QUALIFICATION AND COMMISSIONING OF SUPERCONDUCTING MAGNETS FOR THE S3 SPECTROMETER AT GANIL

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Abstract

In order to achieve optimal performance in terms of transmission and separation for the S3 spectrometer, the project team decided to design superconducting magnets integrating 11 magnetic functions in a single cryostat. There are seven of these magnets, called Superconducting Multipole Triplets, in the spectrometer, and they operate at liquid helium temperature. These are unique objects with no equivalent anywhere else in the world, offering a very high degree of integration. This complexity has resulted in a significant commissioning delay and the need for a dedicated team to operate this set of magnets. This presentation will show the progress made in qualifying the various functions associated with these magnets: the qualification of cryogenic, electrical, and magnetic functions.

GANIL / SPIRAL2

GANIL (Fig. 1) is one of the world's leading laboratories for research with heavy ion beams covering areas such as nuclear and atomic physics, condensed matter physics astrophysics and radiobiology. Since the year 80s, the installation comprising five cyclotrons, two ion sources and ten experimental rooms make it possible to offer scientists a large variety of stable or radioactive beams.

Complementary to these installation, **SPIRAL2** is a superconducting linear accelerator which deliver one of the most intense heavy ion beam at this energy. Two experimental rooms, NFS (*Neutrons For Science)* and S^3 (*Super Spectrometer Separator*) are specifically designed to carry out experiments with beams from the LINAC [1].

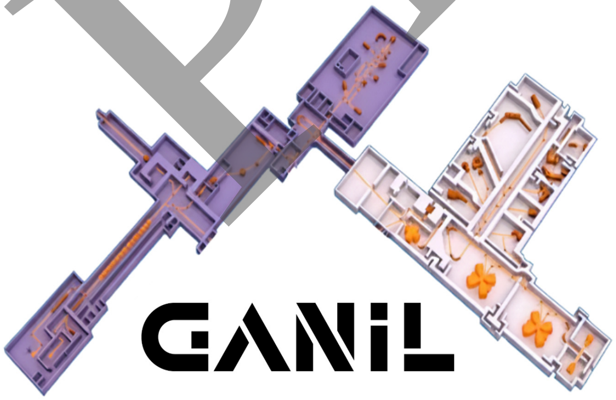

Figure 1: SPIRAL2 and GANIL.

S^3 SUPER SEPARATOR SPECTROMETER

S^3 Project (Fig. 2) aims to push the boundaries of nuclear physics by enabling the study of unstable nuclei and super heavy elements, particularly those beyond 104 in the periodic table [2]. The design of the primary target is optimized for fusion-evaporation production. S^3 is a two-stage optical structure combining a large acceptance momentum achromat and a "high-resolution" mass separator. This high-resolution is obtained by cancelling high order aberrations thanks to sextupoles and octupoles placed along the spectrometer.

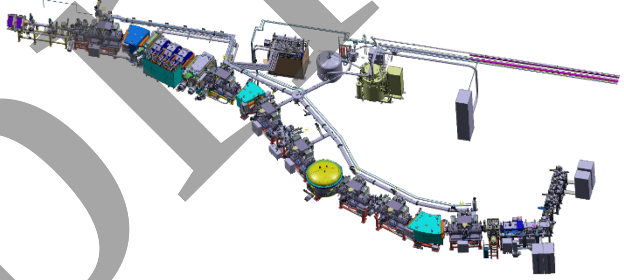

Figure 2: S^3 Spectrometer with 7 SMT.

Each stage includes 2 dipoles and 4 multipoles triplets. These multipoles are quadrupoles superimposed with sextupoles and most of the time, octupoles and steerers. Next to the target station is the beam dump region, where the radiation environment is intense. At that place, the multipoles are resistive magnets. The remaining part of the spectrometer takes advantage of a compact design using 7 Superconducting Multipoles Triplets (Fig. 3). The expected performances of the spectrometer are a mass resolution up to 450, and a transmission of 50% (+/-10%).

SMT

The **SMTs** (Fig. 3) are superconducting iron-free magnets designed to generate multipolar magnetic fields [3]. Each triplet is composed of three singlets, and each singlet is an assembly of independent functions: quadrupoles, sextupoles, octupoles and steerers, allowing precise control of the magnetic field. A SMT has the following characteristics (Table 1):

Table 1: SMT Characteristics

Long [cm]	Width [cm]	Height [cm]	Total mass [t]	Cold mass [kg]	Volume [L]
170	165	188	2.7	365	45 LHe 31 LN2

Figure 3: A SMT.

The multipole magnets were developed by AML [4] and their integration into the cryostat was perform by CMI [5].

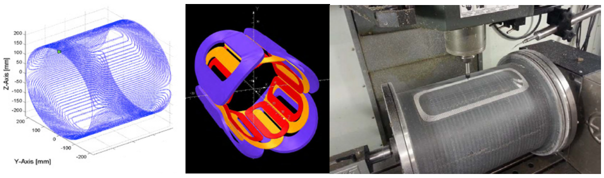

Figure 4: Walstrom design / Coils of a singlet / Singlet manufacturing.

All coils are manufactured from NbTi superconducting wire with a critical temperature of 5.6°K at a maximum field of 2.65T and a critical current of 597A at 4.2°K. The superconducting wire is precisely positioned in a spiral groove machined into an epoxy-impregnated fiberglass matrix (Fig. 4). The operation is repeated to get the appropriate number of layers, as required to produce the correct magnetic field. The winding technique uses Walstrom-type coils that minimize high-order harmonics [6]. The maximum total energy stored in an SMT is 165kJ (primarily in the quads). The system is designed to detect a quench situation very quickly and to discharge each SMT rapidly and safely. The current-carrying conductors are high-temperature superconductors cooled by conduction with LN_2 (top) and LHe (bottom). These HTS are made with BSCCO (Bi2223) and YBCO tapes for flexibility.

Each SMT is powered by a Power Supply System (Fig. 5). A **PSS** consists of 8 power supplies (PS), a Magnet Safety System and a computer based control system. There are 8 PS (one 100A, three 600A and four 400A) for the 11 magnet coils. A wired electrical cabinet ensures adaptation of the loads configuration.

A dedicated interface enables the user to check the loads configuration, adjust the quench detection parameters and control each Power supply of a **PSS**. A standalone FPGA-based system provides quench detection within 100ms and triggers rapid load dumping in less than a second (100% to 10% within 0,5s)

Figure 5: PSS Cabinet (AML).

One of the key components for quench protection are the SMT voltage measurement and protection system. This system measures all voltages (Fig. 6) generated in each SMT (copper; current leads, HTS current leads and coil voltages) in real-time and transmits these information to the PSS FPGA system through a fiber optics link.

Figure 6: Voltage Measurement Cards (AML).

CRYOGENIC QUALIFICATION

The seven cryostats of S^3 use liquid helium (LHe) for superconducting coils and liquid nitrogen (LN_2) for the thermal shield.

These two cryogenic fluids are provided by a cryogenic installation consisting of a Cold Box (Fig. 7), compressor, ORS, atmospheric heater, Dewar of liquid helium, Dewar of liquid nitrogen and a cryogenic transfer line (CTL).

Figure 7: S3 Cold Box (Helial SF from ALAT).

Each SMT has a set of instrumentation—including temperature sensors, liquid helium (LHe) and liquid nitrogen (LN_2) level sensors, pressure transmitters, vacuum gauges, and cryogenic valves—enables the monitoring and supervision of the cryostat's proper operation.

In 2024, a significant milestone was achieved with the successful cool down of six out of the seven SMT. This operation validated the full functionality of the cryogenic system. (Refrigerator, cryogenic distribution line, cryostats). The cooling down of each SMT consisted of two cooling the thermal shield (Nitrogen), followed by the Helium volume (Fig. 8).

This sequence has been adapted recently and the cooling takes place simultaneously, in order to minimize the thermal constraints on critical parts like the HTS current leads.

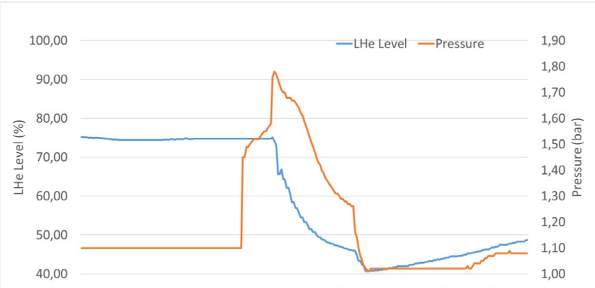

Figure 8: LHe level and tank pressure variations during a fast dump

To validate the security system we did a fast dump at 70% of the nominal current (360A) (Fig. 9).

ELECTRICAL QUALIFICATION

Tests conducted after their integration into the SMT could not be performed at the factory (CMI), with the exception of the first in the series, which was successfully qualified at full power using open-loop helium (without recycling). Remaining tests have been performed at the GANIL site. Once cooled to 4°K with liquid helium (LHe), each magnet is tested one by one at the maximum current specified by the project. These currents represent nearly 70% of the maximum current tested at the factory (Q at 350A; S at 280A; and O at 160A).

During this test, the voltages are recorded during linear current ramps in order to check the self-inductance of the coils. The quadrupole have each a total inductance of 430mH and store each more than 46kJ. Sextupole and Octupole have respectively 110mH and 28mH each for less than 7kJ and 1kJ stored energy.

Then, each magnet is electrically tested to verify the proper functioning of the high temperature superconducting (HTS@77K) current leads and the low temperature superconducting (LTS@4K) coils. The current is increased in steps to the maximum value and the voltages across the HTS and the coils as well as the temperature and pressures in the cryostat are measured.

Finally, a dump test is performed on each SMT with all magnets at 70% of their nominal value to verify proper functioning of all electric parts. The electrical insulation is tested again, (HV test at 1000V) in order to ensure that the dump and the overvoltage have not damaged the SMT.

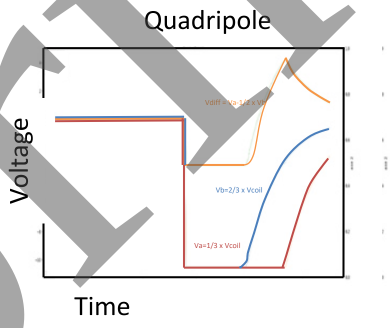

Figure 9: Coils Voltages during dump (with clamping voltage protection)

Electrical tests highlighted current limitations at the LTS wires interconnections between coils at around 300A (Fig. 10). This is probably due to inadequate cooling at the top of the cryostat. This issue is tackled by improving the LHe level regulation (additional level sensor) and modifying the HTS design.

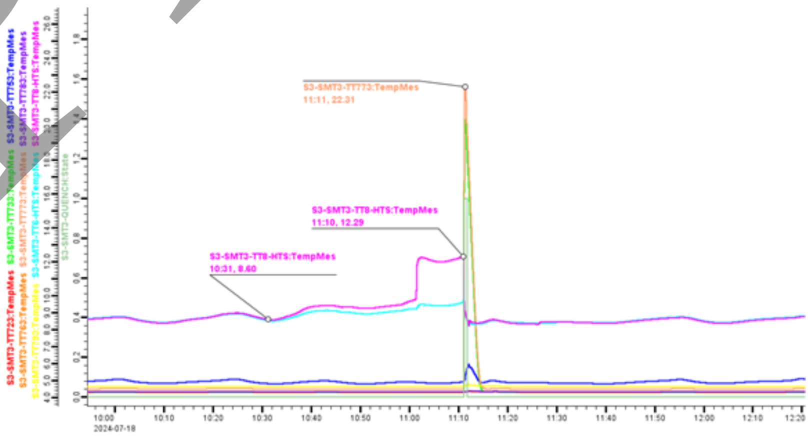

Figure 10: HTS temperature drift (pink down and blue high) at current above 300A and pressure rise in the cryostat after the dump (green and orange).

MAGNETIC QUALIFICATION

All “singlet” magnets were independently qualified by the manufacturer (AML) for their magnetic characteristics during the manufacturing phase, using a rotating detection coil at room temperature (harmonic analysis). In addition to this qualification of the coils at the manufacturer’s site, the project managers decided to verify the magnetic performance of an SMT magnet. This characterization was performed using a 3D measurement bench specially designed for this purpose [7] (Fig. 11).

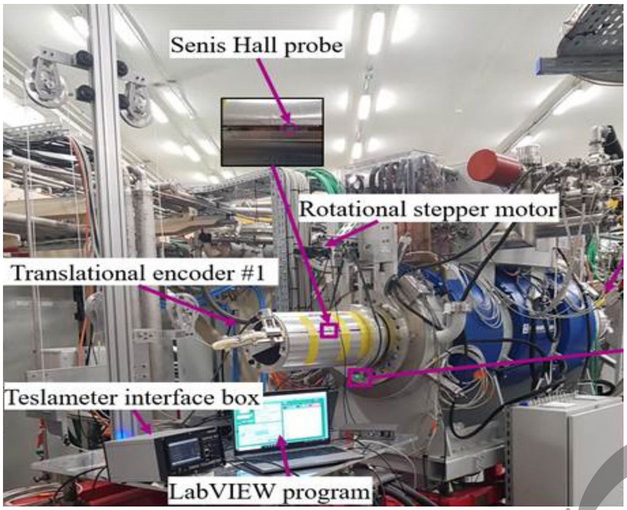

Figure 11: 3D Magnetic bench in S3 room.

These measurements validate the magnetic specifications (harmonics analysis), the effective magnetic length, the magnetic field linearity, the field gradient and the real magnetic effect of each magnet to anticipate the polarity wiring of each power supplies for the expected beam optics (Fig. 12 and Fig. 13).

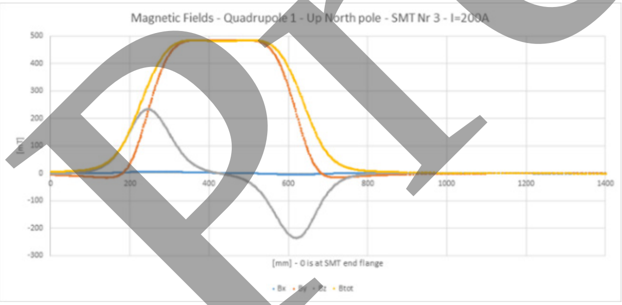

Figure 12: Magnetic length of one quadrupole (x : blue, y : orange, z grey, tot : yellow).

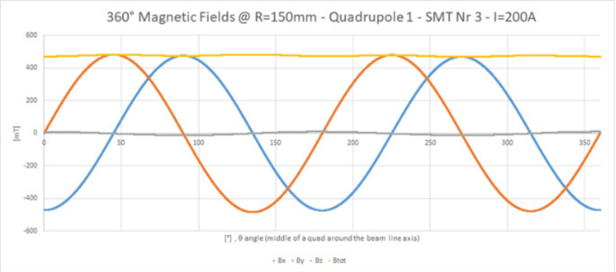

Figure 13: 360° fields of a quadrupole (x : blue, y : orange, z grey, tot : yellow).

The second part of the magnetic work on the 7 SMTs involves aligning their centers with the beam's planned path along the line. This is achieved using several test benches, notably the “thin mapper,” which consists of a Senis 3D Hall probe rotating inside the SMT at its tip. This bench has been validated against the 3D cylindrical bench and has been used so far on two SMTs. This mapper, designed to take up as little space as possible on the line, could not be used at positions 1 and 2 of the spectrometer’s SMTs. Consequently, a third bench, called the “external mapper,” which uses the fringe fields of the quadrupoles, has been developed and will be field-qualified during the next phase of the spectrometer’s commissioning (Fig. 16). For the three magnetic benches, adjustment is performed using four tie rods located at the ends of each cryostat. We monitor the forces acting on the rods using pressure sensors mounted at the top of each one. Moving the cold mass requires very precise and time-consuming adjustments, since the 8 rods are mechanically linked.

At the start of the measurement campaign, we also verified that the cold mass was correctly repositioned between two cooling sequences using the 3D cylinder test bench.

REPAIRS AND IMPROVEMENTS

Following the tests conducted during the first phase of commissioning, the following points have been or will be modified:

Removal of iron yokes to be able to align properly the cold mass: the cold mass is subjected to forces caused by magnetic interactions with the iron yokes when energizing the magnets. Since the 3 yokes are very complex to align, this causes a movement that misaligns the magnets relative to the beam axis.

Repair of the HTS: The initial design of the current leads has shown sign of fragility due to the thermal stress during cooling down. The delamination of the HTS material on its copper substrate reduced its ability to carry current, and in several cases the nominal current could not be reached again (Fig. 14). The lead us to the decision a redesign using a new REBCO material, and letting the flexibility to a copper braid (redesign CEA/IRFU/LEAS and GANIL). This version is currently being updated in order to reduce the volume of copper and provide better mechanical integration.

Figure 14: New design of HTS current lead.

Repair of a low temperature superconducting (LTS) wire inside a SMT, which broke between two quadrupoles. Tests revealed that the internal electrical circuit between two quadrupoles of one SMT was open. The repair required opening the cryomodule to access the connection. This delicate operation was carried out in a four-months period by the GANIL's technical teams in order to replace the defective LTS conductor with a new one and reconnect it (Fig. 15).

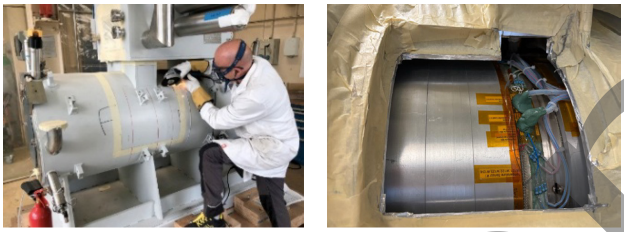

Figure 15: repairing LTS wire inside a SMT.

Addition of an extended level gauge for the liquid Helium (LHe) bath in order to improve cooling of the LTS wire and ensure maximum operating current in the magnets. The tests showed that the connections located below the HTS current leads were not adequately cooled. In order to regulate LHe at a higher level, an extension of the level gauge is installed at the top of the cryostat such that the LTS cables are fully submerged in LHe bath and remain at a temperature of 4K at high current.

Modification of the voltage tap wiring to make quench detection functional on the portion of LTS wire between two adjacent coils. The short portions of LTS cable between the current leads and the coils were not monitored by the safety system. A modification of wiring inside the voltage acquisition system allows this part to be taken into account by the quench protection system.

Development and qualification of the external magnetic mapper. The mapper has successfully been aligned, but a cool-down is not necessary to assess its precision and align the SMT in position 1 and 2. All other SMT will be positioned using the thin mapper.

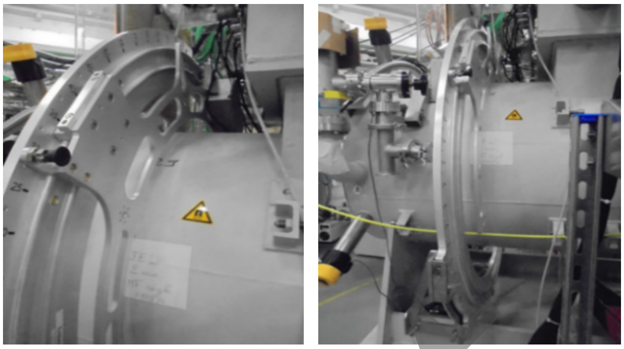

Figure 16: External magnetic mapper.

Routine operation of the cryogenic plant: it is now urgent to overcome the administrative and technical challenges the team has faced in order to proceed with the qualification of the magnets and the entire spectrometer.

Replacement of several ceramic feedthroughs (Fig. 17), situated between the LN2 box and the vacuum. Some of these parts suffer from oxidation of the INVAR material, and generate some LN2 leaks to the vacuum.

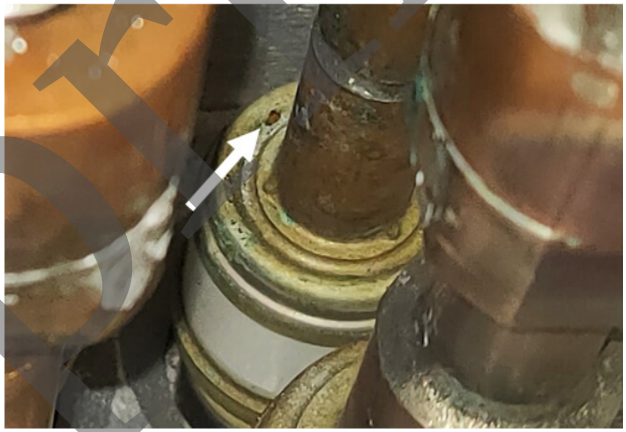

Figure 17: Leak on a ceramic feedthrough.

CONCLUSION

The S^3 spectrometer is a next-generation heavy-ion spectrometer whose impressive performance will be partly due to the ambitious design of its key components: the superconducting magnet triplets. The seven SMTs, with their very high degree of integration, present a challenge in terms of qualification, due to the number of different coils, the complexity of the quench protection system, the difficulty of alignment, and certain issues related to the design of the HTS current leads. The initial test phase has yielded encouraging results, but has also revealed numerous limitations that the team is working to overcome through upgrades and repairs. A long cooling period, required for the commissioning of the spectrometer, will likely enable us to verify the validity of our latest technical choices.

REFERENCES

[1] A. K. Orduz *et al.*, "Commissioning of a high power linac at GANIL: Beam power ramp-up," *Phys. Rev. Accel. Beams*, vol. 25, no. 6, Jun. 2022
`doi:10.1103/physrevaccelbeams.25.060101`

[2] F. Déchery *et al.*, “The Super Separator Spectrometer S3 and the associated detection systems: SIRIUS & LEB-REGLIS3,” *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 376, pp. 125–130, Jun. 2016 `doi:10.1016/j.nimb.2016.02.036`

[3] M. Aburas *et al.*, “Superconducting Multipole Triplets for the Super Separator Spectrometer,” *IEEE Trans. Appl. Supercond.*, vol. 34, no. 3, pp. 1–4, May 2024 `doi:10.1109/tasc.2024.3356434`

[4] AML. Advanced Magnet Lab, 1604 S Harbor City Blvd, Melbourne, FL 32901, USA. `https://mitusmagnets.com/`

[5] CI. Cryomagnetics.inc, 1006 Alvin Weinberg Dr, Oak Ridge, TN 37830, USA. `https://cryomagnetics.com`

[6]] P. L. Walstrom, Design of End Turns in Current-Dominated Dipole and Quadrupole Magnets for Fields with Low Higher-Harmonic Content, EPAC 2002

[7] A. Esper *et al.*, “Superconducting multipole triplet field measurements,” *J. Phys. Conf. Ser.*, vol. 2687, no. 7, p. 072027, Jan. 2024 `doi:10.1088/1742-6596/2687/7/072027`