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FAMU

The FAMU experiment at RIKEN RAL for a precise measurement of the proton Zemach radius

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On behalf of the FAMU Collaboration

The proton radius puzzle

	Charge radius r_{ch} (fm)	Zemach radius R_Z (fm)
e^--p scattering & spectroscopy	0.8751(61)	1.037(16) Dupays et al 03 1.086(12) Friar&Sick 04 1.047(16) Volotka et al. 05 1.045(4) Distler et al. 11
μ^-p Lamb shift spectroscopy	0.84087(39)	1.082(37) Antognini et al 13

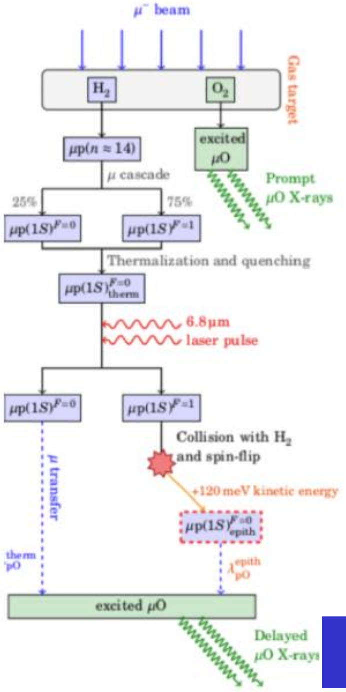
Spatial charge and magnetic moment distributions $\rho_E(r)$, $\rho_M(R)$ in non-relativistic picture .

The complete set of moments $R^{(k)}_{E,M}=\int\rho_{E,M}(r)r^k d^3r$ is related to the observable quantities:

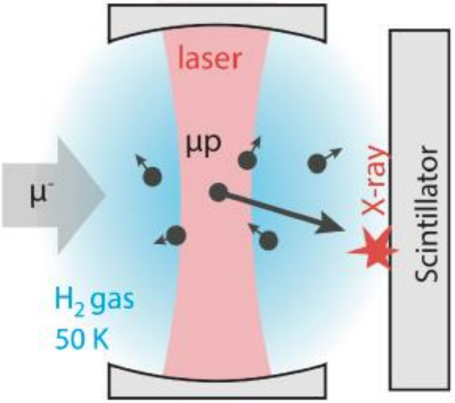
$$r_{ch}=(R^{(2)}_E)1/2$$
$$R_Z=\int (\int\rho_E(r')\rho_M(r-r')d^3r'r)d^3r$$

Three μp-HFS projects

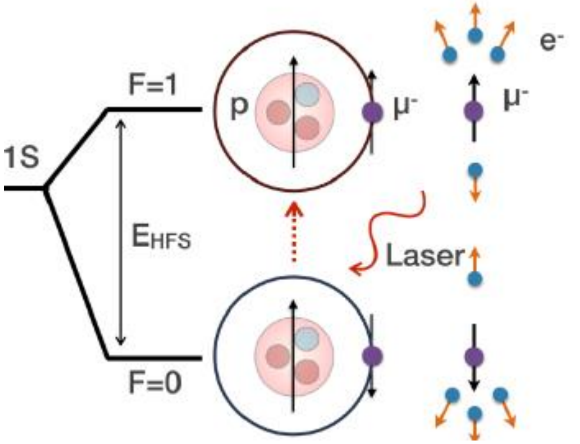
FAMU



PSI

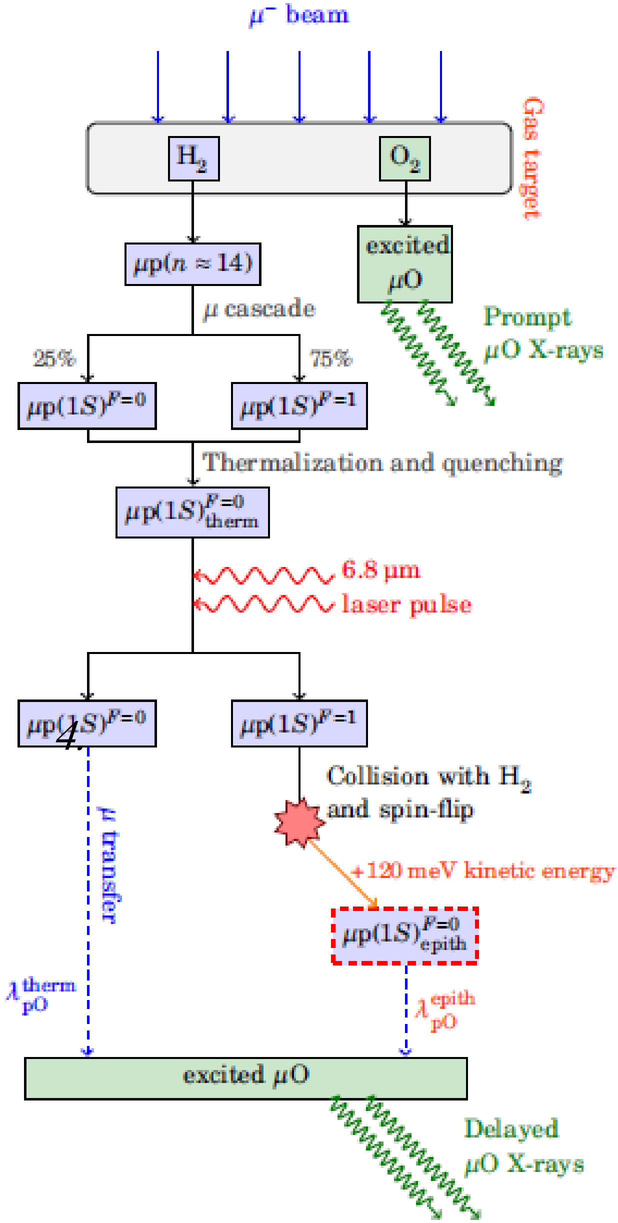


RIKEN



	FAMU (UK)	PSI (CH)	RIKEN (JP)
Method	transfer	diffusion	asymmetry
Laser	DFG-MIR 1-5 mJ		QCL-seeded ZGP-OPO > 20 mJ in development
Detection	X-rays	X-rays	electrons
Beam	pulsed	continuos	Pulsed

The FAMU experimental method



1. Create muonic hydrogen in a hydrogen gas target and wait for its thermalization;

2. Shoot laser at resonance (λ_0 ~6.8μ) spin state of μ^-p from 1^1S_0 to 1^3S_1, spin is flipped: μ^-p(↑↓) → μ^-p(↑↑) ;

3. De-excitation and acceleration: μ^-p(↑↑) hits a H atom. It is depolarized back to μ^-p(↑↓) and is accelerated by ~120 meV ;

4. μ^- are transferred to heavier gas contaminant (O_2) with energy-dependent rate;

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

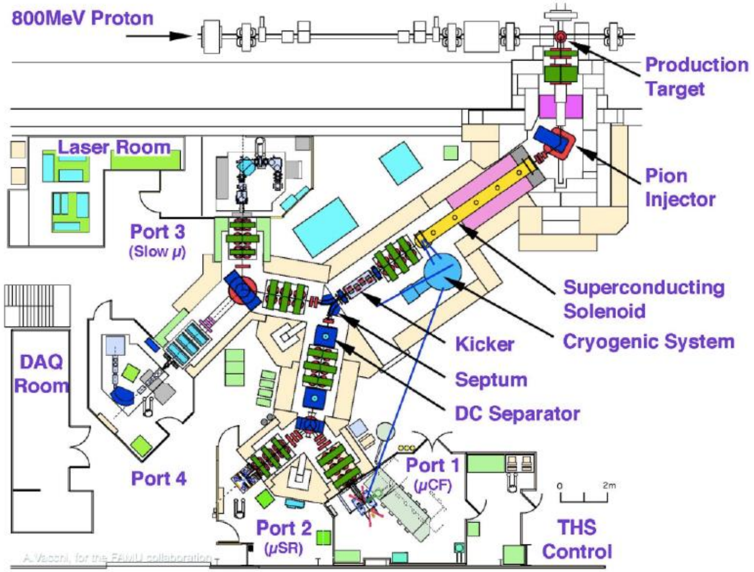
6.At this point ΔE_{HFS} may be determined from:

λ_0=hc/ΔE^{1S}_{HFS} ~ 6.8 μ ~ 0.183 eV

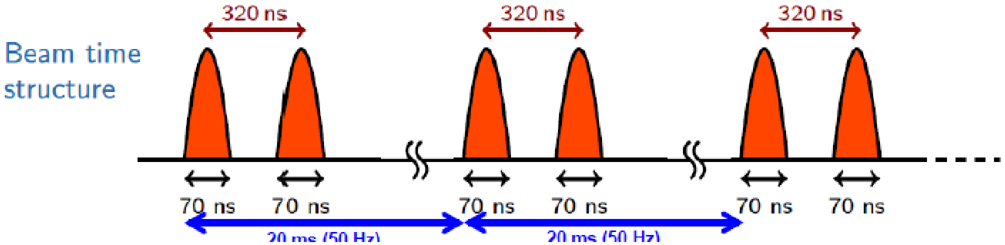
with a precision ~10^{-5}. From this r_Z may be determined with a final precision better than 0.5 % via QED calculations

The RiKEN-RAL muon facility

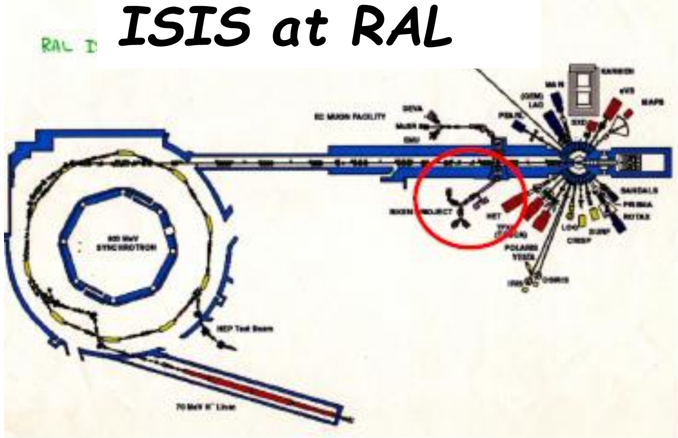
RIKEN-RAL facility



20-120 MeV/c. Typical beam size ~10 cm^2
Δp/p FWHM 10% (decay), 5% (surface)
Double pulse structure (see below)



ISIS at RAL

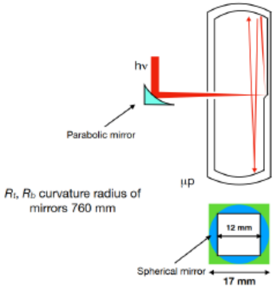


800 MeV p accelerator , 200 mA, 50 Hz

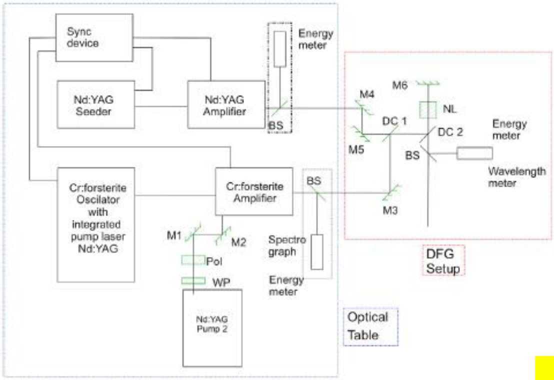
The RIKEN-RAL facility: 4 experimental ports. FAMU presently use port 1 and has used port 4 for previous runs (2014-2016) .

The FAMU experiment steps

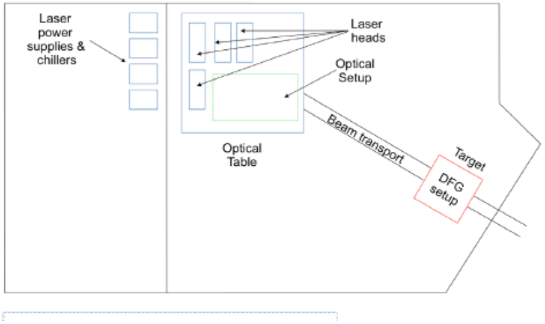
1. *Muon beam study, target and detectors tests, preliminary measure of transfer rate (@ constant conditions of PTV) – 2014 beam test (results later)*
2. *Optimize run conditions: best gas mixture at temperature T and pressure p (to be determined) to observe and measure the transfer rate energy dependence – several runs from Dec 2015 up to December 2018*
   → *At this point the validity of the method to measure HFS is demonstrated*
3. *Full working setup with laser and cavity to determine proton Zemach radius (2019-2020)*



Optical cavity

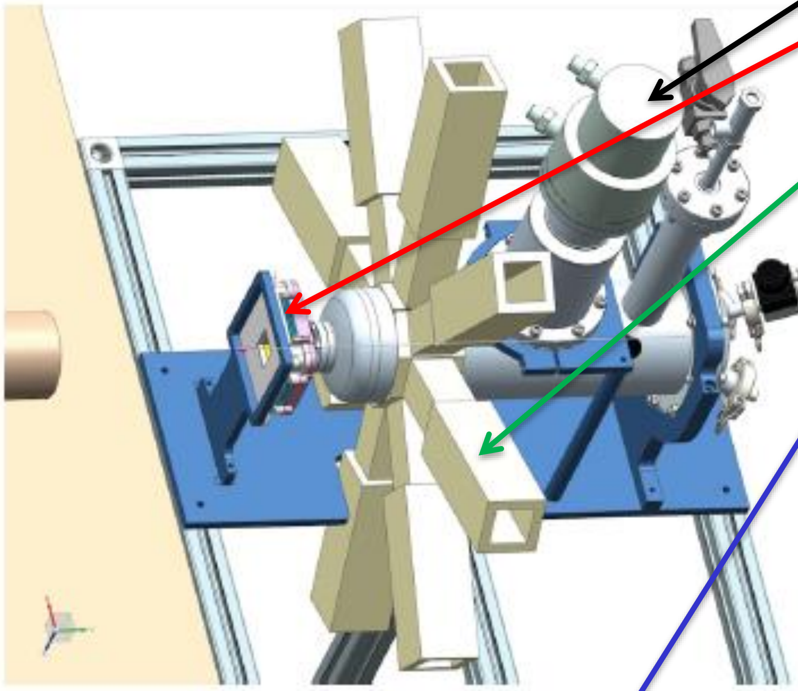


WP - waveplate, Po - polarizer, M1-M5 - bending mirrors, M6 HR mirror at 1064&1262&6785 nm, BS – beamsplitters, DC1 - dichroic mirror (reflecting 1.26μm, transmitting1.06μm), DC2 - dichroic mirror (reflecting 1.06 and 1.26 μm, transmitting 6.76μm)



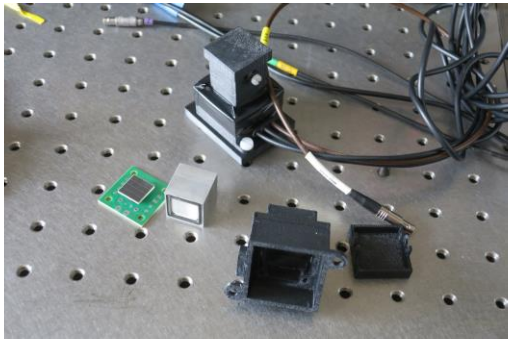
Foreseen laser setup at RIKEN RAL

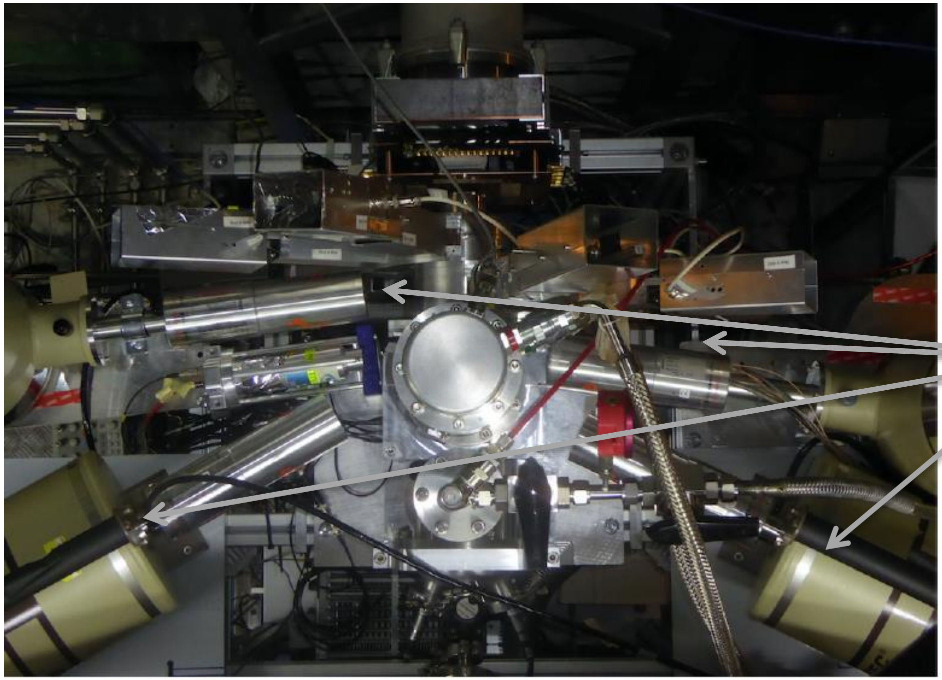
The setup for the 2015-2018 run



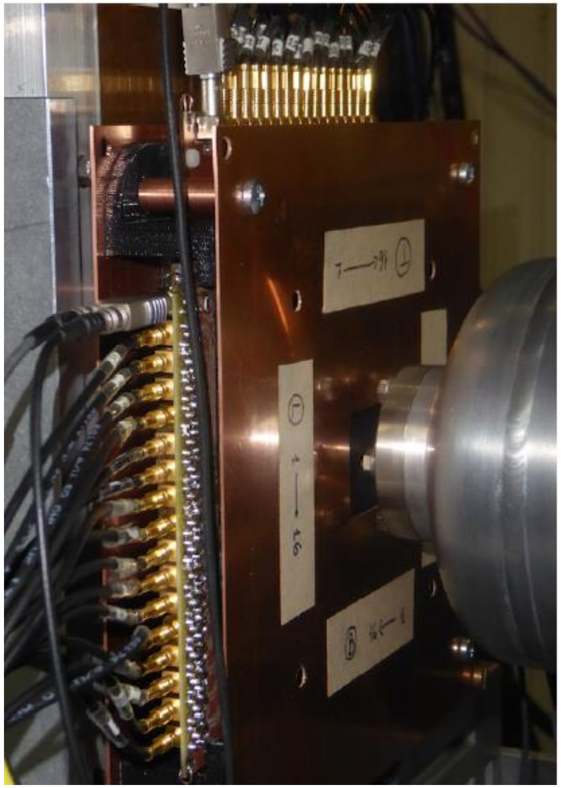
a croppy layout

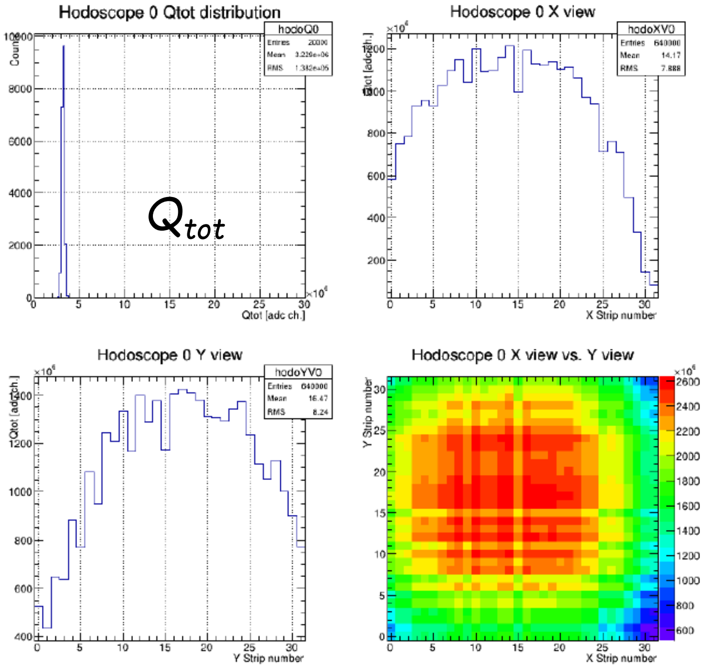
- ☐ *Cryogenic target*
- ☐ *Beam hodoscope with 1 mm pitch (scintillating fiber with SiPM readout)*
- ☐ *LaBr3 crystals with PMT readout (8 detectors arranged as a star) for X-ray fast detection*
- ☐ *Complemented by 8 ½" Labr3 crystals read by SiPM arrays to equip difficult regions*
- ☐ *HpGe detectors for precise X-rays detection (4) [intercalibration]*



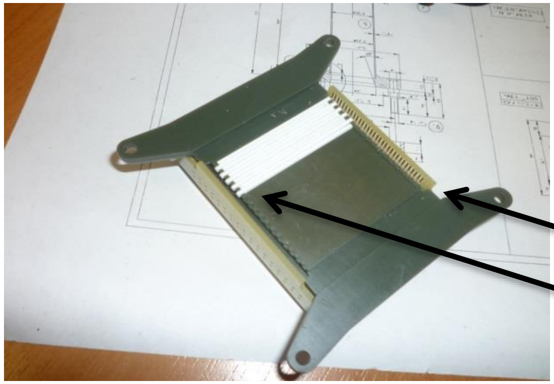


Beam hodoscope





- *1 mm square BCF12 from Bicron with EMA coating (to avoid cross-talk) to minimize material along beamline*
- *Alternate up/down-left/right readout for 32+32 X/Y chs*
- *Mechanics printed out on 3D printer*
- *Readout with CAEN V1742 FADC (waveform info)*
- *One side (16 channels) is powered by a single HV channel*
- ❑ *x/y beam RMS resolution (after collimator) ~7/8 mm*
- ❑ *Muon rate from total charge measure (Q_{tot})*

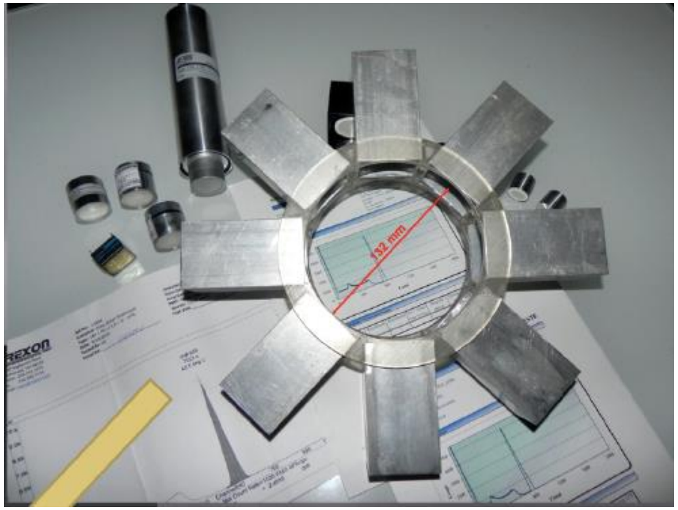


PCB with16 SiPM da 1x1 mm^2

1x1 mm^2 Bicron BCF12 square fibers

Requirements for X-rays detectors

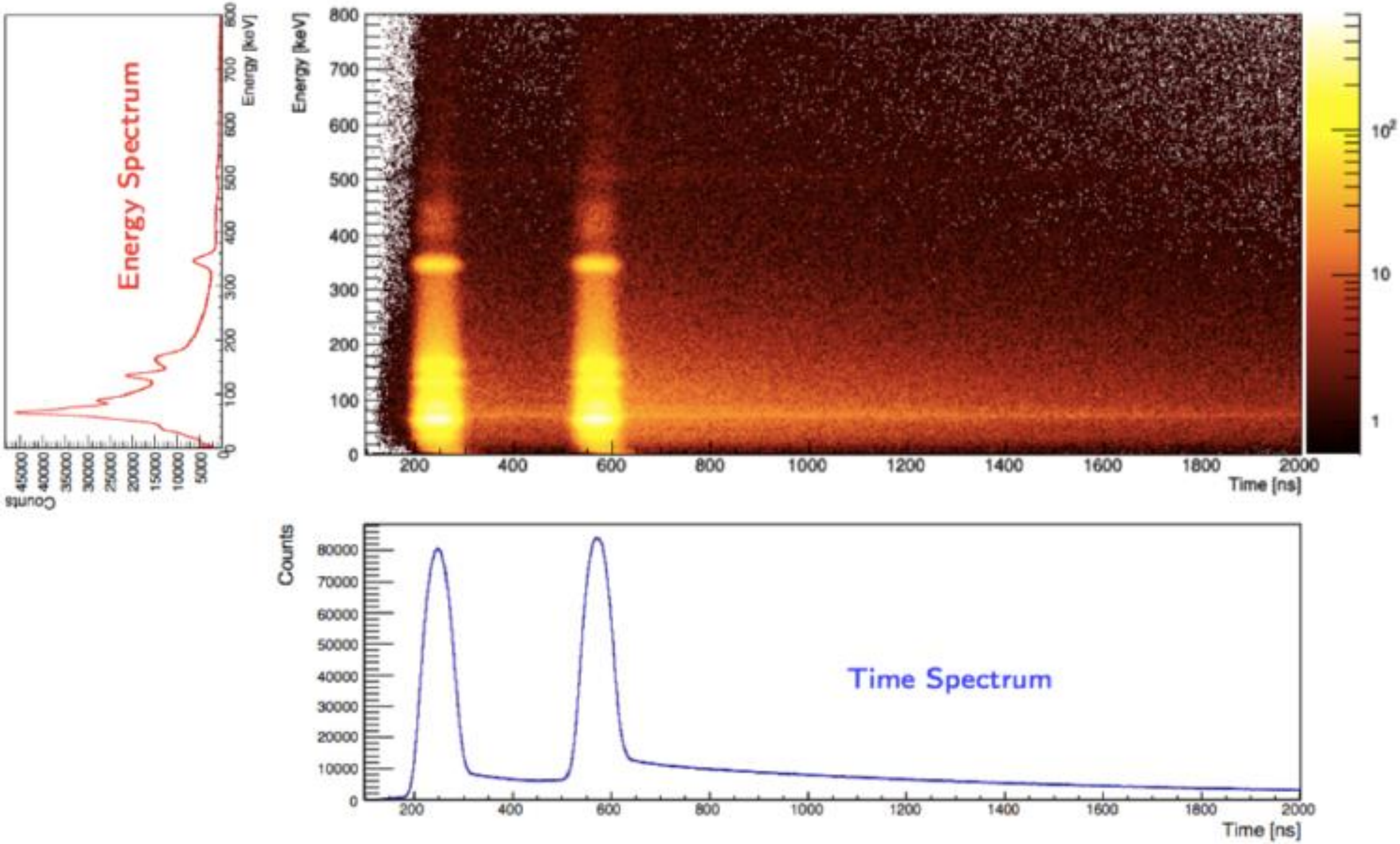
- ❑ *High statistics: maximize solid angle coverage & detection efficiency (fast risetime, pile-up rejection)*
- ❑ *Excellent control of detector behavior: minimize noise and unexpected behavior (tails/cross-talk, undershoots ..)*
- ❑ *Energy range: best @ 100-200 KeV, with some efficiency at higher ones*



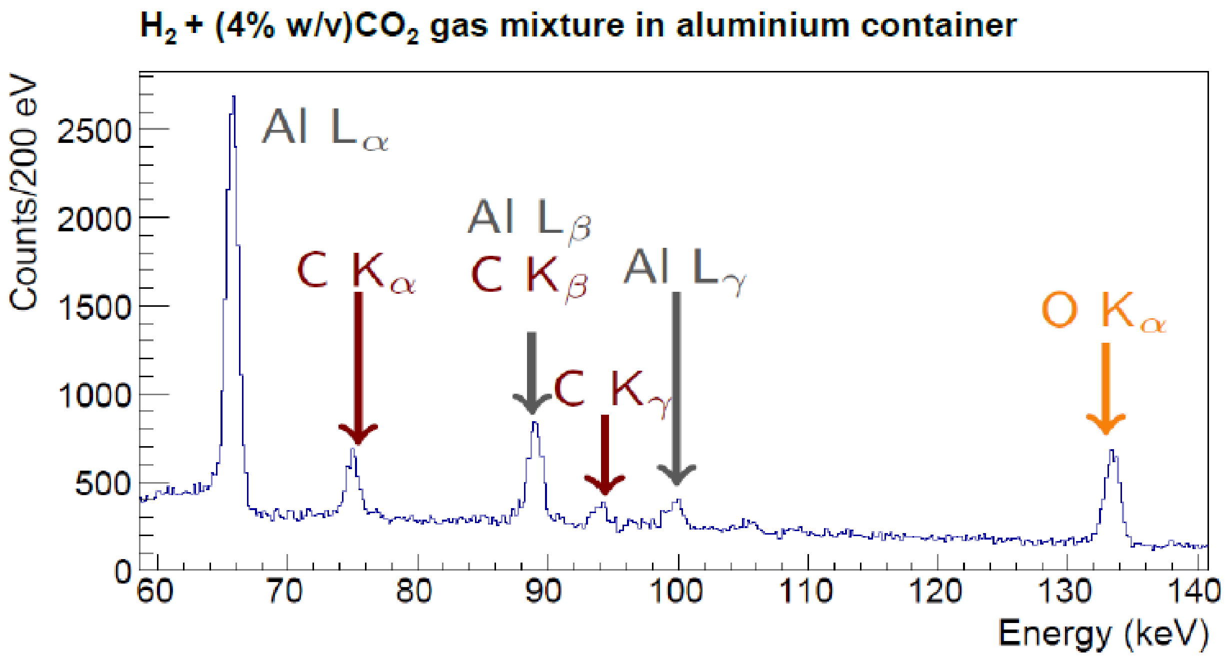
- ❑ *8 1" LaBr3(Ce) detectors arranged in a star. Readout by Hamamatsu R11265-200 UBA PMTs, wth active divider and CAEN V1730 FADC (500 MHz). In addition 8 ½" detectors with SiPM array readout*

- ❑ *4 conventional HPGe detectors , read out with CAEN V1724 FADC (100 MHz) .*

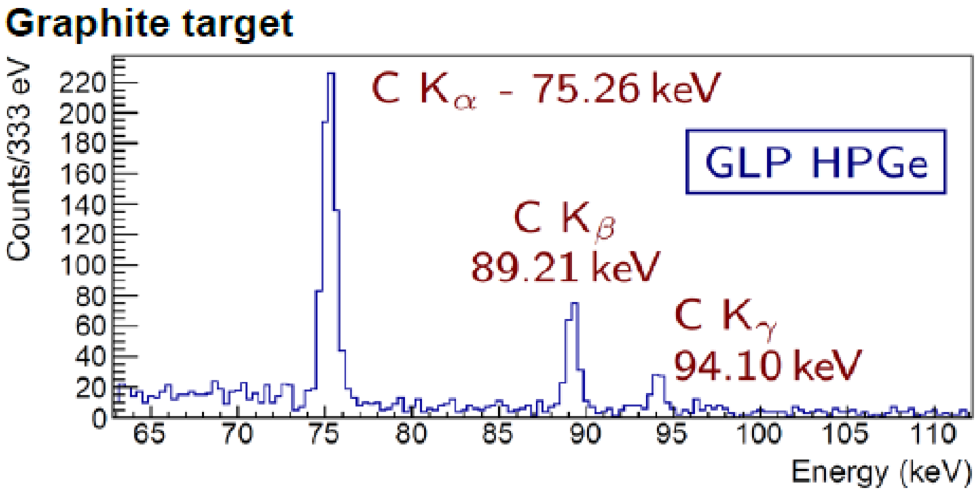
A snapshot of X-rays spectrum



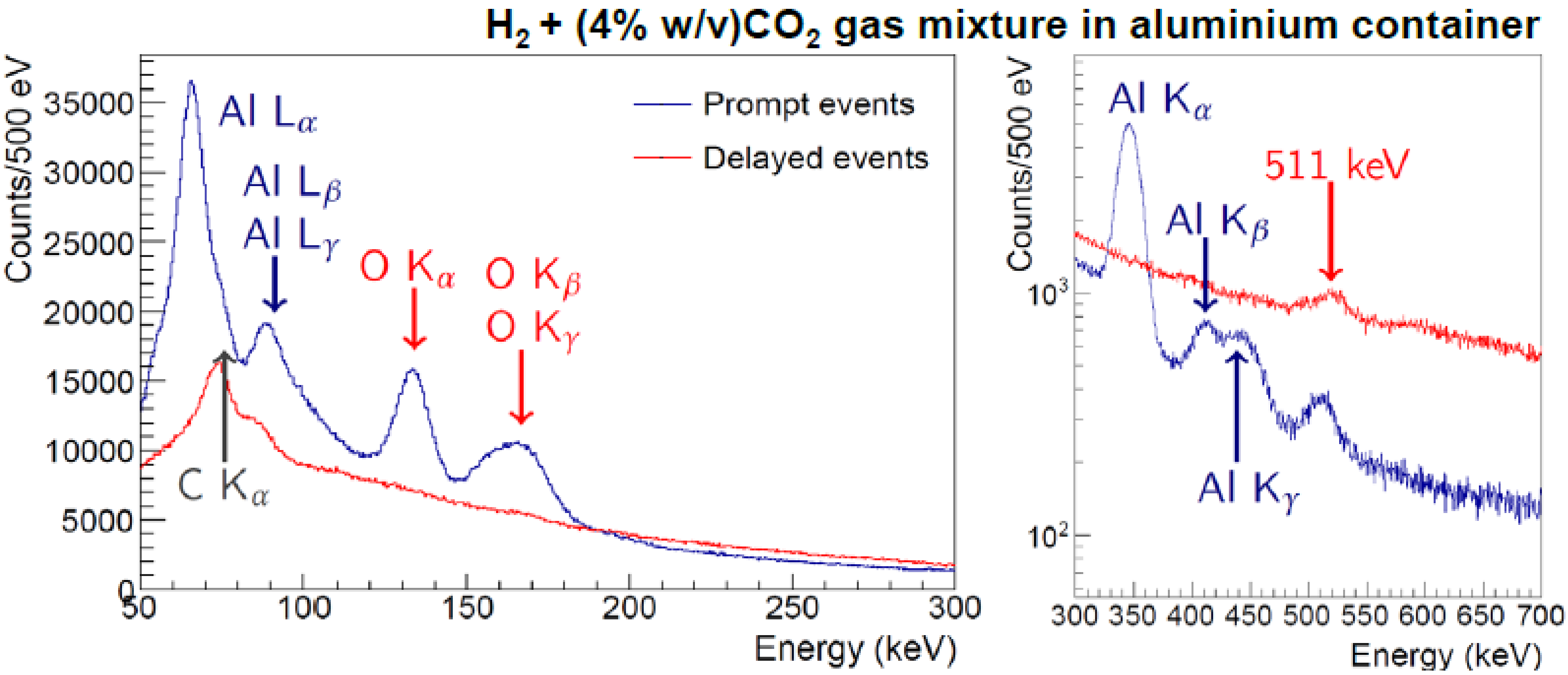
Detector performances: HpGe detectors



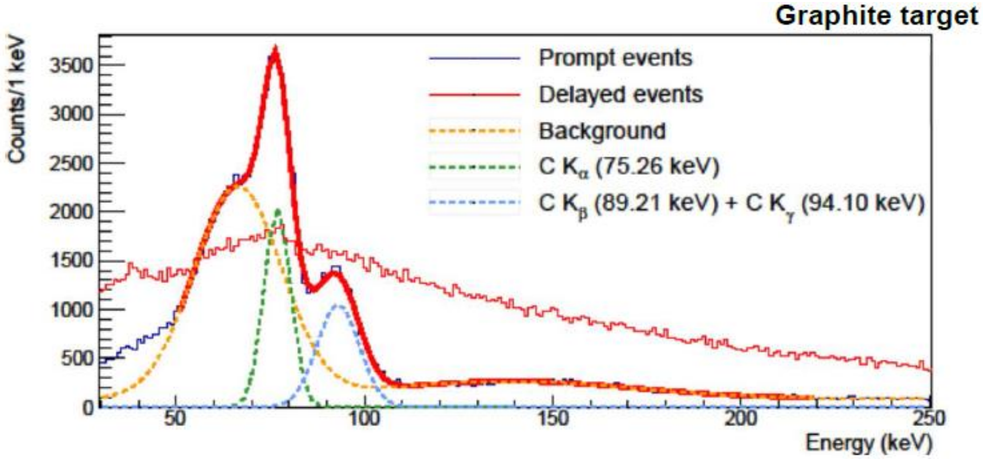
Used for inter-calibration : high energy resolution, limited timing resolution



Detector performances: LaBr3(Ce) detectors

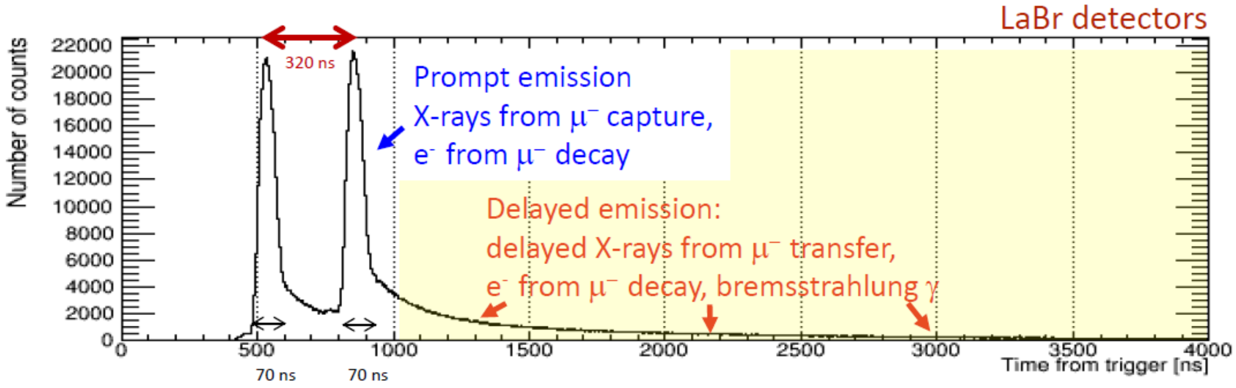

H_2 + (4% w/v)CO_2 gas mixture in aluminium container

- *In these plots we see both*
- *prompt X-rays (in time with beam spill) → reflect beam spill structure*
- *Tails of the distribution (products of μ decay) → convey infos on muonic atom lifetimes*


Graphite target

Physics measurements: transfer rate μp→ μO

- Transfer rate measured as a function of temperature
  - Target filled H_2+(120 ppm)O_2 at 41 bar at 300 K
  - Six temperatures (300, 272, 240, 201, 153, 104 K)
  - Each temperature kept stable for three hours each
- At each trigger we acquire a window of 10 microsecond
  - Produce μp's and wait for their thermalization (about 150 ns)
  - Study the time evolution of Oxygen X rays



LaBr detectors

320 ns

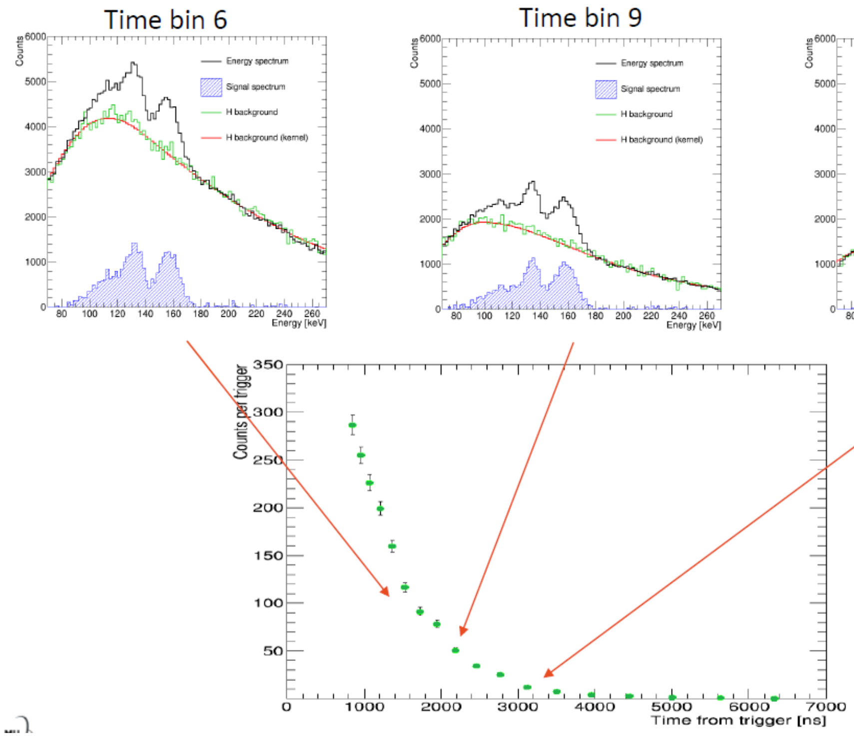
Prompt emission
X-rays from μ^- capture,
e^- from μ^- decay

Delayed emission:
delayed X-rays from μ^- transfer,
e^- from μ^- decay, bremsstrahlung γ

70 ns

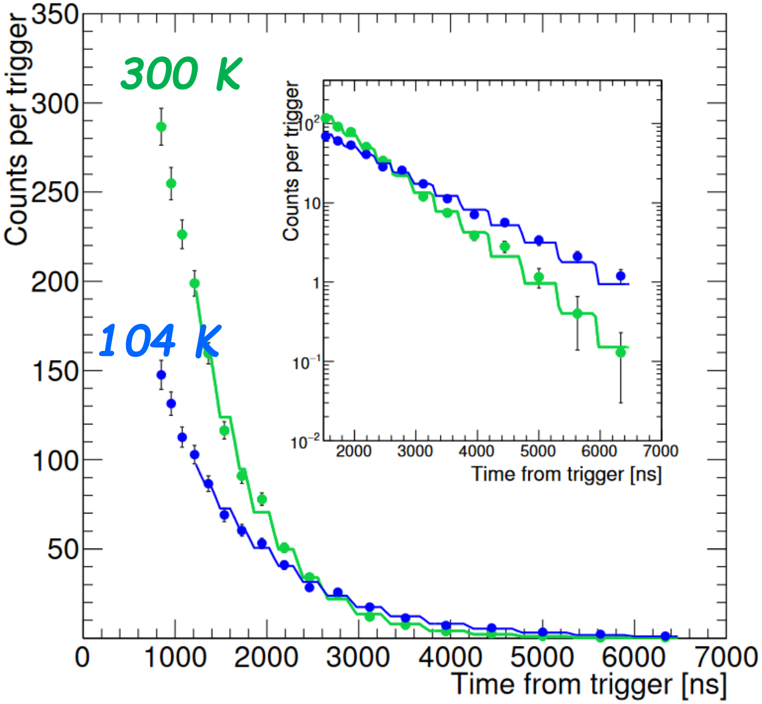
70 ns

Time evolution at fixed temperature

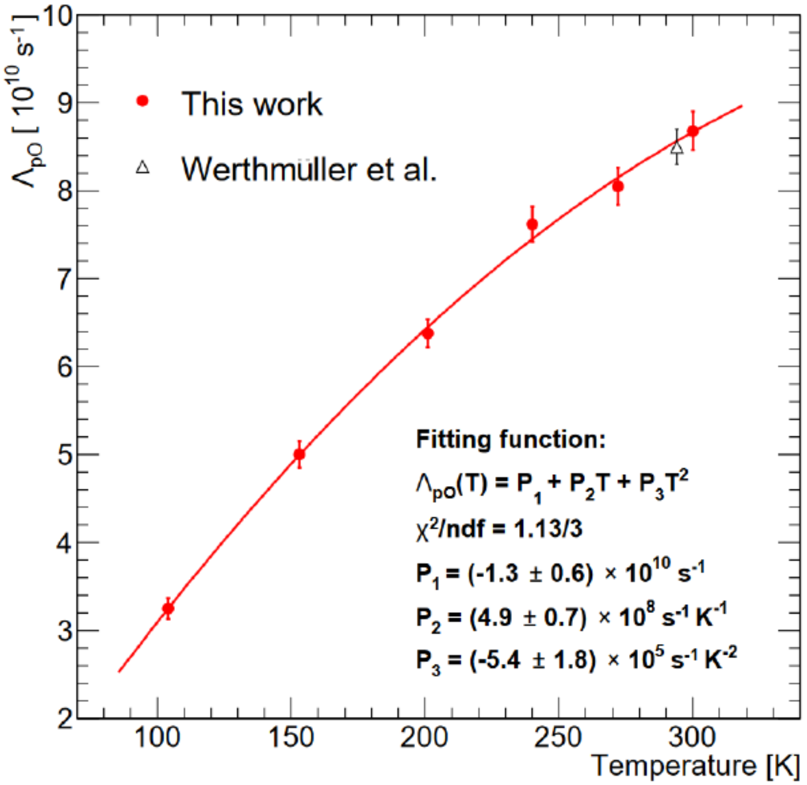


T = 300 K

Data fit

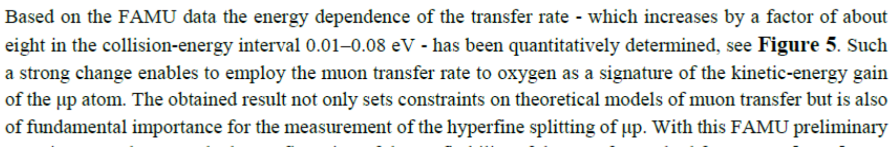


Transfer rate vs temperature / energy

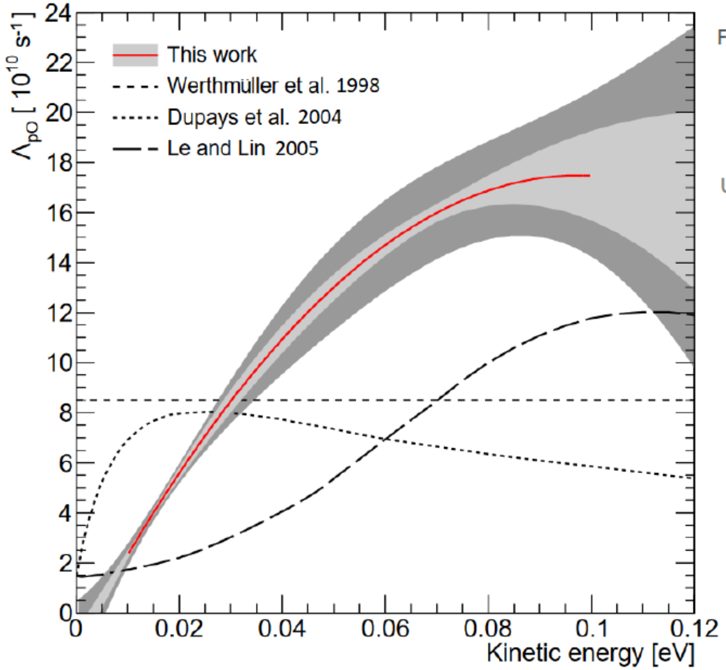


$$dN_{\mu p}(t) = S(t)dt - N_{\mu p}(t)\lambda_{dis}dt$$

$$\lambda_{dis} = \lambda_0 + \phi\left(c_p\Lambda_{pp\mu} + c_d\Lambda_{pd} + c_O\underline{\Lambda_{pO}}\right)$$



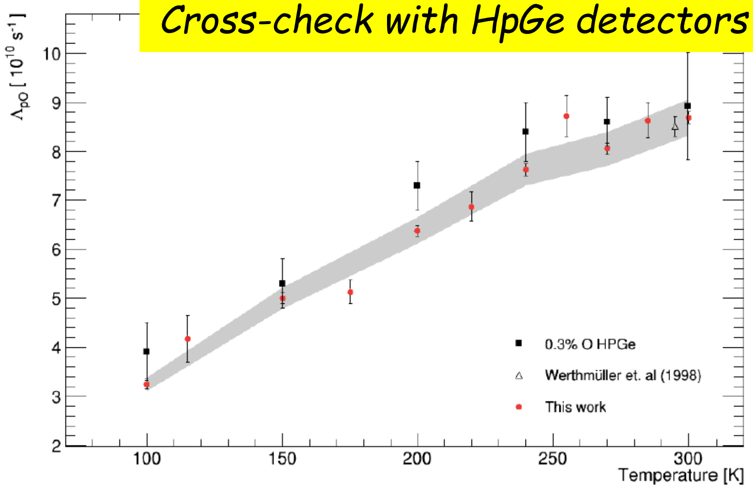
Based on the FAMU data the energy dependence of the transfer rate - which increases by a factor of about eight in the collision-energy interval 0.01–0.08 eV - has been quantitatively determined, see **Figure 5**. Such a strong change enables to employ the muon transfer rate to oxygen as a signature of the kinetic-energy gain of the μp atom. The obtained result not only sets constraints on theoretical models of muon transfer but is also of fundamental importance for the measurement of the hyperfine splitting of μp. With this FAMU preliminary



Fit-model systematics

Uncertainty of the fit

Cross-check with HpGe detectors



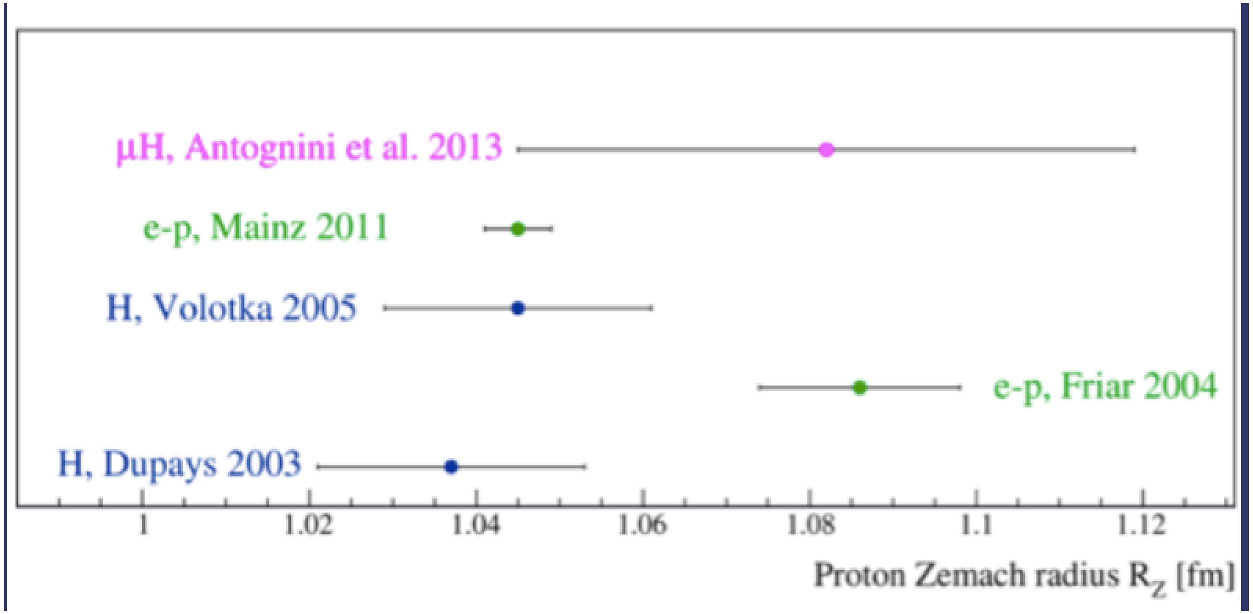
Submitted to PRA and http://arxiv.org/abs/1905.02049

Conclusions

- ❑ *The FAMU Collaboration (Elettra, INFN Bo, Mi, MIB, Na2, PV, RM3, Ts, CNR-INO, Polish Academy of Science, INRNE Sofia, RIKEN-RAL, …) has just demonstrated the feasibilty of the method to measure HFS in muonic atoms*
- ❑ *The high-power 6.8 μm laser + resonant optical cavity are nearly ready*
- ❑ *the X-rays detection system based on LABr3:Ce detectors is capable of detecting low-energy X-rays signals in the range 100-200 keV, even with high background conditions*
- ❑ *Measured for the 1st time the transfer rate for oxygen in the range 100-300 K* → **very important as this is the signature used in the FAMU experiment**
- ❑ *We are preparing the end-of-year 2019-2020 run for the measurement of the Zemach radius of proton*

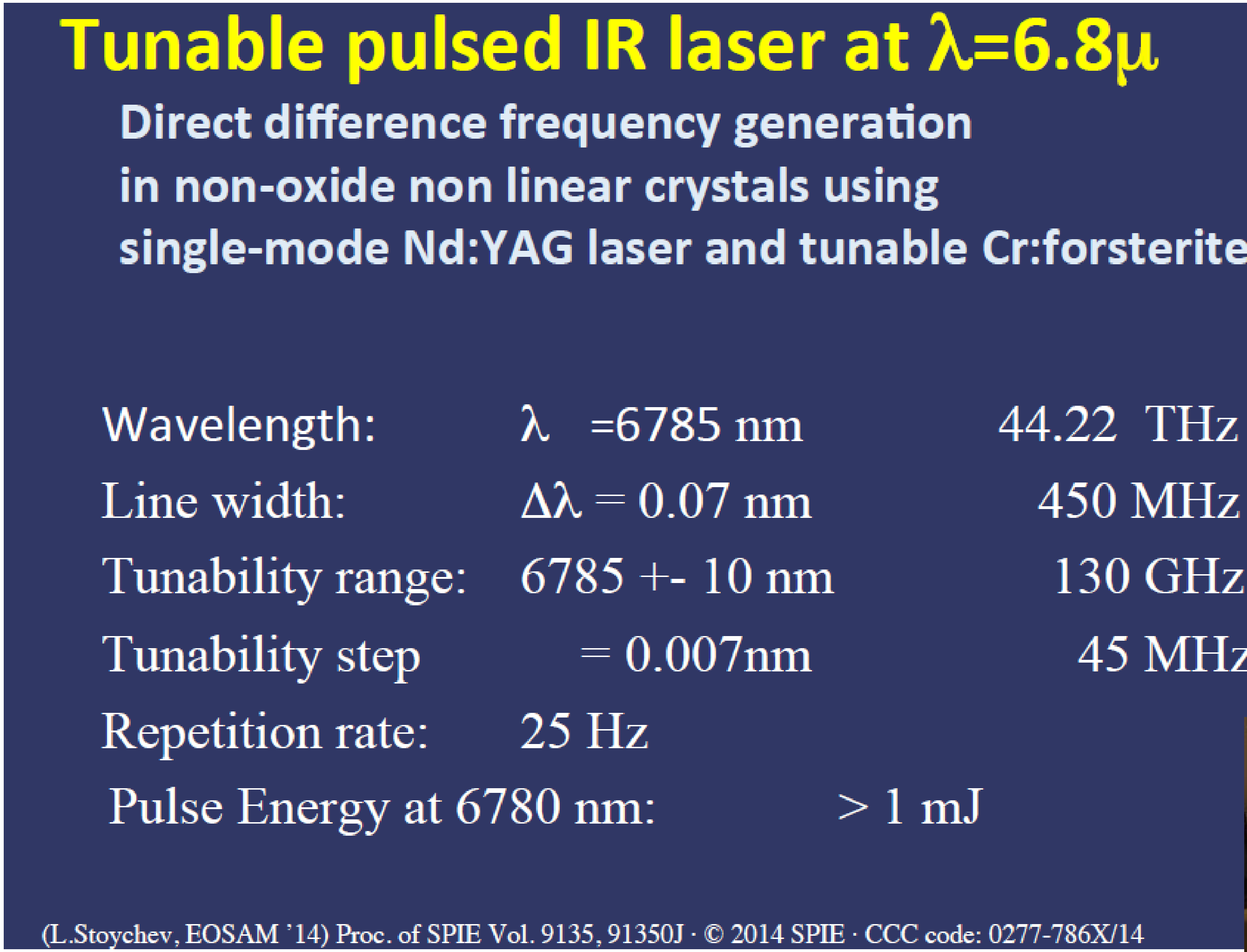
Backup material

r_Z current status



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

FAMU key element: the MIR laser

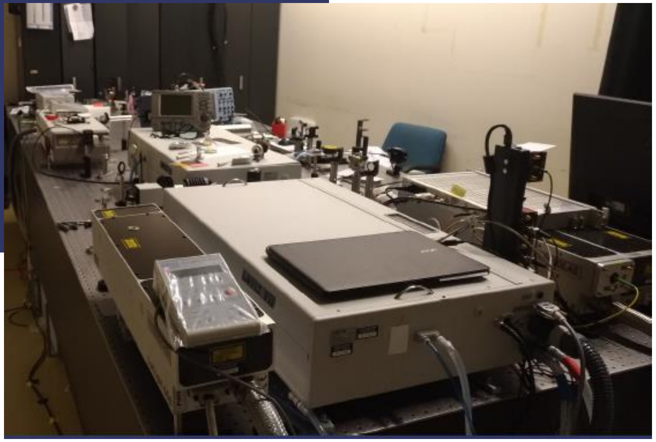


Tunable pulsed IR laser at λ=6.8μ

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:	$\Delta\lambda$ = 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

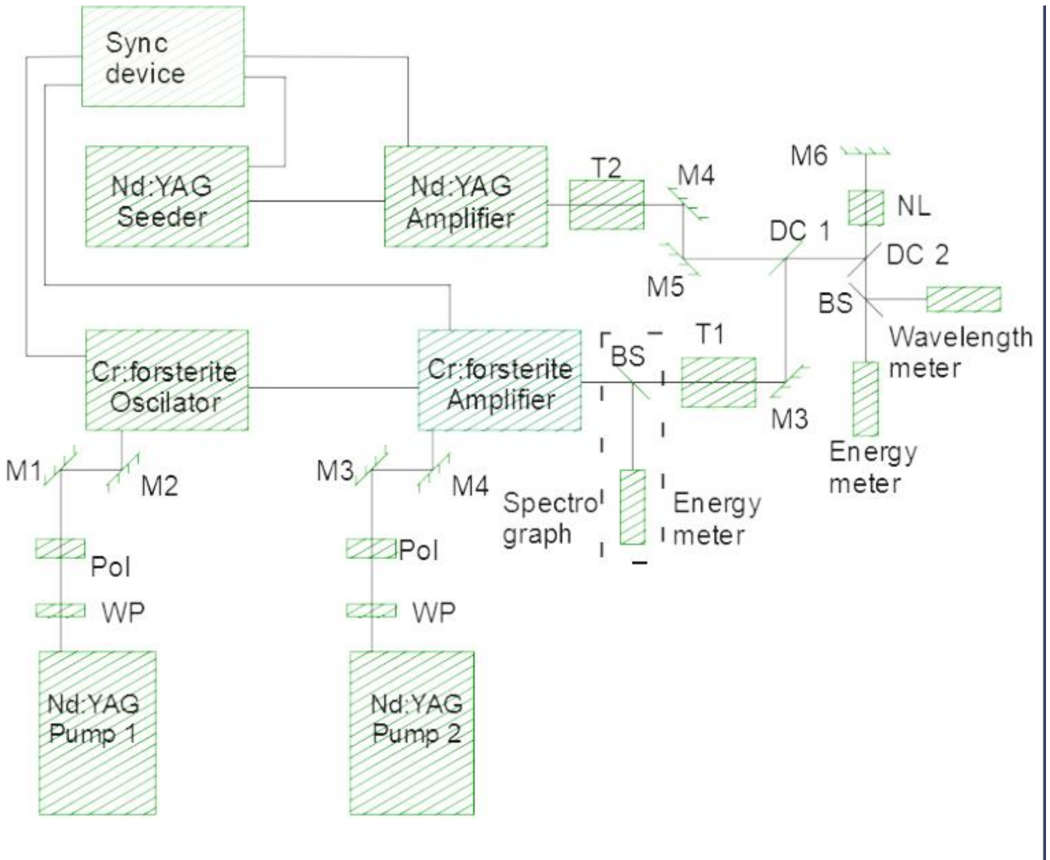


Final scheme of the DFG based laser system

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 ~



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)

Final target for FAMU

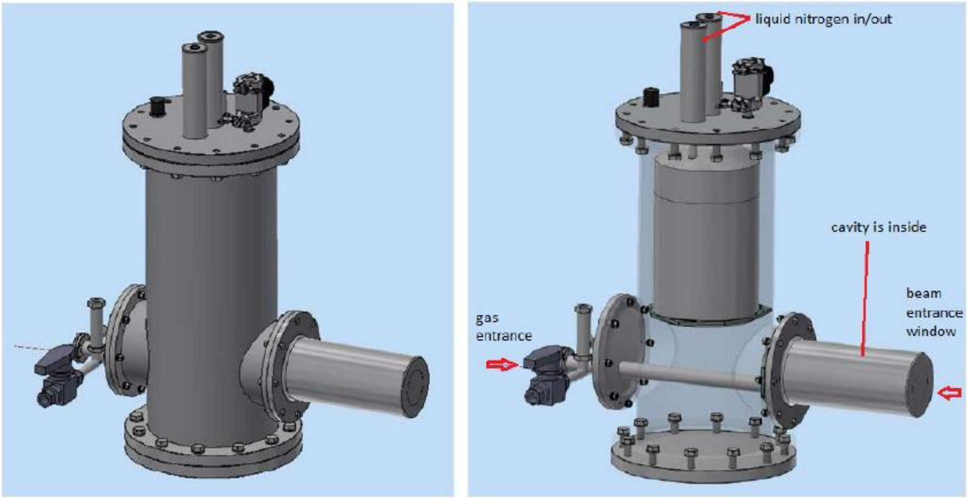


Figure 14 The present design study of the cryogenic gas target system. Left panel: external view. Right panel: a sight on the internal element distribution. To the right of each panel one can see the beam entrance window. The cavity is not visible and is placed just behind the beam entrance window. In the vertical vessel the inlet and outlet to the liquid nitrogen tank, providing 80 K temperature stabilization, are visible. In the left panel, the proposed solution for the laser beam injection is visible.

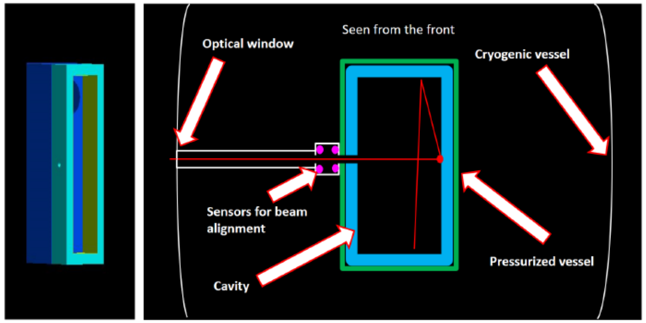
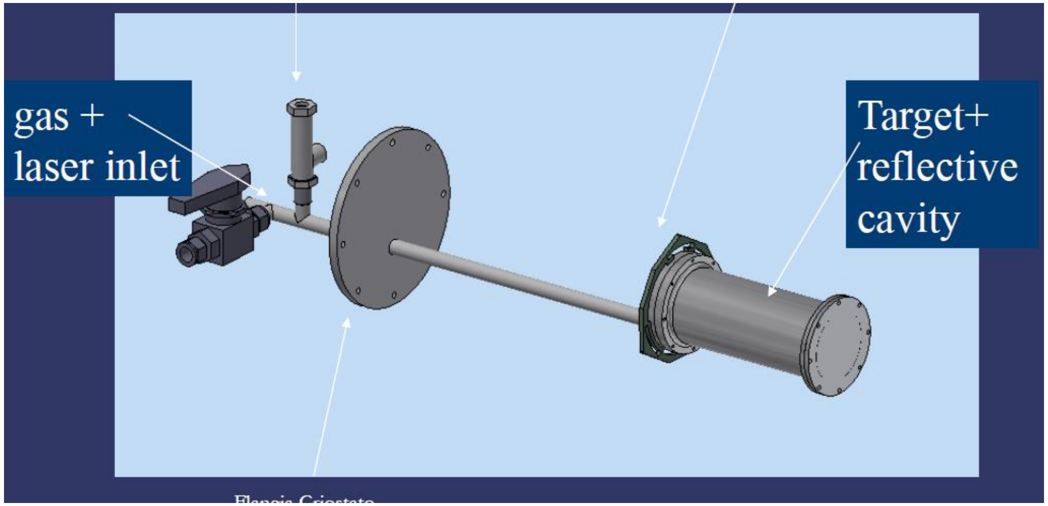


Figure 17 Left panel: perspective view of the optical cavity and beam stopper, visible the gas and optical path opening. **Right panel:** the cross section of the internal gas optical cavity target system is represented as seen from the front beam entrance window. From left to right the laser beam is brought through one single optical window to an entrance hole on the pressurized vessel/optical cavity. Vacuum between the external cryogenic vessel and the pressurized copper vessel (in green) grants the thermal insulation and stability.



Optical cavity

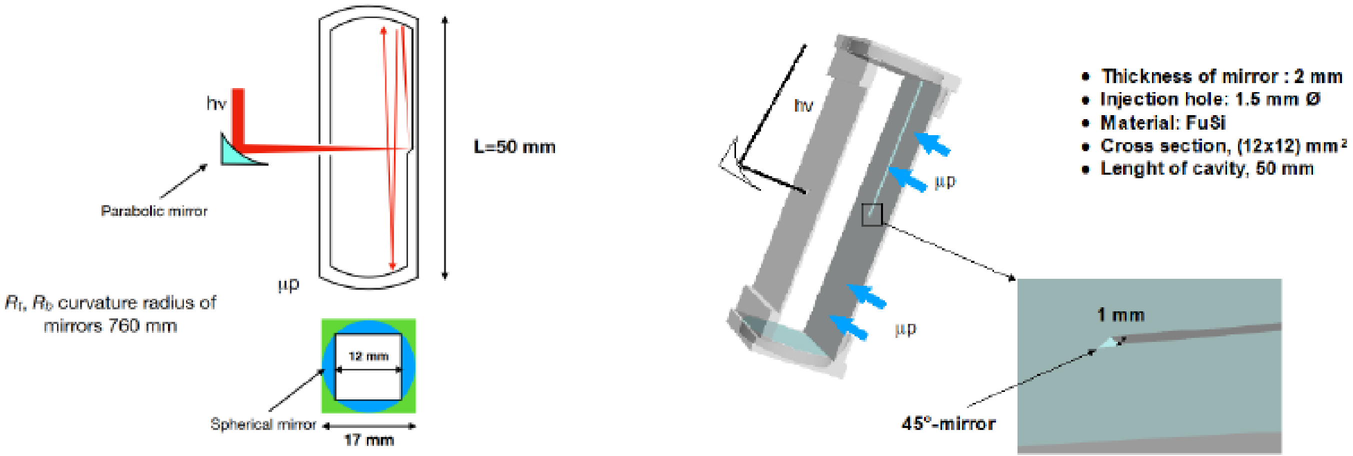


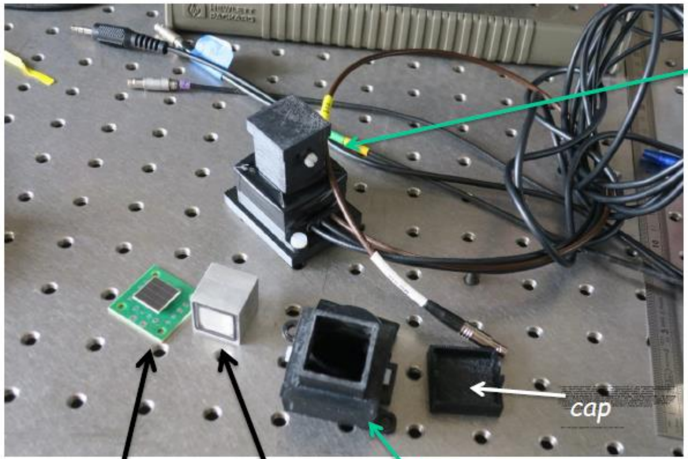
Figure 19 Left panel: Sketch of the transversal closed optical cavity front view. **Right panel:** Perspective view of the optical cavity.. In the expansion, the 45 degree mirror to address the laser light towards the main mirrors.

The probability ***P*** for the laser radiation to stimulate a hyperfine transition is expressed in terms of the energy ***W*** of the laser pulse (in J), the cross section of the laser beam ***S*** (in cm^2), the target temperature ***T*** (in K) and the reflectivity ***R*** of the multi-pass cavity mirrors (under the assumption that the laser line width is smaller than the transition line width) as follows:

$$P=2\times10^{-5}\times W/((1-R)\times S\times\sqrt{T}). \qquad (1)$$

With the following parameters for the FAMU laser source and multi-pass cavity: W= 4 mJ; T= 80 K; S=1 cm^2; R=0.9995, P will reach ~20%.[7] The Doppler broadening is of the order of 10^{-5} at 300K. The main source of

LaBr3:$_{Ce}$ detectors with SiPM array readout

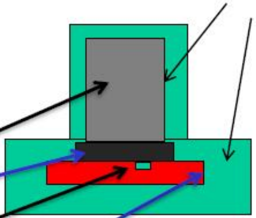


New ½"or 1" long detector from OST Photonics (PRC). Holder in two pieces: upper one contains the crystal (may be disconnected), lower one contains PCB+array

SiPM array on PCB

Crystal

Holder



detachable

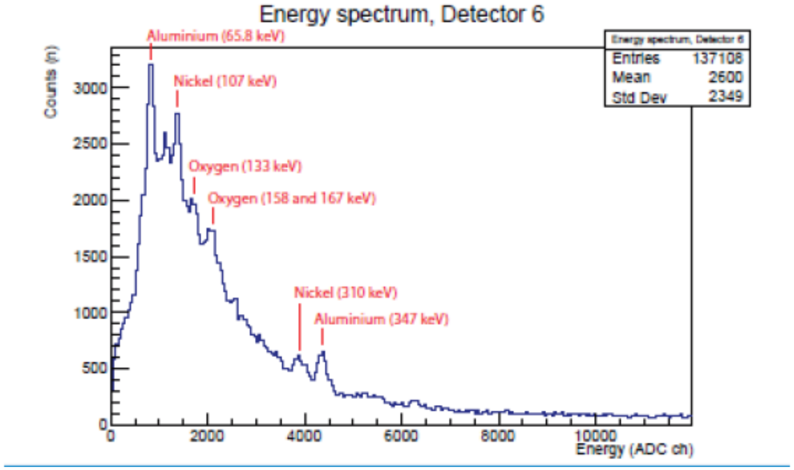
LaBr3 crystal

SiPM array

TMP37 thermistor

PCB+SAMFORD

- ½" cubic LaBr$_3$:Ce crystals from Kinheng (PRC) or from OST photonics
- Optical contact with photodetector via Bicron Silicon grease BC600
- On the PCB an Advanced Technology TMP37 termistor to control temperature excursions and correct bias (using Nuclear Instruments/CAEN modules DT5485P
- Special Hamamatsu S13361 AS with silicone window, instead of an epoxy window to better match LaBr$_3$:Ce emission peak ~390 nm



Measured spectrum at RIKEN-RAL

MC simulation

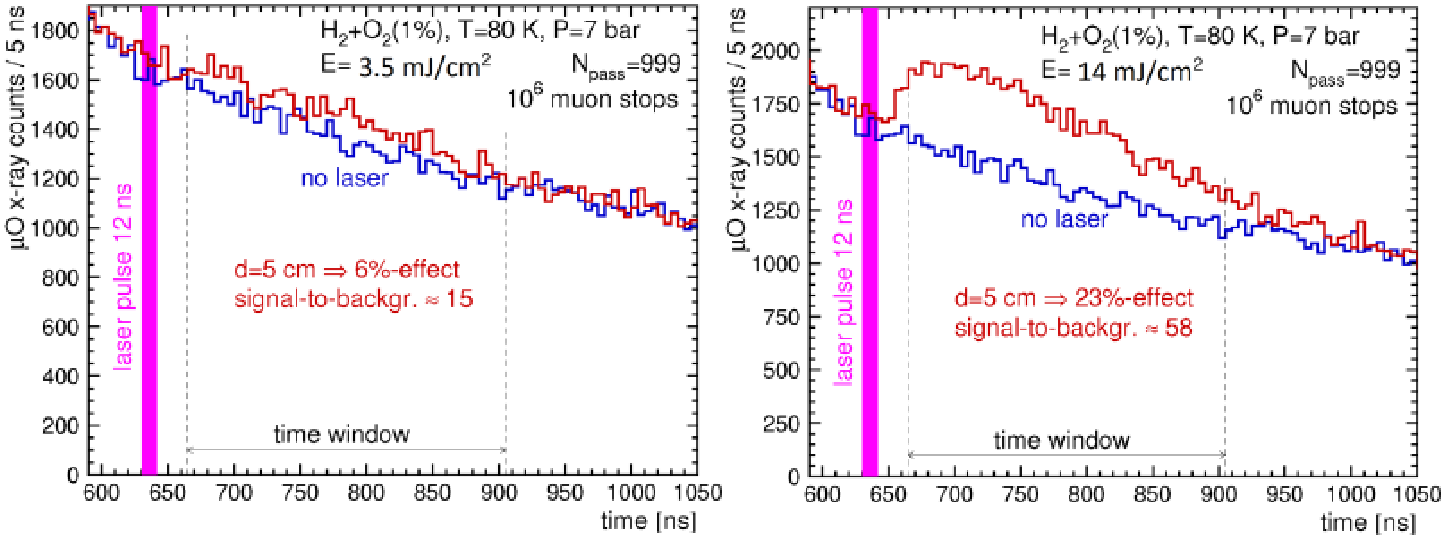


Figure 6 Results of MonteCarlo Simulations of the muonic oxygen delayed de-excitation X-ray time distribution. The delayed de-excitation X-ray time distribution obtained for a fixed oxygen (weight) concentration of 1% and the gas pressure of 7 bars without (blue line) and with laser (red line) inducing the spin flip transition and the subsequent mutation in the X-ray time distribution. Part of this study was focused optimal conditions on the concentration-pressure plane. The only geometry parameter is the fixed mirror distance of 5 cm, which determines the lifetime of laser field. **Left panel:** The simulation has been performed for a laser energy of 3.5 mJ/cm^2, that is the energy currently available. **Right panel**: The final laser energy, after the optimization of the system, is expected to be 14mJ/cm^2. The effect of 6% and 23% mentioned in the figure is calculated on the difference of the oxygen X rays distribution with and without laser (red and blue lines) normalized to the no-laser one.