The fast X-ray detector system of the FAMU experiment at RAL

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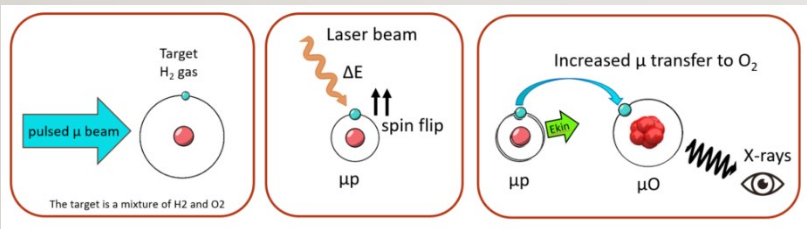
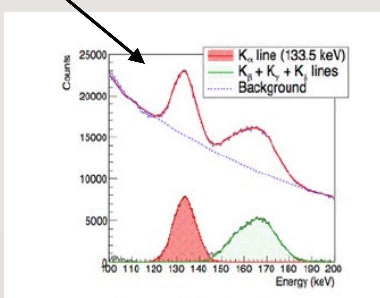
1 – The FAMU experiment at RAL

Study of high-precision hyperfine spectroscopy of muonic Hydrogen, to measure proton Zemach radius and physics beyond SM

- Formation of muonic hydrogen (55 MeV/c μ^- beam @ISIS)
- Spin-flip excitation (via custom MIR laser at 6800 nm)
- Detection of muonic Oxygen X-rays (K_α, $K_{\beta/\gamma}$ lines) , via enhanced transfer probability

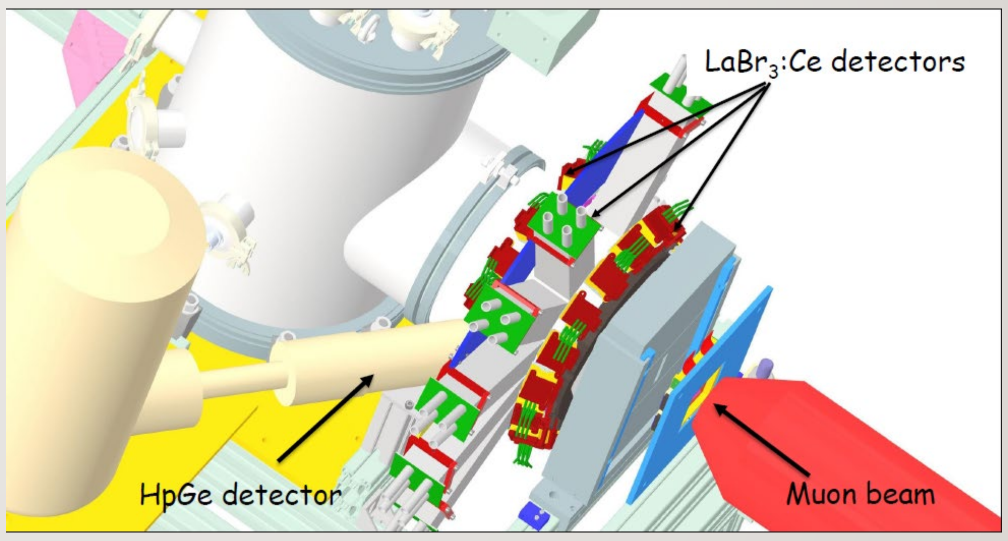




X- ray detectors requirements:

- Good energy resolution at low X-rays energy (~ 130 KeV) to see Oxygen lines
- Short fall time to separate delayed X-rays (signal) from prompt background (< 200-300 ns)
- Simple photon readout (either UBA PMT or SiPM array)

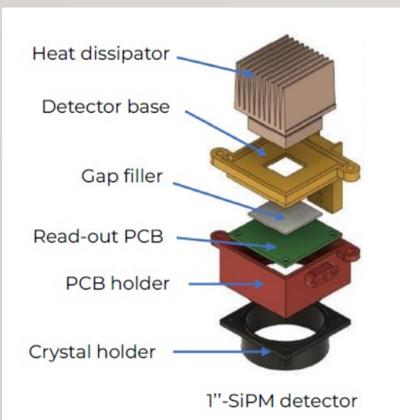
2 – the FAMU X-ray detection system



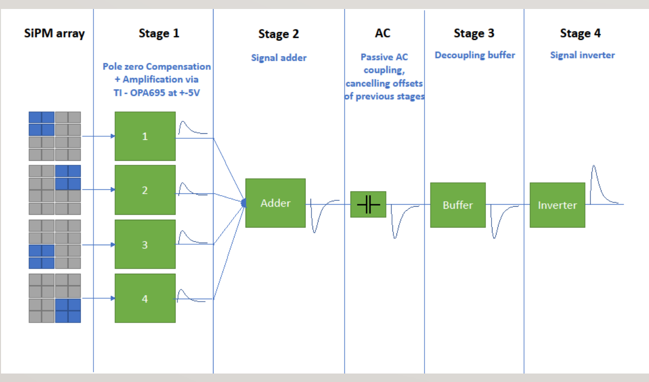
- 2023 setup: cylindrical 1"x0.5"$LaBr_3$:Ce crystals read by SiPM Arrays (16x) and 1"x1" $LaBr_3$:Ce crystals read by PMTs (6x) + $\frac{1}{2}$"x $\frac{1}{2}$ " cubic $LaBr_3$:Ce crystals read by SiPM arrays (12x)
- 2024 setup: $\frac{1}{2}$" detector replaced by new 1"x0.5"detectors

HpGe detector for inter-calibration (slower, but with higher resolution). Coaxial GEM-S for higher efficiency in the region 100-200 keV

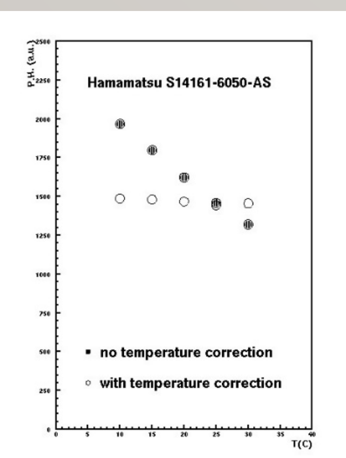
3 – LaBr3:Ce with SiPM array readout



1"-SiPM detectors' mechanics

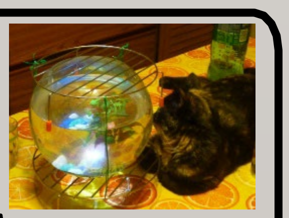


Nuclear Instruments 4- 1 readout



- $\frac{1}{2}$" crystals are equipped with S13361-3050 SiPM arrays (parallel ganging), 1" crystals with S14161-6050 arrays (Nucl. Instr. 4-1 readout scheme), to reduce rise/fall time by a factor 2X
- Further reduction of fall time (another factor 2X) under study
- Reduction in fall time increases separation between delayed X-rays (signal) from prompt X-rays (background)
- Gain drift correction with temperature via a NIM module with CAEN A7585 chip
- For 1" detectors reduction from 41% to 5% in P.H. variation @ ^{137}Cs photopeak in the range 10-30 ^{0}C

Conclusions & references



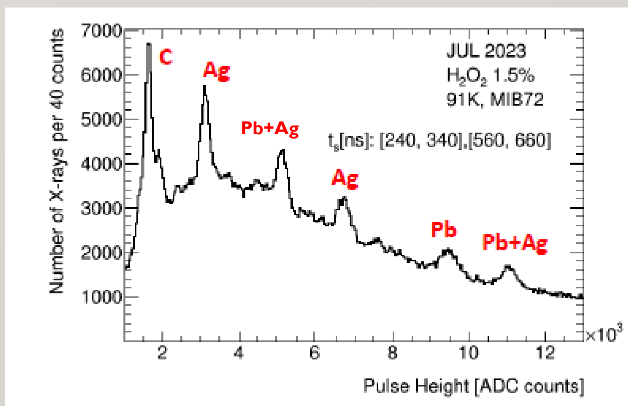
- A good compromise between reducing rise time/fall time and maintaining a good FWHM energy resolution has been obtained for $LaBr_3$:Ce detectors read by SiPM arrays.
- The gain drift with temperature of SiPM arrays is reduced from 41% to 5% in the temperature range 10-30 ^{0}C.
- Results with SiPM array readout compare well with what obtained with a PMT readout (energy resolution/timing)

1. C. Pizzolotto et al., Eur. Phys. J. A56 (2020) 7, 185. A. Vacchi et al., *Nucl.Phys. News* 33 (2023) 4
2. M. Bonesini et al., Condens. Matter 2023, 8, 99
3. M. Bonesini et al., Nucl. Meth. A1046 (2023) 167677
4. M. Baruzzo et al., Opt. Laser Technol. 179 (2024) 111375

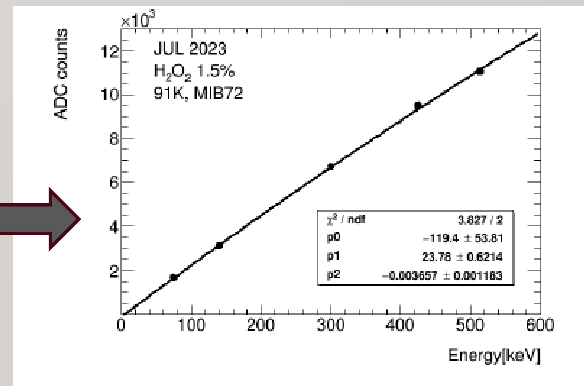
4 – X-ray detectors performances

	Rise time (ns) (lab data)	Fall time (ns) (lab data)	(IR(%)@ 662keV (lab data)	R(%) @120 keV (lab data)	R(%) @142 keV (beam data)
½" –SiPM	42.8 ± 4.7	372.4±17.4	3.27±0.11	8.44±0.63	7.5±0.3
1"-SiPM	29.3 ± 1.5	147.1±12.8	3.01±0.16	7.93±0.38	8.2±0.7
1"-PMT	14 ± 1	~ 60	3.5--4.6	7.2--8.1	11.5±0.2
HpGe	150	1000-2000	0.442 ±0.001	1.010±0.001	1.26 ±0.17

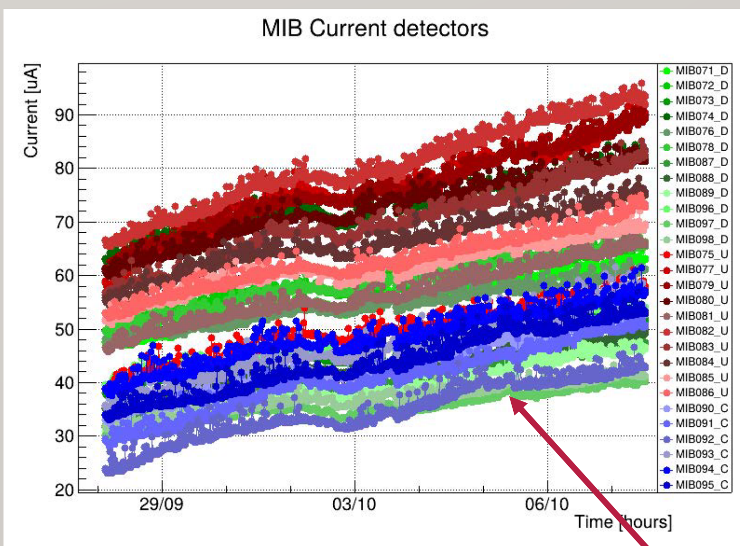
Data from laboratory tests or beam data, with 55 MeV/c μ^-

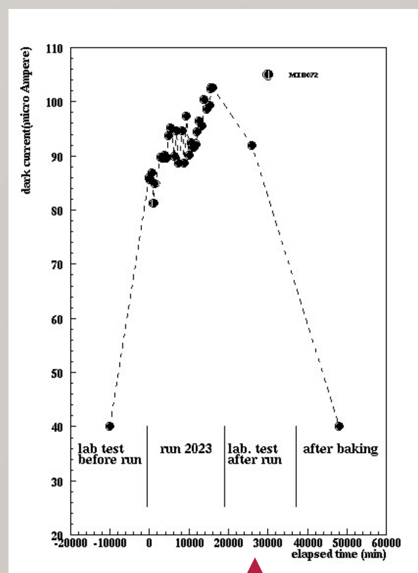


Typical spectrum taken with 1" SiPM-$LaBr_3$:Ce detector, used for calibration

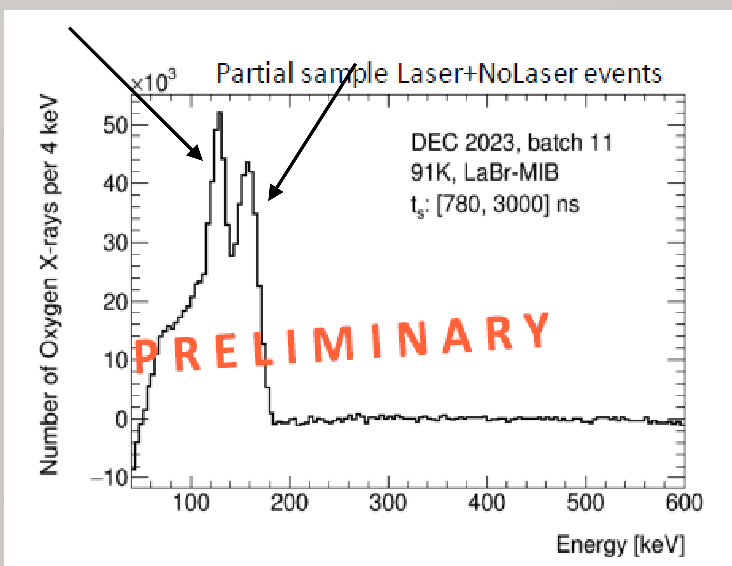


Automatic calibration with beam data (ADC → keV) for all 34 $LaBr_3$:Ce





K_α,$K_{\beta/\gamma}$ lines from O_2 de-excitation (our signal over H_2 background)



- During data collection an increase of dark current of SiPM arrays was observed. Probably due to n-production by μ-Au interactions in the target. Solved by SiPM array baking at 125 °C for 24 h → involves detectors' dismounting
- Max currents are still within safe limits (< 150 μA)