Improving the time resolution of large area LaBr3:Ce detectors, with SiPM array readout

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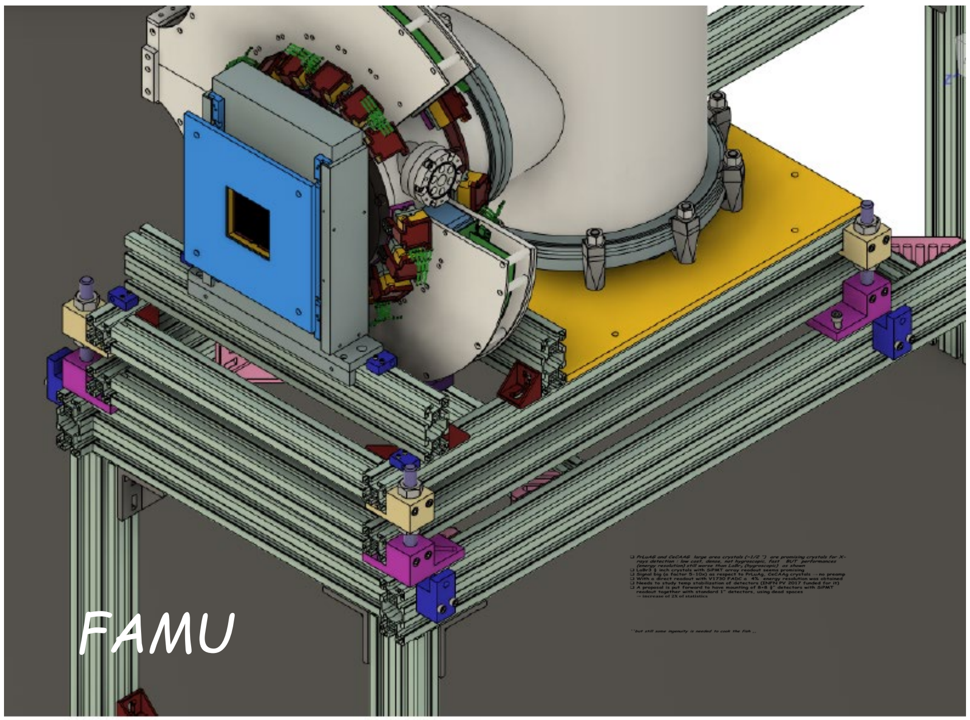
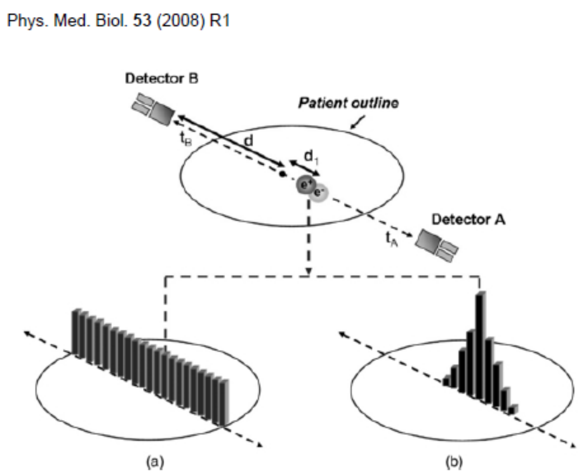
- *Compact X-rays detectors, based on crystals with SiPM array readout may find application in many fields:*
  - *TOF PET imaging*
  - *Fundamental physics: measure of the Zemach proton radius (FAMU at RIKEN-RAL)*
  - *Homeland security*



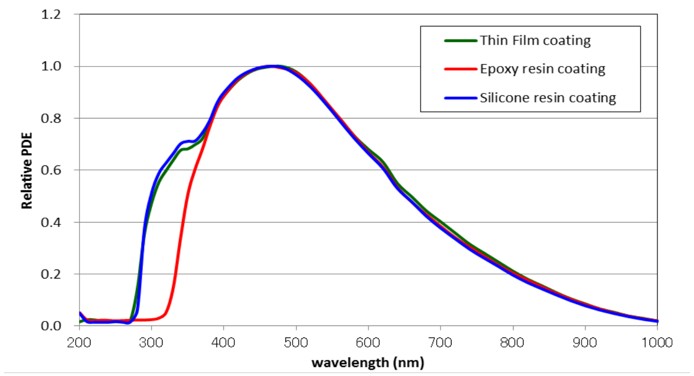


- large soft photon yield per MeV
- high density crystals (stopping power)
- soft photon detection in magnetic fields
- compact design
- high granularity
- non-hygroscopic
- affordable

Detectors requirements:
- *High photon yield + good timing resolution*
- *Good energy resolution at low X-rays energy (~ 100 KeV)*
- *Low cost per channel*
- *Simple photon readout*

Properties of used Crystals/SiPM

Scintillator	Ce:CAAG	PrLuAG	LaBr3:Ce	CeBr3	NAI(Tl)
Density (g/cm3)	6.63	6.73	5.08	5.18	3.67
Light yield (photons/MeV)	57000	22000	75000	4700 0	38000
Decay time (ns)	88 (91%) 258 (9%)	20	30	25	250
Peak emission (nm)	520	310	360	370	415
Energy resolution (% @ 662 KeV) [with PMTs typ]	5.2	4.2	2.6	4.0	7
hygroscopicity	no	no	yes	yes	yes
Melting point ©	1850	2043	783	722	924

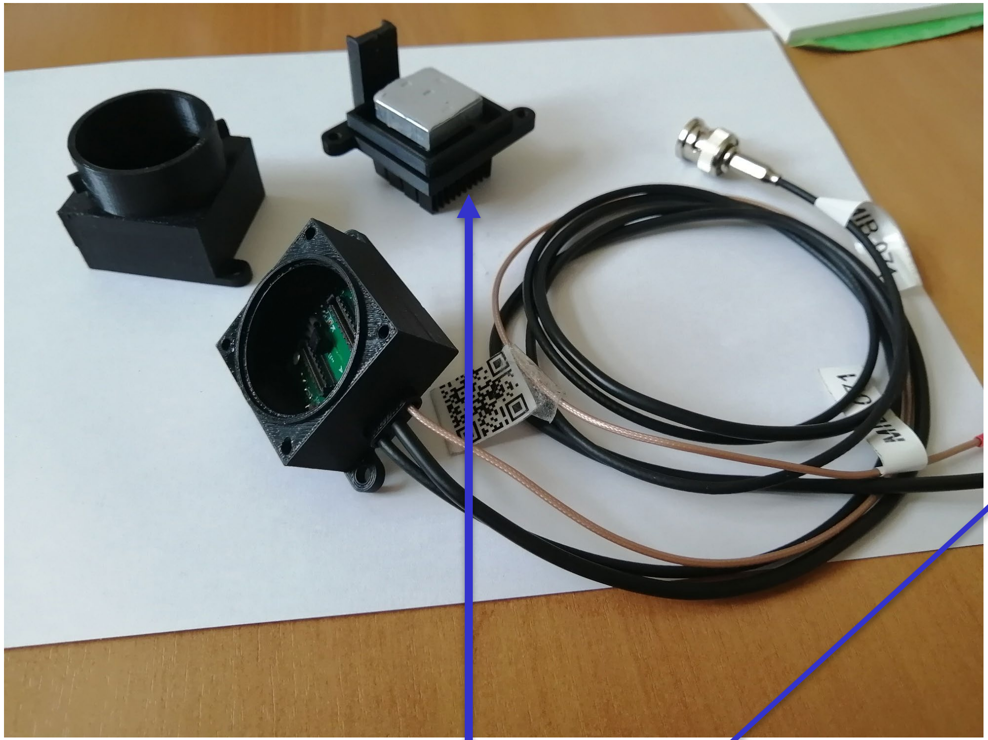


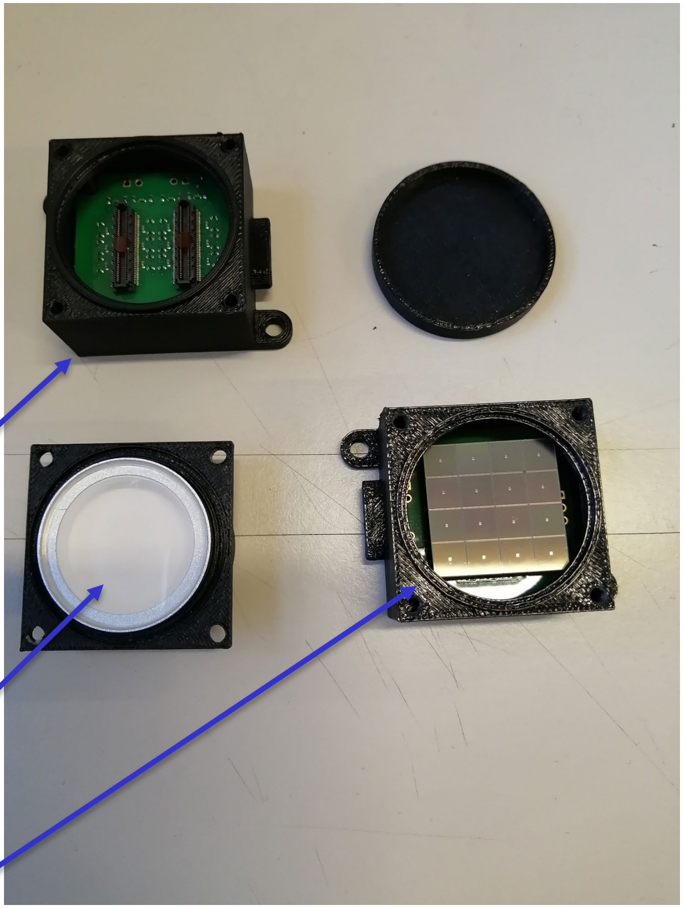
PDEs for used Hamamatsu SIPM array (Silicon window: suitable for UV detection, as in $LaBr_3$:Ce)

	size	Vop	Temp coeff	Peak sensitivity	PDE	Spectral range
Hamamatsu S14161-6050-AS	1 inch	41.1 V	34 mV/C	450 nm	50%	270-900 nm
SENSL Array-J-60035-4P	½ inch	29 V	21.5 mV/C	420	50%	200-900 nm
Advansid NUV3S-4x4TD	½ inch	29.3 V	26 mV/C	420 nm	43%	350-900 nm
Hamamatsu S14161-3050-AS	½ inch	41.1 V	34 mV/C	450 nm	50%	270-900 nm
Hamamatsu S13361-3050-AS	½ inch	53.8 V	60 mV/C	450 nm	35%	320-900 nm

1" LaBr3:Ce detectors

- Mechanics designed to allow inter-mix of ½" and 1" detectors





- ❑ Heat dissipator
- ❑ PCB seen from top
- ❑ Round crystal inside holder
- ❑ Mounted S14161-6050-AS array (with Silicone window)

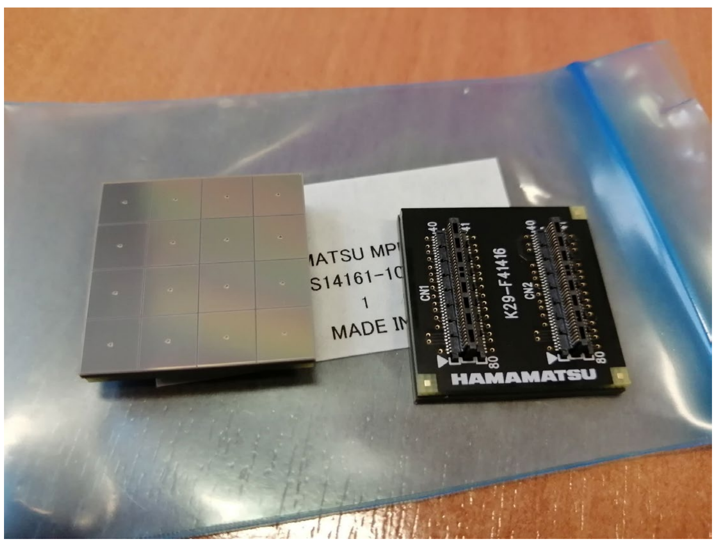
Hamamatsu S14161-6050 SiPM arrays

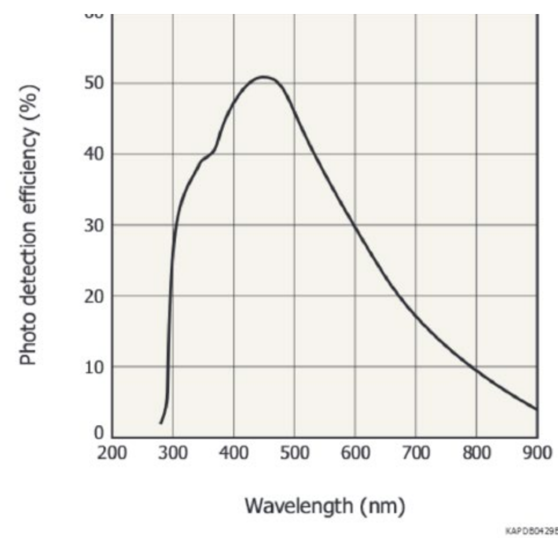
Electrical and optical characteristics (Typ. Ta=25 °C, Vover=2.7 V, unless otherwise noted)

Parameter		Symbol	S14160/S14161 -3050HS-04, -08	S14160/S14161 -4050HS-06	S14160/S14161 -6050HS-04	unit
Spectral response range		λ	270 to 900			nm
Peak sensitivity wavelength		λp	450			nm
Photon detection efficiency at λp*3		PDE	50			%
Breakdown voltage		VBR	38			V
Recommended operating voltage*4		Vop	VBR + 2.7			V
Vop variation between channels in one product*5	Typ.	-	0.1			V
	Max.		0.2			
Dark current	Typ.	ID	0.6	1.1	2.5	μA
	Max.		1.8	3.3	7.5	
Crosstalk probability		-	7			%
Terminal capacitance		Ct	500	900	2000	pF
Gain		M	2.5×10^6			-
Temperature coefficient of recommended reverse voltage		ΔTVop	34			mV/°C

*3: Photon detection efficiency does not include crosstalk and afterpulses.
*4: Refer to the data attached for each product.
*5: The parameter is for the S14161 series (multichannel type)

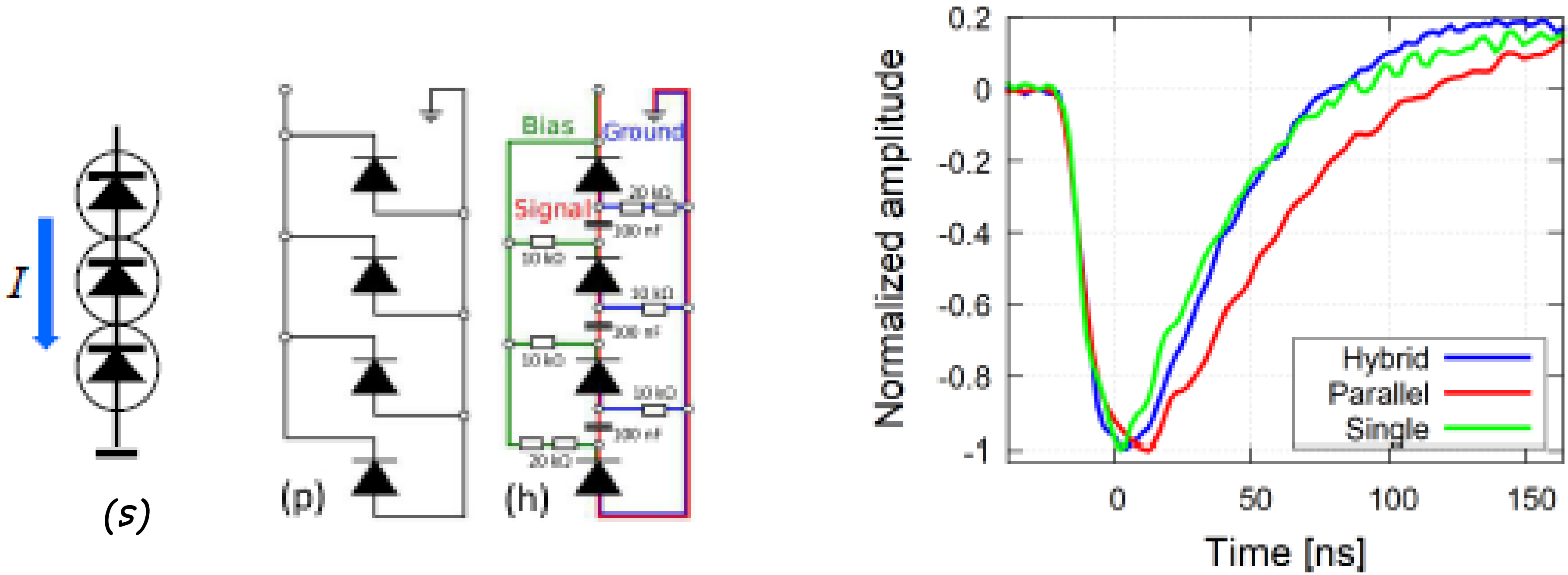
- Higher PDE (50% at λp, Vop=VBR + 2.7 V)
- Lower voltage (VBR=38 V typ.) operation
- Small dead space in photosensitive area
- Low afterpulses and crosstalk
- High gain: 10^6 order
- Excellent time resolution
- Immune to effects of magnetic fields





Photon detection efficiency does not include crosstalk and afterpulses.

Connection of different SiPM in one array : ganging

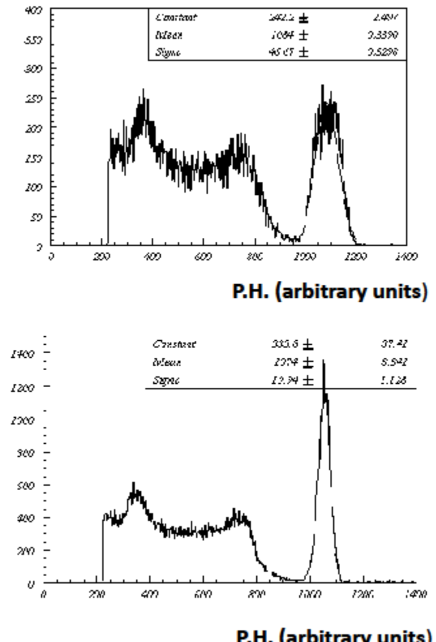


- ❑ Several choices depending on requirements: speed, S/N, granularity, …
- ❑ Active/passive ganging : better S/N and timing with active ganging
- ❑ Parallel ganging (p): better S/N, increased capacitance →slow rise and log falltime ; need to group SiPM with same V_{brk}
- ❑ Series ganging (s): charge/amplitude reduced. Reduced capacitance →fast signal. Needs higher bias voltage (x N)
- ❑ Hybrid ganging (h): connected in series , but with decoupling capacitors in between. Series connection for signal and parallel connection for bias. Common bias voltage.

Main problems with SIPM readout

- Gain drift with temperature

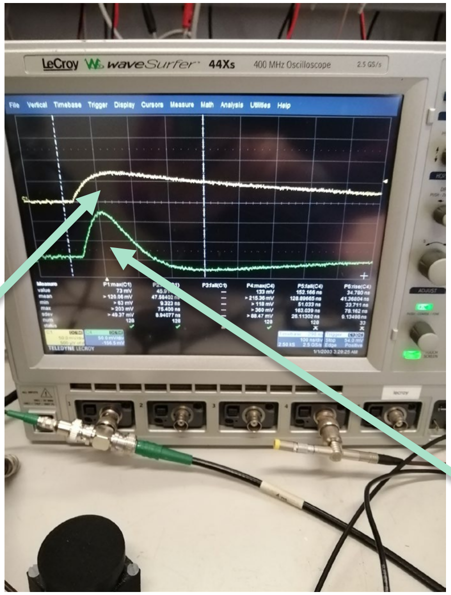
Temperature correction



Temperature scan 20-30 C

- Breakdown voltage $\Delta V_{brk} / \Delta T$ = 34mV/deg (MPPC), 25mV/deg (AdvanSiD)
- Gain can be drastically changed when temperature varies, if V_{bias} is not adjusted accordingly.

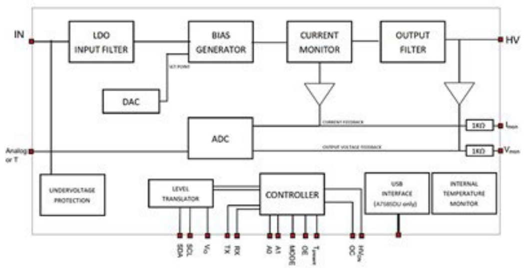
- Bad timing properties, especially for larger SiPM arrays (1")



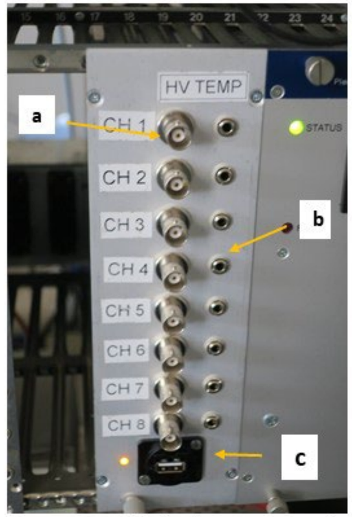
- ❑ *Signal shape with parallel ganging: long falltime and risetime are evident*
- ❑ *Same signal with pole zero suppression + overvoltage to compensate for signal decrease, but undershoot is evident.*

Control of SiPM gain drift with temperature

CAEN A7585D chip

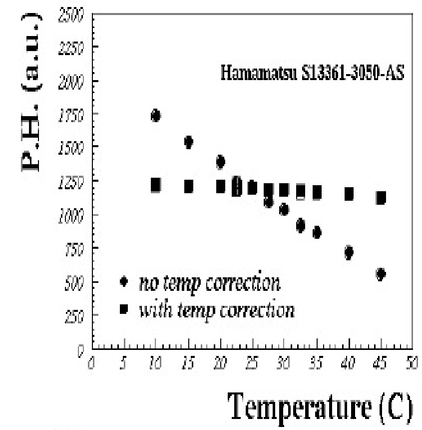


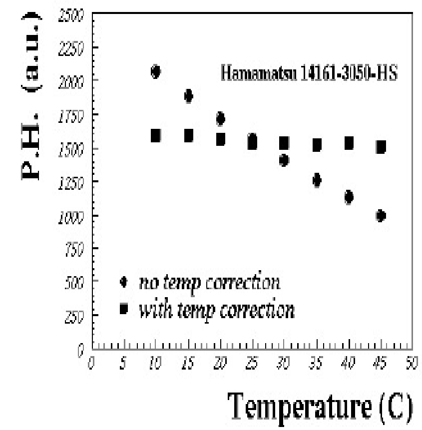
A7585D functional diagram



NIM module front panel

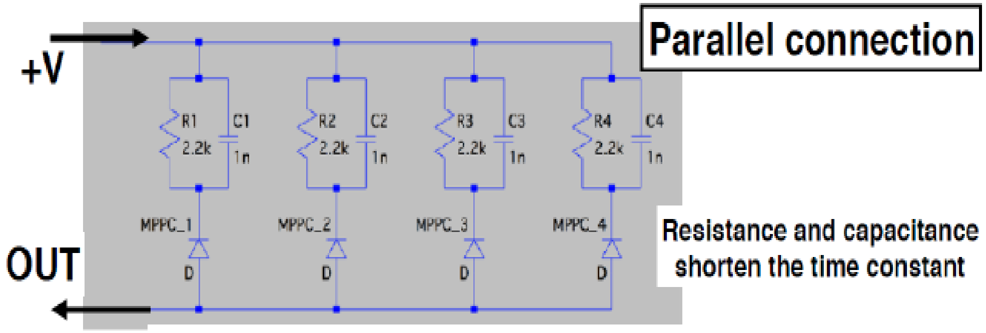
NIM module exploded view

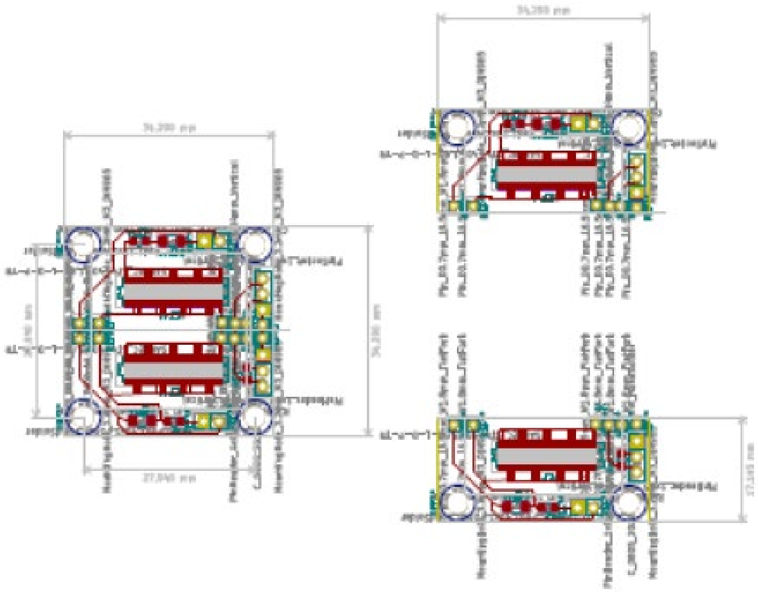




- *SiPM gain drift with temperature → needs correction of V_{op}.*
- *temperature monitor by a TMP37 thermistor*
- *Custom NIM modules (8 channels) based on CAEN A7585D chips*
- *Interface with PC either FDTI USB-I2C or Arduino*
- ***In the range 10-40 ^{0}C the effect is reduced from 60% to 6% for ½" detectors and from 50% to 9% for 1"detectors***

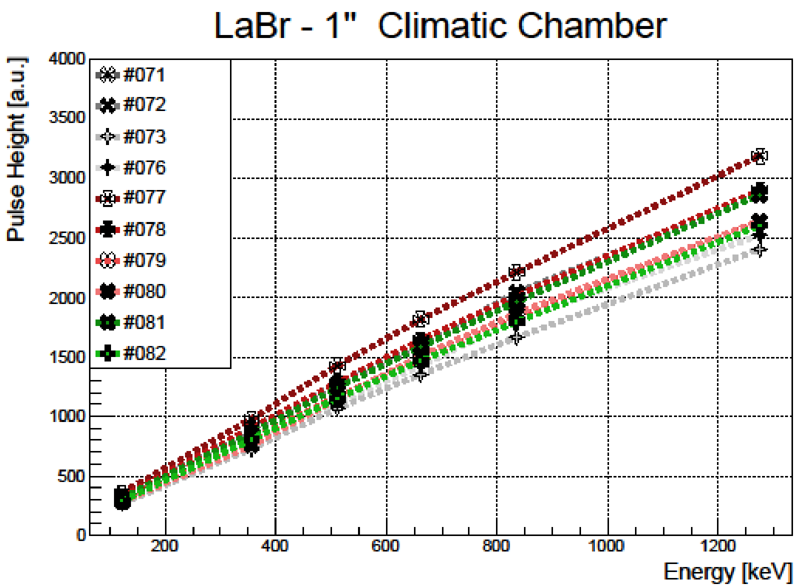
PCB design no 1: parallel ganging



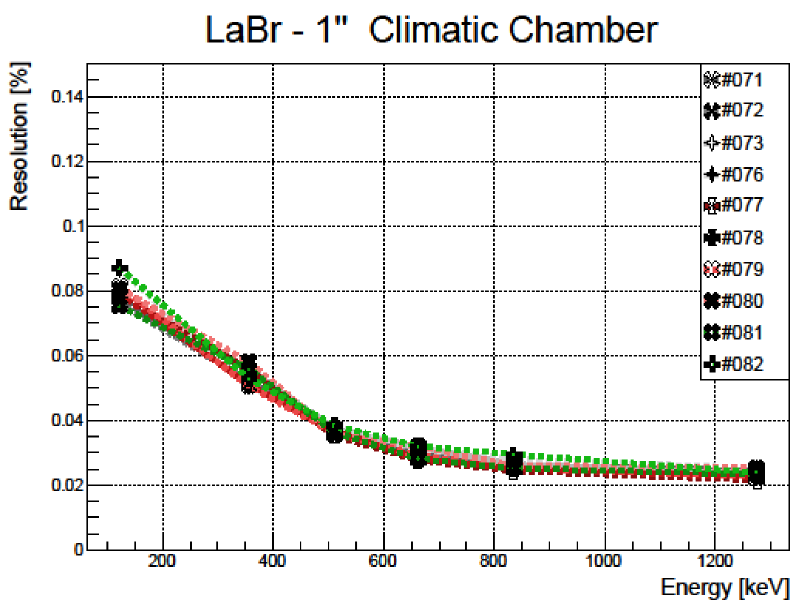


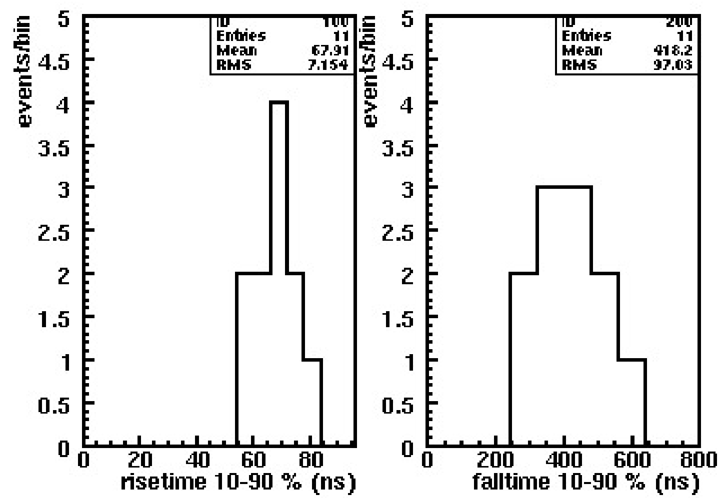
- Charge preserved, but amplitude reduced
- Better S/N
- Increasing capacitance →slow rise and long falltime
- Needs to group SiPM with same V_{brk}
- To avoid problems in mounting PCB has been splitted in two pieces to allow adjustments in mounting, connected by wire bonding

Test results for 1” detectors (// ganging)



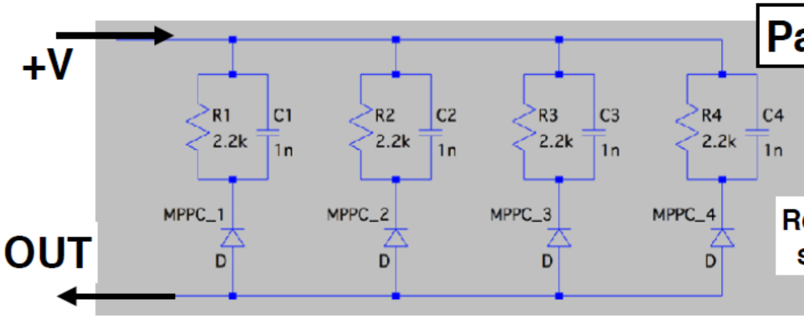
- PCB with parallel ganging for SiPM arrays cells
- S14161-6050-AS arrays with Silicone window
- FWHM energy resolution ~3.0% (~7.8 %) @ Cs137 (Co57) peak
- Risetime ~ 65 ns/falltime ~400 ns (due to high capacitance of array)

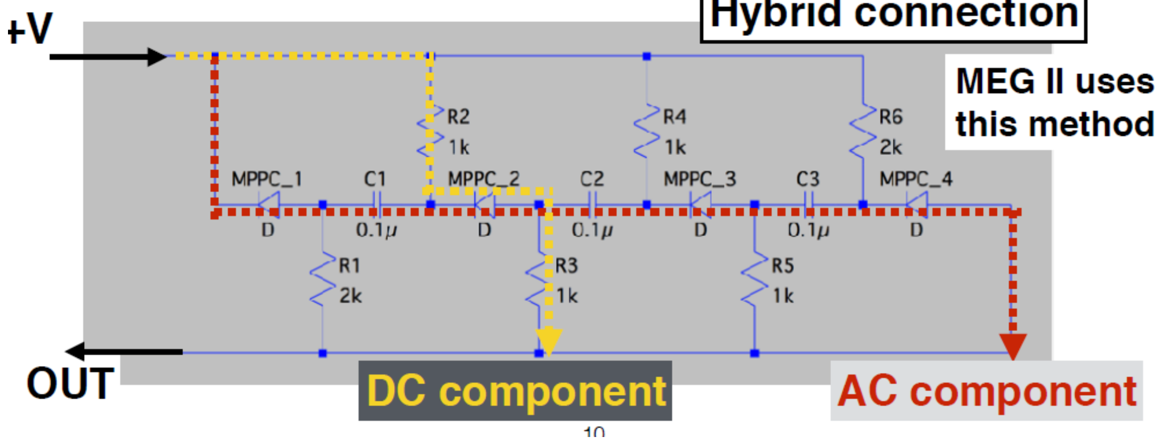




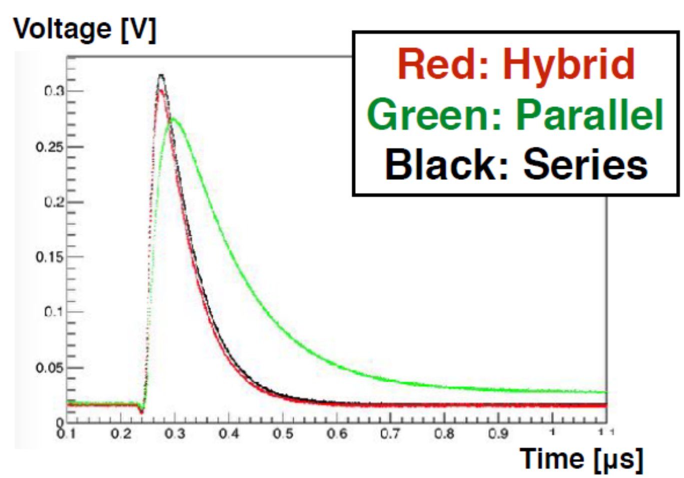
PCB design no 2: hybrid ganging

- Connection methods for MPPCs



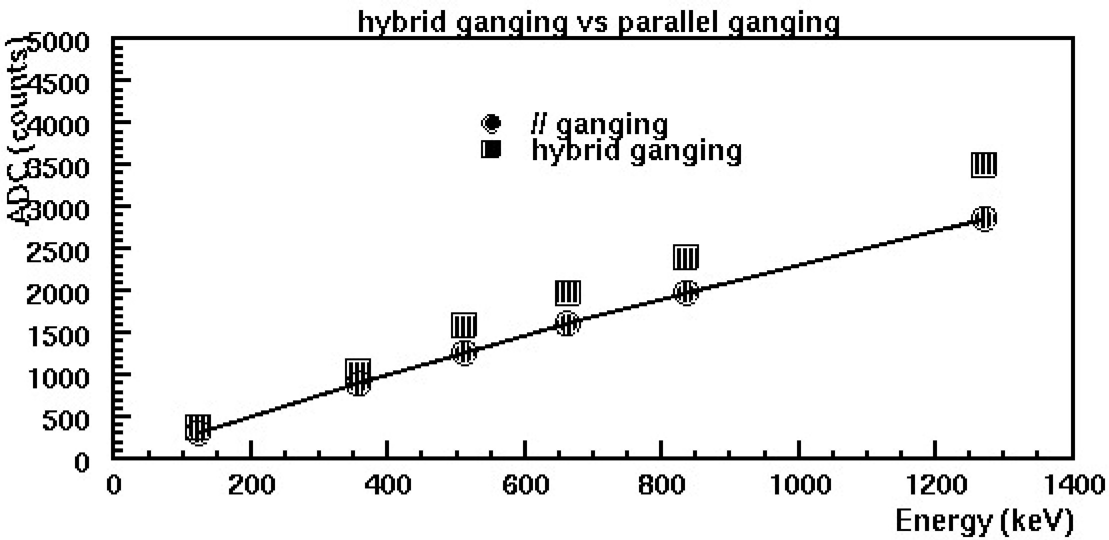


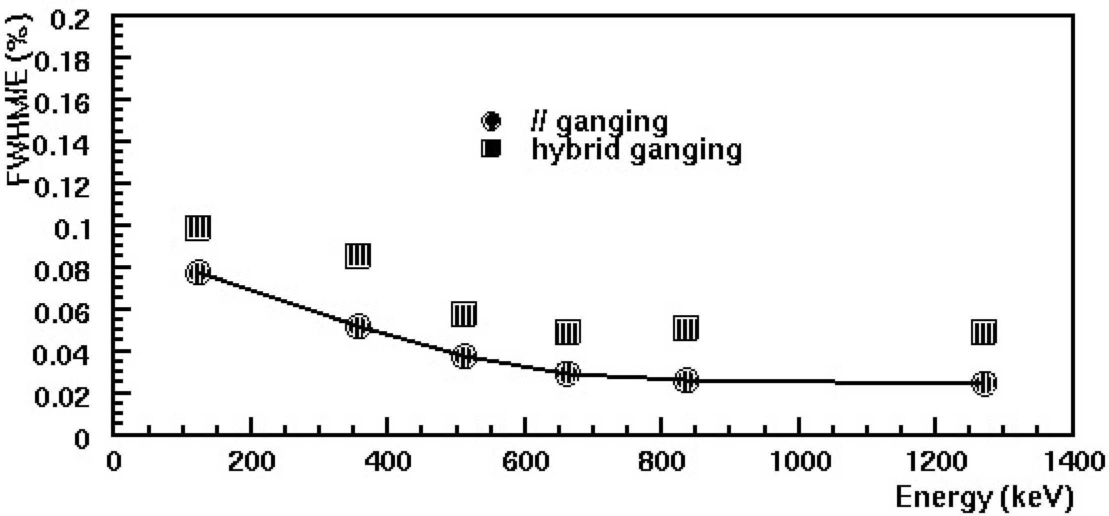
- ❑ series connection for signal and parallel connection for bias
- ❑ Common bias voltage
- ▪ Risetime goes from ~65 ns to 16 ns/falltime down to ~180 ns
- ▪ But FWHM energy resolution deteriorates: from 3% to 6%
- ▪ ??? Trying to understand the problem



Time constant: Series ~ Hybrid < Parallel
Pulse height: Series ~ Hybrid > Parallel

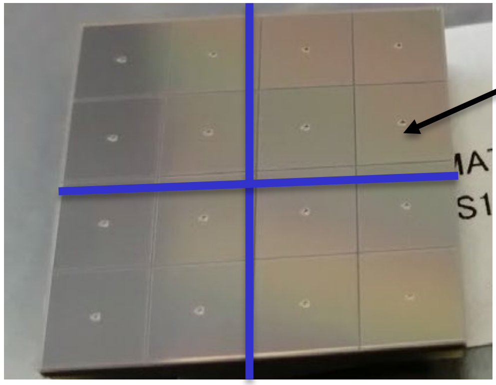
Hybrid ganging vs parallel ganging





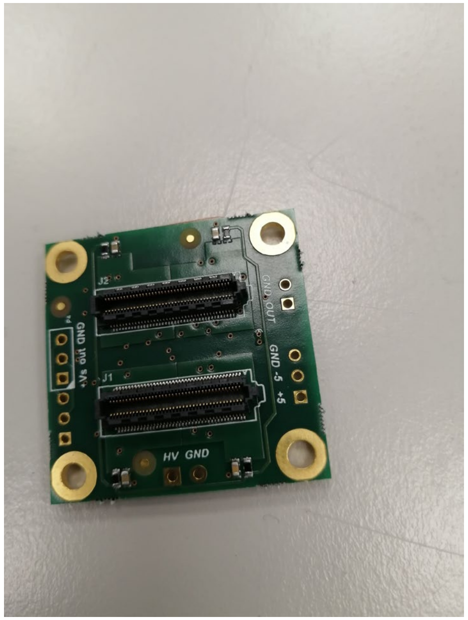
PCB design no. 3: 4-1 Solution with Nuclear Instruments

- ***The circuit schematics:***

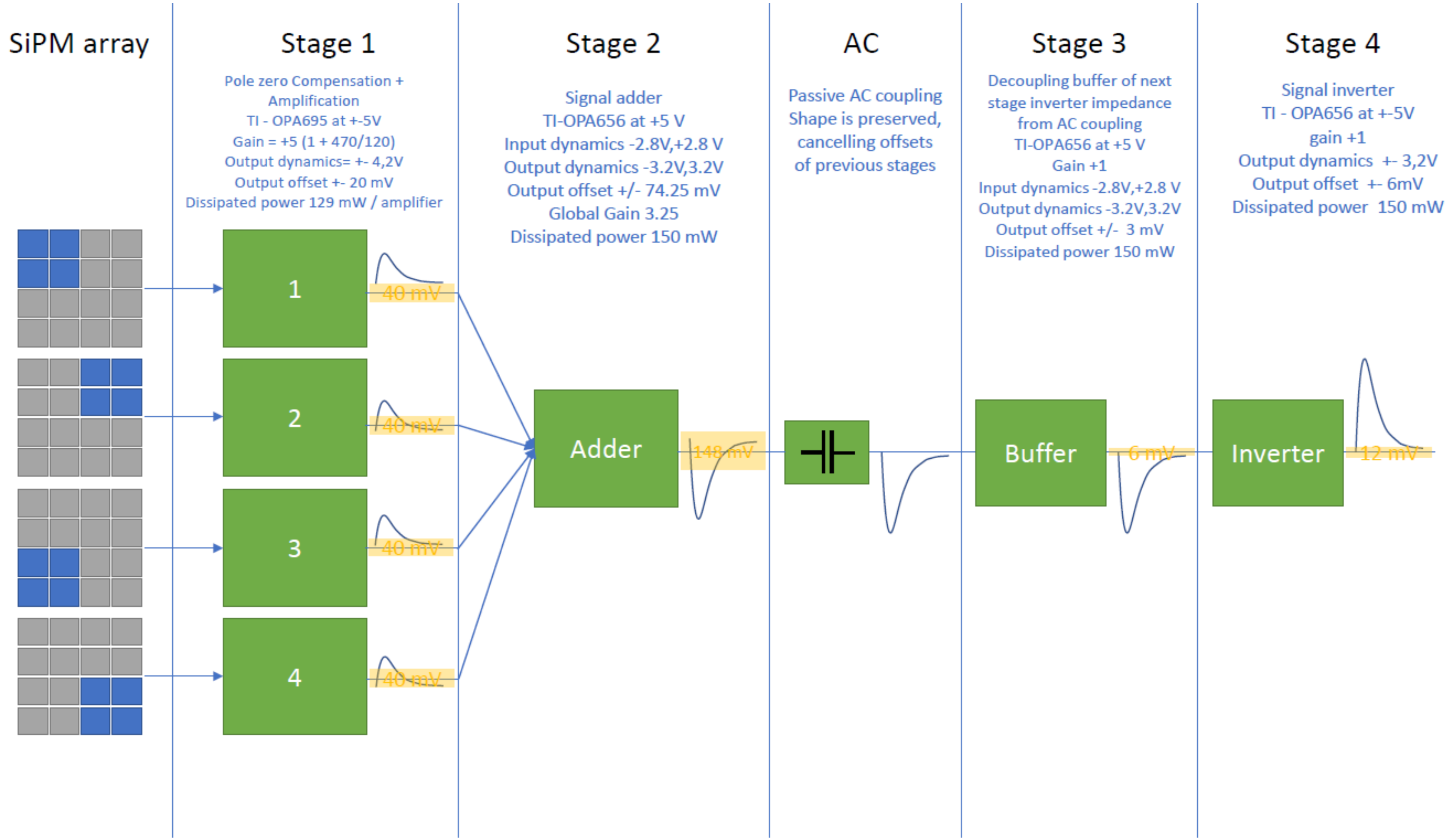


- *parallel ganging inside one sub-array*
- *zero pole subtraction +amplification in each sub- array*
- *add-up of 4 signals*
- *signal inversion*

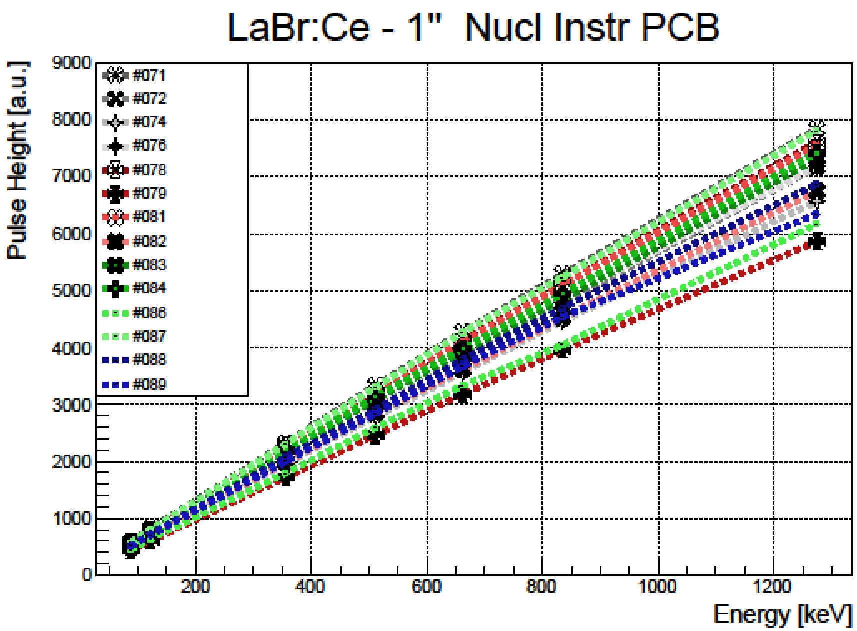
- ***The hardware realization:***

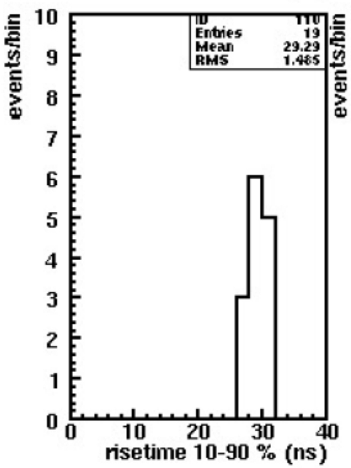


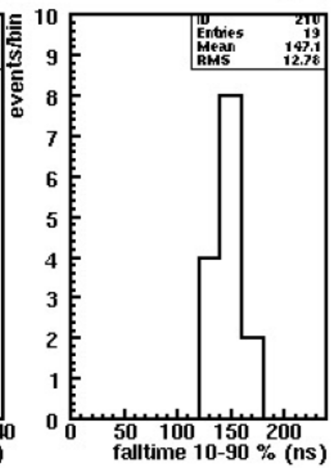
More details



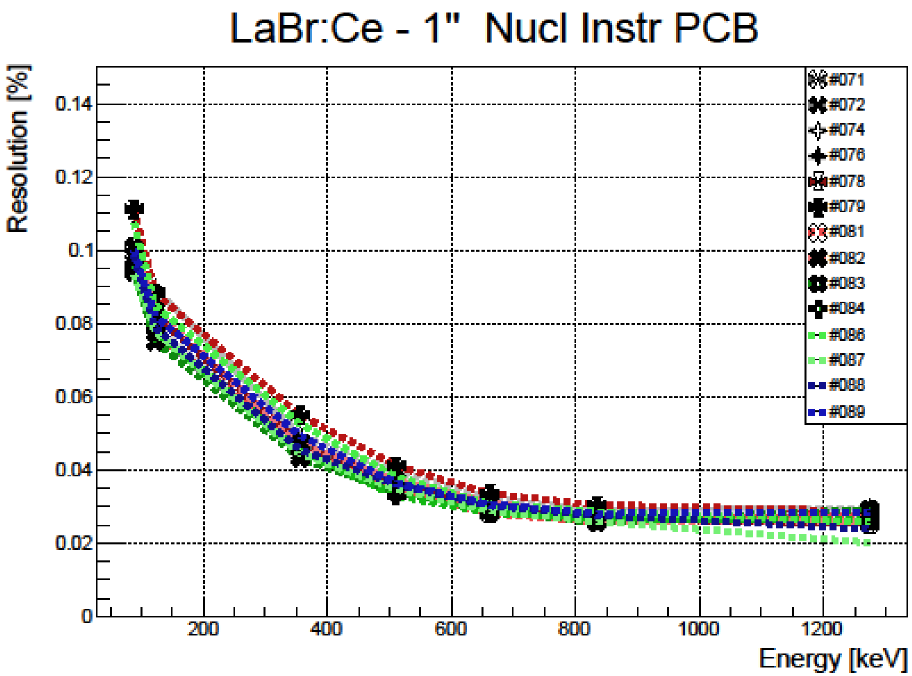
Test results (4-1 Nucl Instr circuit)



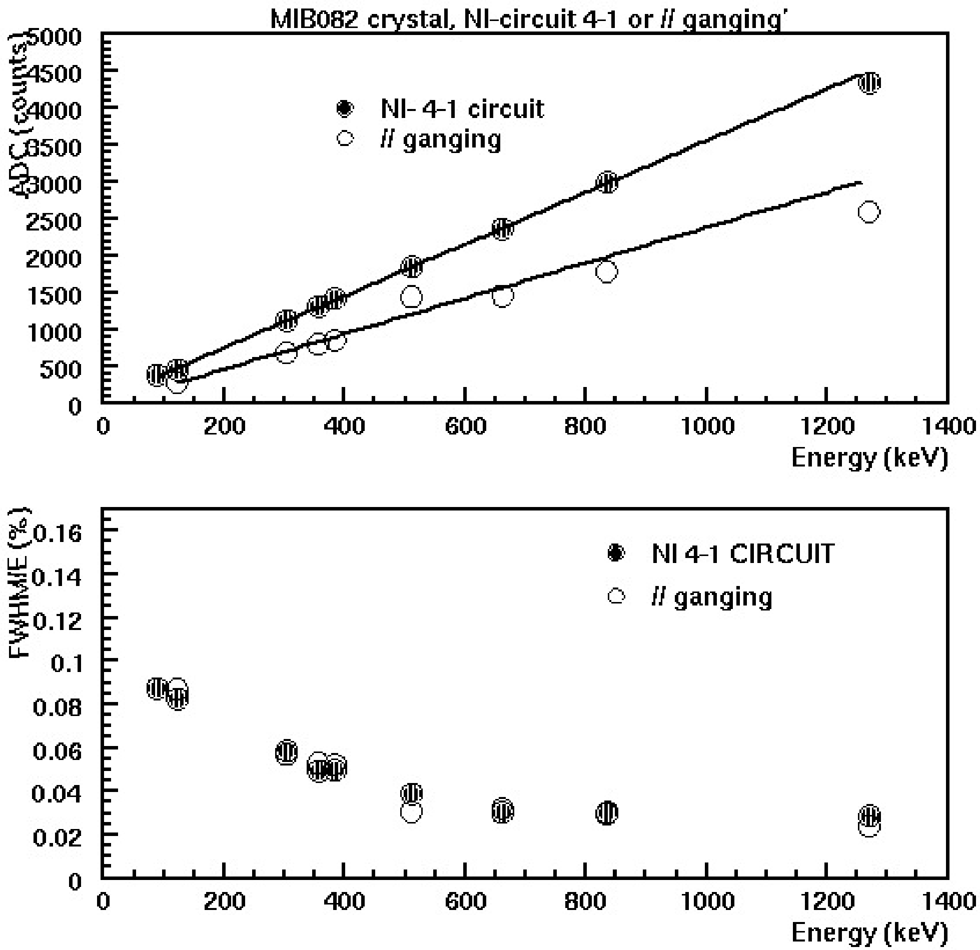




- *With NI 4-1 circuit results for energy resolution are similar to the ones obtained with parallel ganging , but timing is much improved.*



parallel ganging vs 4-1 NI circuit



1" detectors' timing properties

- *Due to increased capacitance (from 500 pF to 2000 pF) from increased area, timing properties are worse for 1" crystals as respect to ½" crystals*
- *Many attempts were done to solve this problem: from using hybrid ganging with overvoltage increase of used SiPM arrays and at last with a 4-1 circuit from Nucl Instr (including amplifier+0-pole suppression)*
- *Typical results are shown below for one typical 1" detector*

	Vop(V)	Risetime (ns)	Falltime (ns)	Res (%) @ Co^{57}	Res (%)@Cs^{137}
// ganging	40.82	68.9 ± 7.8	293.3 ± 43.4	7.78	2.96
Hybrid ganging	41.82	16.1 ± 2.4	176.8 ± 29.0	9.58	6.08
0-pole 2 nF	43.02	58.2 ±15.6	123.4±21.7	-	2.99
0-pole 2 nF +amp	40.82	46.9±12.0	170.8± 48.7	10.0	3.40
NI circuit 4-1	40.84	28.4±4.5	140.6±21.7	7.89	2.98

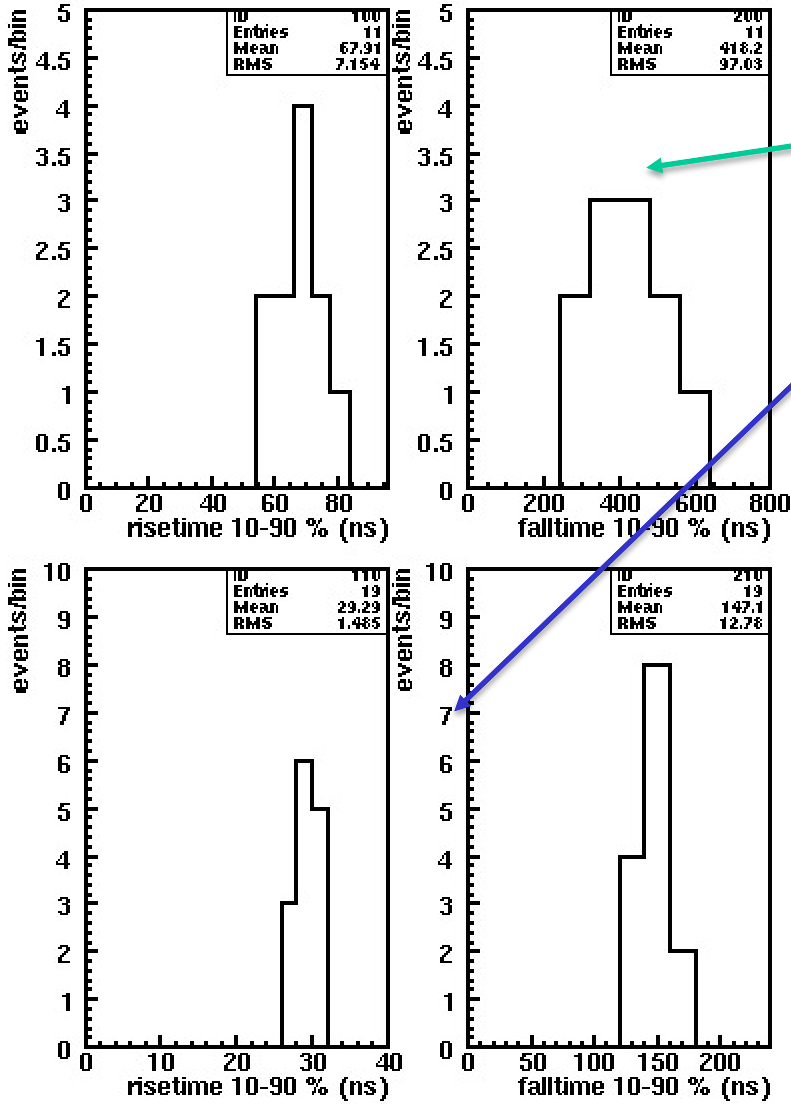
- *Increasing timing implies an energy resolution deterioration. A compromise was found with a 0-pole with increased SiPM overvoltage, to compensate for amplitude reduction. Final solution is the 4-1 circuit developed with Nucl Instr*

Test results for another typical detector

	Vop(V)	Risetime (ns)	Falltime (ns)	Res (%) @ Co^{57}	Res (%)@Cs^{137}
// ganging	41.82	64.0±10.6	472.0± 134.5	7.59	2.81
4-1 NI	40.82	30.5 ± 3.8	150.3 ± 19.0	7.53	3.0
0-pole 2 nF	42.82	44.4 ±11.8	128.7±23.1	-	2.99
0-pole3 nF	42.82	53.4±8.4	130.6± 19.6	7.37	2.90

- *Includes 2nd stage for baseline suppression (~5 mV)*
- *Reach a temperature ~ 37 C in a climatic chamber at 20 C (simulating Port 1 air-conditioning)*
- *Tested over 36 hours*
- *Cooling with gap-filler + power dissipator (→ minimal mechanics changes)*

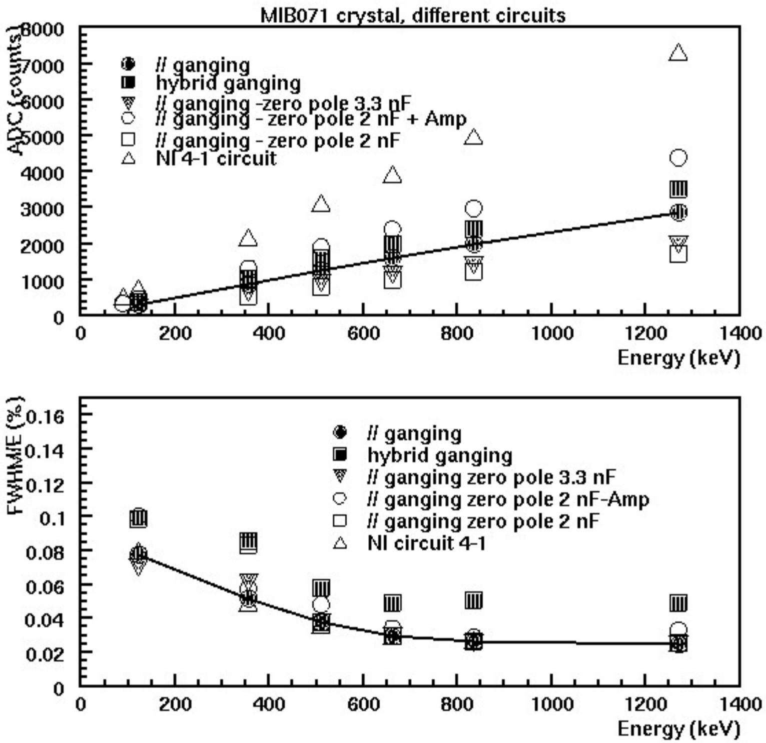
Comparison of timing for 1” crystals



- *Parallel ganging*
- *NI 4-1 PCB*

- *With NI 4-1 circuit risetime / falltime is reduced by a factor 2-3X*

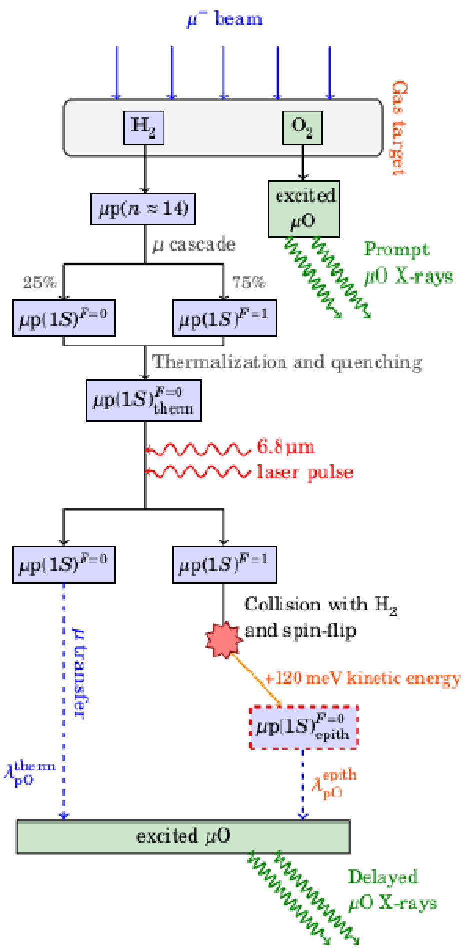
Resume of different readout schemes

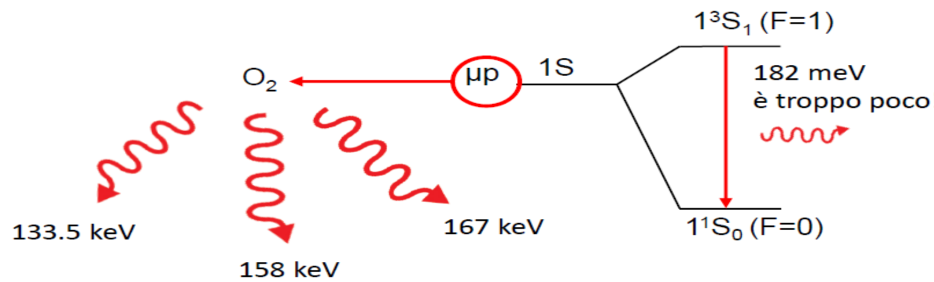


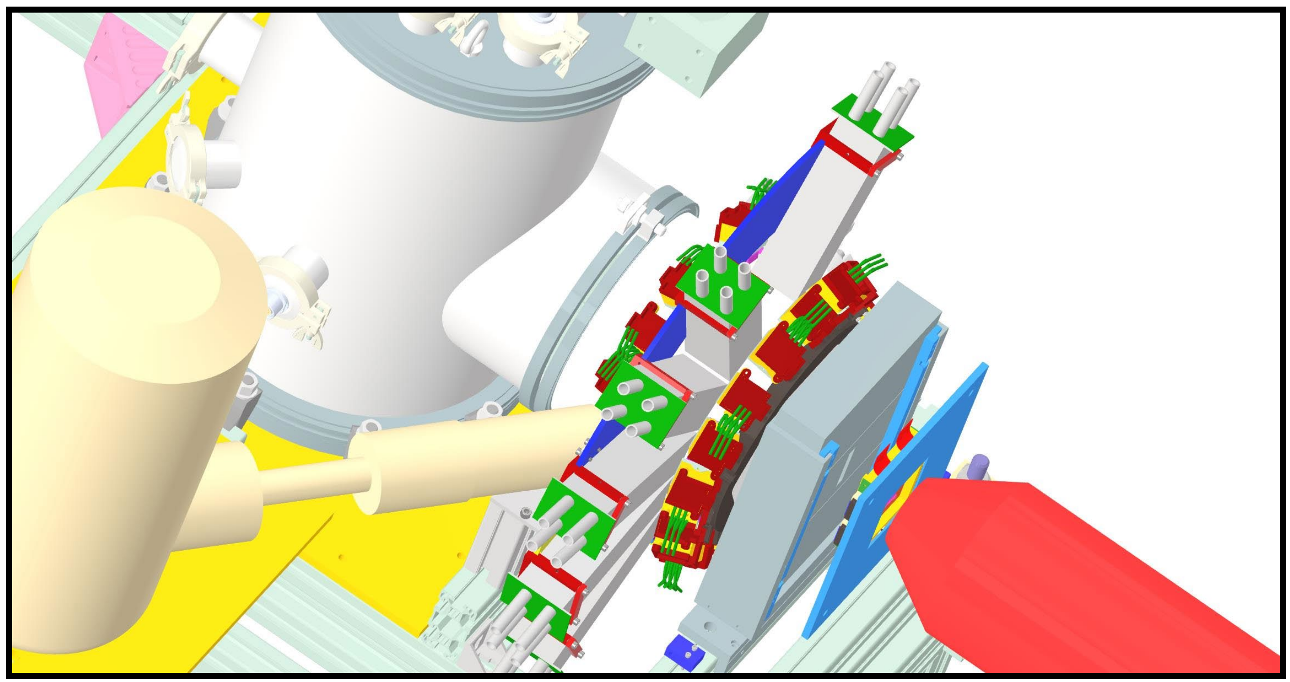
Effects on linearity and FWHM energy resolution for a typical LaBr3:Ce crystal with different readout circuits. The line connects points for the standard parallel ganging of the SiPM cells of the array.

- ***Pole zero circuit + SiPM increased overvoltage (additional 1-1.5 V)*** *reduces falltime, with an increased dark current rate, without compromising too much the FWHM energy resolution. But all this at the expense of a sizeable undershoot*
- ***Hybrid ganging*** *reduces falltime, but at the expense of a worsening of FWHM energy resolution*
- ***NI 4-1 circuit*** *reduces falltime and preserves FWHM energy resolution. The idea is to split a 1" Sipm array in 4 ½" Sipm arrays, to reduce detector's capacitance, apply to each part pole zeo suppression + amplification and then add up results*

16 such detectors are presently installed in the FAMU experiment at RAL, to take data in next July. FAMU aims at the measure of the Zemach proton radius.







Conclusions

- FWHM energy resolution of large LaBr3:Ce crystals is deteriorated by hybrid ganging as respect to standard parallel ganging
- A temporary patch may be obtained by adding a pole zero circuit, with a sizeable increase of overvoltage to compensate for signal reduction
- A more robust solution was found with Nuclear Instruments by designing a PCB where the large area SiPM array is split into 4 sub-array, treated individually (pole zero circuit+amplification)
- In this way we have no deterioration of FWHM energy resolution, with a reduction of falltime/risetime of a factor 2-3X

❖ Many thanks to Mr R. Gaigher, Mr. G. Ceruti of the INFN MIB mechanics workshop and Mr. L. Pastori of Nuclear Instruments for assistance in detectors' mounting and to our FAMU collaborators for many enlighting discussions

THANKS FOR YOUR ATTENTION