The status of the FAMU experiment

Emiliano Mocchiutti
on behalf of the FAMU Collaboration

Sesto Incontro Nazionale di Fisica Nucleare - INFN2024

Trento – 26/28 February 2024

Outline

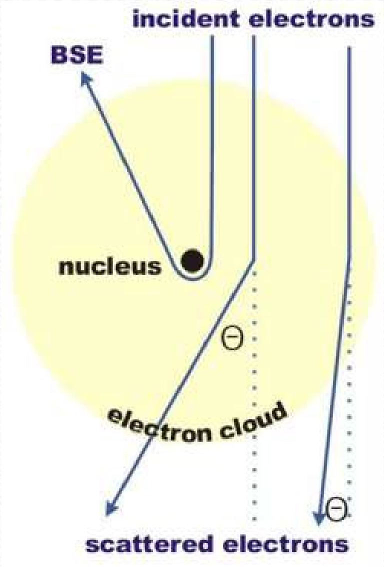
- Introduction
- The FAMU experiment: principle of operation
- Apparatus setup
- Present status and perspectives
- Summary

Introduction

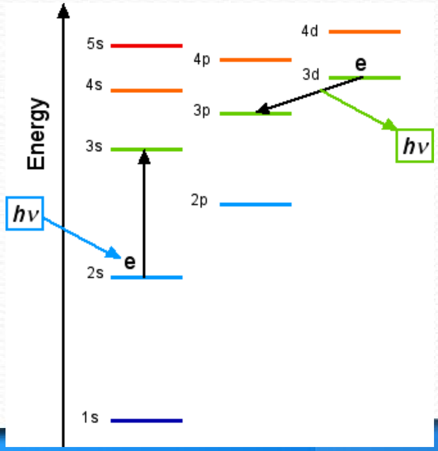
Properties of the proton

Study of the properties of the proton
(charge radius and magnetic distribution)

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



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



HFS of $\mu^{-}p$ ground level

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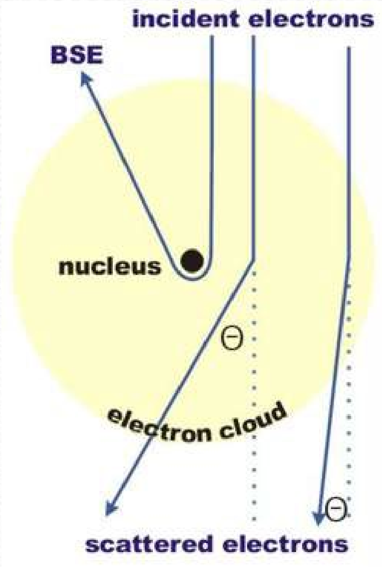

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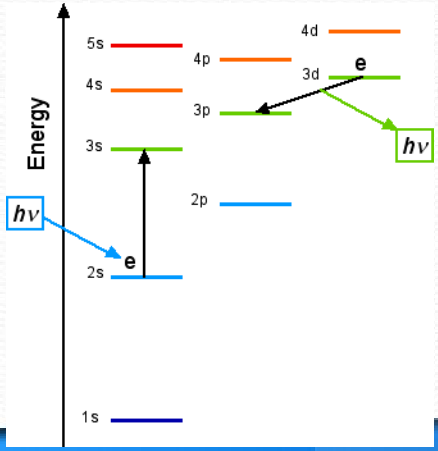
Hyper Fine Splitting (HFS) of muonic hydrogen ground level



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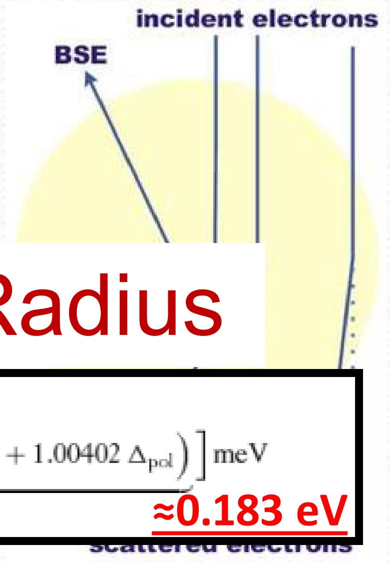

1) scattering: elastic elec
2) scatte

QED, Zemach Radius

$$E_{1S\text{-HFS}}(\mu\mathrm{H}) = \Big[\underbrace{182.443}_{E_F} \underbrace{+1.350(7)}_{\mathrm{QED+weak}} \underbrace{+0.004}_{\mathrm{hVP}} \underbrace{-1.30653(17)\left(\frac{r_{Z_p}}{\mathrm{fm}}\right) + E_F\left(1.01656(4)\,\Delta_{\mathrm{recoil}} + 1.00402\,\Delta_{\mathrm{pol}}\right)}_{2\gamma\ \mathrm{incl.\ radiative\ corr.}}\Big]\,\mathrm{meV}$$

≈0.183 eV

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

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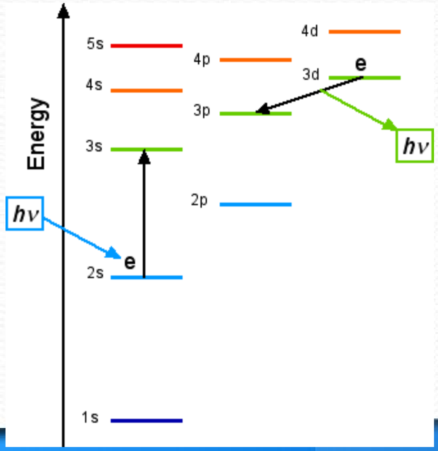
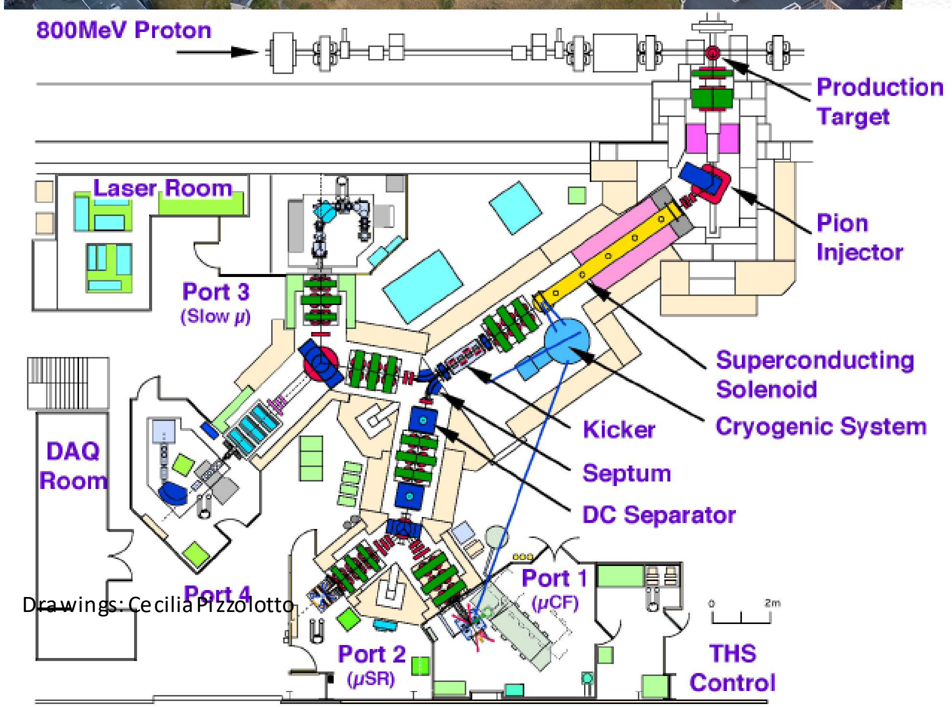


The FAMU (Fisica Atomi MUonici) experiment: principle of operation

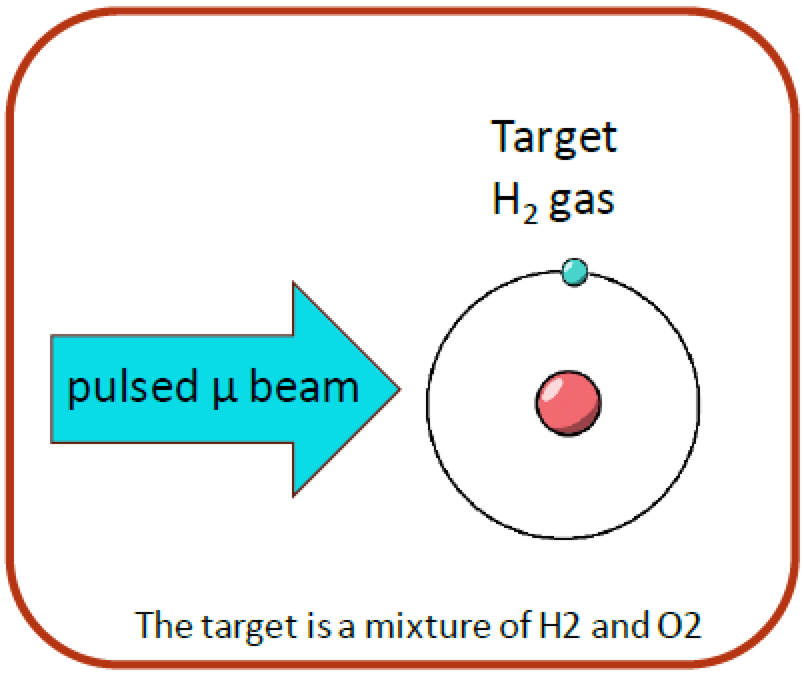
Measurement of the HFS $(\mu^{-}p)_{1S}$ ground level



HFS $(\mu^{-}p)_{1S}$ first measurement

- **RAL (UK), ISIS protosynchrotron @ RIKEN muon facility**
- **Experimental method:**
  1. **Create muonic hydrogen (muon beam + hydrogen gas target)**
  2. **Excite the transition (powerful tunable mid-infrared laser)**
  3. **Wait for muon transfer from hydrogen to heavier atom (oxygen)**
  4. **Detect X-ray emission from muon capture**
  5. **Exploit *kinetic energy dependence* of muon transfer from $\mu^{-}p$ to oxygen to find the resonance (by varying laser frequency)**

Measurement of the HFS $(\mu^- p)_{1S}$ ground level



O2 = 196 ppm

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Drawings: Cecilia Pizzolotto

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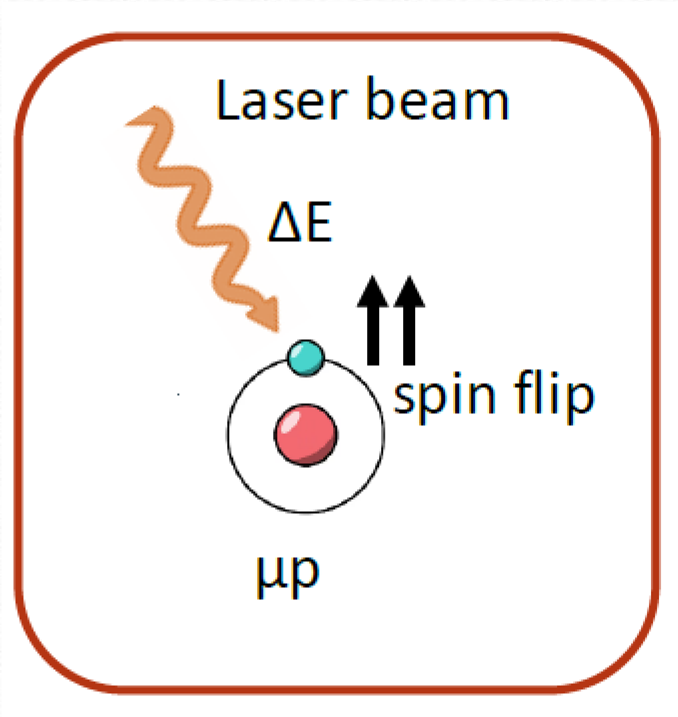

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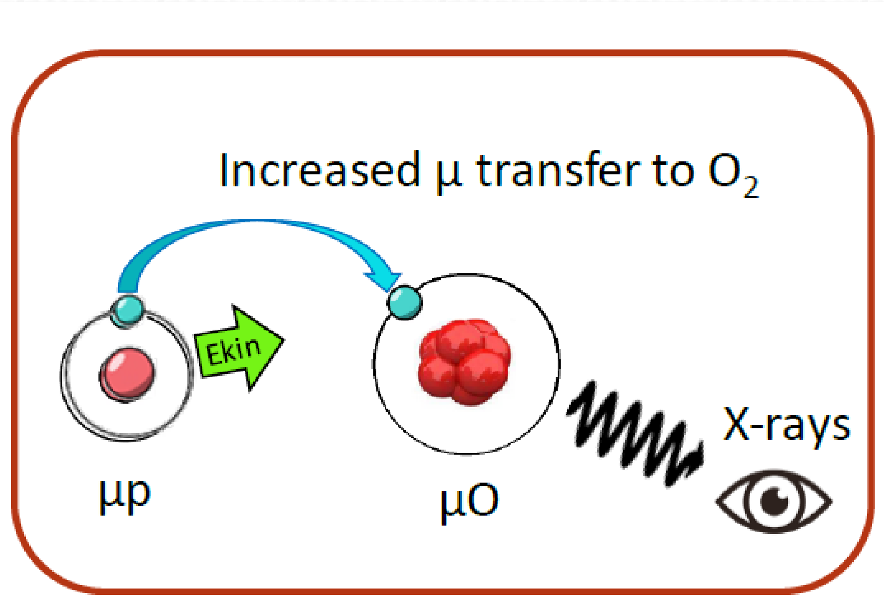

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Data taking planned for March 2020

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… moved to September 2020

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and, of course, since 01 Jan 2021 Brexit took place (end of free movements of goods)

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

FAMU: 2023, data taking!

First muons:

- December 2022 (5 minutes)

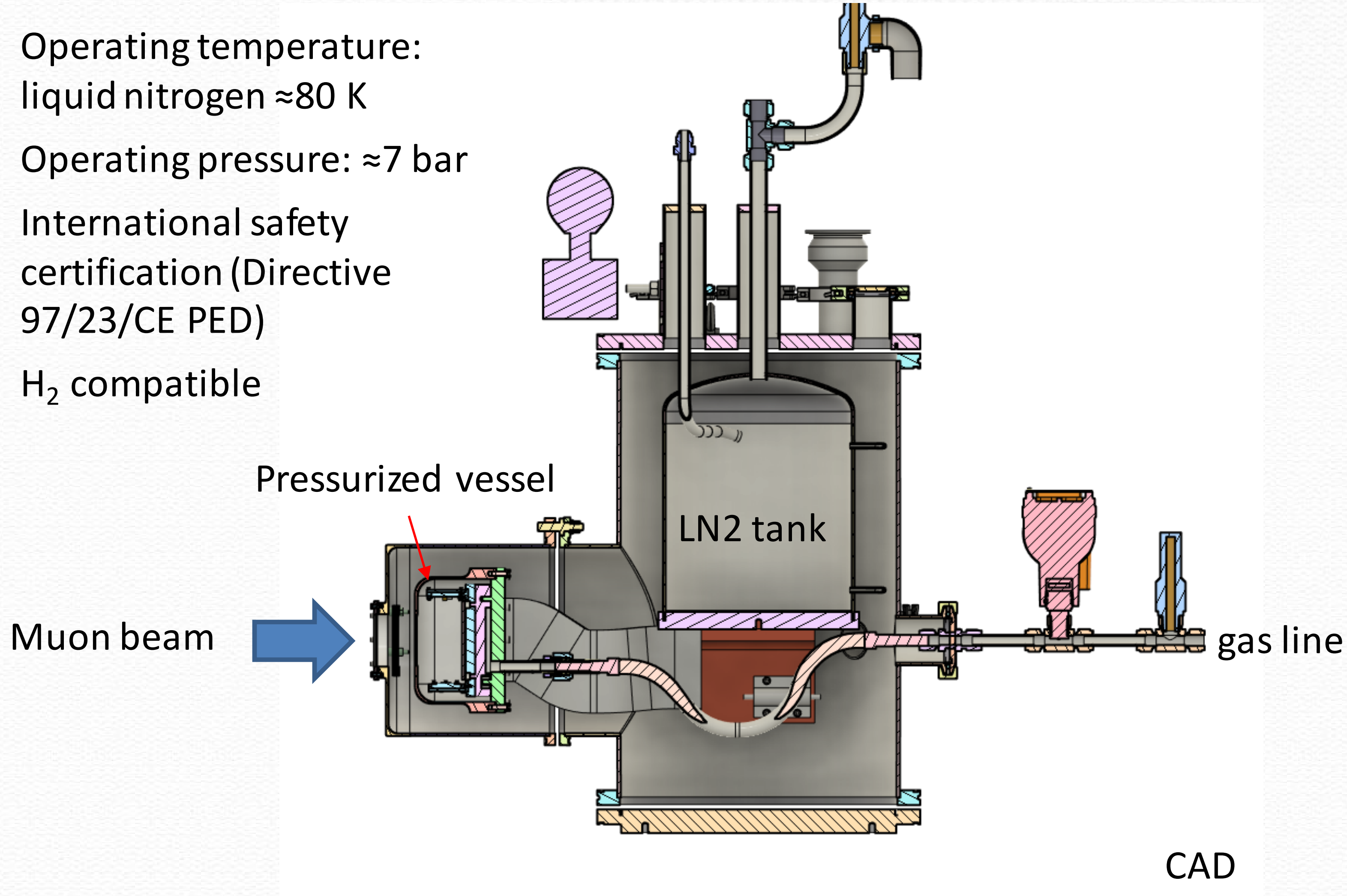
Data taking in 2023:

- May 24th – 26th beam line test
- July 17th – 23rd commissioning and first data
- October 12th – 18th first data set
- December 7th – 18th second data set

Apparatus setup

Target: the design

- Operating temperature: liquid nitrogen ≈80 K
- Operating pressure: ≈7 bar
- International safety certification (Directive 97/23/CE PED)
- H_2 compatible



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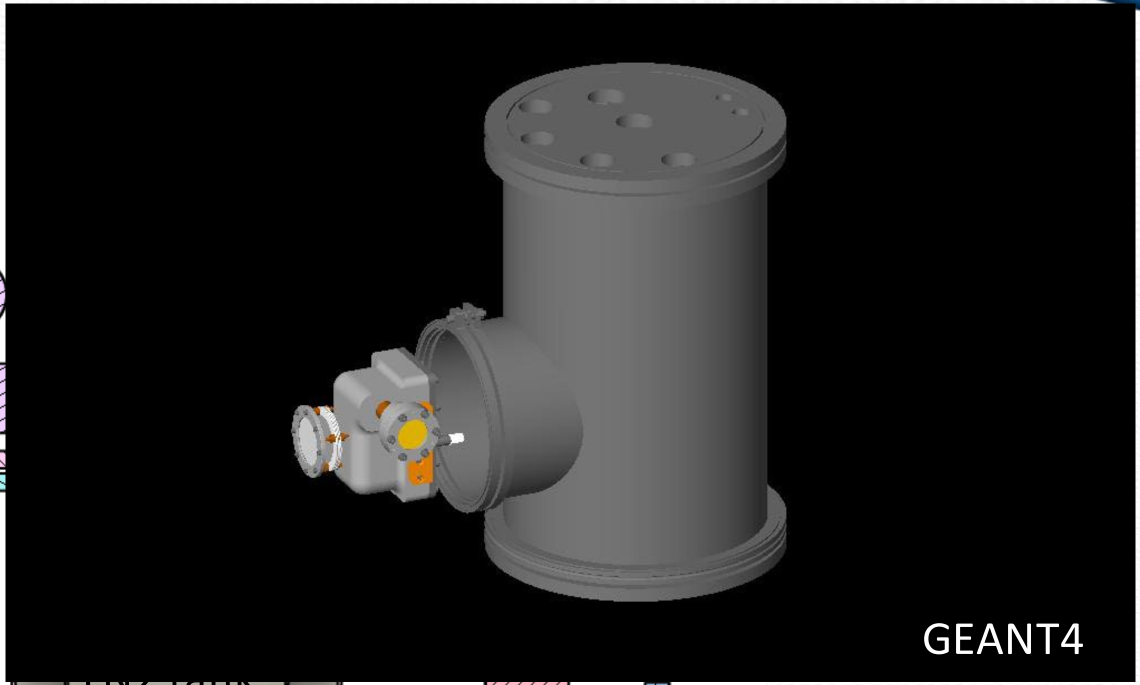

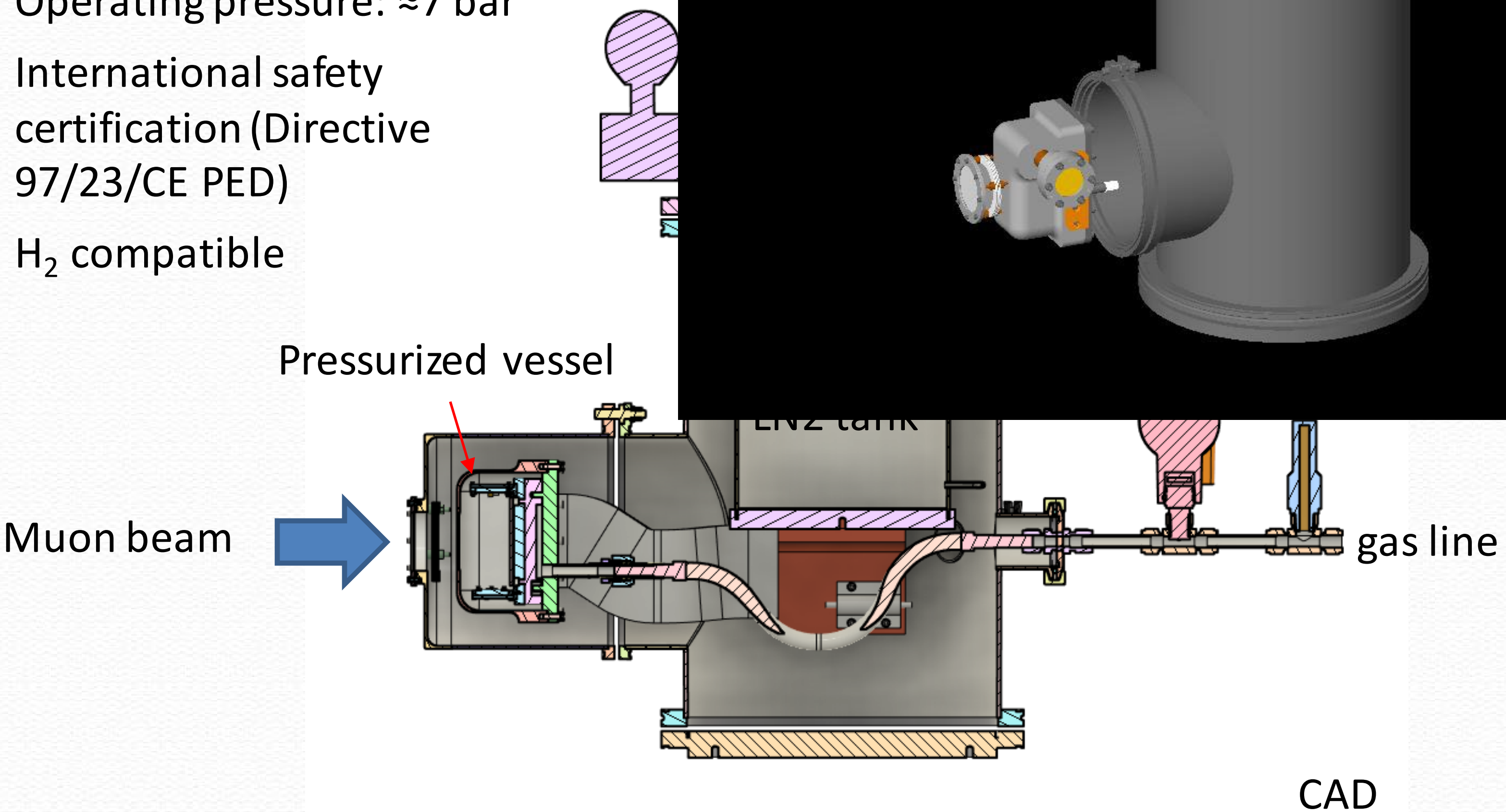

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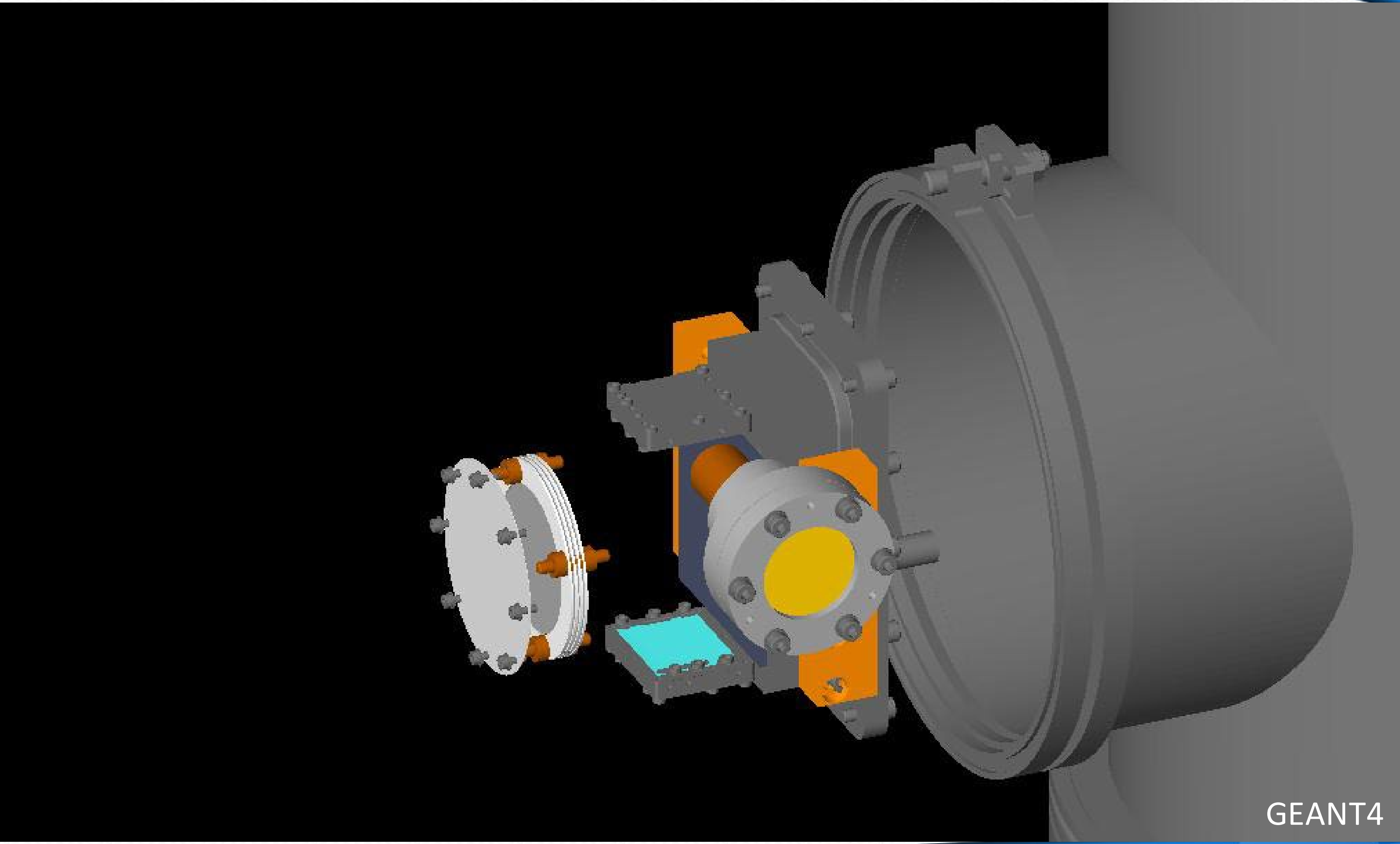

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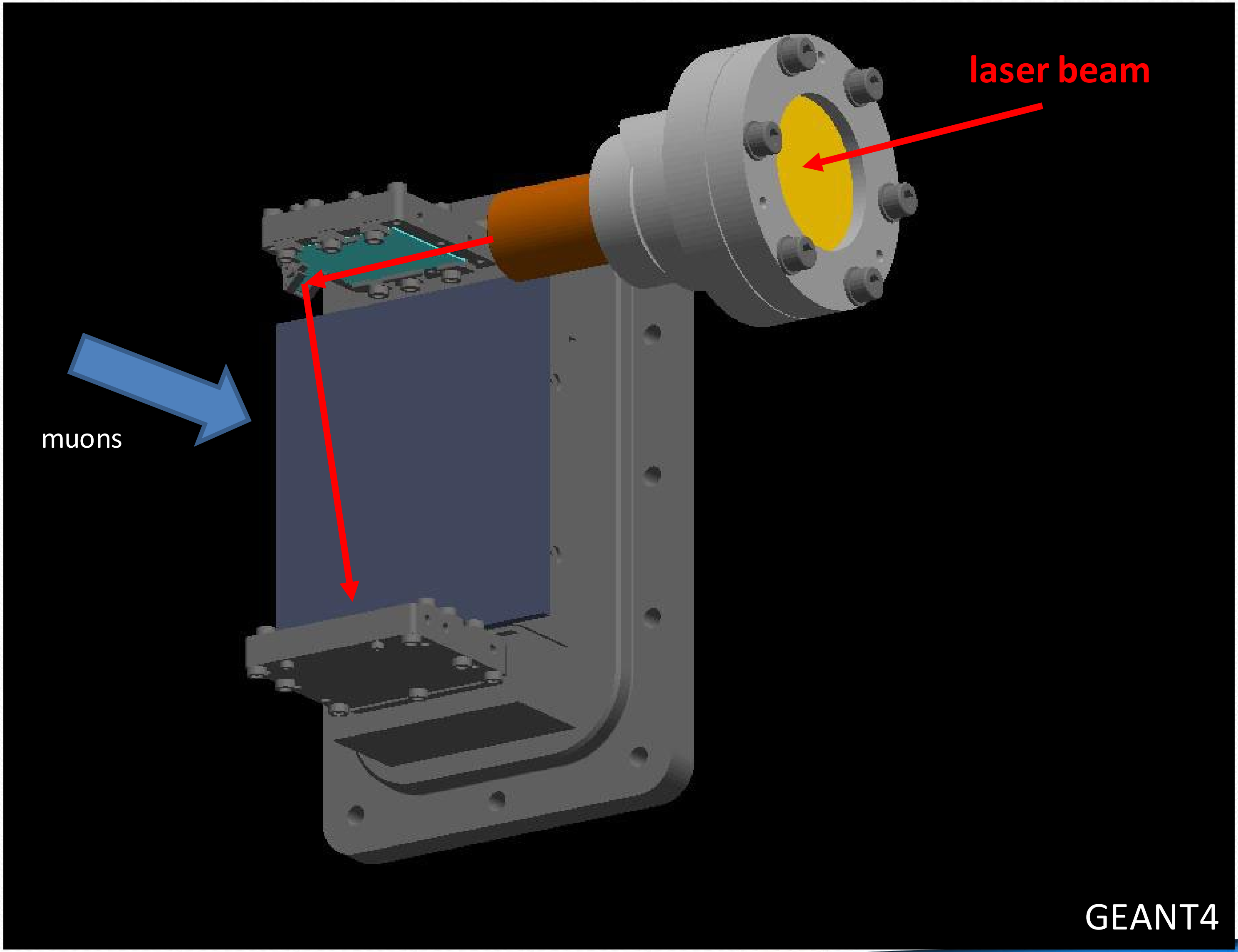
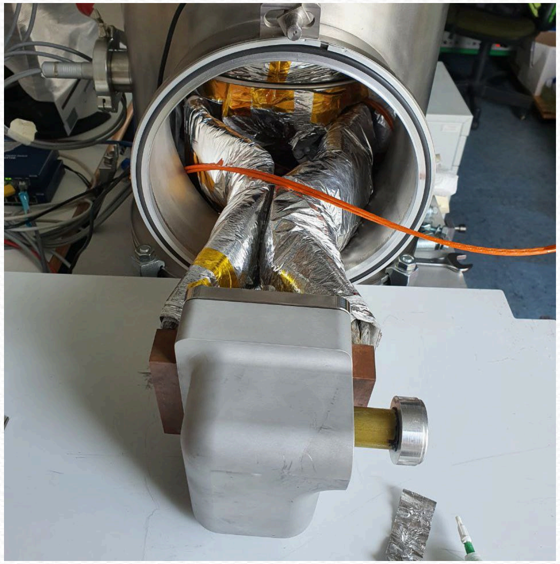
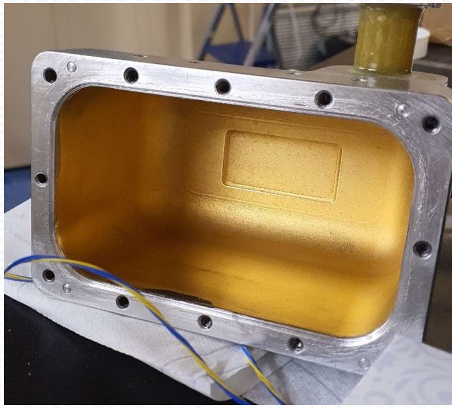
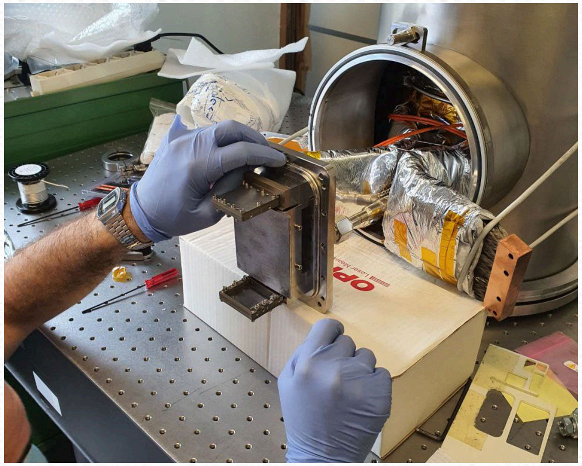
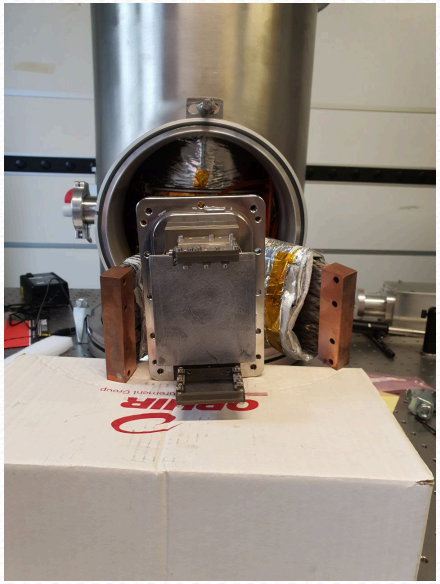


Target: some pictures









Detectors: $LaBr_3$:Ce crystals

Main requirements:

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

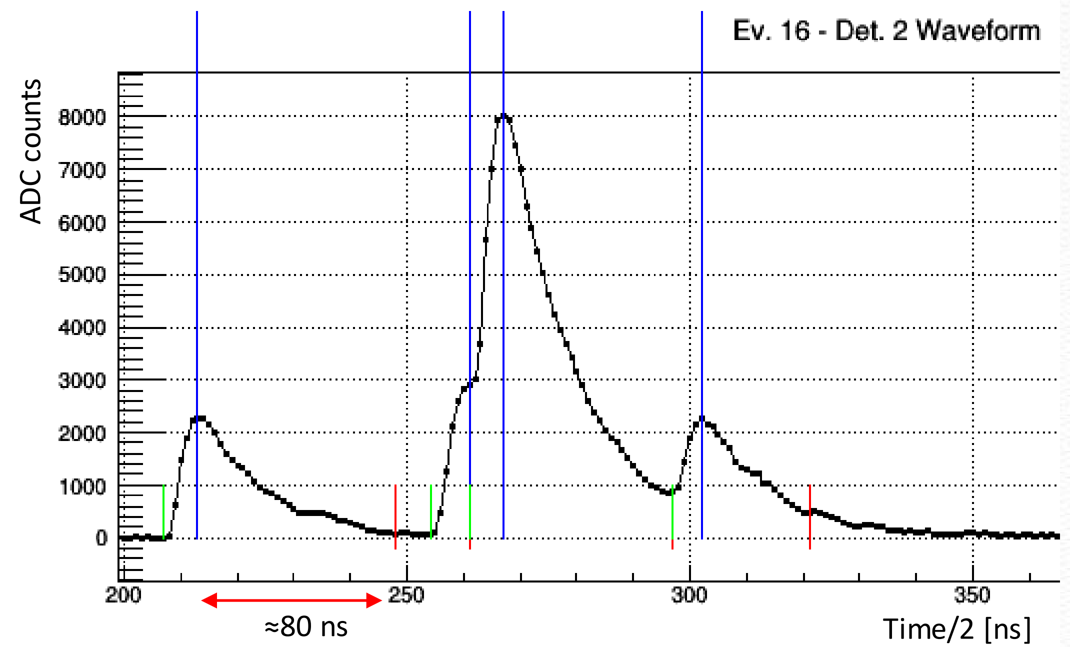
17 LaBr3:Ce 1'' read by PMT

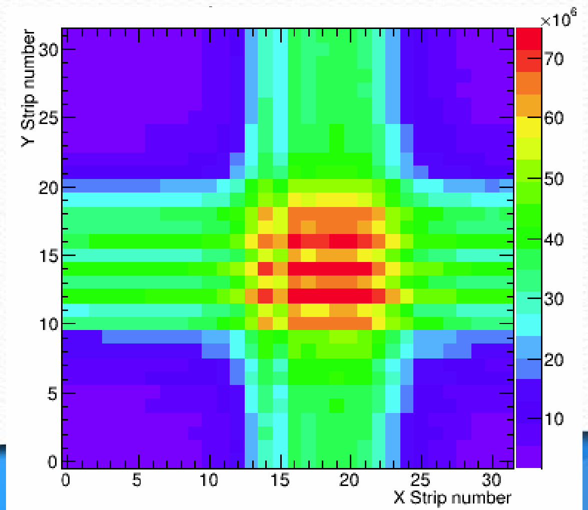
11 LaBr3:Ce 1'' read by SiPM

15 LaBr3:Ce ½'' read by SiPM

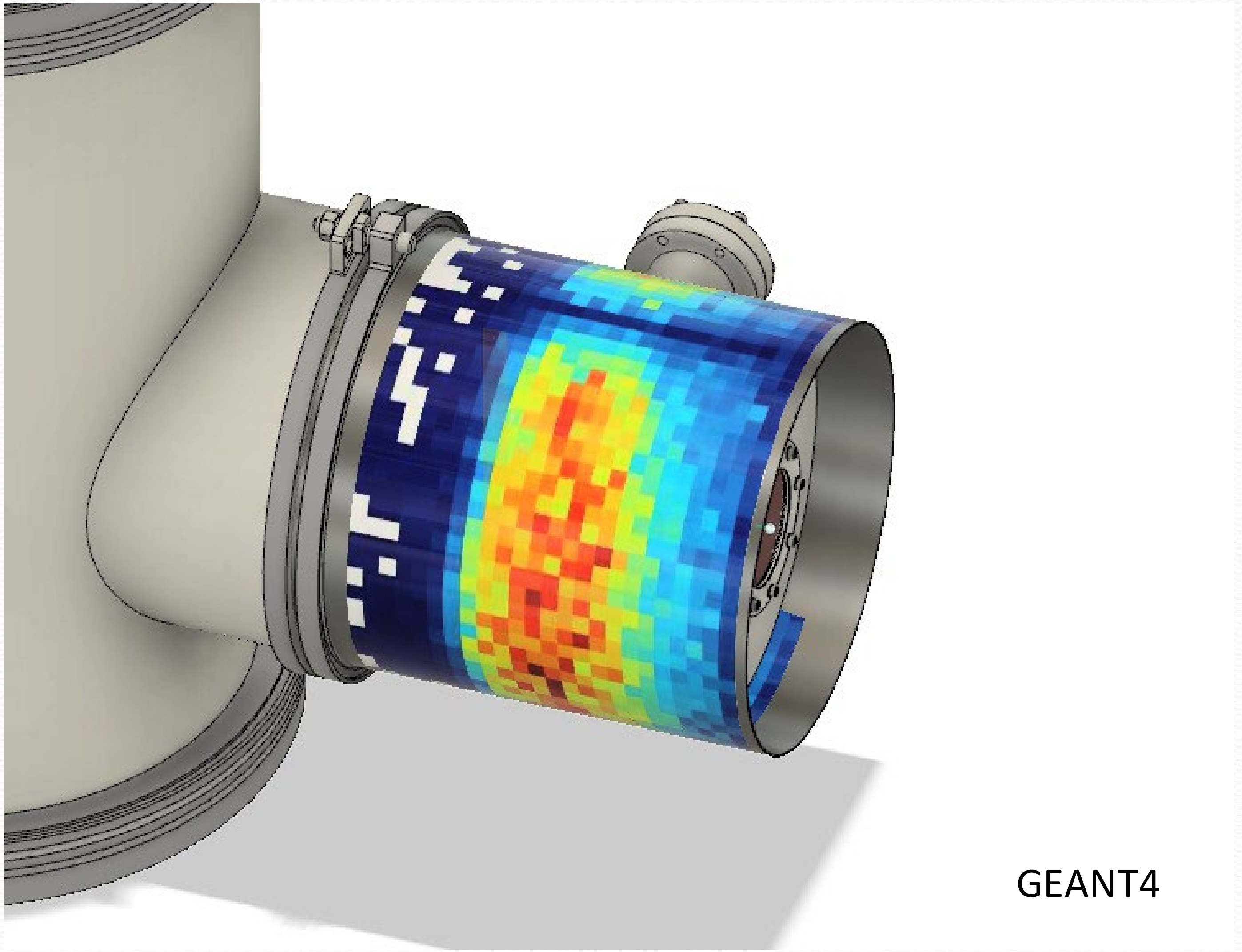
1 HPGe (Ortec GEM-S)

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



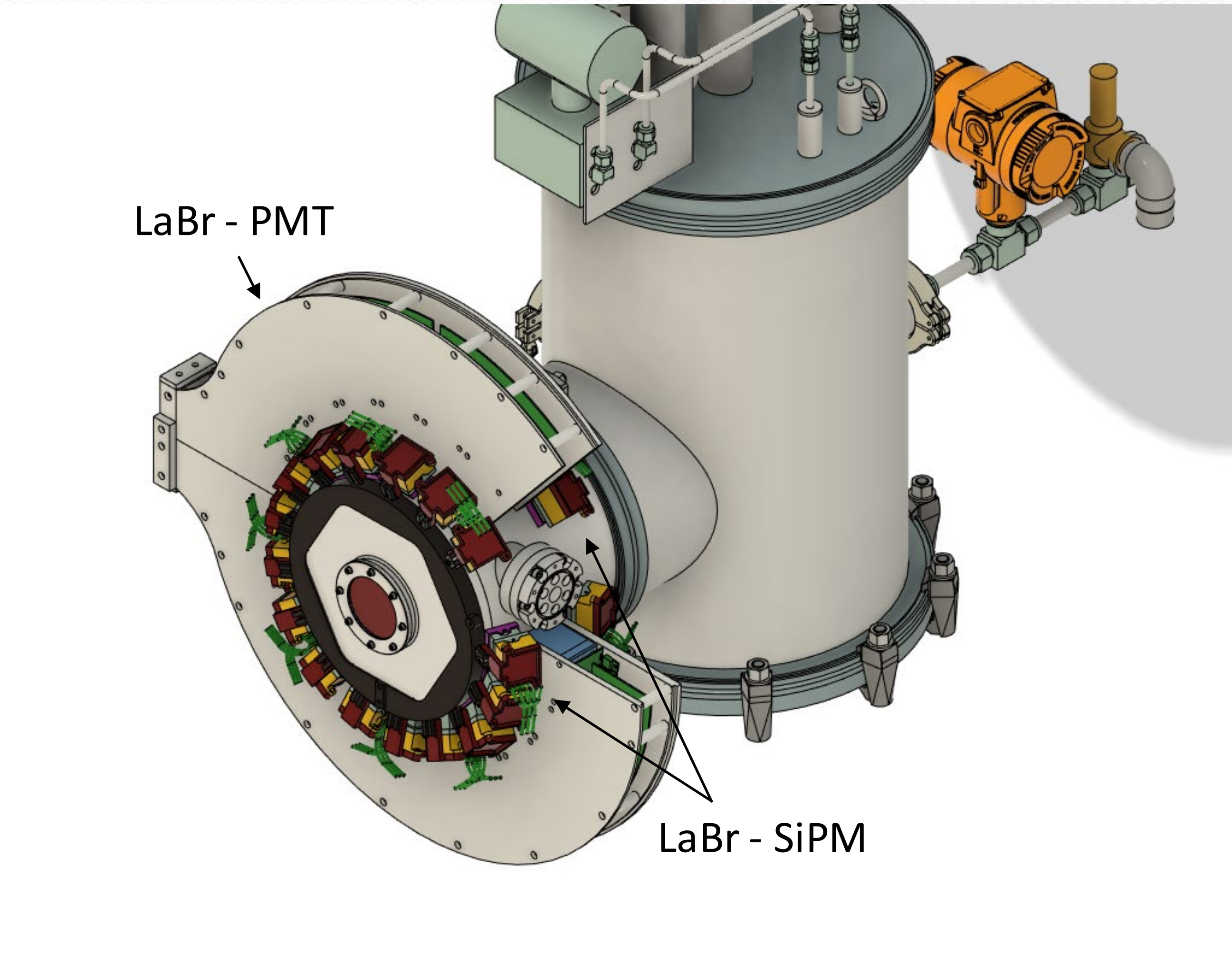


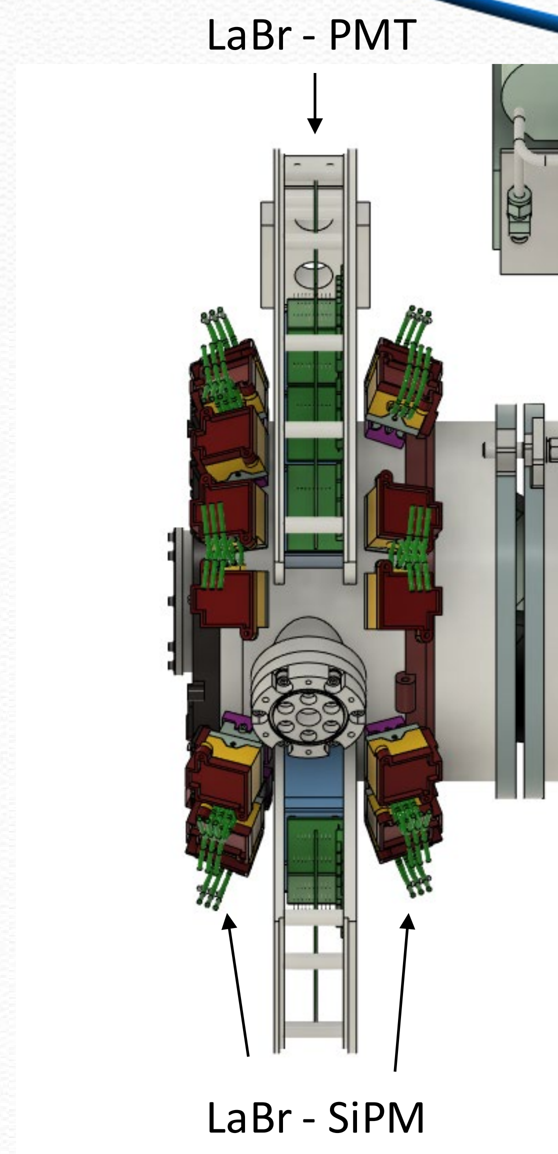
X-rays distribution from simulation



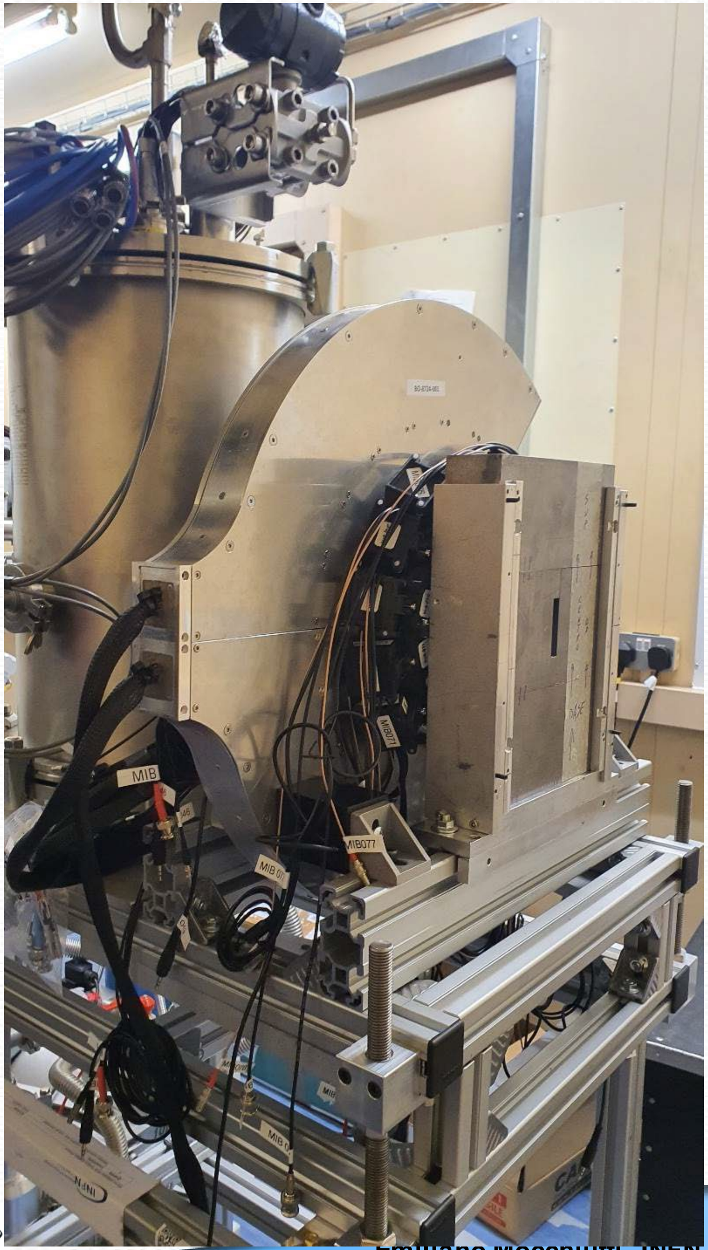
GEANT4

Detectors: placement





Detectors: pictures



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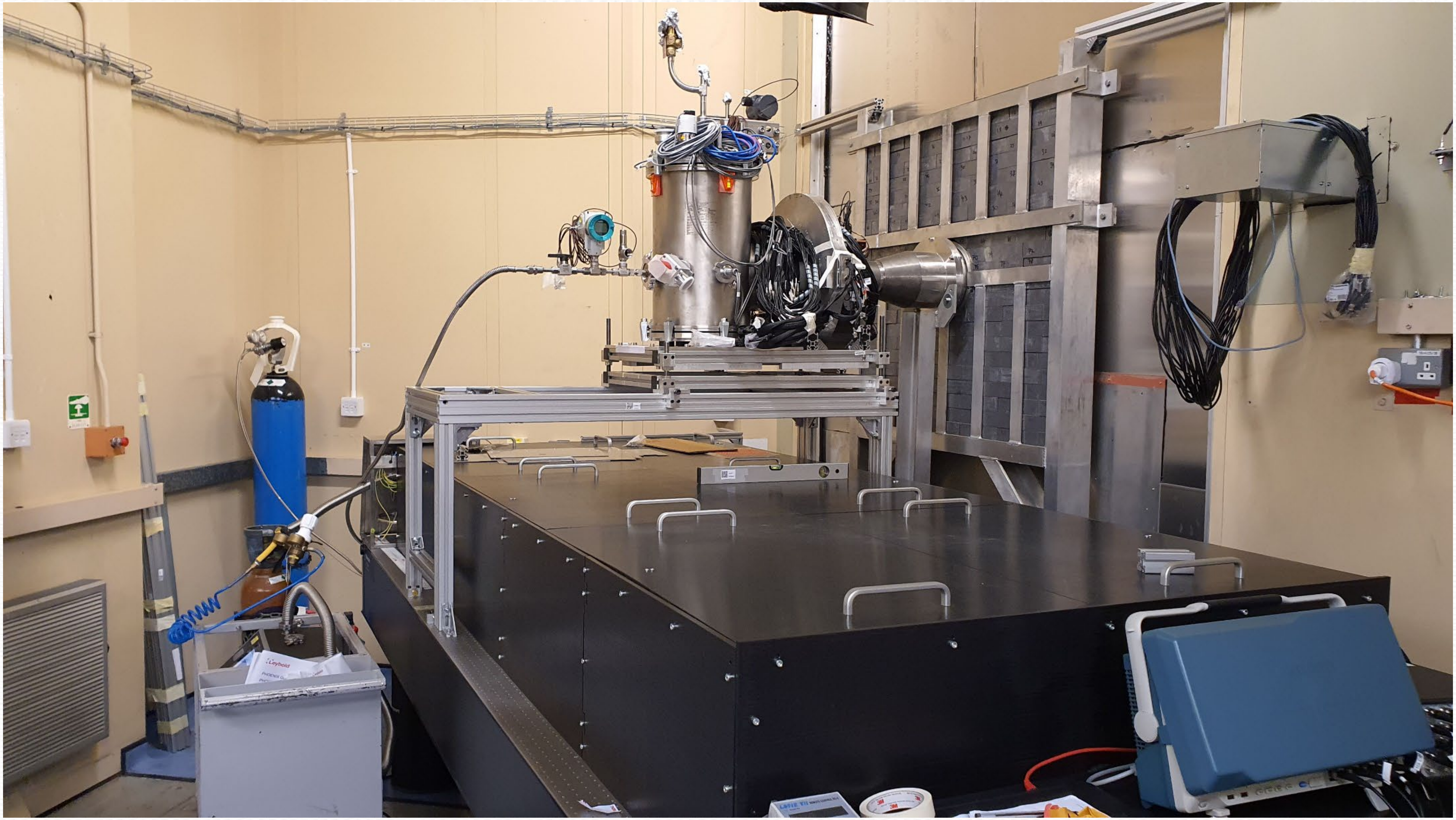
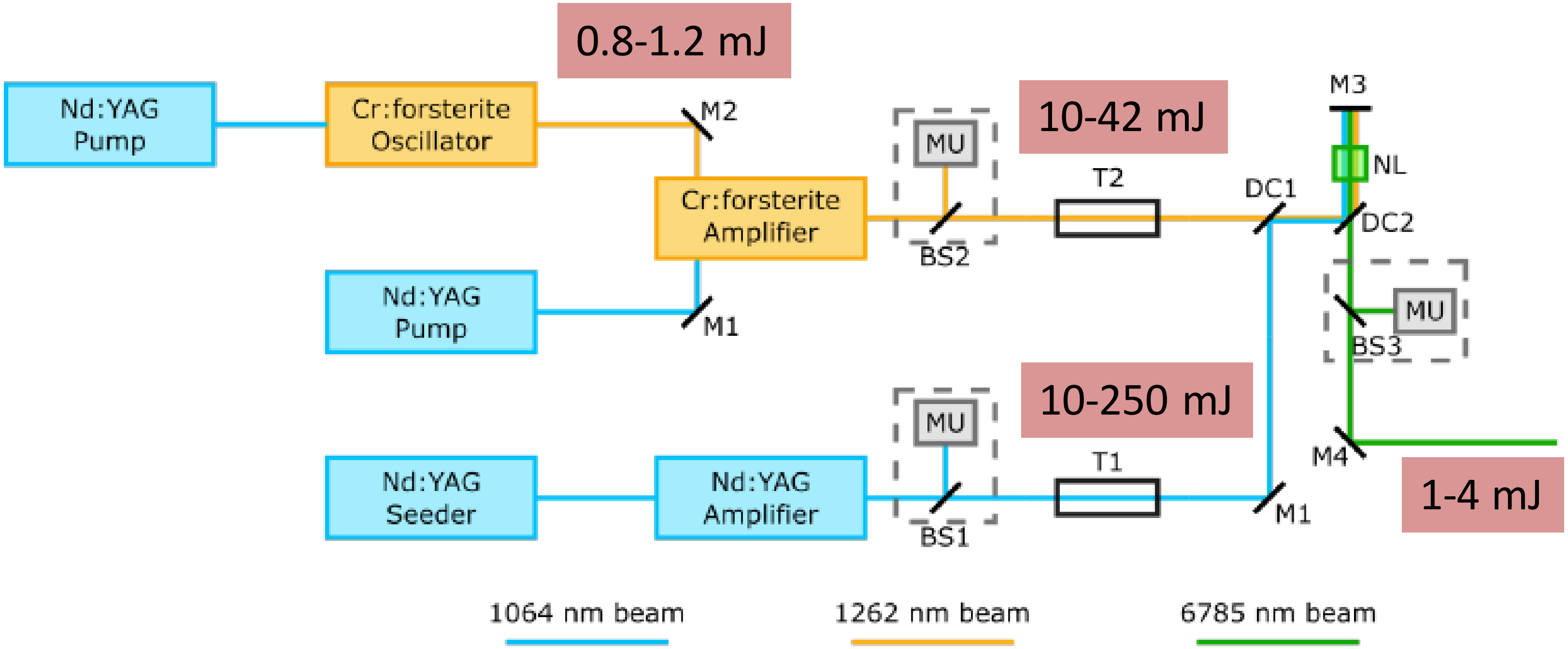


Laser: characteristics

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)

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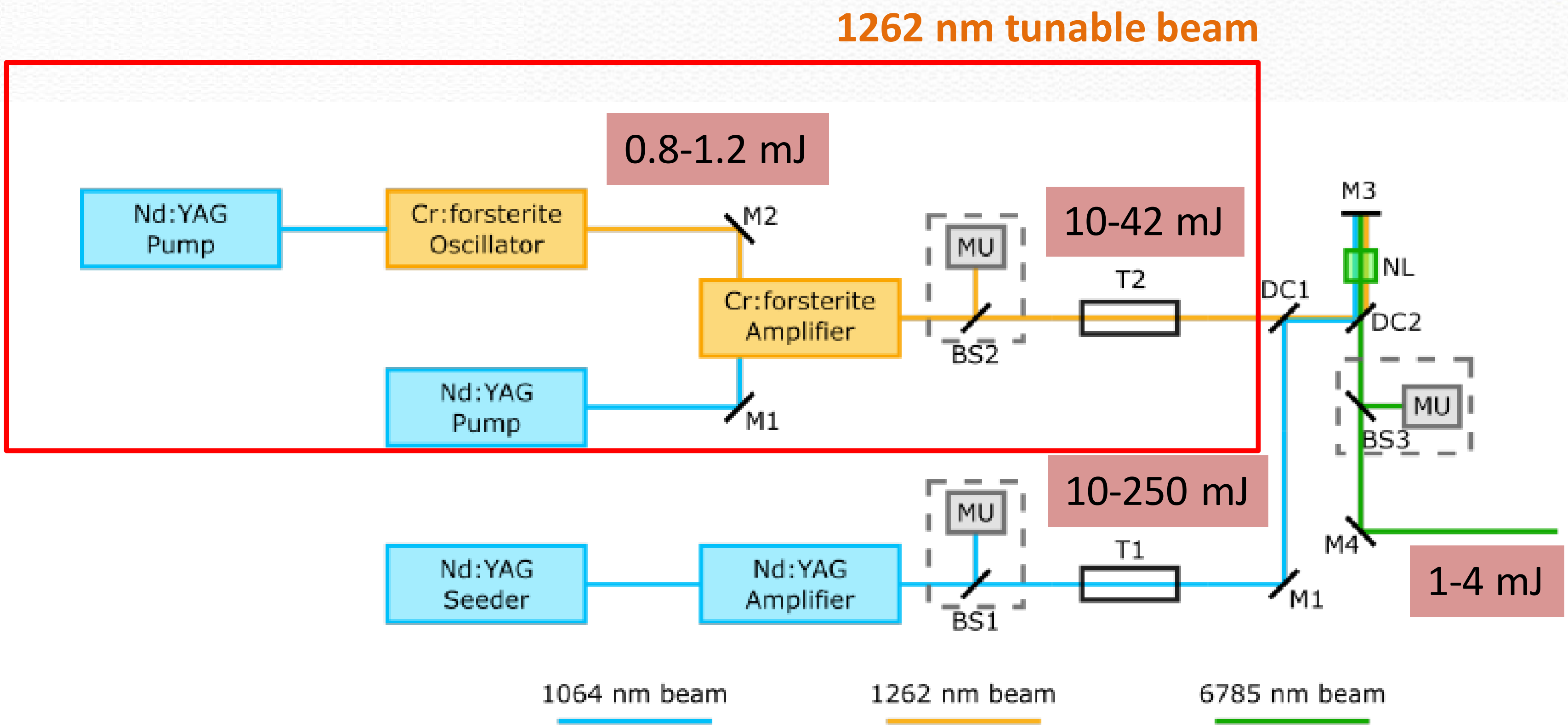

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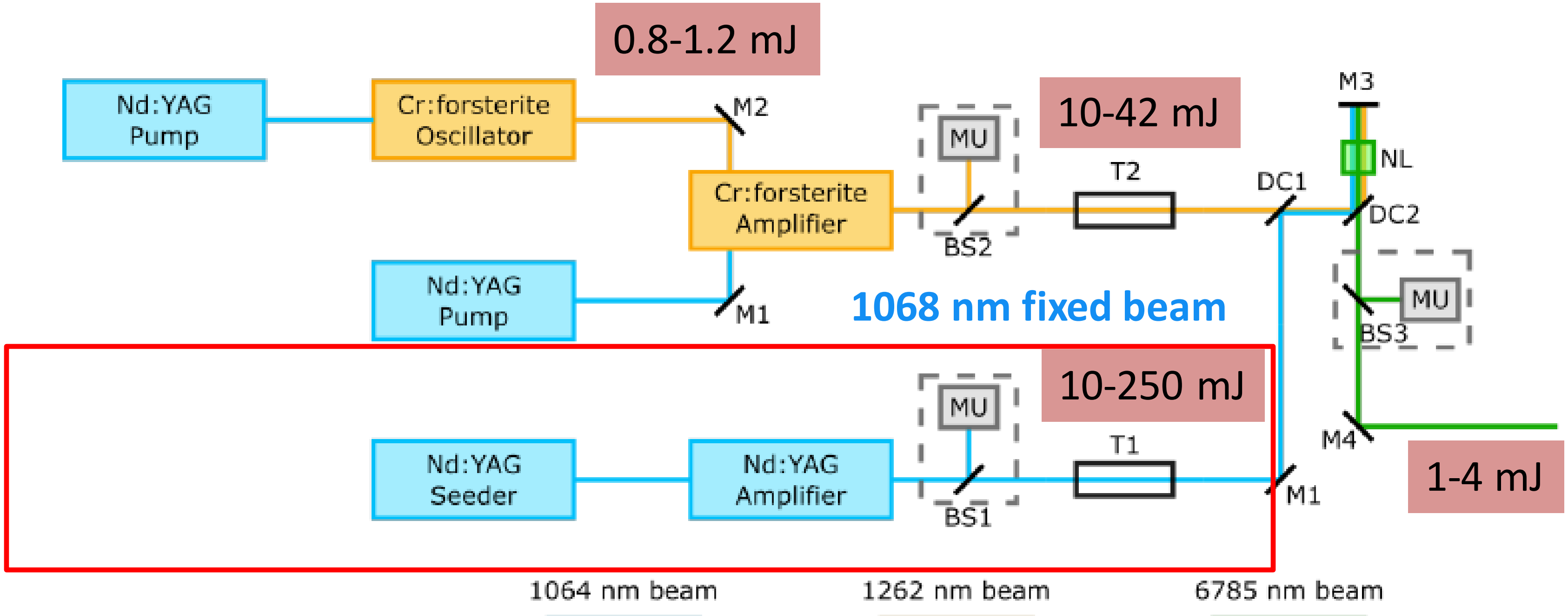

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Laser: difference frequency generation

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

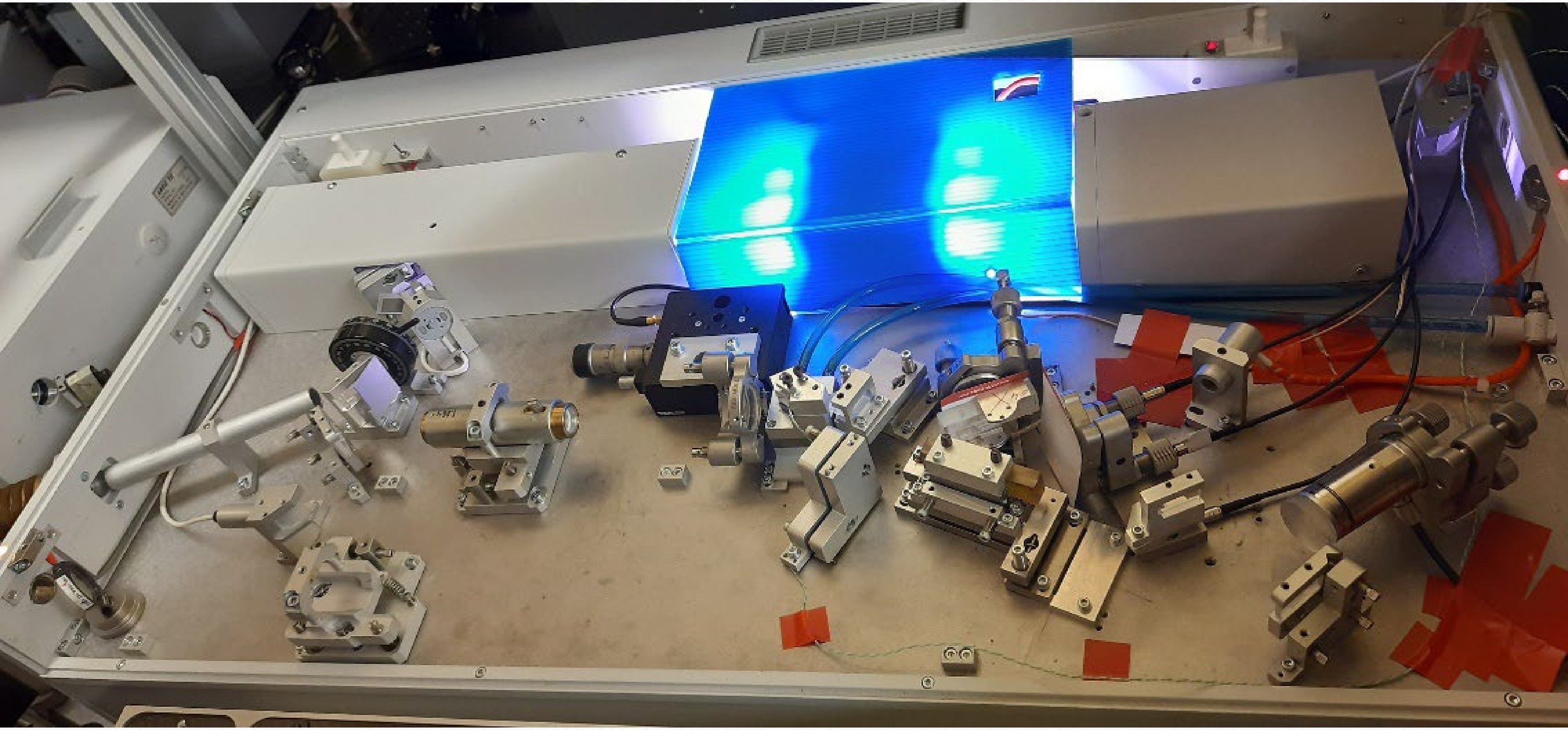
1262 nm tunable beam

1068 nm fixed beam

6800 nm tunable beam

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

Laser: pictures



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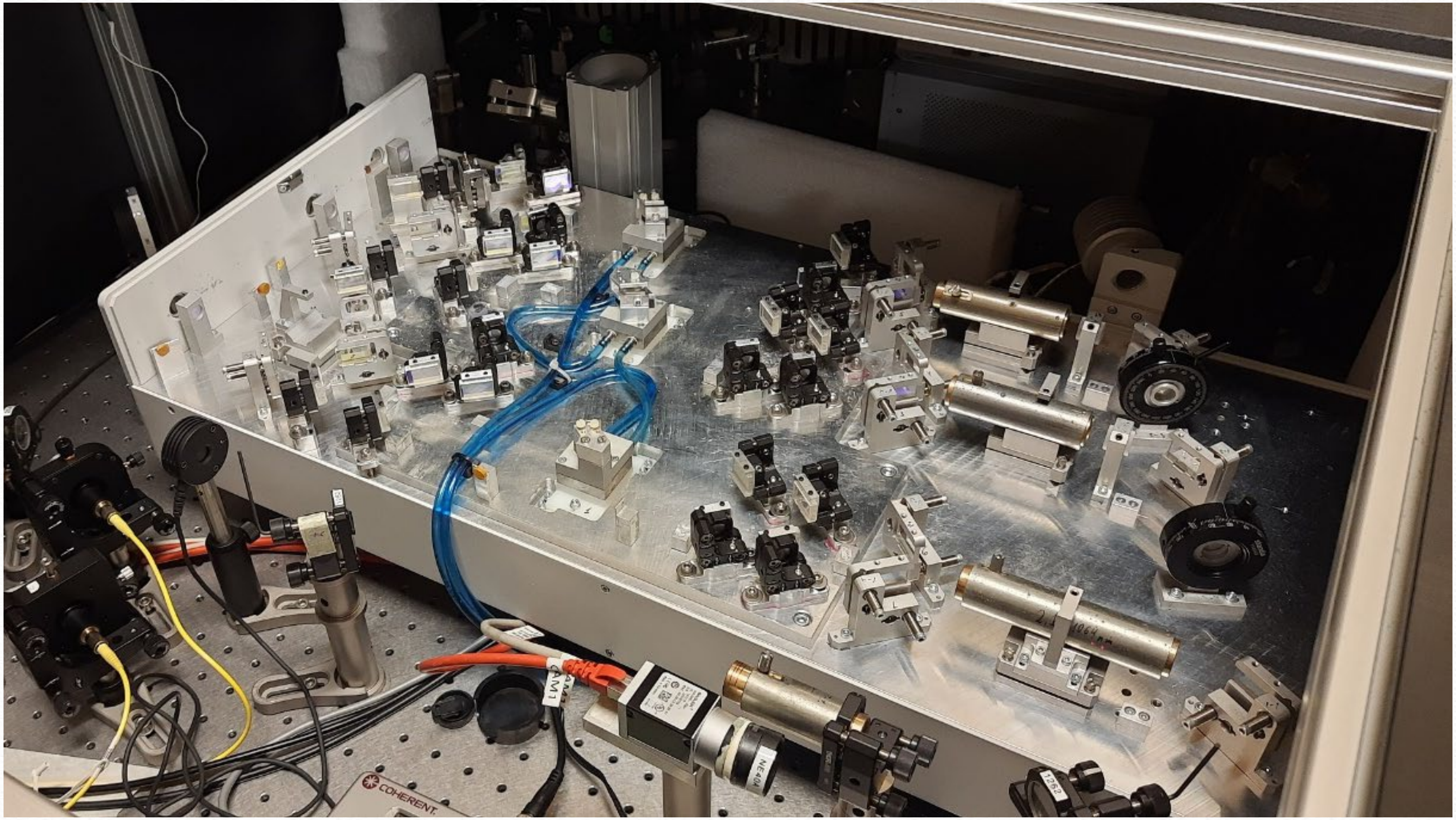

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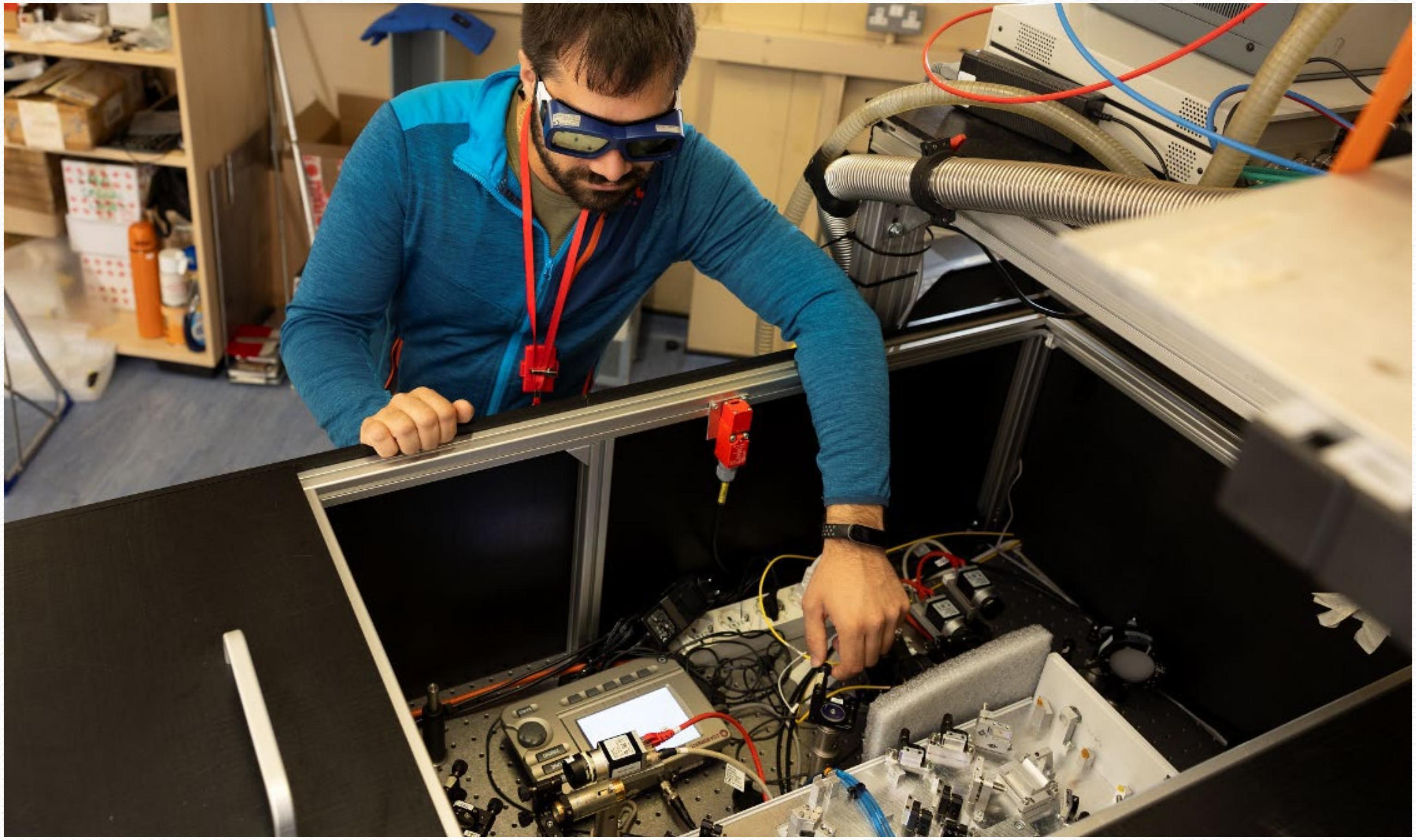


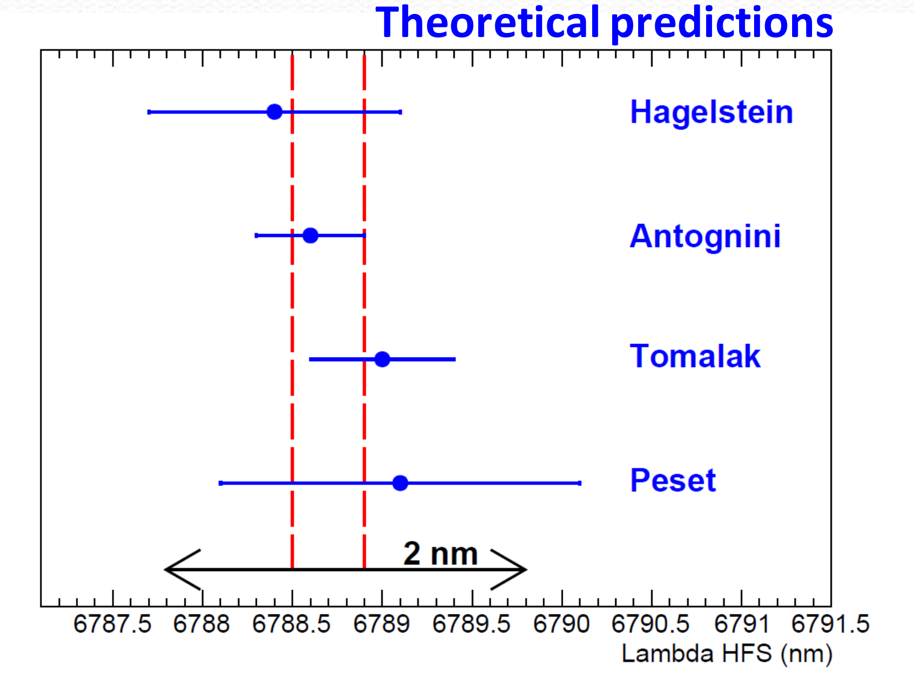
Laser: pictures

Present status

Measurement plan

- Measurement range: ≈ [6786.5 ; 6791] nm (width 4.5 nm)
- Natural Doppler broadening @80K ≈ 45 pm (σ, FWHM ≈ 80 pm)

➡ ≈ 100 steps to cover the whole range with 45 pm steps…



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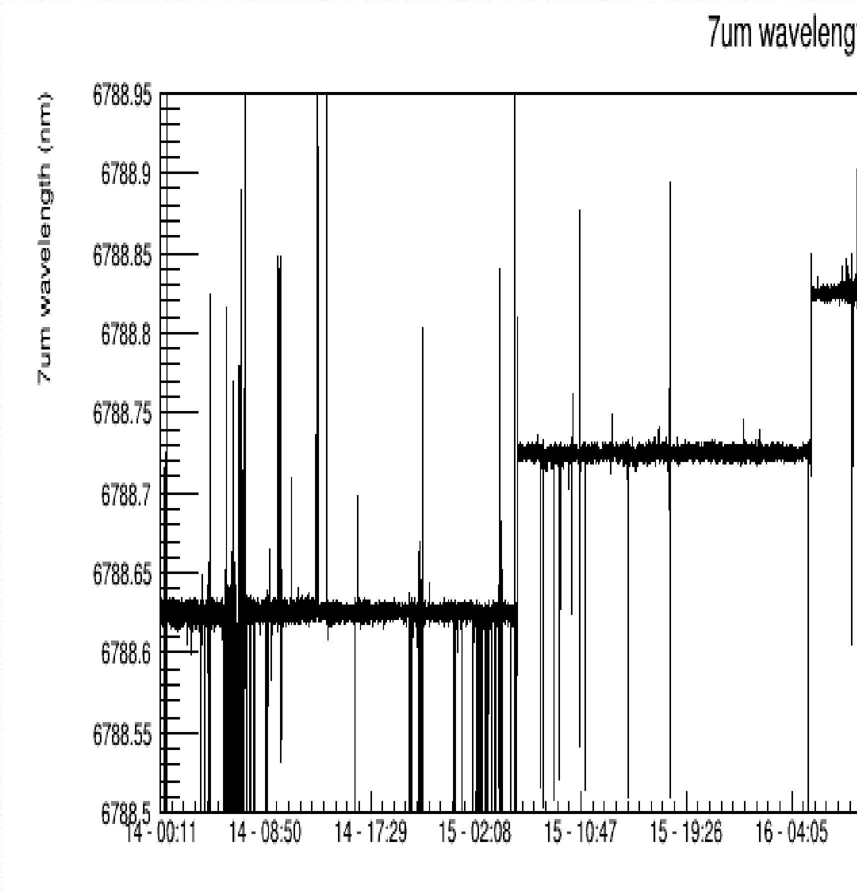
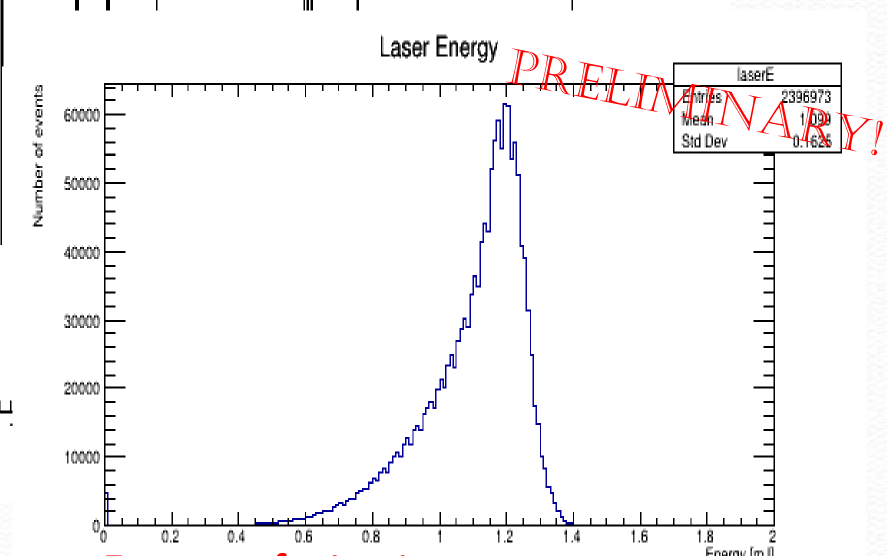
The first already allocated beam time for FAMU sum up to
25 days = 2 commissioning + 3 test + 3 background + 17 data taking

24 hours for one wavelength measurement

Scan of the most probable signal range

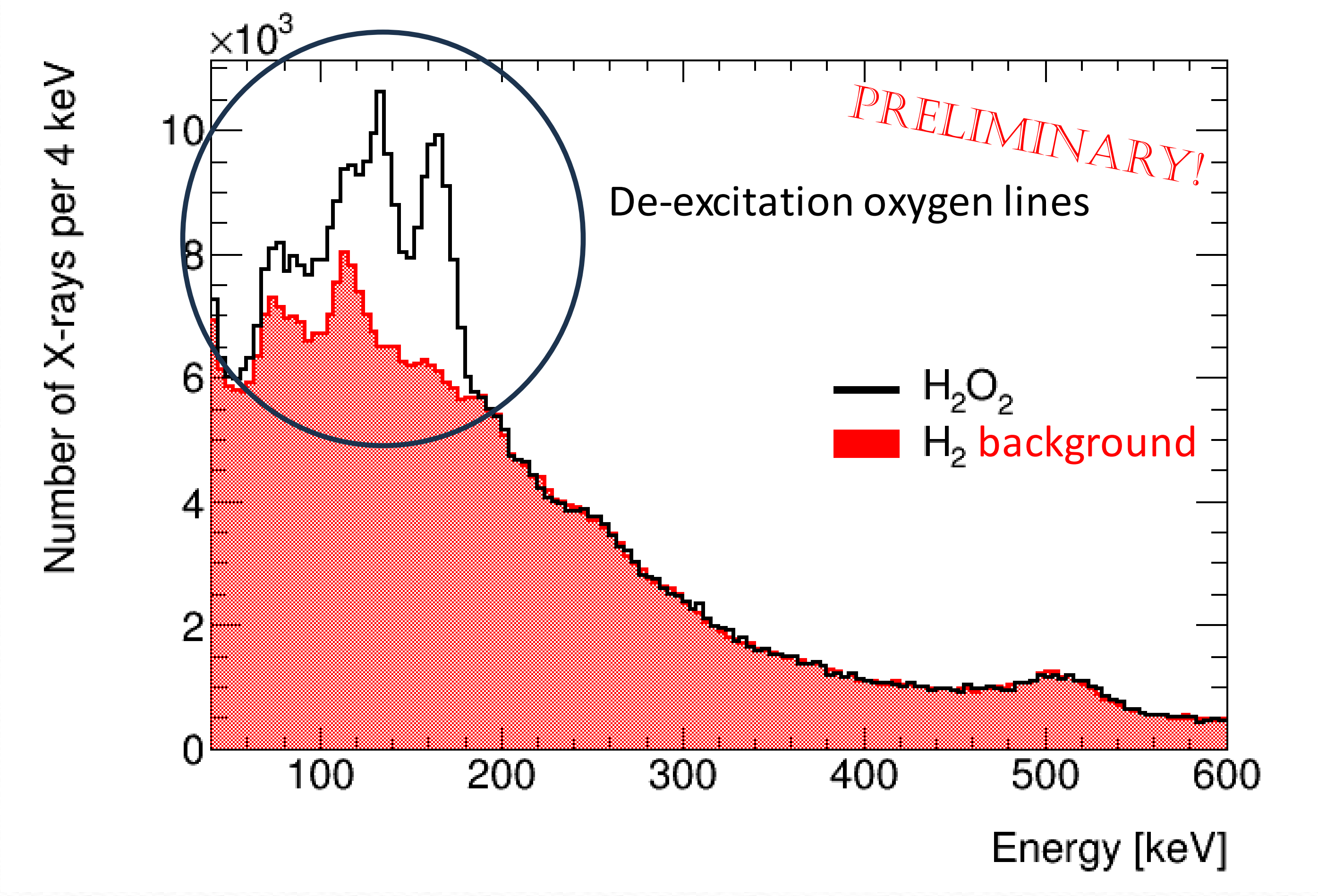
Laser wavelength: excellent stability over time and energy output





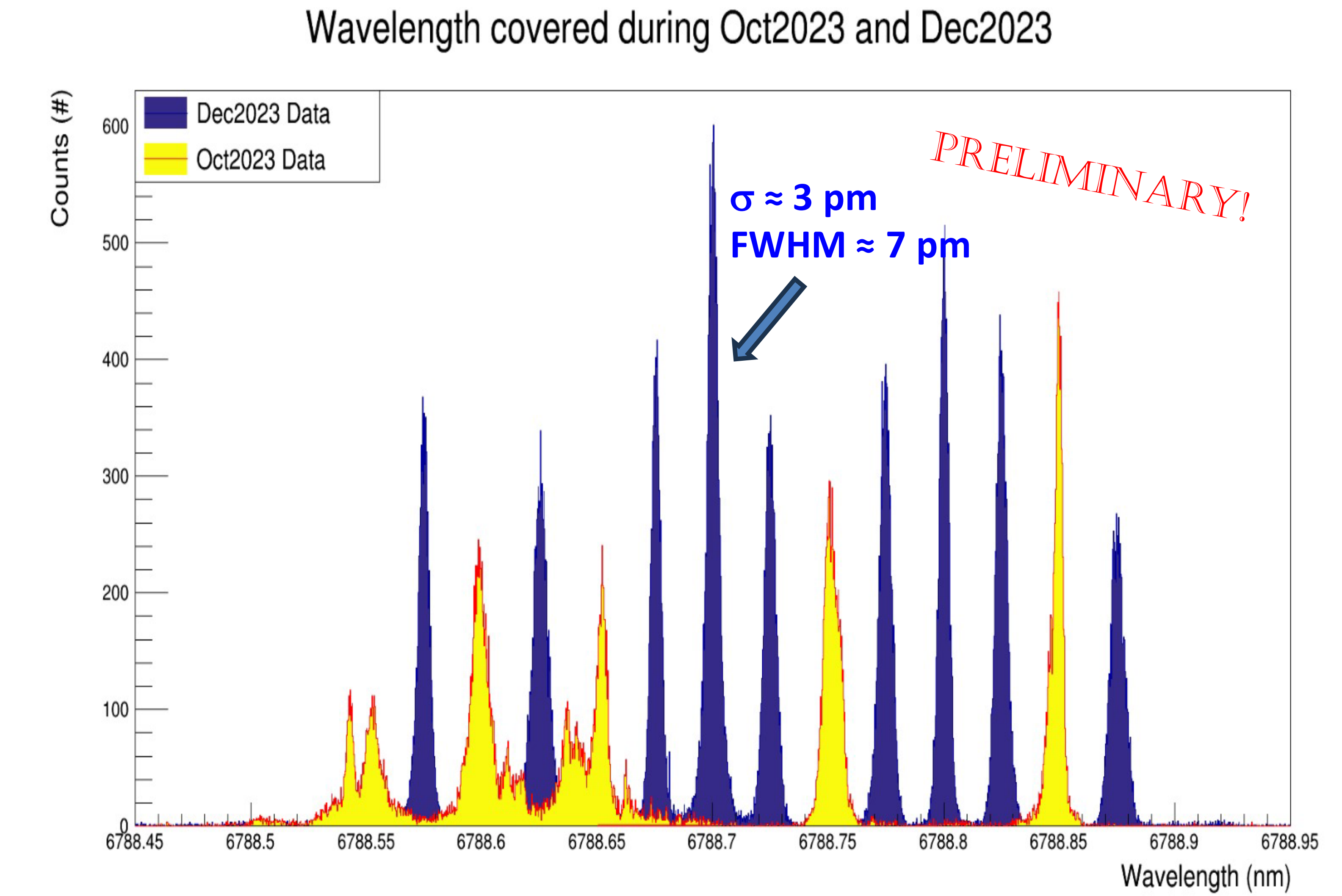
Energy of >1 mJ

Data analysis: oxygen signal



Energy spectrum 500 ns after muons arrival, one detector only, 14 hours data taking

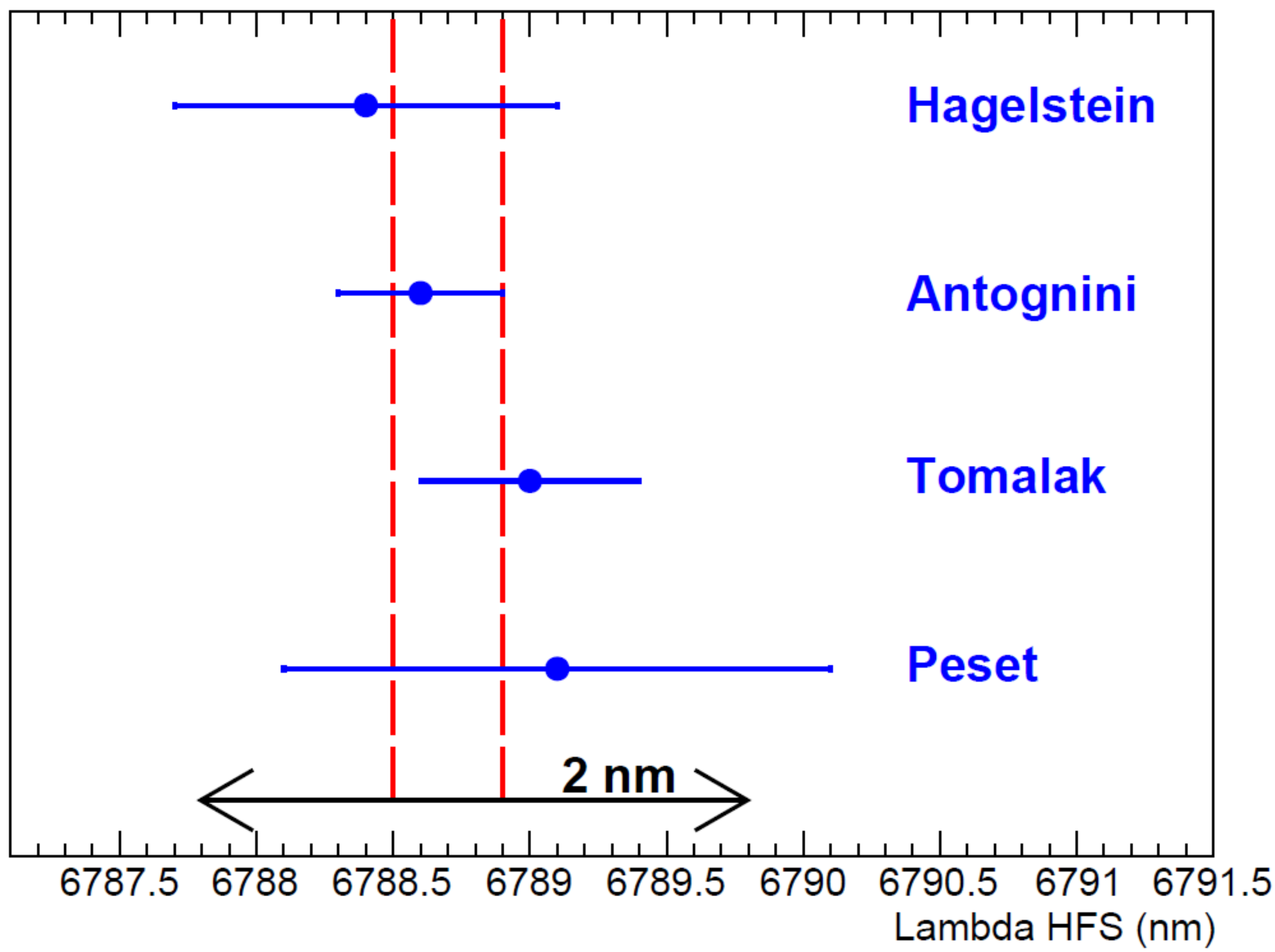
Data taking up to now



14 wavelength measurements (plus background)

Expected accuracy

FAMU expected measurement uncertainty < 5 pm (i.e. < 0.0002 meV on HFS, theo. ≈183 meV)



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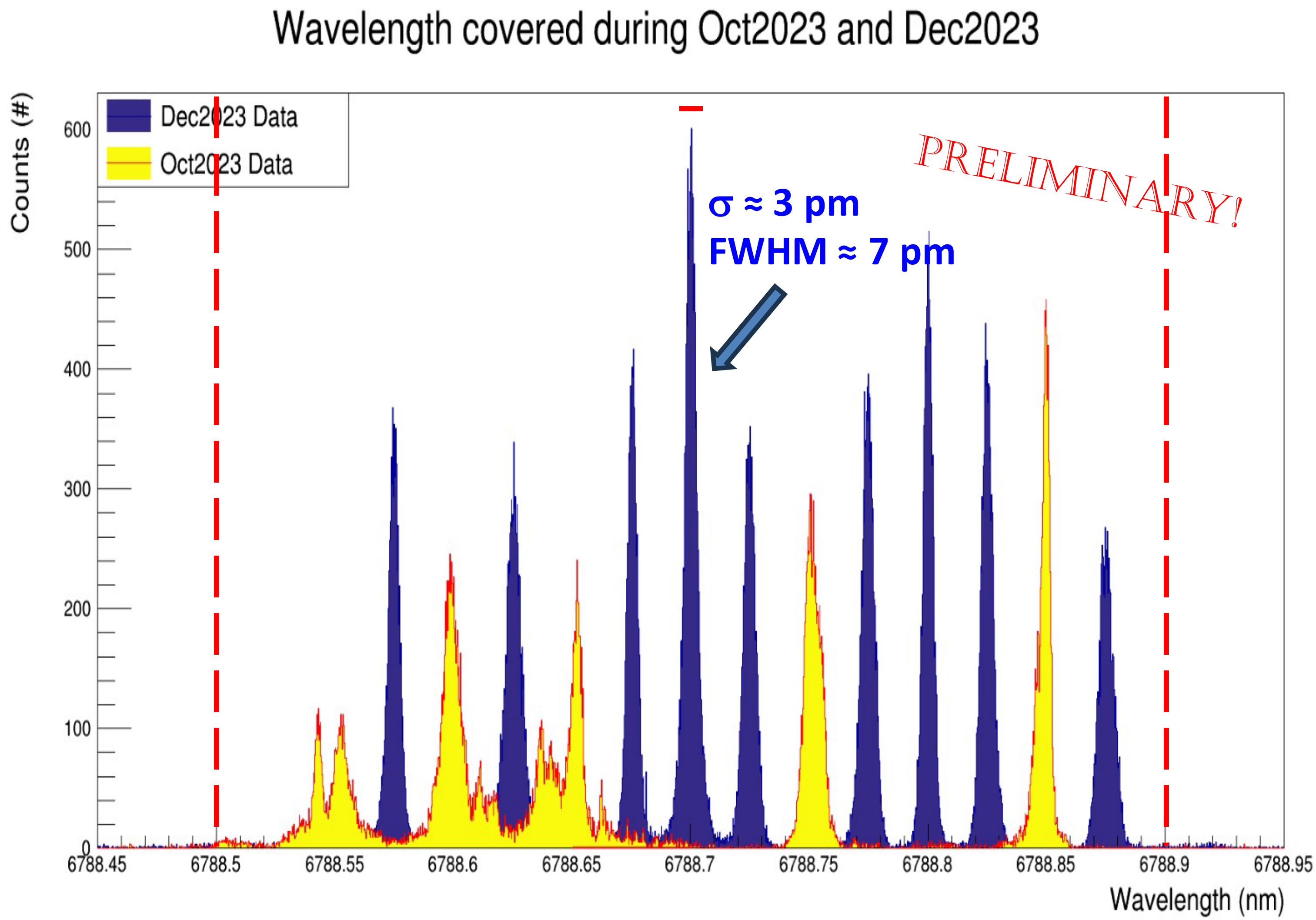


14 wavelength measurements (plus background)

Perspectives

2024 beam time approved

Beam time request submitted in November

Summary of the Proposal
for the continuation of the FAMU data taking at Port-1 in 2024

Experiment: FAMU
P.I.: Andrea Vacchi, andrea.vacchi@ts.infn.it
Goal: Measuremeant of the muonic hydrogen ground state hyperfine splitting to determine the Zemach radius of the proton
Beam time request: three time periods of 12-14 days each.

Background and context

The main goal of FAMU [1] is a laser spectroscopy experiment to measure the hyperfine splitting of the muonic hydrogen ground state and, through this measurement, to determine the proton Zemach radius. Measurement of the Zemach radius of the proton has been achieved up to now only using ordinary hydrogen. FAMU intends to measure the proton Zemach radius with an experimental uncertainty below 1% allowing higher precision than previously possible, disentangling discordant theoretical values and quantifying any level of discrepancy that may exist between values as extracted from normal and muonic hydrogen atoms (see, for example, [3]).

Beam request and time plan

The expectation from the experimental measurement of the hfs has motivated the theory community to coordinate the efforts and indicate a wavelength window of interest. Figure 1, left panel, shows the most recent theoretical predictions for the μp ground state hfs wavelength transition [4]. From Figure 1 we can reasonably define a region to be scanned, that is approximately 2 nm between 6787.8 nm and 6789.8 nm.

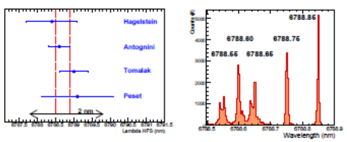


Figure 1: Left: The most recent theoretical prediction for the μp ground state hfs wavelength transition [4] expressed in nm. The red dashed lines indicate the wavelength range where FAMU operated in October 2023. Right: Wavelength distribution of the data collected in October 2023.

The data acquisition alternates triggers with laser and without laser, with a total of 12 hours of data with the laser pulse and 12 hours without laser. From our latest data, we estimate that during 24 hours we are able to collect about 2.3×10^5 muonic oxygen X-rays events in the interesting time range of the laser induced transition.

Figure 2 shows the signal to noise ratio as function of the collected statistics and time, as derived by the on-going data taking. The three lines represent the theoretical values in the case the effect is of 5%, 2%, and 1% (from top to bottom respectively). To measure not just the maximum of the resonance but also the tails, we aim to measure effects as small as 2%, thus we judge that the minimum time needed to collect enough statistics is 24 hours for each wavelength.

To establish the number of days of measurement to be dedicated at each single wavelength, we shall consider two basic parameters: the laser line width and the natural line width of the resonant transition. The line width of the laser is of about 30 pm (see Table 2), while the natural width of the 1S hfs transition in μp is dominated by the Doppler effect which, for the FAMU gas target temperature of 90 K, is about 50 pm FWHM. Hence, it appears natural to consider steps of 50 pm, and cover uniformly with 40 measurements the window of 2 nm. This shall allow to spot the resonance, and afterwards focus on the possibility to enrich the statistic in a particular wavelength region.

Approved in January

Science & Technology Facilities Council
ISIS

Rapid Access Results Notification

Dr Andrea Vacchi.
Istituto Nazionale di Fisica Nucleare sezione di Trieste
ITALY

Dear Dr A Vacchi

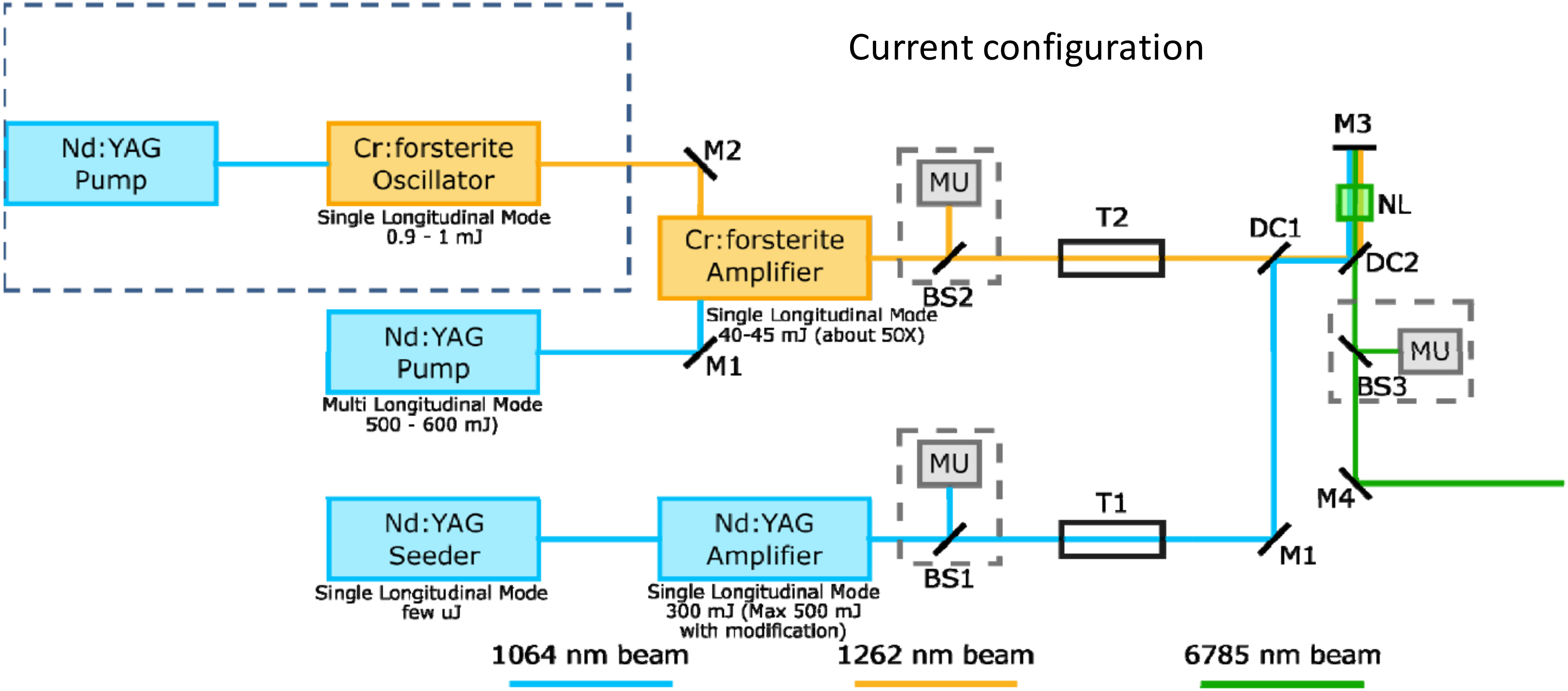
ISIS Rapid Access Application – RB2300091
Title - FAMU

Thank you for your ISIS Rapid Access application. This has now been considered by the ISIS Facility Access Panel and I am pleased to inform you that your proposal has been successful. The following allocation will be made: Instrument allocated: **RIKEN Port 1**; Time allocated:40 **day(s).**

Time allocated: 40 days

Future

Progetto PRIN 2022 “MENPHYS”:
replace the current Cr:Forsterite laser system with tunable emission at 1262 nm with an Optical Parametric Oscillator/Amplifier with improved performances in terms of output energy (x2), stability and spectral purity



Future

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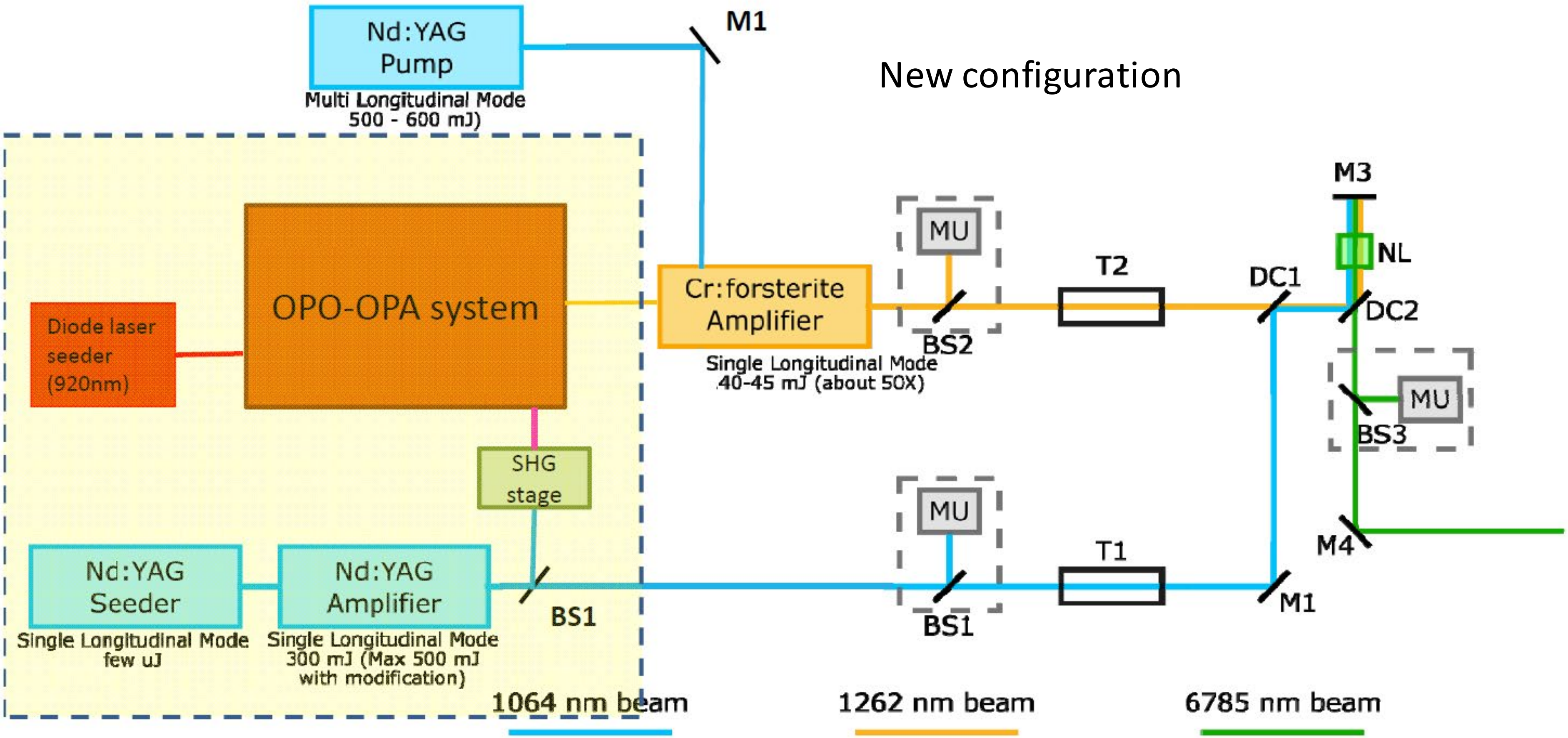
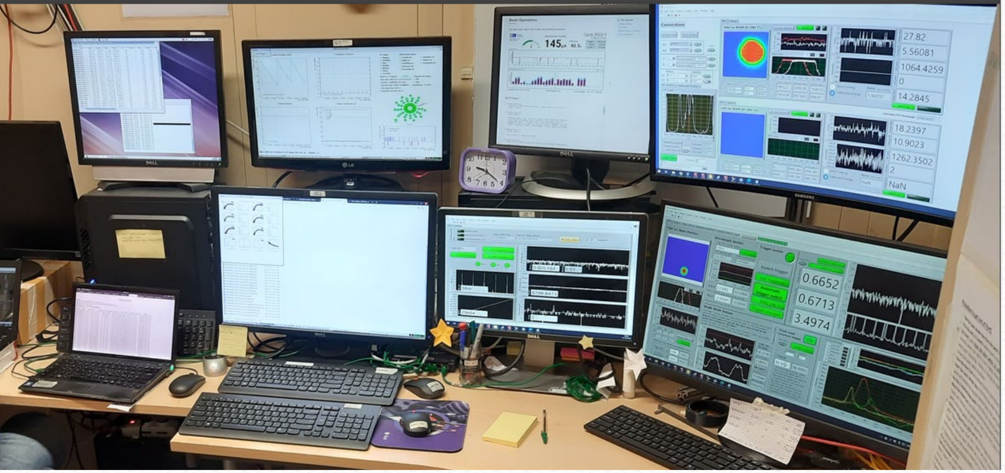


Summary

- FAMU: measurement of the $(\mu^{-}p)_{1S}$ hyperfine splitting
- Target, detectors, cavity, and laser are performing as expected
- Finally in 2023 about 25 days of commissioning and data taking
- Data analysis ongoing
- Future: 2024 new measurements, 1262 nm laser improvement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18.2397
10.9023
1262.3502
2
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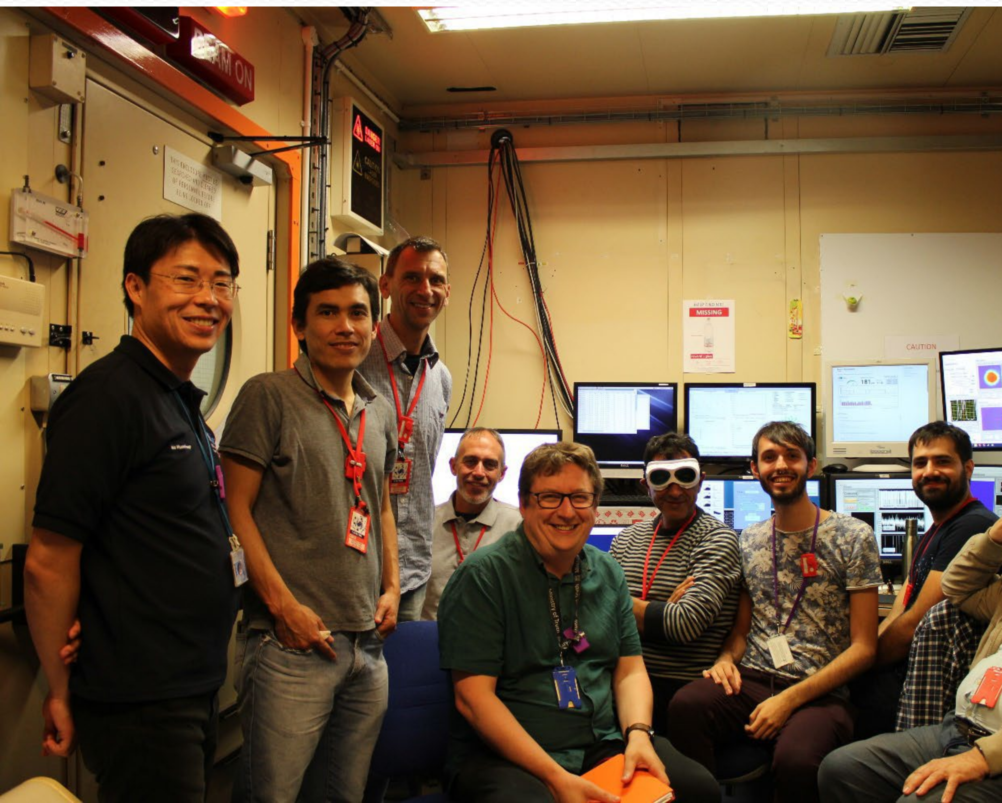
0.6713
3.4974

Thanks!


MISSING
CAUTION


BEAM ON