SPIRAL2 Commissioning and Operations

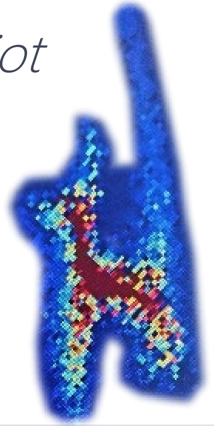
Angie Orduz

Accelerator physicist, GANIL

on behalf of the GANIL teams and SPIRAL2 collaborations, many thanks to all of them!

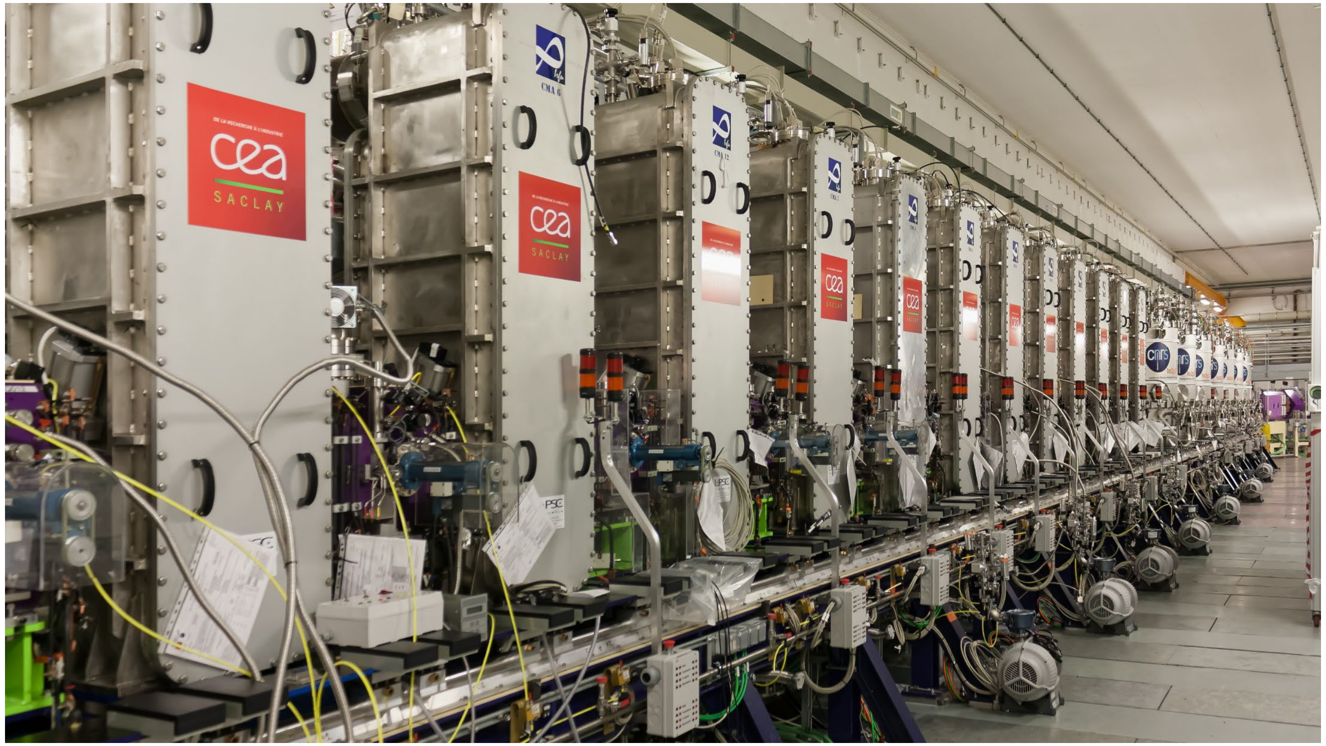
Special thanks to: Marco Di Giacomo, Jean-Michel Lagniel , Guillaume Normand and Didier Uriot

HB 2023



Outline

- Introduction
- Commissioning
- First year of operation
- Perspectives
- Summary



GANIL (CEA-CNRS):
a multidisciplinary and
multi-users laboratory

Collaboration with National Laboratories
and International Partners

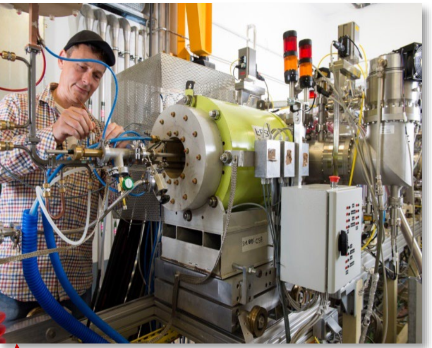
DP2I (DAM)

BARC (India), INFN (Italia)
IFIN-HH (Romania), IFJ-PAN (Poland)
SOREQ (Israel), INRNE-BAS (Bulgaria)

Particles	H^+	D^+	ions	NEWGAIN
A/Q	1	2	3	7
Max I (mA)	5	5	1	1
Max energy (MeV/A)	33	20	14	7
Max beam power (kW)	165	200	44	16

SPIRAL2

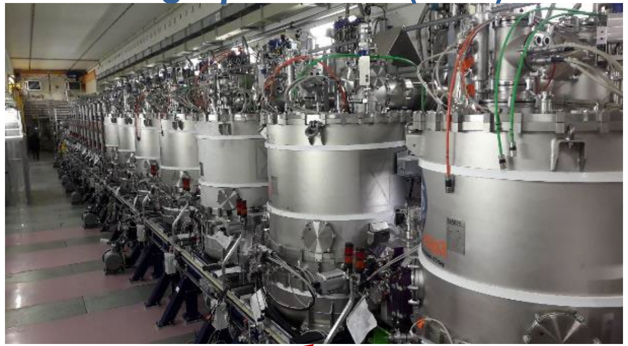
ECR A/Q≤3



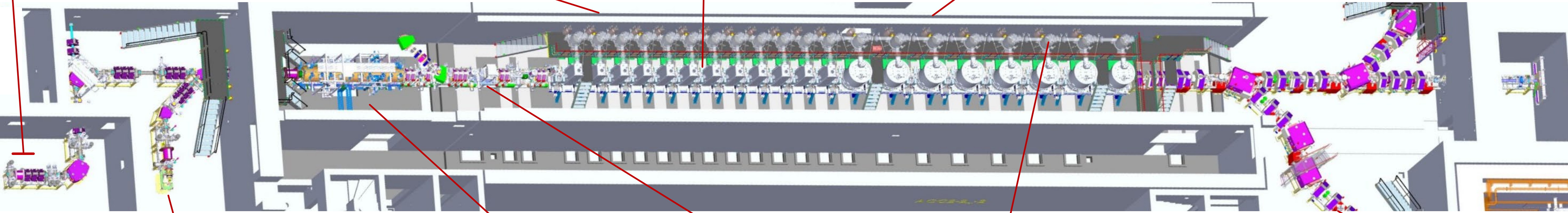
Low β section (0.07)

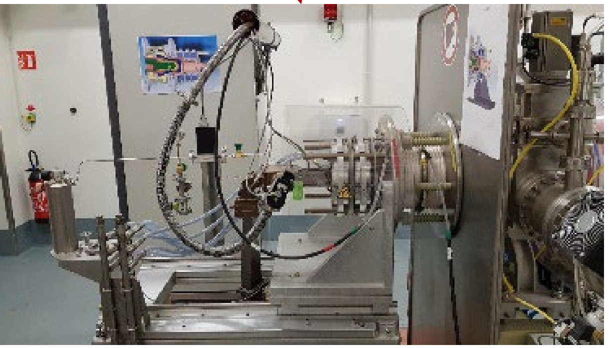
Warm section

High β section (0.12)

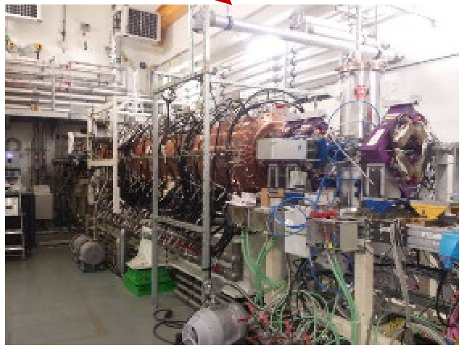


NFS (converter cave)





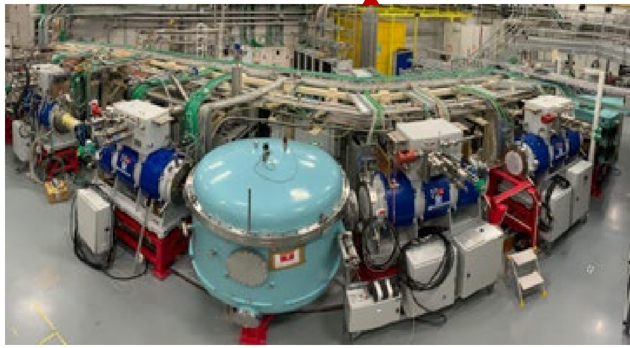
ECR H^+/D^+



RFQ

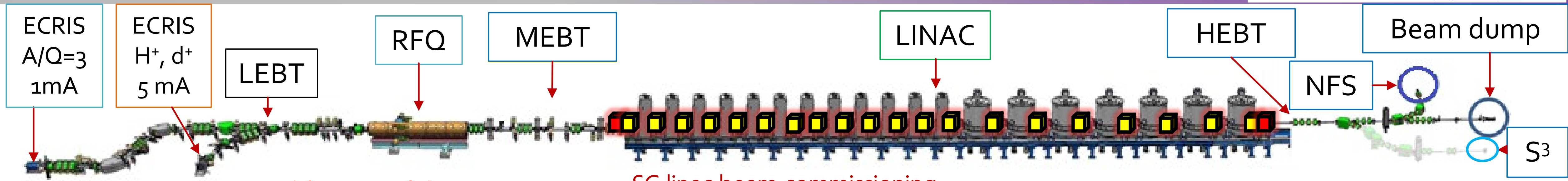
SBS

Cryogenic distribution system



S^3

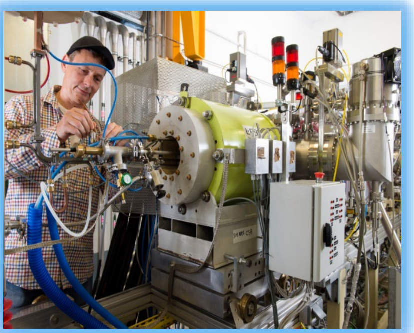
Beam Commissioning Time Line



2009-2012

Qualification of the ion sources and LEBT (LPSC-Grenoble and CEA-Saclay)

Construction building and tools

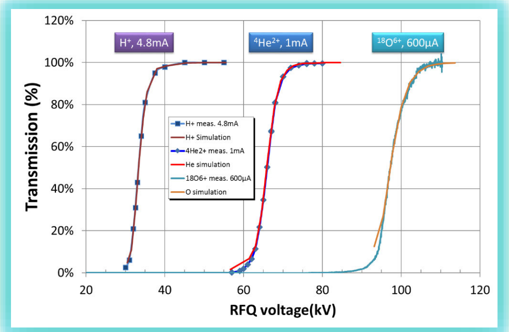


2014-2018

Qualification of the injector on a Diagnostic Plate (GANIL)

- Reproduce previous results
- RFQ performance
- Diagnostics platform
- Beam characteristics at RFQ exit
- 2014 1st H^+ beam @2 mA H/D (Dec)
- 2015 1st Ar^{9+} beam @ 230 µA HI source (Jul) / 1st RFQ H^+ (Dec)

2018 Diagnostic plate commissioning end April –November, removed in 2018



2019-2021

SC linac beam commissioning up to the main beam dump

Authorization to operate SPIRAL2, Jul 8th, 2019

1st beam in the linac, Oct. 28th

1st beam in NFS, Dec. 11th

Characterization and first experiments in the NFS room

33MeV H^+ (2019)

40 MeV $^4He^{2+}$, D^+ (2020)

50 µA D^+ NFS (2021)

2022

First year of SPIRAL2 operation in NFS room

50% beam time for physics

Pre-commissioning for S^3

7 MeV/A $^{18}O^{6+}$, $^{18}O^{7+}$, $^{40}Ar^{14+}$

0.73 MeV/A $^{18}O^{6+}$, $^{18}O^{7+}$, $^{40}Ar^{14+}$

Test Cavity failure

2023

SPIRAL2 operation

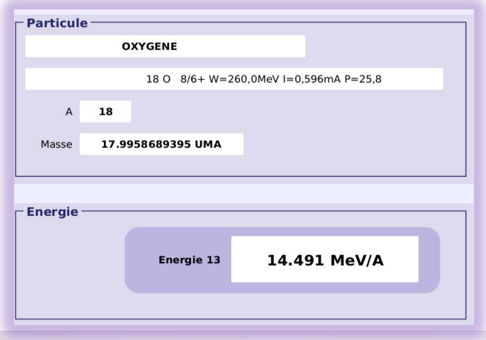
65% beam time for physics

14% for studies

Pre-commissioning for S^3

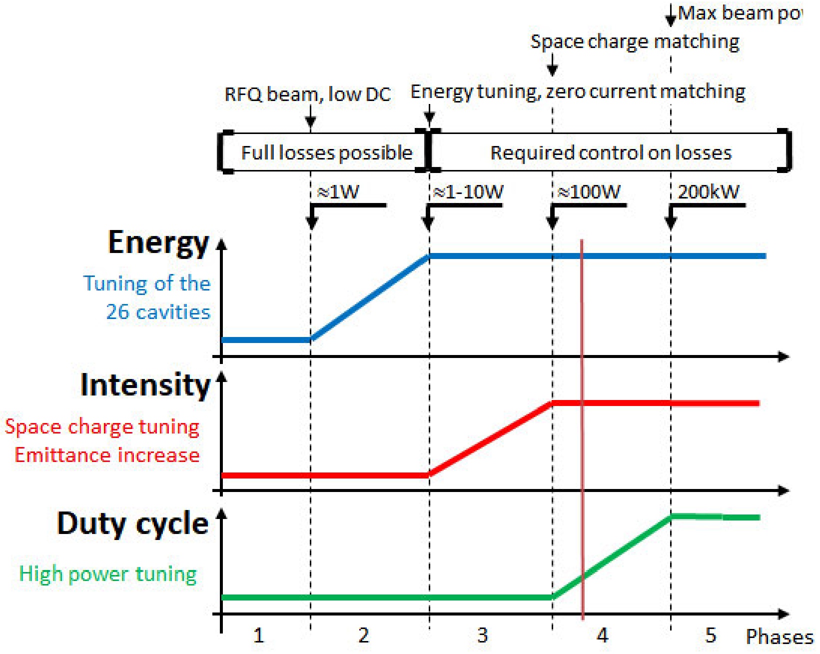
14.5 MeV/A $^{18}O^{6+}$

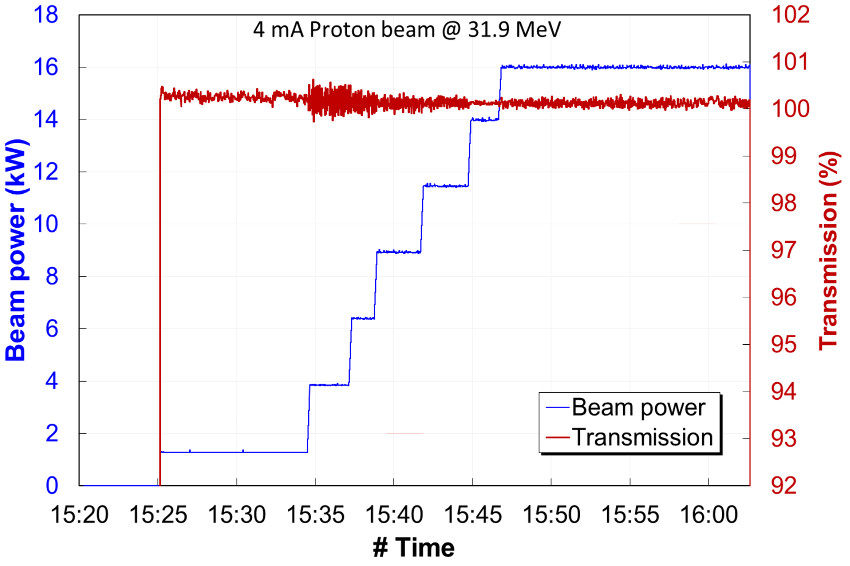
Studies: Test cavity failure and pressure variation in WS

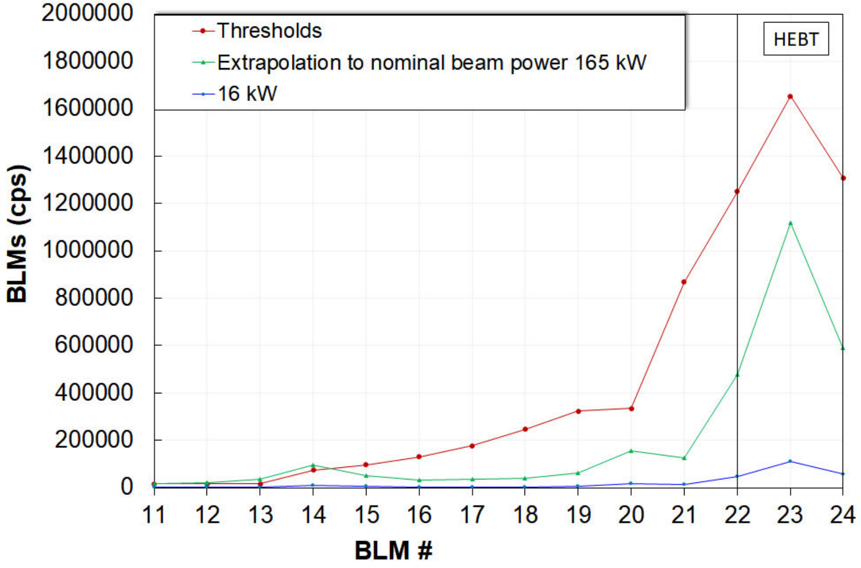


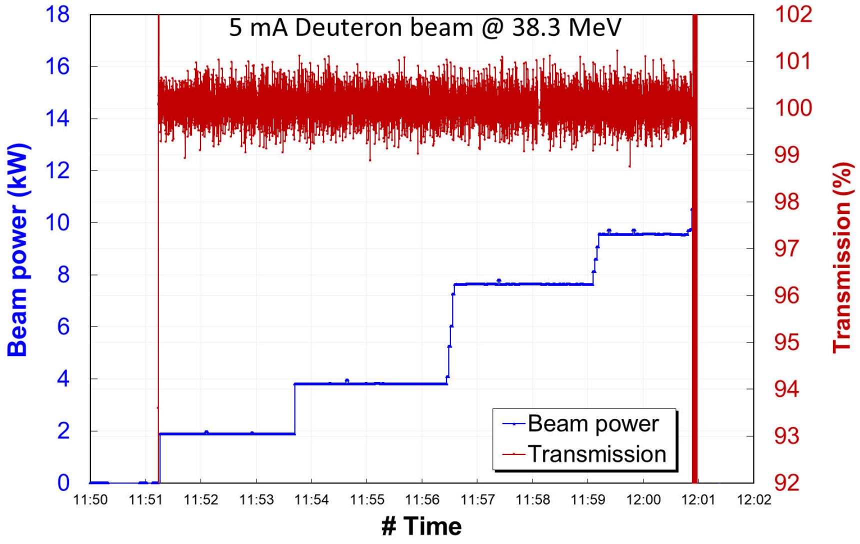
Beam Commissioning Main Results I

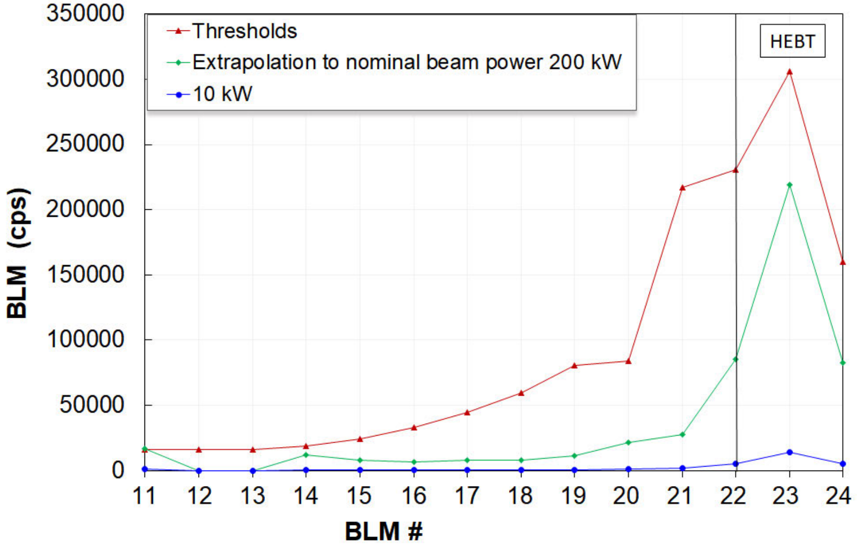
- H^+, D^+ and $^4He^{2+}$ were accelerated to their nominal values.
- Strategy power ramp up: energy, intensity and duty cycle.
- The beam power ramp up with H^+ and D^+ beams demonstrate the reliability of the linac.
  - ✓ H^+, 16 kW, 12 ms, 1 Hz, 12% DC. 2020
  - ✓ D^+, 10 kW, 1 ms, 10 Hz, 5% DC. 2021







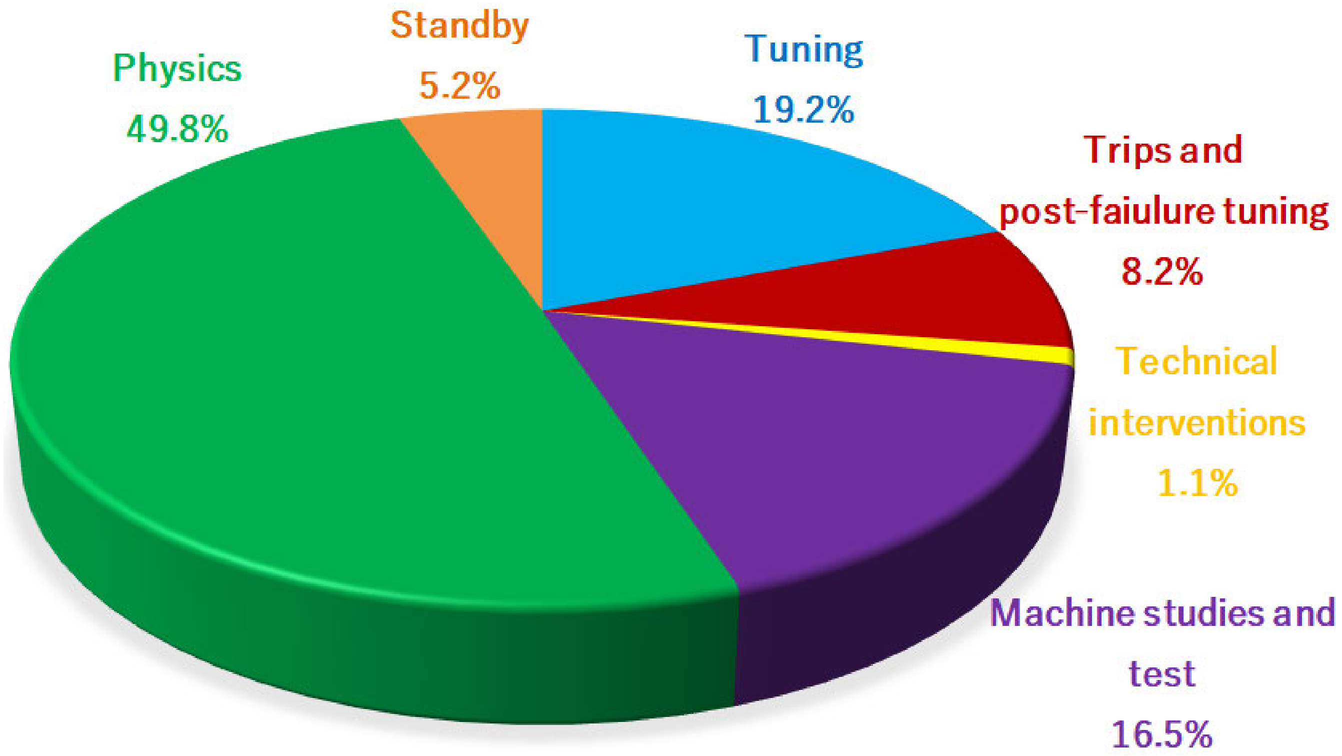




SPIRAL2 Operation 2022

The beam time was in 2022 ≈ 3 months

- 7 experiments and 3 main preparatory studies for S[3] were conducted.
- 76% of physic with D^{+} beams:
  - 9 μA and 47 μA on the target, 1/100 (SBS).
  - H^{+}, D^{+} and $^{4}He^{2+}$ from 10 MeV/A up to their nominal values.
- Tuning time = accelerator beam tuning + HEBT tuning.
- Accelerator trips were reduced from 32% to 8%.
- 75% of machine studies time for beam dynamics studies with $^{4}He^{2+}$, D^{+}, $^{18}O^{6+}$ and $^{40}Ar^{14+}$ beams.
  - Tuning methods validation + heavy ions acceleration
  - Energy variation procedure test
  - Linac operation in case of cavity failure
- Studies related to the RF and diagnostics systems.
- The first experiment for neutron-induced reactions in a ^{235}U actinide target was carried out with a D+.



SPIRAL2 Operation 2023

The expected beam time in 2023 ≈ 2.5 months
August 28 to November 19

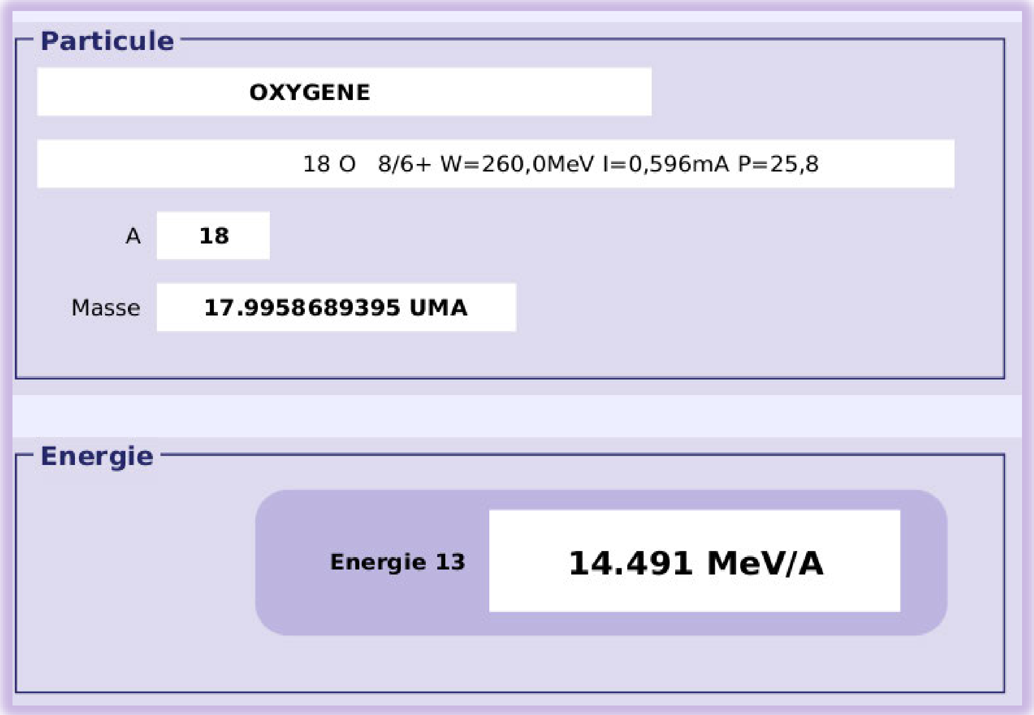
6 nuclear physics experiments and 2 preparatory studies for the S³ experimental room are planned.

- 65% of the total beam time is planned for experiments in physics, 5 of the 6 experiments with D^{+} beams.
  - ✓ Up to 47 µA on target, 1/100 (SBS).
  - ✓ D^{+} et $^{4}He^{2+}$ from 7 MeV/A up to their nominal value.

- 14% of total beam time for studies: 6% for beam dynamics studies with $^{4}He^{2+}$, $^{18}O^{6+}$ and $^{40}Ar^{14+}$ beams.
  - ✓ Tuning applications validation.
  - ✓ Acceleration of an $^{18}O^{6+}$ beam to its nominal energy, 14.5 MeV/A.
  - ✓ Validation of energy variation and A/Q ratio applications.
  - ✓ Linac operation in the event of cavity #6 failure.
  - ✓ Study of pressure variation on the warm sections of the linac.

- Studies on RF and diagnostic systems (emitance, non-intrusive profiler, BPM, Improved procedure for initiating cavities).

- The first test for R&D into the production of innovative radioelements (REPARE project).



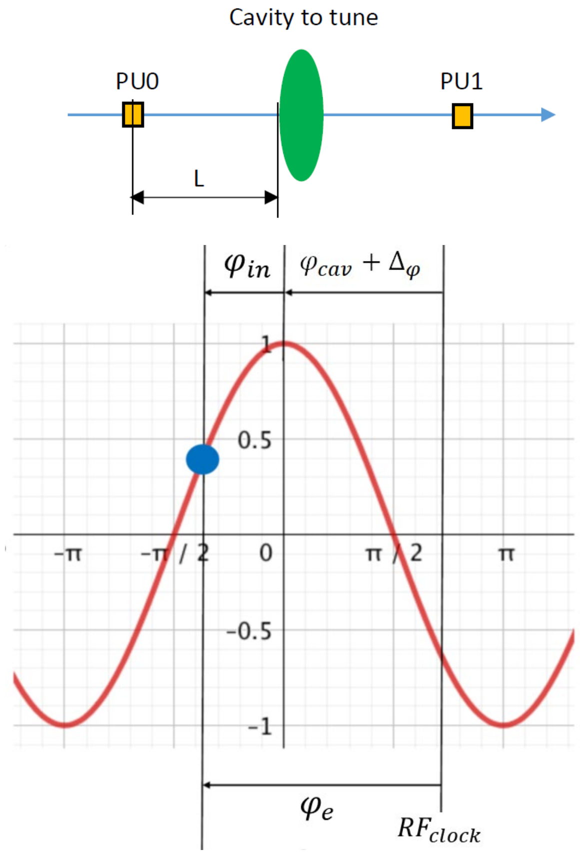
Tuning Methods Cavities

J-M. Lagniel , “Synchronous Phase and Transit Time Factor” presented at HB’23, Wednesday 14:20 paper WEA3I1.

1. Advanced method (1-2 days)
   - Signature matching + avoid the phase measurements errors (non-linear effects deforming the bunch shape)
   - 1 tuning per year: phase and voltage calibration for all tunings.

2. With reference method (<60 min manual)
   - No detune, no phase scan.
   - Phase measurement at cavity entrance.
   - Verification with phase measurement at the PU1.
   - D^+ => @20 MeV/A ΔE/E<1% / @0.73 MeV/A ΔE/E<1.5%
   - Sensitive to accuracy of phase measurements. The $\Delta\varphi$ on the expected/measured post-cavity BPM is potentially > 10° in the early cavities in some cases. As the beam is accelerated, the $\Delta\varphi$ decreases (oscillating).

3. Rapport A/Q (<10 min)
   - Heavy ions at low energy for S^3
   - If the BPMs do not see the beam, a "pilot ion" with a "visible" current and the same acceleration pattern as that required for the "objective ion" is used for an initial tuning.
   - All the $\vec{E}$ and $\vec{B}$ fields will be multiplied by $c = \frac{A_2/Q_2}{A_1/Q_1}$
   - Injection tuning for the new ion (LEBT)



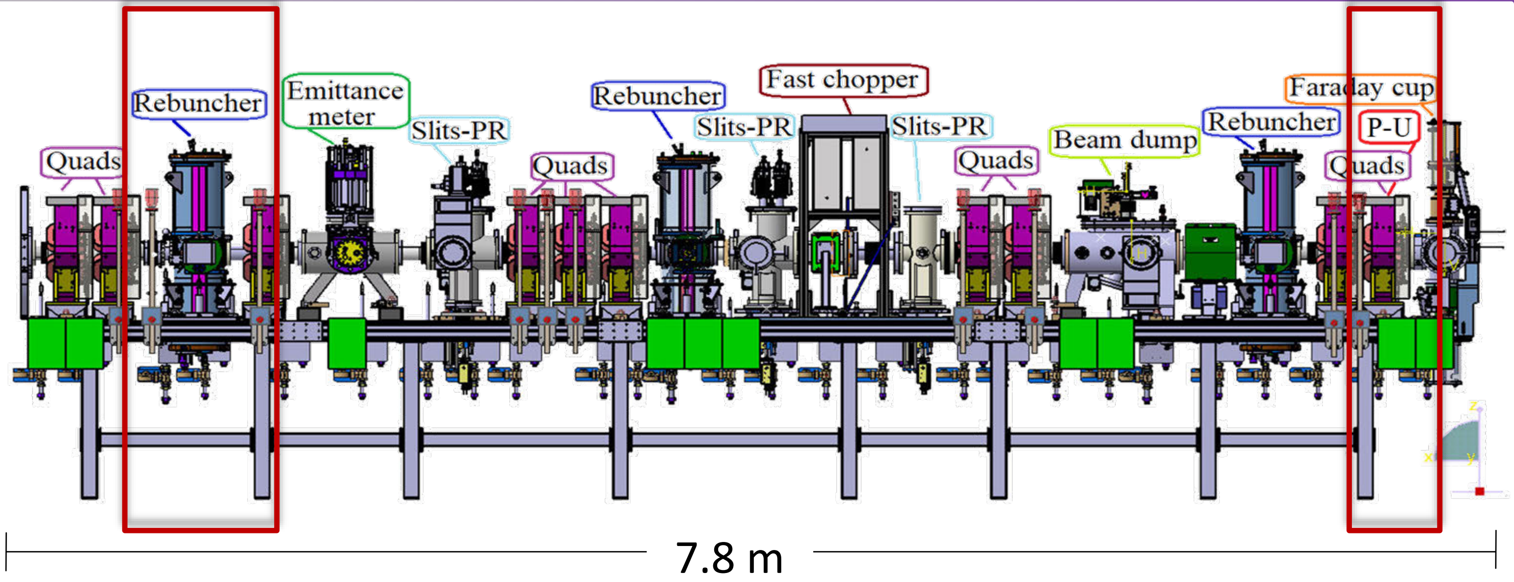
$$\Delta_\varphi = \varphi_{e\_ref} - \varphi_{in\_ref} - \varphi_{cav\_ref}$$

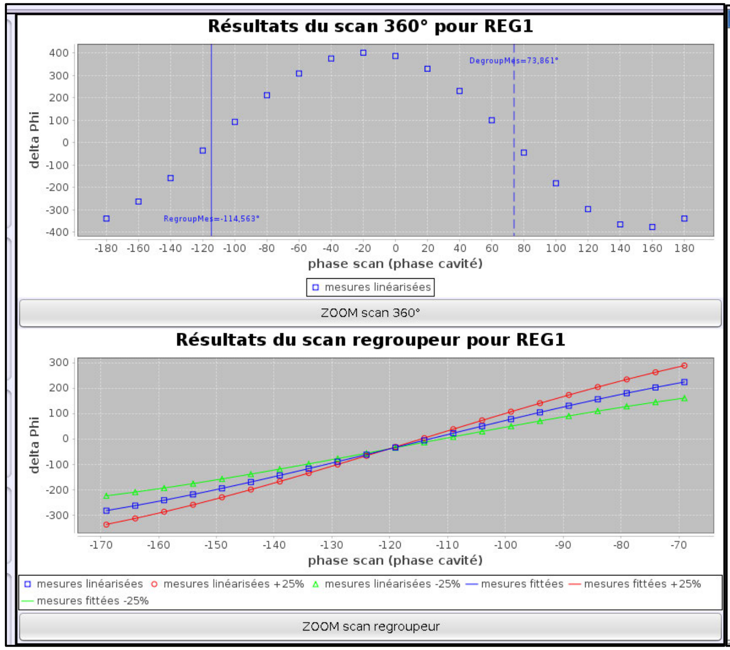
$$\varphi_{cav} = \varphi_e - \varphi_{in} - \Delta_\varphi$$

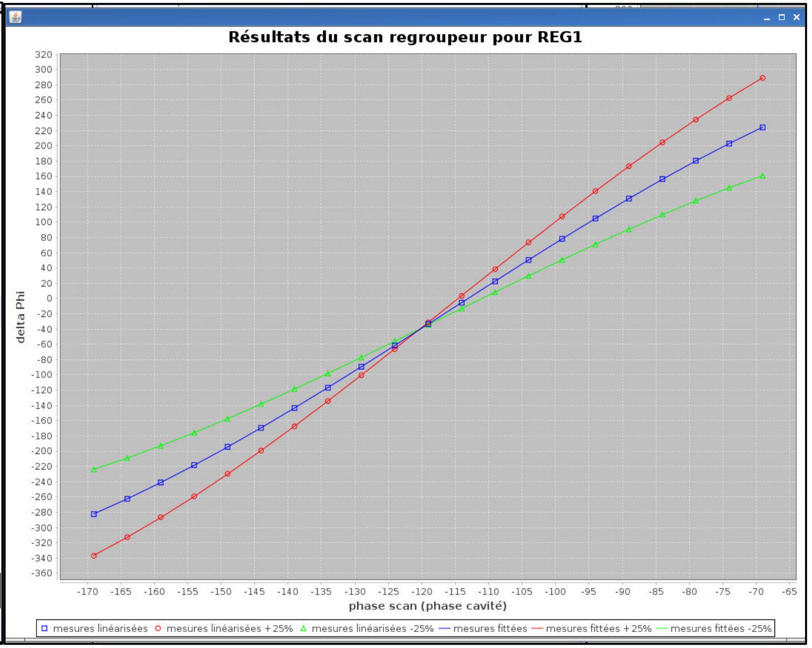
$$\varphi_{e-cav2} = \varphi_{e\_cav1} - \varphi_{shift_{cav1}} + Drift$$

G. Normand, et al, “Strategies for SPIRAL2 linac heavy-ion beam tuning”, presented at the 14th Int. Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper TUPA192.

- Key to longitudinal matching in the linac.
  - "With-reference method" =>no upstream phase measurement.
  - "Advanced method" => not work correctly for 1st rebuncher (phase measurement error).
  - Zero-Crossing tuning method: Rebuncher phase and amplitude tunings are performed.
    I. Fast rebuncher phase scan over 360°
    II. 3 scans ± 20° around rebuncher phase @ 3voltages.
    III. The curves are fitted by 3rd order polynomials =>crossing point (buncher phase)
    IV. Rebuncher cavity voltage is obtained by a comparison with polynomials obtained by simulations (tracking in field maps).
- Matching to the linac was improved by fine magnetic field tuning of the last two quadrupoles and rebuncher #3 of the MEBT, reducing the losses.





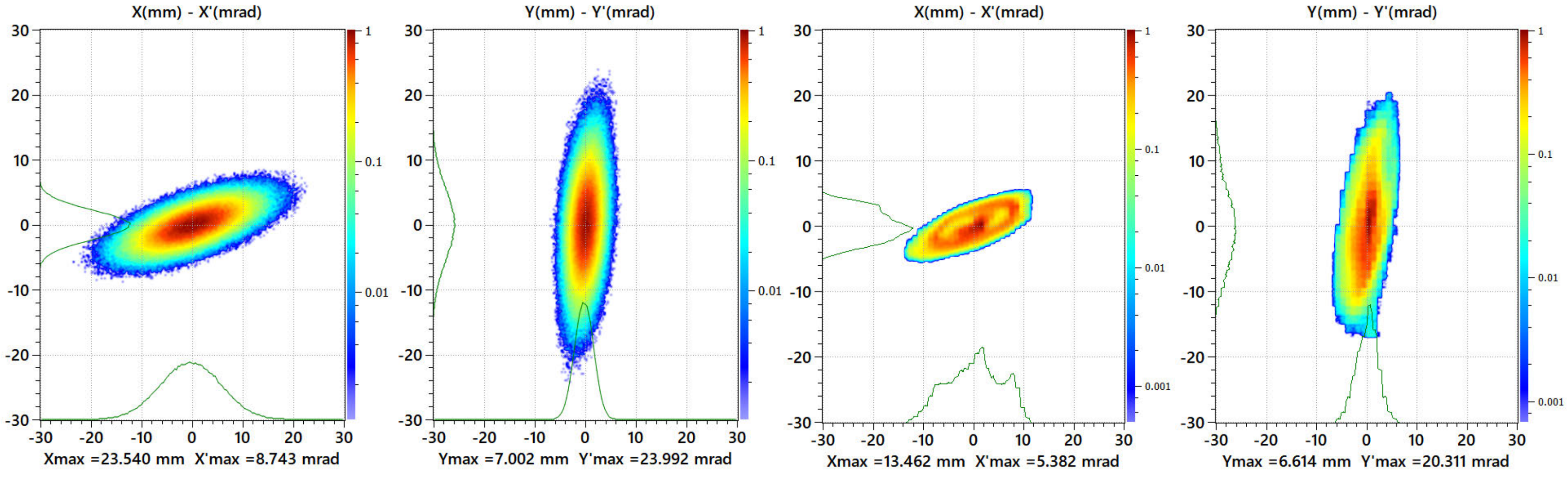


laboratoire commun CEA/DRF CNRS/IN2P3

Transverse rms **emittance measurements** for a 600 μA $^{18}O^{6+}$ beam.

- 0.32 $\pi.mm.mrad$ in horizontal plane
- 0.46 $\pi.mm.mrad$ in vertical plane

Reference simulation 600 μA $^{18}O^{6+}$ — Measurement 600 μA $^{18}O^{6+}$



Parameter	Sim	Meas	Δ(%)
$\alpha_{X,X'}$	-0.83	-0.99	19
$\beta_{X,X'}$ (mm/π.mrad)	3.44	3.40	1
$\alpha_{Y,Y'}$	-0.29	-0.49	69
$\beta_{y,y'}$ (mm/π.mrad)	0.32	0.38	19

Good agreement !

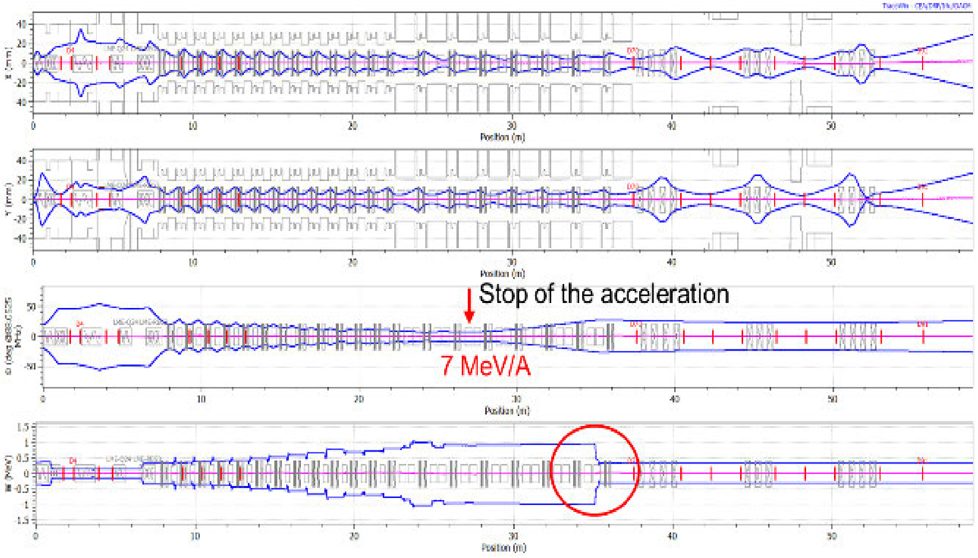
Heavy Ion Acceleration II

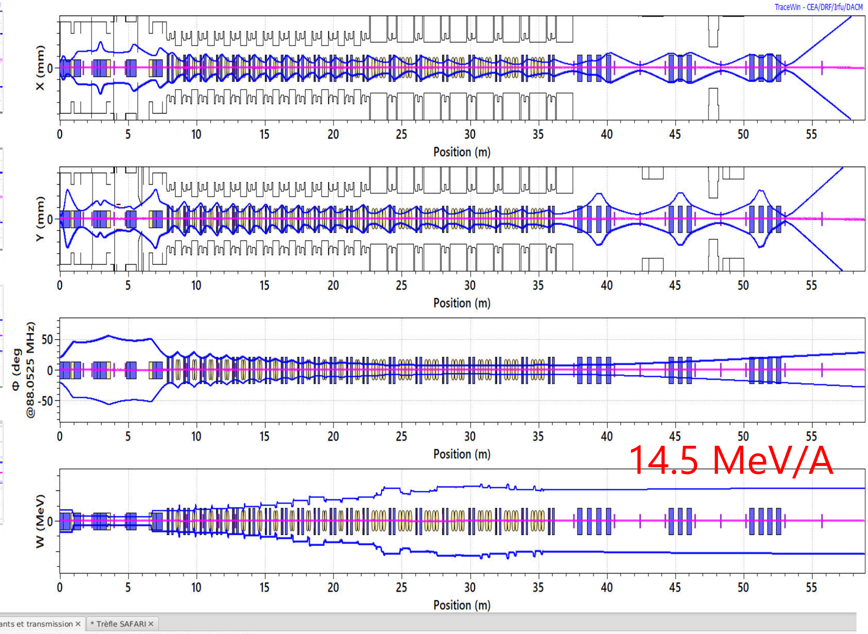
laboratoire commun CEA/DRF CNRS/IN2P3

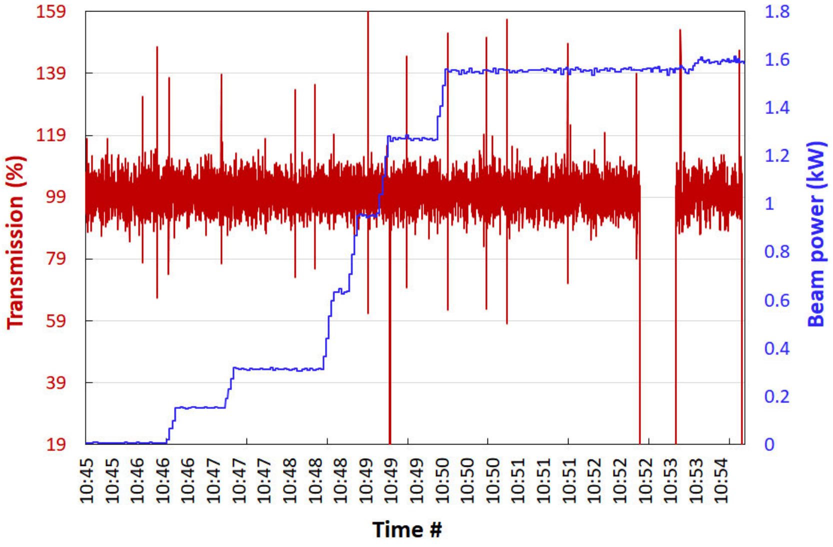
A/Q method test

- The "pilot beam"; $^{18}O^{6+}$ =>A/Q=3, easy to produce with a current >100 µA, good stability.
- The "objective ion"; $^{18}O^{7+}$ => easy and quick change from $^{18}O^{6+}$, current detectable by the pick up to validate the procedure.
- 7 MeV/A => Cavities downstream cavity #15 were switched off and detuned.
- The last cavity was tuned in rebuncher phase, with a voltage such that the energy dispersion was reduce by up to 2 times.
- 50 µA $^{18}O^{6+}$/$^{40}Ar^{14+}$ in rebuncher mode @0.73 MeV/A.

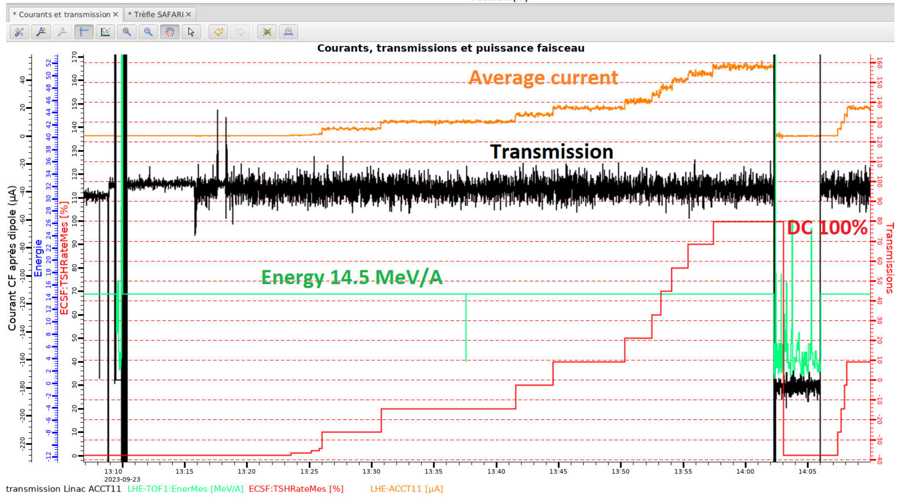
Parameter	$^{18}O^{6+}$	$^{18}O^{7+}$	$^{40}Ar^{14+}$
Max E (MeV/A)	14.5	7	7
Max I (µA)	50	78	80
Transmission (%)	99	98	99
Beam power (kW)	2	0.6	1.6







80 µA $^{40}Ar^{14+}$: beam: Beam power (blue) and transmission (red).



50 µA $^{18}O^{6+}$ beam: : Energy (green), transmission (black), average current (orange) and duty cycle (red).

Cavity Failure

Strategy and tests without cavities #3, #6 and #8 were done.

As the energy ↑ the debunching ↓

- high β cavity failure: solution easy to find.
- last low β cavity failure, possible to recover a beam dynamics without losses.

Retune the up and downstream cavities

required phase acceptance

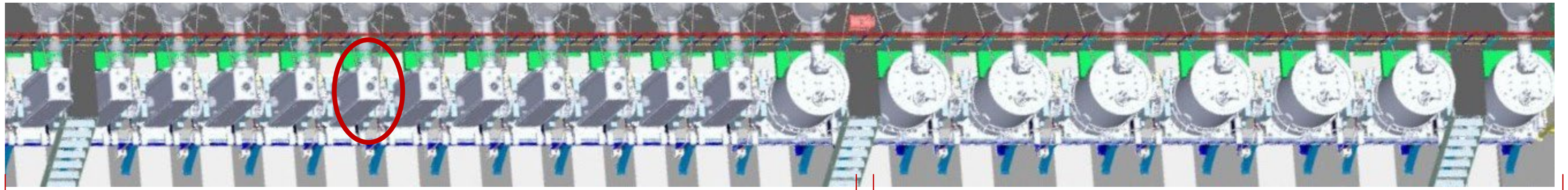
reduction of the linac final energy or increase the cavity voltages.

- low β cavity failure: very difficult tuning at low energy due to a high debunching between two cavities.

Work is currently underway

4.5 MeV

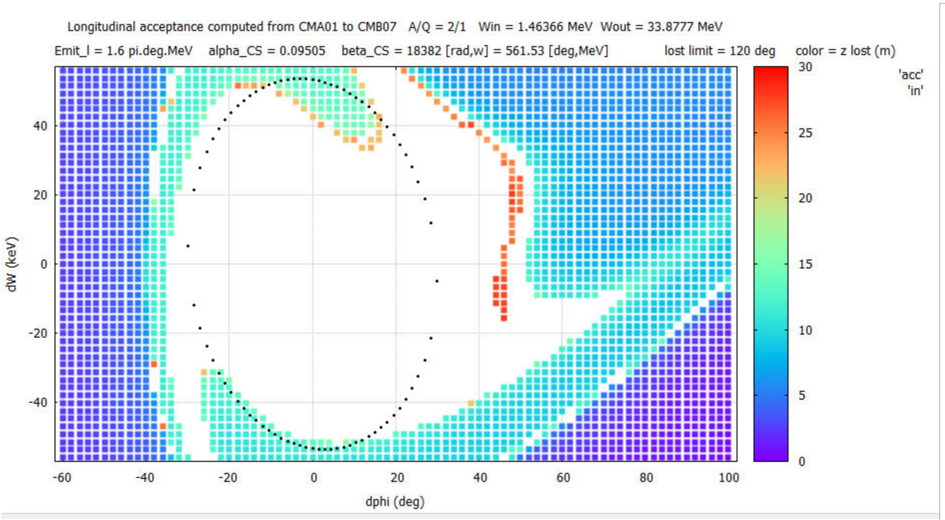
80 MeV

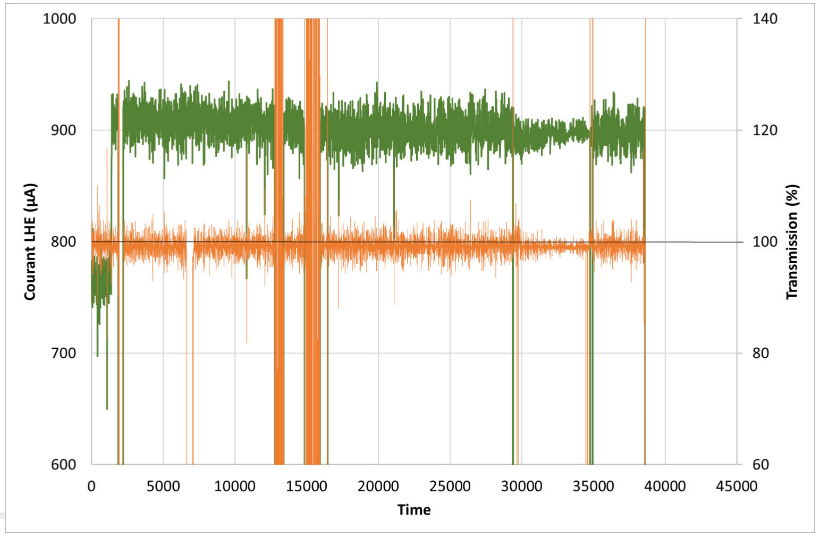


Low β section

High β section

900 μA $^{4}He^{2+}$ / 63.87 MeV / 2 kW





Collaboration with LPSC Grenoble –France.
Frédéric Bouly and Andrien Plaçais

Energy Variation

Beam energy change

- Several energies for 1 experiment.
- Manual switching (process time ≈ ΔE).
- Two methods were tested=>losses study/define a procedure/application

Define last cavity energy

⇓

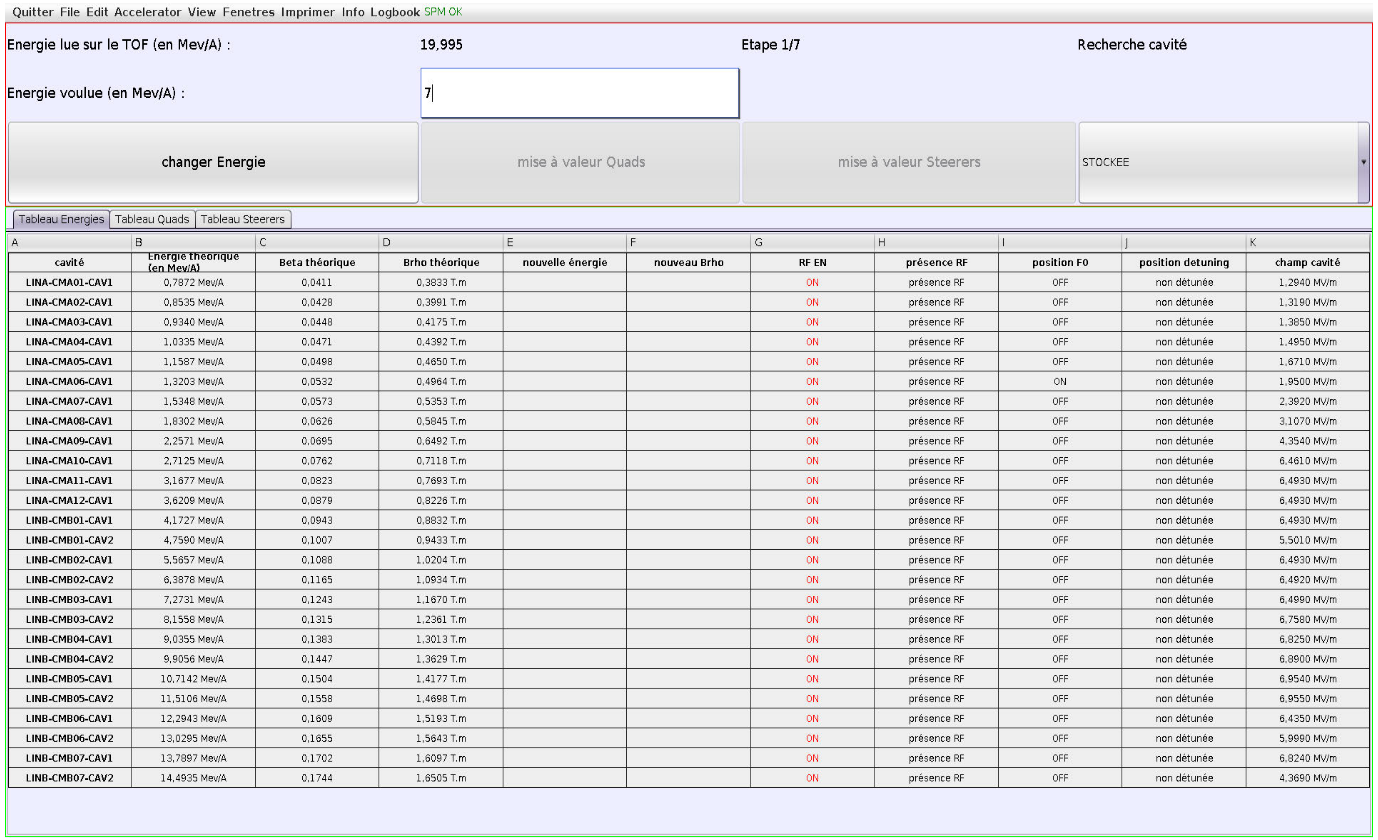
detune all cavities downstream

⇓

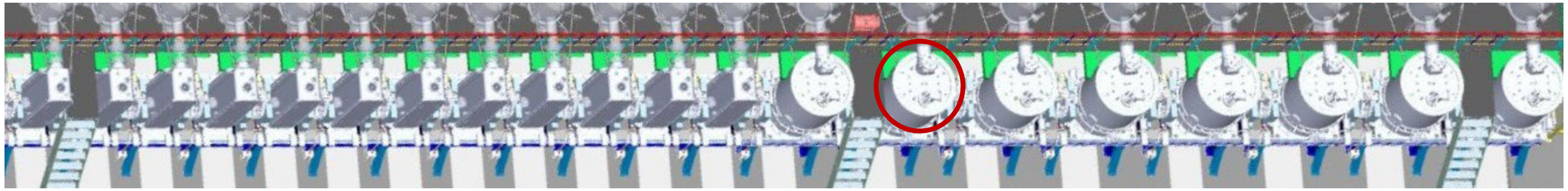
BRho is applied to the magnetic elements

⇓

Steerer tunings and a general alignment



A	B	C	D	E	F	G	H	I	J	K
cavité	Energie théorique (en Mev/A)	Beta théorique	Brho théorique	nouvelle énergie	nouveau Brho	RF EN	présence RF	position F0	position detuning	champ cavité
LINA-CMA01-CAV1	0,7872 Mev/A	0,0411	0,3833 T.m			ON	présence RF	OFF	non détunée	1,2940 MV/m
LINA-CMA02-CAV1	0,8535 Mev/A	0,0428	0,3991 T.m			ON	présence RF	OFF	non détunée	1,3190 MV/m
LINA-CMA03-CAV1	0,9340 Mev/A	0,0448	0,4175 T.m			ON	présence RF	OFF	non détunée	1,3850 MV/m
LINA-CMA04-CAV1	1,0335 Mev/A	0,0471	0,4392 T.m			ON	présence RF	OFF	non détunée	1,4950 MV/m
LINA-CMA05-CAV1	1,1587 Mev/A	0,0498	0,4650 T.m			ON	présence RF	OFF	non détunée	1,6710 MV/m
LINA-CMA06-CAV1	1,3203 Mev/A	0,0532	0,4964 T.m			ON	présence RF	ON	non détunée	1,9500 MV/m
LINA-CMA07-CAV1	1,5348 Mev/A	0,0573	0,5353 T.m			ON	présence RF	OFF	non détunée	2,3920 MV/m
LINA-CMA08-CAV1	1,8302 Mev/A	0,0626	0,5845 T.m			ON	présence RF	OFF	non détunée	3,1070 MV/m
LINA-CMA09-CAV1	2,2571 Mev/A	0,0695	0,6492 T.m			ON	présence RF	OFF	non détunée	4,3540 MV/m
LINA-CMA10-CAV1	2,7125 Mev/A	0,0762	0,7118 T.m			ON	présence RF	OFF	non détunée	6,4610 MV/m
LINA-CMA11-CAV1	3,1677 Mev/A	0,0823	0,7693 T.m			ON	présence RF	OFF	non détunée	6,4930 MV/m
LINA-CMA12-CAV1	3,6209 Mev/A	0,0879	0,8226 T.m			ON	présence RF	OFF	non détunée	6,4930 MV/m
LINB-CMB01-CAV1	4,1727 Mev/A	0,0943	0,8832 T.m			ON	présence RF	OFF	non détunée	6,4930 MV/m
LINB-CMB01-CAV2	4,7590 Mev/A	0,1007	0,9433 T.m			ON	présence RF	OFF	non détunée	5,5010 MV/m
LINB-CMB02-CAV1	5,5657 Mev/A	0,1088	1,0204 T.m			ON	présence RF	OFF	non détunée	6,4930 MV/m
LINB-CMB02-CAV2	6,3878 Mev/A	0,1165	1,0934 T.m			ON	présence RF	OFF	non détunée	6,4920 MV/m
LINB-CMB03-CAV1	7,2731 Mev/A	0,1243	1,1670 T.m			ON	présence RF	OFF	non détunée	6,4990 MV/m
LINB-CMB03-CAV2	8,1558 Mev/A	0,1315	1,2361 T.m			ON	présence RF	OFF	non détunée	6,7580 MV/m
LINB-CMB04-CAV1	9,0355 Mev/A	0,1383	1,3013 T.m			ON	présence RF	OFF	non détunée	6,8250 MV/m
LINB-CMB04-CAV2	9,9056 Mev/A	0,1447	1,3629 T.m			ON	présence RF	OFF	non détunée	6,8900 MV/m
LINB-CMB05-CAV1	10,7142 Mev/A	0,1504	1,4177 T.m			ON	présence RF	OFF	non détunée	6,9540 MV/m
LINB-CMB05-CAV2	11,5106 Mev/A	0,1558	1,4698 T.m			ON	présence RF	OFF	non détunée	6,9550 MV/m
LINB-CMB06-CAV1	12,2943 Mev/A	0,1609	1,5193 T.m			ON	présence RF	OFF	non détunée	6,4350 MV/m
LINB-CMB06-CAV2	13,0295 Mev/A	0,1655	1,5643 T.m			ON	présence RF	OFF	non détunée	5,9990 MV/m
LINB-CMB07-CAV1	13,7897 Mev/A	0,1702	1,6097 T.m			ON	présence RF	OFF	non détunée	6,8240 MV/m
LINB-CMB07-CAV2	14,4935 Mev/A	0,1744	1,6505 T.m			ON	présence RF	OFF	non détunée	4,3690 MV/m



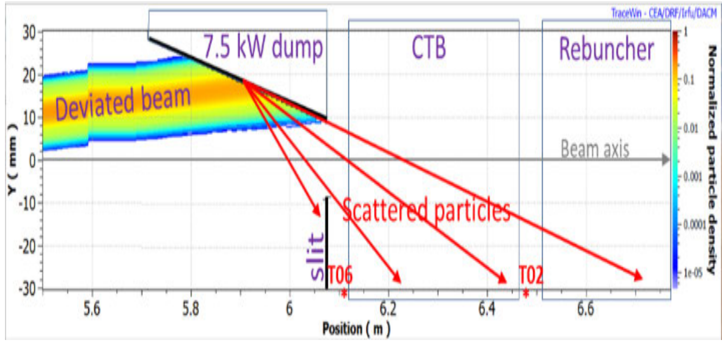
Low β section

High β section

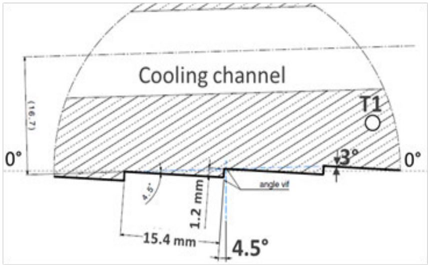
The application was successfully tested!

$^{18}O^{6+}$ beam from 14.5 MeV/A to 7 MeV/A

SBS beam dump



- Current measurements had an offset of ≈ $100\mu A$ in 2019.
- The beam dump receiving the bunches deviated by the SBS (≤ 7.5 kW) was affected by Coulomb scattering => important heating degrading the beam current measurements.
- The beam dump was redesigned (surface changed from flat to staircase), constructed and installed, which successfully decreased the temperature and the current offset.



M. Di Giacomo *et al.*, "Upgrade of the medium energy dump geometry for the SPIRAL2 single bunch selector", presented at the 14th Int. Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper THPA190."

Beam diagnostics

- A new BPM electronics for the RF signals distribution was designed, manufactured and installed.
- All distribution frames are adjusted to have a Δphase<0.5° between the outputs.
- Calibration of all BPMs was reduced from 1 week to 3 days.

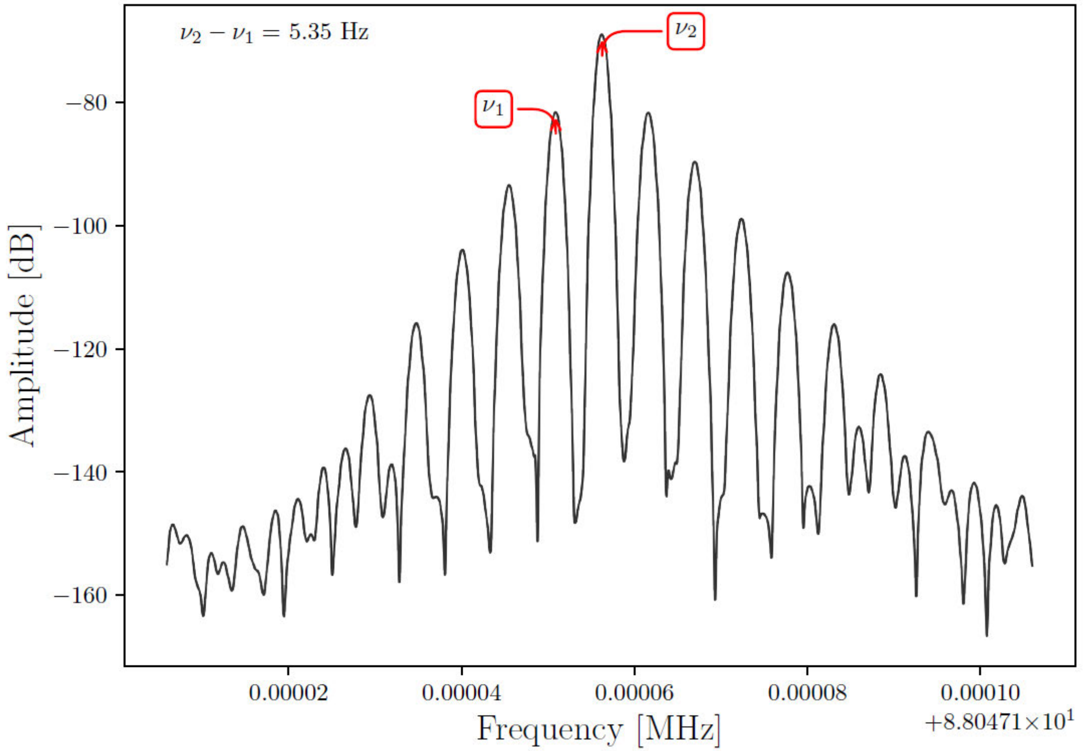
Cavity X-ray emissions

- X-ray emissions have started from 2020 in cavities #2 (low β section), #14 and #26 (high β section).
- The voltage of cavities #14 and #26 had to be reduced (<8%) in order to run them reliability. To compensate, voltage of the neighbouring high β cavities has been increased; most of the high β cavities have been qualified and can operate up to 8 MV/m.

Accelerator Subsystems II

laboratoire commun CEA/DRF CNRS/IN2P3

- Cryogenic system
- Thermo-acoustic oscillations (TAO) were identified late in 2017.
  - **Temporary solution** => restored the cryogenic system stability =>drawbacks (periodical pressure perturbations, helium level sensors measuring range limitation).
  - **A new TAO compensation system was developed**: a RLC resonator which counterbalances the resonance. Successfully tested during 2022.
- Development of a numerical model => cryogenics system
  - A collaboration with Low Temperature Systems Department CEA, 2017 => helium pressure and level control in the PLC.
  - The same model developed as a soft sensor => the heat load on the cryomodule helium bath. Helium parameters (level, pressure) and the control valves positions.
  - Implemented in the cryogenics' PLCs, has been tested during 2022. Pinpoint X field emision in cavity #14 during the 2022.
  - Developments are still ongoing => precision and speed.



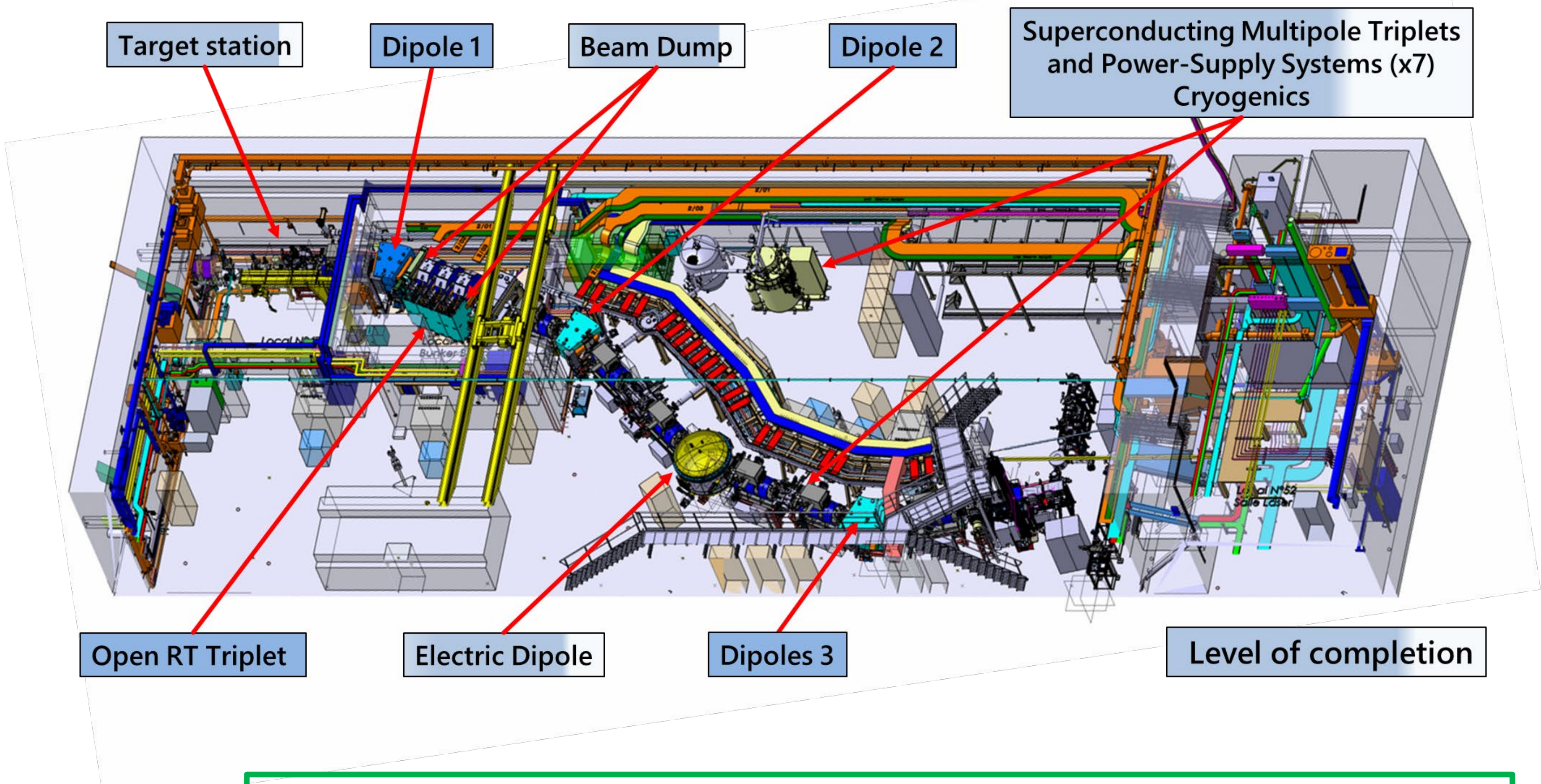
A. Ghribi *et al.*, "Cryogenic thermoacoustics in the SPIRAL2 LINAC," *Cryogenics*, vol. 124, pp. 103487, 2022. doi.org/10.1016/j.cryogenics.2022.103487

Perspectives - I

- Gradual increase of beam time with parallel operation of GANIL and SPIRAL2.
- Commissioning of S³ experimental room in 2024.
  - The S³ experimental room is in the last phase of installation.
  - Test, measurement and conditioning work are currently being carried out on: target station, beam dump, electric dipole, superconducting multipole triplets, power-supply system and the associated cryogenic system.
  - The integration of the S³ Low Energy Branch and the laser system is planned for 2024. As well as the commissioning of: Beam transport, physics measurements, and detection system.

Preliminary proposition

Année	2023												2024											
Opération	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
GANIL																								
SPIRAL2																								



A. Esper et al., "Superconducting multipole triplet field measurements", presented at the 14th Int. Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper THPA043.

DESIR (Decay, Excitation and Storage of Radioactive Ions)

- A "low energy" facility that will work with beam energies down to a few tens of keV.
- Laser spectroscopy, mass spectrometry, decay measurements and various measurements using ion traps.
- DESIR will use the beams produced by both the cyclotrons and SPIRAL2. In particular, the exotic nuclei produced by the S^3 separator.
- GANIL obtained the construction permit on 23 June 2023. Work started in July 2023 with deep earthworks. The aim is to have the building ready by spring 2025.

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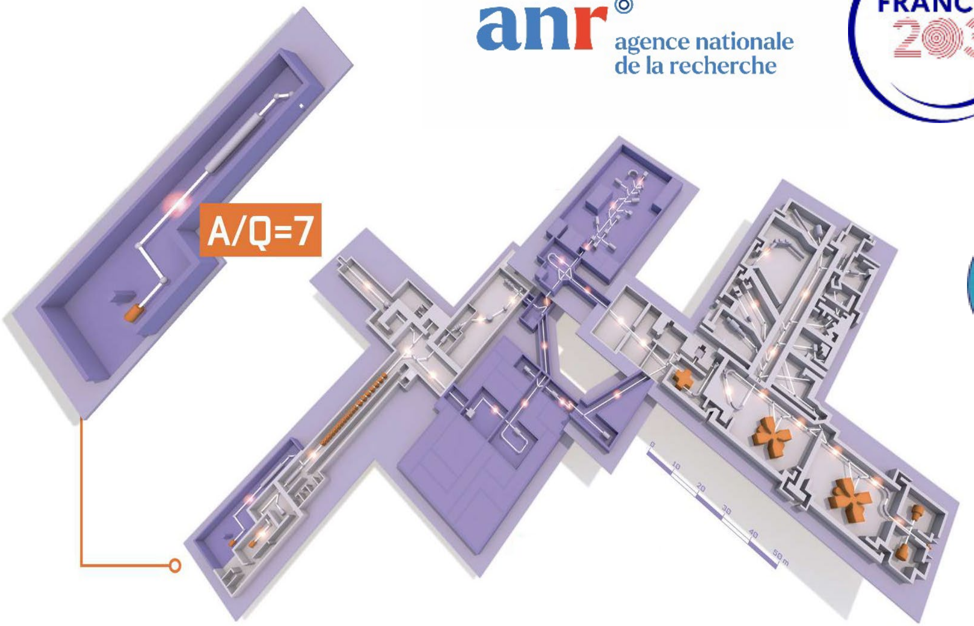
NEWGAIN
NEW GANIL INJECTOR

- The design and construction of this new injector to produce and deliver heavy ion beams $A/Q \leq 7$ with the SC linac started in May 2020. The preliminary design phase was completed in June 2021 and the detailed design phase in April 2023.
- The project is currently in the construction phase.
- This injector will also be connected to the existing PHOENIX V3 source.
- The injector will be located entirely in an existing cave in the SPIRAL2 building.



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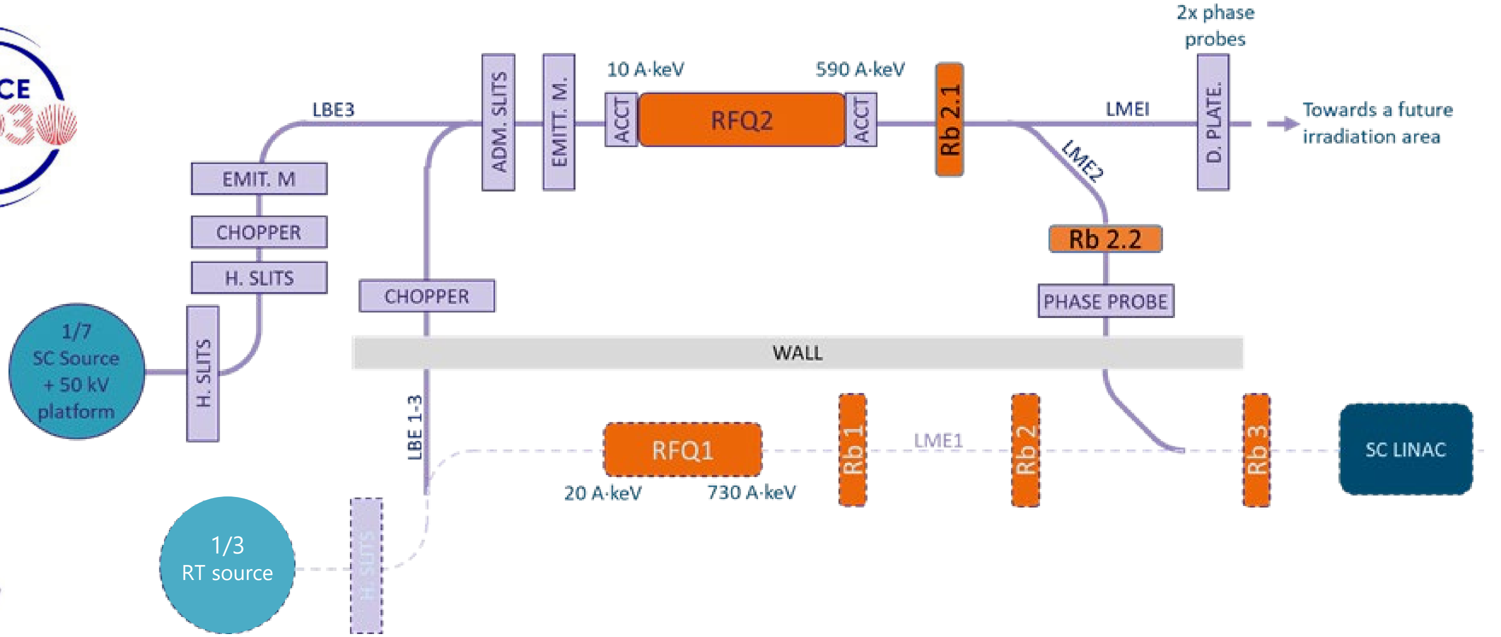

M. Moscatello *et al.*, "NEWGAIN project at GANIL-SPIRAL2 : design of the new heavy ion injector for the superconducting linac", in Proc. IPAC'23, TUPA193.

Summary

- The 4 commissioning phases were completed in time to start full operation in 2022.

- The SPIRAL2 SC linac was successfully commissioned with H^+, D^+ and $^4He^{2+}$ beam.

- The SPIRAL2 SC linac has been running successfully in 2022, during its first year of nominal operation.

- Half beam time has been used for NFS physics experiments, the remaining time being used for beam dynamics checks, tuning applications developments, RF and diagnostics system improvements.

- In the preparatory phase of S3, $^{18}O^{6+,7+}$ and $^{40}Ar^{14+}$ beams were accelerated for the first time in the linac up to 14.5 MeV/A and 7 MeV/A, respectively.

Thank you for your attention!