

The NUSTAR Project at FAIR

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Abstract. The FAIR facility, under construction at the GSI site in Darmstadt, will be addressing a wealth of outstanding questions within the realm of subatomic, atomic, plasma, bio-physics and applications through a combination of novel accelerators, storage rings and innovative experimental set-ups. One of the key installations is the fragment separator Super-FRS that will be able to deliver an unprecedented range of radioactive ion beams (RIBs) in the energy range of 0-1.5 GeV/u. These beams will be distributed to three branches, each with its unique domain with respect to beam energies and properties. The high-energy branch will permit reactions with radioactive beams at relativistic energies, whereas the low-energy branch will supply decelerated beams for high-resolution spectroscopy, traps and laser spectroscopy. Finally, the ring branch will uniquely permit stored and cooled exotic beams for a range of methods only possible in a storage ring. Thus, by developing experimental set-ups tailored for these beams, there are several complementary possibilities to gain information on key nuclei and reaction, to further our understanding on contemporary questions within nuclear structure and nuclear astrophysics. This ambitious programme is to be exploited within the NUSTAR (Nuclear Structure, Astrophysics and Reactions) collaboration.

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1. Introduction

The FAIR (Facility for Antiproton and Ion Beams) facility, currently under construction at the GSI site in Darmstadt, Germany will constitute one of the largest accelerator-based research infrastructures world-wide. Within an international effort, a complex of novel accelerators, storage rings and innovative experimental set-ups will be constructed in order to address front-line research questions within subatomic, atomic, plasma, bio-physics and applications. The envisaged research is to be conducted within four experimental pillars, addressing hadron physics (PANDA[1]), compressed baryonic matter in relativistic heavy-ion collisions (CBM[2]), atomic physics and applications (APPA[3]) and nuclear structure, reactions and astrophysics using radioactive beams (NUSTAR[4, 5]).

FAIR will be constructed in stages, starting with the so-called modularized start version (MSV) [6] with the ultimate goal to reach the full facility as described in [7]. For an up-to-date overview of the FAIR facility, status and time-line of the construction, see [8].

Within the global landscape of RIB facilities [9], FAIR-NUSTAR will be the premiere European in-flight facility [10]. It will deliver the world-wide most energetic secondary beams and has the inherent advantage of “chemical blindness” compared to ISOL-installations, i.e. all elements can be produced in the same manner. Consequently, a broad experimental programme utilising these beams is envisaged, under the umbrella of the NUSTAR collaboration assembling more than 800 members. The scientific questions to be addressed within the NUSTAR sub-projects have fundamental bearing on our understanding of the subatomic world and the inner workings of our universe. In contrast to many other scientific disciplines, there are not only a few, critical issues to be studied but rather a number of highly relevant and interrelated questions. A few examples would be:

- How are complex nuclei built from their basic constituents?
 - What is the effective nucleon-nucleon interaction?
 - How does QCD constrain its parameters?
- What are the limits for existence of nuclei?
 - Where are the proton and neutron drip lines situated?
 - Which new structures arise near or at the limits?
- How does the nuclear force depend on varying proton-to-neutron ratios?
 - What is the isospin dependence of the spin-orbit force?

- How does shell structure change far away from stability?
- How to explain collective phenomena from individual motion?
 - What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?
- Which are the nuclei relevant for astrophysics and what are their properties?
 - What is the origin of the heavy elements?

Any attempt of addressing the above issues is completely dependant on Radioactive Ion Beams (RIBs), covering a variety of energies and nuclear species, as well as state-of-the art instrumentation. Thus, these goals are common for many existing and future RIB facilities world-wide.

2. Accelerator infrastructure and radioactive beam production with the Super-FRS

FAIR builds on the existing accelerator infrastructure at GSI[11] and will rely on the UNILAC and SIS18 as first stages in the injector chain, following upgrades of these systems. The synchrotron SIS100 and a proton LINAC will be added in order to increase the energy for all beams and make production of antiprotons possible. In particular, SIS100 will be able to deliver primary beams of 10^{12} $^{238}\text{U}^{28+}$ at 1.5-2 GeV/u, corresponding to an increase in intensity of 2 to 3 orders of magnitude with respect to the current GSI synchrotron SIS18. It is followed by the Super-FRS for radioactive beam production, target stations, antiproton separator and the CR and HESR storage rings.

The Super-FRS[12] is a superconducting fragment separator that will constitute a crucial and integral part of every experiment using radioactive beams (RIBs) at FAIR. As can be seen in fig. 1, the device consists of a pre-separator (using radiation-hard normal-conducting magnets) and a main separator (using superconducting magnets). The large-aperture design of the elements yields an unprecedented acceptance which, e.g. for production of fission fragments having a large kinetic energy in the centre-of-mass system, will increase the transmission greatly compared to the existing FRS. Combined with the increased primary beam intensity, up to a factor 10^4 improvement in RIB intensity can be expected, furthermore, also the heaviest exotic nuclei can be accessed and identified without charge-state ambiguities at these energies.

The Super-FRS feeds three branches, each having specific beam properties and associated experimental set-ups. The low-energy branch (LEB) houses experiments using energy-degraded beams for intermediate-energy reactions and decay studies with stopped

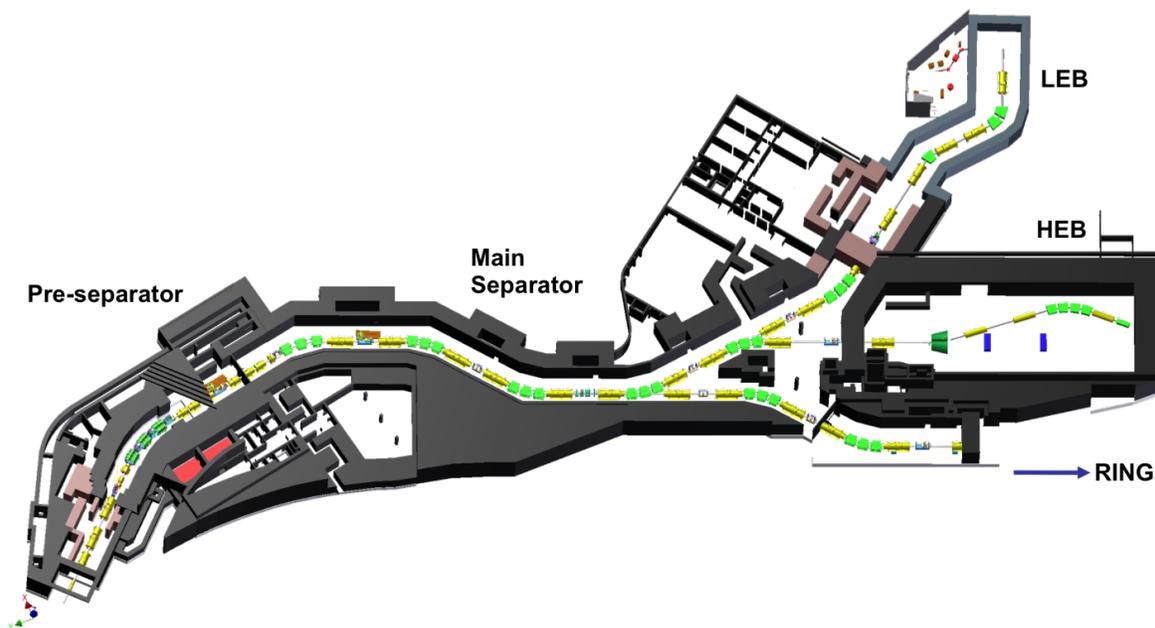


Figure 1. Layout of the Super-FRS with pre-separator, main separator and its three branches, low-(LEB), high-energy(HEB) and ring branch. The LEB hall shown is not included in the MSV.

beams, planned in the HISPEC and DESPEC projects. By combining with a gas-filled stopping cell [13] coupled to an MR-TOF mass filter, low-energy RIBs otherwise restricted to ISOL-type facilities can be achieved. Here, laser spectroscopy and Penning trap mass measurements will be performed in the LaSPEC and MATS experiments. The MSV foresees only an inadequate experimental hall for the majority of the activities of these four projects, thus a concerted action to fund and construct a building outside the startversion has been initiated by the NUSTAR collaboration. This includes a realistic time planning with milestones for secured funding, permissions etc. This building would as well house the energy buncher/spectrometer (inside the MSV) needed to efficiently degrade the energetic beams, as well as opening up the possibility for high-resolution spectrometer experiment in a dispersion-matched design[14].

The high-energy branch (HEB) takes the relativistic beam as produced from the Super-FRS and acts as such as a natural continuation of the device. The associated high-energy cave houses exclusively the R^3B [7] experiment for reaction studies using relativistic radioactive beams. Finally, the ring branch feeds the CR (Collector Ring) with radioactive ions, followed by the NESR (New Experimental Storage Ring) in the full version of the FAIR facility, where the ILIMA[15] in-ring mass measurement, the EXL[16] (reactions at low momentum transfer) and the ELISE[17] (electron-ion

collider) experiments are to be situated. The omission of the NESR in the MSV postpones the full realisation of those projects well into the next decade, however, parts of the ILIMA programme can be performed using the CR only.

3. The NUSTAR projects within the Modularized Start Version - scope and status

3.1. HISPEC/DESPEC

High-resolution reaction spectroscopy using intermediate energy RIBs as well as decay spectroscopy using stopped beams is the domain of the HISPEC and DESPEC projects. The precursor project PRESPEC[18, 19] has been running successfully for several years at GSI, in spite of very limited beam-time availability. Here, the HISPEC key systems LYCCA[20] and the AGATA[21] demonstrator for ion identification and gamma-ray detection, respectively have been employed. Further detection systems for neutrons, fast timing, total absorption spectroscopy etc are foreseen and well underway.

3.2. MATS and LaSPEC

The low-energy beams from the gas cell at the low-energy branch will be used to investigate ground-state properties of exotic nuclei through atomic physics techniques[22], mass measurements in a Penning trap

within the MATS project and laser spectroscopy using a variety of methods in the LaSPEC project. Details on MATS and LaSPEC can be found in the approved Technical Design Report[23]. The projects are already now in a very advanced state, having constructed the prototype TRIGA-SPEC[24], in operation at the TRIGA research reactor in Mainz.



Figure 2. Part of the NeuLAND detector being assembled for beam tests at GSI.

3.3. R^3B

The R^3B (Reactions with Relativistic Radioactive Beams) project aims at complete kinematics detection of all messengers stemming from a very large range of high-energy reactions. Precursor experiments using the ALADIN/LAND setup at GSI have been successfully performed since more than two decades, however, the R^3B detection systems will be state-of-the-art devices meaning a major step forward in terms of resolution and efficiency. The secondary reaction target will be surrounded by a silicon micro-vertex tracker, followed by the CALIFA[25] calorimeter for detection of gamma rays and light ions, projectile-like particles and fragments will be separated in the GLAD large-aperture superconducting dipole magnet[26] and subsequently detected in the NeuLAND[27] detector for high-energy neutrons as well as tracking and time-of-flight detectors for protons and heavy ions. As an option, complementary to the low-momentum transfer experiments foreseen for EXL, an active target can replace the target spectrometer.

Parts of the final CALIFA, NeuLAND and micro-vertex tracker systems have already been constructed and tested with beams at GSI, as shown in fig. 2. Since the GLAD magnet will be delivered early 2015 to GSI, the full R^3B set-up can be assembled and tested in the existing GSI cave, before moving to the high-energy cave after completion. This will permit commissioning

and pilot experiments well ahead of the first beams from Super-FRS become available.

3.4. ILIMA

In-ring mass measurements and decay studies of exotic isotopes is a long-standing activity that has been pursued in the ESR storage ring, see e.g. [28] for a recent overview, and constitutes the basis for the ILIMA project at FAIR. The CR will be a large-acceptance storage ring employing stochastic cooling and is thus suitable for mass measurements using isochronous beams, complemented with ToF detection of individual ions. This method is excellently suited for short-lived nuclides and will, in conjunction with the high RIB intensities available from the Super-FRS, make direct mass measurements of very exotic nuclei possible, including several that are expected to be r-process waiting points.

3.5. Additional experiments

The Super-FRS itself constitutes a device that can be utilised for specific experiments, both for e.g. exploratory rare isotope yield studies as well as a high-resolution spectrometer. Examples using the latter mode would be studies of mesic nuclei or probing the tensor interaction[29] via (p,d) -reactions. The Super-FRS physics collaboration has recently been formed and its scientific programme is currently being evaluated [30] by the FAIR management and scientific bodies.

Another activity being considered to be joined to the NUSTAR collaboration is the SHE (Superheavy Element) collaboration[31], with focus on synthesis, nuclear structure, atomic physics, and nuclear chemistry experiments with elements $Z \geq 104$. Development work for a high-intensity cw-Linac is ongoing, this would benefit the future of SHE research greatly.

4. Prospects for NUSTAR physics using storage rings in the MSV and beyond

The combination of the pulsed beam available from the FAIR synchrotrons with in-flight production and separation of RIBs is the optimal prerequisite for nuclear physics with storage rings[32]. In spite of this fact, the staging of FAIR has in particular impacted the storage ring part of the NUSTAR programme through the delayed construction of the NESR, shown in fig. 4. This obstructs the EXL and ELiSe projects, both due to lack of space in the CR and the absence of electron cooling needed for the stochastically pre-cooled beams. Also the ILIMA project is curtailed by the omitted NESR, in particular the decay studies and high-precision Schottky mass spectrometry.

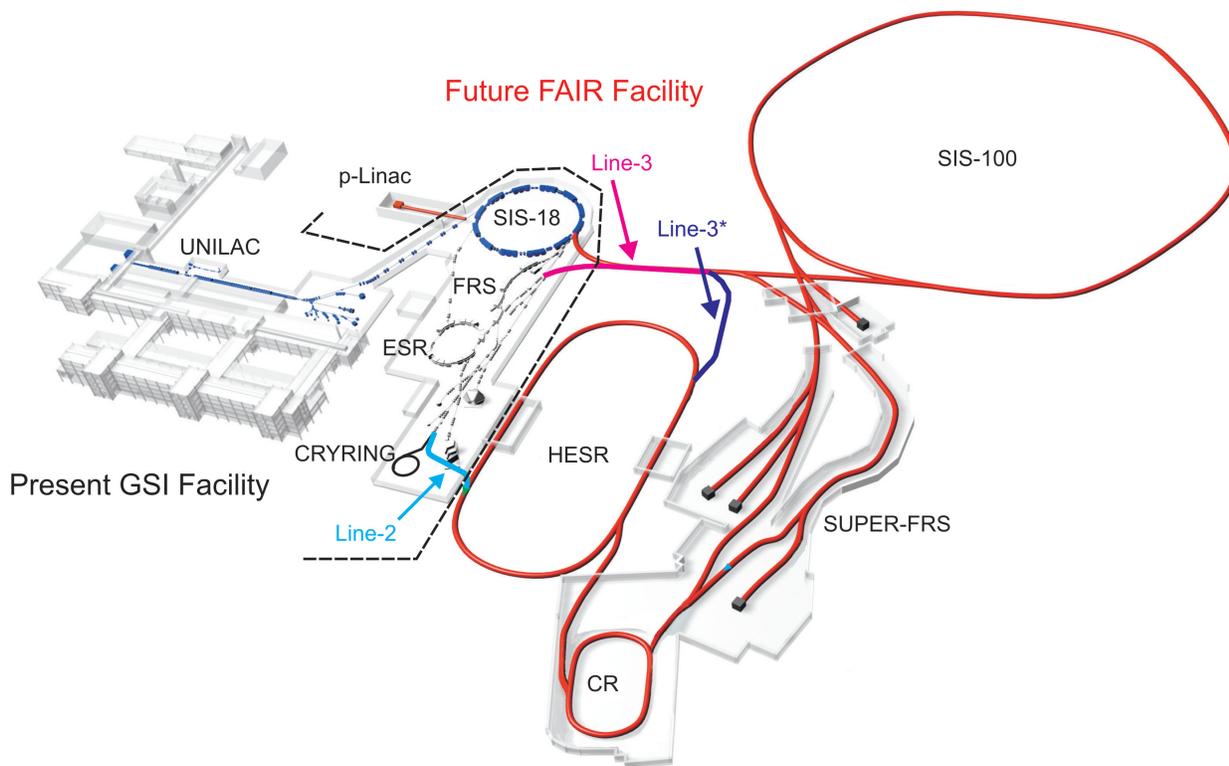


Figure 3. Layout of the FAIR MSV infrastructure showing possible additions (Line-2,3,3*) permitting to perform parts of the NUSTAR storage rings programme in the HESR and/or the existing ESR. Line-2 would permit an early injection of ions from the existing SIS-FRS-ESR complex into the HESR, ahead of completing the construction of the MSV. Line-3 + Line-3* would allow for transporting cooled beams of cooled RIBs and antiprotons to the ESR. The position of CRYRING, currently being reconstructed, is as well indicated. Courtesy of Yu. A. Litvinov.

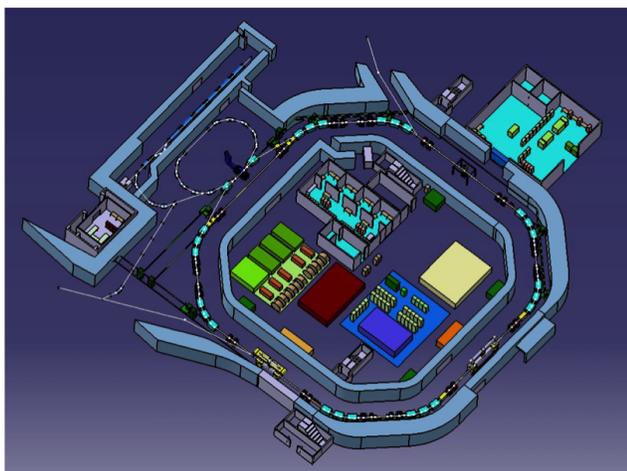


Figure 4. NESR layout including the electron LINAC and collider ring for ELiSe as foreseen for the full FAIR project.

Nevertheless, the delay of the NESR has triggered intense activities in order to realise parts of the here envisaged programme in the storage rings contained in the MSV and/or already existing at GSI (see e.g. [33] for opportunities explored by the APPA-SPARC collaboration), and a joint *NUSTAR-APPA Storage Ring Task Force* was formed in 2013 in order to explore these opportunities further. As previously mentioned, the part of the ILIMA programme focused on nuclei with the very shortest half-lives can be pursued using the CR in isochronous mode. Furthermore, lifetime measurements of longer-lived nuclei could be done by subsequent injection and measurements in the HESR. By adding a return transfer line (depicted as *Line-3** in figure 3) from HESR to the existing installation at GSI, cooled beams of both radioactive beams and antiprotons could be made available in the ESR at rigidities up to 9.5 Tm and, through deceleration and subsequent transfer, as well at low energies (≤ 1.44 Tm) in CRYRING[34].

Having the RIBs of unprecedented intensity from

the Super-FRS available in the ESR would open for an intermediate programme on low-momentum transfer reactions within the EXL project. Here, in-ring reactions on a gas-jet target combined with a complex detector set-up for charged-particle detection is envisaged. A proof-of-principle nuclear reaction experiment using stored beams in ESR was recently performed[35], using a newly developed solution to use DSSSDs as an active vacuum barrier towards the UHV regions of the storage ring[36]. By rearranging the lattice of the ESR, the sections available for experiments would increase and as well open up for an early implementation of the ELISE electron-ion collider[37], still within the boundaries of the existing building. The low energies and excellent vacuum conditions in CRYRING would permit studying key nuclear reactions with unstable beams for astrophysics [38], in addition to an envisaged rich programme within atomic physics and, in a longer perspective, low-energy antiproton physics as planned in the FLAIR experiment. Nevertheless, the NESR would crucially be needed in the future to fully exploit the scientific opportunities at FAIR.

5. Conclusions

The NUSTAR programme at FAIR is well underway to take advantage of the beams from the Super-FRS as soon as they become available. The collaboration has made major steps forward in planning, securing funding and in many cases already constructing state-of-the-art detector systems, ensuring a rich scientific output from the very start. The alternative solutions for NUSTAR physics in storage rings will aid in securing this truly unique part of the programme also on a mid-term basis, training new generations of scientists while generating excellent physics output.

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