The FAMU experiment: present status
(amid Brexit, pandemic, accelerator long shutdown, and war)

Emiliano Mocchiutti
on behalf of the FAMU Collaboration

PREN2022 Convention

Paris – 20/23 June 2022

Outline

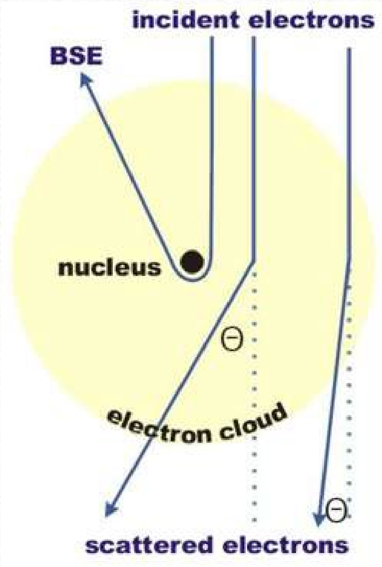
- Introduction
- The FAMU experiment: principle of operation
- Apparatus setup & present status
- Summary

Introduction

FAMU: HFS of μ^-p ground level

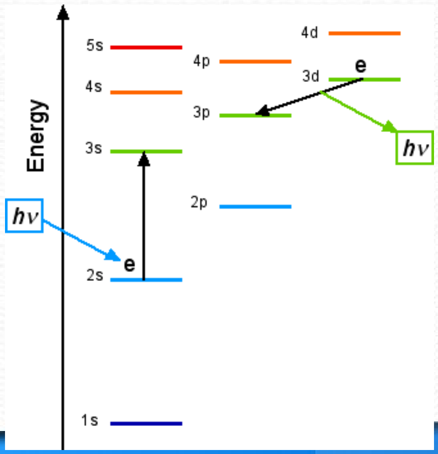
Study of the properties of the proton

1) scattering: electron experiments
2) scattering: elastic muon-proton



3) spectroscopy: electronic atoms and ions
4) spectroscopy: exotic atoms

HFS of muonic hydrogen ground level



FAMU: a bumpy path…

Data taking planned for March 2020

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Hit hard by pandemic!

… moved to September 2020

… then December 2020

… then June 2021

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The FAMU experiment

Fisica Atomi MUonici (Physics with muonic atoms)

FAMU: μ^-p spectroscopy

"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...

HFS de-excitation: μ^-p gains kinetic energy

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

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

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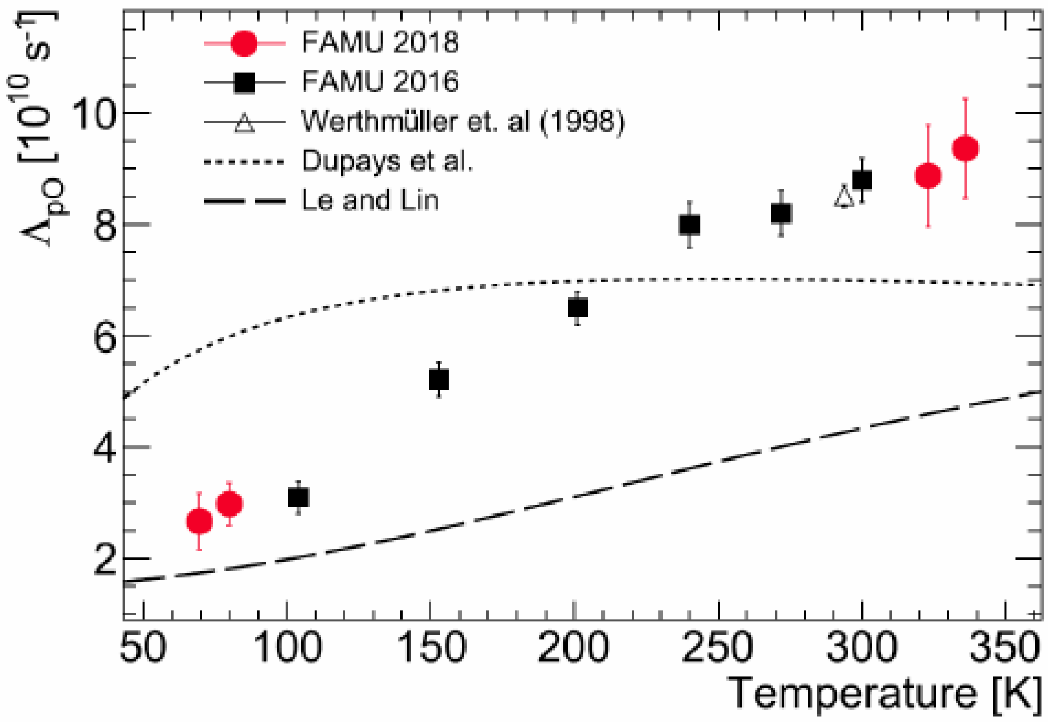
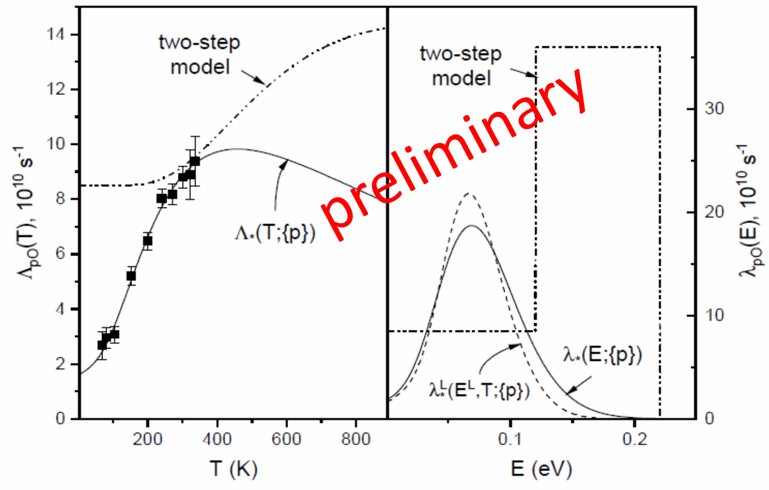
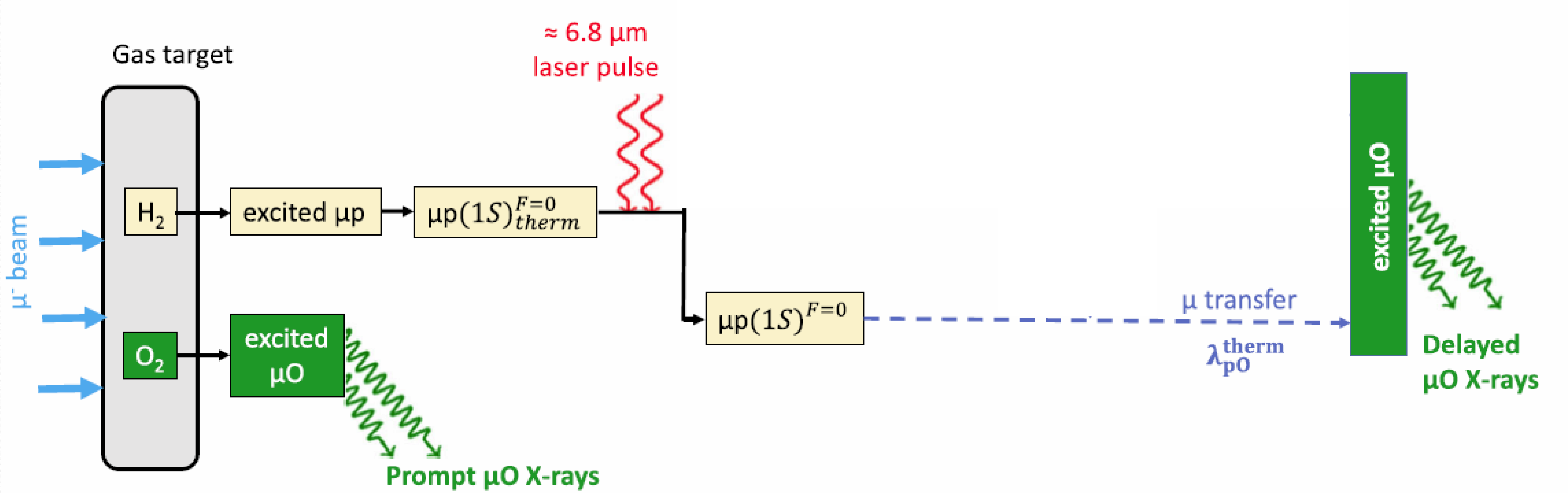
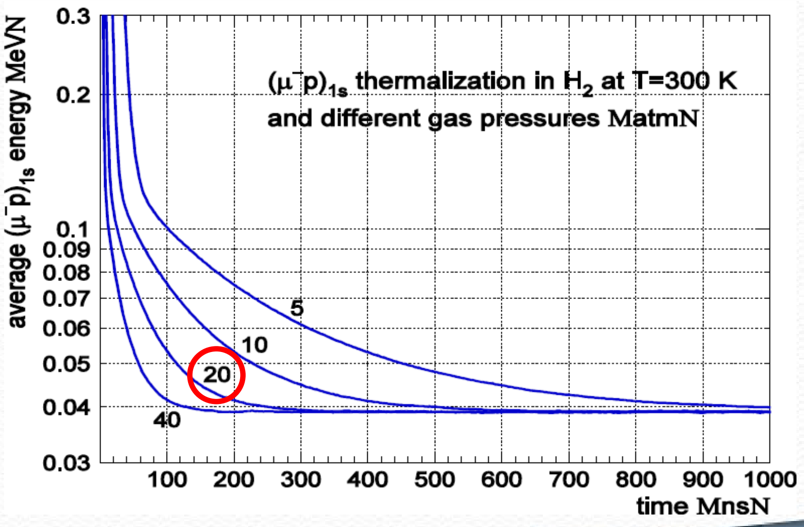




Oxygen transfer rate
C.Pizzolotto et al., Phys. Lett. A 403 (2021) 127401
E.Mocchiutti et al., Phys. Lett. A 384 (2020) 126667

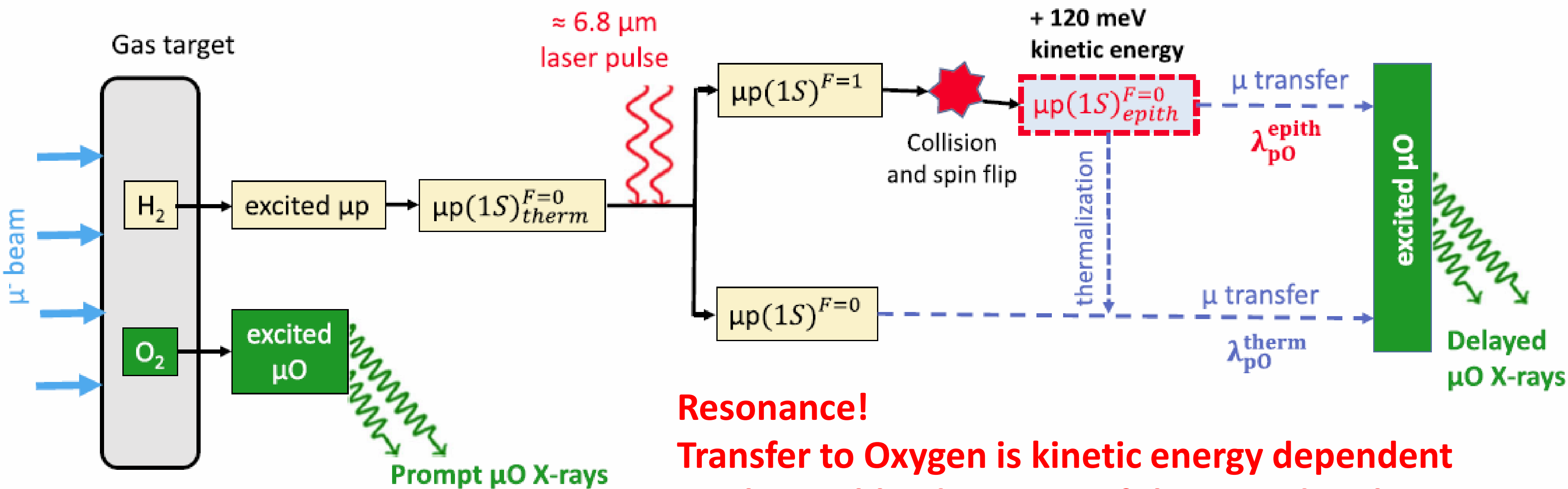
FAMU: μ⁻p spectroscopy





out of resonance

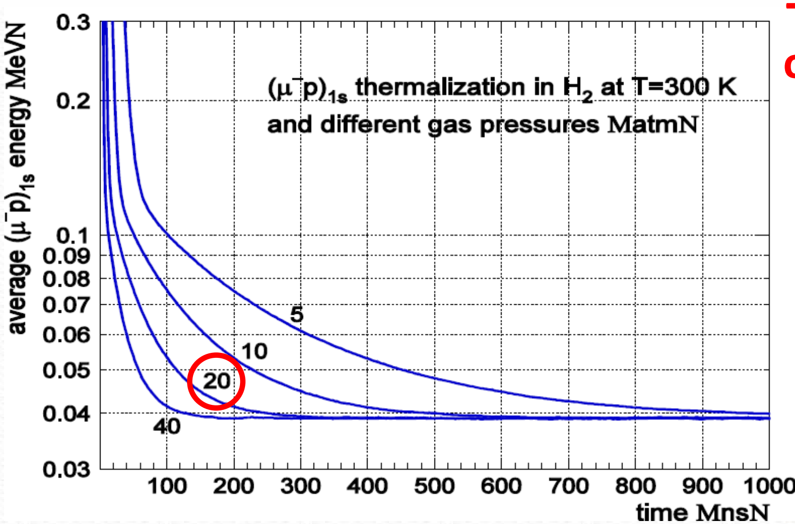
FAMU: μ⁻p spectroscopy

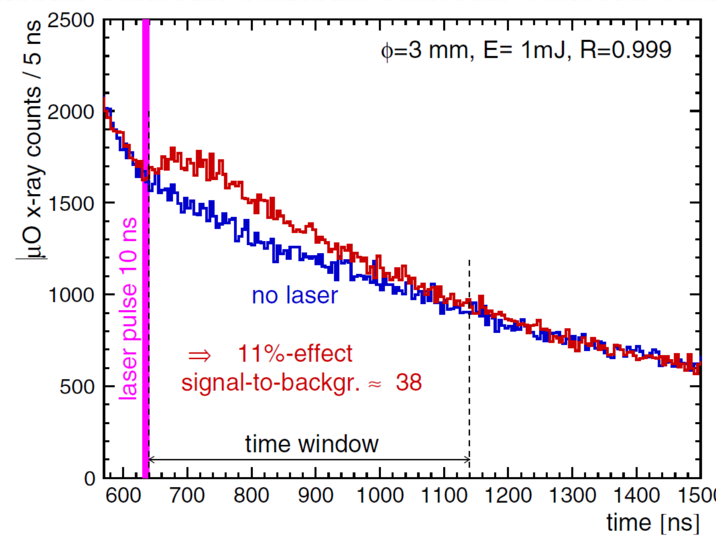


Resonance!

Transfer to Oxygen is kinetic energy dependent

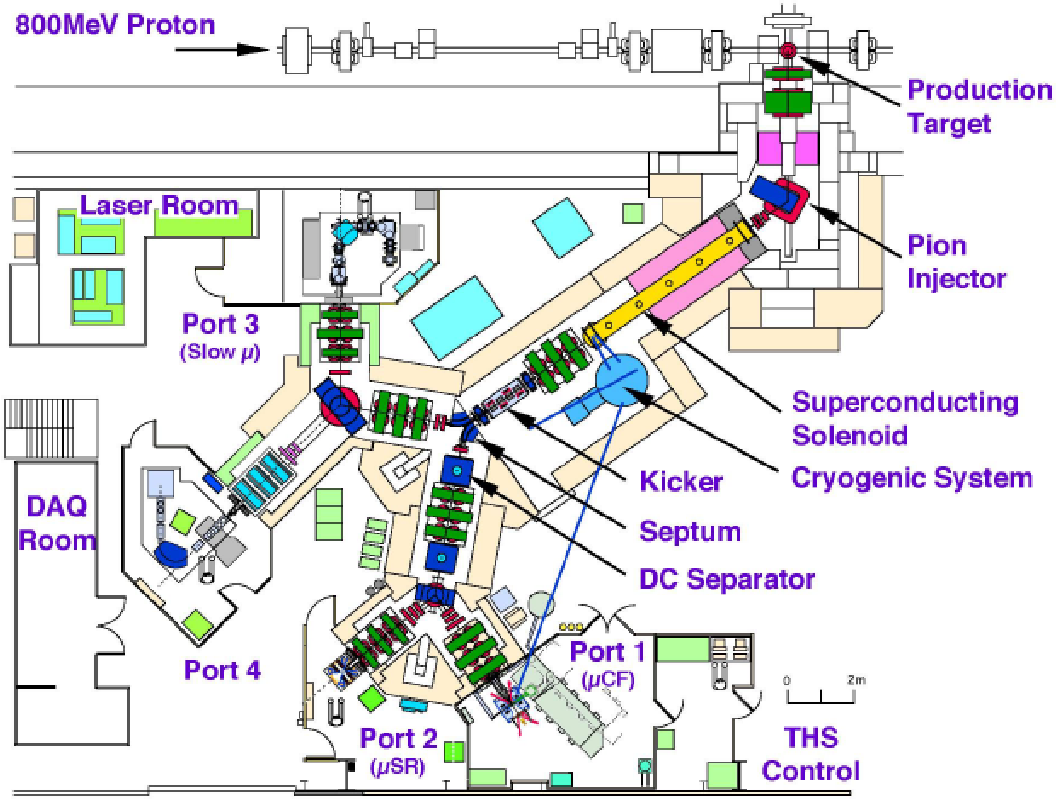
→ observable: distortion of the time distribution of delayed signal



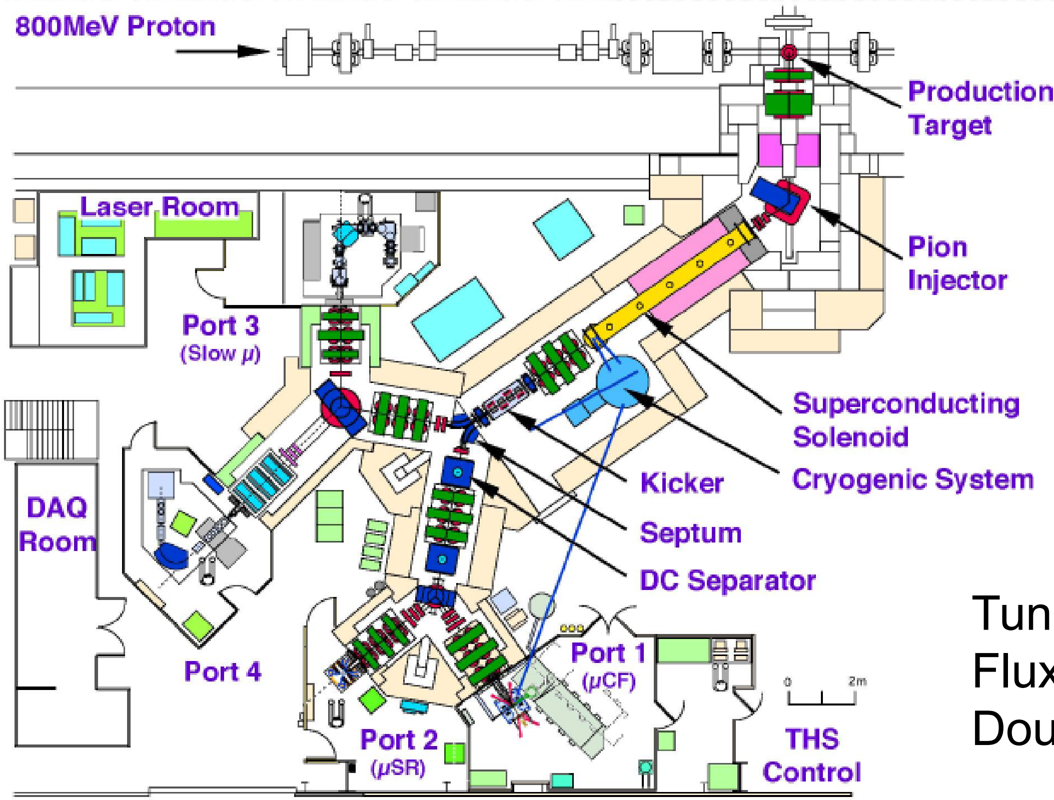


RIKEN – RAL muon facility

Rutherford Appleton Laboratory – Oxfordshire UK
ISIS proton accelerator



High intensity muon beam

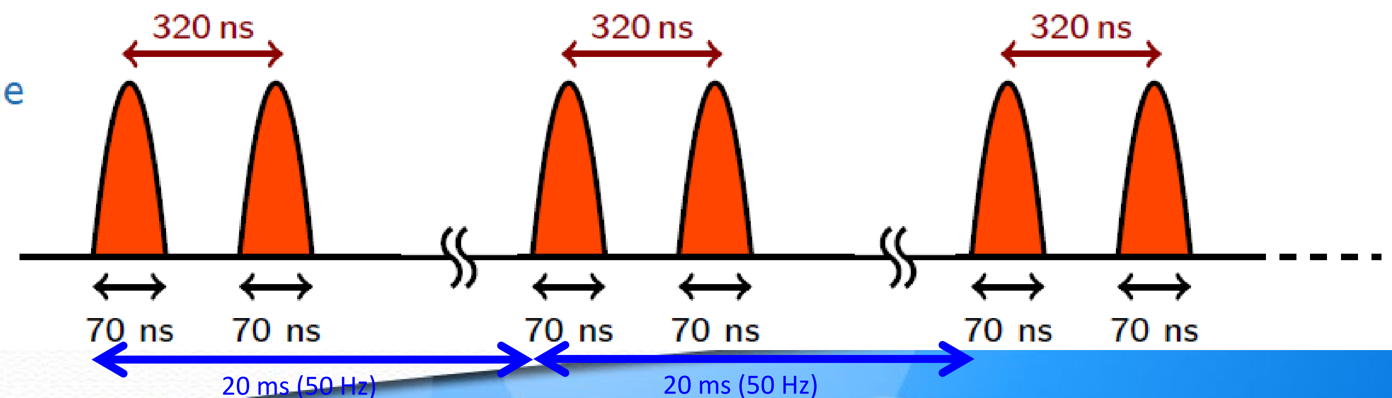


Tunable momentum: 20 – 120 MeV/c

Flux μ^- : ≈10^5 muons/s

Double pulsed beam

Beam time structure



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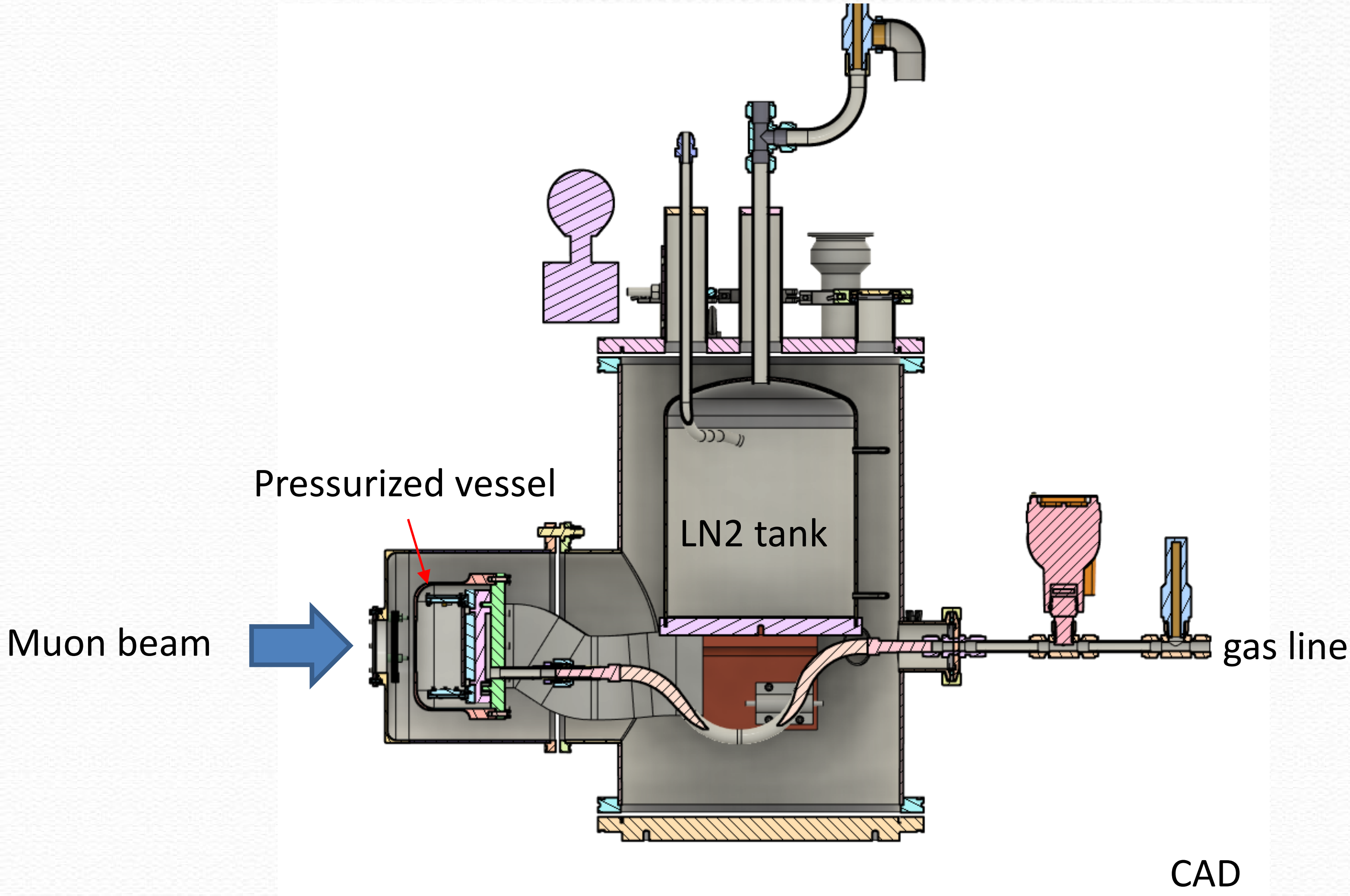
- Operating temperature: liquid nitrogen ≈80 K
- Operating pressure: ≈10 bar
- International safety certification (Directive 97/23/CE PED)
- H_2 compatible

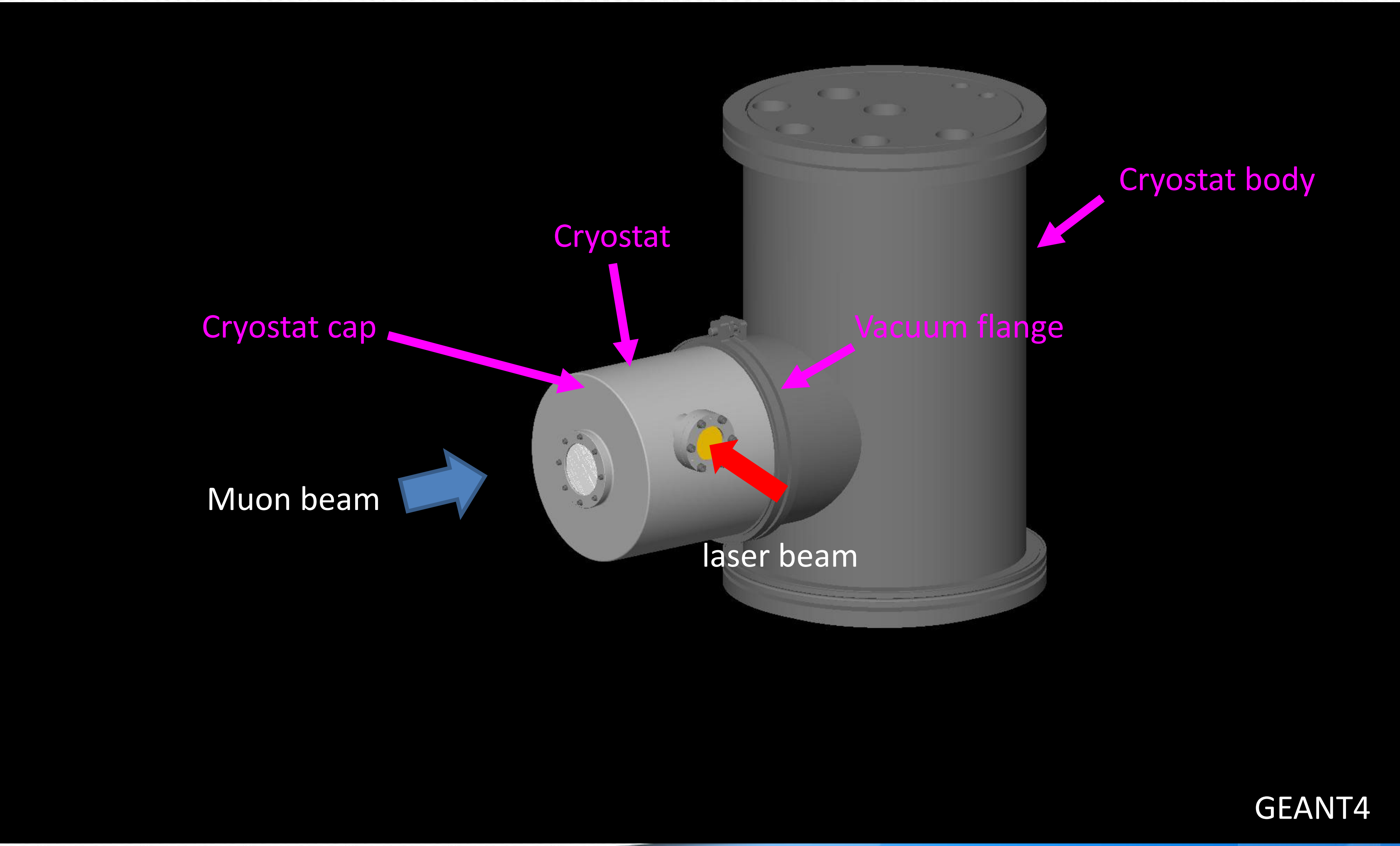
- Very big (to improve statistics) and very small (to increase laser photon density, given a maximum laser power available)
- Made of very heavy materials (to minimize noise in the delayed phase) and of very light materials (to allow X-rays exit)

... and, of course, all the above within time and cost constraints!

Target: the design



Target: GEANT4 simulation



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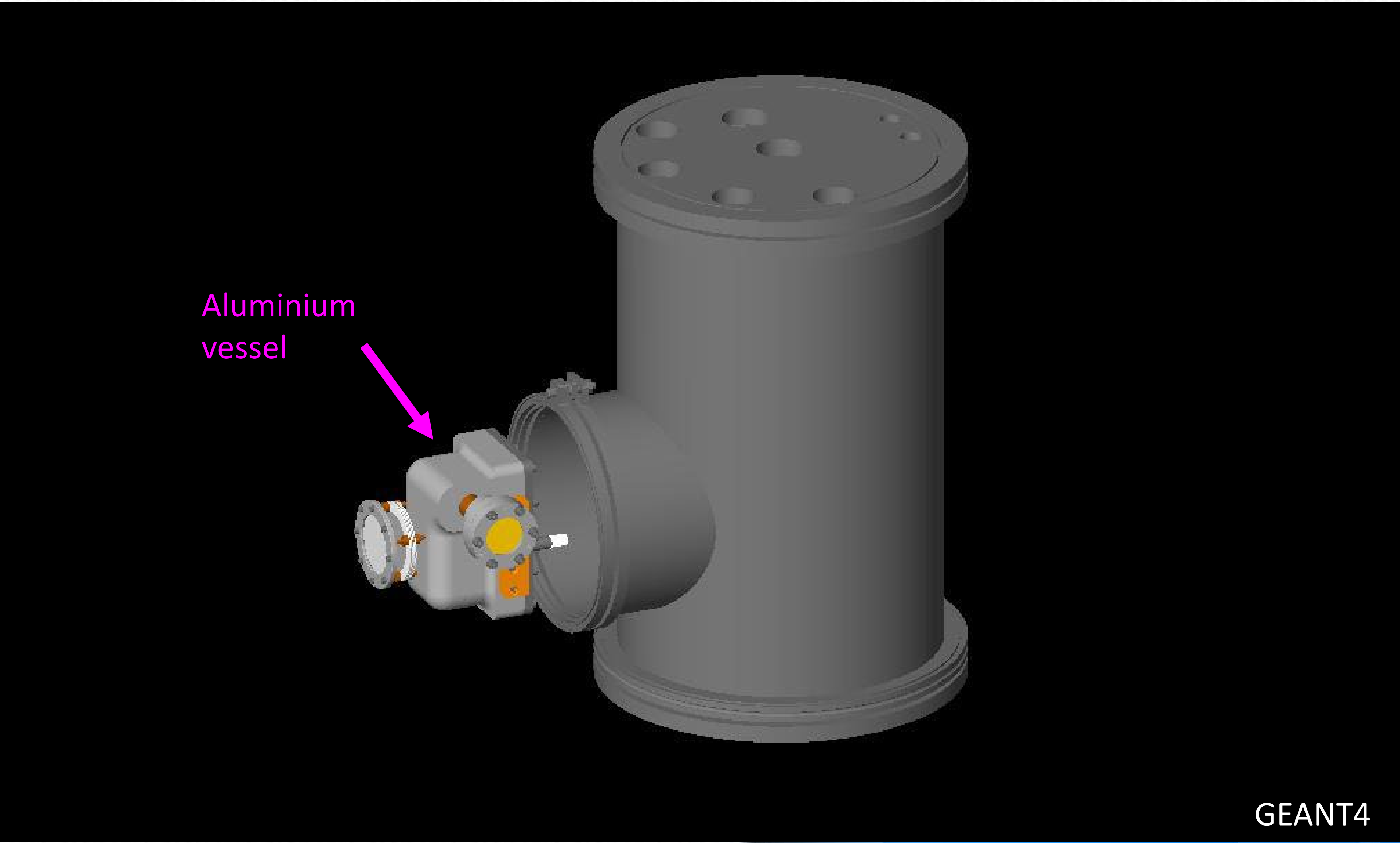

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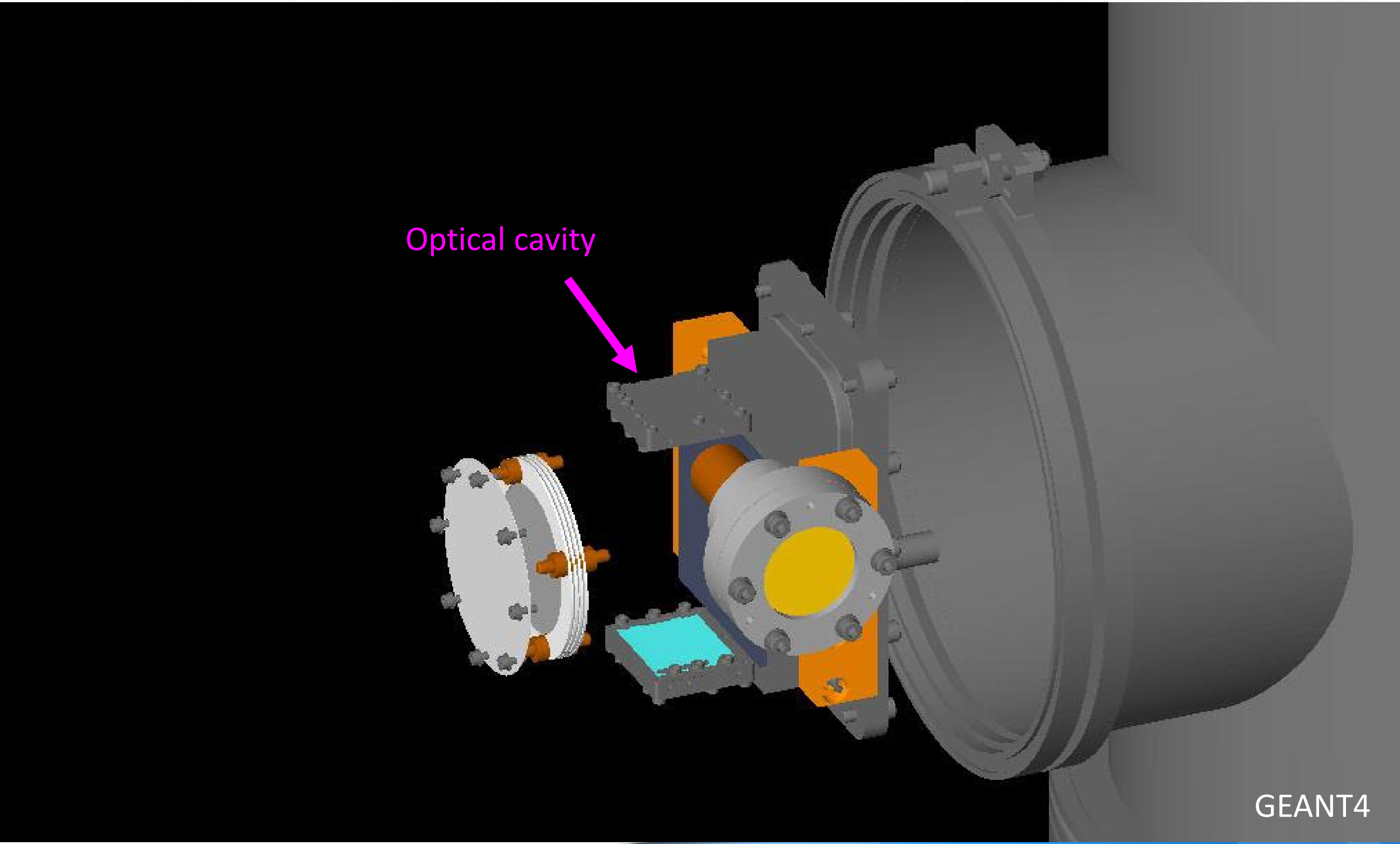

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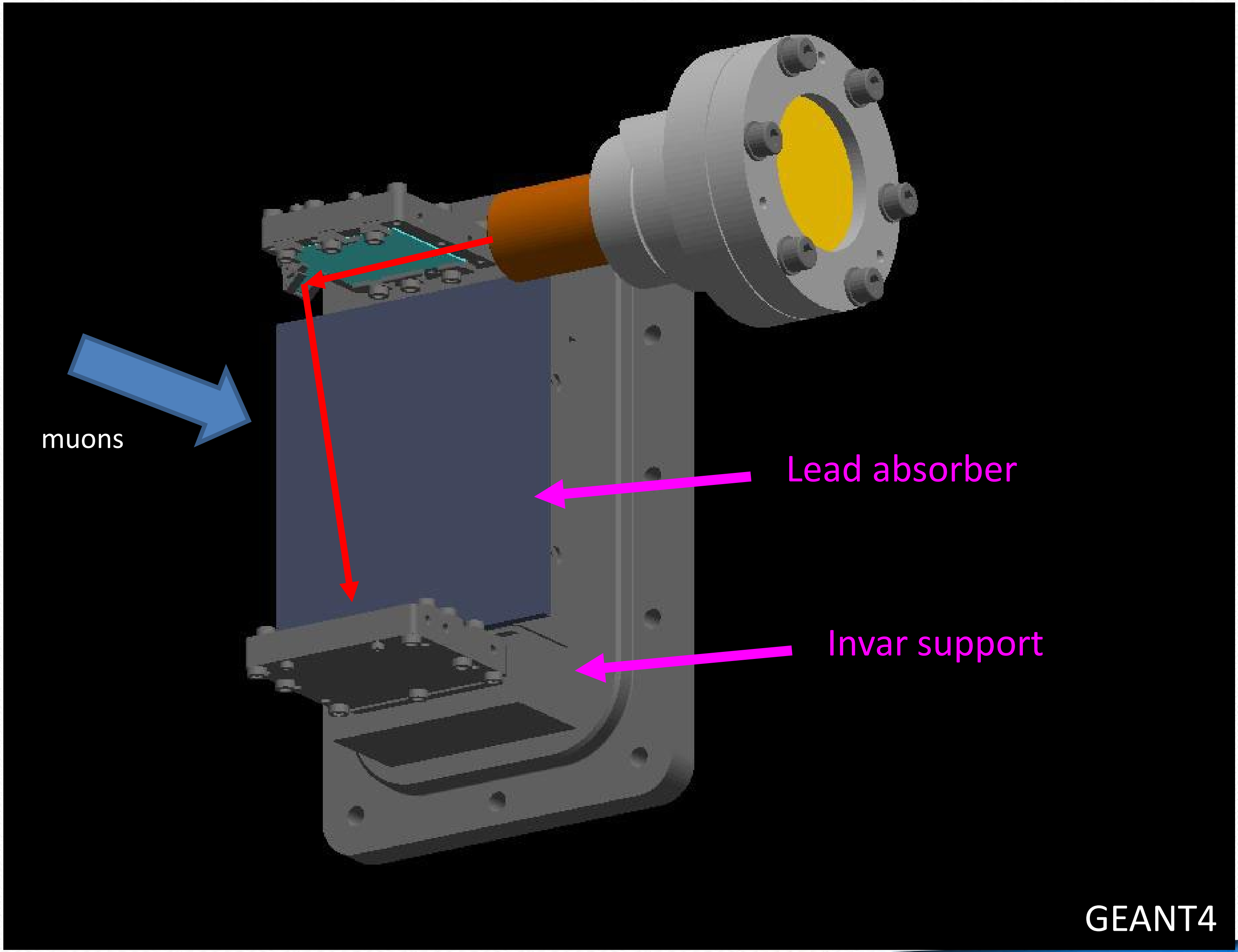

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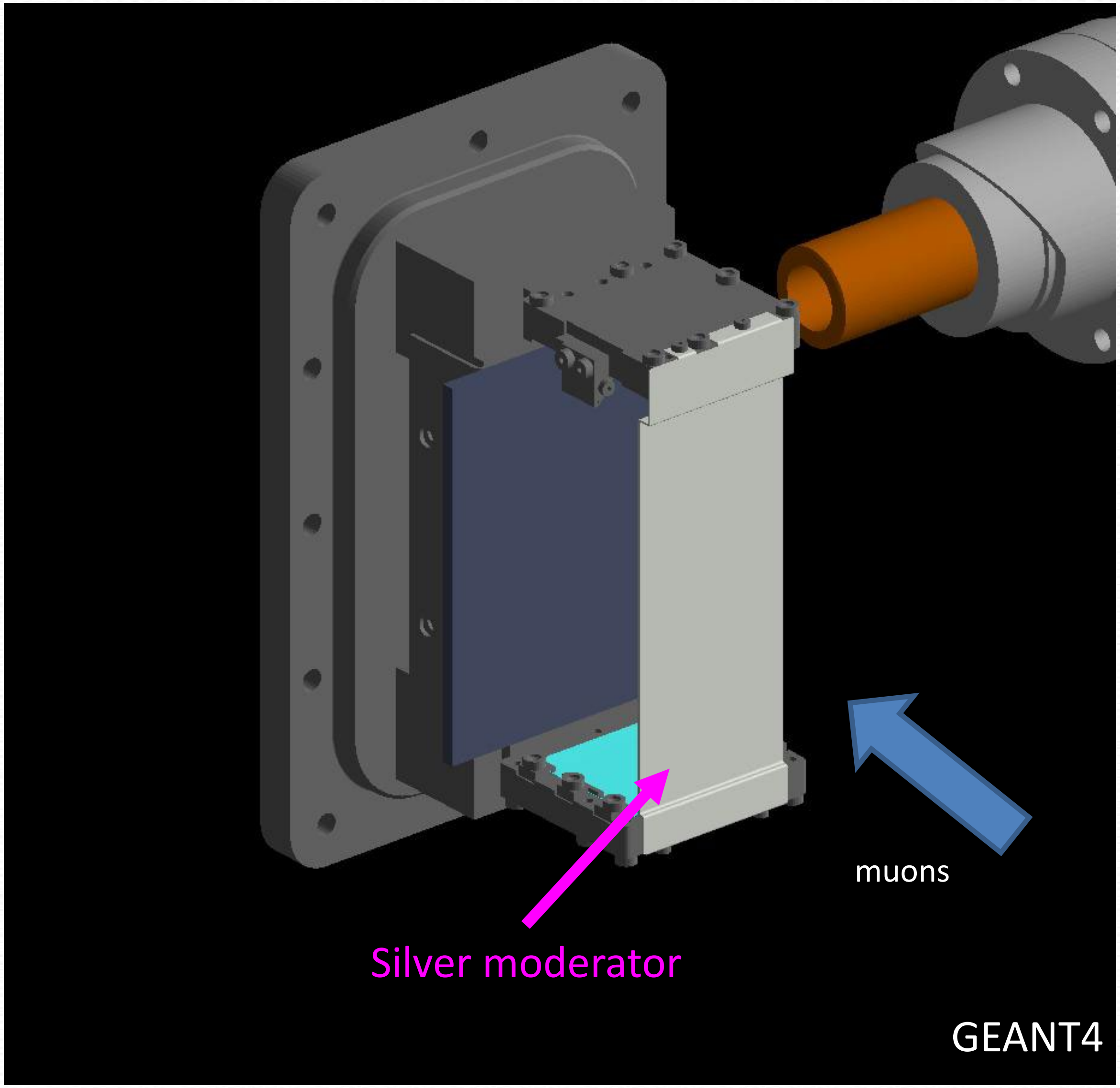
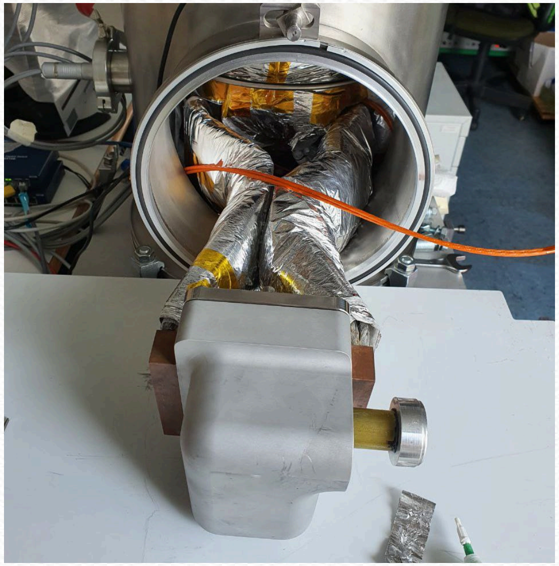
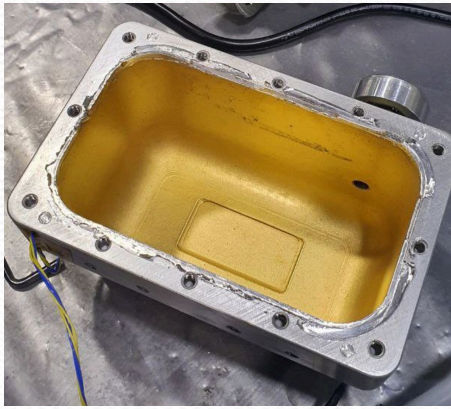
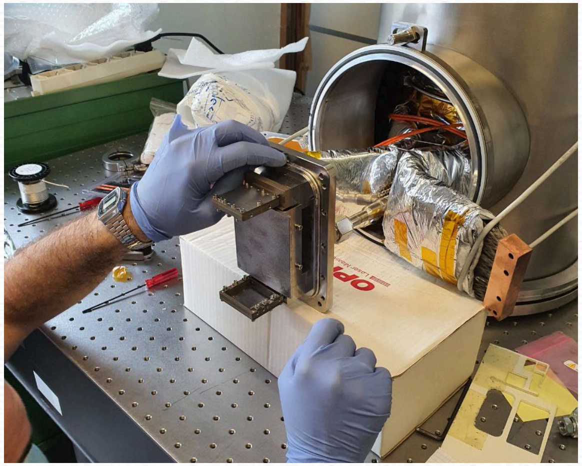
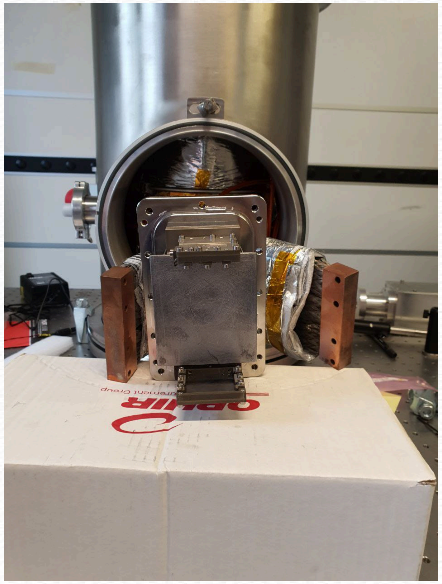


Target: ready in our lab

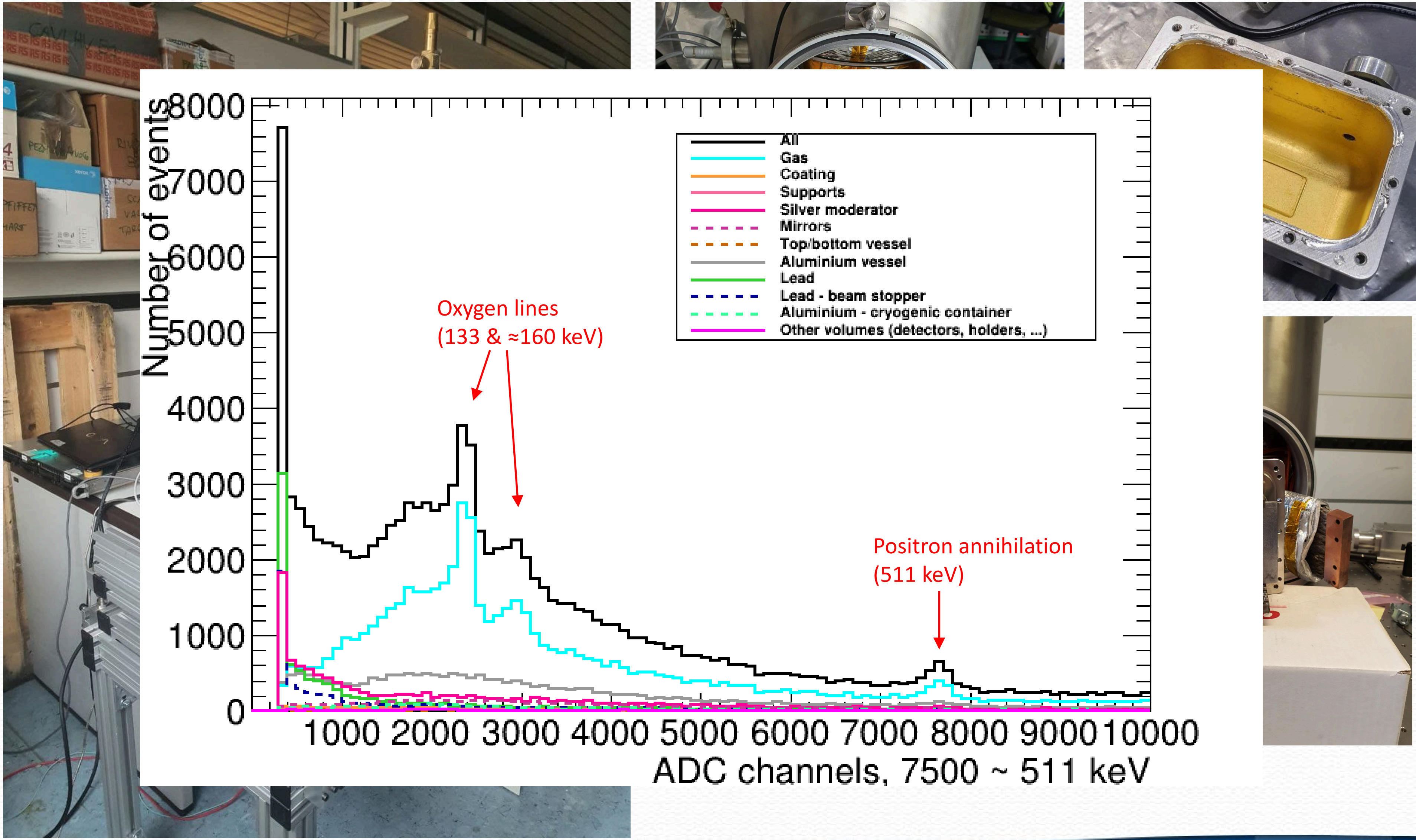








Target: expected energy spectrum



Detectors

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

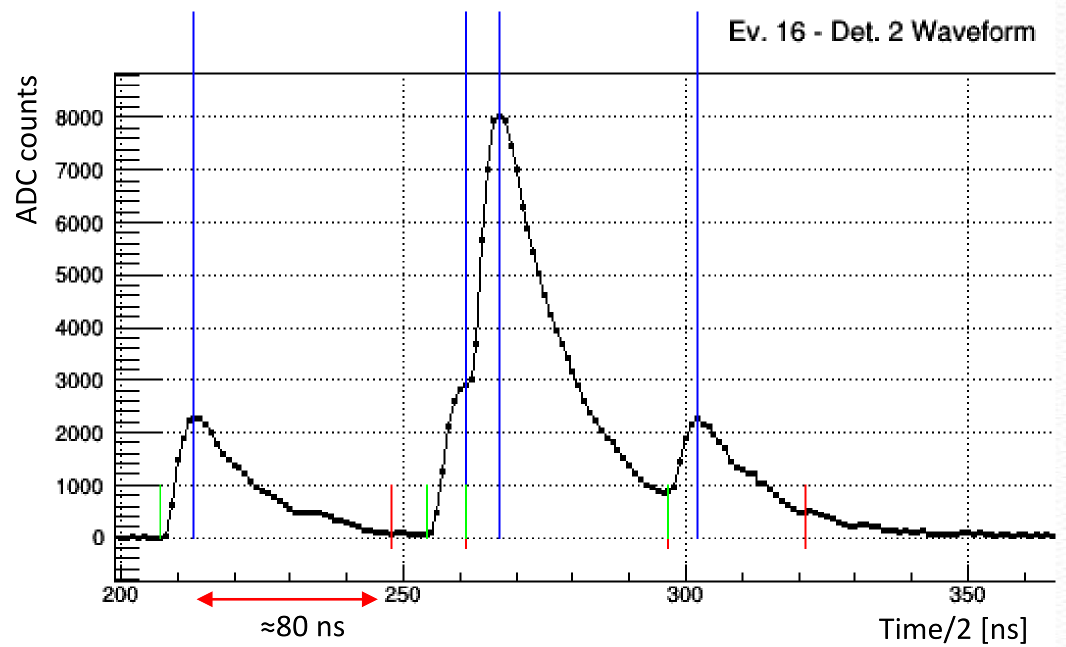
17 LaBr3:Ce 1’’ read by PMT

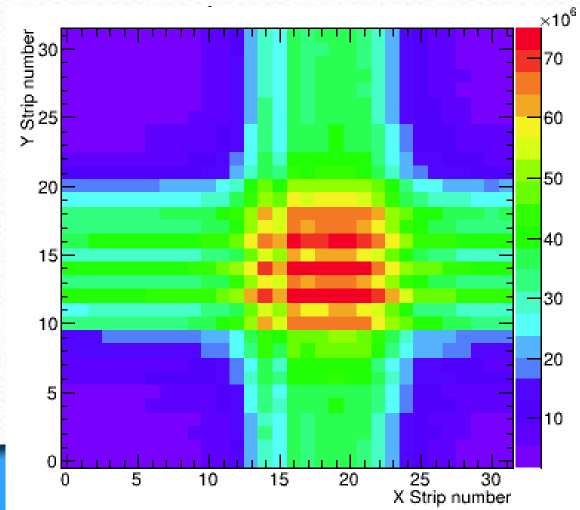
11 LaBr3:Ce 1’’ read by SiPM

15 LaBr3:Ce ½’’ read by SiPM

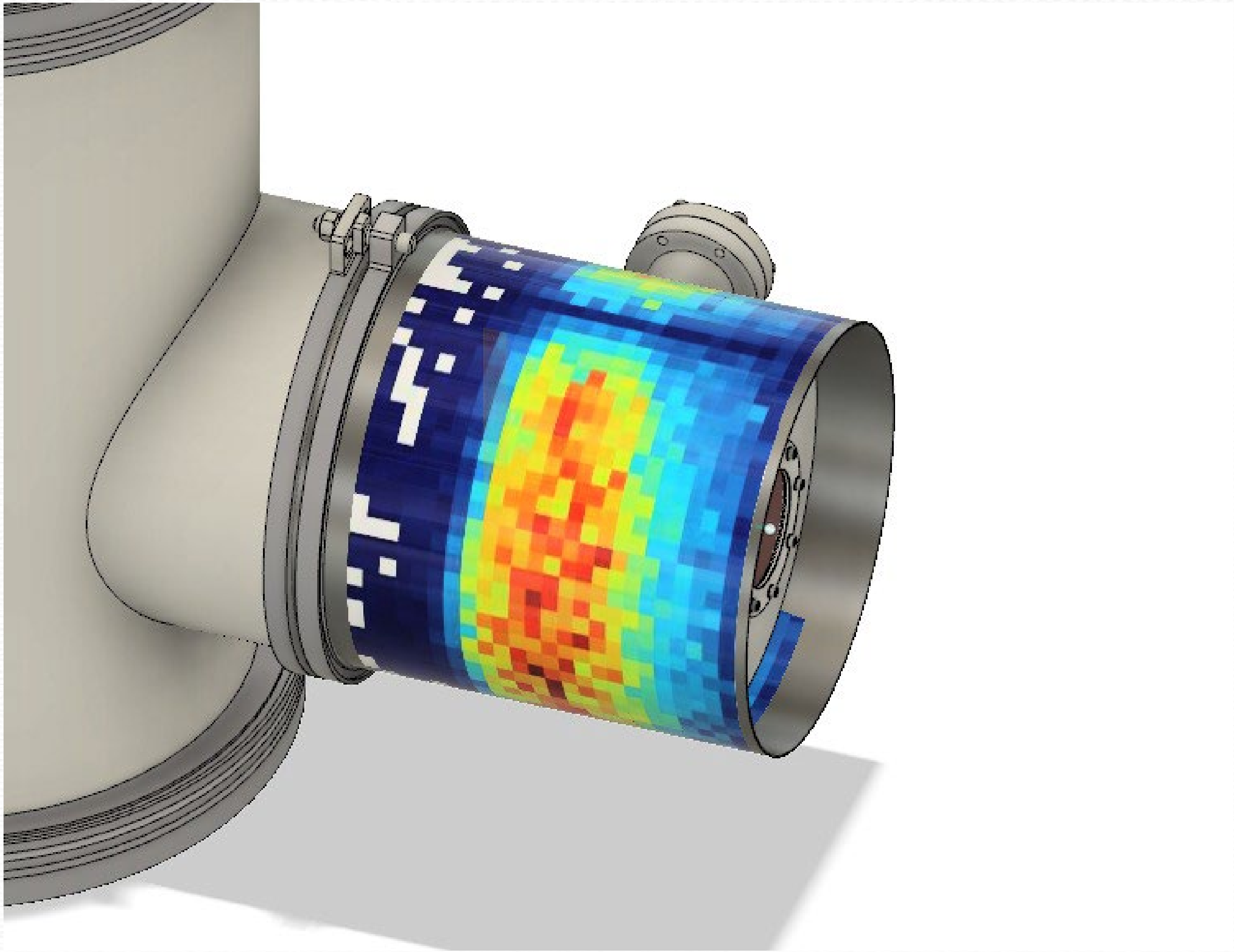
1 HPGe (Ortec GEM-S)

1 hodoscope for beam monitoring (64 channels, 1 mm square fibers read by SiPM)

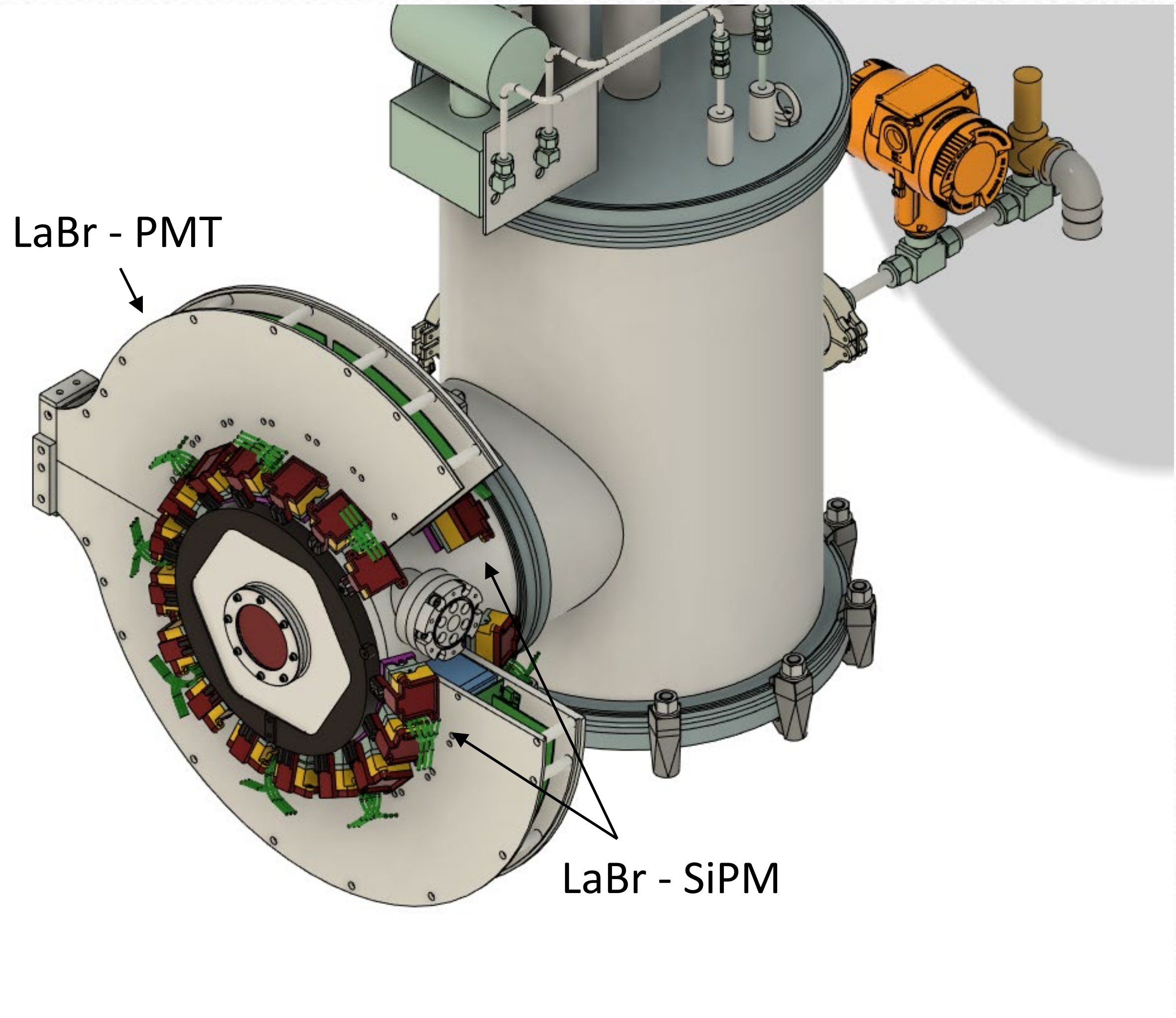


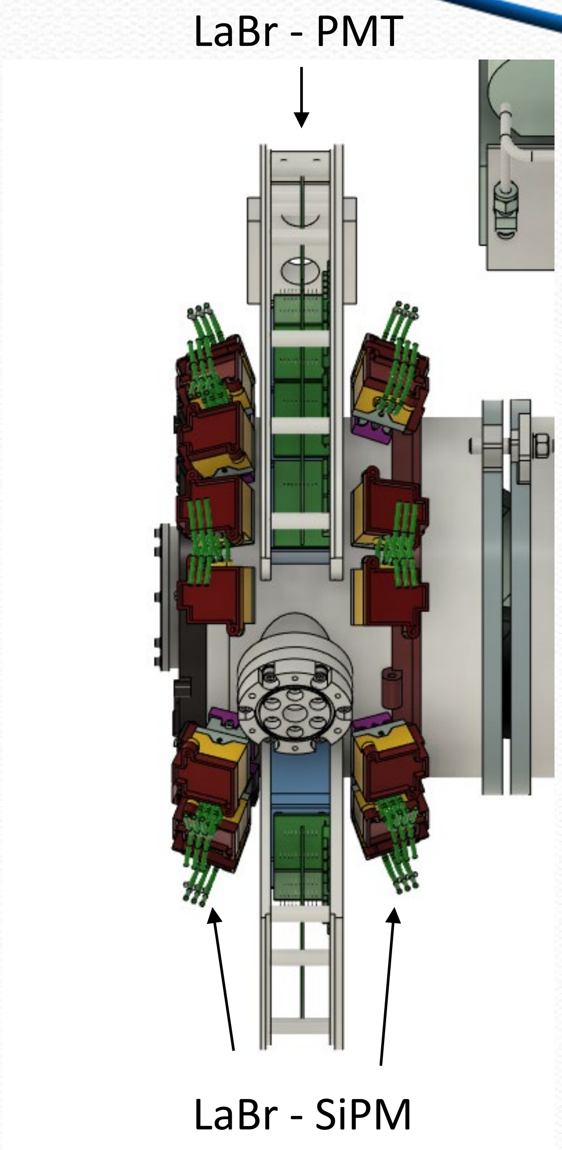


X-rays distribution from simulation

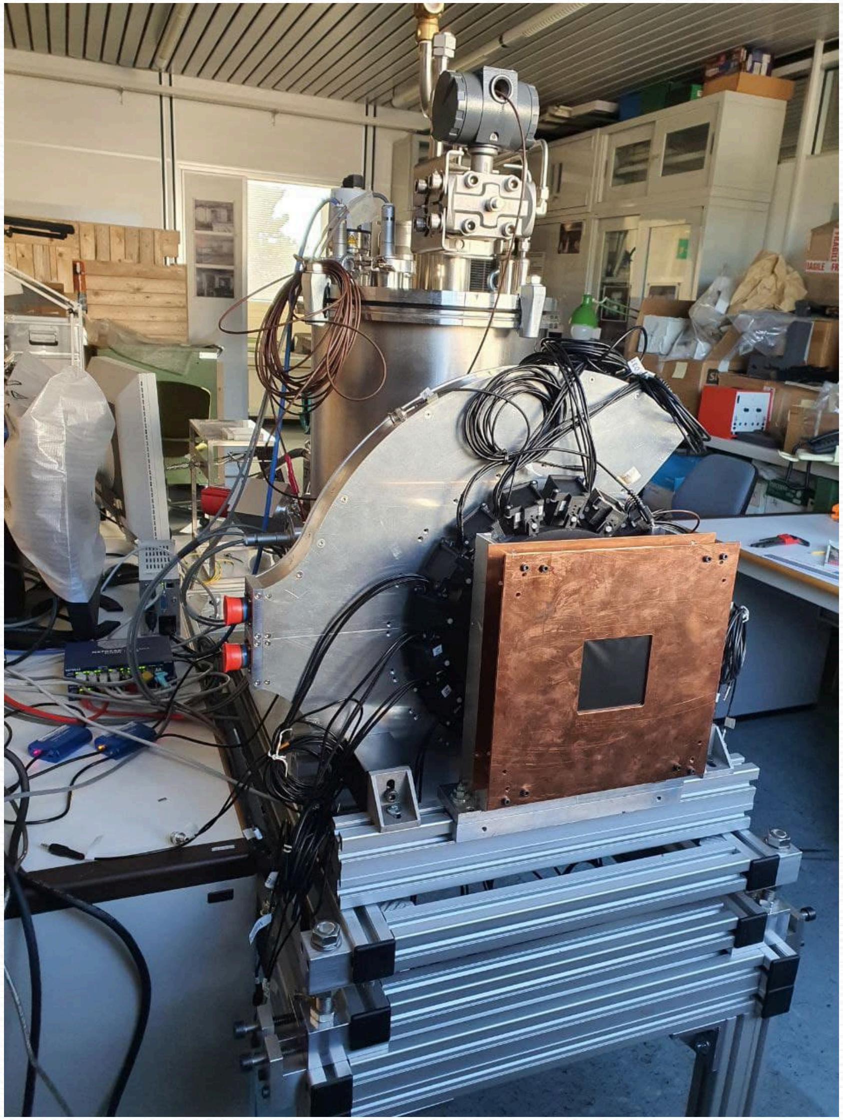


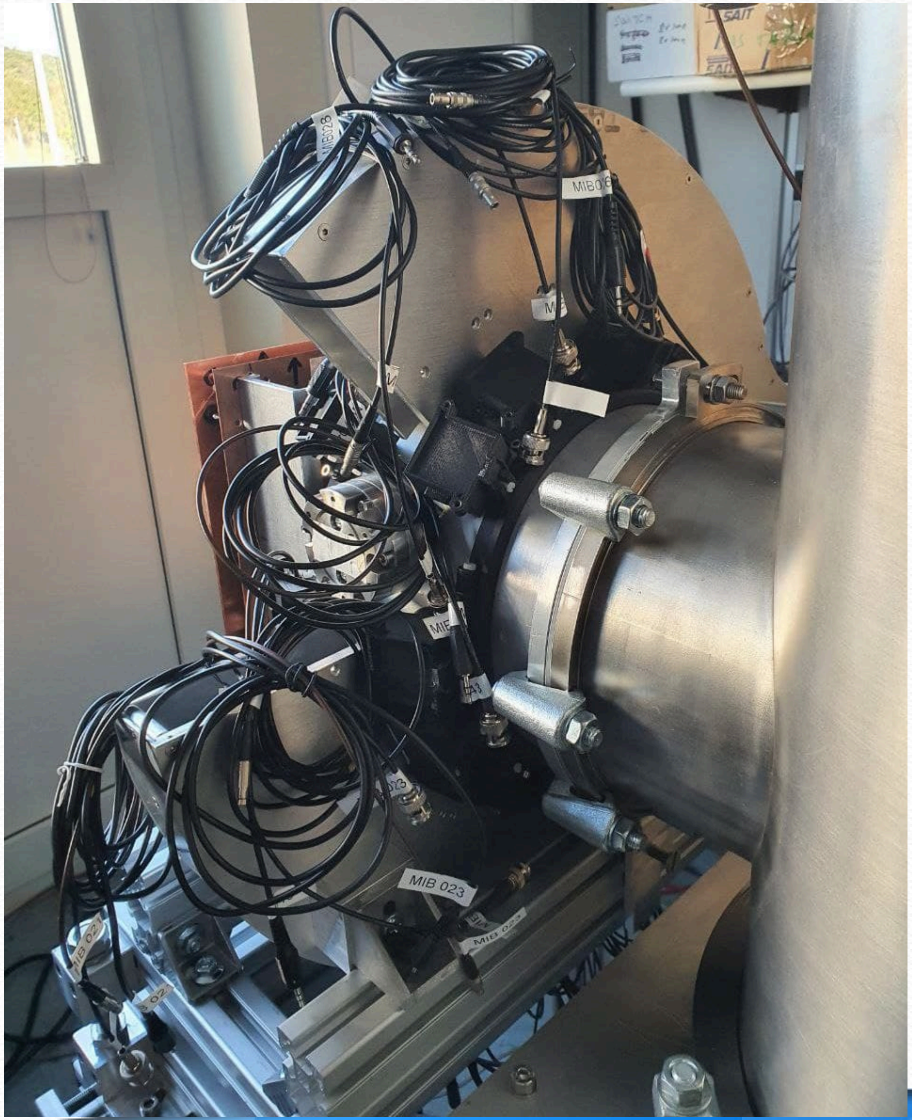
Detectors: placement



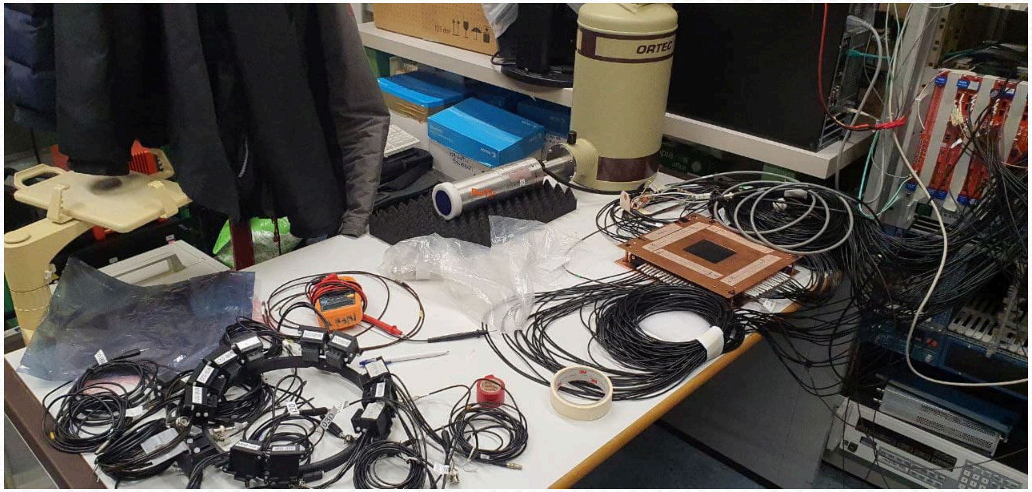


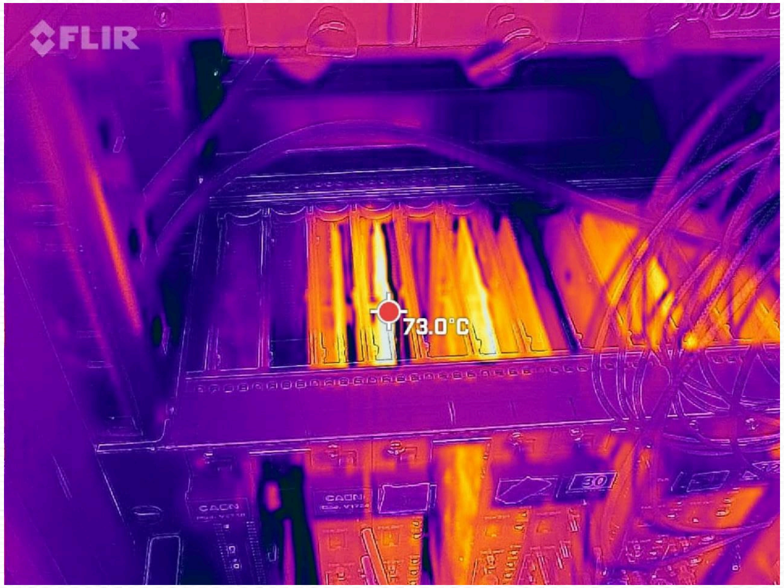
Detectors: mechanical integration

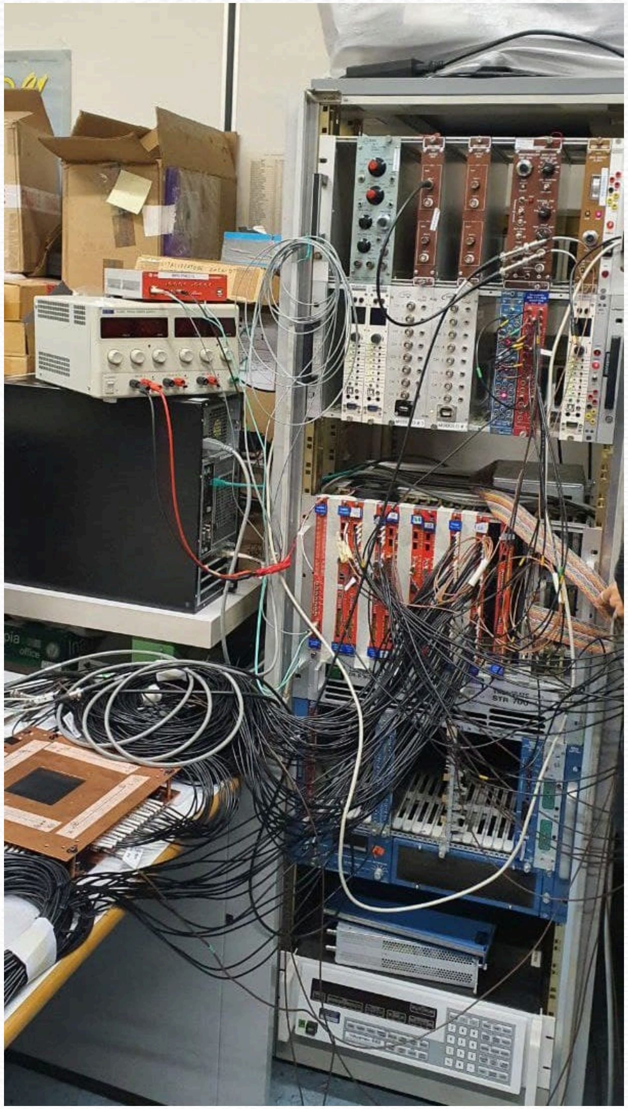




Detectors: electronical integration

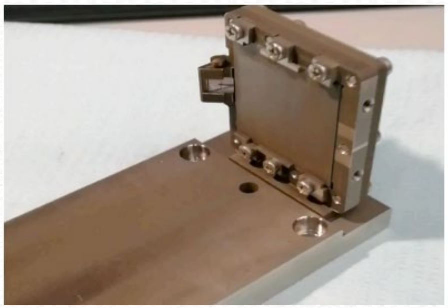


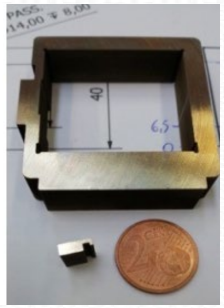


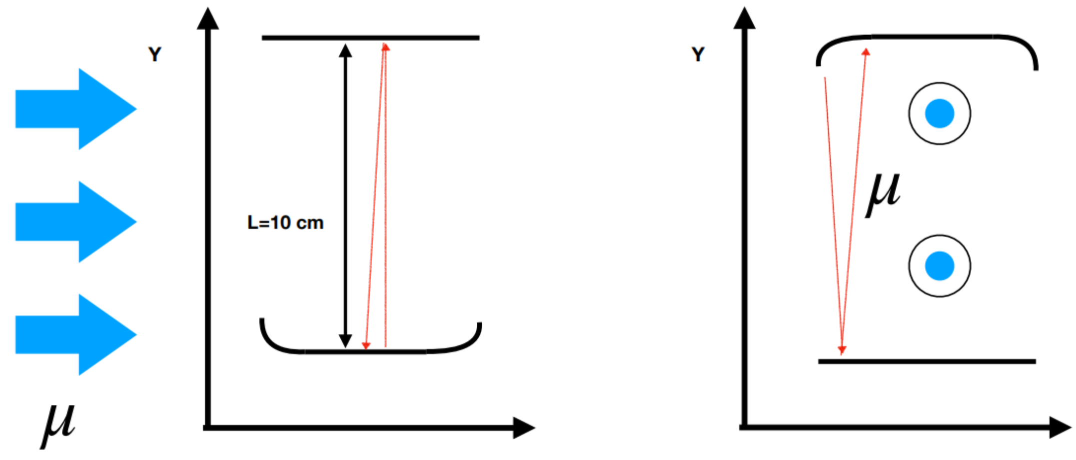


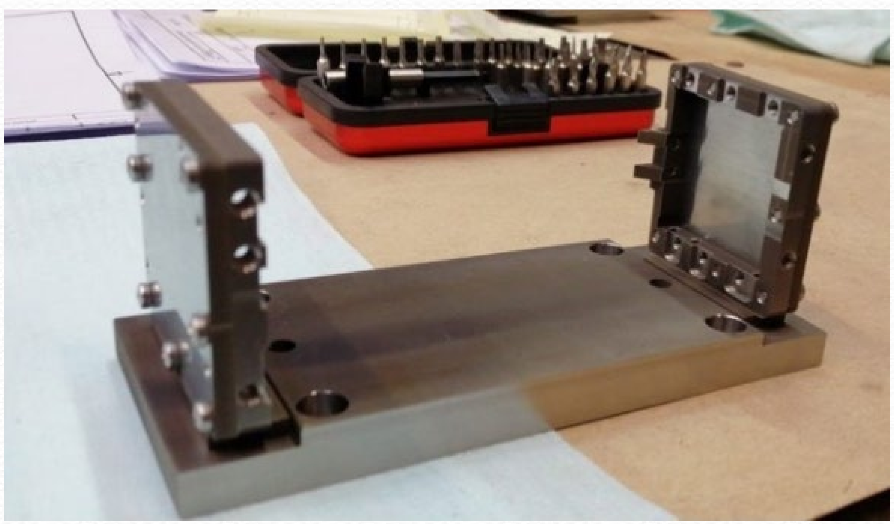
Optical cavity: design

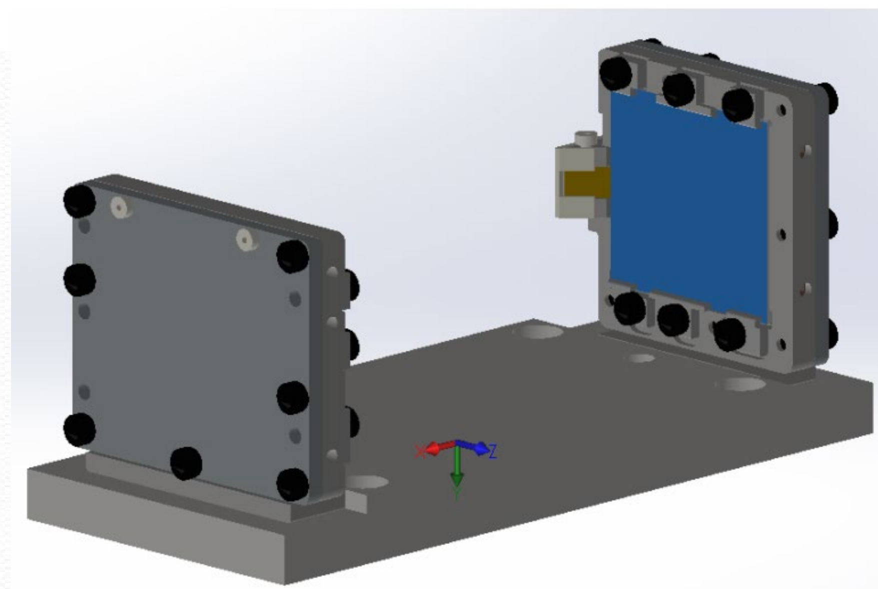
Substrate material: FuSi
HR coating: ZnS/Ge
Support: Invar (CTE<10ppm/K)



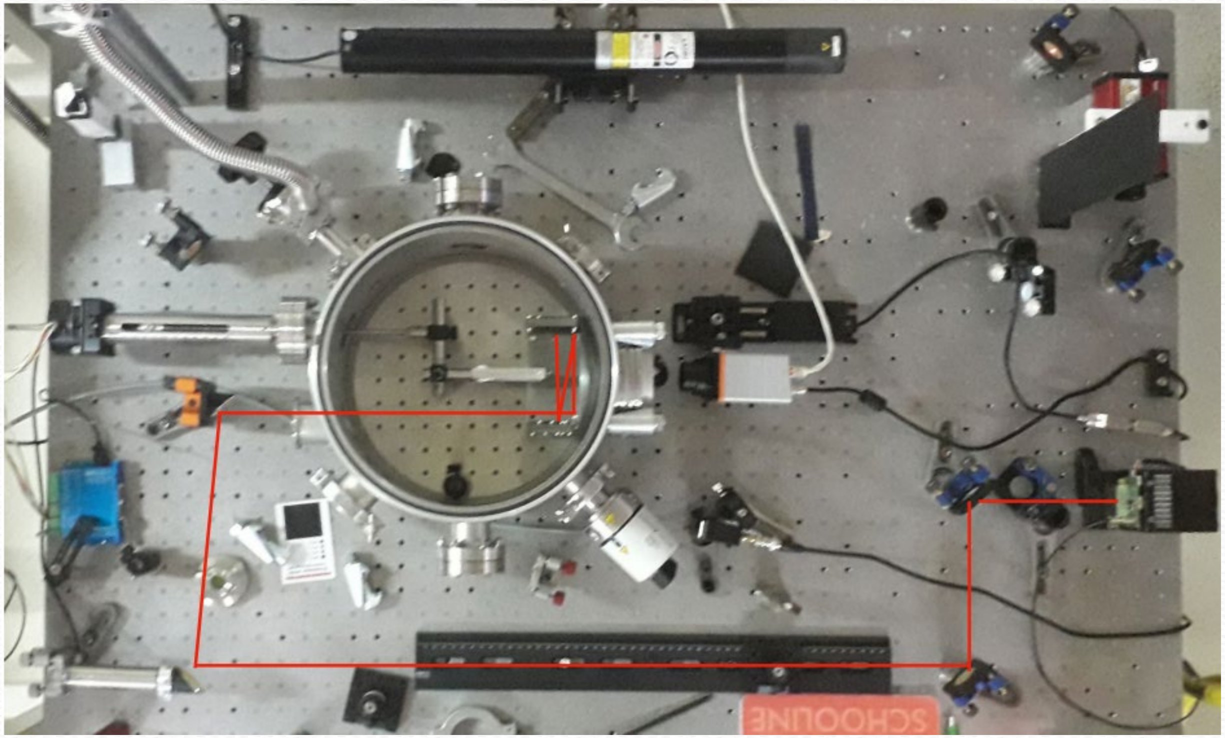




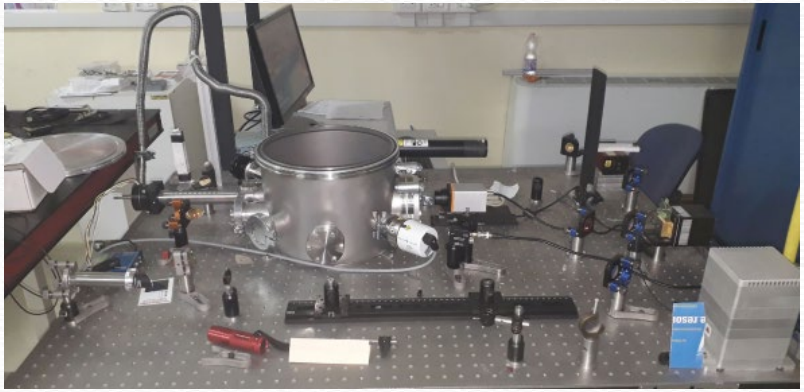




Optical cavity: characterization



- 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.



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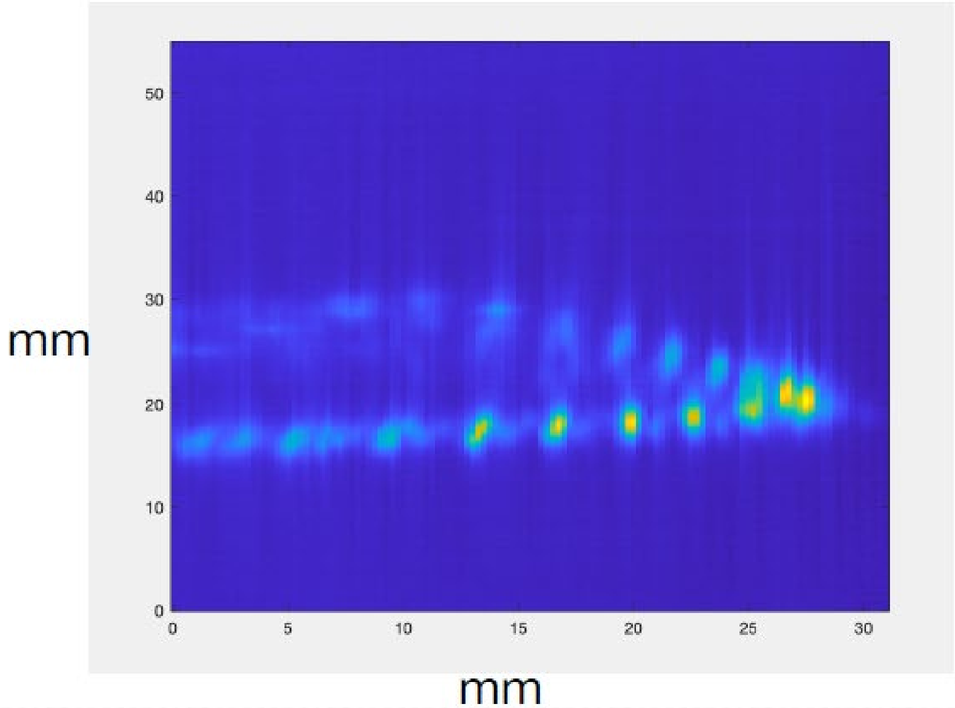
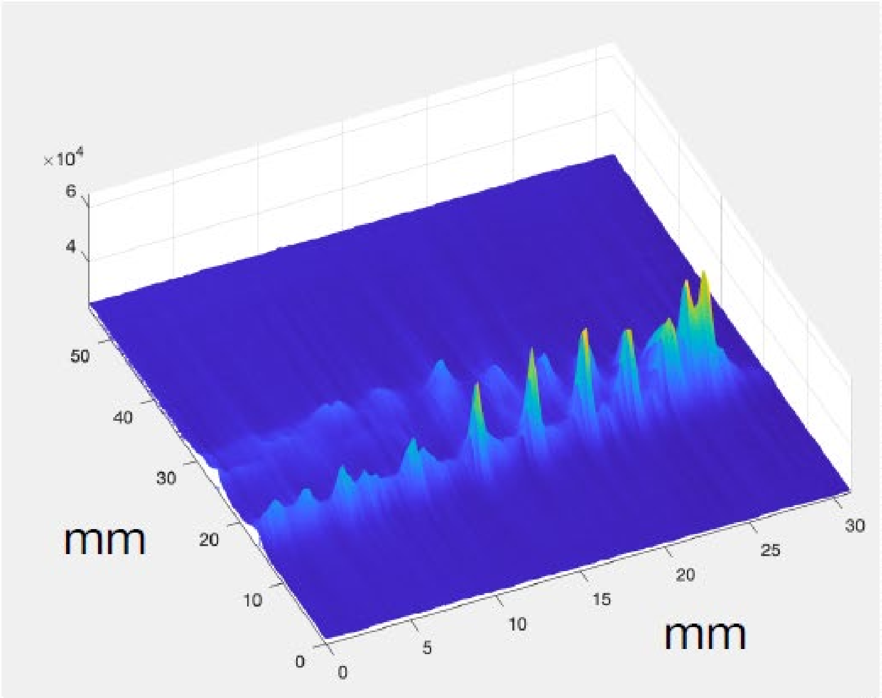


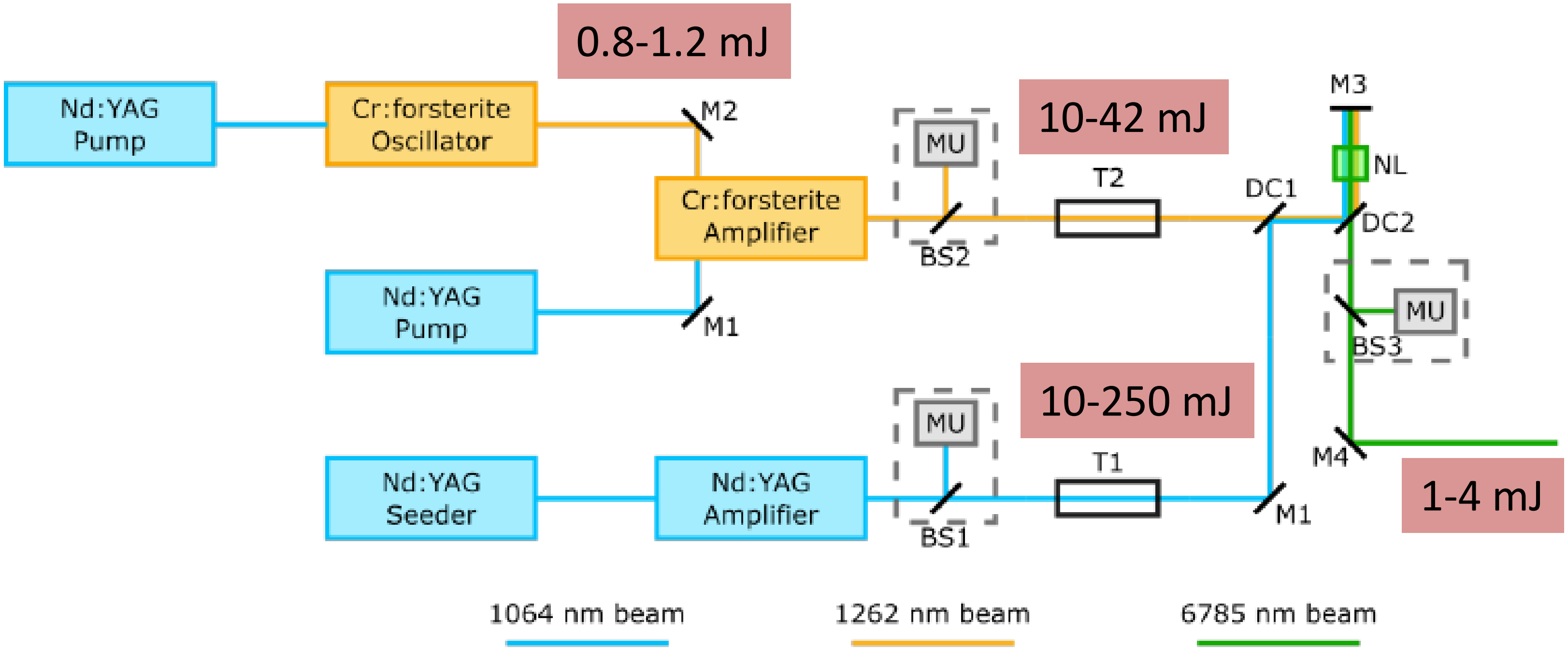


The cavity number of reflections remain stable against small variations of the incident angle (tip/tilt movement)

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

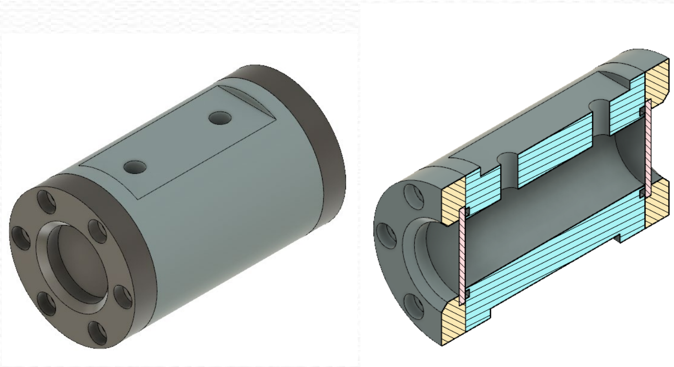
-Center wavelength accuracy 40 MHz @ 1262 nm

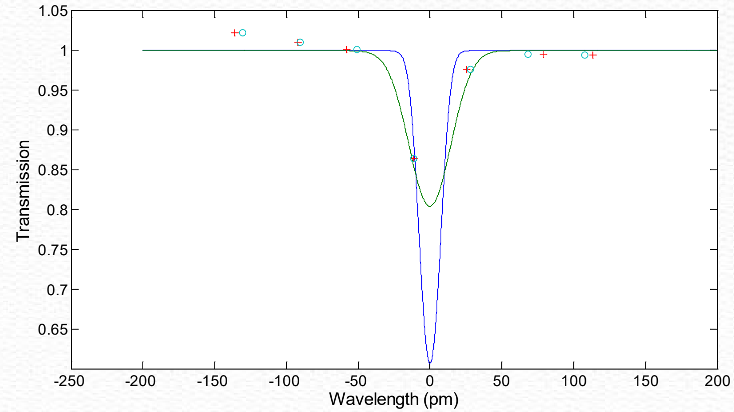
Overall accuracy better than:

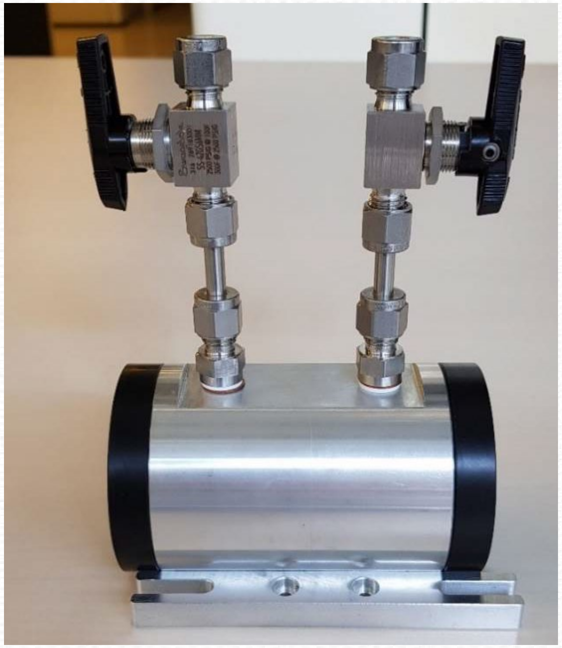
6800.000 ± 0.020 nm

44.0871 ± 0.0001 THz

Laser: absolute calibration cell







C_2H_4 absorption cell

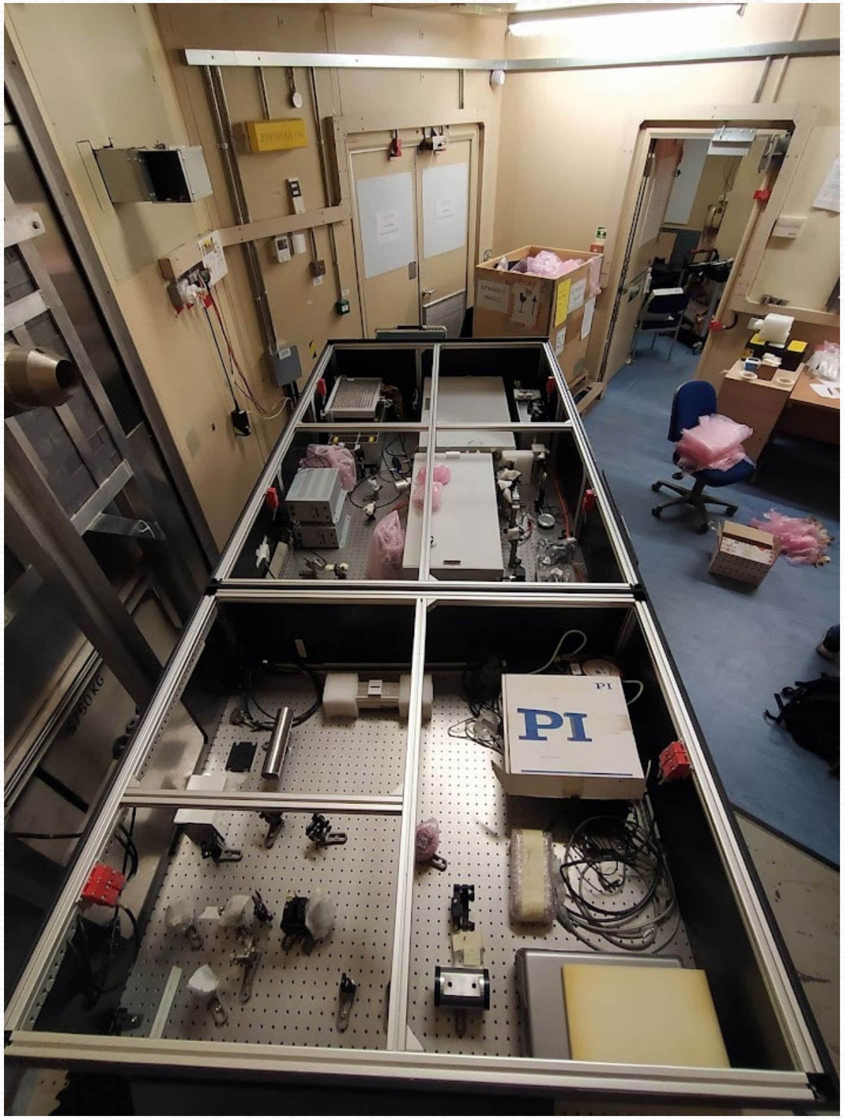
Accuracy (comparing to HITRAN database):
from ±10 to ±140 MHz
depending on the absorption line

Laser status @ RAL

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

- Lotis (Belarus) lasers refurbished and restarted (thanks to RAL staff!)
- Innolas lasers to be restarted by contractor technician (planned on 4th/5th July)
- DFG and cavity calibration setup to be completed

Laser status @ RAL



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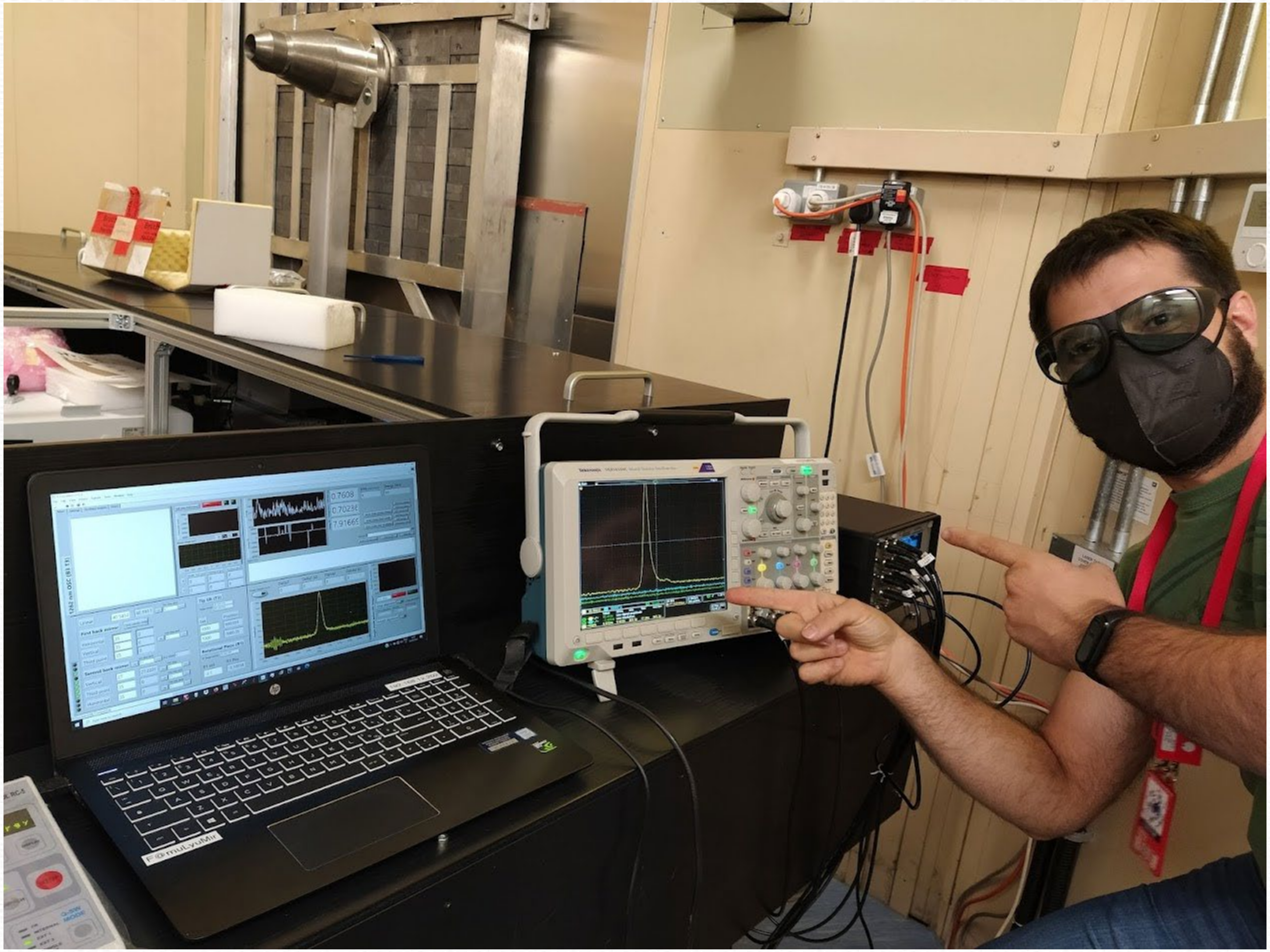
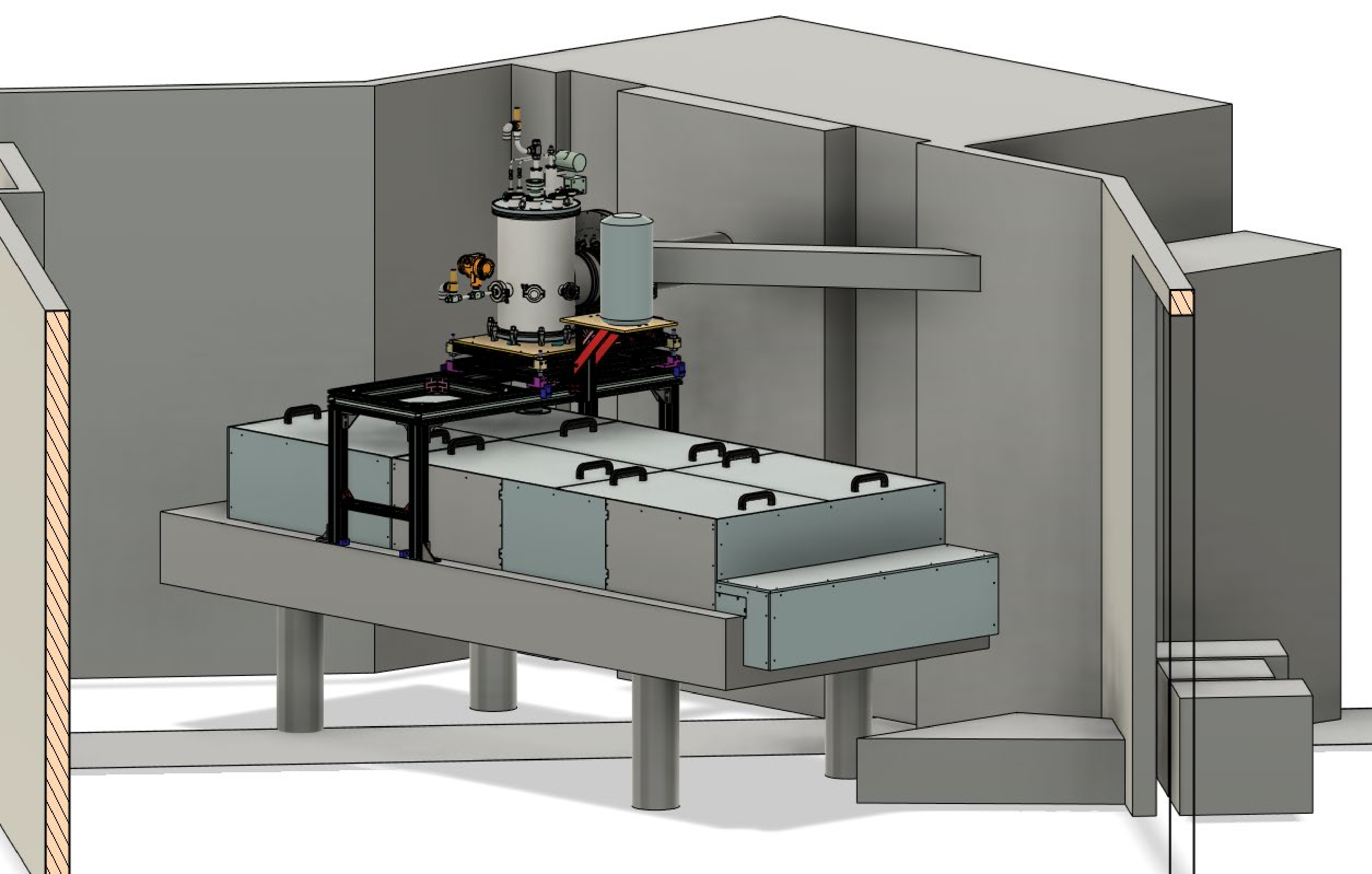


Laser status @ RAL

FAMU setup



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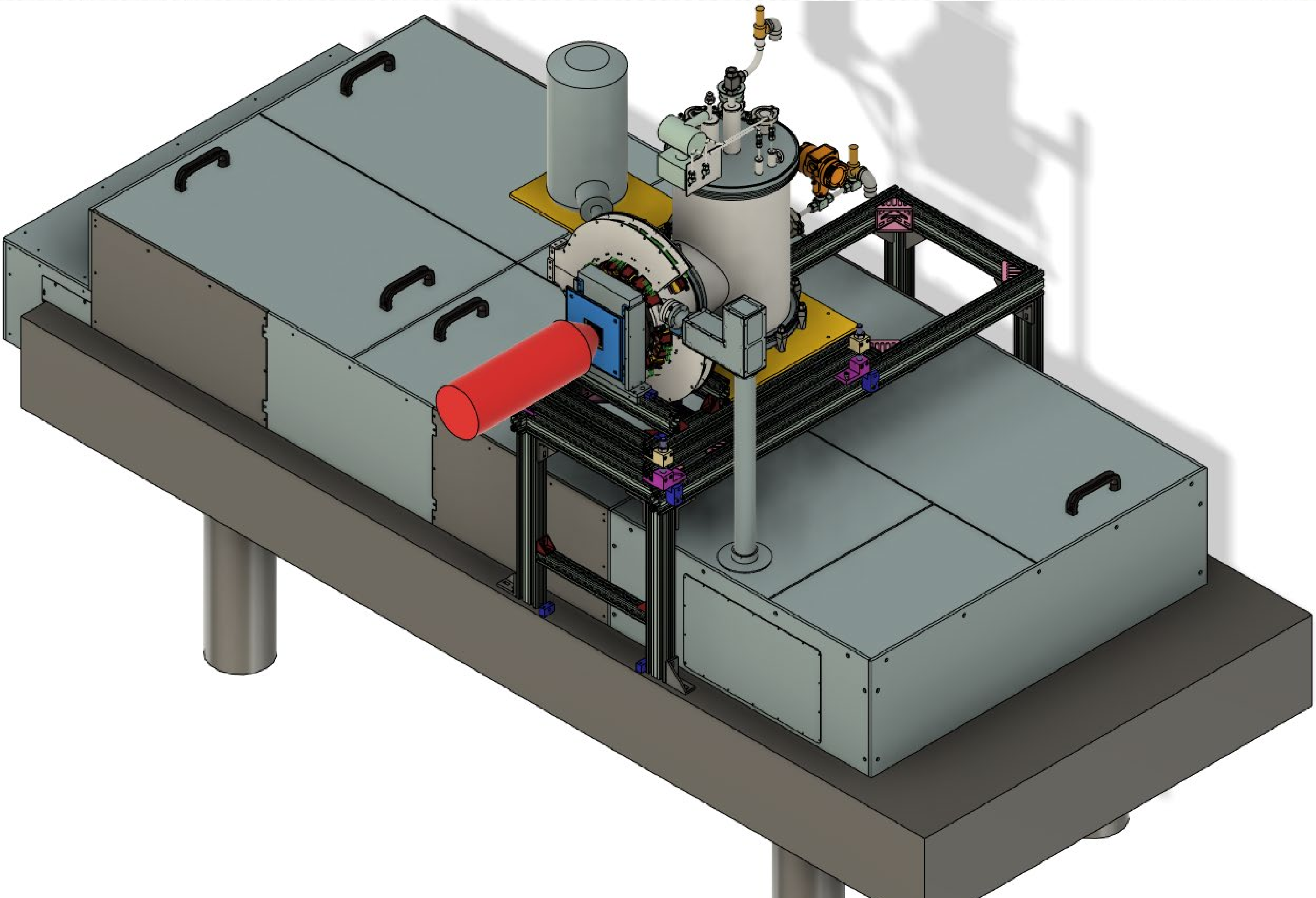

Measurement plan

- 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

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

3rd ISIS Cycle 2022 [20 September – 15 October]: ready for muon beam line commissioning (test of our system)

4th ISIS Cycle 2022 [8 November – 16 December]: our data taking is planned in this cycle

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 by the end of 2022!

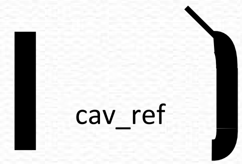
Thanks!

Spares

Summary of muon atomic capture physics (in H gas)

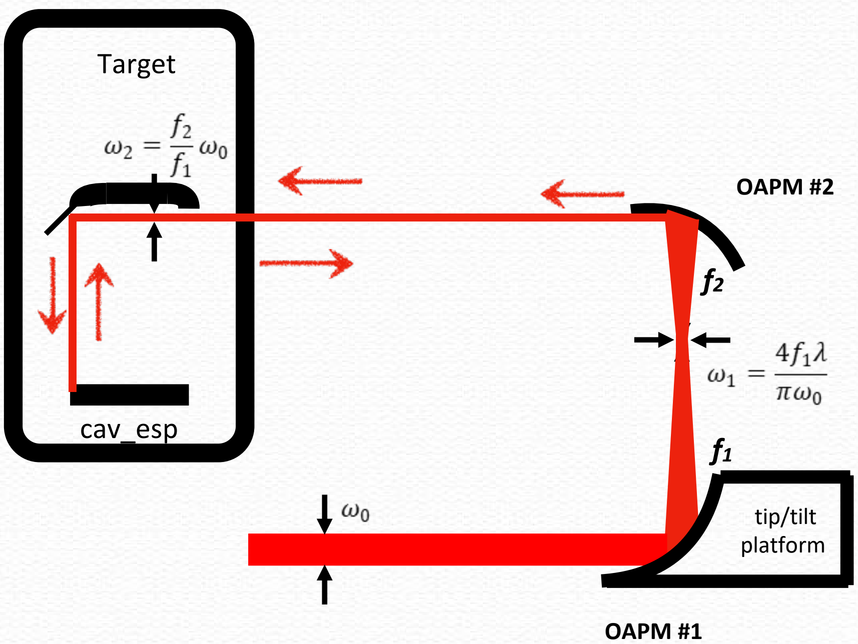
1. Hydrogen gas at room temperature (i.e. H_2 molecules mean kinetic energy 30 meV – 0.03 eV)
2. Muon slows down and reaches a H_2 molecule
3. Muon is captured at high quantum state and H_2 molecule breaks
4. Muon goes down to ground level losing energy by Auger effect (electron is kicked away) and radiative processes (X-ray emission)
5. The system muon-proton (muonic hydrogen) gains kinetic energy (average energy about 2 eV !)
6. The muonic hydrogen thermalizes due to collision with other molecules (thermalization time depends on density and temperature, order of 100 ns @ 40 bar 300 K)
7. The muon decays OR it is transferred OR it undergoes nuclear capture (μ^-+p $\rightarrow$ n+ν_μ)

Optical cavity: alignment



We use a “twin” cavity (cav_ref) to one in the cryogenic target (cav_esp).
With a beam splitter (BS) between the OPAM #2 and the injection mirror of cav_esp we take a part of laser beam to align this cavity.
The alignment procedure is carried out in two step:

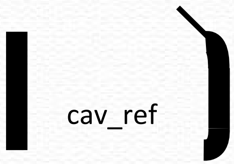
1) alignment of cav_ref referencing to a beam laser that impinges orthogonally on the bottom mirror of cav_esp;
2) alignment of cav_esp by monitoring the optical path in cav_ref.



Alignment procedure

1. We inject in the cavity in the cryogenic target a visible laser (red, green) and we align the cav_esp in a way that the laser impinges orthogonally on the second mirror of cav_esp.
2. A BS at 45° is introduced between the OPAM #2 and the injection mirror of cav_esp. The laser beam is splitin two parts and sent to two cavities. It is crucial that the distance between the BS and the two injection mirrors are the same (in the layout is 32 cm).
3. By means the translators and rotators and monitoring the interference emerging from the two cavities, cav_ref is aligned superimposing perfectly the two beams. This step guarantee that the optical path in cav_ref is the same as that in cav_esp.
4. By moving the OAMPs (OAMP #1, with motorized tip/tilt) to maximize the number of reflections in the cav_ref, with warranty that the optical path in cav_esp will be very similar.
5. The visible beam laser is switched off, the BS is removed and the infrared laser is injected in the cav_esp.

Optical cavity: alignment



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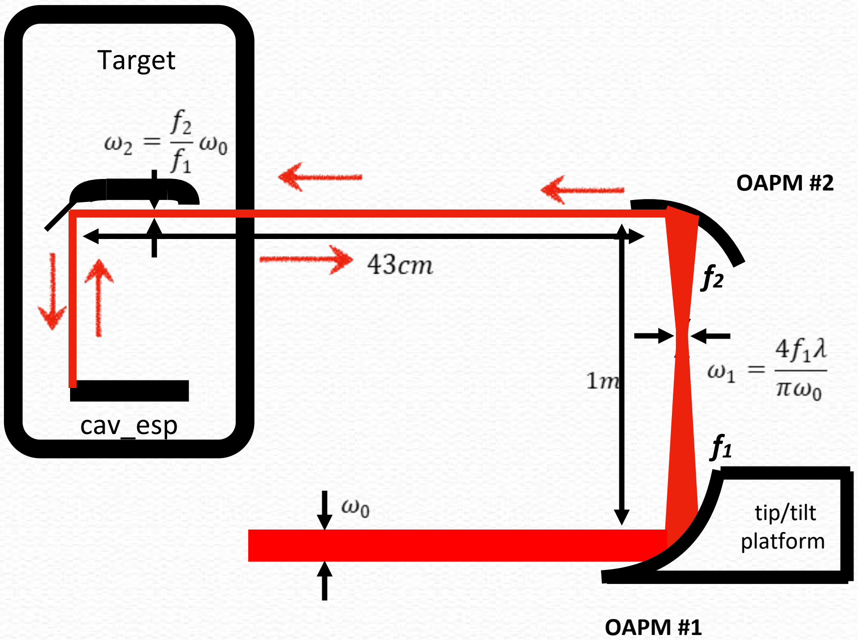

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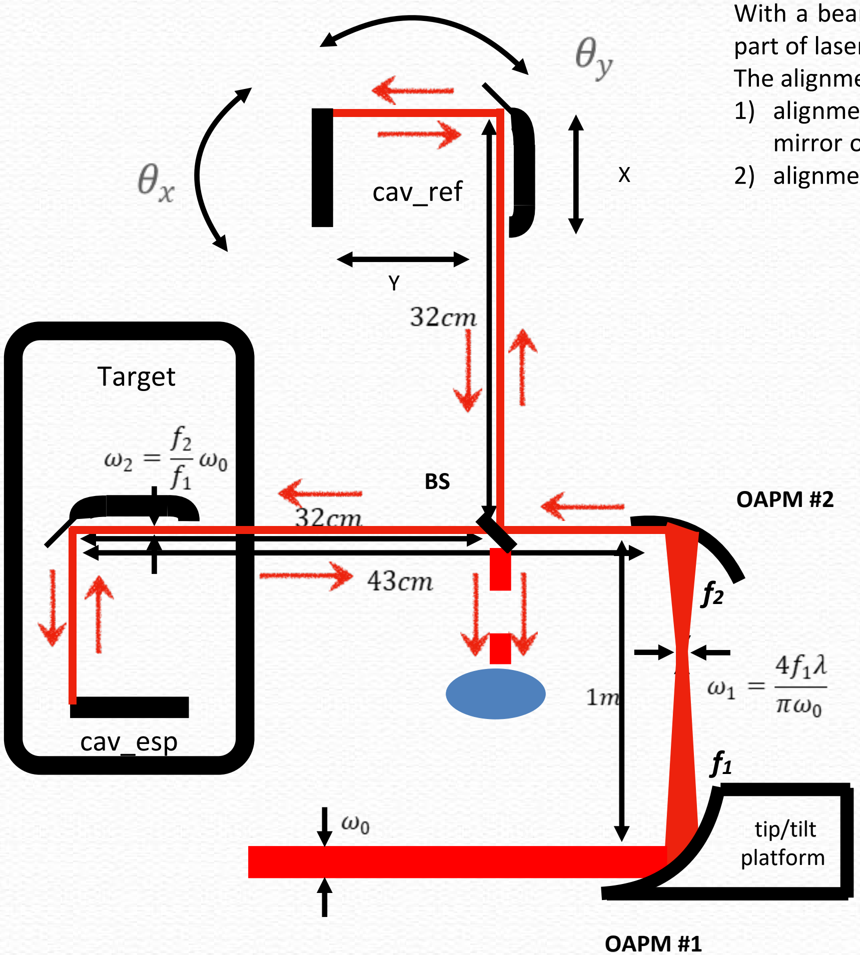

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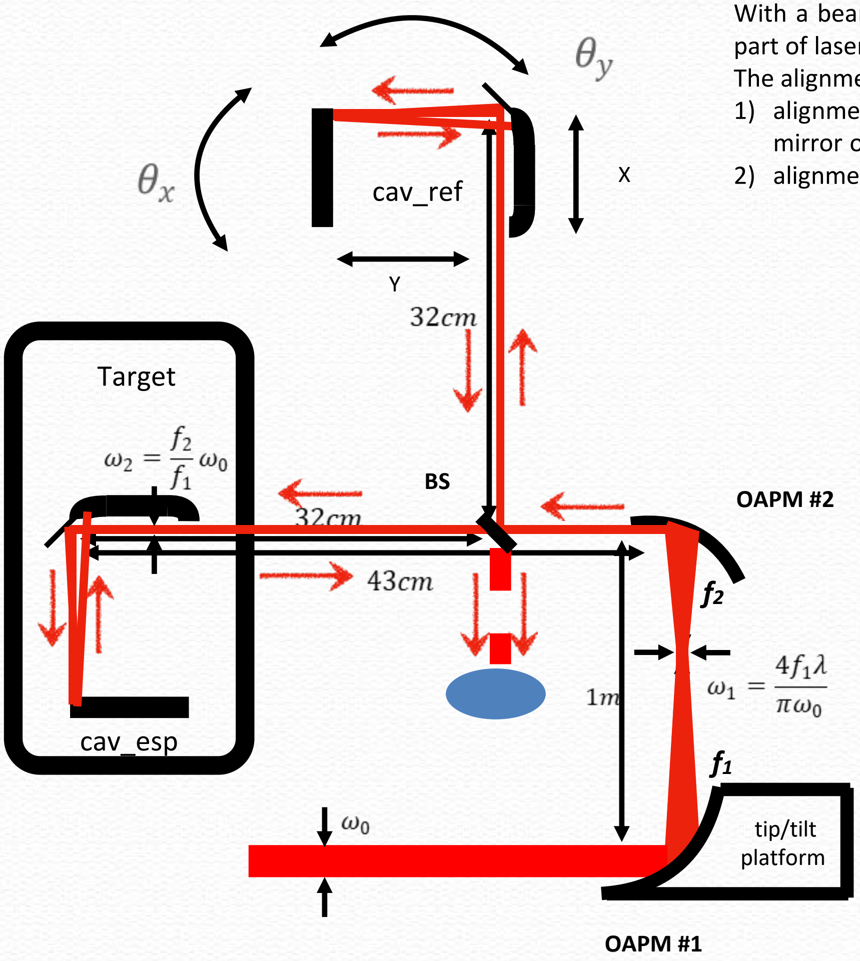

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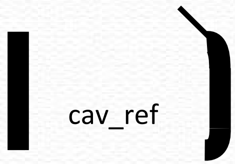
Optical cavity: alignment



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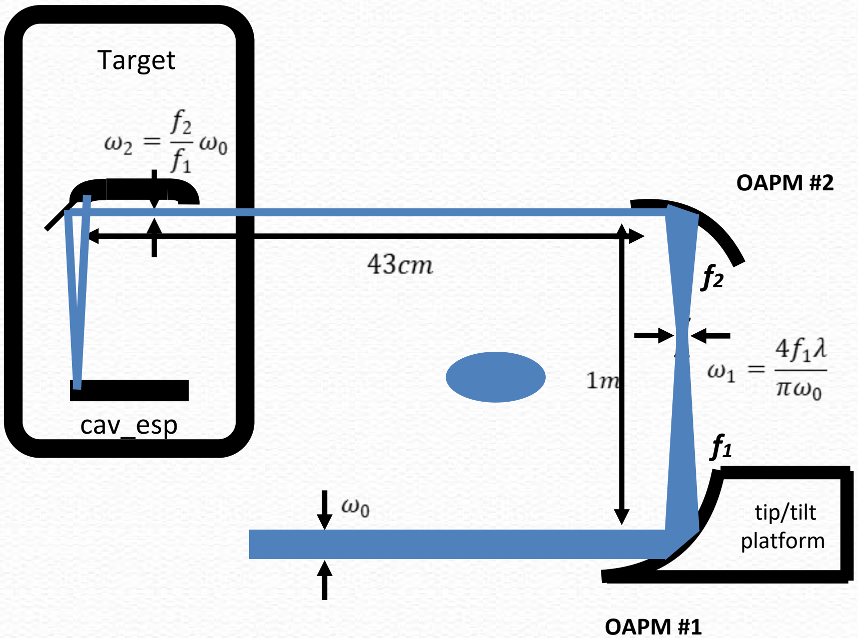

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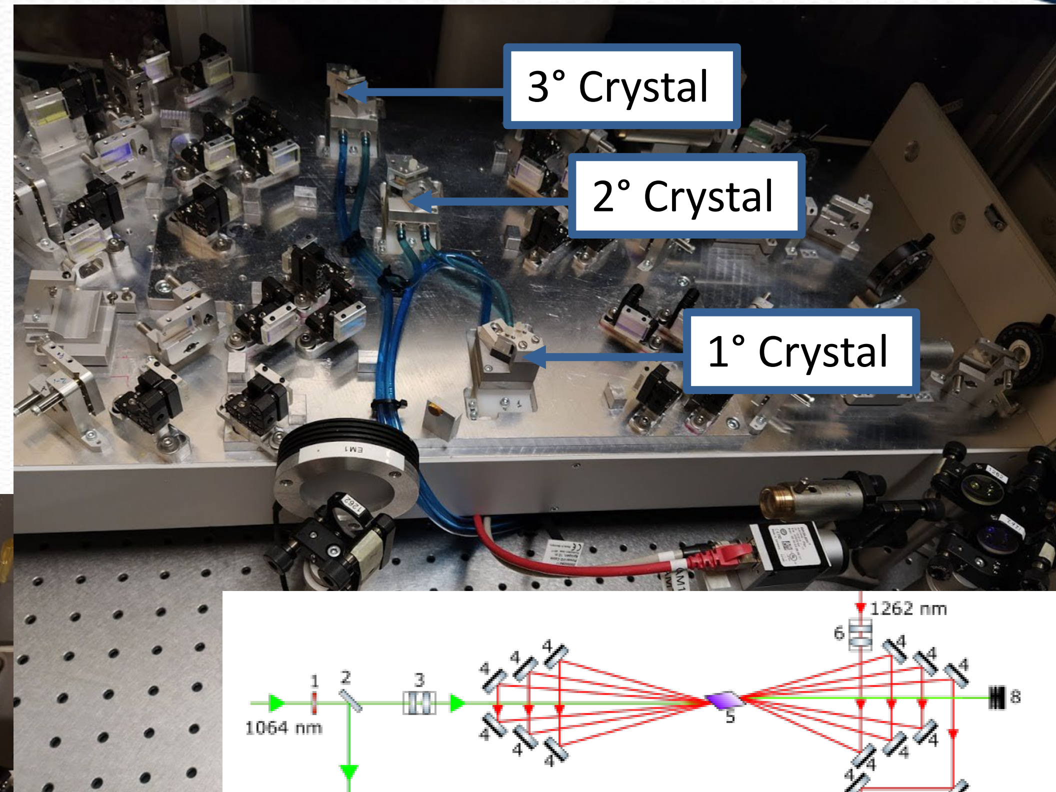
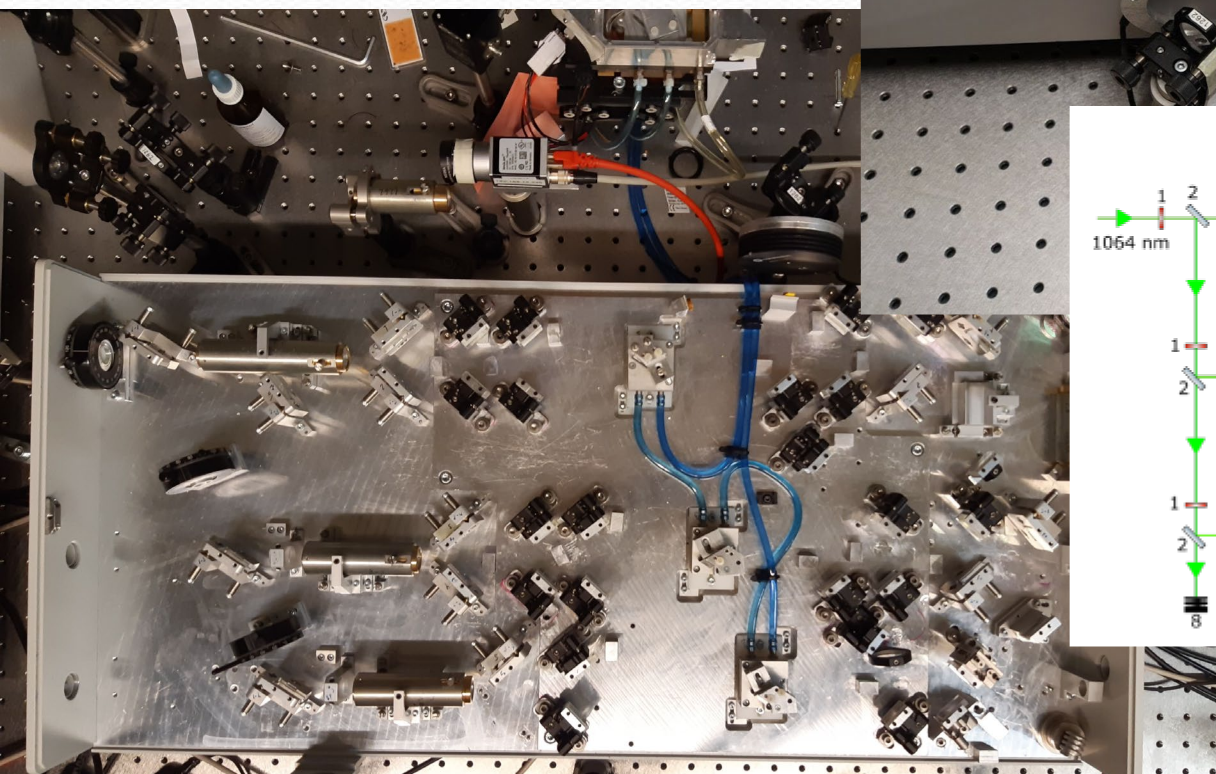
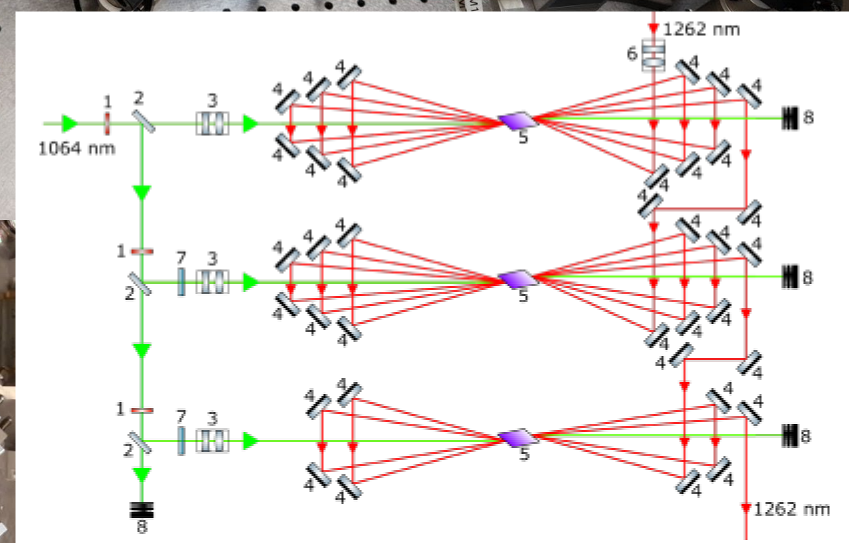
Laser: Cr:forsterite amplifier

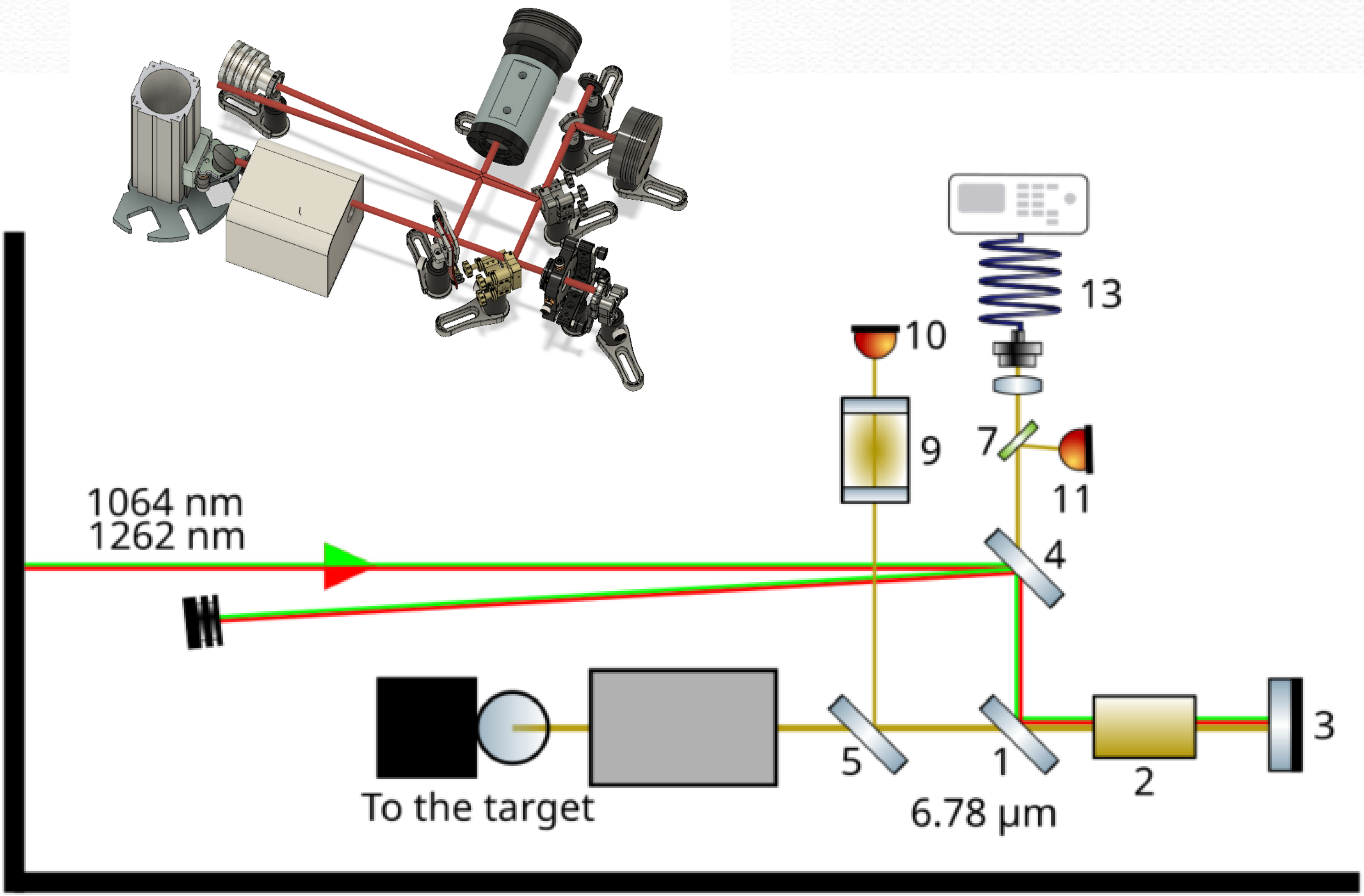
- 3 stages with 6, 6, and 4 passes respectively
- 0.8mJ → 42 mJ , total gain of about 52.







Laser: single crystal DFG setup



1. Trichroic mirror
2. NLO crystal
3. Metallic mirror
4. Trichroic mirror
5. Ge mirror slider
6. -
7. Beam splitter
8. -
9. Calibration cell
10. Energy meter
11. Energy meter
12. -
13. Wavelength meter

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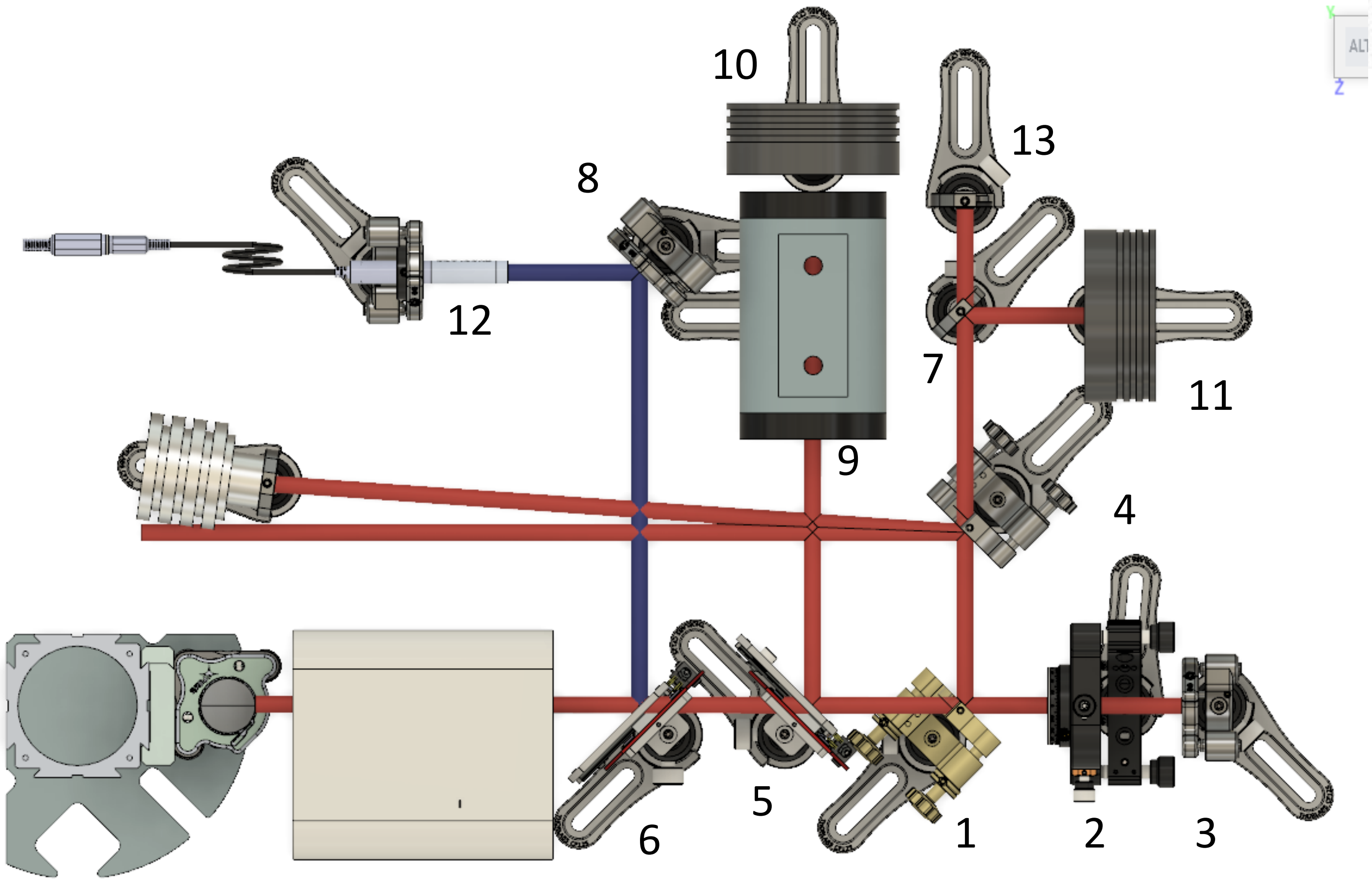
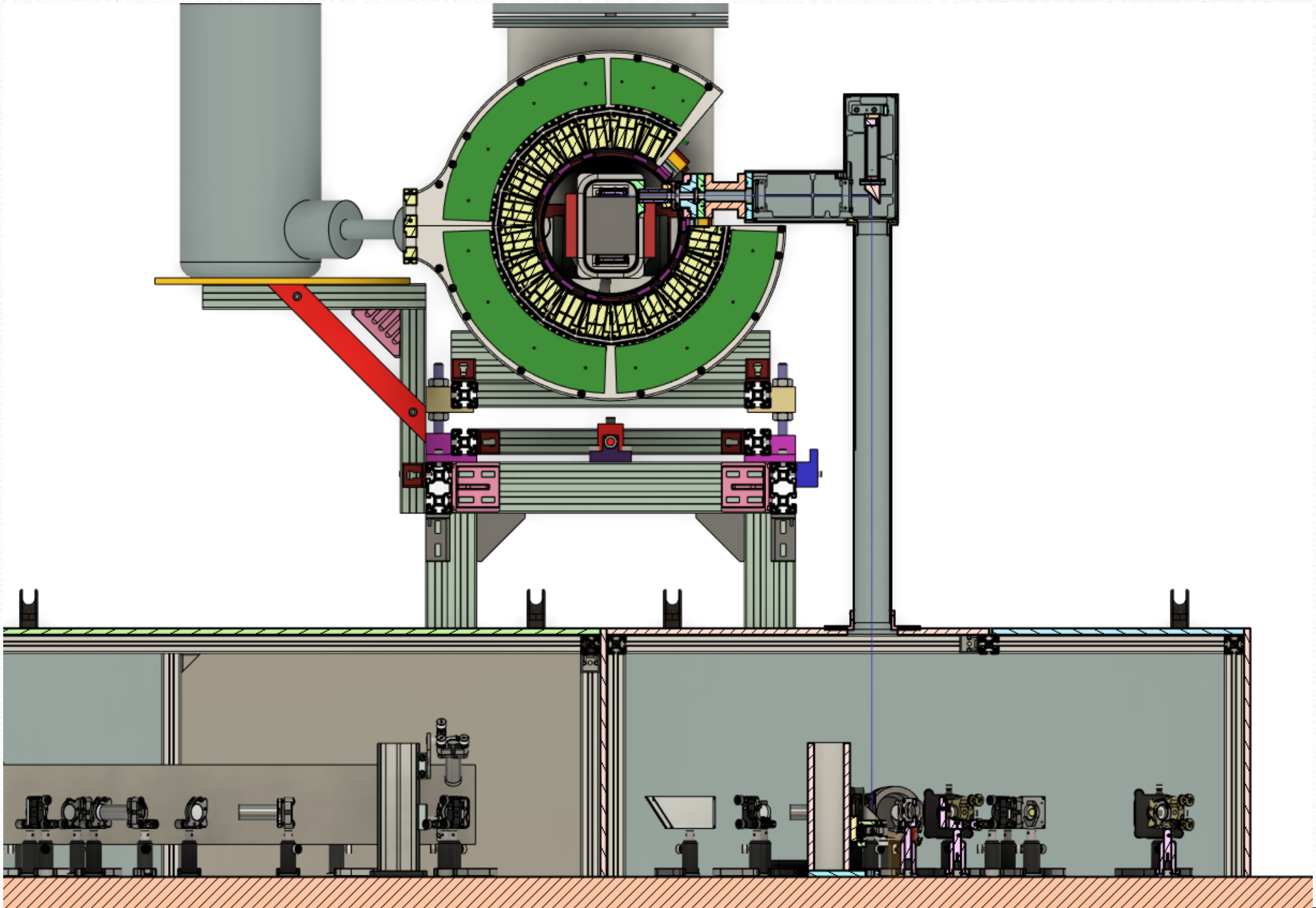
10. Energy meter
11. Energy meter
12. Alignment laser
13. Wavelength meter



Laser injection



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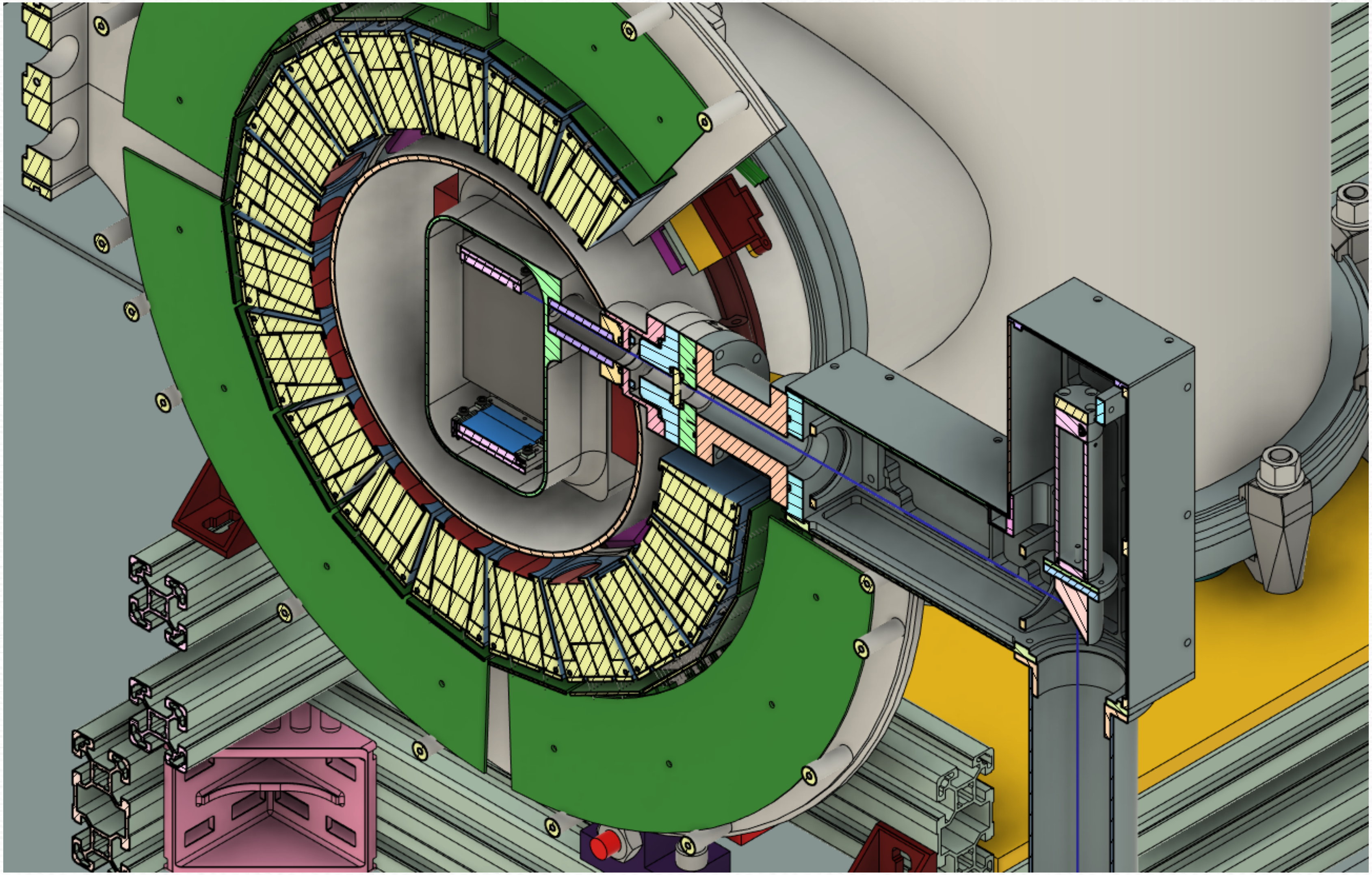
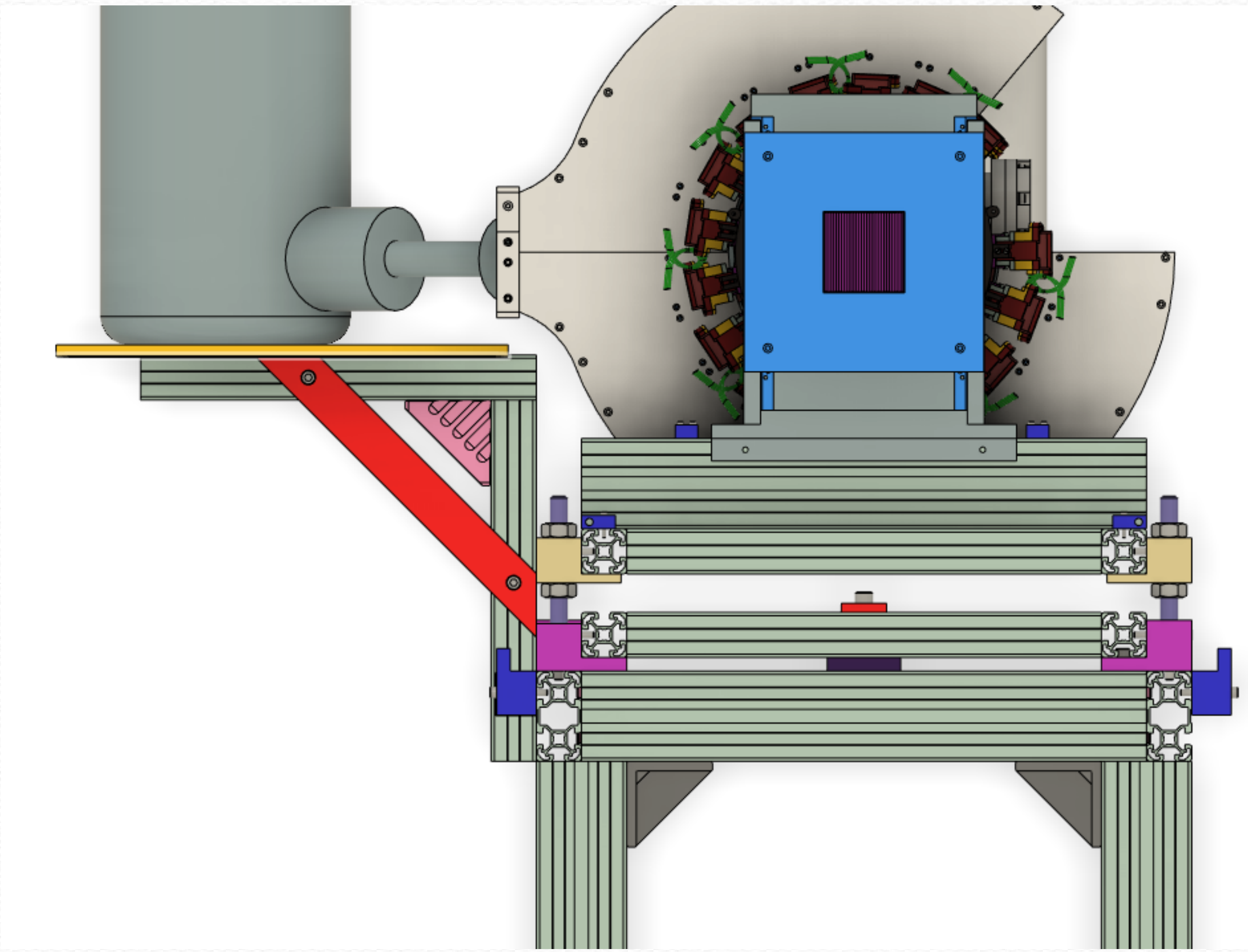
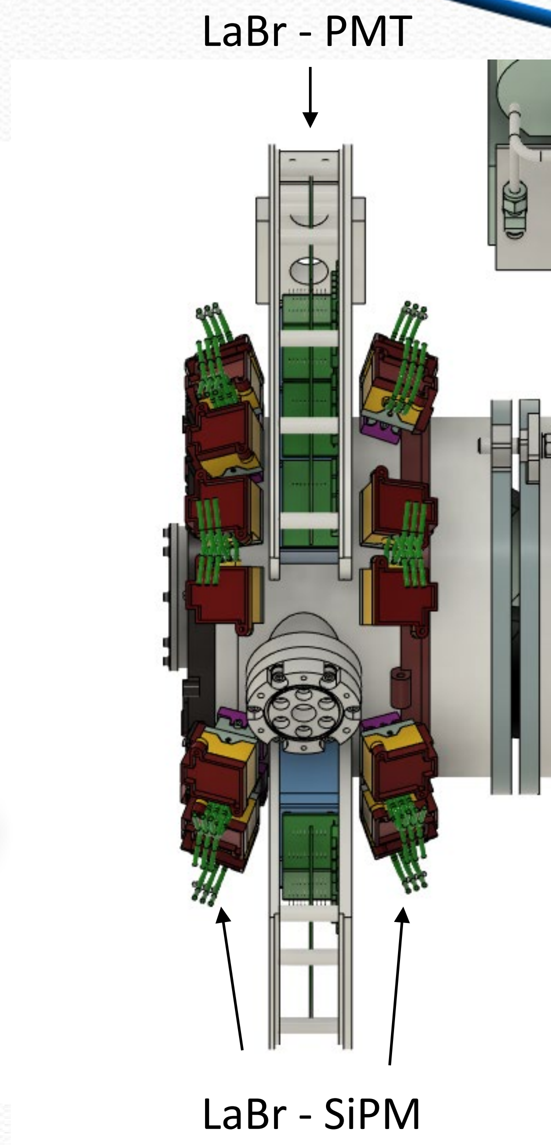
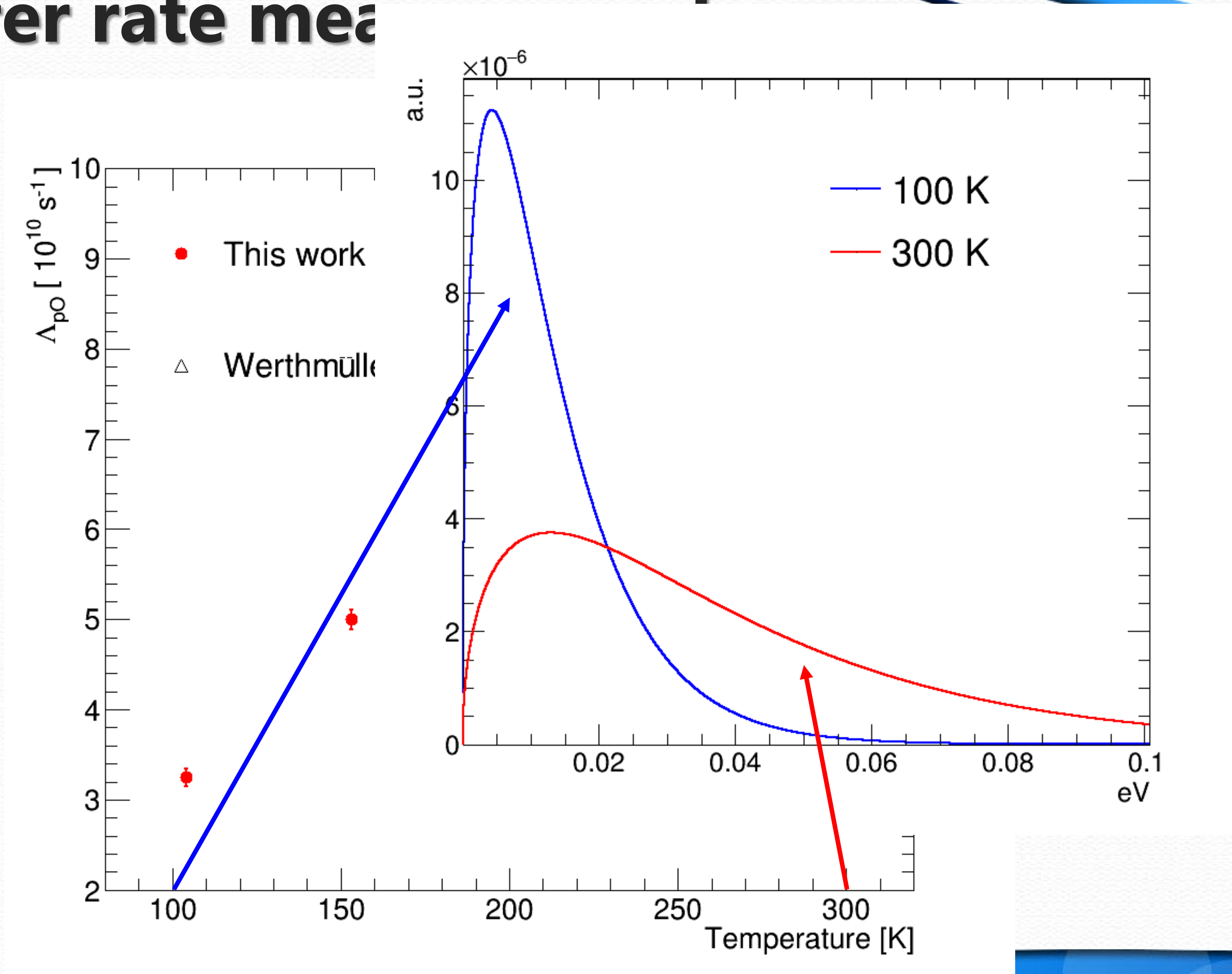


Detectors:

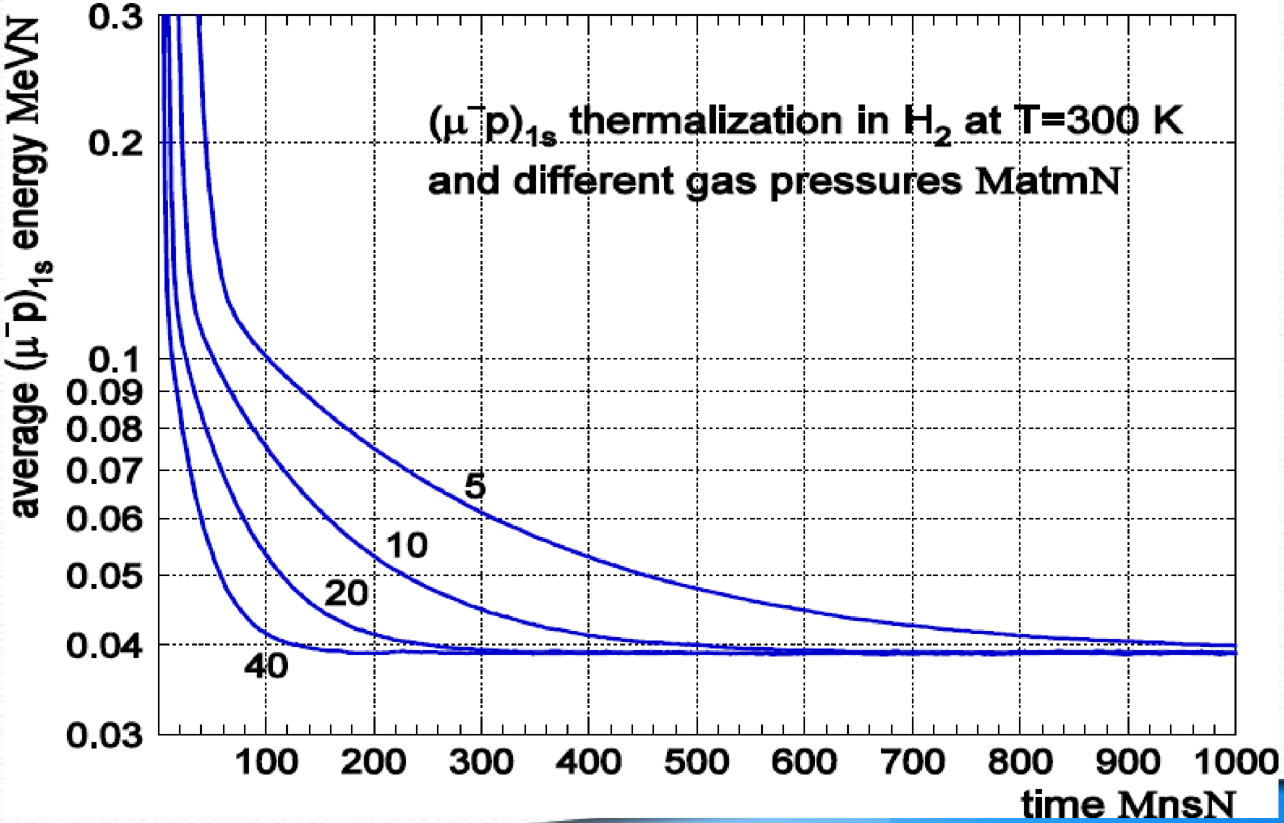




Transfer rate mea



Thermalization of μp



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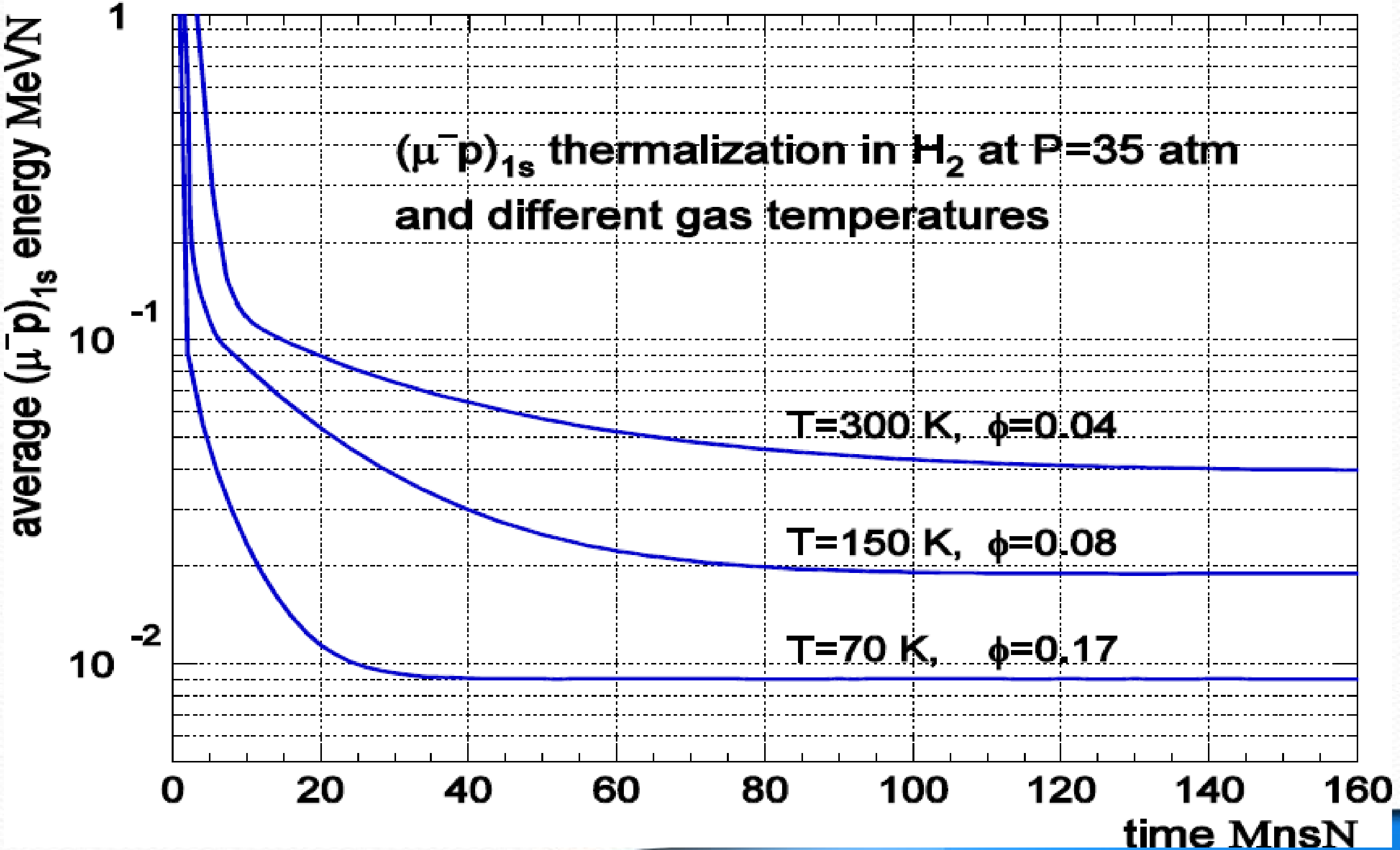
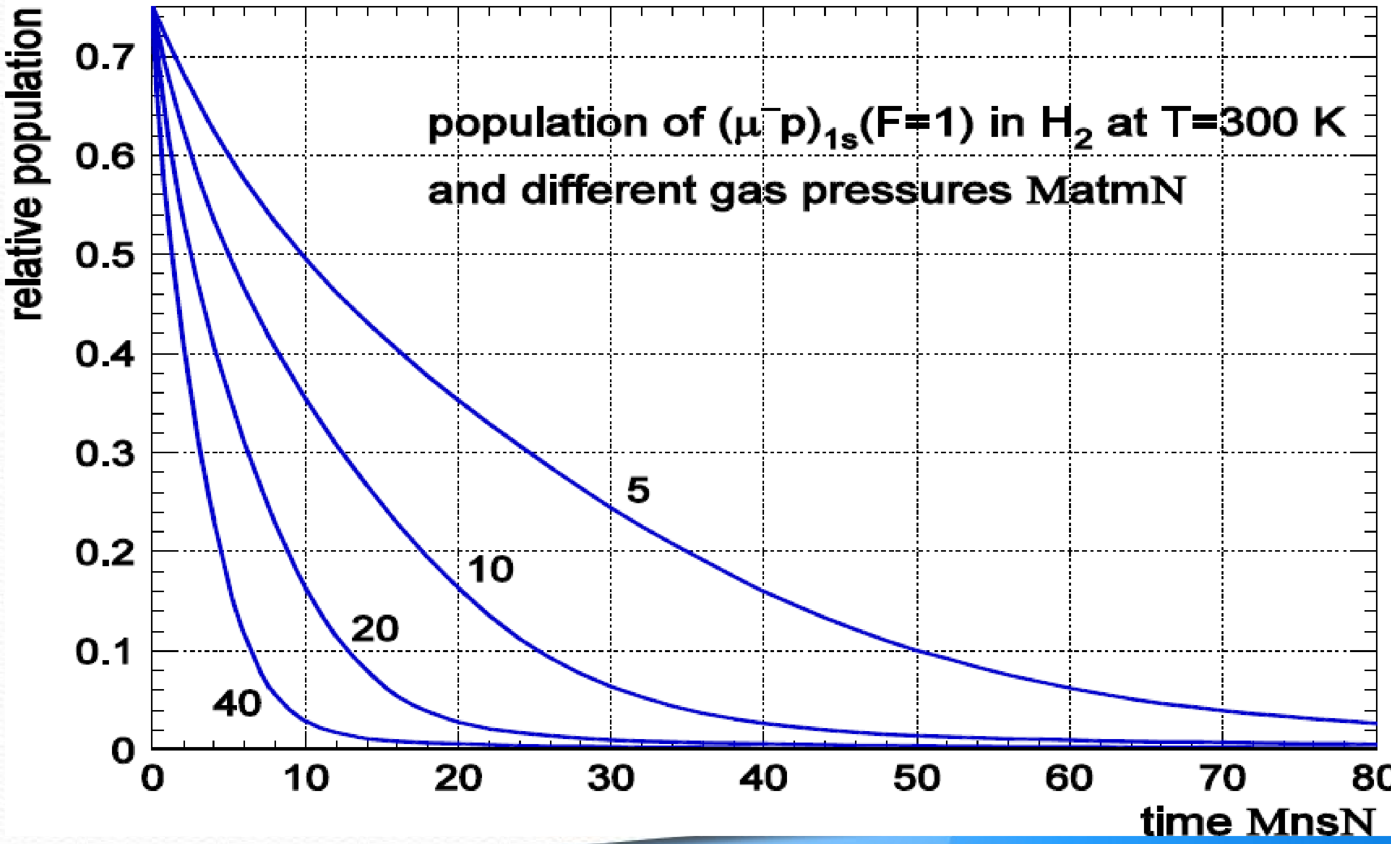


Depolarization of μp



Lifetime of μp and muon transfer