THE SUPER-FRS PROJECT AT GSI

M. Winkler[1,2]*, H. Geissel*[2,1]*, G. Münzenberg*[2]*, V. Shiskine*[2]*, H. Weick*[2]*, H. Wollnik*[1]*, M. Yavor*[3]
[1]University of Giessen, Germany,
[2]GSI, Germany,
[3]Institute for Analytical Instrumentation, St. Petersburg, Russia

Abstract

Over many years the GSI projectile fragment separator FRS has demonstrated the research potential of in-flight separators at relativistic energies. To move closer to the extreme limit of stability the next generation of a large-scale in-flight facility is under progress at GSI. It will provide primary beam intensities of up to 10^{12} ions/s of ^{238}U at an energy of 1500 MeV/u. The key instrument of this facility is a large acceptance **SUPER** conducting **FR**agment **S**eparator, the Super-FRS. It allows an efficient separation of fission fragments as well as high background suppression. Different experimental branches including a combination with a new storage-cooler ring system follow the Super-FRS.

1. INTRODUCTION

The success of the present exotic nuclear beam facilities is the motivation for new projects and plans for next-generation devices worldwide. Of special interest are facilities that can provide beams of rare and short-lived nuclei with kinetic energies above the Coulomb barrier [1,2]. This allows carrying out nuclear reaction experiments with exotic nuclei that have been possible only with stable nuclei in the past. Two complementary experimental methods are applied presently to achieve this goal, the in-flight and the isotope separation on-line (ISOL). ISOL schemes produce the radioactive ions at rest and employ a post-accelerator to provide secondary beams in the energy range of the Coulomb barrier. The in-flight method employs projectile fragmentation and fission of 30 MeV/u to 1500 MeV/u heavy ions. In this case, the thickness of the production target is only a small fraction of the projectile range and thus the spatially separated secondary nuclear beams are provided for all possible energies of the projectiles. The main advantages of the in-flight separation method can be summarized as follows:

- secondary beams of all elements can be provided since it is chemistry-independent
- it allows the study of very short-lived species since the separation and transport to the experimental devices is limited only by the time of flight through the separator (less than a μs)
- high energies allow the use of thick secondary-reaction targets and thus high luminosities even for rare exotic species
- mono-isotopic beams can be provided as well as “mixed beams” of isotopes with similar A/Z if necessary
- with a synchrotron as the driver accelerator, quasi-continuous secondary beams or short-pulsed beams for an efficient injection into storage rings can be provided

Since the proposed Super-FRS project at GSI is in a very early phase this paper will not discuss safety aspects and problems involved in detail. However, a special contribution of this volume is dedicated to the high-power production target [3].

2. PRODUCTION OF HIGH-ENERGY RADIOACTIVE BEAMS

Projectile fragmentation and projectile fission are the two main production mechanism to generate exotic nuclei at high primary beam energies. Projectile fragments are produced by nucleon-nucleon collisions leading to abrasion and subsequent ablation processes while coulomb excitation in peripheral collisions lead to the creation of fission fragments. In the latter case the spread in total kinetic energy is relatively large and thus these beams have a much larger phase space distribution compared to projectile fragment beams as can be seen in Fig.1. However, fission of ^{238}U projectiles is a fertile source for studying very neutron rich fission fragments of medium mass due to their high production cross sections. This became already clear in pioneering experiments [4] done at the FRS at GSI where about 120 new neutron-rich isotopes were discovered by this method.

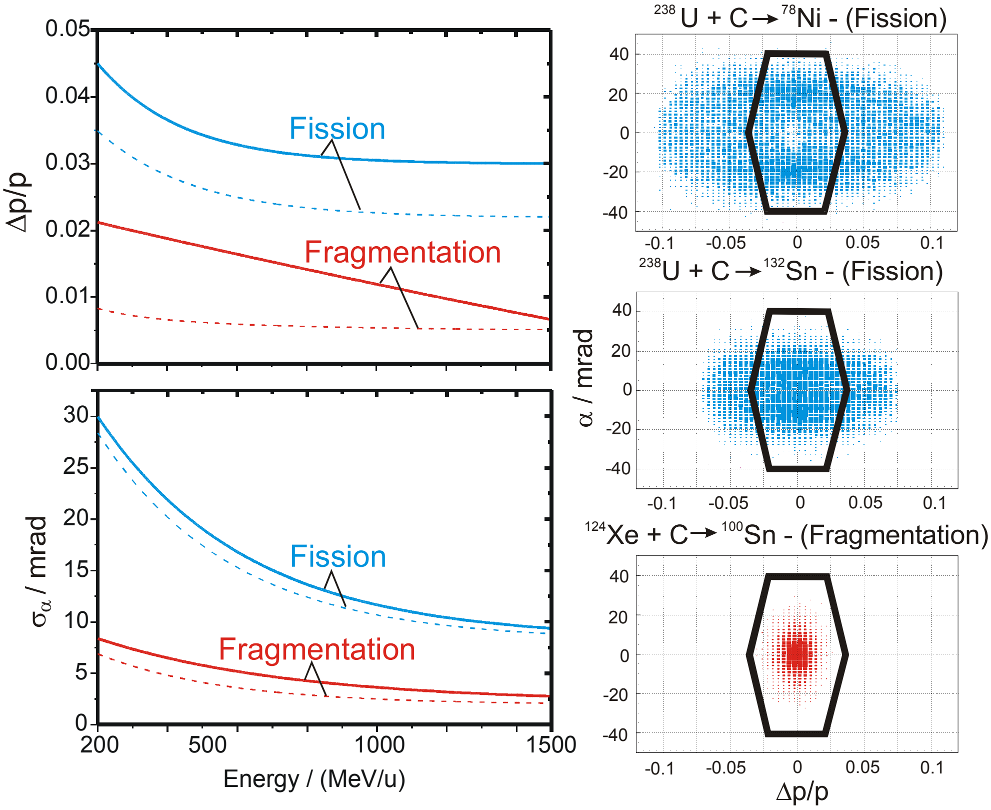

Fig. 1: Left panel: Comparison of the momentum and angular distribution for a ^{100}Sn beam produced by ^{124}Xe fragmentation and a ^{132}Sn beam produced by ^{238}U fission. The dashed lines arise from very thin targets (0.1 mg/cm^2) and thus indicate the pure reaction kinematics, while the full lines include also realistic production targets (several g/cm^2, optimized for the acceptance of the Super-FRS). Right panel: Comparison of the 2-dimensional phase space distribution of exotic beams produced by high-energy (1500 MeV/u) projectile fragmentation and fission, respectively. The thick contour line represents the acceptance of the Super-FRS.

3. DESIGN GOALS OF THE SUPER-FRS

The FRS was primarily designed for the production and separation of projectile fragments [5] and a transmission of 70% or more through the separator is achieved for these beams. The transmission of fission fragments through the FRS is typically only a few percent due to the enlarged phase space distribution of these beams. Consequently in the design of the proposed Super-FRS the accepted phase space is drastically increased. Table 1 compares the main parameters of the FRS and the Super-FRS. Though the acceptance has been strongly increased for the Super-FSR, the ion-optical resolving power has been preserved to guarantee the separation quality and the momentum resolution for the spectrometer option.

Table 1
Momentum and Angular Acceptance of the FRS and Super-FRS

Facility	$\Delta p/p$	$\Delta\Phi_x$	$\Delta\Phi_y$	Resolution
FRS ($B\rho_{max}$ = 18 Tm)	± 1 %	± 13 mrad	± 13 mrad	1500 (20 π mm mrad)
Super-FRS ($B\rho_{max}$ = 20 Tm)	± 2.5 %	± 40 mrad	± 20 mrad	1500 (40 π mm mrad)

The separation method of the Super-FRS is in principle similar to that of the FRS, i.e., a two-fold magnetic rigidity analysis before and after a thick energy degrader. The combination of atomic energy loss and rigidity analysis, the Bρ–ΔE–Bρ separation [5], provides spatially separated isotopic fragment beams. However, special measures have to be applied for the Super-FRS due to the higher phase-space acceptance and the expected much higher primary beam intensities of the new facility, e.g., up to 10^{12} ions/s for uranium [6]. This will lead to larger contributions of contaminants compared to the present situation at the FRS, which can be solved by combining two separator stages, a preseparator and a mainseparator. Both stages are equipped with an energy degrader.

Additionally the fragment- and primary beams should be bare with a negligible contribution of other charge states to avoid ambiguities in identifying the fragments. This can only be achieved if the velocity of the heavy ions is high enough during the penetration through matter (production target, energy degraders, and detectors) within the Super-FRS. On the other hand, it is obvious that the thickness of the matter has to be optimized to prevent substantial losses due to nuclear absorption. The conclusion from optimization processes and the experience with FRS experiments is, that the Super-FRS should accept beams up to a maximum magnetic rigidity of 20 Tm corresponding to 1566 MeV/u $^{238}U^{92+}$, which will yield to a high degree of fully ionized ions (Fig.2)

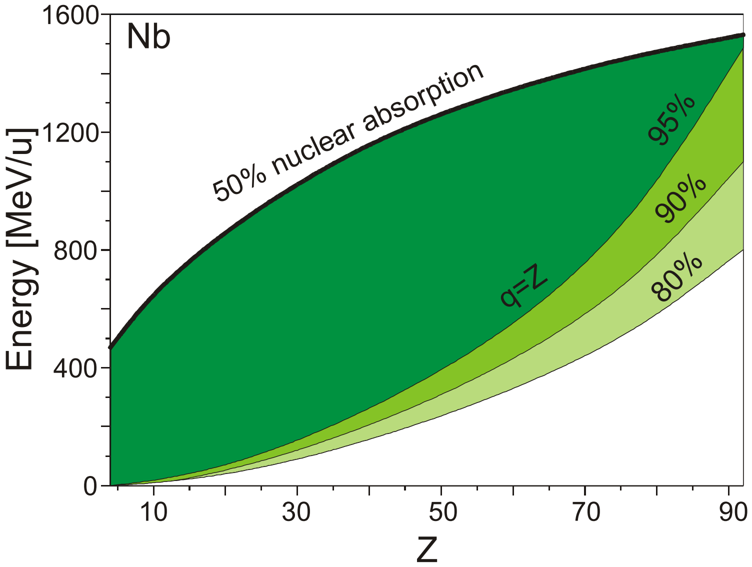

Fig. 2: Operating domain of the Bρ-ΔE-Bρ separation method. The two main restricting criteria, the charge-state population on the one hand and the nuclear absorption on the other hand, are displayed as a function of the atomic number of the separated fragments. Shown are the crucial energies where nuclear absorption of 50% in a niobium energy degrader with a thickness of half of the atomic range occurs and where one reaches charge-state equilibrium for 80, 90, and 95 % fully ionized fragments.

4. LAYOUT OF THE SEPARATOR

The ion-optical layout of the Super-FRS is presented in Fig.3 including the particle trajectories for beams with an emittance of ±40 π mm mrad and a momentum dispersion of ±2.5%.

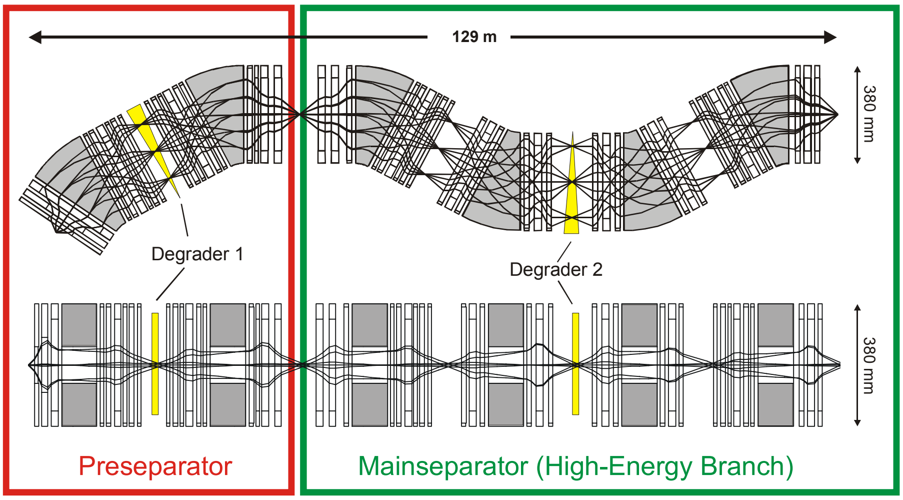

Fig. 3: Ion-optical layout of the Super-FRS, which will deliver the beam into the high-energy reaction cave. Shown are particle trajectories for beams with an emittance of ±40 π mm mrad in x- and y-direction and a momentum dispersion of ±2.5%.

As already mentioned the Super-FRS is a two-stage separator. The preseparator consists of two dipole stages while the mainseparator is build up of 4 dipole stages like the FRS. The dipole magnets have a radius of deflection of 12.5m and bend the beam by 28°. The preseparator as well as the mainseparator are achromatic systems, so the whole system is also achromatic. The achromatism allows an image at the final focal plane that is independent of the momentum spread of the fragments at the entrance of the system. Quadrupole triplets are placed in front of and behind each dipole magnet to fulfill the desired ion-optical conditions at the focal planes and to properly illuminate the dipole magnets. The Super-FRS can handle beams with a magnetic rigidity up to 20 Tm. The high phase-space acceptance creates large optical aberrations. Therefore, also hexapole and octupole correction elements have to be implemented to achieve the necessary separation quality. All magnets have large apertures to achieve the high phase space acceptance. A comparison of the gain factors in transmission of the FRS and the Super-FRS is illustrated in Fig.4 for uranium fission products as a function of the element number.

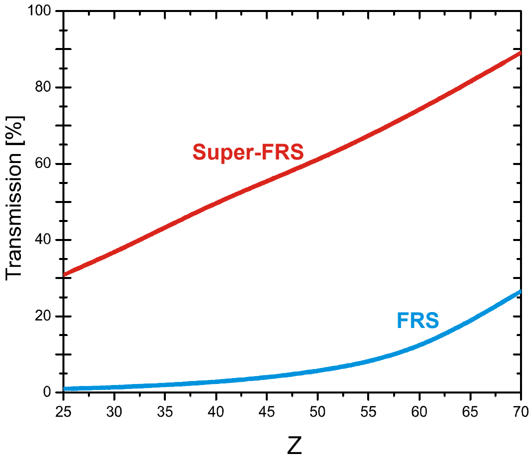

Fig. 4: Comparison of the transmission of uranium fission fragments (A/Z = 2.6) for the Super-FRS and the FRS. The gain of pure transmission with the planned Super-FRS in the region of ^{78}Ni is a factor of 30.

The Super-FRS requires new and challenging magnet designs using super conductivity. The detailed magnet design is still in progress. The most crucial part of the whole separator regarding radiation damage problems and safety issues is the first part of the preseparator including the first quadrupole triplet and the first dipole magnet after the production target. The main bulk of non-desired fragments and the remaining primary beam will be dumped here. The radiation durability, the heat load and the quench probability of super conducting magnets in this region have still to be investigated. Fig. 5 shows typical numbers of expected beam losses producing U fission fragments. The primary beam intensity will be 10^{12} ions/s.

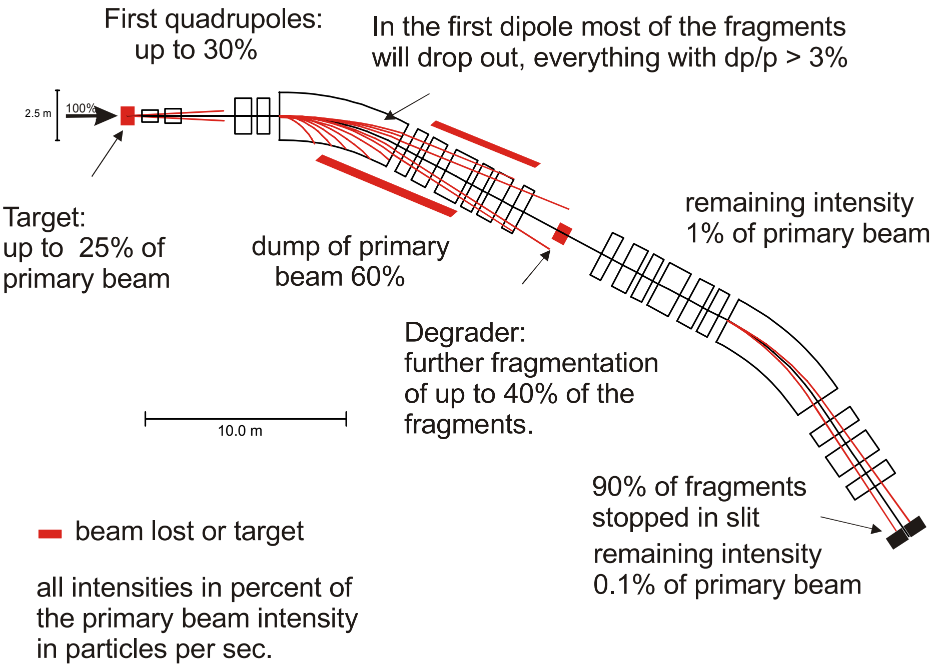

Fig. 5: Expected beam losses in the preseparator producing U fission fragments. Exact numbers depend on the selected isotope of interest.

5. SEPARATION PERFORMANCE OF THE SUPER-FRS

As already mentioned the preseparator as well as the mainseparator of the Super-FRS will be equipped with a degrader stage. The advantages of the two-degrader system can be summarized as follows:

- reduction of contaminants from fragments produced in the degrader
- optimization of the fragment rate on detectors in the main separator
- introduction of another separation cut in the A-Z plane
- possible usage of pre- and mainseparator for secondary reaction studies

Fig.6 demonstrates the separation performance of the Super-FRS for the double-magic nuclei ^{132}Sn. It is produced via fission of ^{238}U projectiles with an incident energy of 1500 MeV/u impinging on a 4 g/cm^2 carbon target. The degrader thickness are $d_1/r_1 = 0.3$ and $d_2/r_2 = 0.7$, respectively. Since the fragment energy at the entrance of the mainseparator is different from that of the preseparator (because of the slowing down in the 1st degrader) both separator stages will have different separation cuts in the N-Z plane such that at the exit of the mainseparator spatially separated isotopes can be provided. The area of the isotopes in the N-Z plane of Fig.6 represents the corresponding intensities resulting from transmission and production probability.

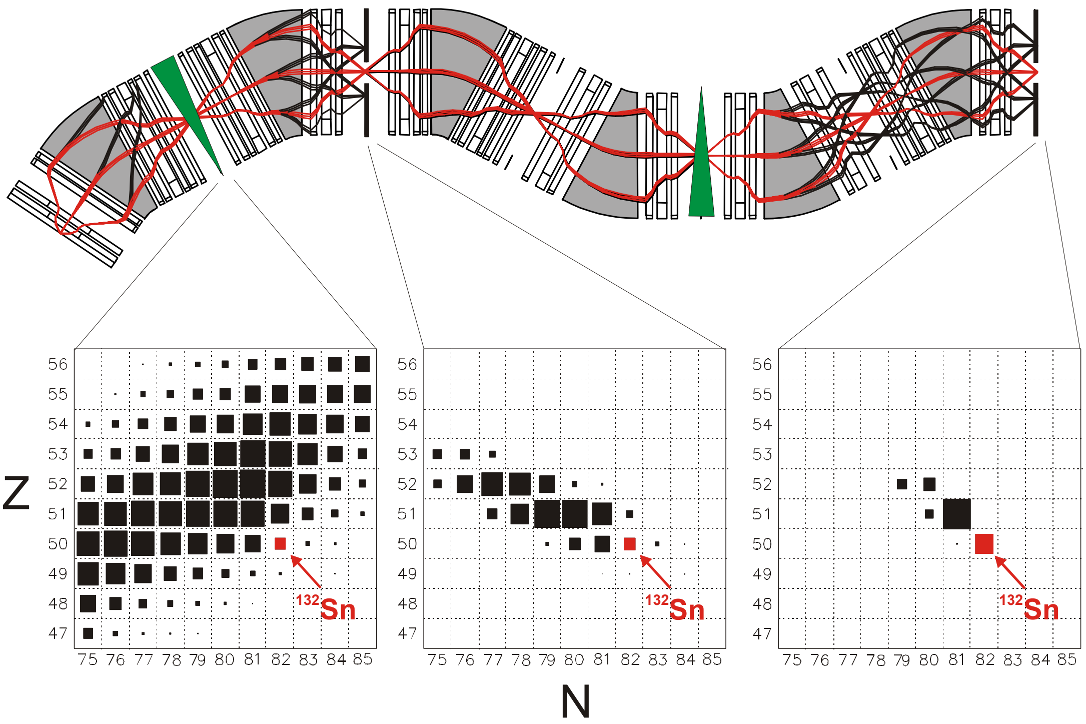

Fig. 6: Separation principle of the Super-FRS consisting of the pre- and main-separator stage. In the presented calculated example a 1500 MeV/u ^{238}U primary beam is focused on a 4 g/cm^2 carbon target with the goal to provide spatially separated ^{132}Sn isotopes. The separation performance is illustrated by a presentation of the isotopes transmitted at different focal planes of the Super-FRS. The area of the isotopes in the N-Z plane represents the corresponding intensities resulting from transmission and production probability.

Here it should also be mentioned that the remaining fragment intensities in the mainseparator are in the order of 10^9 ions/s, which is comparable to the intensities at the FRS nowadays and thus well established particle tracking methods can be used to identify the nuclei of interest.

6. THE EXPERIMENTAL BRANCHES OF THE FACILITY

The Super-FRS will serve three experimental areas, as it was proposed by the NuPECC Working Group on Radioactive Nuclear Beam Facilities [1]. The branches are dedicated to different experimental tasks, which are:

- a **High-Energy Branch** for reaction studies,
- a **Low-Energy Branch** for decay studies and trapping of ions,
- a branch into **a two-ring system** for precision experiments with stored and cooled exotic nuclei.

A schematic view of the proposed next-generation facility to study exotic nuclei is given in Fig.7.

6.1 The High-Energy Branch

The exit of the mirror-symmetric mainseparator of the Super-FRS ends in the high-energy cave where a reaction setup for fast radioactive beams will be placed. The experiments foreseen there cover a large variety of different reactions, such as elastic scattering, knockout reactions, electromagnetic and nuclear excitations, charge-exchange reactions, fission studies, in-beam γ-ray spectroscopy, or multifragmentation. Improvements of the reaction setup have been studied and proposed within the framework of a Europeen collaboration (Reactions with Relativistic Radioactive Beams, R^3B [7]).

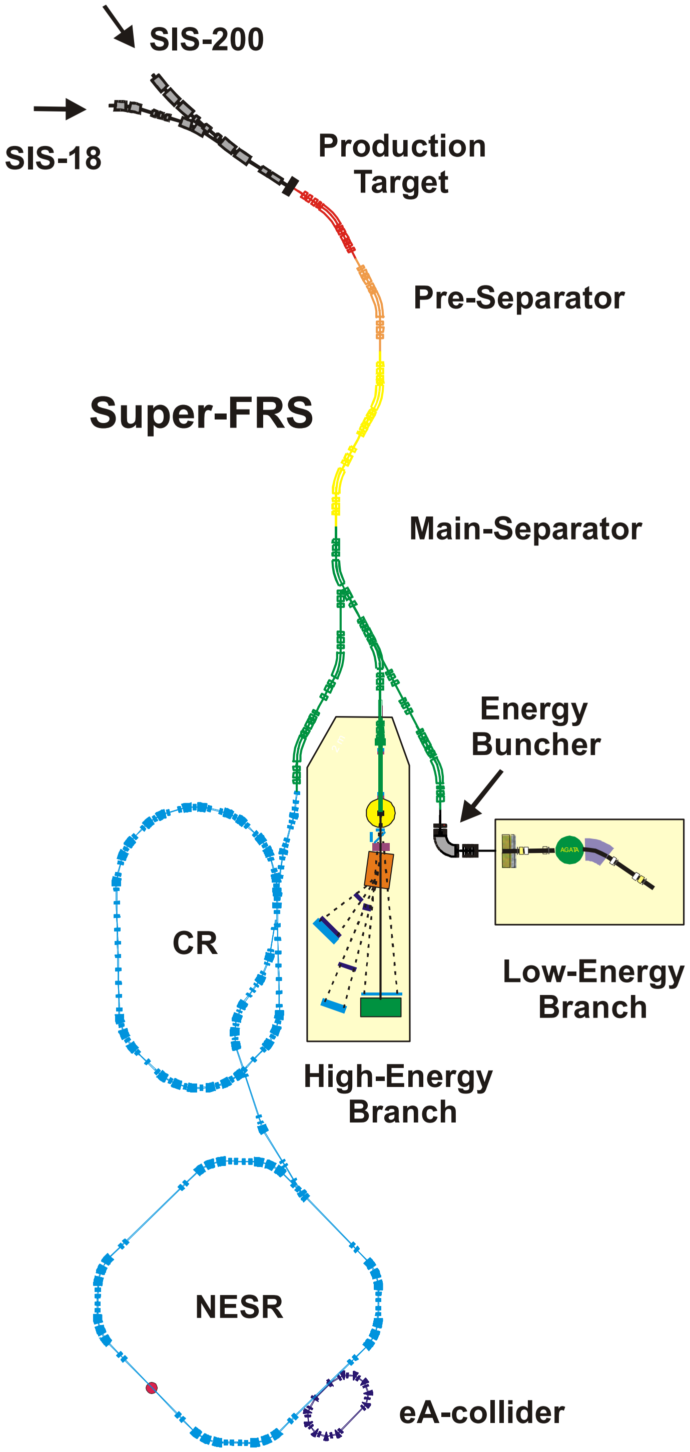

Fig. 7: Schematic view of the proposed exotic nuclear beam facility. The super-conducting two-stage fragment separator (Super-FRS) serves the areas for high- and low-energy experiments as well as a double storage ring system (CR and NESR) including an intersecting electron ring (eA-Collider).

6.2 The Low-Energy Branch

An energy-buncher coupled in combination with a gas-filled or solid-state ion catcher behind the Super-FRS will be the key instruments for advanced spectroscopy experiments with exotic nuclear beams of low energy and for precision experiments with stopped beams, in particular for those in ion and atom traps. The common requirement of these experiments is the need to slow down the separated ion beams quickly and efficiently and to minimize their energy spread, and thus, also their range distribution when stopped in matter, which will be done by the energy buncher. It consists of a high-resolution dispersive separator stage in combination with a specially shaped energy degrader system [8] placed at its dispersive focal plane. With such an energy-buncher stage one can, for example, compress the relative momentum spread of a 300 MeV/u fragment beam to values as small as $\sigma_p/p = 10^{-3}$, which will drastically reduce the range distributions of stopped fragments to approximately 1 to 4 atmosphere-meters of helium gas [9].

6.3 The Ring Branch

Of special importance is the ring branch that consists of two storage-cooler rings [6], the Collector Ring (CR) and the New Experimental Storage Ring (NESR), which will provide excellent research opportunities based on both new and well-established experimental techniques. The main goals are high-precision mass, lifetime and in-ring reaction studies. In addition, a completely new field will be opened with electron scattering of exotic nuclei.

It should be mentioned that fragment pulses as short as 50ns are injected into the CR which requires fast-extracted beams from the synchrotron. This scheme will be completely different compared to slow-extracted beams (quasi DC beams) used for fixed target experiments. The impact of these two different schemes to the high-power production target will be discussed in more detail in [3].

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