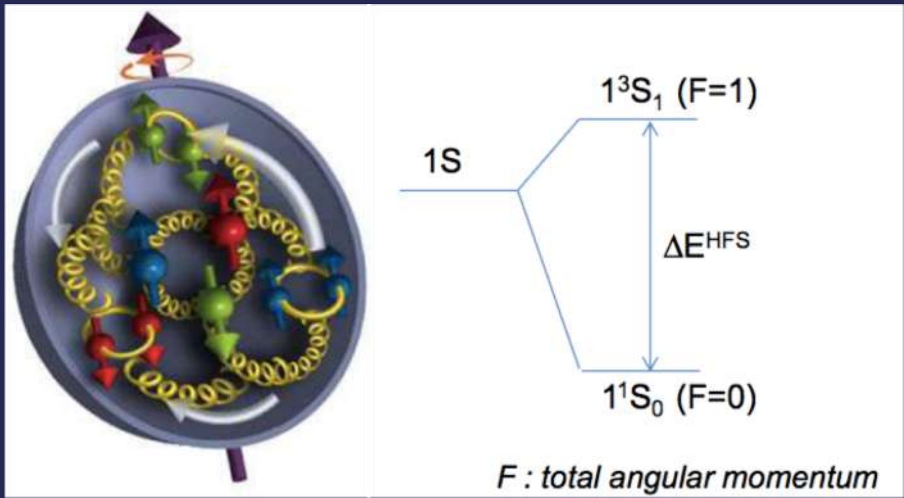
The **FAMU** esperiment:

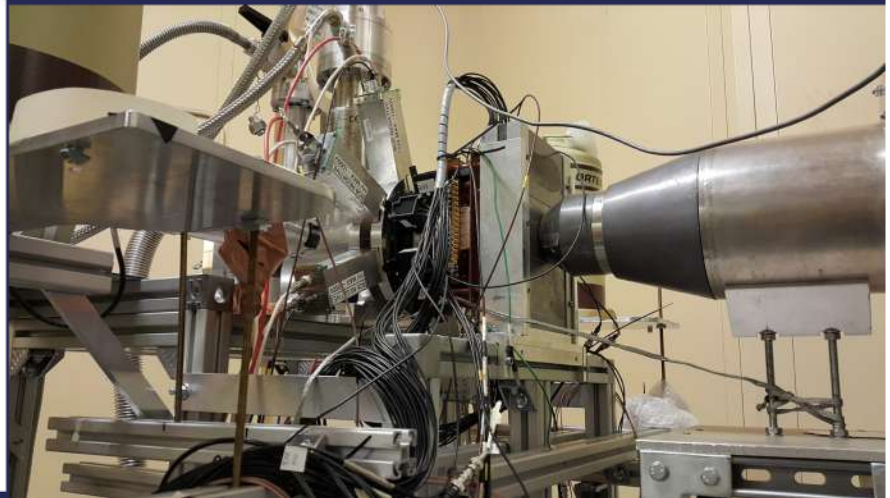
measuring the ground-state hyperfine splitting in muonic hydrogen

$\Delta E_{HFS}(\mu p)_{1S}$

Determination of the Zemach radius of the proton

Andrea Vacchi for the FAMU Collaboration





2018 European Nuclear Physics Conference
September 2nd-7th, 2018: Bologna, Italy
San Domenico Center

Istituto Nazionale di Fisica Nucleare

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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

OUTLINE

- Background & motivations
- FAMU's method to measure the hfs
- 2016 muon transfer rate measurements between 100 and 300 K
- FAMU key ingredients optimization
  - pulsed high intensity muon beam
  - MIR high energy fine-tunable laser
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  - best X-rays detectors (fast and accurate)
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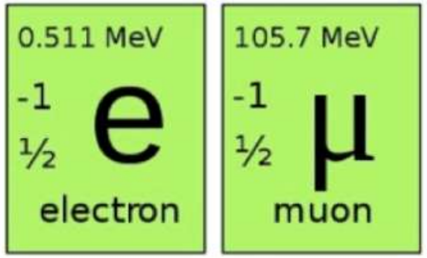
- Conclusions

Muonic hydrogen μH

Muon (e^-'s heavier twin) orbiting the proton instead of electron.

$$m_\mu = 207 m_e$$

$$r_\mu = \frac{1}{186} r_e$$



$$m\mu \,/\, me \approx 2\mathrm{x}10^2$$

- the ***radius of the muon orbit*** is ~ $a_0/200$ ***so that the energy levels of muonic hydrogen <u>are orders of magnitude more "sensitive" to the details of the proton structure</u> than the levels of normal hydrogen***.
- the binding energy of the ground state of muonic hydrogen is of the order of 200 Ry,

why measuring $\Delta E_{HFS}(\mu^- p)_{1S}$?

why new independent high precision measurements on $\mu^- p$ are needed?

- In eH – "ordinary hydrogen" the hyperfine splitting (HFS) is known to 13 digits – in frequency units
  - $E^{exp}_{HFS}(ep)=1420{,}4057517667(9)$ MHz
- while in μH
  - $E^{exp}_{HFS}(\mu p)= 22{,}8089(51)$ meV [224ppm]
- Theory reaches 6 digits of accuracy

muonic hydrogen precision spectroscopy

The muon is tightly bound in hydrogen-like orbits that have very large overlaps with the proton this allows :

- ***very high accuracy tests of quantum electrodynamics and the theory of electromagnetic bound states.***
- ***verify the theoretical predictions of the nature of quantum mechanics in very strong fields.***
- ***precise determination of the values of the fundamental physical constants (particle masses, fine structure constant, proton charge radius, etc.).***
- ***point towards physics beyond the Standard Model of particle physics.***

why measuring $\Delta E_{HFS}(\mu^- p)_{1S}$?

why new independent high precision measurements on μ^-p are needed?

- *surprising Lamb shift measurements points to HFS (next slide)*
- *can check e μ universality*
- *or believing in e μ universality, accurate measurements gives information on the proton structure*
- *accurate data measure the corrections to the leading order*
- *one correction term is sensitive to the magnetic form factor G_M at low momentum transfer, i.e., to the proton magnetic radii R_M*
- *R_M obtained from scattering experiments is a source of controversy*

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The **proton charge radius** can be extracted for each lepton probe from two independent methods

Proton radius puzzle

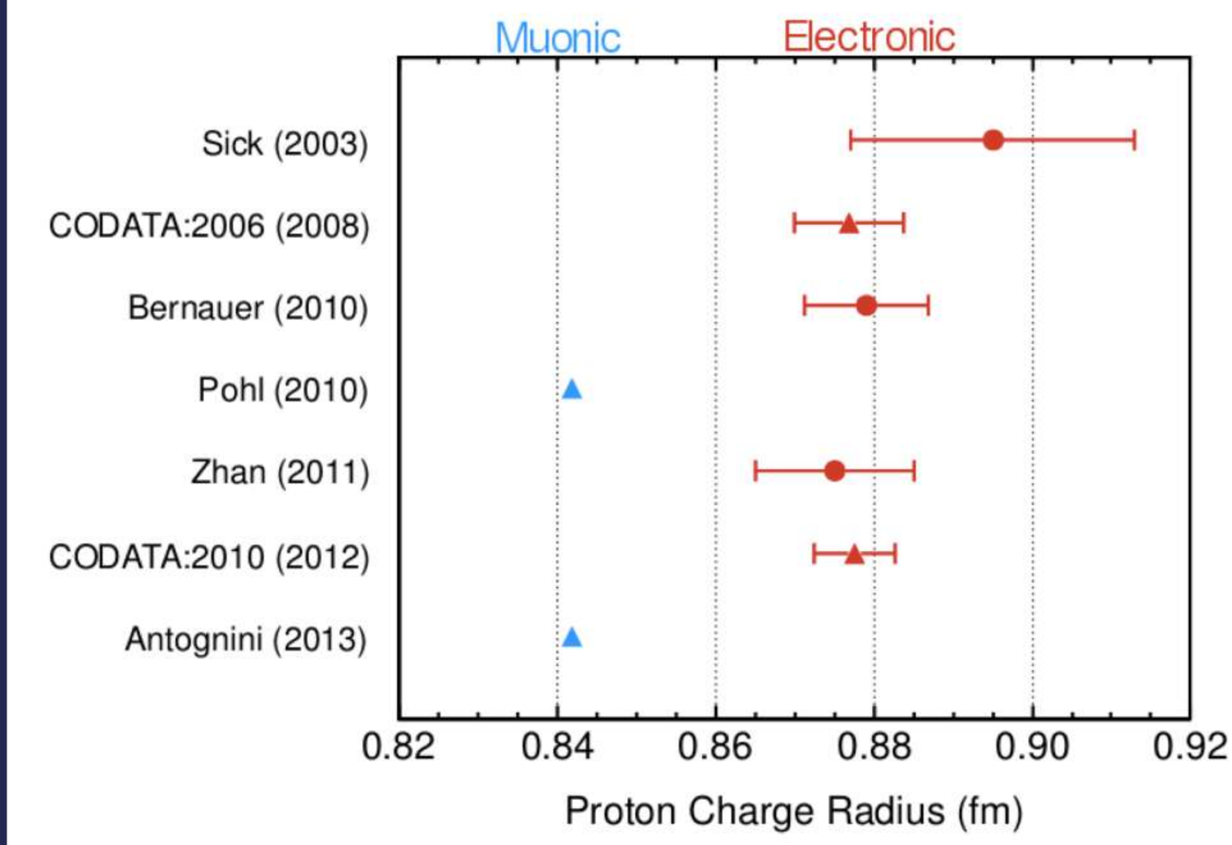
$$[R_{Ep}^{\mu\mathrm{H}} = 0.84087(39)\ \mathrm{fm}]$$

[1] R. Pohl, A. Antognini et al., Nature **466**, 213 (2010).
[2] A. Antognini et al., Science **339**, 417 (2013).

5.6 σ discrepancy

$$[R_{Ep}^{\mathrm{CODATA\ 2014}} = 0.8751(61)\ \mathrm{fm}]$$

[3] P. J. Mohr, et al., Rev. Mod. Phys. **84**, 1527 (2012).



The CODATA value of the proton charge radius as obtained from a combination of 24 transition frequency measurements in H and deuterium and several results from elastic electron scattering is **0.88 fm .** However, the **muonic hydrogen Lamb Shift** measurements yield a radius of **0.84 fm**.

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why measuring $\Delta E_{HFS}(\mu^- p)_{1S}$?

why new independent high precision measurements on $\mu^- p$ are needed?

$$\Delta E_{HFS}^{thy}(ep) = E_F^{ep}(1 + \Delta_{QED} + \underbrace{\Delta_{hvp}^{p} + \Delta_{\mu vp}^{p} + \Delta_{weak}^{p}}_{\text{small terms}} + \Delta_S)$$

Fermi Energy

Accurately known

Proton structure term

Structure term ΔS commonly broken into 3 parts

$\Delta_S = \Delta_Z + \Delta_R + \Delta_{pol}$

- **Δ_Z = NR limit of the elastic contribution**
- **Δ_R = relativistic corrections to elastic contribution**
- **Δ_{pol} = mixture of inelastic with elastic contribution**

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The Zemach term

$$\Delta_Z = -2\alpha m_r r_z$$

$$r_Z = \int d^3_{r1} \int d^3_{r2} \rho_E(r_1) |\vec{r_1} - \vec{r_2}| \rho_M(r_2)$$

or, using momentum space expression

$$r_z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left(\frac{G_E(Q^2) - G_M(Q^2)}{1 + k_p} - 1 \right)$$

$1+k_p$ is the magnetic moment of the proton (in proton magnetons)

$G_M/(1 - k_p) = 1 - R_M^2\, Q^2/6$ ....

shows the dependence on R_M and on R_E

Zemach radius r_z contains information about both electric and magnetic distributions → can help to pin down the magnetic properties of the proton

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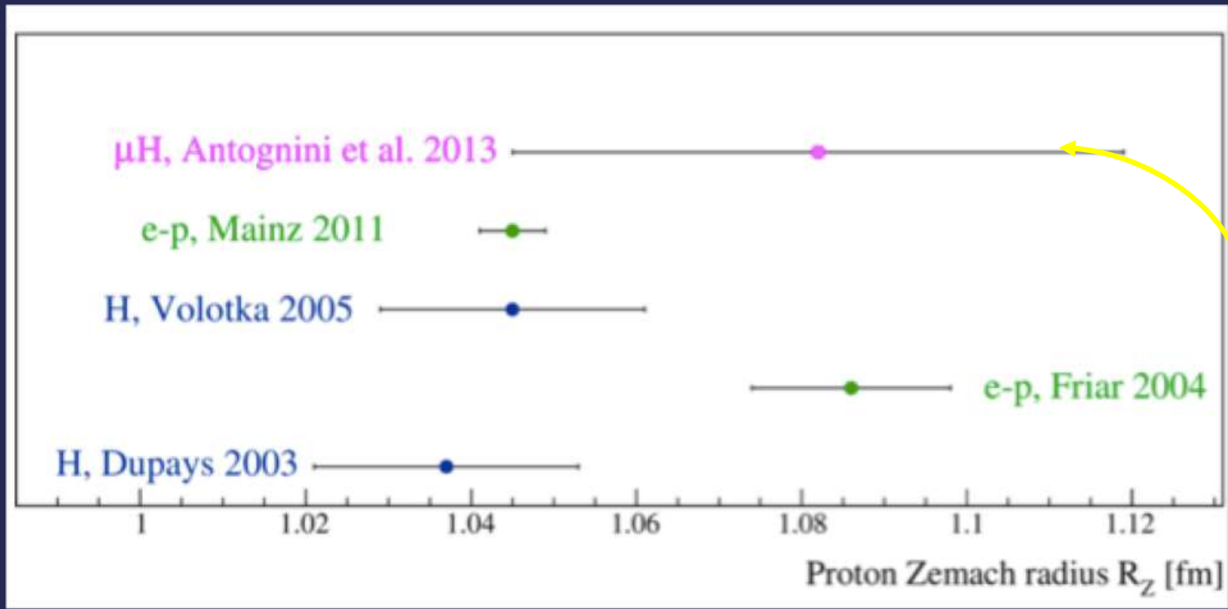
current status of r_{ch} & r_Z

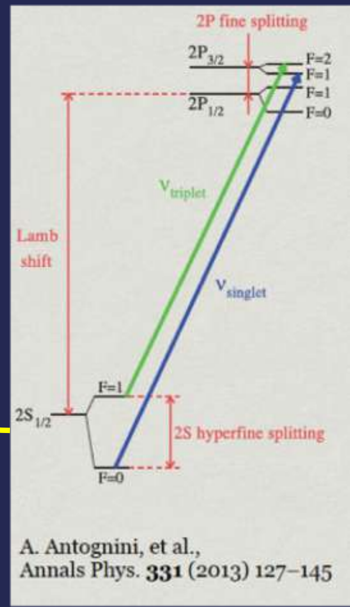
units fm	rms charge radius r_{ch}	Zemach radius r_Z
e^--p scattering & spectroscopy	r_{ch} = **0.8751(61)**	r_Z=1.037(16) Dupays&*al*' 03 r_Z=1.086(12) s Friar&Sick' 04 r_Z=1.047(16) Volotka&*al*' 05 r_Z=1.045(4) s Distler&*al*' 11
μ^--p Lamb shift spectroscopy	r_{ch}=0.84087(39)	FAMU a 20 years old idea: r_Z from HFS of $(\mu^- p)_{1S}$ Either confirm a e^-p value or admit: e^-p and μ^-p differ

Recently : from hfs of $(\mu^- p)_{2S}$ r_Z = 1.082(37) [PSI'12]

=> we need new indipendent measurements

r_Z current status
large errors! we need new measurement

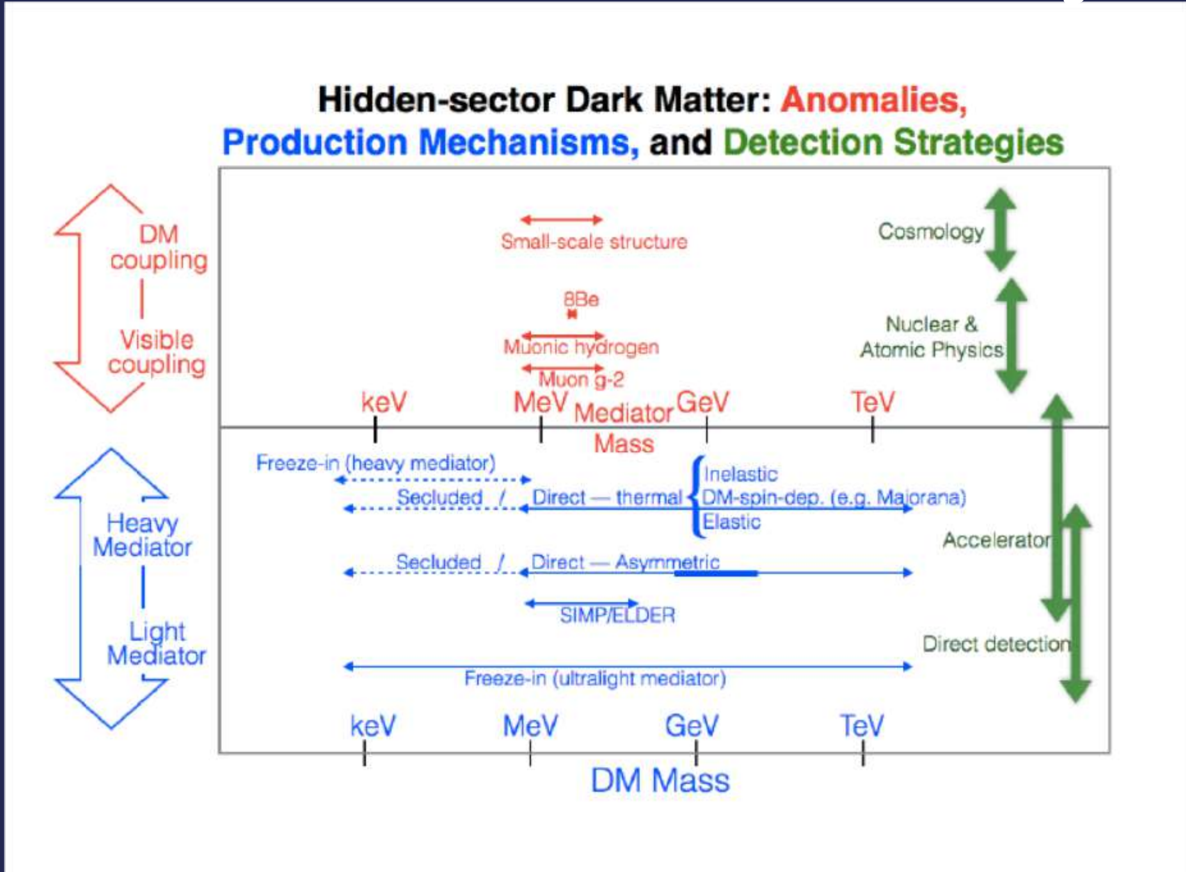




The current theoretical uncertainty of $\mathbf{r_Z}$ significantly exceeds the experimental one.

The experimental results on the proton Zemach radius may be used as a test for the quality of models of the proton in the limit of low transfer momenta.

Experimental Anomalies and Hints
muon-related anomaly



New models, astrophysical observations, and existing experimental anomalies point to the 1 to 100 MeV mass scale as a high value target region for dark matter and dark mediator searches.

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

The FAMU experiment goals

Currently two other independent experiments plan to measure RZ

The spectroscopic measurement of $\Delta E_{HFS}(\mu^- p)_{1S}$, will :

- **provide r_Z, the Zemach radius of the proton, with high precision to disentangle among discordant theoretical values**
  - $\Delta E_{HFS}^{exp}(\mu p)$ **to 5 – 10 ppm**
  - **get Zemach radius to < 0.1%, if theory perfect**
- **quantify any level of discrepancy between values of r_Z as extracted from normal and muonic hydrogen atoms leading to new information on proton structure and muon-nucleon interaction.**

The experimental value of r_Z sets important restrictions on the theoretical models of proton electromagnetic structure and on the parametrization of proton form factors, in whose terms the theoretical values are calculated.

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a 25 years old idea and its evolution

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

PHYSICS LETTERS A

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

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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.

1. Introduction

The theoretical expression for the hyperfine splitting

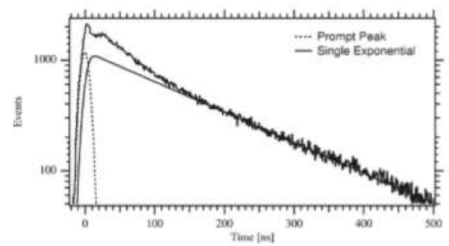

Figure 2. Background subtracted time distribution of muonic oxygen $\mu O(2\text{–}1)$ X-rays measured in a gaseous mixture of $H_2 + 0.4\% O_2$ at 15 bar and room temperature. The prompt peak corresponds essentially to muons directly captured in oxygen whereas the delayed part is due to muon transfer from the ground state of the $(\mu p)_{1s}$ atom. The solid line represents a pure exponential function to stress the additional structure.

F. Mulhauser, H. Schneuwly, Hyperfine Interact. 82 (1993).
A. Werthmüller, et al., Hyperfine Interact. 116 (1998).

For few gases the muon-transfer rate λ_{pZ} is energy dependent

Oxygen exhibits a peak in the muon transfer rate λ_{pZ}^{epith} at epithermal energy.

start with H and O gas mixture (around 1% O) at 80K

I. • μH in F=0, $\mu^- p(\uparrow\downarrow)$

II. • laser photons, at the correct frequency, $\mu^- p(\uparrow\downarrow) \rightarrow \mu^- p(\uparrow\uparrow)$

III. • F=1 revert to F=0 by collisional deexcitation, but get kick

IV. • moving μH have different capture rate on O, see more X-rays

V. • measure the time distribution of O characteristic X-rays.

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

D. Bakalov, A. Adamczak et al., Phys. Lett. A379 (2014).
A. Adamczak et al. Hyperfine Interactions 136: 1–7, 2001.

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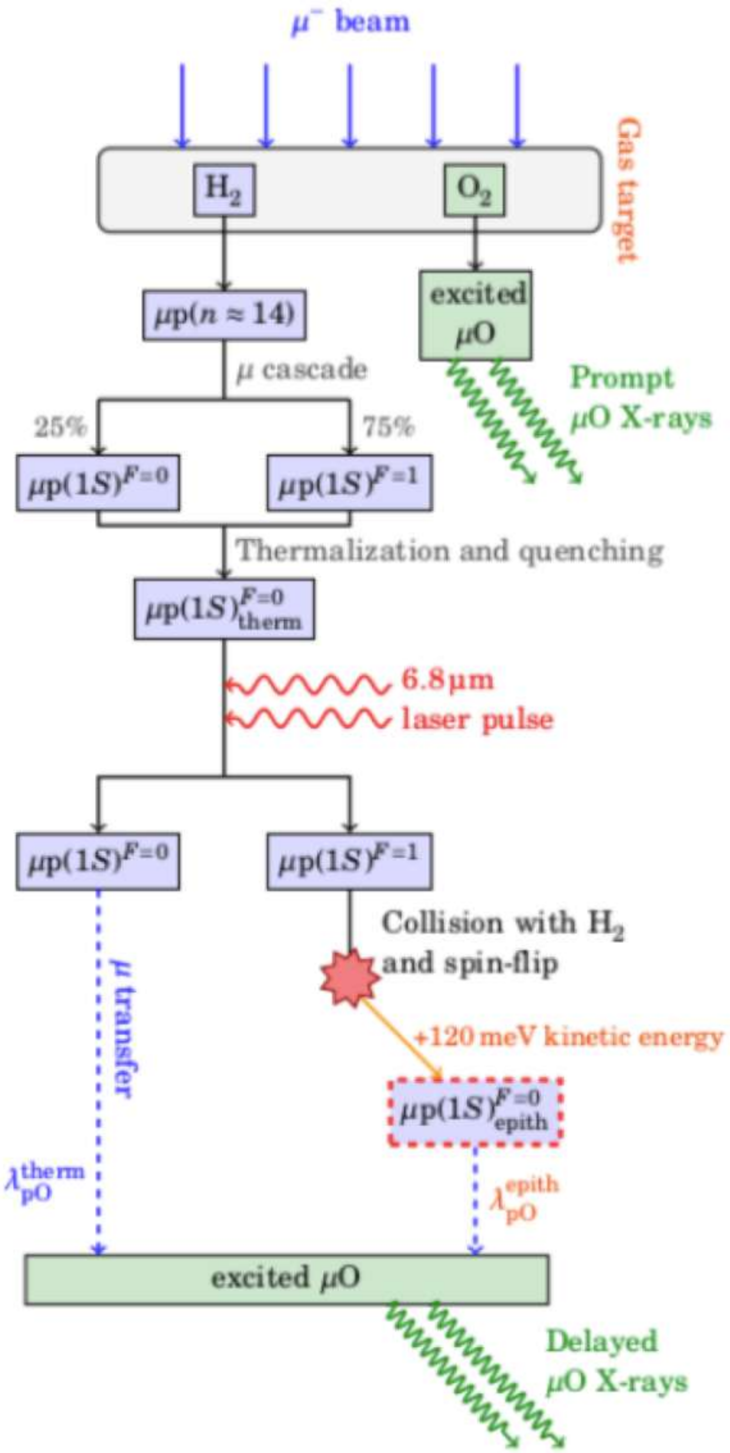
FAMU Principle of operation

μp formation =>>

μp termalization =>>



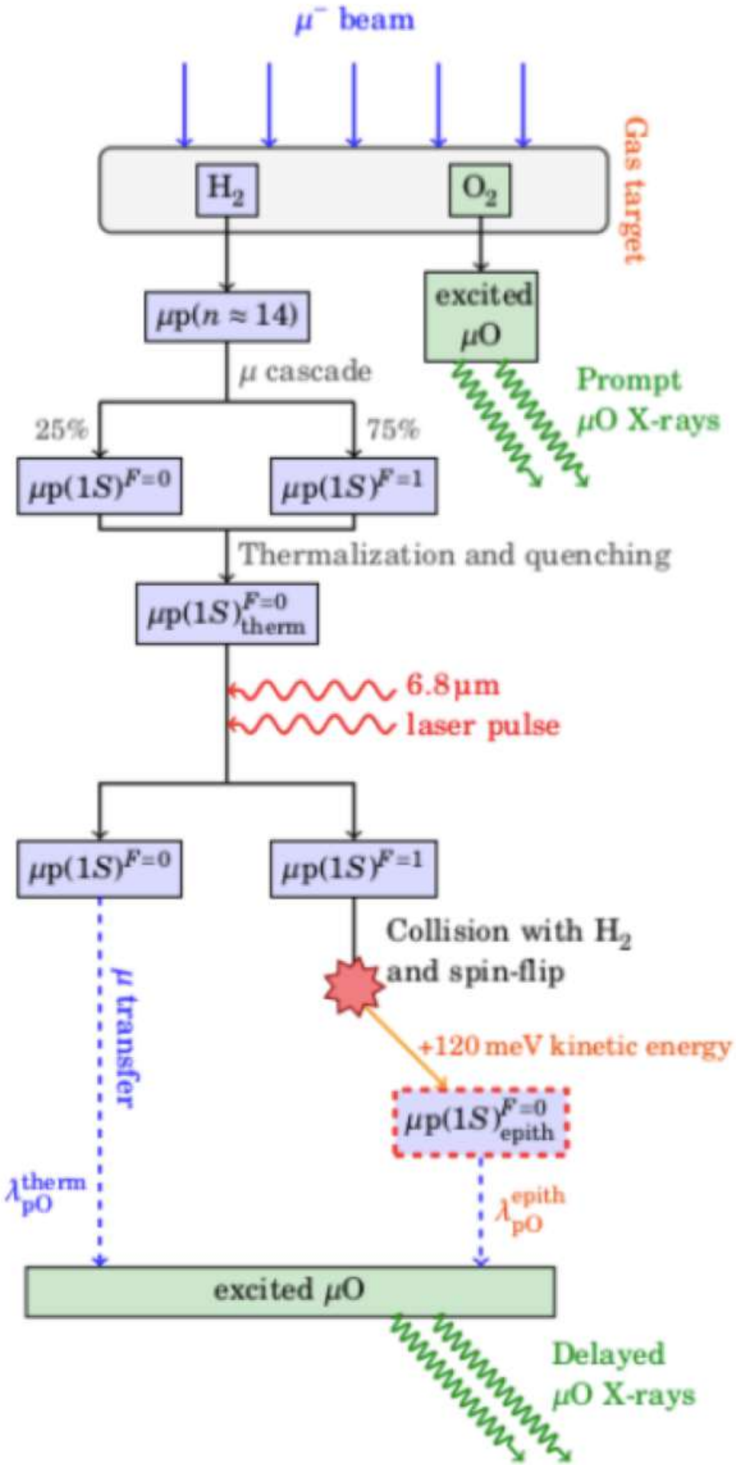
how it works

μ⁻p(↑↓) absorbs a photon

@ ***resonance wavelength*** $\lambda_0 = hc/\Delta E^{1S}_{HFS}$

=> ~ 6.8 μ ~ 0.183 eV

$\mu^- p(\uparrow\downarrow) \rightarrow \mu^- p(\uparrow\uparrow)$



How it works

$\mu^{-}p(\uparrow\uparrow)$ $^3S_1$ atoms

are collisionally de-excited $\mu^{-}p(\uparrow\downarrow)$ $^1S_0$

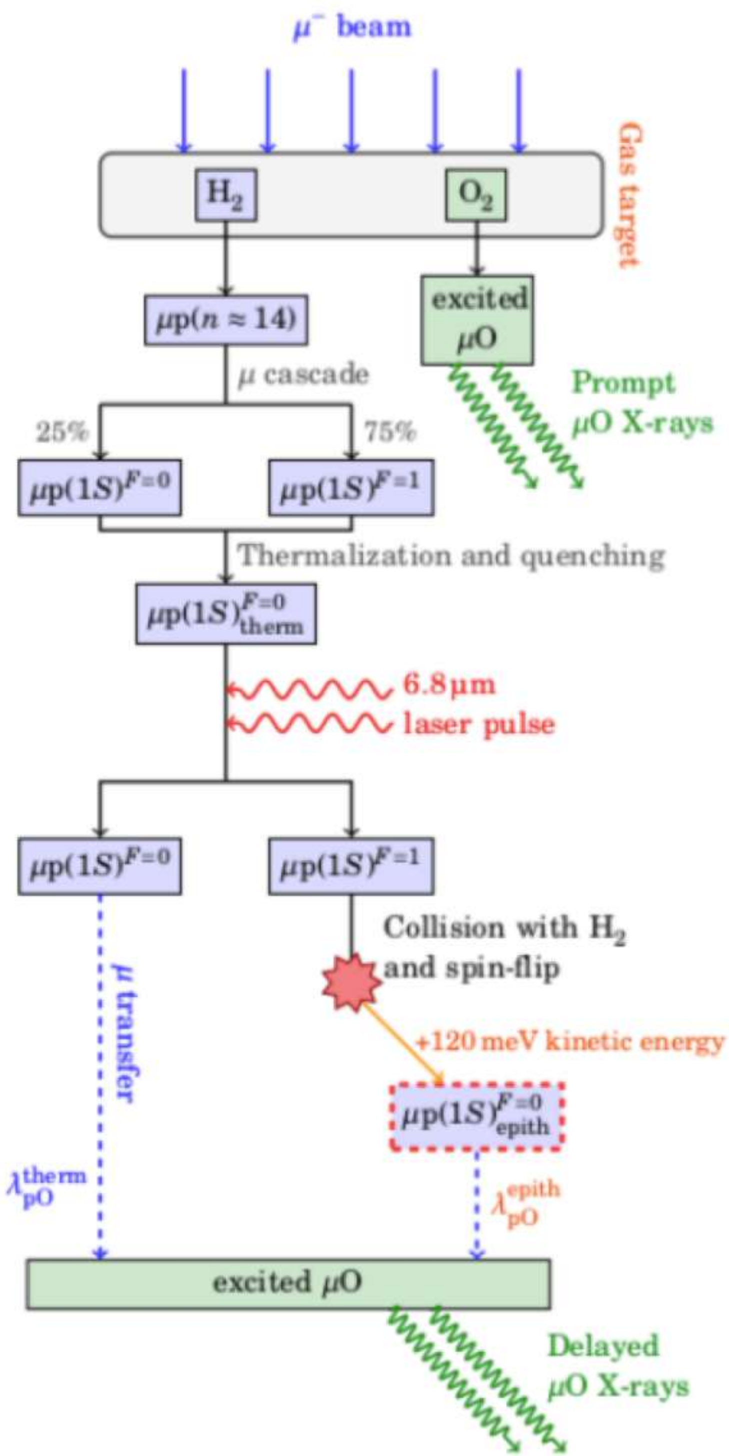
and accelerated by ~ 0.12 eV ~ 2/3 ΔE^{HFS}_{1S}

Energy-dependent muon transfer rate

=> change the time distribution of the cascade X-ray events from $\mu^{-}Z^{*}$

⇒ resonance λ_0 is recognized by

⇒ the maximal response in this time distribution



FAMU's activity summary

- 2014 charaterisation of beam and detector's noise first measurements of transfer rate at room temperature
- 2015-6

  cryogenic target first measurement of transfer rate between 100 and 300 K

  laser parts procurement initiated
- 2017-18

  laser parts delivery completed assembly and characterization on-going

  based on the results of the transfer rate measurements at different temperatures optimization studies are on going

  - optimal optic cavity design
  - new cryogenic gas target design study and simulation
  - muon beam optimization

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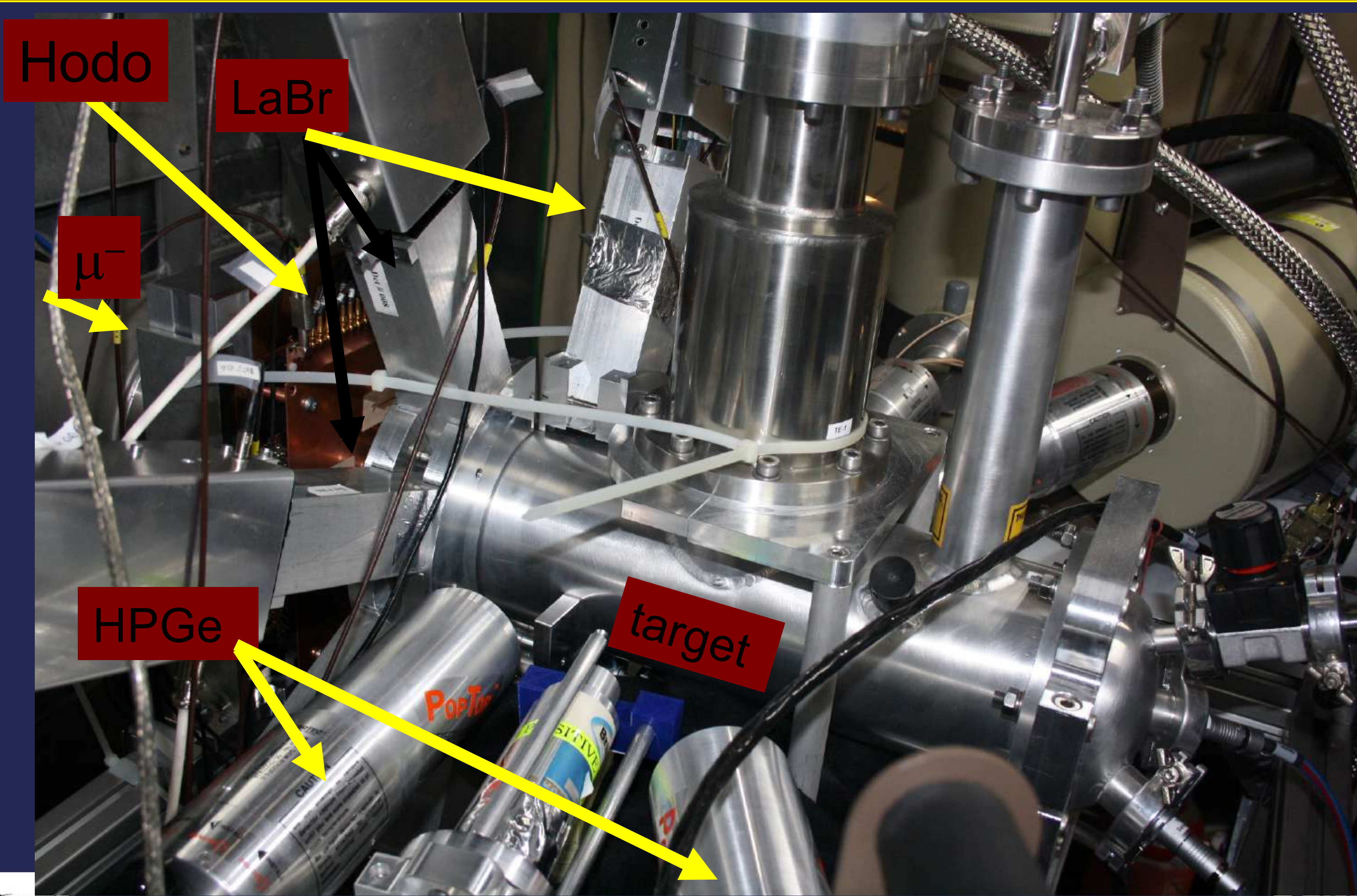
2016: experimental setup

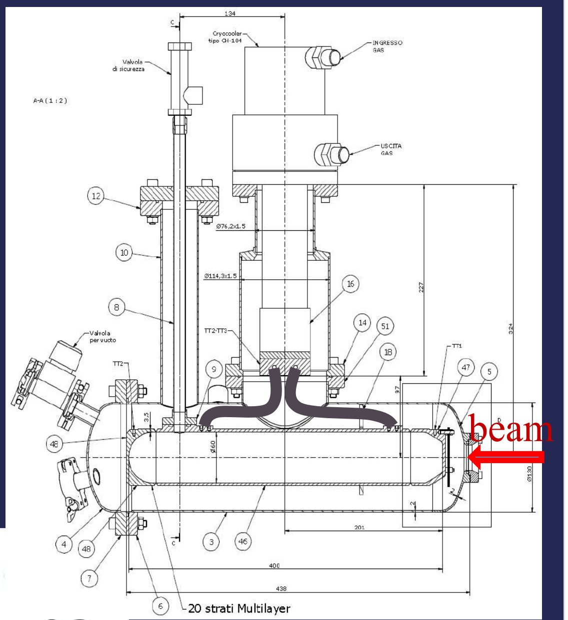


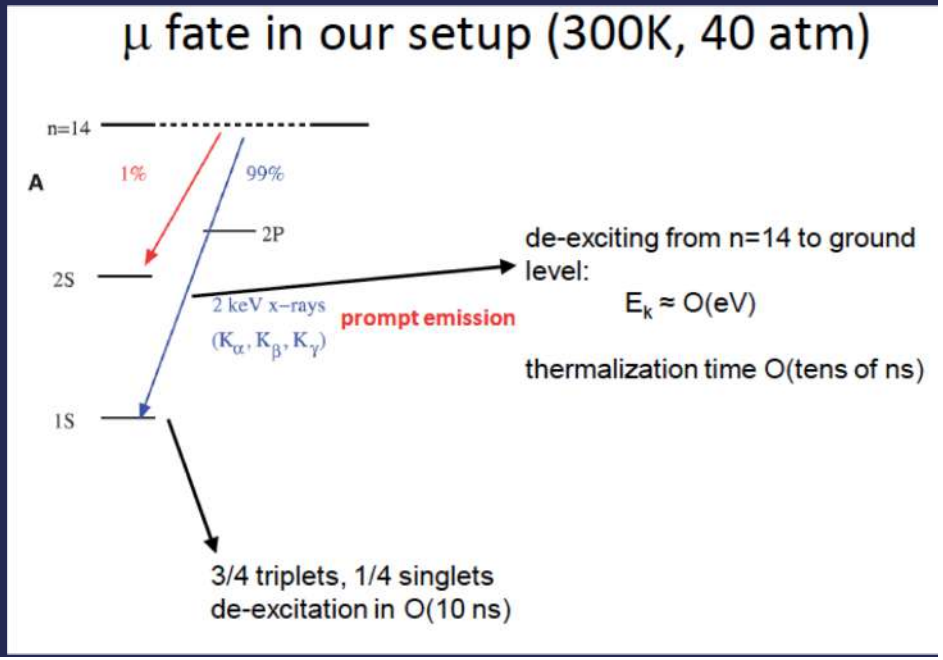
2016: *Energy-dependent muon transfer rate* measurement

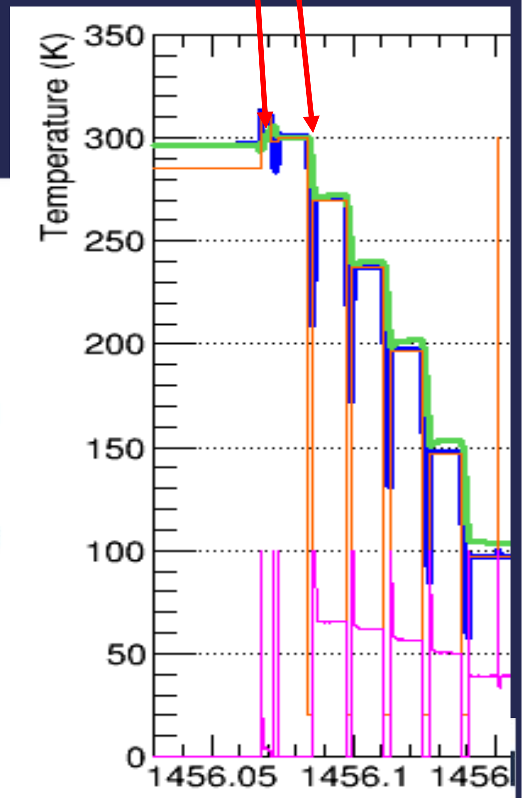
three hours

Steps:

1) fix a target temperature (i.e. mean kinetic energy of gas constant)
2) produce μp and wait for thermalization
3) study time evolution of Oxygen X-rays
4) repeat with different temperature



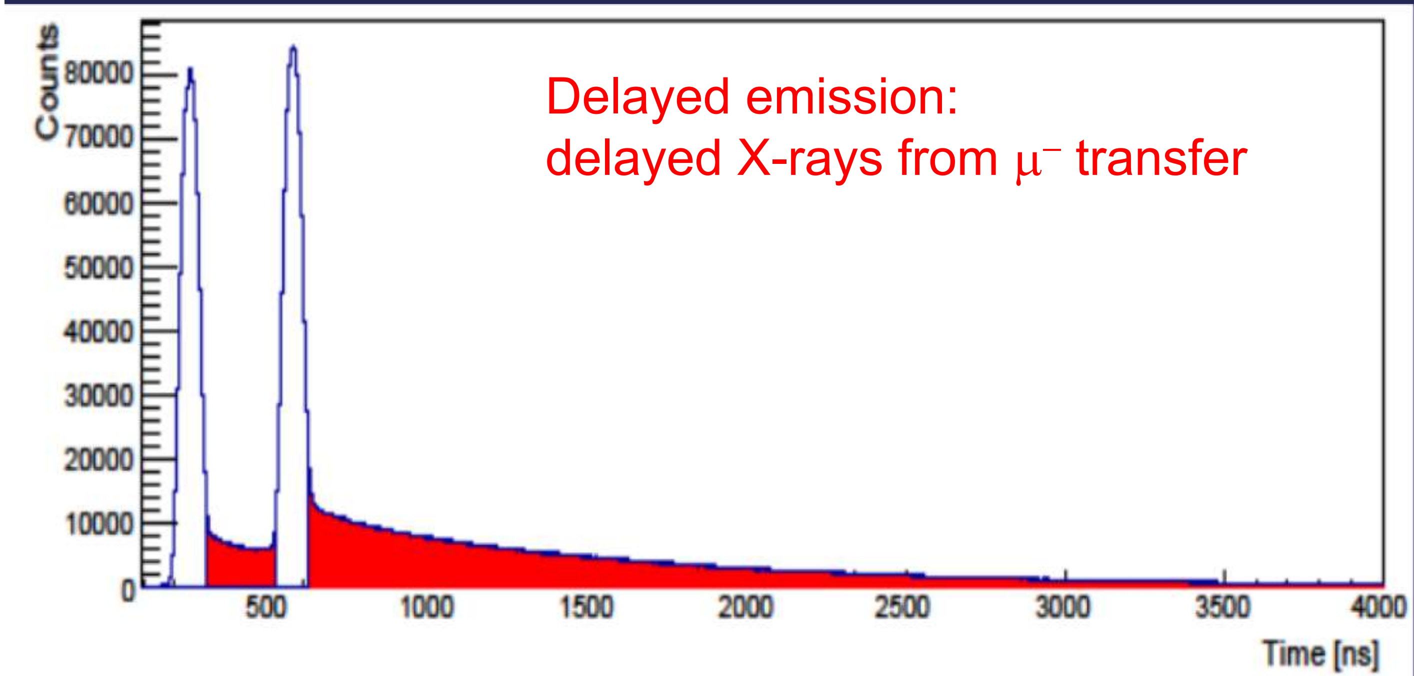


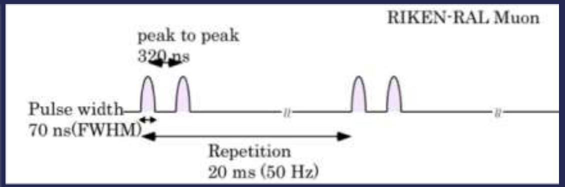


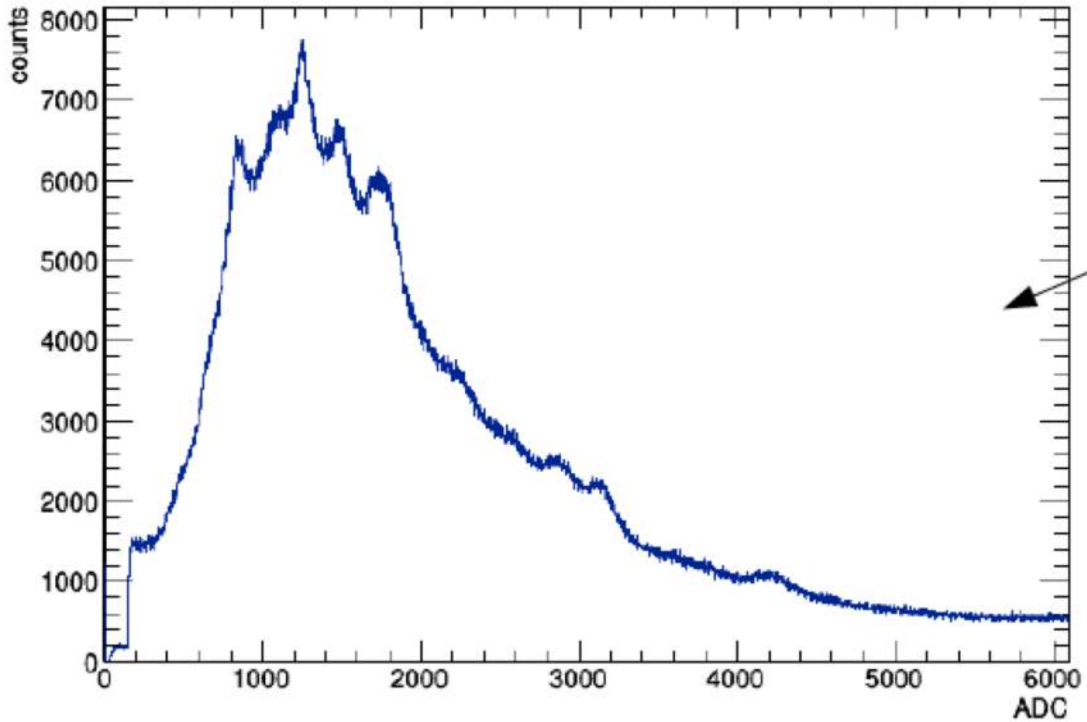
2016: transfer rate measurement

Steps:

1) fix a target temperature (i.e. mean kinetic energy of gas constant)
2) produce μp and wait for thermalization
3) study time evolution of Oxygen X-rays
4) repeat with different temperature





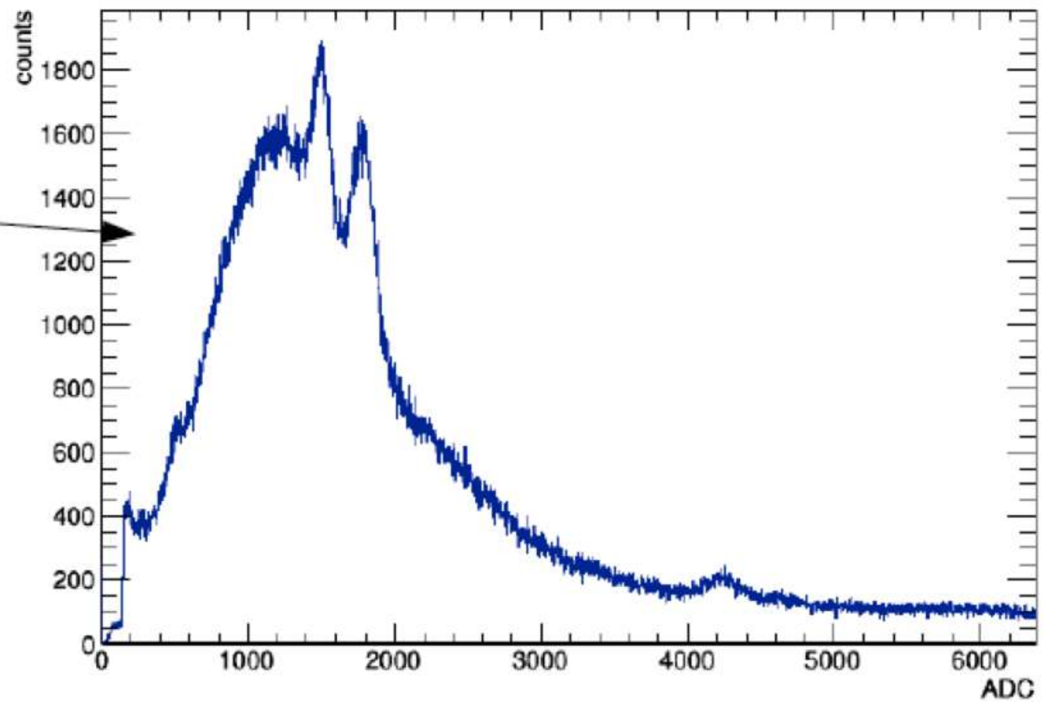


PROMPT SPECTRUM
(t<1200 ns)

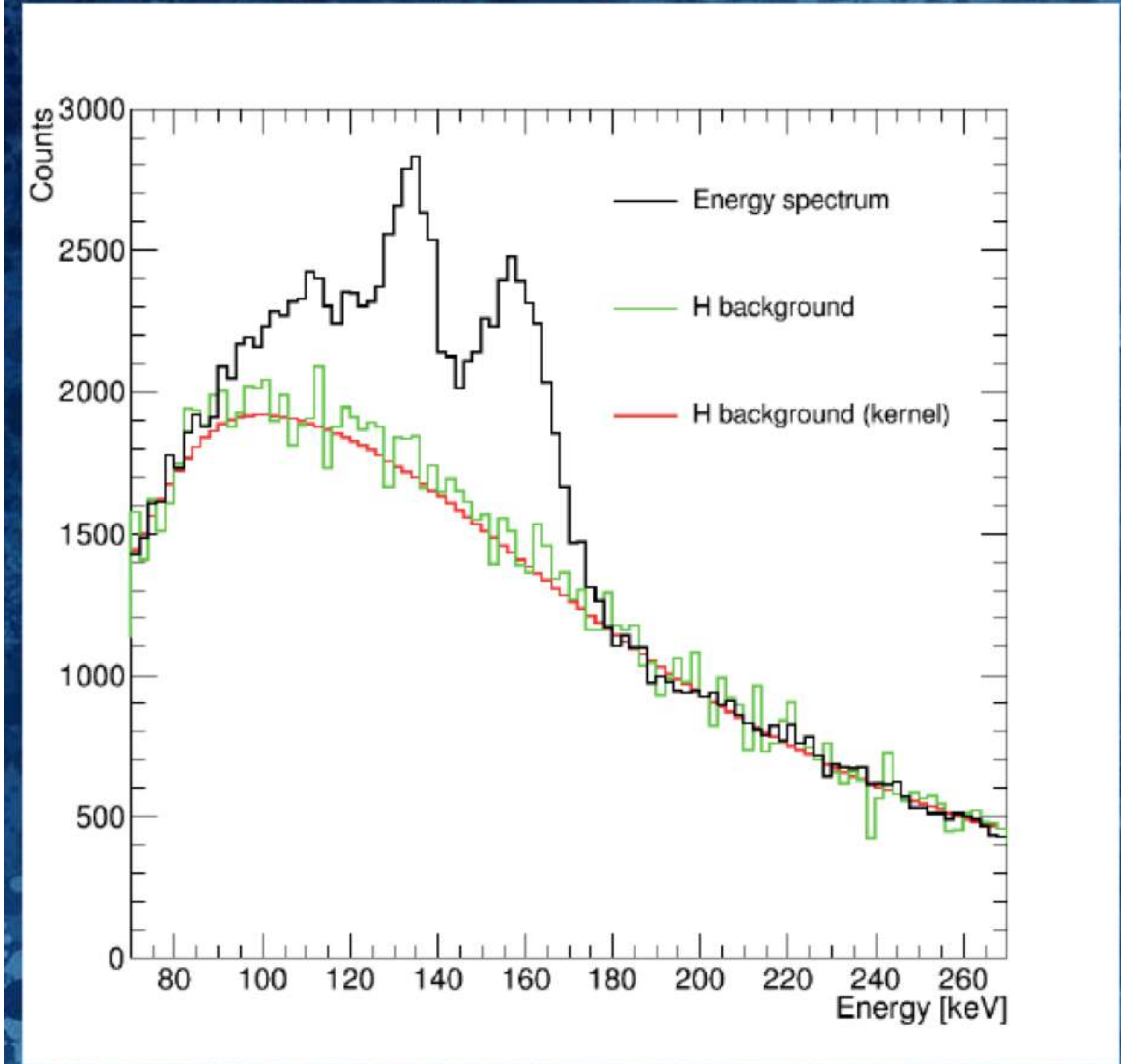
One detector (LaBr 3)
0.3% oxygen
concentration

DELAYED SPECTRUM
(t>1200 ns)

One detector (LaBr 3)
0.3% oxygen
concentration



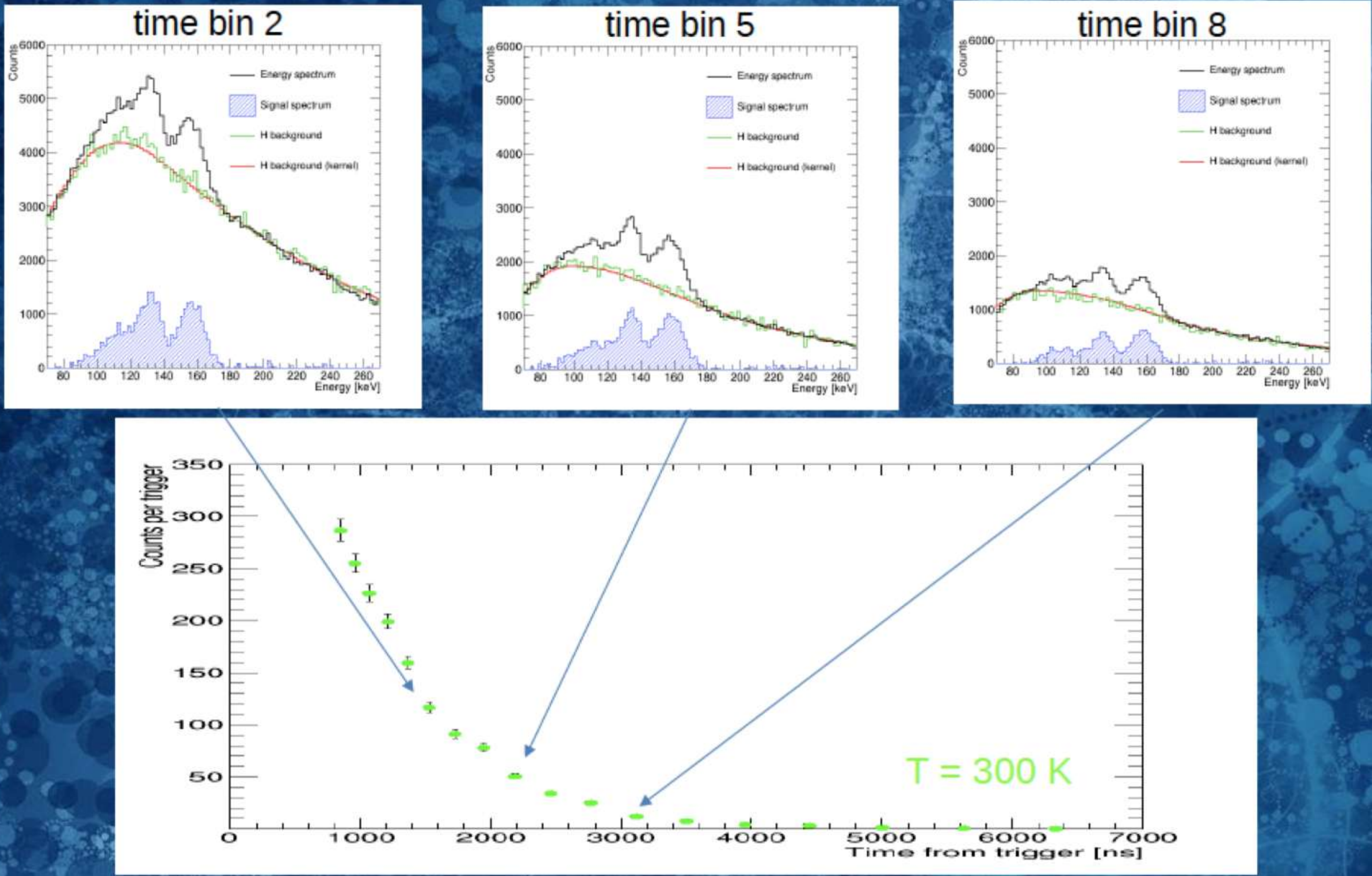
Best solution: pure H smoothing



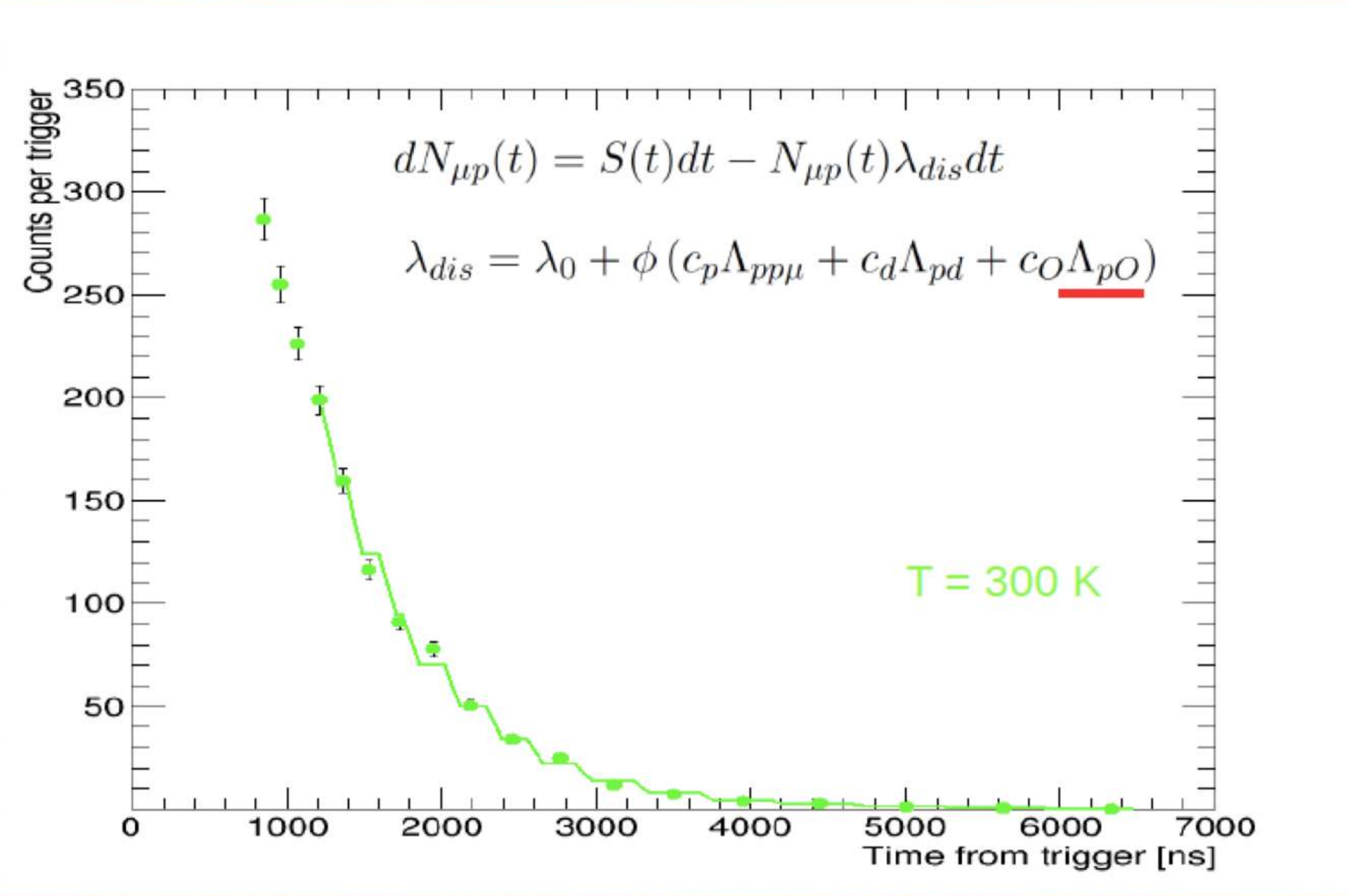
T = 300 K
Time bin = [1450,1650] ns

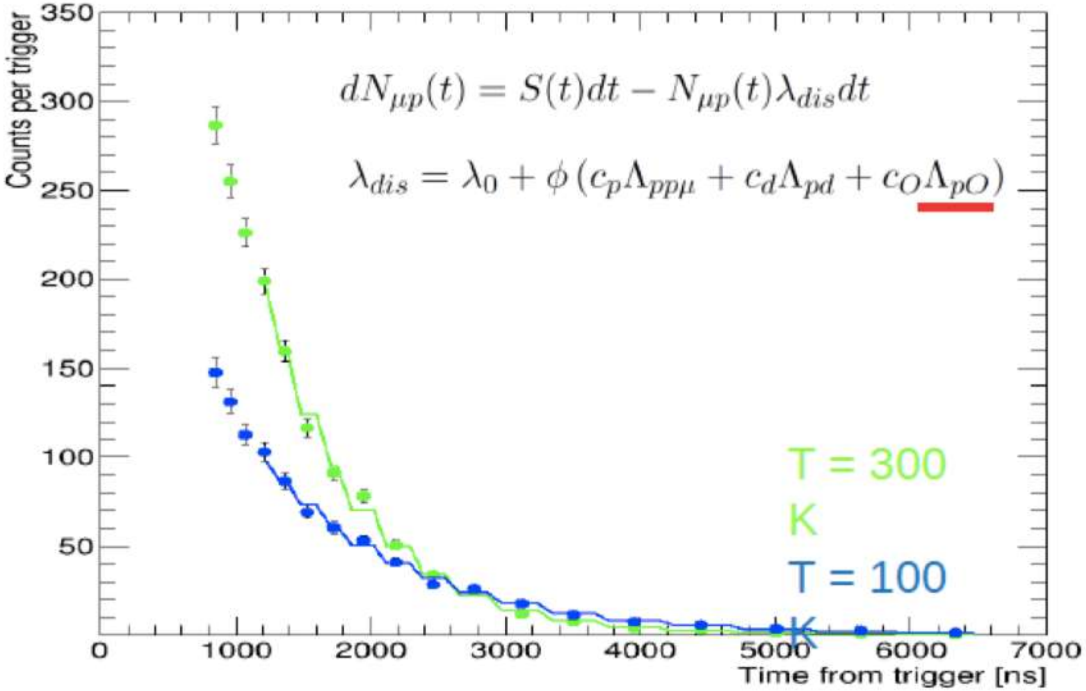
Pure hydrogen data taking within the same beam time and with the same pressure and temperatures.

Fixed temperature: time evolution

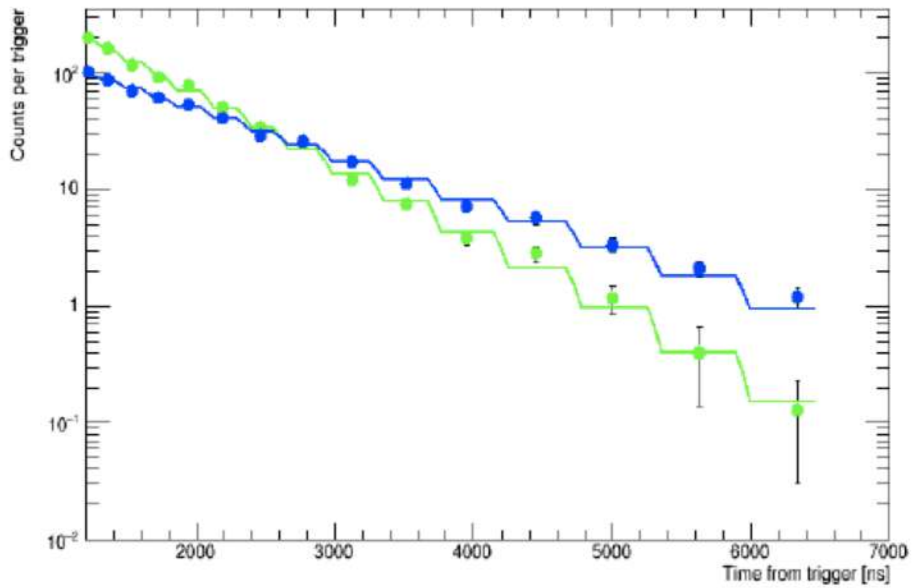


Temperature and time evolution



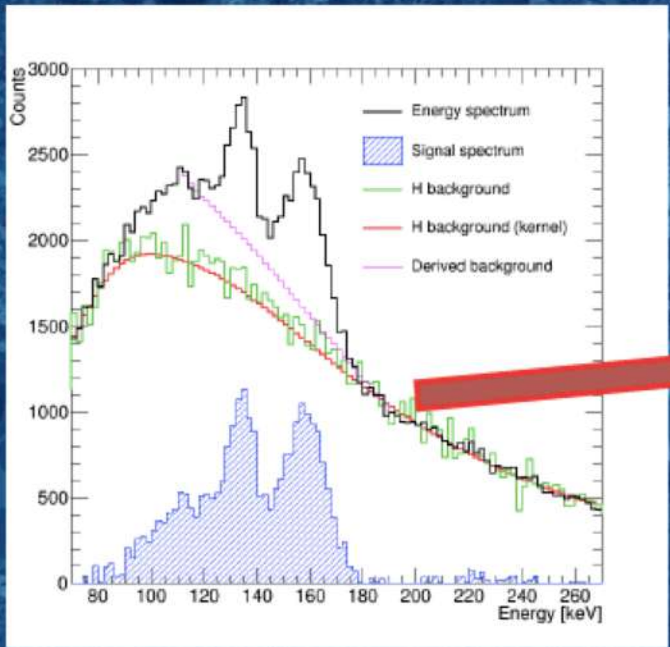


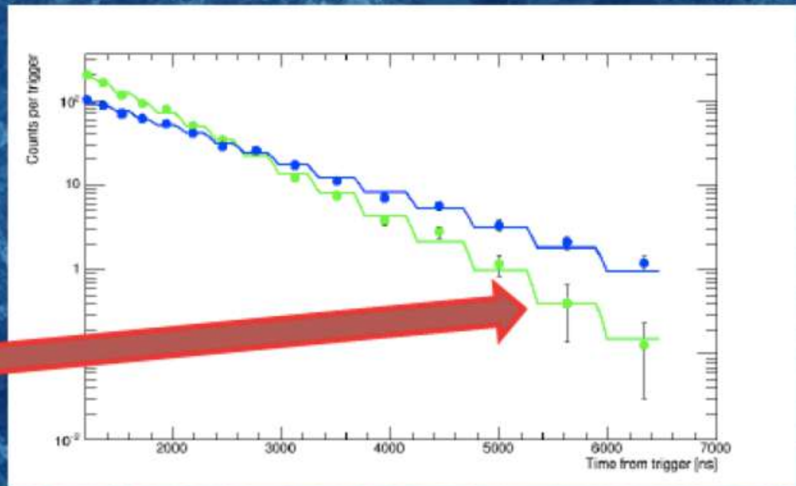
Transfer rate dependence on temperature



Sistematic errors contributions

- 3% given by the O concentration calculation
- 3% given by the density calculation
- About 5% due to the procedure of the background subtraction

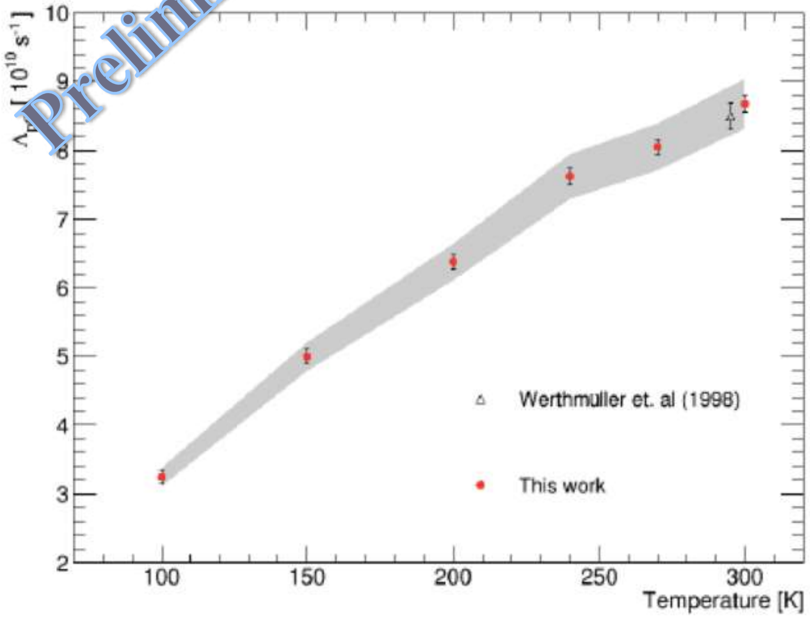


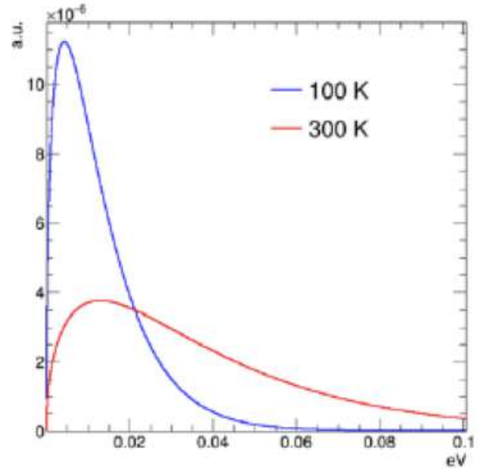


Other uncertainties, negligible (<< statistical error)

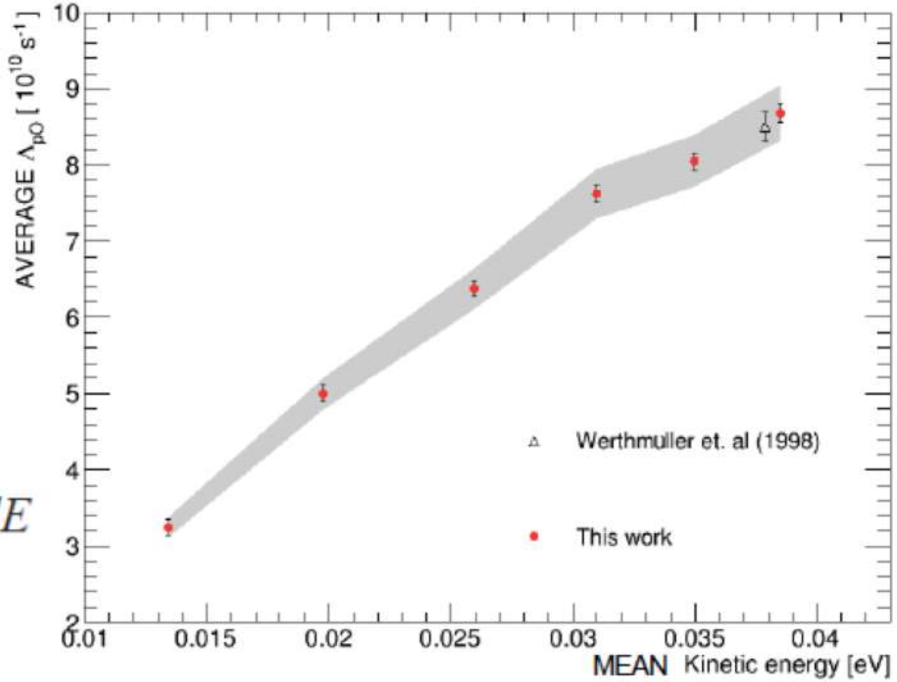
Conversion to kinetic energy

Preliminary





$$\lambda(T) = \int_0^\infty \lambda(E)\sqrt{\frac{4E}{\pi(kT)^3}}\exp(-E/kT)dE$$



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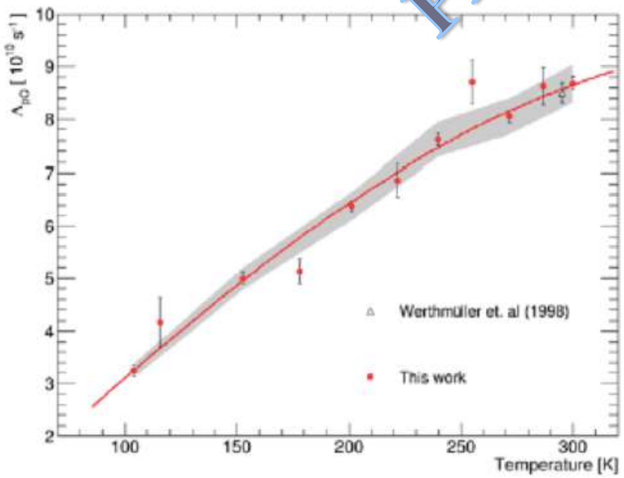
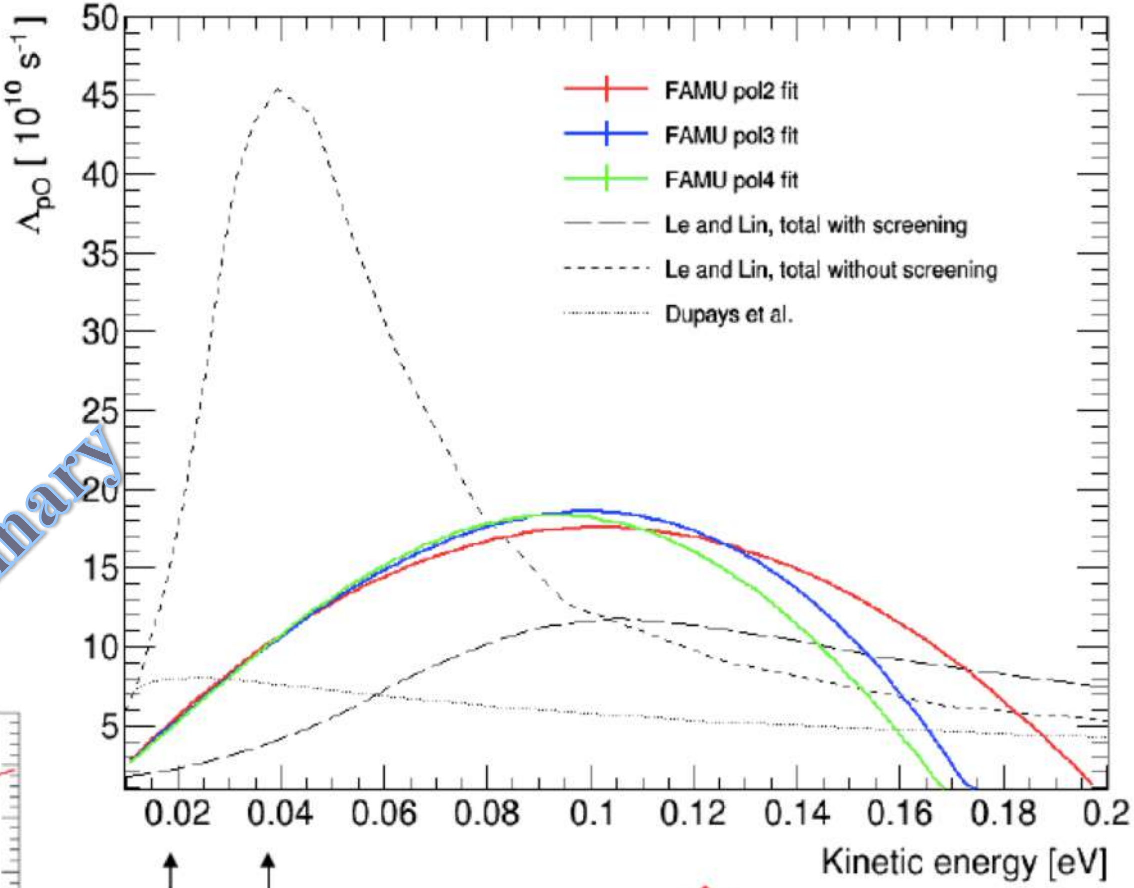
Phenomenological model

$$\lambda(T) = \int_0^{\infty} \lambda(E) \sqrt{\frac{4E}{\pi(kT)^3}} \exp(-E/kT)dE$$





~300 K

~100 K

μp energy after de-excitation

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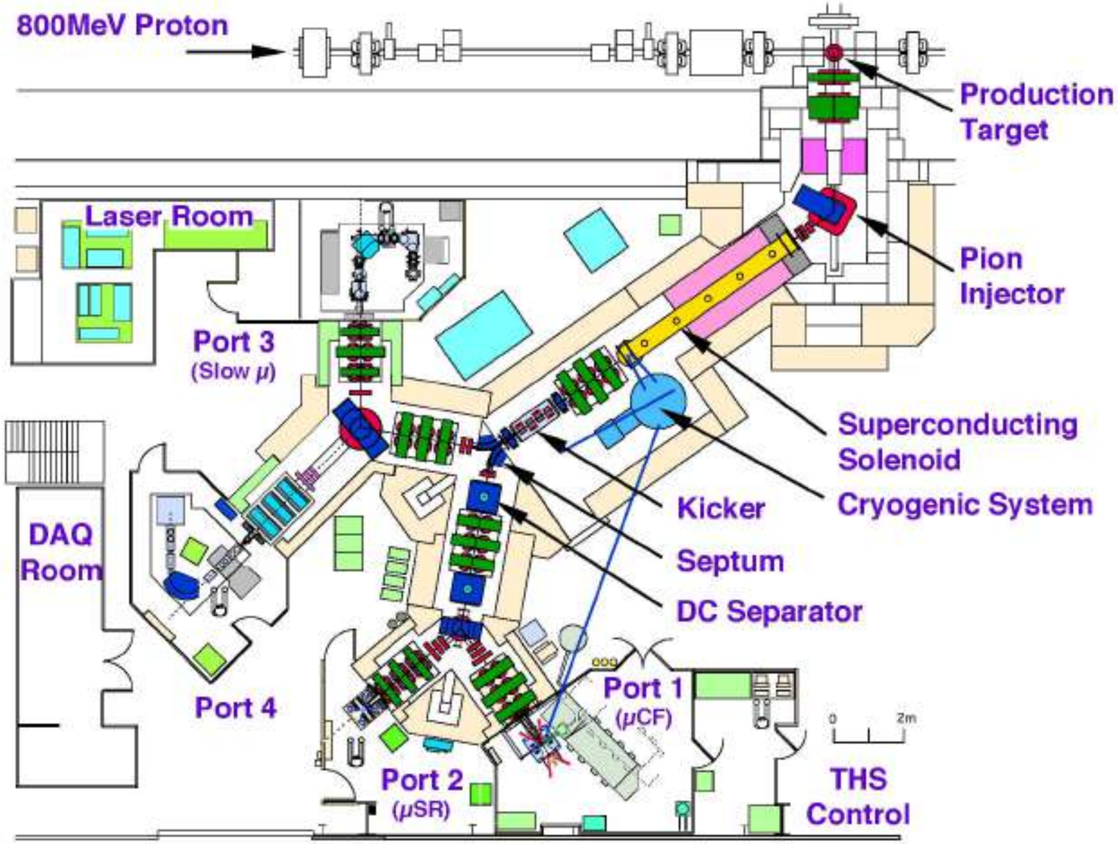
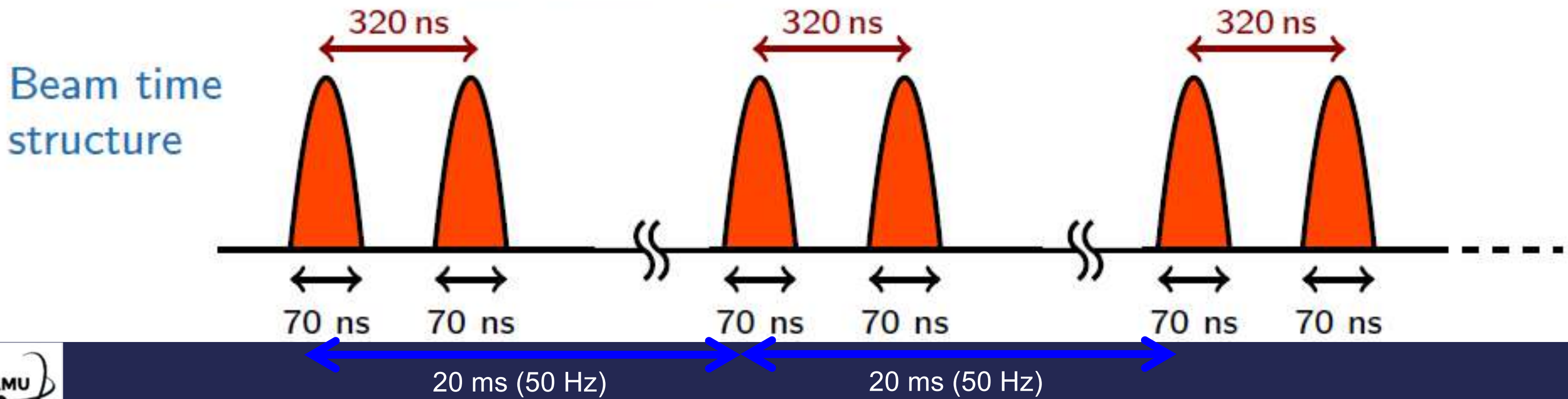
High intensity muon beam



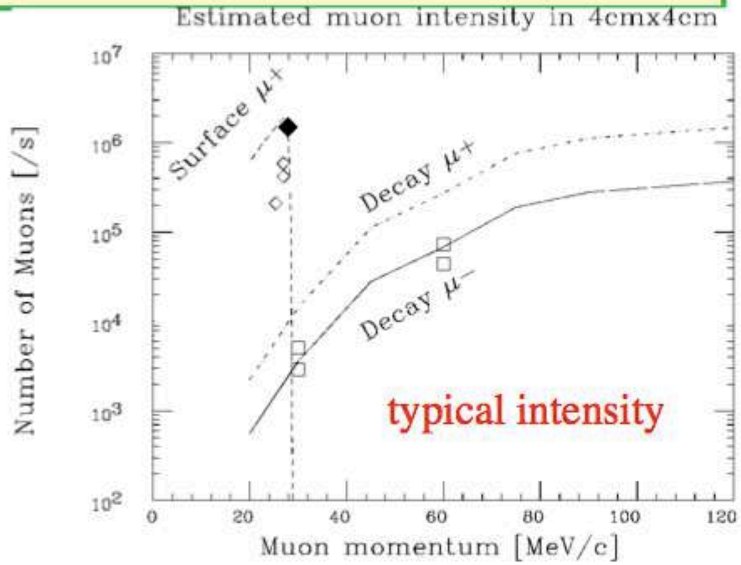


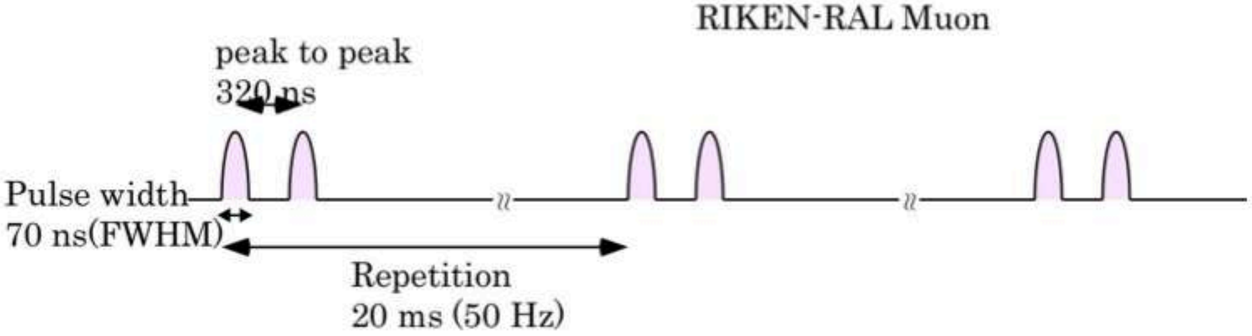
FAMU Key elements

Muon Beam at RIKEN-RAL

Beam properties

surface μ^+ (20~30MeV/c) and
decay μ^+ / μ^- (20~120MeV/c)
typical beam size 10cm^2
$\bar{x}\Delta p/p$ FWHM 10%(decay), 5%(surface)
Double pulse structure
(Choice of single pulse
with magnetic kicker (<30 MeV/c))
Operation
160 days/y of ISIS beam time
~40 days for UK
~120 days for RIKEN





Muon beam density enhancement

- Muon beam density enhancement was observered in a number of experiments carried out both at RIKEN-RAL (UK) and at TRIUNF (Canada) laboratories .

- They used several tapered tubes working with muon grazing angle: glass tubes, copper, gold plated copper.

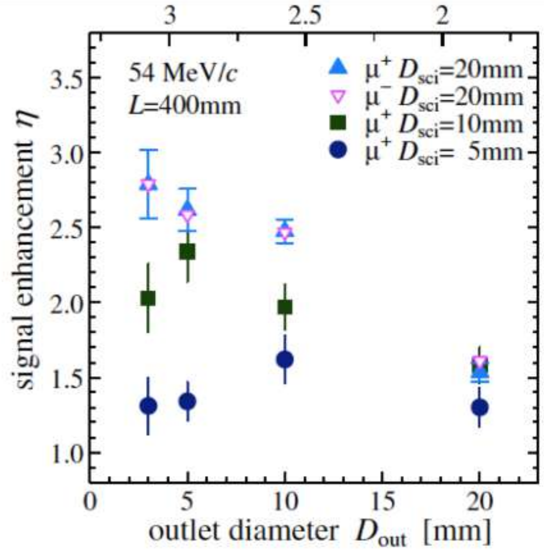
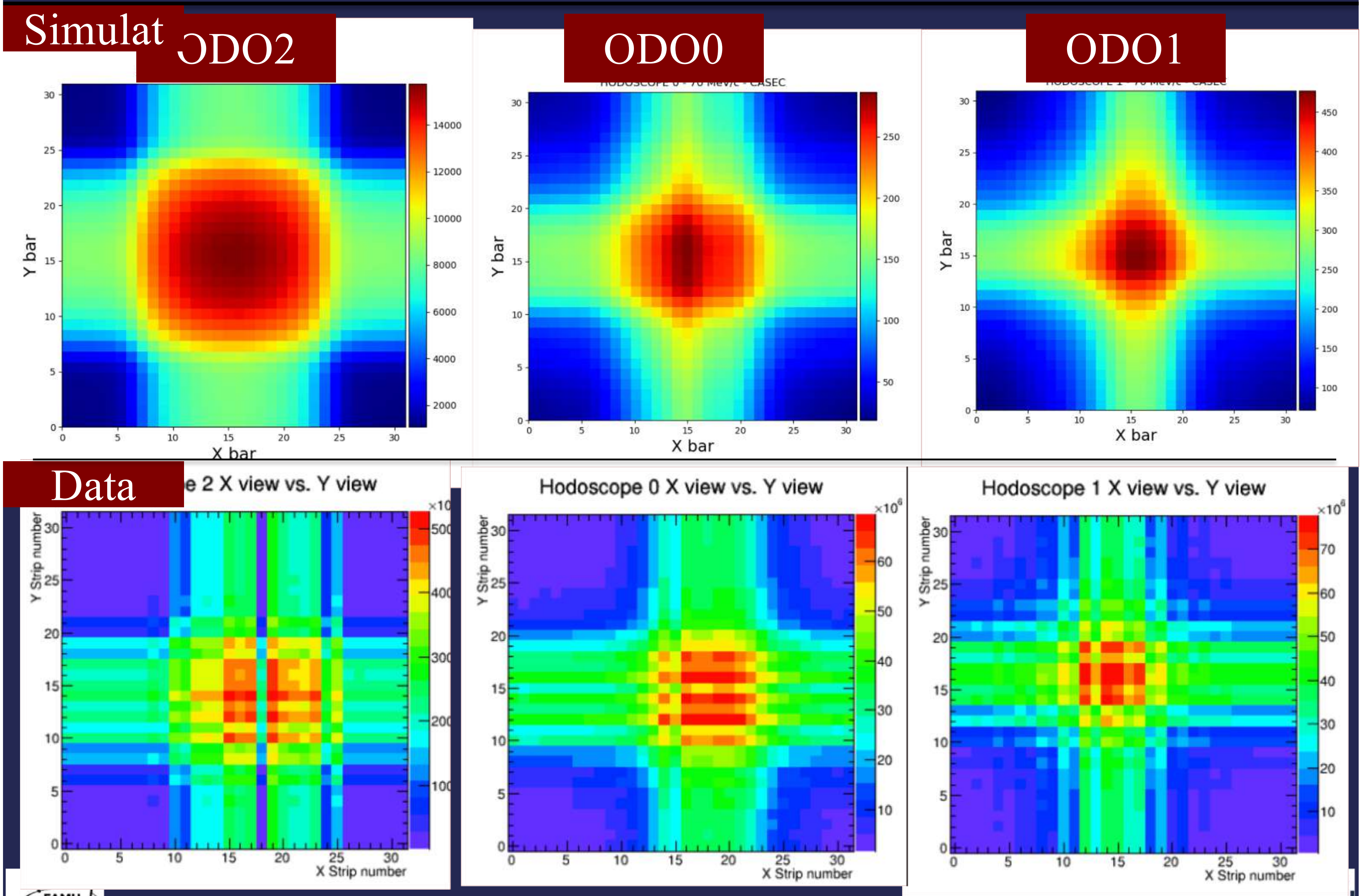


Fig. 2. (Color online) The signal enhancement factor η as a function of outlet diameter D_{out} for 54 MeV/c muons with $L = 400$ mm tubes for $D_{sci} = 5$, 10, and 20 mm. The error bar includes statistical and systematic errors (see text). Data points with "T" shape error bar are the mean of multiple measurements and those with "|" shape error bar are measured only once. Error bars of μ^- data are omitted for clarity.

$$\eta = \begin{cases} V_{with}/V_{without} & \text{for } D_{sci} \leq D_{out}, \quad (1a) \\ V_{with}/V_{without,\, d \leq D_{out}} & \text{for } D_{sci} > D_{out}, \quad (1b) \end{cases}$$

We decided to investigate the possibility to have density enhancement. Several experimental configurations were realized, made of polished copper and of gold plated glass. The analysis is on-going

Case Copper optics – AIR – 70 MeV/c



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FAMU key elements high energy MIR laser

Tunable pulsed MIR laser at λ=6.8μ

Direct difference frequency generation in non-oxide non linear crystals using single-mode Nd:YAG laser and tunable Cr:forsterite laser

Wavelength:	λ =6785 nm	44.22 THz
Line width:	$\Delta\lambda$ = 0.07 nm	450 MHz =>100MHz
Tunability range:	6785 +- 10 nm	130 GHz
Tunability step	0.007nm	45 MHz
Repetition rate:	25 Hz	
Pulse Energy at 6780 nm:	5 mJ	

(L.Stoychev, EOSAM '14) Proc. of SPIE Vol. 9135, 91350J · © 2014 SPIE · CCC code: 0277-786X/14

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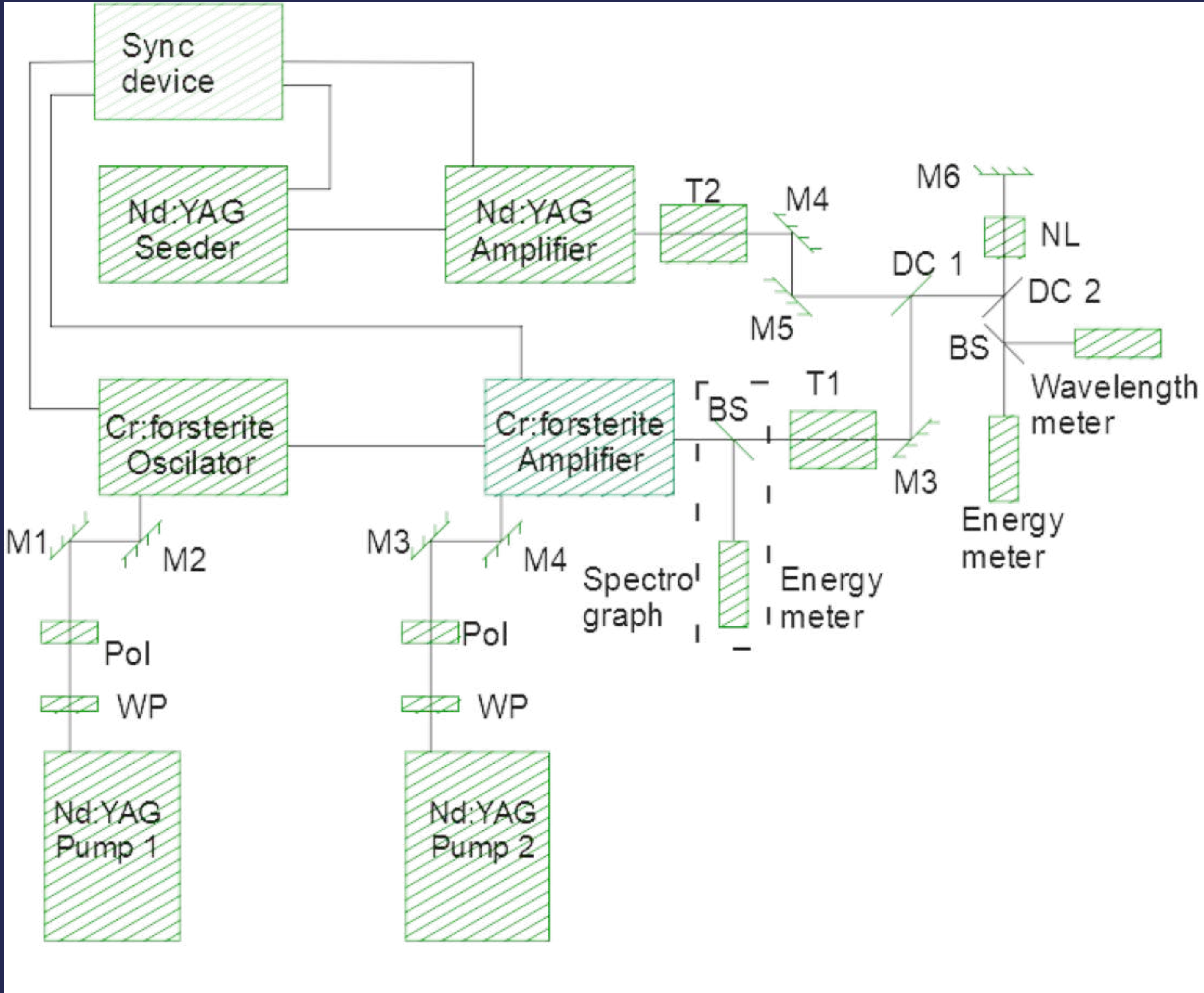
Final scheme of the DFG based laser system

The Nd:YAG will be at "fixed" wavelength 1064.14nm with linewidth max - 0.34pm (90MHz) and min - 0.11pm (30MHz).

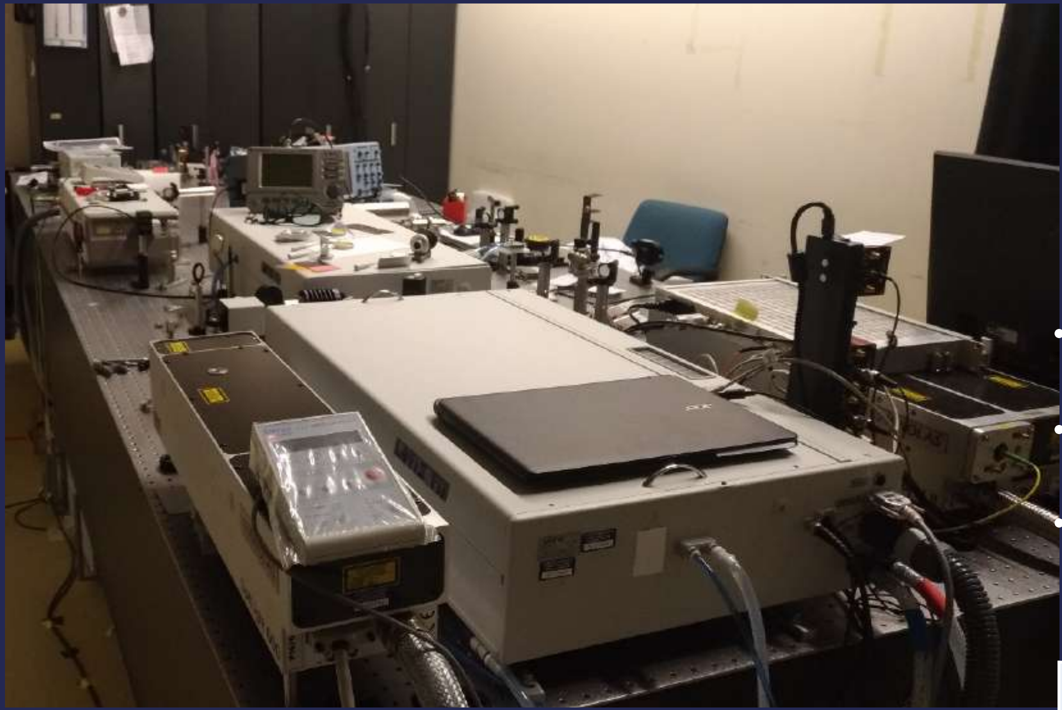
The Cr:forsterite will have linewidth max - 1pm (188MHz) and min - 0.5pm (90MHz).

The Cr:forsterite will be tunable from 1252nm to 1272 nm which corresponds to tunability from 6500nm to 7090nm, which is 3765GHz. The required tunability 6760nm ±3nm corresponds to tunability range ~ 39GHz.



WP - waveplate, Po - polarizer, M1-M5 - mirrors, T1 and T2 - telescopes, BS - beamsplitters, DC1 - dichroic mirror (reflecting 1.26μm, transmitting1.06μm), DC2 - dichroic mirror (reflecting 1.06 and 1.26 μm, transmitting 6.76μm)

The laser lab



- Available - All lasers
- Available - Most optics and electronics
- Available - Most test and measurement equipment

Laser parameters	Baseline laser source	FAMU laser system
Wavelength λ	6785 nm	6785 nm
Linewidth Δλ	450 MHz	250 MHz
Pump Laser Beam shape	gaussian	flat top
$LiInS_2$ crystals	7 x 7 x 20	2 x (10 x 10 x 20)
Nonlinear crystals efficiencies	$LiInS_2$ d_{eff} = 7,38 pm/V	$LiInSe_2$ d_{eff} = 19,5 pm/V
Cr-Forsterite tot energy	15 mJ	35 mJ
NdYag tot. energy	150 mJ	150 mJ
Available Energy$_{@}$6785nm	1 mJ	>5 mJ

The FAMU laser system

Laser parameters	Baseline laser source	FAMU laser system
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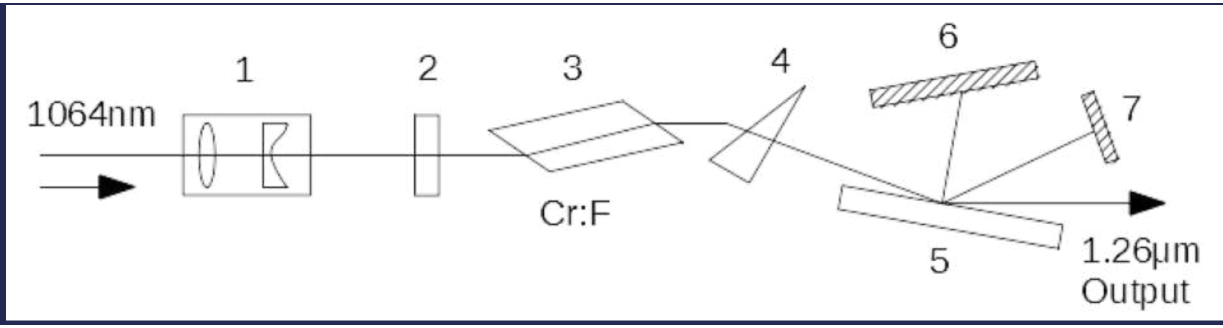
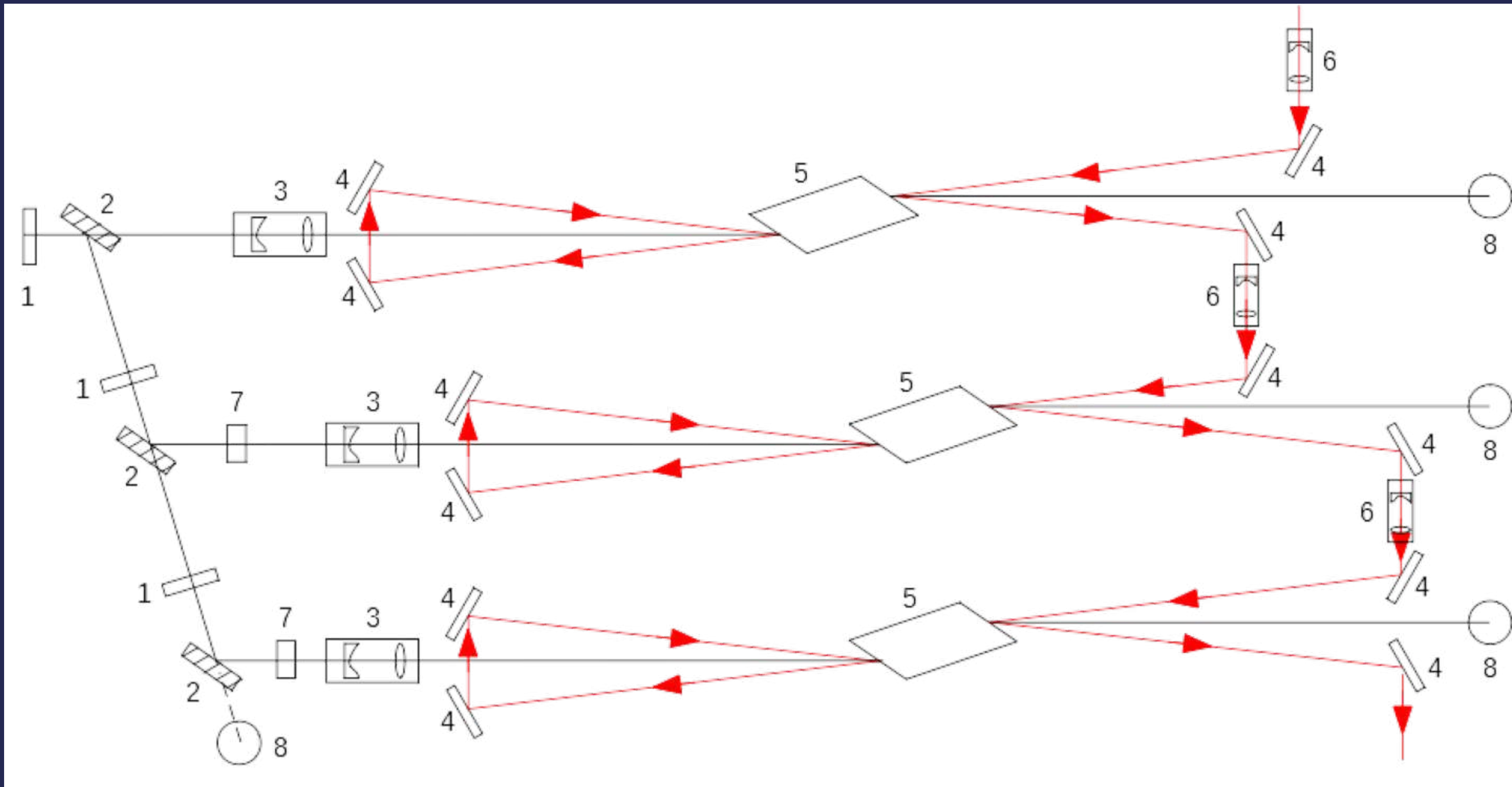
Available $Energy_{@}$6785nm	1 mJ	>5 mJ

The lab at the moment

- Available - All lasers
- Available - Most optics and electronics
- Available - Most test and measurement equipment

Cr:Forsterite oscillator & amplifier stages setups





1 – half-wave plates (λ/2, 1064 nm); 2 – polarizers (1064 nm); 3 – decreasing telescopes (1064 nm); 4 – turning mirrors (1262 nm); 5 – Cr:Forsterite crystals; 6 – increasing telescopes (1262 nm); 7 - rotators (90°, 1064 nm); 8 – beam stops

Available NL crystals & Expected output energies at 6760 – 6780 nm

Nonlinear crystals

Available	Ordered
$LiInS_2$ - 7x7x20 mm	$LiInSe_2$ - 7x7x15 mm
$LiInS_2$ - 8x8x18	LGS – 5x5x4 mm
	$BaGa_4S_7$ – in progress

Expected energies:
$LiInS_2$ & $LiInSe_2$: 1 – 1.5 mJ

$LiGaS_2$ & $BaGa_4S_7$ ~ 2mJ

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2016 Target: a necessary trade-off

Main requirements:

-Operating temperature range: 40 K ≤ T ≤ 325 K

-Temperature control for measurement runs at fixed T steps from 300 K to 50K

-Gas @ constant density, H_2 charge pressure at room T is ~40 atm

-International safety certification (Directive 97/23/CE PED)

-Minimize walls and windows thickness

-Target shape and dimensions to :

- **maximize muon stop in gas**
- **to minimize distance gas – detectors**
- **to be compliant to allowable volume at Riken Port**

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

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2016 Best solution

Target= Inner vessel with high P gas (44

-Al alloy 6082 T6 cylinder D = 60 mm a
400 mm, inner volume of 1.08 l

-Internally Ni/Au plated (L = 280 mm)

-Cylinder side wall thickness = 3.5 mm

-Wrapped in 20 layers of MLI

-Front window D= 30 mm 2.85 mm thic

-Three discs of 0.075 mm Al foil for wir
radiative shield

-304L SS gas charging tube

-304L SS cooler cold-end support

-G10 mechanical strut

-Two Cu straps for cooling

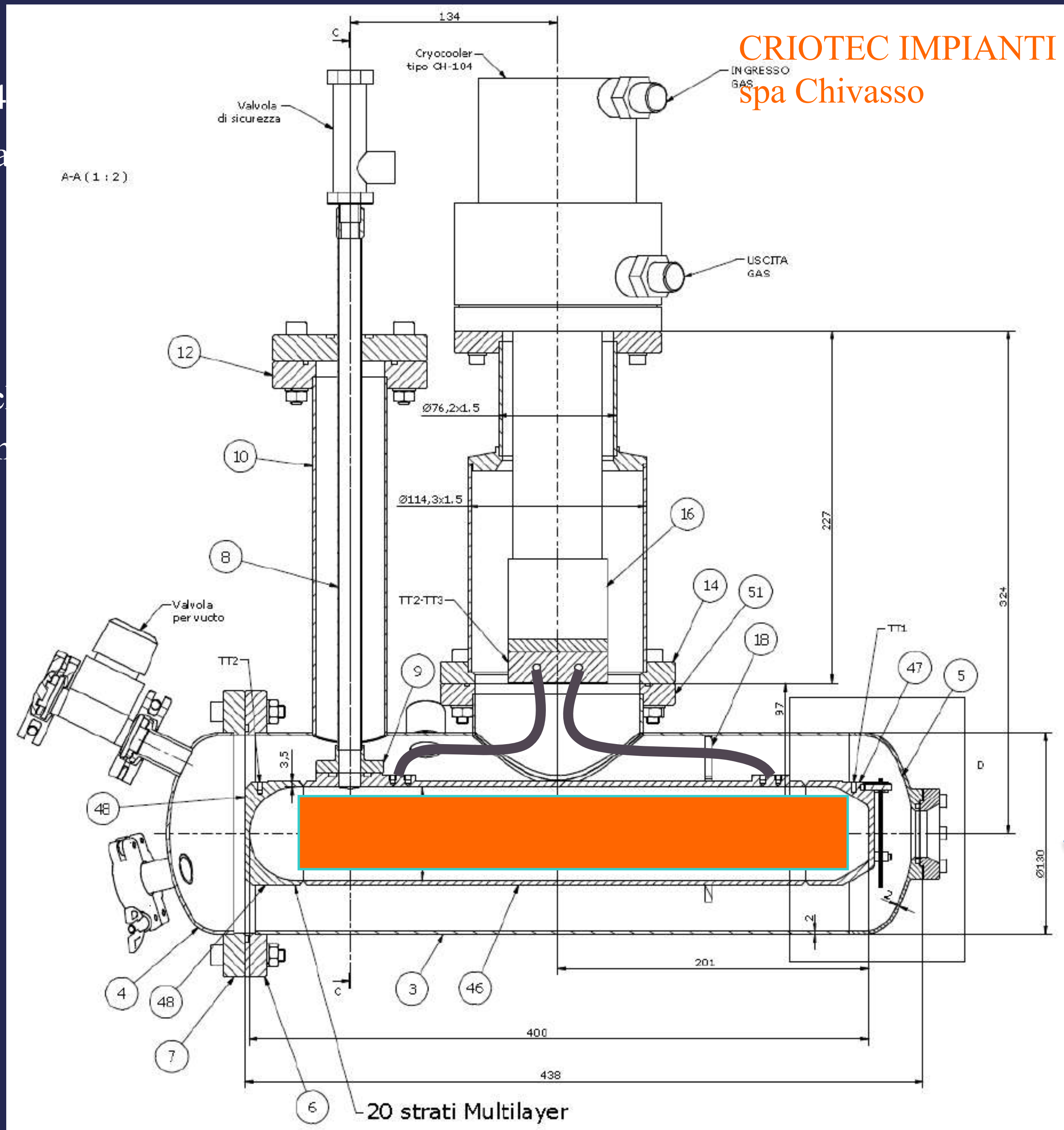
Vacuum vessel = outer cylinder (P atm)

-Al6060 D=130 mm, 2 mm thick walls

-≈30mm between inner/outer walls

-Flanged Al window 0.8 mm thick

-Pumping valve & harness feed-tru’ s



beam

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Target in lab

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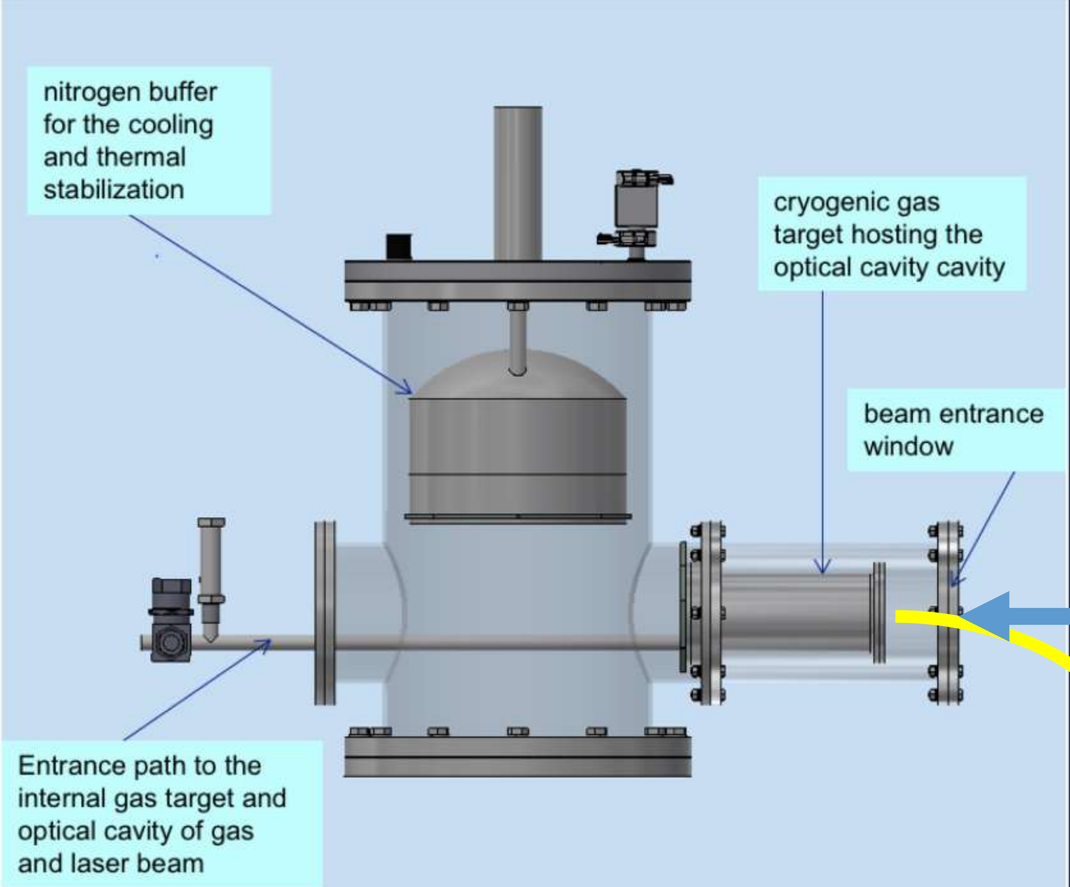
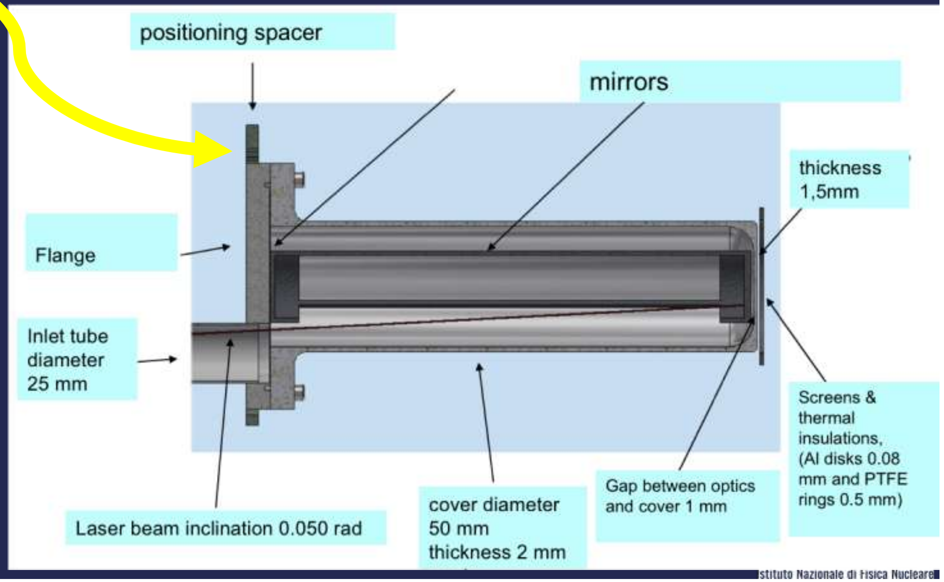
2018 target solution under study



Cryogenic gas target and optical cavity

beam



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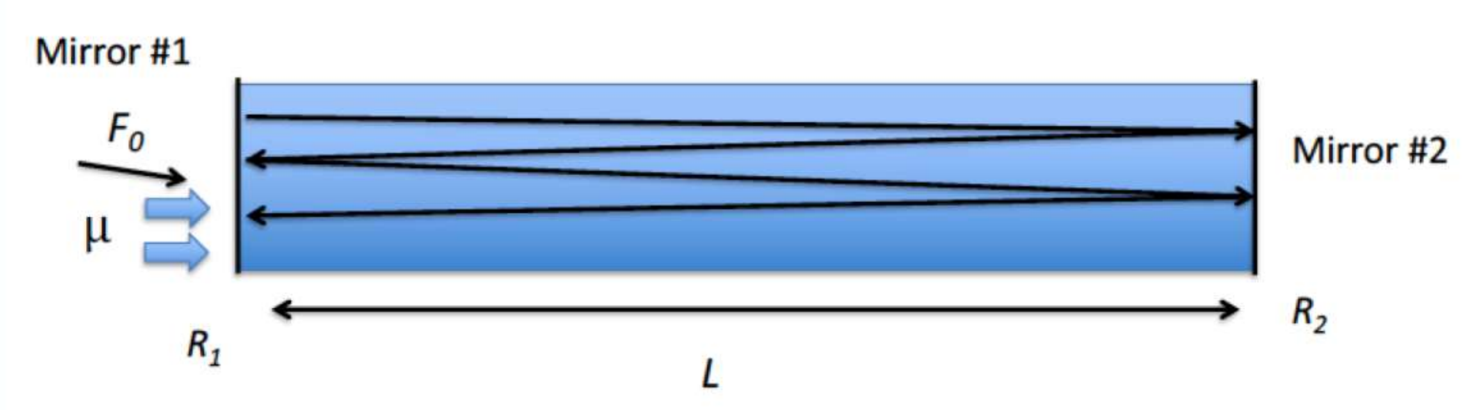
Multipass Optical Cavity

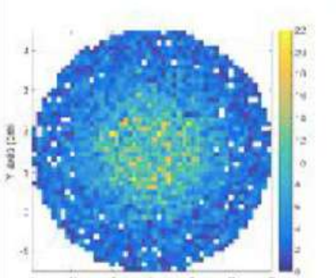
Luigi Moretti, Livio Gianfrani

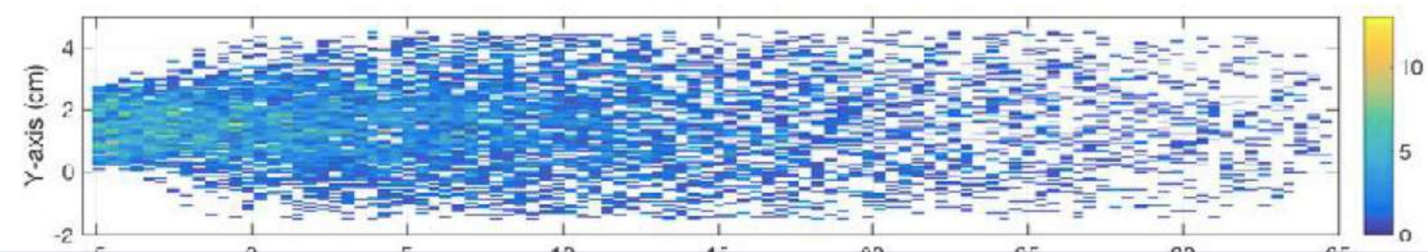
9497 events

$V_{est} = \pi\ (2\ \text{cm})^2\ (15\ \text{cm}) = 94\ \text{cm}^3$

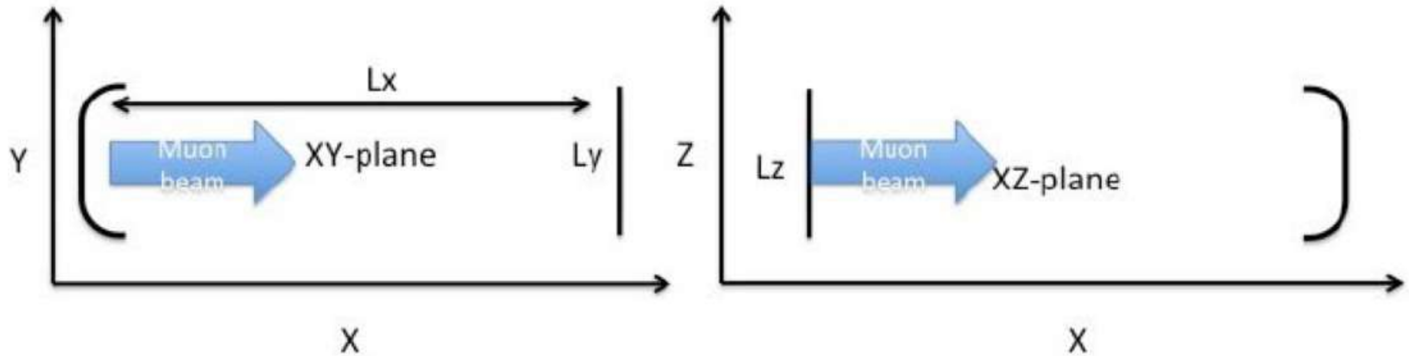


$$L_{eff} = \frac{L}{\alpha} = \frac{20\text{cm}}{12\times10^{-4}} \simeq 166\text{m}$$

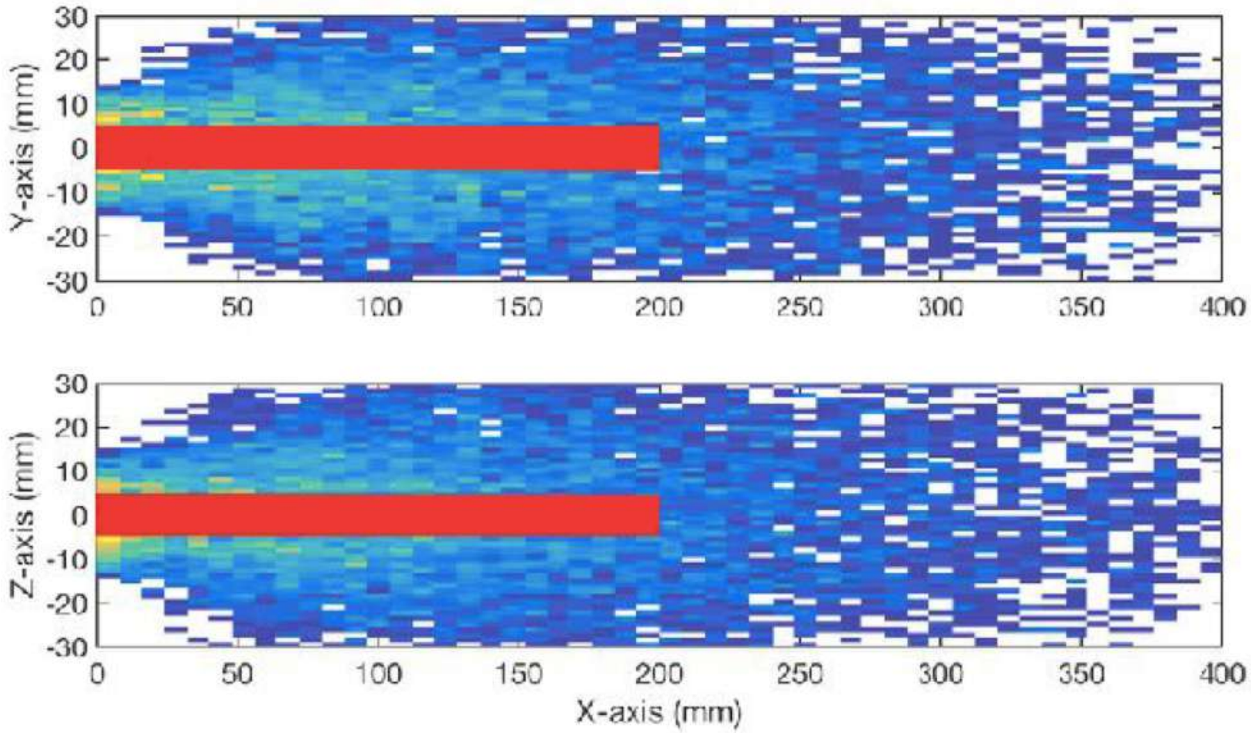




Optical design of cavity



Ly=Lz=2.5 cm
Lx=20 cm



Cavity enhancement effect at glance

$E_l = 2.5\,\mathrm{mJ}$ $\qquad N_R = 700 \qquad R_1 = R_2 = 0.9989$

$$\left.\text{New design} \quad S_{ill} \simeq (2\cdot 2)\,\mathrm{cm}^2 \quad (\alpha = 12\times 10^{-4})\ \right\} \rightarrow D_{cav} = \frac{N_R E_l}{S_{ill}} = 438\,\frac{\mathrm{mJ}}{\mathrm{cm}^2}$$

$$\overline{P} = \frac{D_{cav}}{D_{sat}} \simeq 0.01$$

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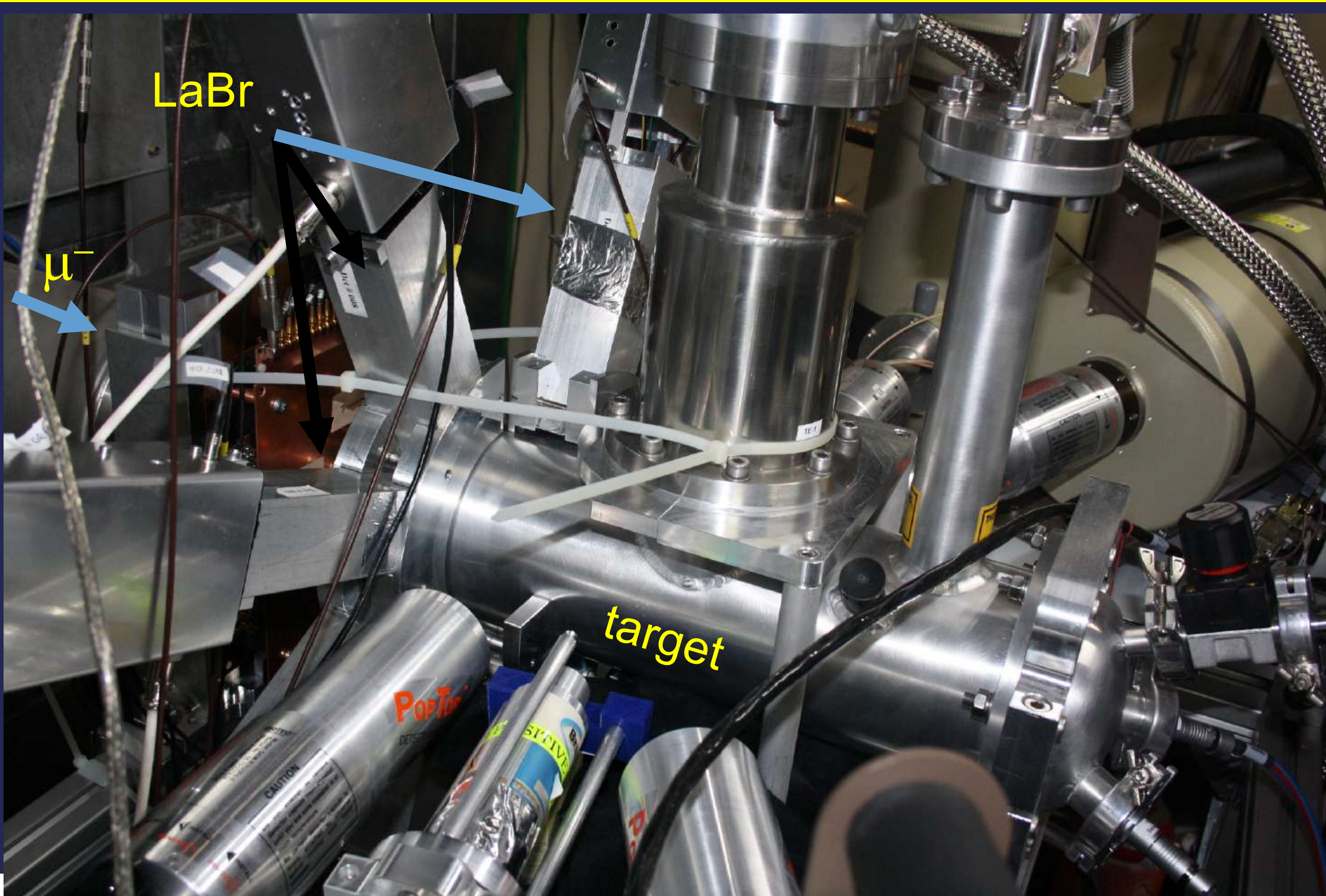
2016: experimental setup



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Detectors: suited for time-resolved X-ray spectroscopy

Germanium HPGe: low energy X-rays spectroscopy

ORTEC GLP:
Energy Range: 0 – 300 keV
Crystal Diameter: 11 mm
Crystal Length: 7 mm
Beryllium Window: 0.127 mm
Resolution Warrented (FWHM):
- at 5.9 keV is 195 eV (T_{sh} 6 μs)
- at 122 keV is 495 eV (T_{sh} 6 μs)

ORTEC GMX:
Energy Range: 10 – 1000 keV
Crystal Diameter: 55 mm
Crystal Length: 50 mm
Beryllium Window: 0.5 mm
Resolution Warrented (FWHM):
- at 5.9 keV is 600 eV (T_{sh} 6 μs)
- at 122 keV is 800 eV (T_{sh} 6 μs)

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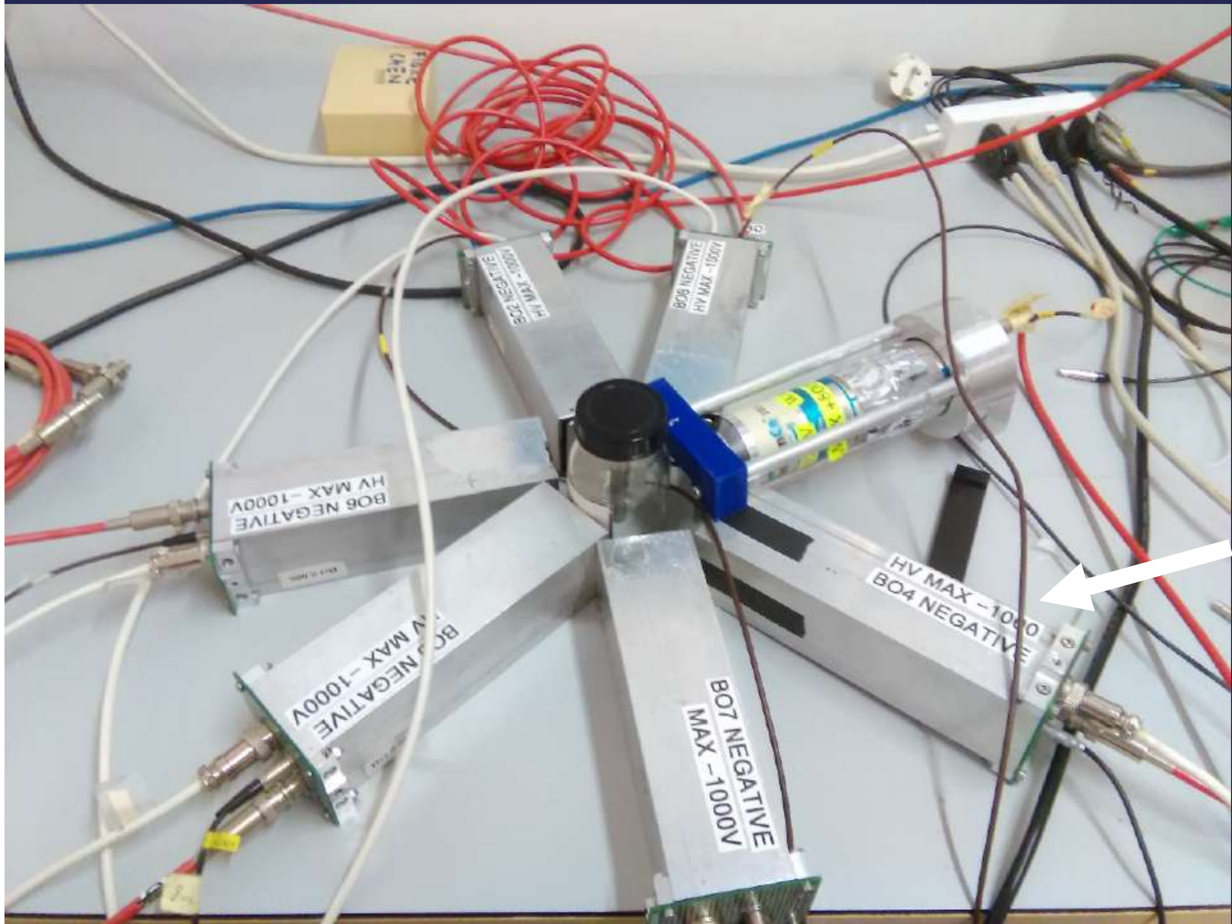
Detectors: suited for time-resolved X-ray spectroscopy

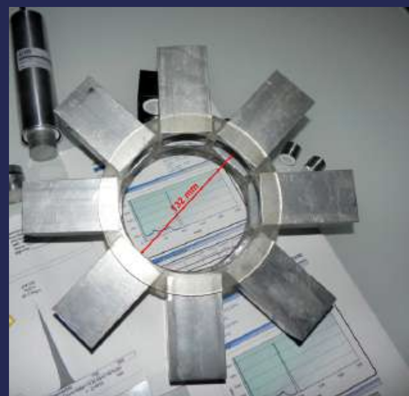
Lanthanum bromide scintillating crystals [$LaBr_3(Ce)$]: fast timing X-rays detectors



Lab test

8 cylindrical 1 inch diameter 1 inch long $LaBr_3$(5%Ce) crystals
read by PMTs.

On purpose developed fast electronics and fast digital processing signal.



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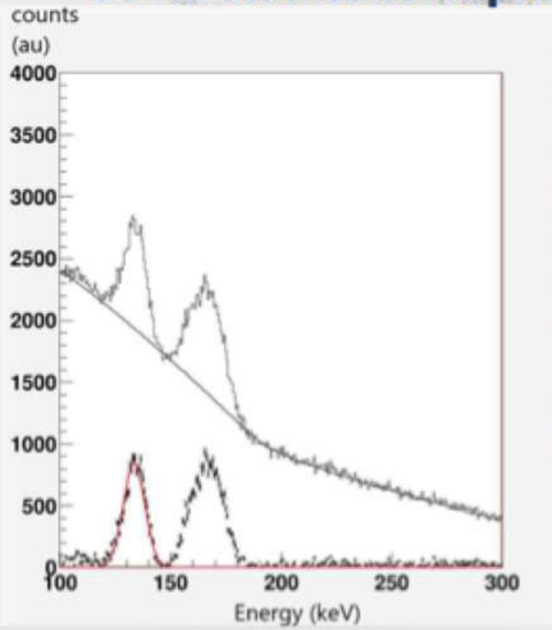
LaBr Bologna detectors

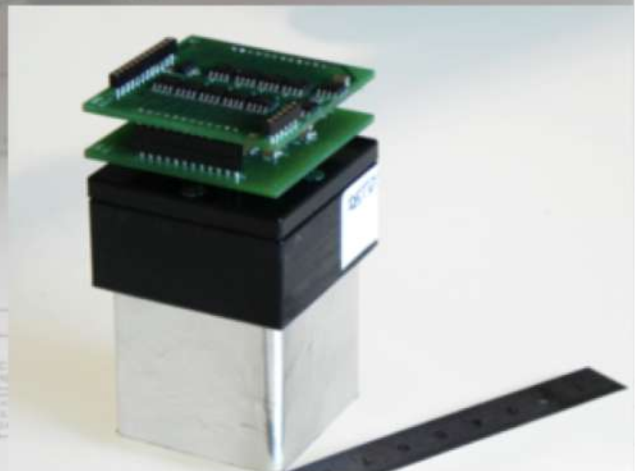
LaBr3 + (UBA) Hamamatsu photomultiplier

- **Custom** active **voltage divider** for high rate applications
- 8 **built and** on beam **tested** + 8 build ongoing
- New **high coverage** detector's geometry in order to adapt to the new work in progress **target**.
- Some studies to **improve energy resolution**

Energy (keV)	Literature resolution	Famu detector
122 keV	7.4%	8.8%
662 keV	2.8%	3.5%



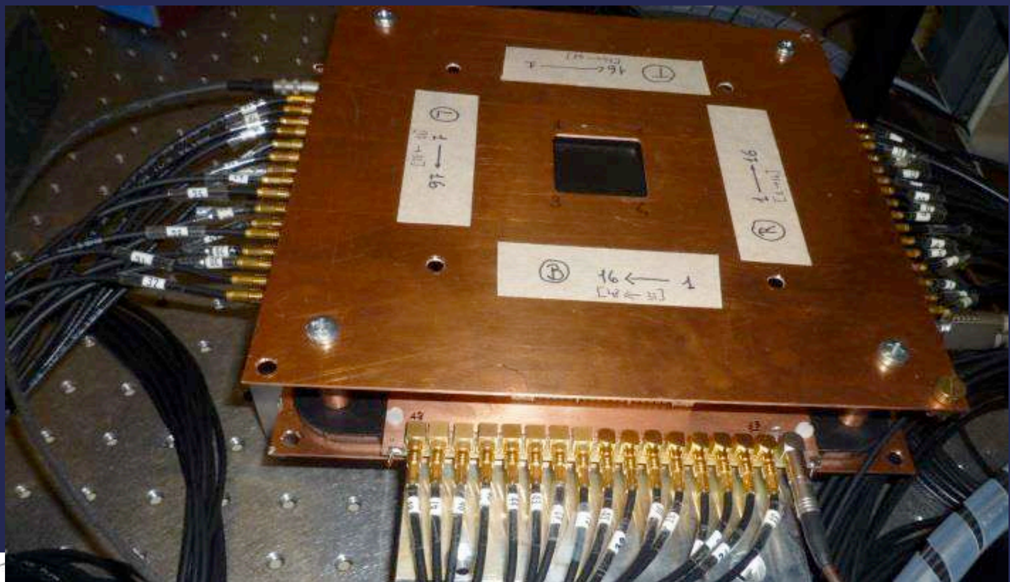
Delayed muonic oxygen lines well resolved.
The 133keV line resolution is 8.5%, slightly worse than the 8.1% predicted

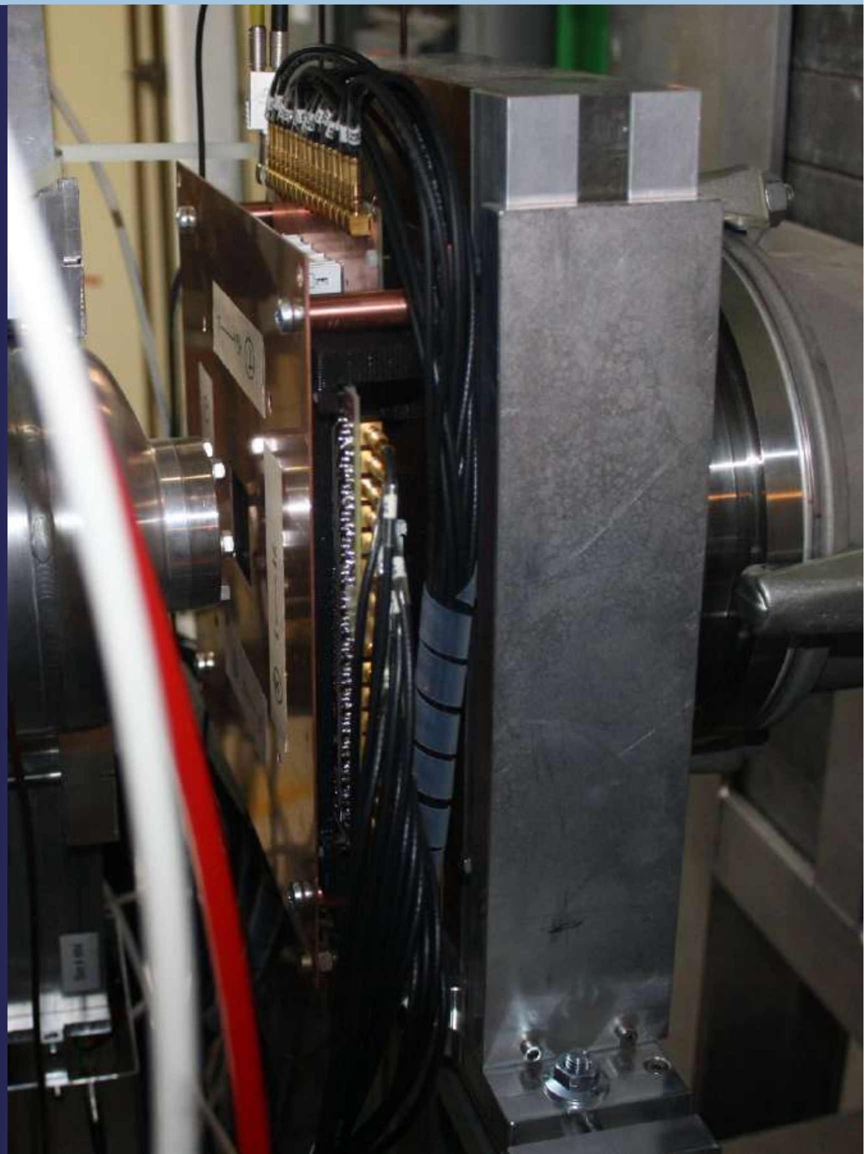


Article: G. Baldazzi and al., The LaBr 3 (Ce) based detection system for the FAMU experiment, Journal of Instrumentation 12 (2017) 03

Hodoscope for beam shape monitoring

Final version:
two planes (X and Y) of 32 scintillating fibers 1 x 1 mm^2 square section
SiPM reading with fast electronics
3D printed supports





hodoscope in the 2016 setup

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two competing processes

- the strength of x-ray signal, from mu-p's accelerated via the laser shot, is proportional to
  - the ratio of the muon transfer rate to oxygen and
  - the thermalization rate.
- both of them are proportional to the target density,

Through simulations optimize the relevant parameters

- The only parameter we can use to enhance the signal is the oxygen concentration - the x-ray signal is directly proportional to this concentration.
- The target pressure cannot be too small. We need a reasonable amount of the muon stops within the volume of laser field.
- The overall optimal condition, for the HFS measurement is thus a convolution of these two optimization functions, is going to be determined by the HFS-measurement simulation, which is underway.

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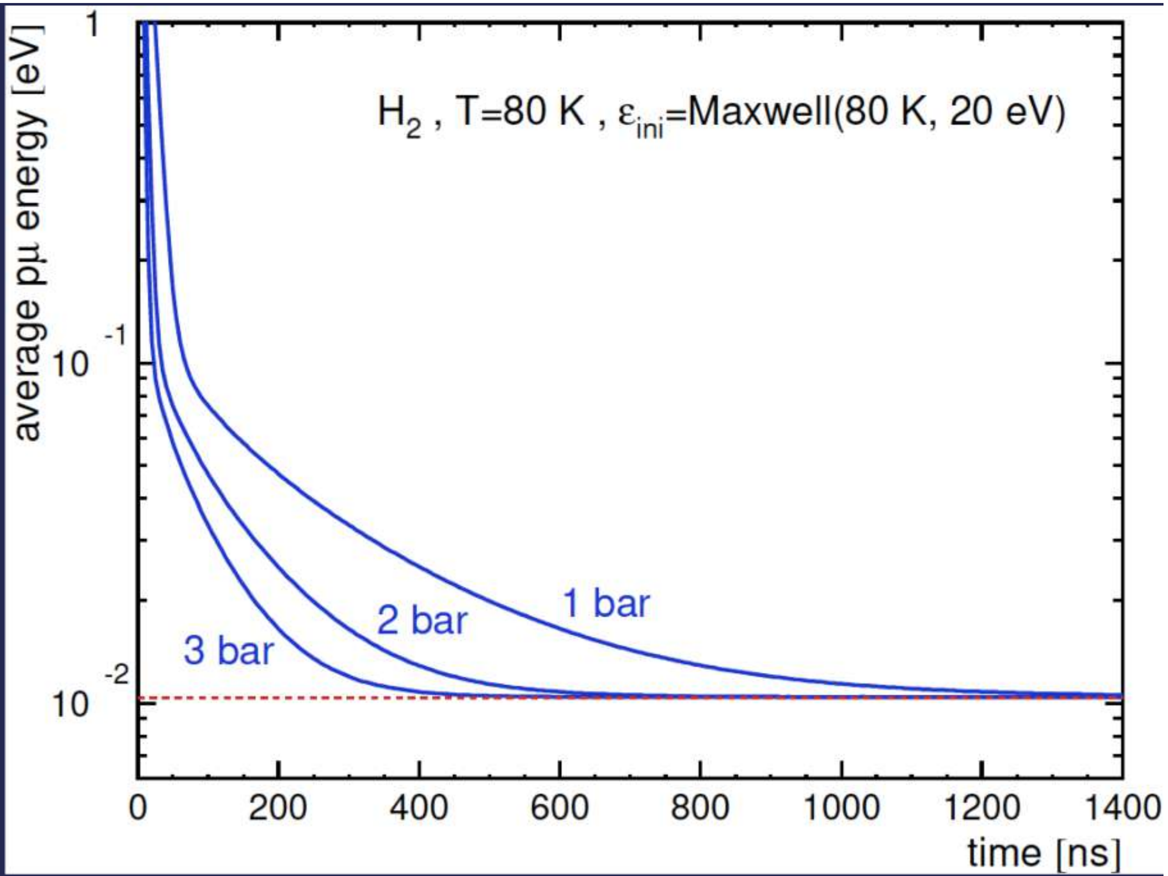
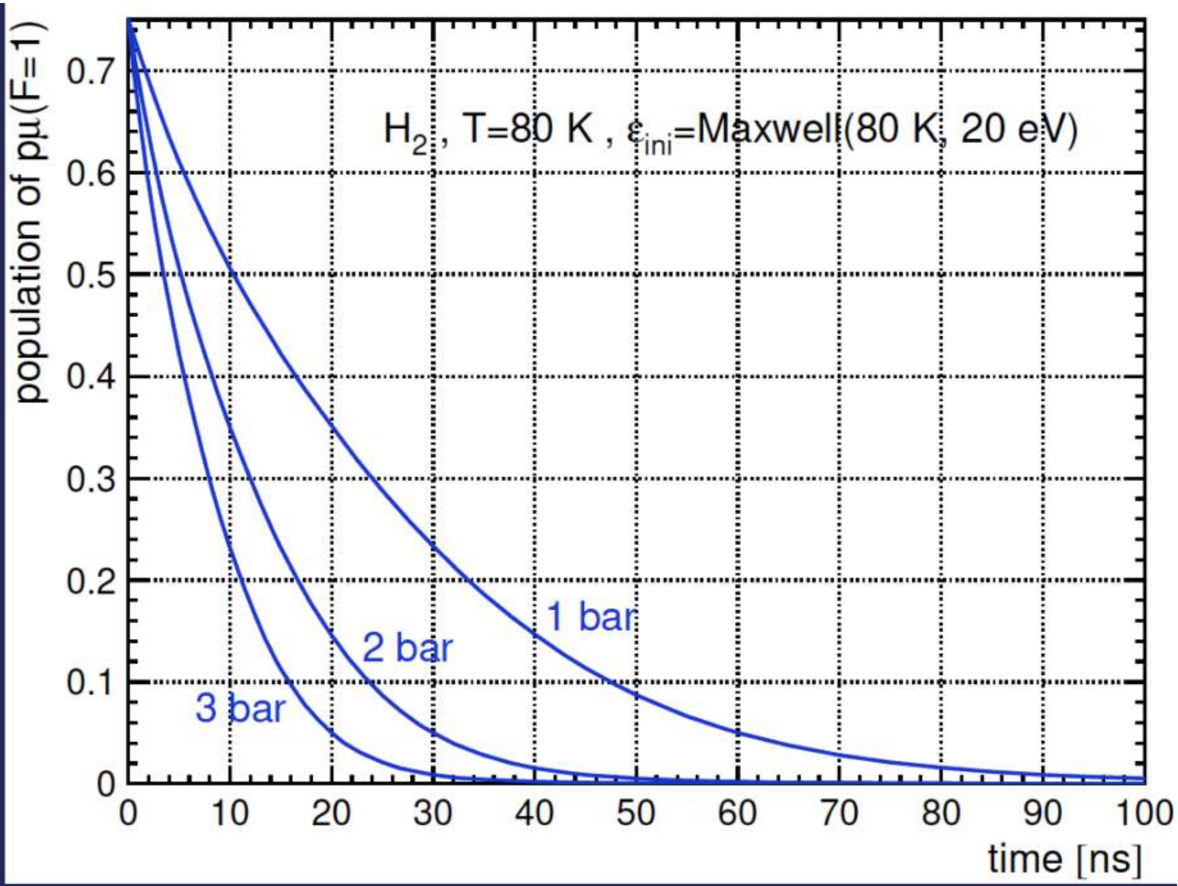
The time evolution of mean kinetic energy, which also illustrates the thermalization time. This indicates the instant of laser ignition when mu-p atoms should be thermalized

Also, this picture shows a mean time of deceleration from about 0.11 eV (meanenergy of mu-p's after the laser excitation and downwards spin flip) to about 0.04 eV (lower energy of a relatively high muon transfer rate to oxygen,).

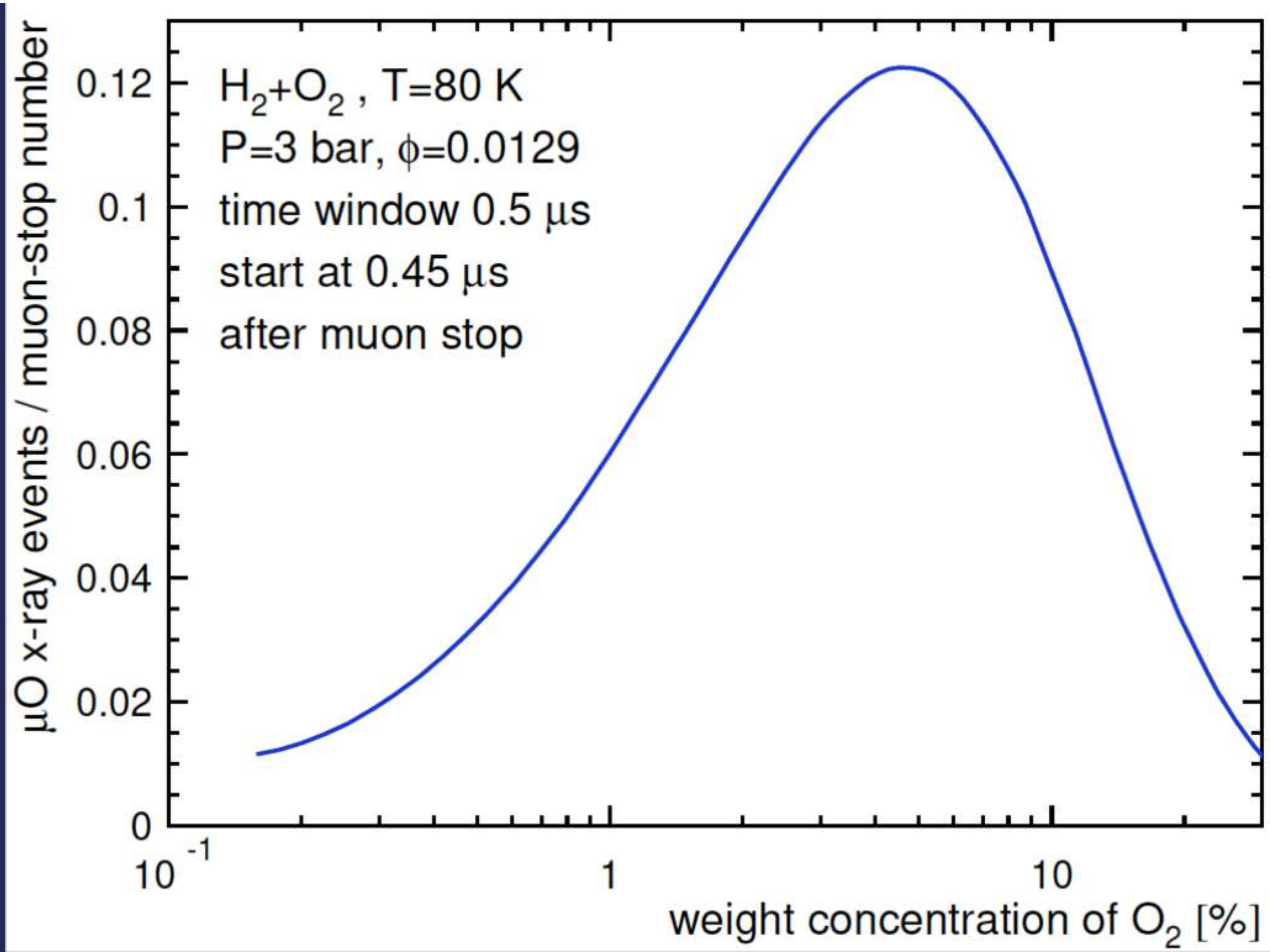
Within this time, the most of muon-transfer events should take place, in order to have a strong signal.

We can increase this signal only by increasing the oxygen concentration, within certain limits.





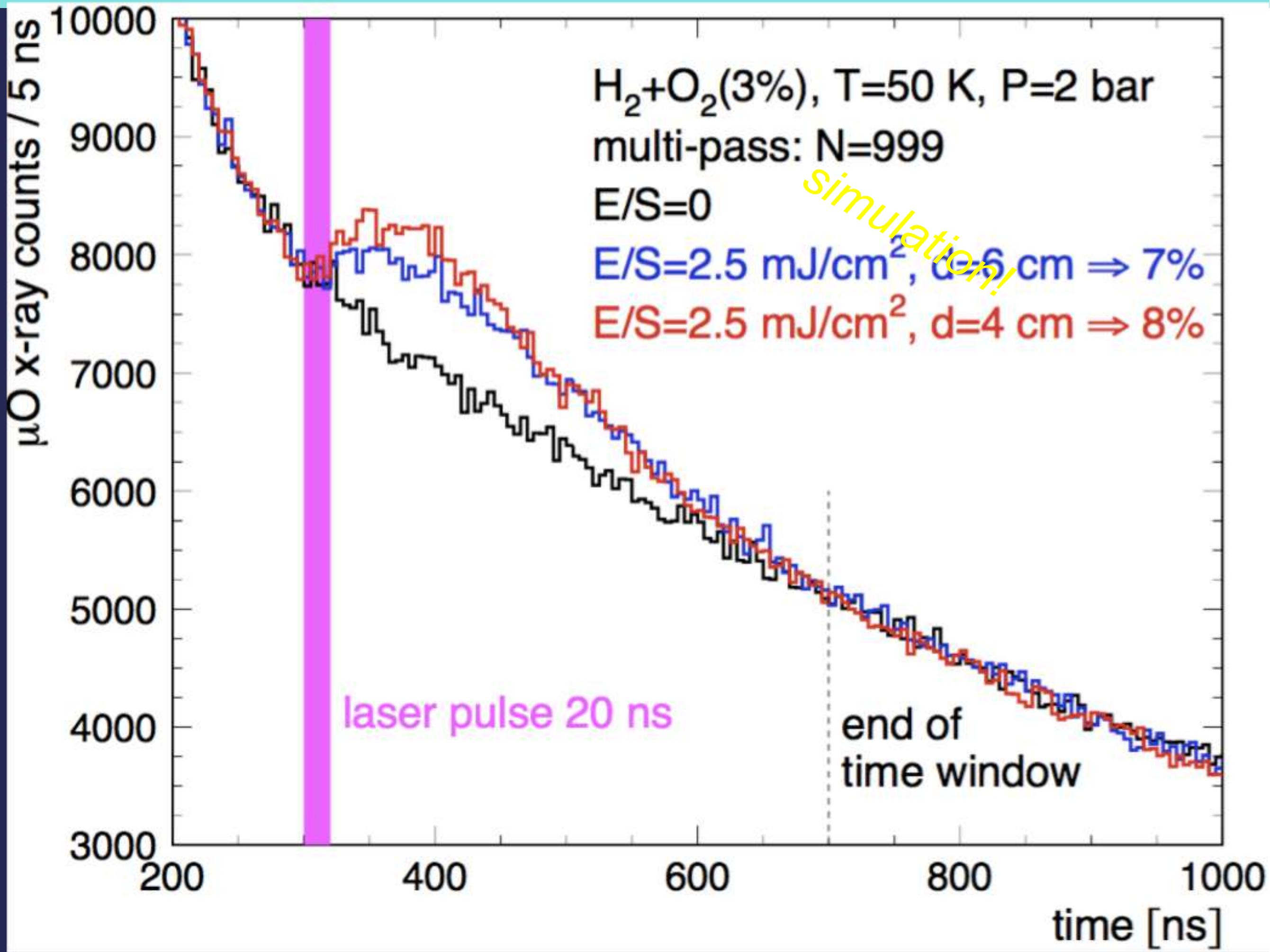
mu-p spin de-excitation versus time.
The de-excitation time informs us about
how long we should wait for
the acceleration of mu-p atom which was
excited by a laser photon.



The plotted functions show a number of existing mu-p's in the time window of 500 ns, divided by the number of muon stops. The beginning of the time window corresponds to the moment of full thermalization. The time windows is approximately equal to the time of laser-field presence in the multipass cavity.

Study of best setup to maximize signal

- Shape and orientation of the optical cavity
- Characteristics of the cryo-target
- Pressure and oxygen concentration



Low pressure !=> New target :

TARGET 2016 vacuum window: 0.8 mm Al
pressure vessel window: 2.84 mm Al
with hodoscope (1mm fibers)
gas: ~cylinder, 6 cm ø 40 cm length
with Ni (100 microns) + Au (10 microns) coating
with multi-layer insulators in front, on sides, on the bottom
lead collimator: wall with hole 3 cm ø

→ **40 BAR @ 300 K**

→ **2 BAR @ 80 K**

TARGET 2018 vacuum window: 1 mm Kapton
pressure vessel window: 1.5 mm fused Silica
no hodoscope
gas: cylinder 2 cm ø 15 cm length
no coating
with multi-layer insulators in front (same of 2016)
lead collimator: wall with hole 2 cm ø

→ **2 BAR @ 80 K**

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New target simulations:

@ 300 K

TARGET 2016 vacuum wind
pressure ve
with hodo
gas: ~cy
with Ni
with m
lead co

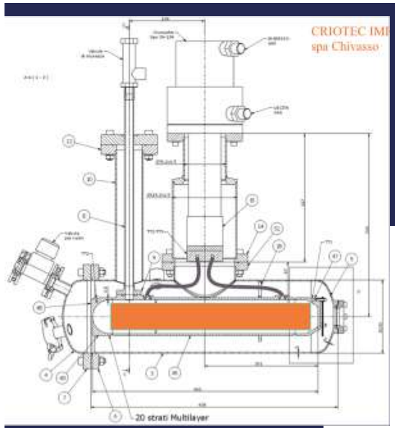
TARGET 2018 vacuum
pressure v
no hodoscop
gas: cylinder 2
no coating
with multi-layer insulato
lead collimator: wall with

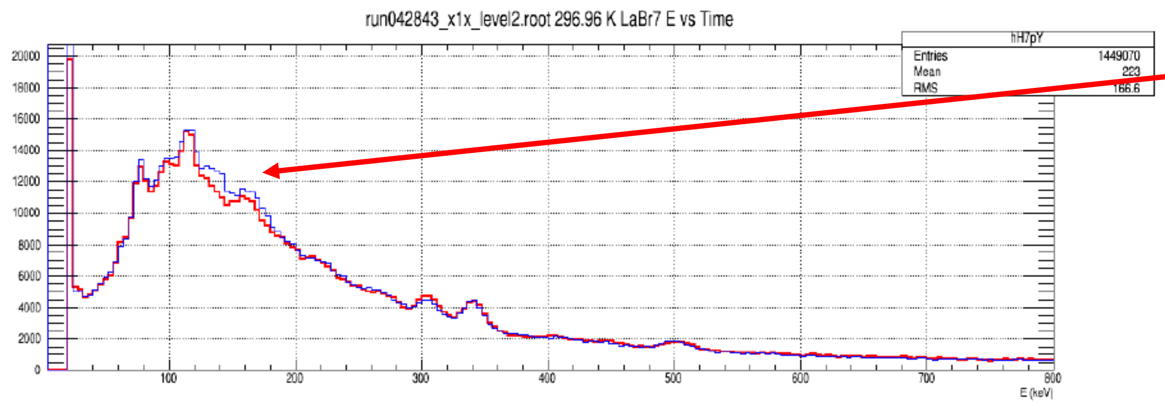
low pressure :

- less stopped muons
- lower momentum = less muons in beam
- & small optical cavity

Need careful optimization
of all elements

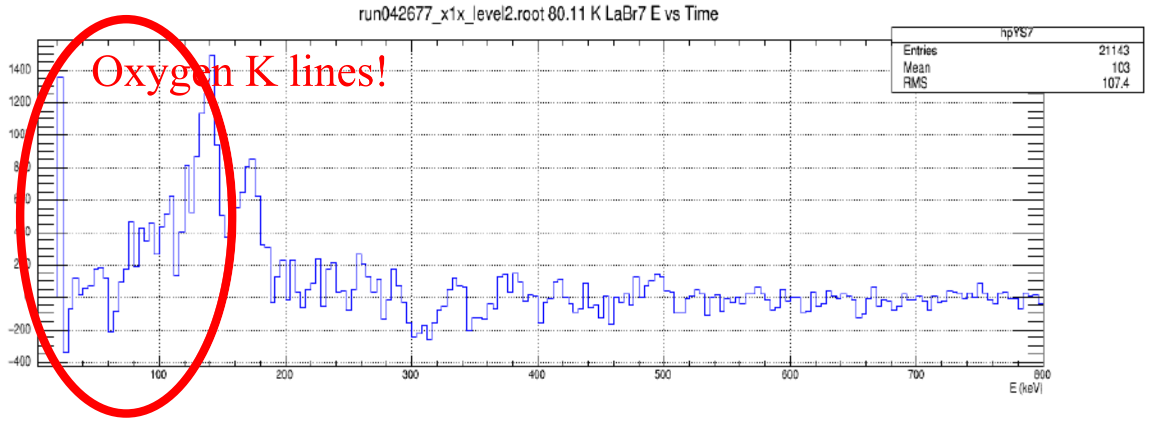
2018 study @low pressure old target



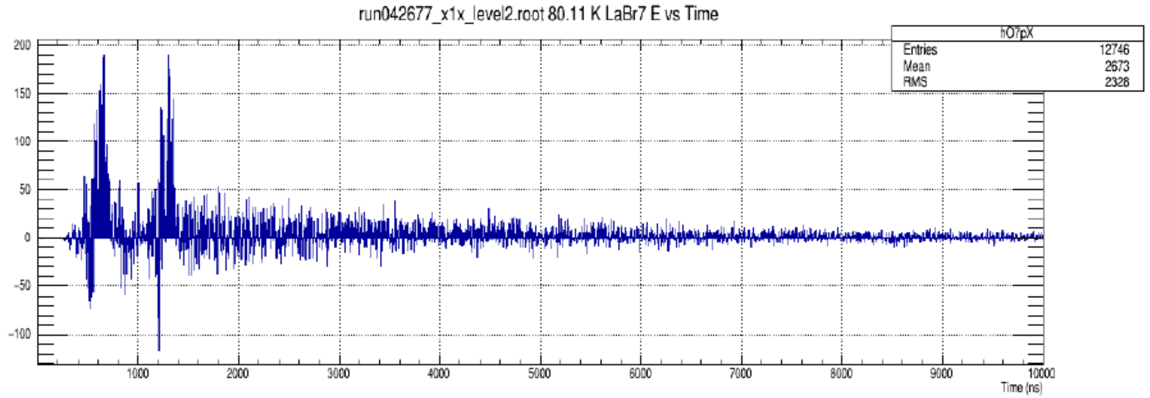


LaBr re-calibrated

Energy spectra
Blue O(3%) mixture
Red pure hydrogen
(3 bar 80 K) (normalized according to acq number of trigger, i.e. time)



Oxygen mixture hydrogen subtracted



Time evolution of oxygen mixture – hydrogen in the energy range 110 – 200 keV

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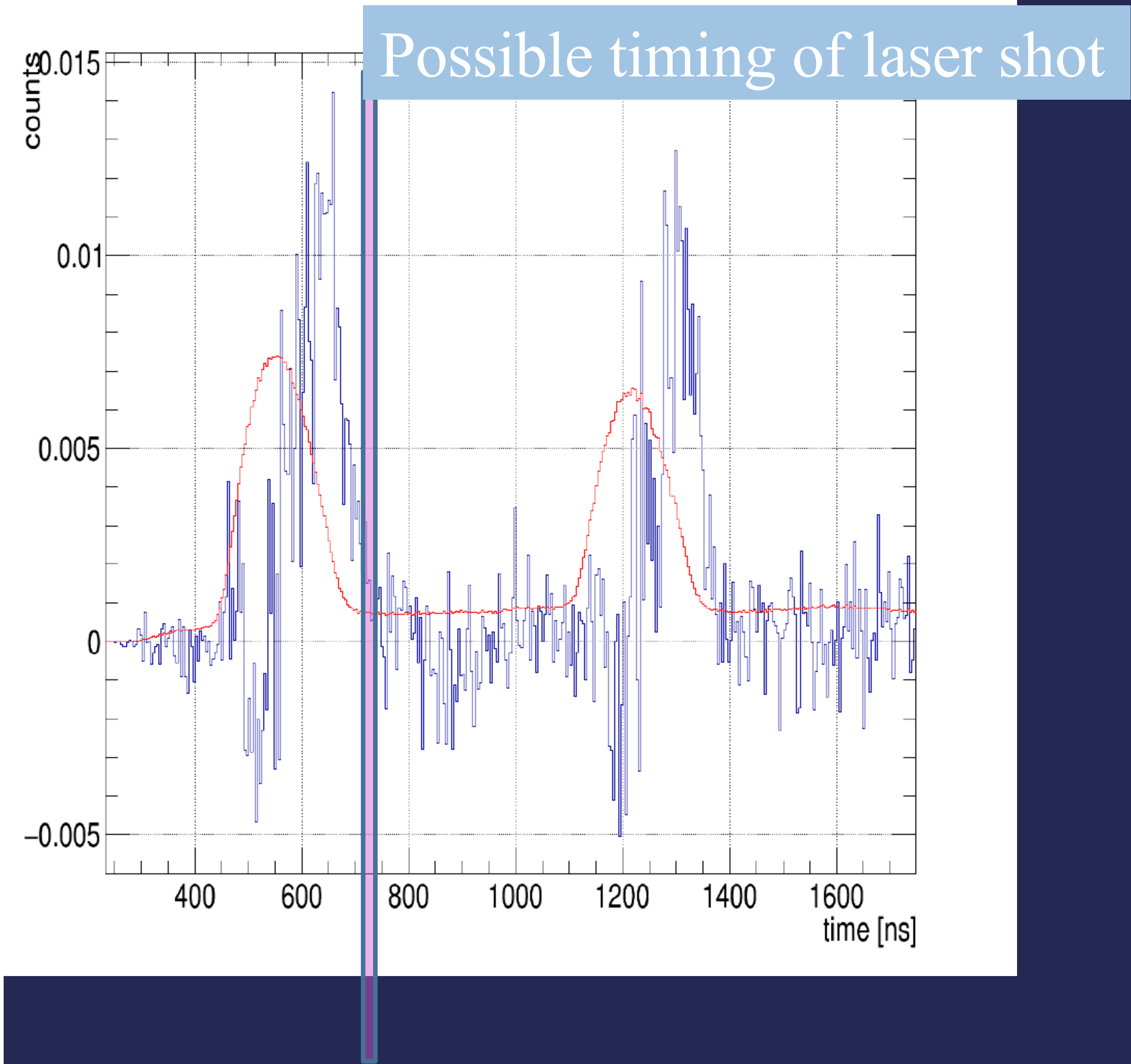

Oxygen lines time evolution
(very fast due to high oxygen concentration).

Comparison with muon beam arrival time (actually prompt X-ray signal).

Oxygen signal is delayed but still overlapping the prompt signal.

First rough evaluation

For 2.2 x 10^4 counts:
Statistical fluctuations: sqrt(2.2 x 10^4) = 148
Expected signal: 2.2 x 10^4 x 0.008 = 176

80 hours = 3.3 days (one frequency measurement). =>

=> Need careful optimization (beam time reduction):

1) Number of detectors (factor 2, 16 LaBr instead of 8)
2) Muon focalization (possible factor 2)
3) Software reconstruction (probably a factor 2, results presented with quick and dirty "quicklook" analysis)
4) laser can be at 8mJ => 4% transition prob (1,6% Signal)
5) optimized target.
6) gas pressure and concentration

NB2: no systematics taken into account, no background measurement
(working at 30/50 Hz but one of the pulses could be used to study the background),
no new target materials and momentum.

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Summary

The FAMU project has made substantial steps towards the

laser spectroscopy measurement of the hyperfine splitting (hfs) in the 1S state of muonic hydrogen

$\Delta E_{hfs}(\mu^{-}p)_{1S}$

preparatory work accomplished :

1. *first measurement* of the temperature dependent muon transfer rate to Oxygen, FAMU method certified!
1. *innovative* and powerful laser system under construction
2. *optimized intense pulsed beam target and optical system*
3. *best detectors* for energy and time observation

expect to initiate the spectroscopic measurements in 2019.

Than you for your attention

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