LINAC2022 LIVERPOOL

SPIRAL2 Final Commissioning Results

Angie Orduz on behalf of SPIRAL2 Accelerator Physics Group and Commissioning Team

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Outline

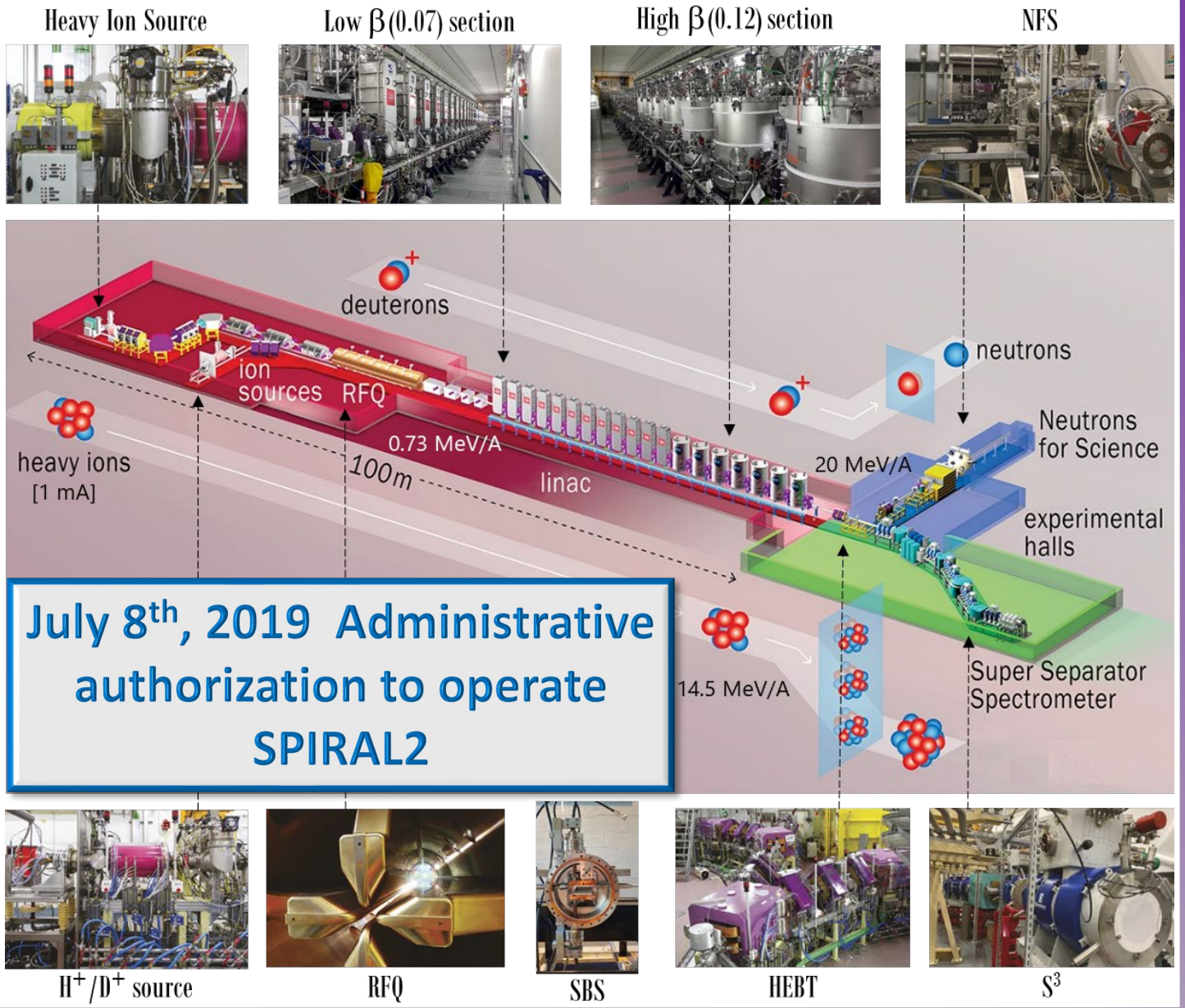
- GANIL-SPIRAL2
- SPIRAL2 SC linac commissioning and results
- Summary and conclusion
- Future perspectives

GANIL-SPIRAL2

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	49

Collaboration with National Laboratories and International Partners

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

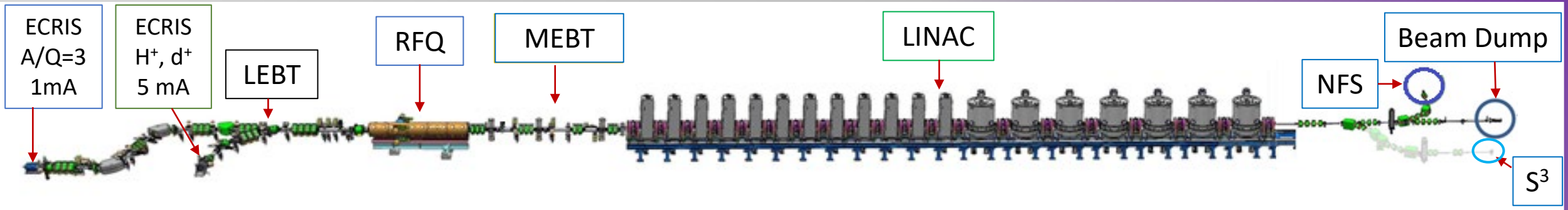


Main commissioning dates and milestones

Beam commissioning in 4 phases
Qualification of the ion sources and LEBT in the laboratories in charge of the development (LPSC-Grenoble and CEA-Saclay) • 2009-2012
Qualification of the injector on a Diagnostic Plate (GANIL) • Reproduce the results from the pre-commissioning • Validate the RFQ performances • Provide a development platform for various diagnostics • Measure the beam characteristics at the RFQ exit. • 2014-2018
SC linac beam commissioning up to the main beam dump • Progressive cool down – started in 2016 • RF validation of all cavities - 2019 • Beam commissioning – Started 2019
"day-1" experiments to NFS and S3 experimental halls • including commissioning • first test experiments in NFS in 2019 and 2020

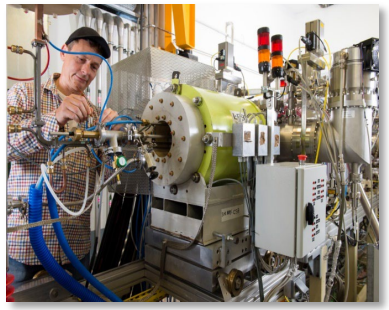
Milestones
J1: Injector qualification with beam on the D-plate
J3: LINAC RF power qualification
J4: LINAC beam up to the beam dump
J5: Beam in NFS experimental hall
J6: Beam in S^3 experimental hall (after the completion of S^3)

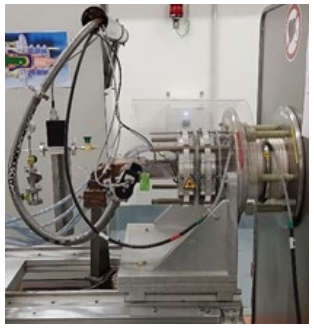
Commissioning Time Line



2014

P/D source: first beam 2 mA H^+. December





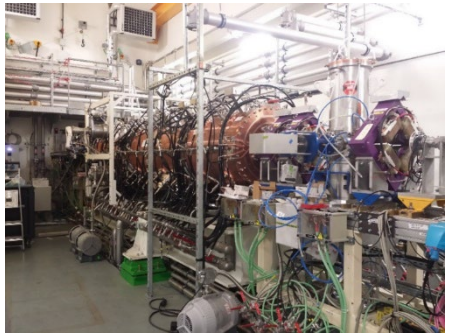
2015

Phoenix V2: first beam 230 µA Ar^{9+} July.

RFQ: first H^+ beam December.

2018

Diagnostic plate commissioning end April-November

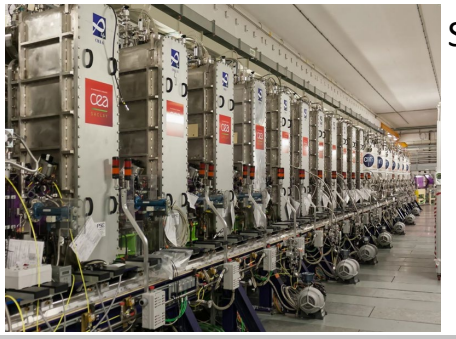


2019

MEBT @5 mA H^+.
SBS* @ 0.2 mA H^+
SC LINAC @ 0.2 mA H^+
33MeV H^+
July-December

2020

SBS @ 5 mA H^+.
MEBT @1.2 mA $^4He^{2+}$
SBS* @1.2 mA $^4He^{2+}$
SC LINAC @ 5 mA H^+
16kW H^+
July – December

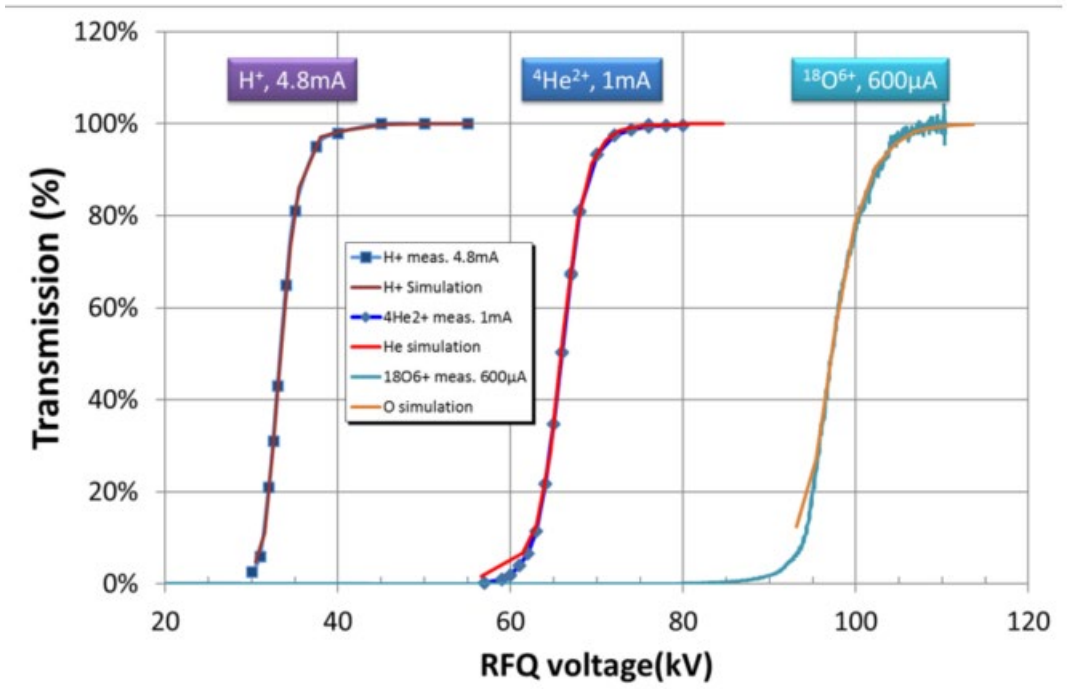


2021

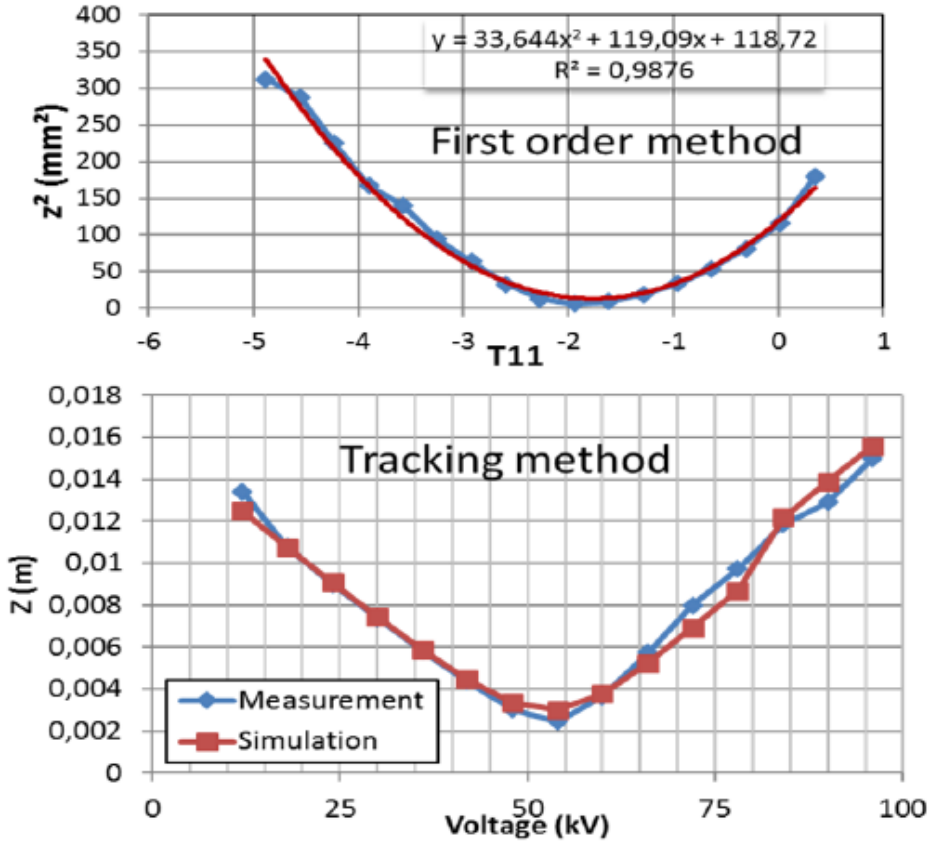
SC LINAC@1.3 mA $^4He^{2+}$
SBS @ 5 mA D^+
SC LINAC @ 5 mA D^+
40 MeV D^+
50 µA NFS
July-September

Injector qualification on a D-Plate

- The SPIRAL2 injector and sources, LEBT lines and RFQ were commissioned in the D-plate.
- CW operation of the RFQ was validated at nominal voltage.
- Transmission, transverse and longitudinal emittances are in agreement with reference simulations with TraceWin.
- 100% beam transmission in the RFQ for H^+, $^4He^{2+}$, $^{18}O^{6+}$ and $^{40}Ar^{14+}$

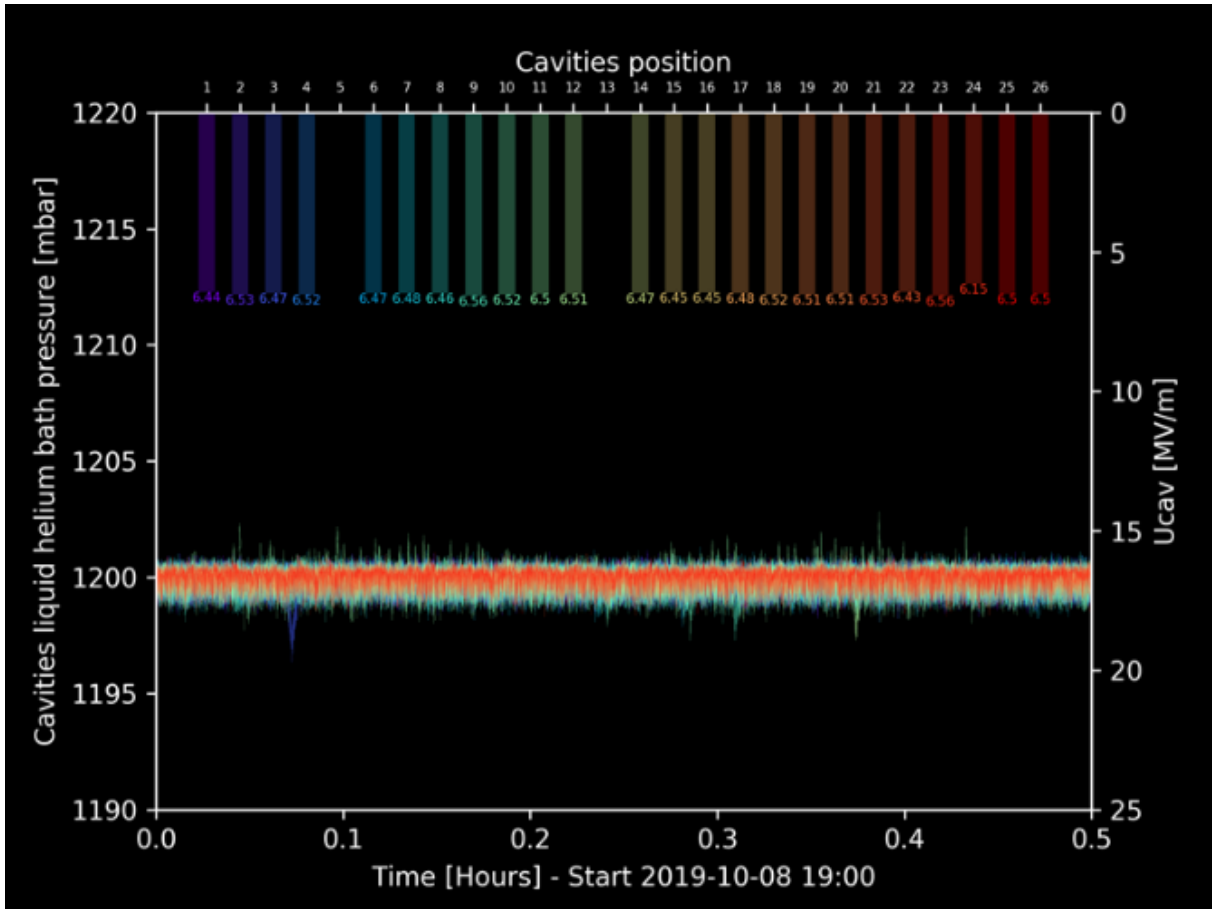


R. Ferdinand *et al.*, Final Results of the SPIRAL2 Injector Commissioning *IPAC'19* doi:10.18429/JACoW-IPAC2019-TUPTS007.



G. Normand *et al.*, SPIRAL2 RFQ Bunch Lengths and Longitudinal Emittance Measurements. *IPAC'19* doi:10.18429/JACoW-IPAC2019-MOPTS006.

LINAC RF and cryogenic systems commissioning



LINAC cavities at nominal fields and cavities L_{He} bath pressure

- J3 : September 24, 2019
  All LINAC cavities ramped up to their nominal fields

- RF : Validation and comparison with earlier performances at the partner labs after at least 4 years of storage (vacuum).
  - Nominal gradient 6.5 MV/m except for cavity 24 (CMB6.2).
  - X-ray (µSv/h)
    => Same values except for CMA11

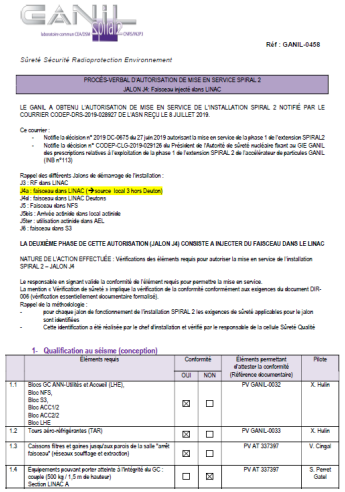
- Cryogenics :
  - He bath pressure regulation < ±5mBar for all cavities with full RF power

Detailed information on RF and cryogenic systems on posters: MOPOPA015, TUPOGE002.

First beam in LINAC - 2019

October 28th, 2019 : internal safety authorization for the first linac beam

Very strong GANIL teams involvement to reach this milestone (J4)
(122 prerequisites, 22 safety systems validated for operation according to safety requirements)



Réf : GANIL-0458

Sûreté Sécurité Radioprotection Environnement

PROCÈS-VERBAL D'AUTORISATION DE MISE EN SERVICE SPIRAL 2
JALON J4 : Faisceau injecté dans LINAC

LE GANIL A OBTENU L'AUTORISATION DE MISE EN SERVICE DE L'INSTALLATION SPIRAL 2 NOTIFIÉ PAR LE COURRIER CODEP-DRS-2019-028927 DE L'ASN REÇU LE 8 JUILLET 2019.

Ce courrier :

- Notifie la décision n° 2019-DC-0675 du 27 juin 2019 autorisant la mise en service de la phase 1 de l'extension SPIRAL2
- Notifie la décision n° CODEP-CLG-2019-029126 du Président de l'Autorité de sûreté nucléaire fixant au GIE GANIL des prescriptions relatives à l'exploitation de la phase 1 de l'extension SPIRAL 2 de l'accélérateur de particules GANIL (INB n°113)

Rappel des différents Jalons de démarrage de l'installation :
J3 : RF dans LINAC
J4a : faisceau dans LINAC (faisceau local 3 hors Dauble)
J4d : faisceau dans LINAC Deutons
J5 : Faisceau dans NFS
J3ab : Armée activable dans local activable
J3ter : utilisation activable dans AEL
J6 : faisceau dans S3

LA DEUXIÈME PHASE DE CETTE AUTORISATION (JALON J4) CONSISTE A INJECTER DU FAISCEAU DANS LE LINAC

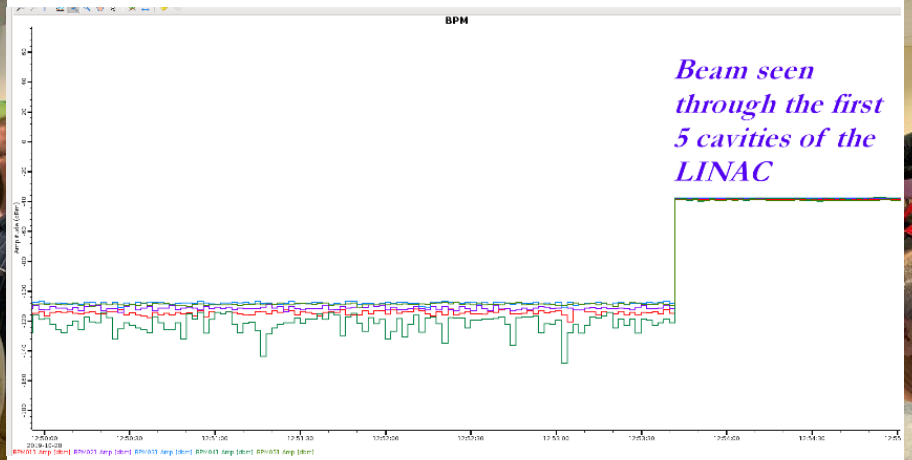
NATURE DE L'ACTION EFFECTUÉE : Vérifications des éléments requis pour autoriser la mise en service de l'installation SPIRAL 2 – JALON J4

Le responsable en signant valide la conformité de l'élément requis pour permettre la mise en service.
La mention « Vérification de sûreté » implique la vérification de la conformité conformément aux exigences du document DIR-006 (vérification essentiellement documentaire formalisée).
Rappel de la méthodologie :

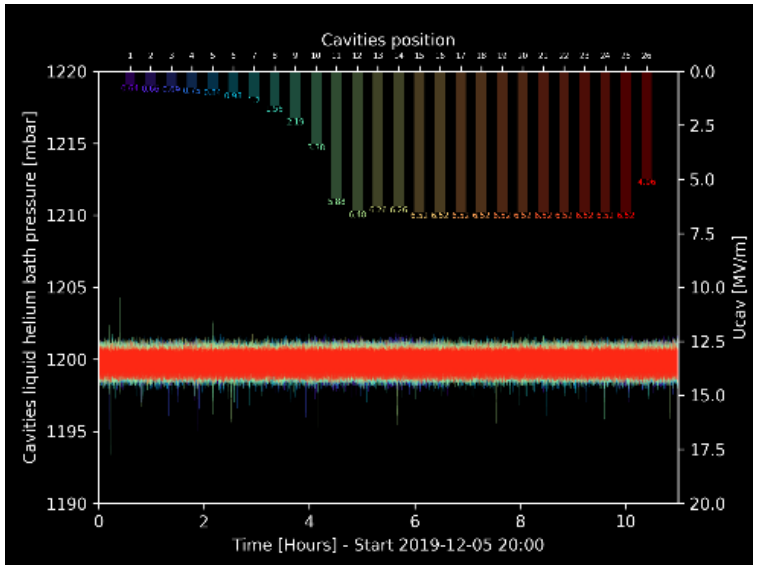
- pour chaque jalon de fonctionnement de l'installation SPIRAL 2 les exigences de sûreté applicables pour le jalon sont identifiées
- Cette identification a été réalisée par le chef d'installation et vérifié par le responsable de la cellule Sûreté Qualité

1- Qualification au séisme (conception)

	Eléments requis	Conformité OUI	Conformité NON	Eléments permettant d'attester la conformité (Référence documentaire)	Pilote
1.1	Blocs GC ANN-Utilités et Accueil (LHE), Bloc NFS, Bloc S3, Bloc ACC1/2 Bloc ACC2/2 Bloc LHE	☒	☐	PV GANIL-0032	X. Halin
1.2	Tours aéro-réfrigérantes (TAR)	☒	☐	PV GANIL-0033	X. Halin
1.3	Caissons filtres et gaines jusqu'aux portoirs de la salle "amont faisceau" (réseaux soufflage et extraction)	☒	☐	PV AT 337297	V. Cingal
1.4	Equipements pouvant porter atteinte à l'intégrité du GC : cruaple (500 kg / 1,5 m de hauteur) Section LINAC A	☐	☒	PV AT 337297	S. Pomet Galal



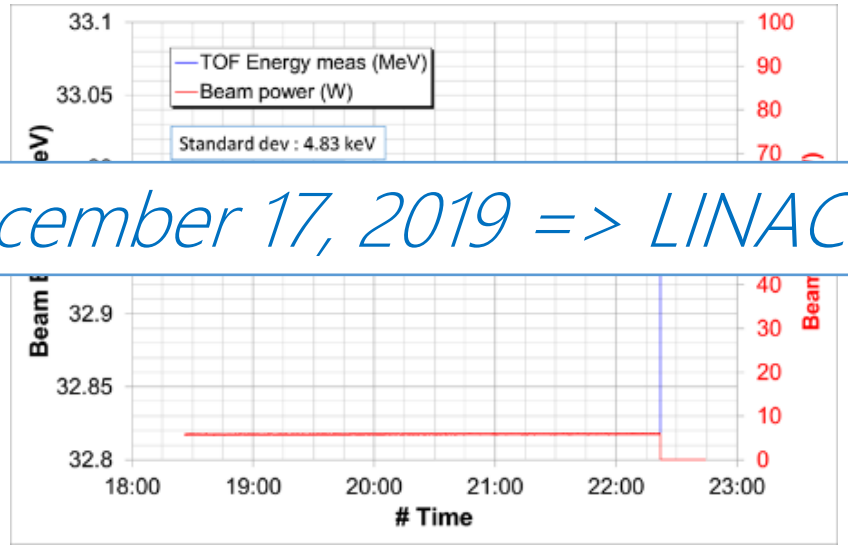
First acceleration H^+ beam 2019



Pressure stability over 10 hours, LINAC tuned for 33MeV proton

November 27th, 2019 : H^+ nominal acceleration, 33MeV

200µA, 960µs/s, 6.34W

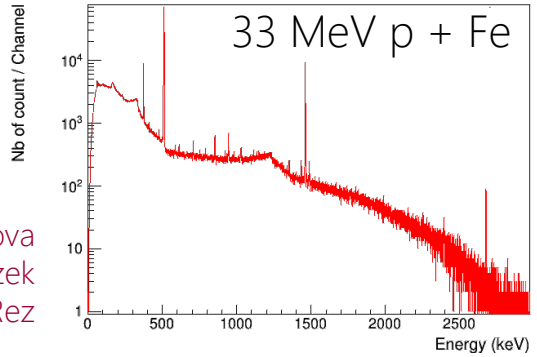


December 17, 2019 => LINAC warm up

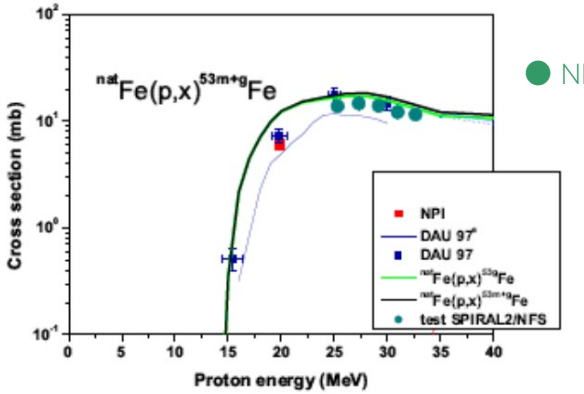
December 11th, 2019 : H^+ beam injected in NFS experimental hall (milestone J5)

First test experiment in NFS Irradiation set up (Collab with the Nuclear Physics Institute of Czech Republic.)
Successful measurement

E. Simeckova
J. Mrazek
NPI, Rez



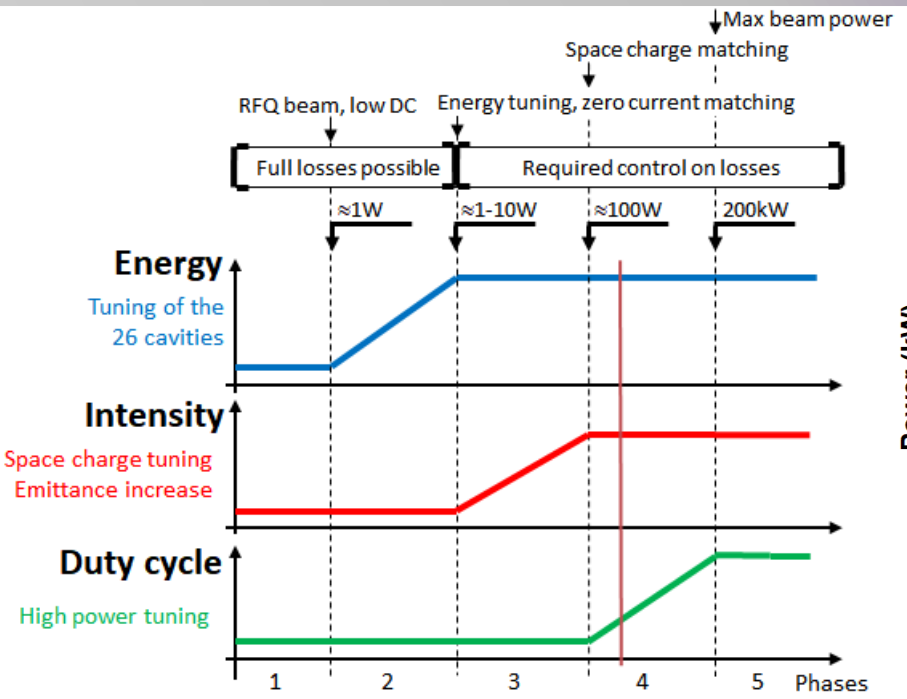
decay spectrum (gamma rays/copper target)



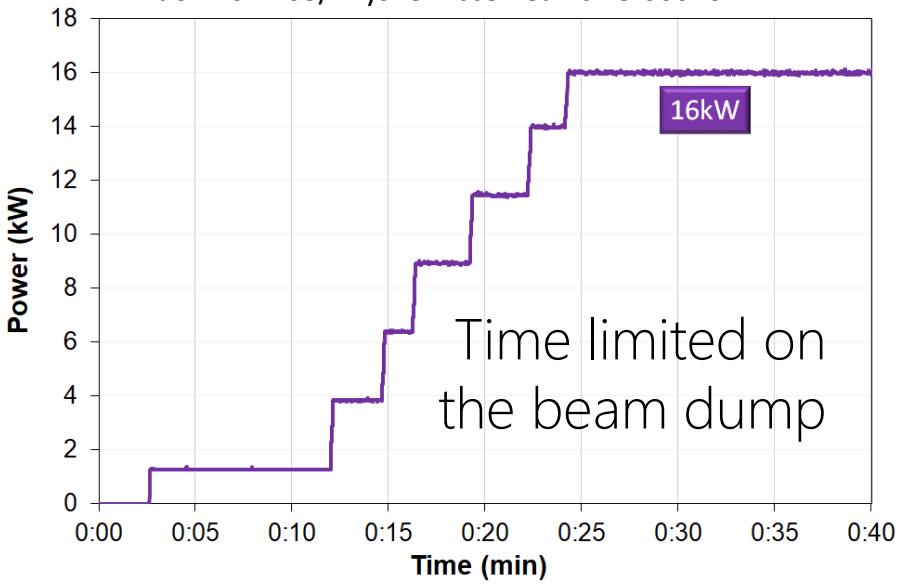
NFS measurements

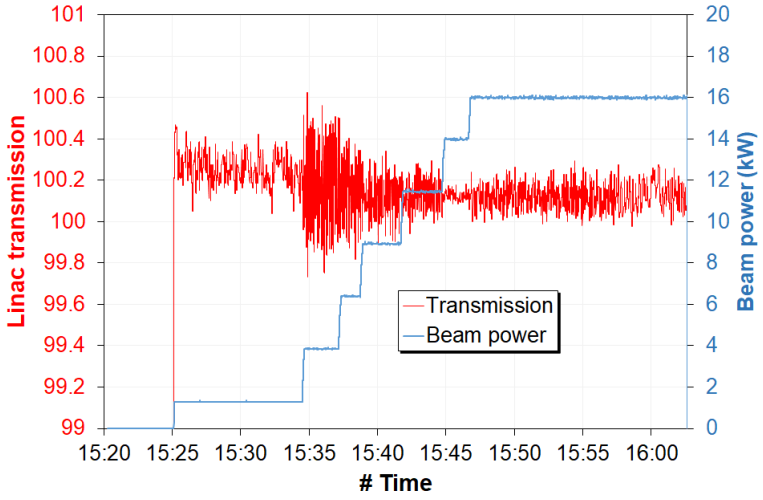
Power ramp-up 16 kW - 2020

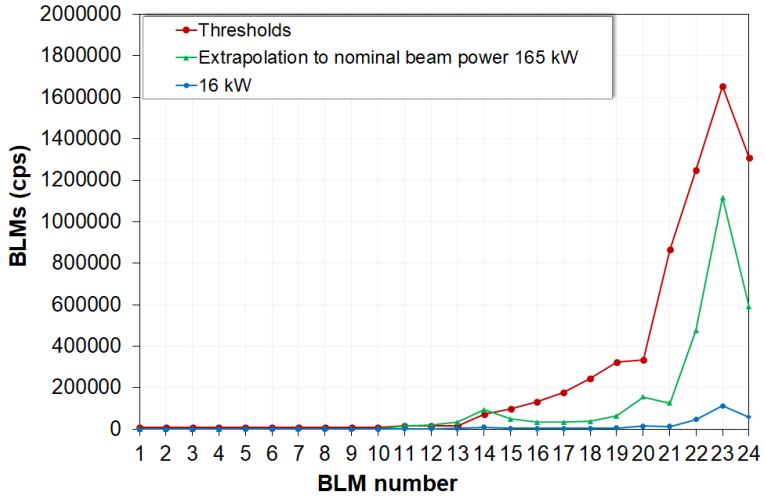
- Major project milestone 2020
- Duty cycle @ I_{max} from 1% to 12.6% - no Single Bunch Selector (16 kW)
- Demonstration of capability to run at 100% duty cycle, I_{max}, W_{max} (165kW)
- 4mA, 10Hz, 12.6ms/100ms, 31.9MeV

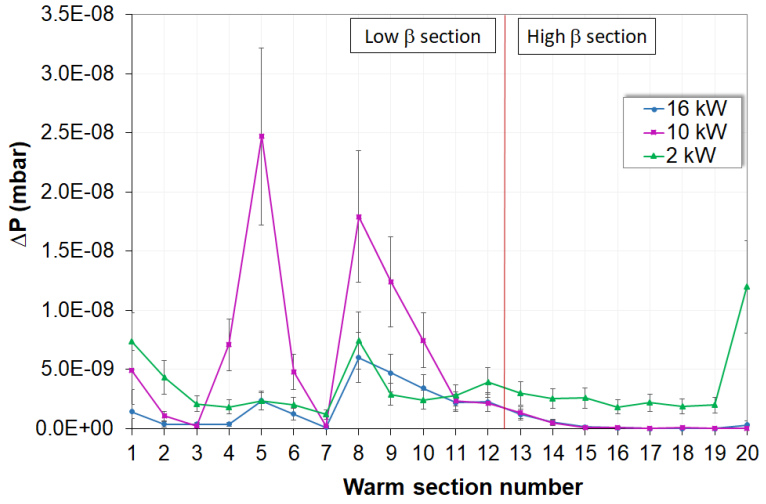


A. K. Orduz *et al.*, Commissioning of a high power linac at GANIL: Beam power ramp-u. PRAB doi: 10.1103/PhysRevAccelBeams.25.060101



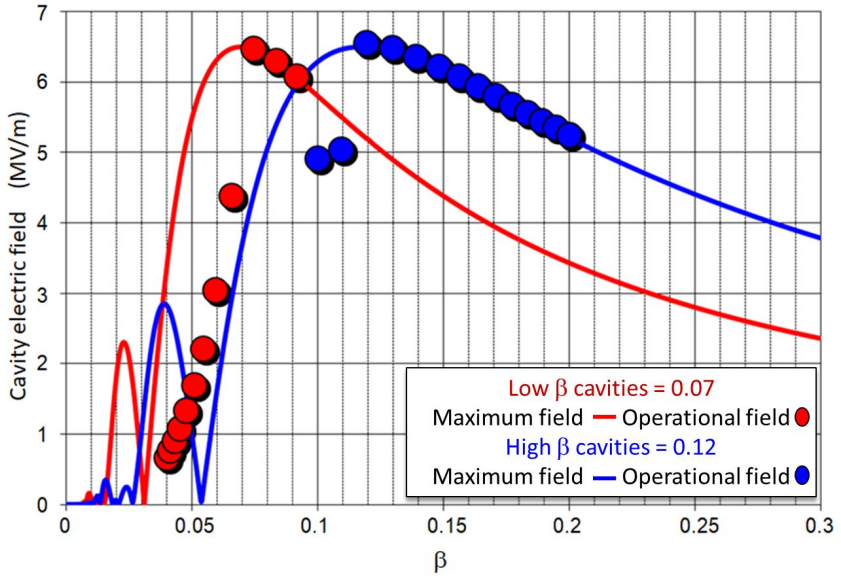






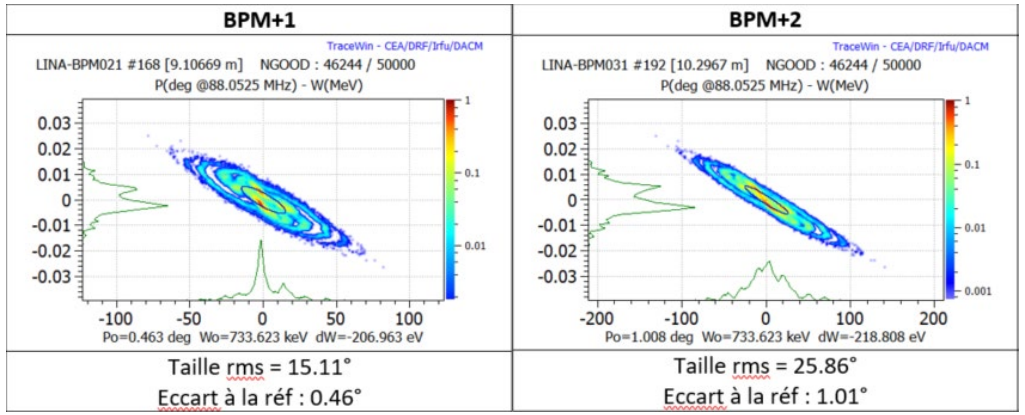
Towards the D^+ acceleration - 2020

- First tuning of the $^4He^{2+}$.
- MEBT validated, including the Single Bunch Selector
- Difficulties with the LINAC tuning with a $^4He^{2+}$: Finally 3 weeks of Helium operation was inserted to optimize the 2021 strategy and valuated the possible difficulties.

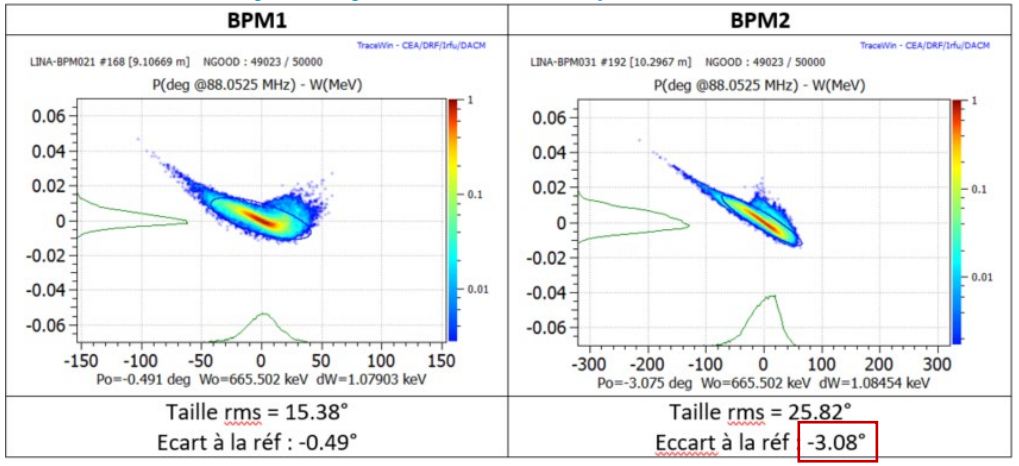


Impossible to differentiate between input energy error and cavity voltage error.

Cavity 1: Synchronous phase - 45°



Cavity 1: Synchronous phase - 180°



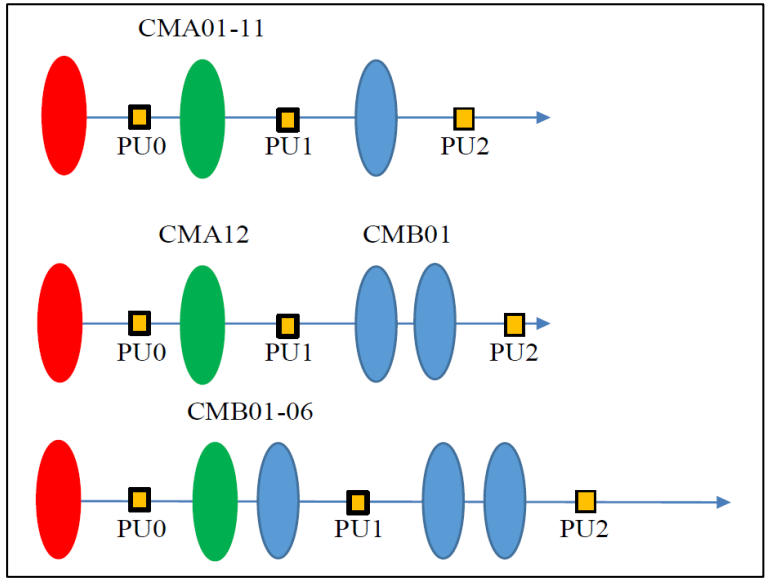
Due to the longitudinal beam size in the first cavities (>100°), the non linear effects during the 360° phase scan is such that the ToF given by the 2 BPMs after the cavity is not the one computed (up to 5° in the worst cases)

2021 cavity tuning procedure

- Cavities ≥N detuned, 3 BPMs phase measurements (N-1, N, N+1)
- 360° fast scan to find buncher phase (~nominal RF field).
- ± 25 ° precise scan (2° step) around this buncher phase (~nominal RF field).
- $Phi_{cav} = Phi_{cav\_rebunchers\_measured} - (Phi_{entrance\_cav\_theorical} - Phi_{entrance\_cav\_rebuncher\_theorical})$.
- U_{cav} obtained by comparison between two slopes around buncher phase :
- $d(\Delta W)/d(phi\_cav)$ theorical vs measured.
- Cavity N tuned with the phase and voltage correction obtained.

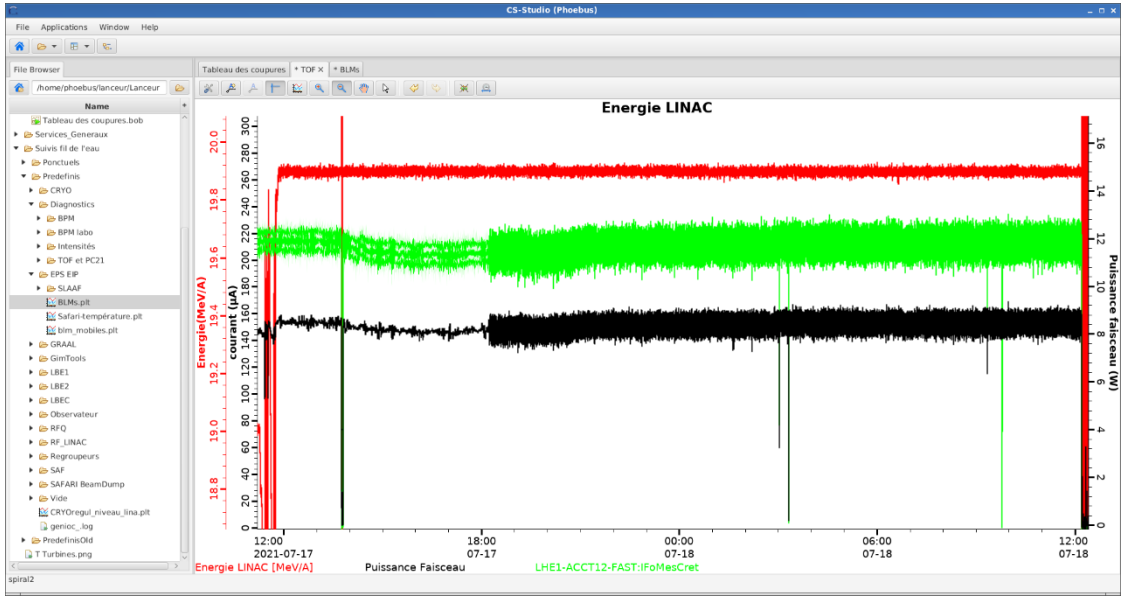
Lots of intermediate and final controls with energy :

- ToF
- BPM (2020) and phase
- BPM (2021)



Accelerated D^+ beam - 2021

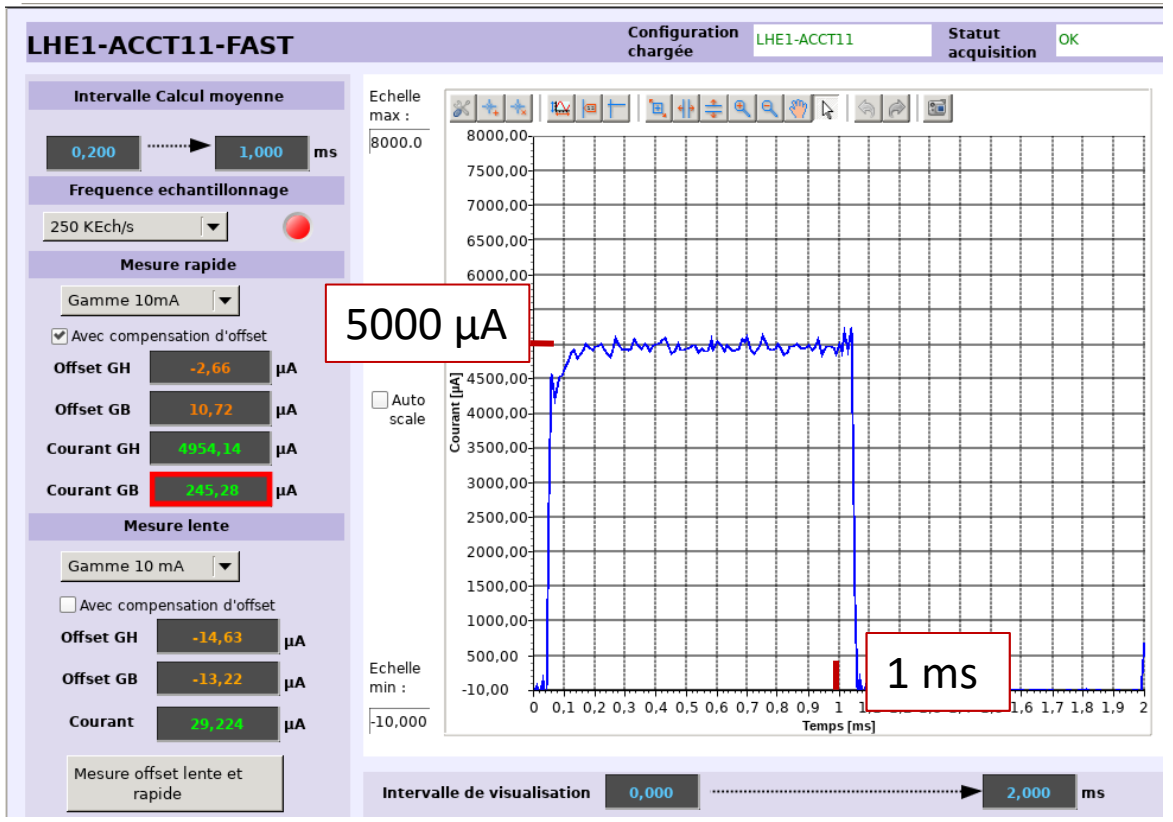
- July 17 - Linac tuned with 1.1 mA of $^4He^{2+}$ @ 20 MeV/A (A/Q=3 source)



- Linac commissioned with D^+ beam current from 0.2 up to 5 mA
  - No retuning of the linac
  - Use of the Deuteron source

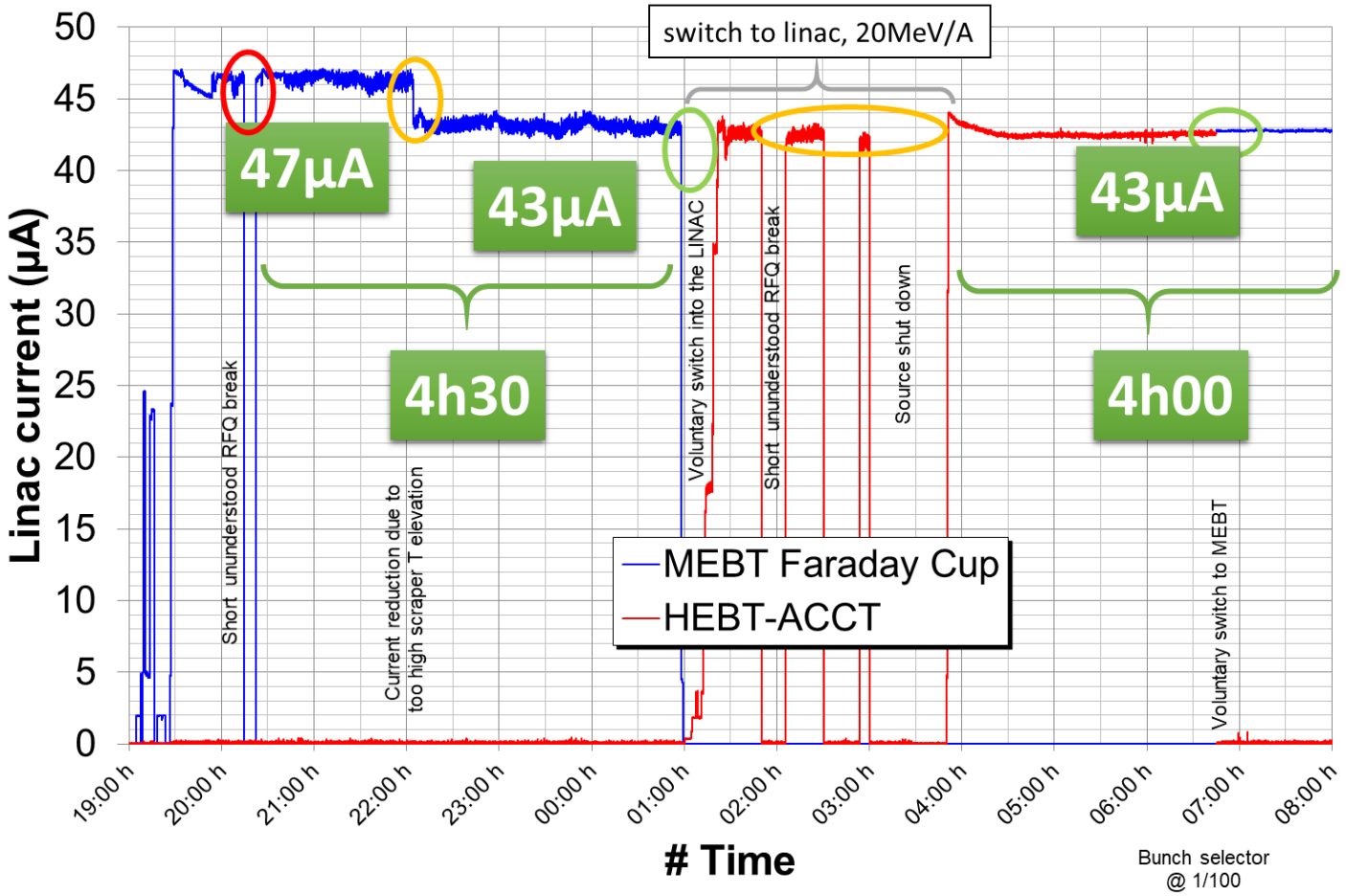
20 MeV/A energy validated

- July 30 – Acceleration of a 5 mA D^+ beam with a 1ms/s pulsed beam (without SBS)
- Transmission in the linac > 99.8% (not yet optimized)



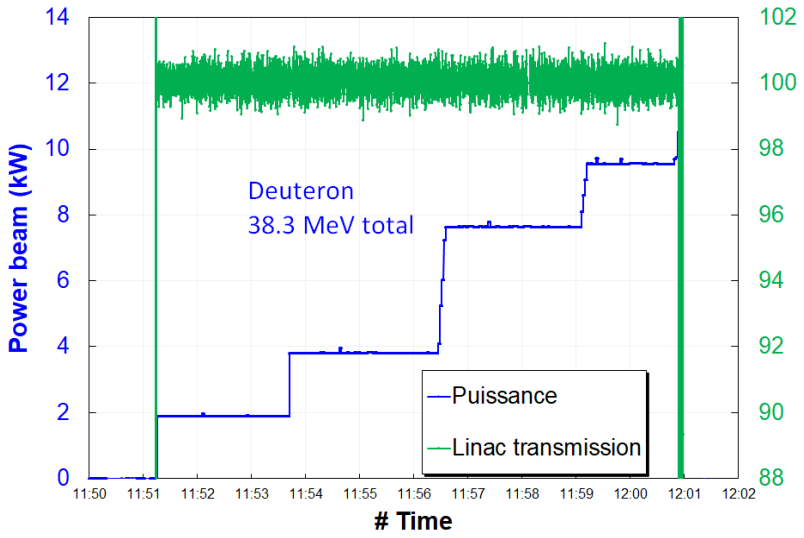
I max tuning on target - 2021

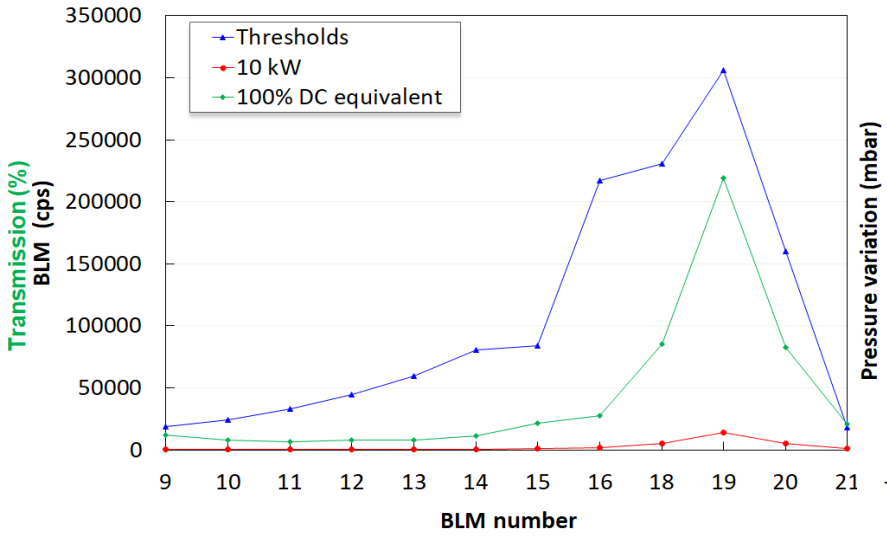
- I max tuning with the SBS 50 µA in target.
- Beam current increase to 46.5 µA in the MEBT and later in the HEBT.
- Stabilized beam at 43 µA average with the SBS (1/100).

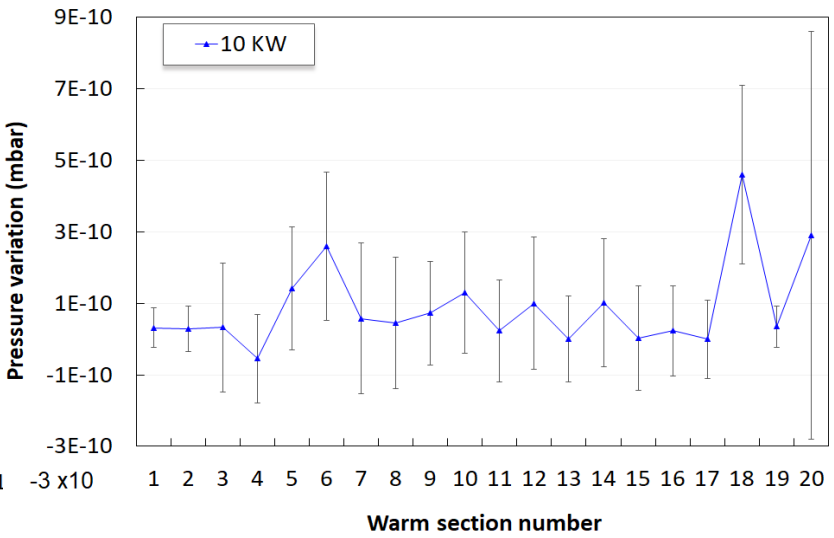


Power ramp-up 10 kW - 2021

- The SPIRAL2 facility has been successfully commissioned with D^+ beam.
- Power ramp-up with a final energy of 38.3 MeV (one cavity not working).
- The margin between the extrapolation and the 1 W/m limit indicates the feasibility to work with the nominal 200 kW deuteron beam power.
- Excellent agreement between measurements and reference simulations.







A. K. Orduz *et al.*, Deuteron Beam Power Ramp-Up at SPIRAL2. IPAC'22. doi:10.18429/JACoW-IPAC2022-MOPOST010

1st Neutron production @ SPIRAL2

- 2020: 6 tests periods from September to November, only with H^+ beam.
  - Tests required to produce and characterize the neutron beam at the Neutron for Science facility :
    - Thin convertor test -> for quasi-mono energetic neutrons
    - Thick convertor -> for continuous neutron spectrum (using max proton beam power available in 2020)
- 2021: 6 periods September to December with D^+ and H^+ beams.
  - Gradual increase in power in the thick Be convertor (200 to 1350 W).
  - Temperature measurements with 3 probes for a comparison with simulations

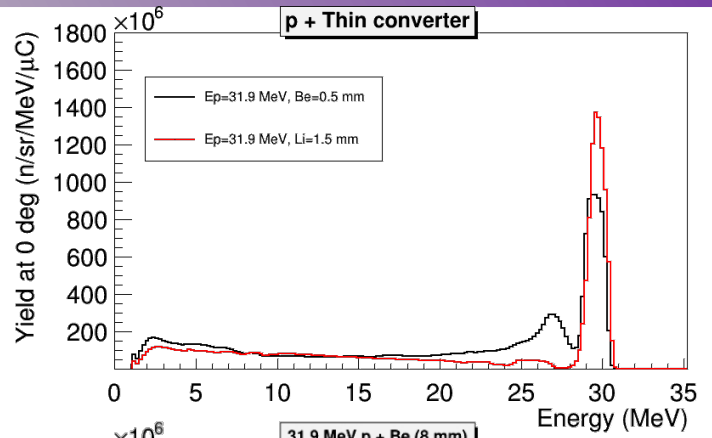
Peak ratio (E>28.5 MeV) / total (E>2 MeV):

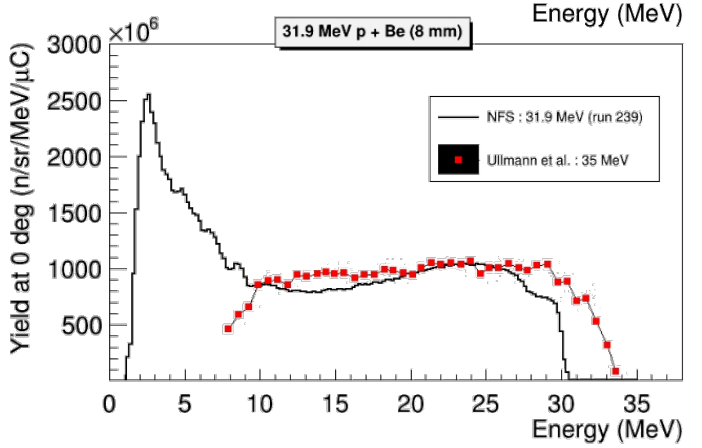
p + Li (1.5 mm) : 51% ($1.77^{E}9$ n/sr/µC)

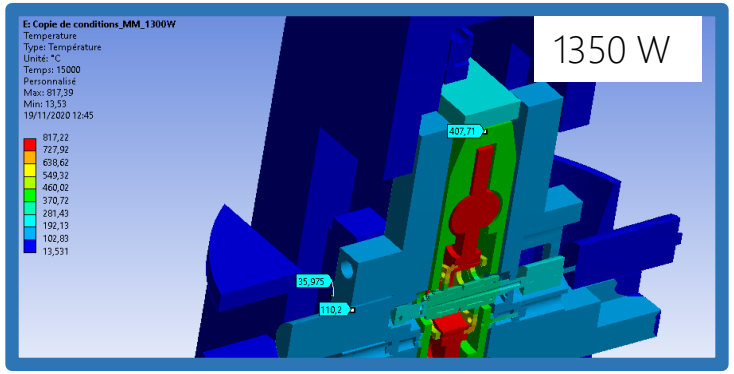
p + Be (0.5 mm) : 32%

p + Be (thick) E> 10 MeV

NFS 31.9 MeV : $1.81^{E}10$ n/sr/µC







Summary

- 2020 50% Physics 50% Commissioning. Tests required to produce and characterize the neutron beam at the Neutron for Science facility
- 2021 60% Physics 40% Commissioning. Gradual increase in power in the thick Be convertor (200 to 1350 W)
- Continuous transfer between the commissioning phase and operation for users.
  - Training of all technical teams (software, data, control, safety) on operation, interfaces and procedures.
- Permanent collaboration with national and international laboratories for the transfer of experience and knowledge.
- SPIRAL commissioning validation with international experts in 2 reviews in 2015 and 2021.
- Developments for machine operation and control improvements.
- SPIRAL2 posters presented at this conference:
  - MOPOPA015, *3 Years of Operation of the SPIRAL2 LINAC* – RF feedback, M. Di Giacomo et al.
  - MOPORI11, *Seismic Analysis Safety requirements for the Spiral2 Accelerator, C. Barthe-Dejean et al.*
  - TUPOGE002, *3 Years of Operation of the SPIRAL2 LINAC – Cryogenics SC RF feedback,* P-E. Bernaudin et al.
  - TUPOGE003, *Advanced Cryogenic Process Control of the SPIRAL2 Superconducting LINAC*, Adnan Ghribi et al.
  - THPOPA13, *Superconducting Cavity and RF Control loop model for the SPIRAL2 LINAC*, F. Bouly et al.

Conclusion

- ✓The SPIRAL2 facility was commissioned successfully.
- ✓The four planed phases were completed in time led to start the operation for users.
- ✓The beam power ramp-up with H^+ and D^+ demonstrate the reliability of the linac.
- ✓Beam physics started already in 2021.

Future perspectives

- Heavy ions required for S3 in 2023
  - Demonstration of cavities fields at their maximum value
    - Individual demonstration already achieved – without beam
  - Machine tunability to be demonstrated @ 14.5 MeV/A
  - S3 Commissioning

- NewGain injector for $A/Q < 7$
  - The new project has already started and reached the construction phase to build a third injector for heavier beams with A/Q up to 7.

Acknowledgements

Thank you for your attention