Abstract

The physics program of the SPARC collaboration at FAIR focuses on the study of collision phenomena in strong and even extreme electromagnetic fields and on the fundamental interactions between electrons and heavy nuclei up to bare uranium. The current report documents the feasibility of the HESR storage ring operating with heavy-ion beams with particular emphasis given to the requirements of the experimental program of the SPARC collaboration.
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1 Preface

In the recent past accelerator-based atomic physics has advanced into hitherto unexplored areas of research, encompassing high energies, high atomic charge states and strong electromagnetic fields. First tentative benchmarks were set by the heavy-ion storage cooler rings, in particular by the experimental storage ring ESR at GSI [1], via precision spectroscopy of relativistic few-electron ions, and via the exploration of the interaction of relativistic ions with atoms, electrons and photons. The expertise atomic physics has already acquired in this field ensures that the unprecedented feasibilities of the facility to come - concerning energy, intensity and experimental tools - can optimally be exploited to provide access to the fundamental facets of relativistic atomic physics and neighboring fields.

At the Facility for Antiproton and Ion Research (FAIR), the central research facilities to be used by the atomic physics collaborations SPARC and FLAIR (SPARC collaboration: experiments with ions; FLAIR collaboration: experiments with antiprotons) are:

- **SIS100/300**: Laser cooling and laser spectroscopy of (mostly Li-like) heavy highly-charged ions. These experiments exploit the fact that the transitions in the ions appear strongly Doppler-shifted in the laboratory frame due to the relativistic velocities. This implies that even fine structure transitions, which normally lie in the inaccessible XUV regime, can now be laser excited and/or cooled by counter-propagating laser beams of standard laser systems [module 1] and [phase B].

- **APPA-Cave, High Energy Cave for Atomic/Plasma Physics/Biophysics/Materials Research**: In this cave the experiments in atomic physics and applications in radiobiology, space and materials research with extracted beams from SIS100 will be performed [module 1].

- **New Experimental Storage Ring (NESR)** is the ”second-generation” ESR with optimized features and novel experimental installations. The NESR will serve also as an accumulator and storage/cooler and decelerator ring both for stable and exotic ions as well as for antiprotons. A large variety of experimental set-ups and installations for atomic physics experiments will be assembled here [module 4].

- **FLAIR Building**: This building is devoted to experiments with decelerated, low-energetic highly-charged ions and antiprotons. The experimental area will be served by the NESR. In the building, different installations (e.g. the Low-Energy Storage Ring LSR and the Ultra-low energy Storage Ring USR) are located. From the LSR the ions can be actively slowed down, even to rest using the trap facility HITRAP. The installations will be shared with the FLAIR collaboration [module 4].

The Modularized Start Version (MSV) of the international FAIR project [2] first foresees the construction of modules 0 – 3 of phase A and and at a later stage phase B. As can be seen from the above list of facilities to be used by atomic physics at FAIR, only experiments at the APPA cave and laser experiments at SIS100 remain to be available during the MSV and consequently only a very small section of the originally envisioned physics program contained in the Conceptual Design Report (CDR) [3]. The modules
Figure 1: Angular dependence of the electric radial field strengths of a point charge moving with a Lorentz factor $\gamma$ ($\gamma = 1, 2, 3, 4$ and $5$ corresponds to $0, 87, 94, 97, \text{ and } 98\%$ of the speed of light) as observed in the laboratory frame. Perpendicular to the trajectory, the electric field of the moving ion steadily increases with $\gamma$ while the duration of the electromagnetic pulse decreases. Note, for large $\gamma$ values the electric and magnetic components become almost equal (natural relativistic units ($\hbar = m = c = 1$)). Along the direction of motion, however, the field decreases by a factor of $\gamma^2$ [6, 7].

4 and 5 of phase $A$ will be inevitably delayed (NESR belongs to module 4). However, the major part of the experimental program of SPARC at FAIR will concentrate on experiments with stored and cooled ions to be either conducted at the NESR or are using the NESR as an intermediate beam transport and deceleration facility for FLAIR (NESR) [4]. Following the timeline of the MSV, we cannot expect that the NESR will be operational for experiments within the next 10 years. Since this creates a difficult perspective for the atomic physics community, the impact of the MSV for SPARC was to some extent compensated by the decision, to keep the ESR accessible for experiments until the NESR will be available [2]. In particular, the MSV has triggered efforts to investigate alternatives which may allow to perform already within the MSV unique experiments in the realm of atomic physics using stored and cooled ion-beams at FAIR.

The High-Energy Storage Ring (HESR) [5], whose primary aim is to allow for experiments with stored and cooled antiprotons, turned out to be a well-suited facility which can accommodate a range of SPARC experiments with high-energy stored heavy-ion beams. Furthermore, the HESR can store cooled beams at energies of up to a few GeV/u and thus can enable unique atomic physics experiments which would even not be feasible at the NESR or at any other place in the world. This is in particular true for the use of cooled ion beams at real relativistic energies ($\gamma \approx 2$ to 6). Therefore, possible experimental activities for atomic physics at the HESR were already mentioned and discussed at a very early stage of the international FAIR project, i.e. within the CDR [3]. Moreover, with respect to the experimental installations needed for SPARC at HESR, we like to emphasize that most of the equipment already specified within the SPARC technical report [4] for experiments at the NESR can be transferred to the HESR and is covered by the FAIR cost book. This is in particular true for the prototype detectors [8–10], and target stations already developed for SPARC@NESR [4].
The purpose of the current report is to prove the feasibility of the HESR storage ring for the use of heavy ion beams with special emphasis given to the experimental program of the SPARC collaboration at FAIR. This feasibility study is considering in particular electron cooling, stochastic cooling, the ion optical properties at the foreseen location of the internal target as well as storage times relevant for the planned in ring experiments.

2 Introduction: The Physics Case

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 $1/\gamma$ (see Figure 1). 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 2) are dramatically affected by the strong dependence on the transverse electromagnetic field of the projectile [11–14].

As an illustrative example, Figure 3 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 [11, 16, 17]. 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 [11, 16, 17]. For such investigations, the spectroscopy of photons as well as electrons and positrons is required. The photon emission gives the details of the specific 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 [12, 13, 18–23]. This higher-order process, presumably requiring high collision energies, is similar to dielectronic 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 ($10^{-22}s < t < 10^{-18}s$) [11]. One goal of future experiments will be the measurement of the complete momentum bal-
Collision times in the sub-attosecond regime
($10^{-22}$ s $< t < 10^{-18}$s)

Positive Continuum
Negative Energy Continuum
Transfer Excitation Ionization
Free Pair Production

Figure 2: Energy diagram of the single-particle Dirac equation and basic atomic processes which occur in ion-atom collisions [3].

ance in relativistic collisions both in transverse and in longitudinal direction by detecting the emitted electrons/positrons in coincidence with the recoiling target ion [3, 11, 14]. 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 [24]. 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. The additional interaction with laser pulses can be expected to create access to new physics phenomena, both by precision spectroscopy and in the combination of static and dynamic electromagnetic fields. Laser spectroscopy enables studies for selected highly-charged ion species and provides access to the properties of stable and unstable nuclei by atomic physics techniques. 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. With this additional possibility, making use of the large Doppler boost, the investigation of the weak interaction in bound atomic systems as well as of fundamental interactions in extremely
Figure 3: Reduced cross sections $\sigma/Z^2_T$ for $1s_{1/2}(\mu_i = 1/2) \rightarrow 2p_{1/2}(\mu_f = \pm 1/2)$ transitions in a hydrogen-like Au$^{78+}$ projectile ion as functions of the collision energy (full line). The partial cross section for the $\Delta \mu_f = 0$ transition (dashed-dotted line) decreases with the collision energy and then saturates. In contrast, the partial cross section describing transitions with $|\Delta \mu_f| = 1$ (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 $\ln(\gamma)$ [15].

strong electromagnetic fields might be possible.

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) [12, 13, 18–23].

- Negative continuum di-electronic recombination (electron cooler, internal target) [12, 13, 18–23].

- Relativistic photon-matter interaction: radiative recombination and bremsstrahlung
2. INTRODUCTION: THE PHYSICS CASE

(polarization phenomena etc.; photon-photon angular correlation (electron cooler, internal target, x-ray spectrometer)) [16, 17].

- Target Ionization: correlated electron motion exploiting the ultrafast, extremely strong transient fields of relativistic ions (internal target, recoil spectrometer) [14, 24].

- Electron impact phenomena (electron cooler, electron spectrometer, x-ray spectrometer) [3, 4].

- Bound state QED and nuclear parameters: laser excitation of fine structure transitions in few-electron heavy ions (laser beam, beam lifetime) [3].

- Exotic nuclear decay modes in highly-charged ions (electron cooler, x-ray spectrometer) [3, 25].

- Test of special relativity (laser beam, beam lifetime) [26].

- Parity Non-Conservation effects in high-Z ions and extreme electromagnetic fields (electron cooler, internal target, laser beam) [3, 27].

For a detailed discussion of the physics program covered by the HESR we refer to the Technical Design Report ”SPARC@HESR”, which is currently in preparation.
3 High-Energy Storage Ring

The High Energy Storage Ring (HESR) [5] was primarily designed for studies with high energy antiproton beams over a broad momentum range from 1.5 to 15 GeV/c. The technical design report on HESR can be found in Ref. [5]. Moreover, the feasibility of experiments with heavy ions stored in the HESR will be addressed in this Section.

The main parameters of the HESR are summarized in Table 3 (taken from Refs. [5, 29, 30]).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>575 m</td>
</tr>
<tr>
<td>Maximum magnetic rigidity</td>
<td>50 Tm</td>
</tr>
<tr>
<td>Magnet type</td>
<td>normal conducting</td>
</tr>
<tr>
<td>Aperture of vacuum chamber</td>
<td>89 mm</td>
</tr>
<tr>
<td>Length of 180° arcs</td>
<td>155.5 m</td>
</tr>
<tr>
<td>Length of straight sections</td>
<td>132 m</td>
</tr>
<tr>
<td>Height of the beam axis</td>
<td>1.40 m</td>
</tr>
<tr>
<td>Transition energy range</td>
<td>$\gamma_t = 6.2 - 23$</td>
</tr>
<tr>
<td>Fixed working point</td>
<td>$\gamma_t = 7.61$</td>
</tr>
<tr>
<td>Injection energy of ions from CR</td>
<td>$\sim 740$ MeV/u</td>
</tr>
<tr>
<td>Acceleration / Deceleration</td>
<td>yes</td>
</tr>
<tr>
<td>Electron cooling</td>
<td>yes</td>
</tr>
<tr>
<td>Stochastic cooling</td>
<td>yes</td>
</tr>
</tbody>
</table>

The operation of the HESR with positively-charged heavy ions requires changing of the magnet polarity after or prior to the operation with antiprotons. Such changes of the polarity are expected to be required 2 – 3 times a year, which is not critical and manual changes would be sufficient [31]. Stable or radioactive ions stochastically pre-cooled in the CR will be extracted from the CR and injected into the HESR at the fixed energy of about 740 MeV/u. Since the HESR is equipped with an RF acceleration/deceleration system, the final energy of the ions will be selected in the HESR according to the needs of specific experiments. Stored and cooled ion beams in the energy range of about 200−5000 MeV/u are considered. Both, coasting as well as bunched beams will be required. The latter shall be possible, since an RF-system for beam bunching is foreseen in the HESR.

3.1 Cooling of heavy-ions

The most essential prerequisite of experiments with heavy ions in the HESR is the beam cooling. A 2 MV electron cooler has been constructed in BINP, Novosibirsk and will be commissioned in the existing COSY ring in Jülich. The electron energies of 2 MeV correspond to ion energies of about 3500 MeV/u. This 2 MV cooler will be installed in the HESR from the beginning and might later be replaced by a more powerful 4.5 MV
3. HIGH-ENERGY STORAGE RING

**Figure 4:** Schematic view of the HESR. Main components and possible locations of the SPARC experimental setups are indicated.

According to the known parameters of the electron cooler, detailed simulations of electron cooling of heavy-ion beams have been performed. The simulations were done with the BETACOOL code [35].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>$0.025 - 2$ MeV</td>
</tr>
<tr>
<td>Ion energy</td>
<td>$\sim 50 - 3500$ MeV/u</td>
</tr>
<tr>
<td>Electron current</td>
<td>$0.1 - 3$ A</td>
</tr>
<tr>
<td>High voltage stability</td>
<td>$&lt; 10^{-4}$</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$0.5 - 2$ kG</td>
</tr>
<tr>
<td>Electron beam diameter</td>
<td>$10 - 30$ mm</td>
</tr>
<tr>
<td>Vacuum at cooler</td>
<td>$10^{-9} - 10^{-10}$ mbar</td>
</tr>
<tr>
<td>Cooling section length</td>
<td>$2.694$ m (can be extended to $\sim 6.4$ m)</td>
</tr>
<tr>
<td>Maximum height</td>
<td>$5.7$ m</td>
</tr>
</tbody>
</table>
3. HIGH-ENERGY STORAGE RING

Figure 5: Schematic layout of the 2 MV electron cooler designed in BINP, Novosibirsk to be installed at COSY, Jülich (taken from [32–34]). Technical characteristics of the cooler are summarized in Table 3.1.

As input parameters, the most recent lattice of the HESR has been assumed (\(C = 575\) m, \(\gamma_t = 6.232, Q_x = Q_y = 7.62\)) with the electron cooler placed in the middle of the HESR cooling section \((\beta_x = 10\) m, \(\beta_y = 120\) m, \(D_x = 0\)). The used electron cooler parameters were: the length of the cooler of \(L = 2.7\) m, the electron beam radius \(r_e = 1\) cm and the magnetic field \(B_{\text{cooler}} = 1\) kG. The electron cooling force was calculated with the Parkhomchuk model [36] using as input an effective electron temperature of 0.01 eV at 740 MeV/u (injection energy) and \(kT_{\text{eff}} = 10^{-1}\) eV for ion energies of 3000 MeV/u.

The electron cooling of ion beams will be done at the injection energy, that is at 740 MeV/u. The emittance of the stochastically pre-cooled coating ion beam in the CR is about \(\epsilon_{x,y} = 0.5\) mm mrad and the momentum spread is about \(\Delta p/p = 5 \cdot 10^{-4}\). The beam in the CR will be adiabatically re-bunched and transferred without beam losses to the HESR, where the beam will be de-bunched leading to the beam parameters \(\epsilon_{x,y} = 0.5\) mm mrad and \(\Delta p/p = 7 \cdot 10^{-4}\).

Results of the simulations assuming electron cooling of \(10^8\) stored \(^{132}\)Sn\(^{50+}\) and \(^{238}\)U\(^{92+}\) ions are listed in Table 3.1. According to the results in Table 3.1, equilibrium beam parameters better than \(\epsilon_{x,y} < 0.05\) mm mrad and \(\Delta p/p < 1 \cdot 10^{-4}\) can be achieved with moderate electron current values. These beam parameters \((\epsilon_{x,y} = 0.05\) mm mrad, \(\Delta p/p = 1 \cdot 10^{-4}\)) are used for ion-optical simulations below.

The cooling time needed to achieve the equilibrium beam parameters listed in Table 3.1 are 11 s and 5.6 s for electron current of \(I_e = 0.5\) A for \(10^8\) stored \(^{132}\)Sn\(^{50+}\) and \(^{238}\)U\(^{92+}\) ions, respectively. Beam emittances and the momentum spread as a function of cooling time are illustrated in Figures 6 and 7, respectively, for \(10^8\) stored \(^{238}\)U\(^{92+}\) ions*.

*Please note, that the equilibrium emittances and momentum spread in Figures 6 and 7 are \(\sigma_{\text{rms}}\) values. According to the standard convention, the full beam emittances \(\epsilon_{x,y}\) are 4 times the \(\sigma_{\text{rms}}\) value.
Table 3: Equilibrium parameters of the cooled $^{132}\text{Sn}^{50+}$ and $^{238}\text{U}^{92+}$ beams. Intensities of $10^8$ stored ions have been assumed for both ion species.

<table>
<thead>
<tr>
<th>electron current $I_e$ [A]</th>
<th>$\epsilon_x$ mm mrad</th>
<th>$\epsilon_y$ mm mrad</th>
<th>$\Delta p/p$</th>
<th>$\epsilon_x$ mm mrad</th>
<th>$\epsilon_y$ mm mrad</th>
<th>$\Delta p/p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>5.6 $\cdot 10^{-2}$</td>
<td>6.0 $\cdot 10^{-2}$</td>
<td>9.2 $\cdot 10^{-5}$</td>
<td>7.2 $\cdot 10^{-2}$</td>
<td>8.0 $\cdot 10^{-2}$</td>
<td>1.1 $\cdot 10^{-4}$</td>
</tr>
<tr>
<td>0.5</td>
<td>3.0 $\cdot 10^{-2}$</td>
<td>3.2 $\cdot 10^{-2}$</td>
<td>7.0 $\cdot 10^{-5}$</td>
<td>4.0 $\cdot 10^{-2}$</td>
<td>4.4 $\cdot 10^{-2}$</td>
<td>8.0 $\cdot 10^{-5}$</td>
</tr>
<tr>
<td>1.0</td>
<td>2.4 $\cdot 10^{-2}$</td>
<td>2.6 $\cdot 10^{-2}$</td>
<td>6.2 $\cdot 10^{-5}$</td>
<td>3.2 $\cdot 10^{-2}$</td>
<td>3.6 $\cdot 10^{-2}$</td>
<td>7.2 $\cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

Figure 6: Beam emittance vs cooling time for $10^8$ $^{238}\text{U}^{92+}$ ions stored and cooled at 740 MeV/u. The electron current of $I_e = 0.5$ A is assumed.

Experiments at much higher energies are also envisaged. However, the electron cooling times at higher energies are significantly longer. For instance, at 3000 MeV/u, the cooling times of $10^8$ stored $^{132}\text{Sn}^{50+}$ and $^{238}\text{U}^{92+}$ ions are 360 s and 180 s, respectively, for the electron current of 0.5 A. This means, that the most efficient operation mode would be to cool the beams at the injection energy and then accelerate them to the required high energy. It is necessary to note, that at energies of a few GeV/u already the reduction of the beam emittances due to relativistic effects (adiabatic $\beta\gamma$-damping) would be sufficient for precision atomic physics experiments, that is, in some cases, no cooling may be required at high energies.

and the momentum spread $\Delta p/p$ is 2 times the corresponding $\sigma_{\text{rms}}$ value.
Figure 7: Momentum spread vs cooling time for $10^8 \, ^{238}\text{U}^{92+}$ ions stored and cooled at 740 MeV/u. The electron current of $I_e = 0.5$ A is assumed.

The 2 MV cooler enables electron cooled ion beams up to beam energies of about 3.5 GeV/u. If upgraded to a 4.5 MV cooler, the electron cooled beams would be available for the entire range of possible magnetic rigidities in the HESR. However, the upgrade of the cooler is not foreseen in the nearest future. Therefore, stochastic cooling is envisaged for cooling of the ion beam at very high energies. Simulations of the performance of the stochastic cooling of heavy ions have been performed [37]. If the lattice and the cooling hardware is not changed (optimized for $\gamma_t = 6.2$), the stochastic cooling of ions is feasible only for high energies above 2 GeV/u. Using stochastic cooling at lower energies would require a lower $\gamma_t$ value which would need additional power supplies for quadrupoles (more investment costs). Thus, at energies below 2 GeV/u the heavy-ion beams can be cooled by electrons, at energies above 3.5 GeV/u only the stochastic cooling will be available in the HESR, and at energies $2 < E < 3.5$ both cooling methods can be applied. We emphasize, that the hardware for both cooling methods will be available from the beginning of the HESR operation at FAIR.

3.2 Beam lifetimes and charge-exchange cross-sections

The operation of the internal target may affect considerably the beam lifetimes of the stored ion beams via beam losses caused by atomic charge-exchange processes. In general, the beam life-time ($\tau$) for cooled and stored ion beams is determined by recombination processes in the electron cooler and charge changing collisions with residual gas atoms/molecules. In addition, for the case that the internal target is used, charge exchange in collisions with gas atoms of the jet target must be considered. Usually, this gives
Figure 8: Total electron-capture cross sections per target electron measured for heavy bare ions ($Z \geq 54$) in collisions with light target atoms or molecules. The results are plotted as a function of the $\eta$-parameter and are compared with the result of a relativistic exact calculation for $Z = 80$ (solid line) as well as with the prediction of the nonrelativistic dipole approximation (dashed line). The data points at 12 and 168 GeV/u, respectively are taken from Refs. [38, 39] (see also [17]).

the most important contribution to beam losses and determines the overall beam lifetime. Target density $\rho$ (particles/cm$^2$) and charge exchange rate $\lambda$ are simply connected by

$$\lambda = 1/\tau = \rho \cdot \sigma \cdot f$$

(1)

where $f$ denotes the revolution frequency of the circulating ion beam and $\sigma$ the atomic charge-exchange cross-section, respectively.

Assuming a beam of stored bare ions, the two most important charge-exchange pro-
3. HIGH-ENERGY STORAGE RING

Figure 9: Electron capture cross-sections for bare uranium beams colliding with atoms of target charge $Z_T$

Figure 10: Lifetimes for bare uranium beams as function of $Z_T$. An areal density of $10^{14}$ p/cm$^2$ has been assumed.
cesses for bare ions are Radiative and Non-Radiative Electron Capture (REC and NRC) (see e.g. [17]). They exhibit a very different scaling relation with respect to the target nuclear charge $Z_T$ and the collision velocity $v$, respectively. With respect to the projectile and the target charge, the scalings are given by

$$\sigma_{\text{rec}} \approx Z_T \cdot Z_P^5;$$
$$\sigma_{\text{nrc}} \approx Z_T^5 \cdot Z_P^5$$

which are valid for both the non-relativistic and the relativistic collision regimes.

For the high energy domain of interest, charge-exchange is almost entirely due to REC, a process which has been studied in great detail both experimentally as well as theoretically. Here, the target electrons are considered as quasifree and the cross-sections can be predicted reasonably well for the whole energy range of interest (see Figure 8). For two cases, 1 and 5 GeV/u, we depict in Figure 9 the cross-section for electron capture into bare uranium as function of the target charge $Z_T$. In addition, we show in Figure 10 the corresponding beam lifetimes for the beam energies of 740 MeV/u and 2 GeV/u, respectively, assuming an areal density of $10^{14}$ p/cm$^2$. Finally, we like to note that the interaction of the circulating beam with a dense atomic target may also lead to substantial energy loss and multiple scattering. For this purpose, BETACOOL simulations have been performed to investigate the influence of dense internal targets on the beam parameters. The simulations showed, that for electron currents of 0.5 A and typical target thicknesses of $\leq 10^{15}$ hydrogen atoms/cm$^2$ the influence of the target on the stored beam properties is negligible. Furthermore, scaling of the target effects indicates, that an operation even with heavy gasses as targets (e.g. Xe) will be acceptable. The mean energy loss induced on the beam by the target can efficiently be compensated also by the barrier bucket RF system, which is foreseen in the HESR from the very beginning.

Finally, the energy dependence of the lifetimes of bare uranium beams are given in Figure 11 for the case of a dense H$_2$ target ($10^{14}$ p/cm$^2$). Due to the small Compton profile of H$_2$, this target species is of particular relevance but also it might be the favorable target for possible nuclear reaction studies by the EXL-collaboration [40].

In summary, for all cases studied, moderate and even long beam lifetimes have been obtained. Due to the moderate charge-exchange cross-sections one may even consider the use of thin fiber targets.

### 3.3 Experimental setup

Different locations of the experimental installations in the HESR were investigated. Possible places could be the missing dipole straights in arc sections of the ring (see Figure 4 and Figure 12).

There are two symmetric positions in the arcs of the HESR. The most essential requirements for the location of the setup is the size of the beam at the internal target and the achievable resolution of charge-exchange reaction products.

For the beam emittance of $\epsilon_{x,y} = 0.05$ mm mrad, the beam size at the foreseen location of the internal target satisfies very well the requirements for the precision experiments.
Figure 11: Lifetime beams of bare uranium interacting with an H₂ target with an areal density of 10¹⁴ p/cm² as function of energy.

and is about δ(FWHM) ≈ ±0.8 mm (10⁸ stored uranium ions). This beam size is comparable with the typical size of the internal gas-jet targets of about ±1 mm.

3.3.1 Ion optical properties

The resolution capabilities have been simulated with ion-optical codes. Figure 13 illustrates the separation of ²³⁸U⁹²⁺ and ²³⁸U⁹⁰⁺ ions. The former is the primary beam, whereas the latter ions are produced by a double electron pick-up from the target. The positions of the target and of 2 particle detectors are indicated. The resolving power is clearly seen on the estimated positions on detector 1 and 2, illustrated in Figures 14 and 15, respectively. From these figures it is obvious that the resolving power is sufficient for the highest-Z uranium ions (Z = 92). For lighter ions the separation of the charge-exchange reaction products will be even better.

3.3.2 Space requirements

The dimensions of the tunnel and the available space are indicated in Figure 12. The length of 4.5 m should be sufficient for the installation of the experimental equipment illustrated in Figure 16.

The vacuum pipe of the HESR (89 mm in diameter) is equipped with cross vacuum chambers with 4 CF100 flanches before and after each dipole magnet. These flanches at positions of detectors 1 and 2 (see Figure 13) could be used for particle detectors to be installed on the inner and outer sides of the ring.
Figure 12: Possible location of the experimental installations in the HESR (shown with a yellow star). The dimensions of the tunnel are indicated on the drawings.

The height of the tunnel is 4 m, which combined with the height of the beam-line of 1.4 m leaves only 2.6 m above the beam axis for the installation of the gas-jet target. This space might be too scarce and a possibility to make a cavern around the gas-jet will be studied in details.

The entire setup might be put on rails in order to remove it from the HESR if it disturbs the antiproton operation.

If one location is occupied by the internal target and the reaction setup, the opposite side can accommodate an electron target for di-electronic recombination experiments. The electron cooler from the CELSIUS ring is available at GSI and can be employed as the electron target.
3.3.3 Internal target station

The realization of the SPARC internal target at the HESR will be based on extensive experimental studies carried out in the past years both at the prototype internal target at Experimental Storage Ring (ESR) [41, 42] and for the PANDA geometry at the test...
Figure 15: Resolution of $^{238}\text{U}^{92+}$, $^{238}\text{U}^{91+}$ and $^{238}\text{U}^{90+}$ ions on the detector 2 (see Figure 13).

Figure 16: Schematic illustration of the SPARC experimental installations.

apparatus in the group of Alfons Khoukaz at the university of Münster [43]. As far as the internal target at the ESR is concerned, the overall features of the prototype have been investigated under real in-ring experimental conditions with the purpose of future applications within the SPARC [44] and EXL [40] collaborations.
Figure 17: Layout of the prototype target station system including the closed cycle cryostat system (1), the new inlet chamber (2), the current ESR interaction chamber (3) and the preliminary target dump system design (4). The target dump will be redesigned with respect to its length in order to fit the HESR building dimensions. The inset shows the skimmer exchange panel which will be located at the bottom of the new inlet chamber. By assembling skimmers with different aperture diameters one can realize a variable interaction length.

The design of the ESR internal target station essentially consists of a high-power closed cycle cryostat that can be operated down to $\sim 4$ K, i.e. at temperatures where condensation of He starts occurring. The target beam is formed by expanding the desired target gas at defined source conditions (temperature and pressure) into vacuum. Whereas different nozzle geometries have been employed, these experiments have clearly shown that Laval-type nozzles as those formerly developed at CERN provide the highest stable target densities for a given orifice diameter. This confirms the seminal results obtained in Münster, where hydrogen target densities close to the $10^{15}$ cm$^{-2}$ level have been demonstrated by employing a cluster target beam in the PANDA geometry [43]. Target beams at the ESR have been produced by using a large variety of gases ($\text{H}_2$, He, $\text{N}_2$, Ar, Kr, Xe) at target densities that can be easily adjusted over several orders of magnitude ranging from $\sim 10^{10}$ up to $\sim 10^{14}$ cm$^{-2}$. In Table 4 we report the achieved target densities for the different gases. Only the hydrogen and helium densities represent the highest
values that can be currently achieved at the ESR. The Münster results, however, strongly suggest that a further improvement by at least one order of magnitude is expected by optimizing the inlet target geometry. More specifically, the current ESR internal target geometry significantly precludes the cooling of the source to lower temperatures, which has been shown to be a necessary condition for achieving higher target densities for the cryogenic low-Z targets [41, 43]. A draft of a possible layout for a new target station based on the existing ESR interaction chamber and target dump system is shown in Figure 17. Here, much lower source temperatures will be achieved, and a significant reduction of the distance between the nozzle orifice and the interaction point would further improve the performance of the target beam. An additional important aspect is the possibility to adjust the interaction length down to about 1 mm by employing exchangeable skimmers with different aperture diameters (see inset in Figure 17).

The possibility to reduce the source temperature would allow reaching conditions, in which the expanding gas starts liquefying. The fact that the vacuum expansion of a liquid may indeed provide a valid alternative to cluster jet targets has been shown recently at the ESR [41], where a cryogenically cooled liquid micro-jet target beam source was employed. These results are further confirmed by recent experiments carried out in Münster, where target densities exceeding the $10^{15}$ cm$^{-2}$ threshold, yet accompanied by unexplained density fluctuation phenomena, have been observed by cooling the source further down into the two-phase supercritical regime, and eventually well into the liquid phase [43]. These studies overall strongly support the observation that the vacuum expansion of a supercritical fluid or even a liquid is fundamentally different in nature compared with a gas jet expansion. In a recent experiment [42] the details of the interaction between a liquid hydrogen target beam and a stored beam of highly-charged ions was investigated in detail, revealing that a liquid droplet beam virtually behaves like a homogeneous gas jet target with respect to both energy loss and ion beam cooling. These findings are particularly crucial for a successful implementation of the new target system into the technical framework of the HESR.

Further work is planned to provide deeper insights into this new regime, and will be carried out in very close collaboration with the group of A. Khoukaz. One important aspect will especially concern the characterization of droplet beams produced by employing alternative orifice geometries beyond the CERN Laval-type nozzles. Since these latter were extremely expensive and are not produced any more, it was recently decided within the PANDA collaboration to start the design and production of Laval-like nozzles, but at
much lower costs. This planned nozzle development, which will involve partners at the University of Genova (M. Macri), Italy, and at GSI (H. Orth), is of outermost importance for the planned nuclear and atomic physics experiments at the HESR.

3.3.4 Coupling of laser beams

In order to perform the laser-spectroscopy experiments, it is needed to be able to overlap the ion and the laser beams in one (or both) straight sections of the HESR. For this purpose, a dedicated viewport shall be installed in the HESR at $0^\circ$. The corresponding part of the HESR lattice is illustrated in Figure 18.

Figure 18: A zoomed up part of the HESR lattice indicating the beam axis along which a viewport for the laser coupling shall be installed.

As can be seen in this figure, parts of the dipole, quadrupole and sextupole magnets lie on the beam axis where the viewport shall be installed. The design of the magnets has been completed [45] and their construction will be tendered soon [31].

Closer investigation of the magnet design has revealed that the part of the sextupole magnet lying in the way is a coupling box of the wire connections. This box can in principle be shifted to an off axis position.

The beam axis goes through the iron yoke of the quadrupole magnet. If no boring is possible, the mirror system to send the laser beam into the HESR has to fit in the space between the dipole and quadrupole magnets (about 1.5 m). Though this is feasible, this solution is not very flexible.

The maximum distance between the coils of the dipole magnet determines the maximum diameter of the viewport vacuum chamber. Together with HESR experts, a dedicated study has been initiated to find an optimal solution for this issue.
4 Cost estimates and time line

The possible SPARC scientific program at HESR has been discussed in details with the HESR working team, see e.g. [46]. Up to now, there are no unforeseen increases of the investment costs identified to the accelerator components as specified in the Modularized Start Version of the FAIR project.

The costs of the experimental equipment are documented in the corresponding FAIR cost book. Since the Experimental Storage Ring at GSI shall stay in operation until the NESR is commissioned, most of the relevant experimental equipment is being designed, commissioned or planned at the ESR. For instance, a prototype of the internal gas-jet target has been commissioned in the ESR recently. Further necessary R&D works are planned in the next three years within the BMBF program SPARC.de where some parts of the equipment can be financed through GSI via the BMBF Projekmitteleintrag. In this respect, the initiation of the SPARC research program at HESR does not cause any unforeseen costs and can entirely be based on the running research activities of the members of the SPARC collaboration.

The time line for the installation of the corresponding set-ups is based on the time line for the construction of the HESR. Since the entire setup can be built on rails to fit into the available space (see Figures 12 and 16), the full setup can be built and as far as possible commissioned already before the completion of the HESR. In this case the SPARC experiments can be started as soon as the heavy ions are available in the HESR. No show stoppers are expected for atomic physics experiments in HESR.

Due to similar setups, a suggestion to work together with PANDA collaboration on the “day-0” experiment in the HESR will be investigated in details [47].

5 Beam time sharing between ion and anti-proton experiments

Based on the experience with beam time scheduling at the ESR, the SPARC collaboration would try to organize experiment campaigns with a typical length of two months. Assuming a preparation time of close to one month, not more than in total three months per year will be devoted to SPARC experiments at the HESR. One may add, that during the MSV no parallel operation for heavy ion and antiproton beams will be possible and therefore the proposed use of the HESR for heavy ions may enhance the effective use of the HESR.

6 Summary

The presented report proofs the applicability of the HESR for heavy-ion research in the relativistic velocity regime. The already foreseen electron-cooling and stochastic cooling will allow to cover from the very beginning almost the whole energy regime accessible for heavy ions at the HESR. Although these installations have been optimized for the storage of antiprotons it turns out they are also well suited for heavy-ion beams. Moreover, the
dense internal target already developed for SPARC at the ESR for future experiments at
the NESR can be transferred to the HESR, enabling sufficient flexibility to serve for a
broad range of experiments anticipated by the SPARC collaboration. The floor space for
the experiments at the currently investigated target position seems to be tight and may
require further optimizations. However, no principle problem appears to be connected
with the floor space. The same holds true for the coupling of the laser to the ion beam
d line which appears difficult but possible. Moreover, the ion optics at the foreseen target
position appears to meet the very well the requirements of the planned experiments, i.e.
small beam diameter and low beam emittance at the target position as well as sufficient
spatial separation for the outgoing charge states upstream from the target area where
the particle detectors are located.
In conclusion, the HESR appears to be almost ideally suited for the envisioned exper-
imental program of the SPARC collaboration for the high and relativistic energy domain.
Beam cooling will allow for an up to now unprecedented beam quality when compared to
single-pass experiments at conventional relativistic ion accelerators in combination with
a gain of luminosity by orders magnitude.

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Wiedner is gratefully acknowledged. We are indebted to the members of the SPARC
collaboration for their help in preparation of the present document.
References


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8 Appendix: The SPARC Collaboration


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