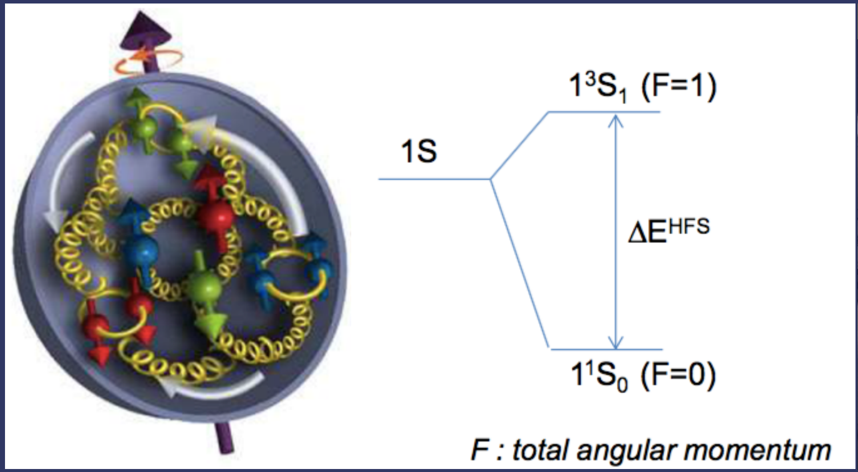
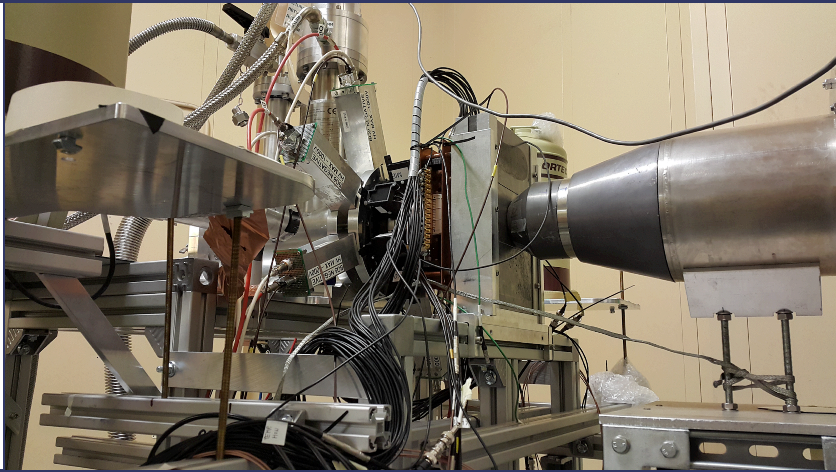
High precision spectroscopy in muonic hydrogen

Towards the measurement of the hyperfine transition in muonic hydrogen $\Delta E_{HFS}(\mu p)_{1S}$

Andrea Vacchi for the FAMU Collaboration





Nucleon Spin Structure at Low Q: A Hyperfine View
ECT* - European Centre for Theoretical Studies in Nuclear Physics
July 2-6, 2018
Trento, Italy

Istituto Nazionale di Fisica Nucleare

FAMU Collaboration

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"The RIKEN-RAL Muon Facility"
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OUTLINE

- Background & motivations
- FAMU's method to measure the hfs
- FAMU's path 2014-2018
- 2016 muon transfer rate measurements between 100 and 300 K
- 2018 low pressure data - rates evaluation
- FAMU key ingredients optimization
  - High efficiency multi-pass optical cavity
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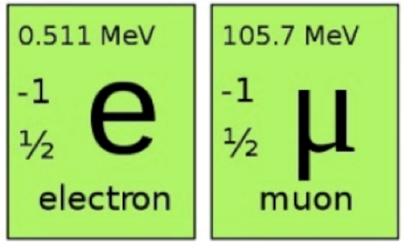
Muonic hydrogen

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

$$m_\mu = 207 m_e$$

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



$$m\mu/me \approx 2x10^2$$

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

muonic hydrogen

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

-Provide ***very high accuracy tests of quantum electrodynamics and the theory of electromagnetic bound states.***

-Moreover, ***the values of the fundamental physical constants (particle masses, fine structure constant, proton charge radius, etc.) can be determined more precisely***.

and how universal is (lepton) universality?

- Very precise spectroscopic measurements of hyperfine splitting offer a way for testing quantum electrodynamics (QED).
- Finding discrepancies between QED and experimental observations
- Could point towards physics beyond the Standard Model of particle physics.
- Verify the theoretical predictions of the nature of quantum mechanics in very strong fields

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

New independent high precision measurements on μ^-p are needed.

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**

- **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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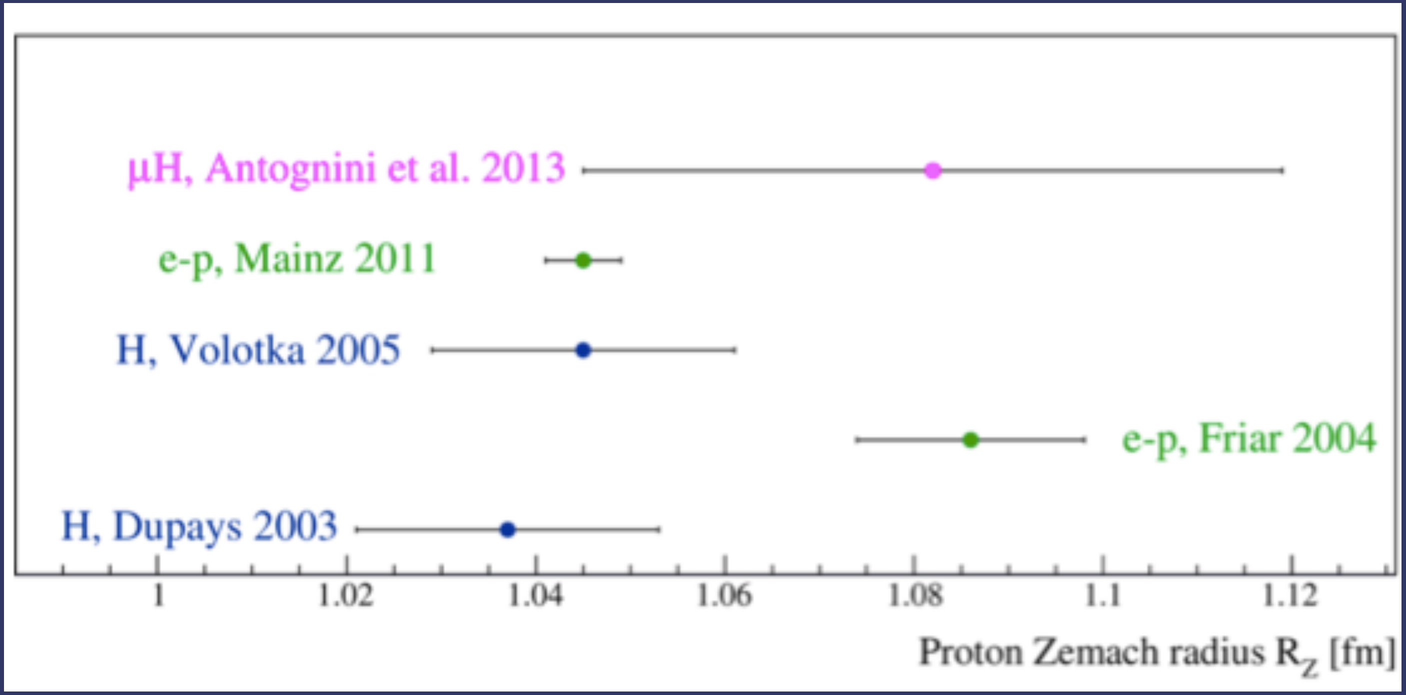
current status of $(\mu^- p)^{1S}_{hfs}$

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)	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.

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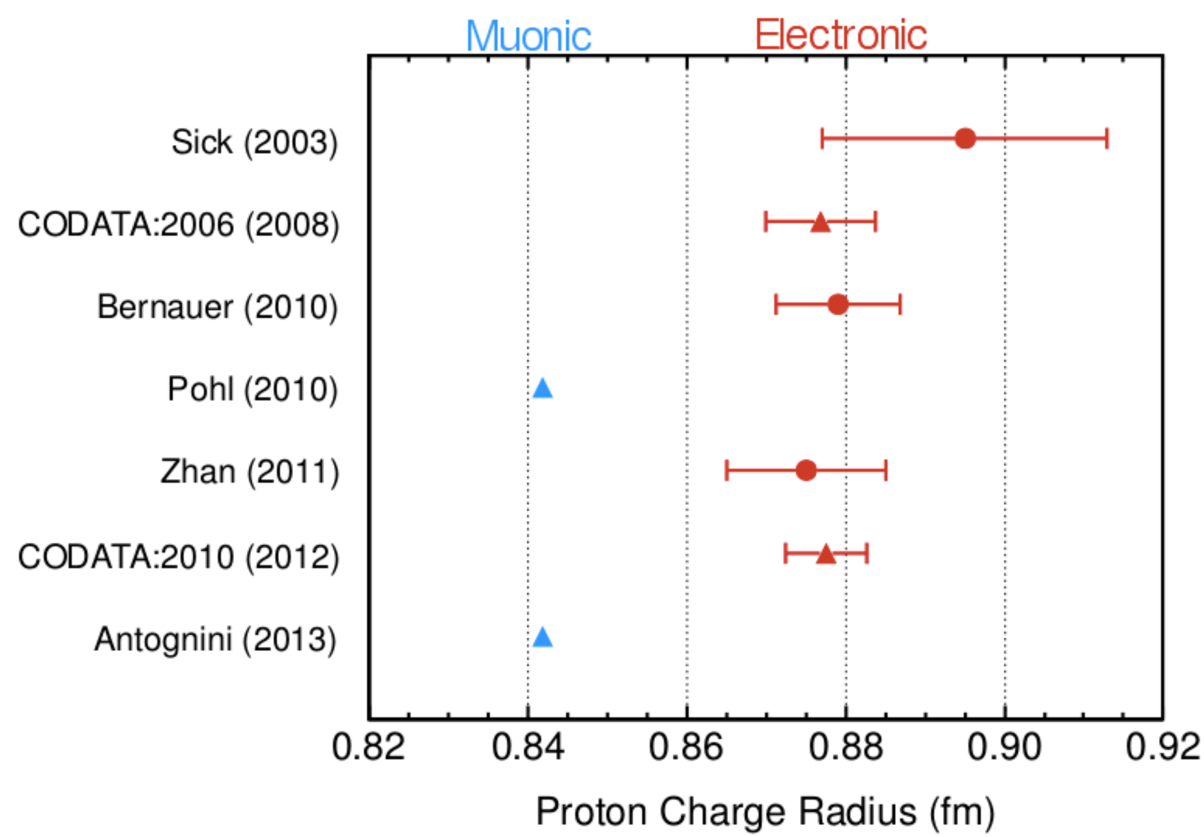
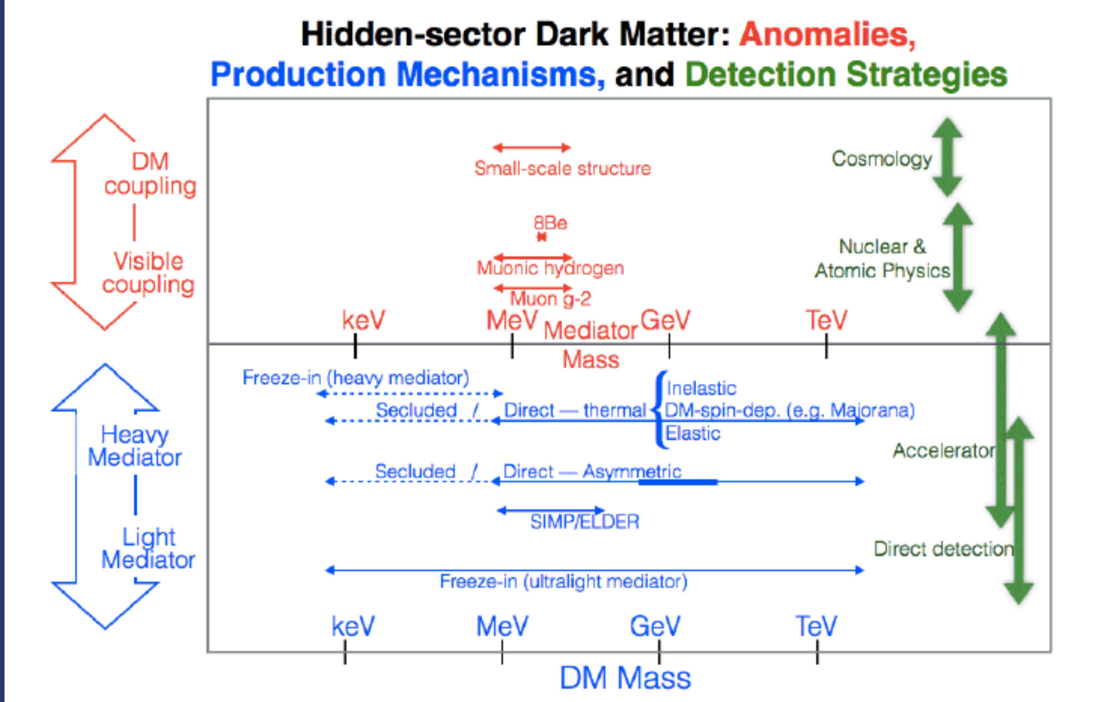
The **proton charge radius** can be extracted for each lepton probe from two independent methods



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**.

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 3 independent experiments plan to measure RZ

- Measure the Hyperfine Splitting (HFS) of $\mu^{-}p$ with accuracy 10^{-5}
- Extract the Zemach radius of the proton with an accuracy of better than 1%

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a 25 years old idea

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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Dipartimento di Fisica dell'Università di Trieste, via Valerio 2, Trieste 34017, Italy and Sezione INFN di Trieste, Area di Ricerca, Padriciano 99, Trieste 34012, Italy

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

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

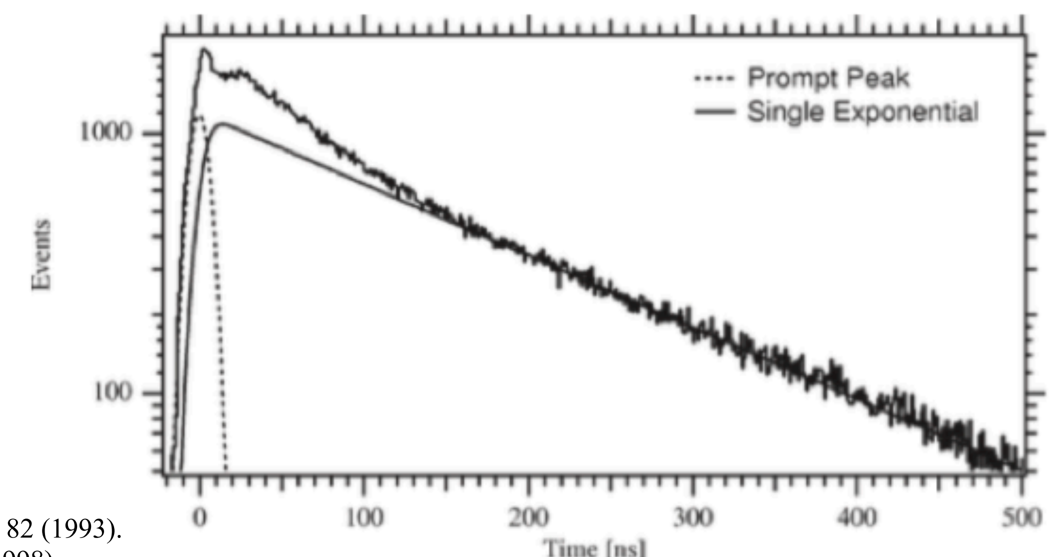
1. Introduction

The theoretical expression for the hyperfine splitting

Exploits the ***energy dependence of the muon transfer*** from muonic hydrogen to higher-Z gas is to detect the spin flip transition in μp.

- 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.



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

Figure 2. Background subtracted time distribution of muonic oxygen μO(2–1) 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.

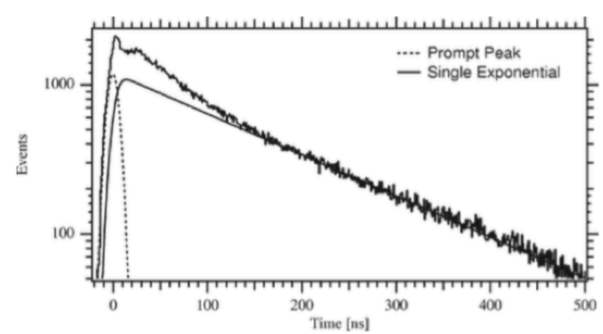
Exploits the ***energy dependence of the muon transfer*** from muonic hydrogen to higher-Z gas is to detect the spin flip transition in μp.

Adding small quantities of oxygen to hydrogen one can observe the number of hpf transitions which take place from the muon-transfer events this by measuring the time distribution of the oxygen characteristic X-rays of the added gas.

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

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

A. Werthmüller et al. / Muon transfer to oxygen 3



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Laser spectroscopy for ΔE^{HFS}_{1S}

HOW ?

Method relying on a two-steps process

excited μp* with n >14

are formed in a hydrogen gas target,
in subsequent collisions with H2 molecules,
the μp de-excite to the

$\mu^{-}p(\uparrow\downarrow)$

thermalized μp in the (1S) F =0 state.

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first step

tunable laser pulse

Converts the spin state of the ($^-\mu$ p) atoms from $^1S_0$ **to** $^3S_1$

μ^-p(↑↓) absorbs a photon @ ***resonance wavelength***

$\lambda_0 = hc/\Delta E^{1S}_{HFS}$ ~ 6.8 μ ~ 0.183 eV

μ^-p(↑↓) → μ^-p(↑↑)

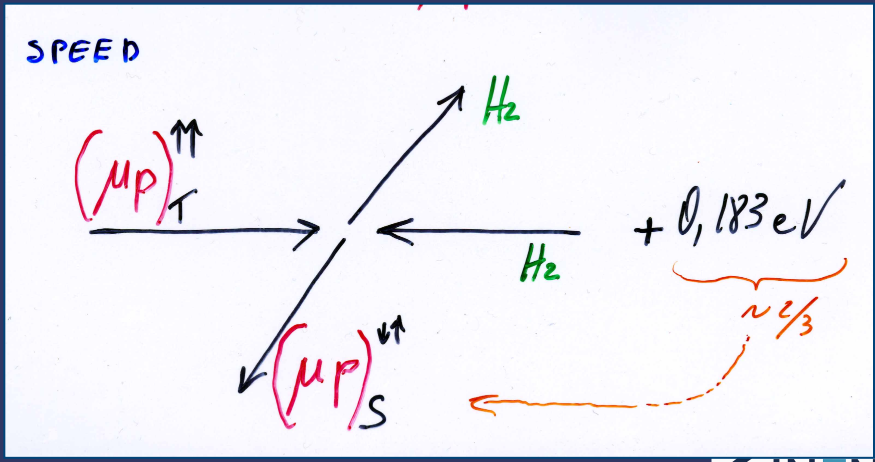
second-step
energy dependent μ transfer

$\mu^- p(\uparrow\uparrow)$ $^3S_1$ atoms are collisionally de-excited and the transition energy is converted into additional kinetic energy of the μp system

$\mu^- p(\uparrow\downarrow)$ $^1S_0$ and accelerated by ~ 0.12 eV $\sim 2/3\ \Delta E^{HFS}_{1S}$

Energy-dependent muon transfer rates change the time distribution of the cascade X-ray events from $\mu^- Z^{**}$

λ_0 is recognized by maximal response in the time distribution



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

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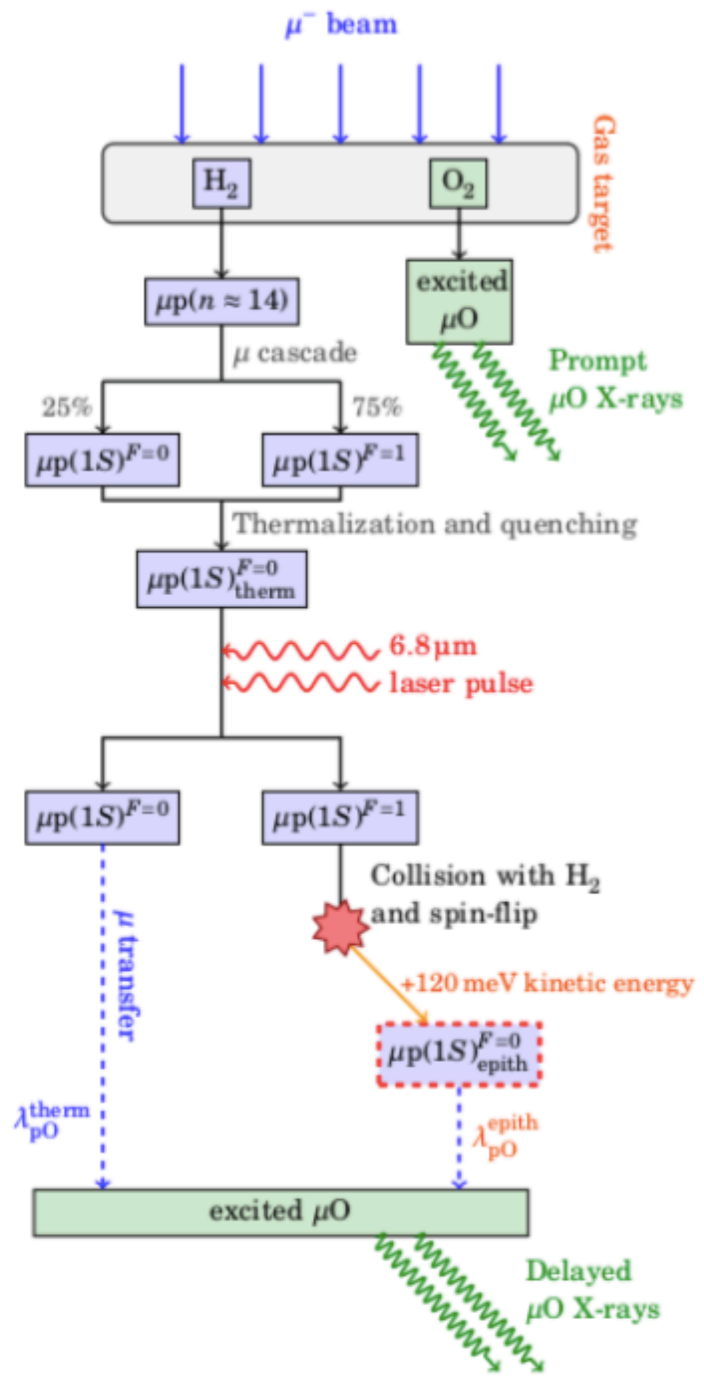
FAMU Principle of operation

μp formation =>>

μp termalization =>>

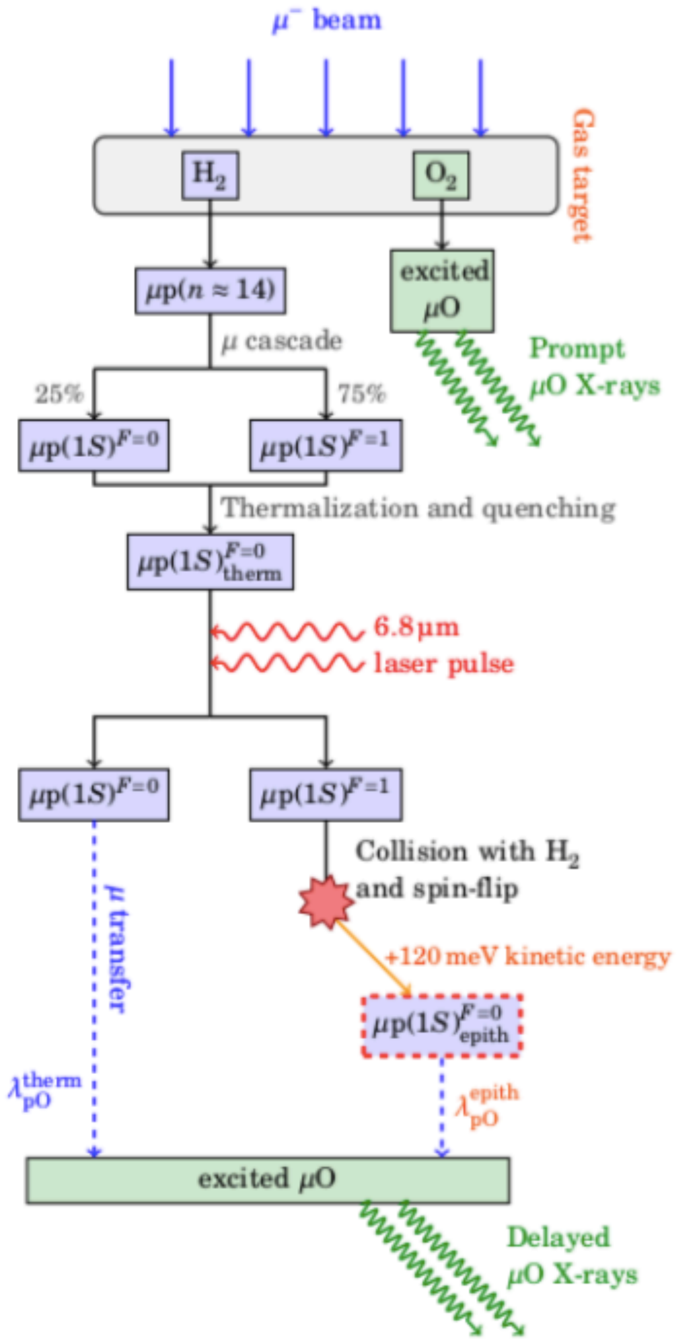


Lay-Out of the experiment

laser exitation F=0 F=1 =>>

μ enhanced transfer to O =>>

μO X-ray time distribution =>



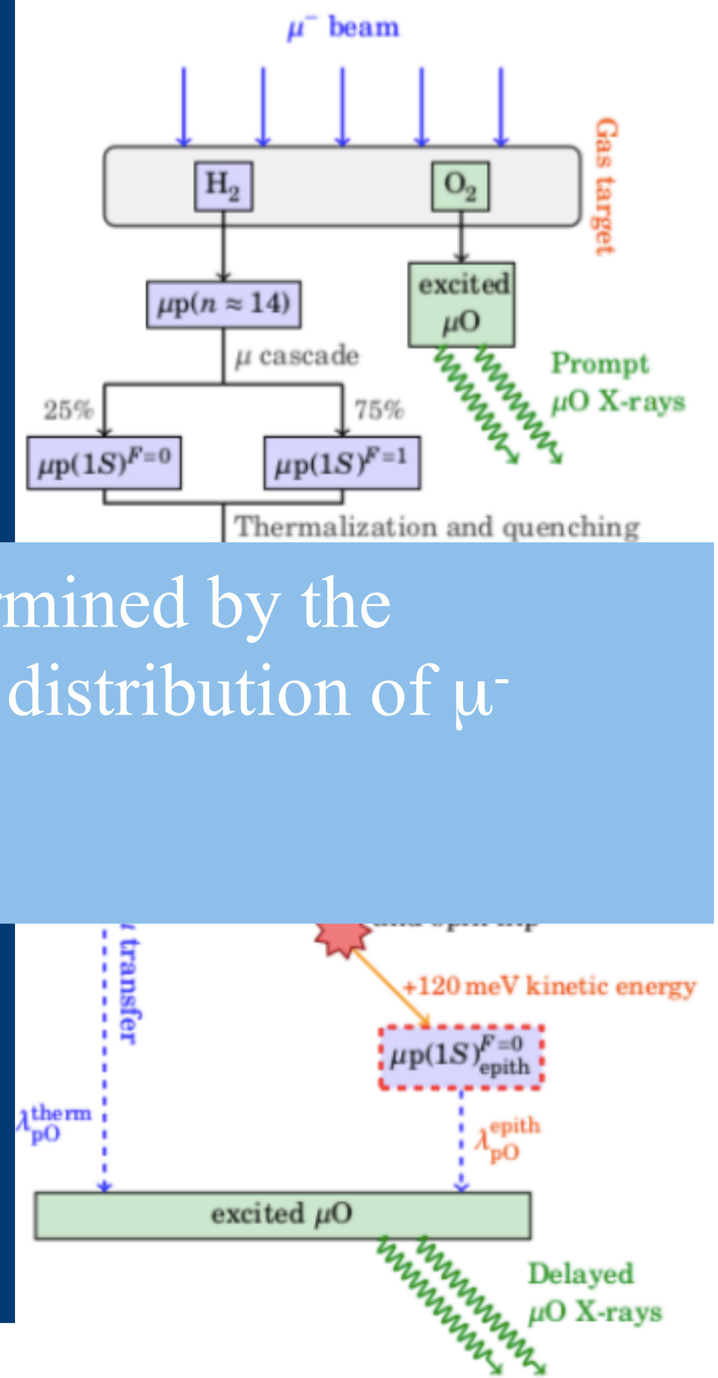
Lay-Out of the experiment

laser exitatio

λ_0 resonance is determined by the maximizing the time distribution of μ^- transferred events.

μ enhanced transfer to O =>>

μO X-ray time distribution =>



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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 new studies are on going
    - optimal optic cavity design
    - new cryogenic gas target design study and simulation
    - muon beam optimization

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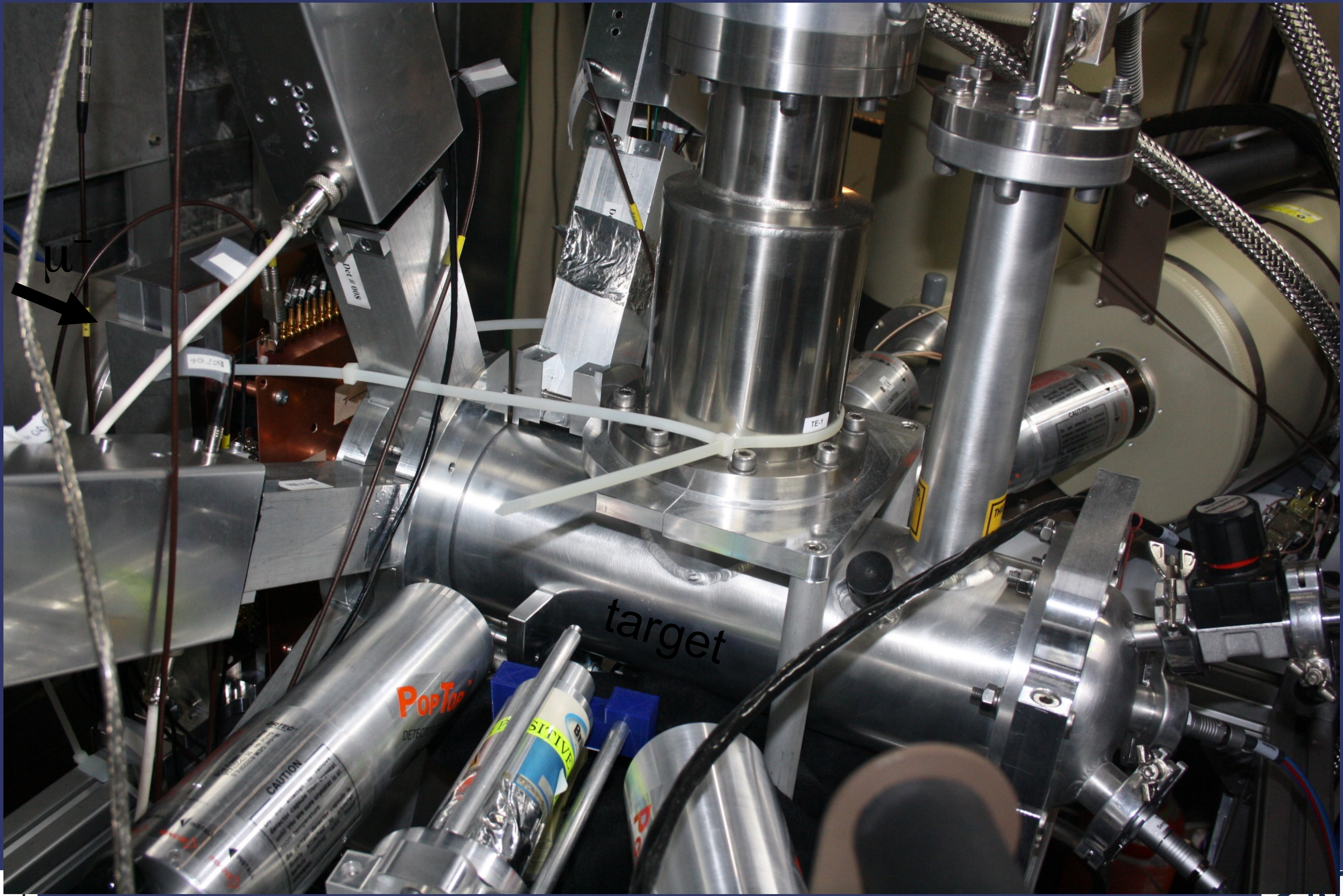
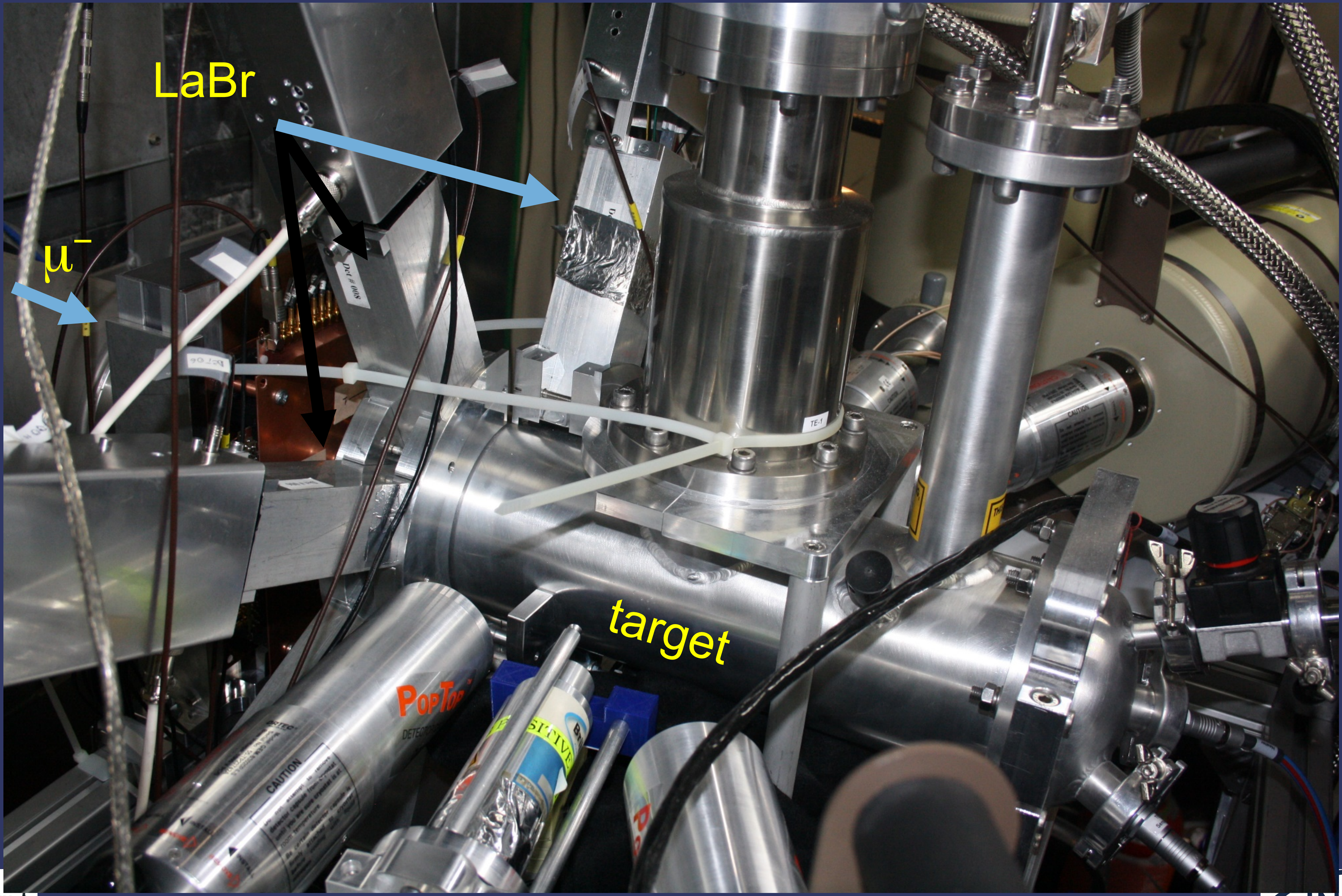
2016: experimental setup



2016: experimental setup



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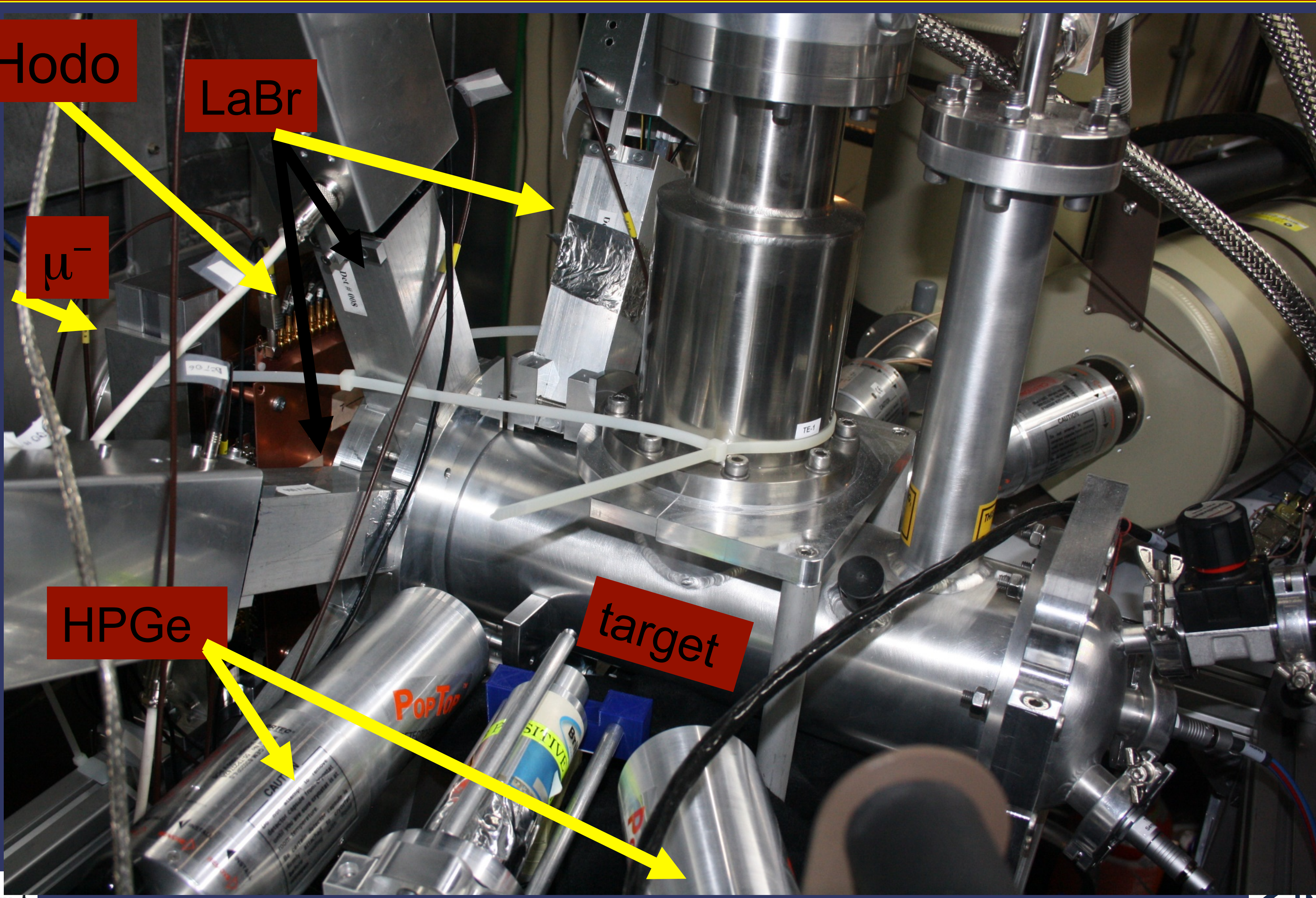


2016: transfer rate measurement

Steps:

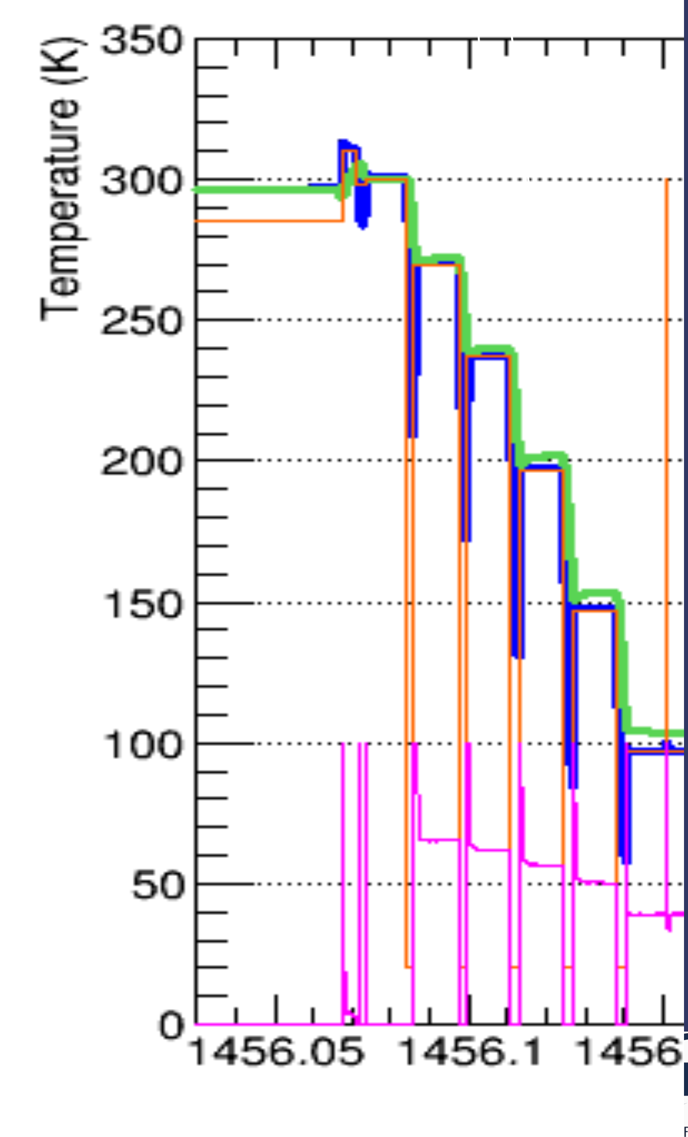
1) fix a target temperature (i.e. mean kinetic energy

2) produce μp and wait for thermalization

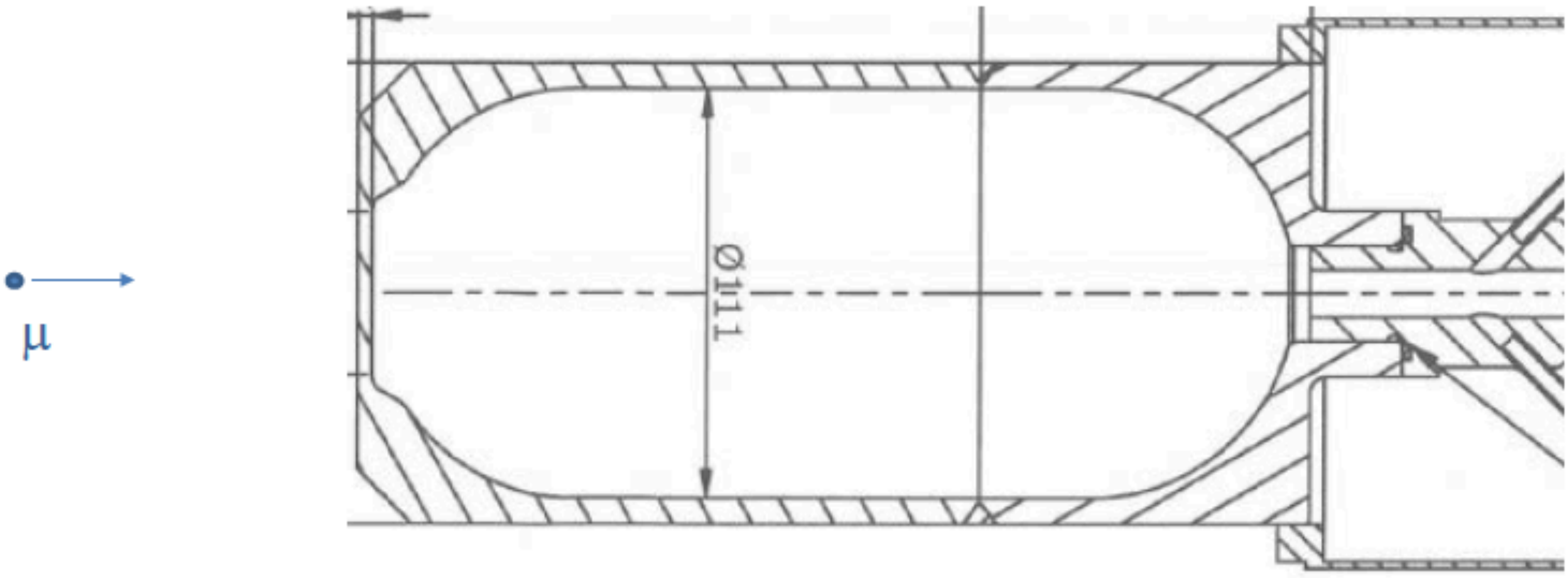
3) study time evolution of Oxygen X-rays

4) repeat with different temperature

three hours

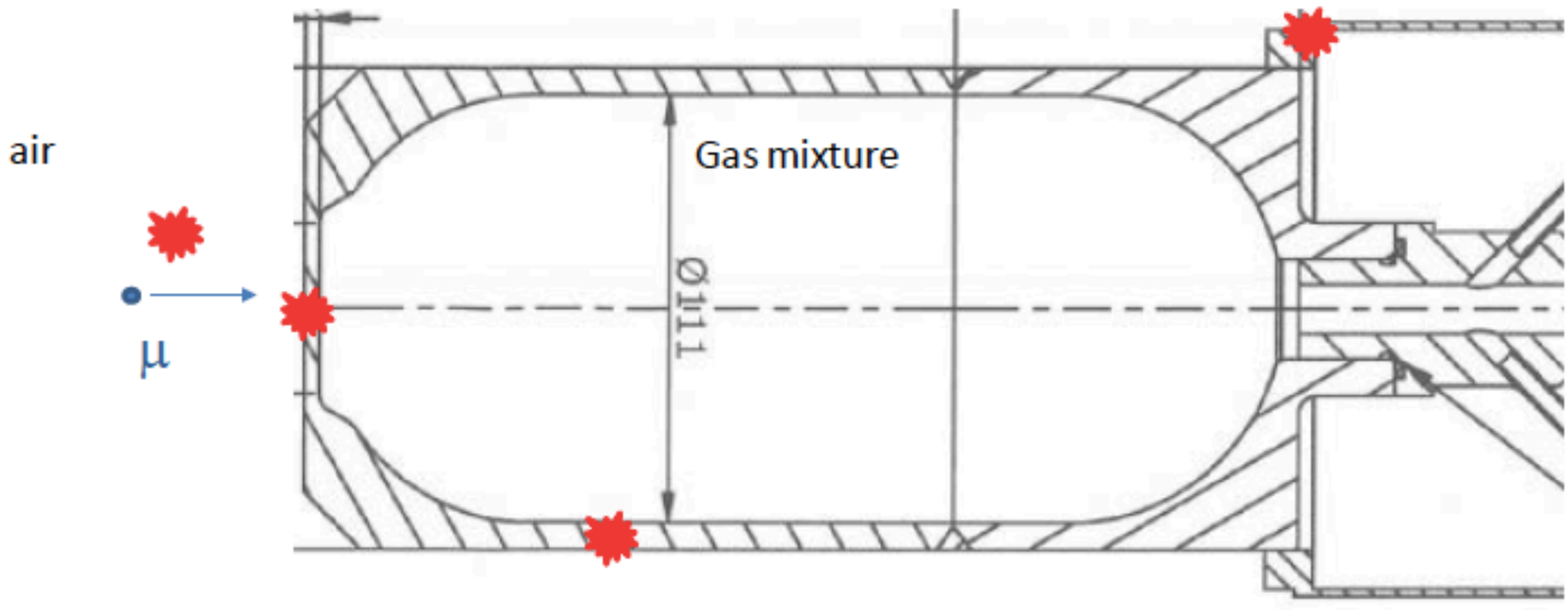


μ fate in our setup (300K, 40 atm)



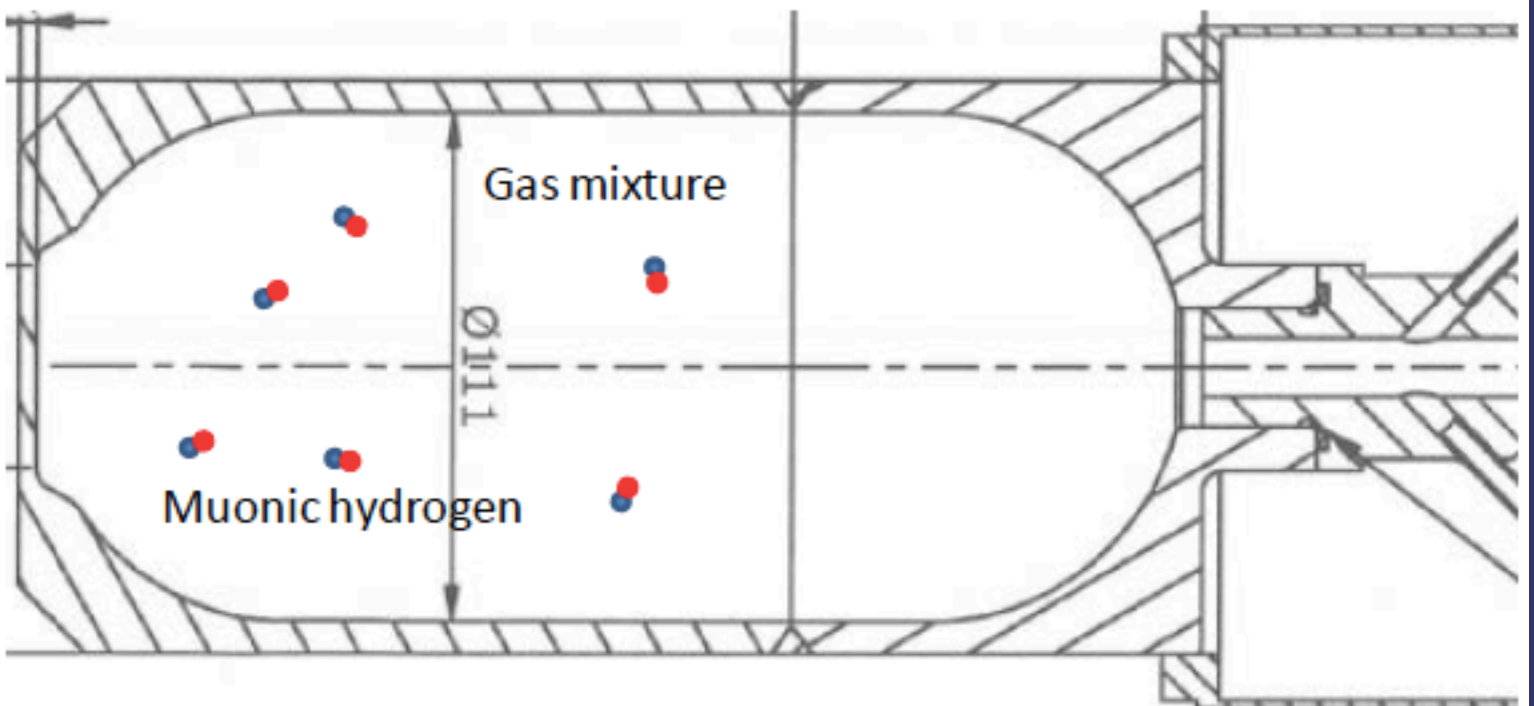
μ fate in our setup (300K, 40 atm)

Muons are capture by target vessel materials: X-ray prompt emission



μ fate in our setup (300K, 40 atm)

Muons are capture by hydrogen: muonic hydrogen forms inside the target



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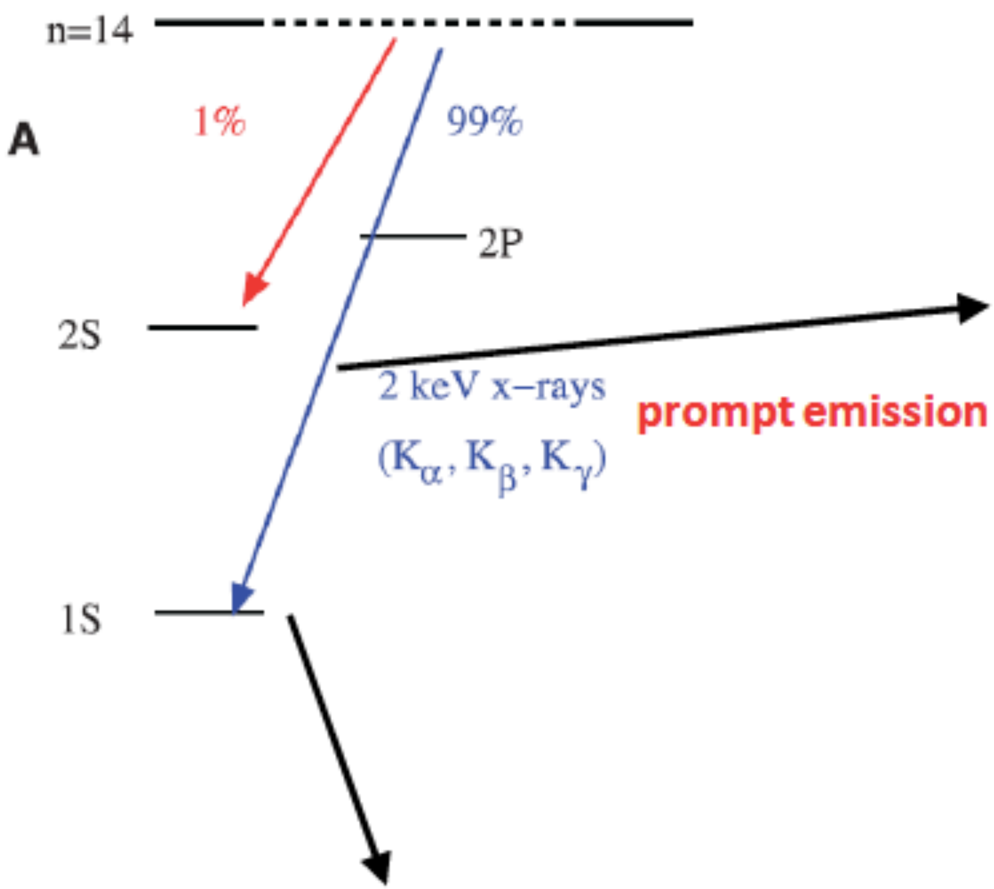


de-exciting from n=14 to ground level:

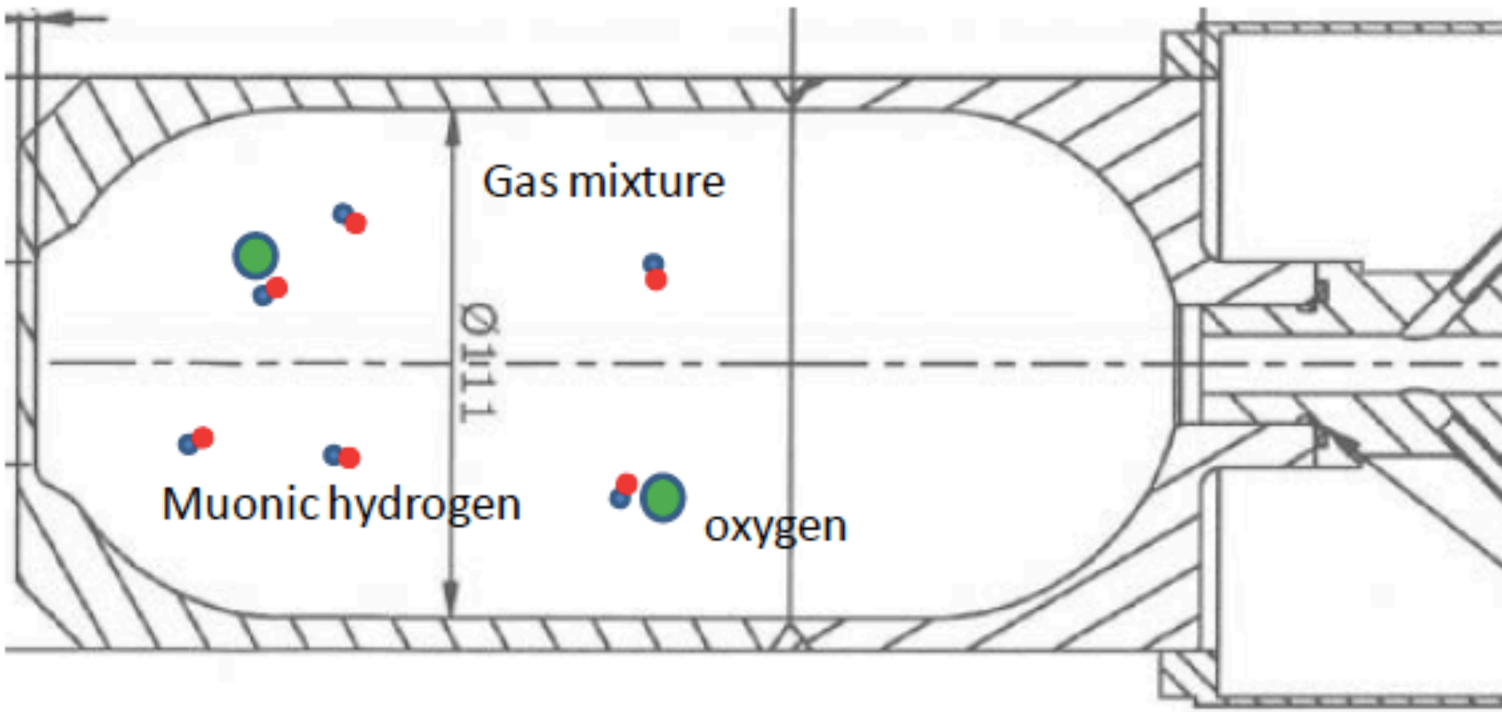
$$E_k \approx O(eV)$$

thermalization time O(tens of ns)

3/4 triplets, 1/4 singlets
de-excitation in O(10 ns)

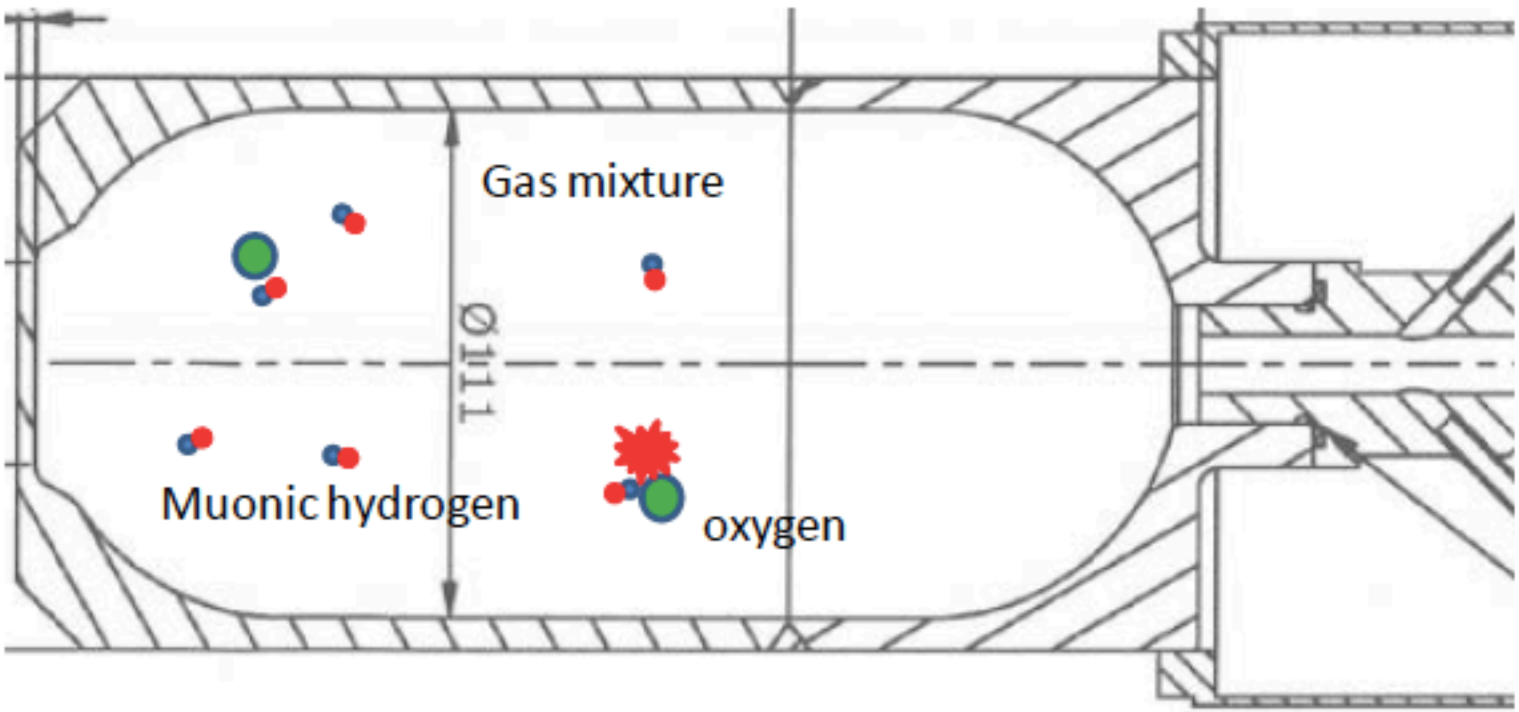
μ fate in our setup (300K, 40 atm)

Muons are transferred from muonic hydrogen to other elements



μ fate in our setup (300K, 40 atm)

Muons are transferred from muonic hydrogen to other elements: delayed emission



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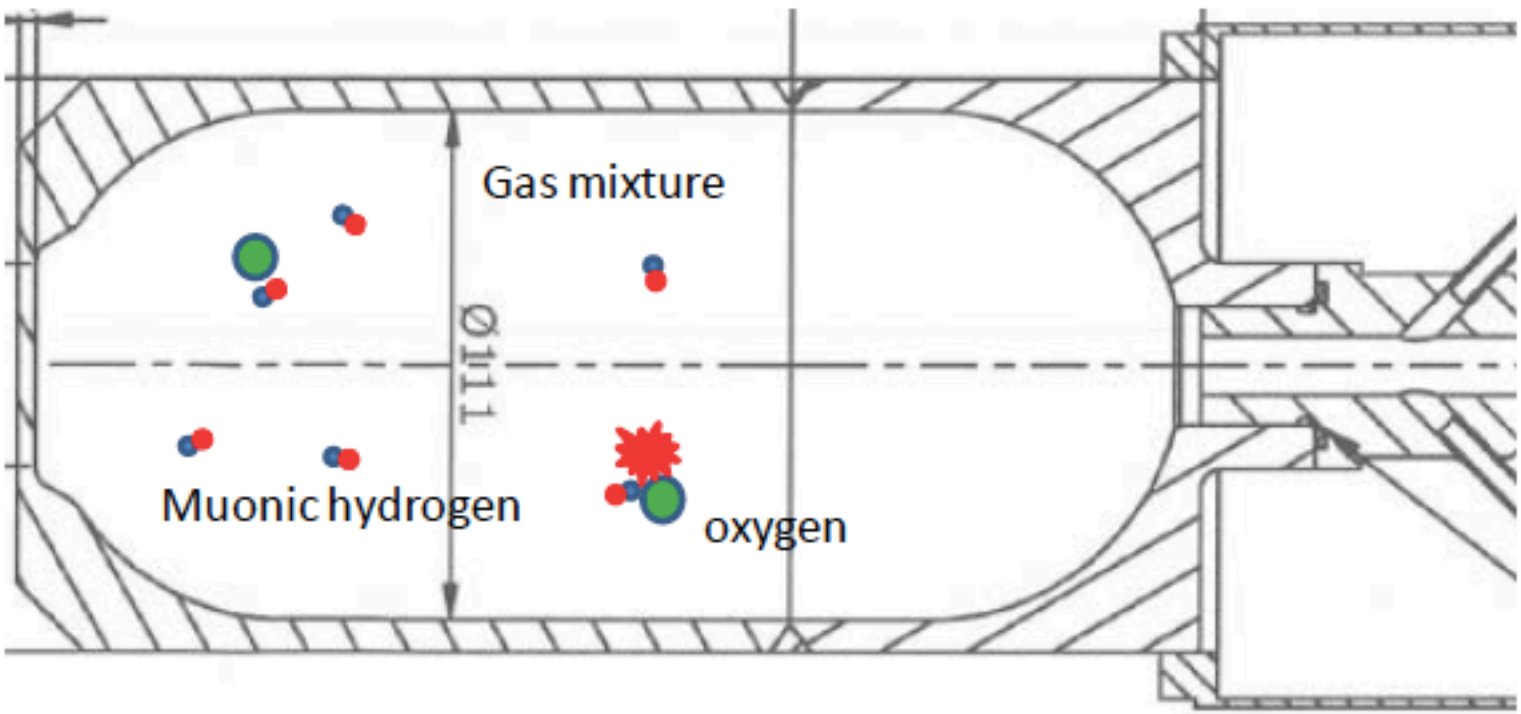
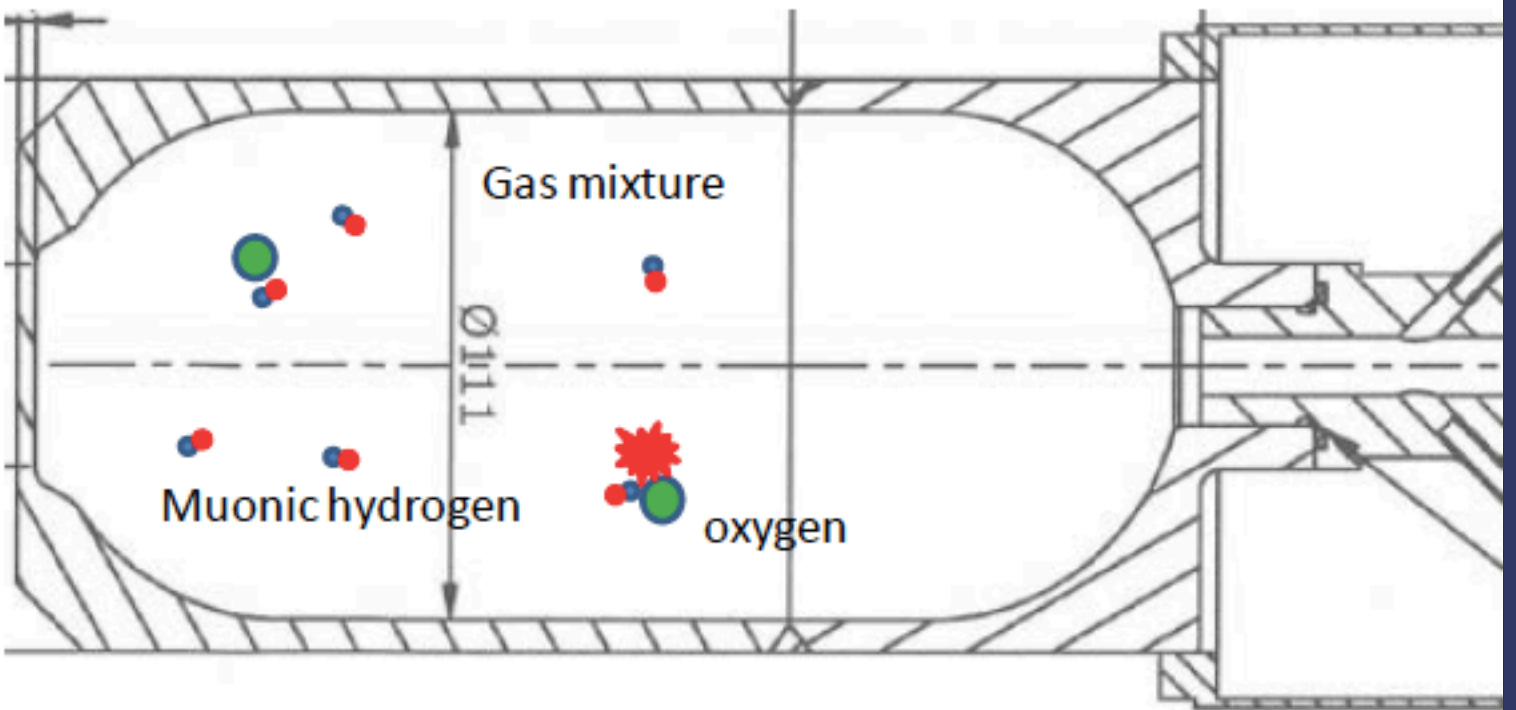


Transfer speed depends on: gas density (i.e. pressure), contaminant concentration, and muonic hydrogen kinetic energy

μ fate in our setup (300K, 40 atm)

Muons are transferred from muonic hydrogen to other elements: delayed emission



Transfer speed depends on: gas density (i.e. pressure), contaminant concentration, and muonic hydrogen kinetic energy
hence fast and strong signal until the thermalization of mu-p

In 2014 so fast that the delayed emission almost completely overlap the prompt emission

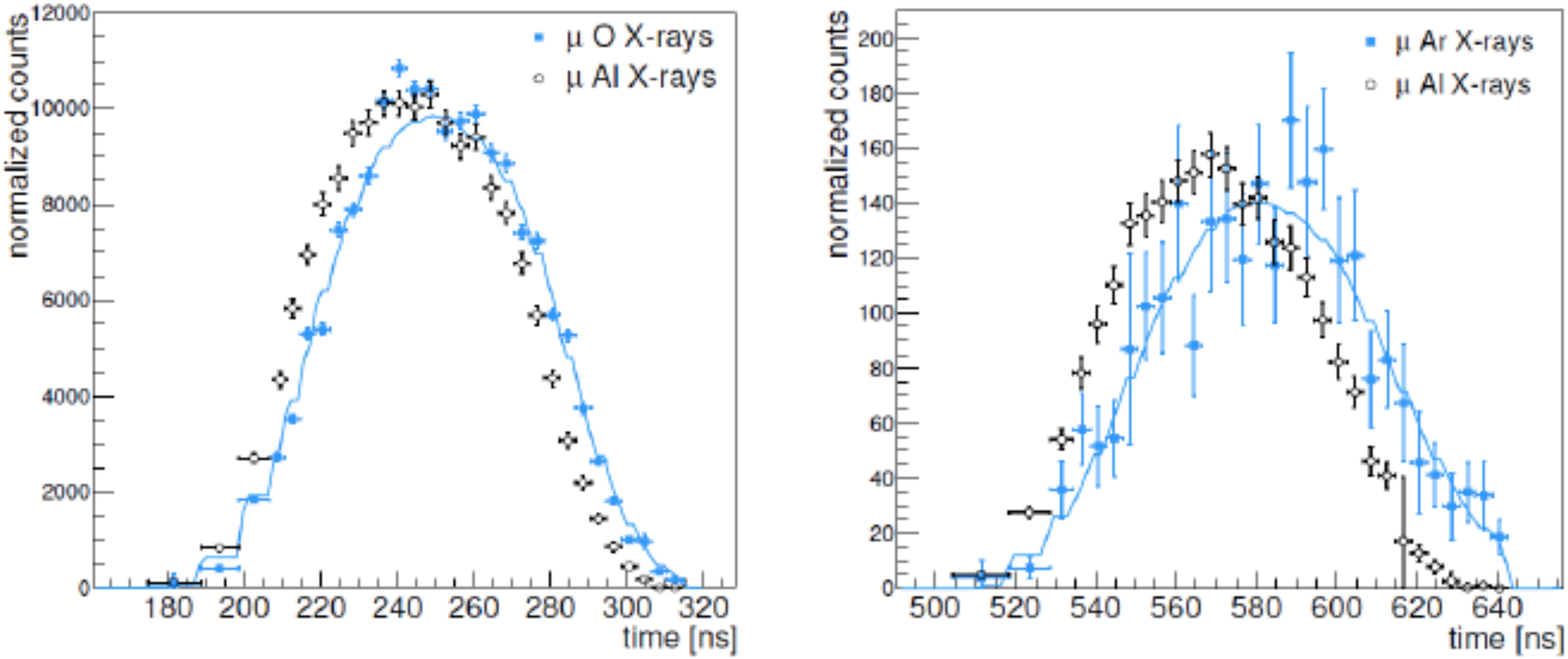
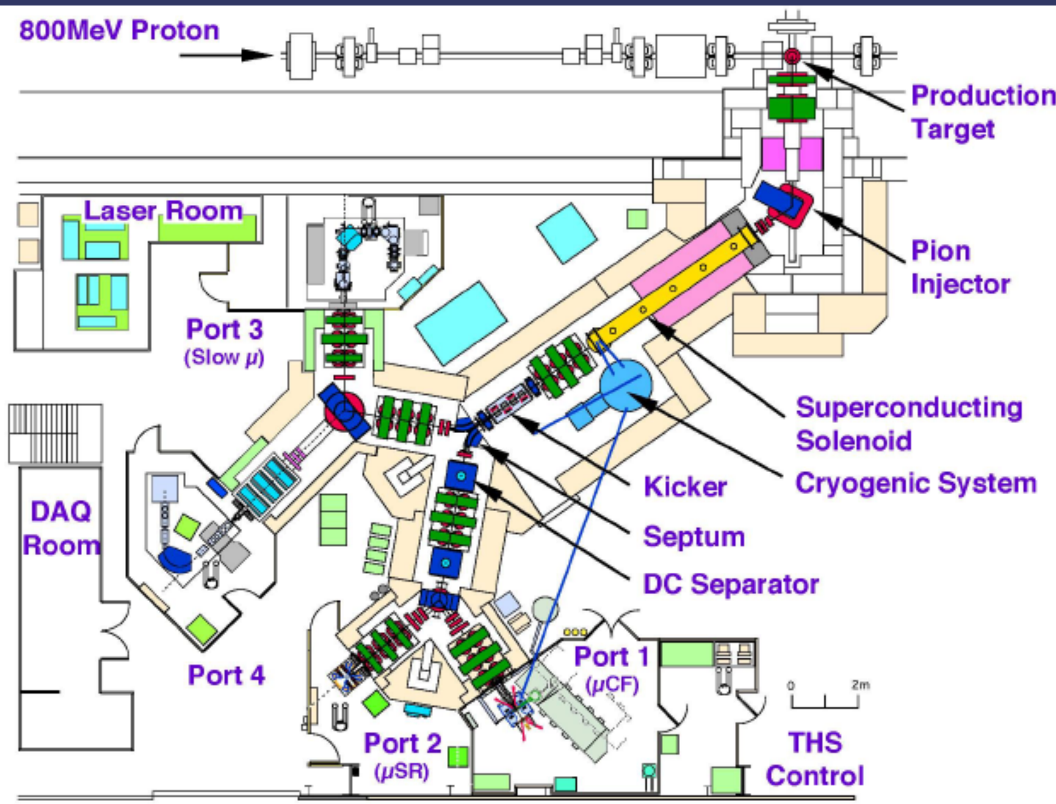
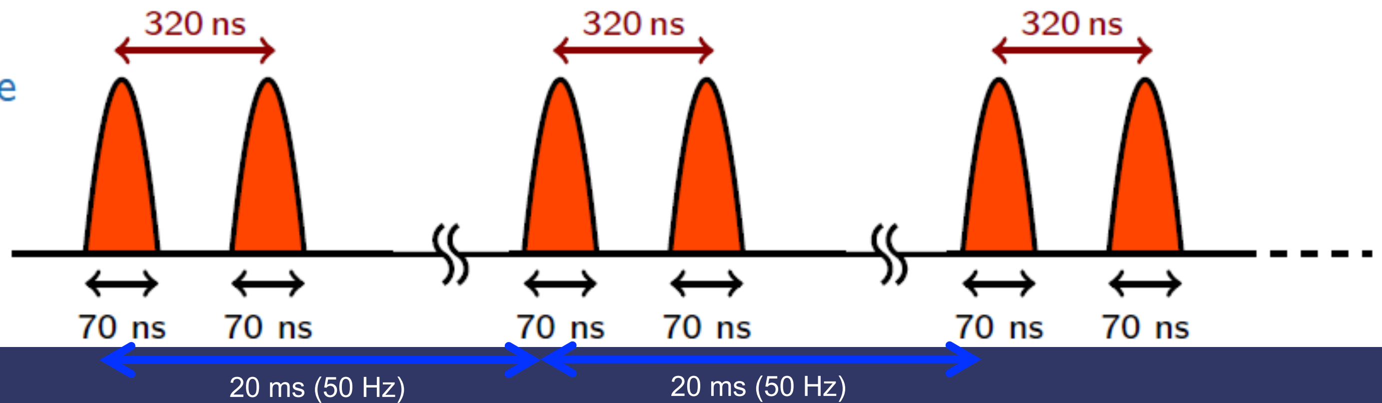


Figure 1. Left panel: time evolution of X-rays emission from aluminium and oxygen. Right panel: time evolution of X-rays emission from aluminium and argon. Lines are a fit to the oxygen and argon distributions, see text.

High intensity muon beam



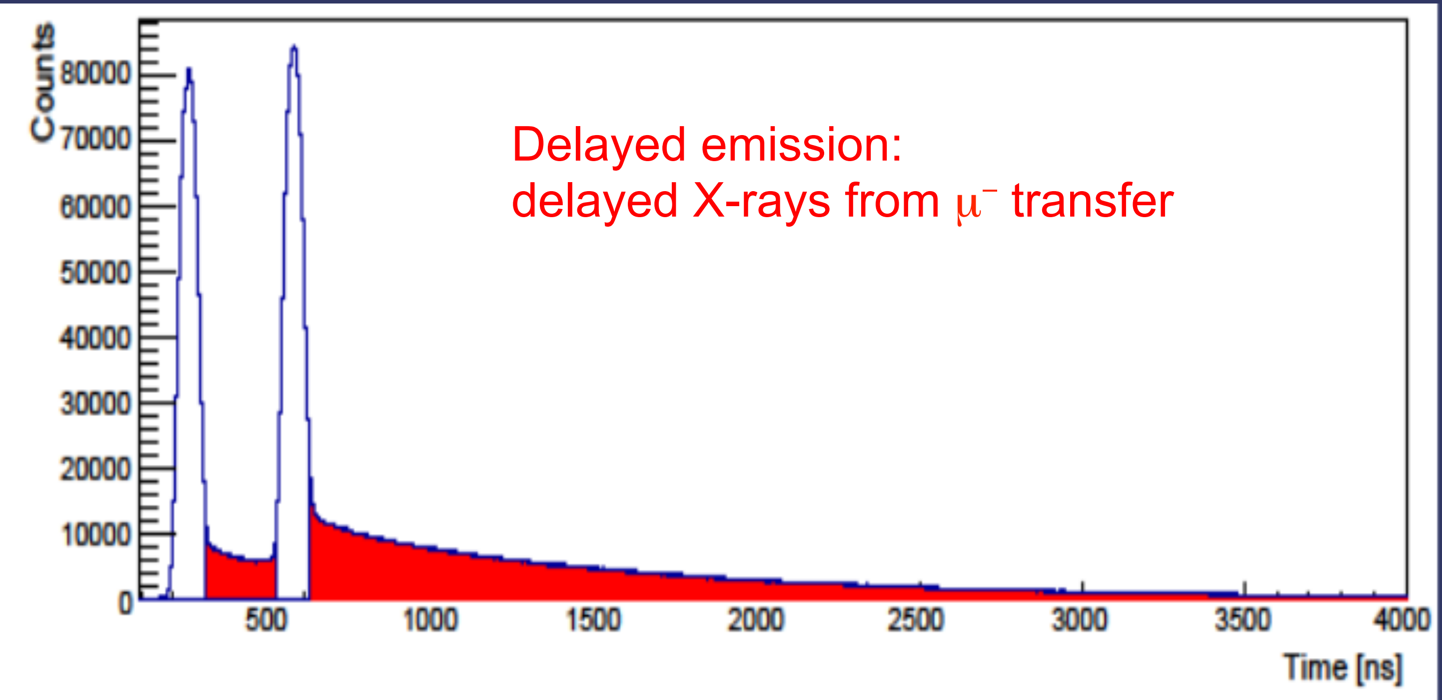
Beam time structure

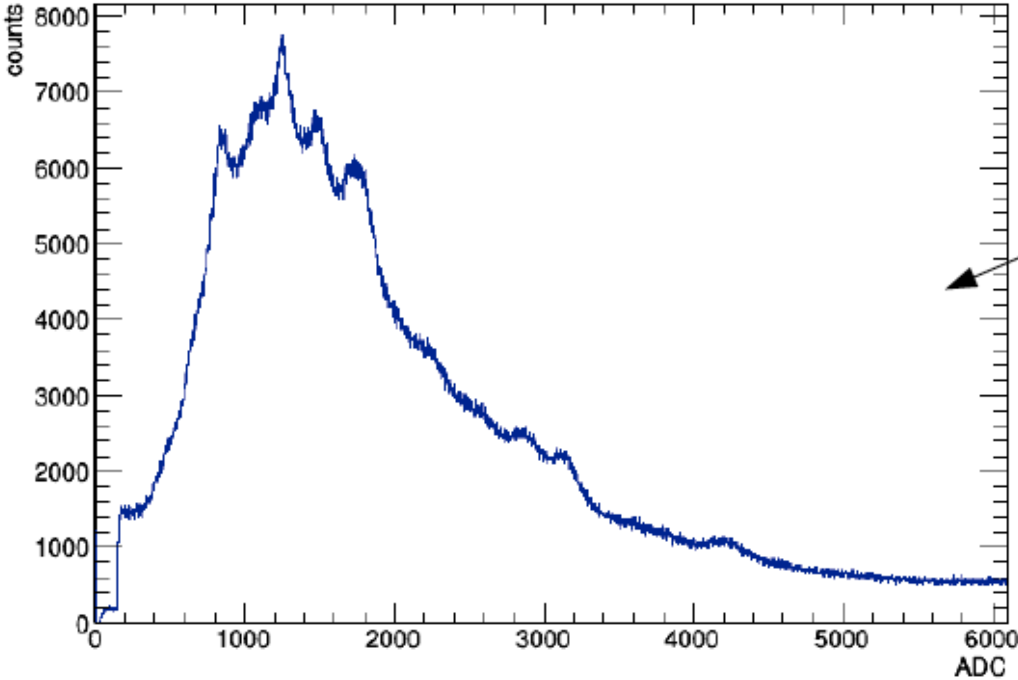


2016: transfer rate measurement

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



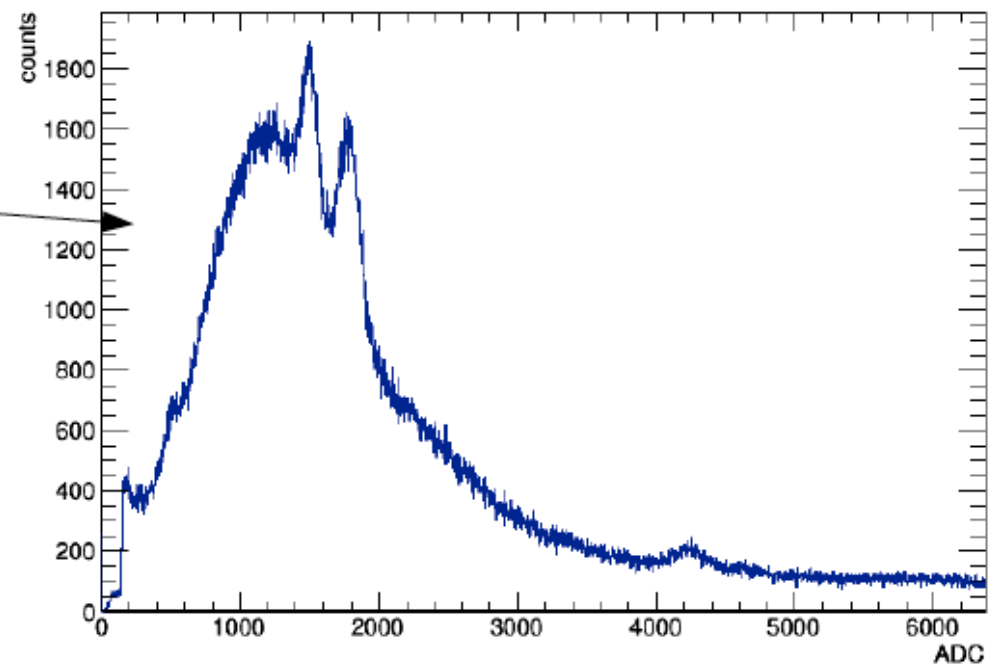


PROMPT SPECTRUM
(t<1200 ns)

One detector (LaBr 3)
0.3% oxygen
concentration

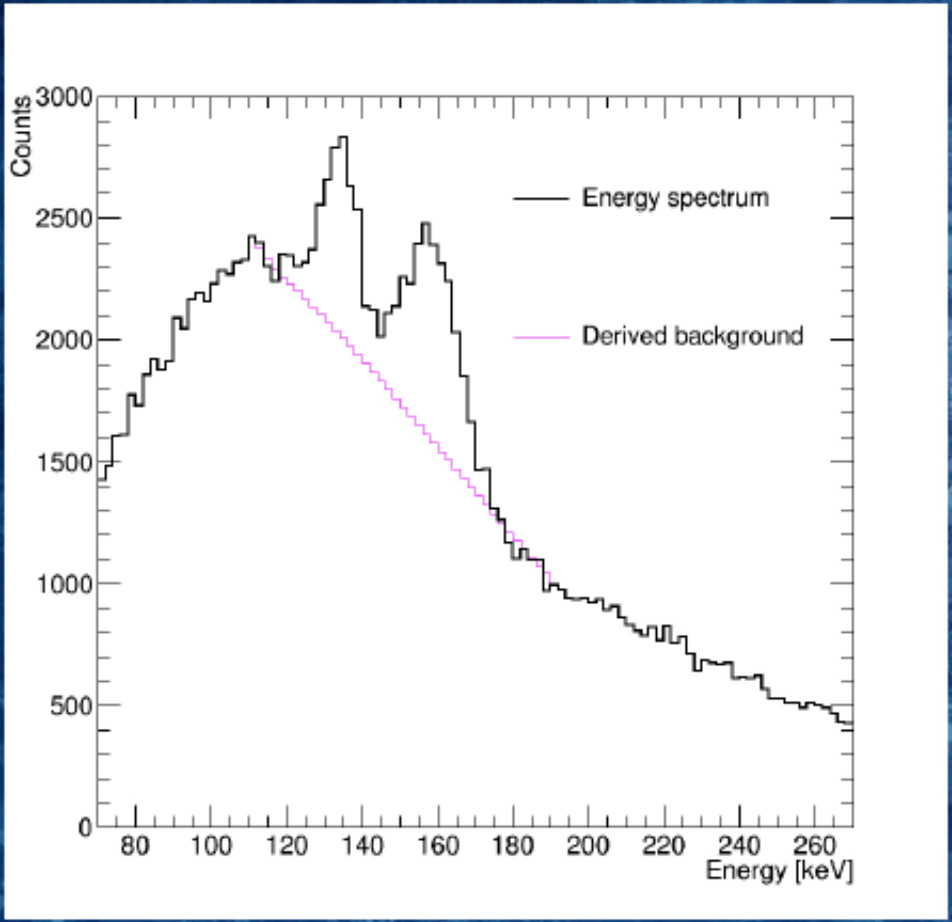
DELAYED SPECTRUM
(t>1200 ns)

One detector (LaBr 3)
0.3% oxygen
concentration



BACKGROUND EVALUATION

Simplest solution: "straight line"



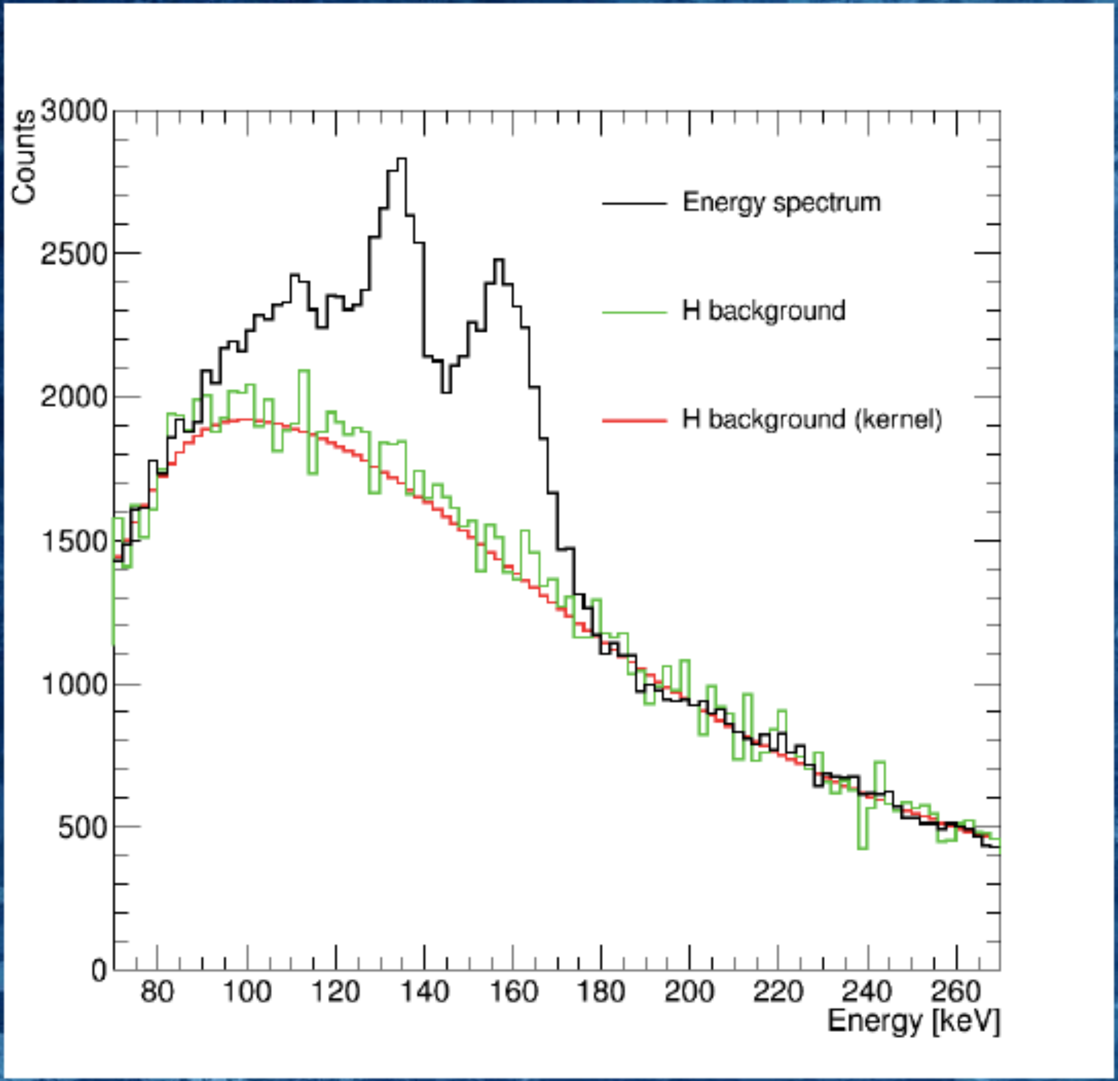
T = 300 K

Time bin = [1450,1650] ns

Using ROOT/"TSpectrum" class – spectroscopic algorithms

Problem: unstable results…

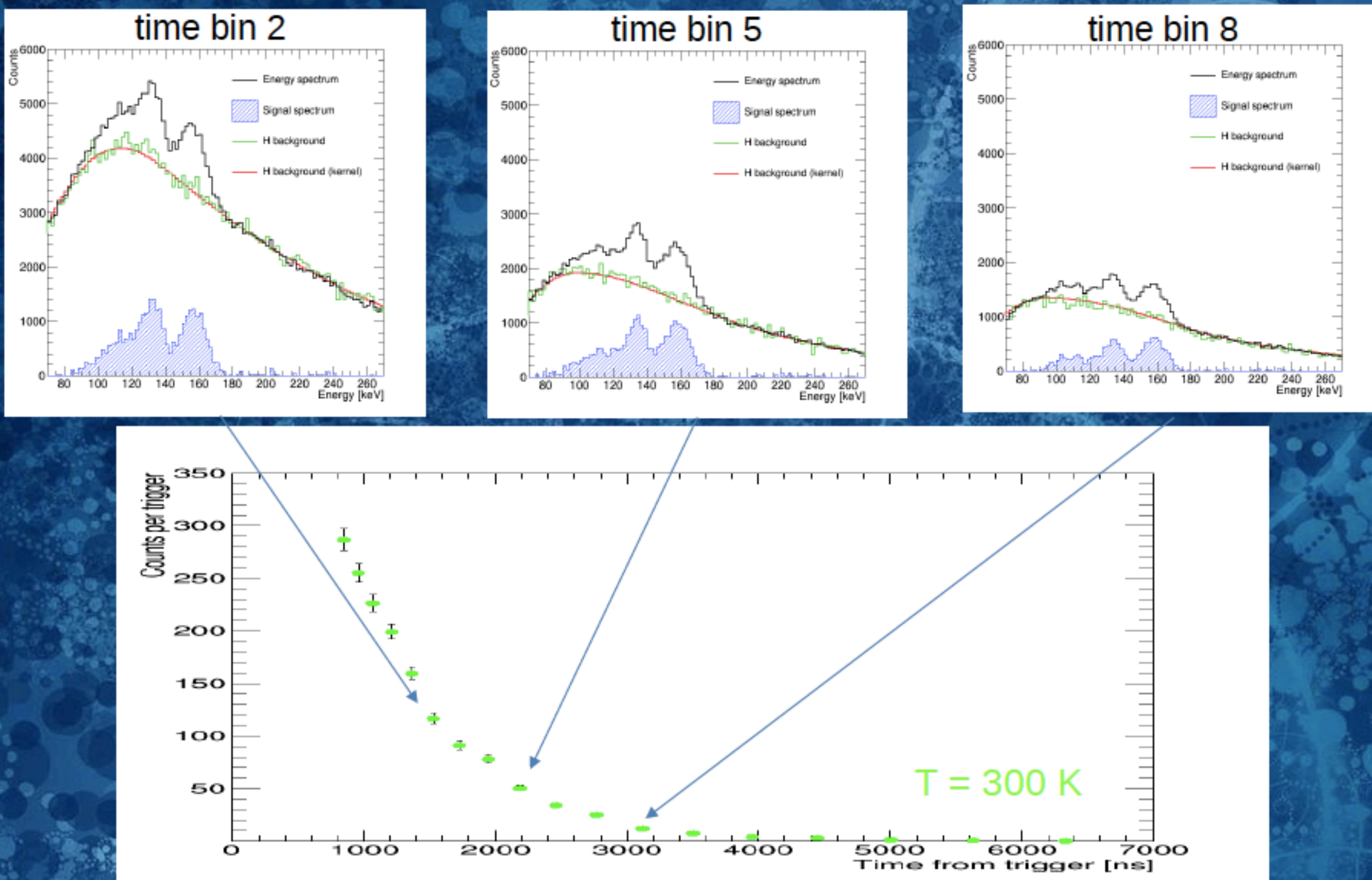
Best solution: pure H smoothing



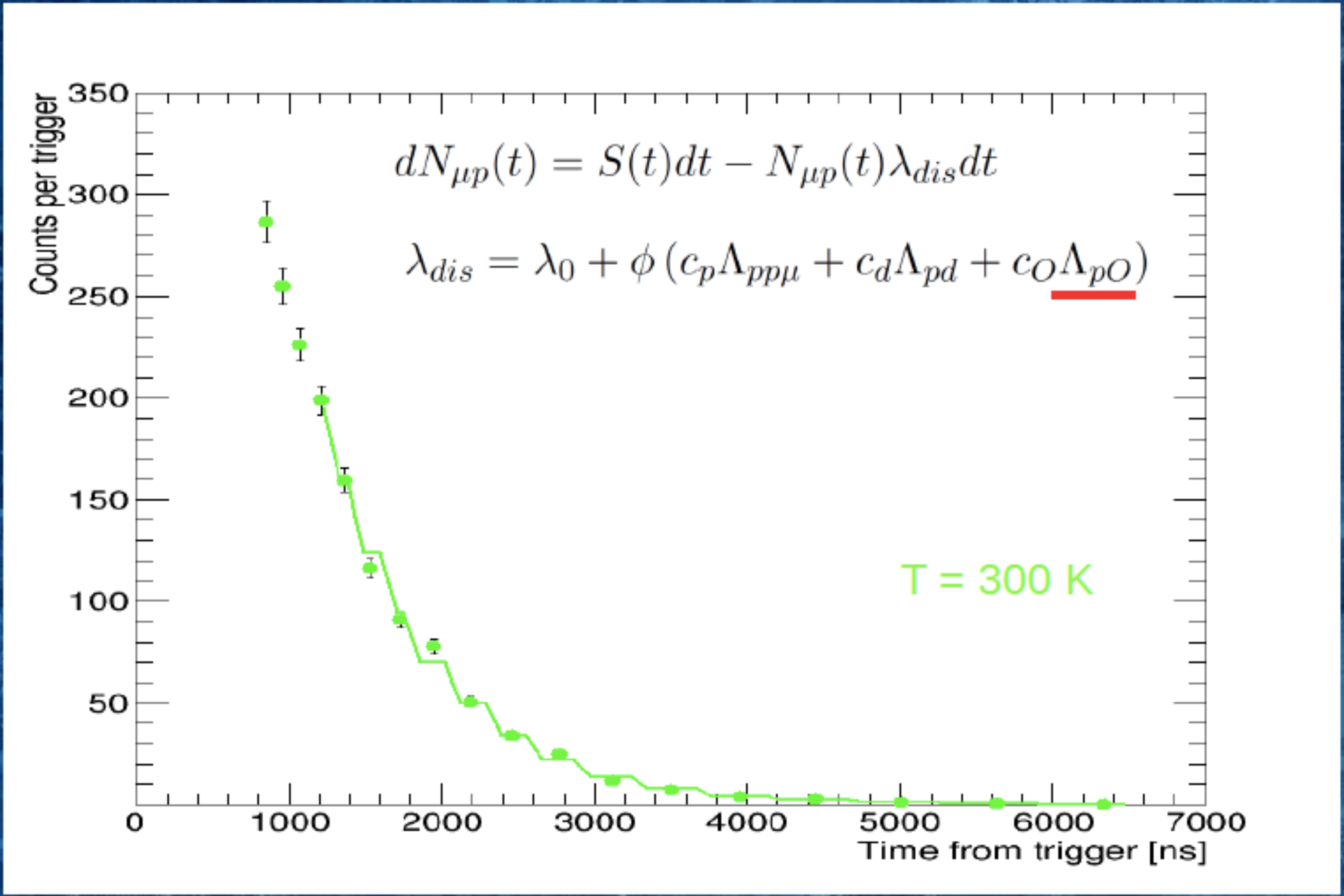
T = 300 K
Time bin = [1450,1650] ns

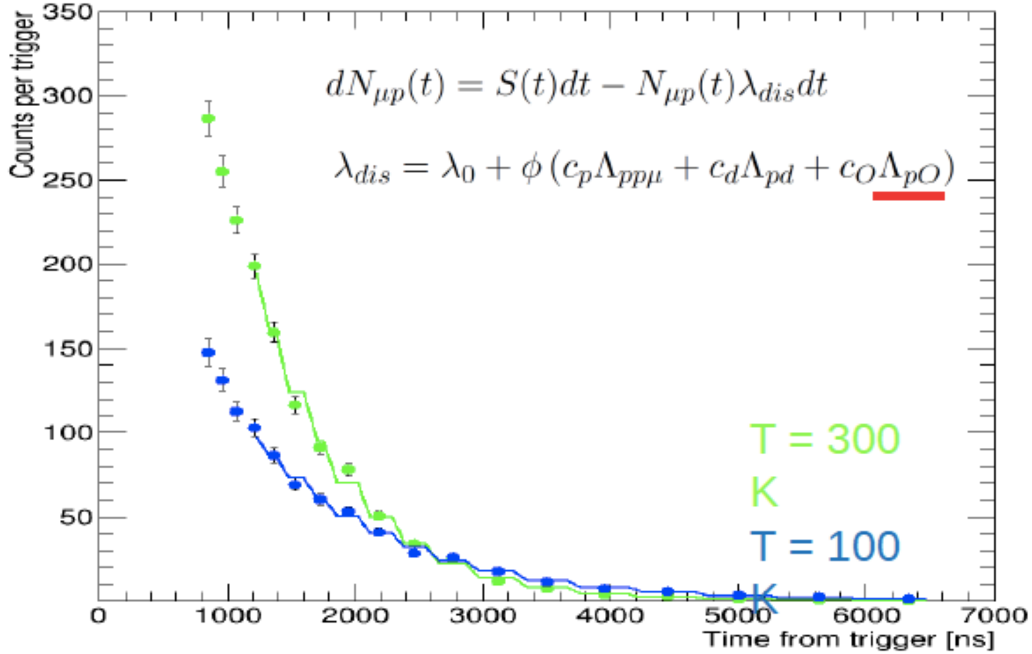
Pure hydrogen data taking within the same beam time and with the same pressure and temperatures.

Fixed temperature: time evolution

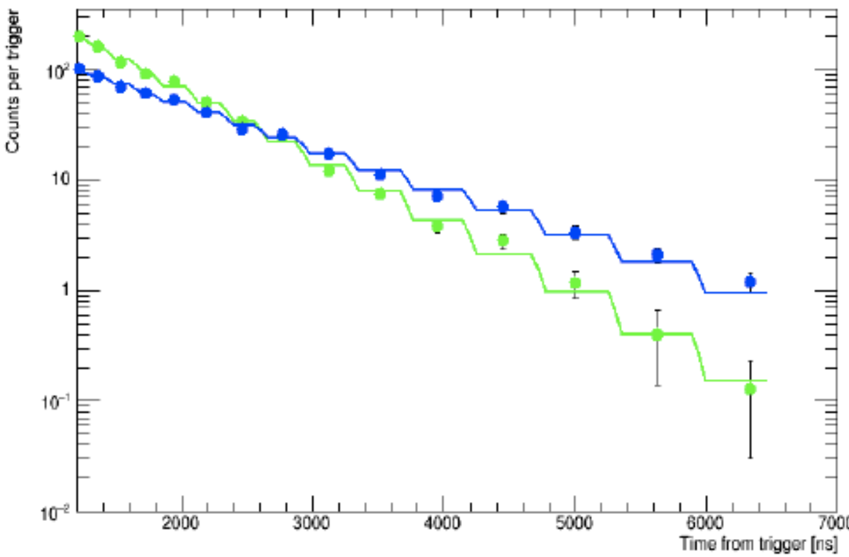


Temperature and time evolution



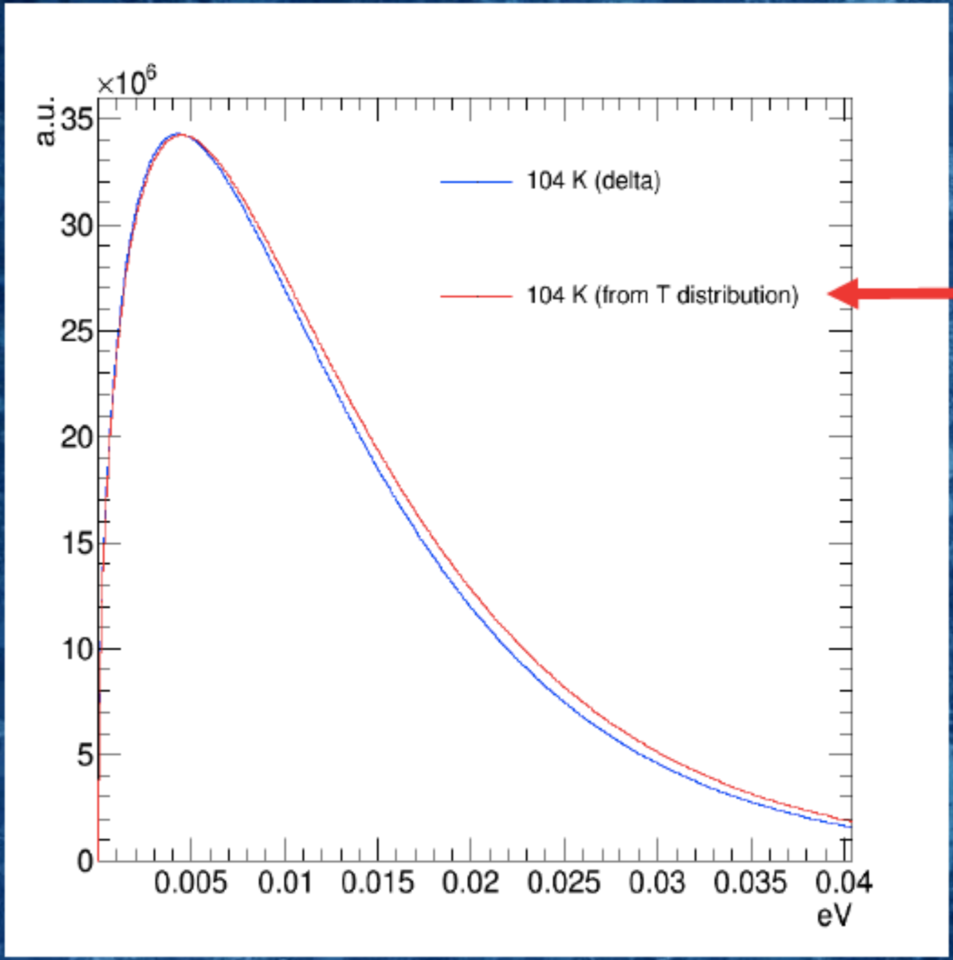


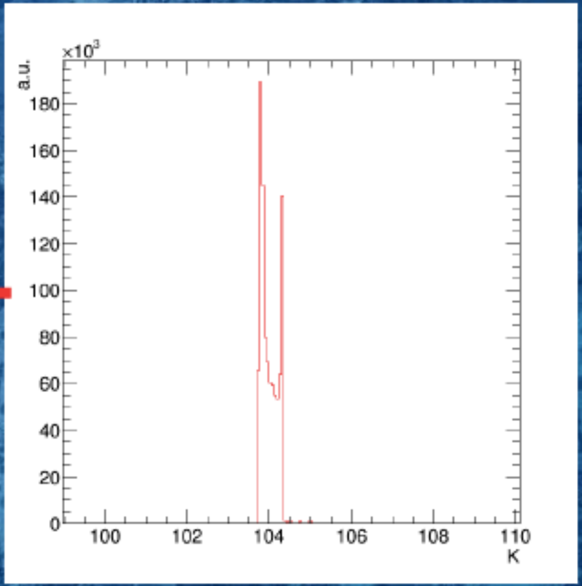
Transfer rate dependence on temperature



Temperature ↔energy conversion

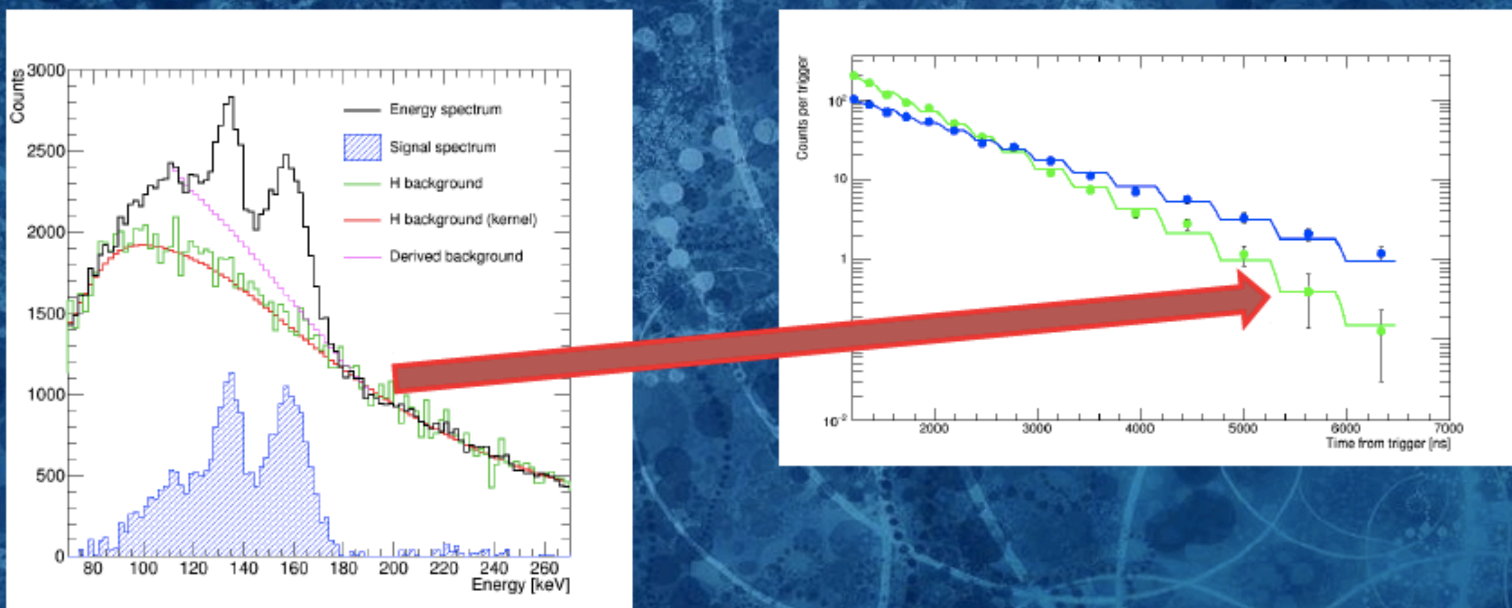
- Definition of temperature interval
- Generation of a Maxwell-Boltzman distribution for each temperature in that interval





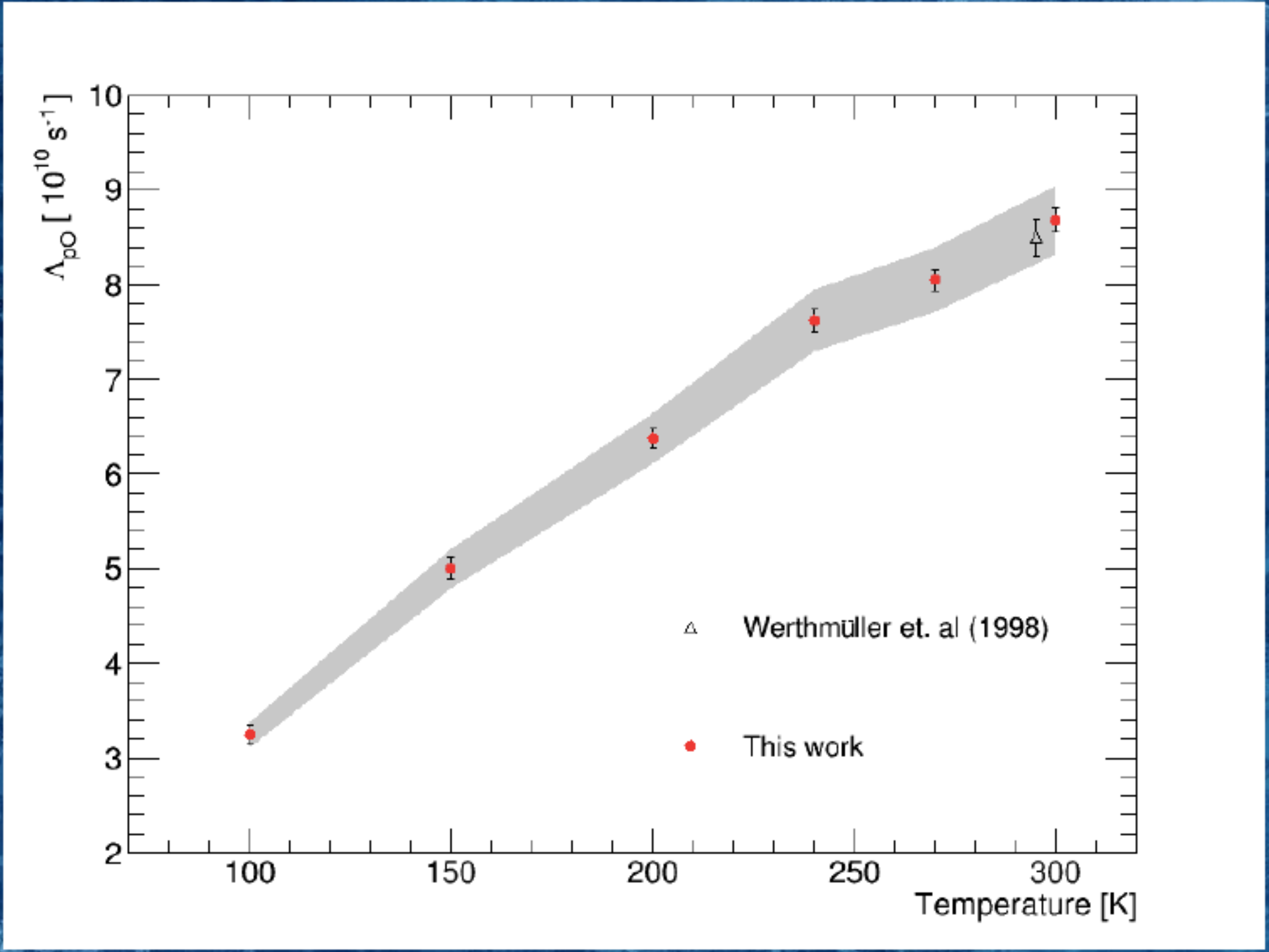
Sistematic errors contributions

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

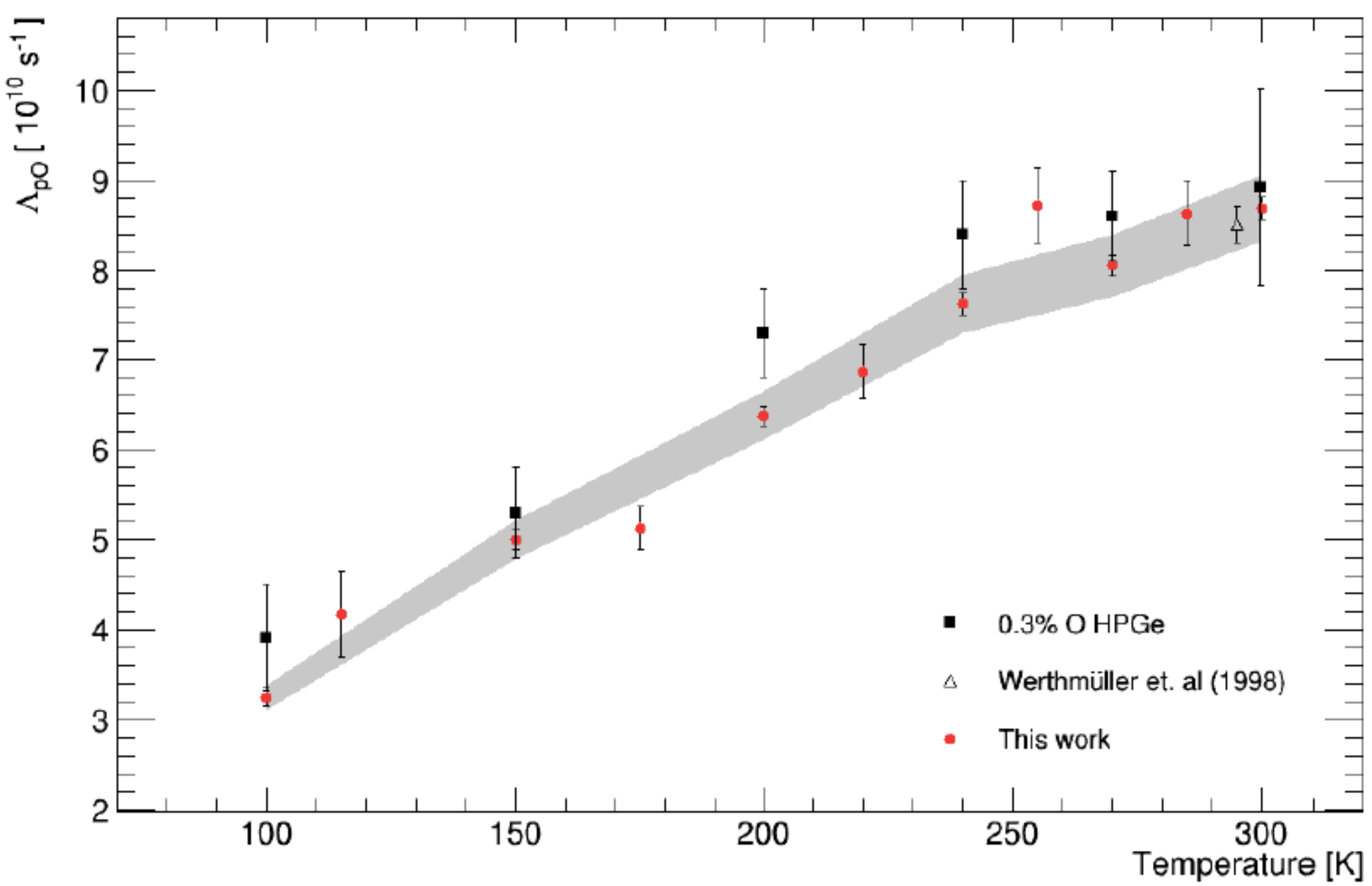


Other uncertainties, negligible (<< statistical error)

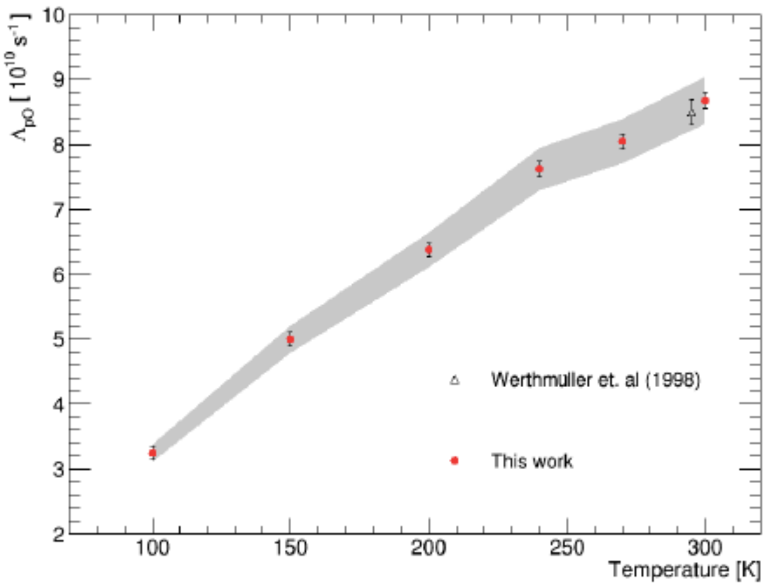
Final result for oxygen concentration at 0.3%

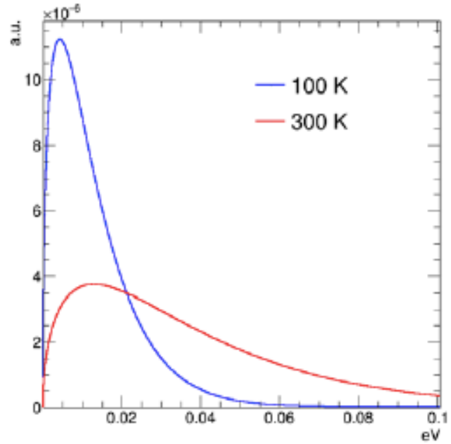


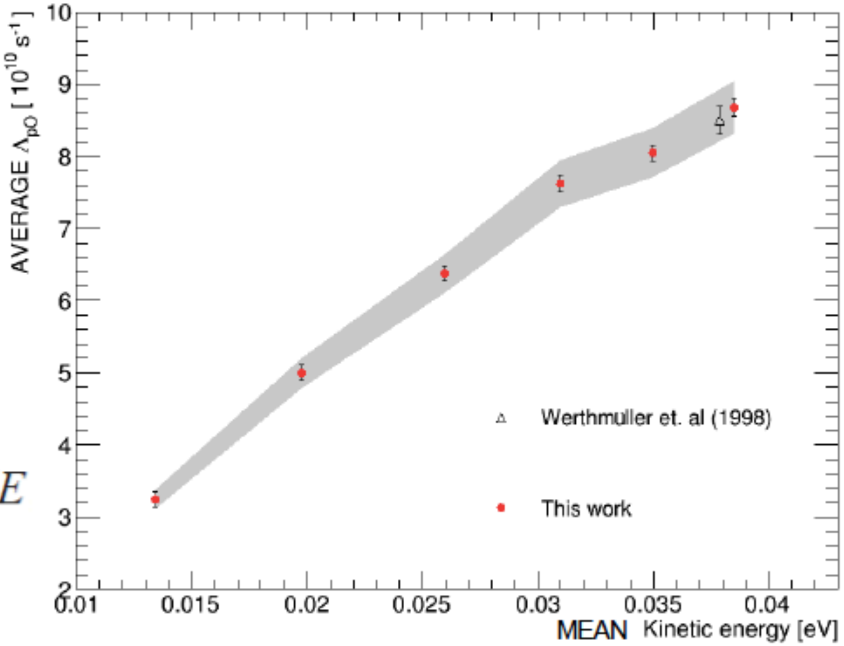
Comparison between the transfer rate result obtained analysing the data acquired with HPGe for the 0.3% oxygen concentration



Conversion to kinetic energy



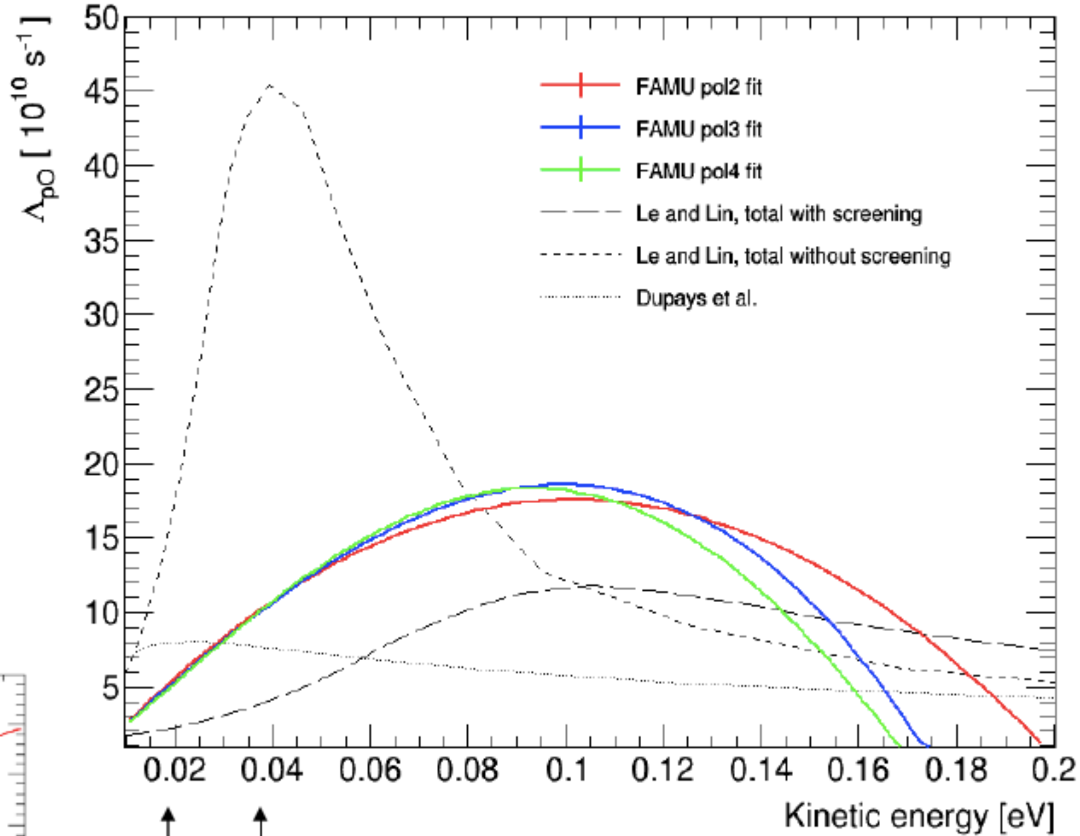




$$\lambda(T) = \int_0^\infty \lambda(E) \sqrt{\frac{4E}{\pi (kT)^3}} \exp(-E/kT) dE$$

Phenomenological model

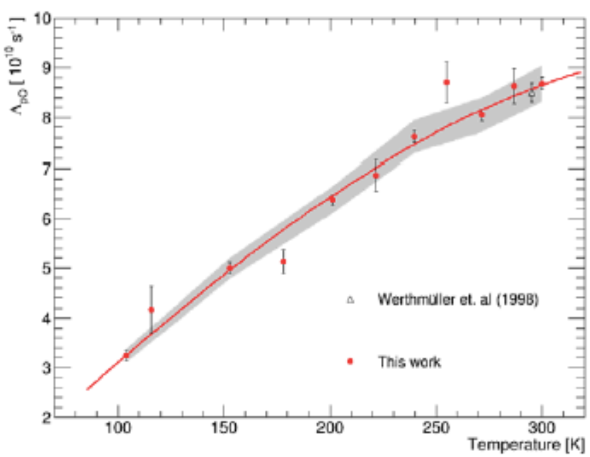
$$\lambda(T) = \int_0^\infty \lambda(E)\sqrt{\frac{4E}{\pi(kT)^3}}\exp(-E/kT)\,dE$$



~100 K

~300 K

μp energy after de-excitation



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two competing processes

- the strength of x-ray signal, from mu-p's accelarated 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,

need to 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.

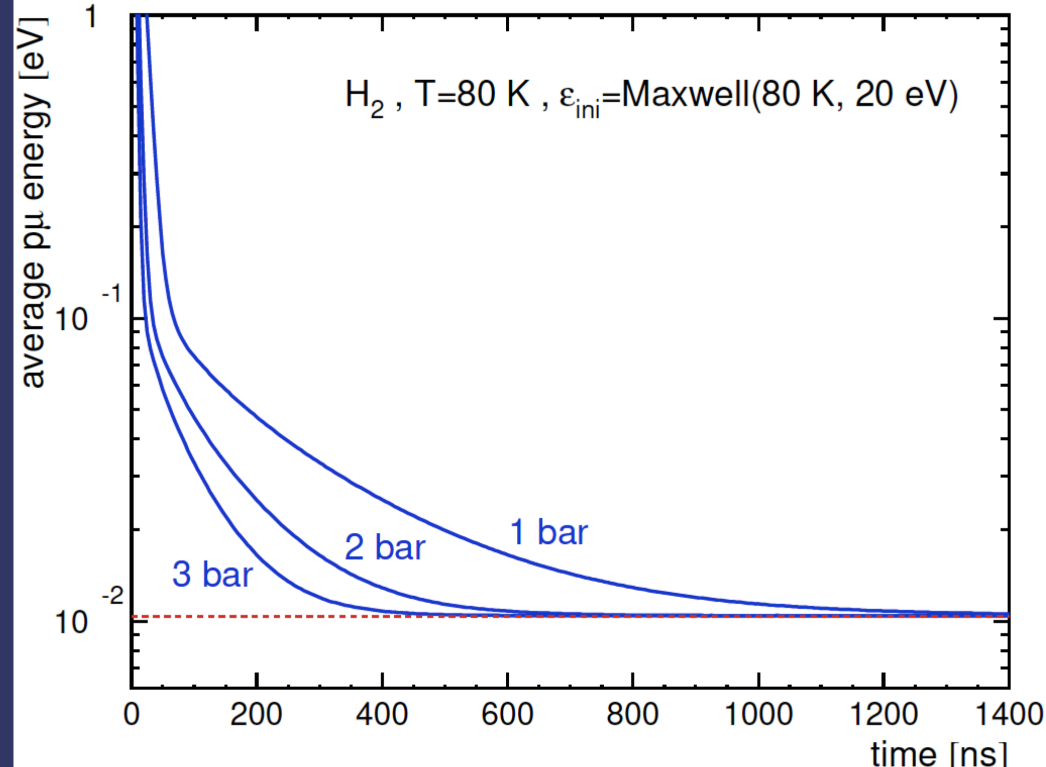
- The overall optimal condition for the HFS measurement is thus a convolution of these two optimization functions is going to be determined by the HFS-measurement simulations, which is underway.

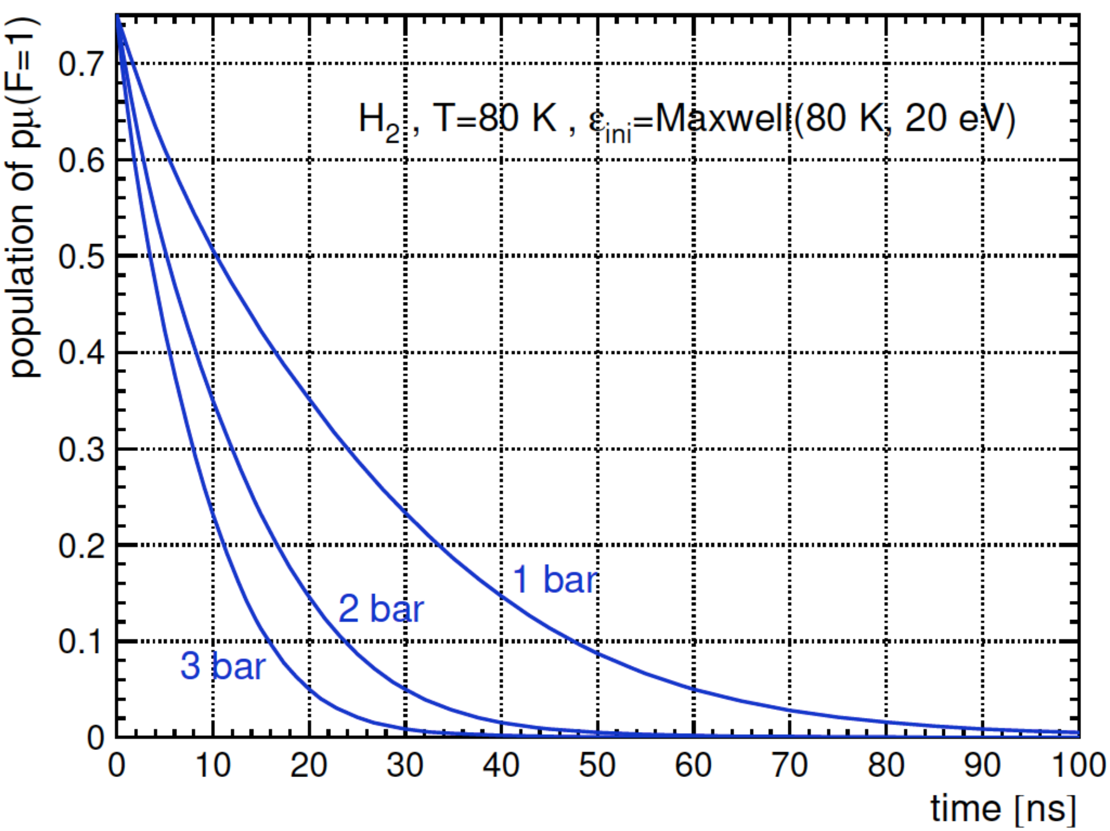
the time evolution of mean kinetic energy, which also illustrates the thermalization time. This is an answer for the moment of laser ignition - mu-p atoms should be thermalized

.

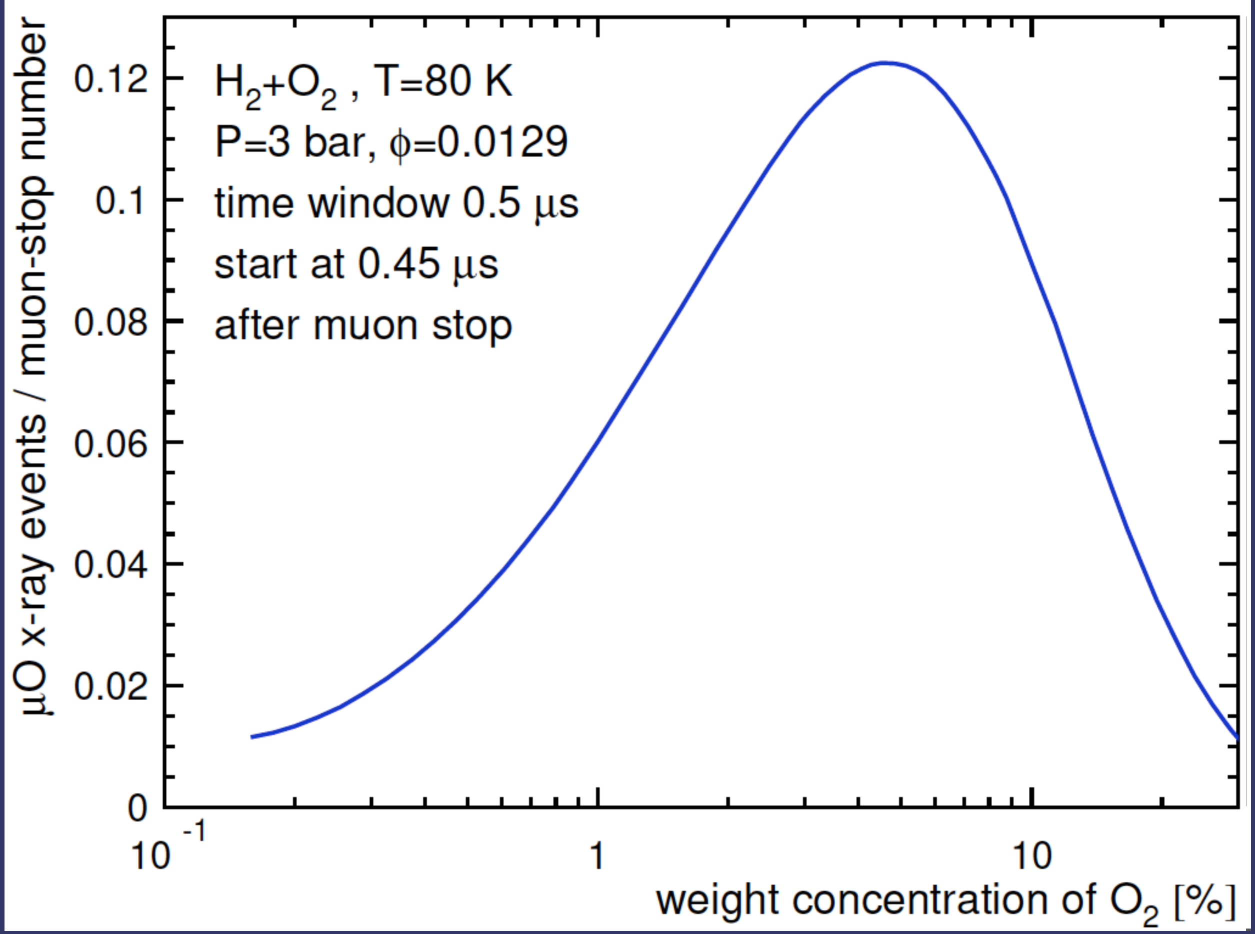
Also, this picture shows a mean time of deceleration from about 0.11 eV

(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.



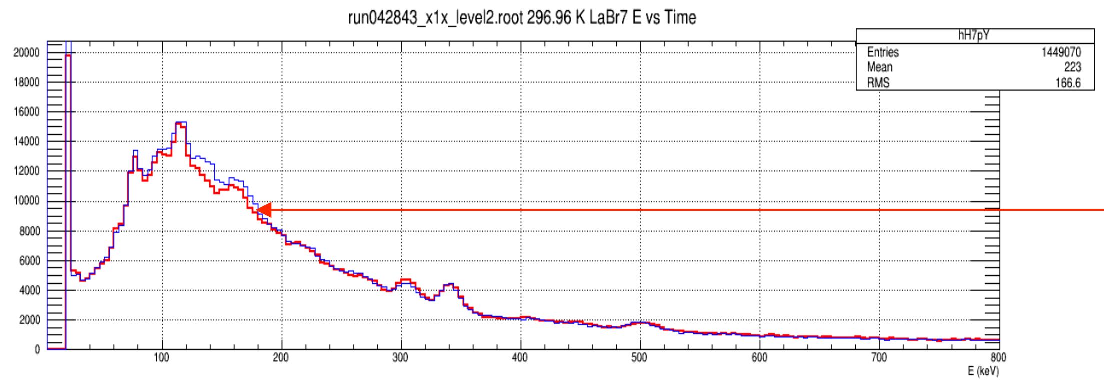


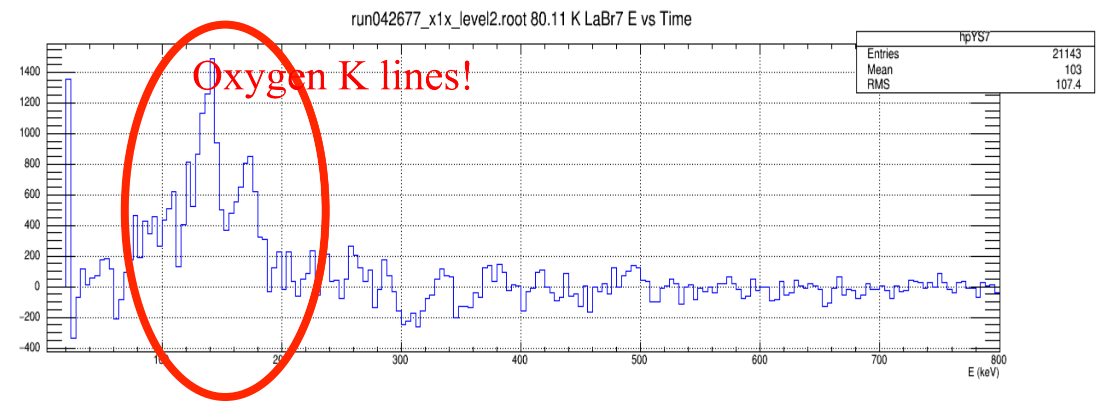
mu-p spin de-excitation versus time.
The de-excitation time informs us about how long we should wait for the acceleration of mu-p atom which was excited by a laser photon.

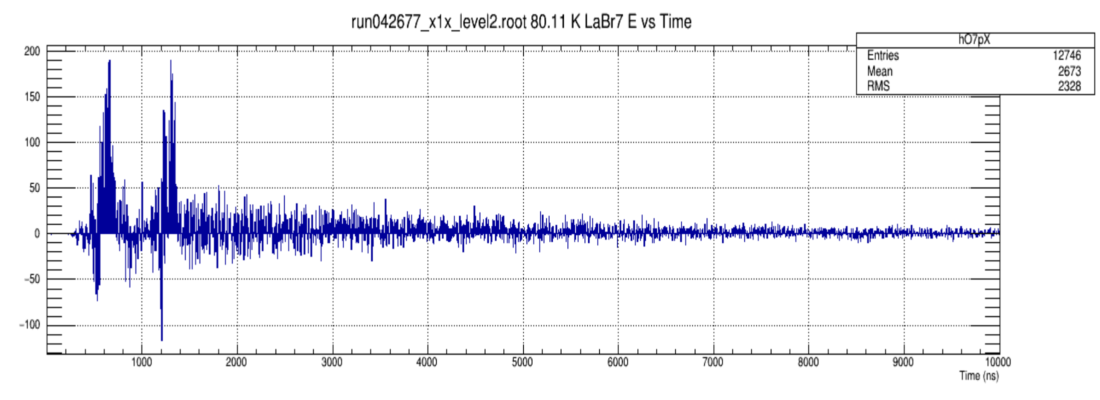


The plotted functions show a number of existing mu-p's in the time window of 500 ns, divided by the number of muon stops. The beginning of the time window corresponds to the moment of full thermalization. The time windows is approximately equal to the time of laser-field presence in the multipass cavity.

from 2018 data old cryo target low pressure







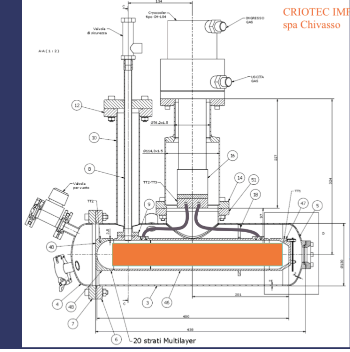
Energy spectra
Blue O(3%) mixture
Red pure hydrogen
(3 bar 80 K)
(normalized according to acq number of trigger, i.e. time)

LaBr re-calibrated

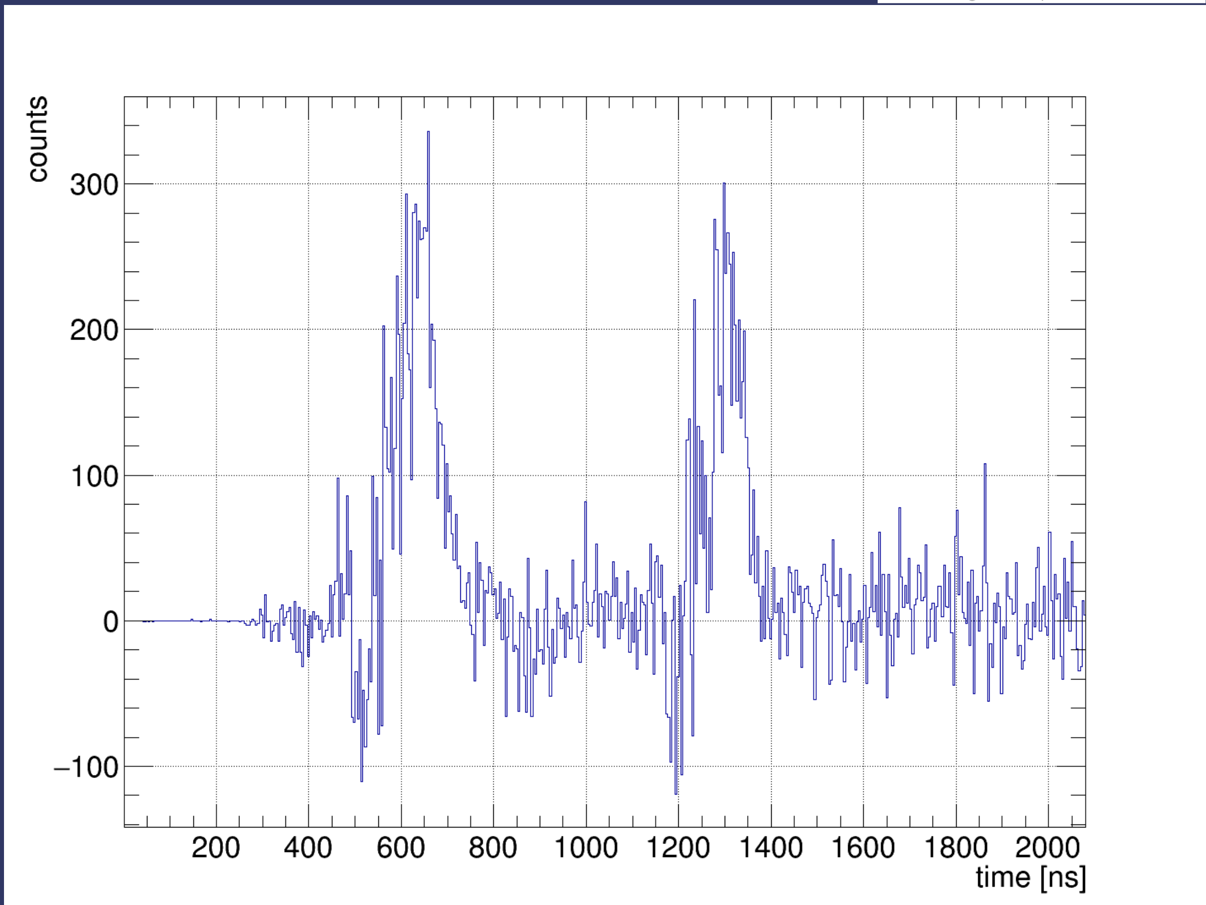
Oxygen mixture - hydrogen

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

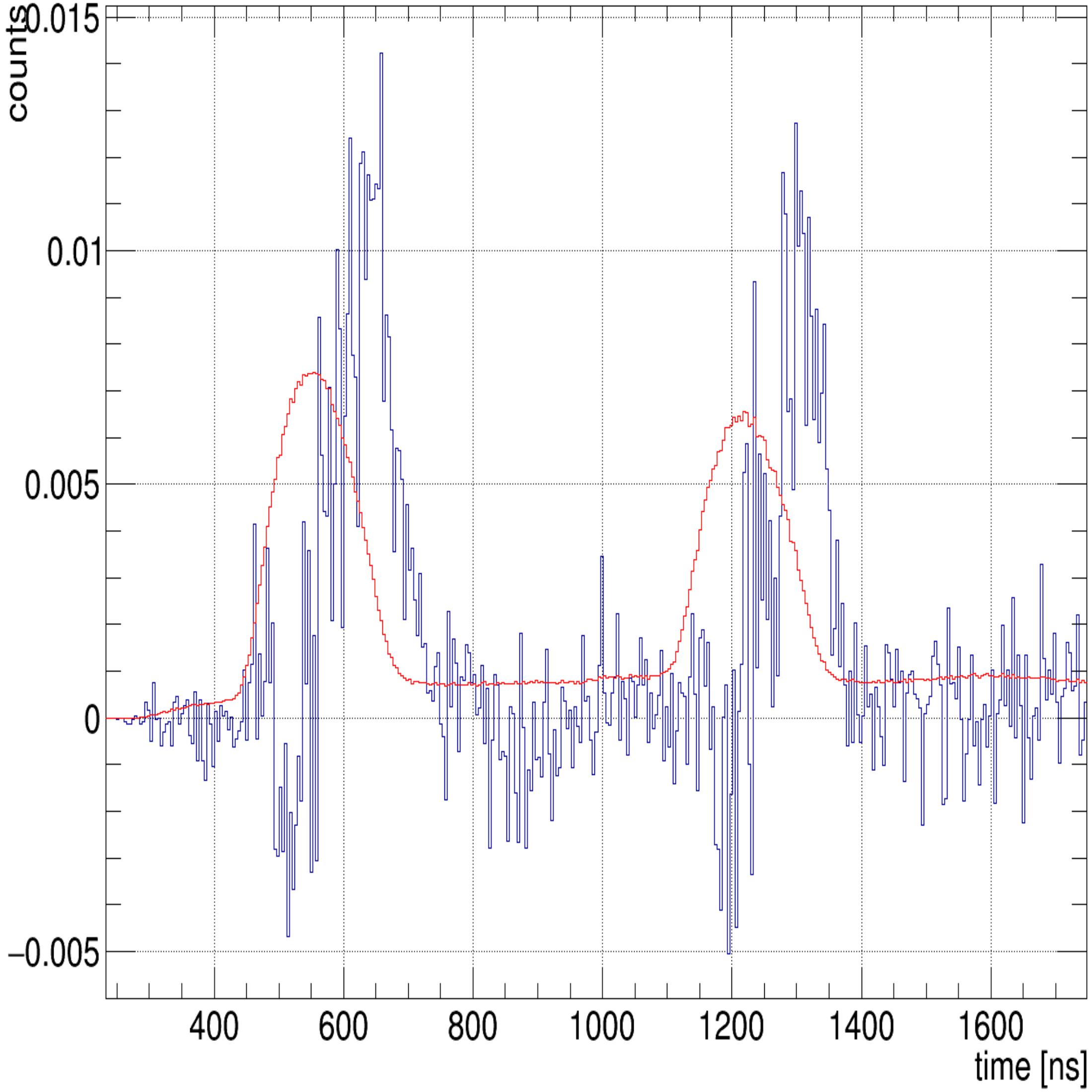
x-ray time spectrum,
for a low pressure and a fixed temperature around 80 K
at 3 bar at 80 K with a mixture of hydrogen
and oxygen 3% (by mass).



time evolution of oxygen lines signal obtained with the target used for the transfer rate Oxygen lines time evolution
(very fast due to high oxygen concentration).



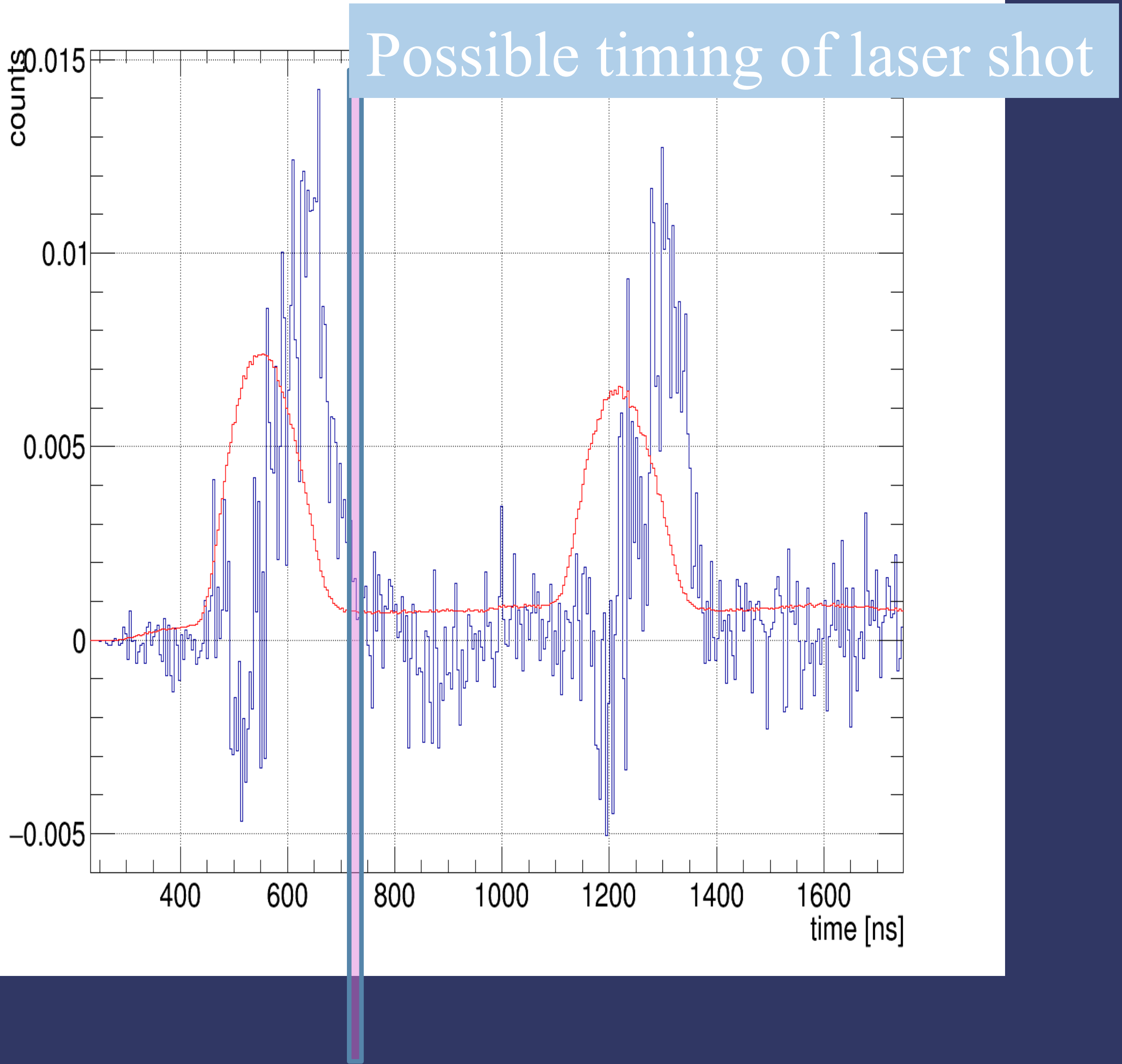
the y axis represents the number of counts with a data taking of *8 hours for two detectors*. Delayed events disappear very quickly.



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.



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.

In order to have a signal/fluctuation >~1
a factor 10 is needed in the acquisition time, in fact:

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).

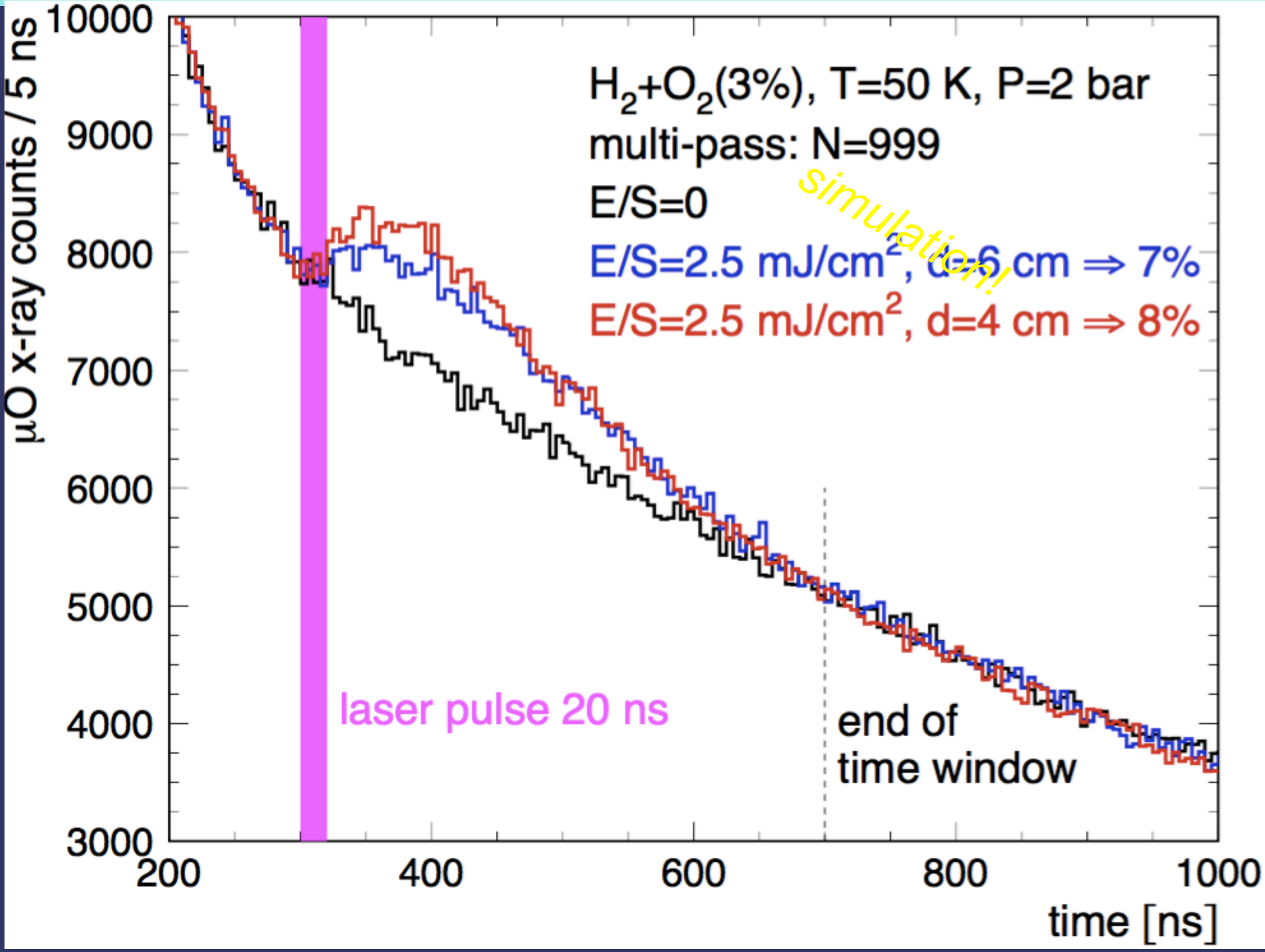
NB: possible optimization and (time) reduction factors:

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.

Study of best setup to maximize signal

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



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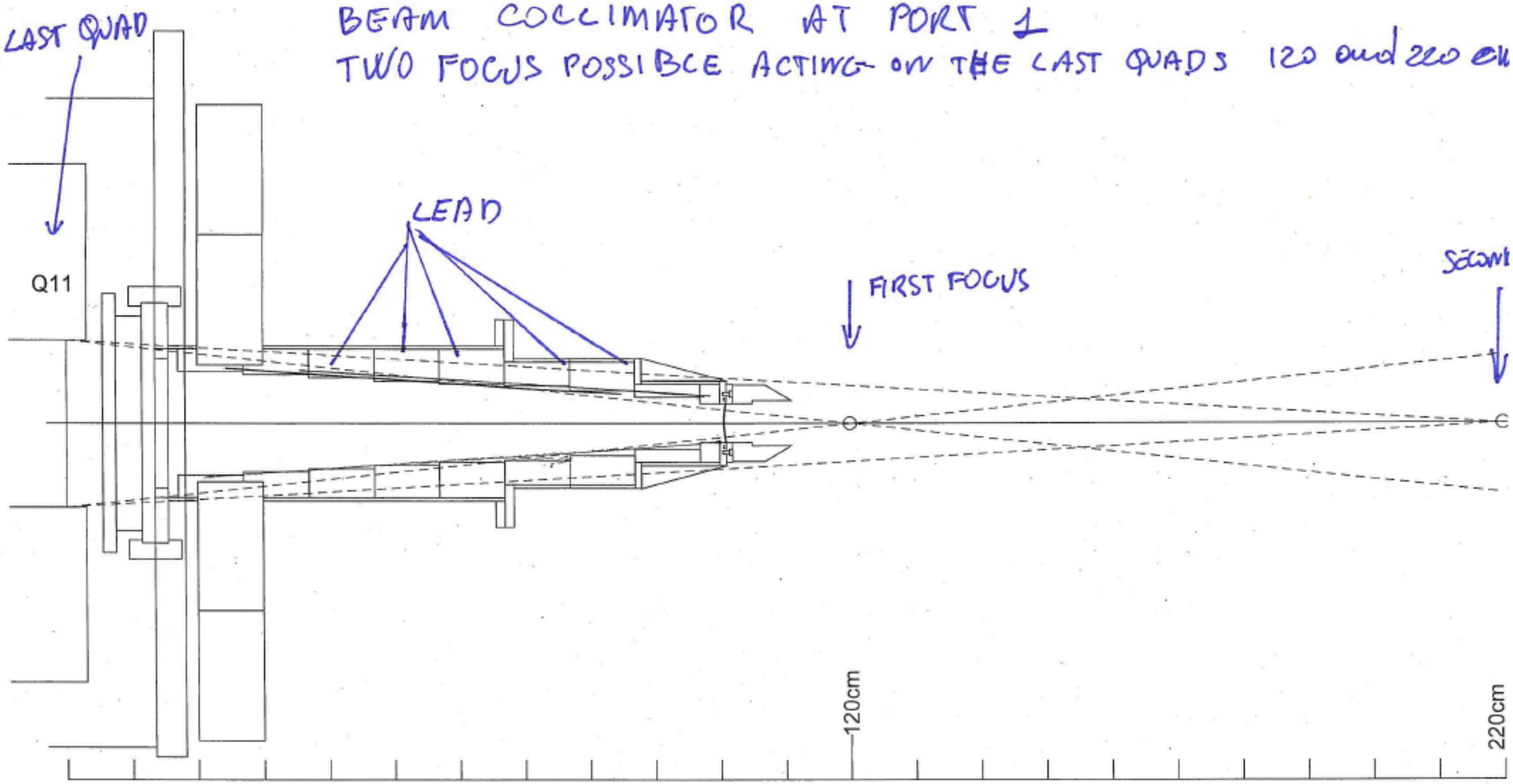
FAMU

INFN
Istituto Nazionale di Fisica Nucleare

BEAM COLLIMATOR AT PORT 1

TWO FOCUS POSSIBLE ACTING ON THE LAST QUADS 120 and 220 cm

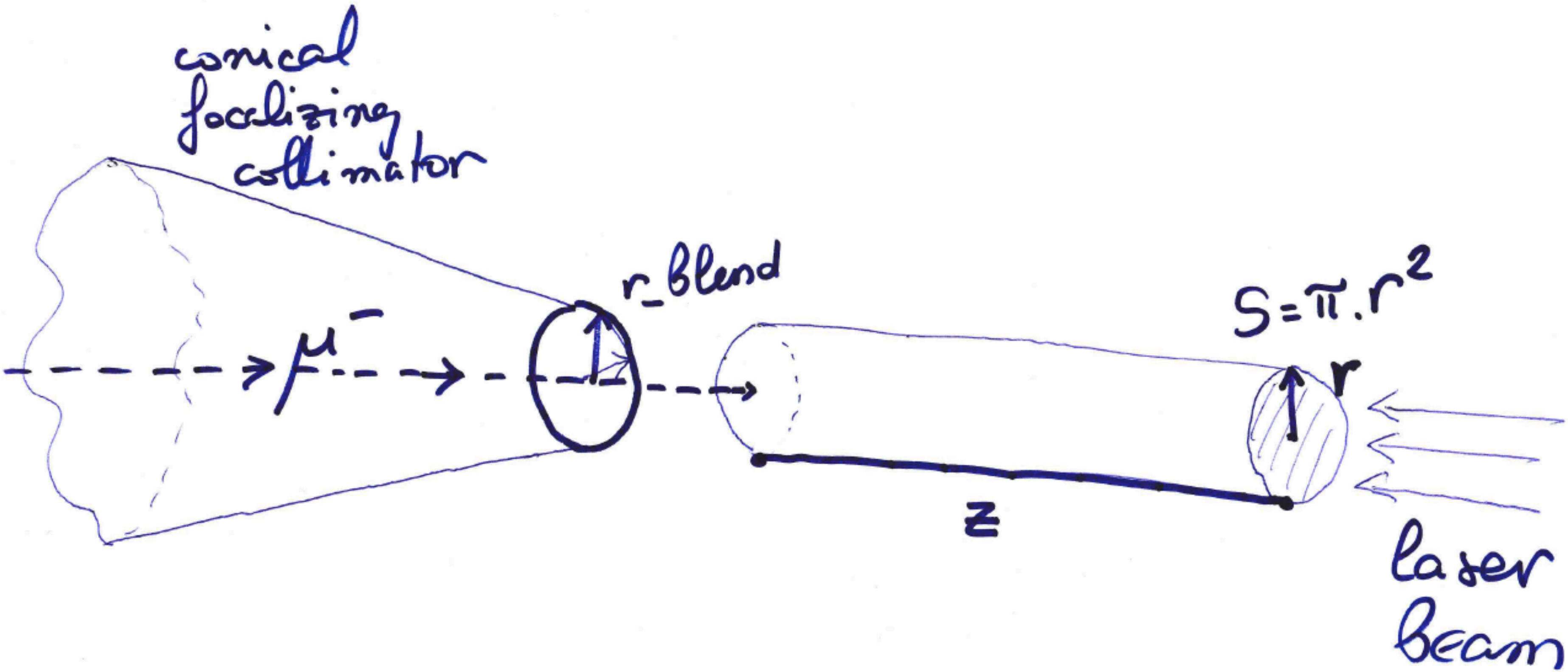


FROM THE PART TO THE RIGHT ONE CAN EXTRACT THE LEAD

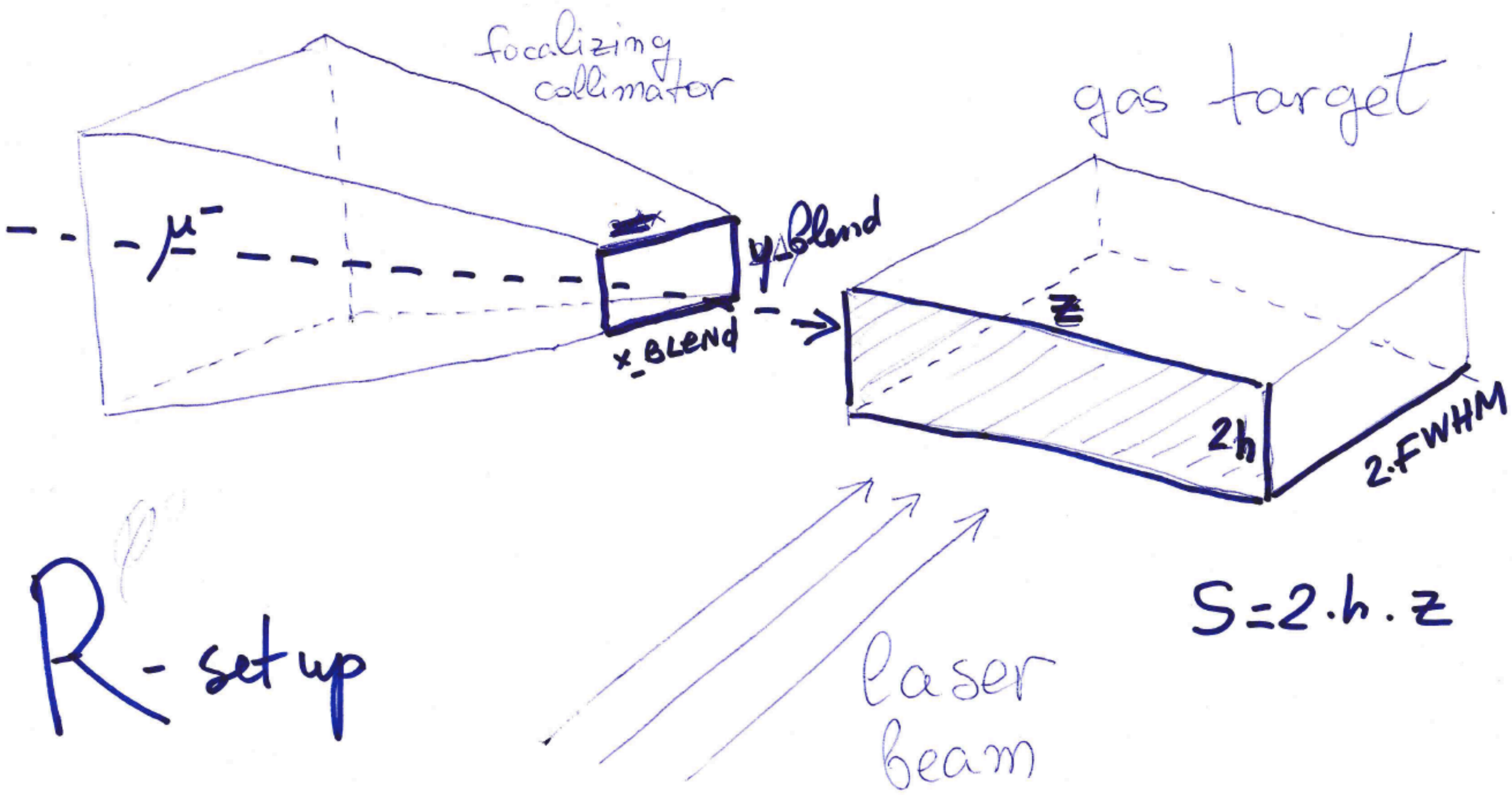
COLLIMATOR

THE PART TO THE LEFT CAN BE DISMOUNTED

THE IDEA IS TO SOBSTITUTE THE COLLIMATOR WITH A FOCUSING STRUCTURE



C - setup

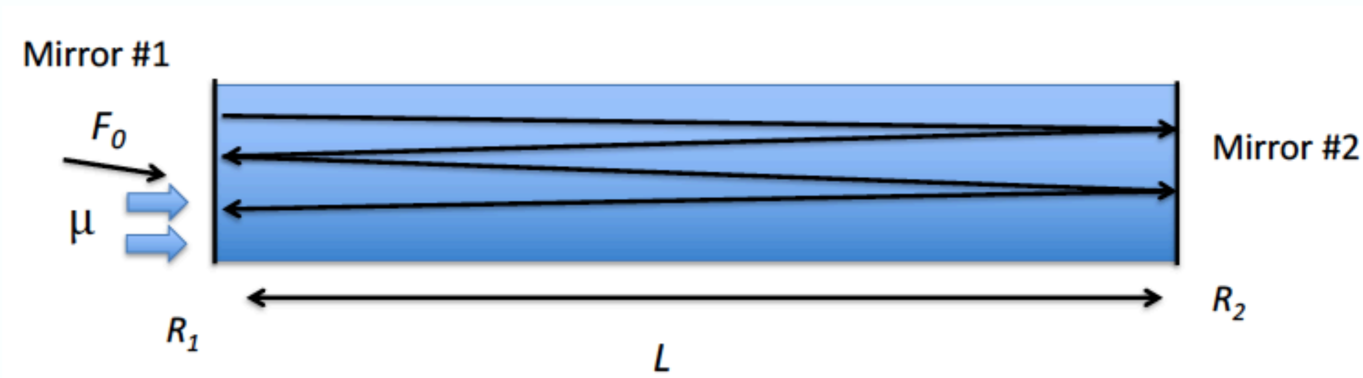

focalizing collimator
gas target
μ^-
y_Blend
x_BLEND
z
2h
2·FWHM
R-setup
laser beam
S=2·h·z

Multipass Optical Cavity

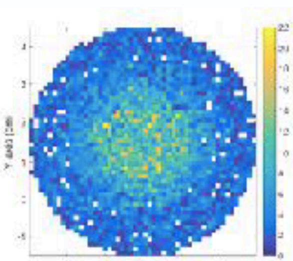
Luigi Moretti, Livio Gianfrani

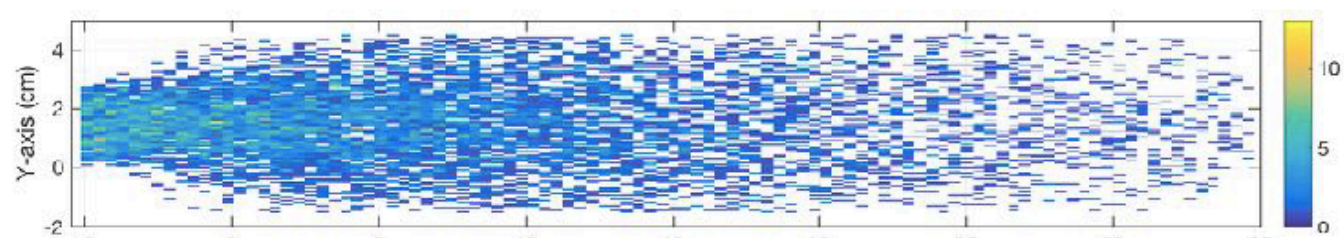
9497 events

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

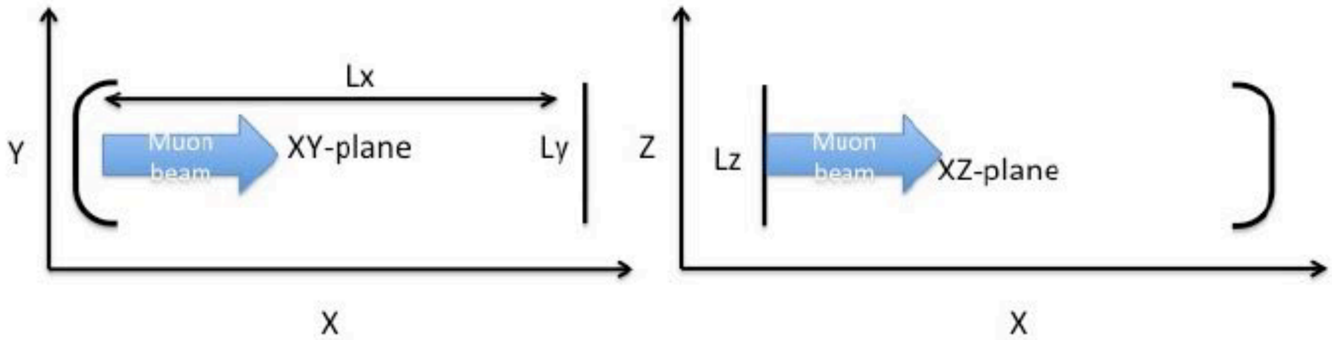


$$L_{eff}=\frac{L}{\alpha}=\frac{20\text{cm}}{12\times10^{-4}}\simeq166\text{m}$$

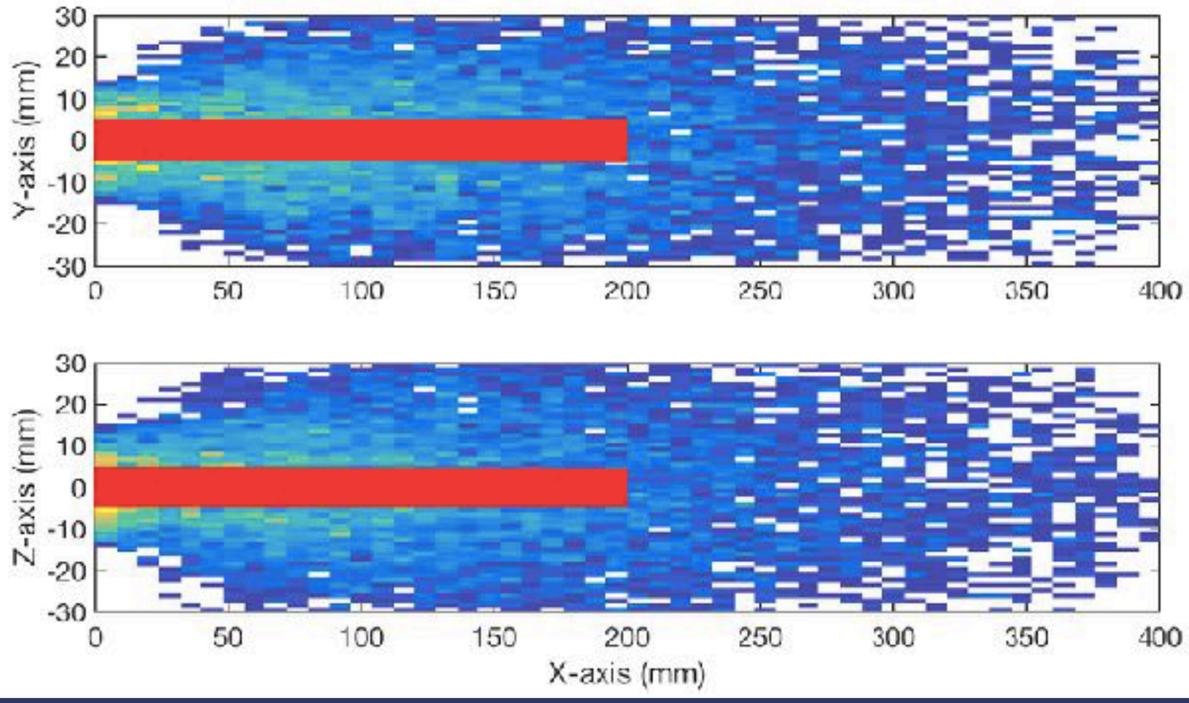




Optical design of cavity



Ly=Lz=2.5 cm
Lx=20 cm



Cavity enhancement effect at glance

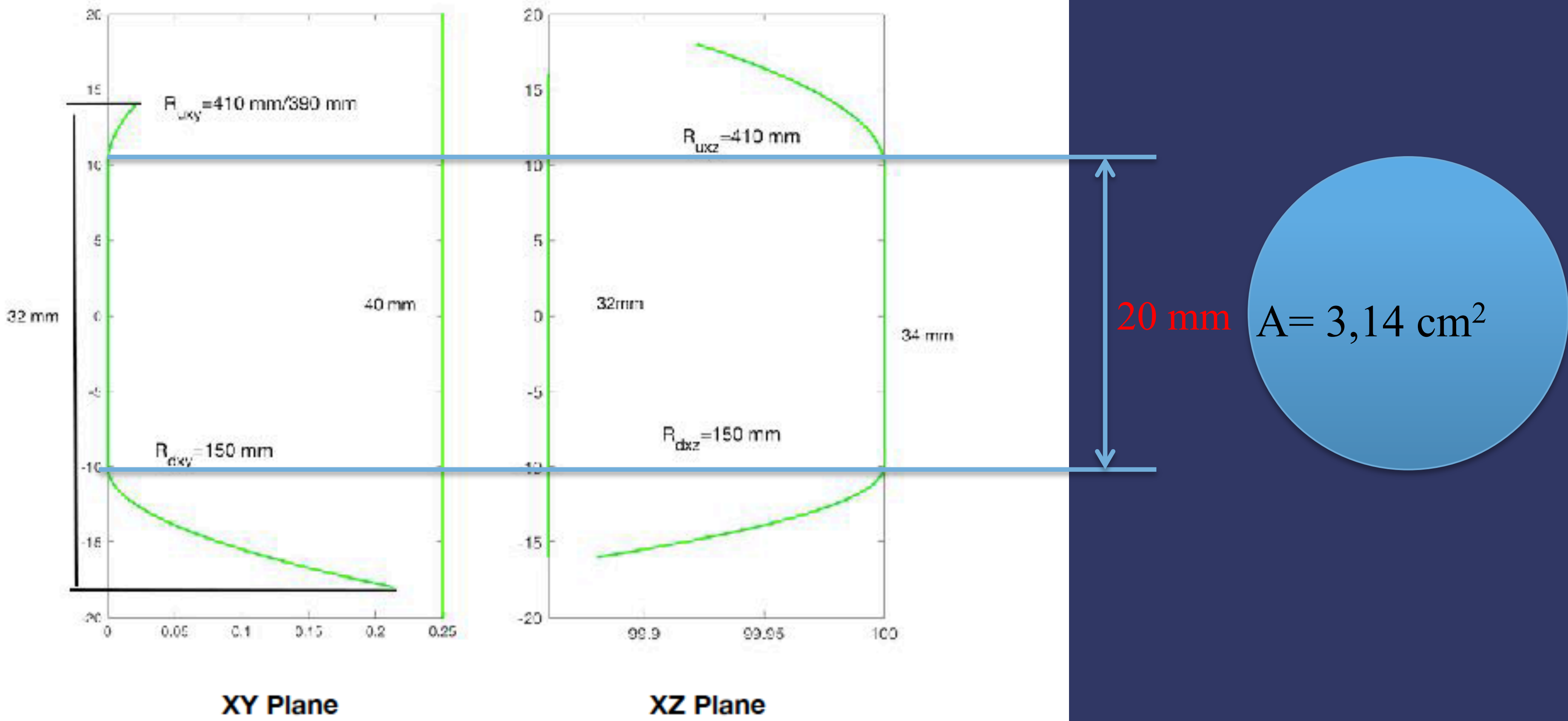
$E_l = 2.5\,\mathrm{mJ}$ $\quad N_R = 700$ $\quad R_1 = R_2 = 0.9989$

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

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

New geometry of cavity-2

HR mirrors

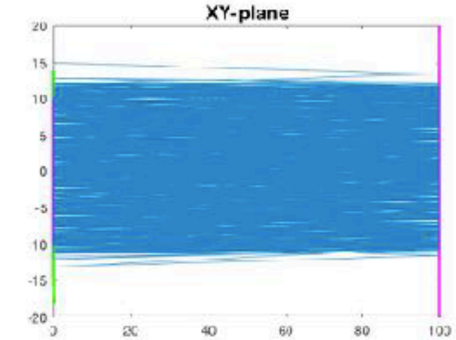


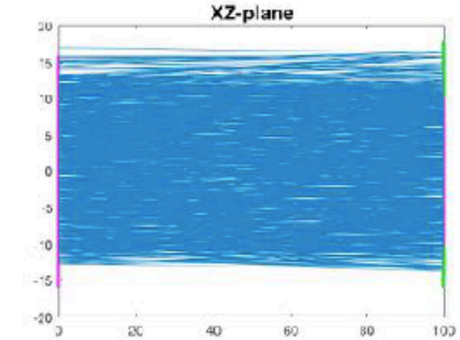
Substrate Fused Silica;

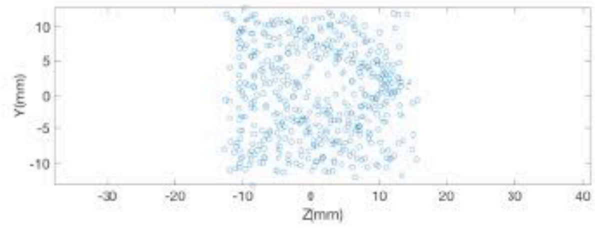
New geometry of cavity-2

$$N_{rif} = 1000$$

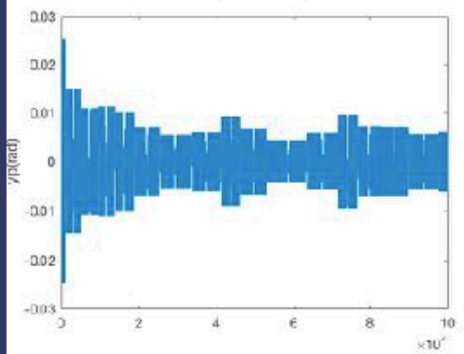
$$\alpha_{xy} = 15\text{mrad} \quad \alpha_{xz} = 6\text{mrad}$$

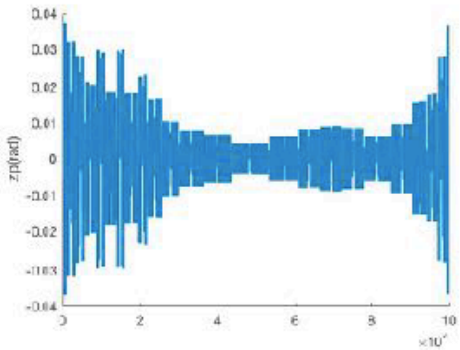


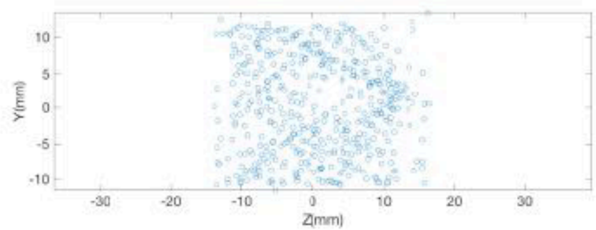




$X(mm)$ $X(mm)$







$$S_{ill} \simeq (2.3 \times 2.5)\text{cm}^2$$

After about 1000 reflection the ray light escape from the cavity

Mirror Fabrication

- **Substrate :** 1) Fused Silica; 2)Stainless steel
- **HR coating:** 1)Semiconductor multilyer Ge/ZnS; 2) Metallic

  Laser Components Company with Optoprim as Italian reference

- Test for the Laser damage;
- Test for the low temperature.

New target simulations:

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**

New target simulations:

@ 300 K

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

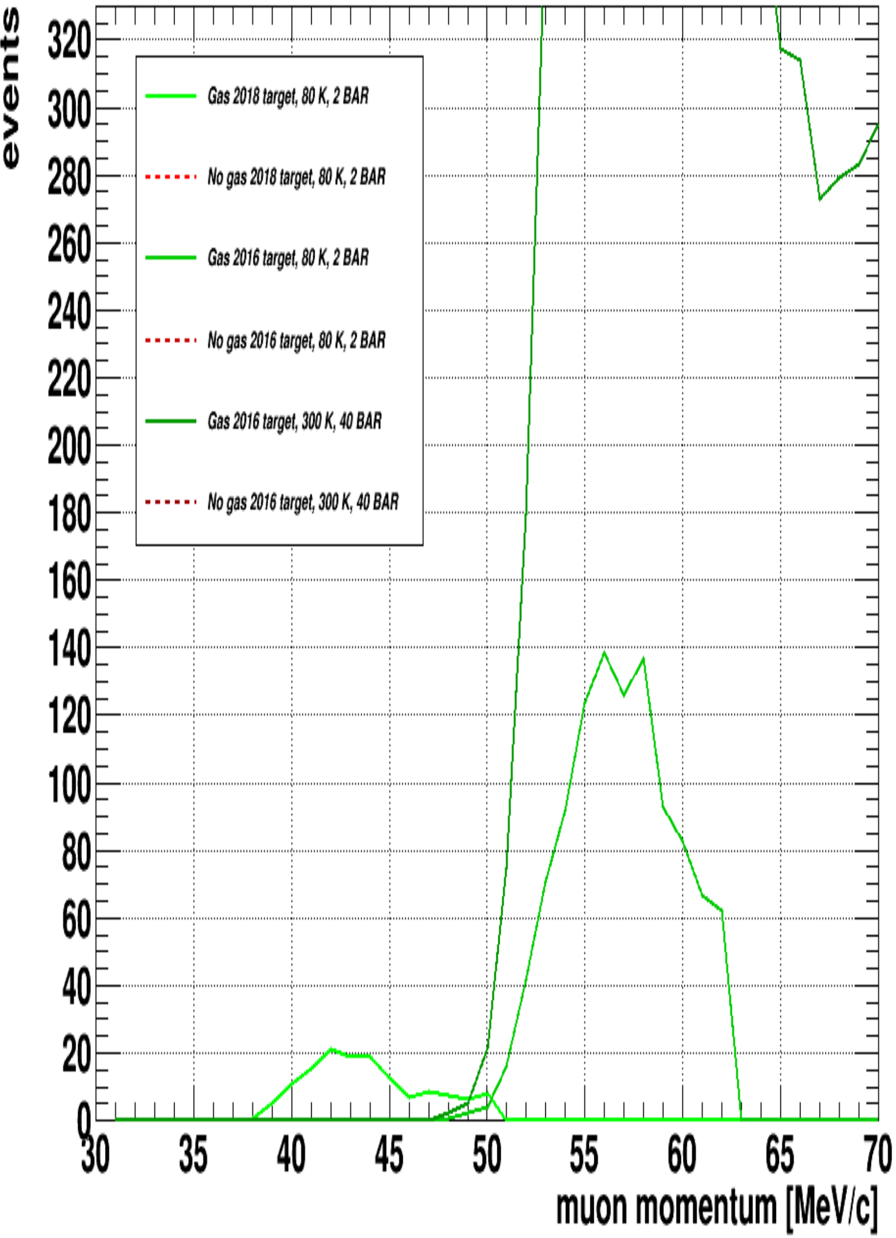
TARGET 2018 vacuum
pressure ve
no hodoscop
gas: cylinder 2
no coating
with multi-layer insulator
lead collimator: wall with

low pressure :

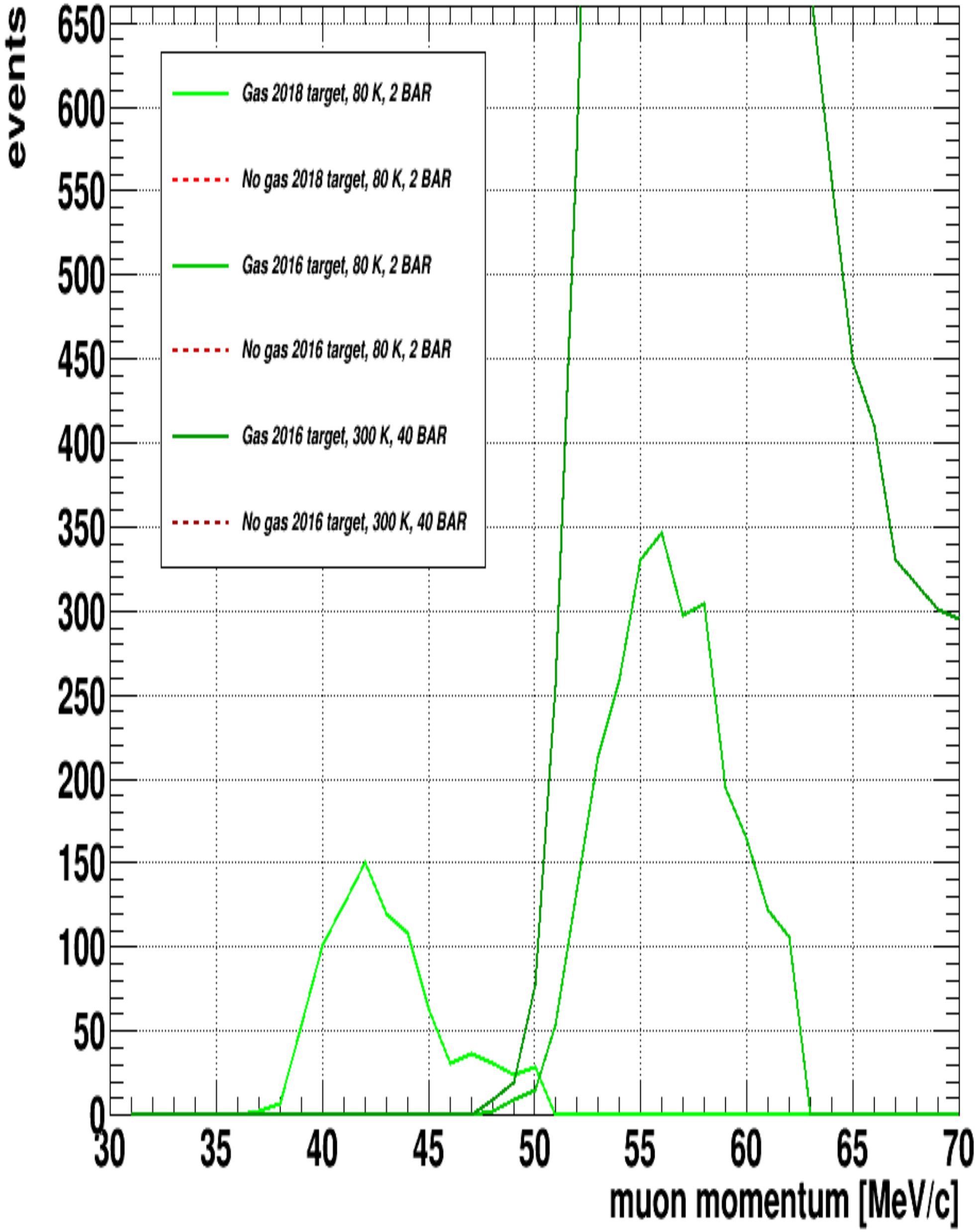
- less stopped muons
- lower momentum = less muons in beam
- & small optical cavity

Need careful optimization
of all elements

Stop in gas weighted with muons in the beam as function of p



Stop in gas assuming constant number of muons as function of p



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FAMU key elements high energy MIR laser

Tunable pulsed IR laser at λ=6.8μ

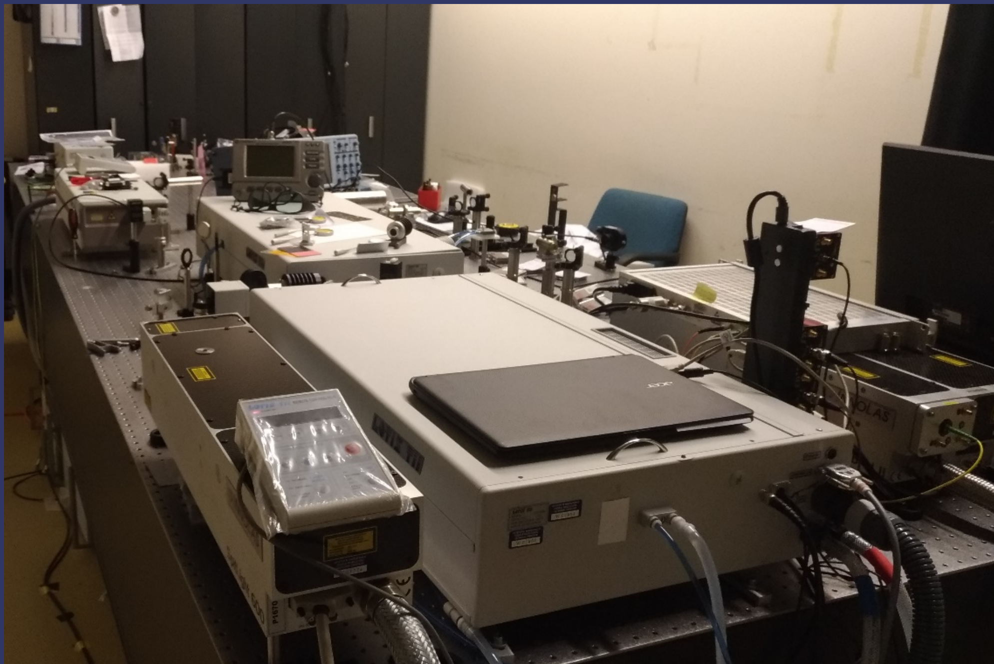
Direct difference frequency generation
in non-oxide non linear crystals using
single-mode Nd:YAG laser and tunable Cr:forsterite laser

Wavelength:	λ =6785 nm	44.22 THz
Line width:	Δλ = 0.07 nm	450 MHz
Tunability range:	6785 +- 10 nm	130 GHz
Tunability step	= 0.007nm	45 MHz
Repetition rate:	25 Hz	

Pulse Energy at 6780 nm: > 1 mJ

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

The lab at the moment



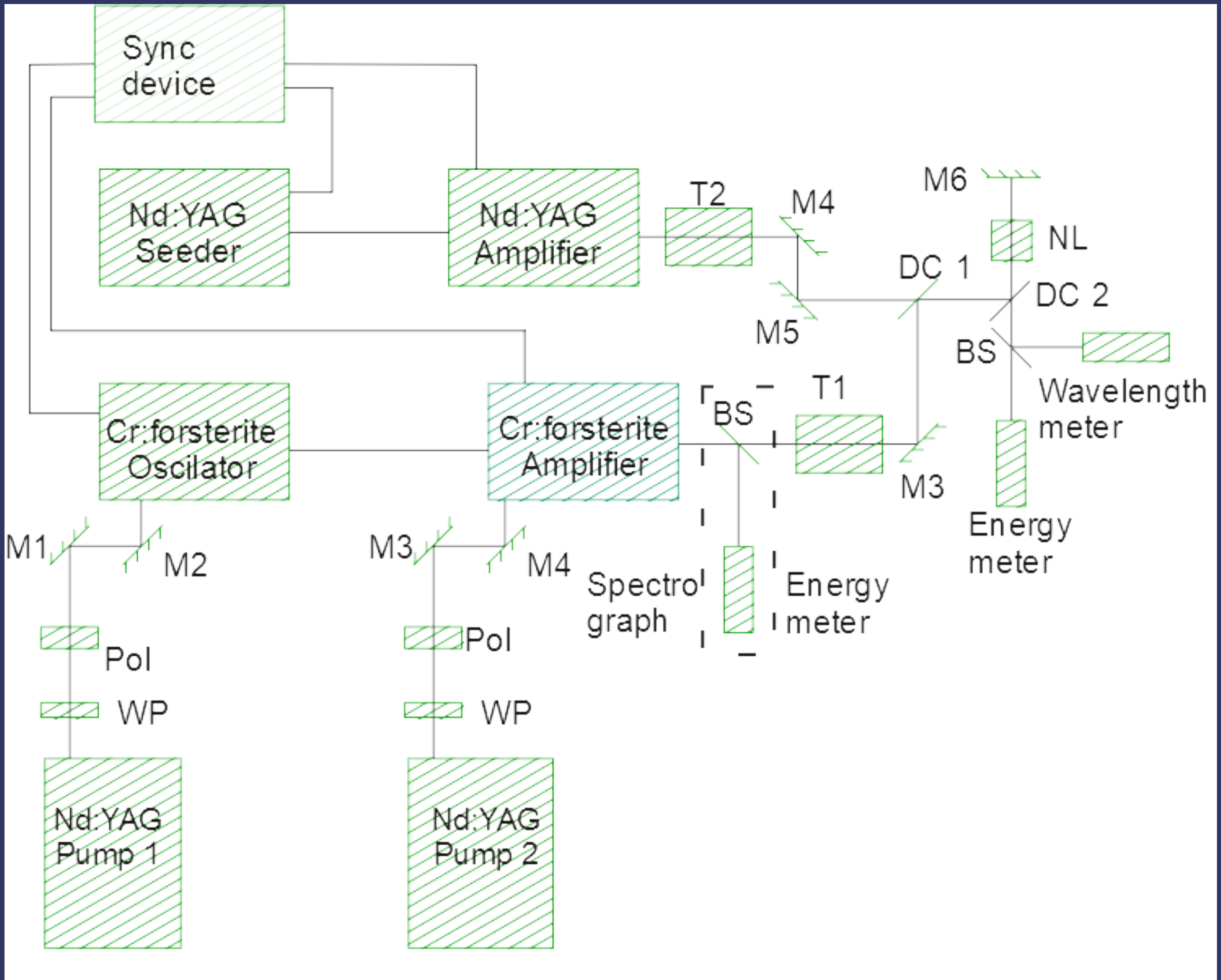
- Available - All lasers
- Available - Most optics and electronics
- Available - Most test and measurement equipment

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).

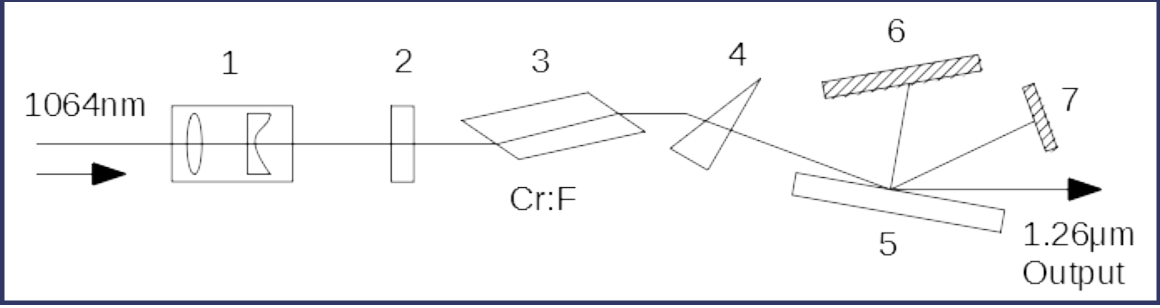
The Cr:forsterite will have linewidth max - 1pm (188MHz) and min - 0.5pm (90MHz).

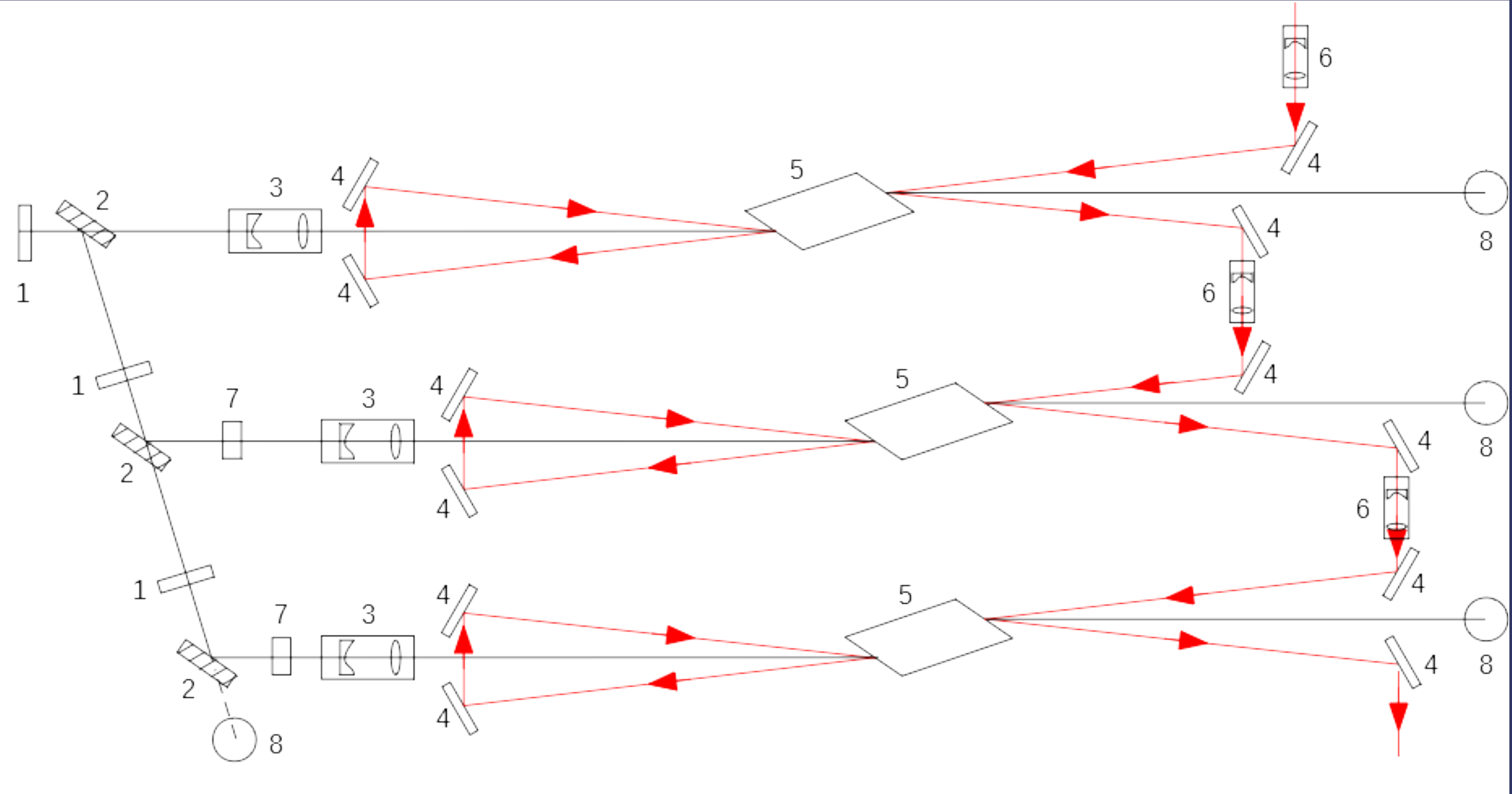
The Cr:forsterite will be tunable from 1252nm to 1272 nm which corresponds to tunability from 6500nm to 7090nm, which is 3765GHz. The required tunability 6760nm ±3nm corresponds to tunability range ~ 39GHz.



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)

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

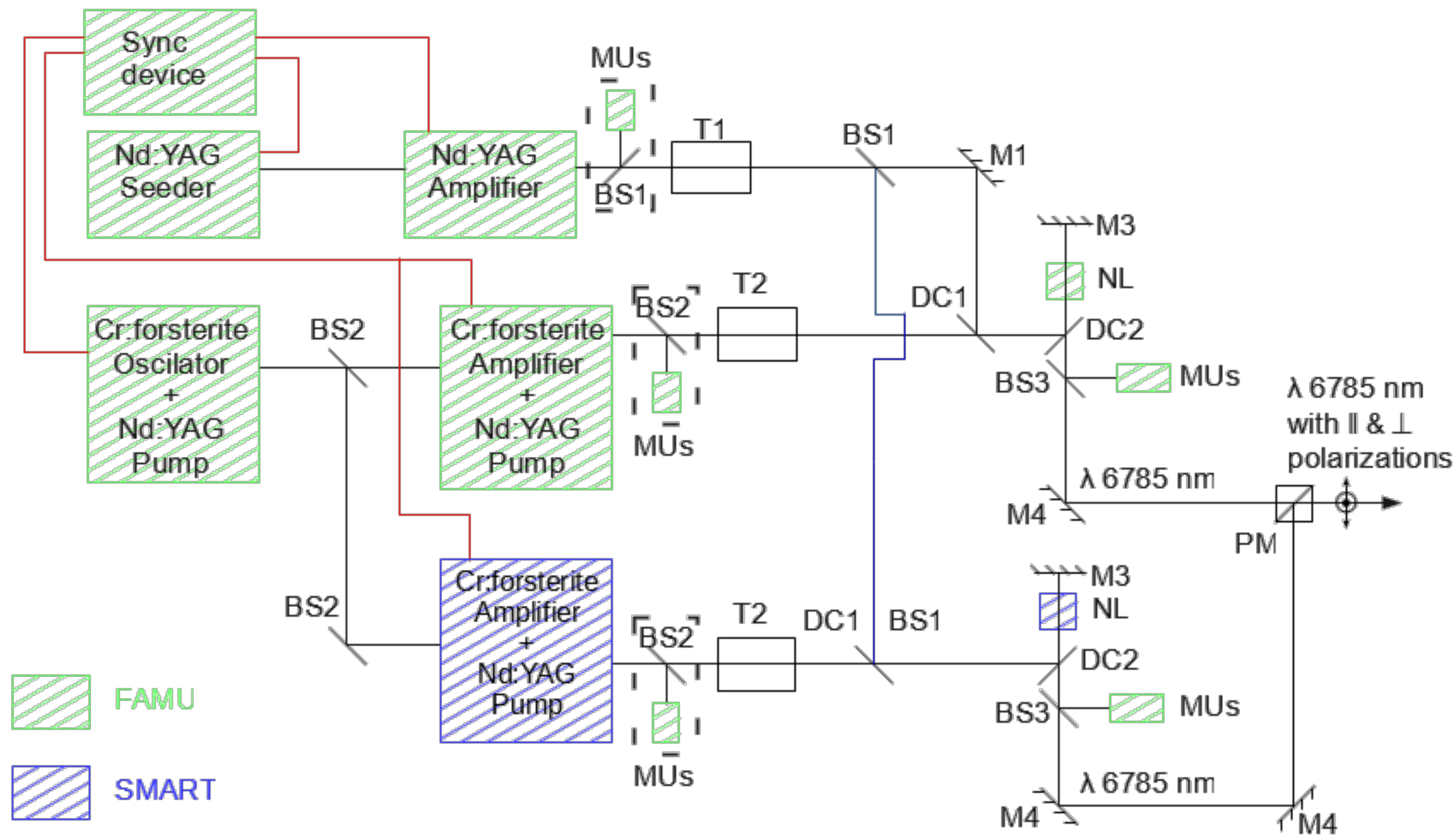
Available	**Ordered**
$LiInS_2$ - 7x7x20 mm	$LiInSe_2$ - 7x7x15 mm
$LiInS_2$ - 8x8x18	LGS – 5x5x4 mm
	$BaGa_4S_7$ – in progress

Expected energies:

$LiInS_2$ & $LiInSe_2$: 1 – 1.5 mJ

$LiGaS_2$ & $BaGa_4S_7$ ~ 2mJ

The scheme of the laser system as proposed for the SMART project – PRIN call



M1 – mirror HR 1064 nm, M2 – mirror HR 1262 nm, M3 – mirrors HR 1064&1262&6785 nm, M4 – mirror HR 6785 nm, T1 and T2 - telescopes, BS1 – beamsplitters/beamsampler 1064 nm, BS2 – beamsplitters/beamsampler 1262 nm, BS3 – beamsampler 6785 nm, DC1 - dichroic mirror (reflecting 1064 nm, transmitting1262 nm), DC2 - dichroic mirror (reflecting 1064 nm and 1262 nm, transmitting 6875 nm), NL – nonlinear crystals, MUs – measuring units: λ meters, energy meters, PM – polarization mixer

Result	Time period
CrFo oscillator linewidth and wavelength shot-to-shot	End of May
Efficiency of cooling the Cr:forsterite amplifiers' stage	MidJune
Damage threshold of the available nonlinear crystals ($AgGaS_2$, $LiInS_2$, $LiInSe_2$, LGS, ?$BaGa_4S_7$)	Mid June
Cr:forterite oscillator-amplifier stable single mode operation and linewidth	End of June
Nonlinear efficiencies of the available nonlinear crystals ($AgGaS_2$, $LiInS_2$, $LiInSe_2$, LGS, ?$BaGa_4S_7$, BGGS),	End of June
Test of wavelength meter shot to shot mode with real DFG pulses	Mid July
Preliminary parameters of the 6785 nm emission (~ 500 μJ): energy, pulse widths, linewidth, divergence, M2	End of July
Maximum (achievable) energies at 6785 nm	Mid August

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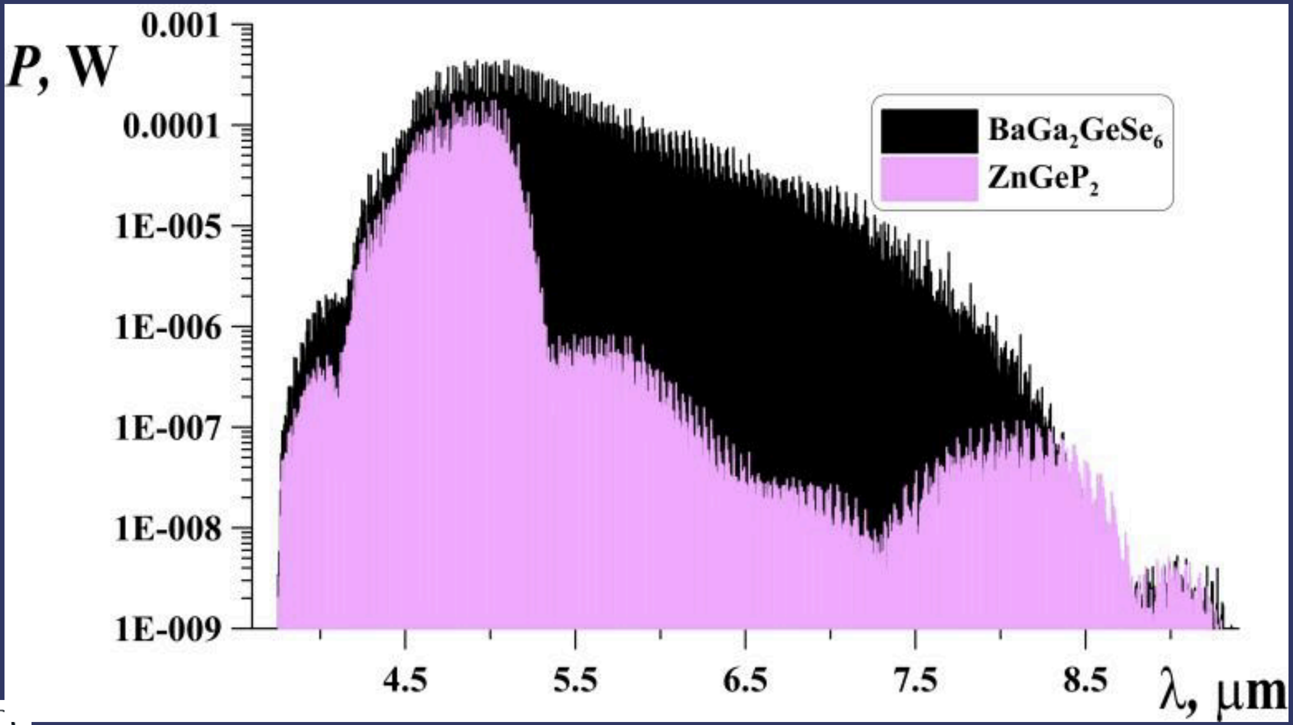
The DFG spectra for both crystals cover the spectral interval from 4 to 9 μm quite densely. The peak power of DFG radiation in BGGSe crystal (up to 0.35 mW) is higher than that of ZnGeP2 crystal (up to 0.16 mW) in the whole considered spectral range. Hence, we can come to the conclusion that under considered conditions the conversion efficiency of second stage in BGGSe crystal is at least 2 times higher than that of ZnGeP2 crystal. Thus, for the broadband two-stage frequency conversion of multi-line CO laser radiation, the new BGGSe crystal is twice more efficient than "standard" nonlinear ZnGeP2 crystal.



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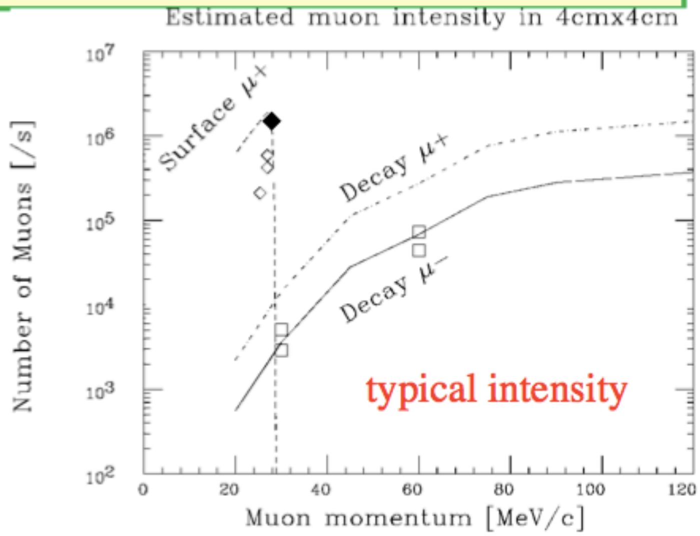
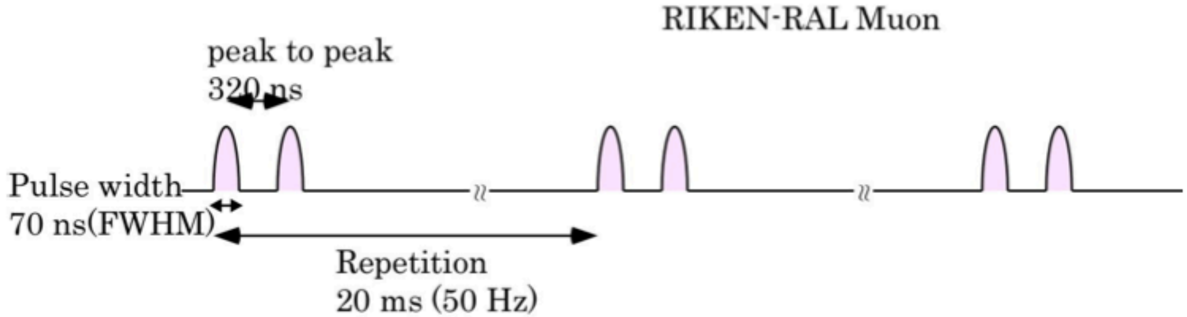
FAMU Key elements

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





beam density enhancement

- Muon beam density enhancement was observed 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.

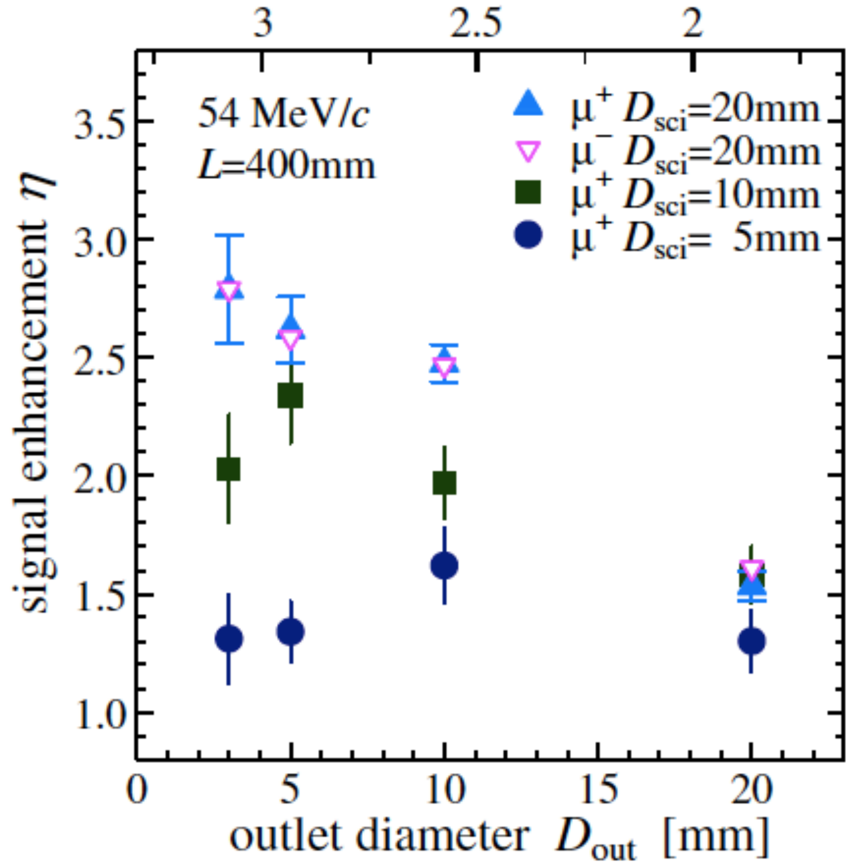


Fig. 2. (Color online) The signal enhancement factor η as a function of outlet diameter D_{out} for 54 MeV/c muons with $L = 400$ mm tubes for $D_{sci} = 5$, 10, and 20 mm. The error bar includes statistical and systematic errors (see text). Data points with "T" shape error bar are the mean of multiple 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 also in FAMU such a density enhancement, thus recovering inside the gas target the part of the beam otherwise lost .

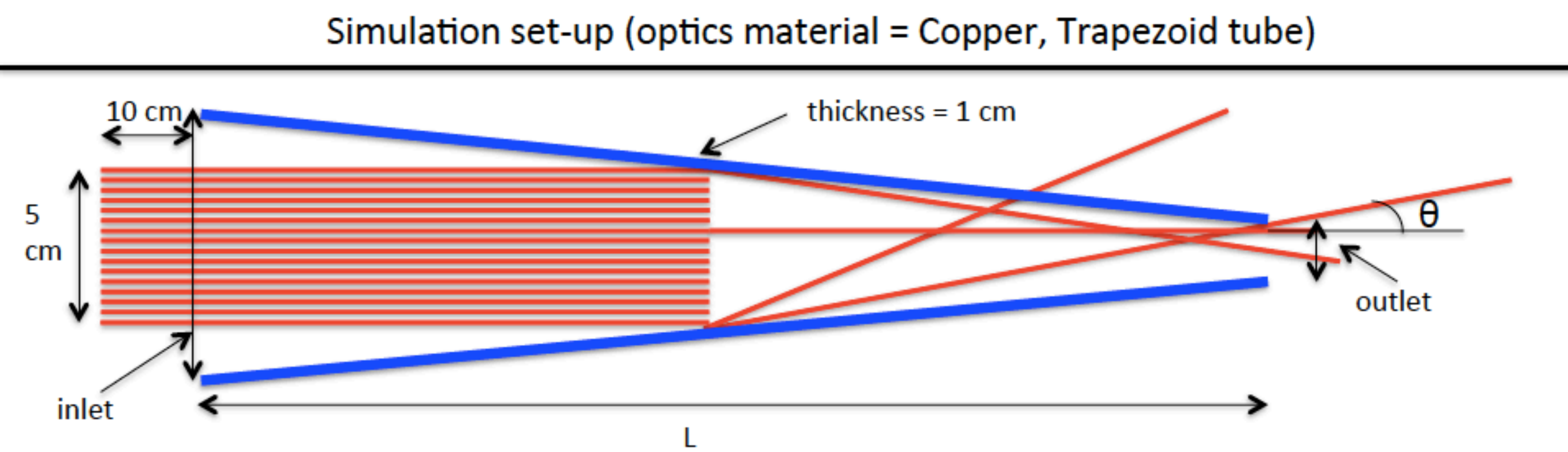
- We profited of a full day of run with RIKEN-RAL beam in Port 1 in March 2018 to collect data to be compared with GEANT4 simulation.

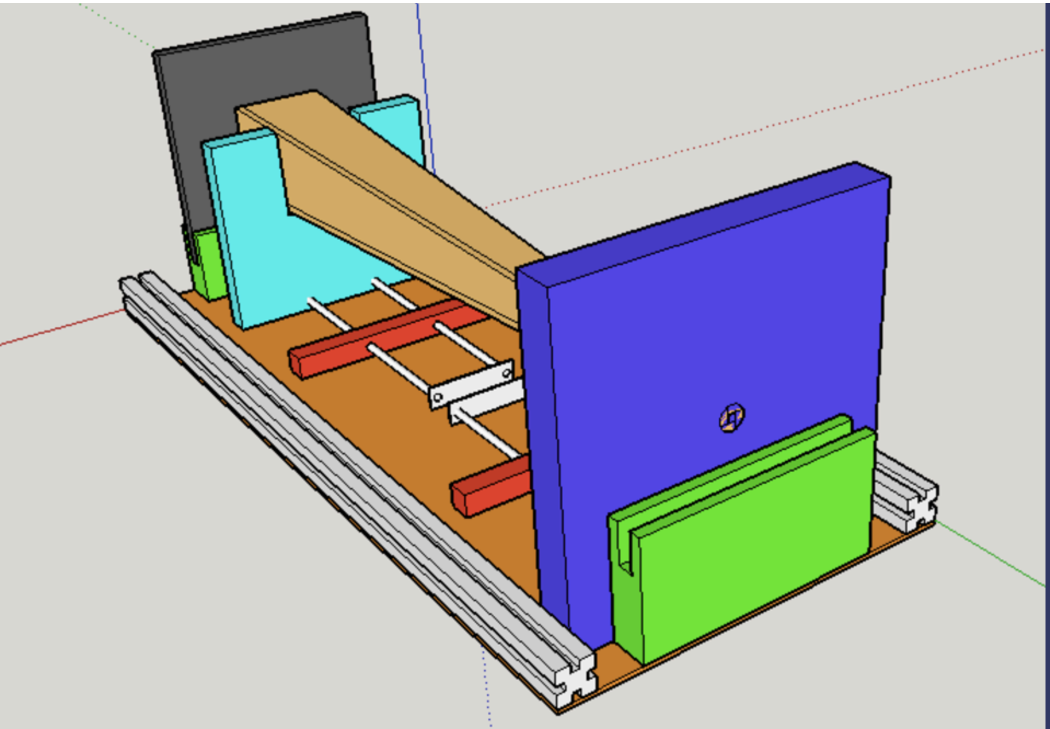
- Several experimental configurations were realized, profiting of the presence of three hodoscopes to monitor the beam intensity before and after the focusing optics: one made of polished copper, the other one of gold plated glass.

θ

outlet

FAMU focusing team



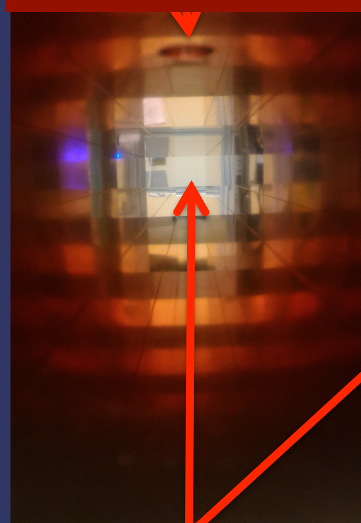


- Copper focusing optics realized in Pavia workshop and then assembled in Port1: mylar and kapton foils used for vacuum tightness. Copper optics dimensions (inlet: 3 cm, outlet: 1 cm, length: 1 m) were chosen after preliminary GEANT4 simulation. Dry scroll pump allowed to operate it with a stable pressure of 23 mbar.

- Another optics with the same dimensions has been realized with gold-plated glass by INAF-Brera group, having expertise with optics for X-ray focusing onto satellites.


Copper optics before assembly

Inlet for tube evacuation


1 cm outlet


Final mounting with the three hodoscopes

- 1 full day of data taken with several setups:

  - ✓ Muon beam momentum scan: from 30 MeV/c to 80 MeV/c.
  - ✓ Use of a 1.4 cm polyethylene thickness before the optics to reduce the beam momentum.
  - ✓ Use of several foils of known thickness for calorimetric beam momentum measurements.
  - ✓ Copper optics in air and vacuum.
  - ✓ Glass optics in air.

- A total of about 100 runs, 5000 events each, has been collected for further analysis.
- The goal is the measurement of beam muon flux starting from the charge deposited by the muons inside the hodoscopes.

- To get the muon flux, two ingredients are needed:

  1. The hodoscope ADC calibration → cosmic ray data from test run available.
  2. Correction for low energy (non m.i.p.) muons of RIKEN-RAL → GEANT4 simulation of all setups is ongoing to evaluate the muon momentum in the three hodoscopes.

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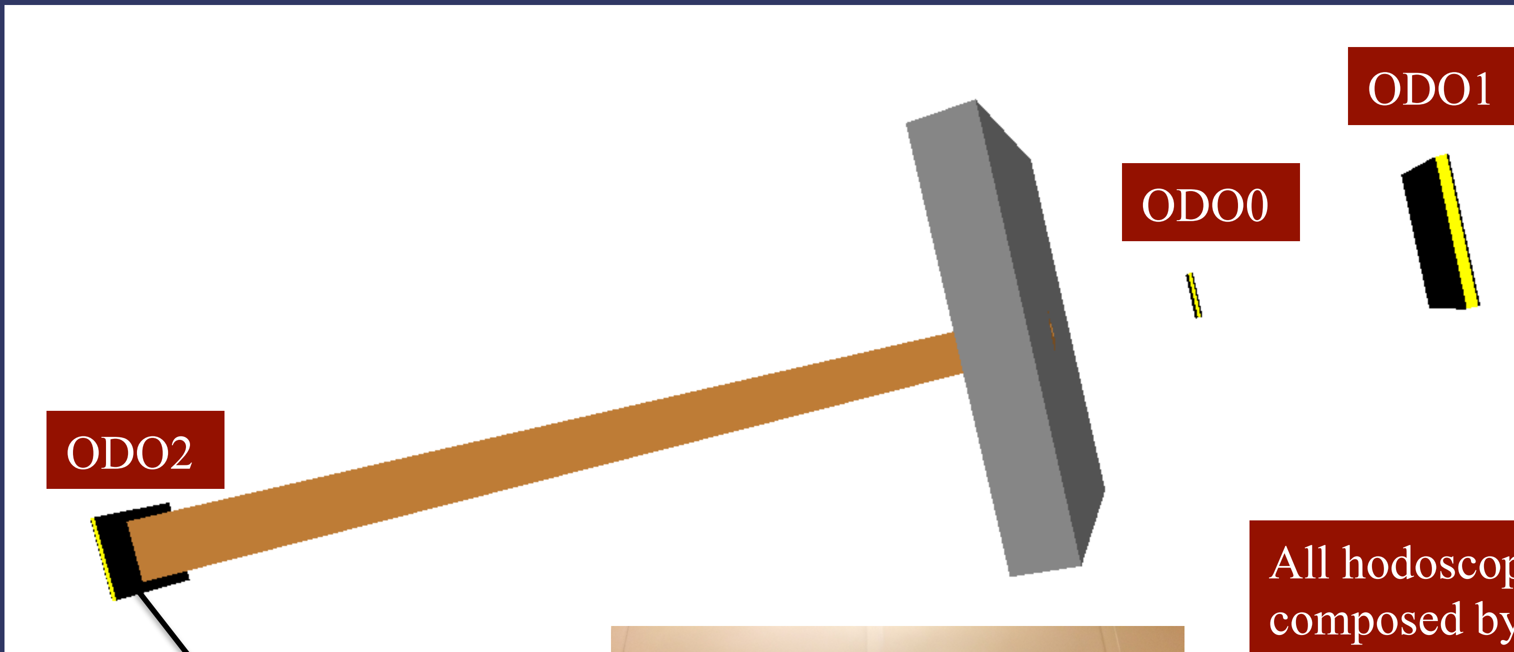
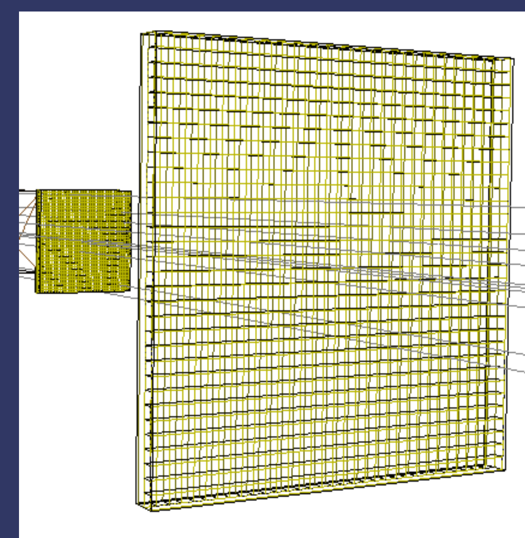
Geometry set-up (Copper optics) – G4 mass model



All hodoscopes are composed by 32x32 bars

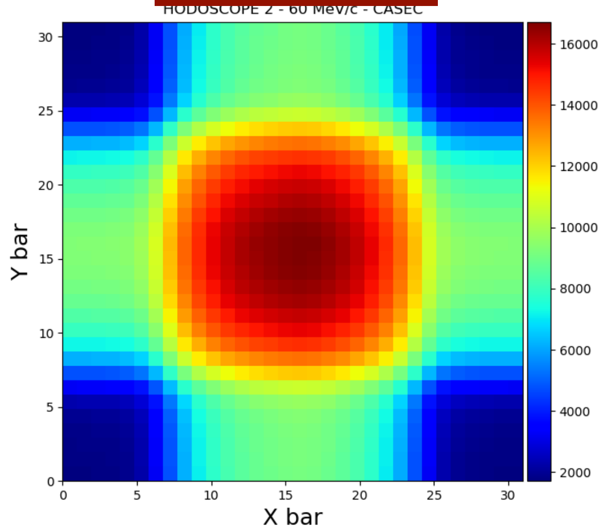
ABS in black



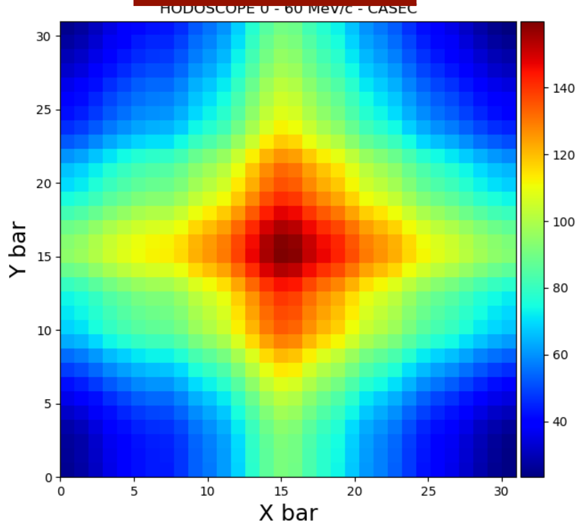
Case Copper optics – AIR – 60 MeV/c

Simulatio

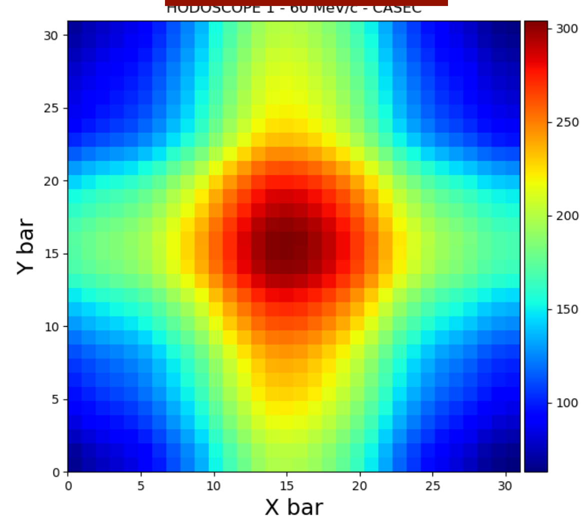
ODO2



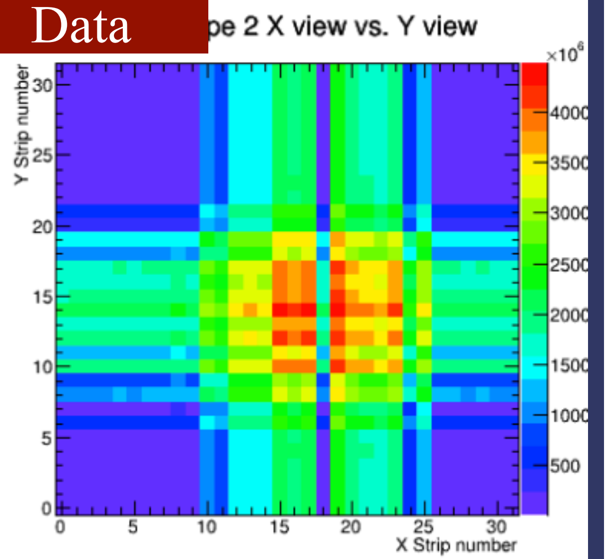
ODO0

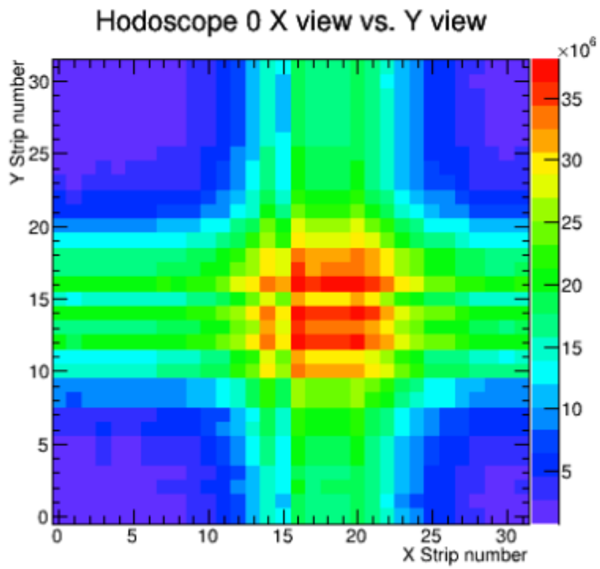


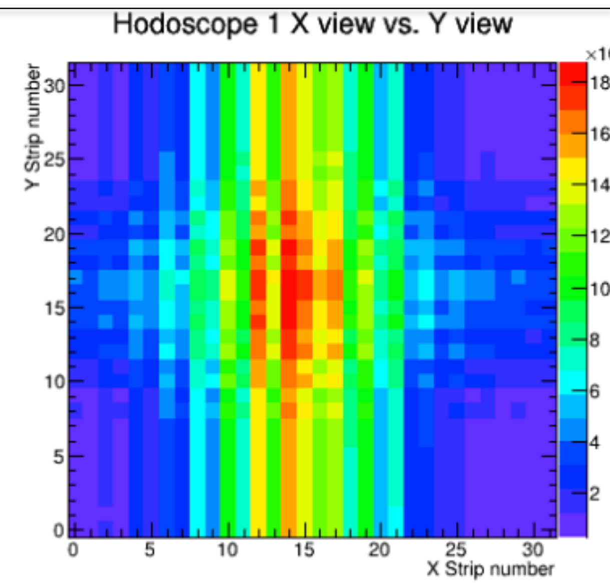
ODO1



Data



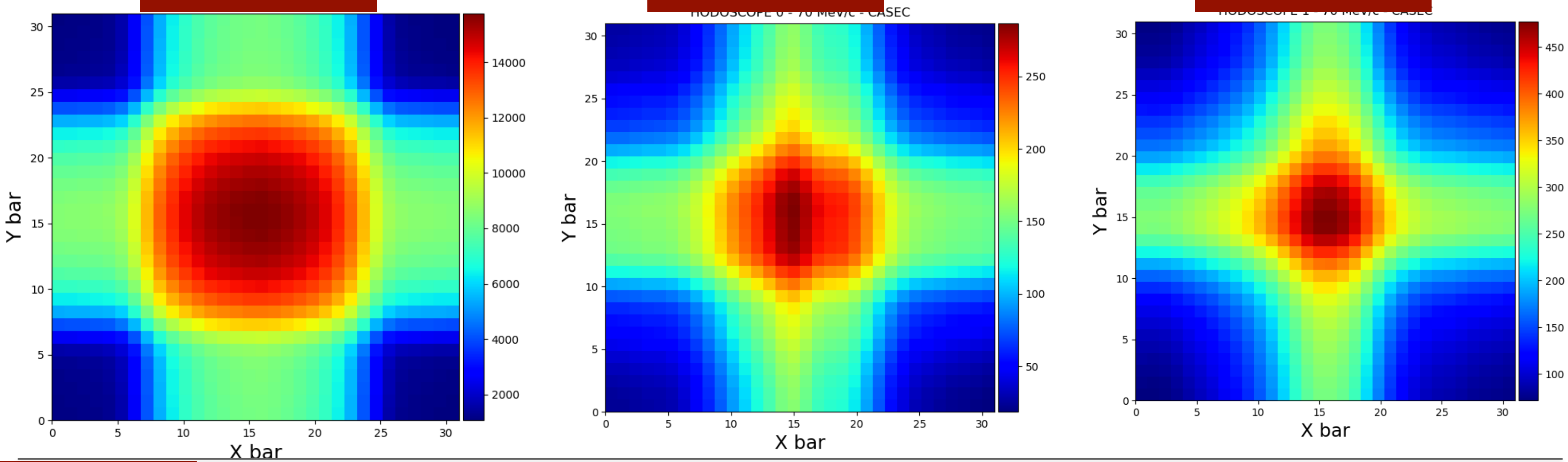




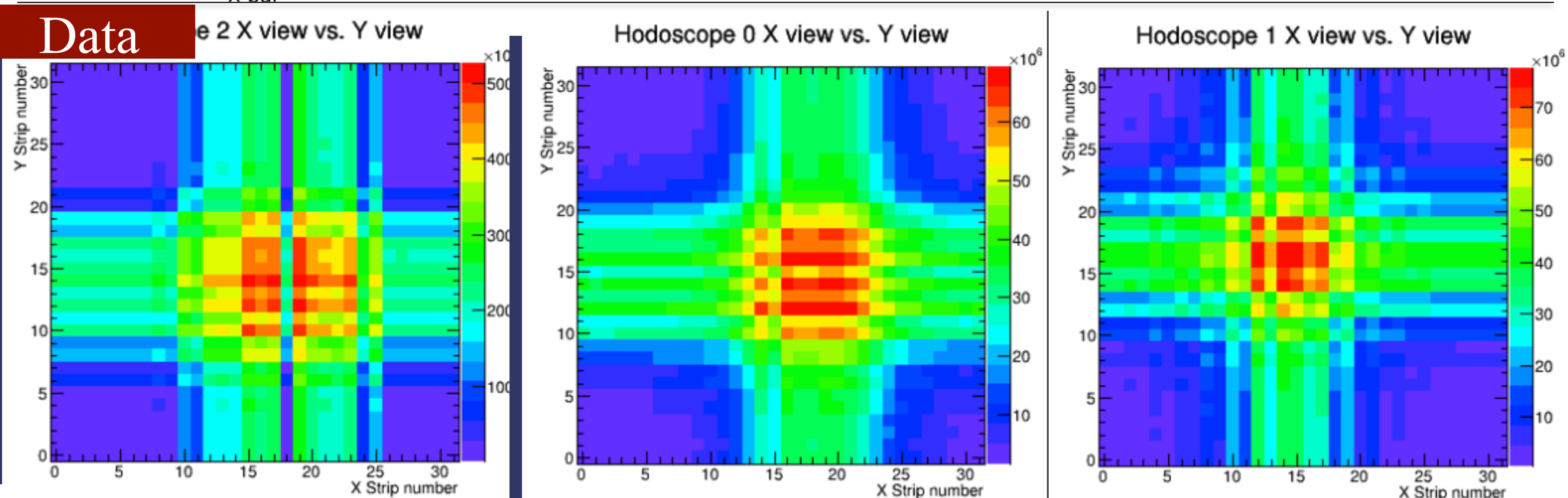
Case Copper optics – AIR – 70 MeV/c

Simulat

ODO2 ODO0 ODO1



Data



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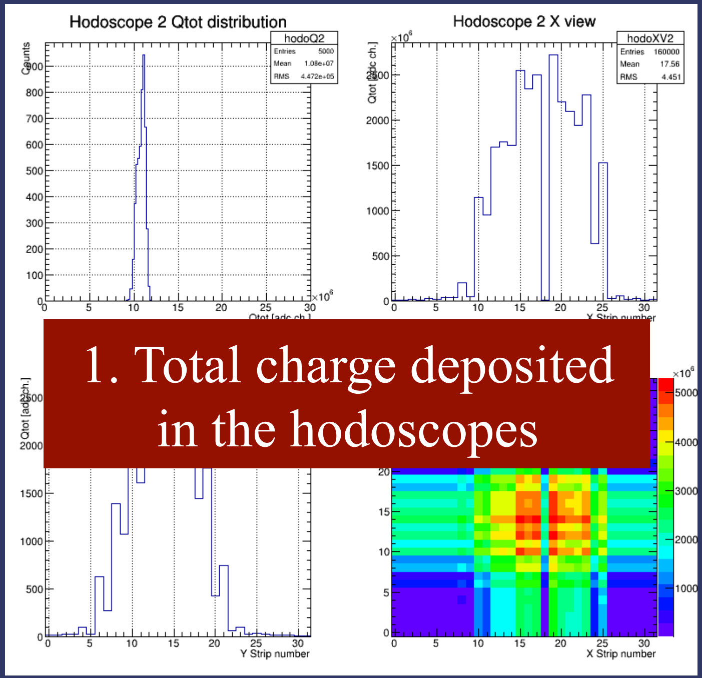
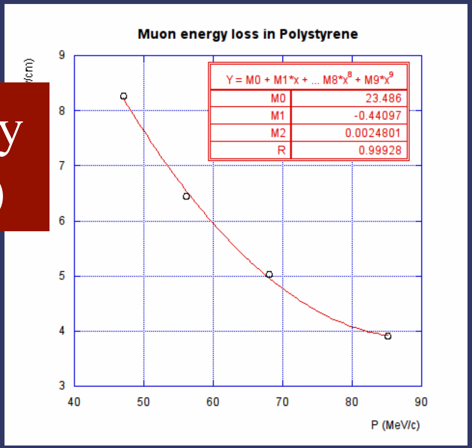
Next steps



1. Total charge deposited in the hodoscopes

2. Calibration with cosmic ray data

3. Correction for low energy beam muon (G4 simulation)



- First evaluation of beam muon flux, to check the beneficial effects of the focusing optics and to choose the best beam muon momentum to operate FAMU experiment.
- Definition of the new cryogenic target as a function of the results from the focusing measurements.
- Possible new test in Port1, with the realization of a more refined focusing optics.

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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**

-H_2 compatible

... 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 wi
radiative shield

-304L SS gas charging tube

-304L SS cooler cold-end support

-G10 mechanical strut

-Two Cu straps for cooling

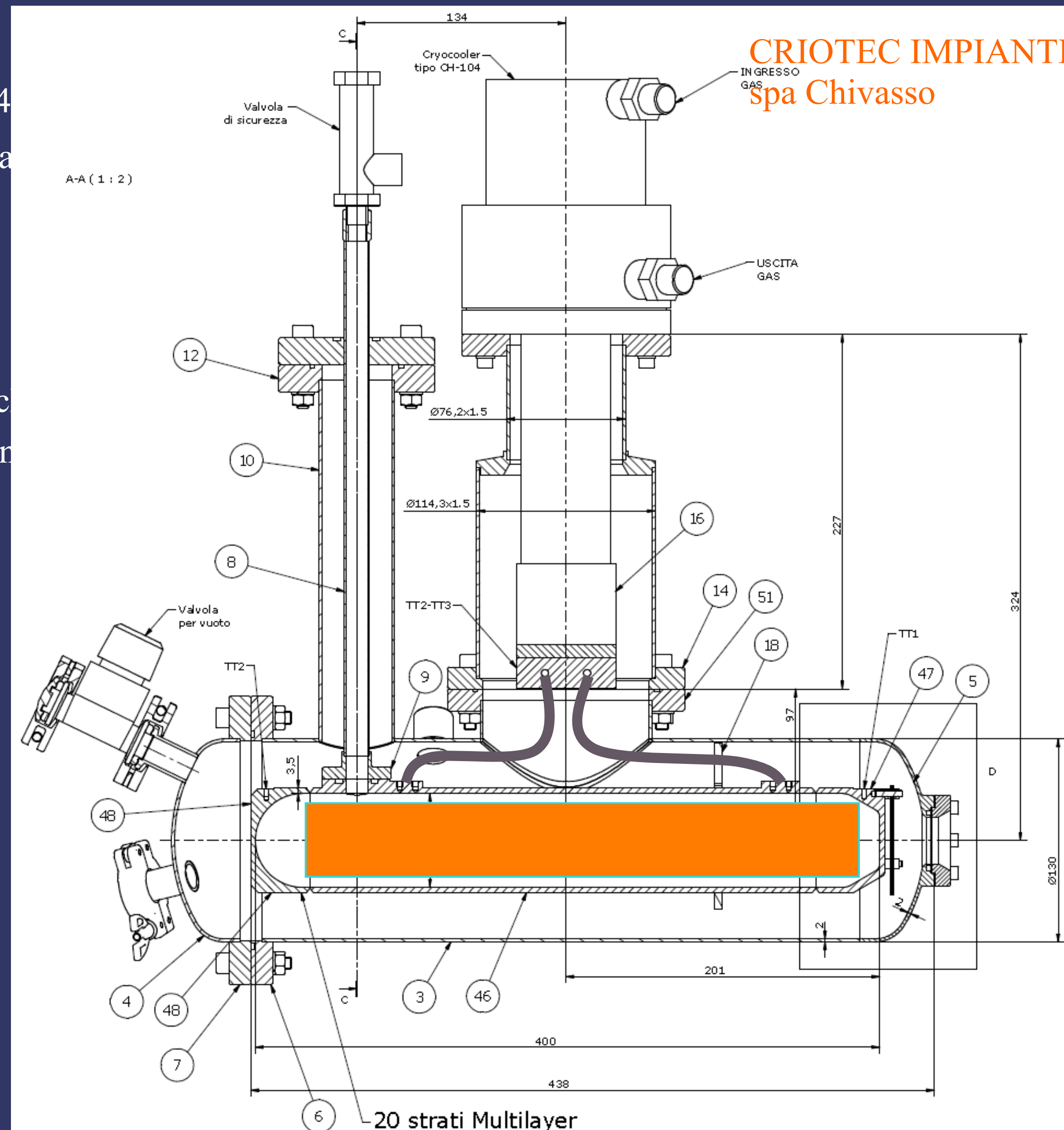
Vacuum vessel = outer cylinder (P atm)

-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



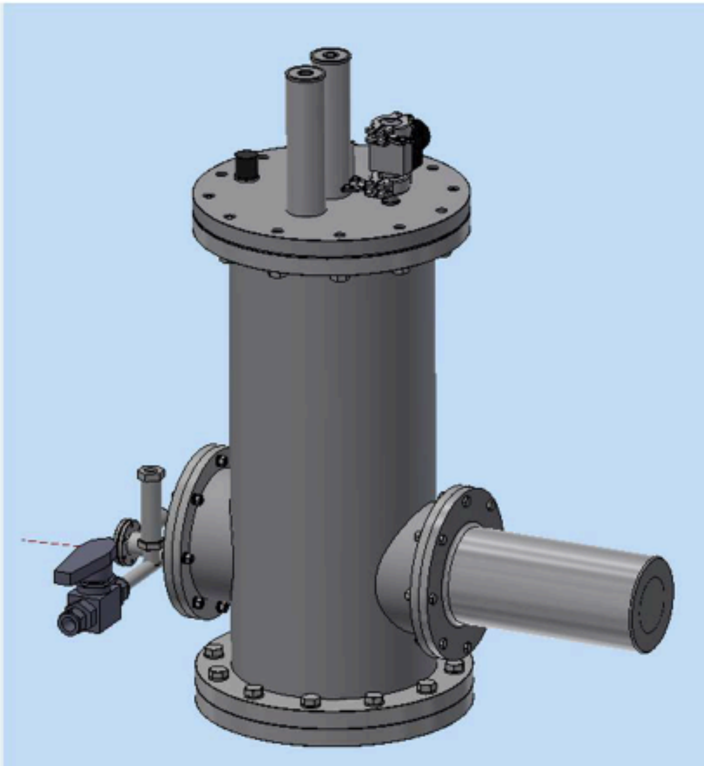
beam

Target in lab

2018 target solution under study

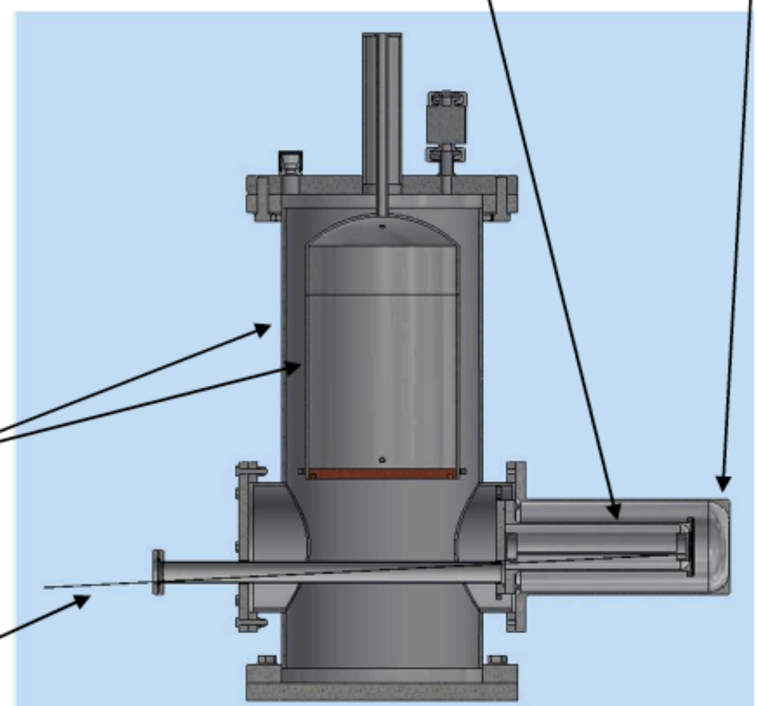
Giotec IMPIANTI S.p.A.

Affinamento studio



Analizzata la possibilità di evitare la flangia di estremità del Target

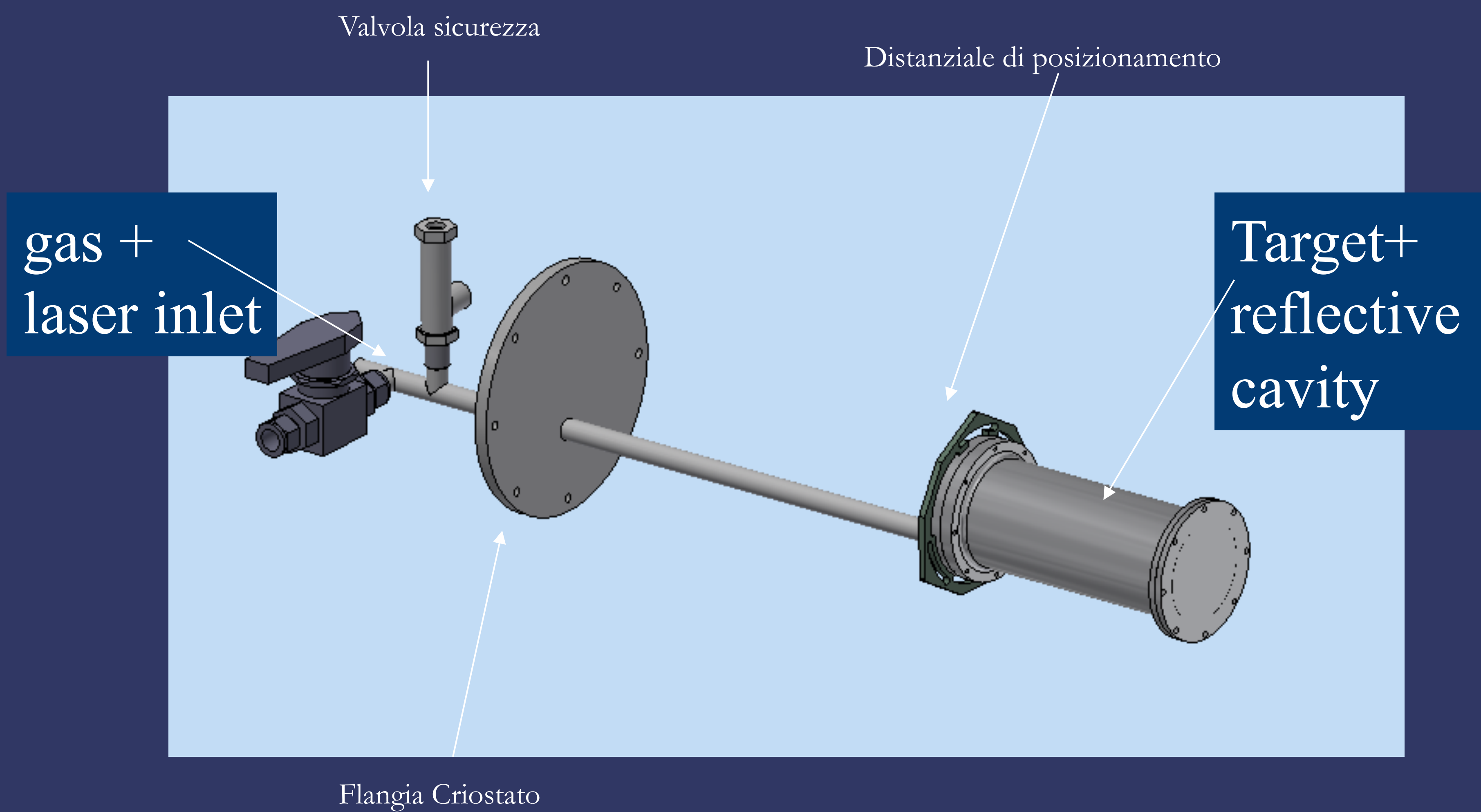
Studio copertura Target



Nell'ottica di ridurre la lunghezza di percorso del laser, i diametri del criostato e del serbatoio sono stati ridotti a scapito della loro altezza

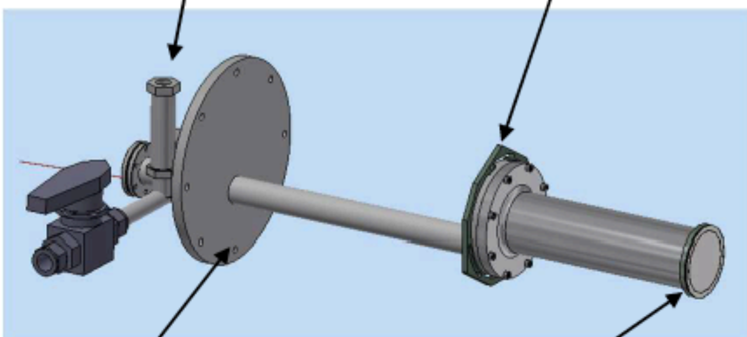
Analizzato percorso laser con inclinazione 0.050 rad

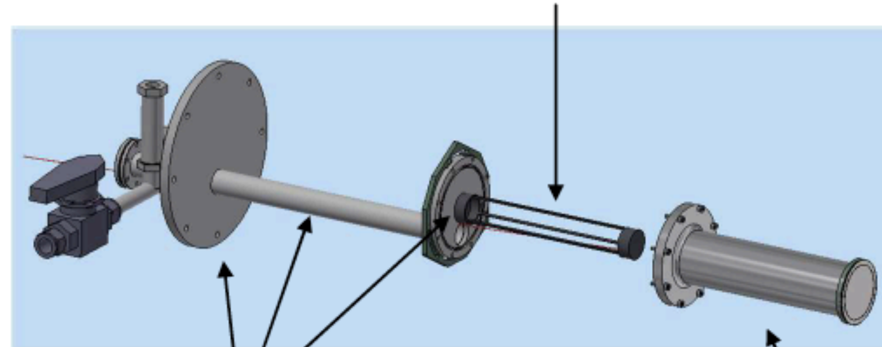
low temperature gas target
very preliminary approach for simulation studies

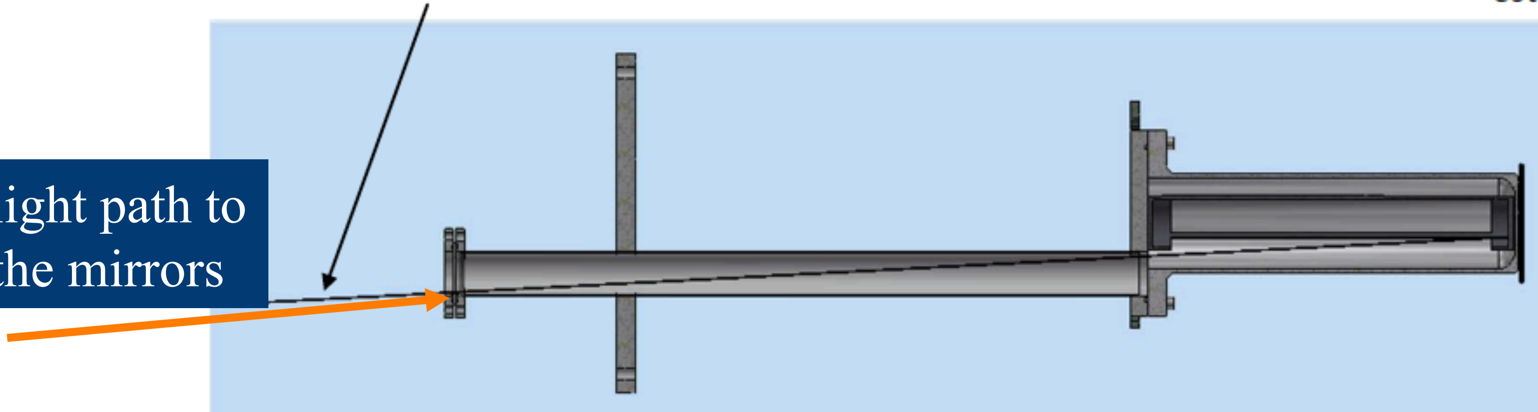


IMPIANTI S.p.A.

Very preliminary approach under simulation studies





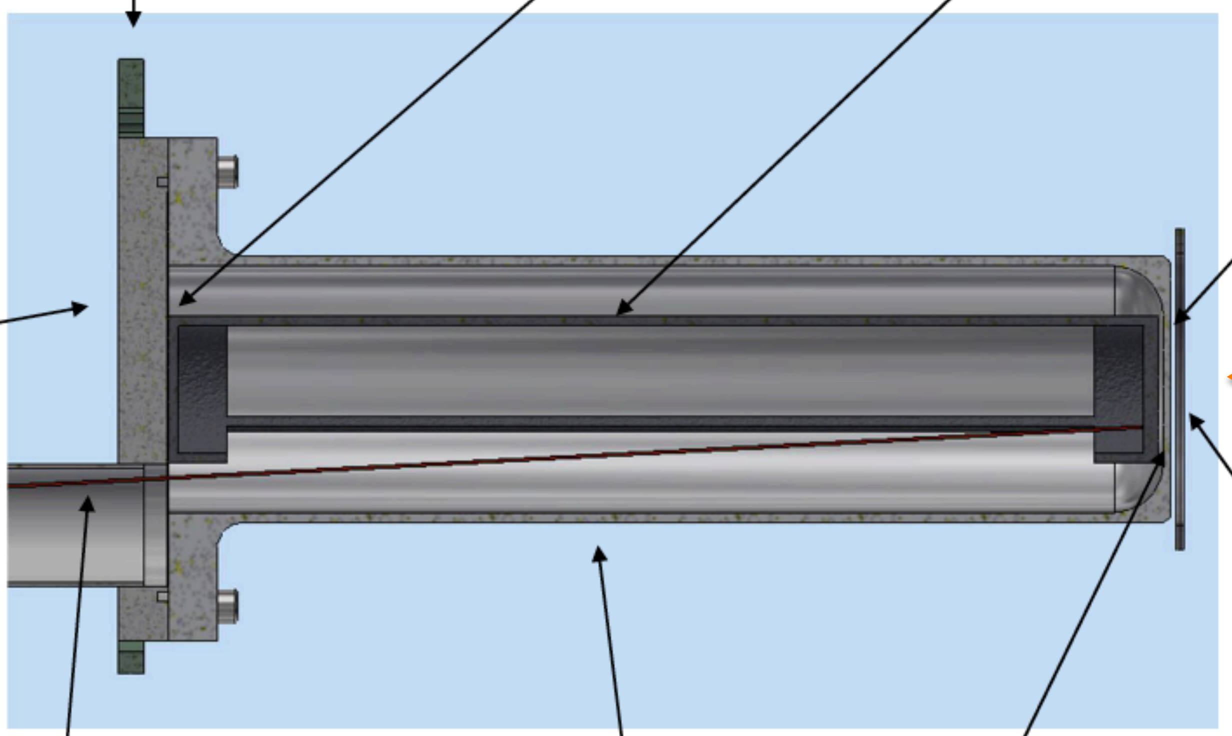


RICHIESTE:

- possibilità di ridurre angolo massimo del laser (magari a 0.030 rad) in modo ridure i diametri del tubo e della flangia del Target

Giotec IMPIANTI S.p.A.

Very preliminary approach under simulation studies



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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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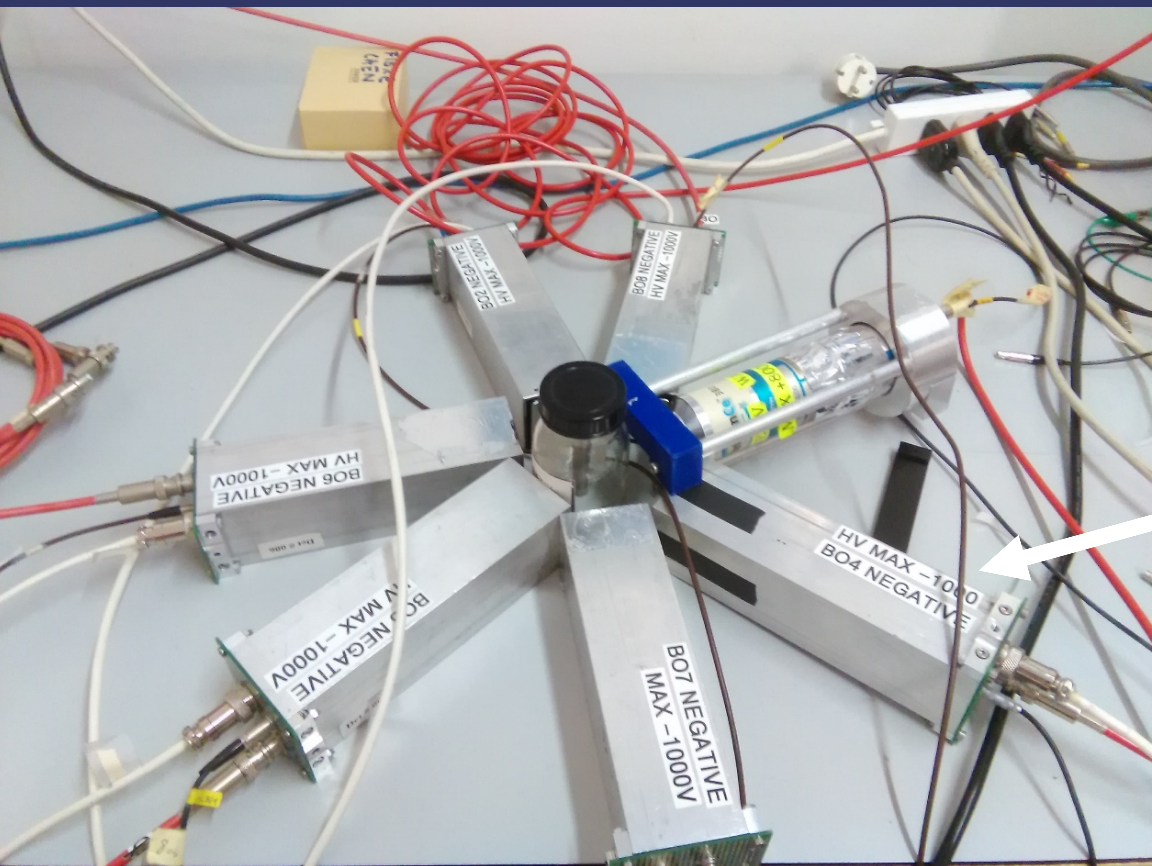
Detectors: suited for time-resolved X-ray spectroscopy

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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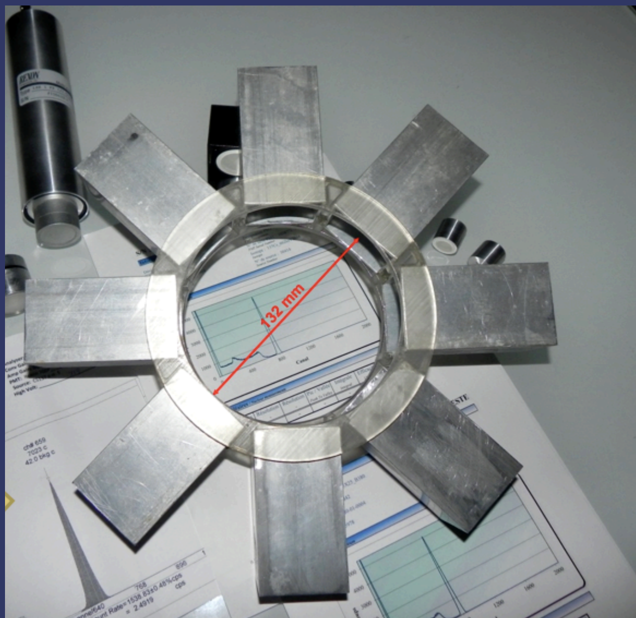
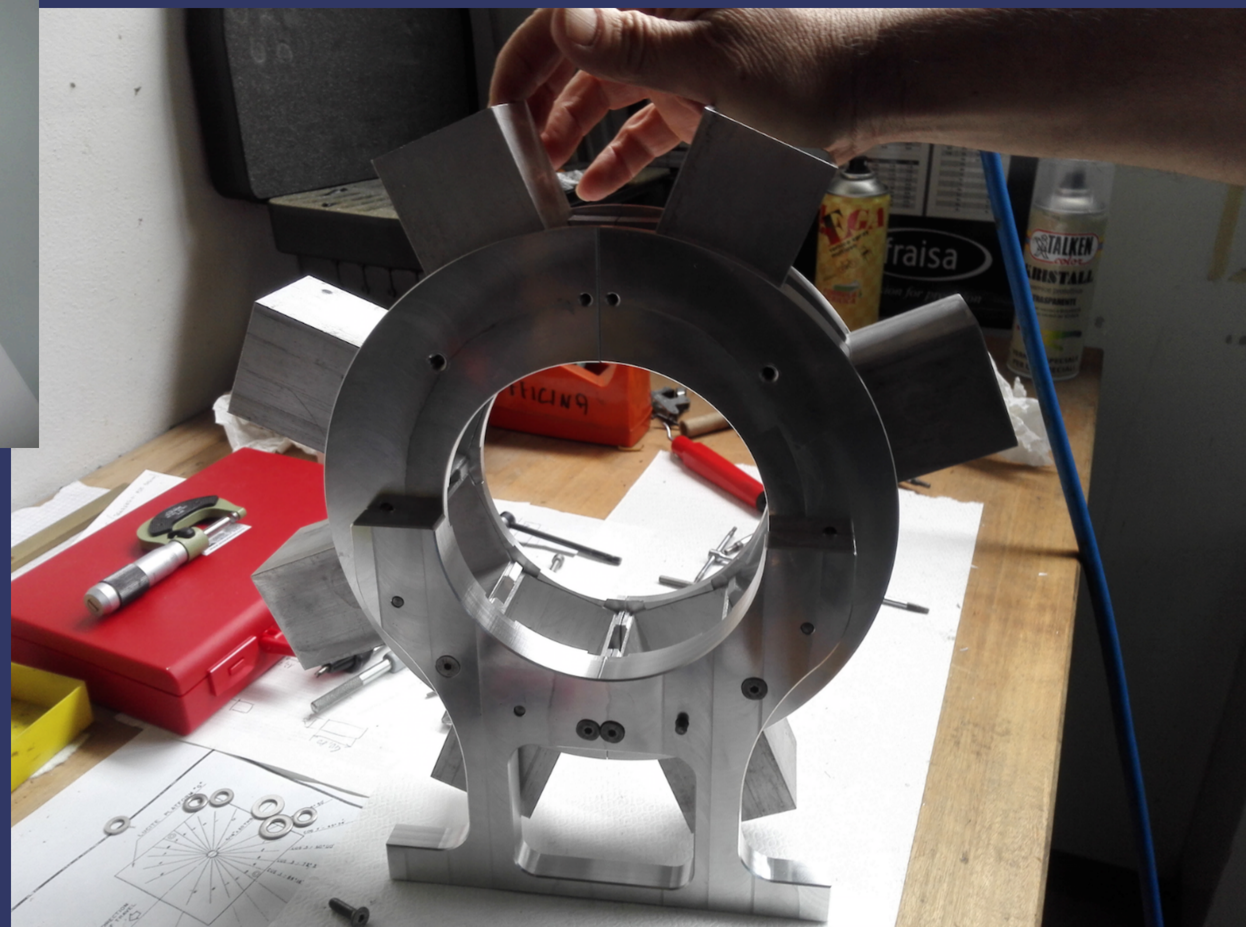
Star-shaped support for detectors



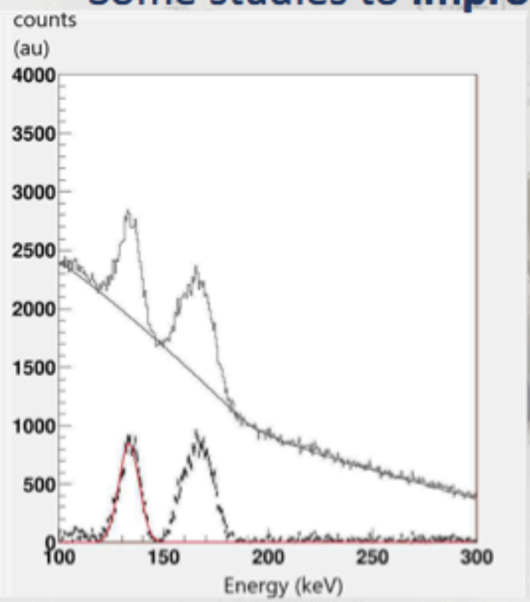


Last steps Bologna detectors

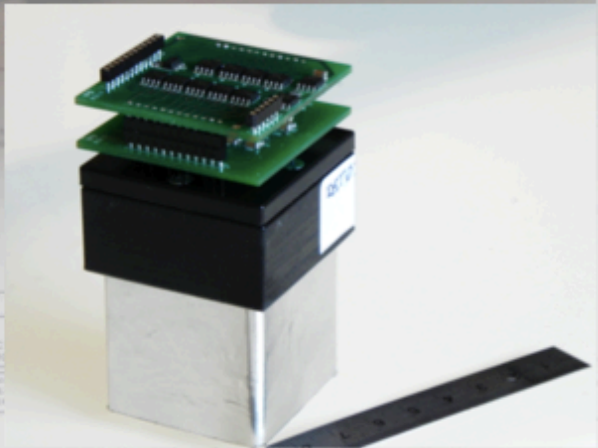
LaBr3 + (UBA) Hamamatsu photomultiplier

- **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

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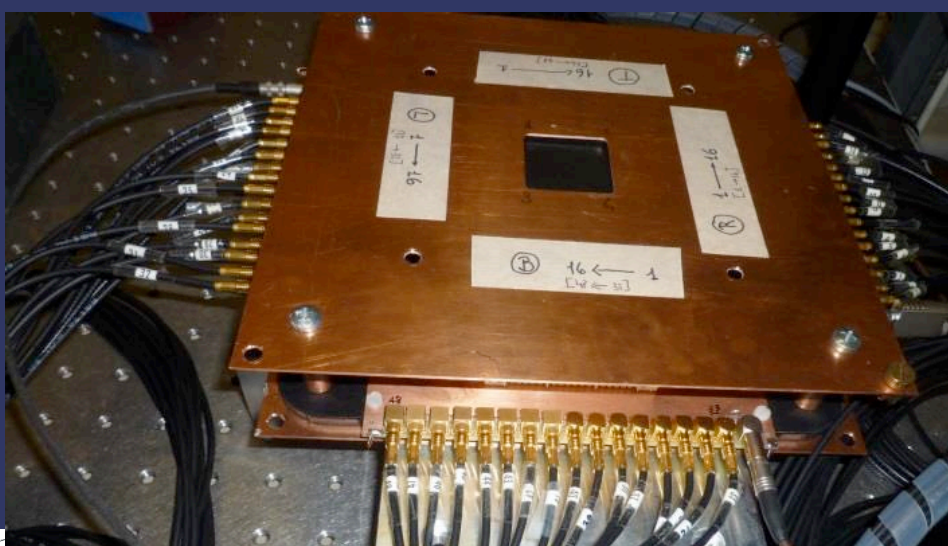
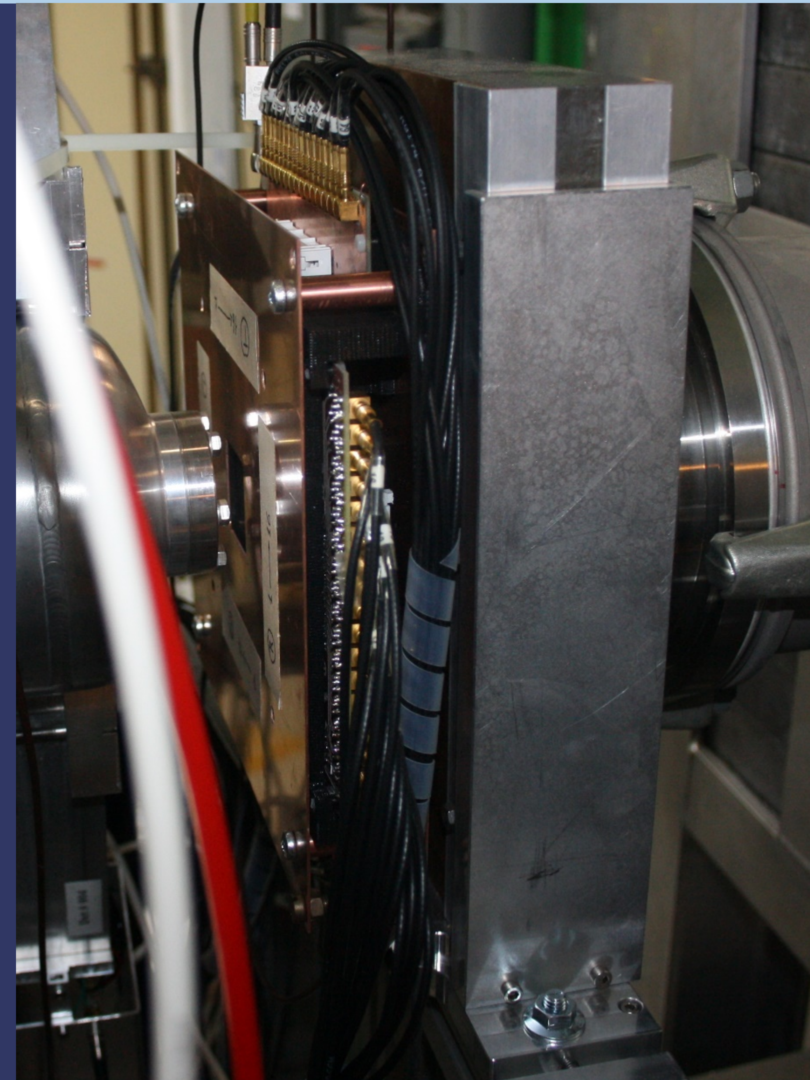
Hodoscope for beam shape monitoring

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

the FAMU collaboration

JINST
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PUBLISHED: *May 12, 2016*

Steps towards the hyperfine splitting measurement of the muonic hydrogen ground state: pulsed muon beam and detection system characterization

The FAMU collaboration

A. Adamczak,[a] G. Baccolo,[b] D. Bakalov,[c] G. Baldazzi,[d] R. Bertoni,[b] M. Bonesini,[b] V. Bonvicini,[e] G. Campana,[d] R. Carbone,[e] T. Cervi,[g,h] F. Chignoli,[b] M. Clemenza,[b] L. Colace,[i,j] A. Curioni,[b] M. Danailov,[e,f] P. Danev,[c] I. D'Antone,[d] A. De Bari,[g,h] C. De Vecchi,[h] M. De Vincenzi,[i,k] M. Furini,[d] F. Fuschino,[d] K.S. Gadedjisso-Tossou,[e,l] D. Guffanti,[e] A. Iaciofano,[i] K. Ishida,[m] D. Iugovaz,[e] C. Labanti,[d] V. Maggi,[b] A. Margotti,[d] M. Marisaldi,[d] R. Mazza,[b] S. Meneghini,[d] A. Menegolli,[g,h] E. Mocchiutti,[e] M. Moretti,[b] G. Morgante,[d] R. Nardò,[h] M. Nastasi,[b] J. Niemela,[l] E. Previtali,[b] R. Ramponi,[n] A. Rachevski,[e] L.P. Rignanese,[d] M. Rossella,[h] P.L. Rossi,[d] F. Somma,[i,o] M. Stoilov,[c] L. Stoychev,[e,l] A. Tomaselli,[h,p] L. Tortora,[i] A. Vacchi,[e,q,1] E. Vallazza,[e] G. Zampa[e] and M. Zuffa[d]

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2016 JINST 11 P05007

The FAMU
Yearly Collaboration Meeting Trieste

Summary

The FAMU project is progressing towards the spectroscopy of the hyperfine splitting (hfs) in the 1S state of muonic hydrogen $\Delta E_{hfs}(\mu^{-}p)_{1S}$

through a measurement of the muon transfer rate to oxygen

open problems progressively faced:

- *first measurement* of the temperature dependent muon transfer rate to Oxygen
- *innovative* and powerful laser system
- *optimized intense pulsed beam target and optical system*
- *best detectors* for energy and time observation

Looking forward to perform the initiate the spectroscopic measurements 2018-19.