Preliminary commissioning plan of the S^3 project

GANIL Scientific Council – January 2023

1 Preamble

The S^3 project is now in its final phase of construction. The separator-spectrometer is expected to be ready to start the commissioning with beam in 2024.

The commissioning plan will take place in three phases.

- The first step is the “optical commissioning” with dedicated diagnostics along the spectrometer and at the focal plane. This phase, dealing with the spectrometer tuning for the beam transport, should last around 1-3 months. At this stage either SIRIUS or LEB can be connected at the focal plane but they will not be used for data taking.

- The second step concerns the “scientific commissioning” to optimize the rejection and the transmission for different relevant kinematics. This phase aims to reach the required performances in the Converging Mode (CM) for day1 experiments. In addition, even if the High-Resolution Mode (HRM) will not be used for the day1 campaign, some beam time will be devoted to test this optical tuning which is important for the SIRIUS scientific program and makes S^3 unique with respect to other facilities. The experience gained in this first HRM tuning will help to optimize this mode for the next beam time campaign.

- The third step is related to the commissioning of the two setups SIRIUS and LEB, which will take place in parallel with the second step. The goal is to have a full setup ready for the first experiments.

Given the complexity of S^3 the commissioning and the associated focal plane detection, two years will be necessary to reach adequate performances to start day1 campaigns with experiments selected by the PAC.

Following the discussions that took place during the S^3 User Collaboration Council (S^3UCC) meeting organized in the framework of the “Physics with SPIRAL2 Heavy Ions Beams workshop” held at GANIL 12-16th December 2022, it has been decided to elaborate 4 detailed scientific commissioning sceneries for the years 2024-2025.

Those sceneries will be discussed in a dedicated S^3UCC meeting in March to select the best sequences to successfully commissioned the spectrometer and the associated setups (SIRIUS and LEB).

At the time of writing this report not all the information is yet available and only a preliminary commissioning plan can be presented.

2 S^3 optical modes

The design of S^3 is highly versatile and allows the development of various optical modes dedicated to different experimental programs and detection systems. Two basic standard optical modes have been developed, and variations of these modes can be considered in future (see Figure 1):

- The converging mode (CM) allow a maximum transmission from the target point to the focal plane. In this mode, the beam rejection is moderate (performed at the momentum dispersive plane of the achromate and at the energy dispersive plane of the mass separator) and there is no mass resolution at the final focal plane.

- The high-resolution mode (HRM), or mass dispersive mode, that sacrifices part of the transmission in order to have a physical separation according to A/q at the final focal plane and thus a better rejection/identification.

For all optical modes a common tuning has been established for the Momentum Achromat (MA). Only the Mass Spectrometer (MS) has a different tuning between the Converging Mode (no high order corrections are required) and the High-Resolution Mode (high order corrections are needed).

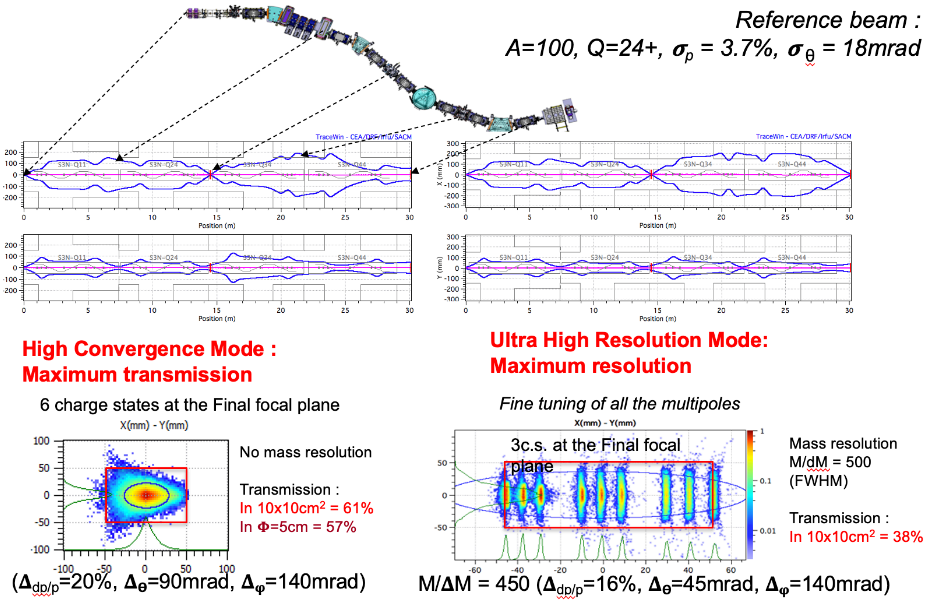

Figure 1: S^3 Optical mode description. Left : Converging mode (CV) ; Right : Mass dispersive mode (or High Resolution Mode HRM).

3 Prerequisites

3.1 Spectrometer

Before the commissioning of the line per se, it is necessary to check, as much as possible, every equipment of the line, as well as the external inputs.

The magnets, power-supplies, diagnostics, beam intensity measurements, slits, control-command equipment, … must have been tested beforehand. Notably, must be checked:

- The alignments of magnets, centering of the fields
- The polarity of power-supplies
- The alignment and orientation of diagnostics
- The alignment and orientation of slits
- The consistency of the control-command equipment

In addition, complex functional qualifications have to be performed (Machine protection, safety systems, beam transport, …).

3.2 LINAC

The commissioning of S^3 requires to increase progressively the beam intensity (from 10nA to tens of µA). This imply new developments to first reduce the intensity easily with pepper pots (1/100 to 1/1000000 reduction) in the LINAC and secondly to be able to measure low beam current with the design of a new AC Current Transformer to be installed at the entrance of the S^3 room. Those developments are ongoing and should be ready in 2024.

The beam on target must be carefully tuned (position, size, angle) and verified by the S^3 team with the help of a series of diagnostics located upstream of the target.

4 Spectrometer optical commissioning plan

In this section, we detail the different steps of the commissioning plan of the optical line, from the target point F0 up to the final focal point F4.

4.1 Principle

The principle of the commissioning is to test the elements progressively along the line by using the multiple diagnostics. At each step, the optical properties of the section will be tested at zero order (central trajectory), first order (dipole and quadrupoles) and higher order (correction of aberrations). Direct pencil beam is used for 0/1st orders, and scattered beam for 1st/Higher orders.

The momentum achromat (MA) optics are common to all modes (converging or mass dispersive) of the spectrometer. It can be tuned by the direct beam from the LINAC, or a moderately slowed beam. The mass spectrometer (MS), because of the electric dipole, must be tuned with a low energy beam (<1MeV/u). It could come either from the LINAC (if this energy regime can give a beam with correct optical properties) or by slowing it down at F0 and collimated in the MA.

Recently, oxygen and argon beams at an energy of 0.73 MeV/u were successfully accelerated up to the end of the LINAC with excellent beam properties. This setting will be preferentially used to tune the mass spectrometer.

Beam intensity will be adapted to the diagnostics (~10nA for emission profilers). Ne/Ar/Kr beams can be sued.

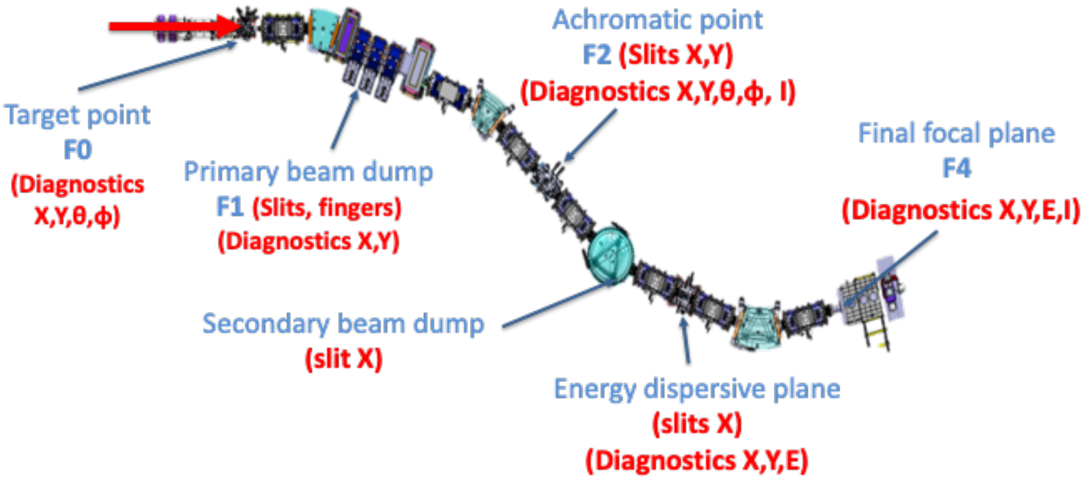

Figure 2: View of the S^3 line with the different focal points, diagnostics and slits location.

The table below summarizes all the beam diagnostics implemented on the S^3 line. They are divided into four categories to adapt different beam conditions:

1. Multi-wire X-Y profilers (EMS)
   Beam energy range: few keV/A to 100 MeV/A
   Beam intensity range: 1 nA to 100 μA
2. Secondary electron emission beam profile monitors (PFE)
   Very low energy limit (E ≈ 10keV/A)
   Beam intensity range: 10-10*^{11}pps
3. Residual gas profile monitors (MIGR)

Because this monitor will employ a residual gas detection strategy, it will not interfere with the beam. It can thus be used as a continuous position an intensity monitor.
Beam energy range: 2-15 MeV/A
Beam intensity range: 1nA-100μAe

4. Silicon strip detector (SSD)
Intensity < 10^4pps

Location	Distance	Type	Operational name
Target **F0**	2,43m upstream	***EMS***	LHS3N-PR22
		PFE	LHS3N-PFE22
	1,5m upstream	***EMS***	LHS3N-PR23
		PFE	LHS3N-PFE23
	1,2m upstream	***MIGR***	LHS3N-PGR24-VE
		MIGR	LHS3N-PGR24-HO
	Target	***EMS***	S3N-PR12
Momentum dispersive plane F1	Dispersive plane	***EMS***	S3N-PR21
Acrhomatic point **F2**	0,5m upstream	***EMS***	S3N-PR31
		PFE	S3N-PFE31
	Acromatic point	***SSD***	S3N-SSD32
		EMS	S3N-PR32
		PFE	S3N-PFE32
	0,5m downstream	***EMS***	S3N-PR34
		PFE	S3N-PFE34
Energy dispersive plane F3	Dispersive plane	***PFE***	S3N-PFE41
		SSD	S3N-SSD41
Final focal plane **F4**	Focal plane	***SeD***	

Table 1: List of beam diagnostic detectors implemented on the S^3 line.

In the context of the optical commissioning, two additional multi-wire X-Y profilers and a dedicated faraday cup are installed at the focal plane (the SeD detector is not used).

4.2 Step 1: momentum achromat tuning

The beam is stopped in the faraday cup at F2 at LINAC energy.

Zero order

One can check all the alignment of the optic elements of line with beam (magnets, diagnostic, slits).

The direct beam is sent along the central trajectory of the MA, checked at F1 and F2. One verifies that the magnets do not alter this central trajectory. Notable, the open sextupoles of the open triplet T2, produced by two compensating dipoles coils, must be carefully adjusted.

First order

Different optics are used to tests each triplet progressively:

- T1 only, focusing the beam on F1 diagnostics
- T1+T2, focusing on F1 diagnostics
- T1-T3, focusing on F2 diagnostics
- T1-T4, focusing on F2 diagnostics

Optical matrix elements are checked at F1 and F2: R11, R12, R33, R34, R16[1].

R16 corresponds to the momentum dispersion value at F1 and achromatism (R16=0) at F2.

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[1] Standard ion-optical notations are used; numbers corresponding to the respective beam characteristics: x,θ, y, φ, s, dp/p: e.g. R12 is the linear dependence of x to θ at a given point.
T126 is the quadratic dependence of the x position to θ and dp/p. T122 is the dependence of x according to θ^2.

[1] U1222 is the third order dependence of x according to θ^3.

Higher order

Some specific aberrations coefficients are measured, through the beam spot size on the diagnostics: T126 at F1, T122 and U1222 at F1 and F2.

4.3 Step 2: Mass spectrometer, converging mode (CM)

The beam is sent directly from the LINAC RFQ (E≈0.73MeV/u), as the accelerator operation in this energy regime gives correct optical properties. The need of low intensity beams requires the operation of pepper pots in the LINAC line. A thin degrader foil can also be used to get different charge states and larger momentum/angle distribution.

In a first stage, the MS is set in converging mode: only the dipoles and quadrupoles are used.

Zero order

This step is similar to the MA, with a special care for the electric dipole.

First order

This step is similar to the MA.

Higher order

In converging mode, the high order aberrations are not corrected. Only the quarupoles and dipoles are used. Sextupoles and octupoles are OFF. Only the full beam size is checked at F3 and F4.

At this stage, it is possible to perform reaction studies that do not require the nominal mass resolution.

4.4 Step 3: Mass spectrometer, dispersive mode (HRM)

The same conditions apply to the beam as in step 2.

Quadrupole tuning is different than in step 2 and the multipoles are used to optimize the mass resolution at F4.

Zero order

This step is similar to the MA, with a special care for the electric dipole.

First order

This step is similar to the MA, with the difference that the dispersion in F4 is non-zero.

Higher order

The multipoles are used to optimize the mass resolution at F4, *i.e.* the beam spot size is minimized for different A/q with the nominal dispersion.

5 Spectrometer scientific commissioning

Given the complexity of S^3, the commissioning will be made in two consecutive phases. The commissioning of the momentum achromat and the characterization of the rejection will be performed in a first stage using the “Convergent mode” of S^3. Following this step, the “High-Resolution mode” will be commissioned and the mass separation will be qualified.

5.1 Tools and detectors at the focal plane

5.1.1 SIRIUS

The diagnostic box with the SeD detector (Secondary electron gas Detector) in the SIRIUS configuration will be used.

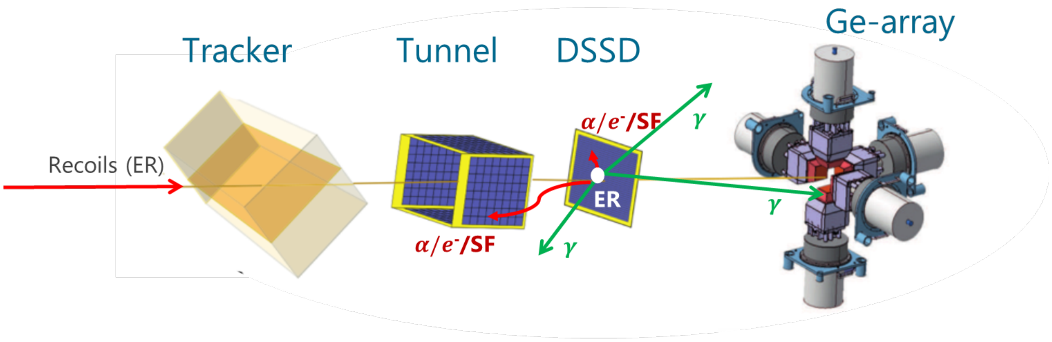


Figure 3: Schematics of the SIRIUS configuration

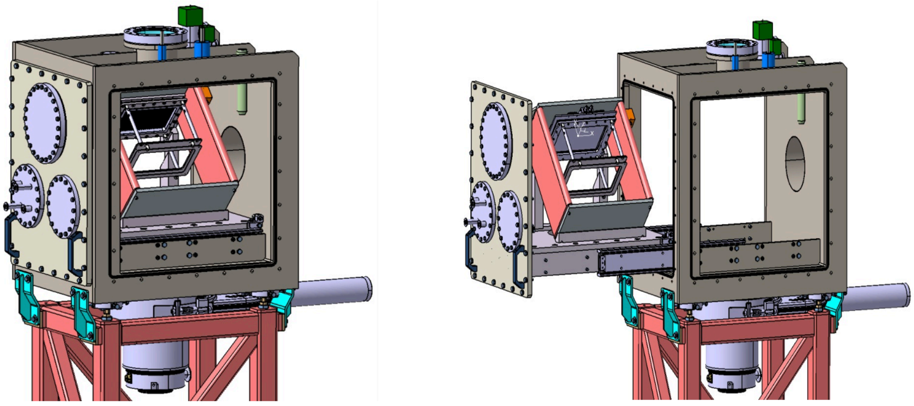


Figure 4: Diagnostic box with SeD detector in the SIRIUS configuration; Left: With the box closed, Right: with the box open, it can be seen the magnet surrounding the SeD detector (orange plates).

The SeD detector is equipped with magnets to reach the nominal position resolution with the tracker (1,4mm FWHM) which is needed for the commissioning of the mass resolution of the spectrometer. In addition, the veto detector placed behind the DSSD of SIRIUS will allow to discriminate the light charged particles from other events. This will provide a better understanding of the rejection of the spectrometer and of the production mechanisms at the target position.

5.1.2 LEB

In the LEB configuration, the diagnostic box is equipped with a time-of-flight SeD detector, a 3-silicon detector wall and a germanium detector, in order to perform basic identification of the nuclei before sending them to the S3-LEB. All detectors can be removed from the beam line to let the nuclei reach the LEB gas chamber.

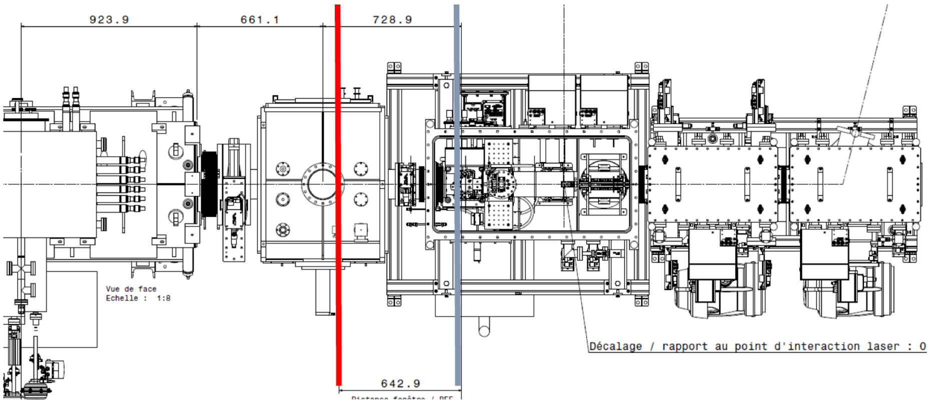


Figure 5: Mechanical study of the diagnostic box implementation in the S3 beam line. The figure shows the distance respect to the middle of the last triplet of S3. The red straight line indicates the plane final focal (PFF) defined as geometrical reference, and the blue straight line designs the position of the LEB entrance window.

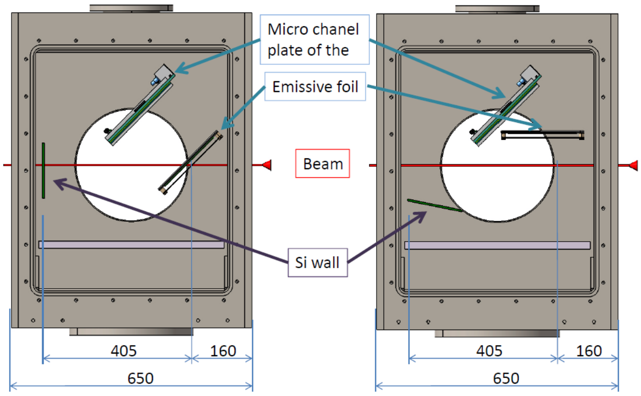


Figure 6: Slide cut of preliminary design of the diagnostic box for the LEB configuration performed by Patrice Gragnant. Left: The detectors are in the beam line. Right: the Si wall and the emissive foil are tilted 90 °, the wire chamber keeps in the same position.

The diagnostic box has lower gamma-ray efficiency (~0.1%) than in the SIRIUS configuration. The SeD without the magnet has a position resolution of the order of 4 mm (FWHM), which can give a rough estimation of the beam size.

In addition, the LEB can also be used as a complementary tool to perform the spectrometer commissioning by doing mass analysis of the beam using the QMF and PILGRIM without lasers and without any voltage on the ion collector (non-neutralized beam).

Finally, additional detector may also help to assess the spectrometer performances (ex: Germanium detectors at the target position for absolute efficiency measurement).

5.2 Reactions

In the following, a number of reference reactions which could be used for the commissioning of the spectrometer are listed. In general, they employ “easy” beams and targets, and produce nuclei which are alpha emitters and easy to identify. Many cases have also been studied elsewhere (e.g. using the gas-filled separator RITU at JYFL, the VASSILISA at JINR DUBNA) allowing a direct comparison of spectrum quality and various other performances, such as primary beam suppression.

Such studies will help us to estimate important parameters crucial for future experimental campaigns: the transmission, rejection, mass resolving power and tuning in general of S^3 for different projectile-target combinations.

As stated during the S^3 steering Committee meeting in 2019, the GANIL management approved the possibility of scientific data taking during the so-called commissioning for SIRIUS and LEB.

The proposed candidates for the reference reactions are detailed below.

Part 1: Asymmetric reaction

The ^{40}Ar + ^{116}Sn reaction to produce neutron deficient erbium nuclei. This reaction will be also use to perform the on-line commissioning of the S^3-LEB using a beam of ^{152}Er produced in the reaction ^{116}Sn(^{40}Ar – 180 MeV, 4n)^{152}Er.

Standard calibration reactions such as ^{40}Ar+^{174}Yb to produce known actinides with various alpha lines in the μbarn cross section range. This reaction is an ideal case to test also the performance of SIRIUS with transitions depopulating the different known isomeric states with gamma-ray transitions detected within μs range after the recoil implantation (isomers of 117 μs in ^{209}Ra and 2 μs in ^{210}Ra). It would also be interesting to vary the beam energies to make excitation functions for the 2-3n evaporation channels (^{211}Ra and ^{212}Ra - with isomers of ~9 μs) and the 6-7n evaporation channels with a longer isomer in ^{207}Ra of 55 ms.

In addition, the ^{40}Ar + ^{180}Hf reaction also produces a wide range of well-known alpha emitters with characteristic energies and several (tens of) microbarn cross sections (see section **Erreur ! Source du renvoi introuvable.**).

Beam	Target	CN	Isotope of interest	T1/2 (s)	Alpha branching (%)	Estimated XS (µb)
^{40}Ar	^{116}Sn	^{156}Er	^{152}Er (Z=68)	4.68	91	7000
^{40}Ar	^{174}Yb	^{214}Ra	^{209}Ra (Z=88)	4.8	90	1400
^{40}Ar	^{180}Hf	^{220}Th	^{216}Th (Z=90)	0.026	100	30

Part 2: Very Asymmetric reaction

Very asymmetric reactions using light projectiles like ^{20,22}Ne on heavy targets (^{197}Au, ^{208}Pb, ^{209}Bi) will be used to test the transmission of slow reaction products in S^3. Those reactions will help to estimate their implantation in SIRIUS and the capability to use thin entrance window with the S^3-LEB gas cell.

Beam	Target	CN	Isotope of interest	T1/2 (s)	Alpha branching (%)	Estimated XS (µb)
^{22}Ne	Pt	$^{216-220}$Ra	$^{210-214}$Ra (Z=88)	s to min	> 80	> 1000
^{20}Ne	^{197}Au	^{217}Ac	^{212}Ac (Z=89)	0.88	100	1000
^{22}Ne	^{208}Pb	^{230}U	^{226}U (Z=92)	0.35	100	6

The reaction ^{197}Au(^{20}Ne,xn)$^{217-x}$Ac is also interesting to study the nuclear structure evolution around N=126 neutron shell closures in heavy actinide nuclei with the S^3-LEB.

Part 3: Symmetric reaction

Identification of reaction channels produced with symmetric fusion evaporation reactions below ^{100}Sn is a challenge since many reaction channels are open in a given compound nuclear reaction and all nuclei β-decay. In some case the contamination at the focal plane can be many orders of magnitude greater than the rate of the nucleus of interest.

For such kinematics, we can use similar reactions as used to test recoil mass separators at LNL (^{58}Ni + ^{64}Ni at 212MeV with 300 mb cross-section) or at HRIBF (^{58}Ni + ^{28}Si at 212MeV). In this case, S^3 is tune in the HRM and the efficiency is measured by the ration of the photopeak intensities of principal γ-lines accumulated at the target position with and without a coincidence condition with a single mass value selected in the mass spectrum at the focal plane (see section 5.4).

Another possibility to tag a reaction channel, is to rely in a well-known isomeric state identification at the focal plane which has a reasonable life time.

Each experiment should be interspersed with off-line tests of two or three weeks in order to optimize the whole set up.

5.3 Rejection

For beam rejection, the tuning is done at the nominal energy of the beam on the nominal target. The intensity is increased progressively in order to maximize its rejection. Again, this is done for the two stages of the spectrometer with different sets of slits and dumps, and notably:

For the momentum achromat

- at the dispersive plane F1 (dispersive according to the Bρ=mv/q ratio) fingers or slits have to be correctly placed to stop charge states of the beam. In this location, the roles of the various dump parts are to eliminate the major part (99.9%) of the primary beam according to the kinematic of the reaction, to contain the problems related to the activation and to the power deposition.

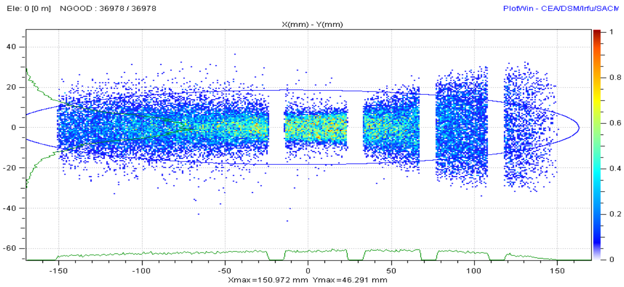


Figure 7: spatial distribution of ^{100}Sn when 4 mobile fingers are positioned in F1.

- At the intermediate achromatic focus point F2, slits are tuned to limit the transmission of scattered products.

For the mass separator:

- At the electric dipole, the anode electrode is split to allow the extraction of the fastest ions (primary beam) to be stopped directly in a beam dump. This beam dump can be used for moderate intensity beams (up to 100W, e.g. 500pnA of ^{40}Ar).
- At the energy dispersive plane F3 (dispersive according to the mv^2/q ratio), slits can be tuned to select the products of interest.

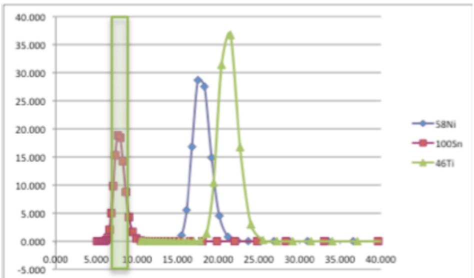


Figure 8: Electric rigidity [MV] distributions of the ^{100}Sn ions of interest (red), the ^{58}Ni primary beam and the ^{46}Ti target nuclei. The green window is the acceptance zone of S^3.

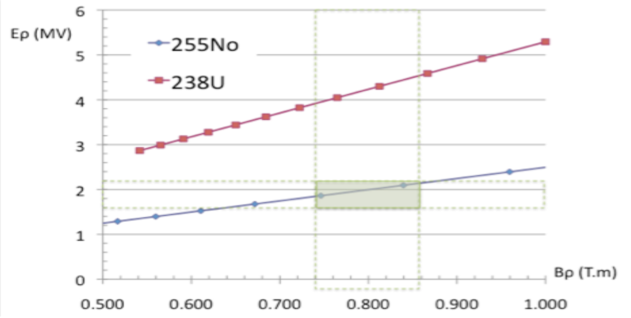


Figure 9: Electric rigidity versus magnetic rigidity for ^{255}No (blue) and ^{238}U target like recoils (red). The green window is the acceptance zone of S^3.

- At the final focal plane F4 when the mass spectrometer is in " ultra-high dispersion " mode in mass on charge.

5.4 Transmission

The absolute transmission efficiency is not a simple quantity to be measured because it is influenced by many factors.

At first, it will be evaluated using well known reactions with known cross sections.

One way is, for one isotope, to compare the counts observed in the γ-ray peaks recorded by germanium detectors at the target position to the counts in the same peaks recorded in coincidence with recoil decays observed at the focal plane. An example of absolute transition measurements with the gas-filled separator RITU is shown below.

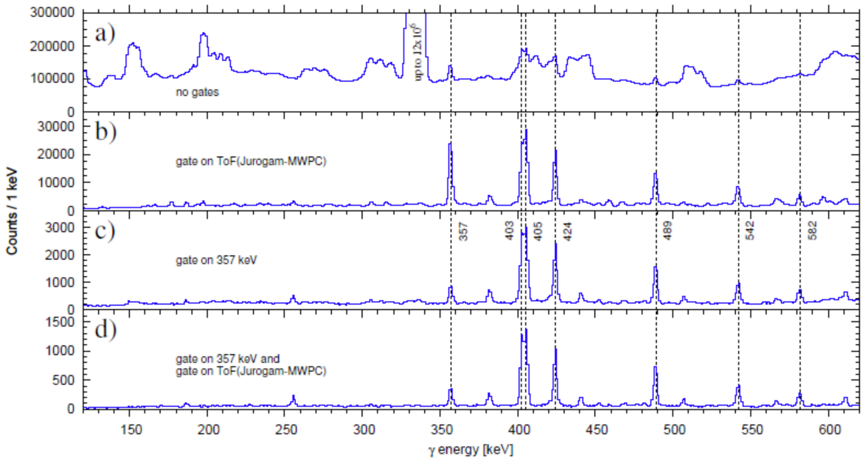


Figure 10: Prompt γ spectra at the target position from the reaction ^{150}SmF(^{40}Ar,4n)^{186}Hg. Most intense transition energies of ^{186}Hg are shown with vertical lines The panel a) shows singles γ spectrum while the panel b) shows singles spectrum of the events following the event in a MWPC of RITU at a time gate. Spectra in coincidence with 357 keV γ transition (mainly 6+ -> 4+) are shown with d) and without c) requiring MWPC coincidence.

One example of a test reaction (that has been used for the commissioning of the RMS at Legnaro), is ^{64}Ni(^{64}Ni,3-4n) fusion reaction to produce ^{124,125}Ba that allows single gamma identification at the target and at the focal plane to evaluate the transmission of the spectrometer.

6 Diagnostic box commissioning

The diagnostic box for S^{3}LEB has been tested with beam in spring 2022. Two independent experiments were performed. The first test was focused on the study of the performance of the SED detector with the magnet (SIRIUS configuration) and the second test was focus on the study of the performance of the detectors for the S^{3}LEB configuration. In the latter experiment, the performance required in the “Cahier de Charge” was successfully achieved. It was proven that the time and energy resolution of the systems was sufficient for the separation of the beam-like products (charge states primary beam among other) and the residues. The coupling NUMEXO2 and GET was achieved successfully as well, allowing to correlate the implantation signal with the position on the SED detector. The online analysis program was partially tested. During the experiment, there was no alpha emitter produced, therefore it was not possible to test the implantation-decay correlations. These correlations will be further investigated offline during 2023 and online during the test SIRIUS at LISE Wien-Filter in 2024.

During the LEB type experiments at S^3, the diagnostic box will serve as a first identification device for the settings of the spectrometer. The setup cannot be used to identify the most exotic channels, but the settings of the spectrometer will be validated through the identification of stronger produced and transmitted reaction channels. It is noted, that for the LEB type experiments, the spectrometer will be set on converging mode.

7 SIRIUS commissioning

7.1 Off-line commissioning

SIRIUS has been installed and tested off-beam at GANIL since 2022. Such Source commissioning will already allow a qualification of most of the components of the setup like:

- Optimization of the filter parameters for the new detectors
- Measurement of the energy resolutions with the new detectors.
- Timing & synchronization tests
- Evaluation of the Time-of-flight resolution with a 252Cf source
- Test of the DSSD/Germanium correlations with a 241Am source

7.2 On-line commissioning

An additional in-beam commissioning is also foreseen to test the full integration of all detectors in 2024, on FULIS. Twice 4 UTs of beamtime have been requested. An experiment has been submitted to the GANIL PAC to study the nuclear structure of ^{217}Pa. This experiment that would allow to commission SIRIUS further on a long run with realistic conditions has unfortunately been rejected…

The expected performances are:

- All Silicon detectors available (4 tunnels, 1 DSSD, 1 Veto)
- Acquisition stable and resilient
- Merging of data from the tracker and the EXOGAM clovers with the Silicon numexo data operational.
- Alpha energy resolution below 20 keV FWHM
- Electron energy resolution below 15 keV FWHM
- Time of flight resolution around 800ps.
- Treatment of the gain switch capability on the DSSD available.

In addition to the reactions described in section 5.2, we propose to perform the ^{40}Ar+^{180}Hf -> ^{220}Th (CN) reaction at 174 MeV. This reaction with cross section greater than 1 μb results in a complex decay spectrum which is a consequence of a large number of different evaporation channels (3n, 4n, α3n, α4n and α-α4n) with many α-active daughter nuclei in a subsequent α-decay cascades (α energies up to 10 MeV). In addition, the transitions exhibit a large difference in lifetimes (200ns to 2μs).

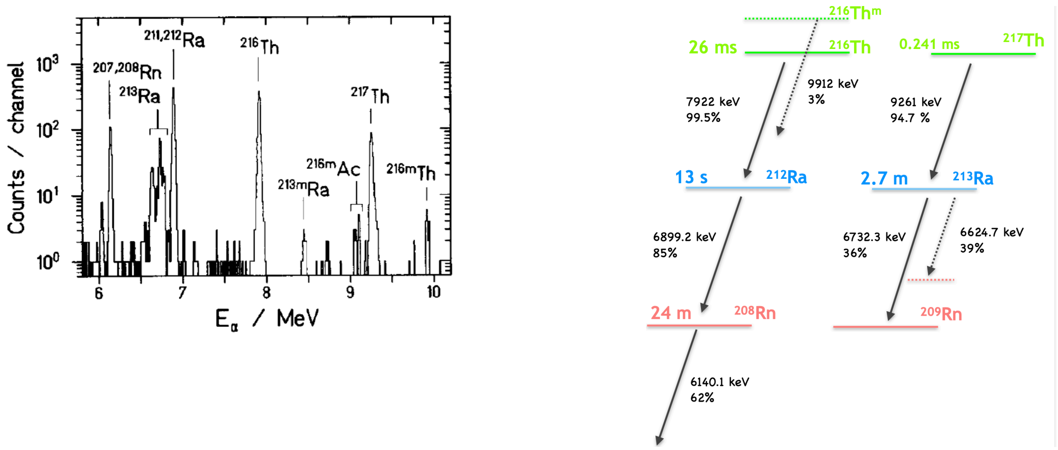


Figure 11: (Right) α spectrum of evaporation residues produced in the reaction ^{40}Ar + ^{180}Hf at 174 MeV [Zeitschrift fur Physic, A318 (1984) 157-169], (Left) decay pattern.

To produce the various reaction channels, we plan to vary the beam energies which give around 10000 detected recoil-α correlations in two hours beam time with 1pμA beam intensity.

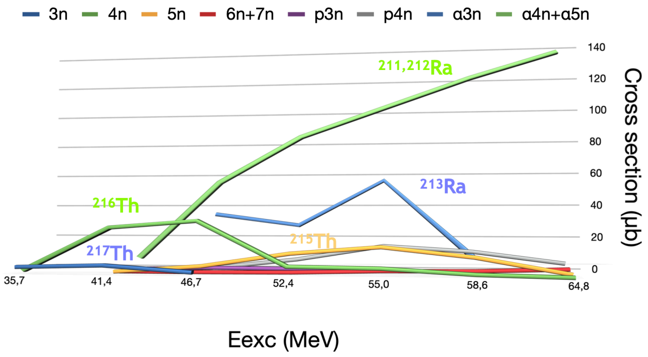


Figure 12: Cross sections of the reaction ^{40}Ar + ^{180}Hf for different compound nucleus excitation energies [Zeitschrift fur Physic, A318 (1984) 157-169], (Left) decay pattern.

Finally, it is also important to test the capability of SIRIUS to detect decay chains with short half-life transitions leading to "pile-up" events. The ideal case is to study the $^{220-221}$Th decay chains with half-life transitions around 200 ns and 2 μs. The propose reaction is ^{22}Ne + ^{206}Pb at 119 MeV to populate ^{224}U nuclei [Eur. Phys. J. A (2014) 50: 132]. The α-decay chains of interest are shown in figure 13.

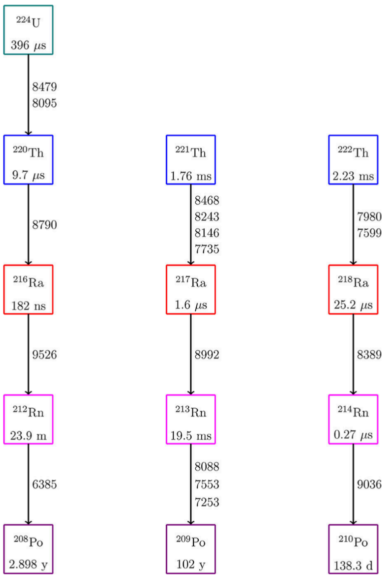


Figure 13: Diagram showing the α-decay chains of interest.

7.3 Possible data taking during the commissioning phase

A proposition to get scientific data during the commissioning could be to perform the following reactions:

- ^{50}Ti+^{208}Pb->^{256}Rf, ^{257}Rf
- ^{40}Ar+^{209}Bi --> ^{247}Md
- ^{18}O+^{238}U->^{252}Fm
- ^{22}Ne+^{238}U -> ^{256}No
- ^{26}Mg+^{197}Au->^{217}Pa

8 LEB commissioning

8.1 Off line Commissioning

The 2023 off-line commissioning time will be shared between proof-of-principle measurements and technical stops for a series of upgrades and tests.

The planning of proof-of-principle measurements will be aimed at the following objectives:

- Assembly, test and operation of a new diode-pumped continuous-wave Ti:sa acting as seed laser for the narrowband cavity.
- The in-gas jet laser spectroscopy of Sn isotopes (or another element corresponding to the N = Z program) and test of another laser scheme for Er, allowing a larger isotope shift (already validated at GISELE).
- A test of the efficiency and extraction time of the gas cell either using a recoil ^{223}Ra source or an in-gas-cell alkali-ion source.
- Validation with respect to resistance and leak rate of the 5 µm and 3 µm Ti foils for the entrance windows and the 1-3 µm Mylar windows, using an off-line test bench constructed in 2022.
- A series of systematic mass measurements using the PILGRIM mass spectrometer.

Following the accomplishment of these objectives, the S^{3}LEB setup will be used for the laser spectroscopy of other Day-1 elements until the scheduled date for installation at S^3.

8.2 On line Commissioning

The on-line commissioning of S^{3}LEB will be performed using a beam of ^{152}Er produced in the reaction ^{116}Sn(^{40}Ar – 180 MeV, 4n)^{152}Er in convergent mode.

With an estimated production rate of ^{152}Er > 10^4/s at the S^3 final focal plane, this case would allow a successful experiment to be performed even with a global efficiency of the setup ≈ 0.01%.

A schematic planning of the commissioning experiment would be:

- Delivery of ^{152}Er beam and contaminants to the gas cell. Optimization of tuning with the diagnostic box.
- Study of beam resulting from the gas cell without lasers and without any voltage on the ion collector (non-neutralized beam). Mass analysis of the beam using the QMF and PILGRIM. Ions are counted on MCPs and MagneToF detectors.
- Optimization of the collector voltage for suppressing non-neutralized beam. Repetition of mass analysis for observation of collector effect.
- In-gas-cell laser ionization and spectroscopy of ^{152}Er using broadband lasers, with detection after PILGRIM on the MagneToF detector.
- In-gas-jet laser ionization and spectroscopy of ^{152}Er using narrowband laser.
- Optimization of ^{152}Er injection and focusing in the gas cell using S^3 optics, in order to maximize the ^{152}Er ion rate obtained in the gas jet. Comparison to diagnostic box result.
- Repetition of measurements after optimization.
- Repetition of laser spectroscopy measurements using Si detectors and alpha selectivity.
- Mass measurements of Er isotopes and contaminants available in the beam cocktail using PILGRIM.

In-gas-jet laser ionization of other Er isotopes available in the beam cocktail, without changing production and S^3 settings.

Required performance of S^3-LEB for day 1 campaign:

- Availability of laser schemes for selected cases
- Availability of entrance window for selected cases

- Gas-cell neutralization + extraction efficiency: 10 to 25%
- Transport efficiency of ion optics until end of PILGRIM: 30% to 80%
- Mass resolving power of PILGRIM > 80 000
- SEASON if needed (not mandatory)

8.3 Possible data taking during the commissioning phase

A proposition could be:

- ^{40}Ar + ^{116}Sn -> ^{151}Er and the more neutron-deficient isotopes plus neighboring lighter elements, to test with the same set up as the commissioning with ^{152}Er the capabilities of S^{3}LEB (lasers, detection with and without alpha emitters, transmission, selection into PILGRIM…), physics around N=82, Ho, Dy, laser spectroscopy + mass measurements.
- ^{40}Ar + ^{175}Lu -> $^{210\text{-}215}$Ac and the area below produced either directly or via in-gas-cell-decay, to test the capabilities of S^{3}LEB in the heavy mass region (gas cell behavior as neutralization with low incident ion rates, lasers, transmission of heavy masses, selection into PILGRIM…), Physics around N=126, laser spectroscopy + mass measurements.
- ^{50}Cr + ^{58}Ni -> $^{100\text{-}105}$Sn and the area around, to test the capabilities of S^{3}LEB in the N=Z region (gas cell behavior with high incident ion rates, lasers, detection without alpha emitters, transmission of medium masses, selection into PILGRIM…), Physics around N=Z, Cd, Ag, Pd… laser spectroscopy + mass measurements.

9 Commissioning scenario timetables

Our commissioning sceneries are based on the beam time plan proposed by the GANIL management for the next ten years.

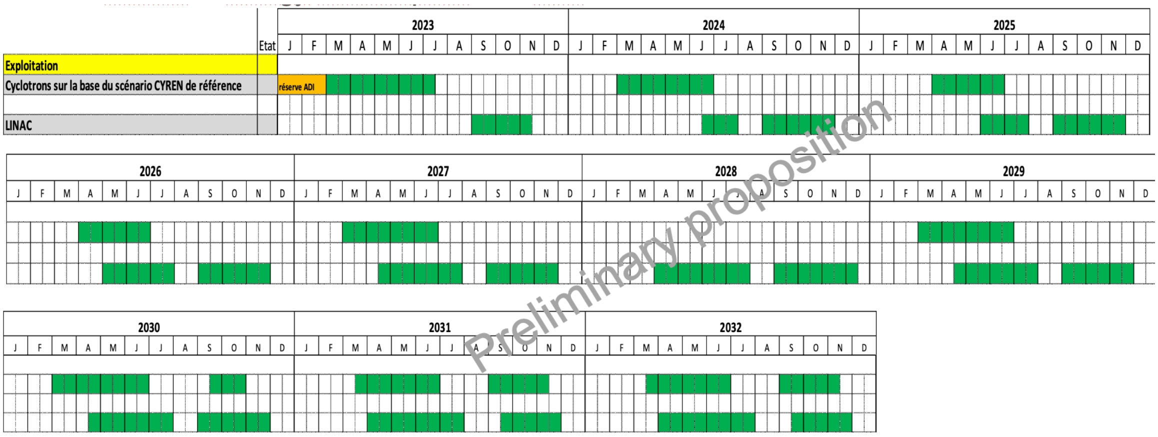


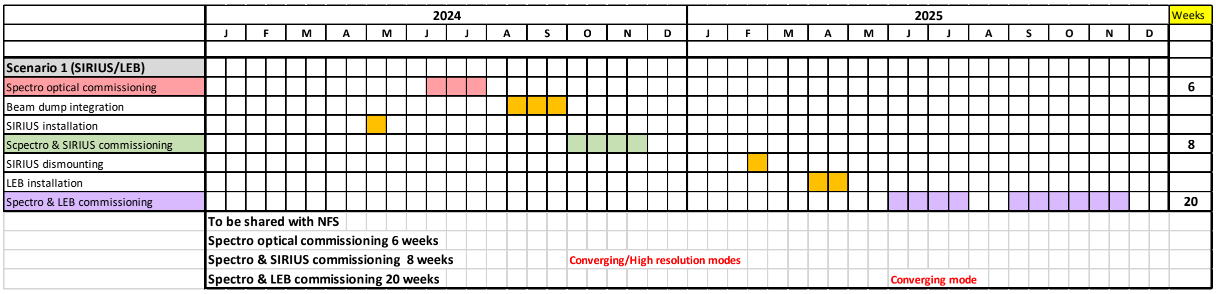
Figure 12: Beam time plan for the next ten years.

The goal is to gradually increase the beam time with parallel operation of cyclotrons and LINAC.

Given the complexity of S^3 the commissioning and the associated focal plane detection, two years will be necessary to reach adequate performances to start day1 campaigns with experiments selected by the PAC.
Following the discussions that took place during the S^3 User Collaboration Council (S3UCC) meeting organized in the framework of the “Physics with SPIRAL2 Heavy Ions Beams workshop” held at GANIL 12-16th December 2022, it has been decided to elaborate 4 detailed scientific commissioning sceneries for the years 2024-2025.

Those scenarios will be discussed in a dedicated S^3 UCC meeting in March to select the best sequences to successfully commissioned the spectrometer and the associated setups (SIRIUS and LEB).

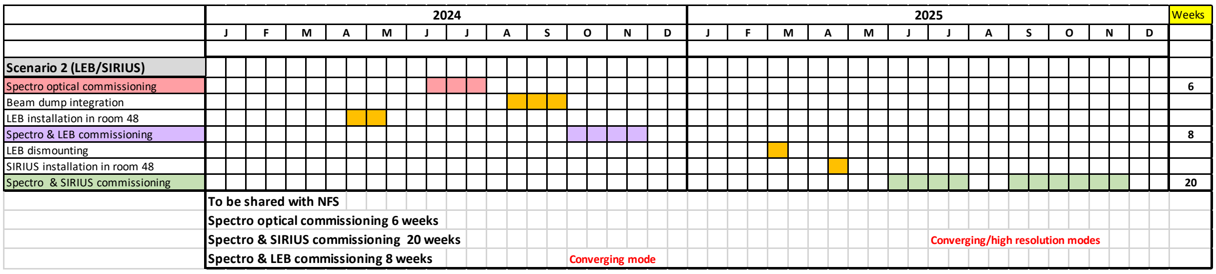
9.1 Scenario 1



Sirius is installed in 2024 at the focal plane of S^3 to start the scientific commissioning and LEB is installed in 2025 to continue and to finalize the commissioning.

In this case SIRIUS is taking most part of the risk that the spectrometer performances are not reached in the early phase of the commissioning.

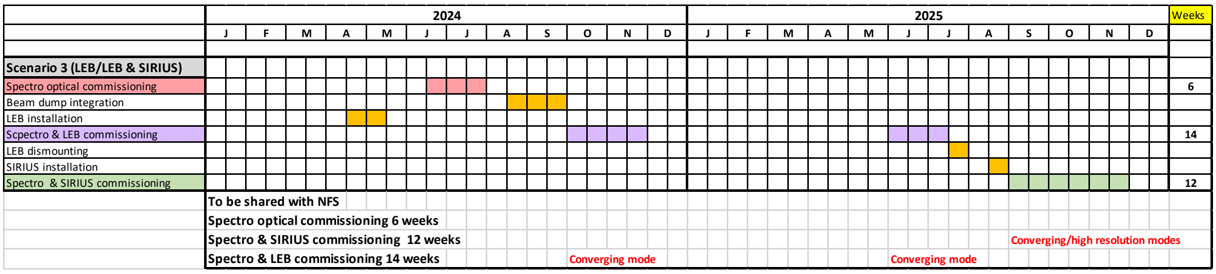
9.2 Scenario 2



LEB is installed in 2024 at the focal plane of S^3 to start the scientific commissioning and SIRIUS is installed in 2025 to continue and to finalize the commissioning.

In this case LEB is taking most part of the risk that the spectrometer performances are not reached in the early phase of the commissioning. However, the LEB requirements in term of rejection are also less stringent than for SIRIUS.

9.3 Scenario 3

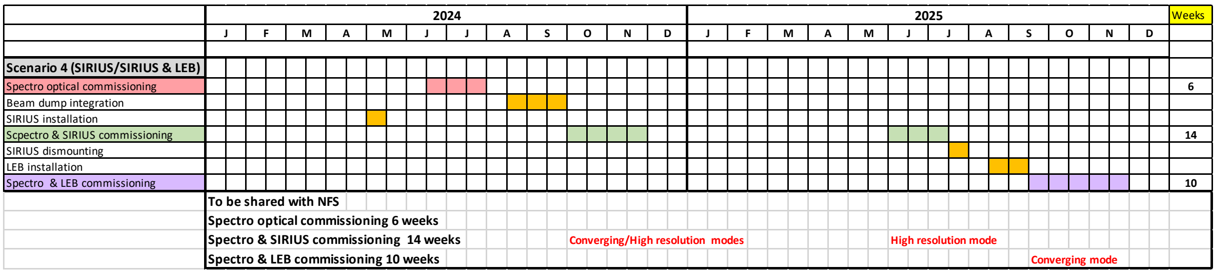


LEB is installed in 2024 at the focal plane of S^3 to start the early phase of the scientific commissioning and continue for the first run of beam time in 2025. SIRIUS is installed for the second run in 2025 to continue and to finalize the commissioning.

This scenario maximizes the beam time sharing between SIRIUS and LEB and gives some time in 2024 prior the commissioning phase to debug the complex installation of LEB.

It should be noted that the on-line commissioning of LEB is more complex than the one of SIRIUS and will require significantly more beam time.

9.4 Scenario 4



	2024																								2025																								Weeks
	J		F		M		A		M		J		J		A		S		O		N		D		J		F		M		A		M		J		J		A		S		O		N		D		
Scenario 4 (SIRIUS/SIRIUS & LEB)																																																	
Spectro optical commissioning												🟥	🟥	🟥																																			6
Beam dump integration																🟧	🟧	🟧																															
SIRIUS installation									🟧																																								
Scpectro & SIRIUS commissioning																			🟩	🟩	🟩	🟩													🟩	🟩	🟩												14
SIRIUS dismounting																																						🟧											
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Spectro & LEB commissioning																																										🟪	🟪	🟪	🟪	🟪			10
	To be shared with NFS																																																
	Spectro optical commissioning 6 weeks																																																
	Spectro & SIRIUS commissioning 14 weeks																	**Converging/High resolution modes**																**High resolution mode**													
	Spectro & LEB commissioning 10 weeks																																								**Converging mode**							

SIRIUS is installed in 2024 at the focal plane of S^3 to start the early phase of the scientific commissioning and continue for the first run of beam time in 2025. LEB is installed for the second run in 2025 to continue and to finalize the commissioning.

This scenario favors beam delivery for SIRIUS due to the time needed to install the LEB setup at the focal plane mid 2025.

10 Collaboration/team

10.1 External experts

Before starting to send beam in the spectrometer a review will be organized with external experts (ANL, MSU, JYFL and TRIUMF) to assess the commissioning plan proposed by the project and the collaboration. The members of this committee have a long expertise in spectrometer like FMA at ANL, RITU/MARA at JYFL and EMMA at TRIUMF. We will also invite Daniel Bazin (MSU) who participated as an international expert to the S3 project review organised in 2018 by the CEA/Irfu and the CNRS/IN2P3.

Proposed expert committee:

- Daniel Bazin (MSU) TBC
- Juha Uusitalo(JYFL) TBC
- Darek Seweriniak (ANL) TBC
- Barry Davids (TRIUMF) TBC

The member of this committee may also be solicited during the commissioning phases.

10.2 Beam optic team

The beam optic team in charge of the tuning of the S^3 spectrometer during the commissioning is composed accelerator/spectrometer physicists from the “Physique des accélérateurs” group at GANIL, one research engineer from the “service des accélérateurs” at IPHC, physicists from GANIL and CEA/Irfu and dedicated postdocs.

Proposed beam optic team:

- Bertrand Jacquot (GANIL)
- Omar Kamalou (GANIL) / part-time
- Mathieu Lalande (GANIL)
- Emil Trykov (IPHC)
- Antoine Drouart (CEA/Irfu)
- Hervé Savajols (GANIL)
- Jean Charles Thomas (GANIL) / part-time
- Alexandre Esper (Postdoc/GANIL)
- New Irfu/CEA postdoc

It is also of very important to rely on GANIL expert referents (cryogenic, magnets, power supplies, PLC, control/command, diagnostics, …) who have to make themselves available on demand.

The commissioning coordinators for the spectrometer commissioning are Bertrand Jacquot /optical commissioning/ and Antoine Drouart (CEA/Irfu)/Hervé Savajols (GANIL) /scientific commissioning/.

10.3 SIRIUS and LEB

- The commissioning coordinators for the diagnostic box are Lucia Caceres (GANIL) and Julien Pancin (GANIL).
- The commissioning coordinators for the SIRIUS commissioning are Julien Piot (GANIL) and Karl Hauschild (IJCLAB).
- The commissioning coordinators of the LEB commissioning are Vladimir Manea (IJCLab) and Nathalie Lecesne (GANIL).

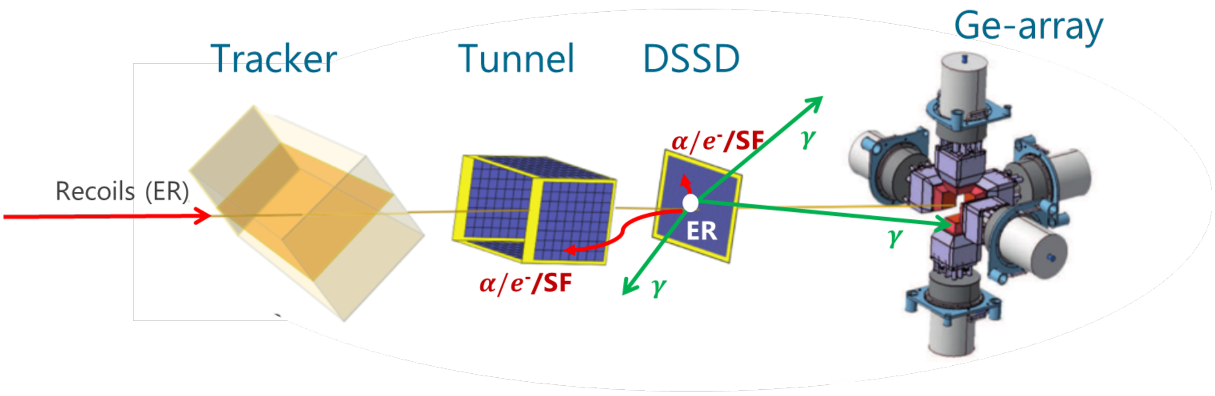
All the scientific collaboration and the project team will be also involved.

11 Appendix

In order to define the different phases from the commissioning to the day1 experiments, the project management asked both SIRIUS and LEB management boards to carefully fill a template detailed in the following.

11.1 SIRIUS day1 campaign template

11.1.1 Status of SIRIUS



Schematics of the SIRIUS configuration

- SIRIUS is assembled at GANIL and mounted on the diagnostic box of S3.
- All silicon detectors are fully instrumented with NUMEXO boards
- Installation of the Veto needs to be checked.
- The connection to the tracker and merge of the acquisitions has been done. BEAST is installed.
- The high gain of all DSSD preamplifiers has been tested. Gain switching of the DSSD has been tested.

11.1.2 How long does it take to install/remove the equipment at the focal plane of S^3?

This was tested last May moving from G3 to G2. Disconnection, dismounting and moving takes two days. Installation and cabling take three days with the necessary staff available.

11.1.3 Commissioning plan

Detailed off line commissioning plan

1. Optimization of the filter parameters for the new detectors
2. Measurement of the energy resolutions with the new detectors.
3. Timing & synchronization tests
4. Measurement of the Time-of-flight resolution with a 252Cf source
5. Test of the DSSD/Germanium correlations with a 241Am source

Detailed on-line commissioning plan and expected performances to perform day1 campaign.

Online commissioning planned for March 2024 on FULIS. Twice 4 UTs of beamtime requested.
An experiment has been submitted to the GANIL PAC to study the nuclear structure of ^{217}Pa. This experiment will allow to commission SIRIUS further on a long run with realistic conditions.

The expected performances for the Day 1 campaign are:

- All Silicon detectors available (4 tunnels, 1 DSSD, 1 Veto)
- Acquisition stable and resilient
- Merging of data from the tracker and the EXOGAM clovers with the Silicon numexo data operational.
- Alpha energy resolution below 20 keV FWHM
- Electron energy resolution below 15 keV FWHM
- Time of flight resolution around 800ps.
- Treatment of the gain switch capability on the DSSD available.

Beams requirements

^{18}O, ^{22}Ne, ^{26}Mg, $^{28-30}$Si, $^{32-36}$S, ^{36,40}Ar, with intensities > 1pμA (5,1pμA of ^{40}Ar already available).
^{40,48}Ca (if available), ^{48,50}Ti, ^{50}V, ^{54}Cr with beam intensities of 1pμA or more.
Beam energies between 4.5 and 7 MeV/A

Target requirements:

^{164}Dy, ^{170}Er, ^{174,176}Yb, ^{180}Hf, ^{181}Ta, ^{182}W, ^{197}Au, ^{204,208}Pb, ^{204,208}PbS, ^{209}Bi, ^{209}Bi$_2$O$_3$, ^{238}U

11.1.4 What will be the availability of the Germanium detectors (SIRIUS and Diagnostic Box)?

The EXOGAM clovers are available from the collaboration as for any other experiment. Since the campaigns of SIRIUS will be defined in advance, the use of the EXOGAM clovers will be planned accordingly. In addition, provision has been secured to buy a clover detector in 2025.

11.1.5 Associated risks

- Actinide target provision not secured.
- ^{48}Ca provision is not secured, ^{50}Ti compound is available for about 1 year operation reserve secured.
- Large scale production of Bi, Pb and U target under development at GANIL.
- EXOGAM detectors unavailable for a campaign would mean the cancellation of the campaign.

11.1.6 Scientific program

What would be the "collaboration experiments" to be performed during the scientific commissioning (outside PAC selection)?

- ^{50}Ti+^{208}Pb->^{256}Rf, ^{257}Rf

- $^{40}Ar+^{209}Bi$ --> ^{247}Md
- $^{18}O+^{238}U$->^{252}Fm
- $^{22}Ne+^{238}U$ -> ^{256}No
- $^{26}Mg+^{197}Au$->^{217}Pa

Is the selection of day one experiments made in 2018 still valid? In case of major changes, you are invited to propose new general scheme for day one experiments?

The absence of ^{48}Ca modifies the program given in 2018. In particular, the letter of intent on the limits of stability of No isotopes will not be feasible. One letter of intent is partially affected by the ^{48}Ca shortage (Alpha-decay spectroscopy of odd-Z isotopes in fermium region). Some LoIs have been affected by recent results but are still of interest (Detailed study of the K-isomer(s) in ^{256}Rf, Decay Spectroscopy of ^{253}Rf and ^{257}Sg).

Additional cases to consider: $^{40}Ar+^{182}W$ ->$^{218}U+4n$

Underline the required performances expected from the spectrometer (transmission, rejection, mass resolution…)

- Mass resolution around 300 with high-intensity beam on target
- Transmission higher than 40% for 48Ca type kinematics. Higher than 10% for O/Ne type kinematics.
- Rejection higher than 10^{12} for beam-like transfer products, higher than 10^{19} for beam.
- Transmission of the following data at a regular rate: beam on/beam off, Target number, Beam energy, beam intensity, Beam dose integration from beam-dump
-

The commissioning of the mass resolution will require SIRIUS as the best resolution can only be obtained with the tracker equipped with its magnet. This configuration is only compatible with SIRIUS.

In addition, the veto detector placed behind the DSSD of SIRIUS will allow to discriminate the light charged particles from other events. This will provide a better understanding of the rejection of the spectrometer and of the production mechanisms at the target position.

SIRIUS can be operated without the tunnel detectors and a lower grade DSSD can be used to reduce the risk of damage to new and costly detectors when the optimal energy resolution is not necessary.

11.1.7 What will be the competition with other facilities in 2023-2024?

- No beam planned in GSI for 2023.
- SHIP has deserted the decay spectroscopy field
- A program for decay spectroscopy is starting at TASCA with a detector designed to measure electrons independently (ANSWERS)
- The SHE factory is running, SHELS+GABRIELA++ as well
- RIKEN is focusing on Z=119, but testing its equipment on the other GARISes
- ANL has started a program on AGFA for in-beam spectroscopy. Beam intensity is lower than the capabilities of S^3.

11.1.8 SWOT analysis: SIRIUS to perform day-one campaign

Strength

- Unique capabilities in the world to perform mass measurement with Ultra High-Resolution mode of S^3 coupled to high transmission and high beam intensities for Light projectiles.
- Presence of a veto detector to reduce background
- Access to fast decay cascades from a metastable state or mother nucleus.

- Minimal deadtime (if we manage to reduce the flushing time to below the trace length)
- Detection of conversion electrons in the tunnel with a ~20% efficiency.

Weakness

- Flight path of S3 is long for the cases where isomeric and/or ground states half-life is very short.
- Large energy loss & straggling in tracker detector. To be improved with thinner emissive foils or a new detector (in development).

Opportunities

- It will be possible to study spontaneous fission in heavy elements (TKE measurement).
- There is potential for isotope discovery
- Identification of pxn channels, which produce less neutron deficient nuclei, some of which can bridge the gap between the decay chains of the heaviest elements produced in hot-fusion reactions in Dubna, Berkeley and GSI and the rest of the nuclear chart.

Threats

- Some proposed experiments can already be performed at other facilities although:

  a) The mass in such experiment will not be univocally identified (or can only be identified for long-lived states – this is the case with FIONA in Berkeley)

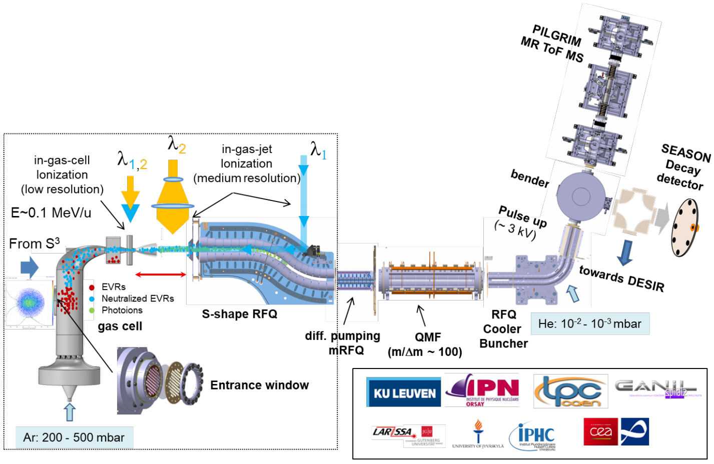
  b) The beam intensities proposed by other laboratories is less intense. (Except at the SHE factory)

- The synthesis and decay spectroscopy are still ongoing at Dubna.
- A few proposed experiments aim at producing new isotopes and therefore the corresponding production cross sections are only tentatively estimated.
- Metallic ^{238}U target provision is not ensured.
- Provision of ^{48}Ca will be very difficult and ^{50}Ti is limited to a few months so far.

11.2 LEB day1 campaign template

11.2.1 Status of S^{3}LEB:

The installation of the S^3-LEB setup in the intended test configuration at LPC has been accomplished at the end of 2021. The setup includes the gas cell with a purified-gas injection line and baking regulator, the RFQ chain, the temporary transfer line to PILGRIM, and PILGRIM. The installation at LPC of the laser safety features and of the laser system required to perform broadband and narrowband laser spectroscopy has been accomplished at the beginning of 2022.



Schematics of the LEB configuration

The planning of the years 2022-2023 is dedicated to finalize the off-line commissioning of the setup at LPC and the completion of the S^3 interface/installation studies. Here we report the main 2022 landmarks:

- Validation of vacuum system with respect to gas-cell operation and pumping capacity
- Laser ionization and spectroscopy of stable atoms of erbium in the gas cell, using broadband lasers
- Laser ionization and spectroscopy of erbium atoms in the gas jet, using broadband and narrowband lasers
- Proof of the required 300 MHz spectral resolution in the gas-jet laser spectroscopy, with the Mach number equal to 8 at the nozzle.
- Bunching of laser ions, transport to PILGRIM and trapping
- Proof of principle of mass resolving power with laser ions on the order of 10^5 and mass accuracy on the order of low 10^{-7}
- Proof of principle of laser scans using detection of mass-separated Er ions after PILGRIM.
- A global transport efficiency on the order of 30% from the first RFQ until the end of PILGRIM.

11.2.2 Construction planning of S^3LEB:

Technical improvement of S^3LEB planned in 2023:

- Implementation of an EPICS control system and EPICS-compatible FASTER communication for PILGRIM
- Cabling and testing the gas-cell translation system
- Leak testing the entrance windows on the gas cell, after validation on the off-line test bench
- Leak testing the bellow interface to the S^3 spectrometer
- Installation and testing of the Si detectors, if the ^{223}Ra alpha-recoil source is approved for use at LPC.
- Design integration, purchase and construction of the 90° bender and injection line to SEASON
- Change of the S^3LEB cables compatible with SPIRAL2 and change of the vacuum controllers compatible with EPICS
- Implementation of an EPICS control system and EPICS-compatible FASTER communication for REGLIS and the laser system

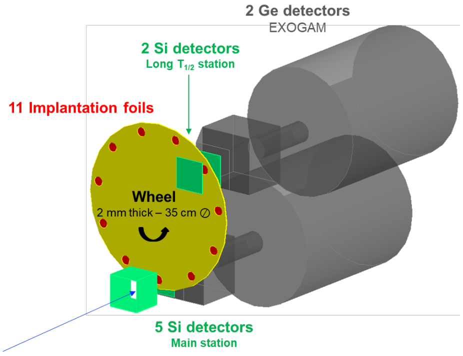
Infrastructure construction for S^3LEB planned in 2023:

- TiSa laser room reception in January 2023
- Laser safety system construction and implementation into the laser room
- S^3LEB gas exhaust system construction and implementation into room 48

11.2.3 SEASON detector

SEASON will be mounted at the end of the S3-LEB for the study of HN/SHN. It is and implantation station, equipped with a rotating wheel and dedicated to:

- Counting laser ionized at atoms (laser ionization spectroscopy)
- alpha, electron, gamma decay spectrosocpy



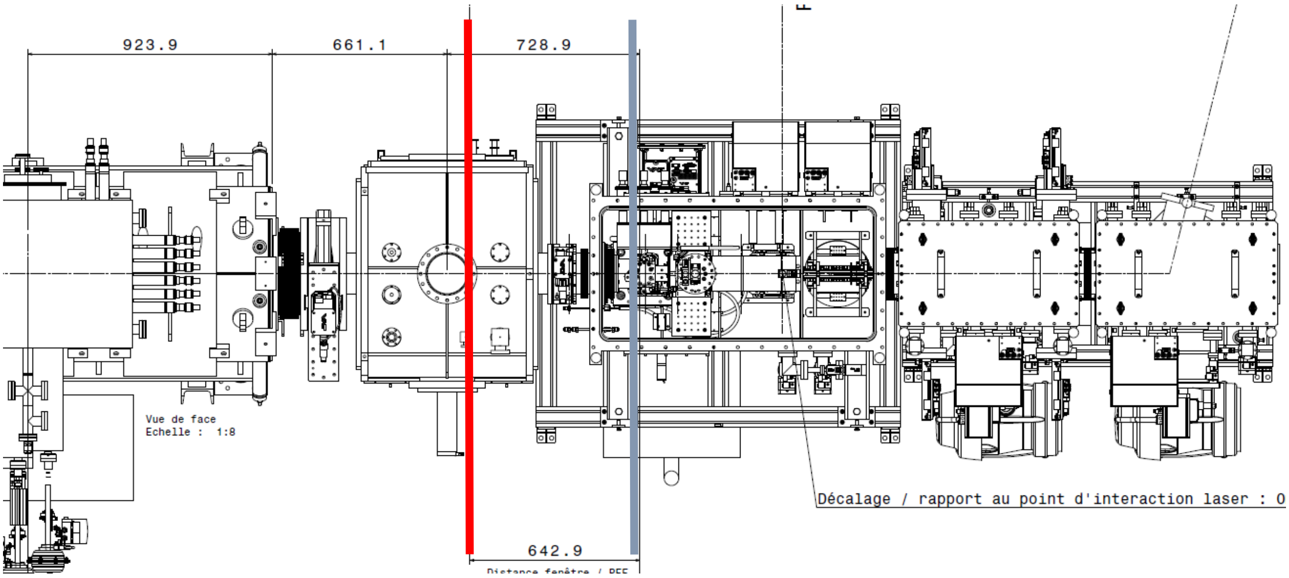
Schematics of the SEASON detector

Construction planning of SEASON:

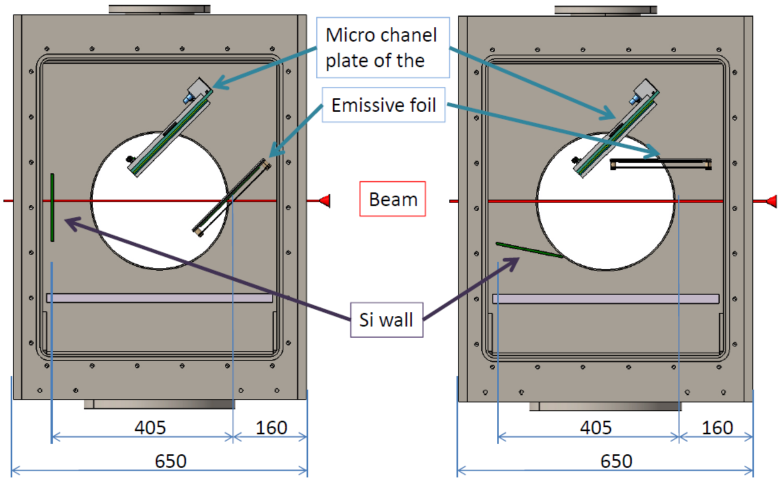
- 3D Mechanical drawings are finalized and 2D drawings will be launched externally in December 2022
- Main items already purchased: calibration arms, motors, one DSSD, High Voltage
- Construction of SEASON in June 2023
- Calibration tests in September 2023
- Installation in JYU for on-line commissioning end of 2023
- Availability of SEASON for S^{3}LEB: end of 2024 or as soon as it is needed

11.2.4 Diagnostic box

In its LEB configuration, the diagnostic box is equipped with a time-of-flight SeD detector and a 3-silicon detector wall (and possibly a germanium detector), in order to perform basic identification of the nuclei before sending them to the S3-LEB. All detetors are removed from the beam line to let the nuclei reach the LEB gas chamber.



Mechanical study of the diagnostic box implementation in the S3 beam line. The figure shows the distance respect to the middle of the last triplet of S3. The red straight line indicates the plane final focal (PFF) defined as geometrical reference, and the blue straight line designs the position of the LEB entrance window.



Slide cut of preliminary design of the diagnostic box for the LEB configuration performed by Patrice Gragnant. Left: The detectors are in the beam line. Right: the Si wall and the emissive foil are tilted 90 °, the wire chamber keeps in the same position.

Construction planning of Diagnostic box:

The diagnostic box for S^3LEB has been tested with beam in spring 2022. Two independent experiments were performed. The first test was focused on the study of the performance of the SED detector with the magnet (SIRIUS configuration) and the second test was focus on the study of the performance of the detectors for the S^3LEB configuration. In the latter experiment, the performance required in the "Cahier de Charge" was successfully achieved. It was proven that the time and energy resolution of the systems was sufficient for the separation of the beam-like products (charge states primary beam among other) and the residues. The coupling NUMEXO2 and GET was achieved successfully as well, allowing to correlate the implantation signal with the position on the SED detector. The online analysis program was partially tested. During the experiment, there was no alpha emitter produced, therefore it was not possible to test the implantation-decay correlations. These correlations will be further investigated offline during 2023 and online during the test SIRIUS at LISE Wien-Filter in 2024.

During the LEB type experiments at S^3, the diagnostic box will serve as a first identification device for the settings of the spectrometer. The setup cannot be used to identify the most exotic channels, but the settings of the spectrometer will be validated through the identification of stronger produced and transmitted reaction channels. It is noted, that for the LEB type experiments, the spectrometer will be set on converging mode.

11.2.5 How long does it take to install/remove the equipment at the focal plane of S^3

- To change the configuration of the diagnostic box from SIRIUS to LEB mode will take 4 days. (1 day for breaking the vacuum and changing detector, 1 day for vacuum, 2 days for detector testing)
- To dismount S^3LEB and transport everything into room 51, it should take less than one week.
- To mount, connect and test S3LEB: one month

The above time estimates assume that the necessary manpower is available.

We will have the experience of dismounting S^3LEB from LPC and mounting it into room 51 beginning of 2024 and then could provide a more precise answer to this question.

11.2.6 Commissioning plan

<u>Off-line commissioning</u>:

The 2023 off-line commissioning time will be shared between proof-of-principle measurements and technical stops for a series of upgrades and tests.

The planning of proof-of-principle measurements will be aimed at the following objectives:

- Assembly, test and operation of a new diode-pumped continuous-wave Ti:sa acting as seed laser for the narrowband cavity.
- The in-gas jet laser spectroscopy of Sn isotopes (or another element corresponding to the $N = Z$ program) and test of another laser scheme for Er, allowing a larger isotope shift (already validated at GISELE).
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- A series of systematic mass measurements using the PILGRIM mass spectrometer.
- Following the accomplishment of these objectives, the S^{3}LEB setup will be used for the laser spectroscopy of other Day-1 elements until the scheduled date for installation at S^3.

On-line commissioning

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With an estimated production rate of ^{152}Er > 10^4/s at the S^3 final focal plane, this case would allow a successful experiment to be performed even with a global efficiency of the setup ≈ 0.01%.

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- Study of beam resulting from the gas cell without lasers and without any voltage on the ion collector (non-neutralized beam). Mass analysis of the beam using the QMF and PILGRIM. Ions are counted on MCPs and MagneToF detectors.
- Optimization of the collector voltage for suppressing non-neutralized beam. Repetition of mass analysis for observation of collector effect.
- In-gas-cell laser ionization and spectroscopy of ^{152}Er using broadband lasers, with detection after PILGRIM on the MagneToF detector.
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- Optimization of ^{152}Er injection and focusing in the gas cell using S^3 optics, in order to maximize the ^{152}Er ion rate obtained in the gas jet. Comparison to diagnostic box result.
- Repetition of measurements after optimization.
- Repetition of laser spectroscopy measurements using Si detectors and alpha selectivity.
- Mass measurements of Er isotopes and contaminants available in the beam cocktail using PILGRIM.
- In-gas-jet laser ionization of other Er isotopes available in the beam cocktail, without changing production and S^3 settings.

Required performance of S^3-LEB for day 1 campaign:

- Availability of laser schemes for selected cases
- Availability of entrance window for selected cases
- Gas-cell neutralization + extraction efficiency: 10 to 25%
- Transport efficiency of ion optics until end of PILGRIM: 30% to 80%
- Mass resolving power of PILGRIM > 80 000
- SEASON if needed (not mandatory)

11.2.7 Beams requirements:

- For the scientific commissioning (see “Scientific Program” below): ^{40}Ar @ 4,5 MeV/A, ^{40}Ar @ 3,5 MeV/A, ^{50}Cr @ 4,5 MeV/A with beam intensities of 2pµA or more

- From the LOI call of 2018: ^{36,40}Ar, ^{22}Ne, ^{24}Mg, ^{40,48}Ca, ^{50}Cr, ^{58}Ni with beam intensities of 1pμA or more, beam energies between 3,3 to 7,9 MeV/A

11.2.8 Targets requirements:

- For the scientific commissioning (see “Scientific Program” below): ^{116}Sn, ^{58}Ni, ^{175}Lu
- From the LOI call of 2018: ^{116}Sn, ^{50}Cr, ^{58}Ni, ^{46}Ti, ^{175}Lu, ^{178,180}Hf, ^{208}Pb with thicknesses from around 0,5 to 1 mg/cm^2

11.2.9 Availability of Germanium detectors:

- For the diagnostic box, the germanium detector foreseen is the one from the SPIRAL1 decay station with a cryocooler
- For SEASON, 2 Exogam clovers with numexo2, common with SIRIUS

11.2.10 Associated risks:

- Low efficiency of laser ionization due to insufficient power (Ti:sa + unfavorable scheme).
- Requirement of too thin gas cell entrance window or too high leak rate for electric dipole.

11.2.11 Scientific program

What would be the “collaboration experiments” to be performed during the scientific commissioning (outside PAC selection)?

A proposition could be:

- ^{40}Ar + ^{116}Sn -> ^{151}Er and the more neutron-deficient isotopes plus neighboring lighter elements, to test with the same set up as the commissioning with ^{152}Er the capabilities of S^{3}LEB (lasers, detection with and without alpha emitters, transmission, selection into PILGRIM…), physics around N=82, Ho, Dy, laser spectroscopy + mass measurements.

- ^{40}Ar + ^{175}Lu -> $^{210\text{-}215}$Ac and the area below produced either directly or via in-gas-cell-decay, to test the capabilities of S^{3}LEB in the heavy mass region (gas cell behavior as neutralization with low incident ion rates, lasers, transmission of heavy masses, selection into PILGRIM…), Physics around N=126, laser spectroscopy + mass measurements.

- ^{50}Cr + ^{58}Ni -> $^{100\text{-}105}$Sn and the area around, to test the capabilities of S^{3}LEB in the N=Z region (gas cell behavior with high incident ion rates, lasers, detection without alpha emitters, transmission of medium masses, selection into PILGRIM…), Physics around N=Z, Cd, Ag, Pd… laser spectroscopy + mass measurements.

Is the selection of day one experiments made in 2018 still valid?

All the LOI 2018 are still valid:

	Title	Spokesperson	Beam	UTs	Comments
1	Mass measurements and laser spectroscopy on n-deficient isotopes in A~80 region of deformation	P. Ascher S. Grevy	36Ar	**42**	The specific isotope to be studied will depend on the ionization scheme development, off-line gas-phase chemistry study and on the competition with MARA facility

2	In-gas laser ionization and spectroscopy of silver isotopes down to (N=Z) 94Ag	R. Ferrer V. Manea	36Ar 40Ca	**30**	Already ionized with the laser-based gas cell system. Identification of auto ionizing state will ease operation (off-line work in progress). Possible competition with MARA but they will not be able to access the most exotic nucleus 94Ag
3	1) Mass measurements and laser spectroscopy around 100Sn 2) Single-particle states and proton-neutron interaction in the 100Sn region studied through the neutron deficient In nuclei	H. Savajols D. Lunney L. Caceres	50Cr	**60**	Two Pre-proposals in one due to the experimental set-up synergy. Need for efficient ionization scheme development. Possible competition with ISOLDE for the mass measurements, the laser spectroscopy part of the most exotic systems cannot be accessed elsewhere than S3 thanks to the high intensity beams delivered by the LINAG
4	In-gas laser ionization and spectroscopy of 210-213Ac and 213-215Th	R. Ferrer V. Manea	40Ar	**21**	Already ionized with the laser-based gas cell system. Laser ionization schemes available and argon gas-phase chemistry under control
5	Search for octupole deformation in 225-226U	M. Vandebrouck I. Moore	22Ne	**42**	Need verification of the ionization scheme. Possible competition with MARA
6	Fundamental properties of Fermium isotopes around N=152	J. Piot M. Laatiaoui M. Vandebrouk	48Ca 18O	**63**	Already ionized in a gas cell, the chemistry is fine. Need for atomic information to extract the nuclear observables.

Requires performances expected from the spectrometer (transmission, rejection, ass resolution…)

- transmission as good as possible
- good primary beam and beam related products rejection (beam intensity into gas cell <10^9pps)
- no need of mass resolution

As a reminder, even with 100 pps in the gas cell, S^{3}LEB commissioning and physics could be done.

What will be the competition with other facilities in 2023-2024?

- MARA-LEB at JYU: 2024-2025, lower intensities
- JetRIS at GSI: 2024. ^{251}No already done at high resolution, even though at low statistics
- KISS at RIKEN
- Collinear laser spectroscopy at FRIB and ISOLDE, but limited beam time

11.2.12 SWOT analysis: LEB to perform day-one campaign

Strength

- Unique capability in the world to perform laser spectroscopy experiments and precise mass measurements with the low-resolution mode of S^3 (converging mode) coupled to high transmission and high beam intensities.
- Unique combination of high-resolution laser spectroscopy, Mr-ToF-MS (PILGRIM) and high-performance alpha and conversion electron decay detector (SEASON) for the study of the ground and isomeric state along the N=Z line and of heavy refractory elements, heavy actinides and super heavy elements
- Mass measurements possible with PILGRIM without lasers (flushing out the remaining ions without charge collector)
- In this flushing mode, PILGRIM could also help to give a rough idea of the composition of the S^3 cocktail beam (qualitatively, depending on the chemical properties with respect to the neutralization aspect)
- Ionization schemes already known for a substantial amount of cases

Weakness

- Mean extraction time currently of the order of 150 to 450ms
- Ionization schemes needed for every element
- Entrance window thickness possibly limiting the use of very asymmetric reactions
- Gas-cell behavior in the anticipated on-line conditions not fully known (ion neutralization, ion extraction efficiencies not known yet, but these can only be measured on-line)
- Experimental complexity

Opportunities

- Nuclei only produced at S^3
- High resolution laser spectroscopy + Conversion electron spectroscopy (SEASON)
- Isomer and ground state mass measurements (REGLIS + PILGRIM)
- Low counting rate measurements (more exotic nuclei accessible)
- Multiple observable measurement simultaneously

Threats

- Beam time availability
- Manpower to run experiments
- Dye laser system to be installed, otherwise the physics program will be reduced
- Conflict with DESIR construction + Emergency exit
- Beam characterization (Energy & Intensity)
- Primary beam contamination
- Competition with other facilities

11.3 SIRIUS and LEB day1 preliminary risk analysis

In the following we will extract information from the SIRIUS/LEB templates (see above) and we will organize them around a list of 7 major risks:

- LINAC beam availabilities
- Target availabilities
- SIRIUS/LEB readiness
- Spectrometer commissioning and qualified performances
- Scientific program feasibility (spectrometer performances)
- Scientific competition

- Scientific impact (To be completed following the SPIRAL2 Workshop in 2022)

11.3.1 LINAC beam availabilities

Beams	**SIRIUS**	**LEB**
LINAC	Heavy ion beam developments ongoing 2022-2024 The recent acceleration of ^{18}O and ^{40}Ar at 7 MeV/u have shown no show stopper for the LINAC tuning	
Beam acceleration Available/need tests (no developments) Required development Not available (Day1)	Very intense: ^{18}O, ^{22}Ne, ^{26}Mg, $^{28-30}$Si, $^{32-36}$S, $^{36-40}$Ar, with intensities > 1pμA Intense ^{40,48}Ca, $^{48-50}$Ti, ^{51}V, ^{54}Cr with beam intensities of 1pμA or more Energies between 4.5-7MeV/A	Very Intense $^{36-40}$Ar, ^{22}Ne ^{24}Mg and ^{18}O; with intensities > 1pμA Intense $^{40-48}$Ca, ^{50}Cr, ^{58}Ni; with beam intensities of 1pμA or more Energies between 3.3-7.9MeV/A
Rare isotope availabilities have to be workout	^{48}Ca not secured ^{50}Ti 1 year operation ^{50}Cr 14000$/g ^{36}S & ^{54}Cr isotopes? SiO/SiO2 isotopic to be investigated	^{48}Ca not secured ^{50}Cr 14000$/g
Comments	The absence of ^{48}Ca modifies the program given in 2018. In particular, the letter of intent on the limits of stability of No isotopes will not be feasible. One letter of intent is partially affected by the ^{48}Ca shortage (Alpha-decay spectroscopy of odd-Z isotopes in fermium region)	The absence of ^{48}Ca modifies marginally the program given in 2018
Risks	Beam unavailability	

11.3.2 Target availabilities

Targets	**SIRIUS**	**LEB**
Target station readiness	In beam test @ GANIL LISE 2K scheduled in July 2023	
Target requirements Available Required development Not available (Day1)	Stables : ^{164}Dy, ^{170}Er, ^{174,176}Yb, ^{180}Hf, ^{181}Ta, ^{182}W, ^{197}Au, ^{204,208}Pb, ^{204,208}PbS, ^{209}Bi, ^{209}Bi$_2$O$_3$, ^{238}U	Stables : ^{118}Sn, ^{50}Cr, ^{58}Ni, ^{46}Ti, ^{175}Lu, ^{178,180}Hf, ^{208}Pb
Comments	• PbS isotopic supply to be investigated • ^{182}W, ^{181}Ta to be investigated with e-gun • Lanthanides: Know-hows at GSI… under development at GANIL	• ^{50}Cr to be investigated with e-gun • Lanthanides: Know-hows at GSI… under development at GANIL

	• ^{181}Ta: magnetron sputtering to be developed at GANIL (Approach with LMA Lyon) • ^{238}U: Know-how at GSI, under collaboration with ORANO and possible development in future at GANIL	
Risks	Target unavailability	

11.3.3 SIRIUS/LEB readiness

Detection Setups	**SIRIUS**	**LEB**
Readiness Ready Need development Difficult	Ready • Radioactive source commissioning (2023) • In beam commissioning at LISE (2024)	Ready • Laser development @ GISESLE • Off-line commissioning at LPC
Setup installation Rather simple Complex Difficult	Rather simple Tested last May moving from G3 to G2. Disconnection, dismounting and moving takes two days. Installation and cabling take a week with the necessary staff available.	Complex To change the configuration of the diagnostic box from SIRIUS to LEB mode will take 4 days. To dismount S^{3}LEB and transport everything into room 51, it should take less than one week. To mount, connect and test S3LEB: one month
Setup on-line commissioning Rather simple Complex Difficult	Rather simple Online commissioning planned for March 2024 on FULIS. Twice 4 UTs of beamtime requested. An experiment has been submitted to the GANIL PAC to study the nuclear structure of ^{217}Pa. This experiment will allow to commission SIRIUS further on a long run with realistic conditions.	Complex Online commissioning is needed to assess the LEB overall performances. Contrary to SIRIUS the performances will also depends on the reactions and elements to be studied.
Comments		The on-line commissioning will be performed using a beam of ^{152}Er produced in the reaction ^{116}Sn(^{40}Ar – 180 MeV, 4n)^{152}Er in convergent mode. With an estimated production rate of ^{152}Er > 10^4/s at the S^3 final focal plane, this case would allow a successful experiment to be performed even with a global efficiency of the setup ≈ 0.01%.
Risks	Scientific program feasibility	

11.3.4 Spectrometer commissioning and qualified performances

Spectrometer commissioning	**SIRIUS**	**LEB**
Optical commissioning	Dedicated diagnostics at the focal plane. SIRIUS and LEB can be partially installed during this phase	
Optical modes	• Optimize the rejection and the transmission for relevant kinematics to reach the required performances in the Converging Mode (CM) for day1 experiments • Test the High-Resolution Mode (HRM) important for the SIRIUS scientific program (*The experience gained in this first HRM tuning will help to optimize this mode for next beam time campaigns). SIRIUS is required for the final stage of the HRM commissioning.*	
Scientific commissioning setups	Diagnostic box (Tracker with magnet) + SIRIUS	Diagnostic box in LEB mode (Tracker without magnet + DSSD + one Germanium) + LEB
Scientific commissioning reactions	VHE-SHE ^{40}Ar+^{116}Sn (High XS) ^{40}Ar+^{174}Yb (High XS) ^{40}Ar + ^{182}W (Low XS) Ne + Pb,Bi,Th,U	VHE & N=Z ^{40}Ar +^{116}Sn-> ^{152}Er
Setup performances to perform the spectrometer commissioning High Medium Low	High • Unique recoil, alpha, electron, gamma, beta, fission efficiencies • Nominal position resolution with the tracker (1,4mm FWHM, important for the HRM commissioning) • Cannot handle high counting rate	Medium • Good recoil, alpha, electron, beta, fission efficiencies • Poor gamma-ray efficiency • Poor position resolution with the tracker (4mm FWHM, no magnet) • N=Z identification without HRM will rely on gamma-rays/isomer decays + LEB measurements (PILGRIM)
Commissioning data taking Scientific impact High Medium Low	• ^{50}Ti+^{208}Pb->^{256}Rf, ^{257}Rf • ^{40}Ar+^{209}Bi --> ^{247}Md • ^{18}O+^{238}U->^{252}Fm • ^{22}Ne+^{238}U -> ^{256}No • ^{26}Mg+^{197}Au->^{217}Pa	• ^{40}Ar + ^{116}Sn -> ^{151}Er and the area around, to test with the same set up as the commissioning with ^{152}Er the capabilities of S^{3}LEB, Physics around N=82, Ho, Dy… laser spectroscopy + mass measurement • ^{40}Ar + ^{175}Lu -> $^{210-215}$Ac and the area around, to test the capabilities of S^{3}LEB in the heavy mass region, Physics around N=126, laser spectroscopy + mass measurement • ^{50}Cr + ^{58}Ni -> $^{100-105}$Sn and the area around, to test the capabilities of S^{3}LEB in the N=Z region
Risks	Commissioning feasibility and first data taking impact	

11.3.5 Scientific program feasibility (spectrometer performances)

Spectrometer performance requirements	**SIRIUS**	**LEB**
Optical modes	Converging and High-Resolution Modes	Converging Mode
Rejection Not required Partially required Essential	Essential Rejection higher than 10-^{12} for beam-like transfer products, higher than 10^{11-12} for direct beam	Partially required Good rejection is required (gas cell can work with 10^8pps)
Transmission Not required Partially required Essential	Partially required Higher than 40% for ^{48}Ca type kinematics. Higher than 10% for O/Ne type kinematics	Partially required The higher the better, but some day1 physics cases can accommodate a spectrometer not at 100% of its performances. The converging mode has the higher transmission efficiency
Mass resolution Not required Partially required Essential	Partially required Mass resolution around 300 with high-intensity beam on target	Not required Not relevant
Risks	• High rejection not reach after the first commissioning phase • Optimised mass resolution not available after the first commissioning phase	

11.3.6 Scientific competition

Scientific Competition	**SIRIUS**	**LEB**
Topics	VHE-SHE decay spectroscopy	
Competing facilities High Medium Low	Medium • No beam planned in GSI for 2023. • SHIP has deserted the decay spectroscopy field • A program for decay spectroscopy is starting at TASCA with a detector designed to measure electrons independently (ANSWERS) • The SHE factory is running, SHELS+GABRIELA++ as well • RIKEN is focusing on Z=119, but testing its equipment on the other GARISes	Medium - MARA-LEB at JYU: 2024-2025, lower intensities - JetRIS at GSI: 2024. ^{251}No already done at high resolution, even so at low statistic - KISS at RIKEN

	- ANL has started a program on AGFA for in-beam spectroscopy. Beam intensity is lower than the capabilities of S^3	
Risks	Experiments done elsewhere	

11.3.7 Scientific impact

Scientific impact	**SIRIUS**	**LEB**
Topics	Decay and isomer spectroscopy of Transfermiums (N=152), Detailed study of the K isomers in 256Rf, odd Z/N nuclei in the fermium region, reaction mechanism studies	Medium-mass nuclides along the N = Z line from Z = 40 (Zr) to Z = 56 (Ba), doubly magic ^{100}Sn, the heavy actinide region (Ac and U) and the super heavy element region (around No Z=102).
Revised S3 LoIs 2018 World leading Important contribution Marginally competitive (or not feasible)	Some of the experiments have been performed but have open new questions / some of the program are still relevant (K-isomers, XS, fission, alpha-decay) / ^{48}Ca shortage is an issue HRM of S^3 is unique for SIRIUS.	Scientific program is still relevant in 2022 with high scientific impact (mass measurement, laser spectroscopy and decay studies)