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INFN Istituto Nazionale di Fisica Nucleare

$LaBr_3$:Ce crystals with SiPM array readout and temperature control for the FAMU experiment at RAL

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The proton radius puzzle

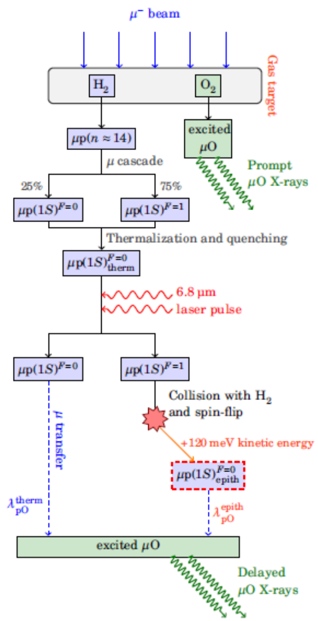
	Charge radius r_{ch} (fm)	Zemach radius R_Z (fm)
e^--p scattering & spectroscopy	0.8751(61)	1.037(16) Dupays et al 03 1.086(12) Friar&Sick 04 1.047(16) Volotka et al. 05 1.045(4) Distler et al. 11
μ^-p Lamb shift spectroscopy	0.84087(39)	1.082(37) Antognini et al 13

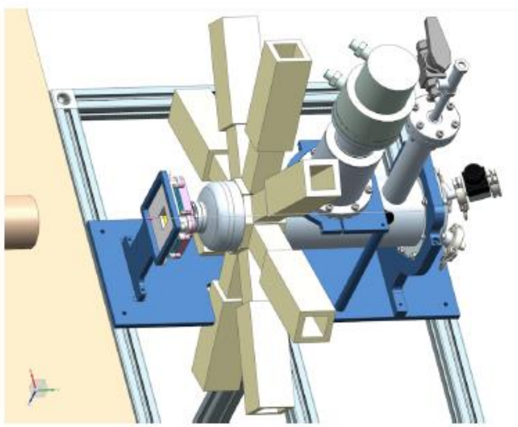
Spatial charge and magnetic moment distributions $\rho_E(r)$, $\rho_M(R)$ in non-relativistic picture .

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

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

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:
$\Lambda_0 = hc/\Delta E^{1S}_{HFS}$ ~ 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

For all this essential to detect X-rays ~100 keV

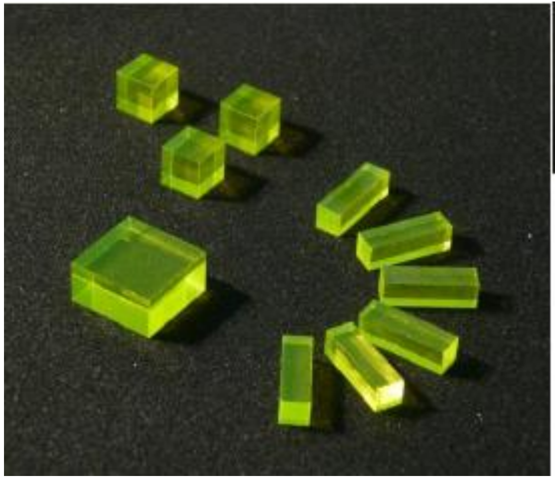
Preliminary setup at Port 1: no laser

Requirements for X-rays detectors in FAMU

- ❑ *Energy range: best @ 100-200 KeV, with some efficiency at higher values*
- ❑ *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 ..)*
- ❑ *Simple photon readout*
- ❑ *Compact detector, to instrument ``difficult" regions under the target*

	Ge	NaI	LaBr3	CeCAAG	PrLuAg
150 keV	0.9 cm	0.5 cm	0.5 cm	0.3 cm	0.2 cm
500 keV	2,8 cm	3.5 cm	2.6 cm	1.8 cm	1.6 cm
800 keV	3.5 cm	4.9 cm	3.6 cm	2.6 cm	2.4 cm

Crystal thickness for 70% X-rays detection efficiency



- ❑ *From datasheets CeCAAG and PrLuAG crystals seems fine and are not hygroscopic*
- ❑ *½ " thickness is optimal*
- ❑ *Preliminary study to see if it was possible to use other crystals [different from $LaBr_3$:Ce]*

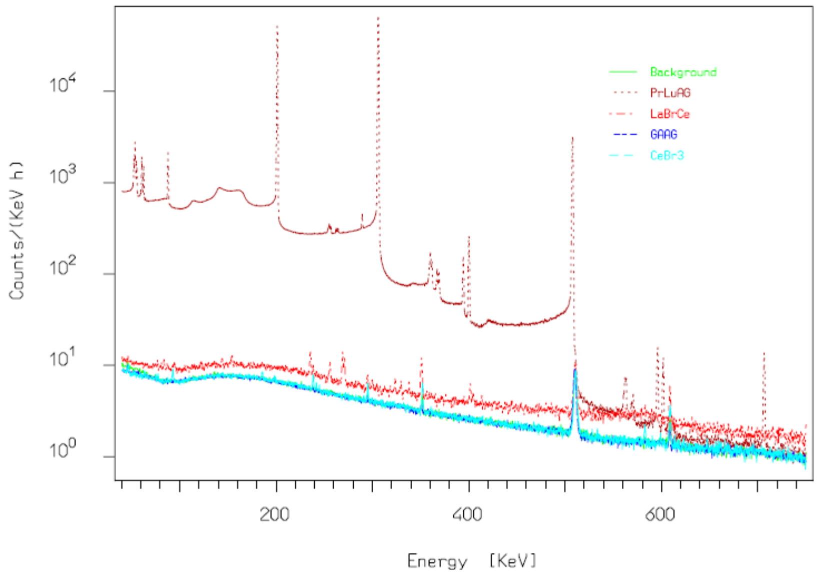
Our survey of crystals with SiPM readout (lab tests)

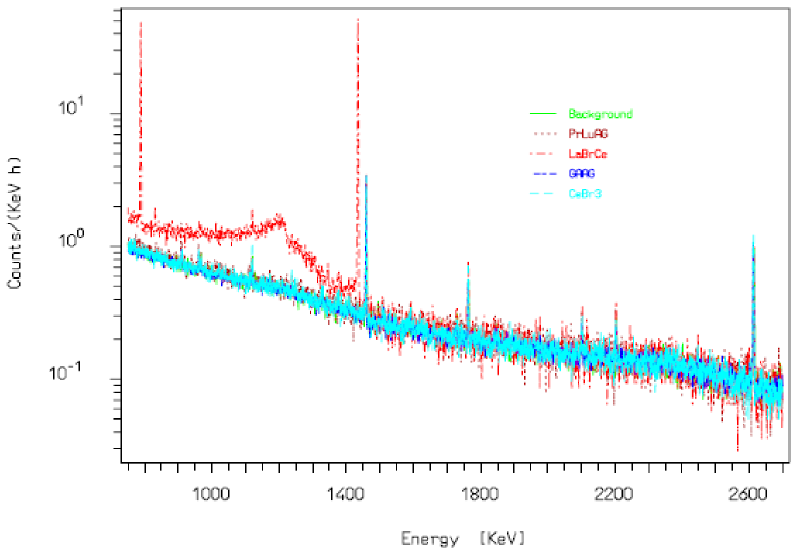
Scintillator	Ce:CAAG	PrLuAG	LaBr3:Ce	CeBr3	LYSO
Density (g/cm3)	6.63	6.73	5.08	5.18	7.1
Light yield (photons/MeV)	57000	22000	75000	47000	34000
Decay time (ns)	88 (91%) 258 (9%)	20	30	25	40
Peak emission (nm)	520	310	360	370	420
Energy resolution (% 662 KeV) [with PMTs typica]	5.2	4.2	2.6	4.0	10
Hygroscopicity	no	no	yes	yes	no
Cleavage	no	no	no		no
Melting point ©	1850	2043	783	722	2150

- ❑ *Preliminary study with standard spectroscopic chain*
- ❑ *3 types of SiPM used:*
  - *SENSL B-extended (V_{op} ~27 V),*
  - *Advansid 4x4 RGB (V_{op} ~ 29.5 V),*
  - *Hamamatsu S13361 TSV (V_{op}~53.8 V)*

Resolution @ Cs^{137} peak	$LaBr_3$:Ce Hama	$LaBr_3$:Ce Advansid	$CeBr_3$ Hama	PrLuAG Hama	CeCAAG Hama	CeCAAG Advansid	CeCAAG SENSL	NAI(Tl) Hama
Ortec 672 spec amplifier	3.4%	4.0%	4.8%	7.0%	6.4 %	-	-	8.4%
Ortec 579 fast amplifier	3.4 %	3.6 %	5.1 %	-	-	9.9 %	10.4 %	8.9%

Intrinsic activity of $LaBr_3$:Ce crystals

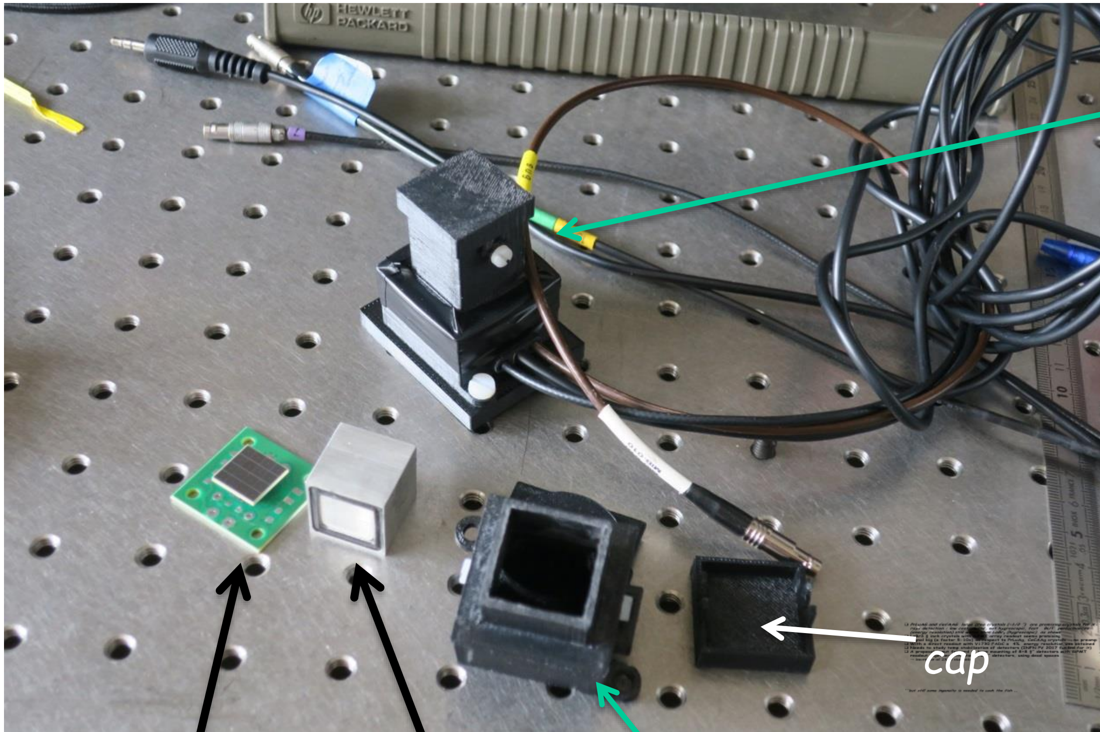




Intrinsic activity measured with a conventional HpGe spectroscopic chain based on Ortec 672 + MCA

LaBr3:Ce detectors with SiPM array readout

A simple solution is a crystal read out by a SiPMT array, where cells outputs are summed up. Analogue signal may then be digitized by a fast (> 500 MHz) digitizer. Holder in two pieces: upper one contains the crystal (may be disconnected), lower one contains PCB+array

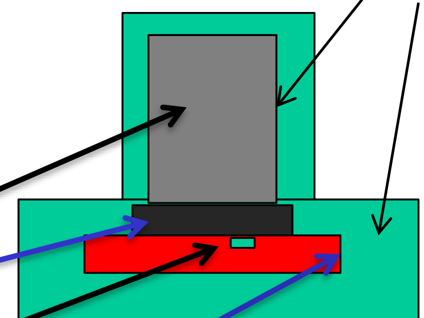


SiPM array on PCB

Crystal

Holder

detachable



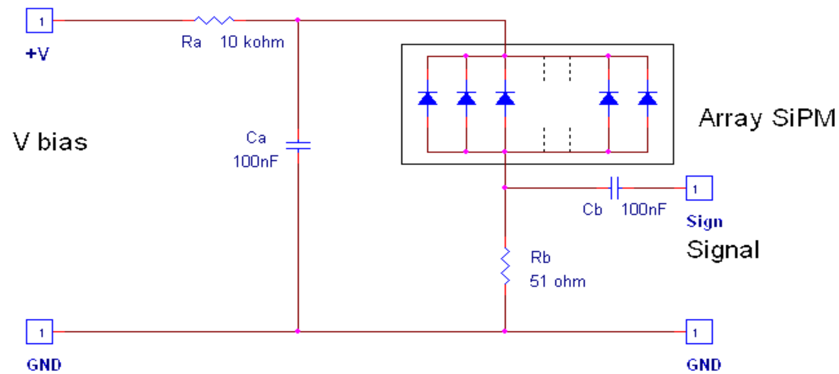
LaBr3 crystal

SiPM array

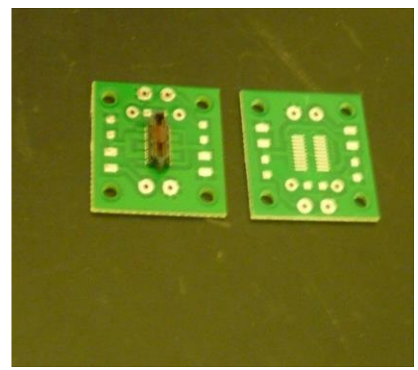
TMP37 thermistor

PCB+SAMFORD connector

Details on SiPM array readout



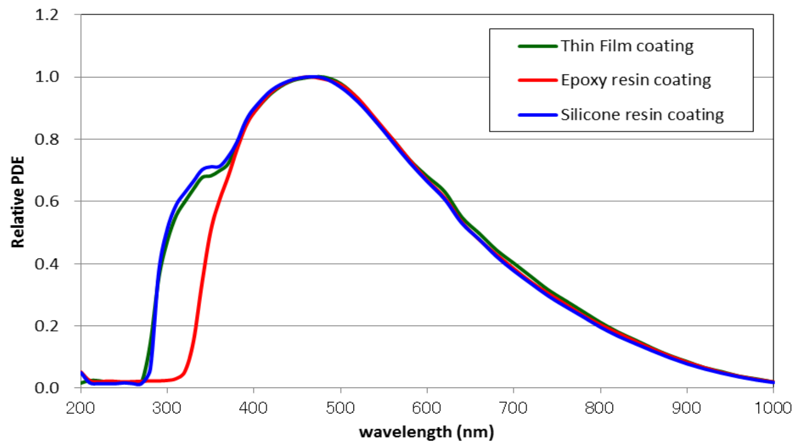
- ***SiPM array custom mount***
- ***16 3x3 mm² cells signals are summed up in the basette and then readout in parallel***



Used SiPM arrays

Tested SiPMT arrays use 3x3 mm² macro-cells arranged in 4x4 arrays.

- *SENSL ArrraySB-4-30035-CER arrays with 3x3 mm² macrocells, V_{op} ~27 V*
- *Hamamatsu S13361 arrays with 3x3 mm² macrocells, V_{op}~53.8V, TSV technology*
- *Advansid ASD-SiPM3S-4x4T (RGB) arrays with 3x3 mm² macrocells, V_{bkw} ~28.5 V*



PDE for Hamamatsu TSV SiPMT (suitable for UV detection)

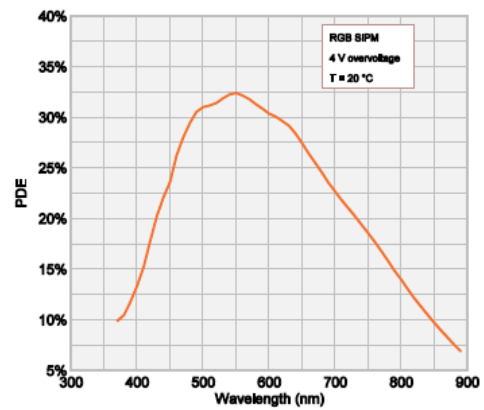
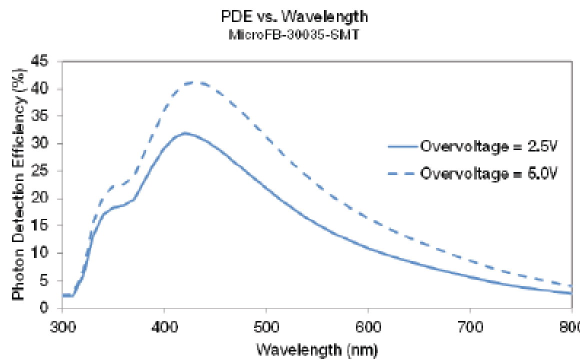


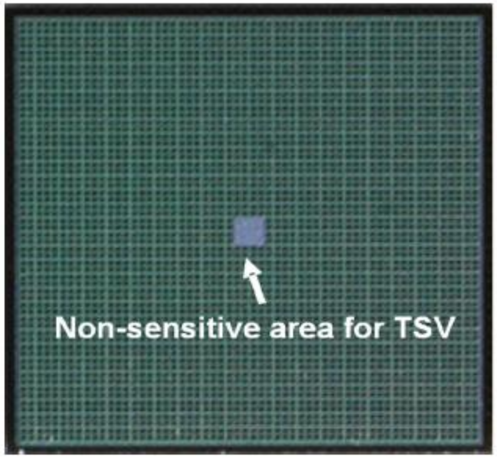
Fig.8 Photo detection efficiency (PDE) in RGB-SiPMs as a function of wavelength (crosstalk and afterpulse not included).

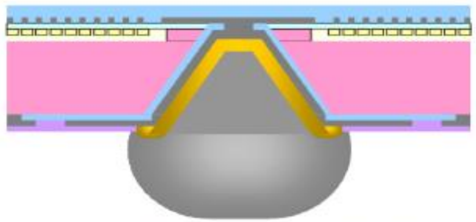
PDE for RGB Advansid SiPMT (well suited for RGB detection)



PDE for B-extended SENSL SiPMT

Some more details on Hamamatsu TSV arrays





- *TSV (``through Silicon Via") technology used to eliminate the need of a wire bonding pad, that creates dead spaces problems*
- *The anode of each channel is traced to the backside pad by TSV*
- *In principle better for timing application (smaller timing jitter)*

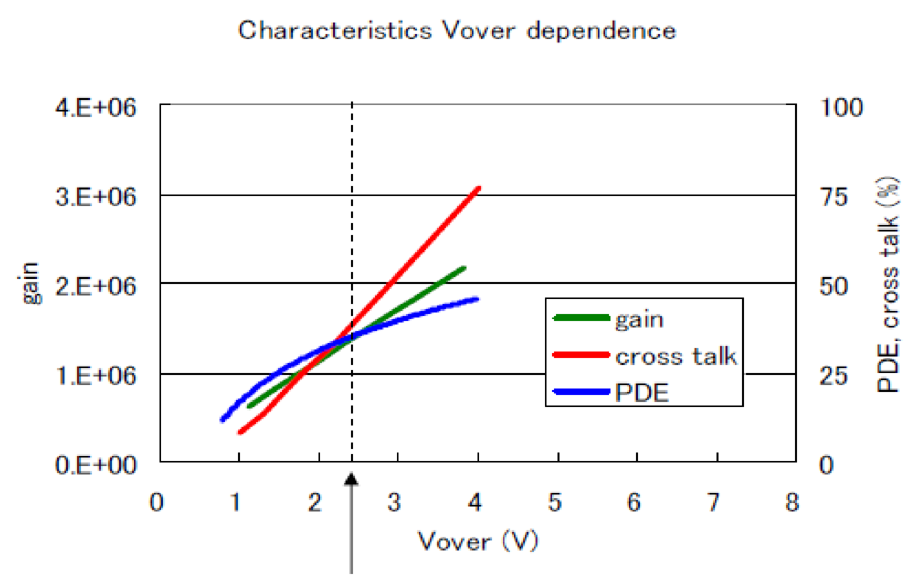
Example: Hamamatsu S13361

■ **Electrical and optical characteristics**

(Typ. Ta=25 deg C, per 1 ch., Vover=2.4V *1 Unless otherwise noted)

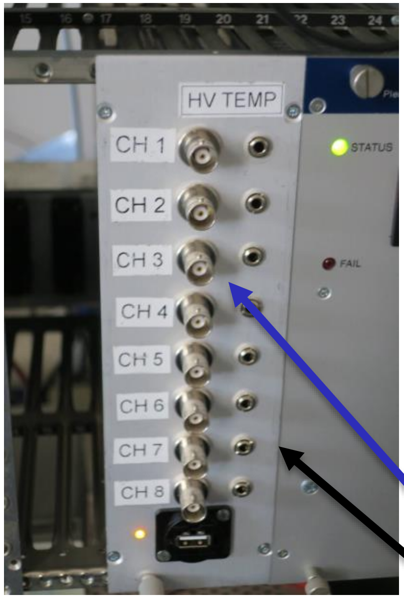
Parameters		Symbol	S12642-0404PA-50 S12642-0404PB-50	Unit
Spectral response range		λ	320 to 900	nm
Peak sensitivity wavelength		λp	450	nm
Photon detection efficiency at λp *1		PDE	35	%
Dark count *2	Typ.	-	2	Mcps
	Max		3	
Terminal capacitance		Ct	320	pF
Gain *3		M	1.25×10^6	-
Breakdown voltage		VBR	65±10	V
Recommended operating voltage *4		Vop	VBR +2.4	V
Vop variation between channels (+/-)	Typ.	-	0.05	V
	Max.		0.15	
Temperature coefficient of reverse voltage		ΔTVop	60	mV/°C

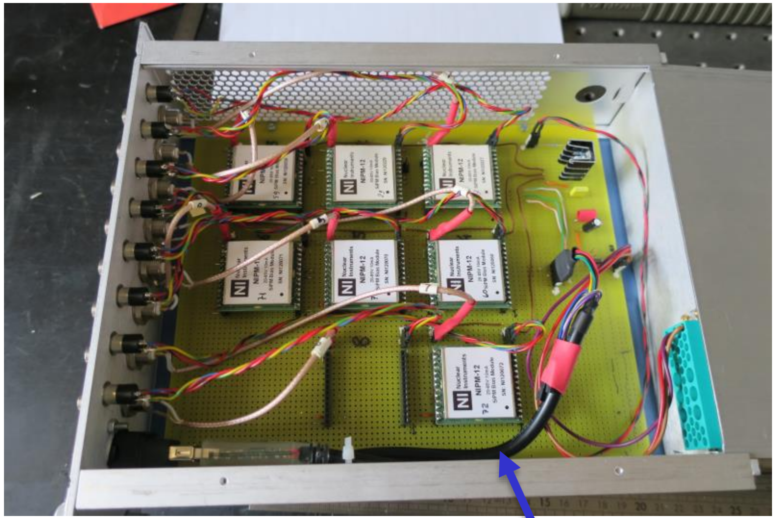
*1: Photon detection efficiency does not include crosstalk and afterpulses.
*2: The data will be measured by current.
*3: Characteristics change with applied over voltage. Please refer to next section in detail.
*4: Refer to the data attached for each product.



A NIM module for HV with temp CTRL

- NIM module takes HV from NIM bus
- I2C protocol avoids bulky control via an USB hub
- Temperature sensors TMP 37
- Modules includes up to 8 CAEN A7585 modules + 1 FDTI USB to I2C controller
- In addition slave modules on the I2C bus

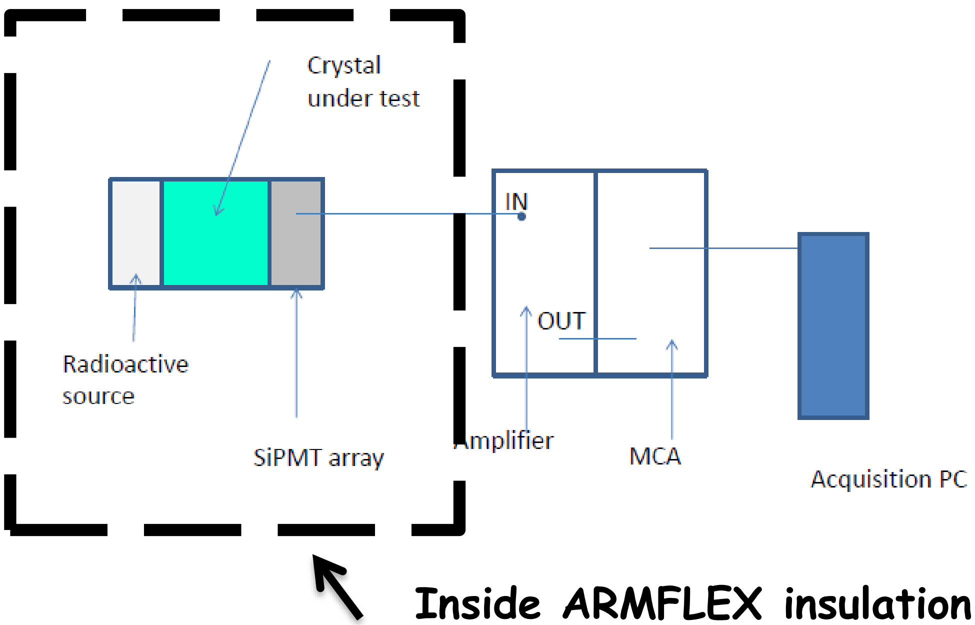




- HV BNC connector
- 3.5 mm stereo jack for temperature sensor
- FDTI USB to I2C controller

Experimental layout for lab tests

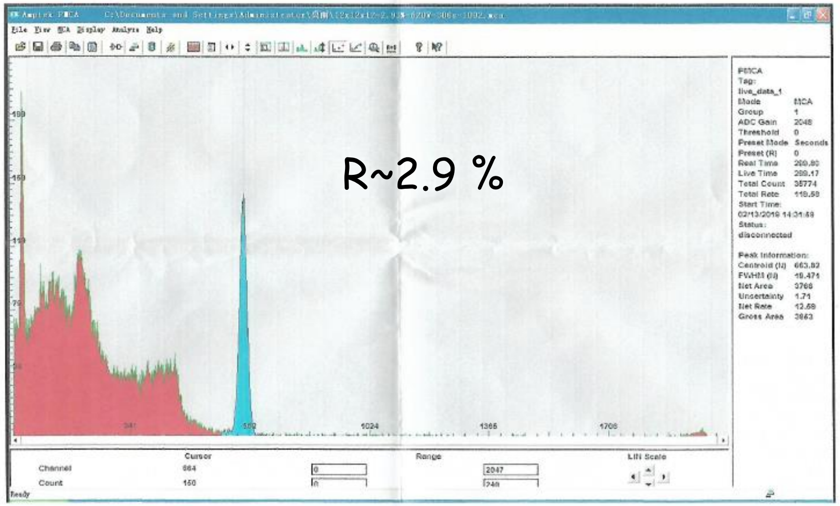
- *Tests with different SiPMT arrays from Hamamatsu, SENSL, Advansid*
- *No signal amplification (100-200 mV)*
- *Standard spectroscopic readout chain . Ortec 570, 579 or 672 amplifiers + CAEN N951 MCA or ORTEC EasyMCA or DT5730 digitizer (same as standard V1730 VME module used in FAMU DAQ)*
- *Different calibrated X-rays sources from Spectrum Techniques*
- *In some tests a climatic chamber was used*



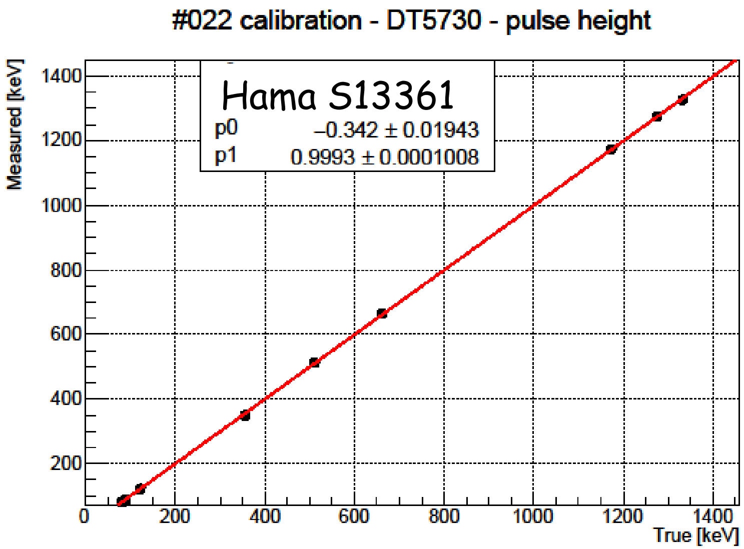
Inside ARMFLEX insulation (at room temperature) or climatic chamber

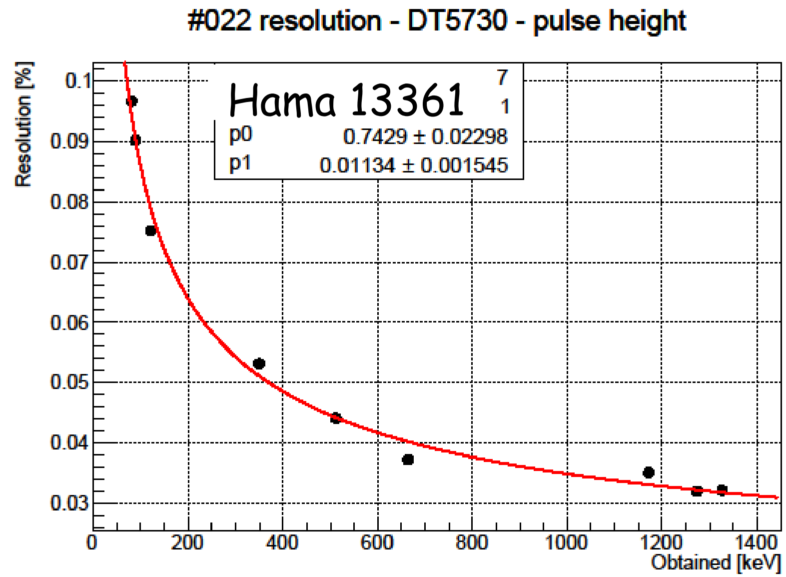
direct SiPMT-array signal , no amplification

Laboratory tests with ½ " crystals



- MCA spectra from producer (OST photonics) using a PMT: resolution R ~3 % for ½" crystals
- Linearity and resolution with calibration sources in lab, using a CAEN DT5730 digitizers and Wavedump (~3-3.5 %)





Good detector linearity: better than 2%

Temperature effects on SiPM gain [to be corrected]

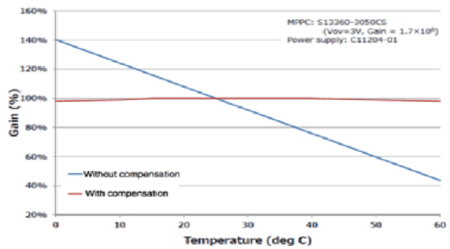


Figure 4. Gain variation versus temperature for Hamamatsu S13360-3050CS SiPM without temperature compensation (blue line) and with compensation (red line) provided by the C12332-01 driver circuit.

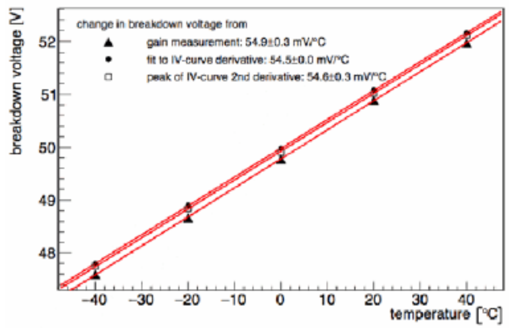
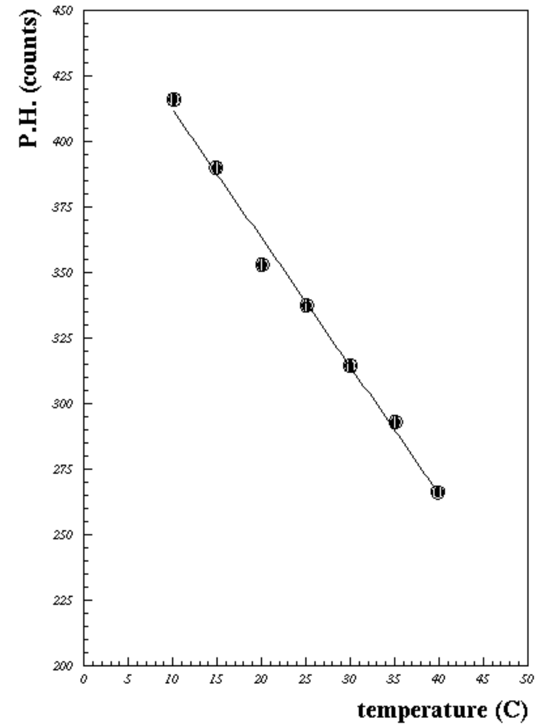
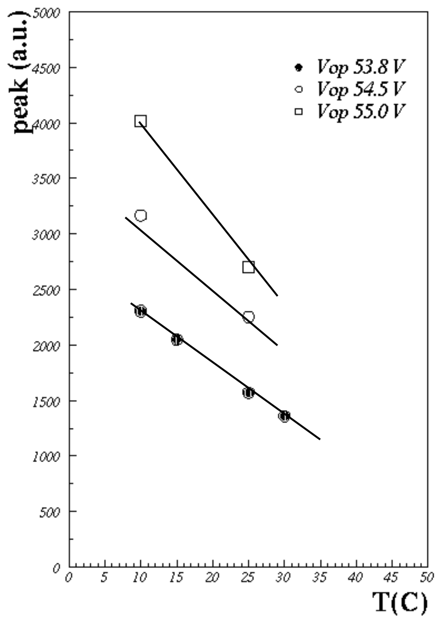


Figure 2. Dependence of breakdown voltage on temperature for Hamamatsu S13360-3050CS SiPM. The figure is from Otte et al. (2016).

LaBr3 with Advansid SiPM array



LaBr3 with Hamamatsu SiPM array

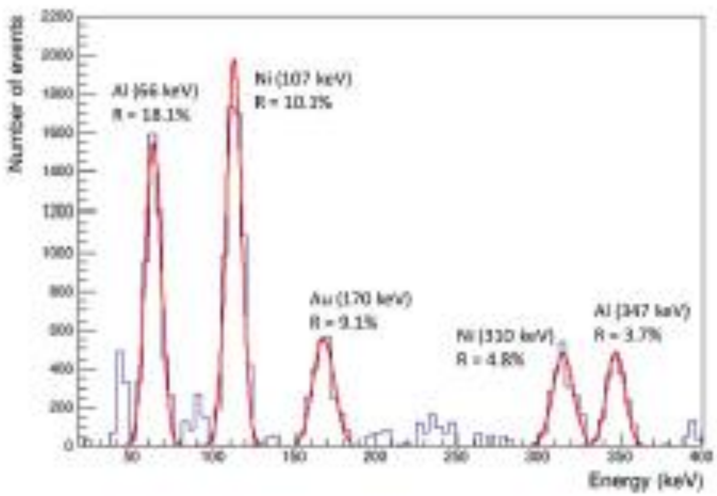


- *Temperature effect ~1%/C (depends on SiPM type),* explained with decrease of V_{brk} with temperature lowering.
- To be corrected offline or online
- tests with a Memmert IPV30 "climatic chamber" (precision 0.1 C between 0. – 70 C)

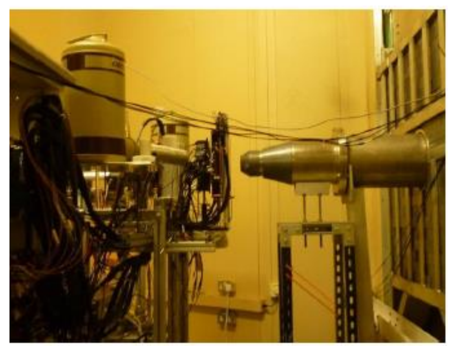
Spectra seen in 2017 run

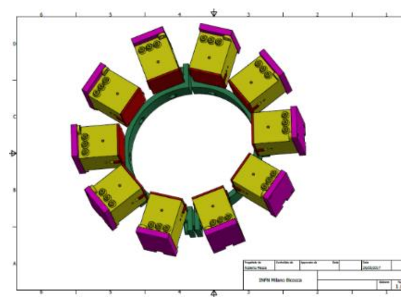
array	59 keV	122 keV	662 keV
Hama 13361-AS (6 pcs)	14.5 ± 1.6 %	9.6 ± 1.4 %	5.0 ± 0.9
Hama 13361-AE (2 pcs)	20.1 ± 1.1 %	13.4 ± 3.1 %	5.1 ± 0.4
Advansid ASD-P-4-TD (1 pcs)	20 %	11.8 %	5.5 %

Obtained FWHM resolution of $LaBr_3$:Ce with SiPM array as measured with calibration runs with ^{57}Co and ^{137}Cs sources at RAL

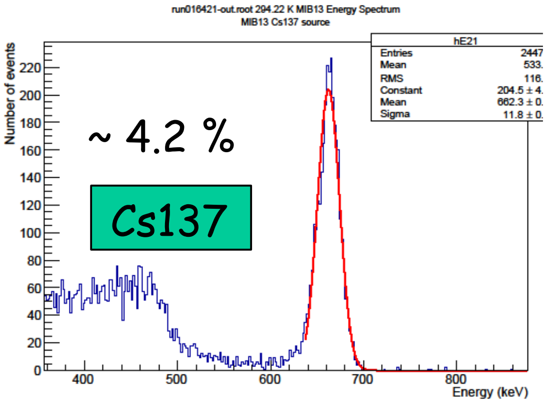


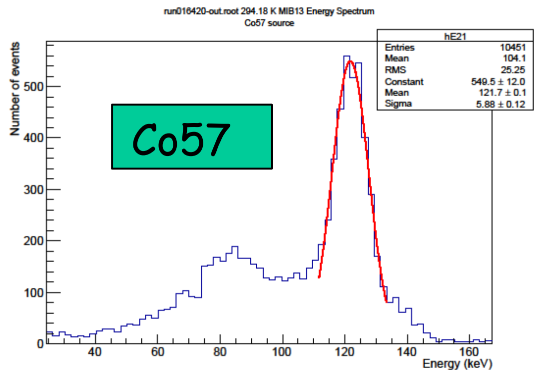
Spectrum with pure Hydrogen filling of the target, as seen with one $LaBr_3$:Ce detector with SiPM readout (Hamamatsu S13361)

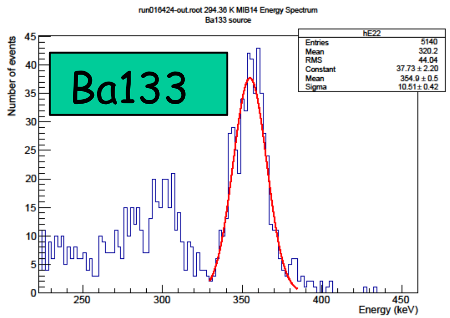




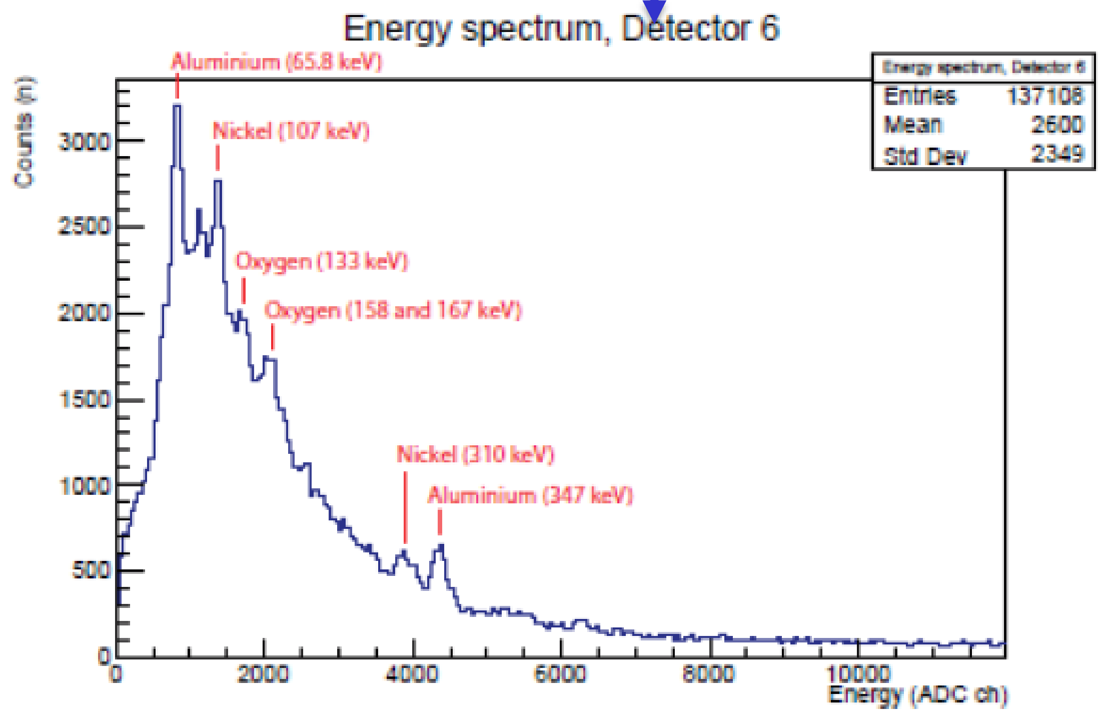
X-rays detection at RAL in the FAMU experiment



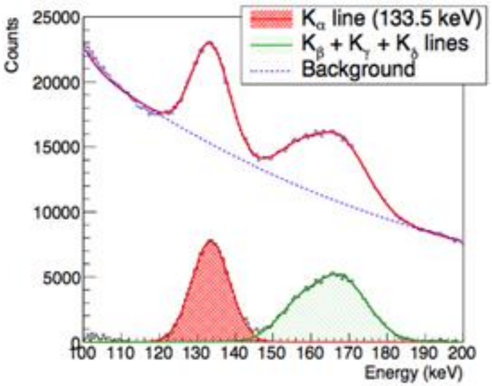




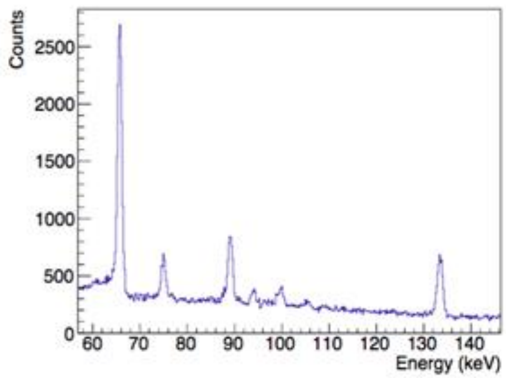
- December 2018 run with $H+O_2$(2%), 80 K, 7 bar at RAL
- Calibration with sources
- Resolution with sources poorer than in lab due to env noise, poor positioning of sources, …
- data taken with muon beam at 56 MeV/c at RAL : peaks are clearly visible in the region 80-400 keV



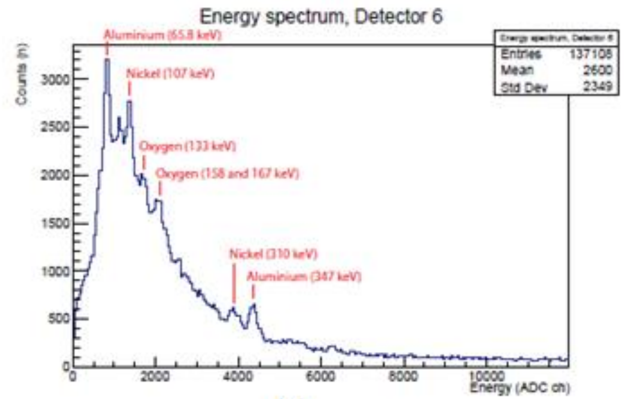
Comparison between different X-rays detectors in FAMU



(a) $LaBr_3$ counters spectrum



(b) HPGe spectrum



(c)

$LaBr_3$:Ce with PMT readout: mature technology , but bulky

HpGe superior resolution, but slower

$LaBr_3$:Ce with SiPM array readout: much more compact. Needs some R&D

All have pro and cons

Conclusions

- *PrLuAG and CeCAAG large area crystals (~1/2 ") have worse resolution as respect to $LaBr_3$:Ce crystals*
- *$LaBr_3$:Ce with SiPM array readout and temperature gain control seems a promising solution with a resolution R (FWHM) comparable with PMT readout (~3.5 %)*
- *this kind of detector is much more compact than the one with PMT readout*
- *It may have promising applications also in homeland security and TOF-PET*
- *To increase resolution use new Hamamatsu S14361 SiPM array (with increased PDE at 390 nm)*

Many thanks to all the members of the FAMU collaboration for their continuos support and encouragement and to Dr. M. Bombonati (Hamamatsu Italia) and Dr. N. Serra (Advansid, Trento Italy) for a lot of helpful discussions and help.

Thank you for attention

Other possible applications

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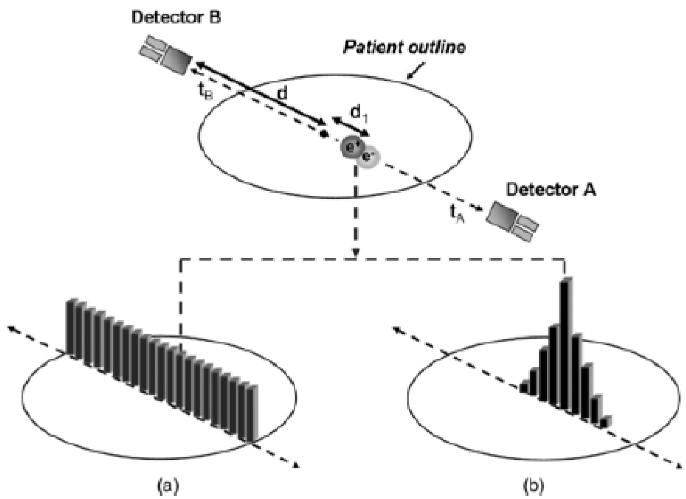

TOF PET imaging (Medical Physics)

- large soft photon yield per MeV
- high density crystals (stopping power)
- soft photon detection in magnetic fields
- compact design
- high granularity
- non-hygroscopic
- affordable

Homeland Security Applications

Nuclear Plant Monitoring

Homeland security