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THE NEW GANIL BEAMS: COMMISSIONING OF SPIRAL 2 ACCELERATOR AND RESENT DEVELOPMENTS

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Abstract

The GANIL installation at Caen in France has been operating with warm temperatures cyclotrons for heavy ion beam physics since 1983. The accelerated stables beams widely ranges from Carbon to Uranium beams. Low energy and post accelerated radioactive ion beams are also being provided.

The GANIL laboratory has newly increased their different ion beams and energies available with the installation and commissioning of a superconducting linear accelerator – SPIRAL2 and its experimental areas. The construction of SPIRAL2 started in 2011, the first beam was extracted at low energy in late 2014 with pre-acceleration in 2017 and since 2021 the new installation delivers beam for nuclear physics experiments.

This paper will cover the commissioning and power ramp up of the SPIRAL2 installation at GANIL with its superconducting LINAC – but also the latest development of stable and radioactive ion beams at the cyclotron facility of GANIL.

GANIL COMPLEX

GANIL will in November 2022 celebrate the 40 years from the first extracted beam from the two separated sector cyclotrons (SSC). The first accelerated and extracted beam was a $^{40}Ar^{16+}$ beam, accelerated to 44 MeV/A. The same beam was used for an experiment 2 months later in January 1983.

Figure 1: The Running GANIL facilities in 2022. On the right is the cyclotron facility and on the left is the SC-LINAC facility.

In the 2015 version of HIAT conference O. Kamalou presented an article of the GANIL Operation Status and New Range of Post-Accelerated Exotic Beams [1]. In the same conference J. M. Lagniel presented the Advances of the SPIRAL2 PROJECT [2] which had just commissioned the ion sources and the low energy beam transfer lines (LEBT), the SC-LINAC was still under installation.

Today GANIL is running two separated facilities, not yet connected as can be seen in Fig. 1. On the right hand side of the Fig. 1 is the cyclotron complex. The ion beams are produced on the far right hand side before accelerated in one or two steps in the two SS cyclotrons up to 95 MeV/A. On the left in the cyclotron buildings are the RIB factory SPIRAL1. The experimental halls, were the users from different fields explore the stable and radioactive beams, are on the upper part of the figure. On the left hand side in Fig. 1 is the SPIRAL2 installation with a more detailed description in Fig. 2. The four injectors used at GANIL are opposite to

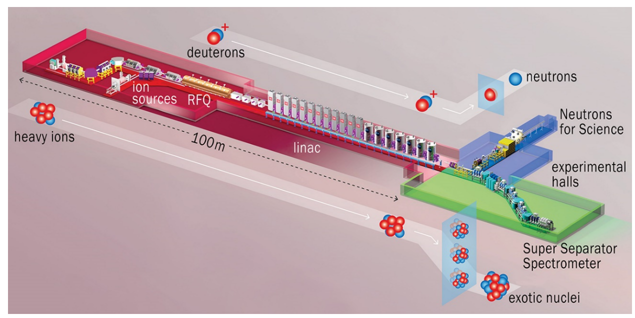

Figure 2: A schematic view over the SPIRAL2 installation, the two injectors on the right hand side.

each other in the two facilities. In the near future the two facilities will be connected and beam from either of the two facilities will be used in a new experimental area as seen in the section "Next steps for GANIL".

From here we will refer to the cyclotron facility and the SC-LINAC facility (Fig. 3). In total GANIL is running seven ECR ion sources, one FEBIAD ion source, one ECR charge breeder, four injectors, five cyclotrons, one RFQ and one superconducting LINAC, delivering stable ion beams (SIB) and radioactive Ion beams (RIB) to nine experimental areas. The facility is operated 24h 7 days a week for 8 to 9 months per year. Since 2019 the cyclotrons and the SC-LINAC facilities are sharing the operation time, meaning that at GANIL there is a cyclotron season and a super conducting LINAC season. This arrangement divide individually the two facilities into separate 4-6 months uptime periods with 6-8 months maintenance and upgrading periods each year. This gives an opportunity to work on upgrades and regular improvements of ion beam transport and new beams while providing beams 8-9 months a year.

While the Cyclotron facility celebrate 40 years of operation the SC-LINAC is still in the first years of regular operation. In here we will present the resent upgrades at the cyclotron facility presented in details in several articles [3] and a short resume of the SC-LINAC commissioning as requested [4].

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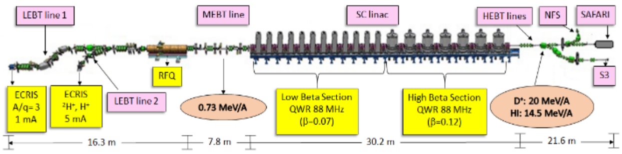

Figure 3: SC LINAC layout. At the left hand side the two injectors coming together in the LEBT beam line. The RFQ and the MEBT beam line and then the 26 accelerating cavities and their cryo-modules, each one separated by a warm quadrupole section and a beam diagnostic.

SC-LINAC – SPIRAL2 PROJECT

The SPIRAL2 project, launched in 2005 was designed to produce high-power proton, deuteron and heavy-ion beams to be accelerated in a superconducting linear accelerator. The beams were to be delivered in three different experimental areas for nuclear physics research. Two of the experimental areas are constructed and the third one was put on hold in 2013 [5]. The experimental areas and the production of RIBs were a part of the initial project. The idea was to produce RIB in one InFlight (S3) and one ISOL facility (Phase 2) to complement the neutron rich side of the table of isotopes and the production of super heavy ion for fundamental applications.

The construction was limited to the injectors and the high-power superconducting LINAC with two experimental areas called "Neutrons for Science" (NFS) [6] and "Super Separator Spectrometer" (S3) [7] (see Fig. 3).

The new facility was constructed with two injectors, the proton/deuteron source is a 2.45 GHz ECR source (SILHI like [8] it is designed to produce 5 mA proton and deuteron beams in CW or pulsed modes or pulsed modes.

The heavy-ion source was initially an 18 GHz ECR source PHOENIX V2 using three normal conducting coils and a large permanent magnet. It was designed to produce heavy ions with $A/q \leq 3$ with a total extracted beam current up to 15 mA CW at 60 kV. The design allows the installation of a dedicated oven reaching 1600 °C for the production of metallic ion beams [9]. It was later on upgraded to a Phoenix V3 [10] also operating at 18 GHz. This modification was performed to be able to provide the intensities of the beams needed for the S3 experiments.

The installation and the commissioning of the accelerator complex was programmed in phases taking into account the availability of the personnel while continuing the operation of the cyclotron facility. The start-up and tests of all equipment have been performed with staff from GANIL and the external collaborating facilities for SPIRAL2. The ion sources and their low energy beam transport (LEBT) lines was commissioned while parts of the SC LINAC was still under installation.

The design goals of the installation are to be seen in Table 1.

The first SPIRAL2 beam at GANIL (protons) was produced by the proton/deuteron source on December 19, 2014. Later on, in January 2020, the first beam of $^{40}Ar^{14+}$ was produced, with an intensity of 100 µAe, and since then ^{58}Ni at 40 kV and 40 eµA have been produced, as requested by the S3 experimental facility. A strong and intense development program is ongoing for the injector, the focus of the next beams to be produced; extracted and accelerated are ^{48}Ni, $^{48,50}Ti$, $^{50,54}Cr$ for the S3 experiments, with intensities up to 2 pµA for A/Q around 3 [3].

Table 1: The Technical Design Goals of the SPIRAL2 Installation

Particle	H^+	D^+	Ions	Future
A/q	1	2	3	7
Max I (mA)	5	5	1	1
Max energy (MeV/A)	33	20	14	8.5
Max beam power (kW)	165	200	44	51

The building of SPIRAL2, is actually constructed by free standing blocks due to seismic reasons. The ion sources and LEBT are in one block and the RFQ, Medium energy beam transport line (MEBT), SC LINAC and high energy beam transport section (HEBT) in a second block and the two experimental halls in a third and fourth block. This was taken advantages of during the installation and commissioning of the equipment in the separated blocks. The RFQ and the MEBT was done in parallel of the commissioning of the ion sources from 2014. The low level RF tuning operations of the RFQ, including the voltage law bead-pull measurements and the 40 plunger adjustments ended in March 2015. From these primary tests the TOUTATIS simulations indicated that the theoretical transmission of beam should be 99.7%. The resonance frequency of the RFQ is 88.0159 MHz, and the beam is accelerate up to 0.75 MeV/A. The RFQ and the MEBT was commissioned using a specific diagnostic box before the SC LINAC, physically separating it from the LINAC but allowing to calibrate the beam and adjust the RFQ operation completely before the commissioning of the LINAC. The RFQ was commissioned at 114 kV with a pulsed 4.8 mA proton beam with 100% transmission in end of 2015 [11].

In the years of 2015–2018 the commissioning the RFQ and the MEBT was performed with beams of H^+, $^4He^{2+}$, $^{18}O^{6+}$ and $^{40}Ca^{14+}$. The diagnostic box installed [12] before the SC-LINAC confirmed 100% transmission [13] showing no beam losses during this first accelerator stage of the installation (Fig. 4).

The diagnostic plate included temporary diagnostic tools for commissioning of the RFQ. The diagnostics used were ACCT and DCCT [14] for intensity monitoring, wire profilers for the beam size and position, Alison type scanners for emittance measurements in H and V direction, TOF (Time of Flight) monitor for energy measurements and phase coupled with two BPMs [15] (Beam profile monitor), a BEM (Beam extension monitors) [16] for the longitudinal emittance measurements [17] and FFC (fast faraday cups).

The validation of the RFQ line was done in November 2018 and the D-plate was removed, the full MEBT was

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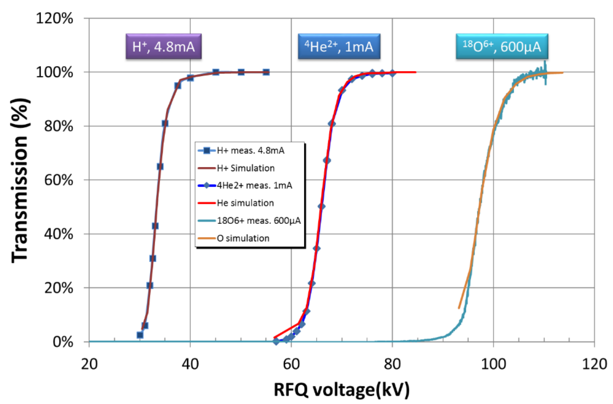

Figure 4: Transmission in the RFQ of the three reference Q/A.

installed and the line was physically connected to the LINAC. In the full MEBT line the three re-bunchers and a beam bunch selector (SBS) [18] was installed. The SBS allows an operation of 1 bunch over 100 up to 1/10000, needed primarily for experiments requiring a precise timing between the bunches to insure that there is no overlap of the bunches for precise energy measurements.

In the meantime the SC-LINAC installation was ongoing and in 2017 the cryogenic system for the cryo-modules were commissioned with a first complete cool down in November 2017 [19]. The RF tests in the LINAC were performed in parallel to the operation of the cyclotrons during the first semester in 2019.

The GANIL cyclotron and SPIRAL2 installations are constructed and operated under French nuclear authority regulations. Before the authorisation of construction a file explaining the full operation and safety measurements were sent in. The different systems for the safety controls were then constructed and tested. The final authorisation to start the facility with acceleration of the beams in the LINAC was followed four months later after having complete testing and documentation of the different safety systems. Only after this the full authorisation was given and the beam could finally be sent to the LINAC.

The SC LINAC is designed with 26 cavities, 12 A-type cryo-modules each comprising one low-β cavity and 7 B –type cryo-modules with two high-β cavities [20, 21].

The Power Up of the Beams

In an early stage of the project the strategy for the beam commissioning of the LINAC was to go in four phases as shown in Fig. 5. The proton beam, were to be sent to the SAFARI beam dump during this commissioning.

1. Beam transmission at low energy as given by the RFQ.
2. Increase of the Beam energy through the LINAC
3. Increase of the Beam intensity while opening the slits cutting the beam in the LEBT.
4. Increase of the duty cycle.

During the phases 3 and 4 the beam losses were controlled in all the LINAC by the beam loss monitors (BLM) installed

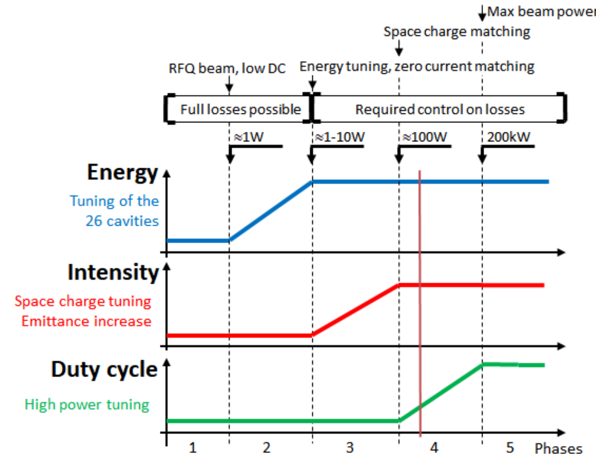

Figure 5: Transmission in the RFQ of the three reference Q/A.

around the LINAC, the intensity (ACCTs) and the pressure variations all along the LINAC.

The first beam, a 1 W proton beam, without energy increase and at low intensity was transported through the SC-LINAC tuned in a rebuncher mode in the middle of November 2019. During the following two weeks a beam energy increase up to 33 MeV with a pencil beam of 200 µA and a full 6.4 W beam was sent to the SAFARI beam dump. Before the winter shut down in December, this beam was sent to the NFS experimental area for full identification of the energy and composition of the beam.

From here on, the LINAC operation is performed with the GANIL teams, also working on the operation of the Cyclotrons. The beam commissioning of the LINAC are therefore limited to 4–5 months every year at the moment.

The phase three continued in the second semester of 2020, after the cyclotron run programmed for the first semester of 2020. After restarting the full complex, retuning the beam and do all the initial tests as in the end of 2019, the proton beam intensity was increased to 4.8 mA and the in the following week, the beam power were then increased to 16 kW (Fig. 6) using a 10% duty cycle, with a beam transmission near of 100% into the LINAC and high energy lines.

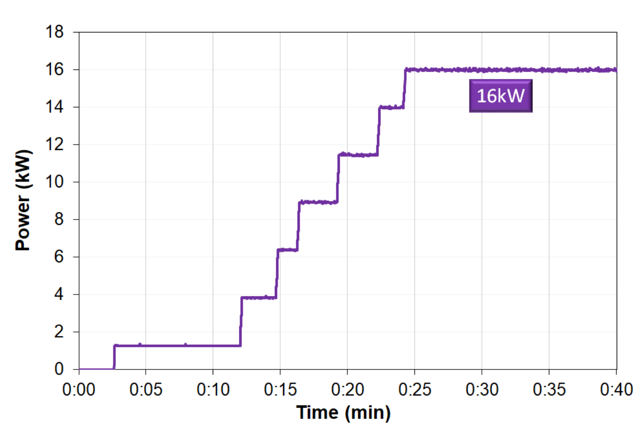

Figure 6: The beam power up to 16 kW proton beam.

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For each step of the power up the beam the transmission was monitored throughout the installation from the MEBT section, all through the LINAC and in the HEBT section [4]. The results was compared to theoretical TRACEWIN calculations for confirmation.

The next step in the commissioning were to proof the capacity of accelerating heavier ions, starting with deuterons. Although, accelerating the deuterons, an eventual problem of activation should be minimized. So, in the last weeks of operation in 2020 a 4He beam were accelerated to simulate the deuteron beam transport.

After the run in 2019 and 2020, 2021 was the start of the physics experiments and real challenges of the accelerator. The different systems (security, RF, LLRF, diagnostics) was pushed to their limits to validate the operation. While in 2020 the technical and scientific goals were to proof the operability and the capacity of the different systems of the installation, showing the capabilities of controlling and maintaining an accelerated beam of high intensity. The 2021 program was to proof different beams for physics could be produced, accelerated and delivered for physics. The commissioning is no longer driven by pushing the limits of the installation as designed but is in concurrence with the need for physics. It should be remembered that the SC LINAC installation was designed for a 200 kW deuteron beam (40 MeV / 5 mA) in continuous mode and the NFS experiments are requesting proton and deuteron beams of very low repetition rate. The constructed S3 experimental area is to be commissioned with beam within two years. Their needs are heavy ion beams from the A/q ≤ 3 ion source in a first time.

The first beam of 2021 was a deuteron beam of 20 MeV/A. Starting with the same procedure as in Fig. 5, the duty cycle went from 1 to 100 Hz using the SBS. A first experiment of 11 MeV/A deuteron beam on a Be and Li converter was performed in the middle of September in NFS followed by a 20 MeV/A beam on the rotational converter for the neutron beam production at NFS. Beam intensities of 47 µA was used during these tests.

During the shutdown periods, technical modifications have been performed and corrections identified during the run have been made. During the 2021 run one of the cavities went out of operation, to continue the program foreseen, the accelerator was tuned without this cavity. The tuning was performed and this mode validated before the correction of the breakdown during the winter break.

Experimental Areas for LINAC

The S3 installation will be ready for stable beams as of end of 2023. During the second semesters of 2022 and 2023 the facility shall proof the possibility to accelerate the ion beams of 48Ni, 48,50Ti, 50,54Cr with intensities up to 2 pµA for A/Q around 3. A new injector increasing the capacities for heavy ion production with a goal of A/q ≤ 7 are under study for GANIL. A superconducting ion source, a second RFQ for pre-acceleration and bunching should be installed. This project is under development, fully founded and should be installed and commissioned in 2026 as of the plans today.

CYCLOTRONS

The Cyclotron facility combined with the SPIRAL1 facility provides Stable Ion Beams (SIB) since 1983 and Radioactive Ion Beams (RIB) since 2001 for Physics experiments.

Two ECR4 ion sources, commissioned in 1992, are coupled to two cyclotrons (C01) and two separated section cyclotrons (SSC) where the beams can be successfully accelerated after striping and bunching in between.

At the cyclotron facility the SIB can be produced at three positions, any of the two injectors consisting of ECR4 (14.5 GHz) ion sources, or by the ECR booster directly.

The beam can therefore be delivered to five experiments in parallel if requested from three points in the production of the SIB. A low energy experimental area directly after the injectors (0.3 to 1 MeV/A), a medium energy experimental area (3.7–13.7 MeV/A) take the beams after the first SSC and finally after the full acceleration (24–95 MeV/A). The beam can then be shared by two experimental areas at the same time. In parallel, a SIB can be produced directly at the SPIRAL 1 installation, either from the ECR1+ ion source or the ECR booster, and sent to a dedicated experimental room.

If RIBs are requested, it can be delivered either as 1^+ low energy or as post-accelerated beams from SPIRAL1, with the ISOL method. In one of the experimental areas there is the possibility to use a rotating or fixed target for beams up to 2 kW for fragmentation reactions with Inflight method to be used directly or on a secondary target.

The eight experimental areas at the cyclotron facility as seen on the right hand of the cyclotrons in Fig. 1 can take any of the SIB for experiments of fundamental nuclear physics, applied physics, industrial applications or any application needed SIB.

There are continuously ongoing upgrades and developments for the stable beams at the cyclotrons, driven by request from the physics.

The most recent developments are presented in [3] as the Tellurium beams and a $^{232}Th^{30+}$ beam have been produced (results should be published in a short time), using LCO heating [22]. Developments on adapting the MIVOC technique to the ECR4 sources are still ongoing to enlarge isotopes available to produce beams. It is the same group that work on the operation and development of the 4 injectors, p/d source, Phoenix V3 and ECR4 ion sources. The development of new beams and more stable operation are therefore mutualised.

Since the 2015 paper [1] an upgrade has been made of the SPIRAL1 facility shown in Fig. 7. This upgrade was motivated by the capacity to produce a larger span of radioactive ion beams at GANIL [23].

At the cyclotron facility there are two possibilities for production of RIBs, either through Fragmentation at the inflight facility LISE or by the ISOL method at the SPIRAL1 facility. The RIBs produced today [24] at the SPIRAL1 facility are seen in Fig. 8, this list is being updated regularly due to the ongoing developments.

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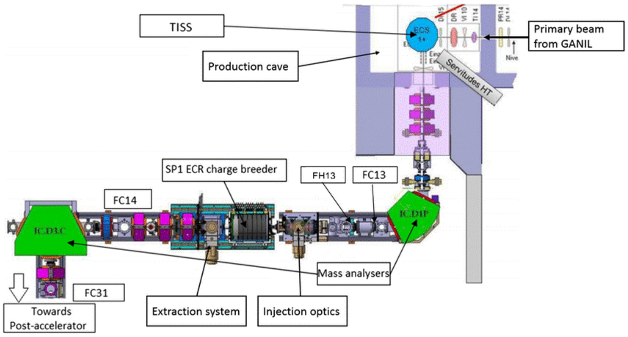

Figure 7: The SPIRAL1 for production of 1^+ radioactive ion beams with the possibility of charge breeding in the ECR booster before post acceleration in the CIME cyclotron.

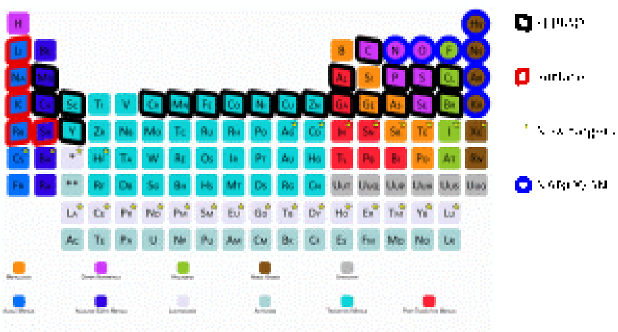

Figure 8: List of beams from the SPIRAL1 facility.

The SPIRAL1 Installation

The SPIRAL1 installation, running in 2001–2014, underwent an upgrade to increase the capacity to deliver RIBs for the physics. This upgrade lead to changing totally the design of the target, ion source and the complete beam lines and install a Charge breeder to continue to permit the post accelerated beams for physics. At the SPIRAL1 installation the target is an ISOL target where the stable beams of ^{12}C at 95 MeV/A up to ^{238}U at 8 MeV/A from the SSC are stopped in a thick target (targets of $Z < 41$) or thin targets (no Z restriction). The elements are ionised either by an ECR or FEBIAD ion source. A charge breeder [25] allows to send all the RIBs to a post-accelerator CIME cyclotrons and use this beam for any of the eight experimental areas.

Since the upgrade a dense program for production of new elements is prepared every year and a new exciting exploration of these beams for physics are in the starting block opening up new scientific possibilities for the users of GANIL. Since 2019 the beams are produced with intensities of 106 pps. A ^{47}K^{10+}@7 MeV/A beam was used for physics in 2021. In complementary to the noble gazes already produced earlier at GANIL beams of Na, Al, Mg, Cl, K, Rb have successfully been produced, the production of Br was recently produced but still under analysis while writing this article and are ready for further explorations for the needs for physics. The use of molecular beams, broken up in the charge breeder are under investigation and opens up further possibilities of RIBs for the users [26]. The charge breeder have been upgraded with variable 8–18 GHz RF injection at a power of 200 W. This allows to optimise further the charge state efficiencies and then the RIBs to be post-accelerated with CIME.

NEXT STEPS FOR GANIL

The installation of the S3 installation is ongoing and the installation should be ready for the first beams in end of 2023. The installation will in the first years use the beams from the A/q ≤ 3 ion source before going to the beams from the A/q ≤ 7 ion source (2026-2027).

In the end of the S3 installation is a low energy branch [27] consisting of a gas cell setup. This part of S3 installation will be installed before the commissioning of the S3.

A seen in Fig. 9 the DESIR facility is to be installed between the current cyclotron and SC Linac facilities. The construction is foreseen to start in 2023, this installation consist of 150 m of transport beam lines from the SPIRAL1 and the S3-LEB installation towards the low energy experimental hall of DESIR. Exploration of the radioactive ion beams from either of the facilities will therefore be possible in this new experimental complexes as from 2026 after the full installation.

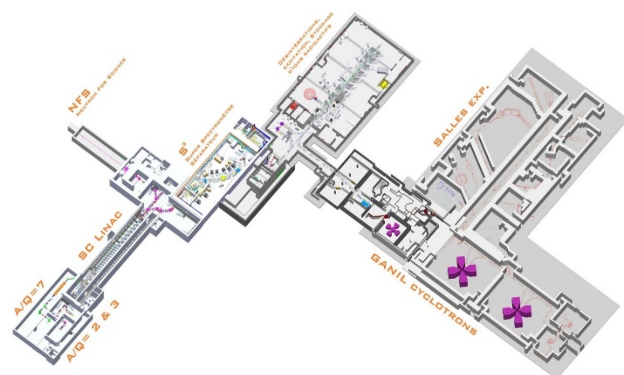

Figure 9: The full GANIL facility as from 2026.

CONCLUSIONS

The last 5 years have been exciting for GANIL, upgrades of the current 40 year old cyclotron facility and the new installation of SPIRAL2 have largely increased the capacity of beams and the capacity of interesting physics to be performed at the installation. The next 5 years will follow by further installations and further commissioning of the installations already in place. As in the span of 5–10 years even more beams, stable and radioactive will come available for the users. For what is the program from 10–30 years from now, new plans are already discussed.

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REFERENCES

[1] O. Kamalou *et al.*, "GANIL Operation Status and New Range of Post-Accelerated Exotic Beams", in *Proc. HIAT'15*, Yokohama, Japan, Sep. 2015, paper MOA1C02, pp. 20–22. doi:10.18429/JACoW-HIAT2015-MOA1C02

[2] J.-M. Lagniel *et al.*, "Advances of the Spiral 2 Project", in *Proc. HIAT2015*, Yokohama, Japan, September 2015, paper TUA2I01, pp. 148–152. doi:10.18429/JACoW-HIAT2015-TUA2I01

[3] M. Dubois *et al.*, "Radioactive and Stable Ion Beam production at GANIL", *J. Phys.: Conf. Ser.*, vol. 2244, p. 1012070, 2022. doi:10.1088/1742-6596/2244/1/012070

[4] A. K. Orduz *et al.*, "Commissioning of a high power linac at GANIL: Beam power ramp-up", *Phys. Rev. Accel. Beams*, vol. 25, p.1060101, 2022. doi:10.1103/PhysRevAccelBeams.25.060101

[5] P. Dolegieviez, R. Ferdinand, X. Ledoux, H. Savajols, and F. Varenne, "Status of the SPIRAL2 project", in Proc. IPAC'19, Melbourne, Australia, 2019, pp. 844-847. doi:10.18429/JACoW-IPAC2019-MOPTS005

[6] X. Ledoux *et al.*, "The neutrons for science facility at SPIRAL 2", *EPJ Web Conf*, vol. 146, p. 03003, 2017. doi:10.1051/epjconf/201714603003

[7] S3 collaboration, "Toward the drip lines and the superheavy island of stability with the Super Separator Spectrometer S^3", *Eur. Phys. J. A.*, vol. 51, p. 66, 2015. doi:10.1140/epja/i2015-15066-3

[8] O. Tuske *et al.*, "Light ion source for proton/deuteron production at CEA Saclay for the Spiral2 project", *Rev. Sci. Instrum*, vol. 83, p. 102A316, 2012. doi:10.1063/1.3665963

[9] C. Barue *et al.*, "Metallic beam developments for the SPIRAL 2 project", *Rev. Sci. Instrum*, vol. 85, p. 102A946, 2014. doi:10.1063/1.4847236

[10] T. Thuillier *et al.*, "First Plasma of the PHOENIX V3 ECR Ion Source", in *Proc. ECRIS2016*, Busan, Korea, Aug.-Sep. 2016, paper TUAO05, pp. 48–49. doi:10.18429/JACoW-ECRIS2016-TUAO05

[11] M. Di Giacomo *et al.*, "RF Commissioning of the SPIRAL2 RFQ in CW Mode and Beyond Nominal Field", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2804–2806. doi:10.18429/JACoW-IPAC2019-WEPRB007

[12] C. Jamet *et al.*, "SPIRAL2 Diagnostic Qualifications with RFQ beams", in *Proc. IBIC'19*, Malmö, Sweden, Sep. 2019, pp. 188–192. doi:10.18429/JACoW-IBIC2019-MOPP036

[13] R. Ferdinand, M. Di Giacomo, H. Franberg, J.-M. Magniel, G. Normand, and A. Savalle, "Final Results of the SPIRAL2 Injector Commissioning", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 848–851. doi:10.18429/JACoW-IPAC2019-MOPTS006

[14] S. Leloir *et al.*, "Measurement Uncertainty Assessments of the Spiral2 ACCT/DCCT", in *Proc. IBIC2016*, Barcelona, Spain, Sep. 2016, pp. 713–715. doi:10.18429/JACoW-IBIC2016-WEPG39

[15] J. L. Vignet *et al.*, "The Beam Profile Monitor for Spiral2", in *Proc. DIPAC'09*, Basel, Switzerland, May 2009, paper TUPB07, pp.176-178.

[16] R. V. Revenko and J. L. Vignet, "Bunch Extension Monitor for LINAC of SPIRAL2 Project", in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 486-490. doi:10.18429/JACoW-IBIC2016-TUPG59

[17] G. Normand *et al.*, "SPIRAL2 RFQ bunch lengths and longitudinal emittance measurements", *J. Phys.: Conf. Ser.*, vol. 1350, p. 1012098, 2019. doi:10.1088/1742-6596/1350/1/012098

[18] M. Di Giacomo *et al.*, "Proton beam commissioning of the SPIRAL2 Single Bunch Selector", *J. Instrum.*, vol. 15, p. T12011, Dec. 2020. doi:10.1088/1748-0221/15/12/T12011

[19] A. Ghribi, P.-E. Bernaudin, R. Ferdinand, and A. Vassal, "Cryogenic Tests of the SPIRAL2 LINAC Systems", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1240–1243. doi:10.18429/JACoW-IPAC2019-TUPMP006

[20] G. Olry *et al.*, "Spiral2 Cryomodules B Tests Results", in *SRF'13*, Paris, France, 2013, pp. MOP010, pp. 95-99. https://jacow.org/srf2013/papers/mop010.pdf

[21] C. Marchand *et al.*, "Performances of SPIRAL 2 Low and High Beta Cryomodules", in *Proc. SRF2015*, Whistler, BC, Canada, 2015, paper WEBA04, pp. 967–972. doi:10.18429/JACoW-SRF2015-WEBA04

[22] F. Lemagnen *et al.*, "New metallic stable beams for GANIL", in *Proc. ECRIS'20*, East Lansing, MI, USA, Sep. 2020, pp. 54–56. doi:10.18429/JACoW-ECRIS2020-MOZZO04

[23] P. Dolegieviez *et al.*, "New exotic beams from the SPIRAL 1 upgrade", *Nucl. Instrum. Methods Phys. Res., Sect. B.*, vol. 463, pp. 339-344, 2020. doi:10.1016/j.nimb.2019.04.063

[24] *Chart of beams at GANIL, stable and radioactive*, https://u.ganilspiral2.eu/chartbeams/

[25] P. Delahaye, L. Maunoury, and R. Vondrasek, "Charge breeding of light metallic ions: Prospects for SPIRAL", *Nucl. Instrum. Methods Res., Sect. A.*, vol. 693, pp. 104-108, 2012. doi:/10.1016/j.nima.2012.07.016

[26] L. Maunoury *et al.*, "Charge Breeder at GANIL: metal charge-bred elements", *J. Phys.: Conf. Ser.*, vol. 2244, p. 1012066, 2021. doi:10.1088/1742-6596/2244/1/012066

[27] R. Ferrer *et al.*, "In gas laser ionization and spectroscopy experiments at the Superconducting Separator Spectrometer (**S**^{3}): Conceptual studies and preliminary design", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 317, pp. 570-581, 2013. doi:10.1016/j.nimb.2013.07.028