NUSTAR at FAIR

The physics of exotic nuclei, having large neutron or proton excess, is one of the main frontiers in contemporary Subatomic Physics. Short-lived, rare nuclei constitute a challenge for our picture of the strongly interacting few-body system of an atomic nucleus. Established entities such as magic numbers cease to be valid when going towards the drip-lines, exotic shapes appear as well as unforeseen decay modes and new collective phenomena. Furthermore, there is an obvious connection to astrophysical processes and the elemental abundances in the Universe, in particular through the r-process, which takes place across very neutron-rich nuclei. The objective of the NUSTAR collaboration is to study the structure of exotic atomic nuclei, to investigate reactions of these nuclei, and to apply the results for answering astrophysical questions.

Fundamental Physics Questions

- What are the limits for existence of nuclei?
- How does the nuclear force depend on varying proton-to-neutron ratios?
- How to explain collective phenomena from individual motion?
- How are complex nuclei built from their basic constituents?
- Which are the nuclei relevant for astrophysical processes and what are their properties?

The central instrument of NUSTAR at the FAIR facility is the Super-FRS, a super-conducting fragment separator enabling the production and in-flight separation of secondary exotic isotope beams. The Super-FRS can also be operated as a high-resolution spectrometer system for nuclear physics experiments. Progress in R&D and construction of the Super-FRS is not subject of this report. Dedicated experiments in three distinct areas or "branches", namely the low-energy branch (LEB), the high-energy branch (HEB) and the ring branch (RB), provide the instrumentation to investigate ground state properties (e.g. mass, matter and charge radii) and decay properties of exotic isotopes, the structure of their excited states and their reaction mechanisms. NUSTAR includes the following experiments respectively sub-collaborations six of which are included in the FAIR Modularized Start Version (MSV):

Super-FRS – the central instrument of the NUSTAR collaboration

- Production of exotic nuclei, in-flight separation, search for new isotopes Z>60, study of reaction mechanism, high-resolution spectrometer experiments (MSV)

Low-energy branch (LEB)

- HISPEC/DESPEC – high-resolution in-beam and decay spectroscopy (MSV)
- MATS – mass measurements using a Penning trap (MSV)
- LaSpec – laser spectroscopy on RIBs (MSV)

High-energy branch (HEB)

- R^3B – reactions at relativistic energies (MSV)

Ring branch (RB)

- ILIMA - mass and lifetime measurements, isomeric beams (ILIMA at CR is part of MSV)
- EXL – light ion reactions
- ELISe – RIB-electron scattering
- AIC – RIB-antiproton annihilations

Only the combination of the complementary results provided by these different but related experiments will lead to consistent answers for the fundamental questions of contemporary nuclear physics and astrophysics.

The NUSTAR collaboration with approximately 800 members from more than 150 international institutions has organized itself with an efficient governance and management structure which considers the multiple complementary sub-projects as well as common activities.

> **The NUSTAR Project**
>
> NUSTAR is the largest FAIR research collaboration, dealing with nuclear structure, astrophysics and reactions employing radioactive ion beams from its central instrument the Super-FRS. Eight different experiments in three branches will provide complementary results in order to find consistent answers for fundamental questions. NUSTAR follows an evolutionary approach with continuously improving detection equipment and exploitation at existing facilities of new components as soon as they become available. This approach helps maintaining leadership in the worldwide competition and preserves uniqueness and excellence over decades to come.

Contrary to other pillars of FAIR research, NUSTAR follows an evolutionary approach. The physics program of NUSTAR has already begun at GSI. The intention is to replace and enlarge those experimental set-ups, which are currently employed with components developed specifically for NUSTAR at FAIR at their earliest availability. This guarantees a steady flow of world-class physics results using continuously improving detection equipment and experimental techniques. In addition, this approach enables a largely physics driven and smooth transition to NUSTAR at FAIR, with a fast start-up phase and thus very early physics results from the new facility.

This transition foresees a dedicated program using the FRS, ESR, TASCA and SHIP at GSI but also other accelerator facilities. Training and providing continued opportunities for young scientists for NUSTAR at FAIR is yet another asset. The NUSTAR facility at FAIR will be built sequentially as soon as possible after completion of the required buildings. Thereafter the corresponding experiments will be installed at the facility, commissioned and exploited for experiments.

The evolutionary approach also assists to maintaining long-term leadership in the worldwide competition within nuclear physics. Experimental set-ups and techniques are continuously improved by adaptations and extensions initiated, for example, by findings and developments in other laboratories. Likewise, isolated experimental questions, which are ought to be answered by NUSTAR at FAIR, might be solved before the Super-FRS and its suite of experimental set-ups become operational. Nevertheless, the superiority of very heavy exotic beams, the universality of beam species, the high beam energies and the completeness of experimental arrangements make NUSTAR at FAIR a globally unique facility with outstanding research opportunities.

The experimental set-ups to be constructed by the sub-collaborations are all well underway. The MATS and LaSpec set-ups already exist as early implementations used for physics research, in the TRIGA-SPEC facility in Mainz. A similar situation is found for the HISPEC/DESPEC and R^3B collaborations, both already doing pilot experiments at the FRS that include prototypes, demonstrators and some final NUSTAR systems. Through the PRESPEC campaign, the first complete implementation of the HISPEC set-up is operational and currently in use for physics experiments. DESPEC has performed the first measurements of beta-delayed neutrons. R^3B will gradually incorporate detection systems and its large-gap superconducting dipole in order to reach a full-fledged experiment in its current location at GSI, before moving to the HEB building at FAIR. ILIMA develops and tests hardware and evaluation methods for pilot experiments in the existing ESR storage ring at GSI as well as in the CSRe ring in Lanzhou, China. The NUSTAR experiments had already resulted in numerous scientific publications, among them several in "Nature" and "Science" and tens of Letters, all reflecting the excellent quality of the instrumentation and the outstanding physics opportunities from using it.

The R&D and TDRs for the components constituting the full NUSTAR projects within the MSV are well advanced; a number of TDRs have been submitted and several are already accepted. The majority of the systems will be covered by TDRs in the first half of 2013, and on average 85% of the estimated funding is either secured, applied for, or covered by "Expressions of Interest" as in-kind contributions. Also the experiments beyond the MSV are making progress in R&D efforts and pilot experiments.

The NUSTAR experiments could thus contribute to the earliest science results with RIBs at the FAIR facility. However, there is one obstacle jeopardizing the predominant part of NUSTAR, namely *the missing LEB building*. This building was omitted in the MSV assuming that the LEB experiments MATS, LaSpec, HISPEC and DESPEC can be accommodated in other buildings. This turned out not to be possible and had led to the situation that the experiments are ready but cannot start their scientific program, with the worrisome possibility that the investments in these collaborations to date would be worthless. Moreover, the magnetic elements for the LEB are fully incorporated in the MSV and need the area for installation. Therefore this fundamental flaw in the MSV planning needs to be remedied by realizing a suitable building in due time. The NUSTAR collaboration seeks support for a new staged approach for the realization of the LEB building, discussed in detail in the LEB section of this report.

In the following sections the status of the NUSTAR sub-collaboration projects is reported in detail.

Low-energy branch (LEB)

A majority of the NUSTAR experiments included in the MSV, namely MATS, LASPEC, HISPEC and DESPEC belong to the LEB. R&D for most of the components of these experiments was successfully finished, major investments took place, and funding for all required additional components has been secured. Early implementations have proven their operation capability. The Buncher/Spectrometer system, which represents an indispensable backbone for the LEB experiments, has been designed and is waiting for technical clearance to be produced. Funding for the Buncher/Spectrometer has been secured by India and is the largest in-kind contribution to the NUSTAR experimental infrastructure. In conclusion, as a result of tremendous efforts and capital investment, technically and financially the LEB experiments are ready for a unique leading edge scientific program at FAIR.

LEB experiments in jeopardy

The NUSTAR experiments will be able to contribute the earliest science results with RIBs at the FAIR facility. However, due to a fundamental flaw in the MSV planning the LEB building, accommodating MATS, LaSpec, HISPEC and DESPEC, was omitted. Without the building none of the four experiments can be performed in any reasonable way, rendering the substantial investment in the instrumentation and the buncher/spectrometer system worthless. To solve this problem, the NUSTAR collaboration has worked out a plan for a staged approach to realize the building in a timely manner and asks the FAIR governance bodies to support this effort.

However, as mentioned before, in the initial planning of the MSV the LEB building was omitted, based on the assumption that the LEB experiments could be temporarily realized in other buildings. Further, detailed technical investigations have proven that this assumption is not possible without the Energy-Buncher system. In fact, none of the four experiments can be performed in any reasonable way without the LEB building. Delaying the construction of the building would furthermore stall the R^3B experiment, since during the construction period ground movements and vibrations disable the use of the neighboring HEB building which houses R^3B. As a consequence, virtually none of the NUSTAR experiments could start their scientific program when the Super-FRS is ready.

The NUSTAR collaboration has worked out a plan for a staged approach to realize the building in a timely manner. The acceptance test and the field mapping of the LEB Buncher/Spectrometer magnets can only be done at their final location because transportation of the up to 115 tons heavy magnets in one piece is technically impossible, while disassembly/assembly would not preserve the required accuracy. Therefore it is conducive to erect a light magnet-testing hall on the foundation of the later LEB building. As soon as all magnets are accepted, the hall will be upgraded to an experiment hall by adding the necessary radiation shielding and technical infrastructure. Contrary to earlier assumptions, it turns out to be sufficient to build a tunnel and cave structure as shielding, which would be similar to the situation in the current SIS experimental hall at GSI. This approach reduces the total costs significantly, allows for staged funding, and enables starting NUSTAR experiments when the Super-FRS beams become available. The NUSTAR collaboration urgently asks the FAIR governance bodies for their support of the new approach to allow us to force planning in order to meet the deadline of the scheduled FAIR building change-request in mid-2013. In parallel, the NUSTAR Collaboration is looking into additional resources for the co-funding of the LEB building.

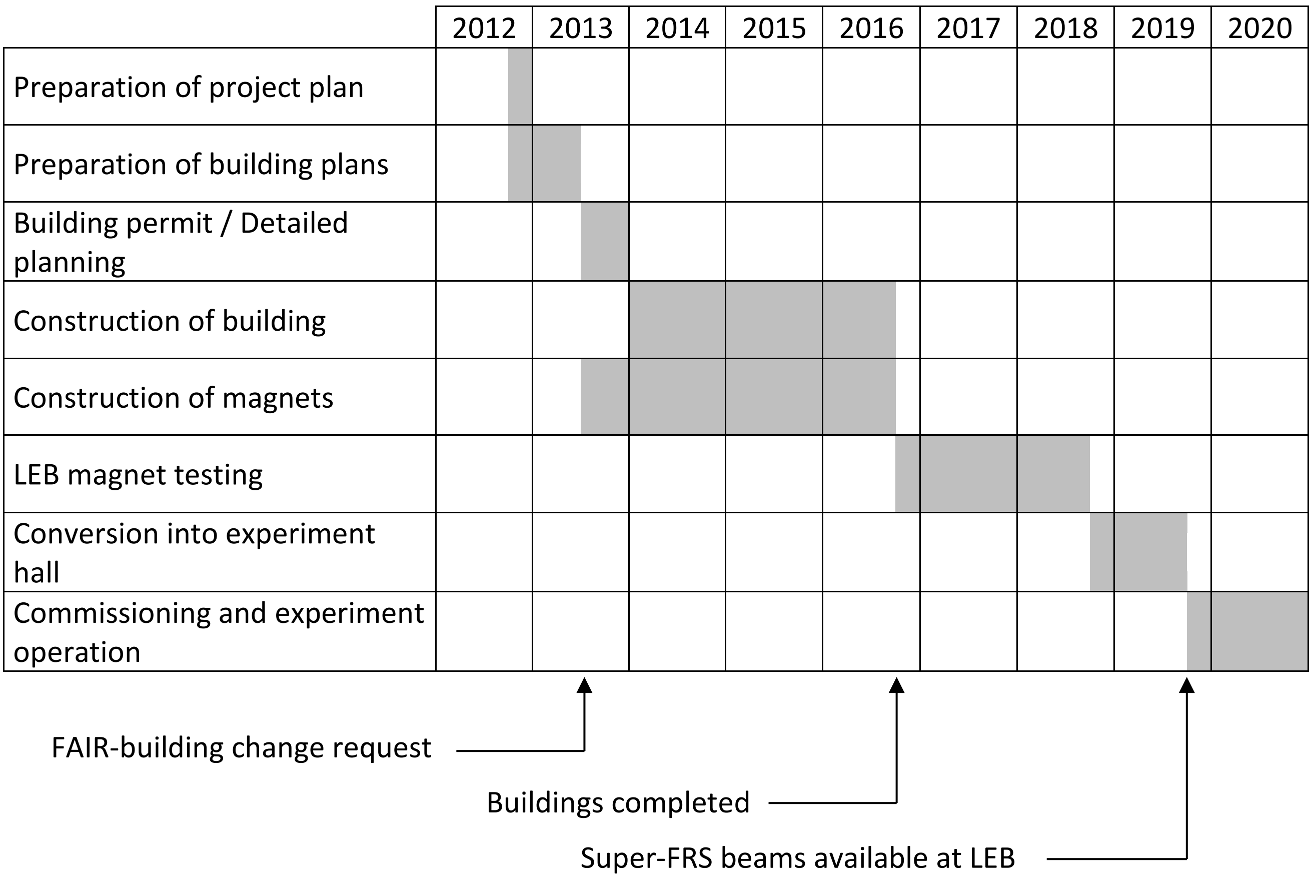

Fig. 1: LEB building time plan

HISPEC/DESPEC

Overview: HISPEC/DESPEC addresses nuclear structure and astrophysics questions using radioactive beams delivered by the Super–FRS with energies of up to 400 A·MeV for in-beam reaction studies, or stopped and implanted beam species for decay studies. The HISPEC set-up comprises a suite of heavy-ion tracking detectors to determine for each radioactive beam particle, its energy, mass, charge and direction towards a secondary (active) target. Beam-like particles from reactions at this target are being detected by the position sensitive ΔE-E-ToF calorimeter LYCCA. For the γ-spectroscopy of nuclei excited in the reactions the AGATA spectrometer is foreseen. AGATA is shared between different European host laboratories, implying concentrated experimental campaigns for HISPEC. The implantation detector AIDA, based on highly granular Si detector stacks, forms the core of the DESPEC set-up. Depending on the physics requirements a compact high-resolution Ge-detector array, a $LaBr_3$ fast timing array (FATIMA), or a total absorption spectrometer (DTAS) is planned for γ-spectroscopy, while the arrays BELEN and MONSTER serve for neutron measurements.

An early implementation of the HISPEC set-up is already operational and in use, as well as the DESPEC arrays FATIMA and BELEN. Characteristic for HISPEC/DESPEC detectors is their modularity, enabling experiments with reduced sensitivity already with sub-arrays at an early stage. Increasing the number of modules to eventually complete the arrays leads the ultimate sensitivity.

Uniqueness: The project focuses on those aspects of nuclear investigations, which can be addressed uniquely with high-resolution spectroscopy set-ups. The emphasis lies on medium heavy and heavy systems with exotic proton-to-neutron ratios. The universality of the beams delivered by the Super-FRS and the high energies avoiding multiple charge states keeps a wide area of isotopes of the highest importance for spectroscopy experiments.

HISPEC/DESPEC – ready to use

High-resolution in-beam and decay spectroscopy experiments are subject of HISPEC/DESPEC. A versatile suite of γ- and neutron-detector arrays as well as particle detectors has been developed and is under construction. A first implementation of HISPEC with complete functionality is currently being exploited for unique physics experiments in the PRESPEC-AGATA campaign at the FRS. DESPEC arrays like BELEN and FATIMA are also already in use at GSI and other laboratories. HISPEC/DESPEC will be ready for outstanding day-one experiments when the Super-FRS and the LEB building become available.

Progress: Following the highly successful Rare Isotope Spectroscopic Investigations at GSI (RISING) during the experimental period 2005-2009, the pan-European PRESPEC collaboration was founded in 2009 in order to bridge the time between physics opportunities at existing facilities and the advent of NUSTAR at FAIR in about 2018-2019.

At the GSI Helmholtz-Center, PRESPEC has been focusing on a stepwise improvement of high-resolution in-beam γ-ray spectroscopy experiments, i.e. pre-HISPEC experiments. In parallel, proposals have been submitted and approved by the GSI G-PAC to commission both HISPEC and DESPEC equipment. A brief DESPEC physics campaign has also been conducted using the BELEN detector in 2011. The overarching goal of the PRESPEC collaboration is to perform physics driven campaigns, which in parallel commission new HISPEC/DESPEC equipment.

The RISING-PRESPEC-HISPEC/DESPEC activities undertaken at GSI/FAIR comprised for example the RISING stopped beam campaign, the commissioning of LYCCA, the commissioning of a liquid H-target, 4π neutron-detector experiments and the commissioning and on-line operation of AGATA.

As HISPEC/DESPEC is well prepared and already has approved beam-time, DESPEC detector commissioning in the FRS-S4 area will be pursued once the PRESPEC-AGATA campaign finishes late 2013/early 2014.

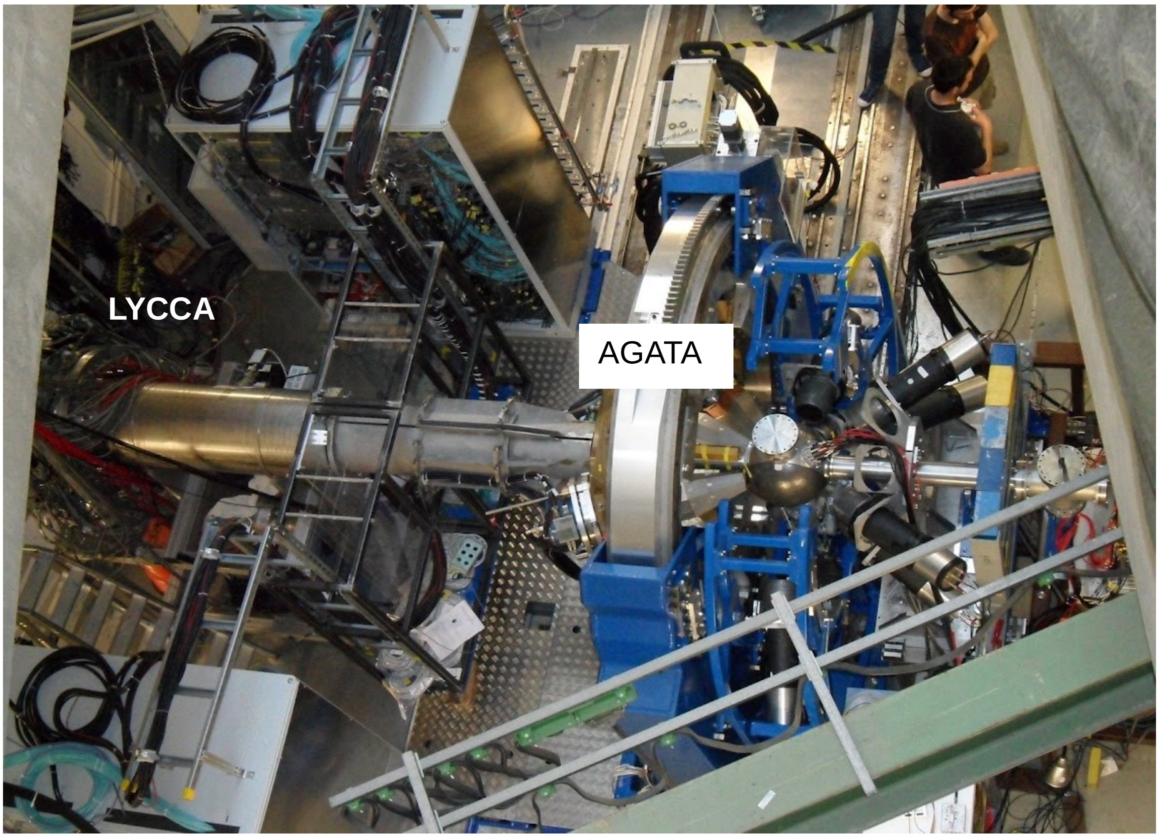

Fig. 2: The PRESPEC-AGATA set-up at GSI, constituting the basic HISPEC set-up with its full functionality.

In parallel DESPEC equipment has been and will be tested and upgraded towards NUSTAR at FAIR at other facilities, e.g. JYFL, LNL, Bucharest, RIKEN (AIDA at Texas A&M; FATIMA at Bucharest and RIKEN; DTAS, BELEN and MONSTER at Jyväskylä and RIKEN).

HISPEC/DESPEC equipment is already being used (LYCCA, AGATA, AIDA, BELEN, RISING-Ge) or will be available at the latest in a few years from now, following the commissioning phase indicated in the previous section. Therefore, both comprehensive decay or in-beam commissioning experiments can be performed side by side with the commissioning of the Super-FRS, thereby ensuring early physics output of the very first FAIR beams. This carries naturally with it, the NUSTAR philosophy of physics-driven commissioning into the FAIR era.

More recently, the major issues during the collaboration meetings have been the preparations and status of FAIR-TDRs, in particular with respect to ongoing commissioning and physics experiments within the PRESPEC collaboration. Naturally, the impact of an existing - or non-existing - LEB building at FAIR has been debated heavily on occasions together with the MATS-LaSpec collaboration. Opportunities have been provided and options have been discussed for HISPEC/DESPEC contributions within the broader NUSTAR frame, e.g. towards detector R&D relevant for the Super-FRS or data acquisition systems.

Comparison with other experiments in the field: Similar type of experiments can be carried out contemporaneously at RIKEN and MSU. However, in the case of HISPEC, AGATA represents a more powerful tool for γ spectroscopy and with Doppler-correction capabilities as compared with the arrays available today at the American or Japanese laboratories. Anyhow, the heaviest beams at the highest energies remain a NUSTAR at FAIR domain.

Day-one experiments: Following physics-driven support of the commissioning of the Super-FRS, first highlight experiments aim at the study of nuclei around ^{100}Sn, ^{208}Pb, and the neutron-rich nuclei near the second and third r-process peaks using nuclear reactions, Coulomb excitation and decay spectroscopy. These experiments will constitute a fundamental test of the nucleon-nucleon interaction and the shell structure evolution as function of N and Z. The ^{100}Sn region is especially suited for such studies, as these nuclei are the heaviest with similar proton and neutron number, and exhibit so far unexplained features such as the enhanced collectivity as we approach ^{100}Sn. Coulomb excitation of very neutron-rich Hg and Pb isotopes will complete studies on the evolution of collectivity in the vicinity of ^{208}Pb. In addition, high sensitivity experiments will be the first ones to provide experimental data on the N=82 and 126 r-process waiting point nuclei. The search for exotic decay modes or radioactivity (two-proton, two-neutron, etc.) is also an exciting piece of physics, which can be investigated at a very early stage of FAIR.

Stopped beams at LEB

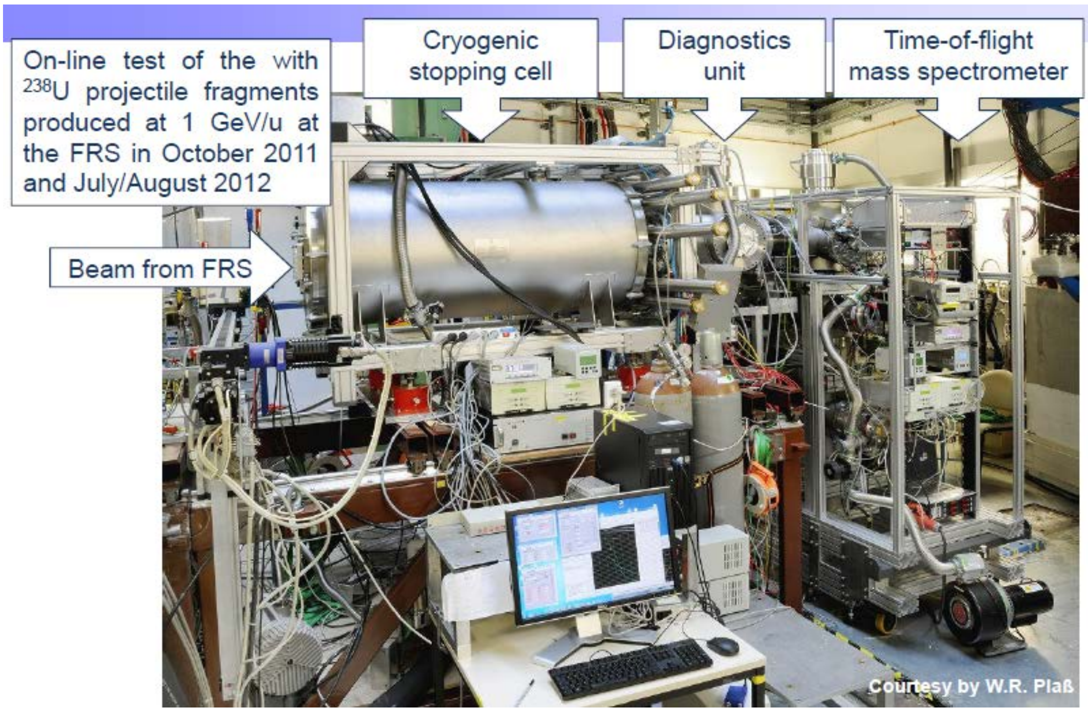

Fig. 3: Gas-catcher prototype tested at FRS.

Overview and progress: With the Super-FRS it will be possible to provide low-energy beams (a few tens of keV) for high-precision experiments utilizing the many variants of laser spectroscopy and ion trapping techniques housed at the MATS and LaSpec facilities. For this purpose, a cryogenic stopping cell customized for the Super-FRS beams has been developed and recently commissioned at the FRS. Energetic radioactive ions are stopped in a helium-filled stopping cell, the first to be operated at cryogenic temperature to ensure helium gas purity. Static electric fields transport the stopped ions to the exit side where a radiofrequency (RF) carpet guides the ions to an exit-hole from which the gas flow sweeps them out. In the first on-line commissioning tests, ^{238}U projectile fragments produced at 1 A·GeV were thermalized using a gas density almost twice as high as ever reached previously for a stopping cell with RF ion repelling structures, extracted from the stopping cell and guided through an RF quadrupole ion guide towards a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS). In characterizing the stopping cell, this fast, multi-purpose, non-scanning mass spectrometer allows identification and diagnosis of the ion beam by mass spectrometry. Very high efficiencies were achieved combined with extraction times on the order of a few tens of milliseconds.

The MR-TOF-MS is a unique and novel device which will enhance the capabilities of MATS and LaSpec via its multi-purpose functionality: operation as a universal, broadband mass spectrometer (utilized in the diagnosis of the ion catcher); as a high resolution isobar separator in order to provide an isobarically pure beam for MATS; as a high-precision mass spectrometer, in particular for mass measurements on nuclides with ms half-lives and production rates of only a few ions per second. This latter mode has been realized at the FRS in 2012 in connection with the ion catcher commissioning with a measurement of ^{213}Rn with a half-life of only 20 ms.

MATS

Overview: Since 2009, the MATS collaboration, comprising more than 90 scientists working at the different Penning-trap installations at Radioactive Beam facilities worldwide, has been actively working towards the implementation of advanced techniques to push forward the limit of mass spectrometry to very exotic nuclei. In 2009, MATS together with LaSpec submitted the Technical Design Report of the facilities, which was approved by the FAIR STI in May 2010.

Progress: Since then, important issues for MATS such as the use of highly-charged ions in mass spectrometry on radioactive isotopes addressing the important r-process in nuclear astrophysics with TITAN at TRIUMF as well as the use of a multi-reflection time-of-flight mass separator (MR-ToF) for mass measurements of the extremely exotic isotope ^{54}Ca with ISOLTRAP at ISOLDE could be demonstrated both in 2012. In addition, the TRIGA-SPEC Facility, used as the MATS and LaSpec prototype apparatus, recently demonstrated the first extraction of radionuclides from the TRIGA research reactor in Mainz. These unique highlights in Penning-trap mass spectrometry pave the way for mass measurements at FAIR of importance among others for the r-process of stellar nucleosynthesis. In addition, many highlight results have been published; in 2010 the first Penning trap mass measurement for an element heavier than uranium was accomplished with the NUSTAR Penning trap experiment SHIPTRAP which demonstrated the accessibility to very low production yields, a record improved with the same facility in 2012 addressing nuclides with Z=103. MATS is, however, not only applicable to mass spectrometry. The interest of using traps to study decays has motivated experimental campaigns at several facilities and new R&D as reflected in the MATS and LaSpec TDR. In this respect, the development of a trap made out of detectors (task of the group at the LMU Munich) is also worth mentioning.

MATS/LaSpec – in operation

Employing the most exotic radioactive isotopes of the Super-FRS, stopped in the gas catcher, extracted and transported by a RFQ, the MATS set-up allows pushing forward the limit of Penning-trap mass spectrometry to very exotic nuclei. LaSpec on the other hand enables collinear laser spectroscopy of the rare species. MATS/LaSpec are the most advanced experiments of NUSTAR producing outstanding physics results since 2010. As soon as the Super-FRS and the LEB with its building become available unique experiments will become possible.

LaSpec

Progress: Members of the LaSpec collaboration are similarly working at different facilities worldwide and are pushing at the frontiers of both sensitivity and accuracy. After the first successful demonstration of the usage of an RFQ cooler and buncher at Jyväskylä a decade ago, similar devices have been installed at ISOLDE (CERN) and at TRIUMF (Vancouver) and are now routinely applied for laser spectroscopy, improving the signal-to-background ratio of the collinear fast beams method by orders of magnitude. While the ions are stored in the RFQ or during extraction, they can be addressed with pulsed lasers to selectively populate metastable states that provide preferential properties for collinear spectroscopy, e.g., more accessible transitions, known atomic hyperfine factors, higher sensitivity for hyperfine structure or charge radius changes, etc. This has been shown at Jyväskylä and will soon be applied at ISOLDE as well. There, it has been demonstrated that β-asymmetry detection can also be used to determine isotope shifts. By modeling the optical pumping and the transition into the strong field, the lineshape of the spectra could be sufficiently well described to extract the isotope shift. With this technique it was possible to study the charge radii of the Mg isotopes along the complete *sd*-shell and observe the transition into the island of inversion. Moreover, the sensitivity of the collinear-anticollinear frequency-comb-based approach for high-accuracy measurements on light isotopes was further increased using a photon-ion coincidence technique. This allowed the determination of the charge radius of ^{12}Be. Just recently, the Collinear Resonance Ionization Spectroscopy setup CRIS at ISOLDE has demonstrated its potential in the spectroscopy on francium isotopes. Such a technique combines the high resolution nature of collinear spectroscopy with the high sensitivity of in-source spectroscopy and can be used in combination with decay spectroscopic techniques.

Day-one experiments at MATS/LaSpec: Once first beams are delivered by the Super-FRS, MATS and LaSpec can immediately address those nuclei which are by then of high importance, since the techniques are rather universal. Currently, such key isotopes would be the neutron-rich Zr isotopes beyond A=102 which will only be available at a fragmentation facility. Here, the Super-FRS might provide isotopes up to ^{106}Zr with sufficient yield for collinear laser spectroscopy, isotopes from ^{106}Zr ($T_{1/2}$ = 186 ms) for mass measurements using the Penning trap, to ^{110}Zr ($T_{1/2}$ = 37 ms) using the MR-TOF-MS system. The demonstrated extraction times of about 20 ms for the cryogenic stopping cell, might even allow laser spectroscopy of ^{14}Be, provided sufficient yields can be delivered. MATS will in addition provide accurate masses of many elements involved in the astrophysical r-process. The doubly-magic nucleus ^{78}Ni, with an expected half-life of 200 ms and a production rate of 8 ions/s will be suitable for the MR-TOF-MS system. The waiting point ^{130}Cd, with a half-life of 162 ms and an expected production at FAIR of 10^6 ions/s is a good example for the Penning trap. On the proton-rich side, the mass of the isotope ^{100}Sn with the expected yield at FAIR of 2 ions/s, can be only measured with MATS, using the Penning-trap single-ion detection technique, as its half-life is beyond 1 second.

High-energy branch – R^3B

The R^3B experiment is designed to measure reactions with radioactive beams with magnetic rigidities of up to 20 Tm corresponding to beam energies of about 1 A·GeV. This is perfectly matched to the RIB production in the Super-FRS and gives access to a large range of reactions as spectroscopic tools. The experimental set-up encompasses systems achieving highest efficiency and resolution for detection of all messengers in complete kinematics following a break-up reaction; neutrons, gamma rays, protons, light ions and heavy fragments.

This requires a large-gap dipole magnet with large bending power to allow neutrons being detected in coincidence in the forward direction. A superconducting iron-free magnet has been designed, and is already under construction (GLAD). In order to achieve the resolution of better than 1 MeV required by nuclear structure and astrophysics experiments, special detectors have been designed for neutron detection (NeuLAND) and photon and particle detection around the target (CALIFA and target-recoil detector). In order to ensure fragment identification even for the heaviest beams around mass A=200, very thin large-area heavy-ion tracking detectors are needed. Finally, the DAQ and readout systems for all detectors have been designed including a high-resolution time-distribution system allowing for free-running sub-systems. The project is well on track and a first version of the setup with 20% detectors will be ready for commissioning and physics runs in 2014.

R^3B – unique opportunities

The RIBs at relativistic energies produced by the Super-FRS open a large range of reaction classes, to be fully exploited by R^3B. The versatility of the experimental set-up in complete kinematics renders it a worldwide unique position in investigating exotic nuclear systems. The foreseen experimental sub-systems are well underway and partly already used for preliminary studies. TDRs for several key systems have been submitted.

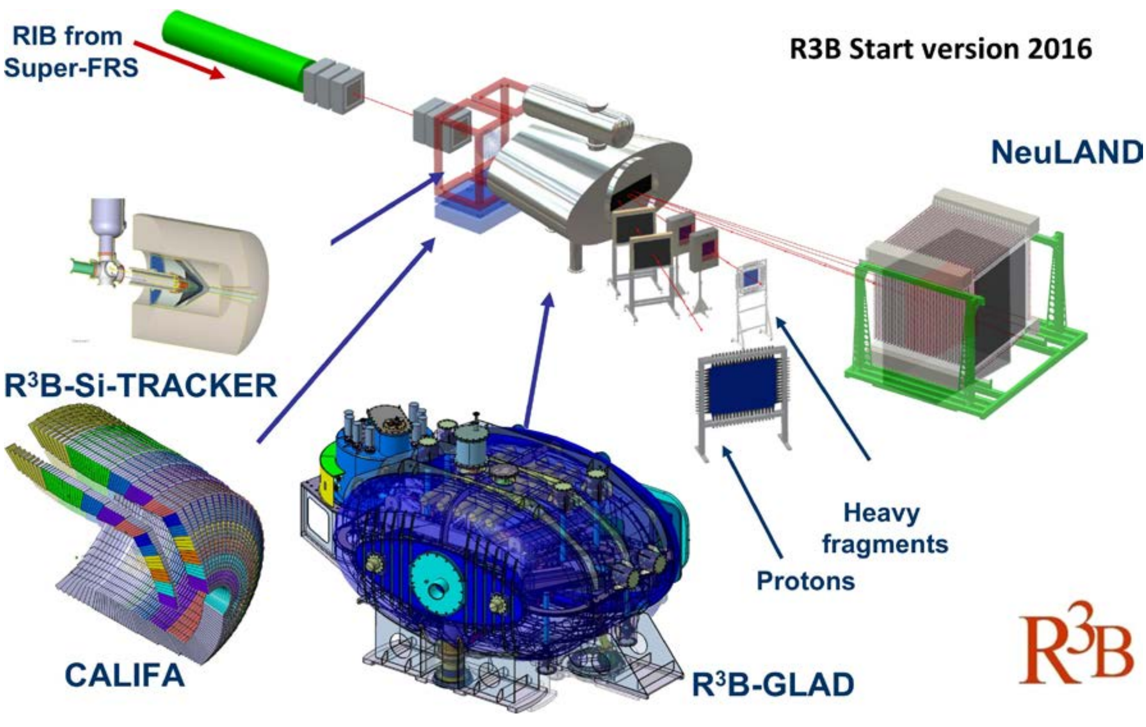

Fig. 4: Start version of R^3B.

Progress since 2009: The large-acceptance superconducting dipole magnet (GLAD) is under construction under the leadership of CEA Saclay. The cold mass including the superconducting coils has been assembled and is presently inserted into a test cryostat for commissioning. The final cryostat has been ordered.

The design of the NeuLAND neutron detector has been finalized. Prototype tests and simulations have shown that the solution of a fully active detector meets the performance criteria on resolution and in particular on multi-neutron recognition power. The TDR has been submitted to FAIR in November 2011 and is in the review process. 200 sub-modules of the detector in the final design have been purchased including 400 PM tubes, HV supply channels, and an ASIC (TAQUILA)-based frontend readout system. These modules have been configured in a special structure for a characterization experiment with mono-energetic neutrons. A call for tender for the first round of construction with so far secured funds from BMBF is in preparation.

The CALIFA calorimeter for γ rays and light ions consists of two parts, a barrel covering angles up to about 45° in forward direction and a front-cap covering the forward angles. The design of the barrel, consisting of 1952 individual CsI crystals, has been finalized. A TDR has been submitted and is being reviewed. A 20% detector consisting of barrel-type sub-modules will be constructed until 2014, allowing commissioning and first physics runs in conjunction with the new dipole GLAD and 20% NeuLAND. The design of the front-cap is in progress, foreseeing a phoswich design of $LaBr_3$ and $LaCl_3$ crystals. A TDR will be submitted in 2014.

The design of the tracker for light charged particles has been finalized, having a three-layer structure of Si micro-strip detectors in a lamp-shade form and a dedicated ASIC frontend. The call for tender has been issued and a first segment has been delivered. The detector is fully funded and a partial detector will be available for beam tests in 2014; the full detector will be implemented in 2016.

Several types of tracking detectors are needed for identification of incoming radioactive beams and outgoing fragments. Prototypes of thin, segmented diamond detectors have been tested as well as position-sensitive silicon PIN diodes. Both options are available. For the fragment tracking, very thin large-area detectors are needed behind the magnet. A thin scintillating fiber detector prototype has been built with an nXYTER-based frontend and tested with Sn beams showing the required performance; such detectors will be built in the next years. Further R&D is foreseen for developing thin, segmented position-sensitive silicon detectors with high-rate capability.

All the systems mentioned above have been developed including dedicated frontend and readout systems, e.g. the TAQUILA and nXYTER-based frontends. A BuTiS clock distribution prototype has been installed, providing a time resolution of better than 50 ps throughout the campus for ToF measurements. The systems have been integrated in the DAQ system and successfully tested.

Comparison with other experiments in the field: The R^3B experiment is unique in several aspects, the most important are:

- Capability of measuring reactions in full kinematics with high resolution at high beam energies up to 1 A·GeV, tracking and identification capabilities even for heavy beams with mass around A=200
- Large-acceptance measurement corresponding to a 4π acceptance in the CM system for a wide energy range, versatility of the design allowing the study of many reaction types
- High-efficiency calorimeter enabling invariant-mass measurements up to high excitation energies
- High-resolution neutron detection allowing astrophysical relevant cross section measurements down to 25 keV excitation energy above threshold, multi-neutron detection capability with high efficiency and accuracy

The experiments worldwide, which can be compared with R^3B, are the MONA-LISA setup at MSU, and the SAMURAI experiment at RIBF at RIKEN. The beam energies available at MSU are much lower, i.e., around 100 A·MeV, resulting in severe acceptance limitations and a limited accessible mass range. Certain reactions cannot be used at these energies, e.g. Coulomb excitation to high-lying states (Pygmy and Giant Resonances), or quasi-free knockout reactions. Similar limitations apply for the SAMURAI experiment, although beam energies are available up to around 250 A·MeV. SAMURAI, which started operation this year, is the current world-leading experiment with respect to beam intensities for exotic nuclei, in particular for lighter ions up to Z≈50. However, a unique identification even in the Z≈50 region is already difficult due to the lower beam energy. Other deficiencies might be improved in the future if new neutron detectors and a γ calorimeter will be built. However, heavier nuclei and reactions needing high beam energies will remain inaccessible with SAMURAI.

First experiments in 2018-2019 and discovery potential: From the unique features of R^3B and the comparison to competing programs worldwide, as briefly outlined above, a number of experiments with high discovery potential and which cannot be done immediately elsewhere follow. Three examples are given below:

Nucleon-nucleon correlations in nuclei as a function of neutron-proton asymmetry

We plan to investigate the role of nucleon-nucleon correlations in nuclei systematically as a function of asymmetry. These correlations are not only of high relevance for the understanding of the single-particle structure of exotic nuclei, but also of properties of asymmetric nuclear matter and of neutron stars. The R^3B systems uniquely allows a kinematically complete measurement of (p,2p), (p,pn) knockout reactions. We also make use of the highest possible beam energy in order to achieve a high sensitivity to large-momentum components.

The multipole response of neutron-rich nuclei

The physics case for these experiments are related to i) the general understanding of the multipole response of nuclei as a function of N-Z, ii) the nucleosynthesis r-process, and iii) constraining the equation of state (EOS) of asymmetric nuclear matter as present in neutron stars. This will be addressed by measuring the electric dipole and quadrupole response of exotic nuclei in two mass regions, accessible at FAIR for the first time, namely the neutron-rich Sn isotopes beyond the N=82 shell gap and the neutron-rich Pb isotopes, both at highest beam energy. The experiments will yield the full dipole strength function and polarizability of these neutron-rich nuclei, putting stringent constraints on the neutron-skin thickness and the density-dependence of the EOS of asymmetric nuclear matter.

Nuclear systems beyond the neutron drip-line

The extremes of neutron-proton asymmetry in nuclei can be studied at, and through, unbound states beyond the neutron drip-line. The present experimental limit is ^{26}O, being the heaviest unbound system studied so far, which decays by 2n emission. Going even further beyond the drip-line limit requires the detection of multi-neutron events. R^3B with NeuLAND is the only experiment capable to measure 4n decays with high efficiency and excellent resolution. Key nuclei will be the 4n tetra-neutron system, ^7H, and ^{28}O. The data are of key importance to test modern nuclear theory including 3N forces and the influence of the continuum.

HEB beyond MSV

The detection systems of R3B will be extended gradually; one example is the inclusion of an active target device, i.e., the detector simultaneously acts as target in order to avoid energy loss inside the latter. This then opens up for low-momentum transfer experiments with light ions like elastic scattering or (α,α') inelastic scattering, in a complementary approach to EXL with respect to half-lives and RIB intensities.

The long-term perspective is to complement the post-target detection systems with a high-resolution spectrometer for fragments. This is already foreseen in the layout of the HEB cave and will achieve the highest resolution also for heavy nuclei.

Ring branch

The NUSTAR experiments of the ring branch generally rely on the availability of the New Experimental storage Ring (NESR) which is not part of the MSV. Only the ILIMA programme can to some extent be performed at the MSV's Collector Ring (CR). EXL and ELISe concentrate on ambitious R&D work while performing early implementation experiments at the ESR at GSI. This approach intends to keep the collaborations active until the ring complex of FAIR can be realized. Obviously the opportunity of using the High-Energy Storage Ring (HESR) and the CRYRING as intermediate instruments for the NUSTAR ring experiments has triggered on-going, thorough studies.

ILIMA

Overview: The ILIMA (Isomeric beams, Lifetimes and Masses) scientific program pursues three main goals, a significant part of which can be performed within the MSV of FAIR.

Mass measurements of exotic nuclei

Most of the mass measurements program envisioned in the original ILIMA proposal for FAIR can be completed already within the MSV. Module 3 of MSV includes the CR, which is one of the main facilities for the ILIMA scientific program. The CR is being specifically designed for operating in the isochronous ion-optical mode, which is the prerequisite for isochronous mass spectrometry (IMS) of short-lived nuclides produced at the Super-FRS. IMS in CR will employ two time-of-flight detectors placed in one of the straight sections of the ring. IMS can be applied to stable nuclei as well as to nuclides with half-lives as short as a few tens of microseconds. Since a single stored ion is often sufficient to determine its mass, nuclides produced with tiny rates like one ion per day or even one per week can be addressed. This ultimate sensitivity and efficiency of the IMS technique will allow studies of the most exotic nuclear species which are at or beyond the limit of accessibility by experimental techniques anywhere else in the world.

> **ILIMA – studies of the most exotic systems**
>
> ILIMA will often require only a single ion to measure its mass. This striking feature enables ILIMA to investigate the most exotic nuclei with production rates as small as one ion per day, week or even month in regions inaccessible by any other technique or experiment. In addition to masses also lifetimes can be measured simultaneously, thus providing two basic nuclear properties. Although various detector setups and data acquisitions techniques are being steadily improved by the collaboration, the experience ILIMA has gained at the ESR and CSRe would allow the immediate start-up of the ILIMA scientific program once the Super-FRS and CR are in operation.

Mass measurements with Super-FRS-CR have a huge discovery potential. Some highlights are:

- Masses of waiting point nuclei in rp- and r-process nucleosynthesis, access to exotic nuclei down to the sub-millisecond range with isochronous techniques.
- Possible quenching of N=82 and N=126 shells in neutron-rich nuclei
- Nucleon correlation energies in nuclei with extreme neutron-to-proton ratios
- Mapping of borders of nuclear existence
- Neutron-unbound high-spin isomers close to the neutron drip-line.

Operation of the HESR with heavy ions injected from the CR was also found to be feasible. It will be equipped with stochastic and electron cooling systems. Thus, the high-resolution mass measurements of cooled nuclides, which were originally foreseen in the NESR, may be possible in the HESR. The Super-FRS-CR-HESR measurements will be conducted on nuclides with half-lives longer than a few seconds. Schottky mass spectrometry (SMS) will be applied for this purpose.

Lifetime measurements and decay modes of exotic nuclei

A new resonant Schottky detector implemented in the ESR allows measurements of the revolution frequencies of single stored ions within a few milliseconds. This time resolution is sufficient to enable lifetime measurements in the CR tuned in the isochronous ion-optical mode. Several Schottky pick-ups will be installed to cover the entire frequency acceptance of the CR, which will allow simultaneous lifetime measurements of many different ion species. Furthermore, since the Schottky detection is non-destructive, simultaneous mass and lifetime measurements will be possible. In addition, the CR will be equipped with position-sensitive particle-detector setups. These detectors will be used to detect daughter ions after an in-ring radioactive decay.

The highlights of the future experimental studies are:

- Decay modes close to the neutron drip-line, e.g. β-delayed neutron decay;
- Possibility to demonstrate neutron emission from n-rich high-spin isomers;
- Half-lives for nuclides lying on rp- and r-process nucleosynthesis path.

Position-sensitive particle detectors will also be available at the HESR. The HESR is equipped with an accumulation scheme, which can be used to study decays of very long-lived nuclides, like for instance:

- Radioactive decays of bare and few-electron ions, bound-state beta decay of nuclei close to stability
- Decays of long-lived nuclides relevant for astrophysics (cosmic radioactivity, high-energy cosmic rays)
- Measurements of weak decay branchings (and associated rare decay modes).

Preparation of isomeric beams and in-ring reaction studies

Pure beams of nuclear isomers can be produced if the nuclear ground state is significantly shorter lived than the corresponding isomeric state, or by mechanical scraping. The former requires a sufficiently long storage time. The latter has been demonstrated in the ESR. It requires electron-cooled beams and a location in the ring with a high-resolution focus for installing the scraper. This will be available in the HESR. Furthermore, the HESR will be equipped with internal targets, like the one of the SPARC collaboration, which will enable reaction studies on pure isomeric beams. The isomeric beams will be of broader interest for the NUSTAR Collaboration once a decision is taken to install the EXL setup in the HESR.

Uniqueness: Coupling of the Swedish CRYRING to the ESR will allow unique experiments with low-energy isomeric beams. One highlight example is the search for the predicted Nuclear Excitation by Electron Capture (NEEC) effect. Furthermore, a transfer line from the CR to the present ESR can be considered after the MSV of FAIR, which will enable the use of beams from the Super-FRS for ESR-CRYRING experiments. In general, ILIMA exploits unique capabilities at FAIR. While some mass (and related) measurements can be carried out at ISOL and IGISOL facilities, the wide-open opportunities for ILIMA assure its vibrant and unrivalled physics program.

Day-one experiments: One from many examples could be: Masses and lifetimes will be measured in the CR for N=126 ground states and isomers, extending from the current limit (for masses) of ^{206}Hg to the r-process path. This will address the issue of possible N=126 shell quenching in the very-neutron-rich domain, which is key to understanding nuclear abundances. r-process waiting-point nuclei will be reached.

Beyond MSV: Although a significant part of the planned ILIMA research program can be pursued within the MSV of FAIR by employing the Super-FRS, ESR, CRYRING, CR and HESR facilities, the full program can only be accomplished once the NESR is constructed and operational. The ESR shall stay operational until the construction of NESR is completed. Here, reaction experiments on isomeric beams employing, for example, the EXL demonstrator detector can be performed.

EXL and ELISe – beyond MSV

The EXL and ELISe collaborations have proposed measurements of reactions of light ions and electrons with radioactive ions in rings. These measurements have been planned such that they can be performed at several stages. The short-term goal of the EXL collaboration was to design detectors, which can already be placed at the existing ESR ring and used in the experiments with the present GSI facilities producing radioactive nuclei close to the valley of stability with reasonable intensities. This goal has partly been achieved. In fact, the first physics runs have been performed in October 2012. After these successful runs, the detector will be expanded to cover a larger part of the phase space for the coming years. Once the FAIR facility starts to run, one can use the present ESR and the future HESR (and also possibly the CRYRING) for these measurements. For this purpose, transfer lines should be provided to bring the beams of radioactive ions to these rings. Some modifications of the rings are also mandatory. The EXL setup can then be used for the studies with even more exotic nuclei. This would form the mid-range plan of the collaboration.

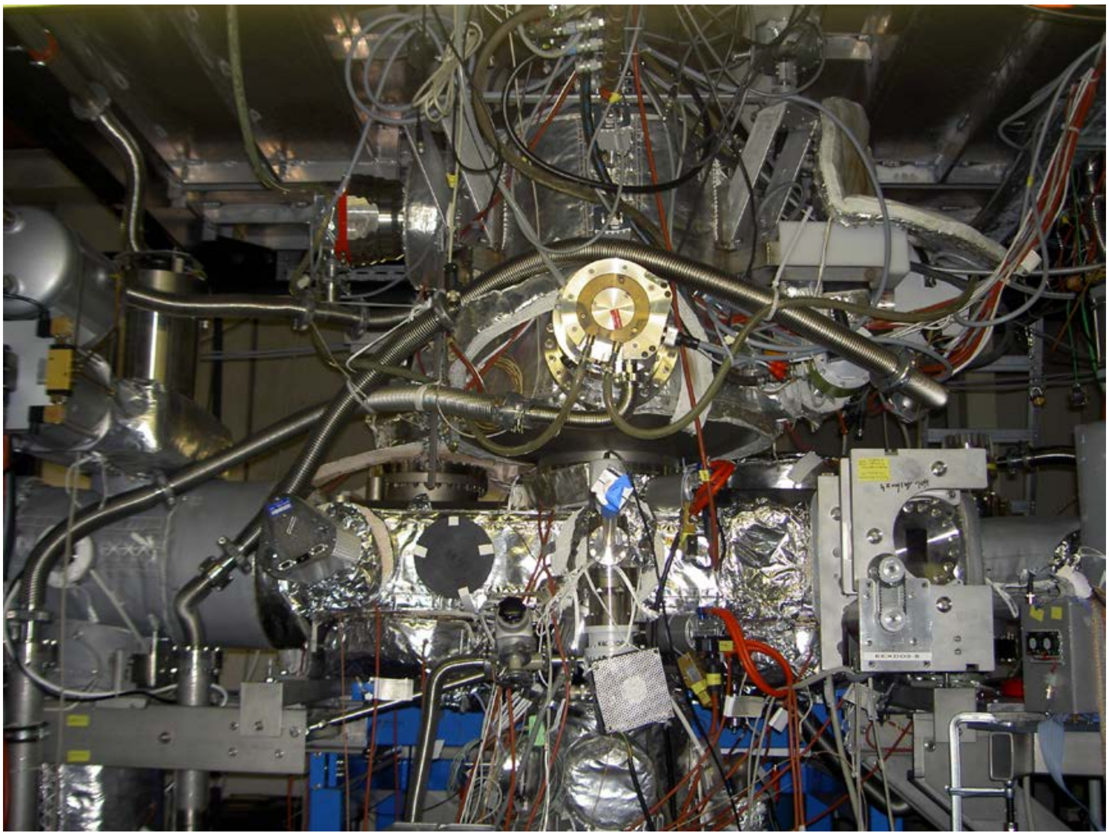

Fig. 5: EXL Test set-up at the ESR at GSI.

The ELISe experiment with its colliding beam setup is expected to be unique for the next decade in terms of achievable luminosity for a given radioactive ion yield and selectivity due to the simultaneous reconstruction of excitation and decay process. The need for such a facility has been demonstrated with the newly built SCRIT facility at RIBF in Japan. In view of the possible activities using the ESR ring facility, a study for operating the ELISe experiment at a modified ESR has been carried out with good success.

To achieve the best performance as proposed in the original proposals, one needs to build a dedicated ring with a large acceptance and more space for various detector systems. This ring (NESR) is, presently, not part of the MSV of the FAIR project and should be included in the long-range plan at a later stage.

J. Gerl, A. Herlert, and T. Nilsson (editors)

on behalf of the NUSTAR Collaboration