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► **To cite this version:**

Angie Orduz, Pierre-Emmanuel Bernaudin, Marco Di Giacomo, Robin Ferdinand, Bertrand Jacquot, et al.. SPIRAL2 final commissioning results. 31st Linear Accelerator Conference, Aug 2022, Liverpool, United Kingdom. pp.TU2AA02, 10.18429/JACoW-LINAC2022-TU2AA02 . hal-03839809

**HAL Id: hal-03839809**

**<https://hal.science/hal-03839809v1>**

Submitted on 5 Dec 2022

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## SPIRAL2 FINAL COMMISSIONING RESULTS

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### Abstract

The commissioning of SPIRAL2 was carried out in different steps and slots from 2014 to end 2021. In a first phase, the proton-deuteron and heavy ion sources, LEBT lines and RFQ were commissioned and validated with  $A/Q=1$  up to 3 particles. The validation of the MEBT (between the RFQ and the linac, including the Single Bunch Selector), linac and HEBT lines (up to the beam dump and to the NFS experimental room) started on July 2019, when GANIL received the authorization to operate SPIRAL2. The linac tuning is now validated with  $H^+$ ,  $^4He^{2+}$  and  $D^+$  and nominal  $H^+$  and  $D^+$  beams were sent to NFS for physics experiments. The main results obtained during the commissioning stages and the strategy used by the commissioning team are presented.

### INTRODUCTION

GANIL (Grand Accélérateur National d'Ions Lourds) is principally carrying studies in fundamental nuclear physics, but also in other fields such as atomic physics, radiobiology, condensed matter physics and medical and industrial applications [1]. The laboratory has a first radioactive ions beams facility operating since 1983, now equipped with 3 sources and 5 cyclotrons with an energy range up to 95 MeV for stable beams, 50 MeV for fragmented beams and 25 MeV for post-accelerated radioactive beams [2]. A second facility started operating in 2019, SPIRAL2 (Système de production d'ions radioactifs accélérés en ligne de 2e génération), is now based on a SC (Super Conducting) linac producing  $H^+$  beams up to 33 MeV,  $D^+$  and  $A/Q=2$  up to 20 MeV/A and heavy ions ( $A/Q<3$ ) up to 14.5 MeV/A. The SPIRAL2 beam characteristics are listed in Table 1.

Table 1: Beam specifications including the NewGain project.

Parameter	$H^+$	$D^+$	$A/Q < 3$	Newgain
A/Q	1	2	3	7
Max I (mA)	5	5	1	1
Max E (MeV/A)	33	20	14.5	7
Beam power (kW)	165	200	45	49

SPIRAL2 comprises a heavy ion source  $A/Q<3$  and a  $H^+/D^+$  source [3], two LEBT (Low Energy Beam Transport) [4] to transport and match the beams to the RFQ (Radio Frequency Quadrupole) [5], a MEBT (Medium Energy Beam Transport) [6], the SC linac with 26 cavities in two cryostat families. The first cryostat family each containing one low beta cavity ( $\beta=0.07$ ) was designed by CEA [7]

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and the second one, each containing two high beta cavities ( $\beta=0.12$ ), designed by CNRS [8]. Three HEBT (High Energy Beam Transport) lines drives the beam to the beam dump and two to experimental rooms: NFS (Neutrons For Science) [9] and S3 (Super Separator Spectrometer) [10, 11].

A Single Bunch Selector (SBS) is located in the MEBT line to select one bunch over  $N$ ,  $N$  ranging between 100 and 10000, for Time-of-Flight experiments and power reduction with same particle density [12]. The beam diagnostics along the linac are positioned in the warm sections (in-between cryomodules) as shown in Fig. 1.

The sources, LEBT, RFQ and beam diagnostics were commissioned in different steps between 2014 and 2018 [13]. The commissioning of SPIRAL2 linac took place from July to December in 2019, 2020 and 2021. During these periods, the MEBT, linac, HEBT and the NFS experimental room were successfully commissioned with the reference particles  $H^+$ ,  $^4He^{2+}$  and  $D^+$ . This paper describes the main results obtained during the commissioning, the transition between commissioning and operation, and the first results obtained by the NFS experiments. The future projects at SPIRAL2 are finally presented.

### COMMISSIONING PHASES AND RESULTS

The SPIRAL2 commissioning was managed in four phases. The first phase was the beam qualification of the ion sources and LEBT in the laboratories in charge of the development. The project decided to preinstall the ECR (Electron Cyclotron Resonance) ion sources and the LEBT in the two French laboratories where they were designed (CEA-Saclay and LPSC-Grenoble), in order to commission them with beam before the SPIRAL2 building availability. These successful tests were achieved by late 2012 [3].

The second phase comprised the qualification of the injector (sources and RFQ) on a diagnostic plate (D-Plate). This was a relevant step with the achievement of various goals:

- (i) Reproduce the results from the ion source pre-commissioning, i.e. validate the source performances on SPIRAL2 site,
- (ii) Validate the RFQ performances for the various main reference particles (Table 1): transmission, beam energy, output emittances in the three planes, and bunch extension,
- (iii) Provide a development platform for various beam diagnostics required either to validate the RFQ beams or later to tune and validate the linac beams, and

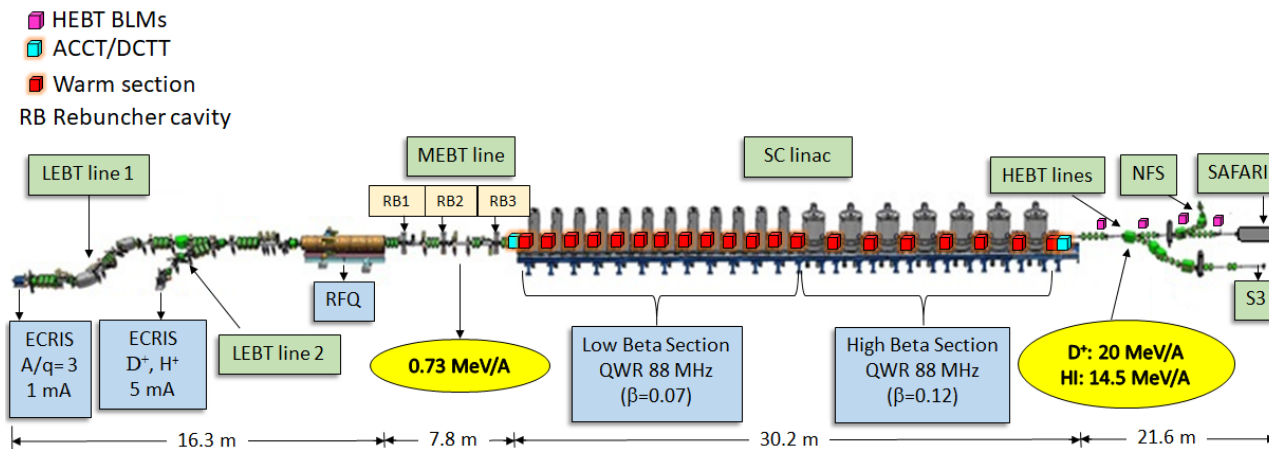


Figure 1: SPIRAL2 SC linac layout.

(iv) Measure the beam characteristics at the RFQ exit, to serve as input parameter for the next stage.

This phase was performed at GANIL in collaboration with the partner laboratories between 2014 and 2018. The first major result of the commissioning was the 100% beam transmission in the RFQ for  $H^+$ ,  $^4He^{2+}$ ,  $^{18}O^{6+}$  and  $^{40}Ar^{14+}$  as presented in Fig. 2 [13]. A good agreement between the measurements obtained for the transversal and longitudinal emittances and the reference simulations with TraceWin was achieved [14, 15].

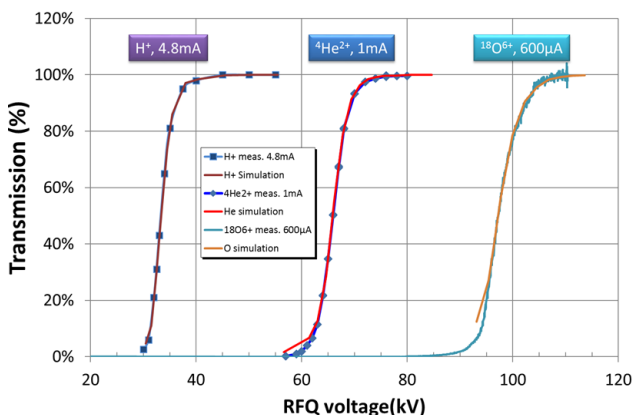


Figure 2: RFQ transmission of the 3 references particles.

Two SC linac cooldowns were performed in 2017 and 2018, followed by 5 months of testing at 4 K. During this time, helium bath level and the pressure stabilities were measured, simulating cavity loss with heater loads, and searching for frequency instability in the cavities via cavity measurements. Strong thermoacoustic oscillations were discovered and suppressed adding a short circuit between the return line tapping and the phase separator of the cryomodule, before the beginning of power commissioning [16].

Preparation work to the RF system commissioning was carried out between 2015 and 2018. All amplifiers and cir-

culators were tested one by one, cables and transmission line length were measured, but only the warm cavities of the MEBT rebuncher could be powered and fully commissioned, the first one during the injector commissioning on the D-plate, and the other two during the MEBT commissioning. The SC linac cavities were powered and the accelerating fields calibrated in 2019.

The linac commissioning phase started with the main objective of transporting the beam to the beam dump. On July 8th 2019, GANIL received the authorisation from the ASN (French safety authority) to operate SPIRAL2. The beam commissioning team started the MEBT commissioning on July 15th, optimising the transport to the linac with a 250  $\mu A$  peak  $H^+$  beam. The beam profile and transverse emittance measurements for  $H^+$  and  $^4He^{2+}$  were compared with reference simulations, finding good agreement. The platform voltage was optimized to match the RFQ input energy. The three MEBT rebunchers were successfully tuned for the beam linac matching. The electric and magnetic fields of the SBS were also qualified to accurately select the required bunches [6]. A  $H^+$  beam (250  $\mu A$ , 730 KeV) of 1 W was transported in buncher mode (no acceleration) from the source to the Beam Dump on October 28th. A month later, on November 27th, the beam was accelerated to its nominal energy of 33 MeV with a useful cycle of 960  $\mu s$ , as shown in Fig. 3.

Finally, the  $H^+$  beam was sent to the NFS experimental hall to perform the first irradiation with an iron target in collaboration with the Nuclear Physics Institute (NPI) of Czech Republic on December 11th, thus achieving phase 4 of the commissioning. The first part of the commissioning was completed with the linac warm up on December 17th [17, 18].

In July 2020 the second part of the commissioning was started, a 5 mA peak proton beam was injected in the linac up to the beam dump and in December the duty cycle was increased to obtain a beam power of 16 kW [19] as shown in Fig. 4. This was possible due to a large analysis of the

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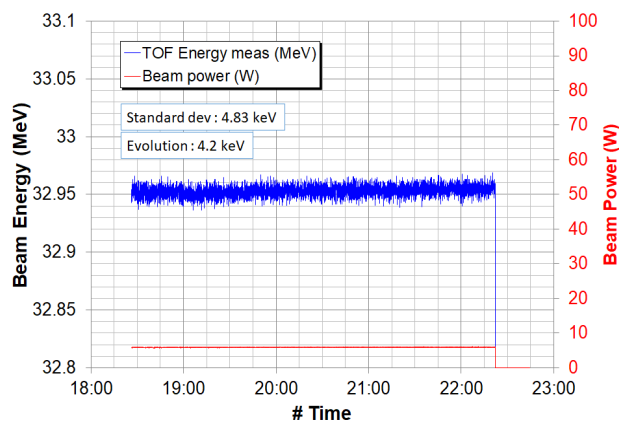


Figure 3: Energy and power measurements of the first accelerated beam in SPIRAL2 (250  $\mu\text{A}$   $\text{H}^+$ ).

transverse and longitudinal tuning and the improvement of the LLRF feedback and feedforward systems [20, 21].

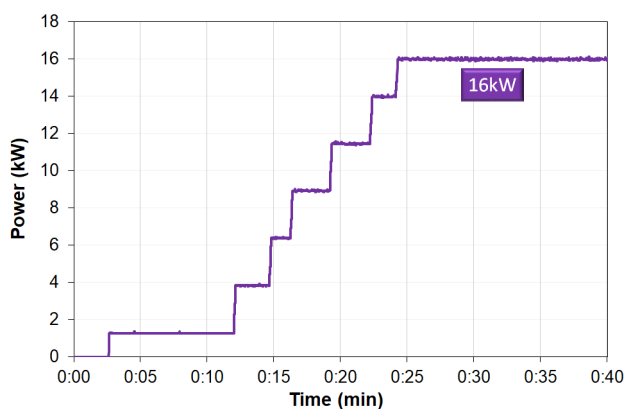


Figure 4: Beam power ramp-up to 16 kW at SPIRAL2.

The preparation of the  $\text{D}^+$  commissioning started in 2020 with the tuning of the linac with a  $^4\text{He}^{2+}$  beam to avoid linac activation. The MEBT including the SBS were successfully commissioned with 1.2 mA, however the signature matching procedure [22] used to tune the linac cavities presented some difficulties. The energy measurement at the linac exit showed a deviation up to 9% with the reference value. Two main problems were found: i) a difference of bunch centroid between the measurement and the reference particle computation, ii) the use of the input energy in the free parameters of the signature matching optimization leads to a divergence in the energy in the SPIRAL2 case for the last 3 cavities of the low  $\beta$  section and all high  $\beta$  section cavities, due to position in the TTF (Transit Time Factor) slopes as is shown in Fig. 5. In this case it is impossible to distinguish between cavity voltage error and input energy error. The origins of these problems were: the cavities are too short (no "real signature"), the energy in the first section is low but the acceleration gradients are strong [23] and the bunch has a large phase spread, mainly in the first cavities. In conclusion, the signature matching method is not adapted to the SPIRAL2

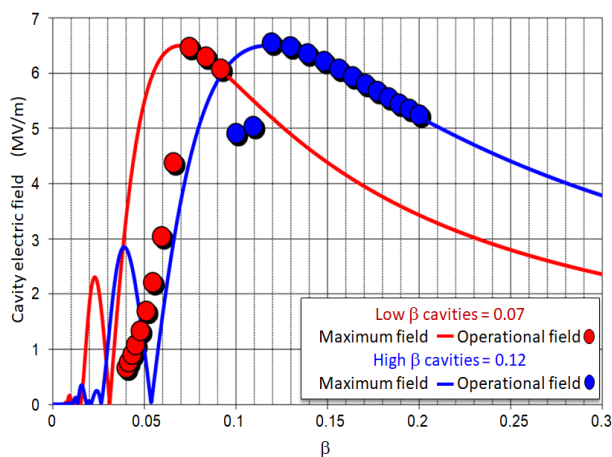


Figure 5: SPIRAL2 Transit Time Factor for: the maximal (line) and the operational (points) electric fields.

case. Having understood the problem, the tuning method was modified limiting the scan around the rebuncher phase and using the theoretical energy at the cavity entrance.

Commissioning in 2021, started in July with the tuning of  $^4\text{He}^{2+}$  with the modified method, and a 1.3 mA beam was accelerated up to the beam dump. Immediately afterwards, a 5 mA peak, low duty cycle,  $\text{D}^+$  beam was successfully accelerated, confirming the new tuning method soundness.

The second 2021 stage objective was to qualify the beam with the SBS to demonstrate 50  $\mu\text{A}$  on target for NFS experiments, the project beam objectives for NFS with SBS. For this purpose, a  $\text{D}^+$  beam at nominal energy (4.7 mA peak) was used with the SBS (1/100), resulting in 47  $\mu\text{A}$  on the beam dump (no macro pulse shape). Fig. 6 shows the measurement of the average beam current in a time period of 13 hours. The blue line corresponds to the current measured at the end of the MEBT and the red line to the current measured at the end of the linac. In the first part of the test, with the beam only in the MEBT the beam current was reduced from 47  $\mu\text{A}$  to 43  $\mu\text{A}$  due to high temperatures in the beam stop device receiving the beam deflected by the SBS. The beam breaks were related to source problems or voluntary breaks by the operation.

The last step of the commissioning was the power ramp-up to 10 kW with a 5 mA  $\text{D}^+$  beam transported to the beam dump without SBS [24]. The measured losses, as for the 16 kW power ramp-up, were controlled and limited using the transmission monitoring (ACCT, DCCT), BLMs, BPMs and pressure variations in the warm sections. During the two power ramp-up, the BLM measurements were below the GANIL safety limits and the operation of SPIRAL2 up to full power was validated from extrapolations [19, 24].

The training for the operation of SPIRAL2 started in 2019, in parallel with the commissioning. The commissioning was carried out with the technical, safety, control, diagnostics and especially the machine operating groups. As a result, manuals, applications and controls were implemented and improved for the optimal functioning of SPIRAL2. Methods



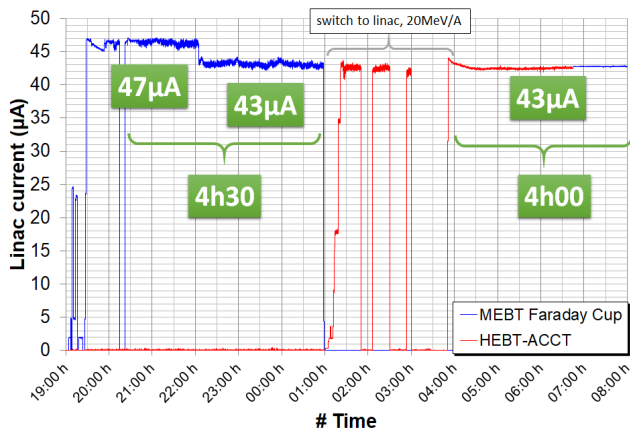


Figure 6: Current measurement in the MEBT (blue) and in the linac (red) during the validation test.

and improvements to the RF and cryogenic systems were implemented [17–20]. In 2021 physics started in parallel with the commissioning, with 24% of the total operation time of SPIRAL2.

## THE NEXT STEPS

The SPIRAL2 operation in 2022 starts on August 29th until December 12th. The programme is mainly devoted to physics (58%) and includes different studies (42%) such as the linac tuning with  $A/Q=3$  ions and the test of applications, control procedures and tools to be implemented in order to speed up the operation. Some of these studies are part of the commissioning of the S3 experimental room.

A new project is launched (NewGain [25, 26]) with the objective to build a third injector for heavier beams with  $A/Q$  up to 7, while the extension of the SPIRAL2 beams for interdisciplinary research and application is under study. NewGain will improve the possibility to provide higher ion beams intensities (from proton to uranium), thus opening up unprecedented opportunities for nuclear structure and reaction studies at the extremes of the chart of nuclides from  $N=Z$  nuclei at the proton dripline to super-heavy species, including the discovery of new elements, and the production of radioisotopes.

## CONCLUSION

The SPIRAL2 facility was commissioned successfully. The four planned phases were completed to start the fully operation for users in time. Beam physics in NFS started already in 2021. The beam power ramp up with  $H^+$  and  $D^+$  beams demonstrate the reliability of the linac. Actual work is focused in the commissioning for S3 and the design of the new injector NewGain.

## ACKNOWLEDGMENTS

The authors would like to thank the Direction de la Recherche Fondamentale (DRF) of the CEA, the Institut National de Physique Nucléaire et de Physique des Particules

(IN2P3) of the CNRS, the Region of Basse-Normandie and local authorities for funding SPIRAL2, and the support of the European Union and international partnerships. Special thanks to all the GANIL staff, the national partner Laboratoire de Physique des 2 infinis Irène Joliot-Curie (IJClab), Institut pluridisciplinaire Hubert Curien (IPHC), Laboratoire de Physique Subatomique & Cosmologie (LPSC), L'institut national polytechnique de Lorraine (INPL), Laboratoire de Physique Corpusculaire (LPC), SBT, Département Projet et Ingénierie des Installation CEA (DP2I), the international collaborators Bhabha Atomic Research Centre (BARC), Istituto Nazionale di Fisica Nucleare (INFN), Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Institute of Nuclear Physics Polish Academy of Sciences (IFJ-PAN), Soreq Nuclear Research Center, Institute for Nuclear Researches and Nuclear Energy (INRNE-BAS) and external collaborators for the huge amount of work that led to a successful SPIRAL2 commissioning.

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