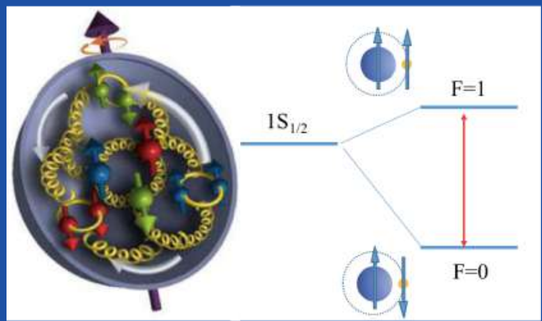
FAMU

Fisica Atomi MUonici (Physics with muonic atoms)

Present status of the Experiment to Measure the ground state HFS of muonic hydrogen



"Proton structure in and out of muonic hydrogen — the ground-state hyperfine splitting"
PSI 14-15 October 2022

Andrea Vacchi INFN Trieste (I) & Uni Udine on behalf of the FAMU collaboration

FAMU Collaboration

INFN Trieste- Udine: A. Vacchi, E. Mocchiutti, C. Pizzolotto, M. Baruzzo, José J. Suárez-Vargas, , S. Monzani , H. Cabrera, E. Vallazza,
Elettra-Sincrotrone: M. Danailov, A. Demidovich*, L. Stoychev,* ***ICTP***: J. Niemela, K.S. Gadedjisso-Tossou,
INFN Bologna**:** L. Andreani, G. Baldazzi,, I. D'Antone, G. Morgante, L. P. Rignanese,

INFN Milano Bicocca**:** A. Baccolo, R. Benocci, R. Bertoni, M. Bonesini, T. Cervi, F. Chignoli, M. Clemenza, A. Curioni, V. Maggi, R. Mazza, M. Moretti, R. Ramponi *(also Politecnico Milano CNR*) ***INFN Pavia*****:** A. De Bari, C. De Vecchi, A. Menegolli, M. Rossella, R. Nardò, A. Tomaselli

INFN Roma3**:** L. Colace, M. De Vincenzi, A. Iaciofano, L. Tortora, F. Somma

INFN Unuversità della Campania: L. Gianfrani, L. Moretti, E. Fasci

CNR-INO: B. Patrizi, A. Piori, G. Toci, M. Vannini

*RI**KEN-RAL***: K. Ishida

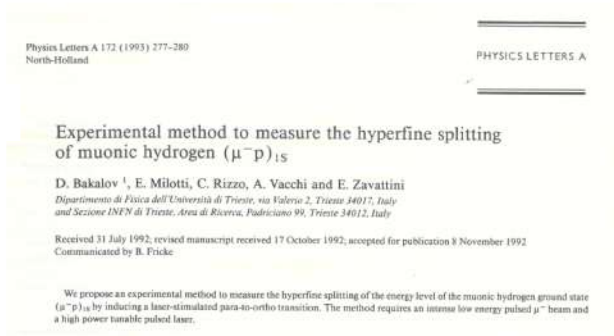
INP, Polish Academy of Sciences**:** A. Adamczak

INRNE, Bulgarian Academy of Sciences**:** D. Bakalov, M. Stoilov, P. Danev
ISIS Neutron and Muon Source STFC Rutherford Appleton Laboratory P. King ,A. Hiller
Dalian Institute of Chemical Physics , Chinese Academy of Sciences (DICP-CAS) Chunlei Xiao

FAMU Timeline

1993 — First idea of the experimental method

Physics Letters A 172 (1993) 277–280


Physics Letters A 172 (1993) 277–280
North-Holland

PHYSICS LETTERS A

Experimental method to measure the hyperfine splitting of muonic hydrogen $(\mu^- p)_{1S}$

D. Bakalov [1], E. Milotti, C. Rizzo, A. Vacchi and E. Zavattini
Dipartimento di Fisica dell'Università di Trieste, via Valerio 2, Trieste 34017, Italy
and Sezione INFN di Trieste, Area di Ricerca, Padriciano 99, Trieste 34012, Italy

Received 31 July 1992; revised manuscript received 17 October 1992; accepted for publication 8 November 1992
Communicated by B. Fricke

We propose an experimental method to measure the hyperfine splitting of the energy level of the muonic hydrogen ground state $(\mu^- p)_{1S}$ by inducing a laser-stimulated para-to-ortho transition. The method requires an intense low energy pulsed μ^- beam and a high power tunable pulsed laser.

2014 - 2018 — Study and preparation

2019/20 — Full set up and measurement of the HFS

March 2020 – first assembly
September 2020
December 2020
June 2021

Meanwhile in our local labs …

- Further studies on laser
- Cavity characterisation
- Detector integration

2021-22 — June 2021- June 2022: RIKEN-RAL shutdown for maintenance & upgrades

Russia – Ukraine war began (we have lasers built in Belarus)

2022-23 — First data taking with full setup 2022-3


BEAM ON
schilding being
reinstalled this days

FAMU: $\mu^{-}p$ spectroscopy

"Usual" spectroscopic flow:

1) form muonic hydrogen
2) shoot laser
3) count triplets

repeat varying laser frequency to find resonance value.

Hyperfine splitting of $(\mu^{-}p)_{1S} \approx 183$ meV...

How to distinguish HFS excited states?

HFS de-excitation: $\mu^- p$ gains kinetic energy

“Usual” spectroscopic flow:
1) create muonic hydrogen
2) shoot laser
3) count triplets repeat varying laser frequency to find resonance value.

How is it possible to distinguish HFS excited states?
Hyperfine splitting of $(\mu^- p)_{1S}$ ≈183 meV...

… but

in the triplet to singlet transition muonic hydrogen gains kinetic energy (≈120 meV, 0.12 eV)

μ^- transfer rate to high-Z atoms is energy dependent

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Key point:

The muon transfer rate to higher-Z atoms in collisions is (kinetic) energy dependent at epithermal energies (≈100/200 meV)

μ^- transfer rate to high-Z atoms is energy dependent

D. Bakalov, et al., Phys. Lett. A172 (1993).
A. Dupays, Phys. Rev. A 68, p. 052503, 2003.
D. Bakalov, et al., NIM B281 (2012).

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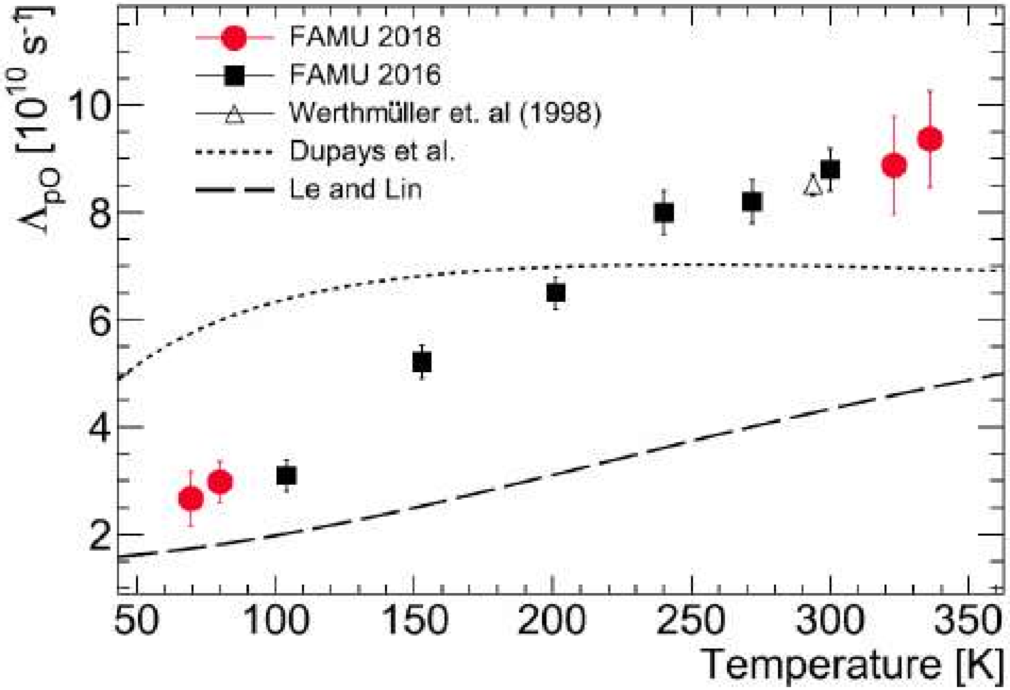
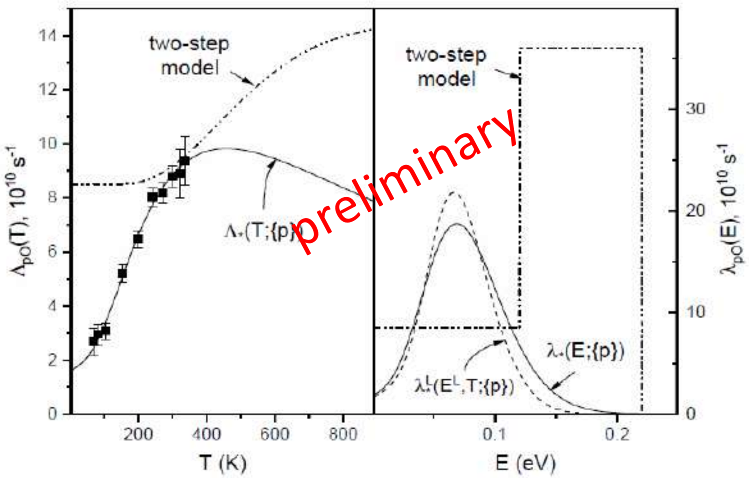
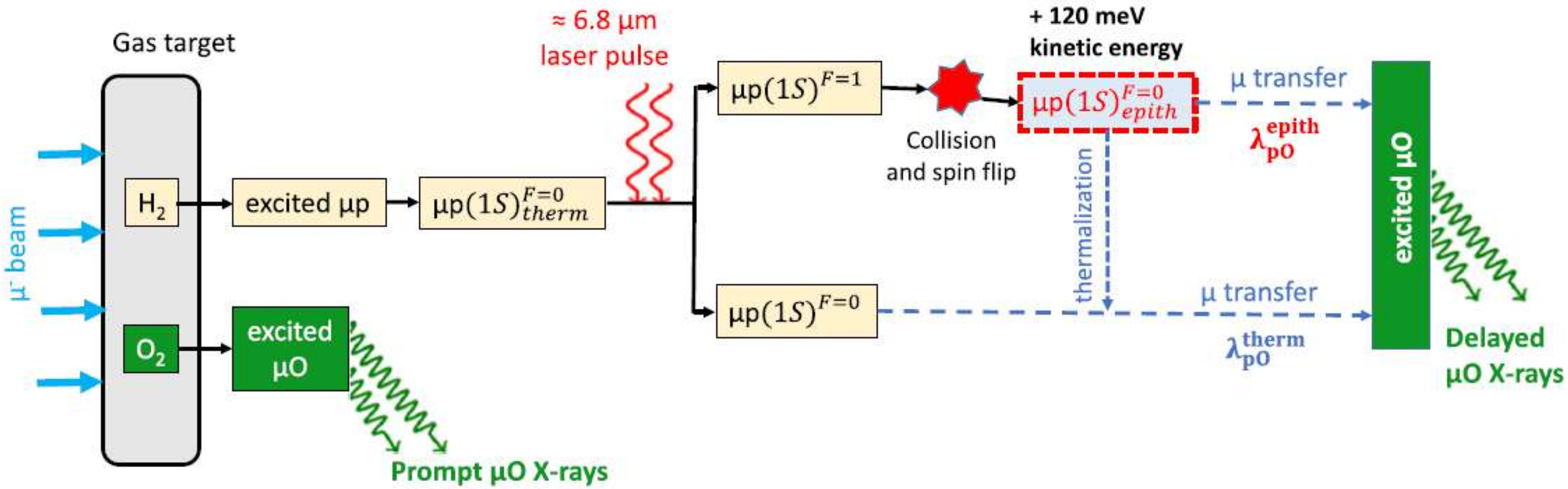


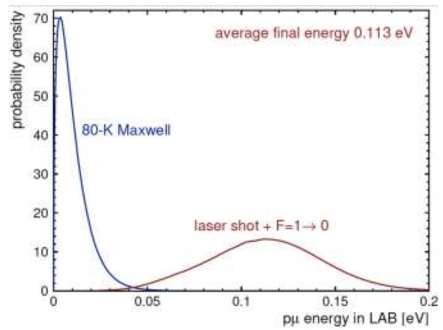


Oxygen transfer rate
C.Pizzolotto et al., Phys. Lett. A 403 (2021) 127401
E.Mocchiutti et al., Phys. Lett. A 384 (2020) 126667

FAMU method

D. Bakalov, et al., Phys. Lett. A172 (1993).
A. Dupays, **Phys. Rev. A 68**, p. 052503, 2003.
D. Bakalov, et al., NIM B281 (2012).

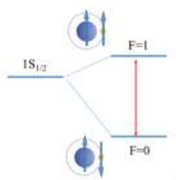




1) Create muonic hydrogen and wait for thermalization;

2) Laser scan at resonance (λ_0 ~6.8μ): spin state of μ⁻p from 1^1S_0 to 1^3S_1 ,

spin is flipped: μ⁻p(↑↓) → μ⁻p(↑↑) ;



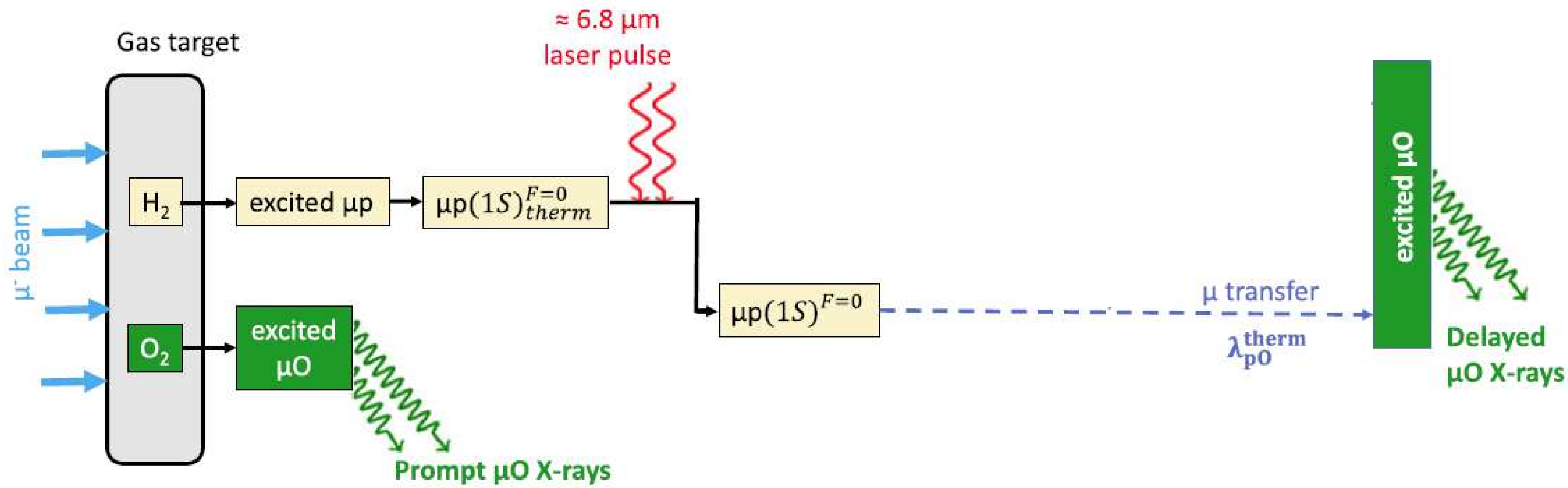
3) De-excitation and acceleration: μ⁻p(↑↑) hits a H atom

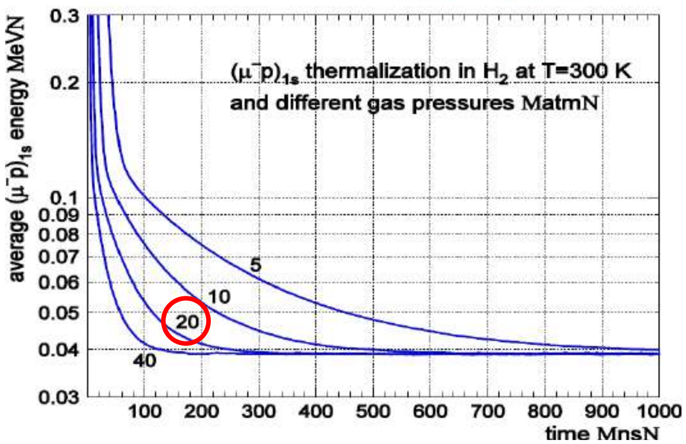
μ⁻p is depolarized back to μ⁻p(↑↓) and is accelerated by ~120 meV ;

4) μ⁻ are transferred to heavier gas with energy-dependent rate;

λ_0 resonance is determined by the maximizing the time distribution of μ⁻ X-rays from μ transfer events.

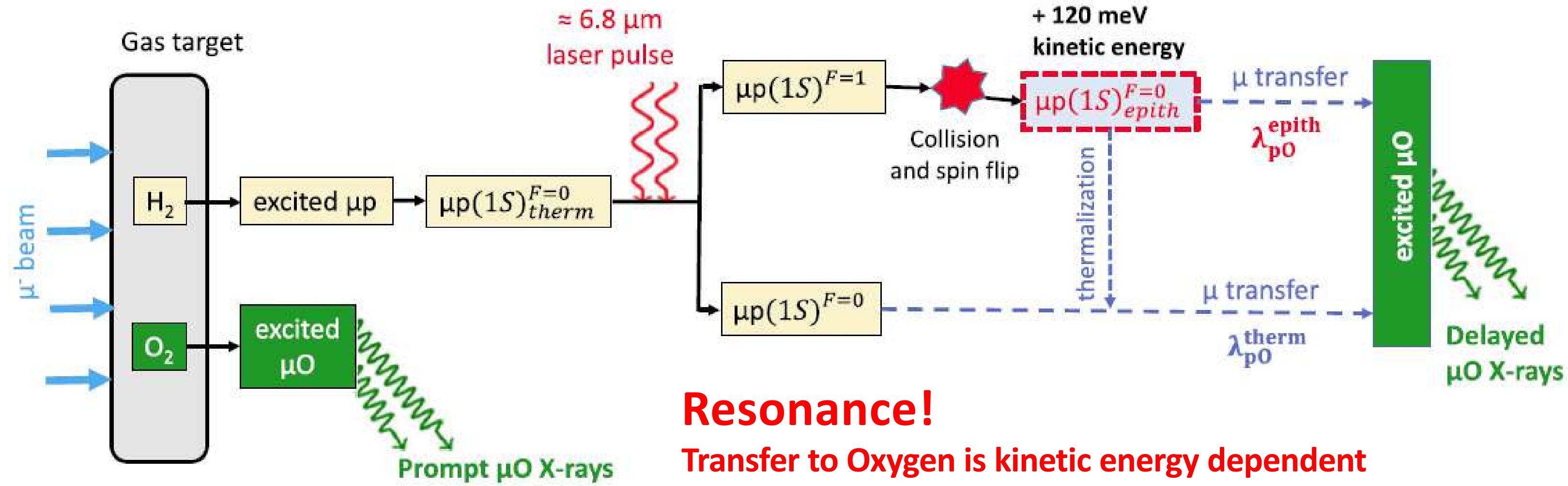
FAMU: μ⁻p spectroscopy





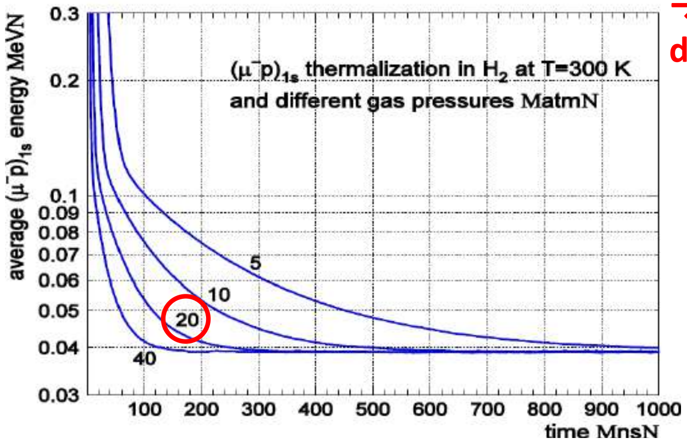
out of resonance

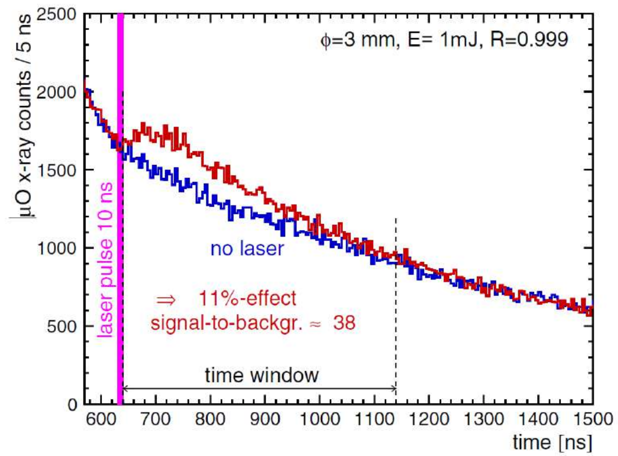
FAMU: $\mu^- p$ spectroscopy



Resonance!

Transfer to Oxygen is kinetic energy dependent
→ observable: distortion of the time distribution of delayed signal

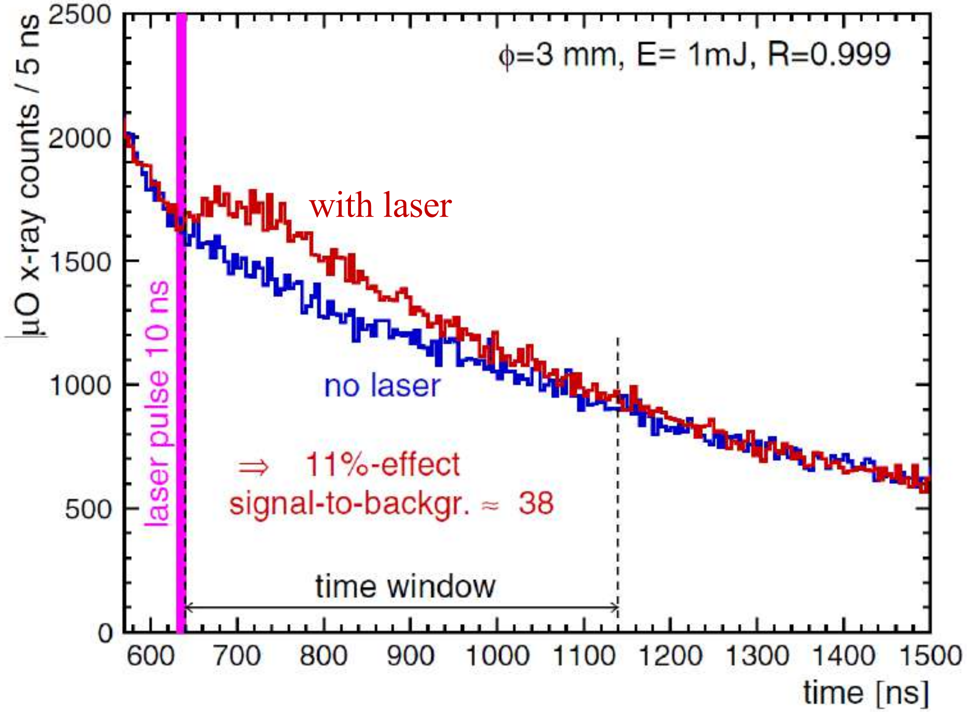




The expected signal

the resonance λ_0 is determined through the maximal response of the time distribution of μ^- transfer events.

Number X-rays form of muonic oxygen deexcitation cascade



Detailed investigation of the muon transfer from μp to higher-Z elements is crucial

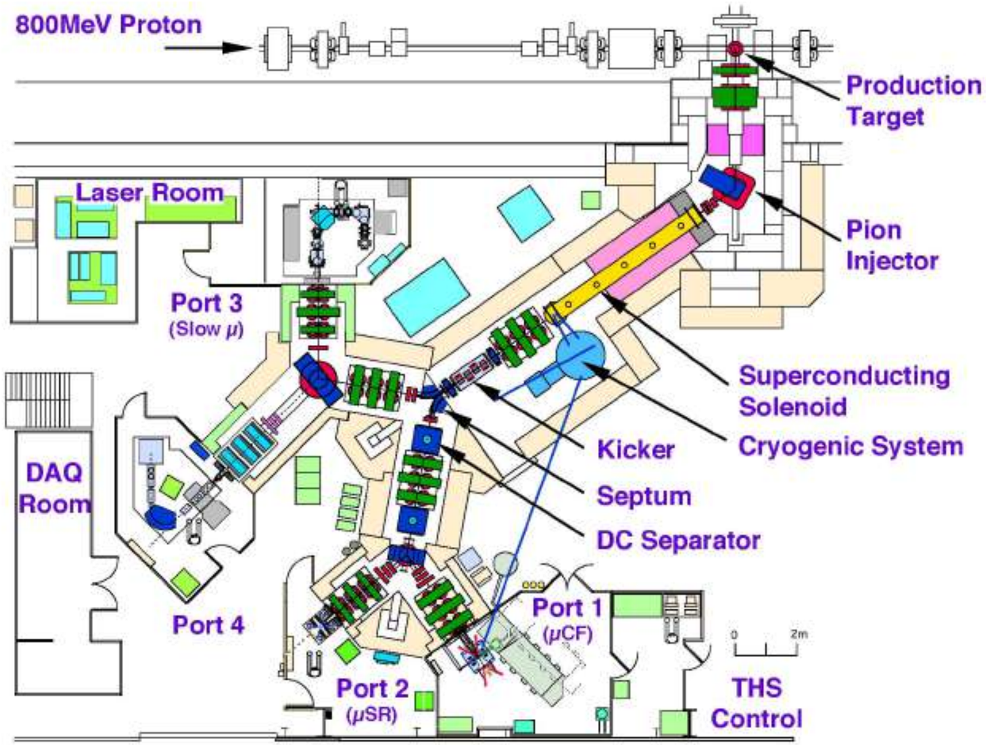
$\mu^- p + Z \Rightarrow \mu^- Z + p$

The higher is the available laser energy the higher is effect

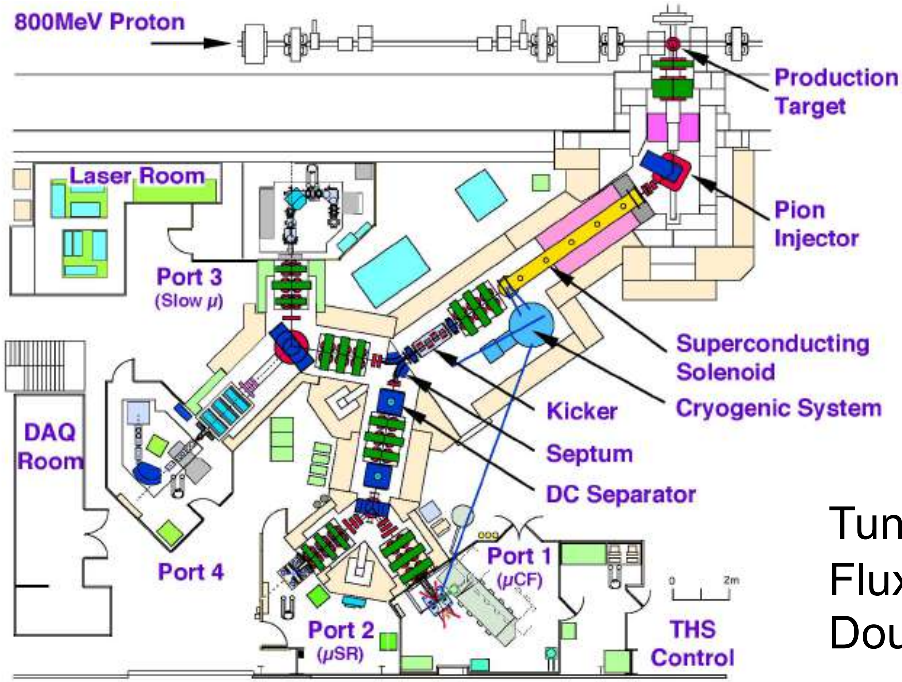
=> MIR laser dedicated development

RIKEN – RAL muon facility

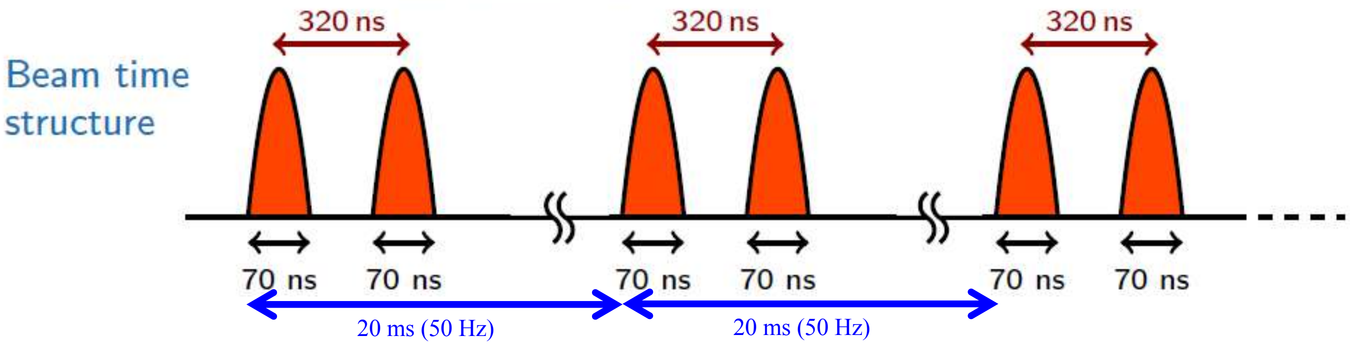
Rutherford Appleton Laboratory – Oxfordshire UK
ISIS proton accelerator



High intensity muon beam



Tunable momentum: 20 – 120 MeV/c
Flux μ^- : ≈10^5 muons/s
Double pulsed beam



Apparatus setup & present status

Target: a necessary trade-off

Main requirements:

- Operating temperature: liquid nitrogen ≈80 K
- Operating pressure: ≈10 bar
- International safety certification (Directive 97/23/CE PED)
- H_2 compatible

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Target: a necessary trade-off

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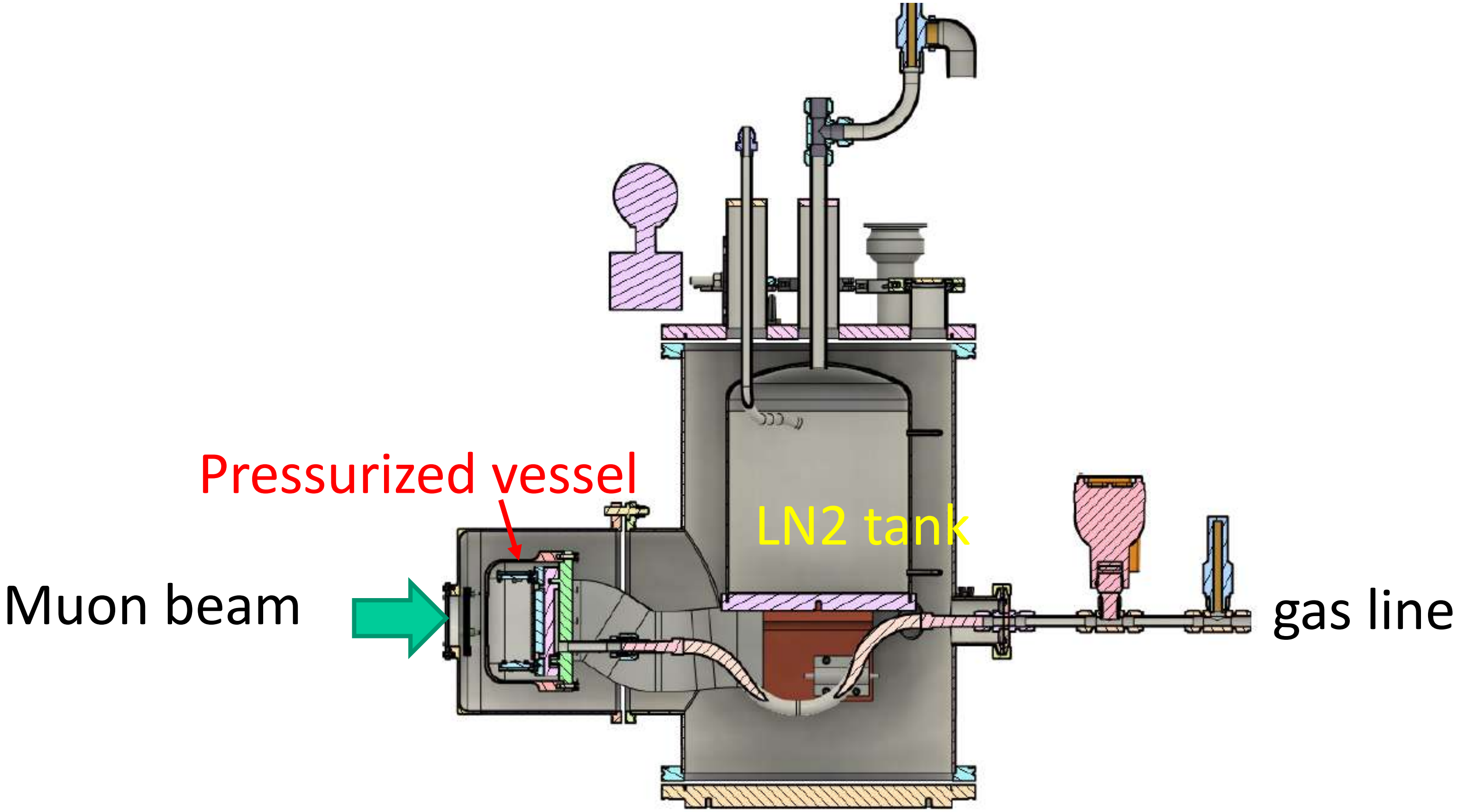
- Operating temperature: liquid nitrogen ≈80 K
- Operating pressure: ≈10 bar
- International safety certification (Directive 97/23/CE PED)
- H_2 compatible

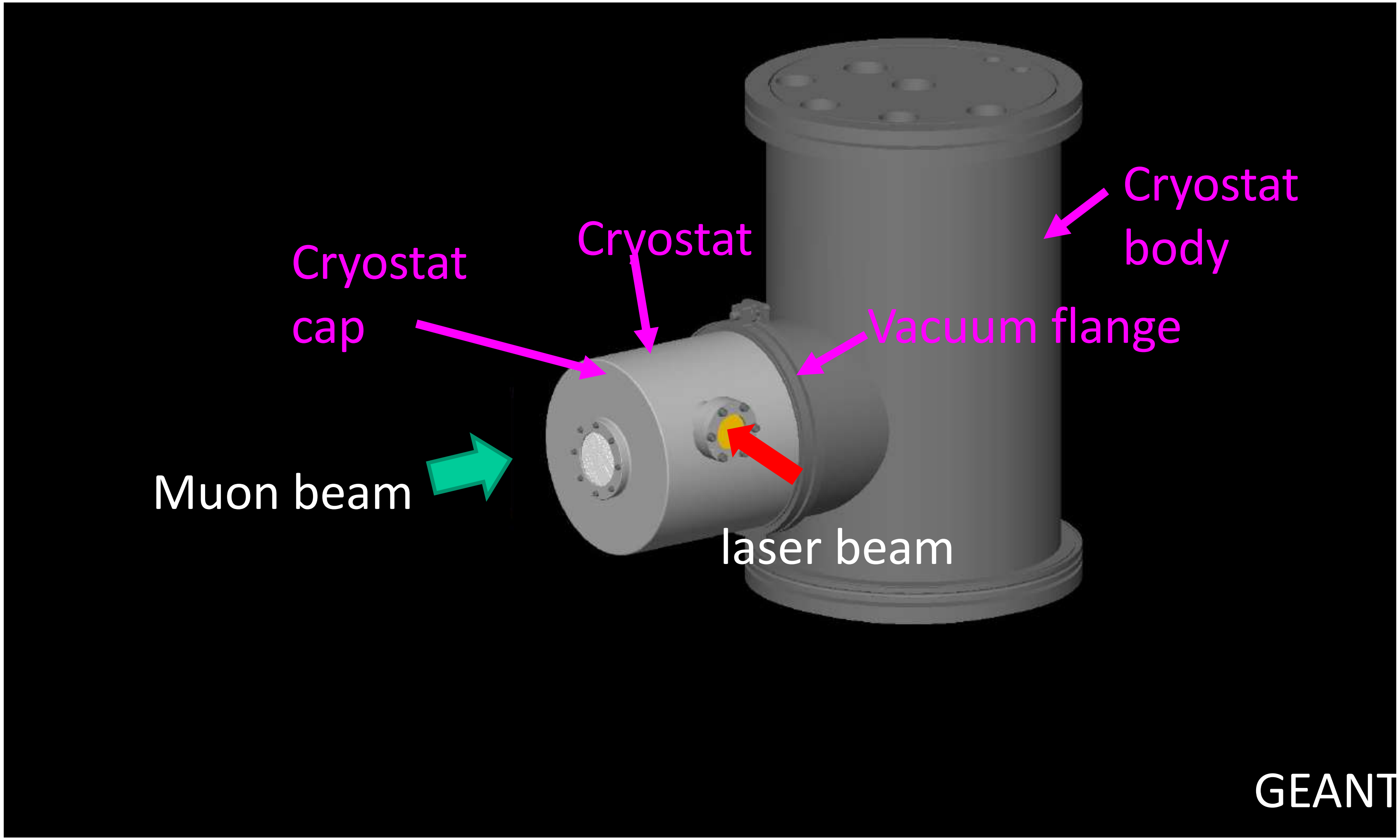
- Very big (to improve statistics) and very small (to increase laser photon density, given a maximum laser power available)
- Made of very heavy materials (to minimize noise in the delayed phase) and of very light materials (to allow X-rays exit)

Target: the design



CAD

Target: GEANT4 simulation



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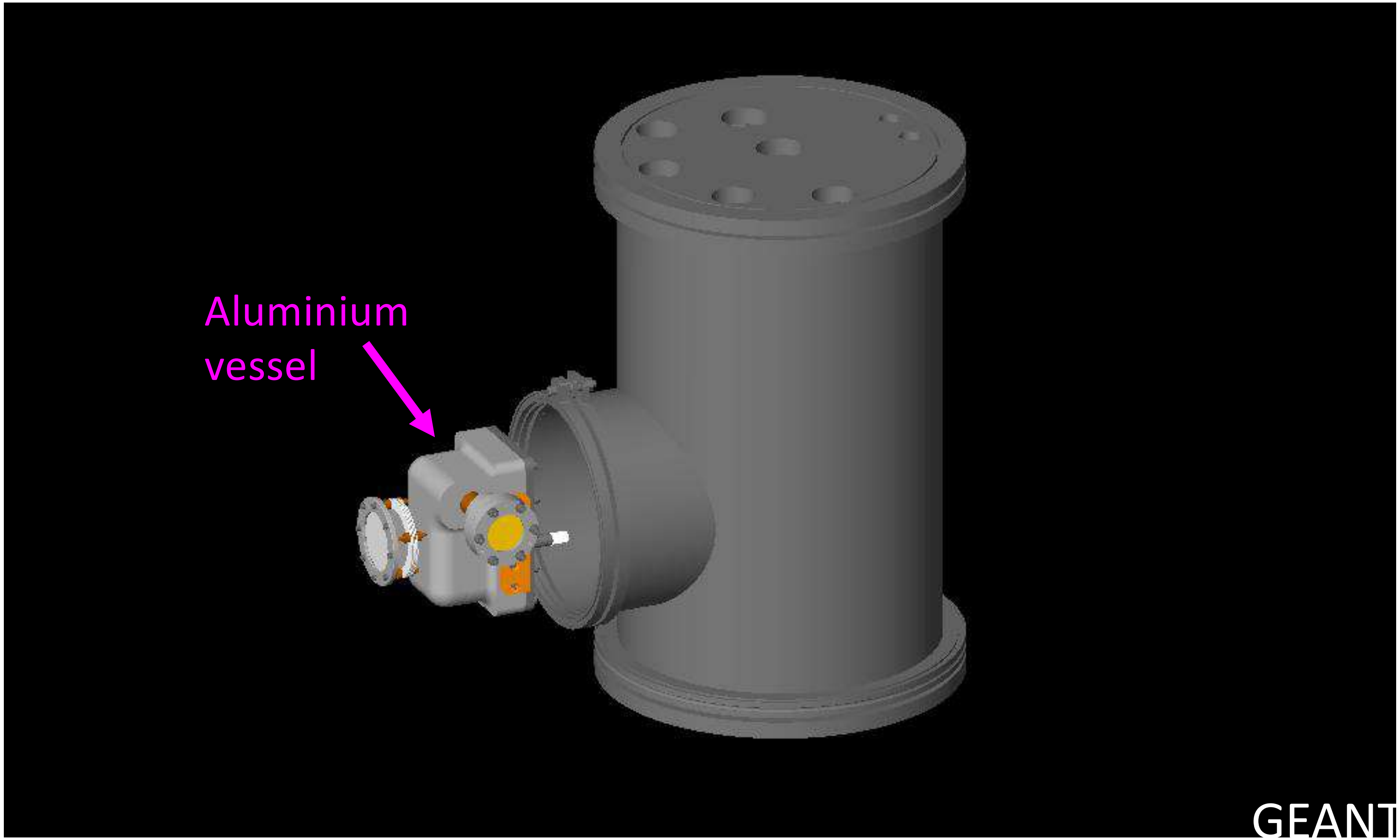
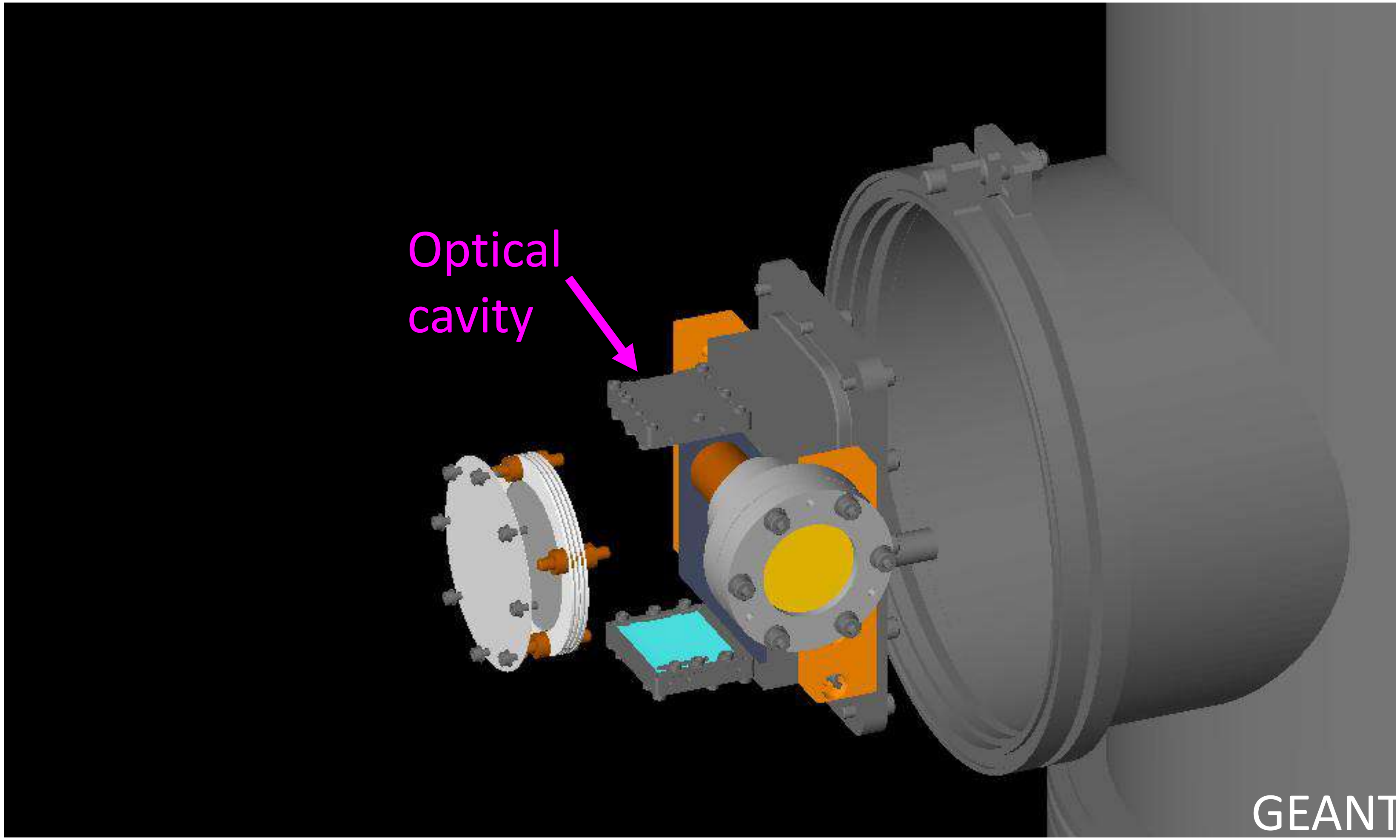


Target: GEANT4 simulation



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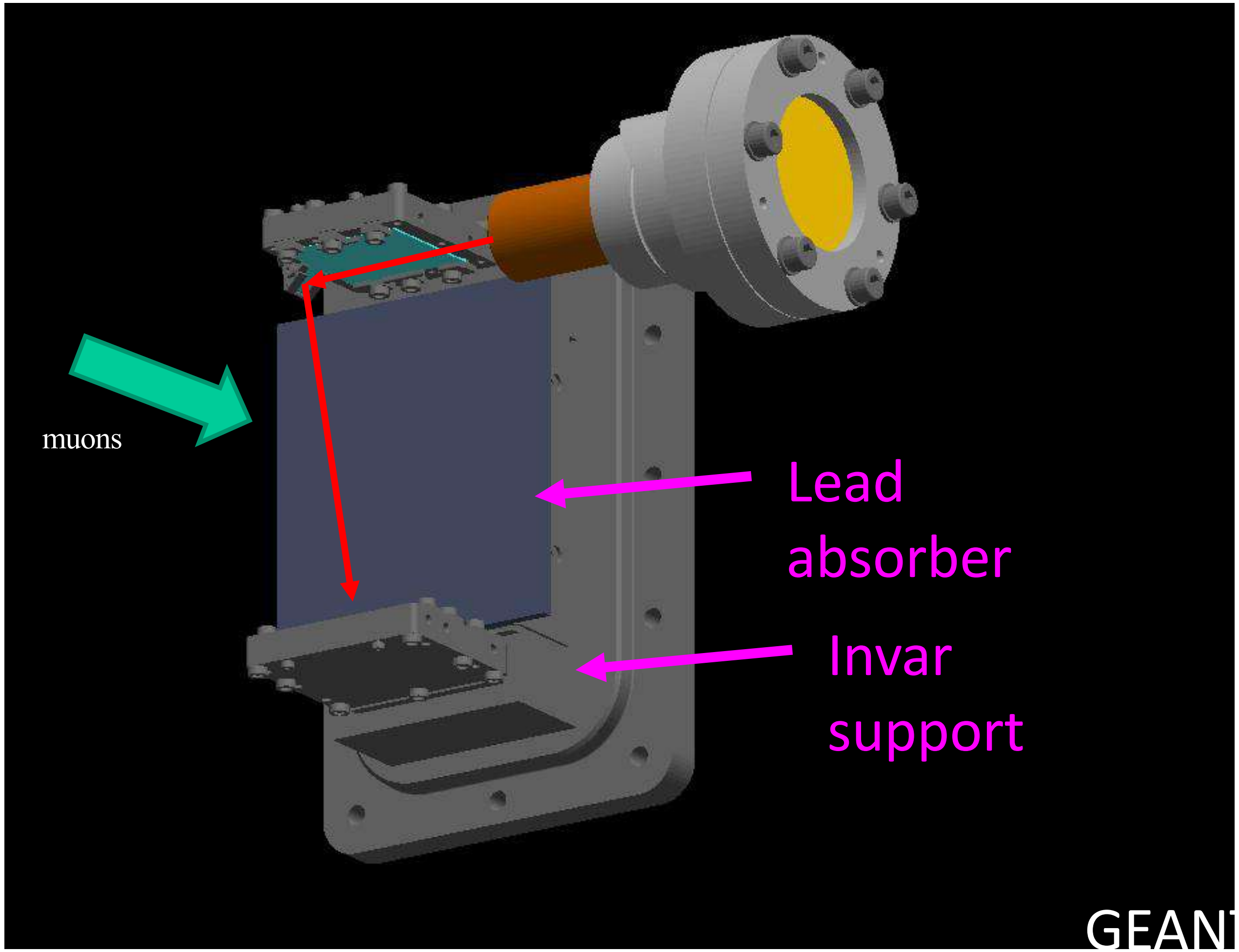

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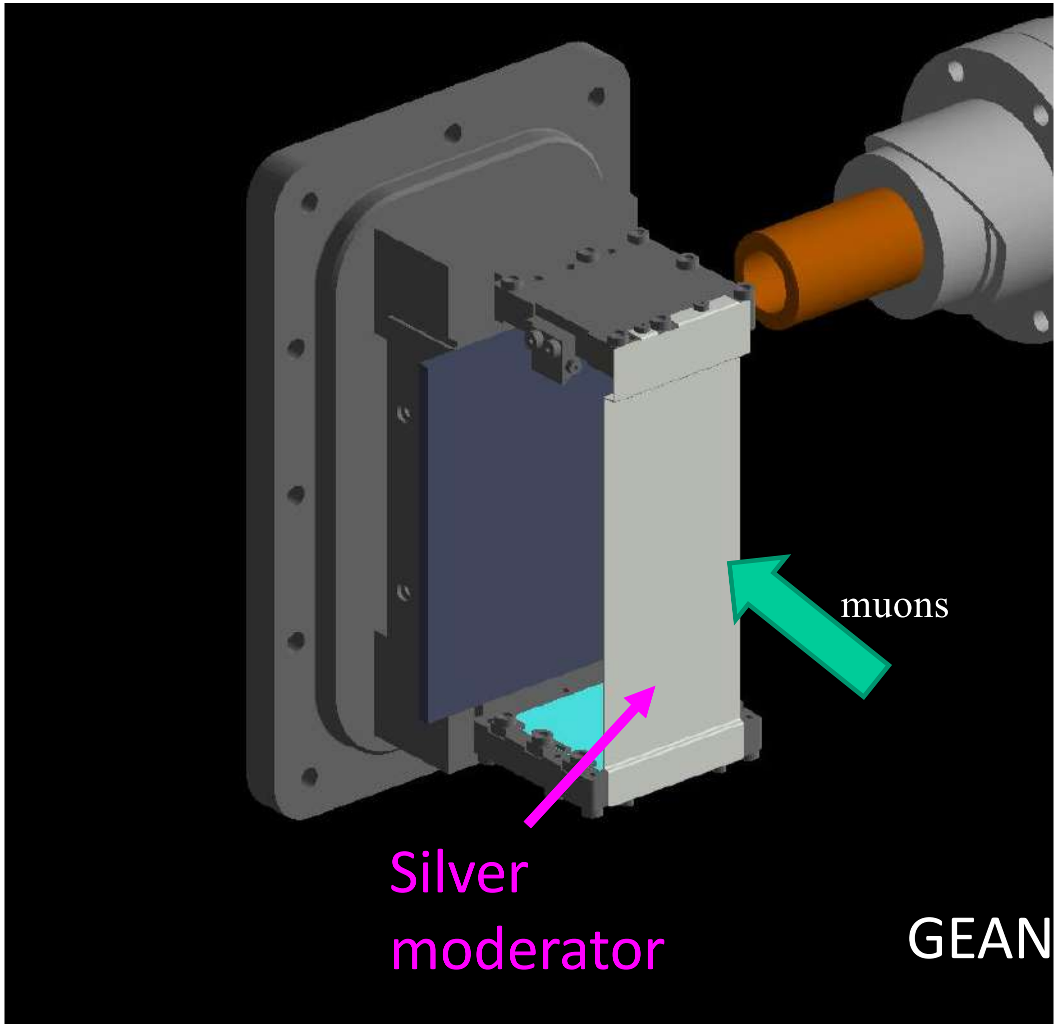
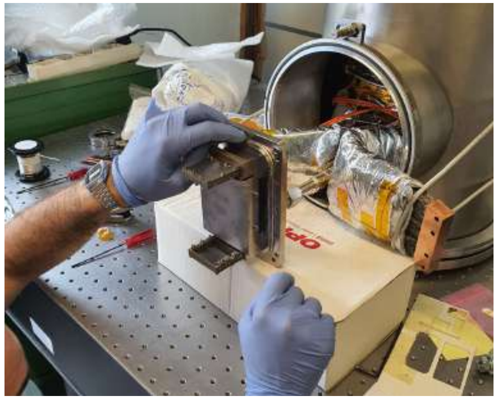
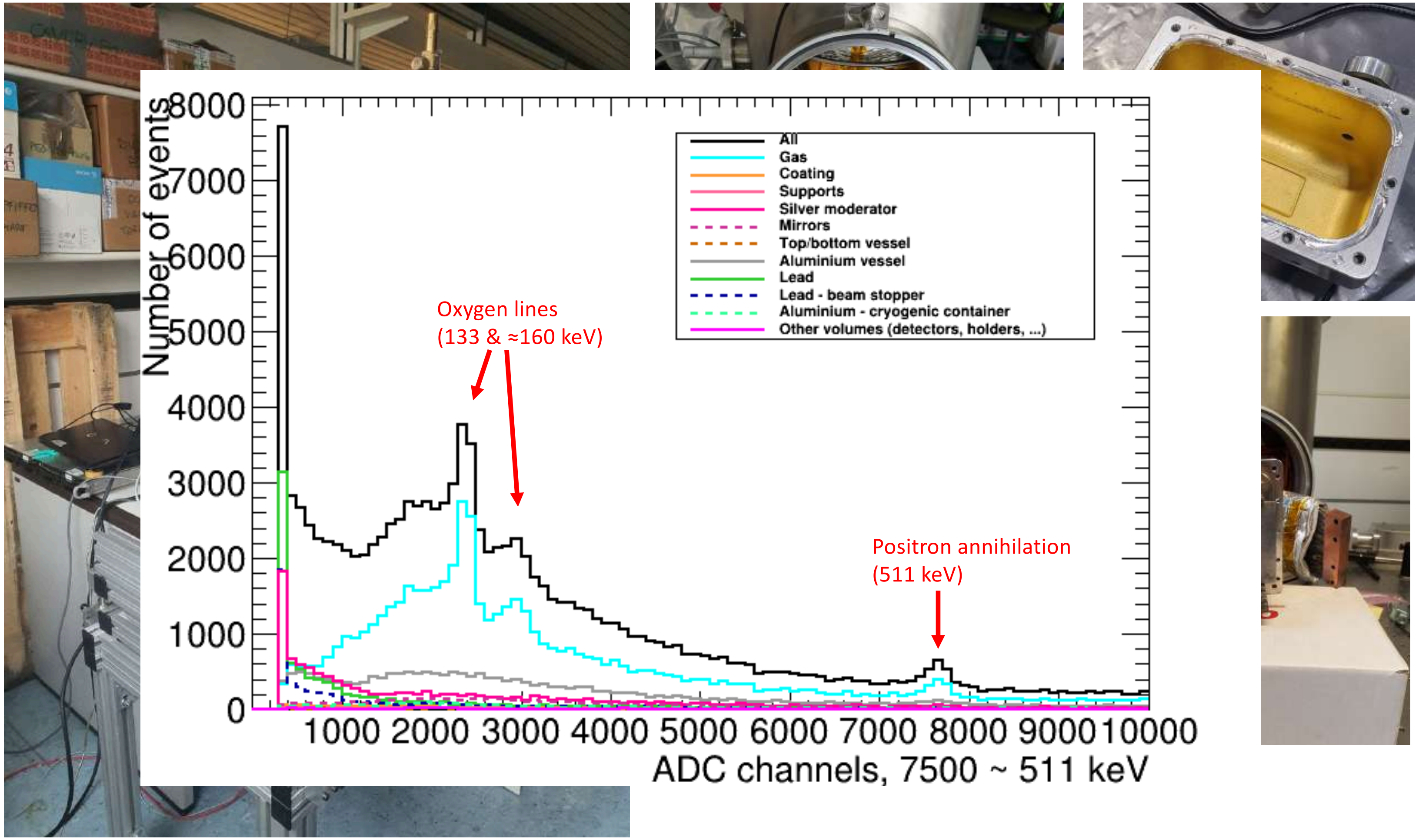


Target: ready in our lab

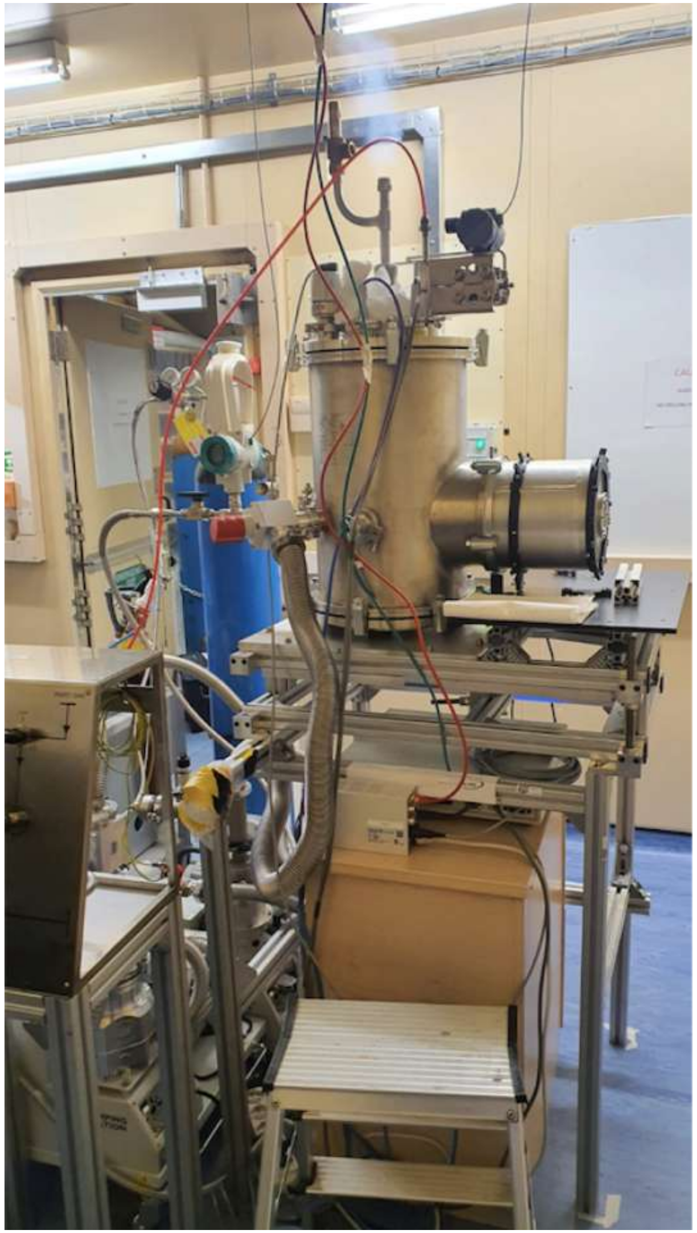



Target: expected energy spectrum



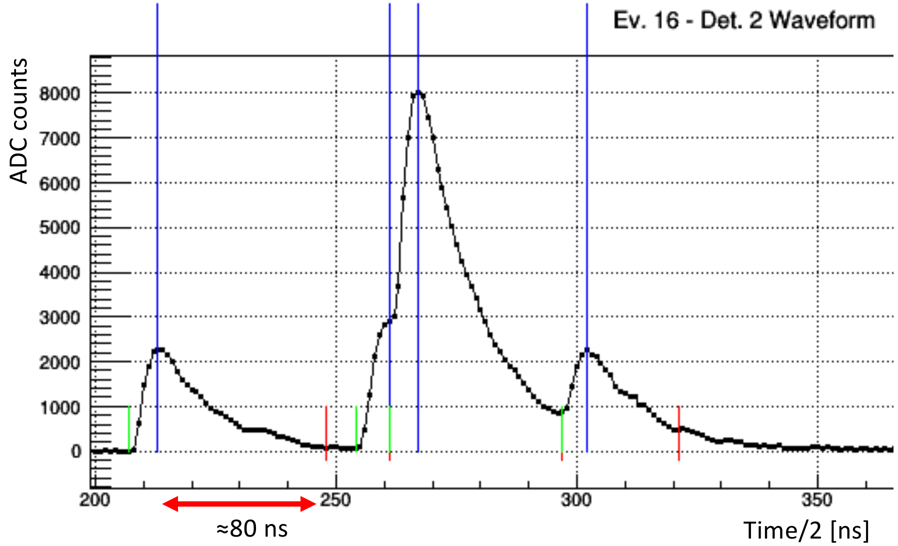
Port 1 @ RIKEN
RAL



Detectors

Main requirements:

- High solid angle coverage
- High speed
- Good energy resolution @100 keV

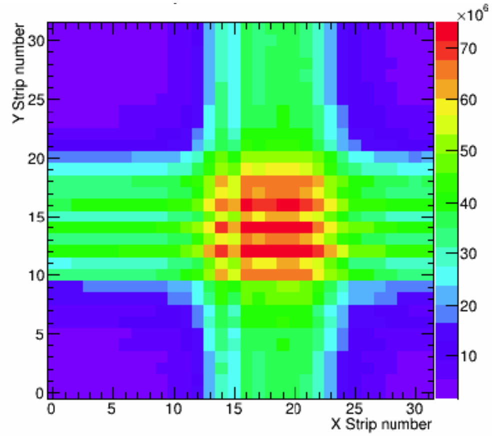


17 - LaBr3:Ce **1”** read by PMT

11 - LaBr3:Ce **1”** read by SiPM

15 - LaBr3:Ce **½”** read by SiPM

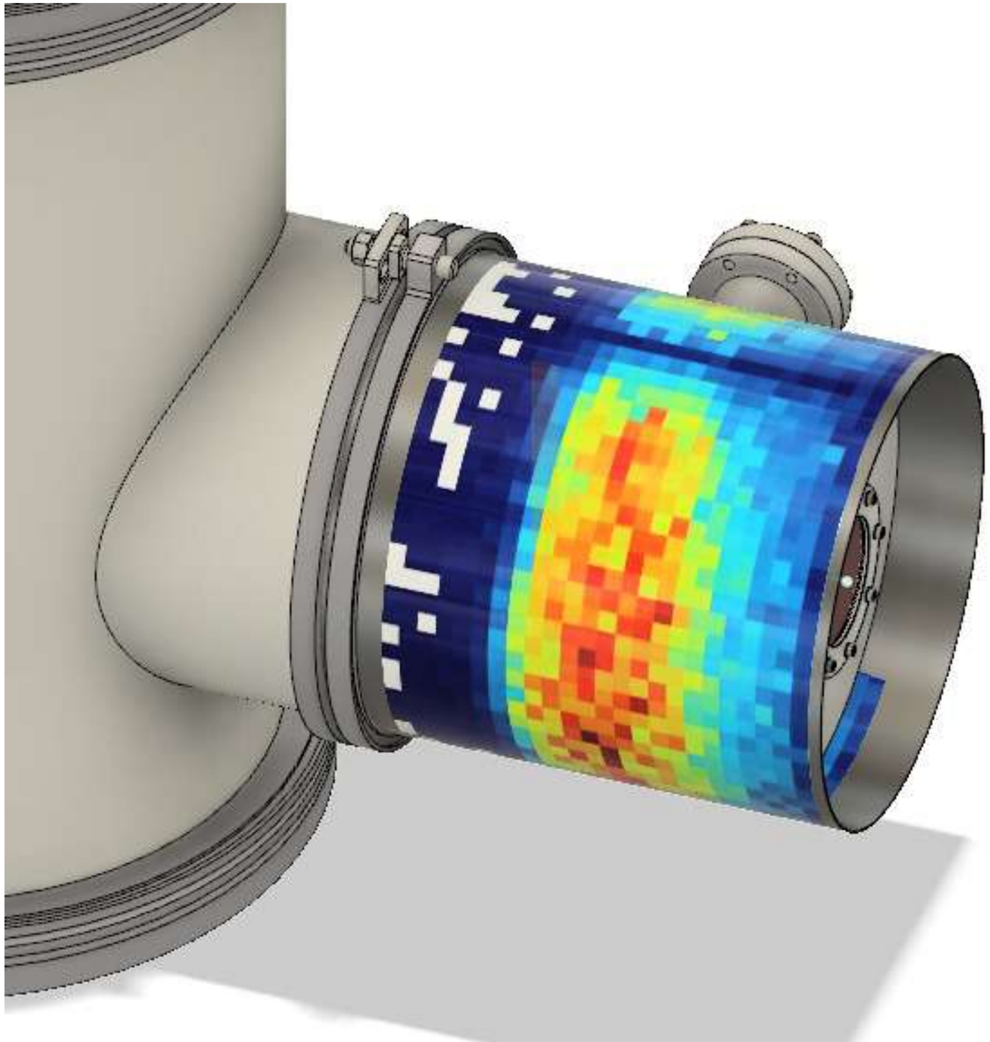
1 HPGe (Ortec GEM-S)



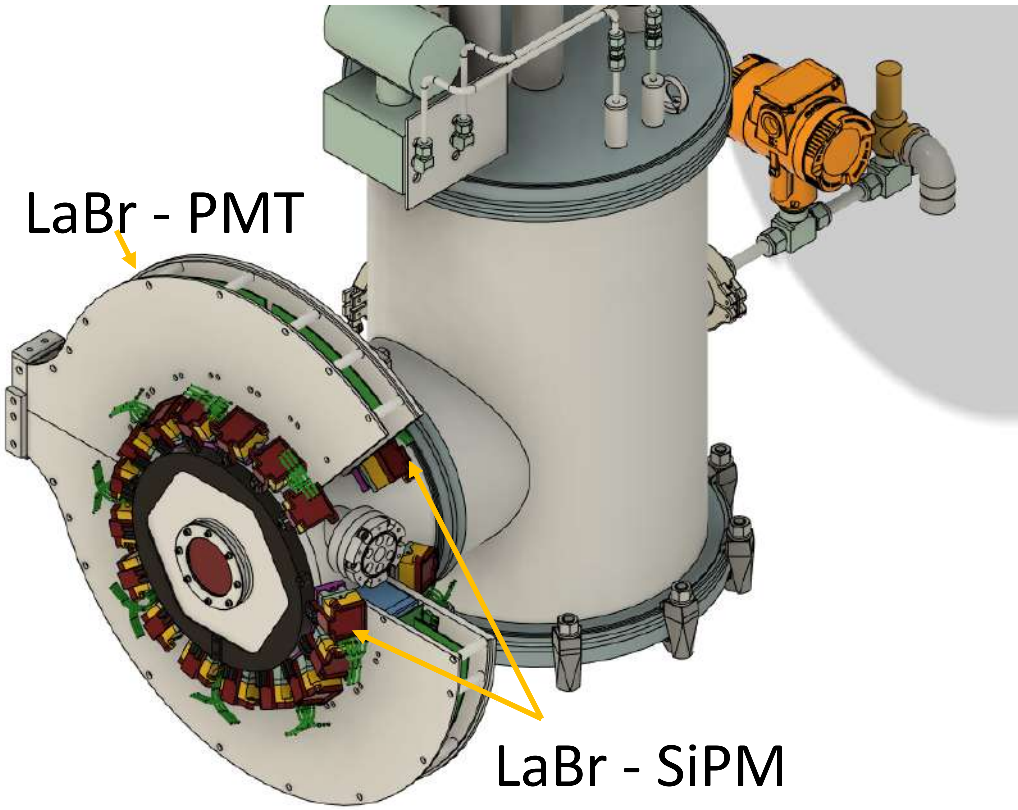
1 hodoscope for beam monitoring

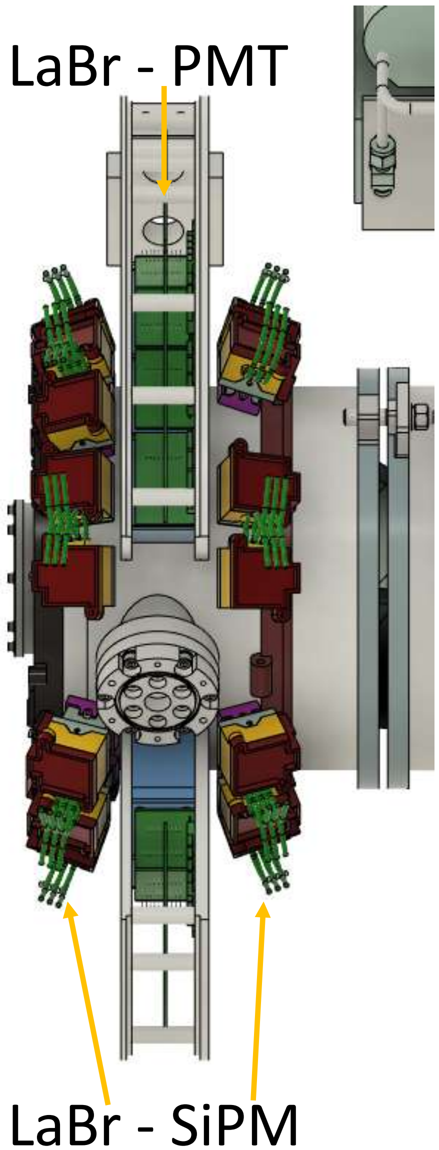
(64 channels, 1 mm square fibers read by SiPM)

X-rays distribution from simulation

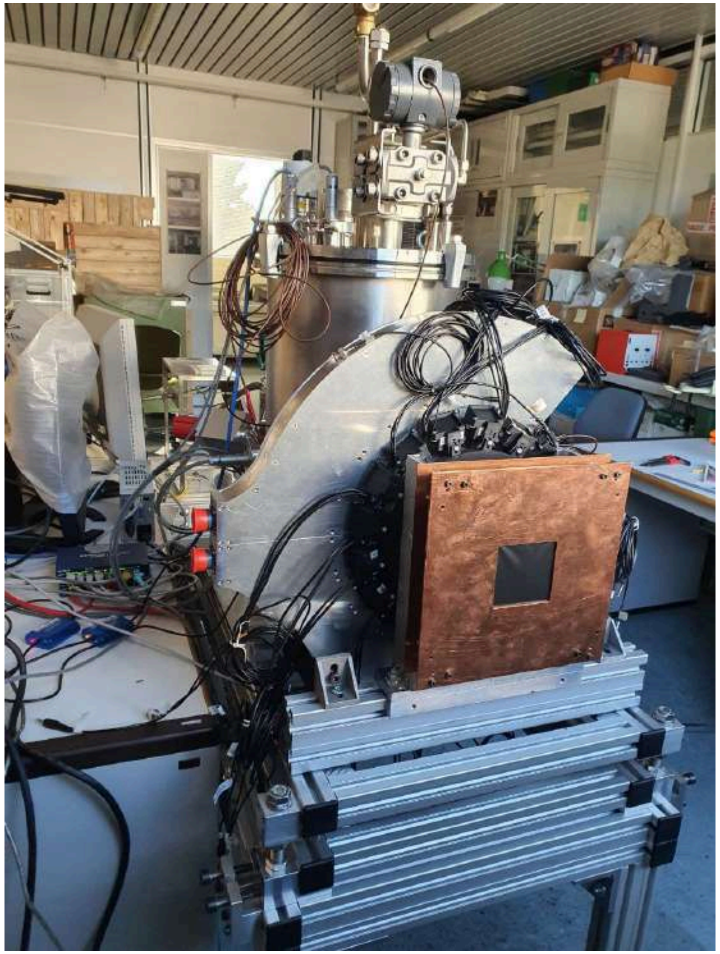


Detectors: placement

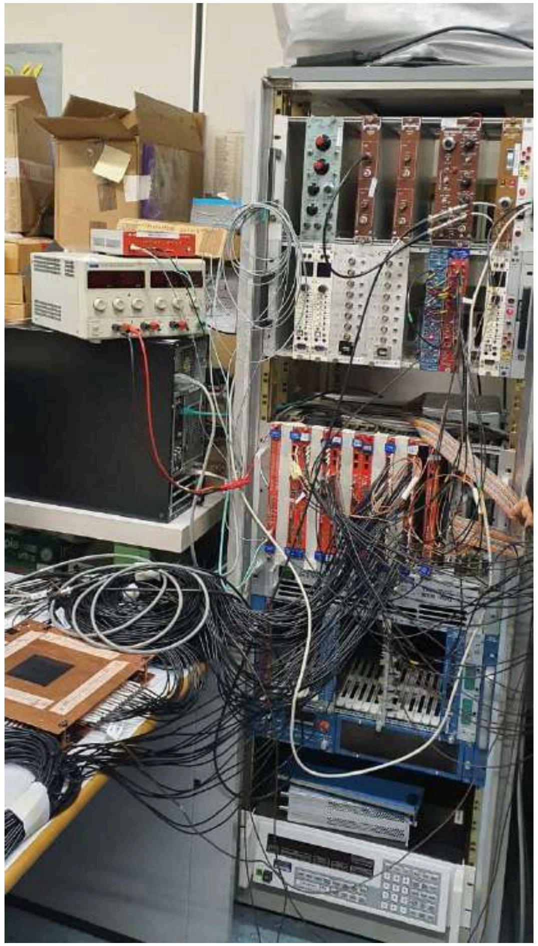




Detectors: mechanical integration

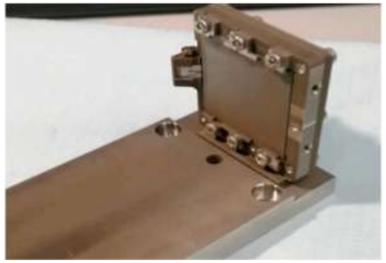


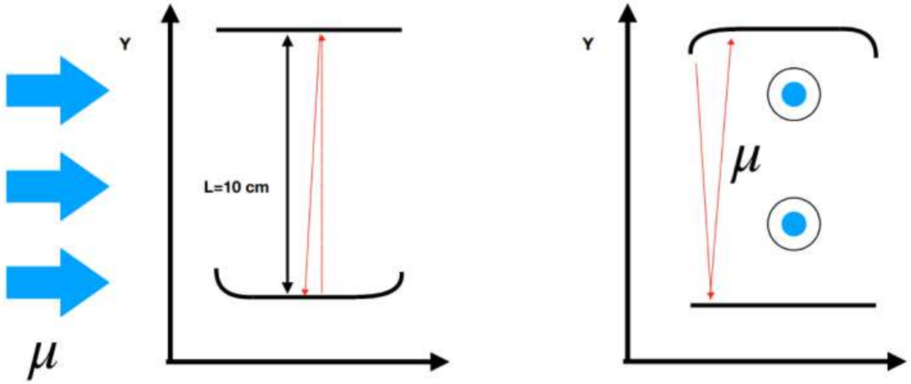
Detectors: electronical integration

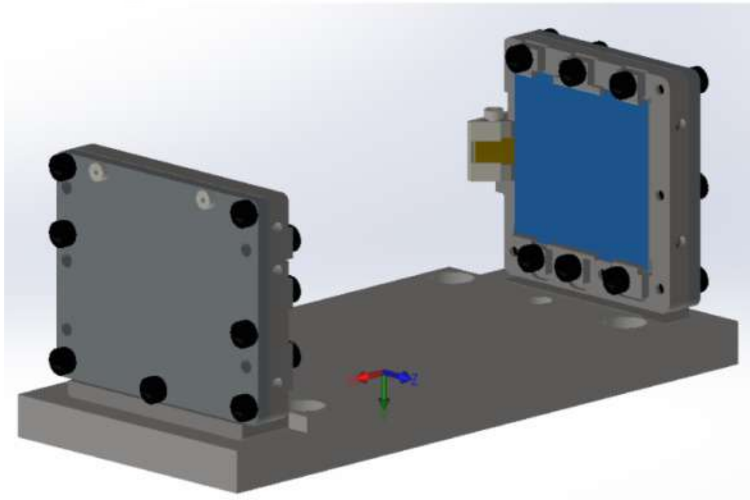


Optical cavity: design

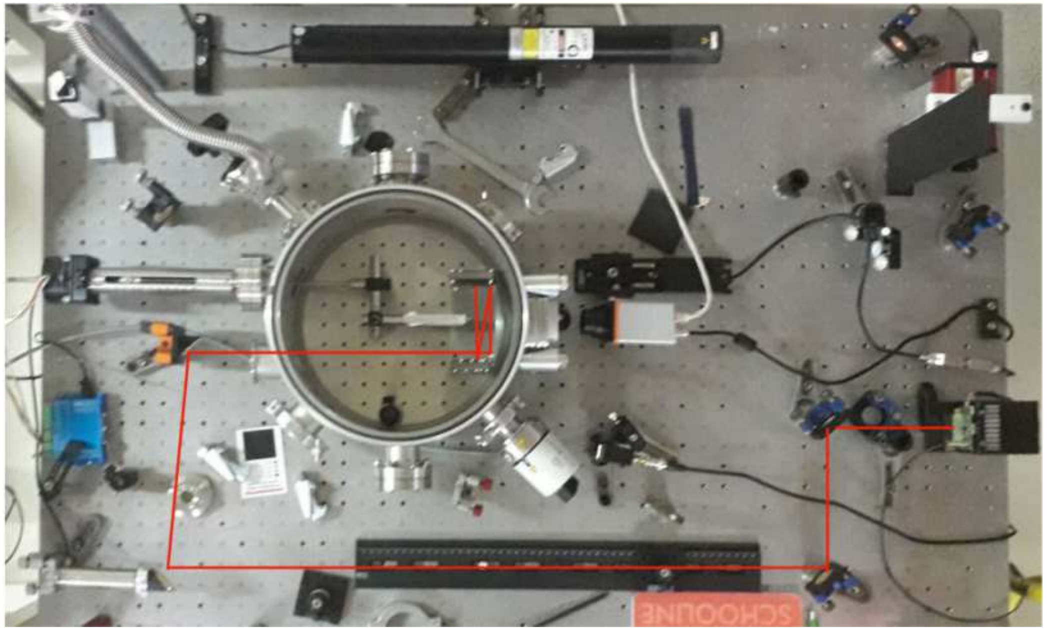
Substrate material: FuSi
HR coating: ZnS/Ge
Support: Invar (**CTE<10ppm/K**)

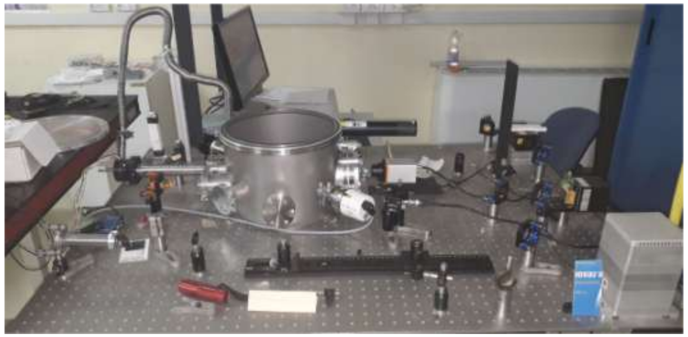






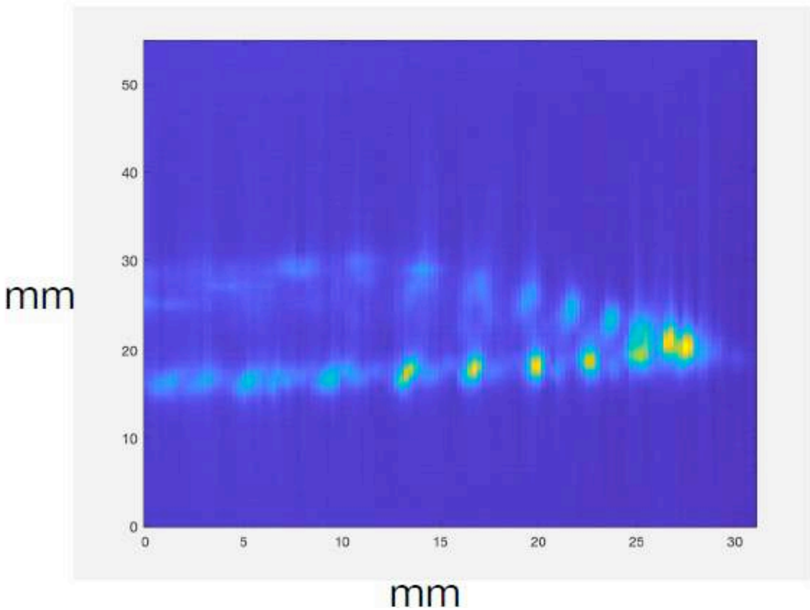
Optical cavity: characterization

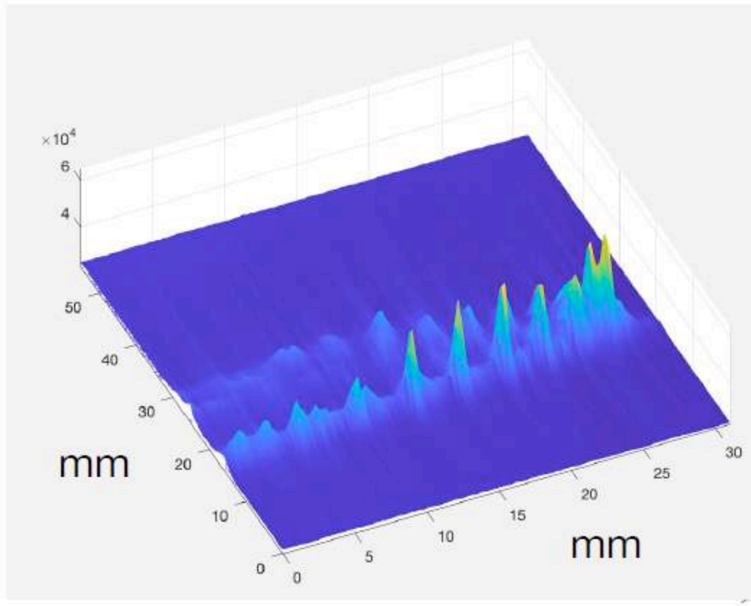




- Vacuum system
- Feedthrough with stepper motor
- Thermal imaging camera
- Tip/Tilt 0-10 mrad
- Quantum Cascade Laser λ@6.13μm (P=80 mW)
- He-Ne Laser λ@0.632μm
- Injection light system based on a telescope with two Off Axis Parabolic Mirror.

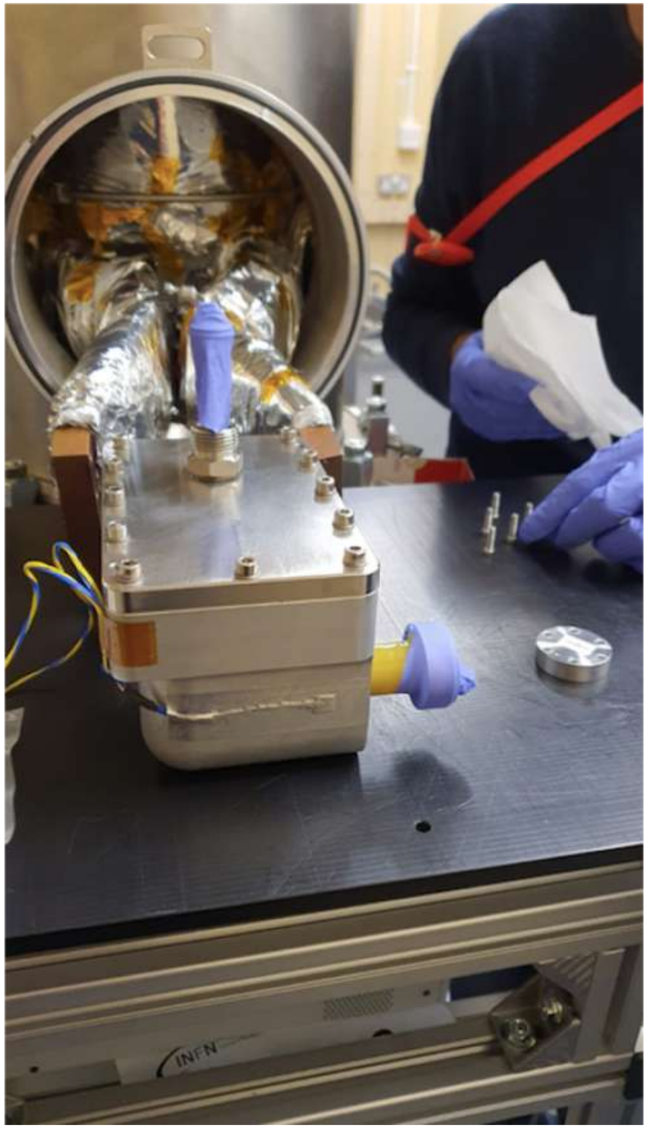
Optical cavity: characterization





The cavity number of reflections remain stable against small variations of the incident angle (tip/tilt movement)

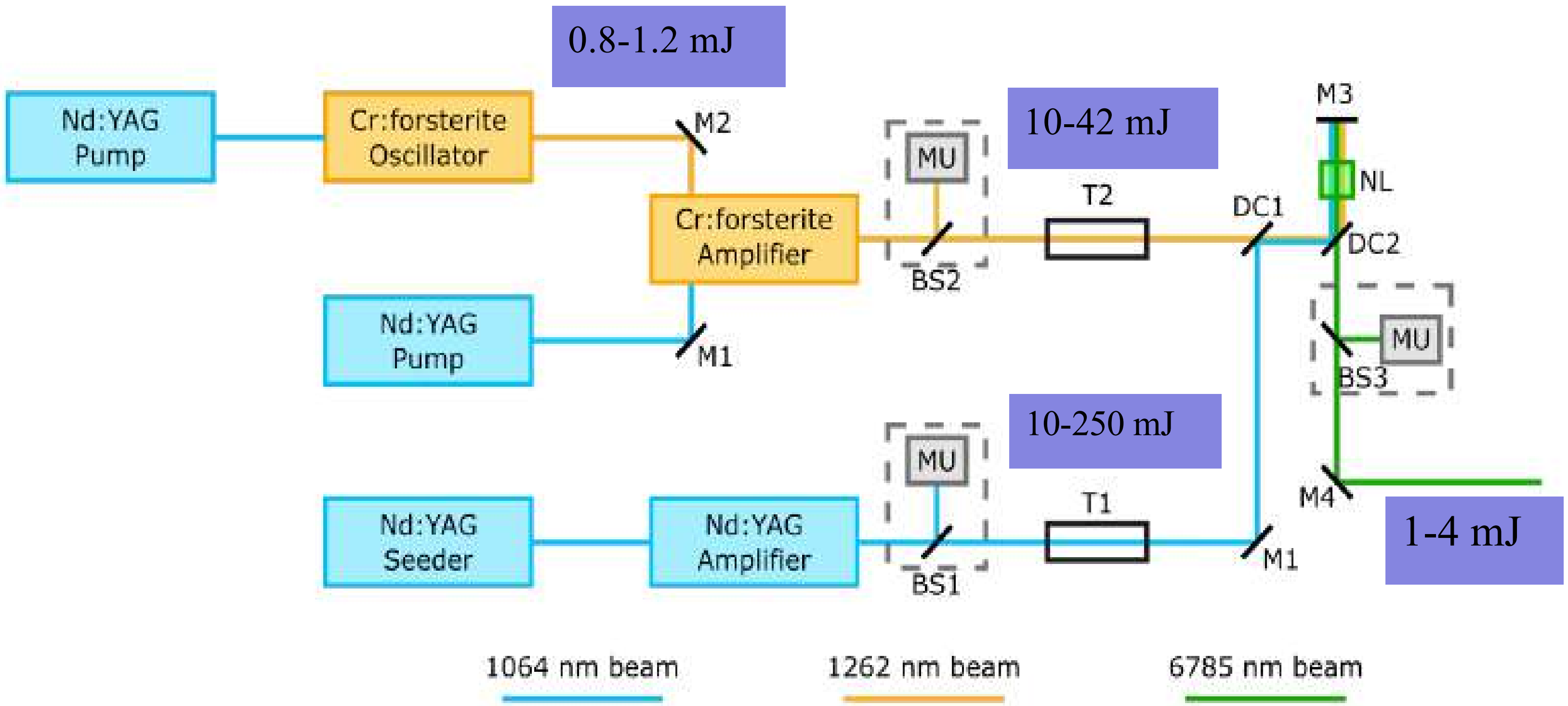

Collo 9


INFN

Laser: characteristics

Wavelength range	6800 ± 50 nm	≈ 44 THz
Energy output	> 1 mJ	up to >4 mJ
Linewidth	< 0.07 nm	450 MHz
Tunability steps	0.03 nm	200 MHz
Pulses duration	10 ns	
Repetition rate	25 Hz	

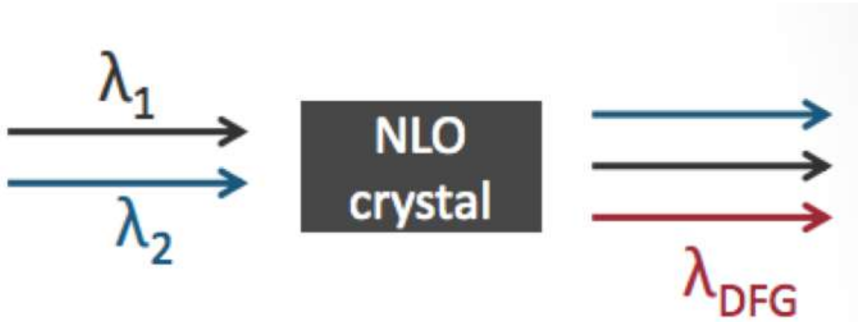
Laser: scheme



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: difference frequency generation

- Required output > 1 mJ
- Inputs: ≈70 mJ @ 1064 nm and ≈35 mJ 1262 nm
- Output Wavelength: 6758 nm



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

Laser: our NLO crystals

Nonlinear crystals

Available
$LiInS_2$ – 5x5x4 / 5x5x3
$LiInS_2$ – 5x5x15
LGS – 5x5x4 mm
$LiInS_2$ - 7x7x20 mm / 8x8x18
$LiInSe_2$ - 7x7x15 mm
$BaGa_4Se_7$ – 10 x 9 x 28 mm, 6 x 6 x 6 mm

Energies:
$LiInS_2$ & $LiInSe_2$: 1.3 – 1.5 mJ (double pass)
$BaGa_4Se_7$ ≈1.5 mJ (single pass)

Laser: frequency measurement

6785 nm wavelength meter

-Center wavelength accuracy 200 MHz

1262 and 1064 nm wavelength meter

-Center wavelength accuracy 60 MHz @ 1064 nm

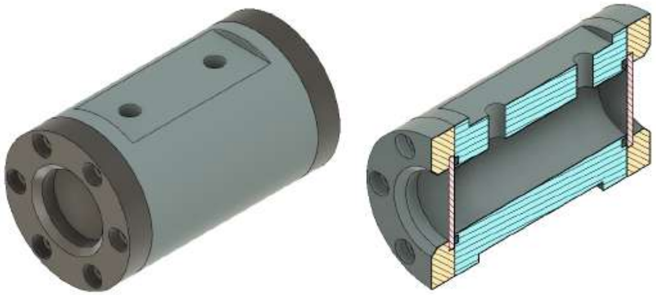
-Center wavelength accuracy 40 MHz @ 1262 nm

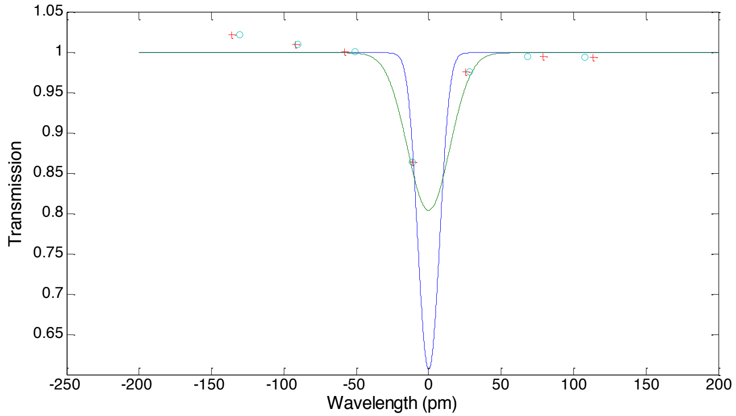
Overall accuracy better than:

6800.000 ± 0.020 nm

44.0871 ± 0.0001 THz

Laser: absolute calibration cell

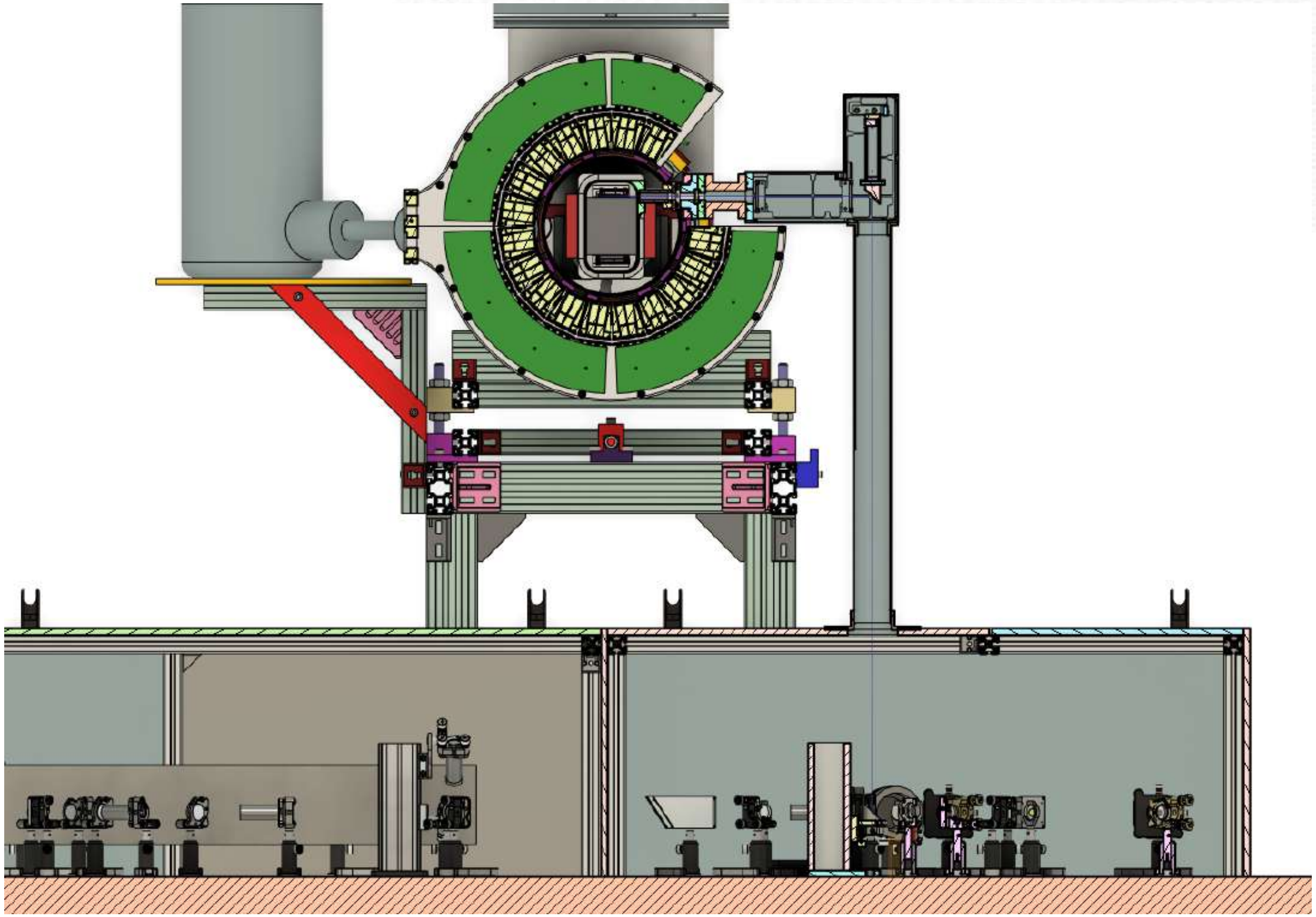




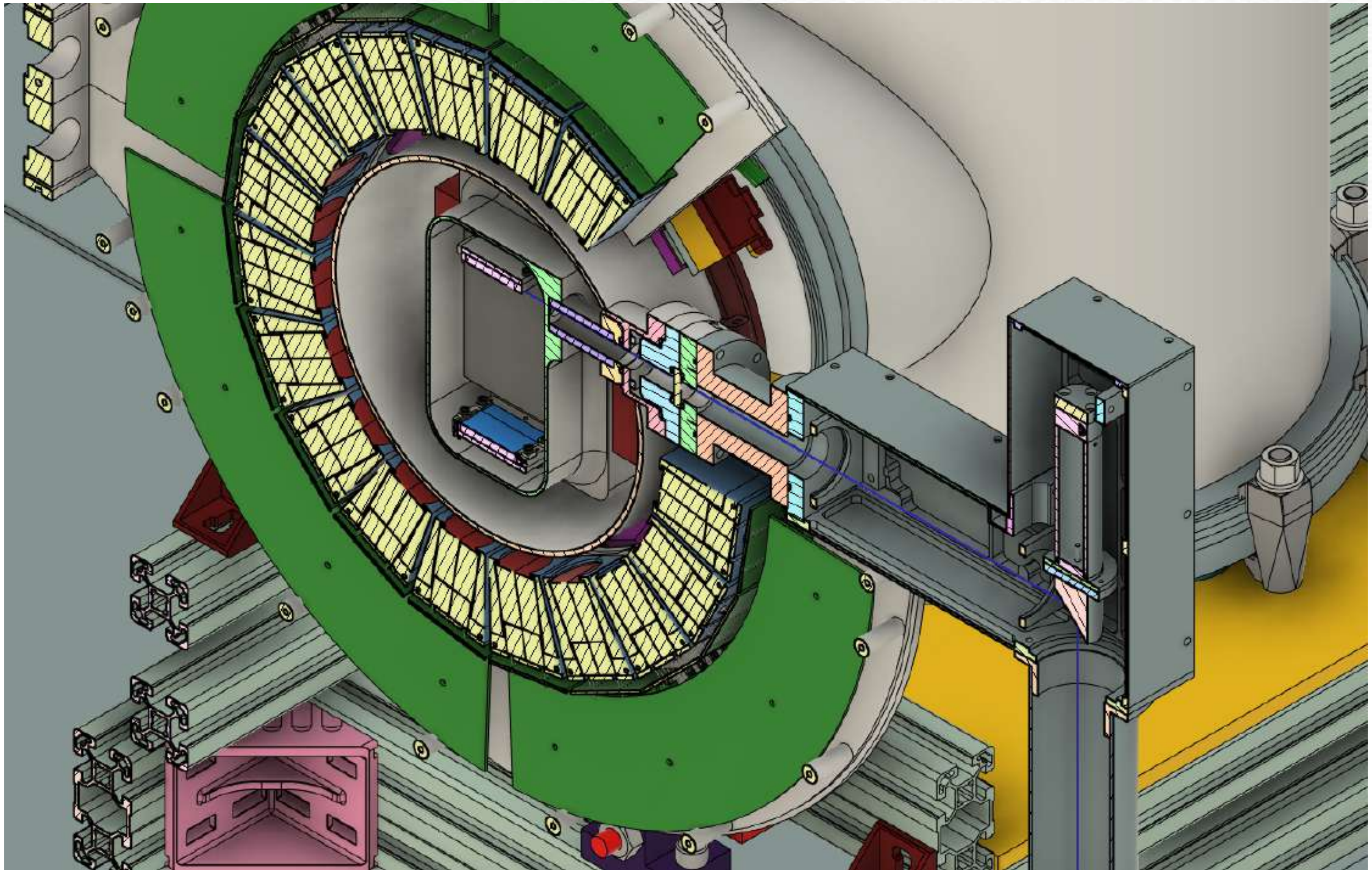
C_2H_4 absorption cell

Accuracy (comparing to HITRAN database):
from ±10 to ±140 MHz
depending on the absorption line

Laser injection



Laser injection



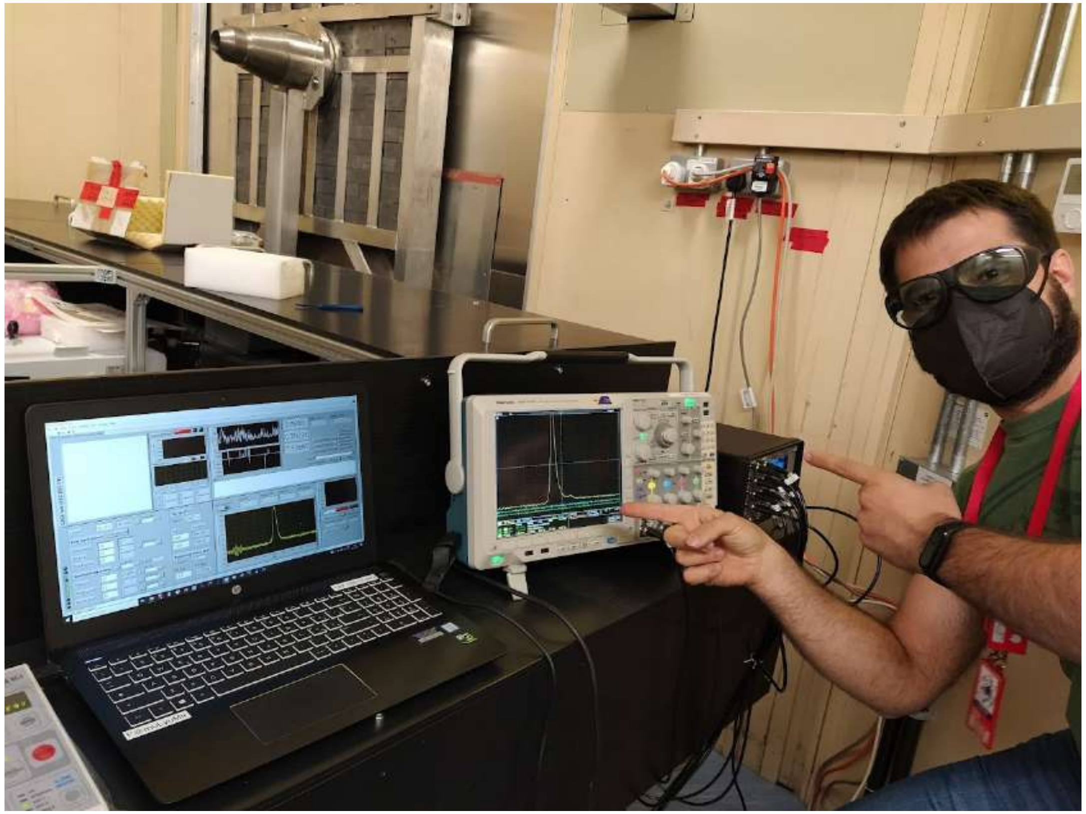
Laser status @ RAL

Laser system remain untouched for about 2 years… maintenance needed!

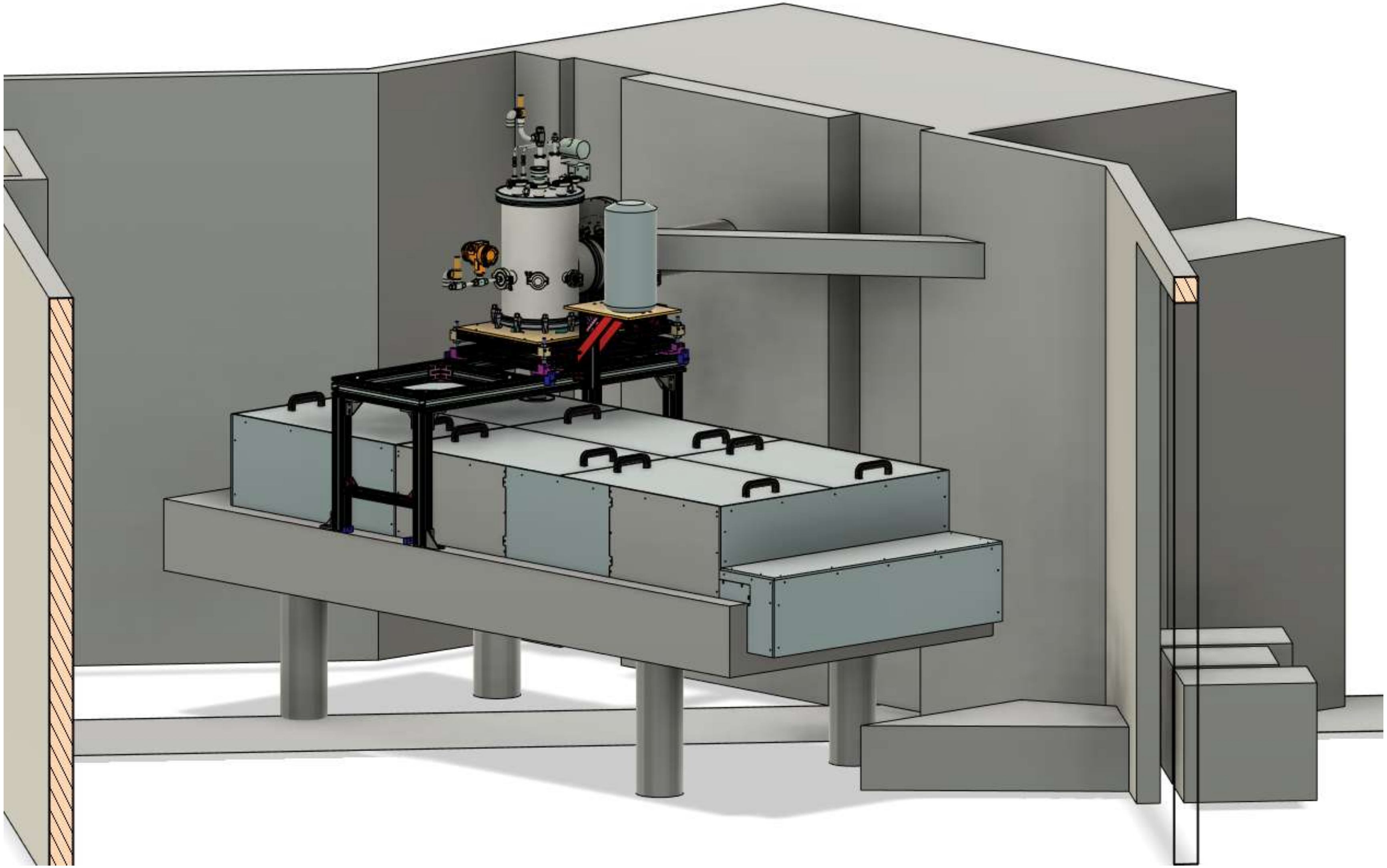
- Lotis (Belarus) lasers refurbished and restarted (thanks to RAL staff!)
- Innolas lasers restarted by contractor technician

- DFG and cavity calibration setup to be completed

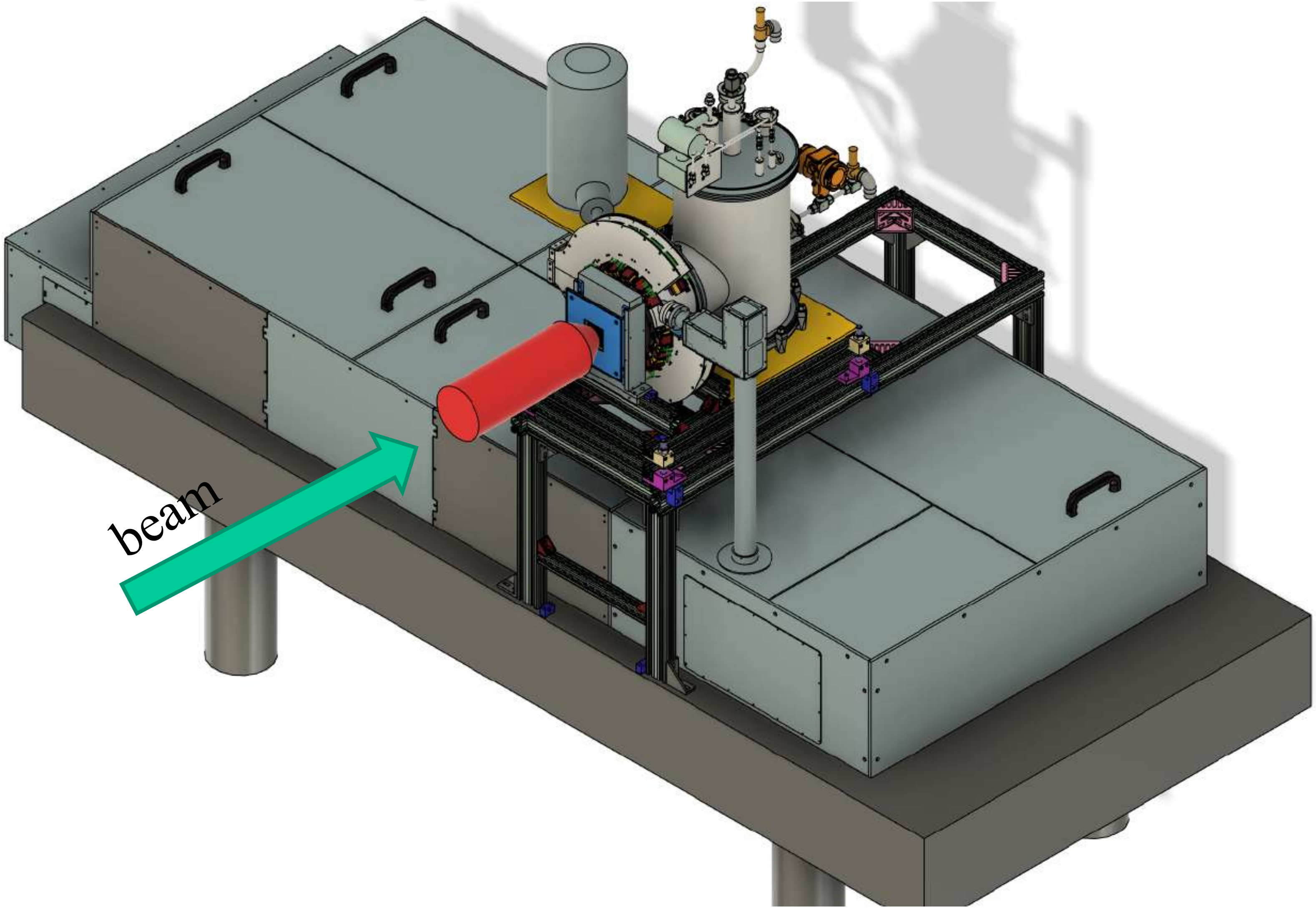
Laser status @ RAL



FAMU setup Riken RAL Port 1



FAMU setup



Measurement plan

- Zemach radius present measurement range: ≈[1.00,1.12] fm → ≈30 GHz range
- Natural Doppler broadening @80K ≈300 MHz

➡ at least 100 steps to cover the whole range with 300 MHz steps…

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The first already allocated beam time for FAMU sum up to 25 days.

We'll start with 24 hours for one frequency measurement (conservative approach)

Scan of the most probable signal range

Time scale
some month delay on this original planning

by end of June: refurbishment of muon line at RAL ends

04-05 July: Innolas technician at RAL to power on our lasers

by July 15th: all equipment at RAL

15-31 July: installation of target and DAQ system starts

1-20 September: installation of detectors and the target on the beam line

today we are about here

3rd ISIS Cycle 2022 [20 September – 15 October]: (test of our system)

4th ISIS Cycle 2022 [8 November – 16 December]: our data taking was planned in this cycle, but will be delayed towards 2023 first months

Summary

FAMU: measurement of the $(\mu^{-}p)_{1S}$ hyperfine splitting

An exciting journey:

- started *25 years ago*
- *one of the most intense pulsed beam* in the world
- *best detectors* for energy and time observation
- *first measurement* of the energy dependence of muon transfer rate to Oxygen
- *innovative* and powerful laser system

Target, detectors, cavity, laser, everything is ready to go

Looking forward to perform the spectroscopic measurement within the first months of 2023!

Thank you!