# Letter of Intent:

# SPARC Strategy for the years 2022 to 2025/2026

**The scope of the present Letter of Intent** is to layout the beam time planning strategy of the SPARC collaboration for the time span 2022 to 2025/2026 (research program FAIR Phase-0 of GSI). At the beginning, we provide short introductory sections related to the collaboration and its physics program and goals. This is followed by a presentation of the overall strategy in light of the various boundary conditions the collaboration is facing. Thereafter and more specifically, a projection of the experimental program for the time span of relevance is presented for all three facilities ESR, CRYRING@ESR, and HITRAP.

**The SPARC Collaboration** (Stored Particle Atomic physics Research; about 440 members from 26 countries) will exploit the ***unrivaled combination of storage and trapping facilities, a unique feature that distinguishes FAIR from all planned or operating particle accelerators worldwide***. FAIR is unique to deliver highly intense, brilliant beams of highly charged heavy ions and radio-nuclei with excellent momentum definition. As depicted in Fig. 1, the FAIR hierarchy of storage and trapping facilities covers a beam-energy range of more than 13 orders of magnitude for virtually all elements in any charge state up to bare uranium [1,2].

**The physics program of SPARC** is related to the physics fields of atomic, quantum and fundamental physics with the focus on the study of matter (electrons, atoms and nuclei) subject to extreme electromagnetic fields as well as to electronic processes mediated by ultrafast electromagnetic interactions. A prominent example for SPARC related research concerns the binding energies of electrons in high-Z one-electron ions where the K-shell electrons are exposed to electric fields (e.g. $10^{16}$ V/cm in $U^{91+}$) close to the Schwinger limit. SPARC has initiated a comprehensive research program to accomplish a significant validity check of non-perturbative bound-state QED. This will even enable high-precision determination of fundamental constants as well as the determination of nuclear parameters such as nuclear radii. At the same time SPARC will exploit the unique research potential of the storage rings and of HITRAP for astrophysically relevant studies including stable and secondary nuclei with the particular focus on the border between atomic and nuclear physics.

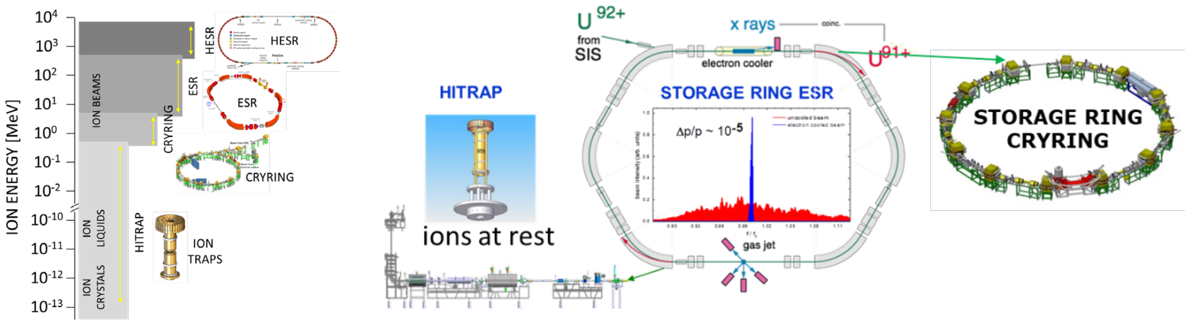


Fig. 1: *(left) Hierarchy of storage and trapping facilities at GSI/FAIR. (right) The ESR storage and trapping complex including CRYRING@ESR and HITRAP [1].*

**Strategy:** For the years to come, the particular focus of the strategy of SPARC is the exploitation of the ESR and CRYRING@ESR cooler and storage rings as well as the trapping facility for highly-charged ions HITRAP (see Fig 1) by utilizing dedicated FAIR instrumentation developed by the collaboration. Important to note, that all these facilities are part of the modularized start version (MSV) of FAIR. Therefore, the strategic positioning of the SPARC collaboration outlined in the current document applies to the research program FAIR Phase-0 but belongs in fact already to FAIR Phase-1 as far as the facilities ESR, CRYRING@ESR, and HITRAP are concerned. This strategic positioning provides the firm basis of the overall SPARC strategy including future research opportunities provided by the HESR and the APPA cave using heavy ions in the multi-GeV/u energy regime.

For the years to come the central priorities of SPARC are:

- To maximize the physics output with concentration on highly visible experiments which utilize the unique features of the storage and trapping facilities of GSI/FAIR;
- To push all the facilities under discussion for providing the full (design) parameter space and reliable operation;

- To provide highest possible flexibility in scheduling experiments in order to react quickly on new developments in the very dynamic field of AMO science;
- To operate the facilities of relevance as open user facilities always promoting new ideas and developments.

**In order to cope with this strategy**, the collaboration faces various challenges closely related to the relative short beam time of three months available per year in combination to the need of commissioning and further optimizing the operation of the facilities until the design parameters of the machines have been reached. ***One may note, that CRYRING@ESR has just been installed and commissioned. However, there is still a long way until reaching the final intensity and beam lifetime goals. Commissioning of HITRAP has been significantly delayed and is expected to take place in 2022.*** Reaching the design parameters will be a quite time-consuming enterprise but a prerequisite for the optimal use of the facilities for physics production runs which is in particular true for the flagship experiments. Moreover, in terms of efficient use of beam time and resources it is also very important to point out that the experiments at the storage rings require in general the integration of parts of the experimental setups into the XUV vacuum of the rings ($\approx 10^{-11}$ mbar) which is not only technically challenging but is also very time consuming and may require substantial personnel resources. Such integration work is mostly unavoidable, however, should be minimized. In particular, the compatibility to other planned experiments needs to be checked carefully. ***Setups and experiments which require substantial construction works and which may block the rings for other experiments for a long time period should be avoided, at least at the present situation of very limited beam time availability.*** Therefore, priority and full concentration should be given for reaching reliable facility operation and for pushing towards the design parameters. Also, one needs to be aware that experiments scheduled for CRYRING@ESR and HITRAP set strict boundary conditions for the experiments at the ESR. Setups which may affect the vacuum of the ESR (e.g. integration of silicon detectors which cannot be baked to the required temperatures) should be avoided as far as possible too since they may seriously affect the deceleration capability of the ESR. In general, SPARC will apply in the future the overall rule that in case experiment installations will affect the performance of the facility, the date of the deinstallation needs to be fixed at the time of installation regardless of the outcome of the experiment. This will avoid blocking the facility for new experiments.

For completeness, we bring to your attention the following additional boundary conditions and commitments which need to be taken into account in case of beamtime planning for the SPARC collaboration:

- Acquired 3rd party funding for SPARC related experiments;
- Milestones of the Helmholtz research programs based on the recommendation of the Helmholtz Senate for the years 2021 until 2027:

  2023: Integration and commissioning of FISIC setup at CRYRING (remark: delayed by one year due to COVID-19);
  2024: Obtaining highly accurate results on bound-state QED in the extreme fields of high-Z ions, which challenge theory;
  2025: Operate routinely a 1k-pixel cryogenic MMC sensor array for precision QED tests at CRYRING.

Finally, and as a very general remark, we like to comment on the overall situation of the SPARC collaboration. Over the years, the collaboration with its research focus has turned out to be very creative and flexible. The loss of the NESR along with the FLAIR facility (at least for the time to come) was at least partially compensated by promoting CRYRING@ESR and its realization which turned out to be a full success (large user request resulting in a very large overbooking). At the same time the collaboration has faced a long time span of basically 10 years with no experiments. Due to the uniqueness of GSI/FAIR there are no alternative facilities to escape to. For the university groups with their PhD students, this situation turned out to be very challenging. Therefore, currently, the highest priority is to enable as many experiments as possible to serve the community and collaboration. Of course, the science case of the experiments needs always to be evaluated by the GPAC***. Since, we cannot escape the various strict boundary conditions, we are eager to promote even stronger than in the past the standalone operation of HITRAP and CRYRING@ESR to compensate for this issue at least partially.***

**Beam time planning and concluding remarks:** When considering beam time scheduling, also the requests of the other collaborations and research communities active at the various experiment stations behind SIS18 need to be considered. This sets additional strong boundary conditions for the beam planning at the storage and trapping facilities at GSI/FAIR in particular with respect to the ion species (elements). ***Therefore, we would like to ask the GPAC to accept more experiment proposals of category A- to allow for a more flexible scheduling***. We also intend to add a short judgement of the collaboration board to each submitted experiment proposal related to the feasibility of the experiment in terms of resources needed and the impact for other experiments.

# The facilities: ESR

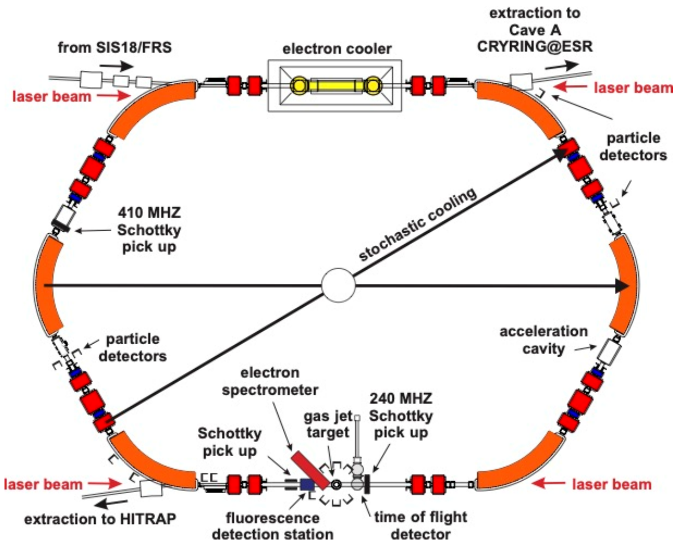


Fig. 2: *Schematic view of the ESR. Main components are indicated. Please note that only a few shown particle detector positions are labelled.*

**ESR** is unique heavy-ion storage ring facility which offers unparalleled experimental capabilities for precision physics with stored highly charged stable or radioactive ion beams [3,4]. The ESR can receive secondary beams either directly from the synchrotron SIS-18 via a TE line equipped with a stripper target station or from the fragment separator FRS. Various operation modes and beam manipulation techniques were developed at the ESR which include isochronous and standard ion optical settings, stochastic and electron cooling, bunched and coasting beams, accurate orbit modifications, multi charge-state operation etc. In recent years, the focus is laid on the ability of the ESR to efficiently decelerate secondary beams either for experiments in the ESR or for extraction the beams towards HITRAP or CRYRING@ESR.

**SPARC@ESR:** The SPARC research program at the ESR is very rich. It focuses on the exploration of the physics at strong electromagnetic fields including the fundamental interactions between electrons and heavy nuclei as well as on the experiments at the intersection of nuclear, atomic and astrophysics. Numerous highlight experiments were conducted in the ESR by the SPARC collaboration. Still the discovery potential is huge, which is reflected by many approved A and A- experiments. In 2020-2021 running period, several A and A- experiments were successfully completed (E121, E125, E127, E132, E135). In 2022, A experiments E128 (hyperfine splitting in $Bi^{82+}$), E137 (extraction to Cave-A), E142 (nuclear hyperfine interaction in $^{229}Th$), and E146 (ERC advanced grant NECTAR) are scheduled. For experiments with extracted beams towards CRYRING@ESR, see the next section.

**Priorities:** As can be seen in Fig. 2, the ESR is densely packed with accelerator and experimental equipment. Basically, no free space is available. Therefore, any new installation affects other experiments and shall be thoroughly coordinated. For any temporarily installed equipment a strict removal time must be fixed.

Tuning the energy of the electrons in the electron cooler is achieved with a dedicated drift tube. Since a few years, there is short circuit in the drift tube. To re-enable the collisions with electrons at the ESR, the electron cooler must be repaired at earliest possible time, preferably during the long shutdown 2022-2023. It is the prerequisite for experiments relying on dielectronic-recombination assisted particle detection.

In addition, an experimental campaign for R&D studies related to the interaction of ions with crystals is planned in Cave-A using cooled highly charged ions from the ESR. This will provide a high-resolution and high-efficiency approach (indirect method also suitable for secondary ion beams) to atomic structure studies with sensitivity to nuclear parameters. The experimental setup to be developed will be used in the APPA-Cave to perform the first SPARC physics runs with highly relativistic heavy ion beams from SIS100.

Absolute majority of the experiments involving the ESR requires decelerated beams either for experiments directly in the ESR or extracted towards HITRAP or CRYRING@ESR. The clear priority of the SPARC collaboration is to improve the efficiency of the deceleration procedure, which include:

- Upgrade of the power supply of the electron cooler. The stabilization of the electron cooler after ramping to the lowest energies requires a few seconds which lead to dramatic beam losses due to interactions with residual gas;
- Upgrade of the vacuum system to reduce beam losses at lowest energies;
- Optimization of the ESR control system to achieve the most efficient deceleration.

# The facilities: CRYRING@ESR

**CRYRING@ESR** is a very flexible experiment facility and offers possibilities for a large number of experiments in the realm of atomic, quantum and fundamental physics based on electronic, photonic, or atomic interactions [5,6]. The ring has in general various areas for setting up experiments: The electron cooler in section YR03 for studies of electron-ion interactions in merged beams configuration, the laser fluorescence setup in section YR07, the straight section YR09 which offers room for a certain number of experimental installations as explained below. Experiments at the electron cooler can be prepared with almost no interference with other experiments, the same is true for laser fluorescence experiments or the current MAT-station at the extraction beamline. These three stations are in operation and have demonstrated readiness for serving granted beamtimes during the 2021 beamtime period. At section YR09 however, the scenario is more complicated. Installations in YR09 are immensely correlated with the ring operation, as they require breaking the vacuum in a sector of the ring. Moreover, any modification of section YR09 is a very man-power intense effort and requires long periods of pumping and baking to re-establish the excellent ultra-high vacuum conditions, which are mandatory for useful storage times of slow highly charged ions.

**Status and timeline:** Despite the COVID-19 pandemic, substantial progress in commissioning of CRYRING@ESR has been achieved. Thanks to the engagement of the local teams at the campus of GSI. commissioning could be completed in 2020 and in 2021 very first physics production runs have been performed successfully: By using the local injector E129 (photoionization of $C^{1+}$), E148 (optical pumping of $Mg^{+}$), E153 (tri-electronic recombination for $O^{6+}$), E140 (absolute rate coefficients of astrophysical relevance for $Ne^{2+}$). Most notably, even the very first experiment with heavy, highly charged ions from the ESR (E131; dielectronic recombination spectroscopy for Be-like lead) ions was conducted successfully. However, the second experiment using beams from the ESR, which focused on X-ray spectroscopy of H-like uranium ions (E138; Lamb Shift in $U^{91+}$), was less successful and documents that there is still room for improvement, as beams with useful intensities could only be provided on 3 out of 14 days. Nevertheless, this experimental endeavor proves that there is no principal showstopper, but the deceleration efficiency and reliability as well as beam lifetimes need further substantial improvements.

Based on accepted TDRs and A ranked experiment proposal by the GPAC, the SPARC collaboration is presently in the process of setting up CARME-0° – Gasjet – Electron target (in line at section in section YR09), which is an endeavor requiring the entire time period of the shutdown-break between the 2021 and 2022 beamtime blocks. An image of the 3D-model and the present state are shown below (see Fig. 3). Commissioning beam time for all three completely new large-scale experimental installations is a necessity to reach the full performance, required for accomplishing the approved GPAC proposals for 2022. A possible timeline is shown below (Fig. 4) which is based on extrapolations from the past beamtime periods and communicated progress from experiment projects. Please note, a reconfiguration of section YR09 before ~2024 is excluded.

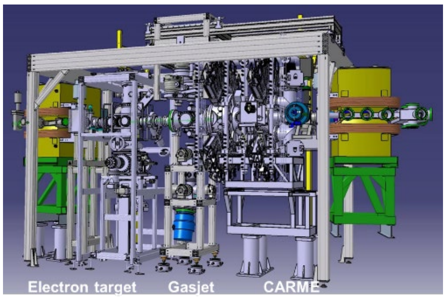


Fig. 3a: *3D-model of section YR09 for 2022. Shown are entry-side dipole magnet – electron-target – gasjet – CARME – exit side dipole magnet, with beam direction from left to right.*

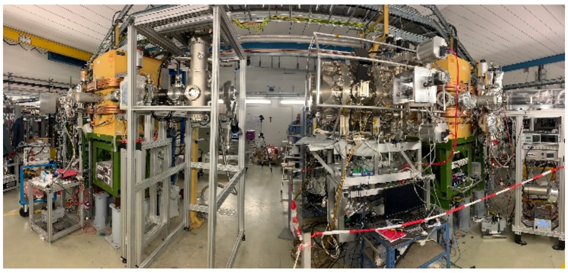

Fig. 3b: *Installation status on Oct. $10^{th}$, 2021. The CARME-chamber is set up, underwent a test-cycle of the baking system and has reached < $10^{-11}$ mbar vacuum, and detectors are currently being prepared. Both electron target and internal gas target are currently getting assembled.*

**Ion beams and ion source developments:** The raison for CRYRING@ESR is experiments with slow, highly charged ion beams being transferred through ESR from the GSI accelerator chain. During the 2021 beamtime period, the first GPAC proposals on highly charged ions were scheduled for beamtime (E131, E138). There, intensities of about $5 \times 10^6$ ions of $Pb^{78+}$ or $2 \times 10^6$ $U^{91+}$ could be transferred from ESR and stored in CRYRING. Dominant losses (>90%) were observed already in the slow deceleration and electron cooling in ESR and about 50% transfer efficiency. It should be noted that the space charge limit of CRYRING is nearly 2 orders of magnitude above the reached intensities and that injection efficiency of beams delivered to CRYRING was near 100%. Thus, it is important that beam losses in the upstream providers will be minimized in the future, so that requested beam intensities of upcoming experiment proposals for CRYRING@ESR can be accomplished.

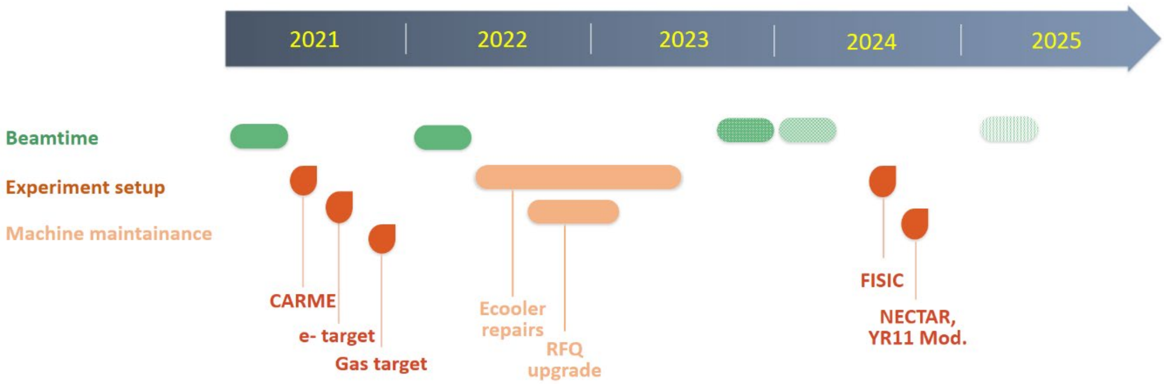


Fig. 4*: A possible timeline of beamtime scheduling for CRYRING@ESR.*

Besides, CRYRING can operate independently with a local ion source and provides beams for testing setups and during phases where ESR beam is not available. In fact, several GPAC proposals using beam from the local injector were approved (E149, E151, E154) or could be realized (E129, E148) or started (E140, E153). At the moment, a compact permanent-magnet ECRIS is installed in CRYRINGs ion source terminal. Experience with this ion source has shown, that CRYRING@ESR can store $10^8$ $d^+$ ions, $10^7$ ions of $Ne^{2+}$, and about $10^6$ of $O^{6+}$ or $Ne^{7+}$. However, the source intensity for even higher charge states drops rapidly. A new, more intense ECRIS is presently being planned within the Hessian LOEWE cluster project ***ELEMENTS*** *"Exploring the Universe from microscopic to macroscopic scales"*, a research network of the Universities at Darmstadt, Frankfurt, and Giessen along with GSI Darmstadt which has granted funding for the years 2021 till 2025. This source can be expected to be available in 2024.

**Planning of future installations beyond 2024:** For this time period (see also Fig. 4), large scale projects for section YR09 such as FISIC and NECTAR but also the COLTRIMS setup are presently under consideration and in the design phase. All of them are already funded but are at different stage of realization. The experiment proposals of the SPARC collaboration for the FISIC project and for the COLTRIMS setup have an already provided accepted TDRs. In case of NECTAR a TDR is in preparation, but beam time has already been granted by the GSI directorate since this activity is based on an ERC advanced grant. For FISIC and COLTRIMS, experiment proposals will be submitted for the GPAC meeting in 2022. Each of them brings strong ion-optical and mechanical boundary conditions for experiments focusing e.g., on the use of electron or internal gas target. Moreover, some of the mentioned projects are also requiring performance parameters which have not yet been reached. The latter needs to be checked carefully before starting substantial and resource intensive rebuilding of section YR09. For completeness we like to emphasize that there are also various ongoing activities related to novel experiments at the other ring sections, e.g., a pair of asymmetric von Hamos spectrometers designed for the electron cooler section aiming on precision spectroscopy (at 0 deg and 180 deg) of X-rays in the regime between 5 to10 keV (in-kind contribution from Poland with accepted TDR). Finally, we note, despite the current midterm planning (s. Fig. 4), we still like to keep scheduling of beam times at CRYRING@ESR as flexible as possible to be able to react quickly on novel physics ideas and developments. Long-term commitments should be handled with careful considerations.

# The facilities: HITRAP

**HITRAP** is an electromagnetic trap facility for decelerating, capturing, cooling and investigating highly charged ions (HCI) produced at GSI in the heavy-ion complex of the UNILAC-SIS accelerators and the ESR storage ring [7,8]. This facility will be unique in its ability to produce and deliver such species up to uranium as bare nuclei, hydrogen-like ions or few-electron systems in a trap. The precision traps for receiving and studying these ions are designed to hold them for long periods of time at cryogenic temperatures. By performing measurements in the trap over such long storage times at cryogenic temperatures, unprecedented accuracy will be possible for studying systems with the highest available electromagnetic fields (close to the Schwinger limit of $2\times10^{16}$ V/cm in hydrogen-like uranium).

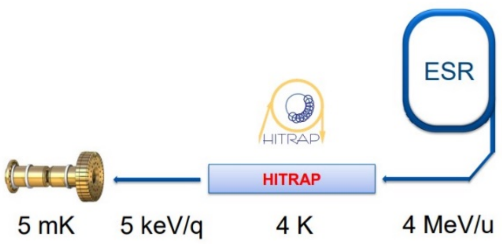


Fig. 5a: *Deceleration scheme applied for HITRAP.*

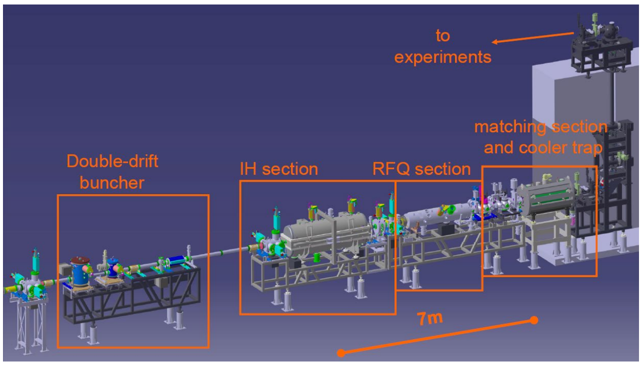


Fig. 5b: *Schematic of the HITRAP decelerator with its components and the experimental area.*

**Current status:** The basic components pertaining to the HITRAP facility are outlined in Fig. 5. HCI are accelerated in the Heavy-Ion Synchrotron SIS, stripped by a foil to the desired charge state and injected into the ESR storage ring at energies of a few hundred MeV/u. The ion beam is cooled by electron cooling for about one second. Depending on the beam intensity several pulses can be stacked in the ESR. The ESR beam is decelerated to 4 MeV/u. A brief cooling with electrons at bottom energy compensates for emittance blow-up due to deceleration. The beam is then re-bunched at a higher harmonic of the revolution frequency to provide bunches with a pulse length of 1 $\mu$s about every 40 seconds. The bunches are then extracted from the ESR and decelerated to energies in the range of keV/u by a linear interdigital H-mode (IH) drift-tube structure operated at 108 MHz followed by a RFQ decelerator. This deceleration of HCI to a few keV/u was demonstrated during beamtimes in the past years (2014).

**Current status and re-commissioning:** Because the last beamtime happened in the year 2014, for recommissioning of the HITRAP decelerator, several actions for refurbishing the facility have/had to take place. A list of those tasks has been established by the accelerator department of GSI. A required time of more than one year has been estimated by the accelerator groups for accomplishing this work and the next beamtime for recommissioning of the HITRAP decelerator is scheduled for May 2022. After deceleration the ions will be transferred to a Penning trap for electron cooling and resistive cooling which is a particular challenge. This cooling trap is being commissioned with HCI from an offline ion source (SPARC-EBIT). From the cooling trap the ions will be transferred to the experimental area located on the second floor. Note, re-commissioning does not rely on the use of heavy ion beams but can also be done with low or mid-Z ions with q/m between 2 and 3. This may relax the requirements for scheduling dedicated commissioning beam times for the HITRAP decelerator.

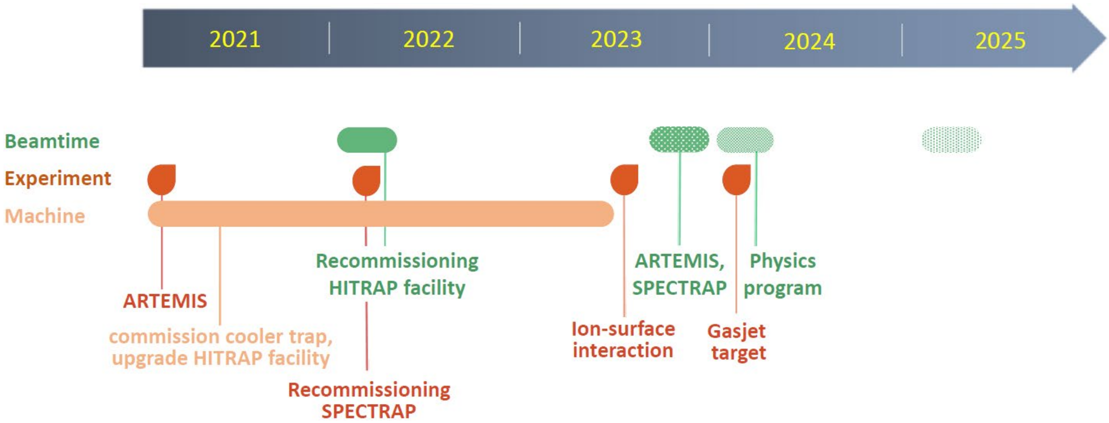


Fig. 6: *Timeline for the HITRAP facility and experiments. The red drops indicate the installation of the experimental setups.*

**A first physics production run** is planned with the precision trap ARTEMIS aiming *'Cooling and precision spectroscopy of $^{209}Bi^{82+}$ ion ensembles with the ARTEMIS and SPECTRAP experiments at the HITRAP facility' (E130).* In preparation for the beamtime in 2022, the ARTEMIS experiment is being commissioned with $Ar^{13+}$ ions from an offline source. The connection of the ARTEMIS setup to the low energy beamline of HITRAP is currently being prepared and commissioned with ions from an offline EBIT ion source. A new superconducting magnet for an upgrade of the SPECTRAP experiment, a Swedish in-kind contribution for FAIR, has arrived and is expected to be operational in 2022. The existing setup of SPECTRAP will be adapted to the new magnet and commissioned with offline ions. After having completed all the required commissioning measures in 2021 and 2022, highest priority for SPARC in 2023 has the very first physics production E130 which has already granted beam time by GPAC in 2017 as well as in 2020.

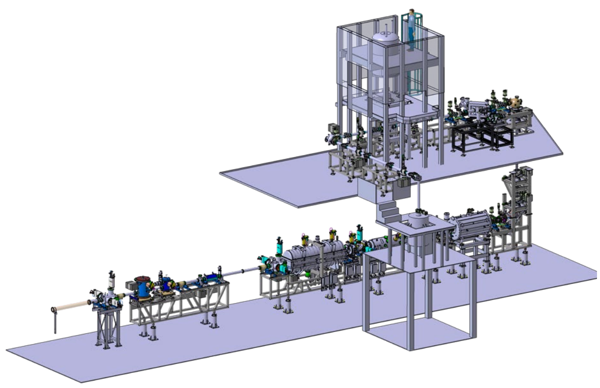

Fig. 6a: *Schematic of the HITRAP facility and the experimental area.*

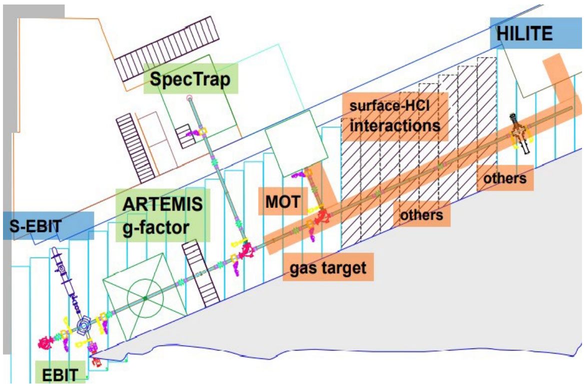


Fig. 6b: E*xperimental user area with the low-energy beamline at HITRAP (orange: planned but most instruments already available; blue: under commissioning; green: in operation).*

**Future beam time planning:** With the novel techniques of deceleration, trapping, and cooling of highly charged ions (HCI), experimental studies on extremely slow HCI or HCI nearly at rest up to U92+ can be performed for the first time which interact with photons, atoms, molecules, clusters, surfaces, microstructures and solids. The low emittance of the beam of slow heavy HCI extracted from the cooler Penning trap will make it possible to perform a new generation of collision experiments with substantially increased momentum resolution and kinematically complete detection of all reaction products (recoil ions, electrons, photons). The study of ion-surface interaction and of 'hollow atoms' formed when an ultra-slow HCI approaches a surface at close distance is of particular interest. Various collaborators within the SPARC collaboration have already prepared adequate instrumentation to be used at the HITRAP experiment platform (e.g. HZDR and TU Vienna for surface studies). A sketch of the user platform of HITRAP is shown in Fig. 6. Starting from 2024 we plan to bring the HITRAP user platform into full operation. In order to re-organize the HITRAP user community within SPARC, we plan for the first half of 2022 an EMMI workshop focused on HITRAP and its unparalleled physics opportunities. The foreseen projects include the following experimental setups provided by the collaboration: Laser spectroscopy, g-factor measurements, atomic binding energies (Lamb-shift) by cyclotron frequency measurement, ion-surface interaction studies, collision studies with magneto-optical trap, collision studies and spectroscopy with a dedicated pulsed gasjet target.

**Ion sources:** As compared to the CRYRING@ESR, for the operation of the various experiment stations at HITRAP, dedicated sources for highly charged ions (EBIT sources) are already in operation or under commissioning. Most prominently are the co-called Stockholm-EBITs (S-EBIT **I** and S-EBIT **II**: contribution from the Stockholm university). S-EBIT: voltage of up to 40 kV; electron current of up to 150 mA. S-EBIT II: voltage of up to 250 kV; electron current of up to 250 mA. The SPARC-EBIT (max. 20 kV) is a commercial device (DREEBIT) and is readily available for commissioning the HITRAP cooler Penning trap, the low-energy beamline and the experimental setups.

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