SPARC@FAIR: Preliminary Research Strategy during the FAIR-FS+ Construction Phase 2023-2028

- **General comment**

The FAIR scientific evaluation from summer 2022 recommended a new staging of the project realization. Following this recommendation, confirmed by the FAIR Council in December 2022 as the new strategy for FAIR, the APPA collaborations will pursue their scientific activities at the existing GSI / FAIR facilities until 2028. For the SPARC collaboration this includes ESR, HITRAP, CRYRING@ESR and cave A.

During the last 4-5 years the development of new theoretical and experimental ideas for SPARC relevant investigations at FAIR was paired with the development of numerous new, technologically advanced instrumentation. The aim of the SPARC collaboration is to make use of the new ideas and instrumentation at the present GSI facilities, at the maximum possible extent. This strategy is essential for the collaboration and for both GSI and FAIR facilities because:

- It assures the survival of the interest of external scientists in the campus and finally the collaboration survival until FAIR MSV will be fully realized.
- The past investments must be translated into new scientific knowledge.
- For further funding (operation, maintenance, upgrade, new projects) the groups must achieve excellent scientific results.
- The full exploitation of the FAIR capabilities will be possible only with a well-educated, and highly motivated generation of young scientists who are now preparing the start of their carriers.
- During the 2026-2027 when the FAIR activities will concentrate on the installation and commissioning of the new machines and experiments, the scientific output of the campus should continue at a visible level.

Various experiments and research projects are explicitly mentioned below. The order of scientific cases given below does not imply or follow any priorities. We also note that for SPARC's dynamic research field, the time span until 2028 is quite long and we expect that many new ideas for novel experiments will emerge in the meantime. SPARC is prepared to adjust the list of projects accordingly.

- **Engineering run 2023**

All experiments which have been granted beam time for the next beam time period, 2023-2025, have been checked in view of beam requirements by the GSI accelerator team and enabled for the G-PAC evaluation. Therefore, we consider that, in principle for all experiments in 2024-2025 the requested beams and beam parameters are realisable with normal working conditions. However, we would like to stress once more, in a concise form, these requirements. The SPARC experiments will need the ESR, CRYRING@ESR, HITRAP and cave A facility for the already approved experiments.

CRYRING@ESR:

For the machine optimization, following operation steps should be tested and demonstrated:

- optimize/increase the intensity of soft beams (e.g. Ne^{3+})
- investigation of alternative detection schemes for ions, especially at low energies; this will give more space in the ring for future experiments installation

– development of additional beam species: $S^{1+,2+,3+}$ and W in different charge states (14+ to 17+)

In addition, for the realisation of the experiments with the local ion source in 2023

1. the e-cooler must be reinstalled and operable
2. the ion source should be reinstalled and able to deliver: Mg^{+}, Ne^{3+}, Ne^{7+} and $^{16}O^{X+}$.
3. the internal Gas Jet Target should deliver He-target in stable conditions and requested density ($5x10^{11}$ atoms/cm^2)

CRYING@ESR run with local source:

Three experiments are ready to run already in 2023:

– Absolute rate coefficients from dielectronic recombination for the astrophysical relevant ions (18 shifts).
– Ion beam and level population dynamics in Mg^{+} in laser spectroscopy at CRYRING@ESR (36 shifts).
– Commissioning and first storage ring experiments of the CRYRING@ESR transversal e-target (42 shifts).

Beams of $Ne^{3+,7+}$ and Mg^{+} are requested.

ESR:

For the approved SPARC experiments, the following capabilities of ESR should be tested and established (also A- experiments should be considered as far as possible):

– Re-commissioning of the electron cooler: stability and precision checks at different voltages and currents.
– Recommissioning of the drift tubes control in the ESR cooler: fast HV-Amplifier TREK 609.
– DR measurements to characterize the cooler after the re-installation: heavy, Li-like or Be-like ions (Z>54) are needed for the tests. Both activities, the drift tubes recommissioning and the test DR measurements are mandatory for the run of the A-rated DR- assisted laser spectroscopy experiment.
– Improvement of the deceleration efficiency: vacuum conditions and, in the close future, the replacement of the power supply unit.
– Test of the accumulation in ESR of RIBs produced in stripping foil: stacking supported by stochastic cooling (similar to Experiment ^{229}Th from) ^{238}U/^{232}Th.

HITRAP:

For the successful run of the approved HITRAP experiment ‘Nanostructuring of monolayer graphene by highly charged ions’ a machine run in advance using a light to medium-heavy ion beam is needed. For this, the ESR should be again in operation and the machine run will need around 7 days. The ion species and beam properties for the experiments will be communicated by the users in March 2023.

Cave A:

The experiment scheduled in cave A needs a stable and efficient slow-transferred beam from ESR to cave A. The beam on target, U^{89+}, should have a medium intensity and the requested divergence (as close to zero degrees as possible). The transfer with these conditions from ESR to cave A was never proven after the control system upgrade.

- **Beam time 2024-2025**

CRYRING@ESR:

For the production runs the experiments will use mostly beams transferred from the ESR. Some A-rated proposals, if scheduled, need also the local ion source.
The main requests are for Uranium in different charge states (bare, He-like and Be-like) and for bare Xe. For another probable run, bare Ar would be also a possibility (depends on the installation time of the setup FISIC).

ESR:

- For the DR- assisted laser spectroscopy (DRALS) the accumulation of Li-like RIBs (Bi^{80+} from primary Bi beam) with a different method (Ecool-stacking) should be tested
- ^{229}Th studies
- Test beam time for the new laser systems to be built for the laser cooling experiment in SIS100 (FAIR- FS). They should be installed in SIS100 as soon as they are ready built and tested (after 2024). Test of the new laser cooling method based on the combination of the three new lasers. This activity should continue beyond 2025 with priority.

HITRAP:

- Finalize the commissioning of the facility in coordination with ACC. The extent of the commissioning activities will be defined according to the beam properties requested for the proposed experiments.
- First pilot experiments on the g-factor and hyperfine splitting of highly-charged, heavy ions at ARTEMIS and SpecTrap.
- First test experiments towards Quantum logic spectroscopy for frequency metrology of heavy and simple ions (new Helmholtz Young Investigator Group program)[1].

- **Strategy and Requirements beyond 2024-2025**

ESR science program 2026 to 2028:

The SPARC activities beyond 2026 will follow two lines: continuation of studies which are now in the program with A and A- ranks as well as the installation, commissioning and use of new setups which are ready for use or already funded and in construction.

The science cases which we propose for studies are:

- Electron impact excitation (EIE)
- Nuclear excitation by electron capture (NEEC / NEET)
- Hyperfine structure investigation of Tl^{80+} and $Pa^{88+,90+}$. These experiments need the extension of the ion production and manipulation method already established in ESR for Bi- isotopes.
- Testing of the possibility to optical pumping in Li^{+}-ion.
- Laser cooling test in Li-like ions (C^{3+}, N^{4+}) as precursor experiments for SIS100 laser cooling in 2028.
- Laser spectroscopy of a Be-like ion (Kr^{32+}) as a test of electron correlation effects in medium-heavy few-electron systems
- The present laser, electron and x-ray spectroscopy studies have follow-ups in the future such as $\Delta n=0$ transitions in high-Z He-, Li-, Be -like uranium isotopes including ^{238}U.
- XUV-laser experiments

[1] *HYIG: VN-NG-19-23, Peter Micke, Jena

- Precision polarimetry applied to ground-state transitions in H-, He- and Li-Like (open-K-shell) ions to study multipole-mixing and higher-order multipole effects.
- Surrogate nuclear reaction studies, NECTAR program
- (p,γ) and (α,γ) studies will continue at ESR and start in CRYRING@ESR

ESR Technical improvements:

- Upgrade of the target station: new gas-jet, additional reaction chambers at the internal target, polarized atomic hydrogen target, flexible, exchangeable target stations.
- Installation of the transverse e-target at ESR: new interaction chamber to be realized at the place of the present ToF – detector. The e-target and the ToF detector can be alternatively operated in different beam time blocks.
- Transverse Schottky.
- XUV-laser installation at ESR.
- Multi-electron transfers detector installation in the dipole.
- Refurbishing of the in-ring particle detectors, drives and control system.
- Extraction of reaction products to the transfer line –specific for (p,γ) experiments.

CRYRING@ESR science program 2026 to 2028:

Similar studies as those proposed for ESR will be continued in CRYRING@ESR at different energies. More specifically we mention:

- CARME experiments (ELDAR ERC grant)
- 1s grounds-state Lamb Shift in H-like uranium
- Dielectronic Recombination spectroscopy (DR)
- Molecular studies using momentum imaging by Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS LoI, setup in construction)
- FISIC: slow ion-fast ion collisions studies for plasma and astrophysics benchmarking. The setup is almost ready and the transfer to GSI could start in 2024.
- Continuation of NECTAR –like studies at lower energies
- Investigation of clock-transitions in medium heavy, highly charged ions. To enable these studies, the production of the ions of interest via ESR or the installation of a new local source (EBIS, ECR) are primary requirements.

CRYRING@ESR Technical upgrades:

- realisation of a high-repetition pulsed laser (optical pumping on Mg^+)
- Linac RF: upgrade to 50 kW (108 MHz)
- ECR source: 14 GHz, 1.5 kW
- exchange of the ring RF with a modern one, smaller in dimensions, faster in acceleration and more efficient in transmission (up to 50%)
- new super-conducting cooler magnet
- ion source for spin-polarized hydrogen

HITRAP science program 2026 to 2028:

- g-factor and Hyperfine splitting of highly-charged, heavy nuclei at ARTEMIS and SpecTrap.
- X-Ray spectroscopy on astrophysical electron capture studies related to slow H-like medium-Z ions.
- Quantum logic spectroscopy for frequency metrology of heavy and simple ions

HITRAP general remarks:

- For regular experiments runs at HITRAP, beam time for machine development and setting will be needed in a continuous mode. This implies **at least** a 7-day machine test run per year. This beam time is independent on the experiment type to be performed and is dedicated exclusively to the machine operation development and stability.
- In addition, for each to be performed experiment the machine setting time is estimated according to today's experience to a minimum of 5 days (this excludes the beam preparation in SIS and ESR).

General infrastructure:

- Internal target lab must be available independent of the PANDA strategy. SPARC will use two gas targets: in ESR and in CRYRING@ESR and further development, tests and upgrades will be needed.
- An experiment assembly and testing work area outside the CRYRING@ESR cave but close to it, located in the TH, is also an absolute long-term necessity. The currently existing, temporary space is a very helpful alternative, but the status of this area or an alternative one with similar possibilities and the use of it should be defined for a long-term use.
- Due to the further-in-the-future perspective of the SPARC experiments in the APPA cave at FAIR an assessment of the cave A use and an upgrade should be soon discussed by the collaboration.