li-like $2s_{1/2} \rightarrow 2p_{1/2}$ transitions can be reached by relatively effective x-ray lasers allowing for studies of highly energetic inner shell transitions or the electronic structure of highly-charged ions (HCl). The latter ones constitute a dominant fraction of the visible matter in stars, supernovae and stellar clouds. For the understanding of those objects, precise knowledge of the emission spectrum is required. To picture the possibilities, Figure 28 (left) shows the transition energies and wavelengths of $2s_{1/2} \rightarrow 2p_{1/2}$ transitions (in the rest frame of the ion) as a function of the atomic number Z, for Z between 50 and 95. At FAIR such experiments will be possible to be performed at the HESR storage ring, where much higher ion velocities up to a Gamma factor of 6 can be reached. The unique combination of a heavy ion storage ring and an x-ray laser thus has great potential, and one could consider several candidate systems for a first experiment. The result will be a unique measurement of the $2s_{1/2} \rightarrow 2p_{1/2}$ splitting in a heavy Li-like ion, which is also a critical test of state-of-the-art atomic structure theory, and in addition the $2s_{1/2} \rightarrow 2p_{1/2}$ can be reached for mid-Z elements.

![Figure 28. Left: $2s_{1/2} \rightarrow 2p_{1/2}$ transition energies (blue) and wavelengths (green) for lithium-like heavy ions with atomic number Z between 50 and 95. Right: Doppler-shifted $2s_{1/2} \rightarrow 2p_{1/2}$ transition wavelengths versus Z. Holmium has Z=67 and its transition at 7.53 nm can, at the maximum energy of the ESR ($\beta=0.73$), be reached by an XRL with a molybdenum target ($\lambda=18.9$ nm).](image)

At the ESR, a series of successful experiments have shown the feasibility of laser cooling of stored ion beams to unprecedented low momentum spreads of $\Delta p/p \sim 10^{-7}$ [108], well below the momentum resolution limit of the best standard beam diagnostic instruments. This technique, which uses an anti-parallel beam of laser light scattered off the ions in a moderately bunched beam [109], is the most effective method for cooling the longitudinal momentum spread of highly relativistic ion beams. As such, it renders a connection to advanced accelerator physics. Moreover, laser cooling in principle can counteract intra-beam scattering and other heating effects, leading to beam crystallization [110]. Crystalline ion beams are the most brilliant beams achievable and are by themselves subject of research in plasma physics when studying large, low dimensional,
strongly-coupled one-component plasmas.

Currently, detailed atomic calculations are being performed to select ion species and transitions of interest. These then are checked against the ion currents reachable with ion sources available at HESR. In addition, the efficiency at which the selected ion species can be produced at the charge state required for laser cooling (fast, Dipole-allowed transitions) has to be estimated and the corresponding transport efficiency and beam life time. This is done in collaboration with the Beam Dynamics Group and the Ion Sources Group.

Based on a 257 nm laser source and the HESR magnetic rigidity of 50 T/m preliminary results indicate it should for example be possible to cool all Li-like ions within a Q/M range of 0.25 to 0.43, which results in a nuclear charge range from 22 to 34 (see Figure 29). First experiments will be performed using ion species, which are easily produced and stored at the required charge state. Discussions on specific precision experiments require more studies of the underlying atomic physics and the underlying accelerator requirements and are still ongoing.

![Figure 29. Estimated accessible systems for laser cooling in the HESR. The estimations are done based on a 257 nm laser source and the HESR magnetic rigidity of 50 T/m.](image)

5.3. Technical requirements

In order to facilitate the possibility of performing the variety of laser experiments, the corresponding infrastructure have to be supplied at the storage rings (HESR, SIS100 and CRYRING) in the years to come. In parallel to the installation and operation of the infrastructure described here, new techniques, like for example new sources of laser light, fluorescence detection devices and – alternatively – particle sensitive detection methods will be developed. The development of new lasers includes novel sources like soft-X-ray lasers or high average power XUV-laser [Jan Rothhard et al.] and specific lasers for the
In common for all of them, laser infrastructure is needed. This includes:

- Laser laboratory.
- Transport of laser beams.
- Pointing stabilization of the laser beams.
- Hardware for temporal and spatial overlap between the ion- and laser beams.
- Fluorescence detection system.
- Development of dedicated laser sources.

### 5.3.1. Laser Laboratory

Even though the laser experiments are going to be carried out at a specific place at the storage ring (the so called laser-ion interaction region) as indicated in Figure 30, a laser laboratory is required in order to setup and run the laser devices as well as to setup the optics needed to collimate and stabilize the laser beams. A laser laboratory offers the following advantages:

- **Safety** Laser beams are hazardous, therefore it is required to operate the laser devices inside closed rooms with restricted access including an interlock system which inhibits the laser system in case of unauthorized access.
- **Accessibility** Laser devices will be easily accessible in case of any planned (or unplanned) intervention. Optimization, relocking, repair etc. can be carried out without the necessity of interrupting the operation of the accelerator and/or other experiments.
- **Stability** Laser devices are sensitive to temperature changes, air pressure changes, vibrations, changes in electric power and dust. Therefore, laser laboratories are typically temperature stabilized and located inside a dust-free housing on a stable ground. Additionally the complete laser setup is located on an optical table, while electronics are usually connected to a specific network shielded from outward disturbances.

The laser laboratory has to be located as close as possible to the laser-ion interaction region (but preferably outside the concrete shielding blocks for reasons of accessibility) in order to keep the transport distance of the laser beams at an affordable length. Large distances increase the influence of vibrations, temperature and pressure changes on the pointing stability of the laser at the interaction region, even though an active stabilization system will be used. When considering high power lasers or short wavelength lasers transport through air can alter the beam profile significantly or prevent transport over long distances. Additionally having short distances saves not only laser power but also saves the installation costs because less optical devices are used for steering the laser beam between the laboratory and the interaction region at the ring. It especially saves installation cost in case the laser beam has to be transported through a vacuum pipe, which will be mandatory when increasing laser power and going to ultra-short wavelengths. A possible location of the laboratory is discussed in Section 2.2. It can be located either on top of the HESR tunnel or next to the HESR building. The final location
will depend on the Civil Construction department of FAIR.

Figure 30. Layout of the HESR at FAIR with the foreseen laser laboratory. The ions circulate in the ring in an anti-clockwise fashion. Cooling and bunching of the ion beams will be possible. An experimental station for SPARC experiments including a droplet target is foreseen between the first and second dipole magnet of the south-bend.

5.3.2. Dimensions of the laser laboratory

The minimum space required for the laser laboratory is 7 m x 9 m, with a minimum height of 3 m. Figure 31 shows a very simplified sketch of the room with the essential components needed to run a laser experiment: An optical table of 1.2 m x 3 m (and a height of 1 m) plus peripheral equipment can be located inside this space.

5.3.3. Basic requirements on the laser laboratory

The laboratory requires the following infrastructure.

- Solid ground, vibration-free (no double floor).
The room has to be temperature stabilized. A standard value is 21.0 ± 1.0 °C.

- Soundproofing better than 20 dB.
- Air conditioning and ventilation (DEU: Klimaanlage).
- Lighting (DEU: Beleuchtung).
- Nitrogen (low flow) for purging.
- Holes in the walls/floor (dependent on the location of the laboratory) for laser beams (see Section 5.4).
- Cooling water. See Table 10.

Table 10. Foreseen power dissipation.

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Power (kW)</th>
<th>Input (°C) / Output (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsed Nd:YAG, Ar-Ion</td>
<td>100</td>
<td>6 / 24</td>
</tr>
<tr>
<td>Ti:Sa, dye laser</td>
<td>5</td>
<td>6 / 18</td>
</tr>
<tr>
<td>Fiber laser</td>
<td>5</td>
<td>6 / 24</td>
</tr>
<tr>
<td>Nd:Glass amplifier</td>
<td>5</td>
<td>6 / 24</td>
</tr>
</tbody>
</table>

- Electricity (single and three-phase).
- Network. 10 x 10 GBit Ethernet LAN.
- BNC-cable connections (standard and SHV) between the laser laboratory and the interaction region as well as the detection region at the ring. Also other signals are important (electron cooler, RF-cavity frequency for bunching) and should be supplied to the laser laboratory as well as to the data acquisition room. Connections between the latter two rooms are also required.
• HV-BNC cable connection between the laser laboratory and the fluorescence detection region at the ring. For timing purposes, real-time measurements should be possible, so synchronization of different signals (e.g. laser pulse rise time relative to bunching frequency, photon arrival relative to revolution frequency, etc.) is essential.

<table>
<thead>
<tr>
<th>Amount</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>230</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>400</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>100</td>
</tr>
</tbody>
</table>

- Optical table with leg kits.
- Additionally rack systems need to be built around the laser table to house the electronics needed to run the laser system. Clean room requirements can be realized by mounting a laminar flow air cleaner on top of the laser table, incorporating appropriate lighting of the laser table, although measures such as additional clean room requirements to the lab itself are favorable.
- The laser laboratory should have its own low noise measurement power network which is shielded from outside networks, especially from the RF of the accelerators. This is important when considering precision frequency stabilization for cw lasers or high repetition Pockels cell drivers for pulsed lasers.
- The room needs to be declared as Class 4 laser laboratory. Laser goggles should be available for all laser systems used in a specific experiment and might vary from
setup to setup. Shielding from spurious laser light will be available by special curtains surrounding the optical tables and shielded pipes for beam transport.

- Illuminated laser warning light (located at the exterior of the entrance door) and door interlocks.

5.4. Transport of laser beams

Laser experiments performed at the storage rings are peculiar because the laser beams generated in the laser laboratory have to be transported outside this room to the interaction region at the storage ring, see Figure 32. According to the laser power and laser wavelength, they can be transported using either optical fibers or using optical mirrors through air. There are also experiments where the laser beams are in a wavelength regime or have such a peak power that they have to be transported in vacuum, in this case a vacuum pipe is needed. Typically the lasers planned to be used in this kind of experiments are classified as Class-4 lasers, this means they have to be transported in a safe enclosure.

5.4.1. Transport using optical fibers

Here the light is already enclosed. However, before the light is coupled into the main vacuum beamline of the ring, it has to be collimated in order to match the ion beam cross section. Therefore an optical setup has to be installed which will be located inside just before the entrance viewport of the ring.

5.4.2. Transport through air

In this case the laser laboratory and the storage ring cage will be connected by at least three holes with a diameter of about 200 mm. One hole will be used for transport of BNC cables and optical fibers, other for a vacuum pipe (see Section 5.4.3) to transport high-power laser beams and the last one to transport low-power continuous and pulsed laser beams. In order to avoid air flowing between the laser laboratory and the storage ring cage, an optical window with anti-reflection coating will be installed at this hole. Inside the laser laboratory the height of the holes has to be different than the human-eye height and inside the HESR tunnel it will be also different to the height of the main beamline. Figure 32 shows a very simplified cross-section view of the arrangement for the laser beam transport. The light generated by the laser in the laboratory is first lifted with a periscope. Inside the tunnel the laser beam is steered using optical mirrors until it reaches the laser-entrance window at the storage ring, the last two mirrors could for example be used to steer the laser beam into the main vacuum pipe of the ring. The isolation of the laser beams can be achieved simply with protective pipes in straight sections and cages at
the knee-points. The exact position of the pipes and cages will be studied and the final design will be provided first. In case the pipes cannot be fixed permanently inside the hall, a removable supporting system will be designed and it will be installed only during the laser beamtimes.

The last cage (cages) has to be aligned with respect to the main beampipe axis of the ring. Installation of additional target stations which are aligned with respect to the main beampipe axis can significantly simplify the alignment of the laser beam into the ring. The laser beam has to be dumped after it exits the ring pipe through the laser-exit window.

As shown schematically in Figure 32, the laser beam transport from the laser laboratory to the HESR will be carried out using motorized mirror mounts. Each mount consists of a 3 inch mirror holder with two motorized actuators and a 3 inch optical mirror. Additionally cameras will be installed at required places for diagnostics.

5.4.3. Transport in vacuum

The proposed laser vacuum beamline will have a total length of about 30 m and it has to support a beam diameter of 100 mm. Vacuum is approximately 10 mbar. The necessary installations for the injection of the laser beam into the HESR, and possibly also a device to convert the radiation into the XUV range, will be close to the interaction region.

Baseline specifications

- Max. Pulse energy: 12 J, Max. Average/DC power up to 2 kW.
- Laser beam diameter: up to 100 mm.
- Repetition rate: According to the laser system it can vary from 1 shot/sec to 1 MHz.
- Pulse duration: According to the laser it can vary from the 100 of fs to 10 of ns.
- Remote beam alignment.
- Remote beam stabilization.
- Camera diagnostics at all mirrors.
- The beam fluence has to stay below 1 J/cm² to avoid laser induced damage threshold.

In order to minimize the effect of beam transport, the image plane at the defining aperture of the laser system has to be image-relayed though the beamline up to the compressor.

The total propagation distance between the last image plane from the lab telescope and the target station is at maximum 50 m, where this distance can be shorter dependent on the laboratory building location. The idea driving the design is to limit the amount of
optical elements in the beamline. For this reason, a small turning box will be used to capture the beam coming from the laser laboratory and sending it along the HESR beamline. The same box will have the input lens to a vacuum telescope and a cross hair for alignment purpose. The goal of the design is to avoid any other elements along the HESR beam line. For this the image relaying telescope must have lenses with a focal distance of about 10 m.

With the afore-mentioned solution, the second turning box will be located in the HESR channel close to the target station and will comprise the vacuum tube exit window, a turning mirror, a cross hair and the second lens of the telescope on a translation stage. All these elements must be in vacuum and thus be fully motorized, controllable from the outside and camera diagnostics should be installed to optimize beam alignment remotely from the laser laboratory and HESR control room.

**Details for the beamline.**

The beam tube will use standard stainless steel ID100 vacuum tubes for the beam transport from the ESR hall to the HESR target area.

All Opto-mechanical components must be vacuum compatible. This includes the motorization of mirrors, cameras and beam alignment mechanics such as additional reference space filters, beam blocks and other installations required to optimize beam alignment.

The complete laser beam path between the laser laboratory and the HESR target station must be remotely controlled and monitored. In particular the beam path in the HESR tunnel area cannot be opened due to safety reasons. Starting from the exit of the IR laser, the laser beam is centered on a motorized target plate which is monitored by a camera. A following crosshair is used for aligning the beam to the HESR tunnel or further towards the HESR target station. This alignment can be monitored using the shadow of this crosshair and the crosshair on a nearfield camera in the laserlab.

A camera looking on an insertable monitor target is used for a rough alignment through the transfer beamline. The fine alignment of beamline in the HESR area is realized with two crosshairs that can be monitored on the camera box at the target location. The input camera box needs to be blocked during a shot with a motorized shutter.

Two motorized mirrors are used to align the beam to the x-ray chamber with its own diagnostics. Laser radiation leaking through the first of these mirrors is used for the exit beam diagnostics, which consists of an attenuator box with two translation stages to move
fixed filters, and a motorized half waveplate for continuous attenuation. In addition, there is a camera box with a near-field and far-field camera, and a single-shot autocorrelator for a measurement of the pulse duration.

For the mirror motorization two actuators are necessary for each mirror mount. The actuators considered here are a commercial stepper motor model from Newport. This unit is fairly standard for PHELIX and also at Bukarest.

**Crosshair / Target plate motorization**

The crosshair and target plate motorization is realized with DC motors and end switches similar to the system used at PHELIX. The motor is controlled via a so-called black-box unit, which was developed at PHELIX. The black-box itself can be connected to the PCS using either a National Instruments USB interface, or a Beckhoff bus system. The costs considered here would allow for both options.

**Beamline cameras**

A relatively cheap CMOS camera (such as “Imaging Source”) can be used here. A suitable objective lens needs to be used to fit the space constraints as well as magnification and field of view requirements. This camera needs to be connected to a computer via a FireWire interface. The FireWire cable length limitation of 4.5 m can easily be bridged with an active extension hub.

### 5.4.4. Point stability of the laser beams

Even after the laser system has been optimized, the laser beam profile and the transport have to be optimized such that the laser beam is overlapped with the ion beam. Variations and drifts of the pointing, position, temporal and spatial profile of the laser beam can still appear. They are produced for example by changes of the pointing of the laser itself, movements of the optic and optomechanics, thermal effects of the optics, air turbulences and vibrations due to vacuum pumps. Especially in time scales of days and because of the long-distance transport across several 10 m, one cannot assume that the pointing and position of the laser beam at the interaction region is passively constant. Therefore, in the laser experiments planned to be performed at the new experimental rings, an active position alignment and stabilization system has to be employed.

A commercial system ALIGNA by TEM Messtechnik has been successfully used in recent beamtimes at the ESR [111,112] and it can be further employed at the upcoming laser experiments at the new rings. It consists of the so-called 4D detectors, two mirror
units equipped with stepper motors and piezo actuators and a signal processing module. The control signal is produced in the module via a programmable control circuit which reads the 4D detectors signals and gives the feedback to the mirror actuators. In this way the drifts on the laser beam can be corrected.

![Diagram of a standard arrangement of the 4D-detector](image)

Figure 33. Scheme the position sensitive detectors within the active stabilization system.

A scheme of a standard arrangement of the 4D-detector is shown in Figure 33. It was taken from [112] and modified for the explanations given here. The main beam is split using a wedge (DEU: Keil). The reflected part passes first a lens and then a second wedge. The position of the lens is chosen such that the reflected laser beam is focused at the 4D angle detector (DEU: Winkeldetektor) and it is collimated at the position detector. Figure 3.10 in reference [111] shows a picture of a complete setup as it was used for example in a beamtime at ESR. A small reflection from the main beam is split several times and attenuated before it hits the detectors. The attenuation is needed in order not to damage the detectors. The signal generated by the detectors is then transported using long cables (at least 50 m cables in this case) to the laser laboratory where the signal processing module is located. The feedback signals are then sent (also using cables) to the actuators of the mirror units. One of the units is located on the optical table close to the laser system, while the second unit is located just before the position sensitive detectors. The software controlling the signal processing module has a self-learning option which allows finding the right feedback signals in order to compensate the drifts of the laser beam along the complete path up to the interaction region. Once the self-learning option has been executed, the stabilization system can be locked and any drifts will be automatically compensated.

This system configuration can be used for a for laser wavelengths in the visible spectrum, however if deep UV lasers are going to be used, then the respective detectors have to be acquired. Moreover, the use of pulsed laser systems at high pulse energies but low repetition rates or the combined use of cw lasers with pulsed lasers can be a challenge to beam stabilization. For special setups, especially for small (UV) wavelengths and

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1 Each detector is built in a modular box which is quite compact and therefore the arrangement can be modified to suit the experimental conditions.
pulsed systems modifications to the optics and detectors in the system must be possible. Besides having active stabilization, independent steering of the beam and the possibility for searching ion/laser beam overlap offline using well determined fix points will be employed, see below.

5.5. Beam Injection into the HESR

Once the laser beam is at the beam height of the HESR, it will propagate freely through the straight section of the HESR to the interaction region.

At the HESR the laser experiments are foreseen to be located at the SPARC target station in the Nord-West (NW) or South-West (SW) parts of the ring. Figure 34 shows schematically these regions. Ions moving in the counter-clockwise direction interact in the NW-section with the laser beam at a place located between dipoles 21 and 22, where the SPARC-setup is to be installed. Because of space constrains at the HESR-tunnel, the laser setup will have to be placed differently as in the case of the ESR. A place, marked in green in Figure 34 HESR-NW, has been requested for the laser setup. This region will be used for coupling the laser beams into the HESR. It can also house a compact station to convert light into the X-UV regime by High-Harmonic-Generation or a compact X-Ray Laser. The HESR beam line has a height of 1.4 m. Therefore the height of the optical table will have to be matched in order to bring the laser beam to this height. The length of the vacuum pipe crossing the dipoles Nr. 21 and 22 and the neighbor quadrupoles is about 21 m. The distance between the laser setup and the entrance of the beam line (laser input) at the south part is expected to be about 5 m. Here an extra construction, e.g. made of ITEM profiles, will have to be built in order to add and additional pipe to transport the laser beam. The design of this extra beam line will have to be coordinated and approved by the contact persons at the Forschungszentrum Jülich. At the exit of the beam line (laser output) the laser beam will have to be dumped because the laser beam line cannot be extended further than dipole Nr. 20.

The iron jokes of the dipoles Nr. 21 and 22 can only be separated by a maximum distance of 20 mm. Therefore this is the maximum vertical space available to accommodate a pipe for laser beams. Assuming a tube with a wall thickness of 1 mm, a distance of 18 mm will be available to couple the laser beam in the vertical direction. In the horizontal direction, it is expected to have a few millimeters more of space to steer the laser beam. At the SPARC setup the inner diameter of the vacuum pipe is about 90 mm. Superposition of the laser and ion beams can be achieved by a couple of the XY-scrapers planned to be installed at the SPARC-setup.

The arrangement in the SW-section is the same except for a mirror symmetry, see
Figure 34. Sketch of the Nord-West and South-West part of the HESR. The SPARC setup is located between dipoles magnets 21 and 22 for the NW-part and 23 and 24 for the SW-part of the ring. The beamline for laser beam injection extends outside these regions. The Nord-West part is foreseen for anticollinear spectroscopy while the South-West part for collinear spectroscopy.

The HESR is operating at a vacuum level of $10^{-9}$ mbar or better, which requires bakeable and metal-sealed components while the components of the beamline setup typically cannot be baked. The transition between and separation of the two vacuum sections is achieved on the one hand by the separation through windows or – in the case of XUV radiation – thin metal filters mounted on high vacuum valves, and on the other hand by a differential pumping scheme, which allows for the high pressure gradient between the $10^{-6}$ mbar of the XRL target chamber and the $<10^{-9}$ mbar of the HESR. Additionally, a bakeable glass window will be mounted inside a UHV valve to
permanently separate the vacuum sections during alignment with a visible laser beam.

Since only a small percentage of the laser photons will be absorbed by the ion beam in the interaction region, most of the XRL beam will propagate straight on and out through the exit port where it is sent onto a second XUV CCD camera to achieve and verify the correct XRL beam position. Due to the limited space this will require a dedicated vacuum chamber with a minimized mirror set-up. The installation of additional target stations which are aligned with respect to the main beampipe axis can significantly simplify the alignment of the laser beam into the ring. The laser beam has to be dumped after it exits the ring (through the exit window).

Figure 35. Cross-section of the XRL setup and input to the HESR.

Figure 36. Cross-section of the XRL beam output.
5.5.1. Synchronization of the laser pulse and the ion bunch

The laser pulses which have to interact with the ions in an HESR bunch at the right moment. Laser and the HESR can be seen as two independent clocks. To synchronize these systems would require a (rather expensive) synthesizer planed for further experiments. In the beginning a much easier timing scheme is suggested deriving a signal from the HESR buncher cavities. A similar strategy is engaged successfully at the ESR.

Precise timing results in the coincidence of ion bunch and laser pulse at the interaction region. While the ion bunch position can be derived from accelerator pick up signals, the arrival of the x-ray-pulses have to be determined in the interaction region by means of a photo diode.

Synchronization is also of interest when combining several pulsed laser sources and synchronizing them to the bunching frequency of the storage ring. Such a scheme is optimum when performing laser cooling of ion beams with large momentum spread as the combination of several laser pulses allows for spectral shaping necessary to achieve ultra-cold beams and avoiding heating of the beam by the laser. This effort is led by the group of Thomas Walther at TU Darmstadt and the groups at Technische Universität Dresden and Helmholtz-Zentrum Dresden – Rossendorf.

Trigger signals foreseen for laser and experimental diagnostic are created on laser side and send to external experiments preferably by fibers. For the planned experiment, such a fiber must be bought and installed.

5.6. Fluorescence detection system

Most laser spectroscopy experiments at the ESR have used fluorescence detection. Monitoring the fluorescence emitted by the ions is not straightforward. The fluorescence is expected to be isotropic in the reference frame of the ions, but in the laboratory frame the fluorescence is neither isotropic nor monochromatic. Due to the Doppler shift and the relativistic aberration, the fluorescence intensity and wavelength depend strongly on the observation angle. An efficient light collection was already taken into account in the first laser experiment performed at the ESR in 1994 [96] and a dedicated mirror system was
designed. The mirror has to be built inside the vacuum beamline and therefore it has to be compatible with high vacuum conditions of the ESR. While the first measurement on hydrogen-like bismuth and lead were performed at about 0.6c, the recent measurements on hydrogen-like and lithium-like bismuth were performed at about 0.71c. Figure 37a and Figure 37b show examples of fluorescence patterns emitted by different ions moving at different speeds.

Corresponding mirror systems, designed to detect the fluorescence in the respective case are also shown. For detection of the most forward emitted photons, a movable parabolic mirror with a central slit for the ion beam was constructed and successfully used in the LIBELLE experiment (see [99]). The geometry of the mirror was optimized to increase the signal to background ratio.

In the XUV spectral range, the forward emitted fluorescence can be efficiently detected by means of a similarly designed setup employing the detection of secondary electrons produced from a movable cathode-plate (see Figure 38). In this case a XUV-photon „hits“ the cathode and low-energy (<3 eV) secondary electrons are emitted. The electrons are guided by a combination of electric and magnetic fields onto a sensitive micro-channel plate (MCP) detector, where the event is registered. The whole assembly will be mounted and operated inside the ultra-high vacuum of the storage ring, which typically has a residual gas pressure of $10^{-11}$ mbar.

![Fluorescence pattern emitted by different ions species $^{207}$Pb$^{81+}$ ($\beta=0.60$), $^7$Li$^+$ ($\beta=0.34$) and $^{209}$Bi$^{80+}$ ($\beta=0.71$). Right: Corresponding mirror system use to collect the fluorescence.](image)
A first version of such a detector was developed and built by the group of Prof. Weinheimer (Uni Münster) [114] and is currently being tested in Münster. Further tests, with XUV and soft X-ray light, will be performed at the FSU in Jena. The HHG light sources available at the FSU Jena radiate down to wavelength of ≈ 10 nm and are thus well-suited to perform such tests. These tests are particularly important since absorption depth (for photons) and escape depth (for electrons) changes with the photon energy to be detected. Besides the „simple“ detection of the fluorescence rate, it would be very interesting to measure the spectral and angular distribution of the fluorescence light. The feasibility and efficiency of such sophisticated detectors will be subject of future research. Combined with high resolution photon arrival time measurements it will in principle become possible to reconstruct the ion phase space from the fluorescence signal. Such optical diagnostics can be used complimentary to standard beam diagnostics. A good example is laser cooling, where the fluorescence rate becomes highest at small momentum spread, when all ions are in resonance with the laser and standard means of measuring momentum spread, e.g. Schottky pickups, are limited in both detection efficiency and momentum resolution. Thus future detector development towards full spectral, spatial and temporal detection of fluorescence photons will be highly profitable both for precision spectroscopy and ion beam characterization.

Figure 37b. Fluorescence emitted by a Li-like Ni$^{25+}$. The rest frame transition energy is 55 eV. In the laboratory frame the forward emitted fluorescence is Doppler shifted to 525 eV. \( \gamma = 5 \) corresponding to 3.72 GeV/u
Figure 38. (Top) SIMION simulation of electron tracks in the XUV detection setup and (Bottom) photograph of the current setup (with external magnet coils indicated) [Uni Münster]

5.7. Laser Sources

5.7.1. CW Laser sources (tunable)

For both ultra-precise spectroscopy as well as laser cooling frequency-stabilized cw laser systems are of critical importance. In spectroscopy of highly charged ions, the wavelength of a resonance is usually not easy to accurately determine by theory. Moreover, the ion beam energy cannot be easily tuned by the precision required for accurate energetic overlap of laser frequency and transition frequency. Thus, a widely tunable laser system that can be stabilized relative to a frequency standard and deliver high output power over a broad frequency range is desirable.

A first design of such as system is depicted below and has been tested at ESR in laser cooling of C$^{3+}$ ion beams at relativistic intensities [114]. It is based on an external cavity diode laser (ECDL) that can be detuned relatively to a frequency-stabilized second diode laser. Complex control of diode current and temperature allows for mode-hop free detuning over several ten GHz in laser frequency and more. Feedback loops provide for optimum amplification and stable power output over the whole scanning range and for scanning times in the sub second range. As such a system operates in the infrared, additional frequency doubling with mode-locked cavities is employed.

As becomes clear from the schematic setup shown below, such a system is complex mainly due to the need for actively stabilizing and locking a variety of cavities in a feed
forward scheme. Thus, high quality electronic control is needed that can only be achieved if not disturbances in the electric power grid are present.

If going to UV or VUV wavelengths, the output of such a system is limited to below 1 W of output power by the frequency doubling cavity design as well as the damage threshold of BBO crystals. It moreover requires a clean and temperature stabilized environment for long-term operation. Still, access to the laser system is vital over the course of a beamtime.

In the visible, such systems can deliver output powers above 10 W. With the laser beam diameters envisioned at HESR, this should be more than enough so saturate most cooling transitions accessible at HESR. Nevertheless, for specific transitions the UV option would allow for going to transitions in very highly charged ions. However, the final choice of laser frequency and output power generally depends on the atomic properties, especially the life time, of the transition of interest.

For laser cooling, fast detuning of the laser frequency will enable the cooling of large momentum spreads. In a cw laser, the relative laser force momentum acceptance is usually comparable to the ratio of the natural linewidth of the transition to the transition frequency and thus orders of magnitude smaller than the momentum spread of a freshly injected ion beam. Scanning the laser frequency will consecutively bring ions of different momentum in resonance with the laser, thus reducing the momentum spread during the scanning time, which in all practical cases limits the laser cooling time.

![Figure 39. Schematic setup of a widely-tunable external-cavity infrared diode laser system developed by the group of Thomas Walther at TU Darmstadt. The tunable diode laser (ECDL 1) can be frequency-locked relative to an external reference (ECDL 2) and is then amplified in a fiber amplifier. The IR-light (1028 nm) is then subsequently frequency doubled to the visible (514 nm) and to the UV (257 nm) wavelength range.](image)

### 5.7.2. Pulsed Laser sources

While cw lasers are interesting for precise wavelength determination, pulsed laser sources are interesting in several other ways. First, they allow to cover a broad range of frequencies in a single laser shot, thus they are very well suited when performing
spectroscopy on a poorly known transition. Moreover, they can interact simultaneously with all ions in a beam of large momentum spread, as the Doppler shift of the transition frequency due to momentum differences in the beam brings the ions in resonance with different wavelengths of the pulsed sources. Finally, when considering high laser powers, pulsed sources can address transitions that can only be saturated at very high laser fluence and can be used to drive XUV sources that deliver pulses at ultra-short wavelengths.

For many setups, such pulsed systems have to be optimized for a certain center wavelength and pulse duration as well as repetition rate. At Technische Universität Dresden and in cooperation with Helmholtz-Zentrum Dresden – Rossendorf a first prototype of a disc laser system using a frequency-selective intra-cavity grating has been built and tested at the CSRe storage ring in Lanzhou, China. With such a setup, tuning of the central carrier frequency and pulse duration variation by two orders of magnitude using a spatial filter in front of the intra-cavity grating is possible. This design can be further optimized for applications by varying the pumping material. Currently extension of this system by a subsequent booster amplifier and a fast Pockels cell for MHz repetition rates is foreseen. Such a source best operates at pulse durations below 100 ps. For longer pulse durations between 100 ps and 50 ns other techniques developed by the laser group of Thomas Walther at TU Darmstadt are of great interest. Moreover, other options such as fiber laser systems could be studied in the future.

Figure 40. Prototype of a pulsed, diode pumped Yb:YAG/Yb:LuAG disc laser system consisting of a regenerative amplifier including an intra-cavity grating. The grating allows for both selection of the carrier wavelength and the pulse duration of the laser pulse. With a dedicated Pockels cell such a system can deliver up to MHz repetition rate. Diode pumping and a subsequent booster amplifier allows for energy efficient operation and pulse energies of a few mJ.

5.7.3. XUV Laser Sources

Besides large scale facilities such as synchrotrons and free electron lasers, only a few approaches for brilliant XUV sources exist. X-ray lasers have been demonstrated employing highly-excited multiple-charged ions as active medium. They can be produced in a laser-induced high-temperature plasma. Since such X-ray lasers are related to well-defined electronic transitions in the active medium they can provide high spectral purity. However, they are not wavelength-tunable and do not support femtosecond pulses. In
addition, due to the unfavorable scaling of the spontaneous transmission probability with the forth power of the laser frequency, extremely high pumping energy is necessary to achieve the required population inversion. Hence, these X-ray lasers have to be pumped by large-scale high energy lasers at correspondingly low repetition rates [115].

The process of high harmonic generation (HHG) provides an elegant alternative for generating photons within the extreme ultraviolet (XUV) and soft x-ray spectral region. Due to its outstanding properties the generated radiation is ideal for applications in spectroscopy, imaging and time-resolved studies. However, HHG sources so far suffered from the low conversion efficiency of the process, which is typically not higher than $10^{-6}$. Thanks to recent advances in solid state laser technology this drawback can be compensated by employing driving lasers with high average power. In particular, femtosecond fiber-based laser systems can provide average output powers of nearly 1 kW [116], which is three orders of magnitude higher than what is obtained from conventional solid state lasers, and pulse energies sufficient for HHG. In addition, the repetition rate of such lasers can be chosen to be as high as a few MHz, which suits very well to circulation frequencies of heavy ions in storage rings. Thus, an XUV source based on HHG with a high repetition rate high power fiber laser system appears to be a suitable instrument for exciting high-energy transitions and related spectroscopy on HCl.

![Schematic setup of the fiber laser based high power UV and XUV source including an oscillator, a pulse stretcher, an active phase shaper, pre-amplifiers, a diode-pumped high power main amplifier, a grating-based pulse compressor and additional frequency conversion the UV and XUV spectral range.](image)

Recently, a photon flux in excess of $\sim 10^{13}$ photons/s has been demonstrated in the XUV at a photon energy of $\sim 30$ eV [117] by employing a 0.6 MHz repetition rate 100W-class femtosecond fiber laser [106]. This world-unique system defines state-of-the-art in tabletop XUV sources and its potential will be extended into the soft X-ray region in the future.

A similarly fast development took place in the case of plasma-soft-X-ray lasers. Developments directed explicitly towards a source for spectroscopy at the storage rings resulted at a compact, highly brilliant source with moderate pump requirements.

Certainly, the novel XUV-lasers will enrich the experimental opportunities of the storage rings at the FAIR facility and enable access to groundbreaking studies on highest Z ions in the future. A design study will be performed in advance in order to clarify the most important physical and technical issues at the new facility:

- Simulations of the spatial and spectral characteristics of the fluorescence emission
- Design of an adequate detector
- Design of the interaction region and specification of the beam parameters
• Coupling of the XUV beam into the storage ring and implementation of the detector
• Design of the beam transport optics for the XUV-laser beam.
• Investigations on the spectral and temporal filtering of the fluorescence signal for highest possible signal-to-noise ratios

These studies (tasks) involve partners from University of Münster, HI Jena, FSU Jena, TU Darmstadt and GSI.
5.8. Time table

The overall work of the proposal covers a wider range of work packages, which will also require test experiments at the ESR, the CRYRING, and possible other installations, in particular the HICSR at Lanzhou. This has to be structured in detail according to the availability of these facilities. A tentative time-line is given below.

WP1: Pulsed and CW laser systems
Based on the experience gained with the pulsed laser design presented in Figure 40, starting 2015 the current system will be redesigned for a broader choice of pulse durations (1-100 ps). In late 2015 to 2016 a MHz Pockels cell will be installed to allow for repetition rates up to 1 MHz. From 2016 to 2017 it is foreseen to build a Booster amplifier to reach higher pulse energies in order to reach saturation fluences suitable for most transitions in highly charged ions. From 2017 on to 2018 temporal synchronization of the pulses to other laser sources and the accelerator itself is foreseen.


WP2: XUV laser sources
This work covers the following
• **Frequency conversion to the UV spectral range.** First experiments shall be performed with the driving laser being converted to the UV spectral range. The much higher conversion efficiency and consequently much higher average power will facilitate beam overlap and temporal synchronization. The frequency conversion in nonlinear crystals however suffers from thermal heating due to absorption in the crystal material. Thus intensive research should clarify which crystals and which configuration is suitable for high power operation. These investigations will be performed with already existing fiber laser systems by the group of Prof. Jens Limpert at the FSU Jena and the HI Jena.

• **Development of narrow band high harmonic sources.** Several approaches have been identified for the efficient generation of narrowband high harmonics. They will be investigated in parallel by the groups of Prof. Jens Limpert and Prof. Christian Spielmann at FSU & HI Jena. The most efficient methods will be implemented in the prototype of the XUV-source later.

• **Prototype of the high power XUV source for FAIR.** A prototype of the XUV sources for experiments at HESR will be developed based on the results of the first two work packages. It will be set up and characterized in the Institute of Applied Physics (FSU & HI Jena). This work is also supported by the INFLPR in Romania (V. Stancalie, D. Ursescu). All elements for remote control and turnkey operation will be implemented and tested at that stage already.

**WP3: Laser beam transport**

The beam transport optics for the UV and the XUV beams that shall be employed for experiments later are an essential part of the experimental setup. Initial tests of the beam transport optics can be performed at the already existing XUV and X-ray sources at the FSU Jena. The technical implementation of the laser beamlines at the HESR will be coordinated together with the colleagues from the FZ-Jülich. The construction of the laser beamline can then take place once the design study for experiments at HESR (WP6) and the complete infrastructure of the HESR (building and machine) are ready. This work package will also receive strong support from the INFLPR group in Romania (V. Stancalie and D. Ursescu).

**WP4: Fluorescence detection**

Based on the experience gained with the tests going to be performed with the detector shown in Figure 38 using the XUV and soft X-ray light at the FSU in Jena, a technical study for the possible detections systems able to detect photons with wavelengths ranging from extreme UV to X-ray (100 eV to several keV) will be carried out. The study will be coordinated by the University of Münster involving partners from GSI, HI Jena, FSU Jena and TU Darmstadt.

**WP5: Test experiments at ESR**

Before the HESR will be operational, the novel developments and instrumentation will be tested in a “real-world” environment at the ESR. These experiments will not only
uncover unforeseen technical challenges, but also provide first exciting scientific results on previously inaccessible transitions in HCI. The experimental campaigns will involve scientists from GSI, Universität Münster, HI Jena, Technische Universität Dresden, Helmholtz-Zentrum Dresden - Rossendorf and FSU Jena.

**WP6: Design study for experiments at HESR**

Experiments at the HESR will be performed in a different technical environment and at much higher gamma factors. Thus, a detailed study of all technical and experimental aspects is required including e.g. the laser / ion interaction, fluorescence emission and detection. Finally a design study will be made available as a guideline for first experiments at the HESR. The study will be coordinated by the group of Christian Spielmann and involve scientists from GSI, University of Münster, HI Jena and FSU Jena. In addition, laser cooling experiments will be conducted at the CSRe storage ring in Lanzhou to test the laser systems and detectors from 2015 to 2018. This will again involve most partners and will be driven by Helmholtz-Zentrum Dresden – Rossendorf and Technische Universität Dresden.

**WP7: Implementation and first experiments at HESR**

First experiments, amongst them the excitation of the 2s_{1/2}-2p_{1/2} transition in li-like uranium, and laser cooling of ion beams will be planned and setup according to the design report. In addition, experiences made in ESR experiments and experiments at external facilities such as the Institute of Modern Physics in Lanzhou will provide additional guidelines. Thus, new laser systems, detectors and the novel XUV-sources will be ready to be successfully operated once the HESR is operational. This involves scientists from GSI, University of Münster, HI Jena, Technische Universität Dresden, Helmholtz-Zentrum Dresden - Rossendorf and FSU Jena.

**Timeline for the different workpackages.**

The time is given in years relative to the year of the commissioning of the HESR, which is set as 0.

<table>
<thead>
<tr>
<th>Workpackage</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
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<tbody>
<tr>
<td>WP1: Pulsed and CW laser systems</td>
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<td></td>
<td></td>
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<tr>
<td>WP2: XUV laser source</td>
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<td></td>
</tr>
<tr>
<td>Frequency conversion to the UV spectral range</td>
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<td></td>
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</tr>
<tr>
<td>Development of narrow band high harmonic sources</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype of the high power XUV Source for FAIR</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>WP3: Laser beam transport</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design study (laser laboratory + laser beamlines)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
### 5.10. Collaboration

Within the FAIR collaboration, a large user group is established, distributed over the subjects Laser Spectroscopy, Intense Laser / Ion Interaction and Laser Cooling. More than 70 researchers world-wide are listed as participants for these subjects. A very active collaboration includes the Helmholtz Centers GSI, HZD and DESY, university groups from TU-Darmstadt, TU-Dresden, and the universities in Frankfurt, Jena, Mainz, and Münster. These groups have already initiated collaborative projects funded by the BMBF and the GSI Hochschulprogramm. Internationally active commitment by the IMP-CAS in Lanzhou (X.Ma), the INFLPR in Bukarest (V. Stancalie, D. Ursescu), university M.Curie and Sud in Paris (D. Ros, P. Zeitoun), and the University of Lisbon (M. Fajardo) is established.
6. X-Ray Polarimetry

6.1 Introduction

Position- and energy resolving detectors for Compton polarimetry and imaging in the hard x-ray regime are key instruments within the x-ray spectroscopy program of the SPARC Collaboration [11]. Within the last decade, the atomic physics division of GSI has developed and commissioned several of such 2D position sensitive detector systems, which have already proven to be an excellent tool for various applications in hard x-ray spectroscopy, see [119] and references therein.

However, when compared to conventional non-segmented, non-position-resolving x-ray detector systems, the segmented detectors show a roughly 5 times worse energy resolution performance of approximately 2.5 keV at 122 keV due to the use of room temperature preamplifier technology. This is a clear limitation for many applications. In spectroscopic applications this limits the resolving power for narrow lying x-ray lines and makes background suppression more difficult. Moreover, with respect to Compton polarimetry the mediocre energy resolution results in a low-energy threshold of approximately 70 keV for the complete event reconstruction of incident x-ray radiation [120]. Assuming an energy resolution well below 1 keV, this threshold could be lowered by roughly a factor of 2. In addition, the present systems have an upper energy limit between 300 to 400 keV for efficient Compton event reconstruction, which is given by the size of the active detector volume in a single planar crystal configuration and the more complex event histories of high-energy x-rays. All these limitations have to be overcome to fully exploit the capabilities of highly segmented hard x-ray detector systems within the frame of the SPARC experimental program. Therefore, two complementary projects are started.

The first project with the working title 'Cryogenic charge sensitive preamplifier readout for precision Compton polarimetry with planar Si(Li)- and Ge(i)-strip-detectors' is aiming for improving the energy resolution of segmented Si(Li)- and Ge(i)-strip detector systems by at least a factor of two, making these detectors suitable for x-ray polarimetry measurements starting from 35 keV and to reduce systematic problems like background suppression. The technical solution is the separation of the preamplifier in two stages. The first stage will be placed in the cryogenic environment close to the detector crystal to reduce significantly the thermal noise contribution. The second amplifier stage will be placed outside of the cryostat in the housing of the detector head at room temperature. This design strategy is similar to the ones employed in the gamma spectroscopy community, but due to the large number of detector segments we are facing tighter geometrical requirements and we work in a significantly lower photon energy range. Besides the geometrical restrictions, the new preamplifier design needs to be optimized for a low thermal load from the first preamplifier stage to the detector crystal, low noise, good linearity and excellent signal stability. The successful preamplifier design will be applied to a new Si(Li) polarimeter system, which is already financed and purchased by the University of Jena. Later also the existing 2D detector systems of the atomic physics division may be upgraded with the new preamplifiers.

The second project with the working title 'Imaging gamma-ray spectrometer' is focusing on expanding the energy range for Compton polarimetry to 1-2 MeV by building a highly versatile gamma ray imaging spectrometer for the future FAIR experiments. This spectrometer will be based on the principle of the Compton Telescope [121]. It will consist of two identical double-sided segmented germanium detectors housed in one
The detectors will be read out using sampling analog-to-digital converters. The analysis of the read out signals will be performed in two steps: first the stored detector pulses will be analyzed to extract the energies and positions of the interactions. The position resolution delivered by this method is 10 times more accurate than that defined by the raw detector segmentation. Thus, also complex event histories where one incident photon undergoes several Compton scattering events inside the detector can be reconstructed. At the second step, the reconstructed scattering events will be used to create the gamma-ray image of the target/source distribution and, using this information, to filter the radiation backgrounds. This spectrometer will be dedicated to the most technically sophisticated spectroscopy studies in the gamma ray regime, such as parity violation studies, lifetime measurements and polarimetry.

The outcome of both projects, namely ‘Cryogenic charge sensitive preamplifier readout for precision Compton polarimetry with planar Si(Li)- and Ge(i)-strip-detectors’ as well as ‘Imaging gamma-ray spectrometer’, will already be tested and employed in pilot experiments at the existing experimental facilities at GSI: the experimental storage ring ESR and the fragment separator FRS. Furthermore, future experimental setups, e. g. in the environment of the future HESR, will also be simulated using sophisticated multiple-purpose Monte Carlo codes as well as in test experiments at other facilities. As the HESR will store heavy ion beams at high relativistic energies, the x-rays emitted by these ions will be Doppler-shifted to the energy range of several MeV. The tests at Mainzer Mictrotron MAMI, where the gamma-rays in the MeV energy range are routinely available, are envisaged to simulate the experimental environment of the HESR ring at FAIR.
6.2. Physics Case and State-Of-The-Art Technology

In collaboration between the detector laboratory of Forschungszentrum Jülich, respectively its successor Semikon GmbH, and the atomic physics division of GSI several double-sided segmented detectors for two-dimensional imaging and polarimetry of hard x-rays were developed in the last decade. Recently, also the Helmholtz Institute Jena, the Institut für Optik und Quantenelektronik of the University of Jena and the Physikalisches Institut of the University of Heidelberg participated in the development and application of such detector systems. More specifically, within the SPARC collaboration the following highly segmented 2D detectors are currently available: Two identical position-sensitive planar Ge(i) detectors, that were built for the FOCAL crystal spectrometer [122,123] and a 2D Si(Li) detector, that was developed as a dedicated Compton polarimeter [124]. In 2014 a second Si(Li) polarimeter was ordered and shipment is expected for spring/summer of 2015. The most relevant technical information of the three detector types are presented in Table 16.

Table 16: Technical information on the three types of segmented 2D position sensitive x-ray detectors being available within the SPARC collaboration.

<table>
<thead>
<tr>
<th></th>
<th>Si(Li) polarimeter</th>
<th>2D Ge(i) detector</th>
<th>new Si(Li) polarimeter (ordered)</th>
</tr>
</thead>
<tbody>
<tr>
<td>crystal size</td>
<td>80 mm × 80 mm</td>
<td>70 mm × 41 mm</td>
<td>50 mm × 50 mm</td>
</tr>
<tr>
<td>active area</td>
<td>64 mm × 64 mm</td>
<td>56 mm × 32 mm</td>
<td>32 mm × 32 mm</td>
</tr>
<tr>
<td>crystal thickness</td>
<td>7 mm</td>
<td>11 mm</td>
<td>&gt; 9 mm</td>
</tr>
<tr>
<td>front-side segmentation (ground)</td>
<td>32 × 2 mm</td>
<td>128 × 0.25 mm</td>
<td>32 × 1 mm</td>
</tr>
<tr>
<td>back-side segmentation (HV)</td>
<td>32 × 2 mm</td>
<td>48 × 1.165 mm</td>
<td>32 × 1 mm</td>
</tr>
<tr>
<td>grooves between strips</td>
<td>ca. 50 µm</td>
<td>ca. 25 µm</td>
<td>&lt; 50 µm</td>
</tr>
<tr>
<td>operating voltage</td>
<td>800 V</td>
<td>900 V</td>
<td>?</td>
</tr>
<tr>
<td>delivered (year)</td>
<td>2007</td>
<td>2006 and 2011</td>
<td>spring 2015 (expected)</td>
</tr>
<tr>
<td>entrance window</td>
<td></td>
<td></td>
<td>0.5 mm Be</td>
</tr>
<tr>
<td>energy resolution (FWHM)</td>
<td></td>
<td>2.5 keV at 60 keV</td>
<td></td>
</tr>
<tr>
<td>time resolution</td>
<td></td>
<td></td>
<td>50 to 100 ns</td>
</tr>
</tbody>
</table>

Each of these 2D detectors consists of a planar crystal which is segmented into horizontal strips on the front and vertical strips on the back side, resulting in a pseudo-pixel structure. The working principle of these detectors is illustrated schematically in Figure 42. Each segment of the detector crystal is connected to its own charge sensitive preamplifier and a subsequent readout chain, thus acting as an individual detector which provides time and energy information for the local energy deposition. As long as the number of interactions is small and the local energy deposition differs sufficiently to overcome the limited energy resolution, it is usually possible to unambiguously assign a pixel-position to each energy deposition event within the detector crystal by combining the energy information from the front side and the back side. More specifically, when only one strip on each side of the detector shows a signal, the detector acts like conventional hard x-ray detector with the additional feature of position resolution. However, when more pixels are involved on both sides, under certain conditions a reconstruction of Compton scattering events is possible, leading to the application in Compton polarimetry.
Figure 42. Working principle of the two-dimensional position sensitive x-ray detectors: Each of the strips on the front side and back side of the planar detector crystal provides time and energy information for the incident photons. a) A single interaction, e.g., photoabsorption, affects only one strip on each side of the detector. b) A Compton scattering event, where the recoil electron and the scattered photon are detected at different positions within the detector, consists of two separated interaction that can be reconstructed. By combining the energy information on the front side and back side it is possible to assign a pixel position to each energy deposition event inside the detector crystal.

X-Ray Imaging
Background suppression using time and energy information

In a beam time with the FOCAL spectrometer in March 2006 at the ESR storage ring a 2D-Ge(i) strip detector was used for the first time behind the analyzing crystal to detect the reflex of the Lyman-α radiation emitted by Pb^{81+} [125]. The production of characteristic Lyman-radiation was performed by electron capture in collision of a beam of 219 MeV/u Pb^{82+} with a supersonic gas jet of Kr atoms. The down charged ion beam projectiles were detected in a downstream particle detector (MWPC). The photons were detected in the FOCAL spectrometer placed at a laboratory angle of 90 degree relative to the ion beam. The MWPC and FOCAL were running in coincident condition.
The x-ray position spectra recorded by the 2D Ge(i) detector are depicted in Figure 43. For illustration of the advantage of background suppression three different cases are shown. Figure 43(a) shows the integral position spectrum without any restriction to photon energy or arrival time. In Figure 43(b) the photons that were recorded in coincidence with down-charged ions are shown. The Figure 43(c) shows all events where the condition of time coincidence between FOCAL and the MWPC was applied and in addition a condition was set on the photon energy to be inside the range from 58 to 65 keV. The additional reduction of background events shows a clear fingerprint of the two Lyman-α lines and demonstrates the absolute need of energy-, timing-, and position-resolving detectors for these kinds of high-background measurements. Figure 43(d) is the projection of the position spectrum along the dispersion axis showing the nicely separated Lyman-α lines.

### Compton Polarimetry

#### Reconstruction of Compton events within a single planar detector crystal

As already mentioned, Compton polarimetry is another important field where 2D position sensitive detector systems are employed. Compton polarimetry makes use of the dependence of the azimuthal Compton scattering distribution on the linear polarization of the incident radiation. The differential cross section for Compton scattering is given by the Klein-Nishina formula:

\[
\frac{d\sigma}{d\Omega} \propto \left( \frac{\hbar \omega'}{\hbar \omega} \right)^2 \left( \frac{\hbar \omega'}{\hbar \omega} + \frac{\hbar \omega}{\hbar \omega'} - 2 \cos^2 \theta \cos^2 \varphi \right)
\]

with \( \hbar \omega' = \frac{\hbar \omega}{1 + \frac{\hbar \omega}{m c^2} (1 - \cos \theta)} \)

The energy of the incident and the outgoing photon is given by \( \hbar \omega \) and \( \hbar \omega' \) respectively. The polar scattering angle with respect to the direction of the incoming photon is denoted by \( \theta \), while \( \varphi \) represents the azimuthal scattering angle, which is defined relative to the polarization plane of the incoming photon (see Figure 44). The scattering of linear polarized radiation is more pronounced perpendicular to the polarization plane, whereas in the polarization plane appears an intensity minimum. In the experimental setup the
incident radiation undergoes Compton scattering in the position sensitive detector crystal. The scattering kinematics is measured by detecting the x- and y-coordinates as well as the energy deposition of both interactions, namely the stopped recoil electron and the photoabsorption of the Compton scattered photon. This position information allows for reconstruction of the azimuth angle $\varphi$ and the energy deposition of the Compton scattered photon as well as the Compton recoil electron, enabling calculation of the scattering angle $\theta$ [123].

Figure 44. Left: Illustration of the Compton scattering process Right: Azimuthal intensity distribution of 100 keV photons interacting with a Ge detector crystal. The data was obtained by a Monte Carlo simulation based on the EGS5 package [127].

For a precise determination of the detection efficiency of the 2D detector systems, especially with respect to their suitability as Compton polarimeter, we performed a beam time at the synchrotron radiation source ESRF. During the experiment at the high energy beamline ID15A we had access to photon energies of 60 keV up to 400 keV with a linear polarization of 98%. The detector was placed in the collimated (50 $\mu$m by 50 $\mu$m) and attenuated primary photon beam. The readout electronics of the position sensitive strip detector was set up in such a way that the energy and time information all strips can be readout simultaneous for each single strip. Using an event-by-event readout with the information of each event available we were able to identify and reconstructed the completely detected Compton events.

In Figure 45 are experimentally obtained position distributions of Compton scattered photons (azimuthal Compton scattering distribution) depicted. Each 2D-projection is related to a fixed Compton scattering angle $\theta$ which corresponds to a fixed energy $\hbar\omega'$ of the Compton scattered photons.
Figure 45. Spatial distribution (zlog-scale) of the Compton scattered photons, detected by a 2D-Ge(i) detector. The incident photon beam had an energy of 210 keV and was 98% linear polarized.

Figure 46: The intensity distribution of Compton scattering at 90 degree as function of the azimuthal angle $\varphi$ (radius 5 mm, red solid line: result of the Klein-Nishina formula).

To underline the excellent quality of this detector as polarimeter the intensity distribution of Compton scattering with $\theta$ at 90 degree shown as function of the azimuthal angle $\varphi$ is shown in Figure 46. In addition the Klein-Nishina formula for 98% linear polarized radiation is displayed as a solid line. The experimental results fit very well with the theoretical one.

During the last 5 years several very successful polarimetry experiments were performed by the SPARC collaboration using the dedicated Si(Li) Compton polarimeter. These measurements were focusing on the polarization of radiation emitted by radiative electron capture (REC) into the K- and for the first time also into the L-shell of U$^{92+}$, U$^{91+}$ and Xe$^{54+}$ [128,129,130]. In addition, we achieved by the simultaneous measurement of the angular distribution and the linear polarization of the radiation in the reaction plane of the experiment a model-independent and very precise determination of the M2-contribution of the radiative transition from the 2p$^{3/2}$ into the ground state (Lyman-$\alpha_1$ line) in hydrogen-like uranium [131]. Furthermore we showed in experiments with spin-polarized electrons on neutral gold atoms the polarization-transfer from the spin-polarized electrons
on the bremsstrahlung emitted by these electrons [132,133]. This is of importance as a diagnosis tool [134] of spin-polarized heavy ion beams, which are discussed and planned for the FAIR facility.

However, due to the limited energy resolution and to this related relatively high detection threshold (Compton recoil electron detection) we were limited to polarimetry experiments with incident photon energies above 70 keV (compare figure 47). This is in contrast to the pure physical limits of the present polarimeter system. If we assume a negligible noise contribution to the measurement process we could perform efficient polarization measurements down to approximately 30 keV of incident photon energy [120]. Thus, to use the polarimeter most efficient, the electronic noise of the charge sensitive preamplifiers of the detector readout electronics has to be reduced significantly. The same is true for the second already ordered Si(Li) polarimeter (compare Table 16).

Figure 47. Efficiency of the existing Si(Li)-detector in the use case as Compton polarimeter [120]. The electronic noise of the used room temperature charge sensitive preamplifiers define the lower spectroscopic detection threshold of approximately 7 keV. This sets the lower limit for the detection of the recoil electron in the Compton process, resulting in the lower threshold for Compton polarimetry measurements of roughly 70 keV for the energy of the incident photons.

**Gamma-ray Imaging and Polarimetry**

*Reconstruction of gamma tracks in a stack of several planar detector crystals*

The technique of Compton imaging was proposed in 1973 to be used on space satellite mission for gamma-ray astronomy. It was implemented in one astrophysical mission COMPTEL — the Compton telescope on board of Compton Gamma Ray Observatory (1991-2000) [121,135]. They are also applied in the Nuclear Compton telescope and in the upcoming ASTRO-H satellite observatory [136], which is planned to be launched in 2015.

In laboratory experiments similar principles were used for the Compton camera to image radioisotopes for medical diagnostics [137]. However, so far only one instrument was built using segmented germanium detector technology. The application of Compton gamma-ray imaging was intensively discussed in connection to the FAIR projects HISPEC/DESPEC. While many design studies in this direction were performed, the Compton imaging principles were never implemented in hardware for this project. In the recent years, within the SPARC collaboration research groups from University of Jena
and University of Heidelberg together with the atomic physics division of GSI have developed a number of advanced detectors and techniques for x-ray spectroscopy. Most notably, segmented Si(Li) and Ge(i) detectors were developed and applied for efficient x-ray polarimetry over the last years, see [119] and references therein. The typical energy range of these instruments is 70 keV up to several 100 keV. A research group from University of Heidelberg followed a complementary path in the developments of novel instruments for higher x-ray energies and gamma-ray spectroscopy, as their techniques are focused for the higher energy range of 100 keV up to several MeV. In particular a sophisticated technique of the Pulse Shape Analysis (PSA) of the detector signals was developed [138,139]. With this algorithm the position sensitivity of the detectors was improved from 10x10x20 mm to 1x1x1 mm in case of single interaction and to 3x3x3 mm in case of double interactions within a single detector. Using this significantly improved resolution it was demonstrated that the principles of gamma-ray tracking [140,141] and imaging [142] can successfully be applied to the segmented germanium detector. The gamma-ray imaging enables a number of unique techniques, in particular the background suppression by a factor of 10 to 100 [143,144]. This will be especially important in the few MeV energy range, typical for the future HESR experiments, where more than 80% of events will contribute to the background of the gamma-ray spectrum. Moreover, additional experimental techniques of gamma-ray spectroscopy for the energy range of 100 keV up several MeV, which is reveal for HESR experiments. Those techniques include the x-ray linear polarimetry [145,132], which was applied in a number of experiments. They also include the gamma-ray tracking, which allows tracking multiply scattered gamma-ray through the detector crystals. This technique is very efficient in its suppression of the unwanted gamma-ray background. Figure 48 shows the results of the simulations that demonstrate that the background suppression by a factor of 10-100 is possible without a significant loss of the efficiency [142].

The complete set of these novel techniques applied to a segmented germanium detector was recently used by our research group in the experiments at Mainzer Microtron MAMI. The test experiments focused to the energy range of 1-2 MeV, which will be relevant at HESR at FAIR. The position resolution of 3x3x3 mm was, in turn, limited by the fact, that both interactions were necessarily happening in one crystal, which lead to the overlap of the signals. The new gamma-ray imager and spectrometer with minimum two segmented
germanium detectors will markedly improve the imaging performance. The gamma-ray tracking algorithm is also sensitive to the rare events which are sensitive to circular polarization of gamma-rays [146]. The circular polarimetry is a complex technique of gamma-ray spectroscopy; its efficient realization requires the detector with excellent position sensitivity. The detector constructed within this project should for the first time allow testing the principles of the gamma-ray circular polarimetry.

6.3 Technical requirements

6.3.1 WP: Cryogenic charge sensitive preamplifier readout for precision Compton polarimetry with planar Si(Li) and Ge(i) strip-detectors

The goal of this work package is to improve the energy resolution of thick planar highly-segmented semiconductor detectors. As a first step, the project focusses on the two dedicated Si(Li) polarimeter systems of the SPARC collaboration. One of these detectors is already routinely employed for Compton polarimetry and a second detector system has recently been ordered. Later, a modification of all segmented detectors systems within SPARC is intended.

We aim for an improvement in energy resolution of approximately a factor of two, namely from 2.1-2.5 keV at 60 keV down to less than 1 keV at 60 keV, by using dedicated frontend electronics to readout the detector segments. Therefore a redesign of the preamplifier section is planned to cope with the demand for higher resolution power, excellent signal stability, a compact form factor, low thermal load, scalability and cost efficiency. Unfortunately, charge sensitive preamplifiers, which would be compatible with the present Si(Li) and Ge(i) strip detectors while fulfilling all these requirements, are at present not available. Thus, an adaptation and optimization of existing and reliable preamplifiers components to our specific needs is the central issue of this project.

To achieve the desired resolution, it is mandatory to use at least a cryogenic input stage for the preamplifier. For non-segmented Si(Li) and Ge(i) detectors cryogenic preamplifiers are the standard configuration since many years. For these detectors the input-FET and the feedback-loop are placed close to the detector crystal with a well-defined thermal coupling to the cold finger to maintain a fixed operation temperature.
However, for highly segmented detectors with typically 40 to 200 individual channels this is quite challenging. The amount of 40 to 200 FETs close to the crystal inside the cryostat is a significant thermal load. Another important point is to avoid electronic coupling (crosstalk) within such a large number of amplifier stages in a small volume. The second amplifier stage will be placed outside of the cryostat at room temperature. Here the space is less limited and a thermal load can be removed by active cooling. However, a high quality low capacitive UHV-feed through for all the signal lines connecting the in-vacuum cryogenic first stage with the room temperature second stage is of great importance.

In first laboratory tests it was already possible to achieve a resolution of 800 eV at 60 keV x-ray energy (see Figure 49) with a 4-fold pixel detector read out by preamplifiers equipped with a cryogenic FET input stage. For a more complex system an energy resolution of slightly less than 1.0 keV at 60 keV seems to be a realistic goal.

Figure 50. Left: Sketch of the new Si(Li) polarimeter, that was recently funded by the University of Jena. Right: Si(Li)-Crystal for the system with a 2D strip-structure.

Taking into account the significant costs of a complete 2D-detector system, it is planned to perform the preamplifier development and tests with a dedicated medium-sized test detector system with cryostat and vacuum stand. In collaboration with the manufacturer company of the 2D-Si(Li) and 2D-Ge(i) detectors used in the SPARC collaboration, the prototype electronics will be tested and optimized with this test detector. The optimized preamplifier design will then be used be adapted for refitting the readout of thick planar structured Si(Li) and Ge(i) detectors. As a demonstrator, we plan equip the new Si(Li) polarimeter, which was financed by the University of Jena, with the new low-noise preamplifiers. This project will be coordinated by University of Jena together with the atomic physics division of GSI. The design of the preamplifiers and the detector test stand will be developed in close collaboration with the detector laboratory of the Forschungszentrum Jülich.
6.3.2 WP: Imaging gamma-ray spectrometer

The aim of this project is to construct an advanced x-ray imaging spectrometer based on principles of the Compton Telescope [121]. The spectrometer will consist of two identical segmented germanium detectors housed in one cryostat.

Each segment will be equipped with an individual 125 MHz 16-bit sampling analog-to-digital converter. The pulse shapes will be stored to the hard disk. The detector segmentation will create 4 mm x 4 mm x 15 mm voxels. This rough position resolution will be dramatically improved by a pulse shape analysis algorithm applied to the waveforms coming from the preamplifiers. The expected position resolution of the reconstructed events will be 1 mm x 1 mm x 1 mm. Here we assume an energy resolution of the readout electronics of 1-2 keV and the working energy range will be 100 keV up to several MeV.

The proposed imaging gamma-ray spectrometer will consist of two identical planar germanium detectors placed in one cryostat. The detectors will be 80x80x15 mm in size. Their active surface area of 64x64 mm will be segmented into 16 + 16 orthogonal strips on each side. A 8 mm wide guard ring around the active area will ensure the uniform bias electric field across the whole active volume of the detector. In order to implement the principles of high resolution Compton telescope, the two detectors will be placed in a single cryostat, see Figure 51. The cryostat will be cooled by liquid nitrogen. The electrical segments will be read out via preamplifiers allowing the energy resolution of
approximately 2 keV, which is sufficient for the Compton imaging. The 64 pre-amplified signals will be read out using the 125 MHz 16 sampling analog to digital converters (ACDs). Such ADCs are commercially available from the company STRUCK (Germany). Our group has experience in using such ADCs for the gamma-ray spectroscopy and imaging.

The digitized detector signals will be stored onto a commercial RAID server. The stored signals will be processed using the Pulse Shape Analysis algorithm. Such an algorithm, dedicated to the geometry of the detector, will be developed within this project. For this, an existing algorithm for 8x8 cross-strip segmentation will be adapted to the new geometry of 16x16 strips. During this development, the charge (electrons and holes clouds) motion in the bias field of the detector and the formation of the detector signals will be simulated using the multi-physics simulation software package COMSOL. These simulations will create the database of all possible signals. The PSA algorithm will represent the fitting procedure to locate the interaction position in three dimensions. The selected segmentation of the detector will allow for the 1x1x1 mm position resolution using the PSA analysis.

With the reconstructed positions of the interactions, the next step of the analysis, the gamma-ray tracking algorithm, will determine the right order of interactions, will create the gamma-ray image and will suppress the gamma-ray background by a factor of 10-100. These algorithms are already developed and tested by our research group, see Figure 44. The significantly improved position resolution of the spectrometer will allow to achieve the imaging resolution of 3 deg. This excellent resolution is the theoretical limit of Compton imaging, which is set by the material of the detector - germanium and its Compton profile. Moreover, no additional development, except for the actual spectrometer and the proprietary PSA algorithm, will be necessary to achieve this imaging and background suppression performance — the existing data analysis programs will be
### 6.4. Time table - Working plan

**Time table for 'Cryogenic charge sensitive preamplifier readout for precision Compton polarimetry with planar Si(Li)- and Ge(i)-strip-detectors'**

<table>
<thead>
<tr>
<th>Quarterly period</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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</thead>
<tbody>
<tr>
<td>1. Constructing and setting up of the teststand (cryostat, vacuum teststand)</td>
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<tr>
<td>2. Electronic design and production of the first preamplifier prototypes</td>
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<td>3. Test and optimization of the prototypes</td>
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<tr>
<td>4. Optimization of the preamplifier heat load to the cryostat</td>
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<tr>
<td>5. Design and production of an electrical baseboard for a larger number of preamplifiers</td>
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<tr>
<td>6. Optimization and production of the final preamplifier design</td>
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<tr>
<td>7. Characterization of a realistic demonstrator system having approximately 32 individual detector segments</td>
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</table>

We start with the setup of a test stand with cryostat and UHV chamber (1st – 2nd quarter). In parallel we start with the preamplifier prototype design and first tests of its components. We expect this to take 1 1/2 years (1st – 6th quarter). The prototypes will be tested at an appropriate test detector. Optimization will be done until 8th quarter. In parallel the heat load of the preamps to the detector crystal/cryostat has to be minimized (5th – 9th quarter.). In addition circuit boards for big numbers of preamps will be designed (7th – 9th quarter). Production of the final preamp system will be done by the 10th quarter. Finally, a complete testing system consisting of a highly segmented detector will be outfitted and characterized as a demonstrator (10th – 12th quarter).
**Time table for 'Imaging gamma-ray spectrometer'**

Although the date of the commissioning of the HESR is delayed, the detectors can be tested and used in experiments at the ESR. Therefore, this time line remains unchanged.

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tr>
<td>Quarter</td>
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<td>2</td>
<td>3</td>
<td>4</td>
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<tr>
<td>Germanium crystal 1</td>
<td></td>
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<tr>
<td>Germanium crystal 2</td>
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<td></td>
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<tr>
<td>Development of the cryostat</td>
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<tr>
<td>Development of the electronics</td>
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</tr>
<tr>
<td>Assembly of the imaging spectrometer. Milestone: hardware should be ready.</td>
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<tr>
<td>Software development. Milestone: software should be ready</td>
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<tr>
<td>Test experiments</td>
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</table>

The imaging spectrometer will be developed within a collaboration between Heidelberg University, GSI and the company SEMIKON (Germany) (from April 1st, 2015 SEMIKON will stop as company and will be converted incl. technology and personal as a part of IKP, Forschungszentrum Jülich). The germanium detectors will be developed by SEMIKON. The company will also design and manufacture the detector holders. The two detectors, mounted into their holders will be tested by the company and delivered in this form. The cryostat will be designed by GSI (I. Kojouharov). The gamma-ray spectroscopy group of GSI has a longstanding experience in designs and manufacture of the efficient cryostats for large germanium detector arrays. The cryostats designed by GSI are also very compact, which is important for their applications at accelerators, where the space is often limited. The cryostat will be manufacture in the mechanical workshop of the Physikalisches Institut of the Universität Heidelberg. The final integration of the complete detector system, including the electronics, will be done at GSI. The collaboration between Heidelberg University, GSI and SEMIKON will allow to significantly reducing the total costs of the project. Moreover, no commercial company is currently able to produce the complete specified spectrometer. CANBERRA confirmed that they are currently not able to provide such a system and ORTEC does not have the necessary technology for the detector segmentation. Thus, the proposed scheme is the only one possible to manufacture the imaging spectrometer for the future FAIR experiments. The ready imaging spectrometer will be tested in Heidelberg using the standard gamma-ray sources.
7. Summary

The storage ring ESR at GSI, as well as the CRYRING, will come in operation in 2017. Most of the SPARC equipment, like, e.g., X-ray detectors, charge-exchange detectors, Schottky detectors, developed electronics, laser systems etc., can be tested at these facilities. In the time until 2017 and also to efficiently use the available beam times, some of the detectors can be used in experiments at CSRe in Lanzhou, which is one of the SPARC collaboration partners.

Furthermore, there is a running collaboration with JINR in Dubna to test/employ SPARC experiments with relativistic ion beams at NUCLOTRON/BOOSTER. These test experiments will allow testing and commissioning of the components prior to their installation in the HESR in the suitable energy range.

Therefore, the components for the HESR can be constructed earlier than the HESR will be built. Nevertheless, most of the components must be ready by the time of the HESR is constructed since they are the integral part of the ring.
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## A1. SPARC Collaboration Board

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<tr>
<th>Name</th>
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<tr>
<td>F. Currell</td>
<td>Queens University of Belfast, U.K</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, US</td>
<td>USA</td>
</tr>
<tr>
<td>G. Garcia</td>
<td>CSIC, Madrid, Spain</td>
<td>Spain</td>
</tr>
<tr>
<td>J. Gillaspy</td>
<td>NIST, US</td>
<td>USA</td>
</tr>
<tr>
<td>R. Hoekstra</td>
<td>KVI, Netherlands</td>
<td>The Netherlands</td>
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<tr>
<td>T. Kirchner</td>
<td>York University, Toronto, Canada</td>
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</tr>
<tr>
<td>X. Ma</td>
<td>Institute of Modern Physics, Lanzhou, China</td>
<td>China</td>
</tr>
<tr>
<td>M. Pajek</td>
<td>Swietokrzyska Academy, Kielce, Poland</td>
<td>Poland</td>
</tr>
<tr>
<td>J. Rangana</td>
<td>CIMAP, France</td>
<td>France</td>
</tr>
<tr>
<td>J. P. Santos (deputy spokesperson)</td>
<td>Faculdade Ciencias Tecnologia / Univ. Nova Lisboa, Portugal</td>
<td>Portugal</td>
</tr>
<tr>
<td>S. Schippers</td>
<td>University Giessen, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>R. Schuch (spokesperson)</td>
<td>Stockholm University, Sweden</td>
<td>Sweden</td>
</tr>
<tr>
<td>V. Shabaev</td>
<td>St. Petersburg State University, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>Th. Stöhlker (local contact)</td>
<td>Helmholtz Institut Jena &amp; GSI, Darmstadt, University Jena, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>A. Surzhykov</td>
<td>Helmholtz Institut Jena, University Jena, Germany</td>
<td>Germany</td>
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<tr>
<td>M. Trassinelli</td>
<td>Université VI (Pierre et Marie Curie), Paris, France</td>
<td>France</td>
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<tr>
<td>L. Tribedi</td>
<td>Tata Institute of Fundamental Research, India</td>
<td>India</td>
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<tr>
<td>A. Wolf</td>
<td>MPI-K, Heidelberg, Germany</td>
<td>Germany</td>
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<tr>
<td>T. Azuma</td>
<td>AMO Physics Lab, RIKEN, Japan</td>
<td>Japan</td>
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<tr>
<td>T. Zouros</td>
<td>University of Crete, Greece</td>
<td>Croatia, Greece, Hungary, Italy</td>
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### A2. SPARC Working Groups

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<tbody>
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<td>Electron / Positron Spectrometers</td>
<td>Xinwen Ma / Siegfried Hagmann</td>
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<tr>
<td>Electron Targets / Cooler</td>
<td>Carsten Brandau / Stefan Schippers</td>
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<tr>
<td>High Energy Single Pulse Experiments</td>
<td>Alexandra Gumberdze / Angela Brüning-Damian</td>
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<td>HITRAP / Traps</td>
<td>Frank Herfurth / Wolfgang Quint</td>
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<td>Vincent Bagnoud / Thomas Kuhl</td>
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<td>Laser Cooling</td>
<td>Michael Bussmann / Danyal Winters</td>
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<td>Laser Spectroscopy</td>
<td>Wilfried Nortershauser / Rodolfo Sanchez</td>
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<td>Photon Detector Development</td>
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<tr>
<td>Theory: Atomic Structure / Collision Dynamics</td>
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### Technischer Support

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