Status of the FAMU experiment

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for the FAMU Collaboration

PSAS'2024 - International Conference on Precision Physics of Simple Atomic Systems
Zurich, June 2024

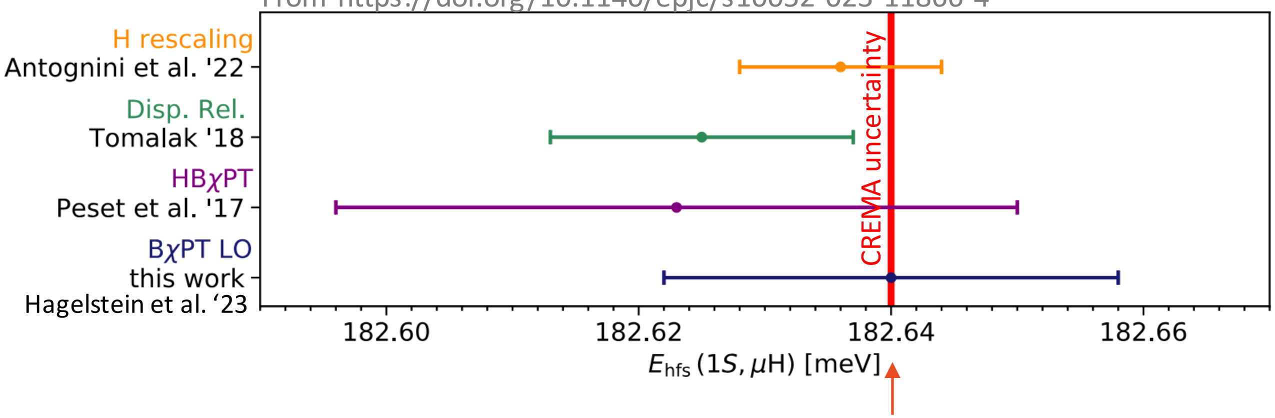
FAMU aims

Measure the Hyperfine splitting (HFS) of muonic hydrogen ground level

→ the Zemach radius of the proton

Theoretical prediction of the HFS energy for muonic hydrogen

From https://doi.org/10.1140/epjc/s10052-023-11866-4



FAMU expected uncertainty in the same order of magnitude

FAMU started the frequency scan in 2023 and will continue in 2024 and 2025

FAMU = Fisica degli Atomi MUonici

≈40 researcher
13 institutions

INFN
Istituto Nazionale di Fisica Nucleare

RIKEN Nishina Center
"The RIKEN-RAL Muon Facility"
(International Research Collaboration between RIKEN and SFTC (Science and Technology Facility Council) in the UK)

INRNE

ALMA MATER STUDIORUM A.D. 1088
UNIVERSITÀ DI BOLOGNA

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Science & Technology Facilities Council
ISIS Neutron and Muon Source

Elettra Sincrotrone Trieste

ROMA TRE UNIVERSITÀ DEGLI STUDI

CNR IFN Istituto di Fotonica e Nanotecnologie

SPIE.

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

ICTP The Abdus Salam International Centre for Theoretical Physics

CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

DALIAN INSTITUTE OF CHEMICAL PHYSICS, CHINESE ACADEMY OF SCIENCES

Università degli Studi della Campania *Luigi Vanvitelli*

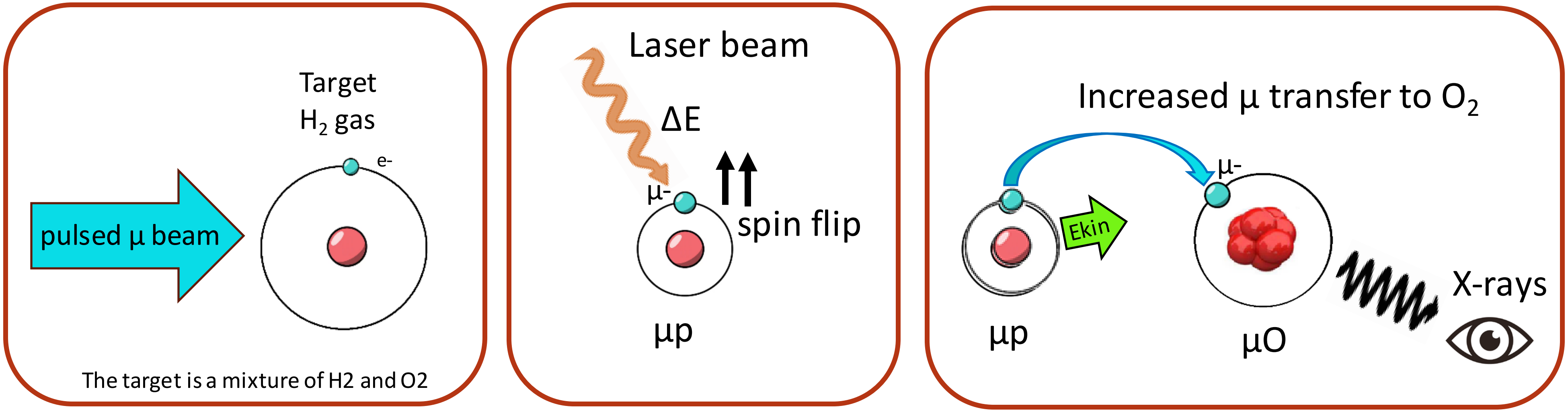
POLITECNICO MILANO 1863

The Henryk Niewodniczański INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

BULGARIAN ACADEMY OF SCIENCE 1869

UNIVERSITÀ DI PAVIA

FAMU method and workflow



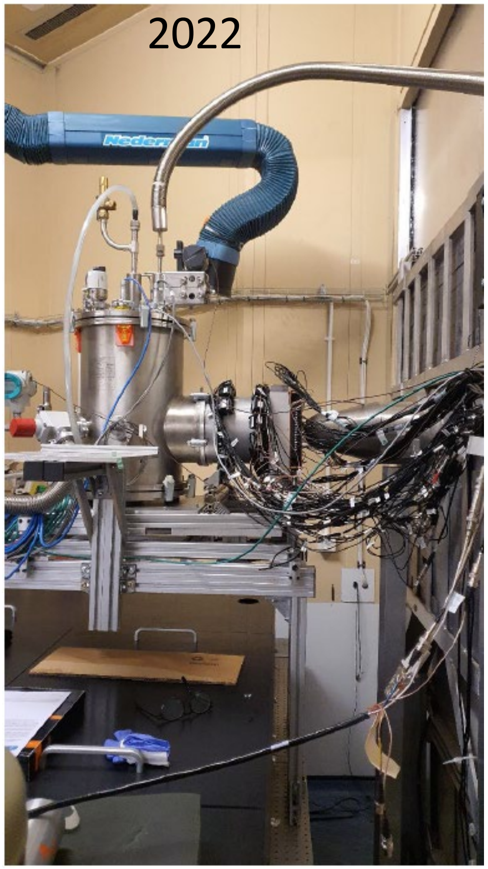
- Create muonic hydrogen and wait for its thermalization;
- Shoot laser at the hyperfine splitting energy (λ_0 ~6.8μm)
  and change spin state of $\mu^- p$ from 1^1S_0 to 1^3S_1,
  spin is flipped: $\mu^- p(\uparrow\downarrow) \rightarrow \mu^- p(\uparrow\uparrow)$;
- De-excitation and acceleration of $\mu^- p$ (~120 meV)
- If $\mu^- p$ are accelerated, the μ^- transfer to Oxygen increases (O2 has an energy-dependent rate);
- The hyperfine splitting energy is determined by varying the wavelength of the laser beam and search the maximum number of oxygen X-rays

Temperature dependence of the μ transfer to Oxygen
https://doi.org/10.1016/j.physleta.2021.127401
https://doi.org/10.1016/j.physleta.2020.126667

FAMU Characteristics

- high intensity pulsed muon beam
- proper gas mixture H+O
- optical cavity
- high energy and fine-tunable laser
- fast and accurate X-rays detectors

2022

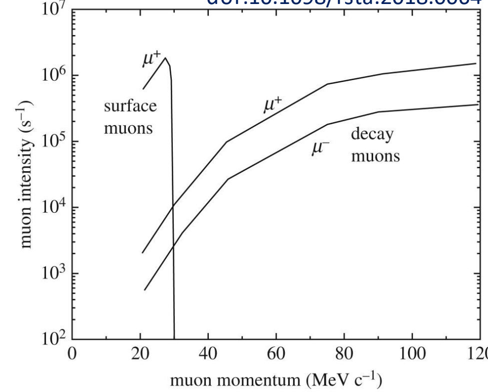


FAMU Setup in PORT1 at RIKEN-RAL

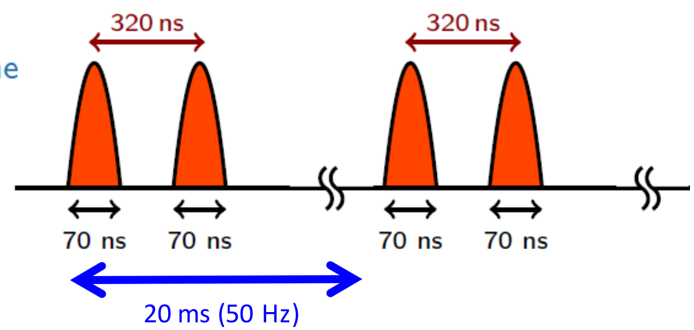
Where: Rutherford Appleton Laboratory - UK

The brightest pulsed muon beam facility in the world!

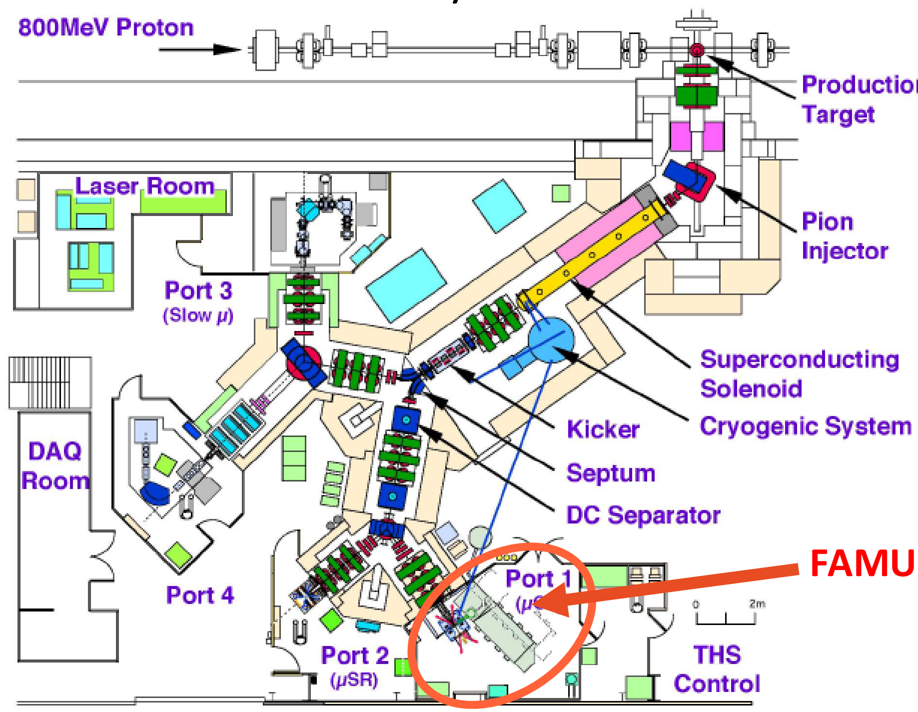
doi:10.1098/rsta.2018.0064



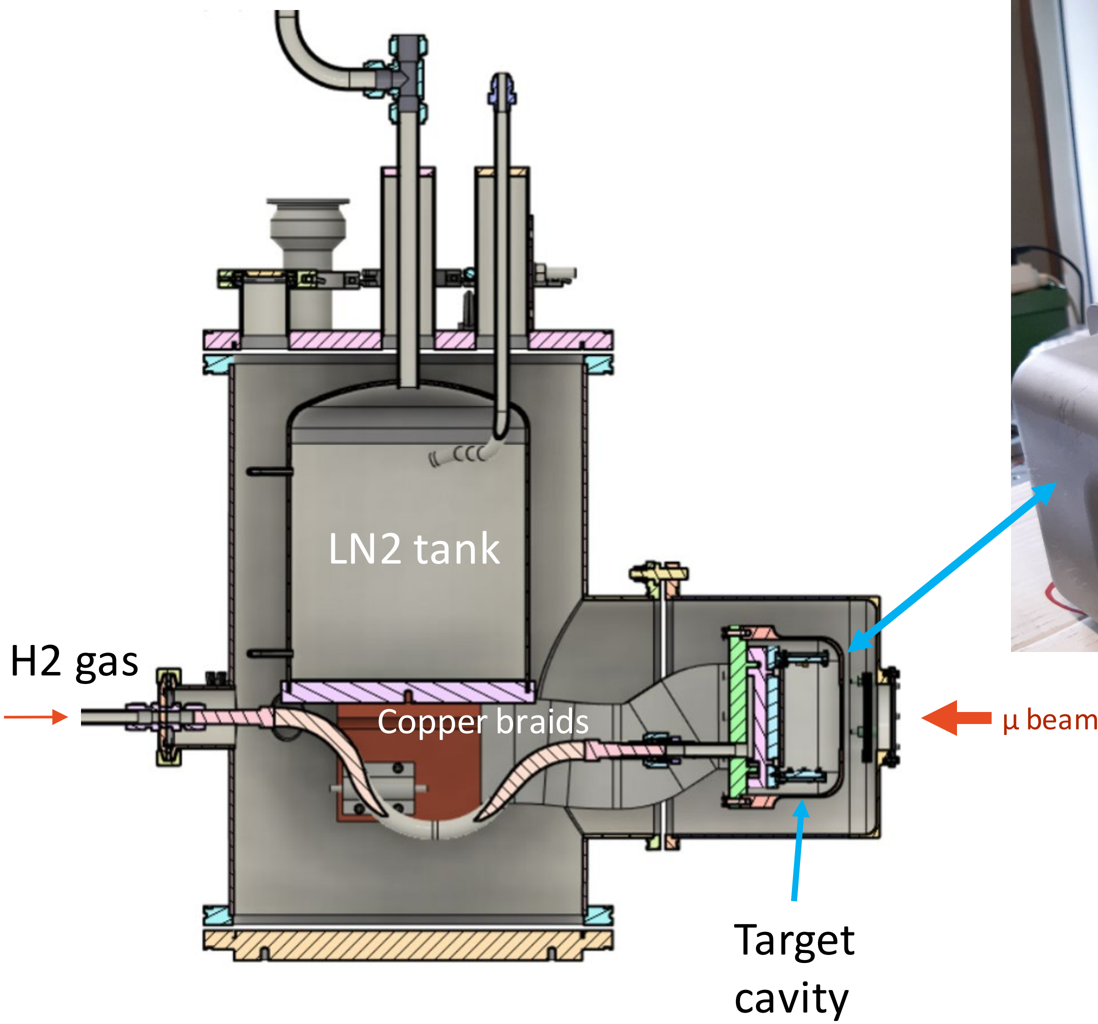
Beam time structure



Riken RAL Muon Facility:

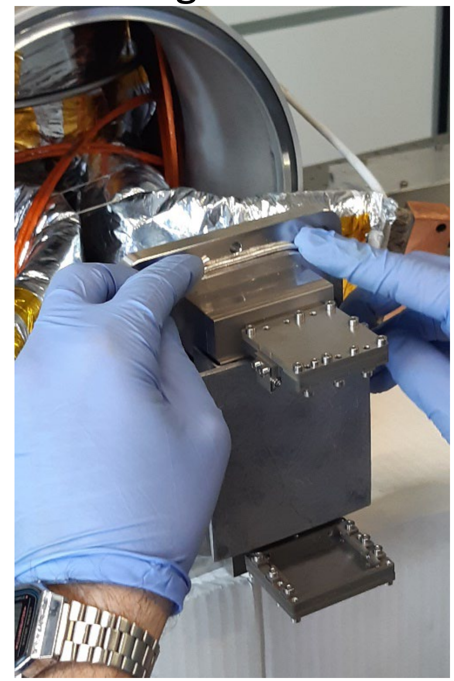


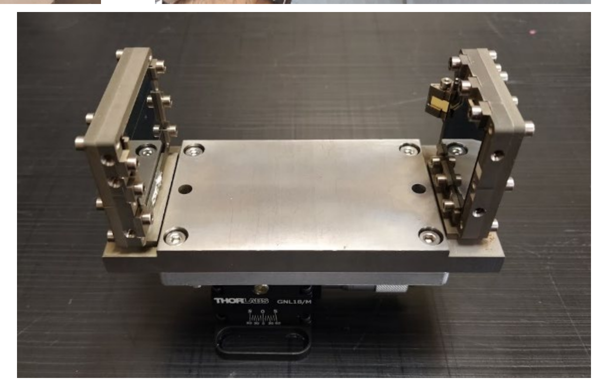
Cyogenic target and optical cavity



Target

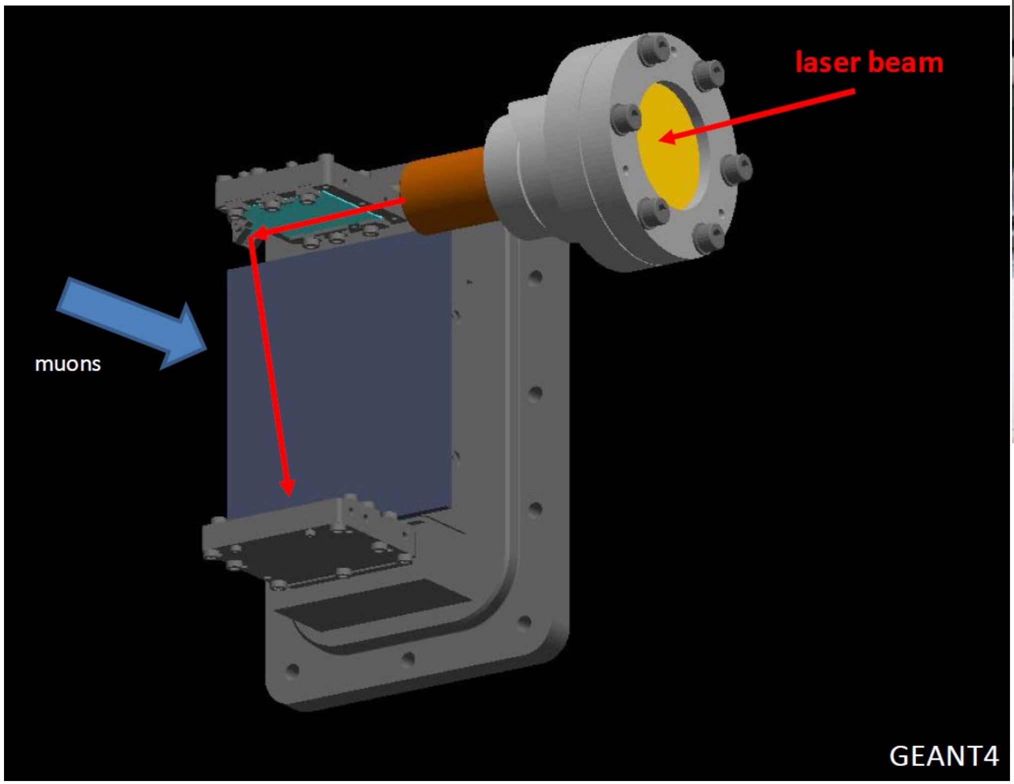
Cavity before inserting the mirrors





Gas mixture of Hydrogen and 1.5% Oxygen at ~80 K

Cyogenic target and optical cavity



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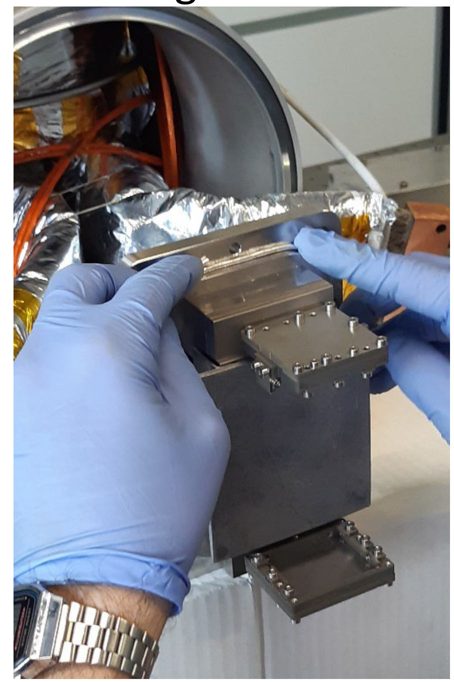
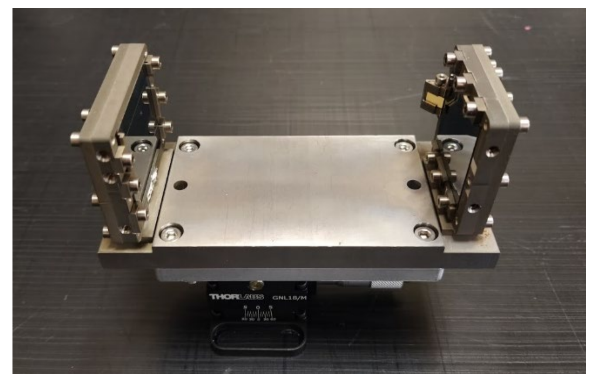
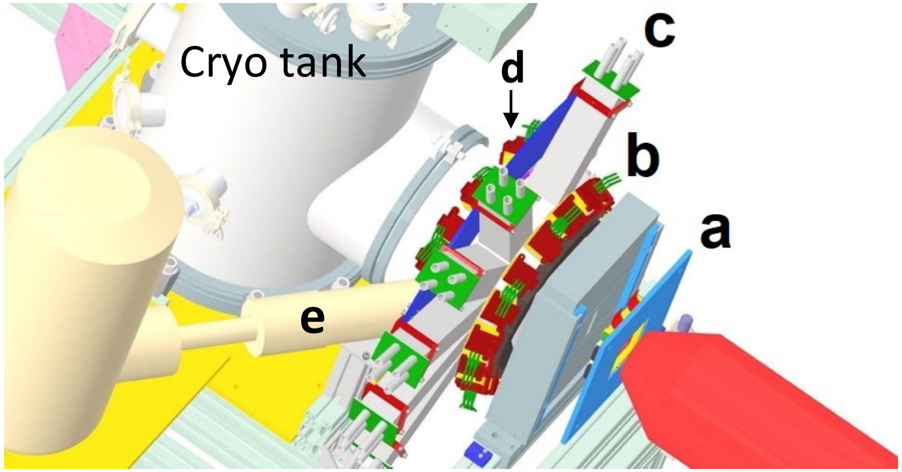




Gas mixture of Hydrogen and 1.5% Oxygen at ~80 K

Detectors



2023 DETECTOR SETUP

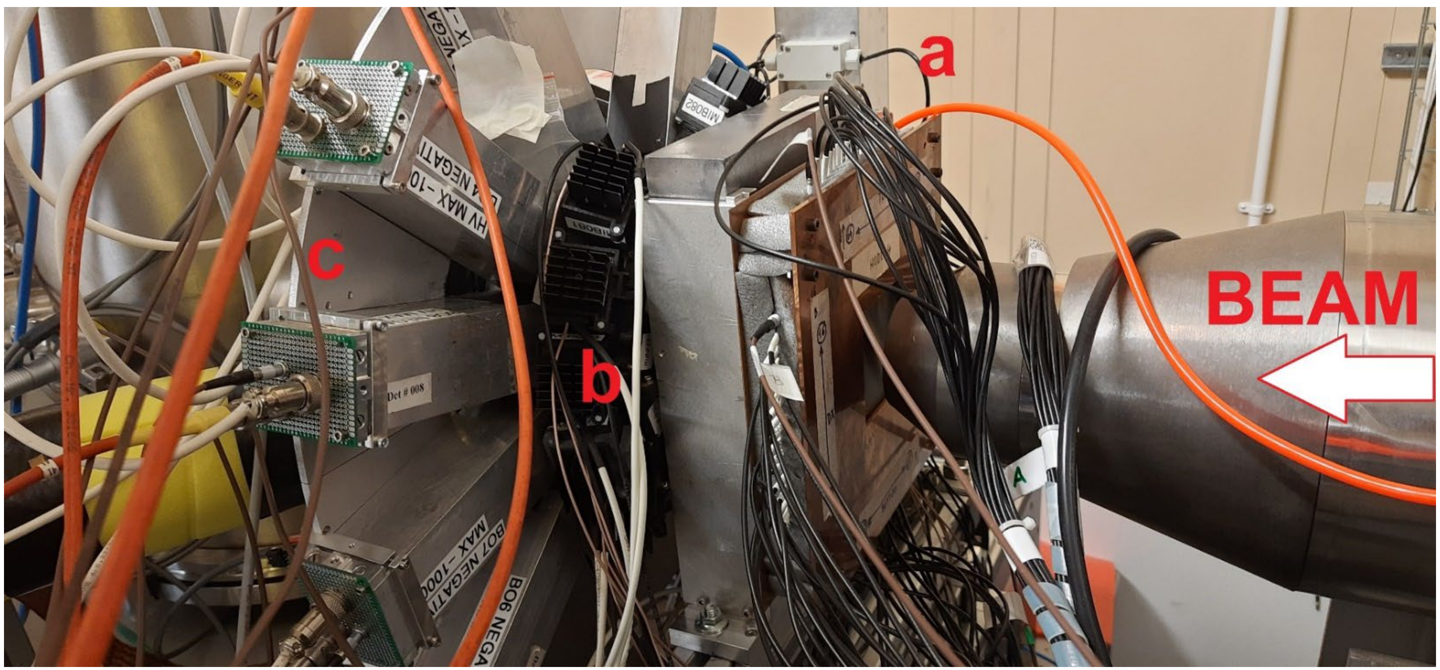
(a) the **beam hodoscope**, 1mm fibers

(b) the upstream ring of 1 inch **LaBr3(Ce) crystals** + SiPM

(c) the central ring with 6 PMT readout prototypes and SiPM

(d) (not visibile here) backstream ring with ½ inch LaBr3(Ce) + SiPM

(e) One HPGe detector for cross calibration



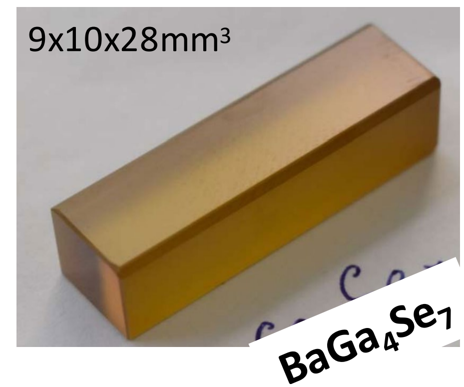
FAMU Laser

Characteristics:

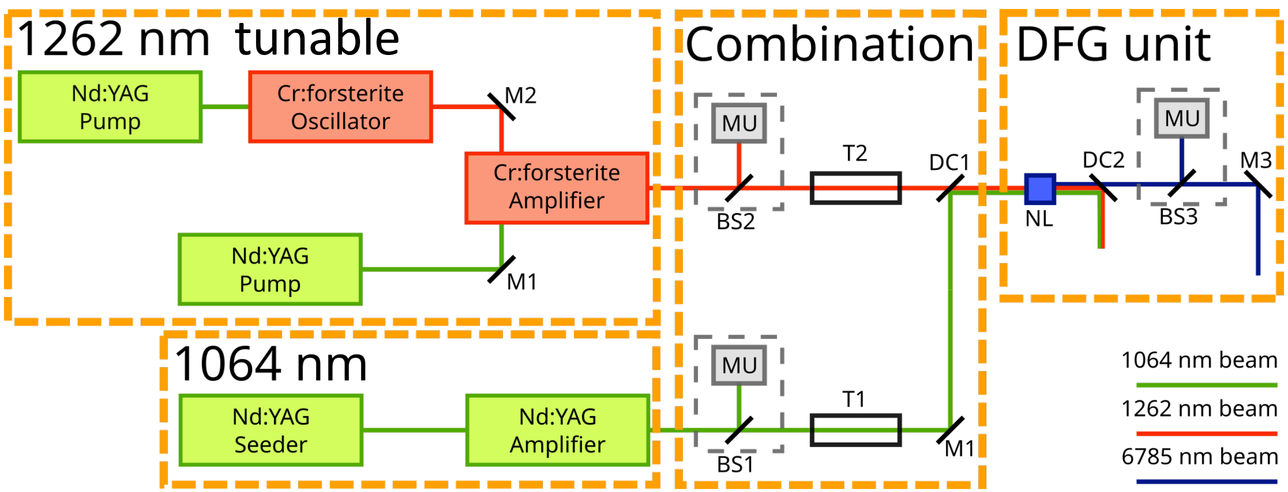
Wavelength range	6800 ± 50 nm
Energy output	> 1 mJ
Linewidth	< 30 pm
Tunability steps	~9 pm
Pulses duration	10 ns
Repetition rate	25 Hz

(Linewidth and tunability steps:) We reached better values than our goal

non linear crystal



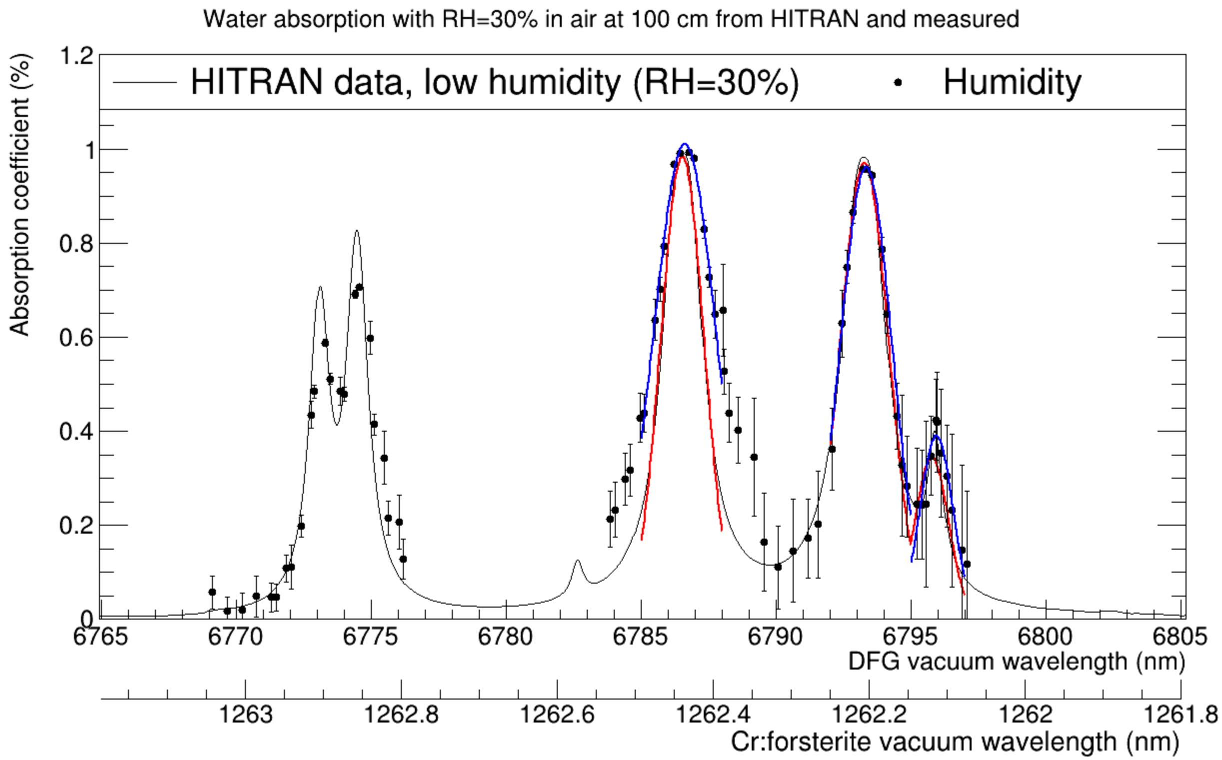
$$\lambda_{DFG}^{-1} = \lambda_1^{-1} - \lambda_2^{-1}$$



M1 - Mirror HR 1064 nm, M2 - Mirror HR 1262 nm, M3 - Mirror HR 1064&1262&6785 nm, M4 - Mirror HR 6785 nm, T1 and T2 - telescopes, BS1 - beamsplitter/beamsampler 1064 nm, BS2 - beamsplitter/beamsampler 1262 nm, BS3 - beamsplitter/beamsampler 6785 nm, DC1 - dichroic mirror (reflecting 1064 nm, transmitting 1262 nm), DC2 - dichroic mirror (reflecting 1064 nm and 1262 nm, transmitting 6785 nm), NL - nonlinear crystal, MU - measuring units (wavelenght meter, energy meter, dimensions)

Laser absolute calibration

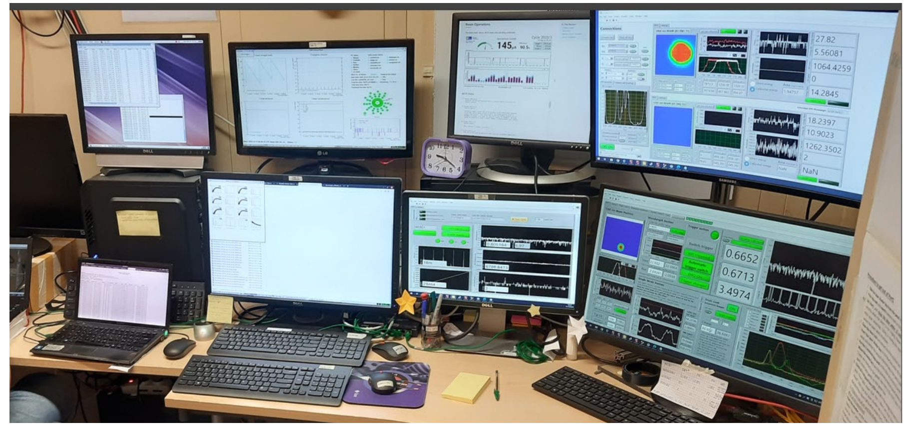
Water absorption measured in 100 cm of air RH 40-45%
for the absolute energy calibration

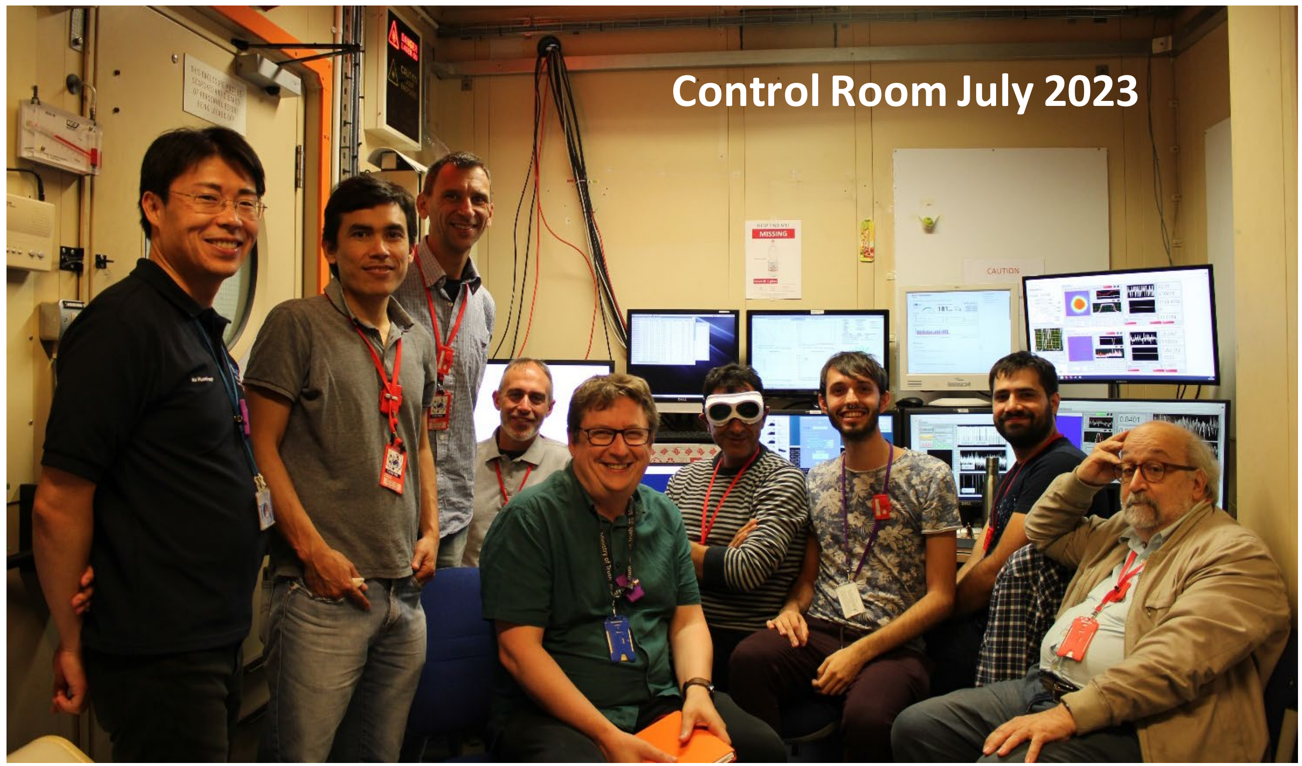


Data taking in 2023

July 2023: commissioning

Physics data taking:
October and December 2023
A total of 21 days

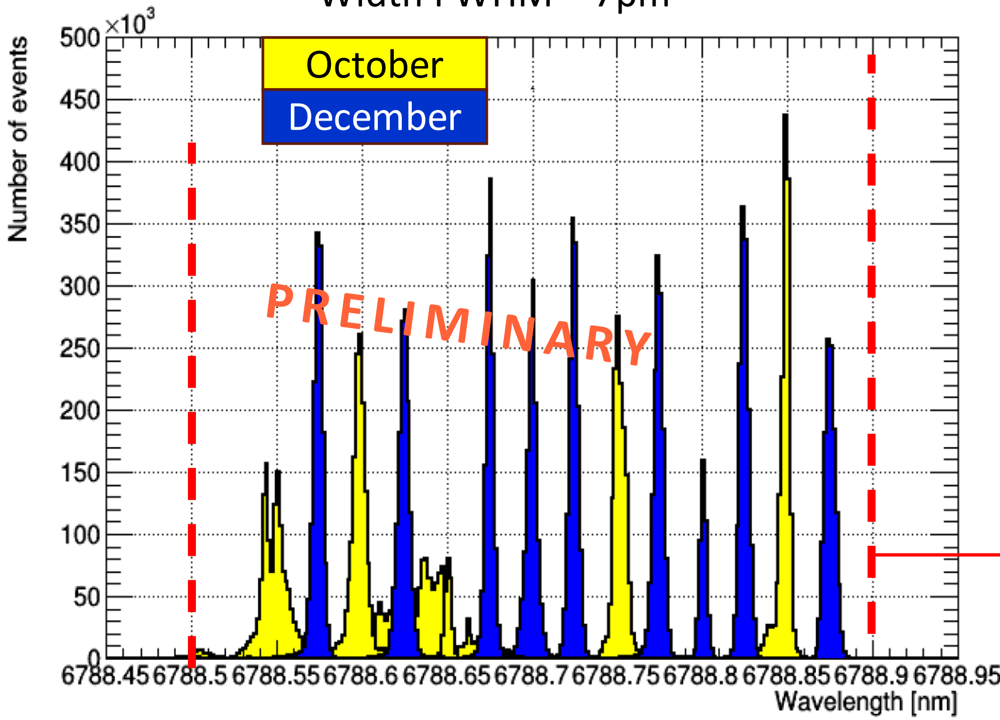




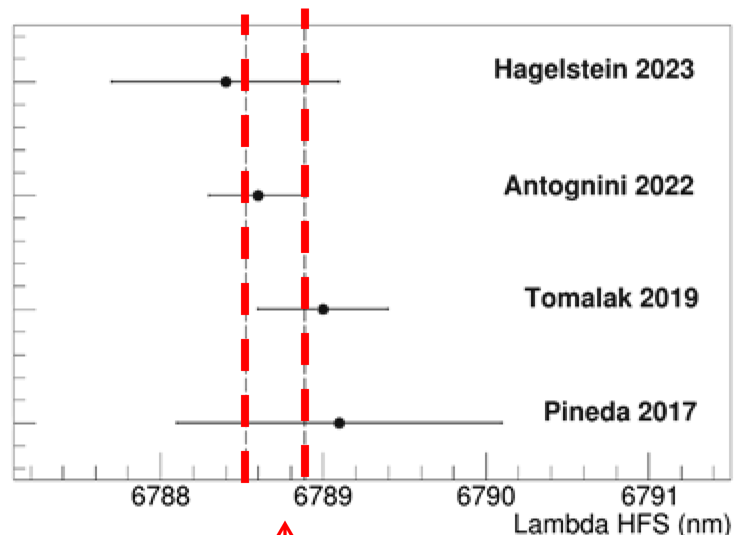
FAMU investigated regions in 2023

Laser wavelengths investigated in 2023:

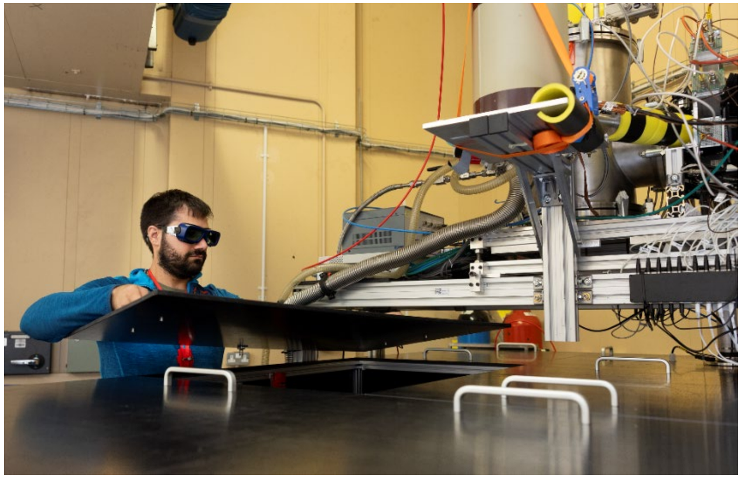
14 frequencies investigated
in steps of 25 pm
~ 24 h for each frequency
Width FWHM ~7pm



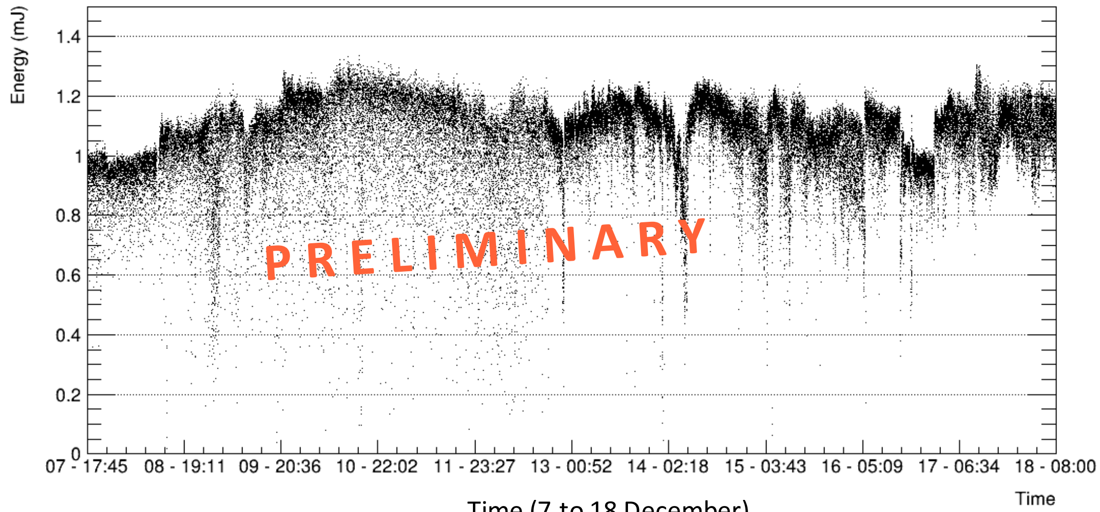
Theoretical prediction of the HFS



Laser operations during beam time



@7um Mean energy 1.05 ± 0.12 mJ



Time (7 to 18 December)

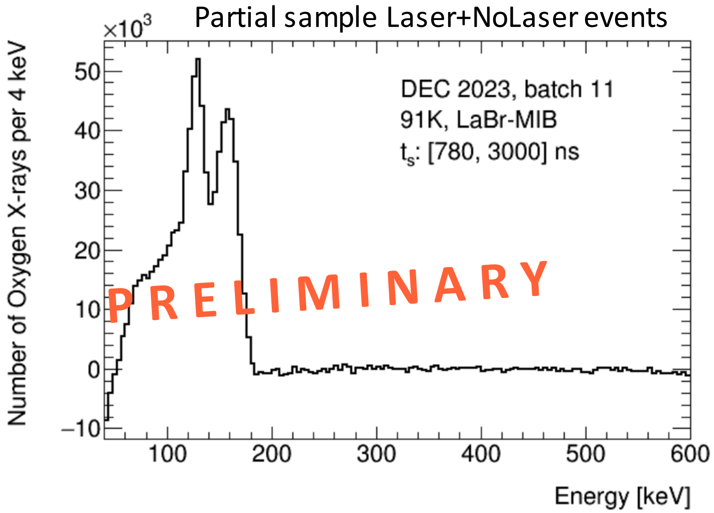
	October	December
Continuous laser operations	9 days	12 days
Number of laser shots	20M	26M
Mean daily uptime (deadtime: WL change, laser checks and alignment)	22h (~90%)	23h (~96%)
Number of measured wavelengths	5	9
Time required to change wavelength	1 – 2.5 hours	30-60 min

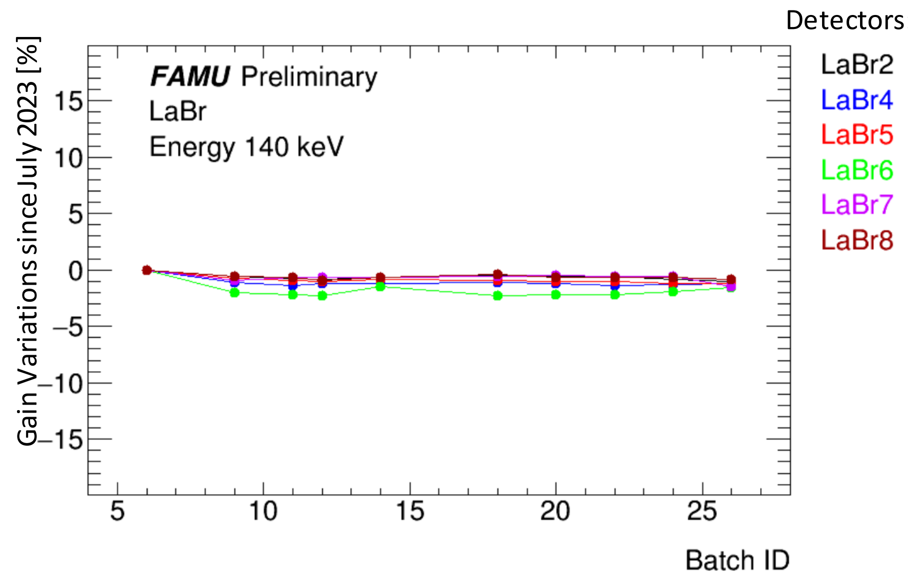
Ongoing data analysis

Presently focused on time effects and systematics.

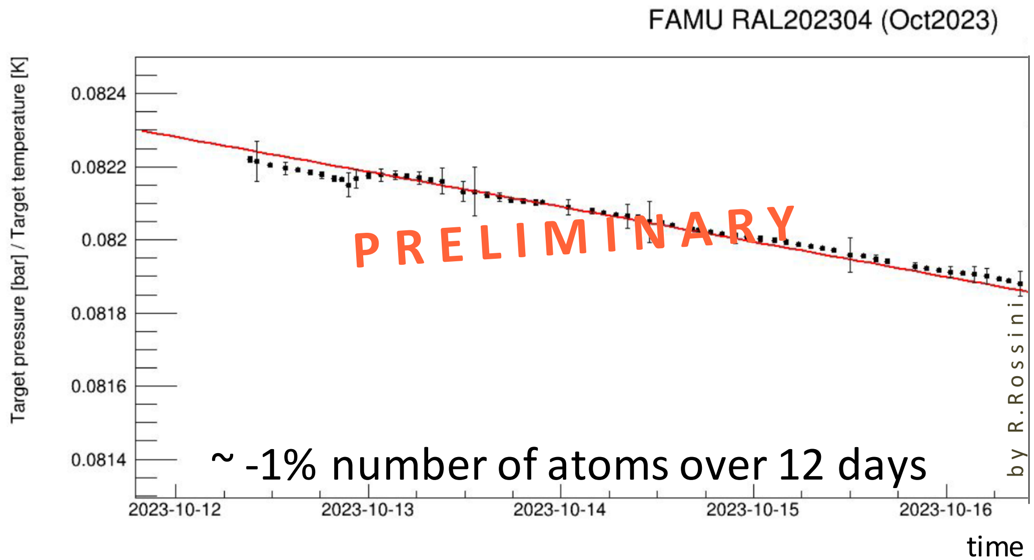
For example:

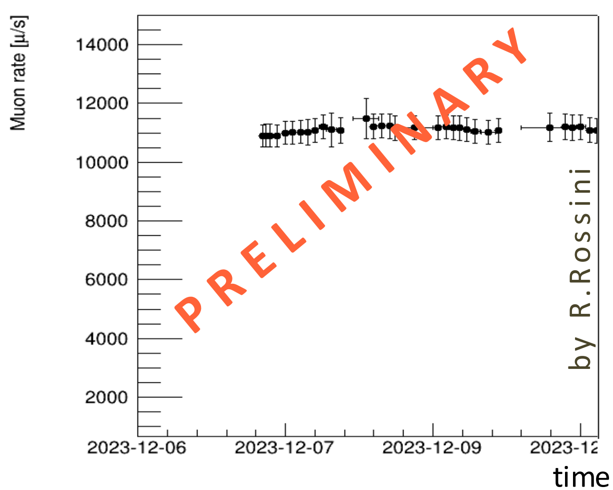
- Detector performances, stability in terms of gain and efficiency
- Monitor of the muon beam flux variation with the hodoscope
- Target condition (T, P) and other time dependencies
- Stability and characteristics of the laser, resolution, etc
- Better understanding of errors with MC



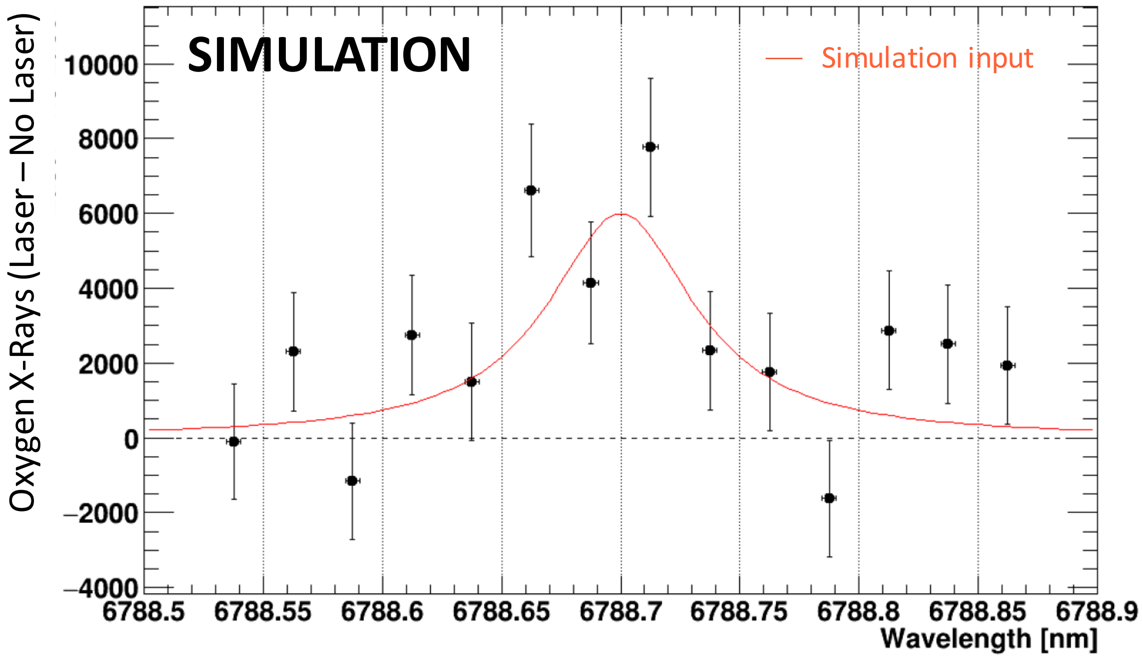


Some studies of stability





Expectations from Montecarlo



Simulation inputs:

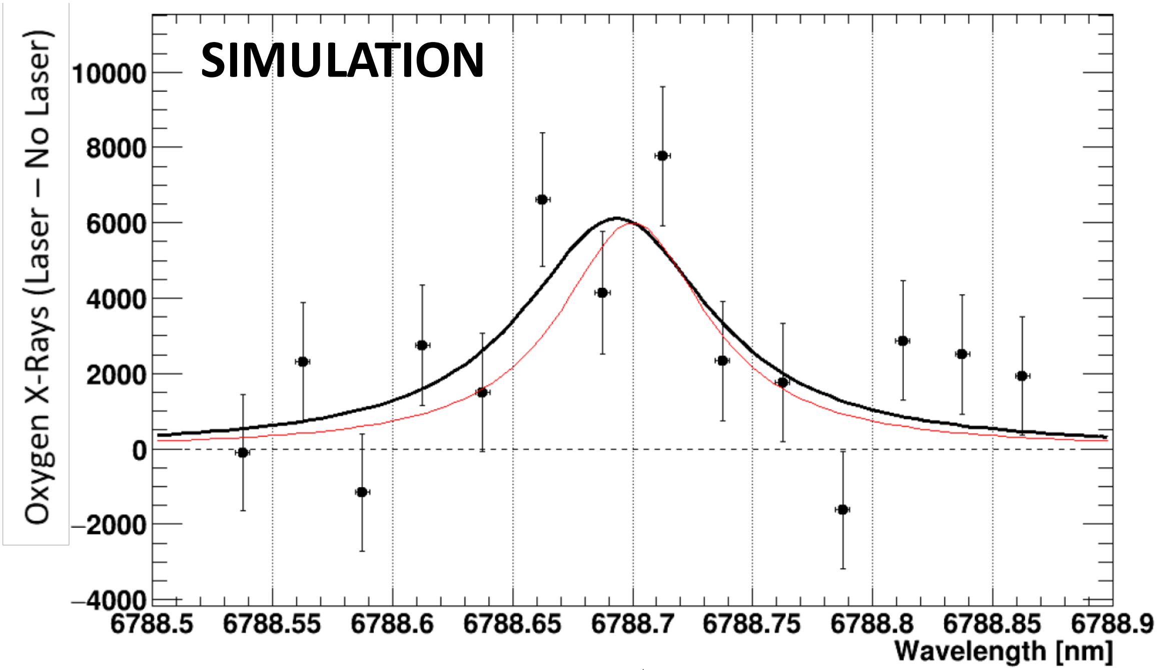
Resonance center 6788.700 nm

Resonance width 75 pm

Effect 3%

Simulation includes our experimental conditions

Expectations from Montecarlo



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≡ less than 2 part per million
Significance 4.7 sigma

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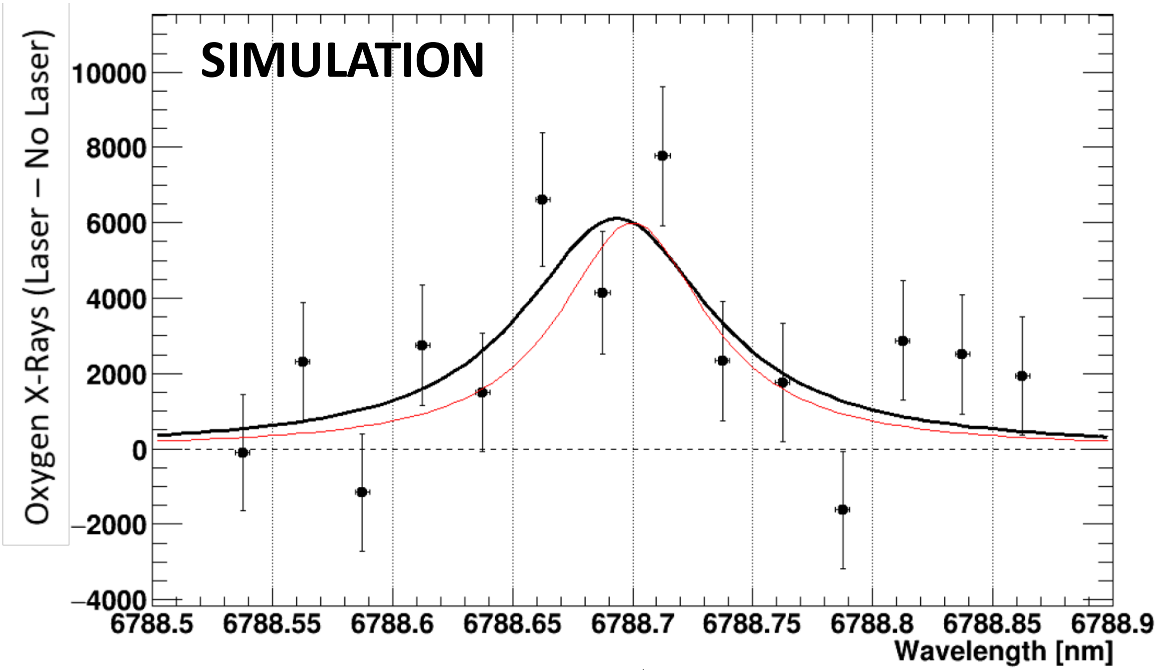

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Effect 3%

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≡ less than 2 part per million
Significance 4.7 sigma

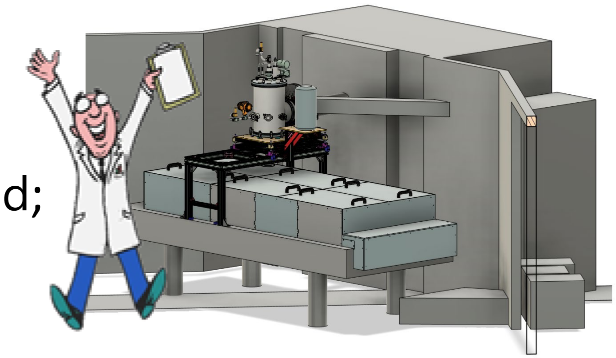
What we can improve:

- Reduce the wavelength step between measurements
- Increase the statistics
- Increase the laser energy

Present laser characteristics are not the main source of uncertainty

Although the target was designed to suppress the signals for materials different by the gas what affect our precision: X-rays background

Summary and outlook



- Successful physics data taking in 2023 ;
  - target, detectors, cavity, and laser are performing as expected;
  - 14 frequencies investigated
- The analysis of the 2023 dataset is ongoing

- New physics data taking planned in July and till 2025
  - Improvement: larger coverage from X-rays detectors
  - Enlarge the investigated WL region by 2/3

Future:

Working on an improvement of the laser scheme in terms of energy and stability

Thank you for your attention