

# SPIRAL2 Commissioning and Operations

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Accelerator physicist, GANIL

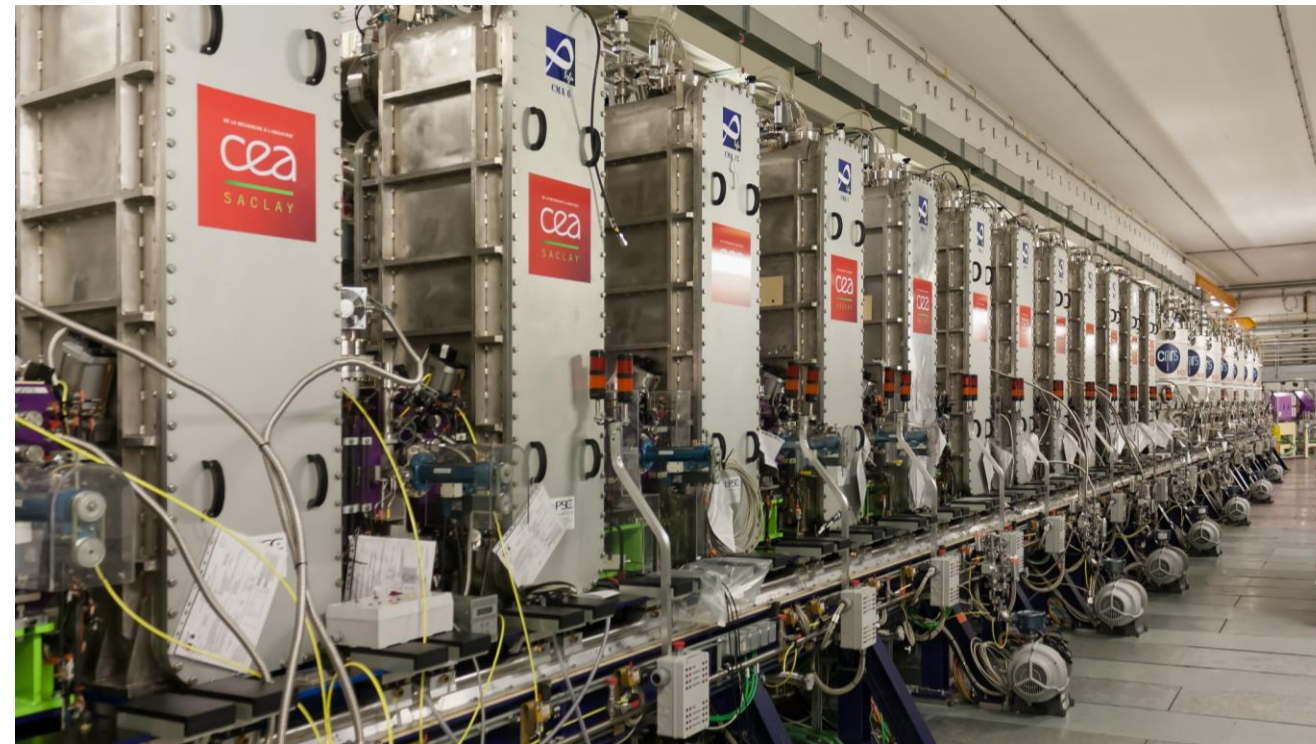
*on behalf of the GANIL teams and SPIRAL2 collaborations, many thanks to all of them!*

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

HB 2023



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







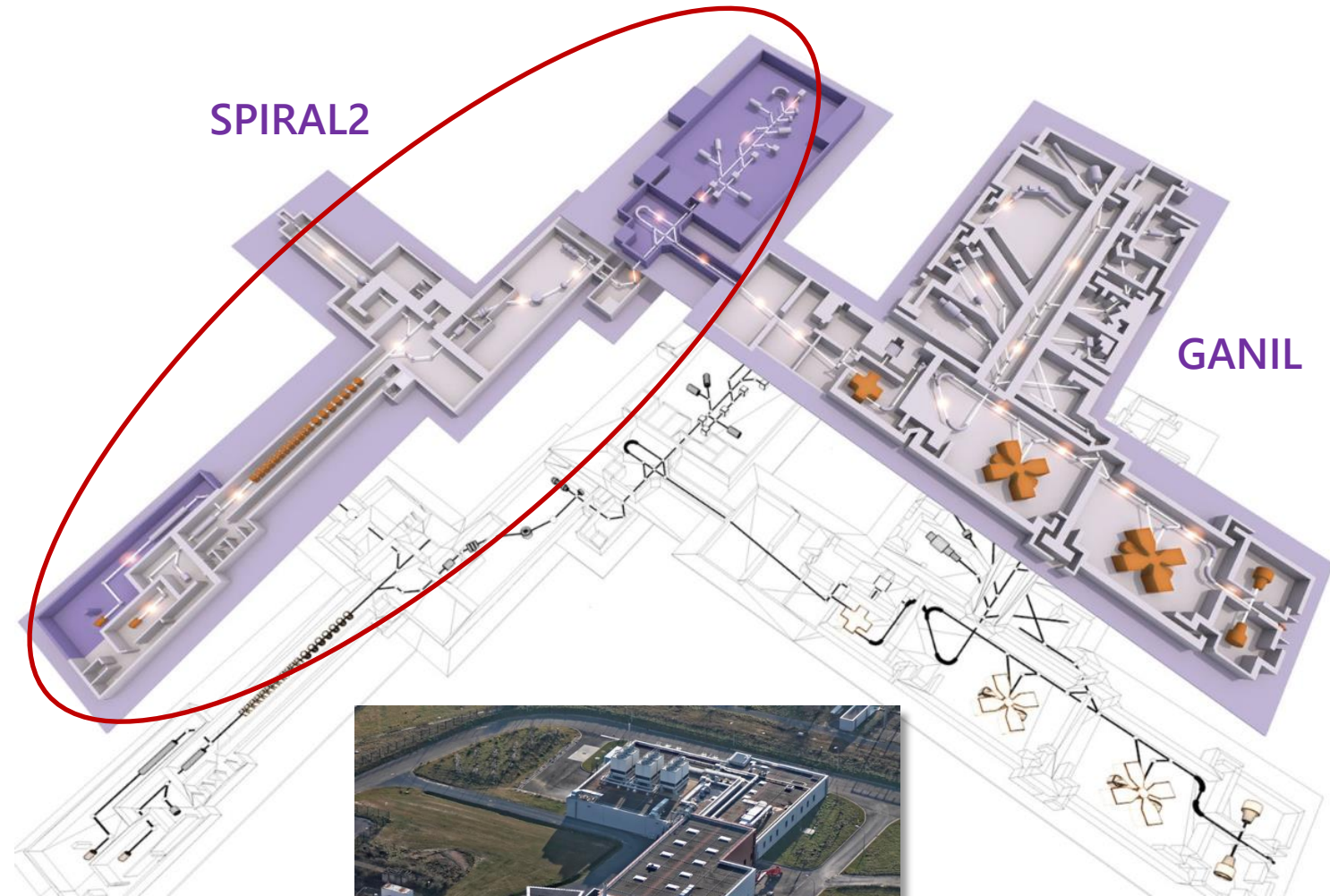
GANIL (CEA-CNRS):  
a multidisciplinary and  
multi-users laboratory

Collaboration with National Laboratories  
and International Partners



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

Particles	H <sup>+</sup>	D <sup>+</sup>	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





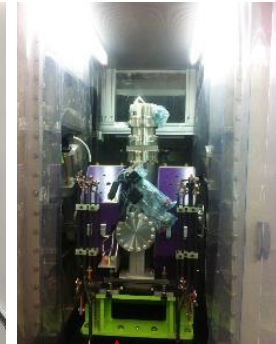
ECR A/Q $\leq$ 3



Low  $\beta$  section (0.07)



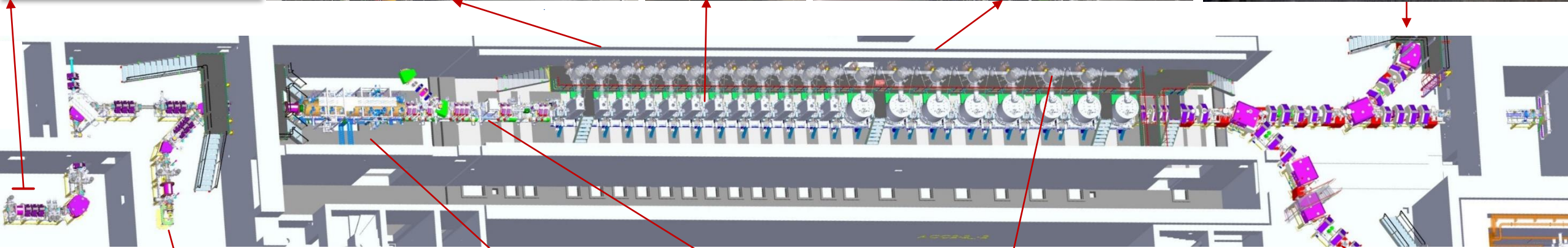
Warm section



High  $\beta$  section (0.12)



NFS (converter cave)



ECR H<sup>+</sup>/D<sup>+</sup>



RFQ



SBS



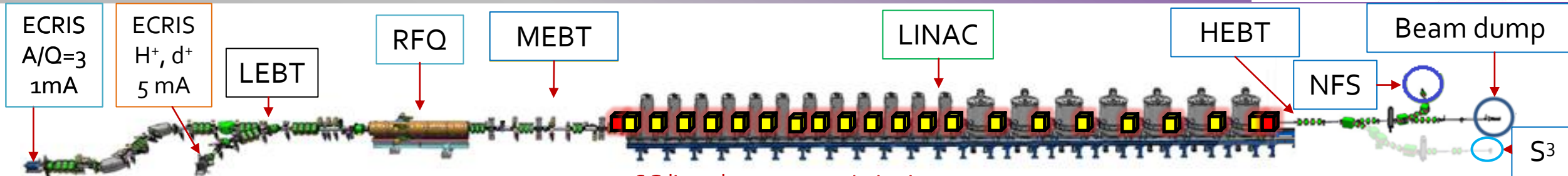
Cryogenic distribution system



S<sup>3</sup>



# Beam Commissioning Time Line



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

Construction building and tools

## Qualification of the injector on a Diagnostic Plate (GANIL)

- Reproduce previous results
- RFQ performance
- Diagnostics platform
- Beam characteristics at RFQ exit
- 2014 1<sup>st</sup> H<sup>+</sup> beam @2 mA H/D (Dec)
- 2015 1<sup>st</sup> Ar<sup>9+</sup> beam @ 230  $\mu$ A HI source (Jul) / 1<sup>st</sup> RFQ H<sup>+</sup> (Dec)
- 2018 Diagnostic plate commissioning end April –November, removed in 2018

SC linac beam commissioning up to the main beam dump  
 Authorization to operate SPIRAL2, Jul 8<sup>th</sup>, 2019  
 1<sup>st</sup> beam in the linac, Oct. 28<sup>th</sup>

1<sup>st</sup> beam in NFS, Dec. 11<sup>th</sup>  
 Characterization and first experiments in the NFS room  
 33MeV H<sup>+</sup> (2019)  
 40 MeV <sup>4</sup>He<sup>2+</sup>, D<sup>+</sup> (2020)  
 50  $\mu$ A D<sup>+</sup> NFS (2021)

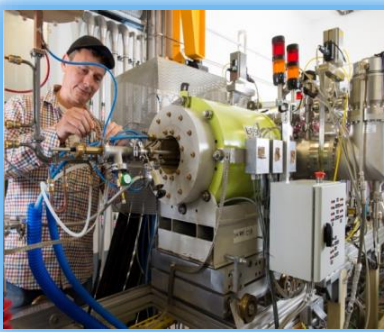
First year of SPIRAL2 operation in NFS room  
 50% beam time for physics

Pre-commissioning for S<sup>3</sup>  
 7 MeV/A <sup>18</sup>O<sup>6+</sup>, <sup>18</sup>O<sup>7+</sup>, <sup>40</sup>Ar<sup>14+</sup>  
 0.73 MeV/A <sup>18</sup>O<sup>6+</sup>, <sup>18</sup>O<sup>7+</sup>, <sup>40</sup>Ar<sup>14+</sup>  
 Test Cavity failure

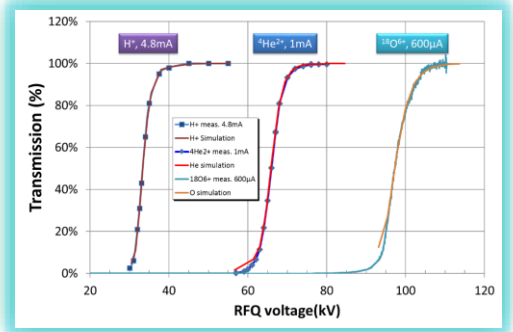
SPIRAL2 operation  
 65% beam time for physics  
 14% for studies

Pre-commissioning for S<sup>3</sup>  
 14.5 MeV/A <sup>18</sup>O<sup>6+</sup>  
 Studies: Test cavity failure and pressure variation in WS

## 2009-2012



## 2014-2018



## 2019-2021



## 2022

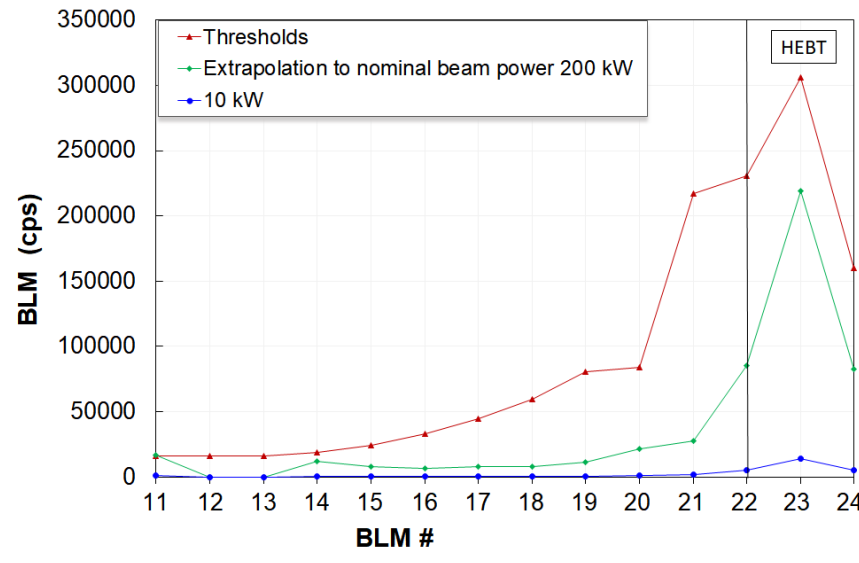
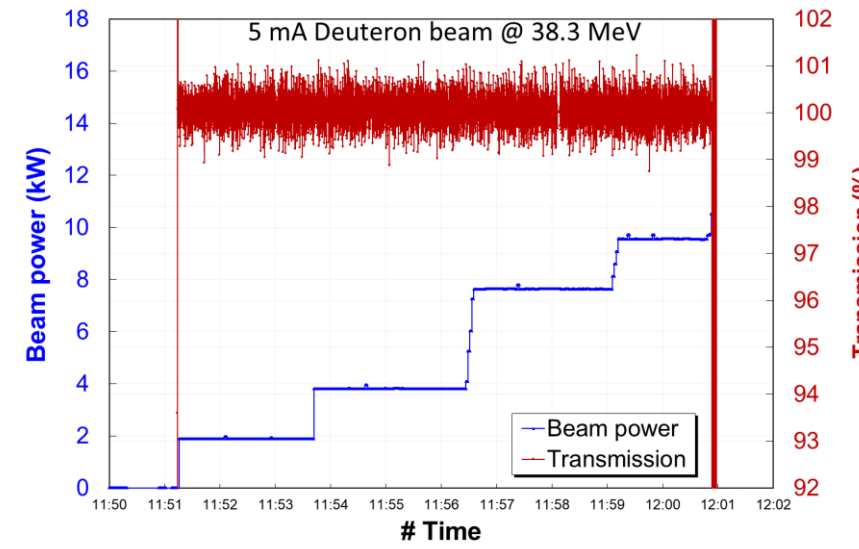
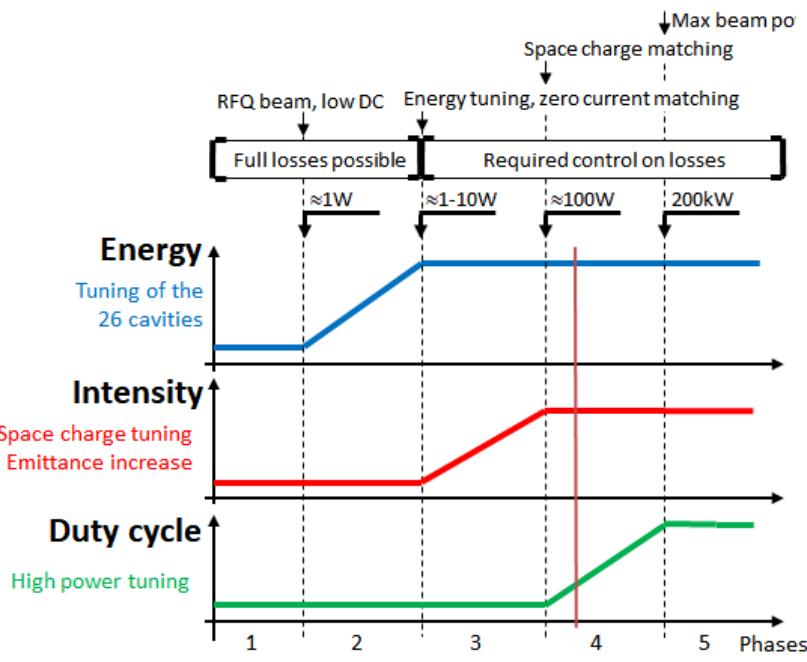
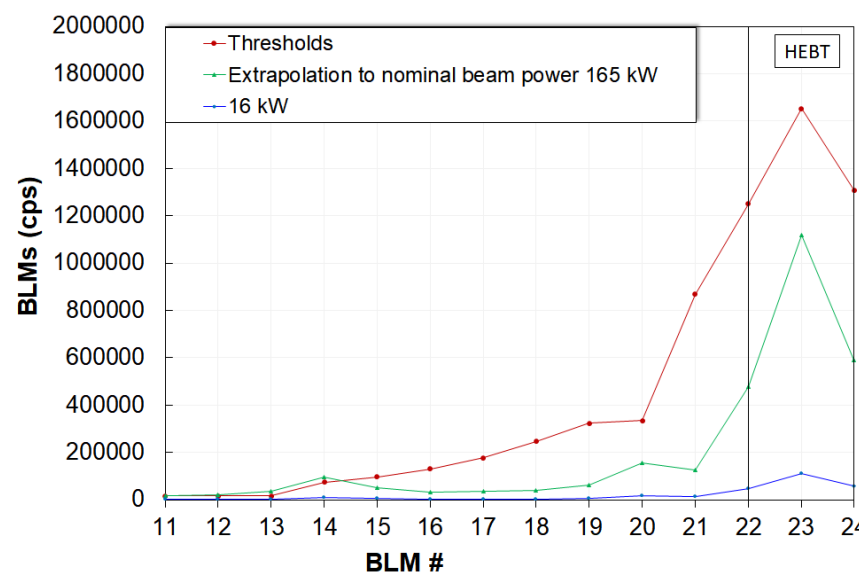
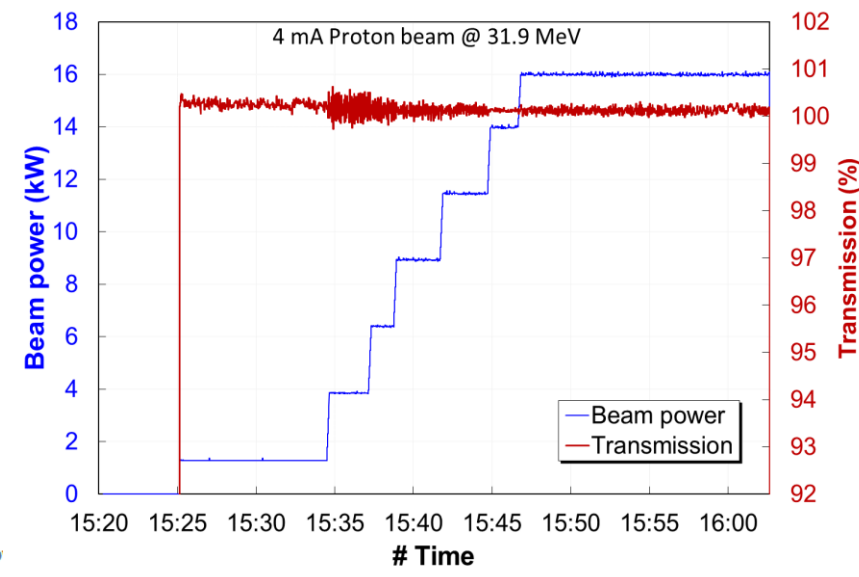


## 2023

Particule	
OXYGENE	
18 O 8/6+ W=260,0MeV I=0,596mA P=25,8	
A	18
Masse	17.9958689395 UMA
Energie	
Energie 13	14.491 MeV/A

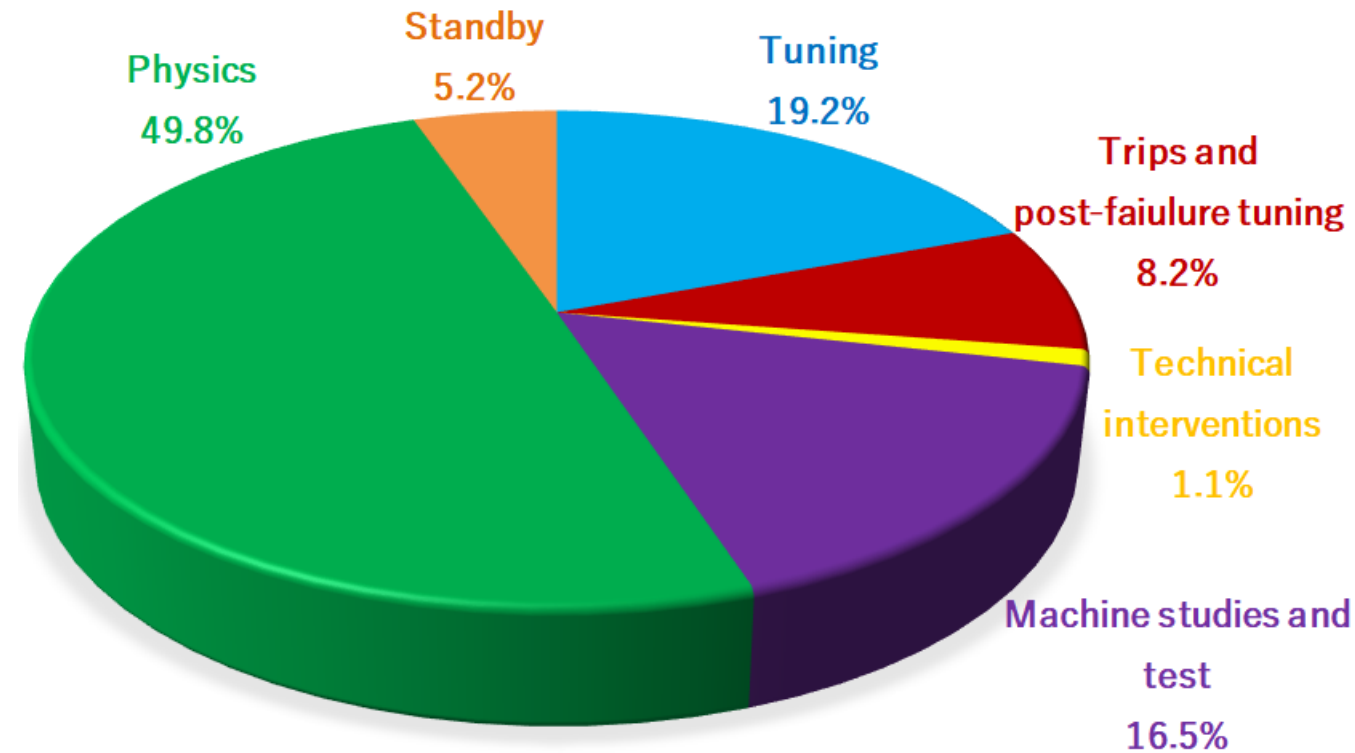
# Beam Commissioning Main Results I

- $H^+$ ,  $D^+$  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



The beam time was in 2022  $\approx$  3 months

- 7 experiments and 3 main preparatory studies for  $S^3$  were conducted.
- 76% of physic with  $D^+$  beams:
  - 9  $\mu A$  and 47  $\mu A$  on the target, 1/100 (SBS).
  - $H^+$ ,  $D^+$  and  $^4He^{2+}$  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  $^4He^{2+}$ ,  $D^+$ ,  $^{18}O^{6+}$  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  $D^+$ .



The expected **beam time in 2023**  $\approx$  2.5 months  
August 28 to November 19

**6 nuclear physics experiments and 2 preparatory studies for the S<sup>3</sup> 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  $\mu\text{A}$  on target, 1/100 (SBS).
  - $D^+$  et  $^4\text{He}^{2+}$  from 7 MeV/A up to their nominal value.
- 14% of total beam time for studies: **6%** for **beam dynamics studies** with  $^4\text{He}^{2+}$ ,  $^{18}\text{O}^{6+}$  and  $^{40}\text{Ar}^{14+}$  beams.
  - Tuning applications validation.
  - Acceleration of an  $^{18}\text{O}^{6+}$  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 (emittance, non-intrusive profiler, BPM, Improved procedure for initiating cavities).
- The first test for R&D into the production of innovative radioelements (REPARE project).

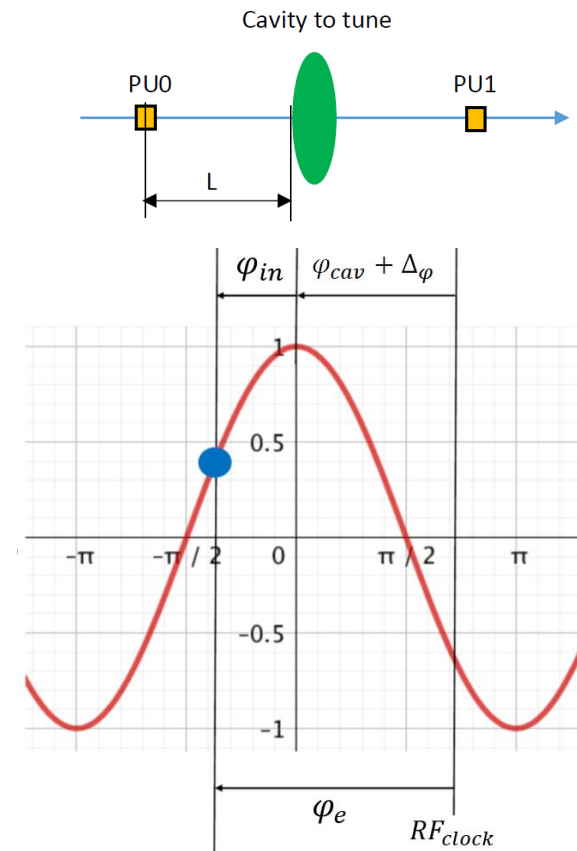
Particule	
	<b>OXYGENE</b>
	18 O 8/6+ W=260,0MeV I=0,596mA P=25,8
A	<b>18</b>
Masse	<b>17.9958689395 UMA</b>

Energie	
Energie 13	<b>14.491 MeV/A</b>



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



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

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

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

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.

## 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<sup>+</sup> => @20 MeV/A ΔE/E < 1% / @0.73 MeV/A ΔE/E < 1.5%
- Sensitive to accuracy of phase measurements. The Δφ on the expected/measured post-cavity BPM is potentially > 10° in the early cavities in some cases. As the beam is accelerated, the Δφ decreases (oscillating).

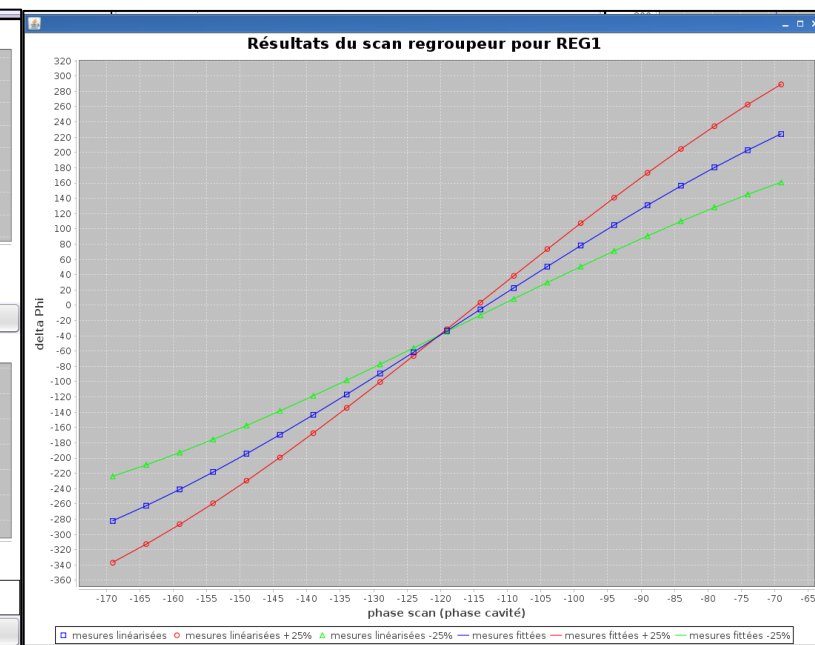
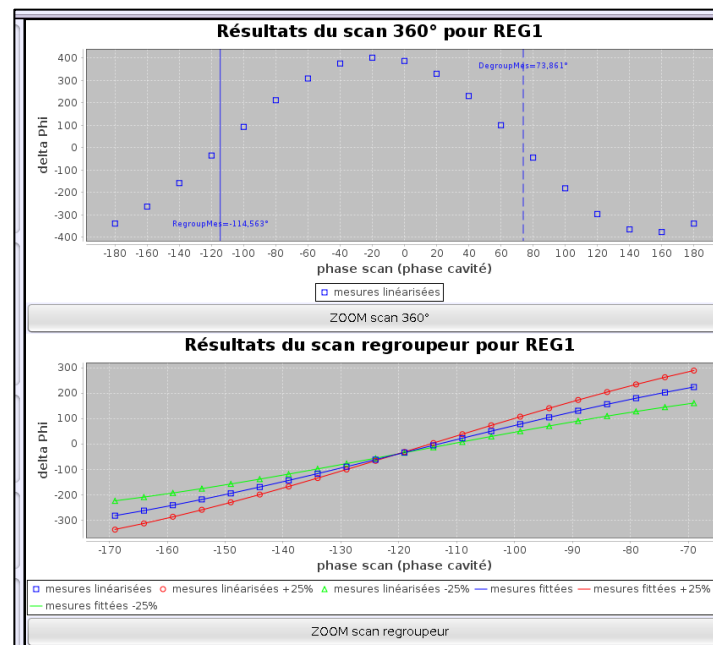
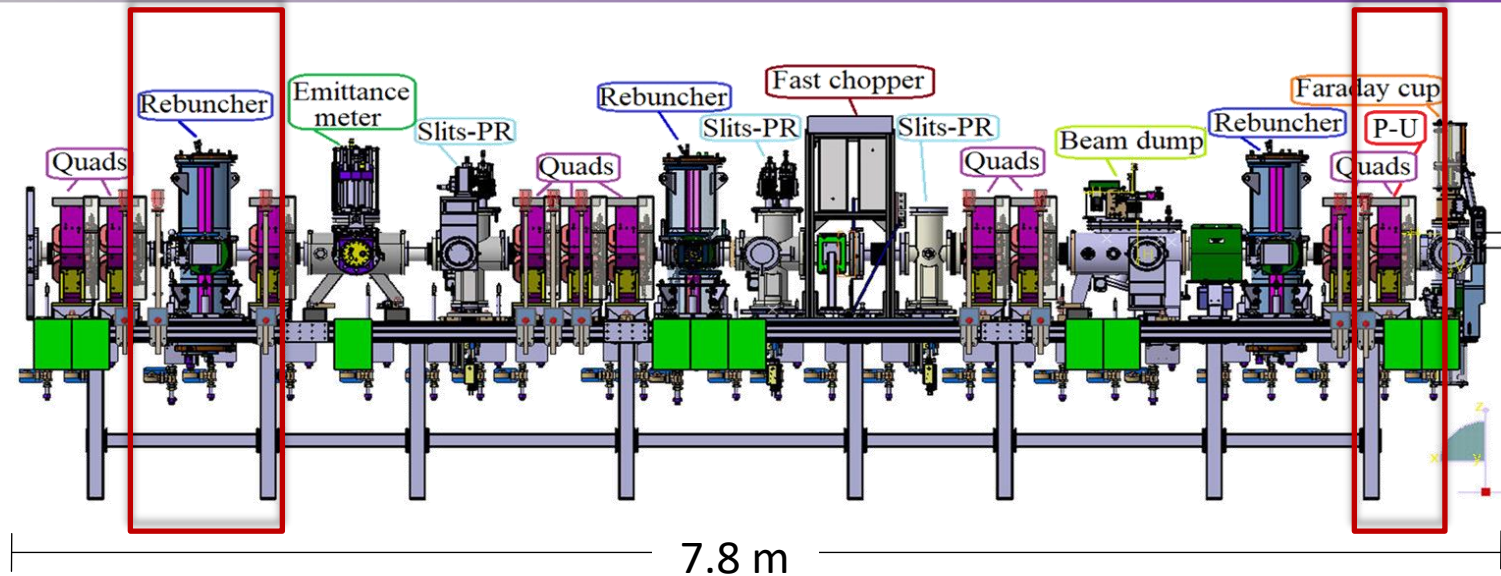
## 3. Rapport A/Q (<10 min)

- Heavy ions at low energy for S<sup>3</sup>**
- 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)

## Key to longitudinal matching in the linac.

- "With-reference method" => no upstream phase measurement.
- "Advanced method" => not work correctly for 1<sup>st</sup> 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  $\pm 20^\circ$  around rebuncher phase @ 3voltages.
  - III. The curves are fitted by 3<sup>rd</sup> 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.

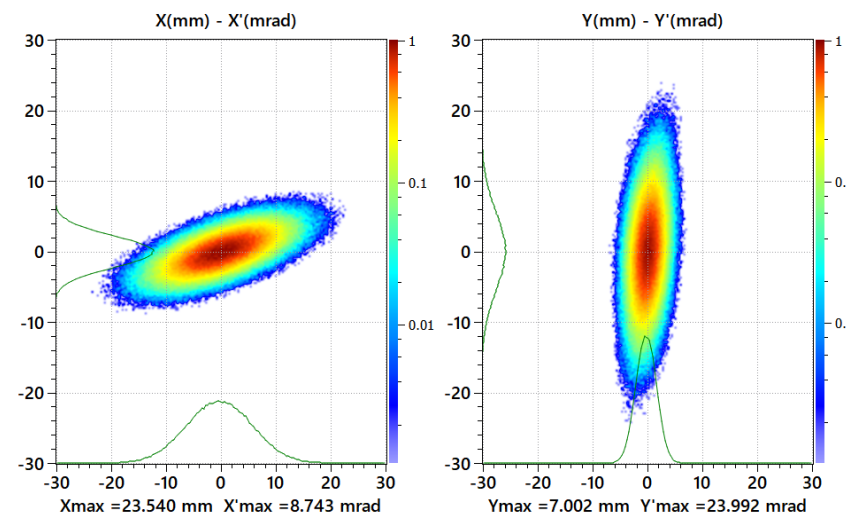




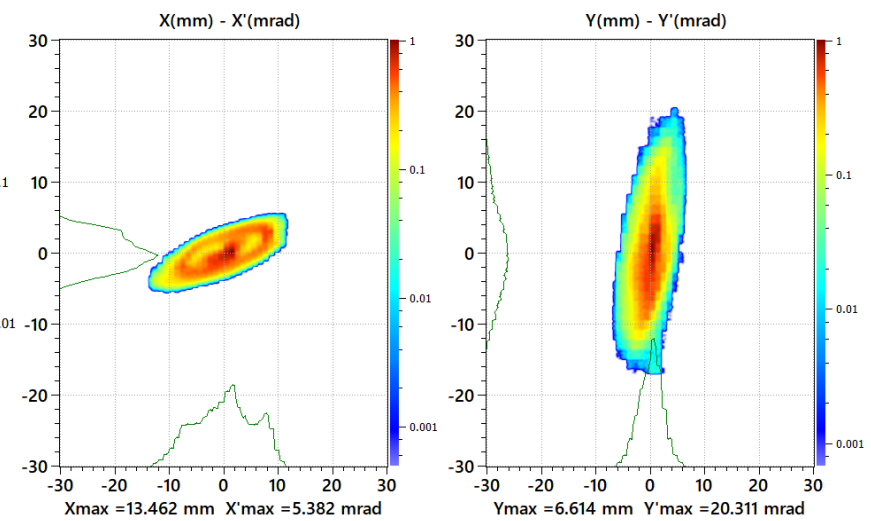
Transverse rms emittance measurements for a 600  $\mu\text{A}$   $^{18}\text{O}^{6+}$  beam.

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

Reference simulation 600  $\mu\text{A}$   $^{18}\text{O}^{6+}$



Measurement 600  $\mu\text{A}$   $^{18}\text{O}^{6+}$

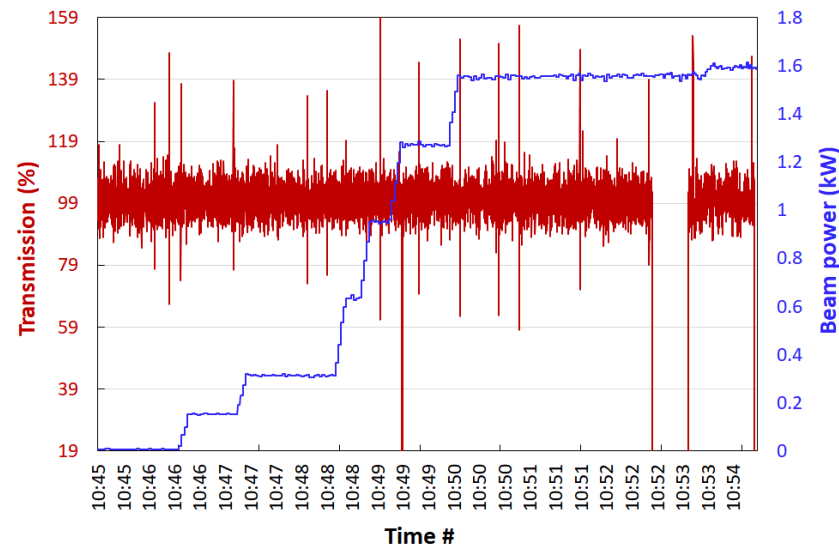
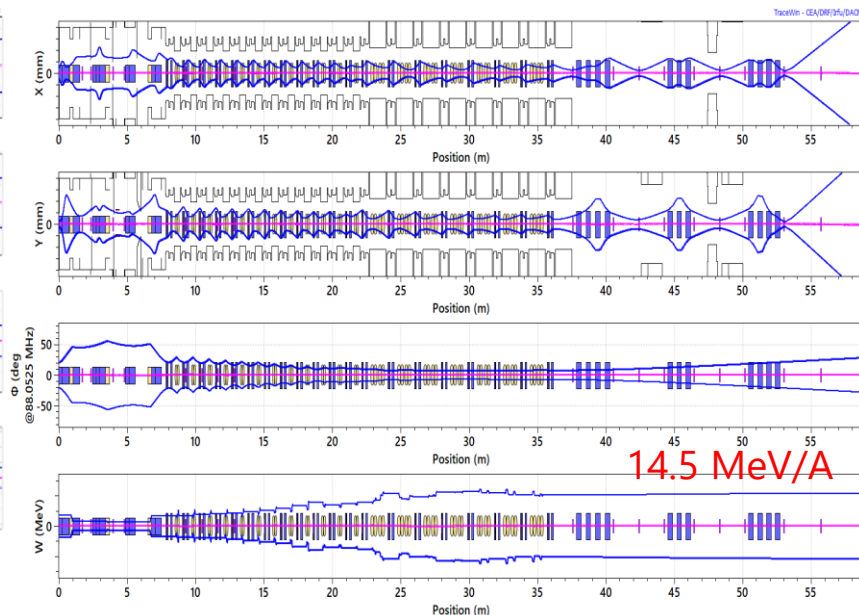
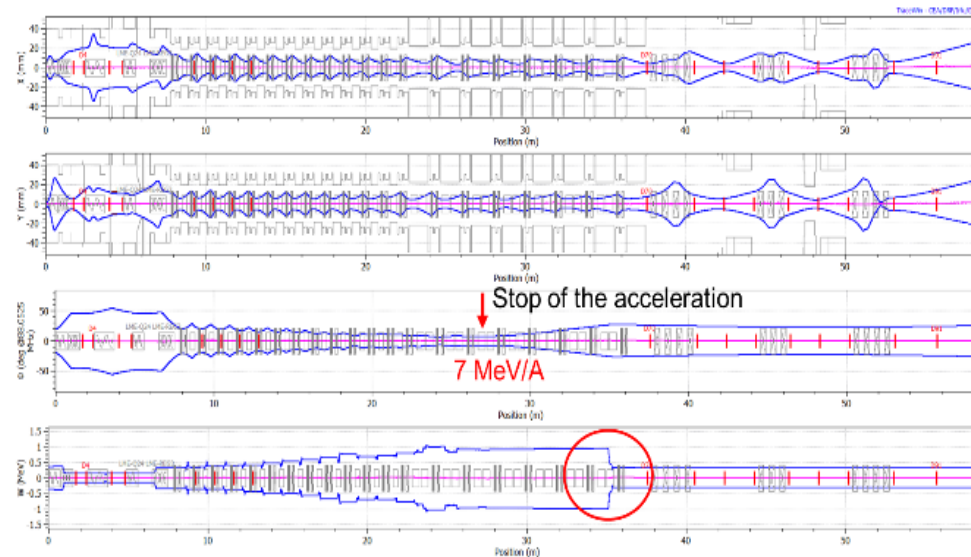


Parameter	Sim	Meas	$\Delta$ (%)
$\alpha_{X,X'}$	-0.83	-0.99	19
$\beta_{X,X'}$ (mm/ $\pi$ .mrad)	3.44	3.40	1
$\alpha_{Y,Y'}$	-0.29	-0.49	69
$\beta_{Y,Y'}$ (mm/ $\pi$ .mrad)	0.32	0.38	19

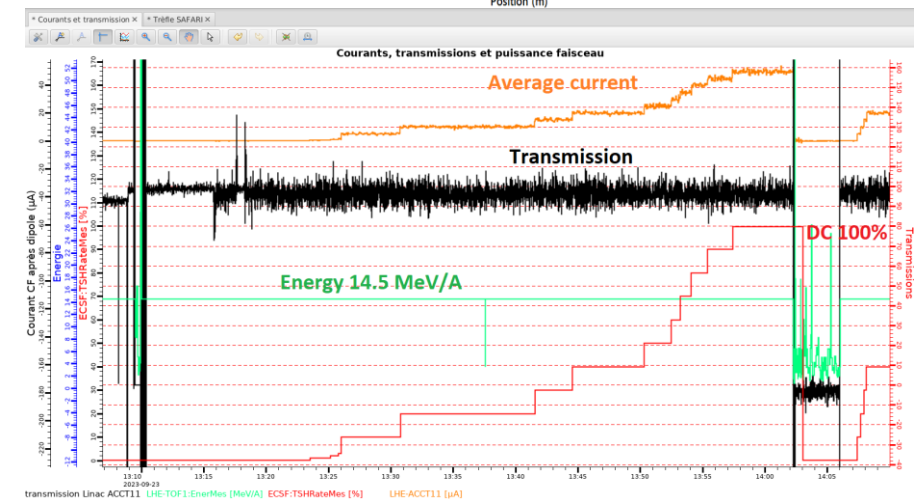
Good agreement!

## A/Q method test

- The "pilot beam";  $^{18}\text{O}^{6+} \Rightarrow A/Q=3$ , easy to produce with a current  $> 100 \mu\text{A}$ , good stability.
- The "objective ion";  $^{18}\text{O}^{7+} \Rightarrow$  easy and quick change from  $^{18}\text{O}^{6+}$ , current detectable by the pick up to validate the procedure.
- $7 \text{ MeV/A} \Rightarrow$  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.
- $50 \mu\text{A } ^{18}\text{O}^{6+}/^{40}\text{Ar}^{14+}$  in rebuncher mode @ $0.73 \text{ MeV/A}$ .



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



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

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



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

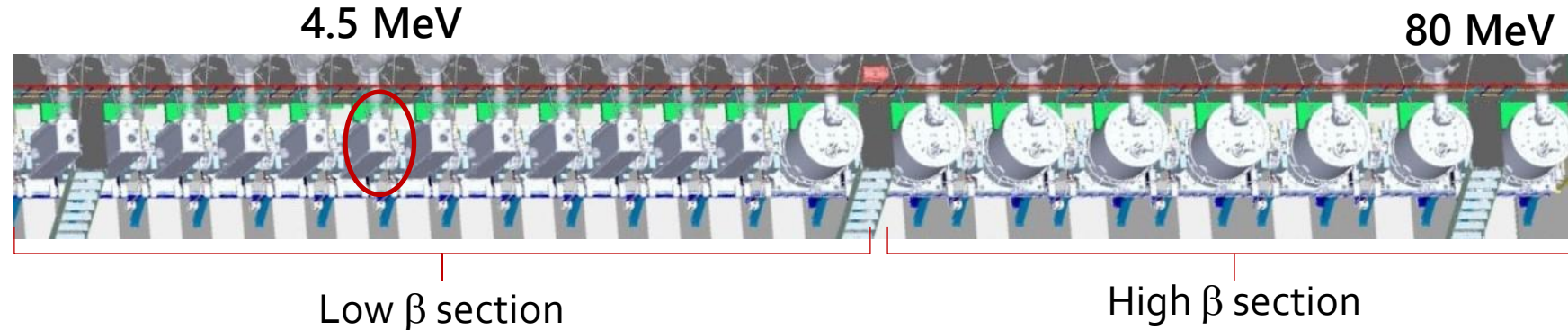
As the energy  $\uparrow$  the debunching  $\downarrow$

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

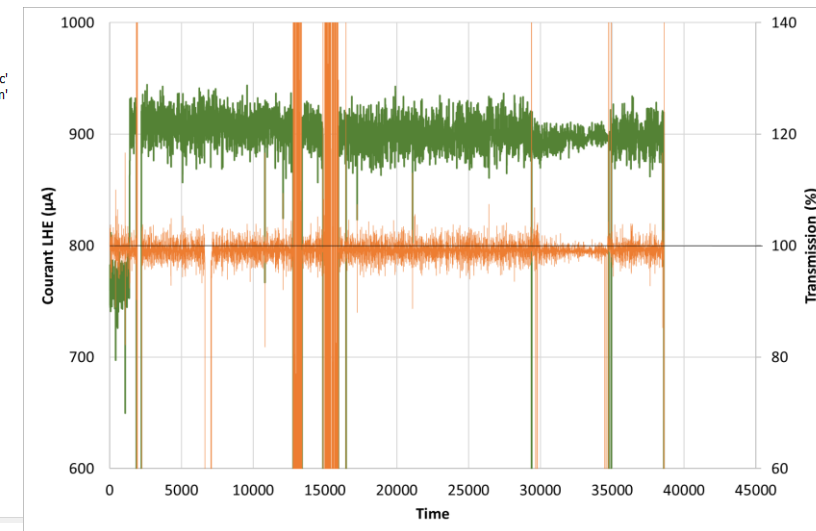
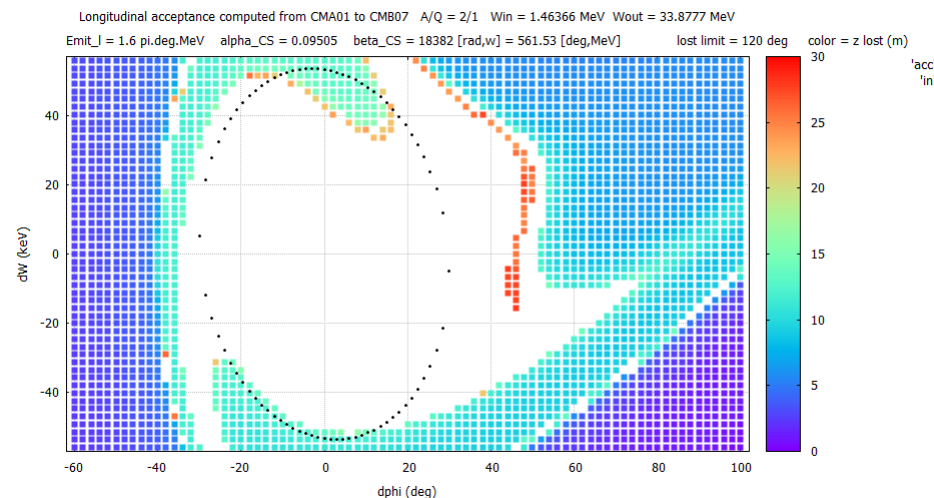
Retune the up and downstream cavities  
required phase acceptance  
reduction of the linac final energy or  
increase the cavity voltages.

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

Work is currently underway



900  $\mu\text{A}$   $^4\text{He}^{2+}$  / 63.87 MeV / 2 kW



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

## Beam energy change

- Several energies for 1 experiment.
- Manual switching (process time  $\approx \Delta E$ ).
- 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

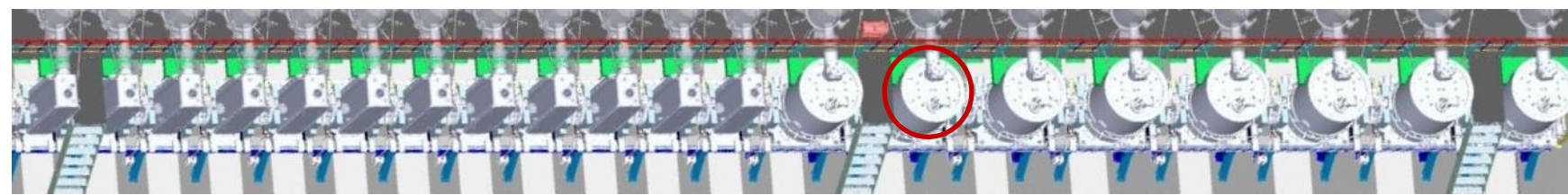
Quitter File Edit Accelerator View Fenetres Imprimer Info Logbook SPM OK

Energie lue sur le TOF (en MeV/A) : 19,995      Etape 1/7      Recherche cavité

Energie voulue (en MeV/A) :

changer Energie      mise à valeur Quads      mise à valeur Steerers      STOCKEE

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 détournée	1,2940 MV/m
LINA-CMA02-CAV1	0,8535 MeV/A	0,0428	0,3991 T.m			ON	présence RF	OFF	non détournée	1,3190 MV/m
LINA-CMA03-CAV1	0,9340 MeV/A	0,0448	0,4175 T.m			ON	présence RF	OFF	non détournée	1,3850 MV/m
LINA-CMA04-CAV1	1,0335 MeV/A	0,0471	0,4392 T.m			ON	présence RF	OFF	non détournée	1,4850 MV/m
LINA-CMA05-CAV1	1,1587 MeV/A	0,0498	0,4650 T.m			ON	présence RF	OFF	non détournée	1,6710 MV/m
LINA-CMA06-CAV1	1,3203 MeV/A	0,0532	0,4964 T.m			ON	présence RF	ON	non détournée	1,9500 MV/m
LINA-CMA07-CAV1	1,5348 MeV/A	0,0573	0,5353 T.m			ON	présence RF	OFF	non détournée	2,3920 MV/m
LINA-CMA08-CAV1	1,8302 MeV/A	0,0628	0,5845 T.m			ON	présence RF	OFF	non détournée	3,1070 MV/m
LINA-CMA09-CAV1	2,2571 MeV/A	0,0695	0,6492 T.m			ON	présence RF	OFF	non détournée	4,3540 MV/m
LINA-CMA10-CAV1	2,7125 MeV/A	0,0762	0,7118 T.m			ON	présence RF	OFF	non détournée	6,4610 MV/m
LINA-CMA11-CAV1	3,1677 MeV/A	0,0823	0,7693 T.m			ON	présence RF	OFF	non détournée	6,4930 MV/m
LINA-CMA12-CAV1	3,6209 MeV/A	0,0879	0,8228 T.m			ON	présence RF	OFF	non détournée	6,4930 MV/m
LINB-CMB01-CAV1	4,1727 MeV/A	0,0943	0,8832 T.m			ON	présence RF	OFF	non détournée	6,4930 MV/m
LINB-CMB01-CAV2	4,7590 MeV/A	0,1007	0,9433 T.m			ON	présence RF	OFF	non détournée	5,5010 MV/m
LINB-CMB02-CAV1	5,5857 MeV/A	0,1088	1,0204 T.m			ON	présence RF	OFF	non détournée	6,4930 MV/m
LINB-CMB02-CAV2	6,3878 MeV/A	0,1165	1,0934 T.m			ON	présence RF	OFF	non détournée	6,4920 MV/m
LINB-CMB03-CAV1	7,2731 MeV/A	0,1243	1,1670 T.m			ON	présence RF	OFF	non détournée	6,4990 MV/m
LINB-CMB03-CAV2	8,1558 MeV/A	0,1315	1,2361 T.m			ON	présence RF	OFF	non détournée	6,7580 MV/m
LINB-CMB04-CAV1	9,0355 MeV/A	0,1383	1,3013 T.m			ON	présence RF	OFF	non détournée	6,8250 MV/m
LINB-CMB04-CAV2	9,9056 MeV/A	0,1447	1,3629 T.m			ON	présence RF	OFF	non détournée	6,8900 MV/m
LINB-CMB05-CAV1	10,7142 MeV/A	0,1504	1,4177 T.m			ON	présence RF	OFF	non détournée	6,9540 MV/m
LINB-CMB05-CAV2	11,5106 MeV/A	0,1558	1,4698 T.m			ON	présence RF	OFF	non détournée	6,9550 MV/m
LINB-CMB06-CAV1	12,2943 MeV/A	0,1609	1,5193 T.m			ON	présence RF	OFF	non détournée	6,4350 MV/m
LINB-CMB06-CAV2	13,0295 MeV/A	0,1655	1,5643 T.m			ON	présence RF	OFF	non détournée	5,9990 MV/m
LINB-CMB07-CAV1	13,7897 MeV/A	0,1702	1,6097 T.m			ON	présence RF	OFF	non détournée	6,8240 MV/m
LINB-CMB07-CAV2	14,4935 MeV/A	0,1744	1,6505 T.m			ON	présence RF	OFF	non détournée	4,3690 MV/m



Low  $\beta$  section

High  $\beta$  section

The application was successfully tested!

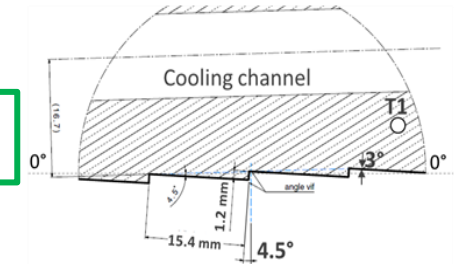
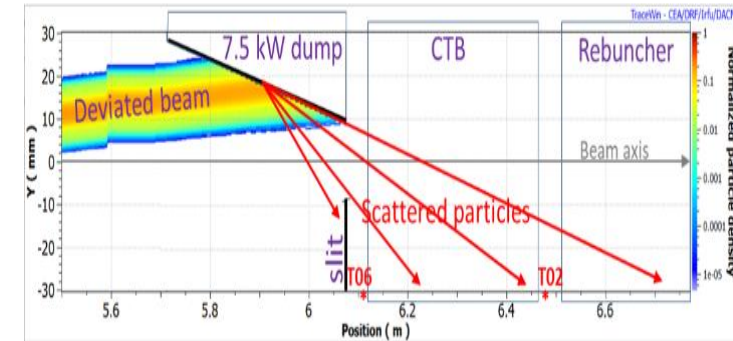
$^{18}\text{O}^{6+}$  beam from 14.5 MeV/A to 7 MeV/A



## ➤ SBS beam dump

- Current measurements had an **offset** of  $\approx 100\mu A$  in 2019.
- The **beam dump** receiving the bunches deviated by the SBS ( $\leq 7.5$  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

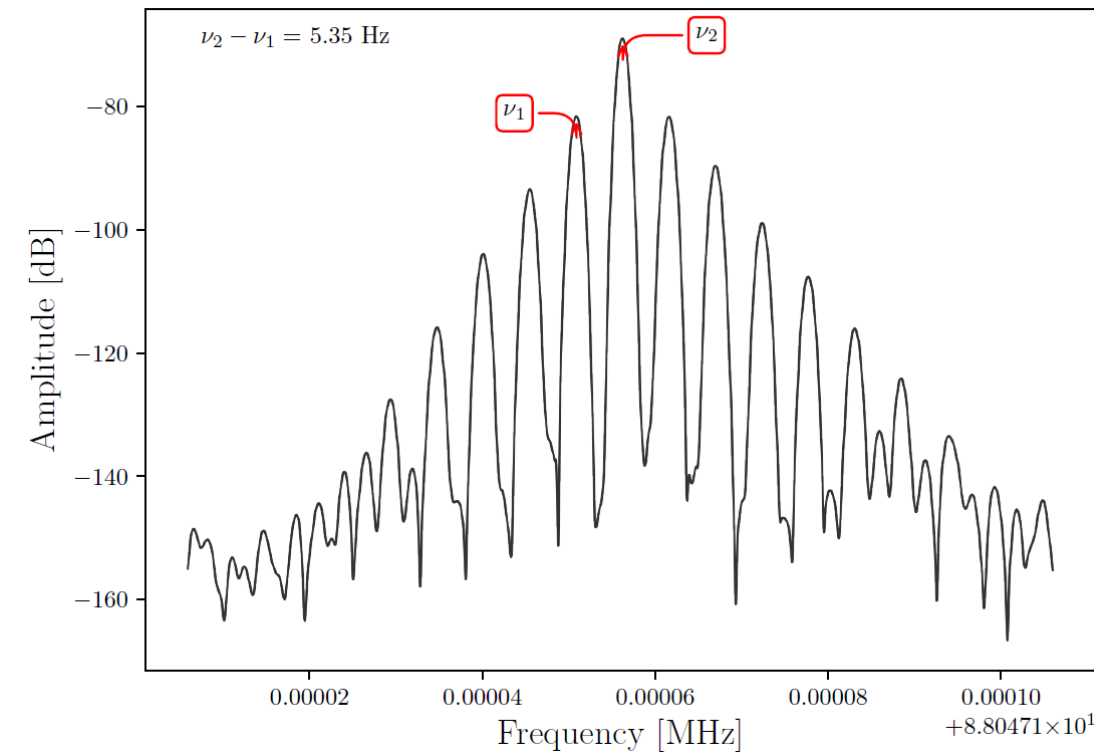
- A **new BPM electronics** for the RF signals distribution was **designed, manufactured and installed**.
- All distribution frames are adjusted to have a  $\Delta\text{phase} < 0.5^\circ$  between the outputs.
- Calibration of all BPMs was reduced from 1 week to 3 days.

## ➤ Cavity X-ray emissions

- X-ray emissions have started from 2020 in cavities #2 (low  $\beta$  section), #14 and #26 (high  $\beta$  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  $\beta$  cavities has been increased**; most of the high  $\beta$  cavities have been qualified and can operate up to 8 MV/m.

## ➤ 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 emission 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

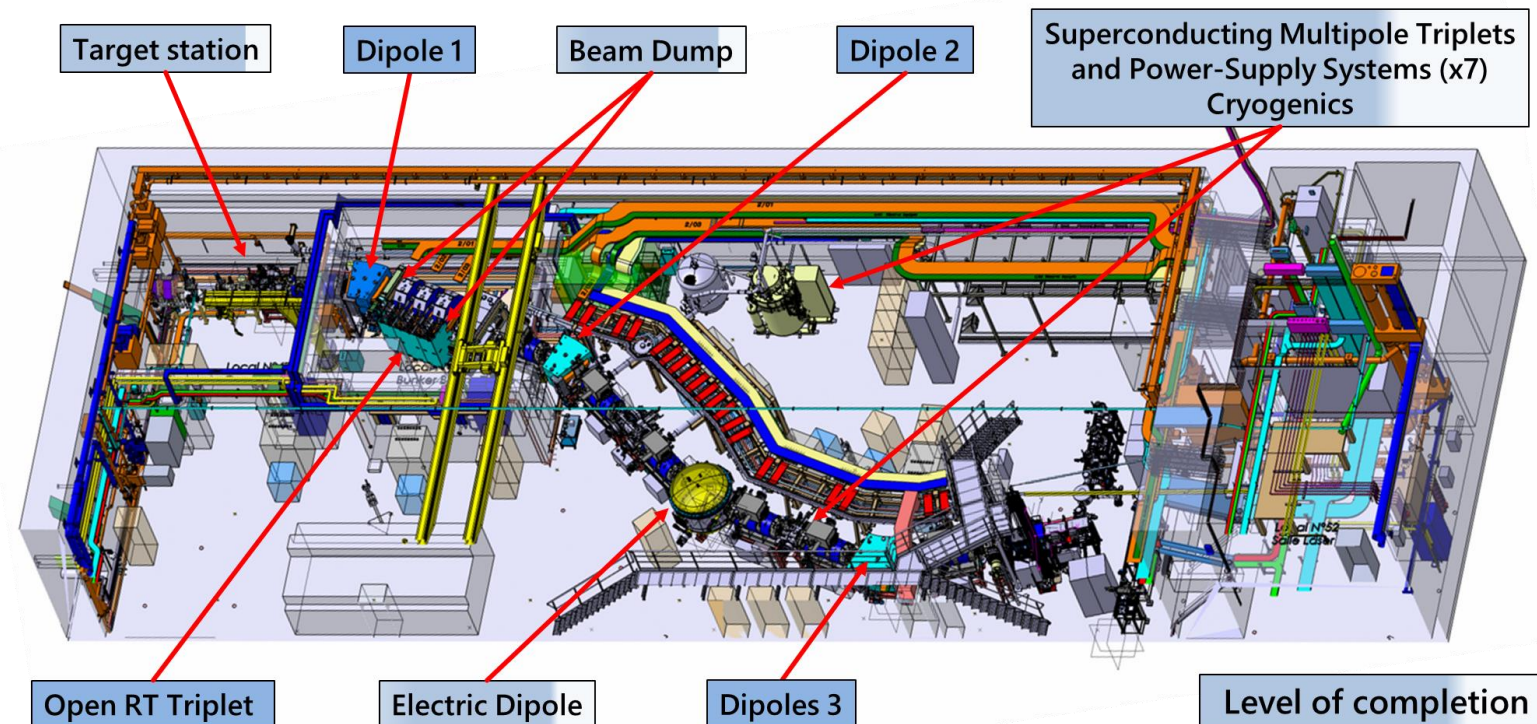
## Preliminary proposition

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																								

➤ Gradual increase of beam time with parallel operation of GANIL and SPIRAL2.

➤ Commissioning of S<sup>3</sup> experimental room in 2024.

- The S<sup>3</sup> 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 S<sup>3</sup> Low Energy Branch and the laser system is planned for 2024. As well as the commissioning of: Beam transport, physics measurements, and detection system.



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<sup>3</sup> 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.



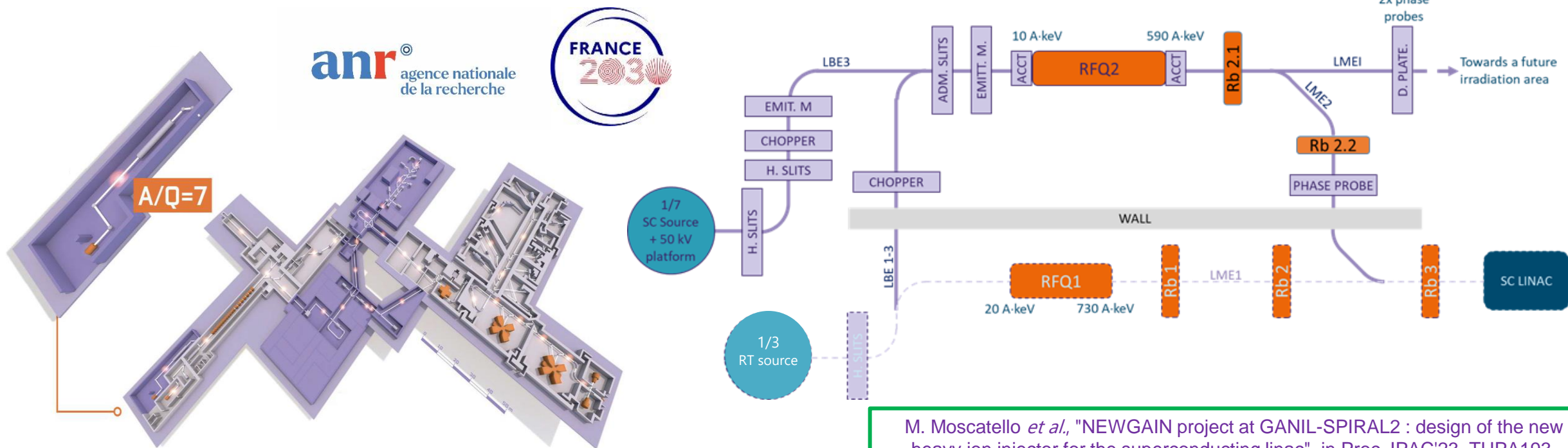
**DESIR**

DESIR a été labellisée par un EQUIPEX (EQUIPement d'EXcellence)



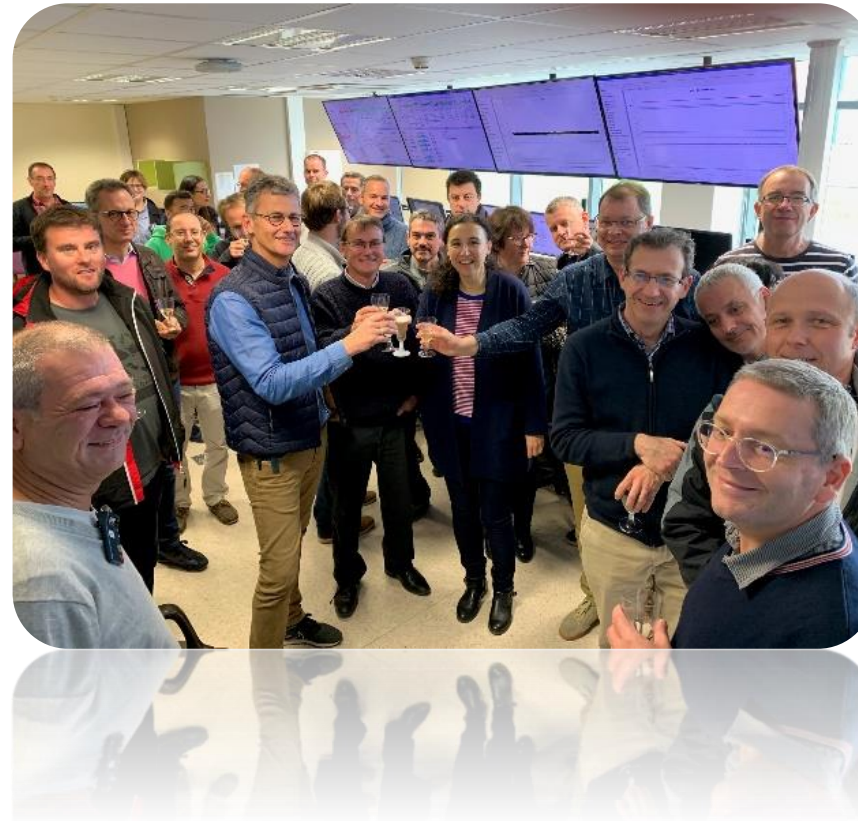
## NEWGAIN NEW GANIL INJECTOR

- 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.



- 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  $S^3$ ,  $^{18}O^{6+,7+}$  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!