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A. Drouart, J.A. Nolen, H. Savajols. The Super Separator Spectrometer (S^3) for the SPIRAL2 facility. 27th International Nuclear Physics Conference (INPC2019), Jul 2019, Glasgow, United Kingdom. pp.012032, 10.1088/1742-6596/1643/1/012032 . in2p3-03134200

HAL Id: in2p3-03134200
https://hal.in2p3.fr/in2p3-03134200

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Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: A. Drouart *et al* 2020 *J. Phys.: Conf. Ser.* **1643** 012032

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Journal of Physics: Conference Series **1643** (2020) 012032 doi:10.1088/1742-6596/1643/1/012032

The Super Separator Spectrometer (S^3) for the SPIRAL2 facility

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Abstract. The Super Separator Spectrometer S3 is, with the NFS (Neutrons For Science) facility, a major experimental system developed for SPIRAL2. It is designed for very low cross section experiments at low (<15MeV/u) energy. It will receive the very high intensity (more than 1pμA) stable ion beams accelerated by the superconducting LINAG accelerator of SPIRAL2. S^3 will be notably used for the study of rare nuclei produced by fusion evaporation reactions, such as superheavy elements and neutron-deficient isotopes. Such experiments require a high transmission of the products of interest but also a separation of these nuclei from unwanted species. Hence S^3 must have a large acceptance but also a high selection power including physical mass resolution. These properties are reached with the use of seven large aperture superconducting quadrupole triplets which include sextupolar and octupolar corrections in a two-stage separator (momentum achromat followed by a mass spectrometer) that can be coupled to the SIRIUS implantation-decay spectroscopy station or to the REGLIS^3 gas cell with laser ionization to provide very pure beams for low energy experiments. S^3 is now in the construction phase. We will present the scientific objectives of S^3 as well as the current status of the facility and its different elements.

1. Physics motivation

The superconducting linear accelerator of SPIRAL2 will provide not only deuteron beams, but also very intense beams of heavy ions, from carbon to uranium, with energies from 2 to 14 MeV/u. This opens new possibilities to study low cross-section reactions and their products. The research program notably aims at fusion-evaporation residues produced near coulomb barrier energy. Two regions of the nuclear chart are of particularly interest:

- The region of superheavy elements ($Z \geq 100$), with the ultimate goal of the synthesis of new elements to extend the periodic table of Mendeleev. Detailed studies (decay spectroscopy, mass measurements, etc.) of "lighter" superheavy nuclei will be possible.
- The region of nuclei at the proton drip line, especially in the region of the self-conjugate doubly magic nucleus ^{100}Sn considered one of the critical benchmarks of nuclear structure far from the valley of stability.

This program also has strong synergies with the Atomic Physics community, specifically in interaction studies in the unknown regime of fast ion-slow ion collisions. The project "Fast Ion Slow Ion Collisions" (FISIC) addresses the remaining open question of energy deposition by charged particles in matter that takes place in irradiated materials when the ion stopping power is at its maximum. The goal of FISIC is to study ion-ion interaction (notably charge exchange) at the achromatic point of S^3. The dedicated FISIC set-up is not described here.

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2. Description

A thorough description of the principles of the spectrometer can be found in [1]. We describe here its most important elements and update on their status. The implantation of the S^3 experimental area is shown in Figure 1. Presently under construction, S^3 is expected to run its first experiments in 2022.

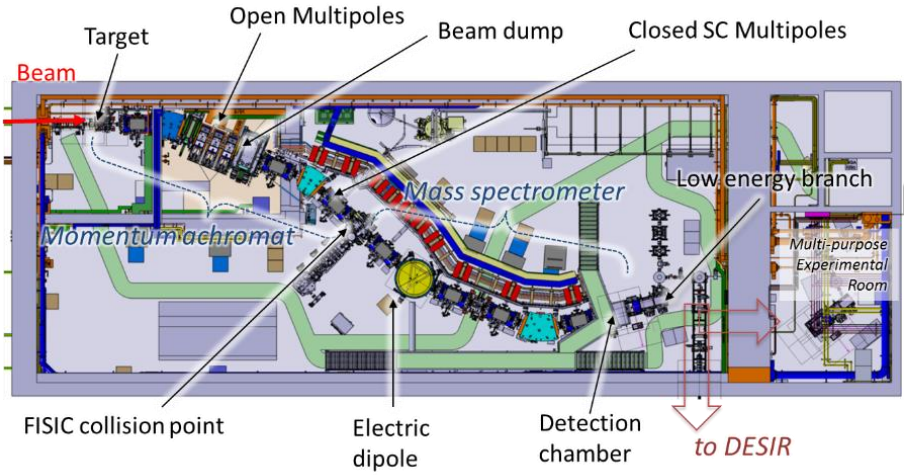


Figure 1: S^3 implantation in the LINAG Experimental Area

2.1. Optical performances

The main performances of S^3 are summarized in Table 1. They are detailed in the following sections.

Table 1. Main characteristics of the S^3 line. (*)Mass resolution is given for an initial distribution of σ_θ=20mrad, σ_p=3.4%.

Parameter	Dispersive mode	Converging mode
Length	29.4 m	
Momentum acceptance	16%	20%
Horizontal angular acceptance	45 mrad	90 mrad
Vertical angular acceptance	140 mrad	140 mrad
Mass resolution* (M/dM; FWHM)	500	None
Maximum magnetic rigidity	1.8 Tm	
Maximum electric rigidity	12 MV	

2.2. Target point

The very high beam intensities require a target that can sustain the high beam power. The obvious requirement of the target is to keep a stable behavior under high primary beams intensity (several particle μA). For that purpose, the incoming beam profile will have a large vertical size, in order to spread the beam over a larger surface area on the target but a small horizontal size, to prevent a degradation of the mass resolution in the spectrometer.

The target station will use a high speed rotating wheel to support the thin targets, to reduce the maximum temperature and the effects of radiation damage. Two target stations are designed, one for stable materials, the other for actinide, radioactive elements. The stable target station has a 800mm diameter wheel, rotating at 3000rpm. It has been constructed and tested at Ganil. In-beam tests are expected in a near future. A prototype of the actinide target station has already been constructed. It has a wheel diameter of 120mm to accommodate for less material and turn at 5000rpm. It has been tested successfully with 100pnA ^{129}Xe beam at 7.7MeV/n, in order to simulate higher intensity of lighter primary beams. Details can be found in [2]. The chamber is equipped with many diagnostics to watch the incoming beam and the target integrity: Silicon for Rutherford scattering (Si ruth), alpha source, beam profile monitor (PR EMS), Faraday cup and electron gun. A photograph of the stable target station in shown in Figure 2.

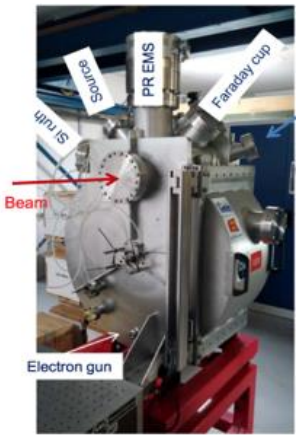


Figure 2 : Photograph of the stable target station. The diagnostics are indicated.

2.3. Separator-spectrometer beam line

At the exit of the target, the ions of interest are only a tiny part of the reaction products. The majority are non-interacting primary beam ions, plus a significant amount of beam-like, target-like or unwanted evaporation products. The selectivity of the line is so of paramount importance. That's why the spectrometer is segmented into two parts: its first half is a momentum achromat. Its goal is to get rid of the most of the primary beam and refocus this ions of interest in a small achromatic point. The second half is a mass spectrometer, combining an electric dipole and a magnetic dipole, to perform a cleaner selection of the ions.

In the momentum achromat, the primary beam can be separated from the nuclei of interest. The first selection stage is a p/q (momentum over charge) dispersive plane. It is intended to provide for a first rough rejection of the primary beam (to the level of 10^{-3}) either by stopping the beam charge states out of acceptance or within the acceptance, if required, using 20mm-wide "fingers" to block the geometrically focused beam trajectories. In the rejection zone, a triplet of quadrupole with a horizontal aperture allows for the ejection of the primary beam charge states outside the acceptance. The second selection step occurs at the collimated achromatic point. There, all the nuclei of interest are focussed, while any scattered ions are more randomly distributed and thus stopped in the collimator. The third level of selection is performed by the mass spectrometer, which has an electric rigidity (mv^2/q) dispersive plane at the middle of the spectrometer. The fourth and final selection stage occurs at the final focal plane, an M/q (M/dM=500 FWHM) dispersive plane. Alternatively, the mass spectrometer can be tuned in a "converging" mode. All the charge states of the ions of interest are focused into a single point at the final detection plane. This mode has larger horizontal and momentum acceptances, but without the mass selection.

As shown on Figure 3, a large part of the equipment is in the vault. The magnetic dipoles, the open triplet, the cryogenic lines as well as the beam line supports are installed. The cold box for helium liquefaction is operational. The beam dump vacuum chambers are being assembled at CEA Saclay, while the electric dipole has been mechanically tested at IPN Orsay.

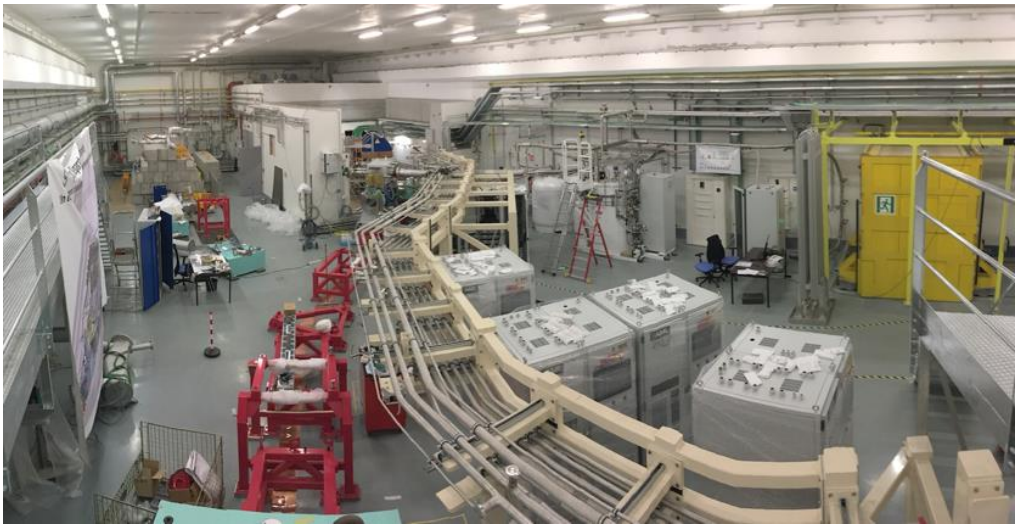


Figure 3: Photograph of the S^3 experimental area

2.4. Superconducting multipoles

The second main feature of the reaction products is their relatively low energy, down to a few 10s of keV/u (for fusion-evaporation residues produced in highly asymmetric direct kinematics). Hence the acceptance of S^3 must be as large as possible, while keeping the required high mass resolution. For that purpose, we have designed superconducting triplets of multipoles. They combine large aperture quadrupoles (30cm bore diameter) with embedded sextupole and octupole correction coils. These coils are used to correct for optical aberrations. In the momentum achromat, they ensure the small size of the achromatic point. In the mass spectrometer, they ensure the high mass resolution (in the second half, they are not used for the converging mode). Each singlet also contains a dipole coil for steering corrections, with the first and third singlets of each triplet having vertical dipole correctors wired in series while the central singlet has a horizontal steerer. To avoid large multipole error terms in the fringe fields of these large aperture multipoles, a new coil configuration has been implemented [3].

Four out of seven superconducting triplets have been constructed. They are presently being tested at Argonne National Laboratory and at Ganil. The seven power supply systems, including the quench protection, has been delivered to Ganil and will be tested before the end of the year with a triplet.

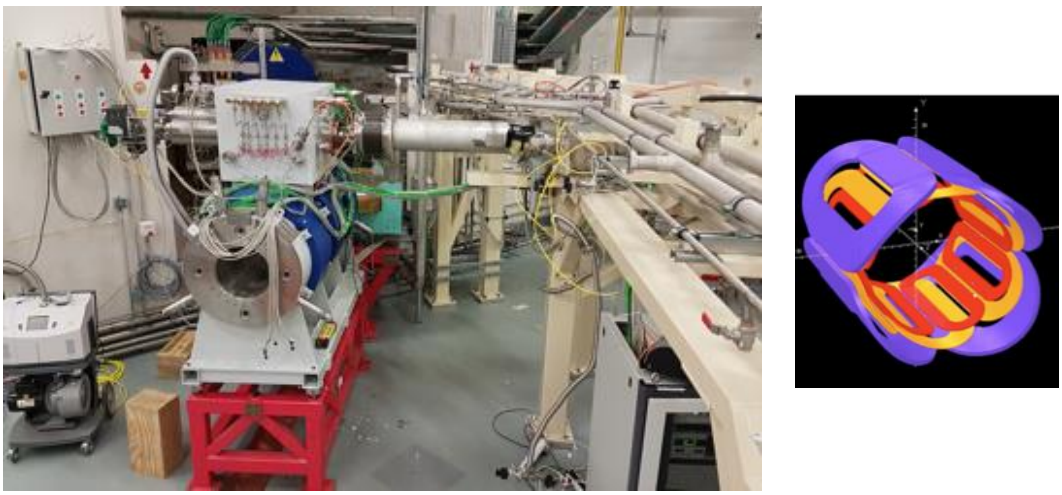


Figure 4: [Left] Photograph of a superconducting multipole triplet under cryogenic tests at Ganil. [Right] Schematics of the quadrupole (violet) sextupole (yellow) and octupole (red) coils.

2.5. Detection setups

The nuclei transmitted to the final focal plane will be studied using complementary detection methods, like spectroscopy of their decay or by measurements of ground state properties (e.g. laser spectroscopy, masses, chemistry, etc.). For that purpose, two detection setups are foreseen at the end of the spectrometer:

- SIRIUS [4] (Spectroscopy and Identification of Rare Ions Using S^3) is an implantation decay station for alpha, electron and gamma decay spectroscopy. It is composed of one tracking detector to measure the trajectory in front of a silicon detector box, surrounded by germanium detectors. Sirius is presently being installed in Ganil and will be tested with a radioactive source and then in-beam in the coming months.
- REGLIS [5] (Rare Elements in-Gas Laser Ion Source and Spectroscopy at S^3), is a low energy line, where the incoming ions stopped and neutralized in a gas cell, then extracted and re-ionized by lasers in order to perform high resolution laser spectroscopy and/or selective ionisation, to be send to other measurement apparatus, like the DESIR experimental area [6]. REGLIS is installed at LPC Caen and connected to the PILGRM multi-reflection time-of-flight spectrometer [7]. It is under tests with stable beams.

Acknowledgments

S^3 has been funded by the French Research Ministry, National Research Agency (ANR), through the EQUIPEX (EQUIPment of EXcellence) reference ANR-10EQPX- 46, the FEDER (Fonds Européen de Développement Economique et Régional), the CPER (Contrat Plan Etat Région), and supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract No. DE-AC02-06CH11357 and by the E.C.FP7-INFRASTRUCTURES 2007, SPIRAL2 Preparatory Phase, Grant agreement No.: 212692. S3 LEB has been funded by the French Research Ministry through the ANR-13-B505- 0013, and the Flemish Research Fund (FWO) under the Big science program and a grant from the European Research Council (ERC-2011-AdG-291561-HELIOS).

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