The FAMU experiment: measurement of the ground state hyperfine splitting of muonic hydrogen

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FAMU Collaboration

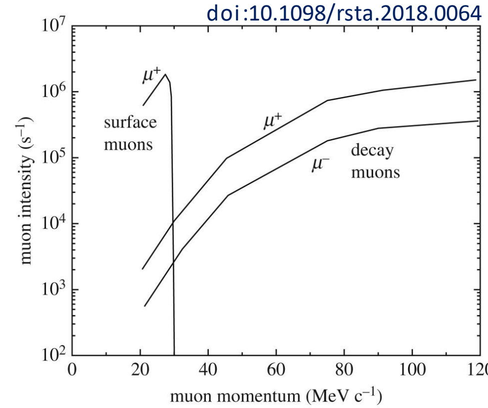
FAMU
Fisica degli Atomi MUonici

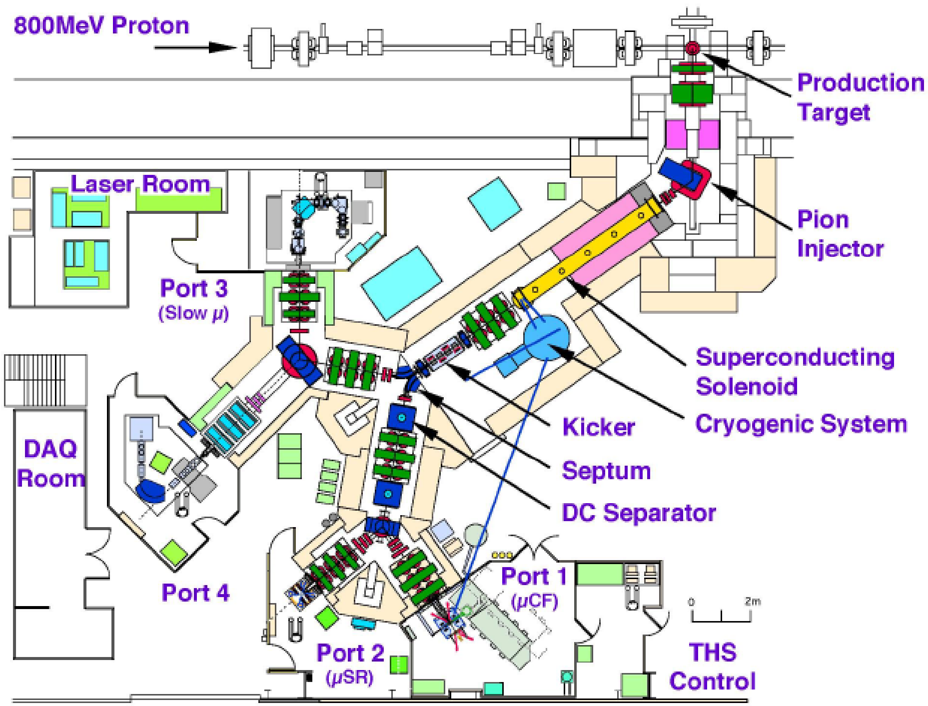
≈60 researcher
20 institutions

Where: Rutherford Appleton Laboratory - UK

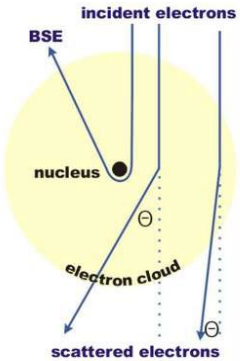
The brightest pulsed muon beam facility in the world!

doi:10.1098/rsta.2018.0064



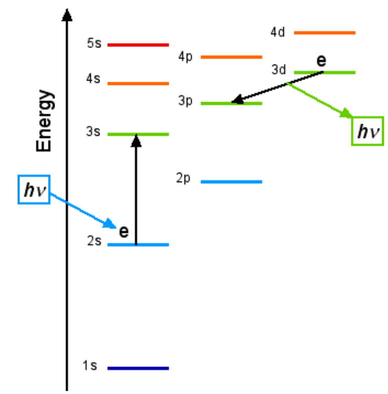


FAMU aim:
Measure HFS of muonic hydrogen ground level



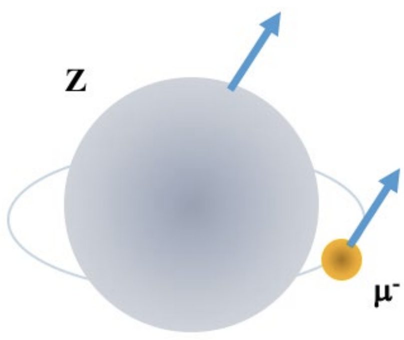
The properties of the proton can be studied with

Scattering or **Spectroscopy** experiments

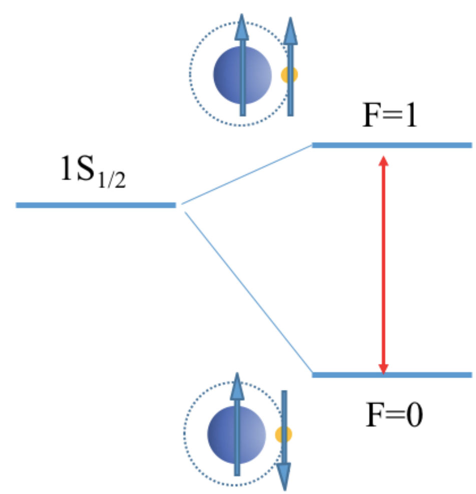


Muonic hydrogen (μp) is more sensitive to nuclear structure effects

Information on **the magnetic structure of the proton is brought by the hyperfine splitting (HFS) of μp**, this arises from the interaction between the magnetic moment of the muon and the magnetic moment of the proton.



Ground state level is split by the hyperfine interaction into triplet (F=1) and singlet (F=0) states

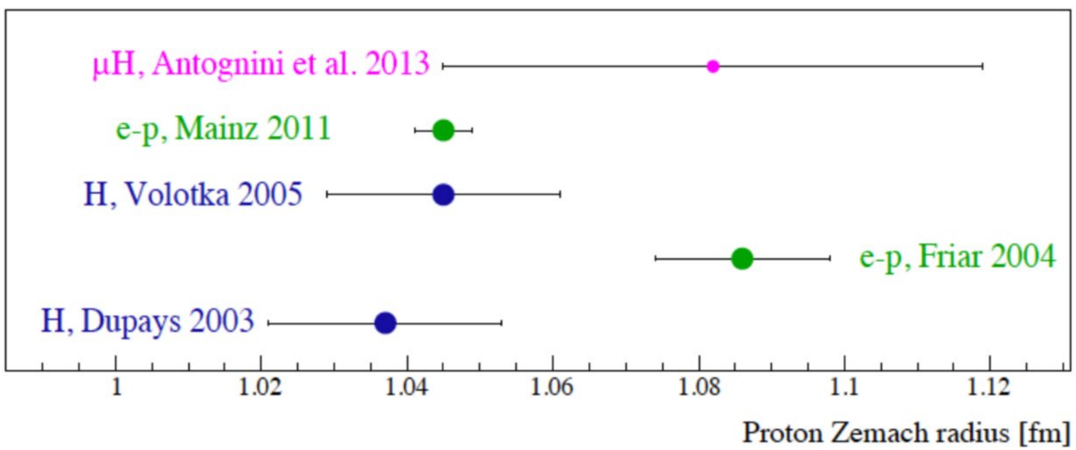


FAMU goals:

- measure the hyperfine splitting (hfs) in the ground state of muonic hydrogen with a **relative accuracy better than 10^{-5}**

- deduce the **Zemach radius** with a relative accuracy better than **1%**.

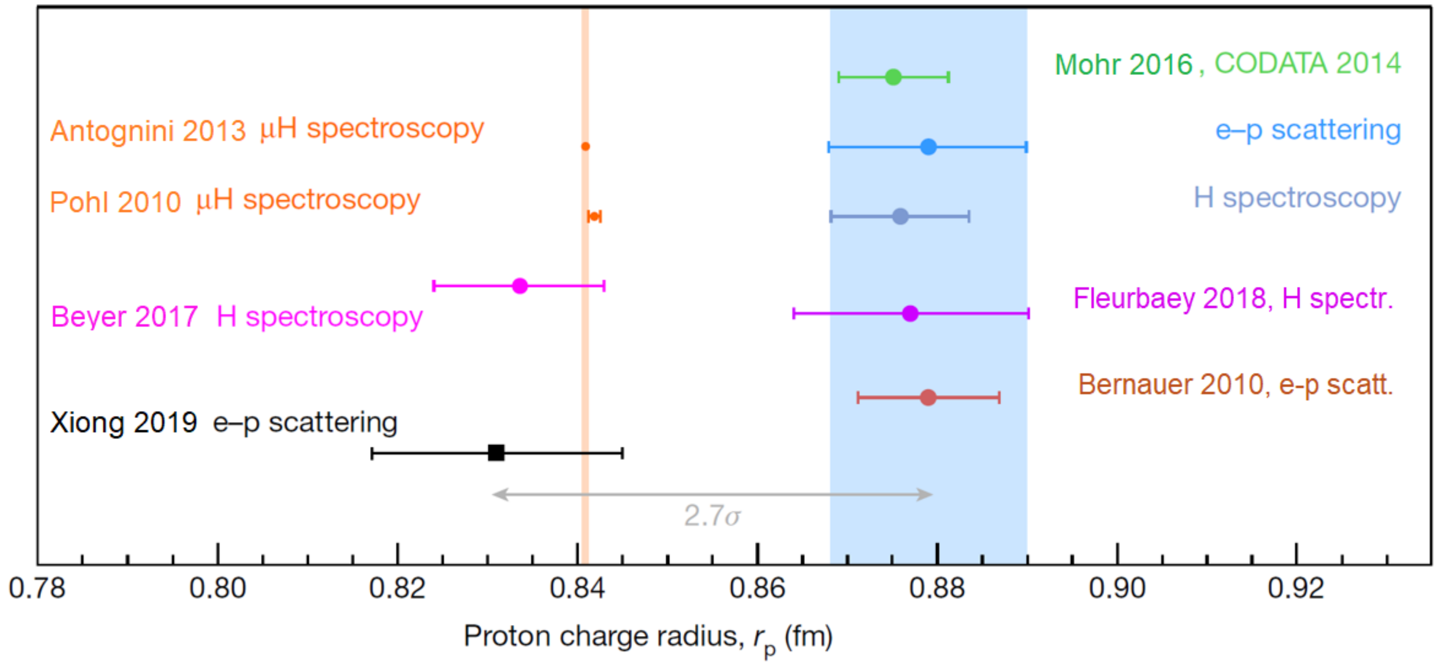
This measurement will provide a benchmark for the models of the proton.



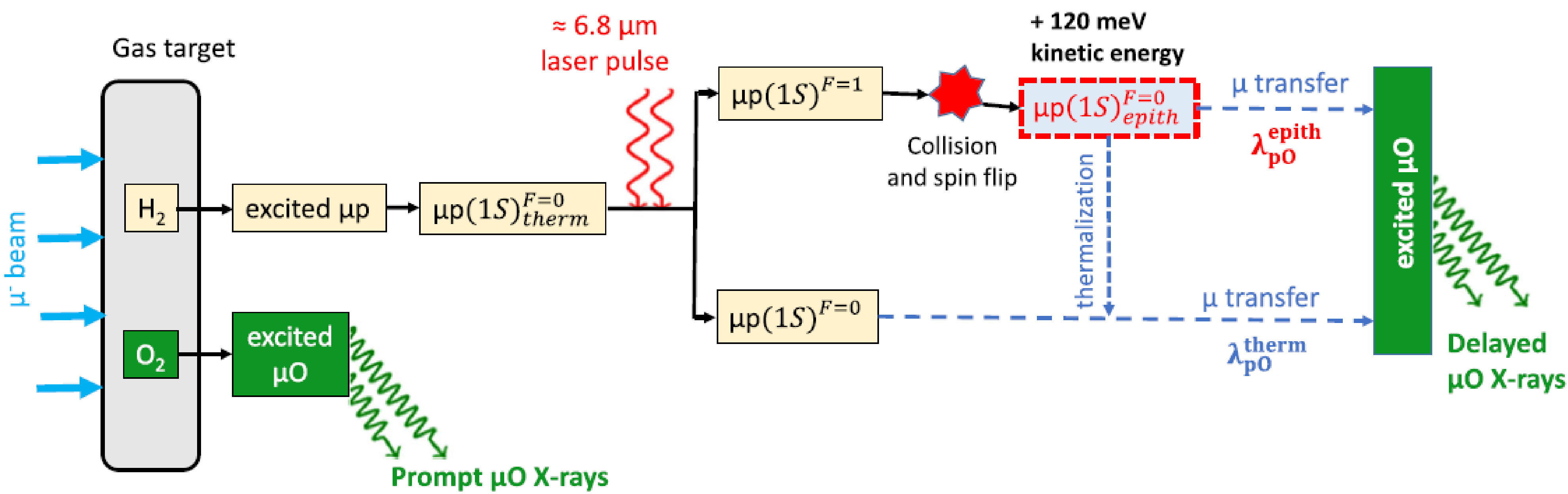
The proton charge radius

- Need of **precision experiments** carried with different techniques
- **Importance of correct estimation** of systematic uncertainties

Modified from Xiong et al. DOI:10.1038/s41586-019-1721-2



FAMU method and workflow



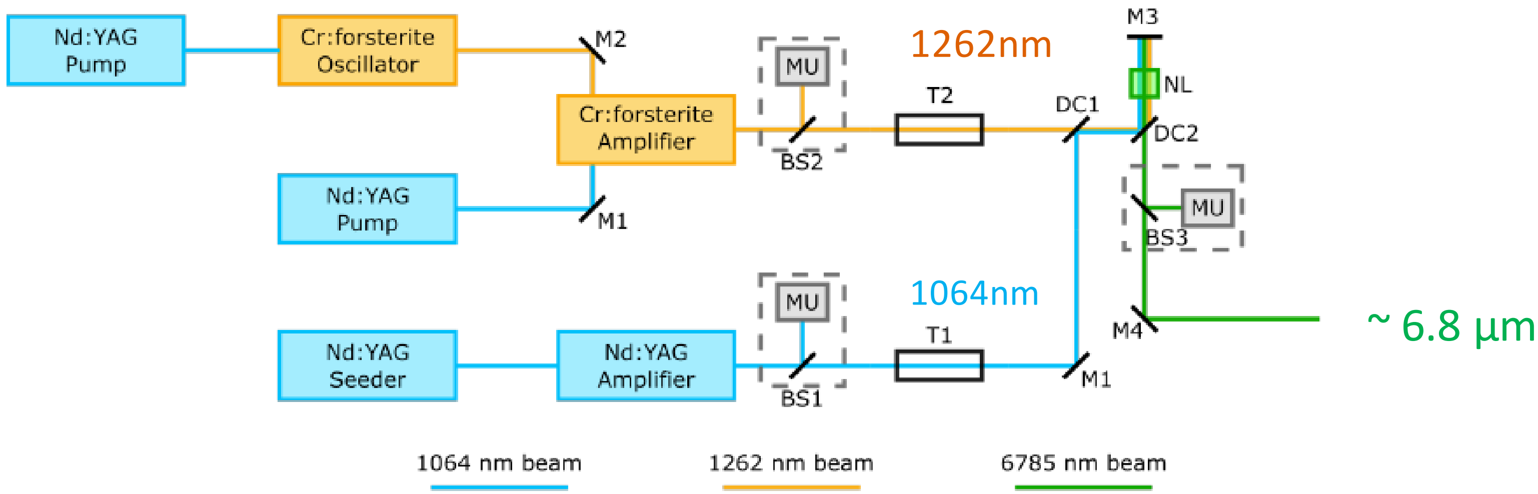
- Create muonic hydrogen and wait for thermalization;
- Shoot laser at variable wavelength (λ_0 ~6.8μ), when it matches the resonance:
  spin is flipped: $\mu^-p(\uparrow\downarrow) \rightarrow \mu^-p(\uparrow\uparrow)$;
- De-excitation and acceleration: $\mu^-p(\uparrow\uparrow)$ hits a H atom
  It is depolarized back to $\mu^-p(\uparrow\downarrow)$ and is accelerated by ~120 meV ;
- μ^- are transferred to heavier gas with energy-dependent rate;
- λ_0 resonance is determined by the maximizing the time distribution of μ^- transferred events.

FAMU Laser

Characteristics:

Wavelength range	6800 ± 50 nm
Energy output	> 1 mJ
Linewidth	< 0.07 nm
Tunability steps	0.03 nm
Pulses duration	10 ns
Repetition rate	25 Hz

Absolute calibration of the 6.8μm energy with CH_4 line absorption



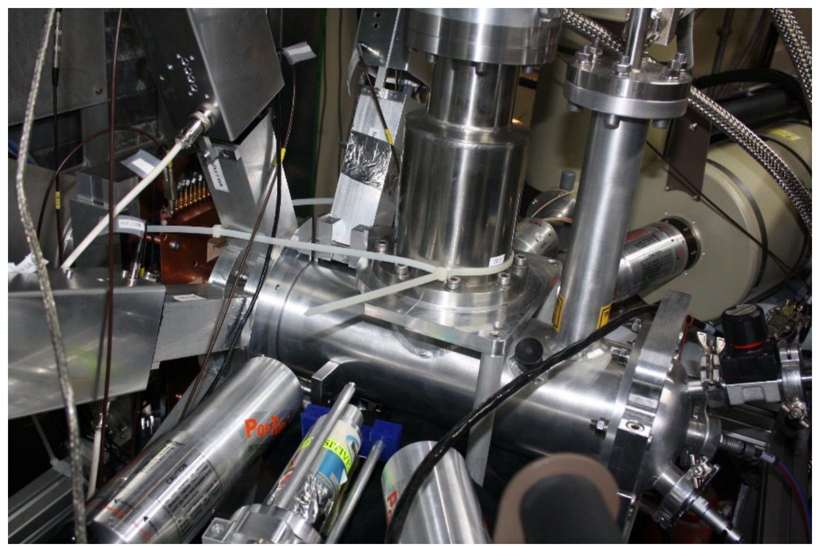
M1 - Mirror HR 1064 nm, M2 - Mirror HR 1262 nm, M3 - Mirror HR 1064&1262&6785 nm, M4 - Mirror HR 6785 nm, T1 and T2 - telescopes, BS1 - beamsplitter/beamsampler 1064 nm, BS2 - beamsplitter/beamsampler 1262 nm, BS3 - beamsplitter/beamsampler 6785 nm, DC1 - dichroic mirror (reflecting 1064 nm, transmitting 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)

FAMU Timeline

1993 First idea of the experimental method Physics Letters A 172 (1993) 277–280

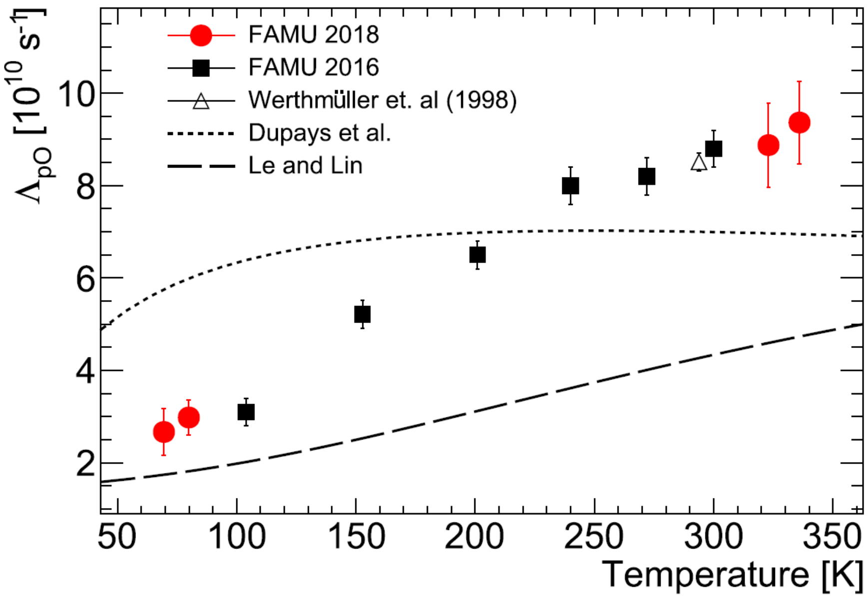
2014 - 2018 FAMU preliminary phase: study and preparation

- Laser development
- Test target and detectors (LaBr and Ge)
- Study the muon beam
- Measure transfer rate of different gases
- Study of the gas mixture
- **Measure the transfer rate temperature dependence for oxygen**



First measurement of the oxygen transfer rate

- measured for the **first** time the **temperature dependence** of the transfer rate for **oxygen** in the range 70-336 K
- the **energy dependence** of the transfer rate **increases by a factor 8** for energies in 0.01-0.08 eV



Oxygen transfer rate

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

*This dependence is **very important** for the FAMU experiment where the **energy dependence** of the transfer rate is used **a signature***

FAMU Timeline

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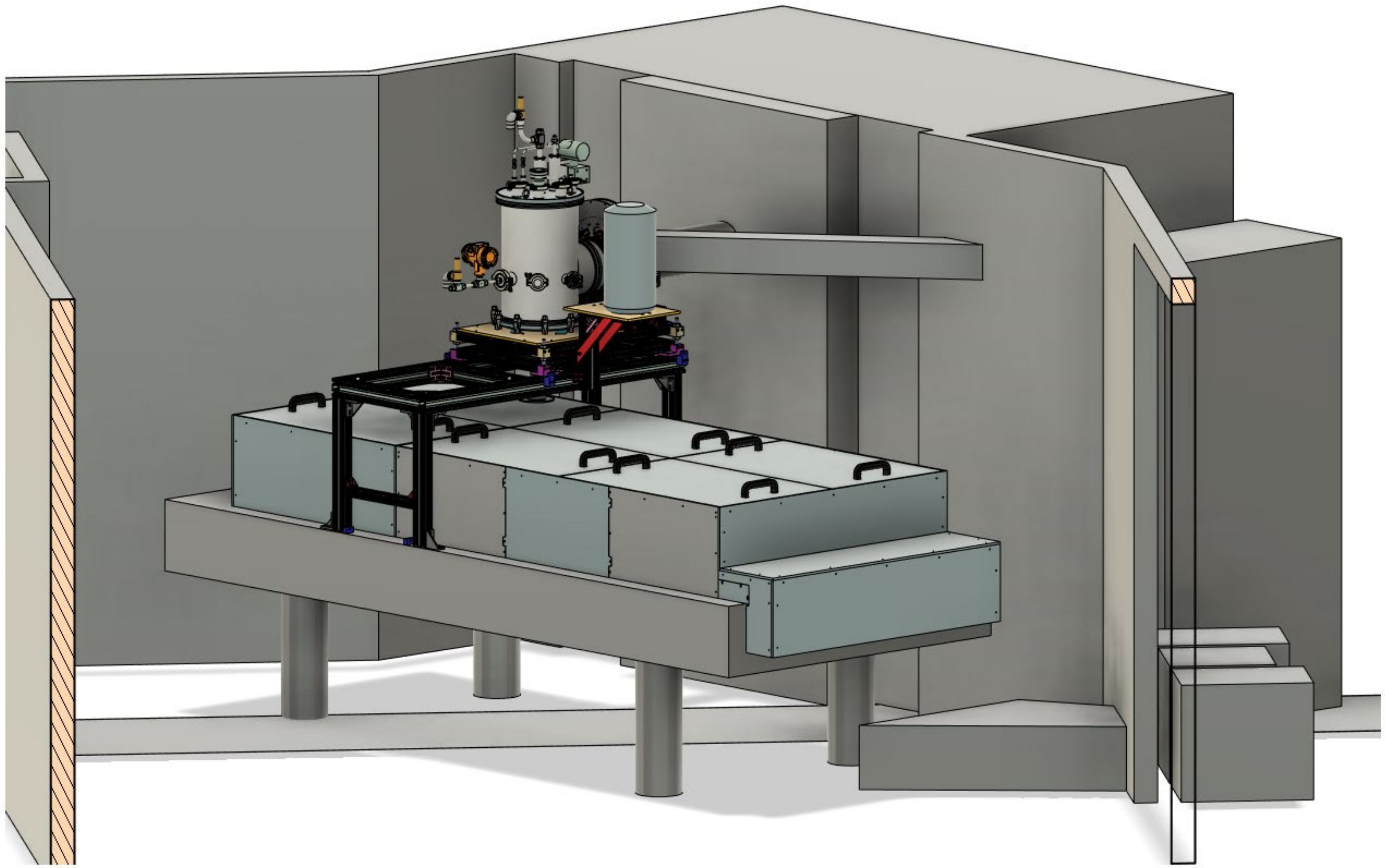
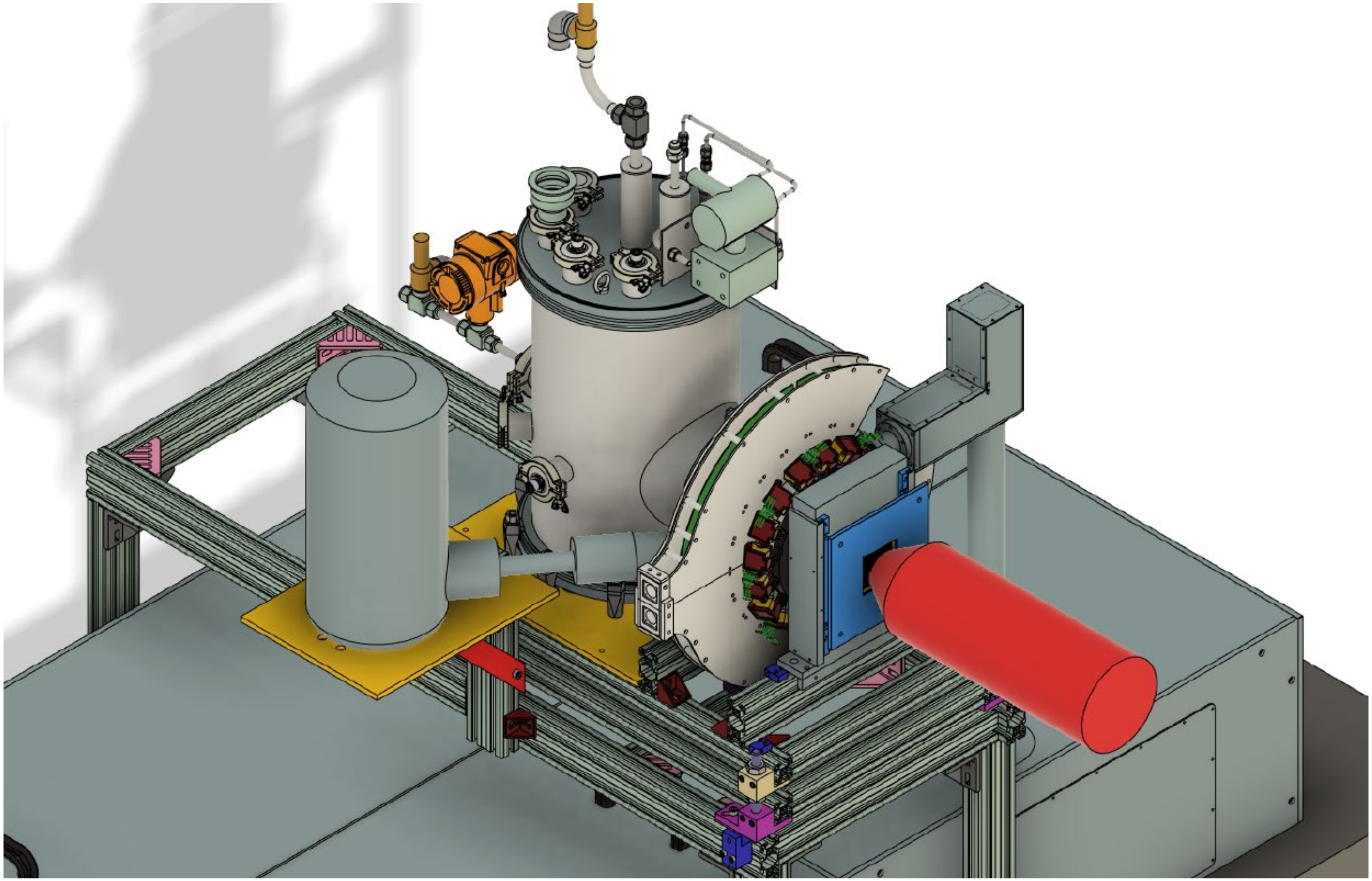
2014 - 2018 Study and preparation

2019-20 Installation of the full set up and measurement of the HFS

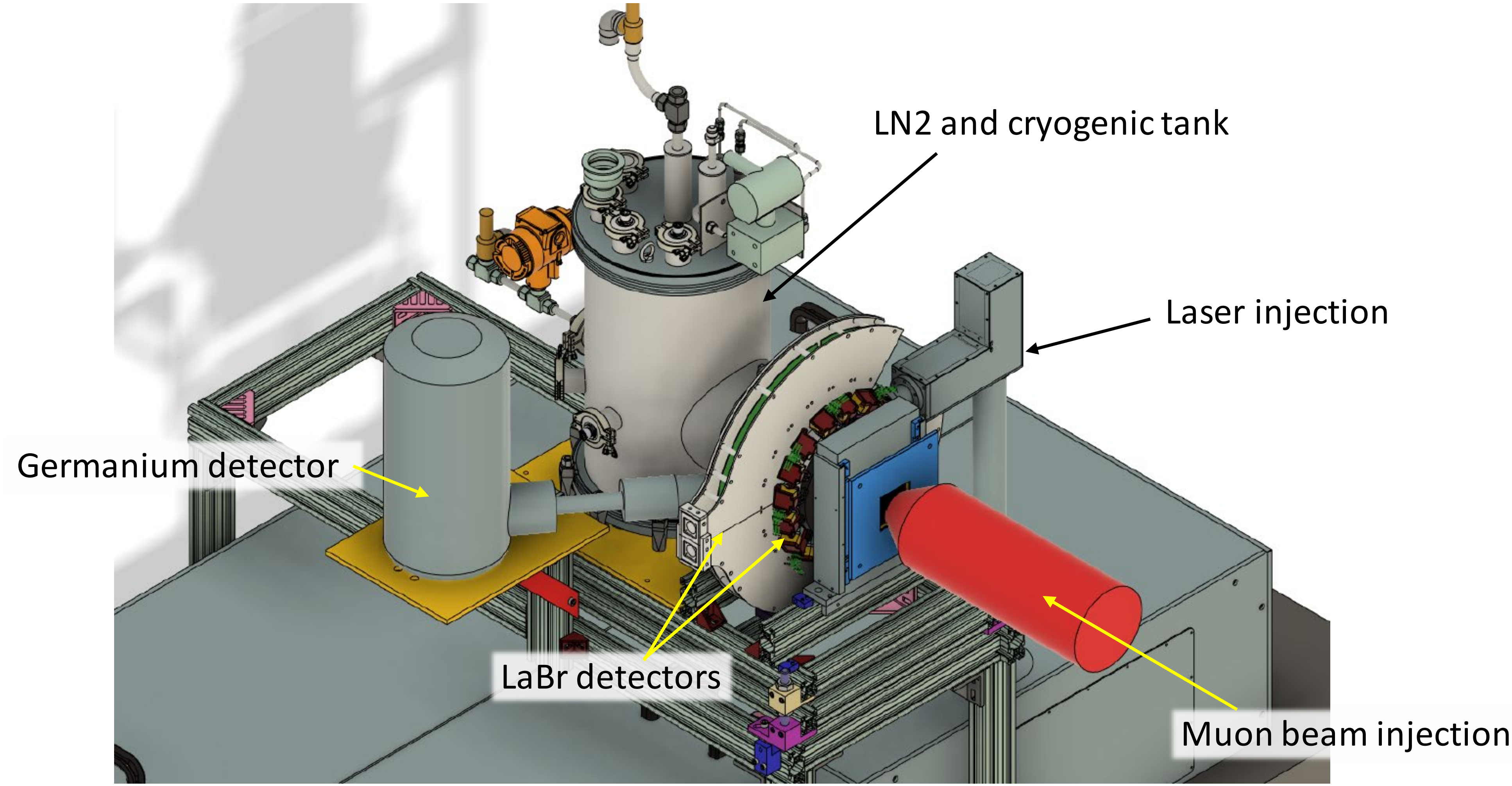
Set up at Port1 at RAL



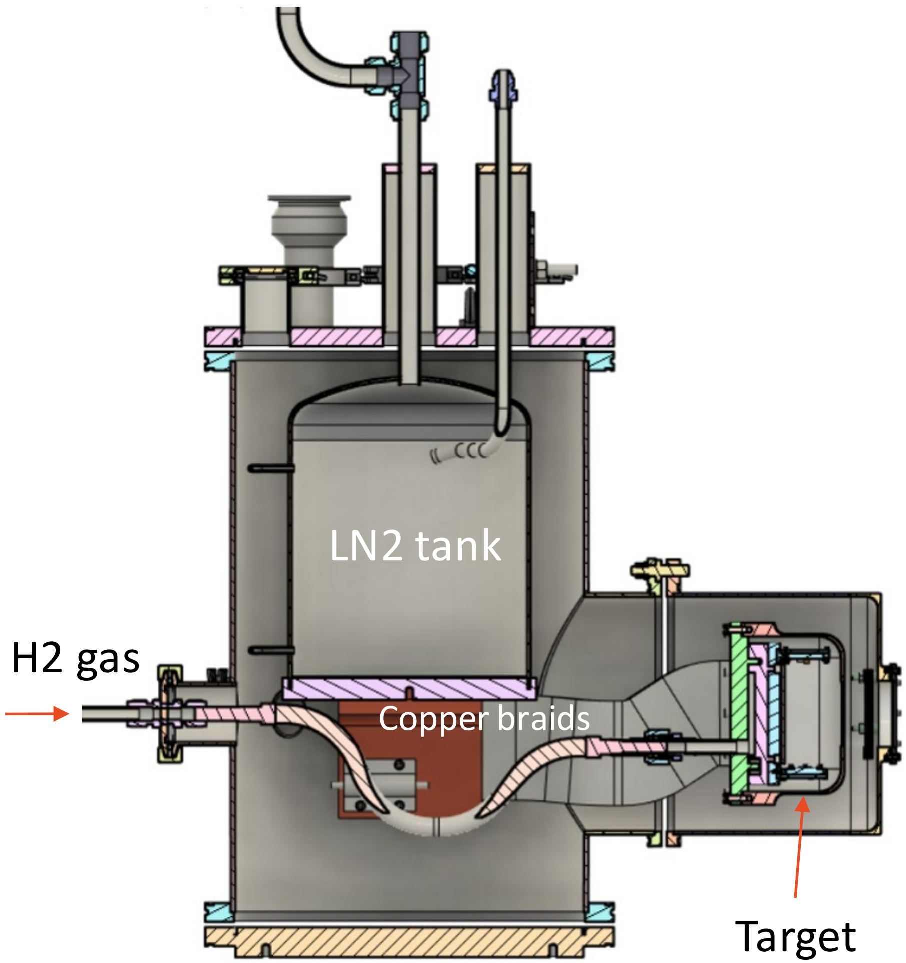
FAMU Set up



FAMU set up

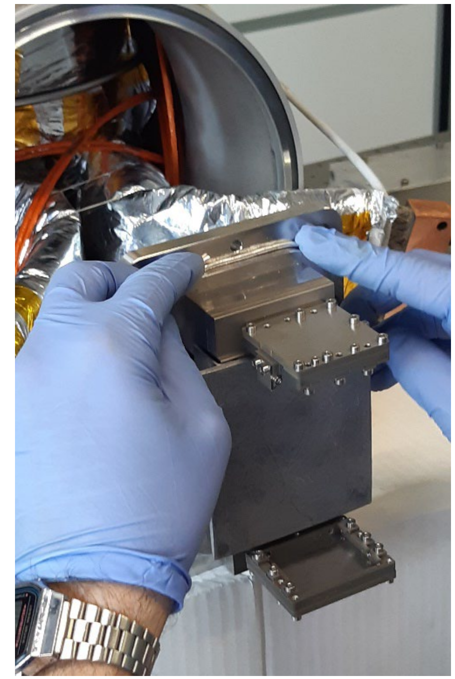

LN2 and cryogenic tank
Laser injection
Germanium detector
LaBr detectors
Muon beam injection

Target and cavity

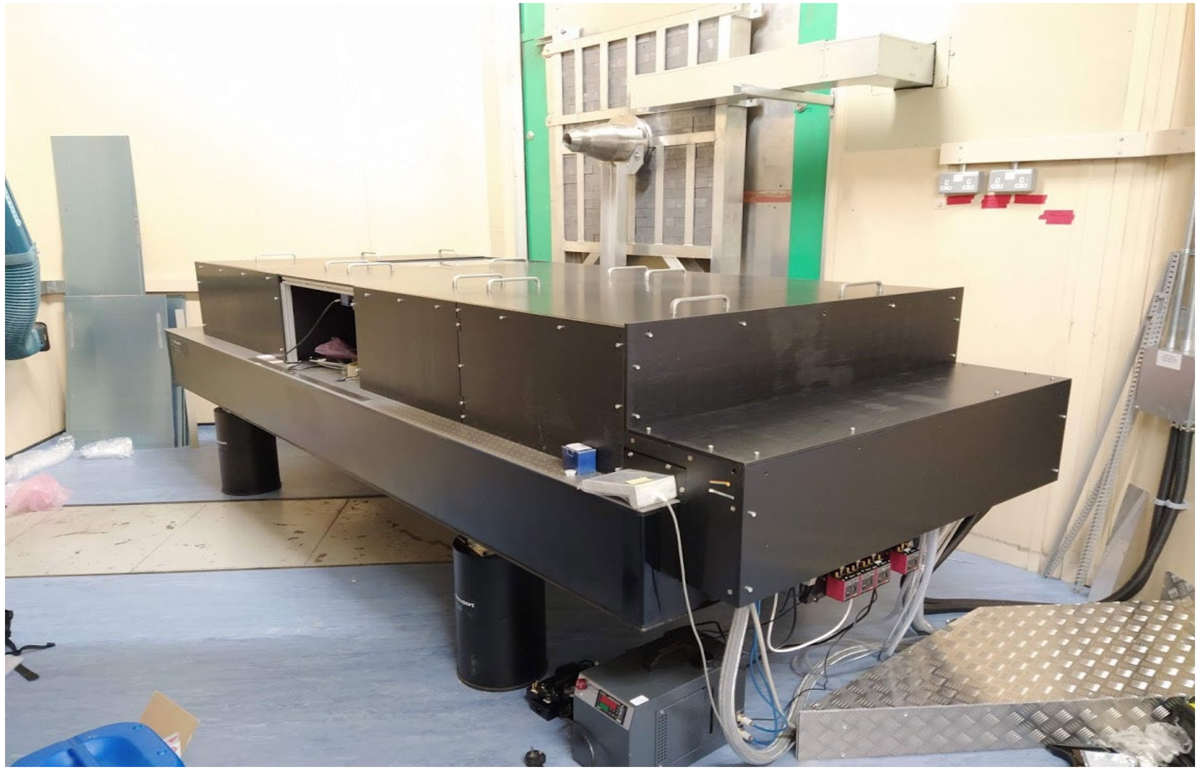


target

cavity



Port 1
February 2020



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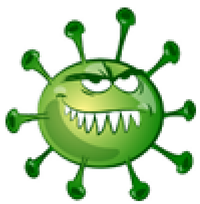


March 2020 – first assembly
September 2020
December 2020
June 2021

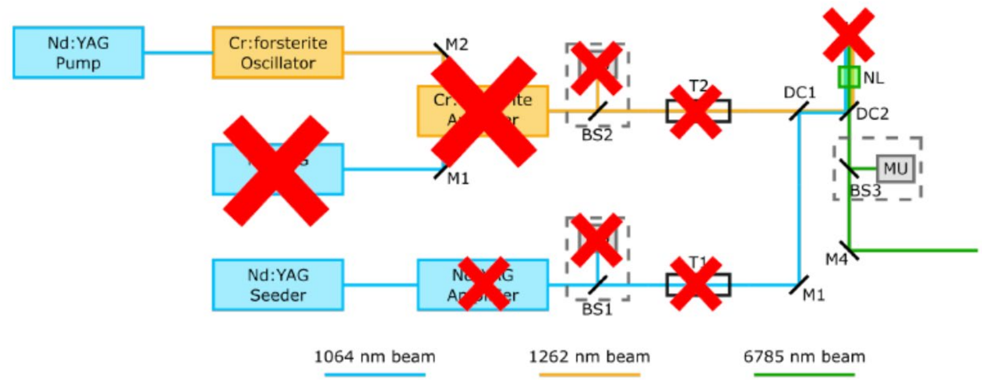
2021-22 June 2021- June 2022: accelerator shutdown for maintenance & upgrades

2022 Data taking with full setup at the end of 2022

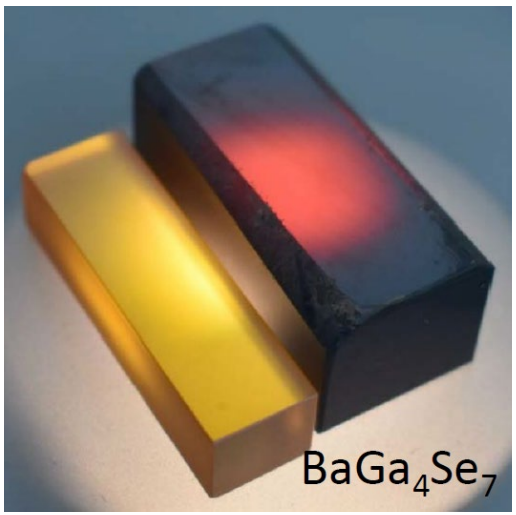
Meanwhile in our local labs …

- Further studies on laser
- Cavity characterisation
- Detector integration

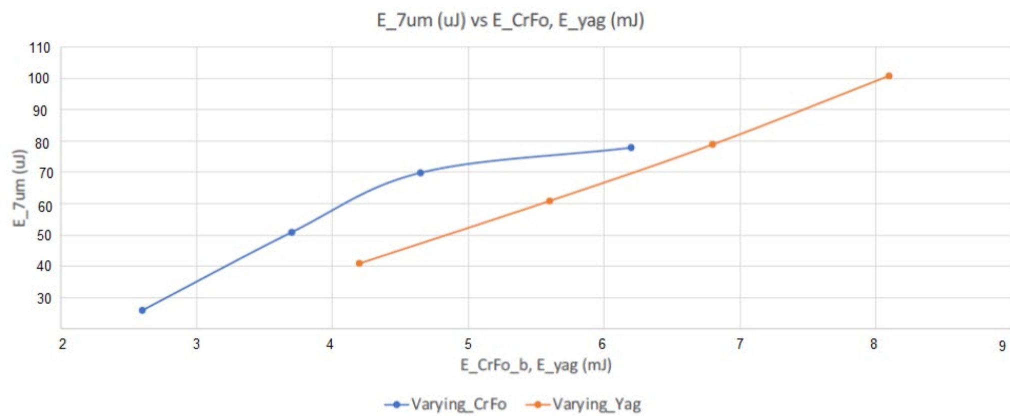
Laser: new setup and further studies at Trieste



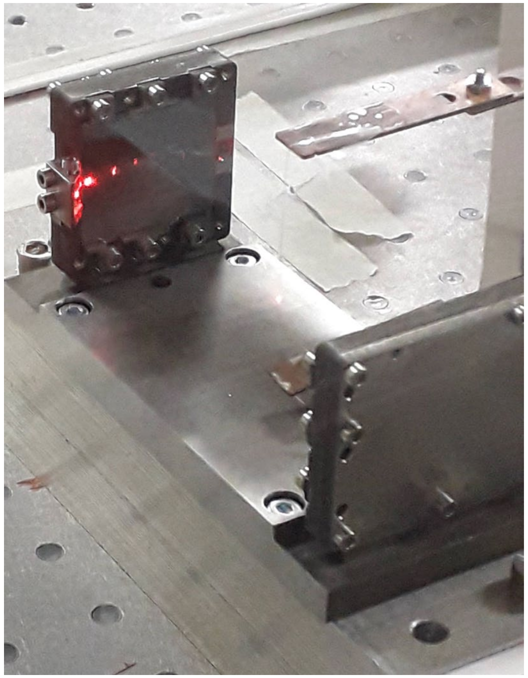
New non linear crystals

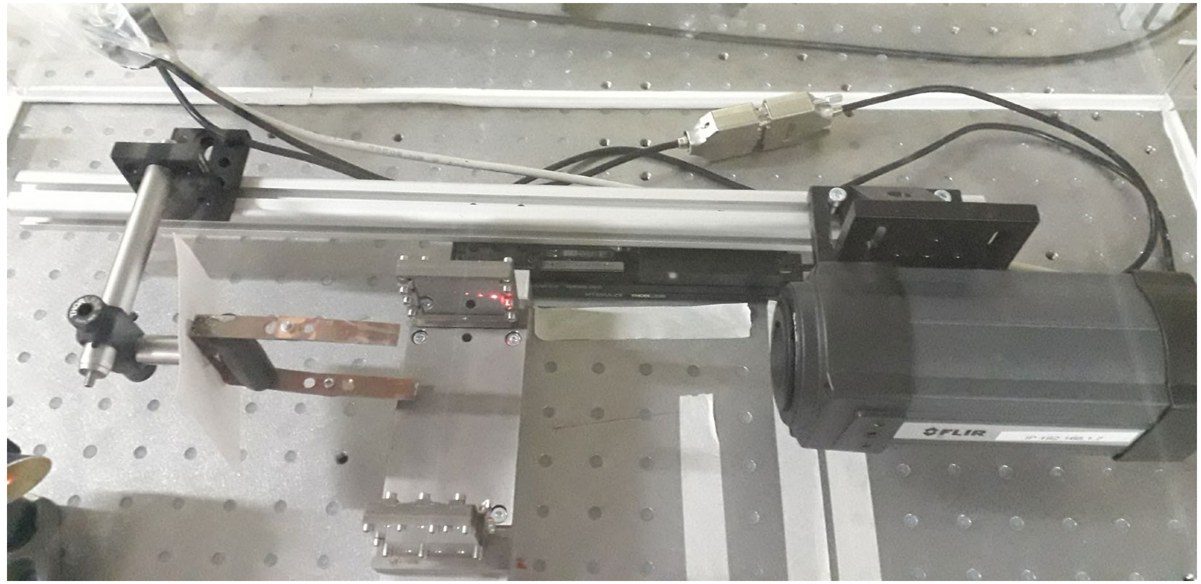


Energy curves $BaGa_7Se_4$ 10x9x28mm

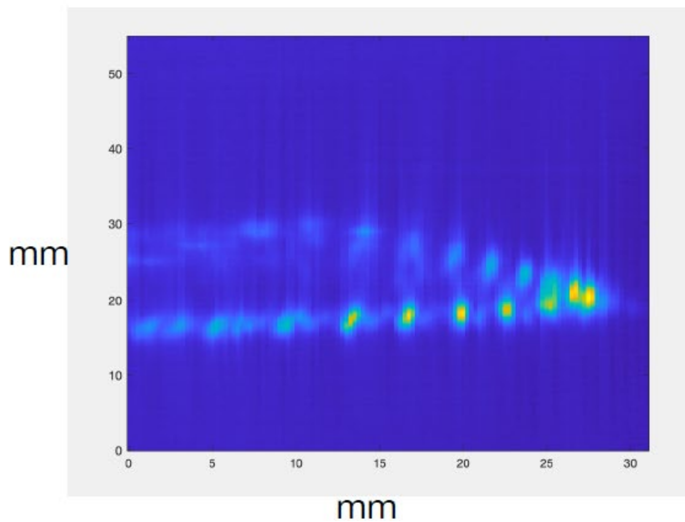


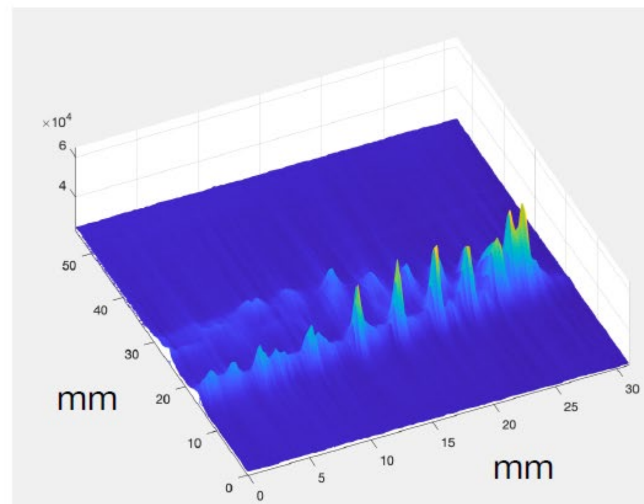
Optical cavity





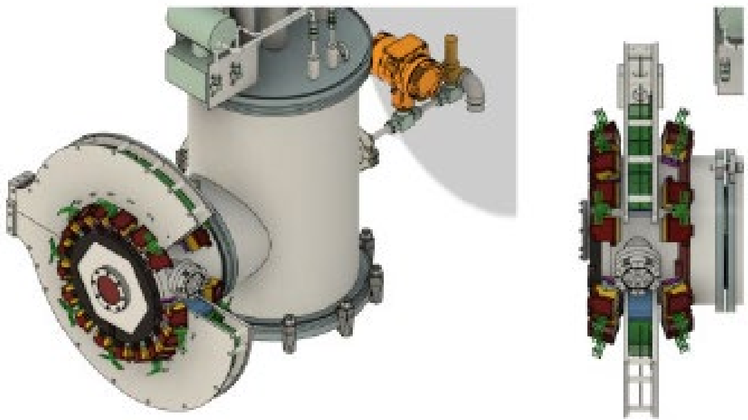
The cavity number of reflections remain stable against small variations of the incident angle (tip/tilt movement)





Detectors: mechanical integration

Trieste, October 2021



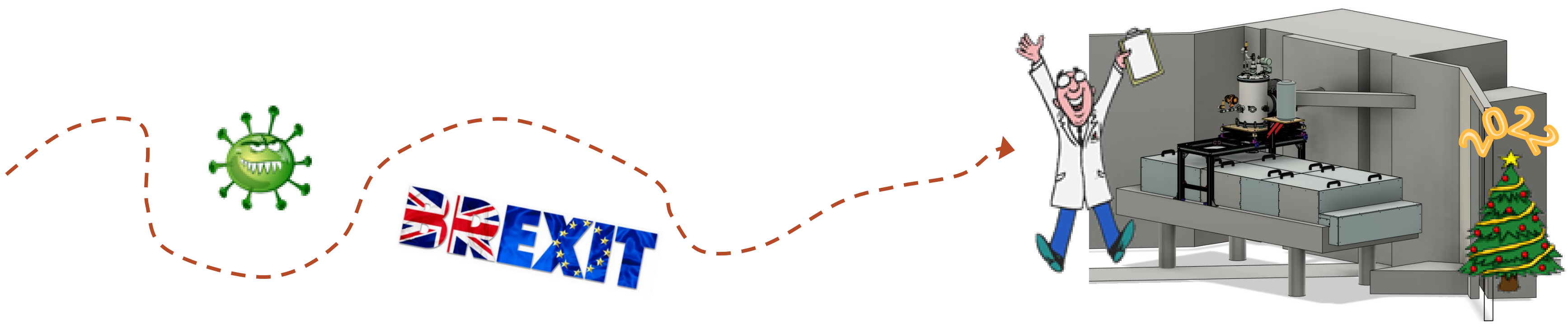
Conclusions

- FAMU aims to **measure the hyperfine splitting** in the ground state of muonic hydrogen with a relative accuracy better than 10^{-5}

- Assembly of the complete setup is foreseen in summer 2022

- **First data taking at the end of 2022**

  About 1 month beam time, a scan of ~30 frequency points



Thank you for your attention