Conseil Scientifique et Technique du SPhN

STATUS OF EXPERIMENT

Title: The Super Separator Spectrometer
Date of the first CSTS presentation: October 2006
Experiment carried out at: GANIL-SPIRAL2
Spokes person(s): H. Savajols (GANIL), J.A. Nolen (ANL), A. Drouart
Contact person at SPhN: A. Drouart
Experimental team at SPhN: D. Boutin, F. Dechery, A. Drouart, W. Korten, B. Sulignano, Ch. Theisen
List of IRFU divisions and number of people involved: Irfu/SACM (5), Irfu/SIS (4), Irfu/SEDI (3), Irfu/SENAC (2)
List of the laboratories and/or universities in the collaboration and number of people involved:
Argonne National Lab (12), Bruyères-le-Châtel DAM (5), CENBG (1), CSNSM (5), GANIL (23), GSI (7), INFN Legnaro (2), IPHC Strasbourg (10), IPN Lyon (1), IPN Orsay (3), Univ. of Jyväskylä (2), K. U. Leuven (6), Liverpool University (2), LMU (1), LNL (1), LNS (2), LPCS (1), MSU (2), Nanjing University (1), Northern Illinois University (1), SAS Bratislava (1), Smoluchowski Institute (5), TAMU (1) TIFR India (2), Mainz University (1), York University (2), Vinca Institute (1)

SCHEDULE

Starting date of the experiment [including preparation]: 2013
Total beam time allocated: non relevant
Total beam time used: non relevant
Data analysis duration: non relevant
Final results foreseen for: non relevant

BUDGET

| Total investment costs for the collaboration: | 7,8M€ |
| Share of the total investment costs for SPhN: | 1,1M€ |
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The Super Separator Spectrometer S$^3$ project

In this document, we will make an overview of the S$^3$ project and of its structure. We will describe the research plan on superheavy nuclei that is the primary interest of the SPhN. Then we will focus on the different technical aspects that Irfu is specifically dealing with:

- Optics of the spectrometer
- The open magnetic multipoles for beam extraction
- The beam dump
- The implantation-decay detection system.

This document is fed with extracts of some S3 collaborations reports and a great amount of contributions come from S3 collaboration members other than IRFU members.

1 Overview of the Project

1.1 Introduction

S$^3$ (Super Separator Spectrometer) is a device designed for experiments with the very high intensity stable beams of LINAG, the superconducting linear accelerator of GANIL, which will be built in the framework of SPIRAL2. These beams, can reach intensities exceeding 100μA for lighter ions - A<40-50 - depending on the final choice of the ECR (Electron Cyclotron Resonance) ion source and injector. These unprecedented intensities open new opportunities in several physics domains, e.g. super-heavy and very-heavy nuclei, spectroscopy at and beyond the dripline, isomers and ground state properties, multi-nucleon transfer and deep-inelastic reactions. An international collaboration has been formed for proposing physics experiments and developing technical solutions for this new instrument.
The basic design of S\textsuperscript{3} involves:

- **Rotating targets** that can sustain the high power beams for stable materials as well as radioactive actinides.

- **The Separator-Spectrometer** itself, with high transmission and high resolving power in two stages using a combination of magnetic and electric dipoles with large aperture multipole triplets:
  - First, a **momentum achromat**, in order to collect most of the interesting reaction products and to extract most of the high intensity beam in a specific dump area,
  - Second, a **mass spectrometer** that will further purify the transmitted nuclei and allow for their mass measurement

- A **standard detection system** dedicated to implantation-decay experiments, for the decay spectroscopy (\(e^{-}, p, \alpha, \gamma\)) of the interesting nuclei.

- Alternatively to this detection system, a **low energy branch**, with a high counting rate gas catcher, an ultra high resolution spectrometer in order to measure ground state properties of nuclei with the relevant detection systems (\(\beta\)-decay station, ion traps, chemistry apparatus...).
1.2 Physics objectives

The physicists’ collaboration has established as a priority the delayed study of nuclei produced by fusion reactions. This covers the study of neutron deficient nuclei as well as very and super heavy elements. The high production rates will permit detailed studies of nuclei that are today produced only with rates of few per day, either through decay spectroscopy (alpha, proton, electron, gamma...) of ground-state property measurements in ion or atom traps or chemistry apparatus. Nevertheless, S3 will be also a versatile device, which could also be used in some cases for studies of light nuclei produced by transfer reactions, or neutron rich nuclei with deep inelastic scattering and secondary reactions with nuclei produced in the primary target.
1.2.1 Superheavy elements

The high intensity beams of LINAG will give unprecedented opportunities for the synthesis of new elements, as well as, for detailed studies of the already known elements, most notably:

- Synthesis new elements, with Z>118
- Get spectroscopic information for elements up to Ds (Z=110) and learn about collectivity around the islands of deformation ($^{254}$No, $^{270}$Hs)
- Hunt for new K-isomers to obtain information about the single particle states
- Produce new isotopes from the neutron poor elements produced by cold fusion to the neutron richer elements of hot fusion, and then have information about their isospin dependent properties.
- Cross-section measurement systematic to gain insight about the mechanisms of fusion and fission.
- Measure ground states properties of SHE like their masses, charge radii, etc.
- Perform transactinium chemistry with the heaviest elements

1.2.1.1 Requirements

This physics program requires the following experimental conditions:

- The highest intensities of beams, especially for masses > 50 (48Ca is a must, heavier beams are required to go to the heaviest elements)
- A wide range of targets, including actinides targets that are necessary for all hot fusion reactions
- High angular and $\beta\rho$ acceptance, due to the large emittance of the produced nuclei and their charge state distributions
- High reaction channel selectivity, to have a background rate at the focal plane as low as possible. This includes physical m/q selection to exclude high-rates of adjacent masses.
- In-flight mass resolution. The mass determination of the produced SHE appeared as critical to validate the production of new elements. It would be a unique property of S3.
- A detection system for alpha, electron, gamma spectroscopy at the focal plane and a gas catcher system to transfer ions to traps.

The physics program on Superheavy nuclei will be further described in a dedicated section, since it is the primary interest of SPhN.
1.2.2 Neutron-deficient nuclei

Fusion evaporation reactions can also produce a wide range of neutron-deficient nuclei with a variety of interesting properties: proton emission, super-allowed beta decays, shape coexistence, isomers with information on single particles states and correlations between nucleons. New isotopes with masses in the range 180-200 could be produced. Masses of these nuclei are of interest for the study of the rp-process. Current facilities can fill in some of the gaps in mass measurements, but only a facility like S3 could reach nuclei such as $^{99,100,101}$Sn, $^{98,99}$In, $^{95,96}$Cd. The region around the $^{100}$Sn nuclei is of utmost interest, since this nucleus is at the drip line with two closed shells and N=Z. It is a benchmark to investigate the states near the Fermi surface and how their wave functions reflect single particle motion. Several aspects have to be studied:

- Masses, lifetimes, and charge radii in the region
- Beta-decay studies
- Beta-delayed particle spectroscopy
- Single-particle structure from transfer reactions in neighbouring nuclei
- Proton-capture rates at astrophysical energies on critical nuclei in the region
- Identification of low-lying states by Coulomb excitation
- Reaction mechanism studies at or below the fusion barrier

1.2.2.1 Requirements

The requirements for such studies are the following:

- The highest intensities of beams, especially for masses > 50. The most interesting nuclei are produced with symmetric reactions, and so in heavy ions fusion ($^{50}$Ni or heavier)
- High angular and $B_p$ acceptance, since few particle evaporation increases the angular distribution of the nuclei
- In-flight mass resolution of 1/300. Due to the high fusion cross section of medium mass nuclei, it is absolutely required to have at least an A/q separation of reaction products, to limit the final counting rate to less than 10^9 pps (for a gas catcher) or 10^6 pps (for secondary reactions).

1.2.3 Production of neutron rich nuclei with transfer/Deep inelastic reactions

Very high primary beam intensities open also the possibilities of producing neutron rich exotic nuclei in large numbers, either through the transfer of few nucleons on light nuclei, or with massive transfer for heavier ones. The physics topics addressed here have been largely presented and discussed in the SPiRAL2 project. Undoubtedly, the neutron rich beam intensities produced by SPiRAL2 through U fission will be much higher in all the regions covered by the fission peaks, but it could be possible with S3 to produce nuclei outside these zones, either lighter or heavier. For examples multiple nucleon transfer in a $^{136}$Xe+$^{208}$Pb reaction can produce neutron rich nuclei on the $^{208}$Pb region and with $^{40}$Ca+$^{208}$Pb reaction, neutron rich nuclei can be significantly produced in the N=28 region. On the light side, the reaction $^{12}$C($^{13}$C,2p)$^{14}$Be can give very high yields (~5.10^8 pps) of $^{14}$Be, competitive with an ISOLDE type facility. The very high intensities on S3 targets will prevent any kind of prompt spectroscopy of these nuclei – which is the “traditional” method to study them. However, it could be possible to study them in an additional reactions with a secondary target and perform a high cross section reaction like nucleon transfer or Coulomb excitation.

1.2.3.1 Requirements

Such reactions have very specific requirements, significantly different from the fusion-evaporation reactions.

- Very high angular and momentum acceptance. Reaction products have a very large angular and momentum distribution, much bigger than the fusion-evaporation reactions.
- For most reactions, the production cross sections are not necessary peaked at 0°.
- High magnetic and electric rigidity. Reaction products have rather large energies (10MeV/n or more), and \( B_\rho \) of 1.5Tm and \( E_\rho > 30 \text{MV} \) are required, the later being the most difficult to reach while still retaining good separator properties for the fusion-evaporation studies described above.

- Nuclei selection. A large number of exit channels are open and the contaminants closer to the stability are most of the time overwhelming. This required a very good selection. A pure momentum selection maybe possible with the lightest nuclei, but it may not be sufficient for heavier ones. A mass selection is very challenging due to the high electric rigidity required. [A possible solution is to have two interchangeable electric dipoles, one with a large gap for fusion-evaporation studies and one with a small gap for transfer and DIC studies.]

1.2.4 Reference Experiments

As previously said, \( S^3 \) is optimized for the delayed studies of nuclei produced by fusion reactions. Hence, we choose two reference reactions for the purpose of optics optimization:

1.2.4.1 \(^{58}\text{Ni}^{+46}\text{Ti} \rightarrow ^{100}\text{Sn}^+4\text{n}^\). This symmetric fusion reaction is typical from \( N=Z \) nuclei studies. Evaporation residues have a large angular distribution, as well as a large electric rigidity that brings \( S^3 \) to the limit of technology.

<table>
<thead>
<tr>
<th></th>
<th>( E/\text{n})[MeV]</th>
<th>( &lt;B_\rho&gt; )[Tm]</th>
<th>( &lt;E_\rho&gt; )[MV]</th>
<th>( &lt;Q&gt; )[cm/n s]</th>
<th>( \Delta \theta )(\pm 2\sigma)[mrad]</th>
<th>( dp/p )(\pm 2\sigma)[%]</th>
<th>dQ</th>
<th>( \Delta B_\rho/B_\rho ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam parameters (^{58}\text{Ni})</td>
<td>2.94</td>
<td>0.660</td>
<td>15.6</td>
<td>21.68</td>
<td>2.37</td>
<td>( \pm 8.6 )</td>
<td>( \pm 0.2^* )</td>
<td></td>
</tr>
<tr>
<td>Recoil parameters (^{100}\text{Sn}^+)</td>
<td>0.882</td>
<td>0.559</td>
<td>7.27</td>
<td>24.17</td>
<td>1.30</td>
<td>( \pm 40 )</td>
<td>( \pm 7.4 )</td>
<td>( \pm 2 ) [26-30] =&gt; 78%</td>
</tr>
</tbody>
</table>

1.2.4.2 \(^{48}\text{Ca}^{+248}\text{Cm} \rightarrow ^{292}116 + 4\text{n}^\). This is an example of superheavy element synthesis, with a large angular distribution and a required mass resolution of 300.

<table>
<thead>
<tr>
<th></th>
<th>( E/\text{n})[MeV]</th>
<th>( &lt;B_\rho&gt; )[Tm]</th>
<th>( &lt;E_\rho&gt; )[MV]</th>
<th>( &lt;Q&gt; )[cm/n s]</th>
<th>( \Delta \theta )(\pm 2\sigma)[mrad]</th>
<th>( dp/p )(\pm 2\sigma)[%]</th>
<th>dQ</th>
<th>( \Delta B_\rho/B_\rho ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam parameters (^{48}\text{Ca})</td>
<td>4.92</td>
<td>0.88</td>
<td>27</td>
<td>(+17)</td>
<td>3.0</td>
<td>( \pm 8 )</td>
<td>( \pm 0.2^* )</td>
<td></td>
</tr>
<tr>
<td>Recoil parameters (^{292}116)</td>
<td>0.131</td>
<td>0.58</td>
<td>3</td>
<td>(+25)</td>
<td>0.5</td>
<td>( \pm 55 )</td>
<td>( \pm 2 ) [22-27] =&gt; 67%</td>
<td>( \pm 8.3 )</td>
</tr>
</tbody>
</table>

1.2.4.3 Additional requirements

To fit the physics of neutron rich nuclei and atomic physics, other aspects of the spectrometer are considered:

- The compatibility with ancillary detectors (EXOGAM, PARIS, MUST 2, GASPARD) at the intermediate focal point for secondary reaction studies.
- The coupling of the spectrometer with a low energy ion source at the intermediate focal point for atomic physics experiments.
- A maximum magnetic rigidity of 1.8Tm.
- The possibility to replace the electric dipole by a magnetic dipole for specific high-energy experiments.

1.3 \( S^3 \) characteristics

Simulations have been performed for different key experiments covering the above mentioned physics topic. From these experiments, we have derived requirements for the \( S^3 \) facility.
1.3.1 Optics

S3 will deal with the high intensity heavy ion stable beams of Spiral2 at GANIL. It is presently in the conception stage. Its physics cases focus on the studies of proton-rich radioactive beams and heavy elements by means of fusion-evaporation reactions and also studies of neutron-rich nuclei outside the fission peaks by deep-inelastic and transfer collisions. The design goal of the spectrometer should satisfy the following characteristics:

- An excellent primary beam suppression (10^13 in most cases) at 0°
- A relative magnetic rigidity (Bp) acceptance: ± 7%
- A large angular acceptance in both planes: ± 50 mrad for ± 2 charge states
- A magnetic rigidity Bp_{max} (for reaction products) = 1.8 Tm
- An electric rigidity E_{rho_{max}} = 12 MV
- A mass resolution of 1/300 (FWHM).

A two-stage system is considered for the S3 spectrometer (see figure 2). The first stage is a magnetic momentum achromat which allows the separation between the primary beam and the recoil products. It is followed by a mass separator which includes an electrostatic dipole and a magnetic dipole for mass selection. In the magnetic momentum achromat, the different charge states of the primary beam have different angular deviations after the first magnetic dipole. Some of them are not accepted anymore and would hit the following multipole magnets, which has to be avoided. To enable the primary beam extraction these magnets have to be opened on one side, which requires a careful design of such a multipolar magnet.

The different characteristics previously listed lead to a dedicated multipole design:

- The angular acceptance implies an aperture diameter of 300 mm
- The magnetic rigidity and charge-state acceptance demand a sextupolar component in each multipole to correct optical aberrations.
- The maximum magnetic rigidity gives quadrupole field gradient of 6 T/m and sextupole field “gradient” of 10 T/m^2, which are reasonable with such aperture for superconducting technology.

In addition, the ion optical simulations indicated that an outer aperture with a vertical gap of ± 50 mm is sufficient to extract the primary beam after the first magnetic dipole.

The optics simulations at Irfu are detailed in section 5.2.

1.3.2 Magnets

In order to comply to the requirements of the optics, the multipole magnets characteristics must be the following:

- Large aperture of 30cm diameter
- Length of about 40cm
- Quadrupole with sextupole correction embedded in all the multipoles
- Additional octupole corrections in the closed multipoles
- Open multipole with ±5cm lateral aperture
- Optics simulations show that the addition of octupole correction in the open multipoles significantly increase the mass resolution.
- The electric dipole has an angle of about 20 degrees with 4meters-radius curvature. This is a “classic” model.
- The magnetic dipoles have classic characteristics.

For that purpose, we are currently studying the following technical solutions for the multipoles:

- closed superconducting magnets that are able to provide superimposed quadrupole, sextupole and octupole fields.
- Open magnets, either of warm temperature technology with quadrupole and sextupole fields, or superconducting “MOSAR” magnets with the possibility to add optupole fields.

These aspects are detailed in the section 5.3.
1.3.3 Beam

1.3.3.1 Upstream beam lines
The best ion source is required in order to reach the highest intensities. The basic $A/q=3$ injector of SPIRAL2 has reasonable performances for the lightest ions (up to Ar), but it is clear that major physics topics require heavier beams ($^{48}$Ca, $^{58}$Ni, $^{136}$Xe...) that could only be produced with competitive yields (10pµA or more) with the $A/q=6$ injector.

The implantation of the High Energy line of SPIRAL2 foresees two incoming beam lines in $S^3$ cave. The northern beam line is the primary beam input that will bring the beams to $S^3$. A secondary line is added so that another equipment (spectrometer...) can be added in the future.

1.3.3.2 Beam spot size on target
The incoming beam must be spread on the target in order to reduce the local heating. A 1mm x 1cm beam is required on the target. Two solutions are currently being studied to reach the 1 cm size:
- The upstream beam line is tuned in order to have a large ($\sigma=5$mm) gaussian profile in the vertical direction.
- A fast Beam Raster Magnet system is positioned in front of the target, composed of several high frequency (~1kHz) magnetic dipoles (~500Gauss) that wobbles the beam on the target. The beam raster enables to divide by a factor 2 the maximum power density on the target, and then multiply by 2 the maximum possible beam intensity.

1.3.4 Target
Rotating targets are required in order to spread the beam energy loss on the largest surface as possible, in order to avoid melting, thermal strains and to reduce the impact of sputtering damages on the target. Two kind of targets are studied in GANIL for $S^3$:
- a large size wheel, to support stable materials.
- A smaller wheel to hold radioactive actinide materials which maximum mass must be as small as possible (45mg on GANIL site).

These wheels will be similar to existing models like Fulis presently used at GANIL and the actinide wheel used at GSI:

1.3.4.1 Stable target
Stable targets have thickness from 0,1 to 2mg/cm$^2$. They are either self supported, or supported on carbon backings that ensure mechanical durability as well as a good emissivity of the surface. The use of stable material is mainly limited by the low melting point of some components (Sn, Pb, Bi). In some cases, it is possible to use high melting temperature compound (PbS, BiO2). This wheel should have a high rotating speed (>2000 rpm) and a large radius (25-30cm).
For example, using a $^{70}\text{Zn}$ beam with 350MeV incident energy and a 2D-Gaussian intensity ($\sigma_x=0.5\text{mm}$, $\sigma_y=5\text{mm}$), the maximum intensity before melting is 7.8pµA with a metallic Pb target and 65pµA with PbS target.

Test are presently done with the Fulis wheel at GANIL (33.5cm radius, 2000 rpm).

1.3.4.2 Actinide targets

Actinides targets (Pu to Cm) are necessary for the full Superheavy element programs. While delicate to handle and use, such targets have already been used in other European facilities (PSI, GSI). Basically, actinide targets are mounted on smaller (14.4cm diameter) wheels. The rotation speed must be very high (above 2000rpm). The material is deposited on 2µm Ti backings with a thin carbon foil to reduce target backscattering. The actinide wheel is encased in an internal box with minimal openings in order to limit the spread of radioactive material in the downstream beamline. The target box itself is fully sealable and is opened only when connected to the beamline.

The integrity of the target is under constant surveillance by various diagnostics:
- An electron gun that give an instantaneous measure of the thickness of the target
- A pyrometer that measure the surface temperature
- A fast gamma detector to the measure an average beam/material interaction (target as well as support)
- A Silicon detector for Rutherford scattering detection.

When an anomaly is detected on a diagnostic, the beam is shut down and fast valves are closed upstream and downstream from the target.

As far as thermal limit is concerned, actinide material and titanium backings have a high melting point. Hence, for a 240MeV $^{48}\text{Ca}$ beam, the maximum intensity on a Ti+Cm target is 20pµA. If Cm$_2$O$_3$ is used, the limitation is 50pµA and comes from the titanium backing. Nevertheless, we also have to consider the thermal stress due to heating/cooling cycles of the target during rotation. For a $\Delta T<100\text{K}$, the intensity limit is now 8.3pµA. This limit is very conservative, but detailed studies of this poorly known phenomenon must be done.

A prototype is currently under design at GANIL and its construction will begin this year:

1.3.4.2.1 Actinide targets and Nuclear safety

Actinide targets are considered as unsealed sources. There is no risk of external exposure provided there is no contamination. Hence the safety requirements are the following:
- Zero contamination during normal operation
- Limited contamination in incidental situations
- Limited consequences for the public
- The following measures are studied to ensure these constraints:
- Glove box to handle target, during mounting, dismounting and decontamination.
- Sealed crate for the transfer to the mounting room to the target point room.
- Nuclear ventilation where the targets are stored
- handling equipment
- High efficiency filtering of air
- Fire sectorisation of the different nuclear areas
- Design criteria to answer to earthquake criteria.
- The target chamber itself is designed to reduce the amount of dispersed material, both in normal condition and accidental situations:
  - Small solid angle apertures (10⁻³)
  - Fast acting valves both up and downstream
  - Constant monitoring of the target to detect any degradation.

The S³ collaboration has established contacts in order to estimate the existing technical solutions and the appropriate safety requirements:
- With the SPIRAL2 SRE (Safety group) for information, safety procedures and rules about the use of radioactive targets,
- With the CACAO Project, which should be able to provide target from thorium to curium.
- With GSI and Munich laboratories, which have already produced and used such targets for internal use.
- With the Irfu/SENAC for the nuclear safety calculations and estimation for technical solutions
- With the IRSN for the administrative procedures and expertise in nuclear safety.

These studies are also done in coordination with the "Neutron for Science" collaboration, which has also the need for radioactive targets.

1.3.5 Detection

1.3.5.1 Decay spectroscopy

The basic detection system for S³ will be an implantation detector for Recoil-Decay-Tagging experiments. Such detector technology already exists (Great at Jyväskylä, Gabriella at Dubna, Best at Ganil...) and, if it can still be improved, it will be sufficient for a large range of experiments. This detector will include:
- Emissive-foil detectors for time of flight and ion tracking. These detectors already exist in a larger version on the VAMOS spectrometer and similar models are currently being studied at CEA-Saclay Irfu.
- An "implantation" stripped silicon detector for the detection of the recoiling nuclei, E and time measurement as well as alpha decay detection. Its size will be 10x10cm, with high segmentation (128x128 strips). In parallel, a collaboration within the S³ project is being proposed by an Argonne National Laboratory R&D program to develop a highly segmented silicon detector with digital electronics and triggerless acquisition, optimized for recoil decay tagging detection with high trigger rates (spectroscopy around ¹⁰⁸Sn).
- A tunnel detector combining 4 silicon detectors perpendicular to the implantation detector. They will detect alpha and conversion electrons escaping from the implantation.
- Gamma detection. The clovers of EXOGAM2 are compatible with this kind of setting, but the IPHC Strasbourg is currently studying a full planar Germanium cube in order to have a very high efficiency for gamma and X.
The silicon and emissive foil detectors will be detailed in the section 5.6 since the Irfu is involved in their development.

1.3.6  Low energy Branch

The connexion of S³ to a low energy branch allows for a wide range of measurement on the ground states properties of the atoms. This branch includes:

- A gas catcher that stops the ions at the end of the spectrometer.
- A low energy beam line that accelerates the ions to 40keV and transports them to the detection set-up.
- The detector itself: ion traps, collinear laser spectroscopy, beta-NMR, chemistry set-up...

Since all these equipments are foreseen to be installed in the DESIR facility, it is clear that a connection to this room is highly valuable. The efficiency of a gas catcher, typically of 10%, can be as high as 40%, down to a few %, depending on the nature of the ions, the total counting rate in the catcher...

1.3.6.1  Gas catcher

The S³ spectrometer will be able to purify the interesting ions from the beam and other nearby contaminants. Nevertheless, as previously underlined, an isobar contamination cannot be avoided in some cases. Therefore, it is required that an additional selection occurs after the gas catcher. In any case, the incoming flux in the ion trap should be less than $10^9$ pps if a good efficiency is necessary.

The gas catcher could be either:

- A gas cell coupled to a RF extractor that sends the ions to a very high resolution mass spectrometer for purification (CARIBU gas catcher and separator). A mass resolution above 20000 allows for the separation of the different isobars.

- A laser ionization trap that ionize a selected isotope that is then brought to a rough mass separator and then to the detection set-up (Leuven Isotope Separator On-Line).

1.3.6.2  Low energy beamline

The low energy beam line should send the selected ions either to the DESIR experimental area when built, or, for some specific cases, into detection devices in the S³ room – surface has been foreseen for this usage.

1.3.7  Beam dump

The role of the beam dump area is to suppress at least 99.9% of the primary beam, in order to limit the intensity in the second half of S³, where the electric dipole is very sensitive, and to contain in a small area the radiological activity that may arise from the interaction between the beam and stopping material. The beam dump is located at the first quarter of S3, on the first momentum dispersive plane. In this location, the ions are distributed according to their
magnetic rigidity ($B_\rho = mv/q$). At first order, the beam ions have a larger $B_\rho$ than the nuclei of interest, but this is not completely true in some experimental conditions. Due to the relatively small emittance of the beam (in comparison to the nuclei of interest), the beam trajectories in this region are very localized. Nevertheless, the interaction with the target induces a distribution of the charge states $q$ of the beam ions, and then on their trajectories. As a consequence, the place where the beam must be stopped may be widely distributed in a given experiment, and can change radically from an experiment to another, according to the difference of magnetic rigidity between the reference nuclei (that must be transmitted) and the different charge states of the beam. The beam dump has been divided in three areas:

- A high magnetic rigidity area, which will basically receive the highest intensities
- An acceptance area, where the beam ions have the same magnetic rigidity than the ions of interest
- A low rigidity area, which receive only high, small population charge states.

In some experimental cases, the different beam charge states will be distributed on all the areas.

The issues concerning the beam dump have several aspects:

- The particle scattered on the different elements of the beam dump may re-enter in the acceptance zone. This proportion must be minimized to increase the rejection of the beam.
- The high density of power of the beam must be dissipated without risk for the surrounding equipment.
- The beam nuclei interact with the beam dump, producing locally a significant amount of radioactive nuclei. The staff must be protected from the radiations in case of intervention on the beam dump. This has also to be considered for the nuclear waste management.
- The beam-material interaction also produces neutrons that may activate the surrounding equipment. This activation must be reduced to be compatible with human intervention and nuclear waste management.

The R&D on the beam dump area is presently in charge of Irfu. We will make an extensive review of this topic in the section 5.7.

1.3.8 Nuclear Safety

Nuclear safety in the $S^3$ project addresses two main points:

- The high intensity beam that will hit the beam dump.
- The use of thin actinide targets in some experiments.

As far as the infrastructure is concerned, the S³ room could be segmented in different safety level zones:
- Target point zone, for target confinement and irradiation protection
- Beam dump zone, for irradiation protection and activation confinement
- Separator/spectrometer zone
- Detection zone, to reduce the amount of background in the detectors.

Other aspects like waste management and dismantling of the facility will also be considered in the project. The Irfu/SENAC and the SPIRAL2 SRE take these nuclear safety aspects in charge. We detail these aspects in the relevant section 5.8.

## 2 Superheavy Elements with S³

S³, with the very high intensities that will be provided by the SPIRAL2 linear accelerator, is an exceptional instrument for the decay studies of superheavy elements. It requires the following experimental conditions:
- The highest beam intensities, especially for masses > 50
- A wide range of targets, including actinides that are necessary for hot fusion reactions
- High angular and Bρ acceptance, due to the large emittance of the produced nuclei and their charge state distributions
- High reaction channel selectivity, to have a background rate at the focal plane as low as possible. This includes physical m/q selection to exclude high-rates of adjacent masses.
- In-flight mass resolution. The mass determination of the produced SHE appeared as critical to validate the production of new elements. It would be a unique property of S³.
- A detection system for alpha, electron, gamma spectroscopy at the focal plane and a gas catcher system to transfer ions to traps.

In this text, after a brief introduction on superheavy element physics, we will present the Letters of Intent in which the SPbN is involved. In a last part, as an illustration of the possibilities of S³, we present a study of the synthesis of the new superheavy element Z=120.

![Figure 4: Excerpt of the nuclides chart in the region of superheavy elements. Indicated regions: Green: nuclides where the decay chains of the heaviest at SHIP synthesised elements (Z=110-112). Brown: at Dubna observed decay patterns for ⁴⁸Ca-induced reactions on actinide targets. Blue: isotopes for which nuclear structure data has been collected at SHIP (bold line: new or improved data; hatched area: reproduced or confirmed data). Red: region of interest for near future investigations. The background pattern: shell correction energies according to R. Smolanczuk et al. Phys. Rev. C 52, 1871 (1995).](image-url)
2.1 Introduction

In the physics case of the SPIRAL2 white book, the field of superheavy element research was identified as one of the major subjects which can be exploited by the stable beam part of the facility with the high heavy-ion beam intensities offered by its linear driver accelerator LINAG. There it was illustrated that the fundamental question "Is there a limit, in terms of number of protons and neutrons, to the existence of nuclei?" can be attacked by employing a broad range of techniques.

The main goal, the synthesis of ever heavier new elements until the "island of stability" is eventually reached, will be driven by applying the most modern, existing or yet to be developed, techniques of nuclear spectroscopy, reaction mechanism studies and even chemistry of heavy and superheavy nuclei. The highly intense stable beams available at SPIRAL2 together with a highly efficient separator and/or spectrometer such as S3 are an ideal combination for low cross-section experiments.

The present status of the field is summarised in Figure 4. One of the major open questions is the connection of the decay patterns observed in 48Ca induced reactions on actinide targets at the gas-filled separator of the FLNR, Dubna (brown framed region in Figure 4). On the other hand, the decay chains leading to the heaviest nuclei in reactions with 208Pb and 209Bi targets have also been observed mainly at the velocity filter SHIP of GSI, Darmstadt (green framed region in Figure 4) and later at the gas-filled separator GARIS of RIKEN, Tokyo, those are not connected to isotopes with known α decays that would settle the unambiguous identification, but end all in fission assigned to unknown isotopes. First attempts to reproduce the data for 48Ca + 238U have been successfully performed at GSI. Impressive progress has also been made for the Z assignment, notably by a group of chemists from the PSI in Switzerland.

The set-up proposed here has the capability to contribute essentially to elucidate this puzzle. Nuclear-structure studies in terms of in-beam and decay spectroscopy begin only to reach these heavy nuclei. They have provided the first information on the structure of actinides and transactinides. The nuclides studied in terms of decay spectroscopy are marked in blue in Figure 4. The development of single-particle levels towards high Z and A is a major ingredient for the localisation of the next shell gap in Z and N. With the LINAG/S3 combination, it is possible to pursue this task and to probe the low-lying states of heavier nuclei (circled in red in Figure 4). As well, the new possibilities offered by this apparatus may allow us to discover elements beyond the Z=118.

2.1.1 Spectroscopy of Transfermium Elements

Since production of heaviest elements is very small, it is clear that their studies must be accompanied by studies of nuclear structure. The production cross-sections of the transfermium nuclides are sufficiently high to make it possible to carry out detailed spectroscopic studies at least up to Z=108.

The different objectives are:

- to determine the orbitals responsible for the observed configurations in such nuclei and their properties;
- to study collectivity, in particular for those nuclei around the small islands of deformation (254No and 270Hs);
- to study the role of K-isomerism with respect to their lifetimes and α/sf-ratios and compare this to the ground state;
- to determine the masses of the nuclei and to estimate the fission barriers.

S3 addresses this physics domain through the decay spectroscopy method: a combined electron and γ spectroscopy after α decay, when the ions are implanted in the final focal plane detector at the end of the spectrometer. Alpha decay is very selective since it is sensitive to the details of the initial and final wave functions. Alpha-electron and α−γ coincidences provide additional information concerning the spin and parities of populated states. Since no detector is installed around the target, the highest possible beam intensities can be used.
2.1.1.1 **Shell Effects**

The first information that can be obtained after synthesis is the decay properties of the nucleus, since they are often used as an identification method. The alpha energy and lifetime, as well as the fission lifetime, give a first hint at the structure of the nucleus and at its stability. While the calculated shell correction energy estimated through different models agree on the lightest SHE, a discrepancy appears for higher masses, notably on the position of the stability island. It is clear that additional and precise measurements are required to refine the structure models. Moreover, these predictions hold for spherical nuclei. Other stability zones can appear with deformed nuclei, like in the experimentally known Z=108, N=162 region.

2.1.2 **Mass Measurements of Superheavy elements**

Mass spectrometry of transuranium nuclides is an important part of the scientific program, as it gives a direct observation of the binding energy. Since predicted mass values in this region often vary by about 1 MeV, direct experimental values serve as a test of theoretical models. Furthermore, they allow for the calculation of shell corrections in the stabilized, deformed region around Z=108, as well as the shell closure of the superheavy elements. Recently, the team of the SHIPTRAP experiment at GSI has determined the mass of the \(^{252,254}\)No nuclei with uncertainties around 10keV/c\(^2\). [M. Block & al., *Nature* **463**, 785-788 (2010)]

2.2 **First Day Letter of Intent**

A program of superheavy element study program has been proposed by a large collaboration of physicist where the SPhN is fully involved. This program is presented in a Letter of Intent “*Production and spectroscopy of heavy and superheavy elements using S3 and LINAG*”\(^1\) that has been proposed to and approved by the SPIRAL2 Scientific committee in September 2009. This letter presented an experimental program that can be lead with S3, with several topics:

1. Neutron deficient actinides around Z=92 N=126
2. K-isomerism studies in the Z=100-110 region
3. Study of neutron rich isotopes produced by asymmetric reactions

In this document, we will present the cases 2 and 4, which are of primary interest for the SPhN.

2.2.1 **Collaboration**

These letters of intent have been proposed by a wide collaboration of physicists from different laboratories:

- Ankara University, Turkey
- Argonne National Laboratory
- CSNSM Orsay, France
- FLNR JINR Dubna
- GANIL, France
- GSI, Germany
- IFJ PAN Krakow, Poland
- IPN Lyon, France
- IPHC Strasbourg, France
- Irfu CEA Saclay, France
- Nanjing University, China
- University of Jyväskylä, Finland
- University of Liverpool, U.K

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2.2.2 Study of K-isomerism in the region Z=100-110

The spokespersons are: PAUL GREENLEES (Department of Physics, University of Jyväskylä), Karl Haushild (CSNSM), Amel Korichi (CSNSM), Christophe Theisen (Irfu/SPhN) Stodel Christelle (GANIL).

6:03 PM The goal of these studies is to search for, and characterize K-isomeric states in the Z=100-110 region. K-isomeric two-quasiparticle states have been observed in isotopes of Fm, No, Rf and Ds. Candidates for three- and four-quasiparticle states have also been observed, for example in $^{255}$Lr and $^{254}$No. There is clearly scope to extend these studies, both in terms of better characterisation of known isomers, and in identification of new isomers, for example in Sg and Hs isotopes. Seaborgium and hassium are the only elements in the region Z=100 to 110 where isomeric states have not been identified in even-even nuclei. The study of K-isomers in heavy nuclei is also very demanding of the focal plane detection setup. Normally, a cascade of conversion electrons is emitted in the decay of the isomeric state. The energies of these electrons are summed, giving a calorimetric signal which can be observed above threshold in the implantation double-sided silicon strip detector (DSSD). It is also necessary to detect both high- and low-energy gamma rays in coincidence with these electrons. In some cases it is desirable to observe and correlate with spontaneous fission events, which requires a large dynamic range for the DSSD. A range of essentially 0-250 MeV is therefore required, with a low energy threshold of the order of 100 keV or less. It is also necessary to maintain good energy resolution for detected alpha particles (approximately 20 keV). As an example, a level scheme obtained from a typical measurement and the deduced level schemes are shown in Figure 6, from the recent study of $^{254}$No [R.-D.Herzberg et al., Nature 442, 896 (2006)].

The production cross sections for nuclei of interest range from a maximum of 2 microbarns ($^{254}$No) down to the level of 100 picobarns (e.g. Sg isotopes). In order to determine the existence of an isomer, of the order of 100 correlated electron events are required (c.f. $^{248}$Fm, unpublished but identified at JYFL). It should be noted, however, that at this level of statistics it is almost impossible to characterize the isomeric state (K-value, etc). Thus with the parameters given in the table Tableau 1, one week of beam time would represent a "borderline" study of isomeric states in Sg isotopes. In cases where the cross section is of the order of tens nanobarns, one week would allow a reasonably detailed study to be performed. Initial day one experiments could be carried out with beams of Ar, Ca, Si or S. In later experiments, beams such as Ti, Cr, Fe and Ni would be desirable.

Figure 6: The upper part of the chart of the nuclides, showing possible reactions for "first day" experiments at S3 with uranium target. The isotopes that can be produced are marked by shaded rectangles.
2.2.3 Production of superheavy elements with Z=106,108 and 112

It is clear that a "direct assault" on the region of the predicted island of stability with Z=114-120 is extremely challenging, and beyond the scope of a "first day" experiment. Ultimately this assault will require implementation of the A/q=6 injector for LINAG, to obtain the highest possible beam intensities. However, a number of interesting and feasible first day experiments can be proposed with the goal of studying lighter nuclei with Z=106,108 and 112. The isotopes that can be reached lie in a region between the chains produced through cold fusion and hot fusion (especially in the case of Z=112). It should therefore be possible to produce new isotopes, and to study those already produced with more details. A number of example reactions are shown in Figure 6.

The study of lower Z nuclei will also provide valuable knowledge concerning the operation of S3. In order to make studies at the level of 1 picobarn, a thorough understanding of the spectrometer will be required, and the counting rate of background events must be minimised. An estimate of the beam time required for such studies can be gained from the measured cross-sections for xn evaporation channels for the $^{238}\text{U}(^{30}\text{Si},xn)^{268-x}\text{Sg}$ reaction shown in Figure 2 (taken from K.Gregorich et al., PRC 74, 044611 (2006)).

As can be seen in Figure 7, the maximum production cross section for $^{263}\text{Sg}$ through the 5n evaporation channel is approximately 70 picobarns. The corresponding cross section for the reaction $^{238}\text{U}(^{26}\text{Mg},5n)^{259}\text{Rf}$ is approximately 1500 picobarns (Gates et al., PRC 77, 034603 (2008)), a factor of 20 greater than for the reaction to produce Sg isotopes. On this basis, it could be assumed that the maximum cross section for $^{32}\text{S}$ induced reactions to produce Hs isotopes will be of the order of 5 picobarns. The table below gives an estimate of the number of alpha decay events per week which could be observed at the focal plane of S3 for a number of different cross sections. The following is assumed: $^{238}\text{U}$ target, thickness 0.25 mg/cm$^2$, S3 transmission 30%, beam intensity 10 pμA, full energy alpha detection efficiency 55%.

![Figure 7: Cross sections for Sg isotopes produced with the $^{238}\text{U}(^{30}\text{Si},xn)^{268-x}\text{Sg}$ reaction as a function of the excitation energy of the compound nucleus [Gregorich & al., Phys. Rev. C 74 (2006) 044611]](image)
Table 1: Counting rate estimations versus the production cross section

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<th>Cross Section</th>
<th>Events / Week</th>
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<tr>
<td>1pb</td>
<td>2.4</td>
</tr>
<tr>
<td>10pb</td>
<td>24</td>
</tr>
<tr>
<td>100pb</td>
<td>236</td>
</tr>
<tr>
<td>1nb</td>
<td>2364</td>
</tr>
<tr>
<td>10nb</td>
<td>23640</td>
</tr>
</tbody>
</table>

The table shows that with these estimates, an experiment to produce a new isotope of Hs should be possible with approximately one to two weeks of beam time. A similar amount of beam time would be required to make a slightly more in-depth study of Sg isotopes. An experiment to produce an isotope of element 112 would require of the order of one month of beam time.

2.3 Synthesis of a new element: the Z=120 case

An ultimate step in Superheavy Element research is the synthesis of a new element. This is a difficult and laborious task, since the cross sections involved are very low: at most of the order of the picobarn, or, probably, less. Such kind of task requires a precise knowledge of the experimental apparatus: an experiment can last several months without a single event even if all the parameters are correctly tuned... and even if they are not... Nevertheless, the unique characteristics of the LINAG beam and S3 seem to fulfill the required conditions to add a new element to the Mendeleiev table.

In this section, we describe what could be the synthesis of the Z=120 element with S3.

2.3.1 Physics

2.3.1.1 The island of stability

Two family of nuclear structure models are used for the description of SHE, each type with several possible parameterization:

- Microscopic-Macroscopic Models (MMM) are based on a liquid drop model, adjusted to the heavy nuclei. They are corrected by a shell correction method of Strutinsky type, that is also fitted to the known properties of trans-uranium elements. These theory are highly phenomenological, but nevertheless have a fair success in the description of the observed properties in this region.

- Microscopic models are based on self consistent mean field approaches. They are either using density dependant effective interactions (e.g. Skyrme, Gogny) or Relativistic mean field models (RMF).

More information on these models could be found in the review article A. Sobczewsky and K. Pomorski, Prog. Rep on Part. And Nucl. Phys. 58 (2007) 292.

Briefly, the predictions of these models and the present experimental data on this topic are the following:
There is a deformed stability zone around $^{270}$Hs$_{108}$. Indeed, experimental results seem to confirm this stability, even further studies still needs to be done in this region (that can be reached with the $^{30}$Si+$^{238}$U proposed in the previous section).

The neutron closed shell is predicted to be at N=184. Data clearly show that the most stable nuclei have also more neutrons. Nevertheless, since the most neutron rich nucleus that has been produced so far is the $^{293}$116 with 177 neutrons, the experimental confirmation is still lacking.

The predictions on the proton closed shell are diverging. MMM models predict a close shell for Z=114, while microscopic models varies from Z=120 to Z=126 (RMF). Experimental evidences are not decisive. If the Z=114 is the real number, then the sensitivity to the proton closed shell would be less than for the neutron one. Indeed, several indirect approaches are more in favour of a Z≥120 shell. Spectroscopy of lighter transfermium nuclei which probe the $\frac{1}{2}^+$-[521] orbital involved in the Z=114 shell, are compatible with a small gap, not sufficient to form a major shell [Chatillon & al., EPJA 30 (2006) 397]. Fission times measurements [M. Morjean & al., Phys Rev Let 101 (2008) 072701] show a significant increase of fission times, and so of the fission barriers, from Z=114 to Z=120,124. On top of that Adamain and collaborators [G. G. Adamian, N. V. Antonenko, and V. V. Sargsyan, Phys. Rev. C 79 (2009) 054608], using the Di-Nuclear System reaction model, have shown that the synthesis cross-sections are strongly linked to the fusion barriers of the nuclei and that the present result points at a closed shell for Z≥120. We find an illustration of this effect in the Figure 8 from [Yu. Oganessian, J. Phys. G: Nucl. Part. Phys. 34 (2007) R165], that shows the correlation between cross-section for heavy nuclei and their calculated fission barriers. Indeed, the cross section and decay properties of the Z=120 element will be a critical measure for the localisation of the spherical closed shell of SHE.

2.3.1.2 Possible reactions

Several attempts at the synthesis of the Z=120 element have been done so far. The two latest with the best upper cross-sections have been performed:

- In Dubna [Yu. Ts. Oganessian & al., Phys. Rev. C 79 (2009) 024603], where they attempt to produce element 120 in the $^{58}$Fe+$^{244}$Pu reaction, with an upper cross-section of 0,4pb.
- In GSI [D. Ackermann, Nucl. Instr. & Meth. A 616 (2009) 371], with an upper cross-section of 0,1pb with the $^{64}$Ni+$^{238}$U reaction.

To reach the Z=120 element, can consider the following possible fusion reactions:

1. $^{88}$Sr + $^{208}$Pb → $^{296}$120$^*$ (E*=−4,5MeV at the Bass barrier)
2. $^{50}$Ti + $^{249}$Cf → $^{299}$120$^*$ (E*=28,6MeV at the Bass barrier)
3. $^{54}$Cr + $^{248}$Cm → $^{302}$120$^*$ (E*=30,5MeV at the Bass barrier)
4. $^{58}$Fe + $^{242}$Pu → $^{300}$120$^*$ (E*=30,3MeV at the Bass barrier)
5. $^{64}$Ni + $^{238}$U → $^{302}$120$^*$ (E*=26,4MeV at the Bass barrier)

Reaction 1) is a "cold fusion" reaction, with low excitation energy. Up to Z=113, the cross sections for such reactions using a $^{208}$Pb target decreased by roughly a factor 10 for each 2Z added, down to 0,0 pb [K. Morita & al., Nuclear Physics A 834 (2010) 338c]. If such slope remains constant, this would mean a cross section around 10 attobarn, impossible to reach experimentally. Nevertheless, some theoretical calculations do predict higher values. [R. Smolanczuk, Phys. Rev. C 78 (2008) 024601] calculates a cross-section of 1,2femtobarn, while [Z.-Q.Feng, G.-M.Jin, J.-Q.Li, W.Scheid, Phys.Rev. C 76, (2007) 044606] gives 70femtobarn for the $^{87}$Sr+$^{208}$Pb→$^{294}$120+1n reaction.

Reactions 2) to 5) are "hot fusion" reactions with a major evaporation of 3 or neutrons. Several theoretical calculations have studied these systems:
- [V. Zagrebaev & W. Greiner Phys. Rev. C 78 (2008) 034610] gives cross section around 0,04pb for the $^{50}$Ti+$^{249}$Cf → $^{295,296}$120+3,4n reaction.
- [Z.H. Liu & Jing-Dong Bao, Phys. Rev. C 80 (2009) 054608] predict 0.06 pb for $^{50}\text{Ti}+^{249}\text{Cf} \rightarrow ^{296}120+3n$ (and 200 fb for $^{50}\text{Ti}+^{252}\text{Cf} \rightarrow ^{298}120+4n$). By scaling to the fusion probabilities that are calculated for the same compound nuclei, cross-sections of 0.1 pb are expected for reaction number 3), 0.025 for reaction 4) and 0.02 pb for reaction number 5).

- [A. K. Nasirov et al., Phys. Rev. C 79 (2009) 024606] predict a maximum cross-section of 8 pb for $^{54}\text{Cr}+^{248}\text{Cm} \rightarrow ^{299}120+3n$, 0.07 pb for $^{58}\text{Fe}+^{248}\text{Pu} \rightarrow ^{299}120+3n$ et $2 \times 10^{-6}$ pb for $^{64}\text{Ni}+^{238}\text{U} \rightarrow ^{298}120+4n$. The cross-sections steeply decrease with the symmetry of the entrance system.

- [G. G. Adamian, N. V. Antonenko, and V. V. Sargsyan, Phys. Rev. C 79 (2009) 054608] predicts the same evolution with the symmetry of the system. Moreover, the cross-section is shown to be strongly dependant of the localization of the closed shell, equivalent to the choice of the model for predictions of the nuclei masses. For $Z=120$, the predictions range from 0.5 fb to 700 fb for the $^{50}\text{Ti}+^{249}\text{Cf}$ (see Figure 9), and from 0.07 fb to 50 fb for $^{54}\text{Cr}+^{248}\text{Cm}$.

Indeed, for a shell closure at $Z=126$, the cross-sections may even be higher with increasing $Z$ above 120!

As a conclusion, we can say that it seems that the most favourable reactions to reach the $Z=120$ are the hot fusion reactions that lead to a neutron rich compound nucleus. This has to be weighted with the technical feasibility of each reaction that we will investigate in the following sections. In any case, for a reasonable chance of success, a sensitivity of the order of 0.01 pb must be reached.

2.3.1.3 **Produced isotopes**

With 1 neutron evaporation channel for cold fusion and 3 or 4 neutrons for hot fusion, we expect to produce the isotopes with $A=294$ to $A=299$.

As shown on Figure 10, only the $A=299$ and 298 have decay chains that connect on existing nuclei. All other will have unknown alpha decay chains. Nevertheless, S$^3$ is capable of mass measurement, so it is possible to validate the synthesis of a SHE even if the alpha chain is unknown.
On the other side, it is also clear that the neutron richer isotopes will be closer the the N=184 shell. That should enhance their stability as well as increase their production cross section.

Figure 10: evaporation residues produced for the Z=120 element and their alpha daughter nuclei (shaded areas) superimposed with known nuclei.

2.3.2 Experimental parameters

2.3.2.1 Orders of Magnitude
Several parameters have a role in the production rate for a synthesis experiment:
- The beam intensity (1 particle.µA = 6,24x10^{13} particle per sec)
- The target thickness (around 0,4mg/cm²)
- The target effective surface, since the target frames on a rotating wheel cause “dead zones” where the beam cannot impinge (80% of the circumference of the target is useful)
- The spectrometer transmission (in the case of S³, for the ^48Ca+^{248}Cm→^{292}116+4n reaction, the simulations give a transmission around 50%)
- The evaporation residues detection efficiency (linked to the limited size of the implantation detector, estimated to 90% according to the optics simulations)
- The alpha decay detection efficiency that identifies the produced nucleus (80% if a tunnel detector is used)

According to this figures, the number of detected events with one alpha decay is 4,62/pb/month/µA. Conversely, if one event is detected during a 3 months experiment, the resulting cross section of 0,072 picobarn/µA. As a consequence, in order to reach 0,01pb limit, the intensity of the beam must be around 10pµA, since it is the only parameter that can be significantly increase.

2.3.2.2 Beam
Considering that the LINAG accelerator is able to transmit 100% of 1mAe beams (charge space effects are not significant here), the two limiting factors of the intensity before the spectrometer...
are the ion source and the injector. The ECR ion source provide ionized ions, with a give charge state distribution, and the injector will provide an initial acceleration for a given A/q of the ions. The most efficient ion sources today are ECR (Electron Cyclotron Resonance) ions sources that provide highly charged ions. The latest models used superconducting magnet technology and operate at high frequencies (18 or 28GHz). The three major projects in this field are:

- The A-Phoenix source, under development at the INPG Grenoble and IPNL Lyon, [Th. Thuillier & al., Rev. of Scientific Instr. 81 (2010) 02A316]. The A-Phoenix source should be installed at the SPIRAL2 facility.

Intensities from the VENUS and SECRAL sources have already been measured for some ions. We can expect that similar results could be obtained for the A-Phoenix source (presently, a smaller version, the Phoenix V2, is being tested). The intensities depend on the chemical properties of the elements. Rare gases are the easiest to produce. Then metallic ions with low melting point are also fairly possible (there is roughly a factor of 2 less for \(^{40}\text{Ca}\) than for \(^{40}\text{Ar}\)). High melting point metals, like Ni and Cr, are more difficult. Such elements are currently under study at GANIL [G. Gaubert et al, Rev Sci. Instr 79 (2008) 02A309].

As well, Figure 11 shows the intensities extracted from the present GANIL source, and the expected intensities from the Phoenix-V2 and A-Phoenix source with A/q=3 or A/q=6.

![Figure 11: Intensities expected from the new Phoenix-V2, A-Phoenix sources compared to the present GANIL intensities, for different A/q ratios.](image)

What can be concluded from these results is that from ions up to A=40, with A/q=3, it is possible to reach 10pµA for metallic ions. But as soon as the masses increased, only higher charge states are extracted from the source and a A/q=6 injector is then required. On that favourable base, it is already possible today to get 7pµA of \(^{59}\text{Ni}\), 5,6pµA of \(^{52}\text{Cr}\), or 10.4pµA of \(^{56}\text{Fe}\). Hopefully these figures will increase in the coming year with the present development and optimization of the new generation sources with metallic beams.

2.3.2.3 Targets

\(^{3}\) targets have been presented in the “general overview” section. In superheavy elements synthesis, the main aspect is the durability of the target when impinged by the very high intensity beam, and the need to use actinide targets.
For the $^{88}$Sr+$^{208}$Pb case, thermal simulations show that the maximum intensity with a metallic lead target is 5.6 µA and 47 µA for PbS target. It is clear here that the use of a high melting point compound is required.

For actinides targets, extrapolating from $^{40}$Ca beam calculations to $^{54}$Cr, the maximum intensity is 15 µA for metallic Cm, and 37 µA for Cm$_2$O$_3$. It is compatible with a 10 µA beam. Nevertheless, if it is required to have a temperature variation of the target less than 100 K during the rotation cycle, this limit is reduced to 6.1 µA. The role of this limiting factor has clearly to be quantified, since it has the most important effect.

Of course, all the safety aspects emphasized in the target section must be enforced.

2.3.2.4 S3 performances

Input reaction

The S$^3$ spectrometer has been optimized with the $^{40}$Ca+$^{248}$Cm→$^{292}$116+$^4$n fusion-evaporation reaction. Its parameters are very close to the reactions foreseen for the Z=120 synthesis, so we reproduce this results here as a reference.

Figure 12:

- Upper left: angular distribution (dσ/dθ [u.a.] vs θ [rad]) of evaporation residues
- Upper middle: excitation energy distribution [MeV] of evaporation residues
- Lower left: angle [rad] vs energy [MeV] of emitted neutrons
- Lower middle: kinetic energy distribution [MeV] of evaporation residue
- Right: transmission vs geometrical half aperture [rad]
Figure 13: Charge state distributions of evaporation residues (Z=116), beam (48Ca) and backscattered target atoms (248Cm)

From these calculations, we can calculate the kinematics data for the evaporation residue and projectile, summarized in Tableau 2.

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<td>27</td>
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<td>3.0</td>
<td>± 8</td>
<td>±0.2*</td>
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<td>± 55</td>
<td>±2.3</td>
<td>±2</td>
<td>±8.3</td>
</tr>
</tbody>
</table>

Tableau 2: Kinematics data for $^{48}$Ca$^{+}$ $^{248}$Cm $\rightarrow$ $^{292}$116 + 4n

Main issues:
- Evaporation residues are kinematically clearly separated from the beam. The rejection is then easier, but it is also the case where it must reach a very high value of $10^{13}$. Even very improbable charge states or extreme tails of the beam geometry have to be carefully checked to reach this value.
- Large angular and charge state acceptances are required; these will put strong constraints on the size of the magnetic elements.

Simulations

So far, we have calculated the transmission of the spectrometer as well as its mass resolution and image at the final detection plane. The rejection of the beam is also an important aspect, but full simulations of the rejection are very complex and not done yet. What can be said today is that the beam and the evaporation residues are fairly separated in magnetic rigidity (see Figure 13), and so most of the beam will be rejected in the “high rigidity” zone of the beam dump. The simulations presented here involve ray-tracing simulations performed with the Tracewin software. They involve realistic 3D field maps of the magnets. Octupoles are included in all the magnets requiring superconducting technology (this aspect will be dealt with in the optics section).

The Figure 16 shows that the mass resolution (1FWHM) is superior to 300 far all but one charge state (in this case, the 28+ that is 12,8% of the total distribution). The position of each nucleus is well identified on the detection plane (Figure 16) according to its mass, provided the detector has a position resolution less than 1mm. Then, the production of a Superheavy element would be validated with an independent mass measurement in addition to its alpha decay detection. The transmission simulations (Figure 16) show that, thanks to the very large acceptance of S1, more than 50% of the nuclei produced at the target are transmitted to the focal plane.

Such simulations have also been performed using the COSY matrix code. While realistic field maps cannot be computed in COSY (fringe fields are nevertheless included), the results are very similar and fully compatible.
Figure 16: Image at the detection plane of the $^{291,292,293}$\textsuperscript{116} with five charge states from 24$^+$ to 28$^+$. For the purpose of the simulation, all the components have an equivalent population.

Figure 16: Mass separation (1 FWHM) of $^{292}$\textsuperscript{116} with its closest isotopes, with field maps of the new design of the Mosar open multipoles, octupoles in the mass separator and the momentum achromat. $\Delta q=0$ corresponds to $Q=26^+$

Figure 16: Transmission of the five major charge states of the $^{292}$\textsuperscript{116} nucleus and its two closest isotopes. $\Delta q=0$ corresponds to $Q=26^+$. Total transmission is 51.6%.

2.3.2.5 Detection system

For superheavy element synthesis, the detection system is the implantation-decay station described in the detection chapter, that is:
- Emissive foil detectors to measure time of flight
- Stripped silicon detector to detect implantation – alpha decays correlation
- Tunnel silicon detector to detect escaped alpha particle.

The Germanium detectors are not required in this application.

The most important constrain here is the efficiency of the detector for the implantation and for the alpha decays. The technical aspects that come into play are:
- The implantation detector must cover the full focal plane of the detector. As seen on Figure 16, the image is a little bit larger than the 10cmx10cm that is the maximum size for silicon detectors. If, we can go to 10x20cm by putting two detectors side by side (MUSETT actually has 4 adjacent detectors).
- The tunnel detector is required to detect escaped alpha particles, increasing the efficiency from 50% to 80%.
- The electronics dead time must be very small, in order to be able to detect fast alpha decay chains.
3 S³ organization

3.1 Organization chart

The management board is made up of the scientific coordinator (GANIL), two spokespersons (IRFU and ANL) and one technical coordinator (IRFU).

At the upper level of the project a group is responsible of the transverse aspects of the project (system, interfaces, safety), has to drive the technical productions of the subsystems and to ensure of the coherence of the whole.

S3 is not in a construction phase yet. Subsystems are organized in a workgroups approach. After all choices and trade are done and when every laboratories has committed for products to deliver, each subsystem should be leaded by a scientific responsible and a project manager.

3.2 S³ Steering Committee

Following positive opinions of the SPIRAL2 Steering Committee, the SPIRAL2 Scientific Advisory Committee and the GANIL and SPIRAL2 managements it has been proposed to create a Steering Committee of S3.

This Steering committee will evaluate the various steps to be taken and advise the agencies on the course of action and will help the funding agencies to take the critical decisions on the final design, organisation, budget and construction schedule of the project.

It has been proposed that the Committee is initially composed of the representatives of the main funding agencies that are currently likely to be contributing to the S3 construction phase, i.e. the DOE Office of Nuclear Physics, IN2P3/CNRS, Irfu/CEA and GANIL/SPIRAL2.
3.3 Reviews and reports

3.3.1 Introduction

Some reports and reviews will form the communication between the S3 project and the S3 Steering Committee and will enable the Steering Committee to allow the next future steps of the project.

The construction phase will get a green light by the S3 Steering Committee after a S3 Critical Definition Review (CDR). As the multipoles procurement is on the project critical path, this CDR could be preceded by a technical specific detailed design review at the end of the spectrometer design phase (Detailed Design Review or Technical Design Review), allowing some contacts (call for tenders) with industry before the CDR.

There will be overall project reviews commissioned by the S3 Steering Committee and internal reviews in the institutes, following their own procedures, to precisely examine their work packages and give green lights for their duties, deliveries, financial and human resources: CSTS IRFU/SPhN, DOE Alternative Selection and Cost Range Reviews (Critical Decision 1 review), IRFU Kick-off review, DOE Critical Decision 2 and 3b review...

3.3.2 S3 project reviews / reports until construction phase

Spiral 2 Scientific Advisory Committee (SAC) reports and reviews

The Spiral 2 Scientific Advisory committee meets on a biannual basis and notably examines the status of Spiral 2 experiment. At each occurrence, the S3 project provides and presents its status report.

Magnet Conceptual Design Report (end of Magnet Preliminary Design Phase)

The aim of this CDR is to present the status of the ion-optical design, magnet designs and technology options, safety studies and mechanical integration of the full S3 system to provide a basis for a decision on technologies to be used for the hardware components (mainly the technology of multipoles magnets: superconducting or conventional). This includes performance evaluations, construction and operating cost estimates and a project timeline. This document does not include discussion of sub-systems such as target systems, focal plane detection system and the low energy branch except where necessary for clarification of interface issues and overall budget estimate.

We foresee to release this report early June and to send it to a panel of experts, with about 1 month for reading and initial feedback. One month later meeting(s) can be scheduled for discussion of the comments from the panel of experts.

We then will continue our paper studies of S3 beam line with the chosen technologies and so be able to define more precise requirements and interfaces for all the other S3 equipments.

Spectrometer-target Detailed Design Review (end of detailed design phase)

(or Technical Design Review)

In Fall, the project will have finished the detailed definition of the spectrometer components (including the upstream beam line and the dispersive plan beam dump system) and a technical analysis will be needed to validate these designs.

The documentation will be the current S3 status/progress report and specific documentation for the magnets and surrounding systems (specifications, definition, design, risk analysis, development plans, schedule, budgets, commercial approach, safety, radioprotection).

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**S3 project Critical Definition Review**

The goal of this review is to give a green light for the project procurement and construction phase. It will examine the technical conclusions of the Spectrometer-target Detailed Design Review and will review the remaining aspects on the budgets needs and availability.

### 4 Main S³ milestones

The overall schedule of S³ project is driven by multipoles schedules. If we assume that we may start relations with the industry after a Detailed Design Review in Fall we could have the preliminary assessed following milestones, with respect to the different options, for the multipoles procurement:

- 7 superconducting closed triplets
  - Start of call for tender: October 2010
  - Order placement: February 2011
  - End of qualification of prototype: May 2011
  - End of production (24 months): March 2013

- 3 conventional closed triplets
  - Start of call for tender: October 2010
  - Order placement: April 2011
  - End of production: August 2012

- 1 superconducting open triplet (MOSAR)
  - Start of call for tender: November 2010
  - Order placement: April 2011
  - End of qualification of prototype: December 2011
  - End of production: January 2013

- 1 conventional open triplet
  - Start of call for tender: November 2010
  - Order placement: April 2011
  - End of production: April 2012

Thus, we foresee an installation in S³ room in the first half of 2013.

### 5 Technical involvement at IRFU

#### 5.1 Introduction

IRFU is now strongly involved in:

- the scientific management of the project (one of the three scientific spokespersons)
- the technical management of the project (responsibility of the overall technical coordination of the project)
- the design of the spectrometer and optics optimizations
- the definition and technical assessment of the S3 detection in participating very significantly to the five work-groups and in being responsible of the Si detectors work-group
- the S3 nuclear safety; SENAC has been involved, for the Spiral 2 project, in the preliminary dimensioning of the concrete walls of S3 room, is now in charge of the S3 project optimization for all nuclear safety aspects
the preliminary studies of the open triplet, as well for the room temperature open triplet as for the IRFUs new concept of large acceptance superconducting multipole based on racetrack coils (MOSAR)
- the Beam Dump system at the dispersive area

All these tasks have been spending almost only human resources so far and are performed in S3 definition and conceptual phases. IRFU did not commit on Financial and Human resources for the realization phase yet. We expect an IRFU kick off meeting in fall which will review the overall feasibility of the project on one side and precise assessment of tasks and financial resources needs to enter the construction phase for the expected IRFUs work-packages on the other side.

5.2 Status and future tasks of optics studies

5.2.1 Collaboration
The Optics and magnets have been so far the major work topic of S3. Three institutes have been collaborating:
- The GANIL, involved in optics simulations and in the design of warm temperature magnets (closed and open)
- The Argonne National laboratory involved in the optics and in the closed superconducting magnet design
- The Irfu, involved in the optics and in the design of (principally) open magnets (classic and superconducting).
In this text, we will put more details about the work of Irfu.

5.2.2 Reminder of S3 configuration
The S3 optics configuration is the following:
- A target point, with a large beam spot size
- A momentum achromat, with an intermediate dispersive plane where the majority of the beam is separated from the nuclei of interest.
- An intermediate achromatic point, image of the target point
- A mass separator, combining an electric and a magnetic dipole
- A final mass dispersive plane, where the detection set-up is located.
5.2.3 Optical simulations

5.2.3.1 Saclay Studies

The Saclay optical group has been in charge the evaluation of the 4-fold symmetric lattice type. The main feature of the 4-fold symmetric lattice is to define basic cells that are reproduced all over the system. Each cell is composed of a multipole triplet (for the beam focalization in the horizontal and vertical), and a half-dipole (for the spatial separation). Two cells form a dipolar stage, four cells form a separation stage (in mass or in momentum), and eight cells form the whole spectrometer. In the mass separator, the two dipoles are not of the same nature (one electric and one magnetic), and the symmetry is not perfect.

For each cell, the goal is to obtain in first order a transfer matrix having diagonal elements equal to zero. This is done by adjusting the magnetic field of the three quadrupoles and the distance between the last quadrupole and the dipole. The transfer matrix of two cells is the unitary matrix \([-I]\), and the transfer matrix for one separation stage is the unitary matrix \([I]\). Such optical design insures the cancellation of the geometrical second order matrix elements for each separation stage. The complete spectrometer is achromatic, as well as each separation stage. The optical functions are displayed in Fig 1. The beam envelope of the first order optics is shown in Fig 2b.

![Fig 1: optical functions of the spectrometer, horizontal beta function (red line), vertical beta function (blue line), dispersion function (green line). The basic cells defined in the first order optics are indicated with square black boxes, as well as the combinations making unitary transfer matrix.](image)

![Figure 2](image)

(a) S3 layout from the first order calculation performed by the Beta code. The spectrometer has to fit into an area of (26 x 12) m².

(b) \(^{100}\text{Sn}\) first order beam envelopes, in the horizontal (red line) and the vertical (blue line) planes.

A first order lattice satisfying the geometrical and the optical requirements was produced with the Beta code. That lattice was built with a theoretical description of the magnets (quadrupole, sextupole, bending magnet and electrostatic dipole), without taking into account the fringe field of these magnets. In addition to the first order optics requirements, other constraints were to keep the first order beam envelope below 15 cm [see fig 2b], to limit the magnet strengths in
order to avoid the iron saturation, to preserve enough free space around the intermediate focal planes for the insertion of several diagnostics and/or equipments (movable finger, beam dump, detectors,...) and to keep the total dimensions of the line inside the imposed limits [see fig 2a].

This lattice model was imported into the tracking code TraceWin. The TraceWin code transports, taking into account all orders, a cloud of particles which has the same kinematic distribution than the recoil products after the target. The $^{100}$Sn reaction products were chosen for the optimization because this nuclide has a momentum and angular distribution close to the nominal acceptance of the spectrometer [Fig 3]. Different optimization constraints and methods have been experimented in order to reach the mass separation requirement at the final focal plane. The retained optimization method uses as variables all the sextupoles, all octupoles wherever they are inserted, and the last quadrupole triplet in order to maximize the separation of 3 different particle beams transported to the final focal plane (named F4) of the spectrometer.

The TraceWin code was modified in order to track successively 3 charge states of the same particle distribution, which cover the useful final focal plane area (± 50 mm in the horizontal plane). Once the optimization process has converged, the magnet setting is adapted to the super-heavy element reaction case ($^{48}$Ca + $^{248}$Cm -> 4n + $^{292}$116). The spectrometer mass separation power is then calculated from the beam FWHM sizes and positions at the focal plane F4, using the distribution of the $^{292}$116 reaction products. The same first-order lattice is employed for all the following optimizations, in order to compare the different magnet technologies for each combination of multipoles. Each higher-order multipole component can be inserted or not in each separator stage, and in each magnet type (closed or open).

The first simulations are performed with the hard edge models for the magnetic elements. These simulations have showed that, to obtain the required separation [as seen in Fig 4], a sextupolar component is needed in all quadrupole magnets located in the dispersive regions, that have to correct the chromatic aberrations. The compensation of the geometrical aberrations introduced by these sextupoles has to be done with other sextupoles in the non-dispersive part of the beam line. The simulations show also that octupole corrections in the mass separator improve strongly the mass separation [Fig 5]. The insertion of octupole components in a magnet multipole implies the superconducting technology for this magnet.

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Fig 4: Mass separation power in the hard edge case with sextupoles correction components only. \( \Delta q \) represents the charge compared to the reference charge-state (\( q = 26^+ \) for \( ^{292}116 \)).

Fig 5: Mass separation power in the hard edge case with sextupoles and octupoles correction components (octupoles only in the mass separator). \( \Delta q \) represents the charge compared to the reference charge-state (\( q = 26^+ \) for \( ^{292}116 \)).

Afterwards, the quadrupole, sextupole and octupole theoretical magnets were replaced by realistic field maps provided by the Opera3D code. It has to be noted that the TraceWin code does not implement yet magnetic and electrostatic dipole field maps, which means the fringe field contributions for these elements are not taken into account. At first, field maps of classical closed magnets were used for all elements, including the second triplet which has to be “opened” (see section xxx). The closed magnets used for the simulations are: iron-dominated type for the room temperature quadrupoles (section 4.1.1), air core coils proposed by GANIL for room temperature hexapoles (section 4.1.1), and flat race track multipoles developed at Saclay for the superconducting magnets (section 4.1.2.2). As the magnet apertures is large compared to their length, the perturbations due to the magnet fringe fields are significant. One of the disturbing effects of the quadrupole fringe field is to create an octupolar-like perturbation to the beam which deteriorates the previous optimization results. Figures 6, 7 and 8 show the results obtained for different correction with or without octupoles. Octupolar corrections were needed in the mass separator stage to achieve the desired separation [Fig 6 and 7]. Moreover, simulations also showed that the introduction of octupolar correction in the closed quadrupole magnets of the momentum achromat improve significantly the final mass separation [Fig 8].
Furthermore, open multipole field maps (quadrupole and sextupole) were introduced at the position of the second multipole triplet. Two different types of open multipole magnets were developed and tested at Saclay, a conventional open multipole working at room temperature and a first design of an open superconducting multipole (Mosar, see section xxx). For both multipoles the sextupolar component is obtained by subtraction of two dipolar fields with different transverse extension. The main dipolar component is cancelled and the dipole harmonics, mainly the sextupole, remain. In both cases the spectrometer performances were reduced [Fig 9 and 10] and are comparable on average, though they exhibit a different behavior. Compared to the designs with closed multipoles, the main difference comes from the sextupolar component. As the dipolar fields have not the same transverse extension, a dipolar component remains in the
region where the dipolar fields are not overlapping [Fig 29, see section 4.1.2.2]. Therefore that residual dipolar field varies in the transverse direction. The particles which propagate at different transverse positions don’t feel the same dipolar field integral. For these particles the system is no more a first order achromat and the chromatic correction doesn't work efficiently. This effect is difficult to correct on the warm magnets. On the other hand, a new design of the Mosar magnet gives a sextupolar component with a quality similar to a closed sextupole magnet, without unwanted dipolar field (see section 4.1.2). The resulting mass separation of the spectrometer with the new Mosar magnet design is still under optimization, a preliminary result is shown in Fig 11.

![Fig 9: Mass separation power with field maps of room temperature open multipoles, octupoles in the mass separator and the momentum achromat.](image)

![Fig 10: Mass separation power with field maps of Mosar open multipoles, octupoles in the mass separator and the momentum achromat.](image)

![Fig 11: Mass separation power with field maps of the new design of the Mosar open multipoles, octupoles in the mass separator and the momentum achromat.](image)
5.2.3.2 **GANIL studies**

In parallel, the GANIL group has studied alternative configurations with 2-fold symmetry. The breaking of symmetry implies that some of second order aberrations cancellation due to symmetry the configuration. On the other hand additional degrees of freedom are gained to tune the spectrometer and specially to adjust the distances between the optical elements when constrains from other aspects (compatibility with other detectors, need of specific inserted equipments...) comes into play.

In order to perform these simulations, the matrix COSY code was used. COSY is capable of calculating systems at an arbitrary order of Taylor expansion and can include at least 2d field maps for realistic optical elements. In practice however, using ever increasing expansion order and more precise descriptions of optical elements—from Enge coefficient fringe fields, to z-dependent all-order multipoles, and finally to 2d field maps—results in prohibitively long map computation time. For example, calculating a fifth-order transfer map for a single quadrupole element using a symplectically scaled Enge function fringe field takes less than one second, while the same map calculation based on a quadrupole field map takes more than 20 minutes.

In addition to generating the transfer maps, calculating the system performances in the Taylor expansion method requires evaluating the result of a large number of rays acted on by the system. At some point, after adding successively higher orders to the Taylor expansion, the mapping of a single ray through the Taylor expansion begins to take a comparable amount of computation as a full ray-tracing treatment. Also, the map method is more difficult to parallelize, since the computation is of a coarser granularity. Thus COSY is more suited to early stages of the design project, where higher order behavior is important, but before detailed element designs are being considered.

**Figure 172**: Distribution at the final focal plane (top), transmission (bottom-left) and resolving power (bottom-right), calculated for the full-width at half-maximum, for five charge states and three masses centered on 292 116\(^{+}\) taken from a Monte Carlo calculation using a third-order COSY map. Note that the \(x\)-space in the top plot presents species of decreasing \(Q\) from left to right.

We show here the performances that have been achieved in third-order COSY calculations for the superheavy element production case, using sextupole corrections throughout the system and octupole corrections in the M/Q separator. Transmission of all produced particles of mass 292 is 62\%, and the resolving power—calculated based on the full-width at half-maximum—is above
300 for all five charge states within the acceptance. We can see that these results are fairly comparable with Tracewin simulation using hard edge magnet models.

Third-order COSY calculations including only sextupole correction elements throughout the system were unable to reach the desired M/Q resolving power, in agreement with Tracewin simulations. Also, the simulations show that the inclusion of octupole corrections in the momentum achromat increases the performances of the spectrometer.

Going to 5th order simulations shows that the performances of the transmission and the resolution decrease. This emphasizes the important and unavoidable role of high order aberrations in the spectrometer.

**5.2.3.2.1 Next step of optimization**

The COSY and Tracewin simulations show that the performances simulated are robust versus the exact configuration of the spectrometer. They are independent of the precise angles of the dipoles, or the distances between magnets. This makes us confident to think that even if some slight modifications in the configuration are required due to external constrains (e.g. mechanics) the estimated resolution and transmission levels can be maintained.

So far, no simulations are perfects. It is necessary to include fully realistic files maps of the dipoles and of the multipoles and optimize the configuration with them, which is not possible with Tracewin nor COSY. Two paths of progress are currently foreseen:
- include field maps in the Tracewin code for magnetic and electric dipole (Irfu/SACM)
- improve the optimization algorithm of the Zgoubi code, which is able to use field maps for all elements (GANIL).

Also, with the progresses of the detailed design of the different elements of the spectrometer (target, beam dump, electric dipole, magnetic multipoles...), it will be possible to make more and more realistic simulation of the full device.

Simulations of the rejection power must also be done. They are very complex since they involve rare and stochastic events: beam halo, scattering of ions on every element all along the beam line, interaction with residual gas...

Finally, we have to take into account the imperfections of a realistic tuning of the spectrometer: beam quality, precision of the tuning of the fields and of the positioning of the magnets... that will inevitably decrease the performances of S3. The further simulations have to take all these aspects into account as much as possible.

**5.2.3.3 Primary Beam rejection**

It is very dangerous to have very intense projectile beams of 10pµA or more possibly hitting all elements of the S3 beam line, including the electric dipole which is required for the high mass resolution. Hence, the goal of the momentum achromat is to perform a preliminary rejection of the beam, such that ~0.1% or less of the beam can enter the mass spectrometer. We have studied the beam trajectory for symmetric (100Sn, ) the direct (Z=116, figure 3) and fusion kinematics.

According to these simulations, the beam can be stopped in two main sectors:
- Outside the beam pipe, after going through the first multiplet located after the first dipole (figure 3). In the direct kinematics (SHE production, for example 292116) case, 100% of the beam impinges in this zone. In the 100Sn setting, 73% of the 58Ni primary beam can be stopped in this region. A beam stopper is necessary to protect this area. The magnets of this multiplet have to be ‘open’ in order to allow the beam extraction.
- At the intermediate focal plane of the momentum achromat, at several well-defined points, depending on the projectile charge-state (figure 2). 27 % of the primary beam can be stopped in this region, in the 100Sn setting. Water-cooled fingers with a width of about 1cm can be inserted at each of these positions (which vary according to the kinematics). Each finger stops up to a few tens of % of the projectile beam. Transmission simulations show that the presence of fingers with a horizontal width of 1 cm in this focal plane causes a loss of 19% of the 100Sn evaporation residues.
The distribution of $^{58}$Ni charge-states at the intermediate focal plane is shown in figure 13.

![Figure 13: Charge-state distribution of the $^{58}$Ni beam at the intermediate focal plane. The beam pipe area limit at $x = +150$ mm is indicated by a black line. The positive horizontal positions correspond to the higher rigidities.](image)

In the beam pipe area, the distributions are well defined, as the projectile beam has a small momentum and angular distribution. The maximum area necessary for a finger to stop each charge state is around $(10 \times 20) \text{ mm}^2$.

The charge states going outside the spectrometer acceptance have a much less defined distribution because they travel through the vertical gap of the open magnets, where the field is not quadrupolar anymore. Therefore they can have a very large horizontal and vertical distribution when hitting the beam dump. In the case of $^{58}$Ni it is less critical because the most exotic charge-states are weakly populated, but with very asymmetric fusion reactions it could be more problematic. The beam dump should have a total vertical width of about 400 mm.

At the image point of the momentum achromat, a small collimator placed at this point can remove most of the scattered ions. After this first stage of rejection, the beam counting rate is reduced to a tolerable fraction that allows it to be filtered in the mass spectrometer. The mass spectrometer is still necessary to suppress all the evaporation residues with masses close to the nuclei of interest.

### 5.3 Status and future tasks of magnet studies

All the optical simulations have shown that sextupole corrections are required in all the elements of S$^3$. Also, octupole corrections are required in the Mass Spectrometer part, and use of octupoles in the Momentum Achromat significantly increases the performances. That’s the reason why we have to use superconducting technology for the magnetic multipôles. This is the only solution to embed in the same element quadrupole, sextupole and octupole field. Nevertheless, if this technology is fairly common for closed magnets, it is not the case for open magnets that are required in the beam dump area. For that specific case, we have studied two basic designs that enable to superimpose quadrupole and sextupole fields:

- One use conventional, room temperature technology.
- The other design use superconducting technology in a very innovative way, called MOSAR (#French acronym of flat Racetrack based large Acceptance Open Superconducting Multipole). Several paths for MOSAR design are described. One of them include octupole corrections.

### 5.3.1 Closed superconducting multipôles

We are also studying the use of superconducting multipoles. While technologically more complex, this solution remains cost effective since it substantially reduces the number of power
supplies needed (due to the high power consumption of room-temperature magnets) and could provide further savings through reduced power consumption in the long term. Note that while their application to a low energy spectrometer is original, such magnets do not show specific technical difficulties and their construction process is well known. Superconducting elements also have the advantage of enabling the addition of octupole fields that could be used to further correct higher order aberrations. The figure below shows the preliminary design with and without an iron shell enclosure. Other options based on a double helix coil design are also being considered.

![Coils](image1.png) ![Coils with Iron Shell](image2.png)

Figure 14: Superconducting multipoles, including quadrupole, sextupole, and octupole components, both without (left) and with (right) an outer iron shell.

A design study including field uniformity, quench safety, cryogenic performance, ease of construction, manufacturing cost and potential technical risks has been completed soon by ANL and the Advanced Magnet Lab company in US-Florida and is under study within the collaboration.
5.3.2 Design of open multipôles

5.3.2.1 Saclay conventional magnet design

The quadrupole design was developed with a similar approach than the GANIL design, except that a return leg is needed in addition for the sextupolar field. The first studies showed a high saturation of the quadrupole iron. The pole geometry was optimized [Fig 15] in order to reduce this saturation down to 1.55 T when the sextupole component is turned off. For 51764 At per coil a maximum gradient of 5.7 T/m is reached. A fraction of the magnetic flux goes through the leg, depending on the proximity between the leg and the pole.

![Fig 15: Transverse cut of the room temperature open multipole. The sextupole is obtained with the combination of the dipolar coils close to the magnet pole and the coils placed around the return leg.](image)

The sextupolar component is achieved by the subtraction of two dipolar fields. One is obtained by coils around the return leg (S1), the other by dipolar coils close to the magnet pole (S2). The geometry of the S2 coil is highly critical. Its shape and its position around an angle of 45° near the pole tip have a strong influence on the sextupole field quality. The S2 coils geometry has been optimized in order to reduce the current density. Each coil must be placed above the 45 degrees line and its surface minimized close to this position.

With the following setting, for the S1 coils NI = 10500 At/coil, and for the S2 coils NI = 23500 At/coil, the sextupolar “gradient” obtained is about 10 T.m⁻². The superimposition of the quadrupole and the sextupole leads to a difference in the pole saturation, that is due to the dipolar field. The saturation is modified from 1.55 T to 1.7 T in the iron.

The field maps have been produced in a full triplet configuration to take into account the proximity between each multipole. Fig 16 illustrates a triplet configuration where all quadrupoles are switched on, without sextupoles.
For each field map calculation, each element of the triplet is switched on or off. In addition to the first natural harmonic of the quadrupole, the dodecapole (C6), dipolar (C1) and sextupolar (C3) terms appear. These are created by the dissymmetry of the magnet due to the leg.

The harmonic analysis for the sextupole component in a half-triplet is shown in Fig 22. In addition to the unwanted natural harmonics of the dipole, the decapole (C5) the 14-pole (C7) and the 18-pole (C9), a strong dipolar (C1) term remains in the fringe field region.

5.3.2.2 Ganil design

For the open triplets of multipoles that are close to the beam dump, an alternative solution was designed by GANIL, minimizing the dipolar effects found in the previous solution. This closed RT solution uses a combination of two dipolar coils to create a kind of sextupole field. The curves below show how the sextupole is created. Green and blue represent the field of the dipole coils, and the black the resulting sextupole field. The red, dot-dashed curve shows the theoretical ideal sextupole field.

Figure 17 Comparison of an ideal sextupole and the GANIL room-temperature open sextupole. The good field region extends, in this case, to around 100mm. This design is still to be improved, but the result will stay significantly away from the ideal sextupolar field. Adjusting the ends and lengths of the two coils will enable the minimization of the residual dipolar effect.
This design requires high current density in the coils, and significant power.

Figure 18: The GANIL room-temperature, open multipole, including quadrupole and sextupole components.

Different length of the several multipoles – closed and open- have been studied, for the different optics solutions.

5.3.3 Superconducting Open Multipole

C-shaped quadrupoles are common in magnetic spectrometers. Usually, open quadrupoles are realized with conventional ferromagnetic structure at room temperature. When quadrupole and sextupole fields have to be combined, the sextupole component is obtained by the superposition of two dipolar coils with opposite field, the dipolar field is cancelled and the first sextupolar harmonic is the main component left. One of these dipolar coils, located on the magnet pole, limits the vertical acceptance.

With the 300 mm aperture diameter and the 1.8 T.m maximum magnetic rigidity needed for S³, an increase of the pole tip radius, in order to restore the vertical acceptance, leads to a very bulky and heavy object. Moreover, it is difficult to control the remaining higher harmonics without additional coils which are difficult to place. In the S³ case, the maximum magnetic rigidity requirement means that the saturation is reached in the iron, which contributes to a non-linear behaviour of the magnet. To avoid the problem of iron saturation while respecting a low level of higher multipolar harmonics, novel superconducting solutions are proposed.

The use of specific superconducting flat racetrack coil arrangement (MOSAR*), instead of usual saddle-shaped coils, achieves similar or even better specifications than conventional technology. Such structure can integrate sets of coils for sextupolar and even octupolar component. A proper control of the harmonics would give a more efficient magnet than in the ferromagnetic design. Moreover the magnet size and weight are notably reduced as well as its power supplies.

Nevertheless, the magnet length and its aperture have the same order of magnitude, leading to difficulties to realize in some cases a large homogenous field area.

5.3.3.1 Multipole geometry

The magnet geometry is governed essentially by the ±50 mm of the vertical gap used for primary beam rejection. This gap has also to integrate the thickness for mechanical and vacuum components and cryogenic constraint. The total gap is estimated to be ±90 mm.

*French acronym of flat Racetrack based large Acceptance Open Superconducting Multipole
The quadrupole coils configuration is in standard 45° symmetry but the coil extension is reduced to leave the vertical gap free. Consequently, due to a mismatch between the current distribution and the \( \cos(2\theta) \) law, the main quadrupole windings create a dodecapole component which is compensated by an opposite quadrupole winding.

Sextupolar and octupolar field can be obtained by different coil arrangements depending on field level, field quality and magnet compactness.

5.3.3.2 Compact coil configuration

Like in the open classical quadrupole, the sextupole field is obtained by two dipolar windings which create naturally a sextupolar harmonic. In order to cancel the next natural harmonics of the dipole, the decapole, a third dipolar winding is added (see Fig. 19).

The size, the arrangement and the assembly of the coils is crucial for a good magnetic behaviour and for the limitation of the current density (Table 1).

The use of a staged flat racetrack configuration allows the increase of the straight section of the winding, which effectively creates the wanted field. To obtain that, it is needed to use thin windings to realize the winding ends perpendicularly to the straight part with a low winding radius.

![Figure 19: MOSAR compact design. The red and blue colours indicate the different current signs.](image)

Table 1: MOSAR compact design characteristics.

<table>
<thead>
<tr>
<th>Coil type</th>
<th>Size (mm)</th>
<th>J (A/mm²)</th>
<th>Gradient</th>
<th>Peak Field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole</td>
<td>60 x 20</td>
<td>150</td>
<td>6 T/m</td>
<td></td>
</tr>
<tr>
<td>Anti-dodecapole</td>
<td>30 x 20</td>
<td>115</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 20: 3D-model of coils using OPERA-3D© [2].](image)
<table>
<thead>
<tr>
<th>Component</th>
<th>Size</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>30 x 20</td>
<td>344 T/m²</td>
</tr>
<tr>
<td>Anti-dipole</td>
<td>35 x 35</td>
<td>244</td>
</tr>
<tr>
<td>Anti-decapole</td>
<td>40 x 20</td>
<td>210</td>
</tr>
</tbody>
</table>

The 12-pole component of the quadrupole is cancelled at the magnet center by the dedicated coil, but an amplification of this component arises at the winding ends, as shown on Figure 21. An optimization of the end shape could lower this effect.

![Quadrupole harmonic components along z.](image)

About the sextupole, an important number of harmonics remain and for some of them with a relatively high level (Figure 22). This implies a reduction of the transverse sextupolar good field area.

![Sextupole harmonic components along z.](image)

Moreover as the sextupole is build by combination of two dipolar fields with different horizontal size, a residual dipolar field remains which varies with the horizontal extension (Figure 23).
The sextupole design, which gives a compact multipole magnet, has a relatively small useful horizontal aperture compared with the S3 need.

5.3.3.3 Symmetric coil configuration

To extend the sextupolar good field area, it is possible to place the sextupole coils with similar rules than for the quadrupole. The sextupole coils configuration is in standard 30° symmetry and the transverse coil extension is reduced to not overlap with the vertical gap. To obtain sufficient coil aperture the coils distance to the magnet axis is increased (Figure 6). In this configuration, only the first high order harmonic remains at a relative level of $1.4 \times 10^{-3}$ at 120 mm radius and at maximum current (Table 2). With symmetric coils, there is no more dipolar component.

With a gap height up to ±90 mm, it becomes possible to insert an octupolar symmetric set of coils (Figure 24) which gives similar behaviour as the sextupole, with only the first natural octupole harmonic at a relative level of $10^{-4}$ at 120 mm and at maximum current.

<table>
<thead>
<tr>
<th>Coil type</th>
<th>Size (mm)</th>
<th>J (A/mm²)</th>
<th>Gradient (T/m)</th>
<th>Peak Field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole</td>
<td>60x20/30x20</td>
<td>150/115</td>
<td>6 T/m</td>
<td>5.6</td>
</tr>
<tr>
<td>Sextupole</td>
<td>20x30</td>
<td>280</td>
<td>11 T/m²</td>
<td></td>
</tr>
<tr>
<td>Octupole</td>
<td>43x25/34x25</td>
<td>180</td>
<td>18 T/m³</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Figure 23: Sextupole residual dipolar harmonic component variation along z and the magnet radius R.

Figure 24: MOSAR design with octupole.

Table 2: MOSAR symmetric design characteristics.
In this case the maximum peak field is about 5.6 T located on the quadrupole and octupole coil ends.

The sextupolar correction satisfies $S^3$ requirement in terms of gradient. But for the octupole the maximum gradient is limited.

5.3.3.4 **Specific octupolar design**

With an increase of the free gap up to ±96 mm, the previous octupole design leads to excessive values for the peak field and the current density. To keep the octupolar component available, an original design with “radial coil arrangement” is studied. The principle is to put coils by pairs at an angular position where the amplitude of both $\cos(12\theta)$ and $\cos(20\theta)$ are minimized and $\cos(4\theta)$ is quite high. An octupole could be obtained by using 8 pairs of coils alternatively polarized (Figure 25).

If we suppress one set of coils with the same polarity, we still obtain an octupole but with half the amplitude by the field superposition principle. We can remove the horizontal and vertical coil pairs to create an opened octupole close to the magnet axis. Because the geometrical symmetry of the quadrupole is compatible with this specific octupole coils geometry, it is possible to insert these coils inside the quadrupole coils and above the anti-dodecapole coils (Figure 26). The octupolar field is then enhanced with lower current density and the peak field remains acceptable (Table 3).

![Figure 25: “Radial coil” octupole configuration.](image1)

![Figure 26: MOSAR with “Radial coil” octupole.](image2)

Table 3: “Radial coil” octupole design characteristics
<table>
<thead>
<tr>
<th>Coil type</th>
<th>Size (mm)</th>
<th>J (A/mm²)</th>
<th>Gradient Field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole</td>
<td>44x19/32x11</td>
<td>225/170</td>
<td>6 T/m 6.3</td>
</tr>
<tr>
<td>Sextupole</td>
<td>40 x 28</td>
<td>190</td>
<td>11 T/m²</td>
</tr>
<tr>
<td>Octupole</td>
<td>35 x 20</td>
<td>120</td>
<td>25 T/m³</td>
</tr>
</tbody>
</table>

### 5.3.3.5 Conclusions on MOSAR

We have studied different magnetic designs to realize an open superconducting multipole for S³ able to include quadrupolar, sextupolar and possibly octupolar components. All three designs are so far compatible with S³ performances, but some show better results than others:

- A “compact sextupole” design, where the sextupole field comes from two compensating dipole coils. This design has so far poor field homogeneity, but it is still under optimization.
- A “symmetric coil” configuration, that gives a natural very good sextupole field, at the cost of encumbrance and size.
- An “octupole added” configuration, where axial coils can provide additional corrections to improve the spectrometer performances, but with great echanical complexity that has to be further studied.

The use of flat racetrack coils will give easier winding. As the coils arrangement depends strongly on the free vertical gap size, the magnet final design will be determined by the cryogenic and mechanical space constraints and needs as well as final cost. These studies are still ongoing.

### 5.4 Conclusion on optics and magnets

So far the different optical studies made in Irfu, GANIL and ANL converge on a possible configuration that will meet the requirements of S³:

- Transmission better than 50% for large emittance experiments
- Mass resolution better than 300 for superheavy element production experiments.

For that purpose, we need:
- Sextupole correction in all the quadrupoles of the line
- Octupole correction in the multipoles of the mass separator.
- Octupole corrections in the momentum achromat, at least in the three triplets except the second one, in the beam dump zone.

These corrections require the use of superconducting technology to embed sextupole and octupole within a quadrupole. This technology is “standard”, as can be obtained with reasonable cost.

As far as the open multipoles are concerned, simulations show that better results are obtained with superconducting magnets than with room temperature magnets. On top of that, superconducting technology could allow the addition of helpful octupole corrections. But since these magnets have a very innovative design, we still have to check if no major flaw appears.

Meanwhile, the collaboration is still investigating and defining all the possible configurations, in terms of final performances reached construction cost, operating mode and cost, and planning. A "Magnet Conceptual Design Report" will be submitted to the S³ Steering Committee in the coming weeks in order to have its agreement on the next steps of the project.
5.5 Status and future tasks of detection studies

5.6 Detection System

The focal plane detection system for S$^3$ will be an implantation detector for decay spectroscopy of heavy and super heavy elements, therefore optimised for the study of nuclei produced with very low cross section down to the level of femtobarn. It will be a highly efficient device for the identification of evaporation residue based on energy and time of flight criteria; thanks to spatial and time correlation of the events for charged particle, it will possible to observe and characterize long lived decays. Moreover, it will play an important role for the measuring of the mass of the incoming ions. To achieve these objectives a combination of several detectors is required.

5.6.1 Implantation detector

The heavy ions will be implanted in a double sided strip silicon detector. These nuclei subsequently undergo via radioactive decay by spontaneous fission or emitting low energy beta particles, protons, alpha particle, neutrons and gamma rays. The DSSD strips identify where and when the nuclei were implanted. Subsequent radioactive decay at the same position at specific time can be correlated with the implant. Observation of a number of such correlations enables the determination of the energy distribution of the radioactive decay and its half life. The schematic layout of the detector system is shown in Figure 18.

![Figure 18 Schematic layout of the focal plane](image)

Required capabilitiesThe area of the DSSSD will be 100x100 mm$^2$ in order to match the focal plane size, which will accept more than 90% of all evaporation residues reaching the focal plane. If required, in some specific case, it would be possible to use 2 detectors side by side, to reach 20x10cm$^2$. It will have 128 front side (Y axis) and 128 back side (X axis) strips, which is currently the available technology used for the MUSETT detector., It represents a good comprise in order to have a good mass separation. The detector spatial resolution has to be low enough (<1mm) in order not to impair the mass measurement that comes from the spatial distribution of the ions on the focal plane. The simulation (Figure 19) shows having 780 µm pitch width on the front side and back side of DSSD will be possible to well separate three masse
A=291,292,293 ions and five charge states from q=22+ to 26+. Its thickness will be determined for an optimal efficiency regarding alpha as well as electrons detection.

Figure 19 Simulation of the image at the detection plane of A=291,292,293 ions with q=22 to 26+. Mass resolution is here around 300 (FWHM)

The main challenge to achieve is of measuring alpha particle (E_{alpha} ~10 MeV) and electron of low energy (E_{electron} < 1 MeV) and heavy ions with much higher energy in the same silicon detector with very good energy and time resolution for both types of events, with a difference in time between two events that can be very short (down to 10µs). The alpha particles have a total energy around 10 MeV that have to be measured with 15 to 20 keV resolution. The heavy ions will deposit in the same silicon detector a maximum energy of 500 MeV that have to be measured with 5-10 MeV resolutions. A decay event, either alpha or electron, can occur very fast after the implantation of a heavy ion in the same silicon strip; in the most extreme case, the heavy ion implanted can be followed by its decay after few microseconds. Therefore, the dead time for the electronics should be very low in order to be able to handle low energy very fast decays coming just after the high energy implantation signal.

High counting rates (~1 kHz /channel) may occur by measuring medium mass nuclei produced with high cross section, this may create serious damage on the detector (a silicon detector can accept ~4e6 ions/mm² (fission fragments) before getting seriously degraded. In the paper of Livingstone NIMA370(1996)445, they observe a degradation of the resolution from 30keV to 50keV at 8e6/mm2). In this case, it is necessary to investigate different type of detector like “p-type” silicon detectors that are recently available in large size and that have a high resilience to radiation damage. A second possibility is to shift the silicon detector away from the focal plane. The distributions are widened and the local counting rates reduced, or it could be measured with an emissive foil detector that has a higher counting rate. In these cases, the mass resolution is degraded, but the maximum value of 300 is not required for such medium mass ions. It is really required in the case of super heavy elements studies, when the counting rates are very low.

Mandatory is the absence of dead layer not to stop the low velocity recoils on the surface of the detector.

5.6.1.1 Summary
- Implantation
  - Large size detectors (100x100mm²)
- Position resolution < 1mm
- Windowless detectors
- High energy: 10 MeV to 500 MeV (dynamic 50) Resolution FWHM 1%
- Low energy: -7.5 MeV to -250 keV FWHM TBC
- Low energy: 100 keV to +15 MeV FWHM < 2 x 10^{-3} WITH 15 keV @ 8 MeV
- Timing resolution 1 ns with emissive foil
- Counting rate 1 kHz / channel, 10 kHz on whole detector
- Ability to detect large (> 50 MeV) pulse quickly (≈ 10 µs) followed by a weak (<15 MeV) pulse.
- No dead time to detect short lived decay chains.

5.6.2 Veto detector

A veto detector of the same size of DSSD has to be placed 10 mm downstream from the implantation detector. This detector provides a further tool to discriminate a heavy ion from light fast ions that penetrate the DSSD. It will have a thickness of ~1 mm in order to stop also electrons of 1 MeV of energy.

5.6.3 Tunnel detector

Heavy ions are typically implanted into the DSSD at 1-10 µm depth, depending on the target-projectile combination. Conversion electron and alpha particle that are emitted during a subsequent radioactive decay process have a significant probability of emerging from the DSSD in the backward hemisphere relative to implantation. It is for this reason that four silicon detectors will be mounted perpendicular to the implantation detector in a box arrangement to measure alpha particles, conversion electrons and fission fragments escaping the DSSD. The energy deposit in the tunnel detector will depend on the implantation depth, emission angle and dead layer thickness.

5.6.3.1 Required capabilities

The size of tunnel detector could be variable. If we will choose a detector having the same size as the implantation detector we can reach 24% detection of backscattered alpha particle and conversion electrons. For the latter ones, are already available large size silicon detectors of 2 mm thick.

Figure 20: Electron detection efficiency of the tunnel detector versus its length.

Simulation performed by K. Hauschild (IN2P3/CSNSM)

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5.6.3.2 Summary

- Si Tunnel
  - Large size (60x100mm²)
  - 0 to 15 MeV for electrons and escaped alpha
  - Resolution FWHM < 5 keV for electron, 15 keV for alpha)
  - Time resolution: 10 ns

5.6.4 Germanium detector

Due to the low production cross section of heavy elements and super heavy elements, the gamma sensitivity of the focal plane is one of the main issues. Gamma rays from the de-excitation of daughter nuclei will be measured by an array of HPGe detector, the typical energy is between few keV and 1-2 MeV.

5.6.4.1 Required capabilities

The gamma-array will be constituted of an optimised geometry gamma-ray array with the highest possible photopeak efficiency at 1.33 MeV as well as a good efficiency at lower energy. For the first day experiments, the array will consist of HPGe detector from the EXOGAM collaboration. Between 5 and 8 detectors will be installed and only core information recorded. In the simulation (Figure 21) is shown the gamma ray efficiency curve when 8 Exogam clovers (60 mm diameter. Crystals) are placed in a ring around the implantation detector at a radius of 110 mm, and a ninth EXOGAM clover is facing upstream.

![Figure 21 Simulated gamma rays singles detection efficiency for an EXOGAM clover array. Simulation performed by K. Hauschild (IN2P3/CSNSM)](image)

5.6.4.2 Summary

- Gamma detection
  - Low Range: 0 to 4 MeV FWHM < 2 keV @ 1.3 MeV TR: 10 ns OR
  - High Range: 0 to 20 MeV (TBC)
5.6.5 Time of flight detector

The use of TOF measurement has demonstrated power of selection brought to the detection of heavy nuclei. These detectors will have very high time resolution in order to provide time of flight measurements and ion tracking, and it will be located in front of the DSSD. They must have a high efficiency in order to discriminate the ions than comes from the target from the charged particle decays that originate from the implantation detector. The $S^3$ detectors will be similar to the Se-D detectors that are used with the VAMOS spectrometer since several years [A. Drouart & a.l, NIM A579, (2007) p1090], only with a smaller size (20cm width instead of 40cm). They will be equipped with the new AGET electronics.

![Figure: Se-D (Secondary electron detectors) currently used with the VAMOS spectrometer](image)

It will be constituted by a series of 1 to 3 removable Se-D (Secondary electron detector coupled with an emissive foil) devices. These detectors are known to have good timing (~300ps) and position (~1.5mm) resolutions, with a very low material thickness (~50µg/cm² of carbon). The maximum counting rates per channel is expected to be of the order of 1kHz. These detectors will be partially or totally removed for slow recoil speed experiments.

5.6.5.1 Summary

- Large size (200x100mm²)
- Very low thickness
- Time resolution < 1ns
- Position resolution = 1mm
- Counting rate 1kHz / channel, 1MHz full detector with 10kHz trigger

5.6.6 R&D for $S^3$ Focal Plane Phase: Silicon detectors

5.6.6.1 Acquired Experience/Starting point

In 2009 at CEA Saclay was built the new focal plane detector MUSETT (Silicon wall for the study of transfermium by tagging). Musett is the new detection array for the study of very exotic nuclei. Coupled to VAMOS magnetic spectrometer and to exogam gamma multi-detector, Musett allows the spectroscopy of new exotic heavy and super heavy ions (Z>100). Musett is made up of four identical blocks of 10x10 cm. The silicon detectors (10x10cm) are highly segmented (128 vertically x128 strips horizontally) on each side, and they are windowless in order to allow the detection of very slow and heavy ions. Due to the high number of high resolution channel (1024), a new low noise ASIC, the ATHED (Asic for Time and High Energy Deposit), has been designed at Saclay. To minimize the noise the front end electronics are installed as close as possible to the detectors. Because of the high power dissipation, electronics and the detectors are kept at a constant temperature inside the vacuum chamber. The readout and the slow
control of the front end electronics are performed using a new VME board designed at SACLAY (Figure 22). The controlled data acquisition software has been developed at SEDI SACLAY using a labview framework. Unfortunately, MUSETT electronics cannot be used as such for S3. The energy resolution of around 35keV (15-20keV are required for S3) and the electronics is not designed to have a very low dead time.

As shown in Figure 23, a test-bench was developed at Saclay for the MUSETT characterization: the Si detector, its associated front-end electronics and mechanics, vacuum chamber, the remote controlled cooling system and power supply, VME electronics and computers for data acquisition and sorting. All the prototypes of the MUSETT Si wall were therefore tested in the laboratory: test and validation of the detectors, front-end electronics, mechanics, read-out electronics and data acquisition. The test bench was also used to test and validate series before the integration at the focal plane of VAMOS.

5.6.6.2 Development Plan

In order to fulfill all the features required for the implanted and backward detector, several tests have to be performed and R&D is valuable. The aim of this R&D is to define detectors qualification and integration test.

Summary of constraints:

- Implantation detector
- Large size detectors (100x100mm²)
- Position resolution < 1mm
- Windowless detectors
High energy: 10 MeV to 500 MeV, Resolution FWHM ~ 10 MeV
Low energy: 2 MeV to 20 MeV, Resolution FWHM < 20 keV
Hardness to radiation damage: Counting rate 1kHz / channel, 10kHz on whole detector
Si Tunnel
Large size (60x100mm²)
0 to 15 MeV for electrons and escaped alpha FWHM < 5 keV

5.6.6.2.1 Actions DSSSD

The large size of the silicon detector requires a marketing investigation to establish the different options available and the best compromise in term of measures quality, costs and schedule. We will profit of previous experience on MUSETT acquired:
- Good collaboration with different Detector’s producer (Micron, Canberra etc...),
- Handling the whole problematic concerning the cable and connections
- Knowledge on the physics of DSSSD

The test bench can be used for S3 R&D tests and developments and qualification. It is equipped with:
- Vacuum chamber
- Turbopump for high vacuum
- Cooling system (temperature measurements probes and sensors) (Low-temperature Thermostats LAUDA with control remote)
- Multichannel power supply system (CAEN) (all the parameters can be remote controlled via Ethernet) for high and low voltage
- good groundings
- no electronics noises

5.6.6.2.2 Tests to perform and features required:

- P-type, n-type: chose the best detector hardness to radiation damage
- Detector Thickness: 300 μm, 500 μm according to the different type of radiation (alpha particle or conversion electrons or high energy betas)
- Chose the number of pixel: compromise between a pixel size as small as possible and the number of electronic channels. Constraint: <=1mm strip in X in order not to degrade the mass resolution of the spectrometer. In the Y direction, an increased segmentation would only help to divide the counting rate per strip.
- Windows less
- High resistivity in order to have good energy resolution

5.6.6.2.3 Actions Tunnel

- Define the segmentation of the tunnel detector:
  → Stripping silicon detector, e.g. 10x6 mm
  → Pad silicon detector e.g 1 cm²
- Thickness: 300 μm, 700 μm, 1 mm
- Windowless might be required for good alpha energy resolution
- Investigate the possibilities of having the n+ side as the front face (like the Fazia detectors) in order to have alpha-electron discrimination. This is especially important for shallow implantation depths and when alpha decay is followed by electron conversion. The escape alpha may leave a little energy in the tunnel and obscure the electron. If for a given energy, the shape discrimination could discriminate an alpha from an electron - then the problem would be solved.

5.6.6.3 Actions Si veto

The silicon “veto” detector will be placed behind the focal-plane as close as possible from the viewpoint of detector. A veto detector is necessary to reject light fast ions that penetrate the DSSSD and creating no signal in the TOF module.
• P-type, n-type to choose the best detector hardness to radiation damage
• This detector could be of the same type as the focal-plane detector (DSSSD) or pad silicon detector.
• Thickness : 700 µm, 1 mm,

To perform this test we can use Musett electronics for basic test and AFTER electronics for low energy high resolution measurements.

5.6.6.4 Coordination within the S³ collaboration

The focal plane for S³ project profits of the expertise and collaboration from different laboratories.
- Know-how on the detectors from JYFL (GREAT-SAGE), GSI(SHIP-TASCA), Argonne
- Test bench at IPHC will help the qualification, analysis and integration of the Tunnel detector and DSSSD with different preamp/amp/adc/daq components as well as the frontend electronics.
- Ganil and SEDI are working on the R&D for ToF detectors. Different prototypes are foreseen to test in beam in summer.
- The front end and back electronics will be a result of the collaboration between GANIL-CNSM-SEDI

5.6.6.5 IRFU contribution

We will focus on the test of implantation detector DSSSD using the present MUSETT test bench and the AFTER electronics presently developed for gas detectors.
• Test bench for the SED detector
  - Readout of the X & Y Strips with AFTER (T2K) and AGET(GET). This electronics as a dynamic range too low for our application. Nevertheless, it has a very good resolution and then could be used to quantify the detector resolution before a fully satisfying electronics is available for S3.
  - Readout of the GRID with MUSETT preamplifier. They have well known performances and will be used as benchmark electronics.
  - Connection between preamplifier and AGET (external preamplifier mode)
  - Data rate validation
  - 20MHz readout
  - 4 gains: 10 pC, 1 pC, 120 pC, 7 pC
  - Test is previewed in June 2010 with the SED preamps GANIL.

5.6.7 R&D for S³ Electronics

5.6.7.1 Problematics

The specifications of the S³ detection, as well as the budget and planning, require specific R&D for the electronics solution. A classical solution based on preamplifier, shaper and channel multiplexing could respond to the need at a reasonable cost in term of material and manpower. Using the architecture developed for the ANR GET R&D, it could be possible to optimize the number of people working in S³ project. A study must be started in this way.

The R&D paths proposed here are the following:
- Electronics for the emissive foil detectors, based on the AFTER (Asics for TPC Electronic Readout) and AGET (Asics for GET) Asics
- Back-end electronics for all S³ detectors based on the GET architecture
- Very front-end electronics for the silicon detectors compatible with the GET architecture.

5.6.7.2 Description of the system
The idea is to build a system to read emissive foil, implantation and tunnel detector based on the back-end of the GET project. One part consists of building a new electronic card based on a “MEMEC minimodule” directly controlled by software and to use the AGET chip developed in the GET context.

Concerning the Emissive foil and the implantation detector, we plan to use a new board called AGET-SED, which controls and acquires up to 128 channels. It is based on AGET circuit and the GET firmware.

5.6.7.3 Electronics for emissive foils detectors

The Irfu is already involved in the R&D on Beam Tracking with Secondary electron Detectors (BTSeD). These detectors would be suited to the SPIRAL2 low energy radioactive beams trackers, as well as to the emissive foils detectors for the S³ and NfS (Neutron for Science) projects. This R&D in made in collaboration with GANIL and the Sevilla University.

From tests realized in 2009 with the T2K electronics (AFTER Chips) on low-pressure gas detectors in Irfu/SEDI, we have measured a good energy resolution that would answer the needs for all the foreseen applications. Moreover, the AFTER electronics will evolve in 2010 into the AGET chip with higher counting rate, which will make it completely suitable for the SPIRAL2 beams and S³ that do have higher (1kHz per channel) counting rate requirements.

Preliminary tests are planned in GANIL at the end of June 2010 to validate a modified AFTER chip with emissive foil detectors.

5.6.7.4 Electronics R&D for the Tunnel Si Detectors

Irfu plan to study the preamplifiers used to read the tunnel detectors (few tens channels). The main challenge is to reach the high resolution required for the detection of conversion electrons and alpha particle, but without the high dynamic range required for the implantation detector.
5.6.7.5 **Electronics R&D for the Stripped Silicon Detectors**

Implantation detectors requirements are stringent to find a DAQ solution answering the need. We need to launch a R&D phase to evaluate the optimal system in terms of measures quality, cost and schedule.

Concerning specifically the implantation detector, we plan to use the complete GET system based on µTCA crate developed by GANIL. Each Hardware part will be connected to a PC through a Gigabit switch. The main interest of this proposal is to standardize the DAQ of Silicon and beam tracker detectors while taking benefit of the efforts made by Irfu and GANIL in the readout of Active Target TPCs. The cost of this solution is expected to be 4 times smaller than the one of the “full digital” solution.

Nevertheless, the standard front-end electronics of GET is not suitable for the S3 implantation detector, mainly due to the high dynamics and low resolution needed. Consequently, it is required to develop a discrete VFE for the implantation detector using AGET chip as a sampler and a 64-to-1 multiplexer. Then, we plan to use the back end acquisition of GET to process, select and store data.

But, the Signal over Noise ratio of the sampler part itself of AGET (~11 bits) may be not sufficient to fulfill the requirements of the Si detector. A careful R&D study on this aspect must be performed before to go further.

A major important barrier is to develop a VFE with the required dynamic range, the needed energy resolution and dead times compatible with implant/decay experiment. Independently to the DAQ, there is no existing proven solution for the very front-end. Irfu proposes to investigate two of them:

- A solution based on a discrete high dynamic range preamplifier followed by a two gain shapers (discrete electronics) similar to the one used on the ATLAS Liquid Argon Calorimeter (CERN).
- A (partially) integrated solution based on a floating point preamplifier. This R&D will be studied in collaboration with the GANIL.

The two solutions are compatible with a “fully” digital DAQ solution as studied by CSNSM.

5.6.7.5.1 **Coordination within the project**

Presently, other solutions are also considered for the silicon detectors electronics. They are based on a fully digital electronics involving:

- Preamplifiers adapted to the detectors signal, with two dynamics (high range for heavy ion events, and low range for decay events) and low occupation time.
- An interface for gain and off-set adjustment
- Fast ADC sampler in order to digitize the full signal shape
- MIDAS DAQ and slow control system.

The GANIL and the CSNSM Orsay are also working on these different aspects.

**It is planned to choose the best solution after one year of R&D on the different options, in parallel with the R&D detectors.**

5.6.7.6 **Planning and costs**

5.6.7.6.1 **Planning**
5.6.7.6.2 R&D Costs

- **AFTER-SED**: 3k€/board, 2 boards required for R&D
- **AGET-SED**: identical to AFTER SED
- **R&D instrumentation**: for tests, measurements and validation of the analogical line. Fast signal generators, cabling and acquisition board are required. The estimated cost is 5k€.
- **Acquisition simulation**: workstation for the Matlab simulation of the GET system. Cost is 1500k€

Very Front-end electronics:
- Si-tunnel:
  - 2 kEuros for prototyping of discrete preamplifiers.
- Si-Wall:
  - 3 kEuros for a floating point preamplifier ASIC prototype (cost shared with GANIL)
  - 3kEuros for prototyping the discrete preamp + bigain shaper solution (purchase of preamplifier and test boards)

The total cost of the R&D phase (2 years) is estimated to 24200€.

**Missions**: R&D is in collaboration with GANIL, and Sevilla University for emissive foil detectors. In-beam test are planned in GANIL. The estimation of Mission cost is around 5k€ for two years.

**Manpower**: For a period of 18 months:
- GET electronics study: 50% of an electronic engineer.
- GET Electronics and VFE study: 70 % of an electronics technician.
- Preamplifiers for Tunnel: 20% of an electronics engineer.
- R&D on VFE: 15% of a microelectronics engineer.
- Test boards layout: 20% on an electronics CAD technician

Do note that this R&D is also directly linked to other projects:
- BTSED, beam tracking detectors for SPIRAL2 radioactive beams
- Nfs (Neutron for Science), emissive foil detectors for the detection of fission fragments produced with SPIRAL2 neutron beams.
- The ACTAR (ACtive TARgets project) through the use of the GET electronics.

5.6.7.7 Cost of a final system

These costs assume that the GET solution finally fits to the S³ requirements and is chosen for the S³ project.
### Investments

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### Manpower:
For the final deployment of the S3 electronics and DAQ, the following manpower will be required during an extra period of 18 months:
- 50% of an electronic engineer.
- 50% of an electronic technician.
- 100% of a software/DAQ engineer

### R&D for S^3 Focal Plane Phase: Time of Flight

The R&D on the time of flight spectrometer detectors is made in collaboration with the GANIL, who is the leader of this group.

The Irfu/Sedi has an important experience in emissive foils detectors, and specifically with the detection of secondary electrons with low-pressure gas detectors. The basic principle (see next figure) is to accelerate the secondary electrons emitted from a thin foil with an electric field (10kV), so that the electrons can enter in the detector chamber. A longitudinal magnetic field is added to focus the electrons – it is required to have a good position resolution. The camber contains isobutene at 4Torr. The detector is a multi-wire proportional counter (MWPC), with two cells: one central anode and two cathodes on each side. The electric field in the detector creates an avalanche amplification of the electrons. The fast signal create is used on the anode to get a time signal, and on both cathodes to get X (stripped plane) and Y (wire plane) position measurements.
5.6.8.1 **Irfu implication**

Presently, the detectors in operation at the focal plane of the VAMOS spectrometer at GANIL fully fit to the $S^3$ requirements (except that they are 40mc wide instead of 20cm). The major development for $S^3$ is linked to the fast electronics, as previously described. Nevertheless, other paths of improvement are followed:

- Precise characterization of the detectors under high counting rates, light ions...
- Use of micromegas amplifiers instead of MWPC, to increase the maximum counting rate
- Improvement of mechanics for a better durability and easier maintenance
- Improvement of time resolution by a new fast amplifier
- 2D position measurement through a pixellized plane, to suppress one if the anode plane.

The Irfu/Sedi is mainly involved in the test of detectors with source and takes part in the “in beam” test and in the mechanics developments.

The construction of the emissive foil detectors for $S^3$ will be taken in charge by the GANIL. These developments also directly concern the BTSED project (beam tracking for SPIRAL2 radioactive beams) and NFS (tracking of fission fragments for the Neutron for Science Project). So, apart from the electronics developments, no money is asked specifically through the $S^3$ project, but it will benefit from the developments of the other projects (10-15k€ per year).

5.7 **Status and future tasks of Beam Dump studies**

5.7.1 **Functional requirements**

5.7.1.1 **Dump areas**

Nuclei produced or transmitted after the $S^3$ target are dispersed in p/q by the first half of the achromat in the horizontal plan. The different charge states are specific trajectories in three distinct areas:

- One "high magnetic rigidity area" for particles exceeding the upper acceptance limit of the spectrometer. This area is particularly in demand in direct reactions (light projectile on heavy target) which will in principle request the highest intensities. It is thus the area which must withstand the highest power deposits as well as the most important radioactive emissions and activations.
- One "low magnetic rigidity area" for particles below the lower acceptance limit of the spectrometer.
- The "acceptance area", where primary beam particles trajectories (dependant of the reaction type) are superimposed with ions of interest trajectories.
5.7.1.1.1 Acceptance area

In this area, nuclei are distributed in the horizontal plane, at first order, as a function of their magnetic rigidity, or ratio of their momentum over their charge state \((B\rho=p/Q)\). Beam ions momentum is dependant of the primary beam, the energy loss and the stragglng in the target.

The beam charge states are thus distributed by several different trajectories. The intersection between these trajectories and the focal plan is a set of distinct areas:

The ions of interest occupy the same area, often more evenly.
To intercept at the least these nuclei, we have to minimize the size of dump parts. The idea is to position fingers that will specifically stop some primary beam charge states.

Moreover, shutters will be placed on each side of the acceptance area. They will stop charge states on limit and will ensure the dump continuity with the high magnetic rigidity dump.

Each moving finger will be equipped as to be able to measure the stopped intensity. This will allow the fine-tuning of the fingers positions and charge states distribution measurements.

5.7.1.1.2 High magnetic rigidity area

The beam ions should have a higher energy than the reaction products to be studied. Then, it is the high magnetic rigidity area beam dump parts that will have to stop the most powerful parts of the beam, especially in the case of super heavy elements synthesis experiments. These experiments will be the longer experiments and requesting the highest intensities. Thus, the high magnetic rigidity area is the place where the energy deposit, the neutron production and the activation will be the highest.
The different charge states are distributed on a width, limited on one side by the acceptance area and on the other side by a limit corresponding to the ions that would not be deviated by the magnetic dipole placed upstream. The downstream multipoles with respect to the magnetic dipole are open multipôles. This allows trajectories of the beam outside the acceptance area without interception by the beam pipe or the magnets. It is then possible to stop the beam outside magnetic elements allowing:
- To shield the high magnetic rigidity beam dump and to limit the dose rate due to its activation
- To help intervention on the dump and its remote removing
- To limit neighbouring material activation by neutrons productions in the dump.

### 5.7.1.1.3 Low magnetic rigidity area

Low energy products and high charge state products will be steered in the low magnetic rigidity area. These extreme charge states should be the "less" intense. Nevertheless, we need to verify their impact as far as thermal and radiological aspects are concerned. Moreover, they can scatter on the walls and cause noise on the downstream side. The low magnetic rigidity area dump will gave to meet the following requirements:
- To shield the vacuum chamber and the magnets against the beam power
- To limit the radiological effect of the implantations
- To limit ion scattering after impact; anti-scattering plates could be implemented on this dump.

### 5.7.2 Functional description, beam dump sub-system breakdown
5.7.3 Beam Dump functional sketch (Room temperature magnets option)

5.7.4 Current layouts
5.7.5 Safety

5.7.5.1 Nuclear safety / radioprotection

The beam dump is the main source of activation and radiations. Moreover, it generates neutrons radiations which activate surrounding materials. Residual γ dose rate coming from the beam dump has been calculated since it is the main contributor to the external dose when the beam is off.

This is why the two first work packages studied by SENAC are:

- Analysis of the effect of the dump parts material. The outputs of this work package are the assessment of the residual dose rate with respect to the dump parts materials (and thus constraints on the dump parts materials), the neutron production rate (relevant for the dose rate when the beam dump is on, activation of surrounding equipments), the associated decommissioning aspects and the preliminary definition of the needed shielding;

- Preliminary radiological characterization of the Beam Dump system. The outputs of this work package give the approximate knowledge of:
  - the neutron flux distribution in the Beam Dump bunker and in the target bunker
  - the activation of the Beam Dump subsystem equipments and the neighboring fluids (notably the cooling water and the surrounding air) with the associated gamma dose rates
  - the determination of the radiological shielding characteristics

The design must be optimized in terms of choice of stopping material (beam dump) and the material for the surrounding equipments in order to minimize de dose rate. This can also be achieved by using an effective biological shielding (some proposals given in this chapter) or by
very reliable equipments with low maintenance needs (limit the time of exposure - ALARA concept).

5.7.5.2 **Conventional safety**

The supports and anchorages must meet the requirement that, in case of a SMS earthquake (Séisme Majoré de Sécurité), nothing can alter the integrity of the target room in order to avoid any contamination in this case.

The beam dump supports are concerned by this rule.

This will request specific supports designs, which will, on another side, have to meet dimensional constraint imposed by the small size and the big number of equipments in the Beam Dump bunker.

The pumped gas of the beam dump vacuum sector will have to be collected in storage bottles to allow decay and control before throwing back.

The cooling pipes of the beam dump elements will be connected to a tertiary circuit. A leak on this circuit must be collected in a watertight retention. If the heat exchanger is located outside the Beam Dump bunker it has to be designed and built in a way it complies with the nuclear safety level of the S3 principal room.

5.7.6 **Critical items**

The following preliminary critical item list will help us in a very next future to precise our development plan, to determine the qualification procedures and equipements and to precise the needed resources (financial resources and human resources).

5.7.6.1 **Shieldings**

Due to the dumps parts activation, shielding will be needed to allow access in the Beam Dump bunker when the beam is off. Movable shielding plates will have to completely enclose the dump parts, would it be in a nominal case (all fingers and shutters being at their rest location) or in a failure case (fingers or shutters blocked in the acceptance area).

The shielding thickness (under investigation) is a critical point for the beam dump design as it leads to overall mass and to a large needed space along the z axis.

5.7.6.2 **Cooling**

The movable finger must sustain 1 kW on approximately 1 cm². The power density is thus 10 MW/m².

Today IRFU’s experience is limited to 0.5 MW/m² but the tokamak Tore supra has been using solutions to deal with 10 MW/m² for years and current ITER studies are targeting 20 MW/m².

A particular study has to be performed at IRFU and we foresee a paper study until the end of 2010 followed by qualification on a support model until mid of 2011.

Fingers cooling pipes have to be dimensioned in the horizontal plan to be hidden behind the dump area. Their extension along the beam axis must be limited in order to allow a compact finger arrangement along the beam axis and finger position not far from the focal plan.

Thus, the pipes will have a limited section and their design will not be conventional.

5.7.6.3 **Vacuum**

The pressure inside S3 vacuum vessels, including the beam dump vacuum chamber, must not exceed 5 \(10^8\) mbar.

This will impose constraints on all the parts located in the vacuum chamber. For instance, the shielding, probably lead, must have surfaces or coatings compatible with the required vacuum level or must be enclosed in an adequate box.

The heating of vacuum vessels will maybe be needed and the space allocations of all the very near neighbouring equipments will have to be consciously worked out.
5.7.6.4 *Reliability*

Access to the Beam Dump bunker will be controlled and, despite the shielding (movable shieldings and stationary shielding) that will completely surround the dumps parts, the activation of neighboring equipments could imply some delay (of the order of one day, according to the present simulations, see next chapter) before entering the bunker.

A failure of the beam dump devices (fingers/shutters displacement, cooling, current measurement...) may then lead to a non-negligible unavailability period before any maintenance operation.

Thus, we have to ensure a high level of reliability. A very low fingers and shutter failure occurrence probability will be specified.

This will lead us to pay specific attention in the design and the qualification of the beam dump devices.

5.7.6.5 *Integration wrt. the second (open) triplet*

The vacuum chamber of the open triplet and the beam dump must be studied to allow integration in the triplet.

If the second open triplet is made of room temperature magnets, it will be possible to install the upper part of the magnets when the vacuum chamber is in place. The integration constraint is, in this case, quite light.

This will not be possible if the second triplet is made of superconducting magnets surrounded by a cryostat. The open triplet chamber has a particular profile in the x-y plan due to the beam stay clear profile in this plan and the aperture of the magnets "c". So we will probably have to slip on the chamber into the triplet, requiring some particular studies of the vacuum flanges and combined studies of the vacuum chamber and the superconducting open magnet design. This combined study and the very constrained interfaces between these two parts should benefit by the lodging of these two work-packages in the same institute.

Due to the small size and the cumbersome fixturers of the beam dump bunker, the vacuum chambers have to be placed in the triplet before moving the equipment in the beam dump bunker.

5.8 *Safety issues in the beam dump area*

5.8.1 General safety issues

The following statements concern the S3 area, but are elaborated within the framework of the AEL (LINAG experimental rooms, including NFS) and more generally of the SPIRAL2 project safety plan.

The present analysis deals with the nuclear risks related to the normal operation and the accidental conditions of S3. Even if the aspects related to the dismantling of the facility are considered in a further stage, one must take them into account in the preliminary studies since the waste generation is directly correlated to the activation level.

Concerning the nuclear safety, several aspects must be considered in the framework of the S3 project:

- Use of radioactive actinide materials as target
- Production of radioactive nuclei for experiments
- Activation of the beam dump
- Activation of equipment by neutrons

The following study focus on the beam dump room, the most critical area for radioprotection and safety point of view. The target area is also being considered because of the possibility of using actinides targets. The main objectives for safety issues are:

- target area: no contamination problem, limited activation
- beam dump room: activation limited under the radioprotection control
- main spectrometer area: limited activation, no contamination
Concerning the impact of magnet technology the following safety aspects are:

- equipments activation in the beam dump room
- activation of fluids
- accidental scenario
- maintenance and handling

Present studies focus on activation calculations for the main materials. This is a key issue in the establishment of the radioprotection constraints and furthermore in the analysis of the maintenance and accidental scenarios. We do not speak about the risks linked to the use of actinide targets for some experiments.

### 5.8.2 Assumptions on operating scenarios

For nuclear safety purposes, four main assumptions are considered for S3:

- A "covering scenario" used for the design of the S3 room (wall thickness, beam dump room confinement, underground building...) concerning the interaction of the beam with stopping material. A $^{12}$C beam of $14.5$ MeV/n and intensity $1$ mA ($1.6 \times 10^{13}$pps for $Q=4+$) was chosen as the envelope case to determine wall thickness and earth activation. Do note that $1$ mA beam of $^{12}$C at $14.5$MeV/n is an extreme case since it corresponds to the highest, most penalizing energy for $A/q=3$ with the highest intensity. After interacting with the target, the primary beam is directed towards a beam dump located in a dedicated place in the physics hall. Other reaction products are transmitted by the spectrometer up to a detection plane.

- A "realistic scenario" and "conservative scenario" used to assess the radioprotection issues inside S3 room and mainly in the beam-dump room. The "realistic scenario" is based on the operating scenario (see 2.7) and used during 10 year of operation. The "conservative scenario" corresponds to a $^{12}$C at $14.5$MeV/n for an intensity of $30$ pµA ($1.8 \times 10^{14}$pps) intensity which is more realistic than the "covering scenario". These two scenarios are used for activation calculations and its impact in terms of radioprotection.

### 5.8.3 Mechanisms for induced activation

Interaction of primary beams with the material (vacuum chamber walls, beam dumps, etc.) induces activation by two different processes:

- Direct interaction of the primary beam ions with the material,
- Indirect activation by the neutrons produced in nuclear reactions.

The first mechanism is very localised, limited to the path of the ions in the material (of the order of a few hundred micrometers for a Carbon beam) and limited to the elements impacted by the primary beam. Maximum activation is therefore specific to the beam-dump, for which the design is presently in progress. Indirect activation results in specific activity of the surrounding equipments. Note that composition and geometry of the main components of the magnet (for Classical multiplet and Superconducting multiplet) are a key for the calculation of induced activation and associated dose rate.

### 5.8.4 Neutron and $\gamma$ radiation

External radiation exposure risks results mainly from:

- neutron production when the ion beam interacts with the stopping material of the beam dump,
- $\gamma$ rays emitted by the different activated materials when beam is off.
The external prompt dose rate due to neutron production has been studied on the basis of a preliminary conceptual design of the super separator spectrometer room. The calculations results are resumed in this document and the safety and radioprotection issues discussed in terms of recommendations.

The activation of different materials has been calculated taking into account both primary interaction (ion beam interaction with the stopping material of the beam dump) and the one induced by secondary neutrons in the beam dump and surrounding materials. Residual γ dose rate coming from the beam dump has been calculated since it is the main contributor to the external dose when the beam is off.

The access of workers inside the different rooms must be allowed as soon as possible after operating the S³ separator. This is necessary for maintenance of equipments and for the preparation of the next experience. It is planned to carry out at maximum 2 runs a year (90 days duration for each experience). To reach this goal, the design must be optimized in terms of choice of stopping material (beam dump) and the material for the surrounding equipments in order to minimize dose rate. This can also be achieved by using an effective biological shielding (some proposals given in this chapter) or by very reliable equipments with low maintenance needs (limit the time of exposure - ALARA concept).

5.8.4.1 Preliminary analysis for the first building design

In order to evaluate the external dose rate when the S³ separator is in operation a first preliminary analysis has been performed. The "covering scenario" was used and two different stopping materials have been considered (copper and nickel). The modelling of the S³ beam dump location and surrounding material (wall concrete and optical elements) was done based on the first preliminary design. Activation calculations were done for many types of equipment as beam dump, multipole, vacuum chamber...

These first calculations allow recommendations for safety and radioprotection issues:

- S3 room has been underground in order to optimise the thickness of concrete wall and to limit external dose rate outside the facility. The walls must be at least 60 cm thick in order to limit the activation level of the surrounding earth to 10% of the allowed value. Moreover, the concrete ceiling must be 65 cm thick (plus 2 m of earth above) to reach a dose rate lower than the limit of 0.5 µSv/h at the surface.
- The beam dump room must be circumscribed by a wall of concrete up to 50 cm thick. The backroom wall must be 220 cm thick in order to reduce the neutron flux to an acceptable level of 1 µSv/h (limitation for public access).
- High level of beam-dump activity calculated imposes the use of a setup with a local shielding around the beam-dump to protect workers from external exposure to γ radiation resulting from activation.
- Activation of optical elements must be investigated with the new design and more realistic irradiation scenario. This study is presented in this document for the Classical multiplet option.

As an example of the first preliminary analysis, Figure 25 shows the results of neutron dose rate inside S³ room. Presently, the final drawings of S³ room have been updated by taking into account the above recommendations and with radioprotection margin for concrete wall. This modification must be further validated by new calculations with respect to the radioprotection objectives.
5.8.4.2 Methodology for beam dump and classical multiplet option

Methodology used for the first analysis is adopted in the present case for the activation and dose rate calculations by taking into account the last beam-dump and classical multiplet design (April 2010). A more complete study for the definition of the beam-dump stopping material was realised but it is not described in this document. PHITS code is used for transport and nuclear reaction calculations while activation calculations have been performed with CINDER’90. Note that other models must be prospected to evaluate the level of confidence of the results. However, few of them (MCNPX and FLUKA) are not appropriate to model heavy ion interaction at low energy. Equivalent dose rate is evaluated using MERCURAD code and compared with MCNPX results (photon transport).

An example of the isotope yields produced by $^{12}$C on Nickel stopping material is shown on Figure 26. At this low energy nuclear reactions are dominated by fusion process and nucleon transfer between beam and target. A large amount of light particles (from neutron to alpha) are also emitted during evaporation and pre-equilibrium phases. These mechanisms are described by PHITS even if it is very difficult to guarantee the quality of the results. Note that the choice of the evaporation model impact on the emission of light particle as neutron (for neutron induced activation, the most conservative model is used for safety margins).
5.8.4.3 Radiological impact of the beam dump

As mentioned above, the critical point for radioprotection issues is the activation of the beam-dump. The first analysis shows that a local shielding must be considered. Activation calculations were realised with a large amount of reactions (evolution of beam, energy and stopping material) in order to analyse several radiological spectra reachable during S3 operation. Activation takes into account direct reactions as well as secondary (neutron and proton induced) reactions. Three irradiation and decay scenarios are taken into account for radioprotection and waste management purposes. Dose rate calculations are performed to give information on the thickness of the local shielding according to the feasibility criteria (radioprotection, space limitations, mass...). Lead material is considered as the best choice for photon absorption (good X-ray attenuation coefficient) and due to its low activation expected. Dose rate calculations were performed for several lead thicknesses (from 0 cm to 25 cm) with the most recent beam-dump design. Results are presented in Figure 27 for several configurations (couples beam/target for available energies). In order to agree with the access management (presently the objective correspond to controlled green area under French regulatory legislation), the dose equivalent rate must be below a maximum of 25 µSv/h (red line showing the limit in Figure 27). Figure 27 presents the equivalent dose rate for two decay times (1 hour on the left and 1 day on the right). 10 cm of lead seems to be a good choice to reach this objective. Indeed, the dose rate is below 25µSv/h for each configuration after 1 day of decay time and for most of them after 1 hour. Note that 10 cm thickness of lead is admissible from the point of view of additional considerations (space limitations and mass). Other considerations have to be evaluated:

- Dose equivalent rate coming from other activated materials, mostly from optical element close to the beam-dump. Preliminary results are given later on in this document.
- The decay time objectives according to maintenance needs for the equipments.

Figure 26: distribution of isotope yields produced by 12C on Nickel at 5, 7, 10 and 15 MeV/n.
Although the beam dump and its local shielding design are not yet completely defined, the activation of other equipments inside the beam dump room by neutrons produced in the beam dump can be evaluated at this stage, provided that it will not be much affected by the final shielding. Outside the beam-dump room the level of activity is expected to be significantly lower.

5.8.4.4 Radiological impact of the optical magnet

Concerning the choice of optics (classical multiplet or superconducting multiplet option), only the classical option has been studied. Indeed, the design of the superconducting multiplet is not defined yet and the cooling fluid is not decided. However, limited information on superconducting multiplet composition is available (it contains mainly steel, iron and Nb-Ti materials). Therefore, we found interesting to evaluate by a preliminary study the radiological impact related exclusively to material composition (without taking into account multiplet geometry).

Activation calculations for the classical multiplet option were performed with the two scenarios described in chap 5.8.2. Results after 10 years of operation are given in Figure 28 for a dose equivalent rate at 30 cm from the most activated opened multipole. This value takes into account the contributions from the three multipoles. The model used for one multipole is presented on Figure 28.
After one hour of cooling time (reasonably corresponding to the minimum decay time for entering into the beam-dump room) the equivalent dose rate are close to 170µSv/h (conservative scenario) and close to 40µSv/h (realistic scenario). There values are not compatible with the radioprotection objectives. Consequently, a longer decay time (between 1 or few days) is required before entering the beam-dump area. At this stage, this configuration is acceptable from the radioprotection point view.

As mentioned above, for the superconducting option, geometry design is in progress. To evaluate radiological impact on material (expected for superconducting option), a simple analysis has been performed. Using a reference neutron flux and the same irradiation scenario (6 months/year of irradiation during 10 years of operation), activation and dose rate calculations have been performed with seven materials (chemical composition is taken from a data library from GANIL, instead of Nb-Ti where composition was arbitrary chosen 50%Nb and 50%Ti). Nb-Ti seems to be the most penalizing material only for the lowest decay time (accidental scenario, eventually). Copper and Steel are the most penalizing materials for with respect to maintenance activities. Note that for the classical multiple, dose rate (Figure 28) mainly comes from copper activation. Aluminum and iron are the most interesting materials (iron for long decay times).

At present the superconducting magnet is planned to be made of steel (for instance no information on chemical composition), Nb-Ti (very low masses) and probably Iron. Note that mass of the magnet is important for the evaluation of equivalent dose rate, but is expected to be lower than the classical option. Also note that steel activation comes partially from impurities as for example cobalt. If necessary, the activity of steel can be decreased by requiring low impurities concentration for the chosen material.

To go further, geometry must be included for activation and dose rate calculations. This is fundamental to conclude on safety and radioprotection issues. Moreover, activation of cooling fluids is needed to assess the consequence of accidental leakages (contamination) and waste management.

This simple analysis shows that more precise calculations are needed to conclude even if for the moment this solution cannot be yet rejected.

### 5.8.5 Conclusions

There preliminary evaluations have to be considered by taking into account their limits:
- Only one reaction code has been used. A comparison with other codes is underway, as well as a validation by experimental results.
- Concerning the superconducting multiplet option design, activation and dose rate calculations will involve a more detailed design when it will be available.

However, by using several scenarios dedicated to specific goals these calculations allow to obtain orienting values for the activity spectrum and dose rate expected in the S3 room and more precisely in the beam-dump room. The hall biological protections are designed according to the maximum intensity and energy of the most conservative beam likely to be used in each hall.
Beam dump design
Local biological protections will be installed to limit the external exposure to $\gamma$ radiation resulting from the activation of equipments, especially the beam dumps as the main activation comes from the stopping material. The first preliminary results show that a local shielding of 10 cm of lead seems to be appropriate for radioprotection purposes. A more complete calculation must be done with all the equipments inside the beam-dump room, each equipment bringing its own contribution. In addition, a more realistic beam-dump design (based on optical constraints) and more precise beam loss localisation is needed to optimise the design of this local shielding. For example, a specific shielding (in term of thickness) is expected around the interceptive fingers. Activation calculation for this local protection has to be investigated even if lead seems to be a good candidate from the activation point of view. In addition, a solution for a removable local shielding is under study. Indeed, this could be an interesting feature under accidental conditions (confinement) and from the radioprotection point of view (replacement if activation too high). Installation of biological protection is clearly a strong link with the global optics design.

Optical model option
At present, only activation and dose rate calculations for classical option have been realised. The results showed an important radiological impact due to the large amount of materials in this case (10 tons of copper and iron per multipole). For radioprotection issues, a delay for access into the beam dump room is needed, according to access management defined by radioprotection objectives. Concerning superconducting option, no calculations are available because of the lack of information concerning the preliminary design and material composition. Moreover, one study concerning only the type of material, shown that steel (main component of superconducting element) is not the best candidate from radioprotection point of view. However, the total mass of material is actually lower than in the classical option. Therefore, an activation calculation must be done using a realistic geometry to verify the compatibility of radiological impact of this option with GANIL objectives. Remember that activation comes from neutron produced by nuclear reactions into the beam-dump and at this moment no neutron attenuation material is planned around the beam dump.
Finally, for safety issues, fluids activation must be evaluated.

5.8.6 Irfu implication
SENAC will take in charge the nuclear safety and nuclear design of the $S^3$ room, specifically of the beam dump area. This will notably include activation and dosimetry simulations. This work is splitted in different stages from preliminary calculations (which have been presented in this document) up to a full radio-activation study:
   1) Analysis of the impact of the beam dump material
   2) Preliminary calculations of the radio-activity for the beam dump area
   3) Realistic radio-activity simulations and calculations for the whole $S^3$ room.
   4) Realistic simulations of the impact of radioactivity on the $S^3$ equipment
   5) Risk analysis
   6) Radio-protection analysis
This work amounts to 1.3 man.year for 2010, 1.6 man.year for 2011. It is performed in collaboration with the SPIRAL2 SRE (Safety Group), but also with the other relevant teams as far as the design of $S^3$ is impacted: SIS (Beam dump design), SACM (Open magnet design) and SEDI (detectors and electronic design) within Irfu, but also with other partners in the project.
### 5.9 IRFU assessed schedules and needed resources

#### 5.9.1 Schedule

<table>
<thead>
<tr>
<th>Subsystem</th>
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<th>2012</th>
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<td>architecture</td>
<td>design</td>
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<td>preliminary design</td>
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5.9.2 Cost Estimation for Irfu

These costs are preliminary estimations. They are currently under study at Irfu.

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Supports of MOSAR are supposed to be included in the full support of the S3 line.

The total does not take into account the final detection system.

The full cost of the project is under estimation within the collaboration. It is currently estimated to 7.8M€.