# Physics at $S^3$: the Low Energy Branch

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GANIL, Caen, France

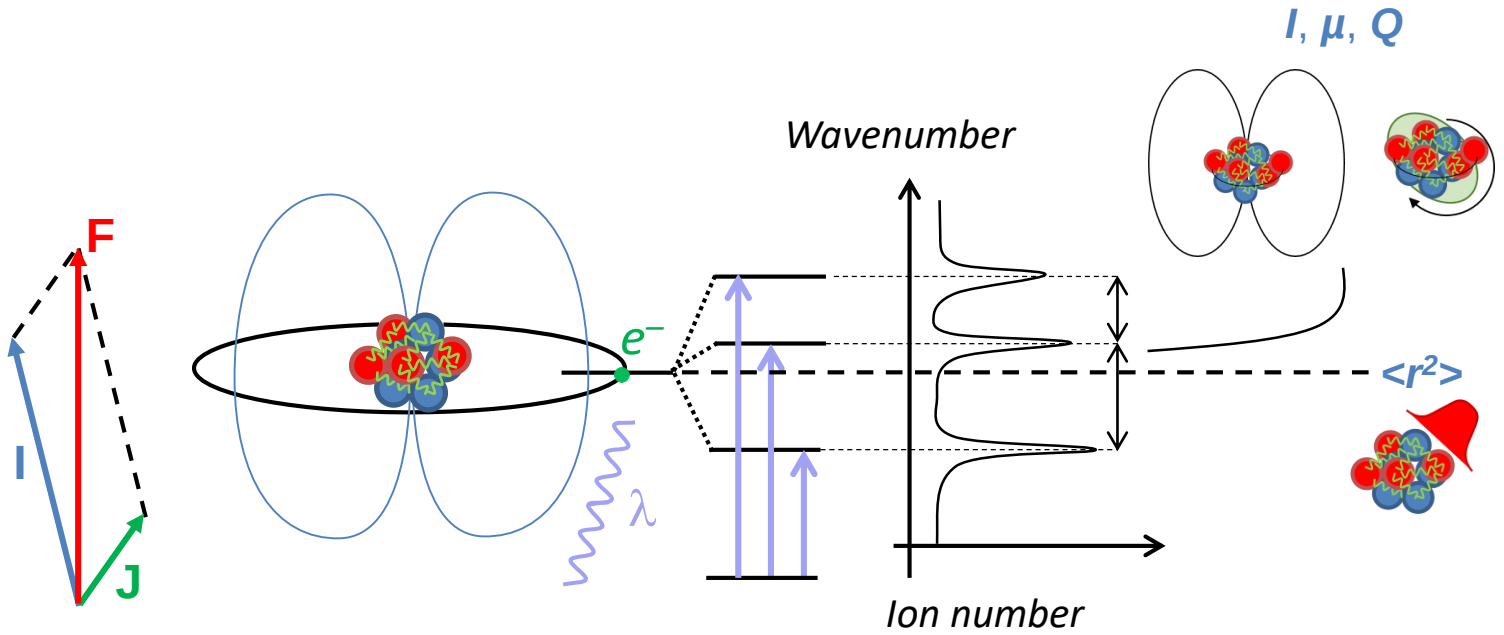
for the $S^3$-LEB collaboration

# Outline

- Laser spectroscopy in a supersonic jet
- $S^3$-LEB, description and physics
- Status and perspectives

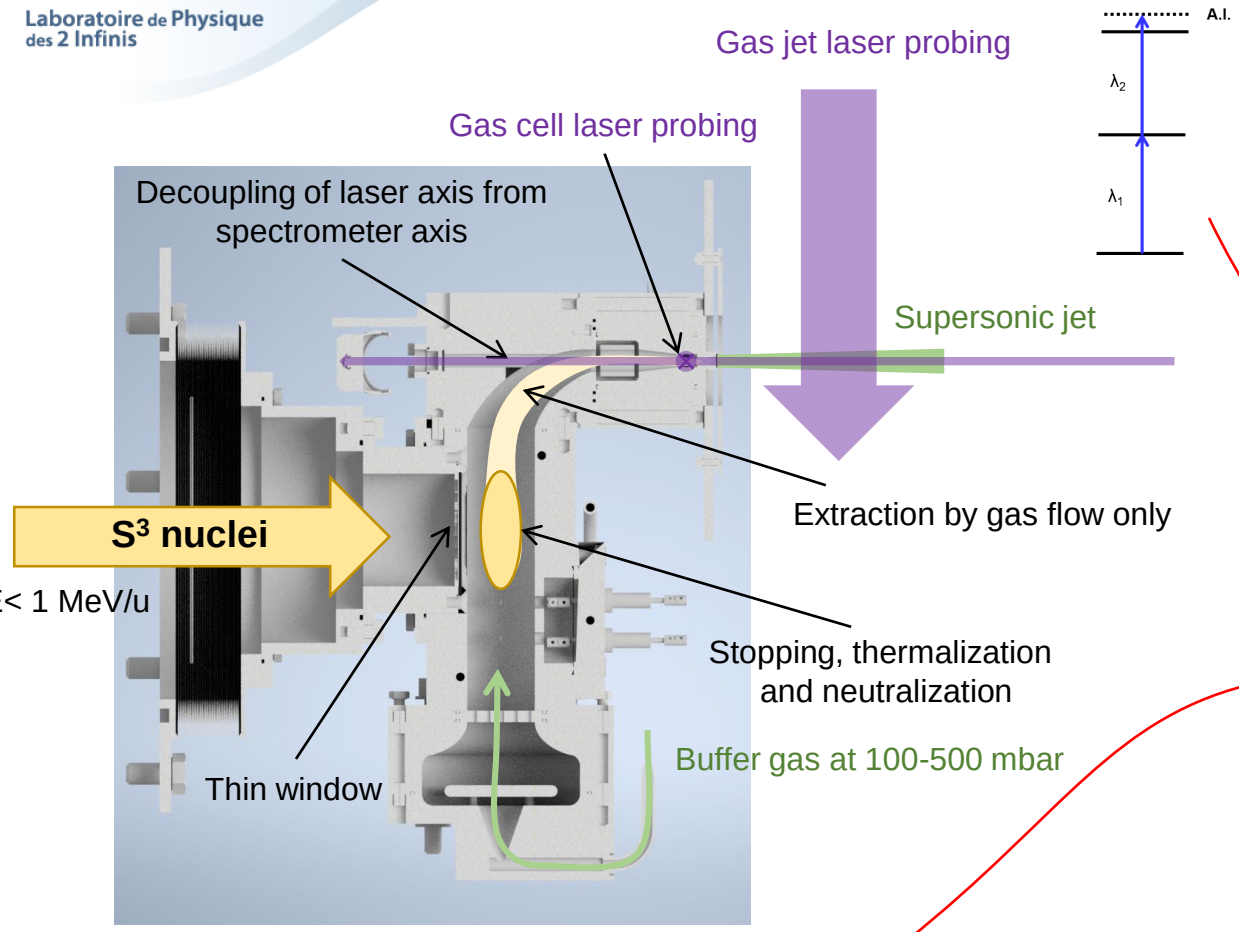
# Laser spectroscopy for nuclear physics

- Exploits the hyperfine interaction to extract nuclear observables




- Key parameters when working with rare isotopes:
  - Resolution
  - Efficiency
  - Sensitivity

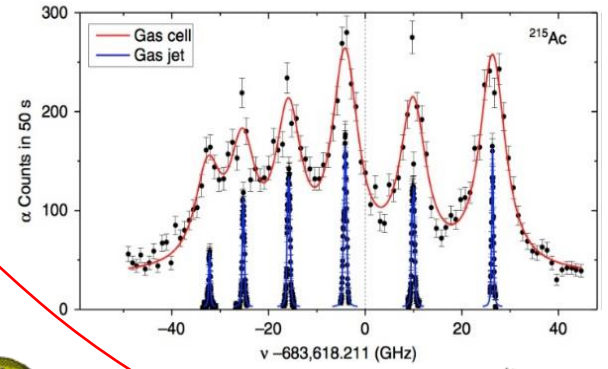
# A gas stopper for fusion-evaporation products

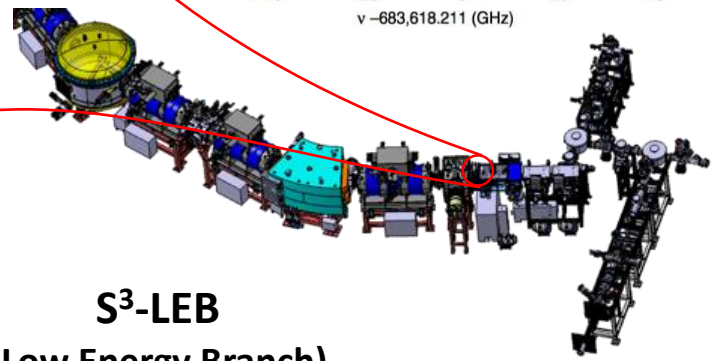






- Critical performance criteria :
  - Chemical survival/neutralization efficiency
  - Stopping efficiency
  - Extraction efficiency and time



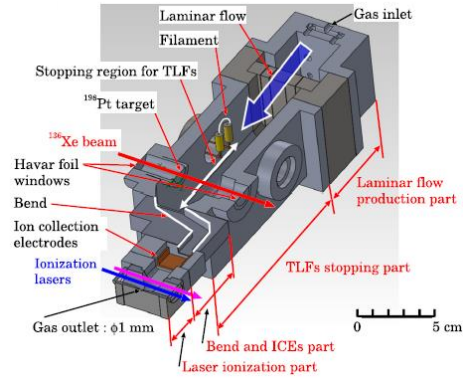



**S³-LEB**
**(Low Energy Branch)**

R. Ferrer, Nature Comm. 8 14520 (2017)

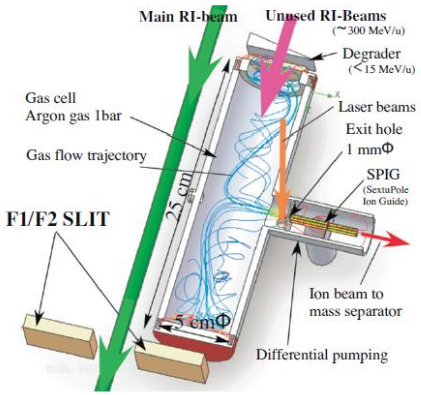
# Gas-cell laser spectroscopy setups

## KISS



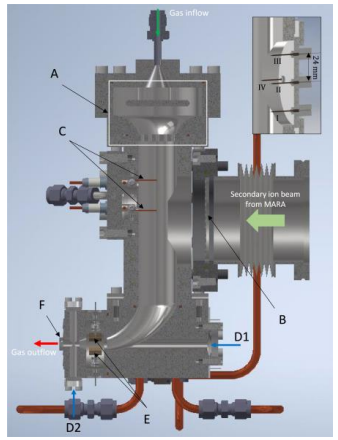

Y. Hirayama et al., NIMB 412, 11–18 (2017)

## PALIS



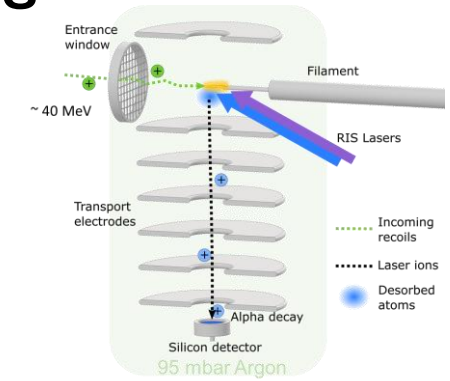

T. Sonoda et al., NIMB 295, 1-10 (2013)

## MARA-LEB



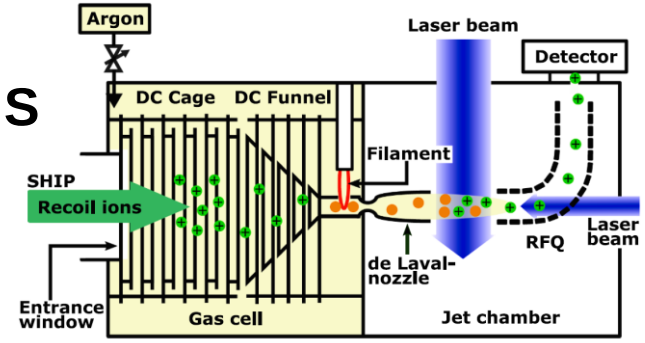

A. Zadvornaya et al., NIM B 539, 33-42 (2023)

## RADRIS



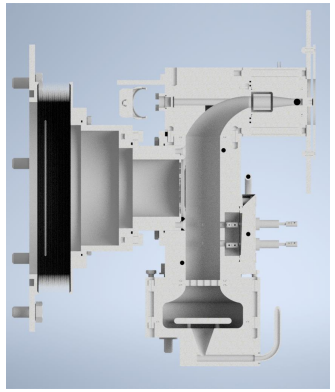

M. Laatiaoui et al., Nature 538, 495–498 (2016)

## JETRIS




S. Raeder et al., NIM B 463, 272-276 (2020)

## S³-LEB



A. Ajayakumar et al., NIMB 539, 102–107 (2023)

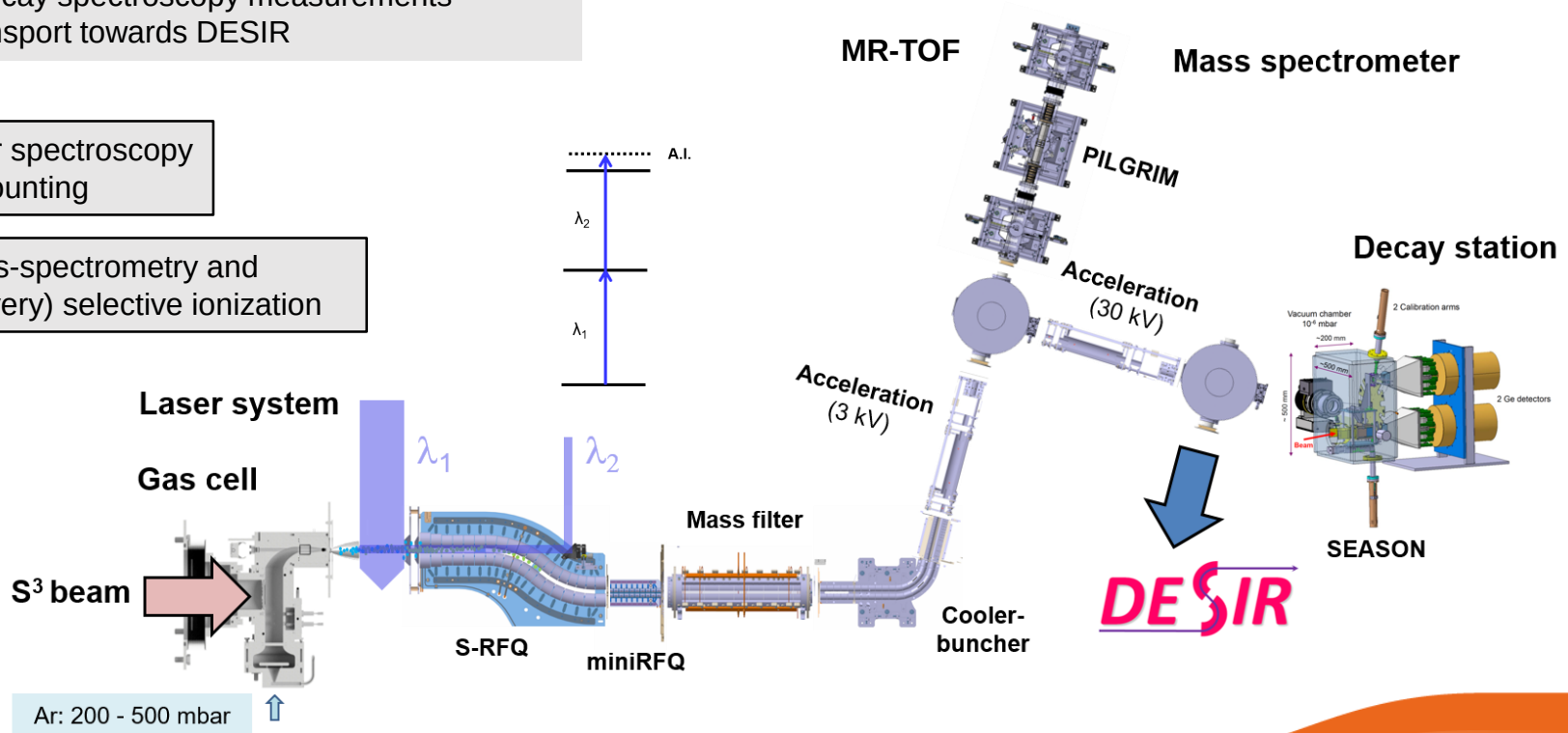
# S³-LEB setup

KU LEUVEN (Gas cell, laser system) · IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis (Gas cell) · LPC Caen (RFQs) · GANIL SPIRAL2 (mr-TOF-ms, laser system infractructure, safety, RFQsdetectors) · LARISSA JGU GUTENBERG UNIVERSITÄT MAINZ · UNIVERSITY OF JYVÄSKYLÄ (narrow band-width laser pre-studies at MARA) · cea (decay station)

- Laser spectroscopy on S³ products in a supersonic jet at intermediate resolution (200 MHz)
- Mass and decay spectroscopy measurements
- Possible transport towards DESIR

⇨ Low (or no)-background laser spectroscopy due to mass/decay-tagged counting

⇨ Low (or no)-background mass-spectrometry and decay spectroscopy due to (very) selective ionization





R. Ferrer et al., Nucl. Instr. Meth. B 317, 570-581 (2013)
J. Romans, et al., Atoms 10, 21 (2022)
A. Ajayakumar et al., NIMB 539, 102-107 (2023)

# The S$^3$-LEB collaboration

**GANIL:**

Anjali Ajayakumar; Dieter Ackermann; Lucia Caceres; Samuel Damoy; Pierre Delahaye; Patrice Gangnant; Nathalie Lecesne; Thierry Lefrou; Renan Leroy; Franck Lutton; Alejandro Ortiz; Benoit Osmond; Julien Piot; Blaise-Maël Retailleau; Hervé Savajols; Gilles Sénécal

**LPC:**

Frédéric Boumard; Jean-François Cam; Philippe Desrues; Xavier Fléchard; Julien Lory ; Yvan Merrer ; Christophe Vandamme

**IJCLab:**

Wenling Dong; Patricia Duchesne; Serge Franchoo; Vladimir Manea; Olivier Pochon

**KU Leuven:**

Arno Claessens; Rafael Ferrer; Mark Huyse; Fedor Ivandikov; Sandro Kraemer ; Yuri Kudriavtsev; Jekabs Romans; Simon Sels; Paul Van den Bergh; Piet Van Duppen; Matthias Verlinde ; Elise Verstraelen

**JGU:**

Sebastian Raeder; Dominik Studer; Klaus Wendt

**JYU:**

Ruben de Groote; Iain David Moore; Michael Reponen; Juha Uusitalo

**IPHC:**

Emil Traykov

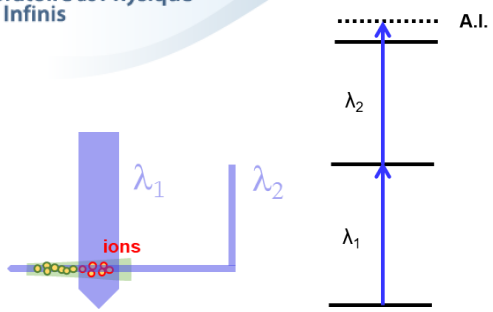
**IRFU:**

Martial Authier; Olivier Cloue; Antoine Drouard; Thomas Goigoux; Emmanuel Rey-Herme; Damien Thisse; Marine Vandebrouck

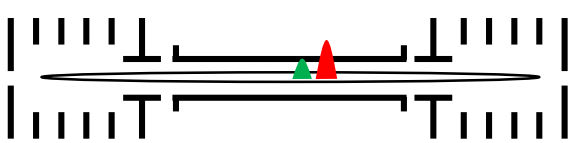
**and the RESIST network in ENSAR2**

# S³-LEB scientific program

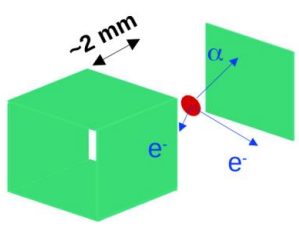
- Call for pre-proposals in 2018
- 9 pre-proposals, in total 267 UTs (3 months)
- Scientific program maintained at *Wokshop on Physics with SPIRAL2 heavy-ion beams* (2022)




Laser spectroscopy



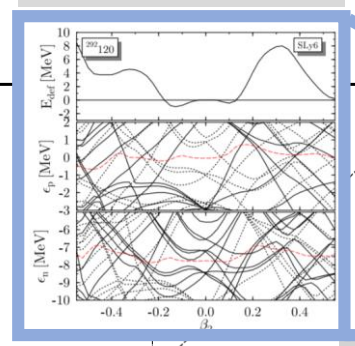
Ion-trap mass spectrometry



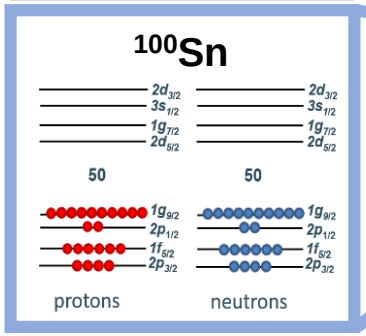

Decay spectroscopy

**Other physics cases possible**

**Very heavy nuclei**

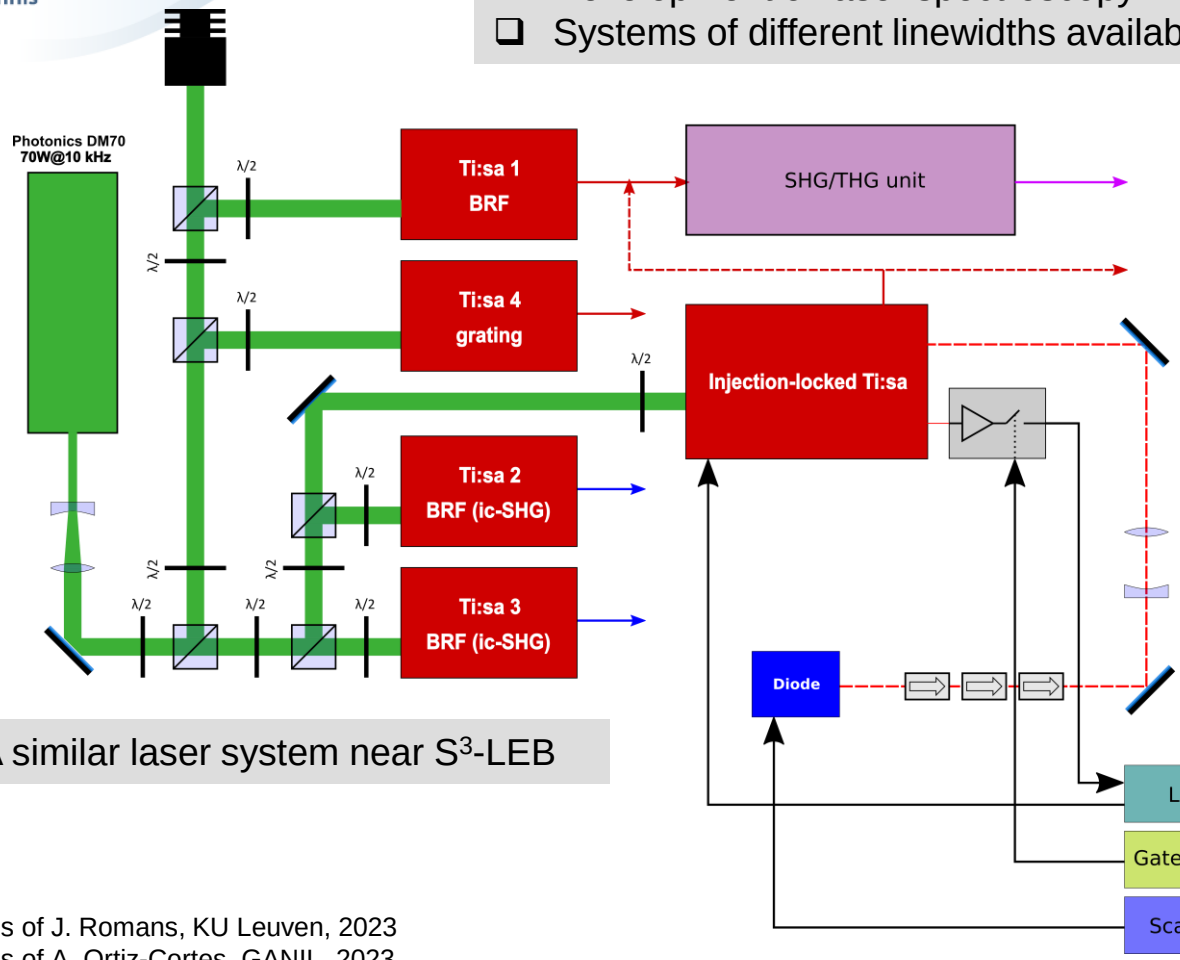


**N = Z nuclei**

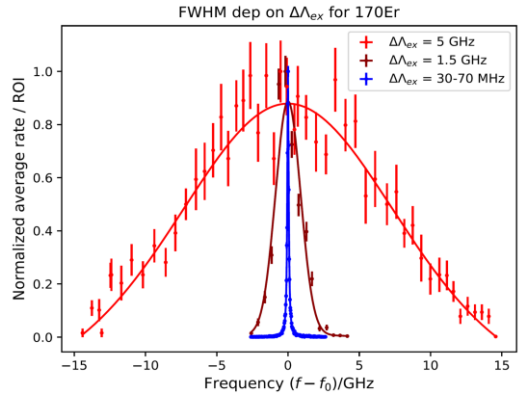


# S³-LEB status: GISELE laser lab

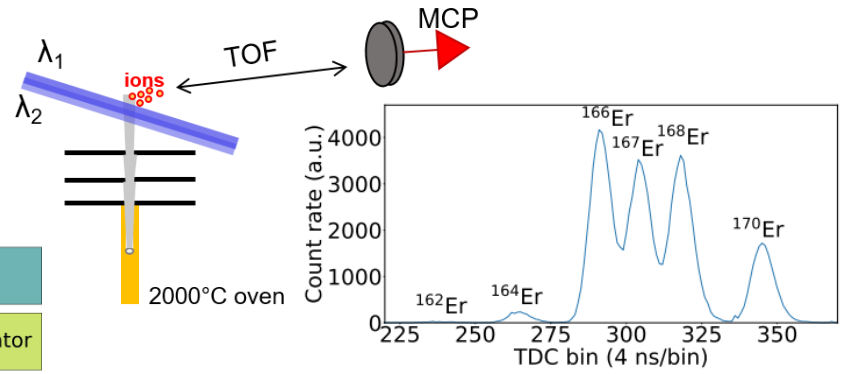
- Development of laser spectroscopy methods
- Systems of different linewidths available




- A similar laser system near S³-LEB



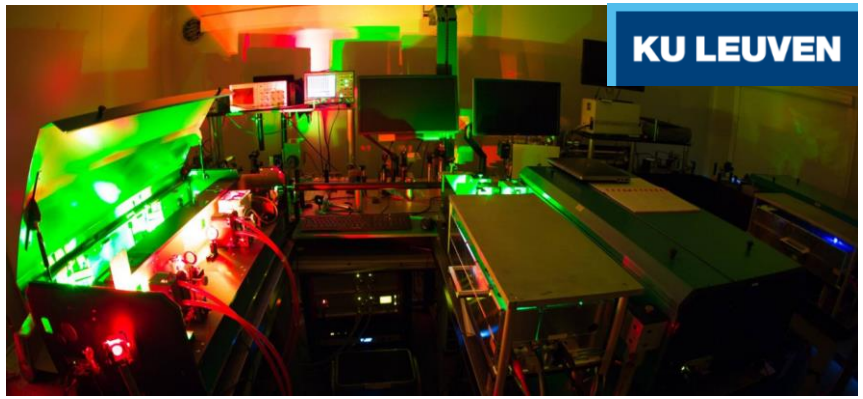

- Atomic beam unit for laser scheme development (Er, Sn, Pd)



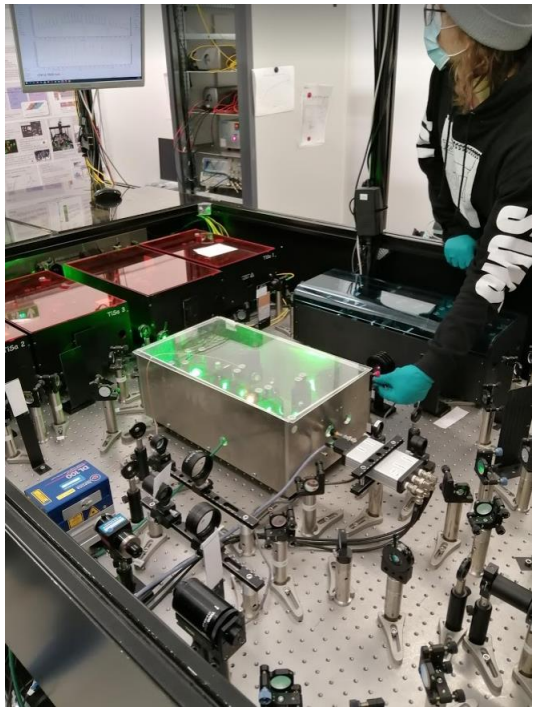

PhD thesis of J. Romans, KU Leuven, 2023
PhD thesis of A. Ortiz-Cortes, GANIL, 2023

# S$^3$-LEB status: laser system

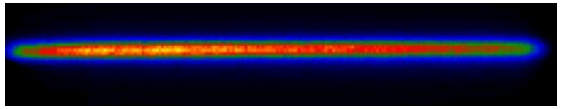
- Dye laser system in development and use at KU Leuven



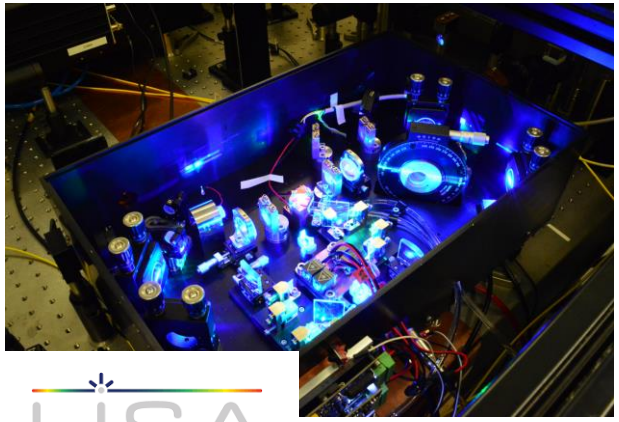

- GISELE Ti:Sa laser lab @ GANIL



A. Zadvornaya et al., PRX 8 (2018) 041008

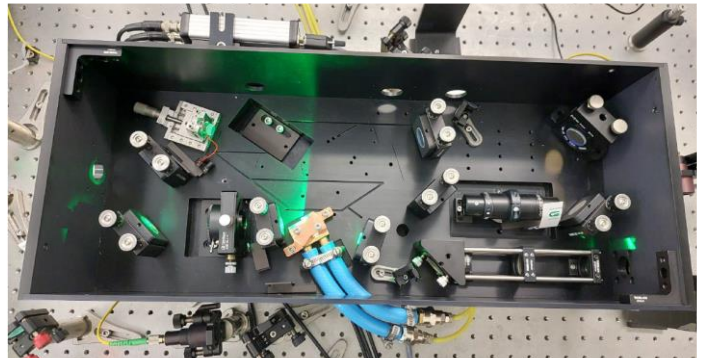


- New continuous wave Ti:sa laser in collaboration with Uni. Nagoya (V. Sonnenschein et al.)



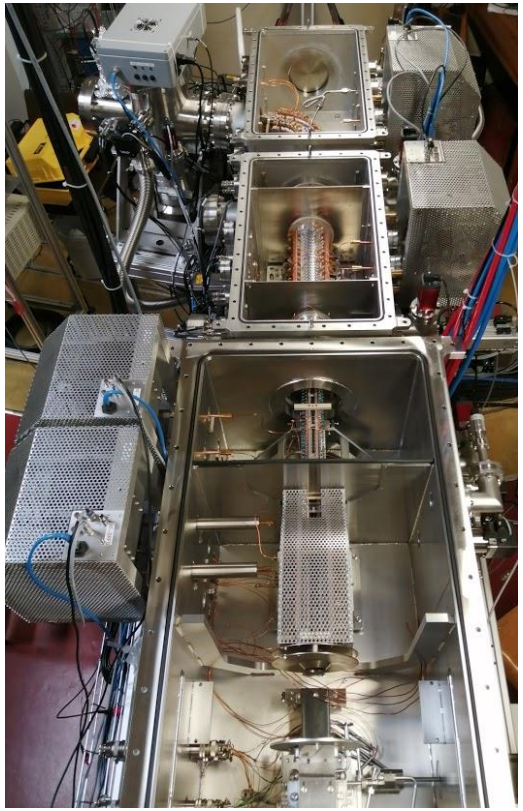
LISA
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

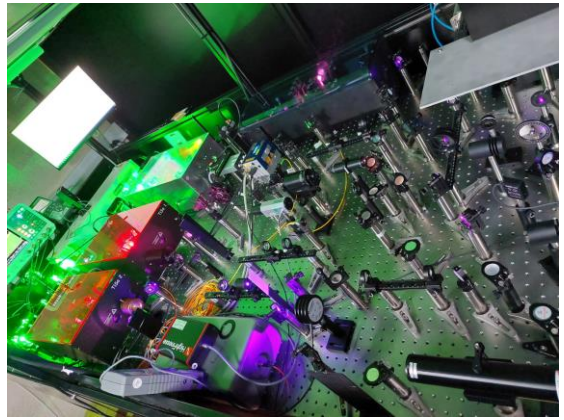
- New injection-locked Ti:sa cavity in collaboration with JGU Mainz (Dominik Studer et al.)



# S$^3$-LEB status: off-line commissioning

- Installation finished 2021 at LPC Caen: gas cell, RFQs and mass spectrometer





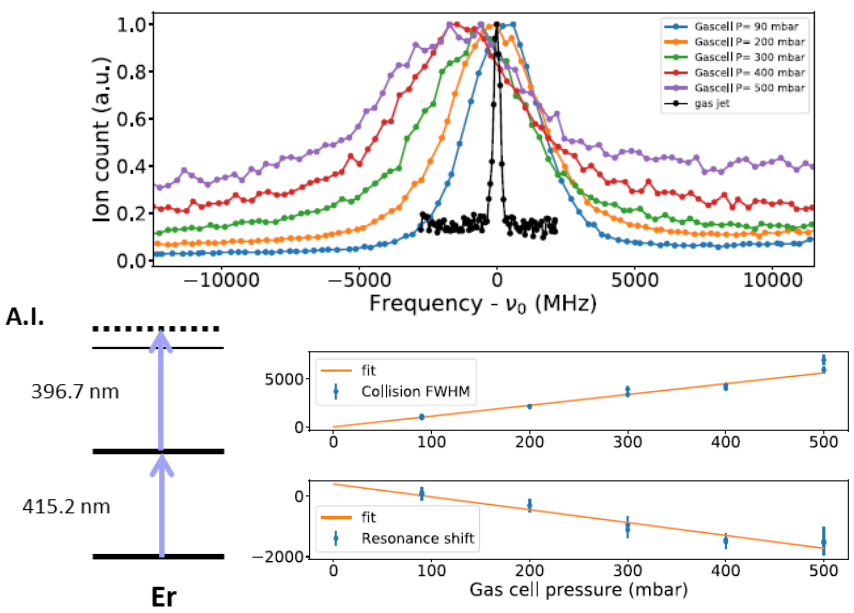
- SEASON developped in parallel at CEA-Saclay



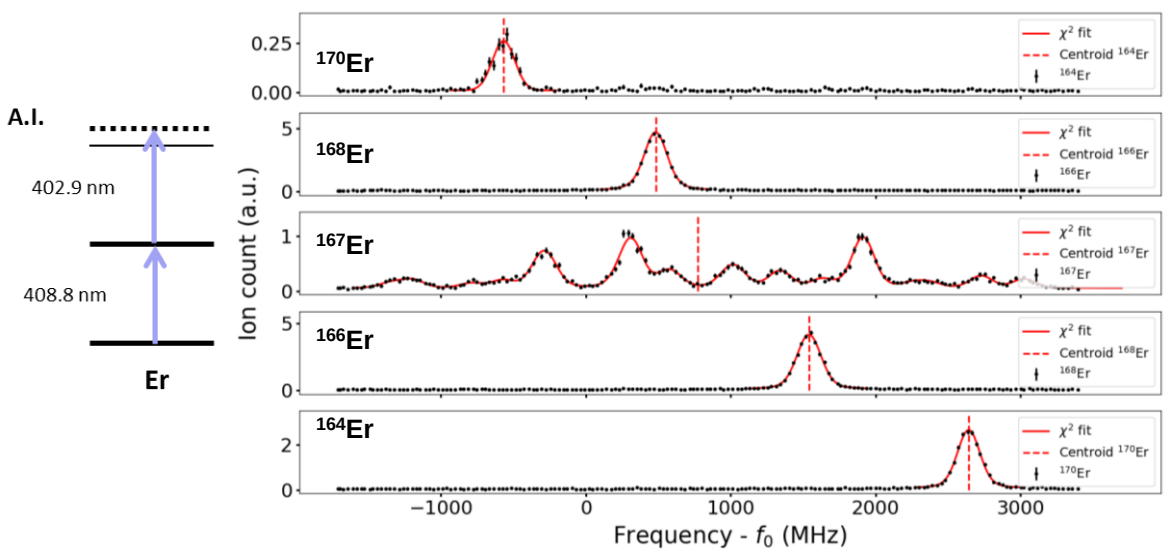

# S³-LEB status: off-line commissioning

- 2022-2023: in-gas-cell and in-gas-jet laser spectroscopy with stable erbium isotopes
- Optimization of laser resolution and transport efficiency

## Gas cell laser spectroscopy: pressure shift and broadening




## Gas jet laser spectroscopy



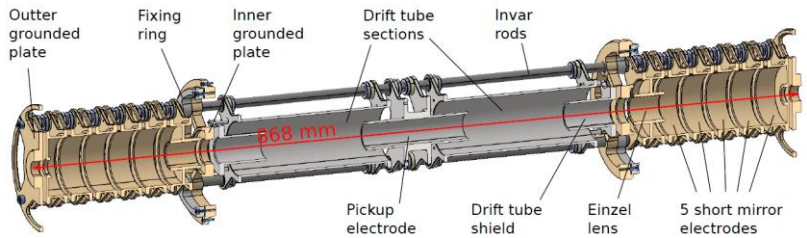

J. Romans, et al., Atoms 10, 21 (2022)
A. Ajayakumar et al., NIMB 539, 102-107 (2023)

PhD thesis Anjali Ajayakumar, GANIL
PhD thesis Wenling Dong, IJCLab

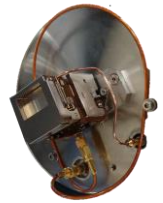
# S³-LEB status: PILGRIM

- Multi-reflection time-of-flight mass spectrometer designed in collaboration with Uni. Greifswald

3-keV beam from S³-LEB cooler-buncher



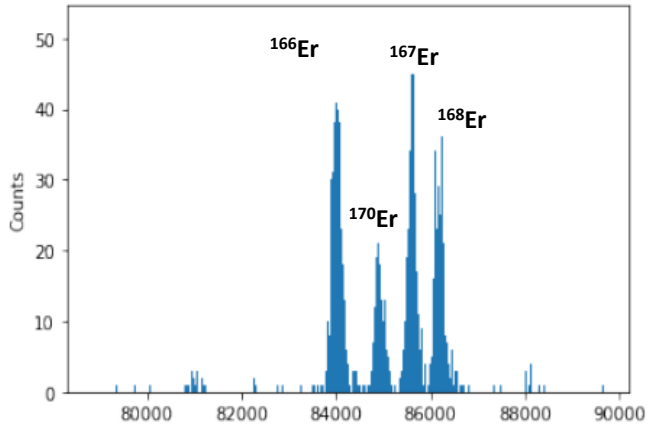

MagneTOF



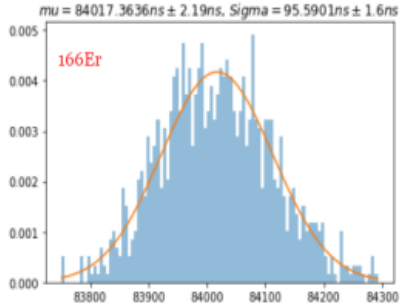
Pierre Chauveau et al., Nucl. Instrum. Meth. B **376**, 211-215 (2016)

- Mass separation and measurements tested with bunches from the S³-LEB cooler-buncher
- Resolving power ≈ 100 000
- Mass accuracy tested on a few cases to a few ≈ $10^{-7}$

$^{170}$Er at 1000 turns (other isotopes on different numbers of turns)




TOF – acquisition offset (ns)




TOF – acquisition offset (ns)

PhD thesis Pierre Chauveau, GANIL
PhD thesis Blaise-Maël Retailleau, GANIL
Master thesis Yazeed Balasmeh, LPC

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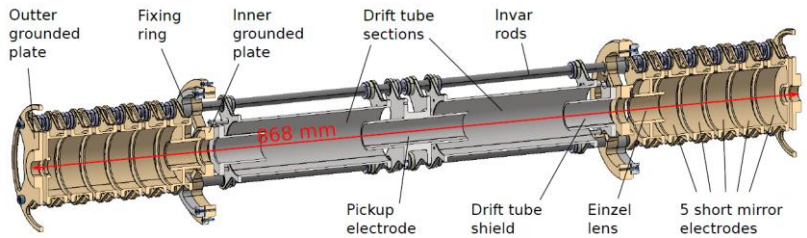
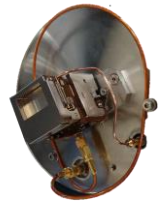



MagneTOF



Pierre Chauveau et al., Nucl. Instrum. Meth. B **376**, 211-215 (2016)

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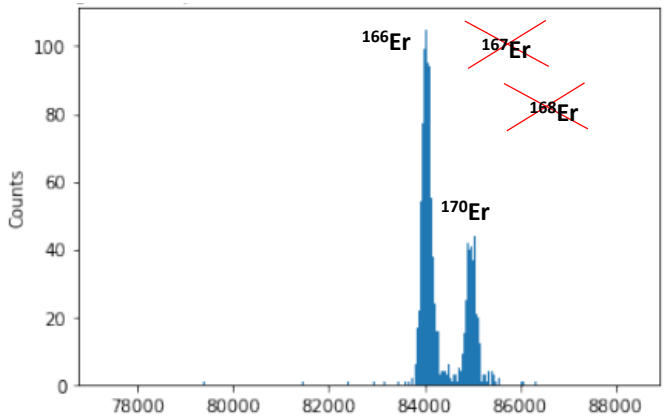
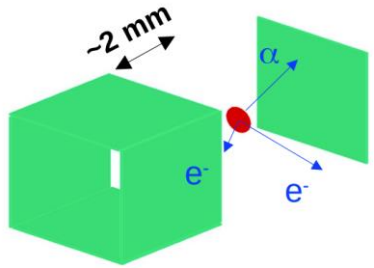


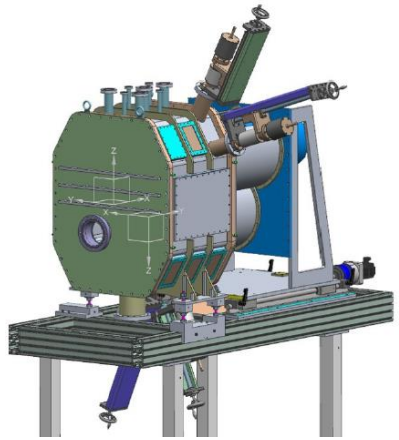

- Remove contaminants at lower number of revolutions than ejection of ion of interest.

PhD thesis Pierre Chauveau, GANIL
PhD thesis Blaise-Maël Retailleau, GANIL
Master thesis Yazeed Balasmeh, LPC

# S³-LEB status: SEASON

Marine Vandebrouck, Thomas Goigoux, Emmanuel Rey-Herme, Damien Thisse et al.

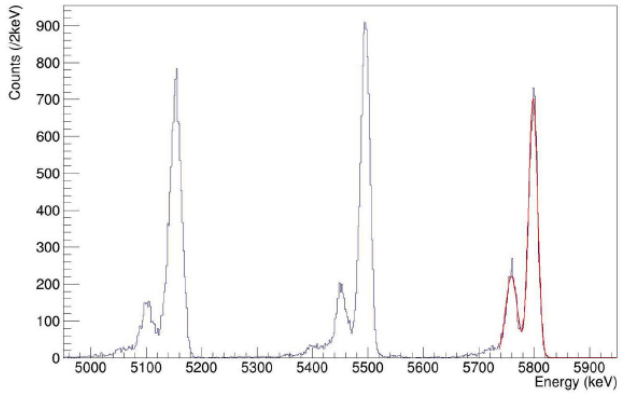


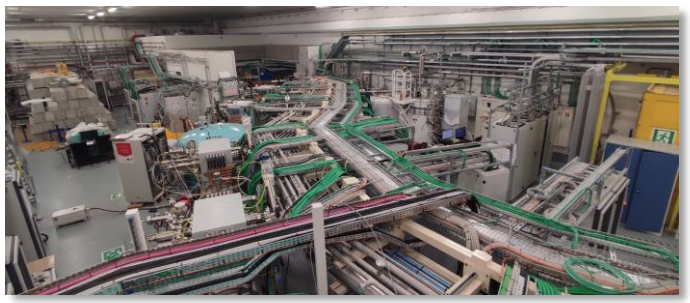
- Developed at CEA Saclay
- « Windmill » of implantation foils
- Silicon box detector (DSSSD) for alphas and electrons
- Germanium detectors

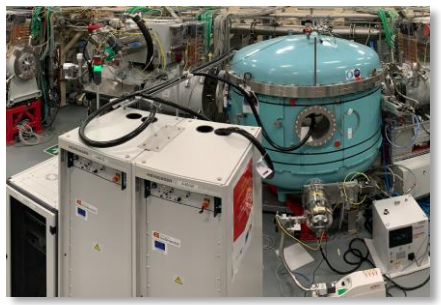
- Mechanical design finished, construction imminent
- First DSSSD tested, target resolution achieved with radioactive sources:
  - 17.2 keV FWHM for alpha at 5.8 MeV
  - 10.2 keV FWHM for electrons at 320 keV

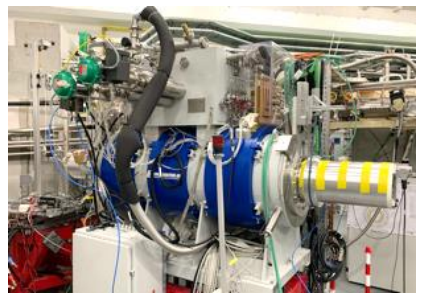
3-α calibration source ($^{239}$Pu, $^{241}$Am, $^{244}$Cm)



# Perspectives





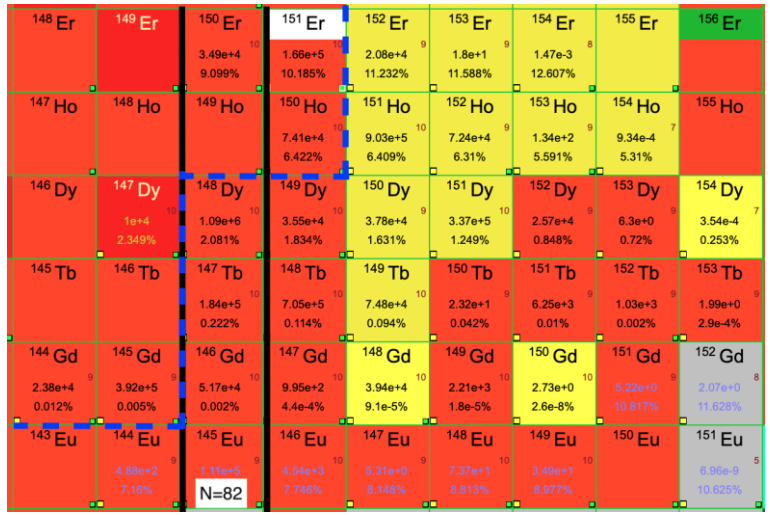


- 2024: $S^3$-LEB will be installed at the focal plane of $S^3$

- Mid-2025: Physics commissioning of $S^3$ with the reaction $^{116}Sn(^{40}Ar – 180\ MeV, 4n)^{152}Er$:
  - Opportunity to study the single-particle states and high-spin isomers around the *N* = 82 shell closure

- In 2026:
  - Production of actinium by asymmetric reactions ($^{40}Ar + {}^{175}Lu$ and $^{20}Ne + {}^{197}Au$)
  - Production of N = Z nuclei ($^{50}Cr + {}^{58}Ni$)

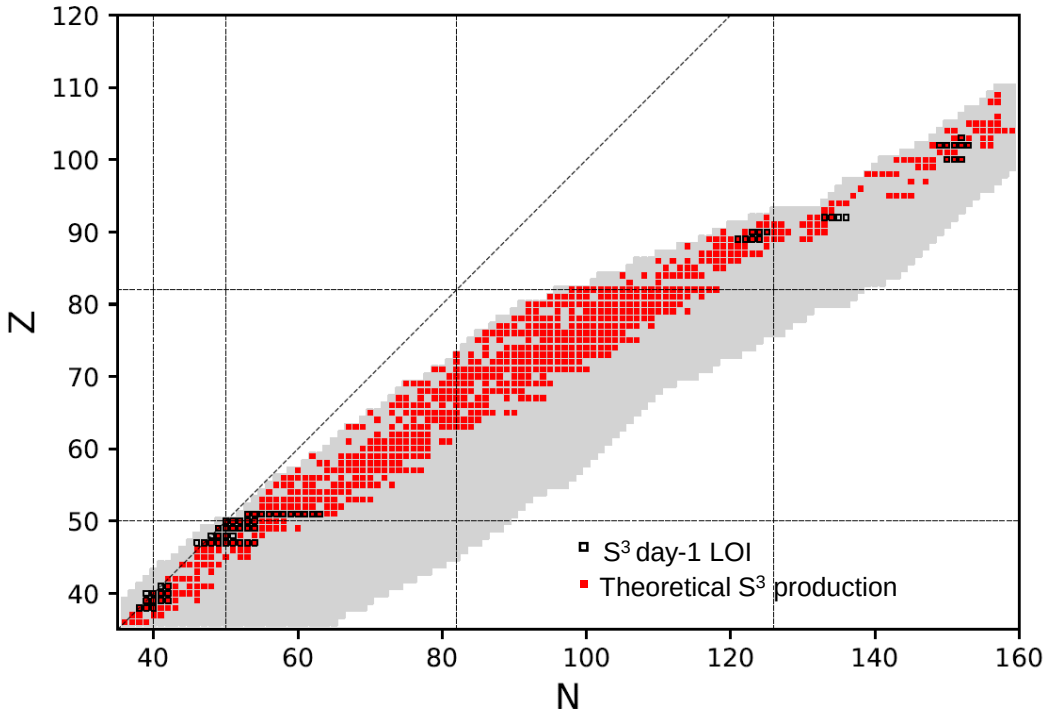
- Scientific program following




*LISE++ simulation (courtesy Hervé Savajols)*

# Conclusions

- $S^3$ and its LEB bring new avenues for low-energy experiments with neutron-deficient isotopes across the nuclear chart
- The experiment is a rich laboratory grouping diverse technologies in lasers, ion traps and detection systems
- Continuous development of gas stoppers, laser spectroscopy and ion manipulation technologies




- Many opportunities (and different ways) to collaborate