Improving Crystal PMTs and voltage dividers

M. Antonello
S. Cerioli
D. D'Angelo
G. Di Carlo
C. Vignoli

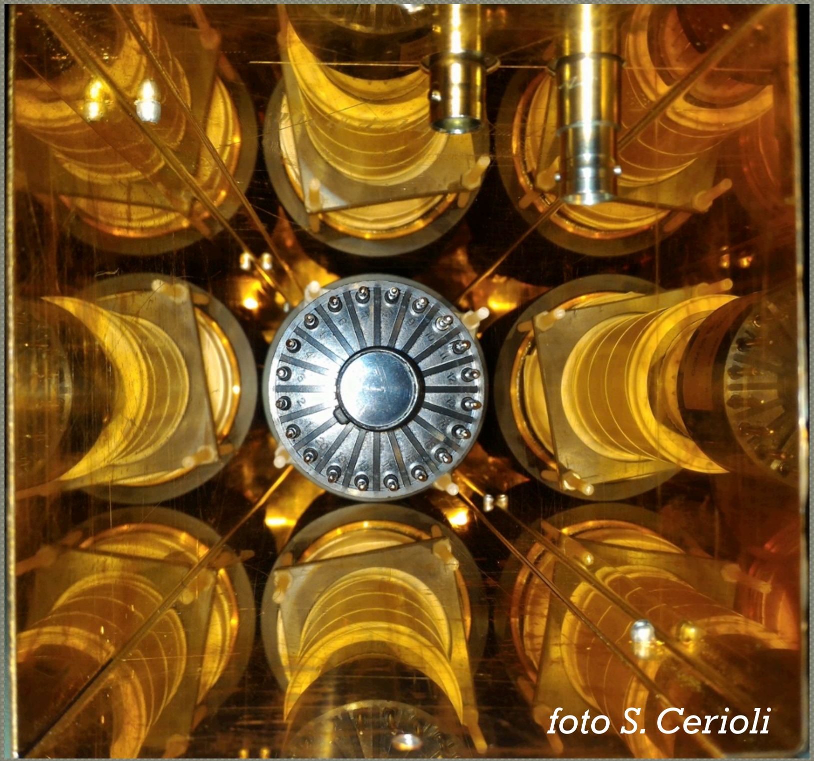


foto S. Cerioli

SABRE General Meeting
LNGS, 4th-6th Oct 2017

Improving PMTs

Desiderata for crystal PMTs

1. High Quantum Efficiency: >35%
2. Low dark rate: ~100 Hz
3. Low radioactive background: <10 mBq/PMT
4. Large surface: up to 4" (crystal size)
5. Low afterpulse and afterglow

Default SABRE choice

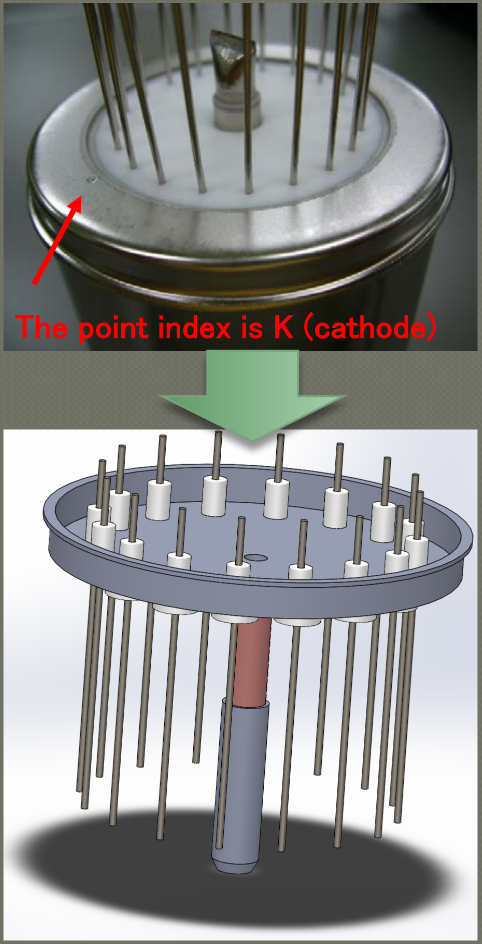
- Default option: Hamamatsu R11065-20:
  - 3" flat window
  - metal body, ceramic stem
  - low-T Bialkali photocathode (designed for DarkSide-50)
  - also available as R11410 with a xenon-optimized photocathode. (used in Xenon-1T)
- For the PoP we have 5 PMTs in Princeton
  - selected: QE and Dark Rate better than average.
- 6 more ordered?

3 R&D possibilities

1. Replace ceramic stem with individual feedthroughs.
2. Replace low-T Bialkali photocathode with SuperBiAlkali (SBA).
3. Move from 3" to 4" devices

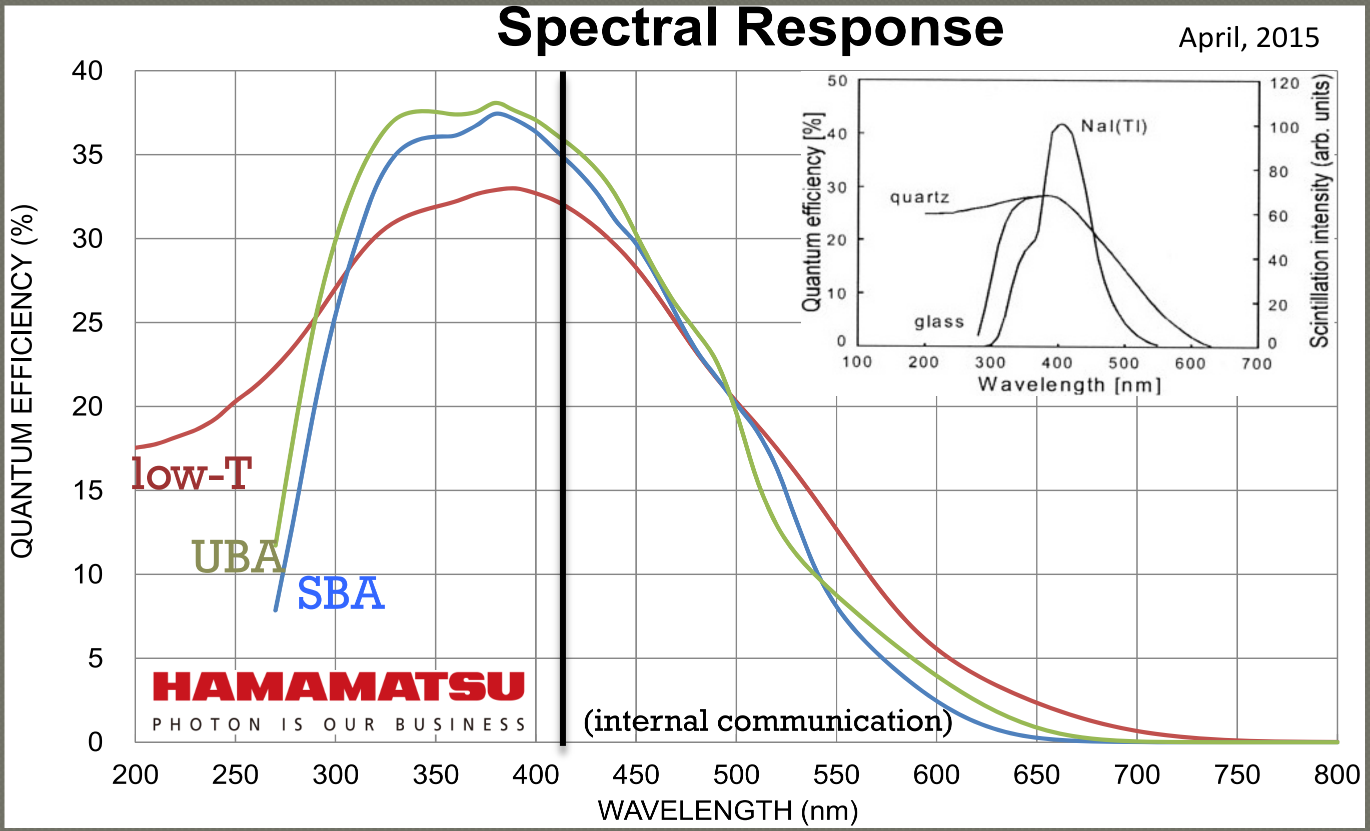
Stem replacement

- Pursued by Princeton University
- Replace ceramic stem with individual ceramic pin feedthroughs
  - Improved stability?
  - Lower light emission (after-glow)?
  - Less background
- Previously delayed due to brazing problems, now solved.
  - what's the status?



Replace low-T with SBA

1. higher <u>average</u> QE at 415nm (peak emission)
2. lower dark counts at room T: 5-10kHz -> <500Hz

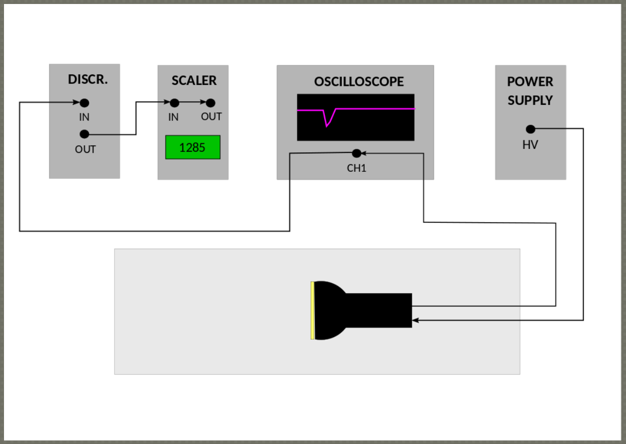


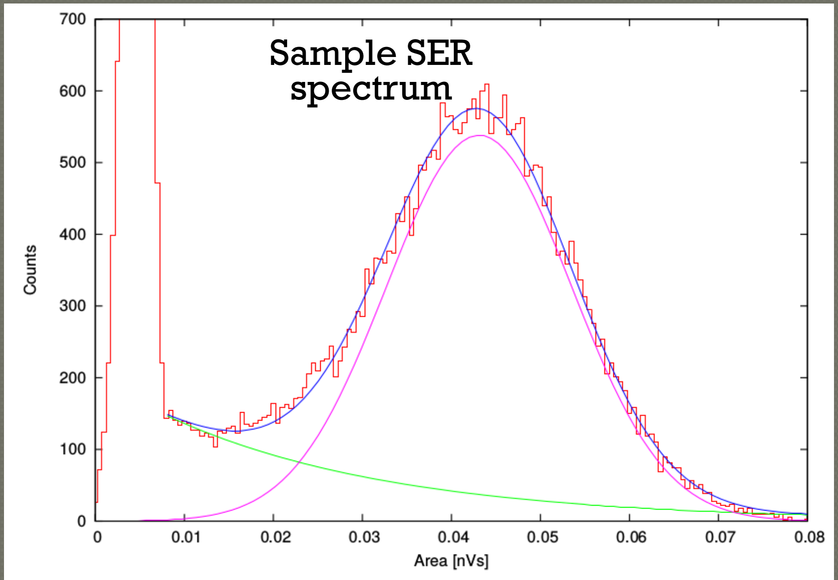
Replace low-T with SBA

- In 2016 we purchased 2 R11065-20MOD with SBA photocathode.
  - 3 have been produced: 1 was faulty -> replaced.
- We have tested them
  - in a test setup at LNGS, first in HdM (also in "Borexino" PMT test facility), then underground in SABRE Hall B space.
- We borrowed an R11065 (a.k.a. "-0") from Hamamatsu for a few months, named PMT-std
- Details of this job in Sara Cerioli's master thesis at:

  wiki.sabre-experiment.org/index.php/Common/documents

PMT characterization

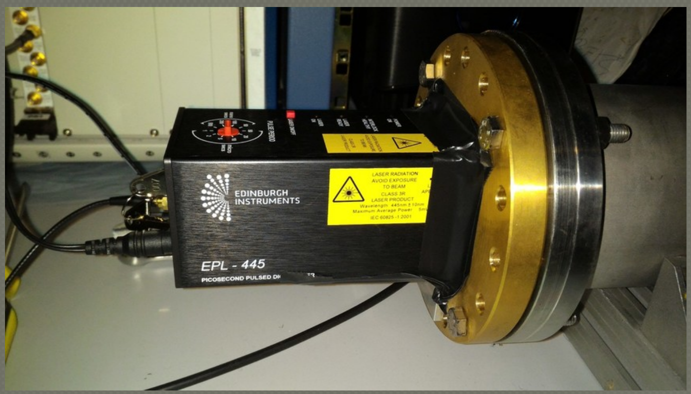




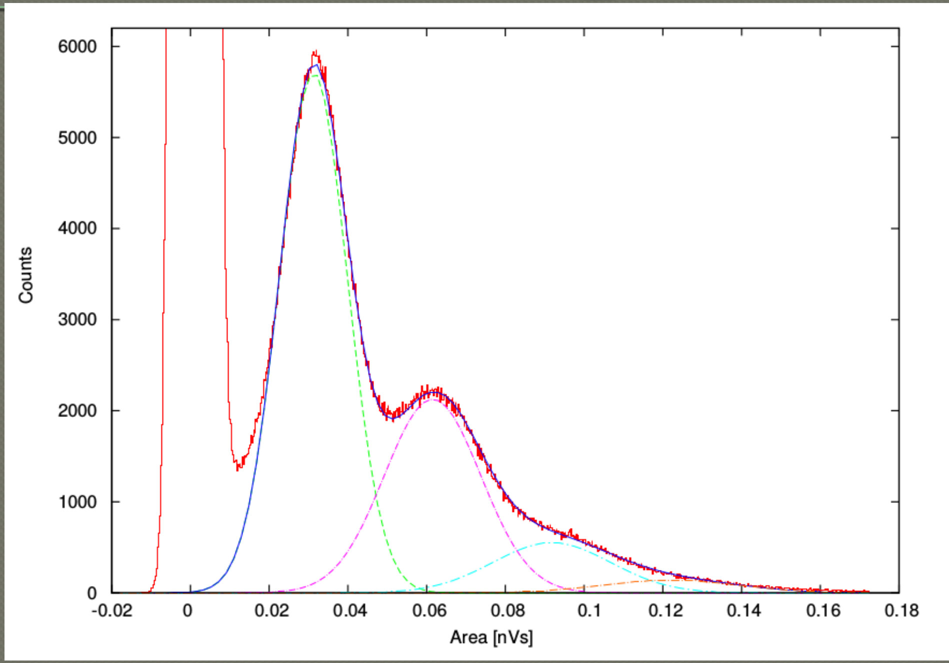
PMT characteristics analyzed:

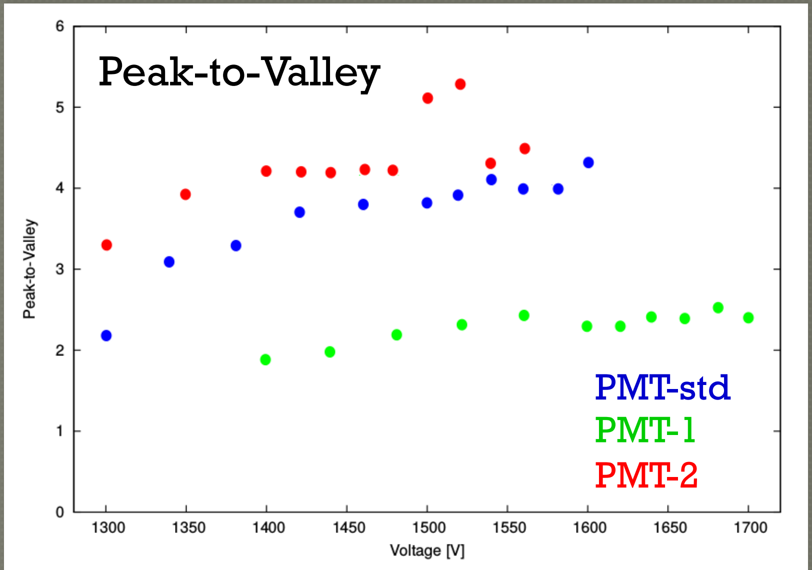
- Single Electron Response (**SER**)
- **Gain,** Peak-to-Valley ratio **(P/V)** and **dark rate** as a function of HV
- Multi-photoelectron spectrum
- **Dark rate** vs T.
- Comparing +HV e –HV biases.

Multi-photoelectron spectra



Pulsed light laser

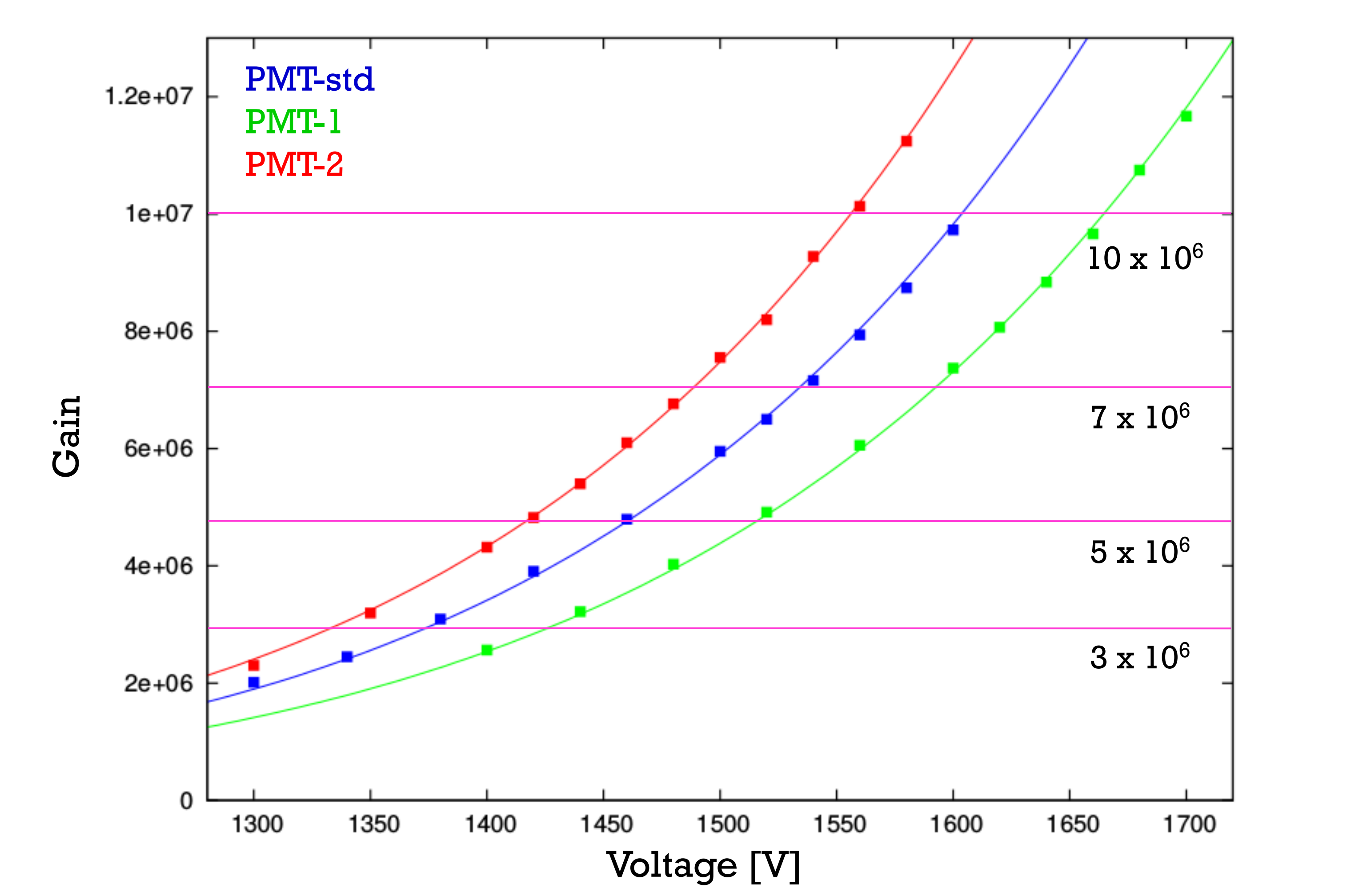




PMT std		PMT-1		PMT-2	
HV [V]	P/V	HV [V]	P/V	HV [V]	P/V
-1380	3.3	-1400	1.9	-1350	3.9
-1460	3.8	-1520	2.3	-1440	4.2
-1520	3.9	-1640	2.4	-1520	5.3
-1600	4.3	-1700	2.4	-1560	4.5

Gain

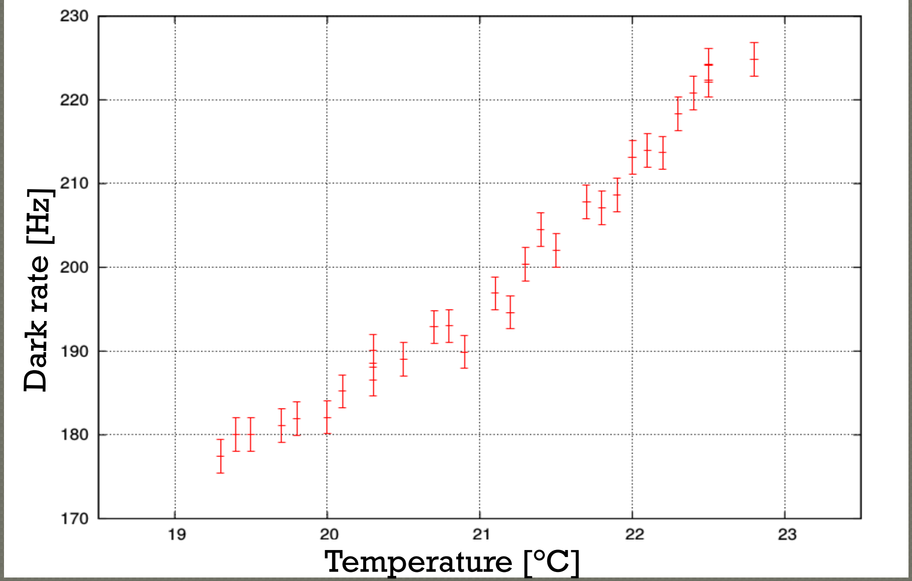
$$G = \frac{Q_{tot}}{e} = \frac{\int_{t_0}^{t_1} V(t)dt}{eR}$$



Dark Rate

- The 2 prototypes behaved very differently:
  1. PMT-1 > kHz;
  2. PMT-2: ~200-300 Hz
- But the PMT-std was also good
  - above average "-20" performance of 5-10kHz (source: DS-50 tests).

Gain	PMT-std [Hz]	PMT-1 [Hz]	PMT-2 [Hz]
$3x10^6$	206.6 ± 0.5	878.9 ± 1.3	310.5 ± 1.0
$5x10^6$	209.8 ± 0.7	1126.2 ± 2.0	283.2 ± 0.6
$7x10^6$	211.1 ± 1.0	1258.1 ± 1.1	268.5 ± 0.4
$10x10^6$	235.8 ± 0.5	1518.4 ± 1.9	269.9 ± 0.6



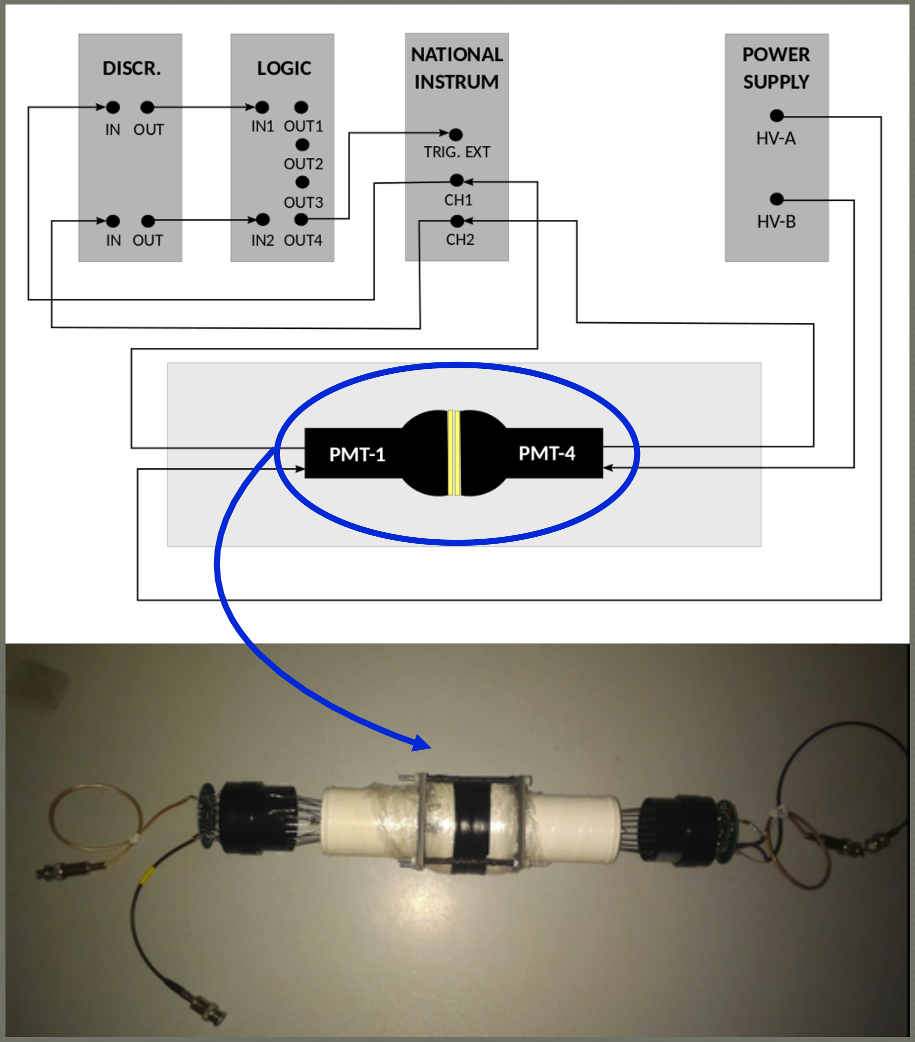
Studied Dark Rate dependency on Temperature

1° C Temperature variations

↓

4-5% Dark Rate variations

After-glow



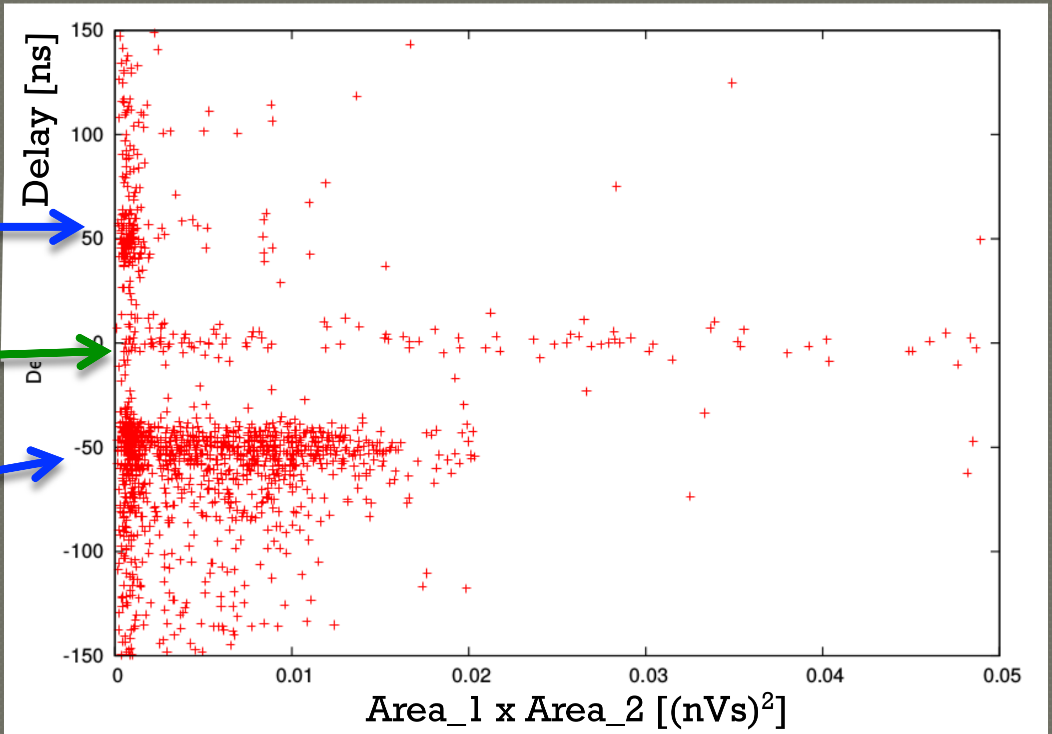
- PMT can generate light in the last dynods that could travel through the crystal and be seen by the opposing PMT
- It triggers: very dangerous background!
- We studied this
  - pairing PMTs face-to-face
  - triggering on coincidences

After-glow

Light produced by PMT-2 and seen by PMT-1

Light produced in the crystal

Light produced by PMT-1 and seen by PMT-2



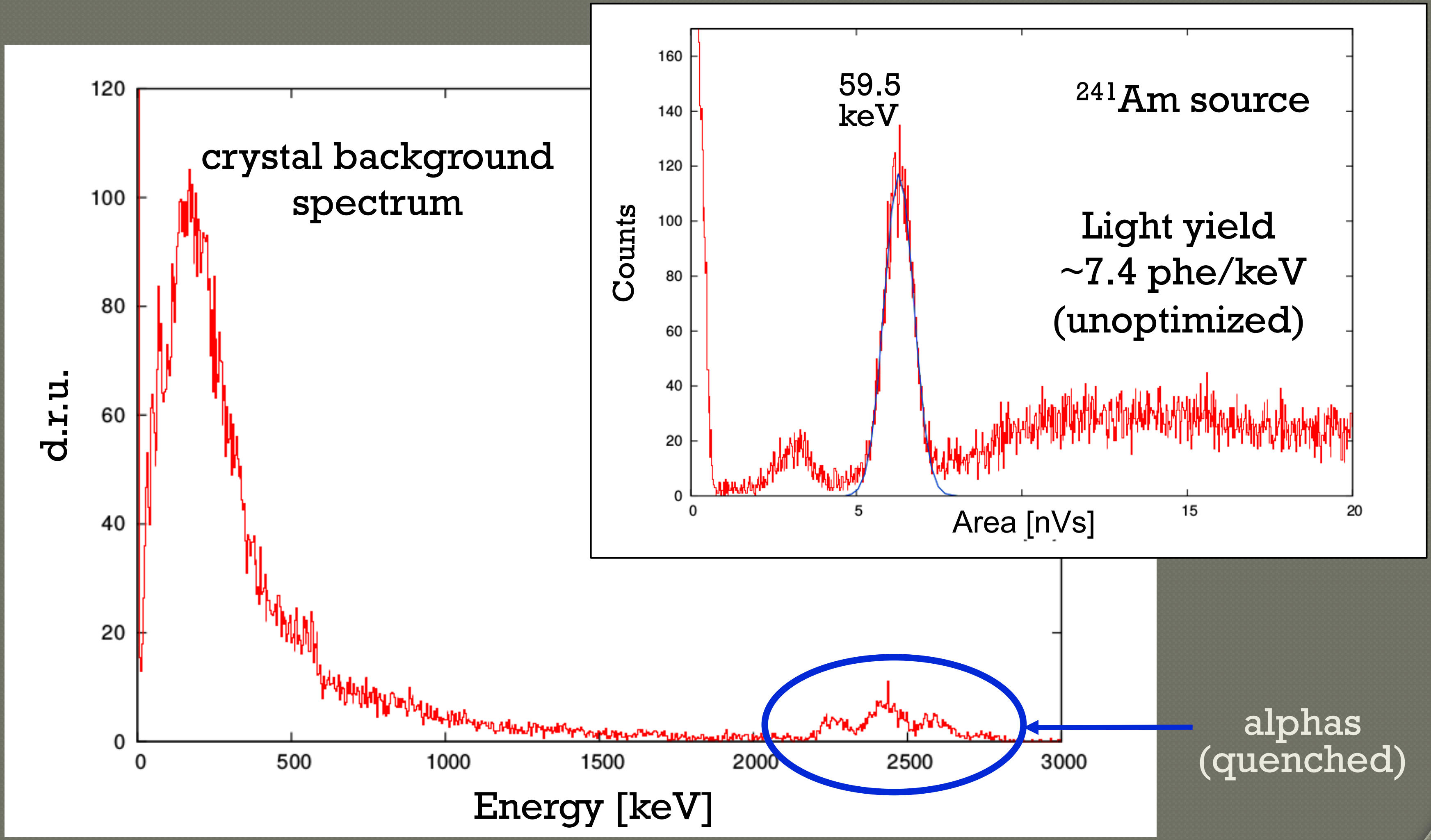
Gain	PMT-std	PMT-1	PMT-2
$3x10^6$	4%	37%	4%
$5x10^6$	4%	44%	4%
$7x10^6$	7%	48%	7%
$10x10^6$	7%	54%	8%

After-glow probability at different gains

Setup with crystal

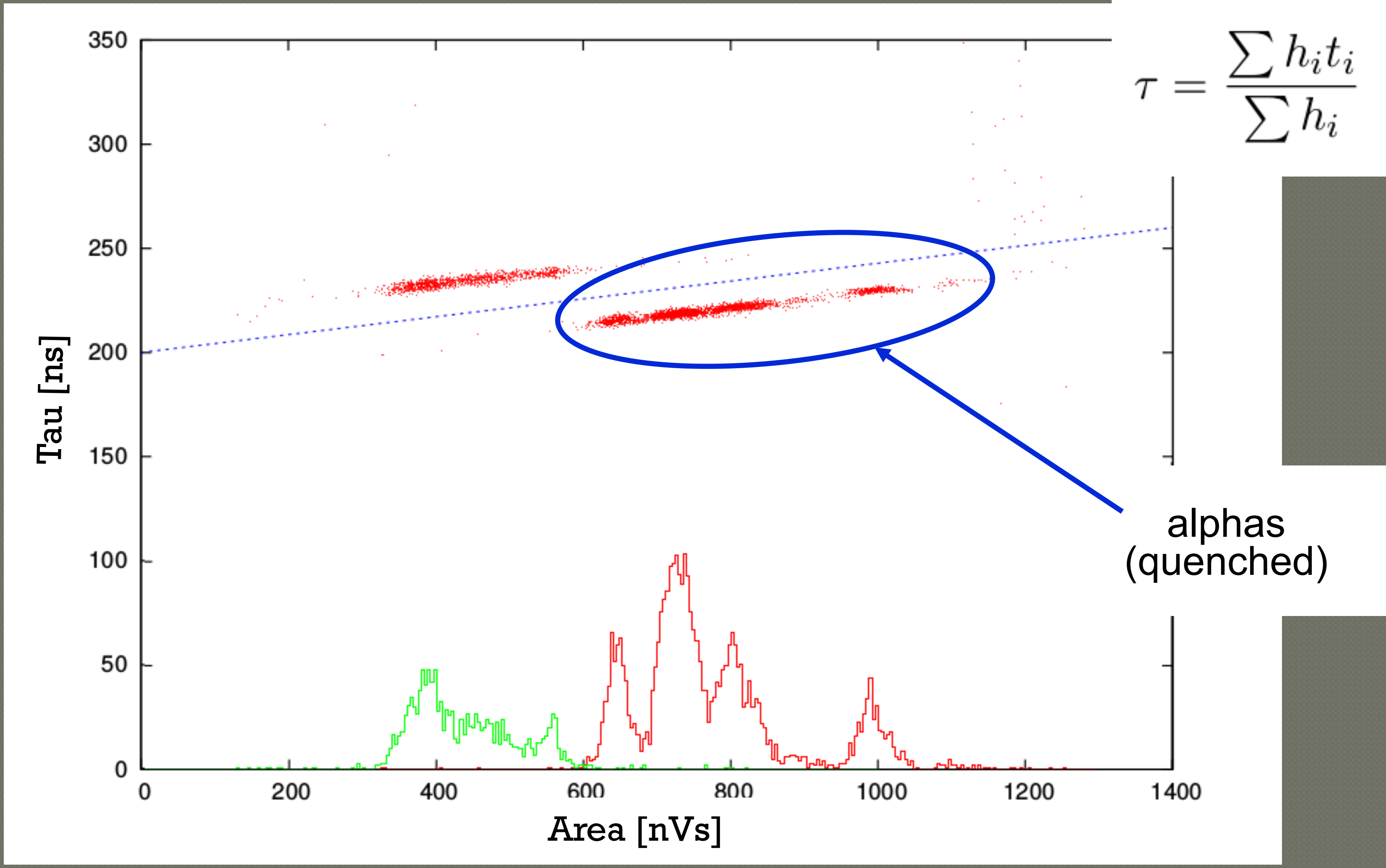
- Standard grade NaI(Tl) crystal (copper-cased)
- Copper and lead shielding
- Multi-purpose facility to test:
  - PMTs
  - voltage dividers and pre-amplifiers
  - crystals
  - pulse shape discrimination
- We excercised
  - calibrated with Am and U sources
  - light yield and crystal backgrounds
  - basic PSD

Calibration and backgr. spectrum



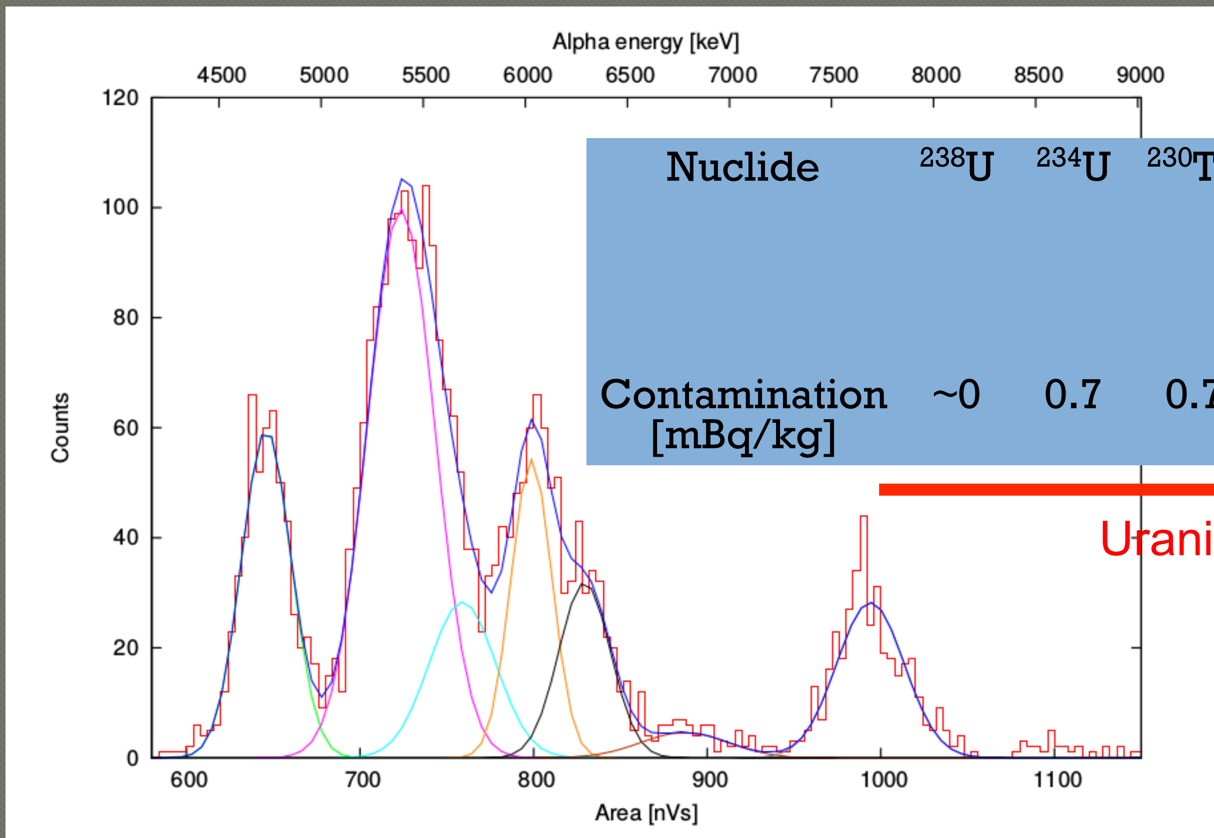
alphas (quenched)

Pulse Shape Discrimination



$$\tau = \frac{\sum h_i t_i}{\sum h_i}$$

alpha identification



Nuclide	^{238}U	^{234}U	^{230}Th	^{226}Ra, ^{222}Rn, ^{218}Po, ^{214}Po	^{210}Pb, ^{210}Po	^{232}Th	^{228}Ra, ^{228}Th, ^{224}Ra, ^{220}Rn, ^{216}Po
Contamination [mBq/kg]	~0	0.7	0.7	2.0	3.7	~0	2.1

Uranium — Thorium

- Multigaussian fit identifies 7 groups of isotopes from U and Th chains

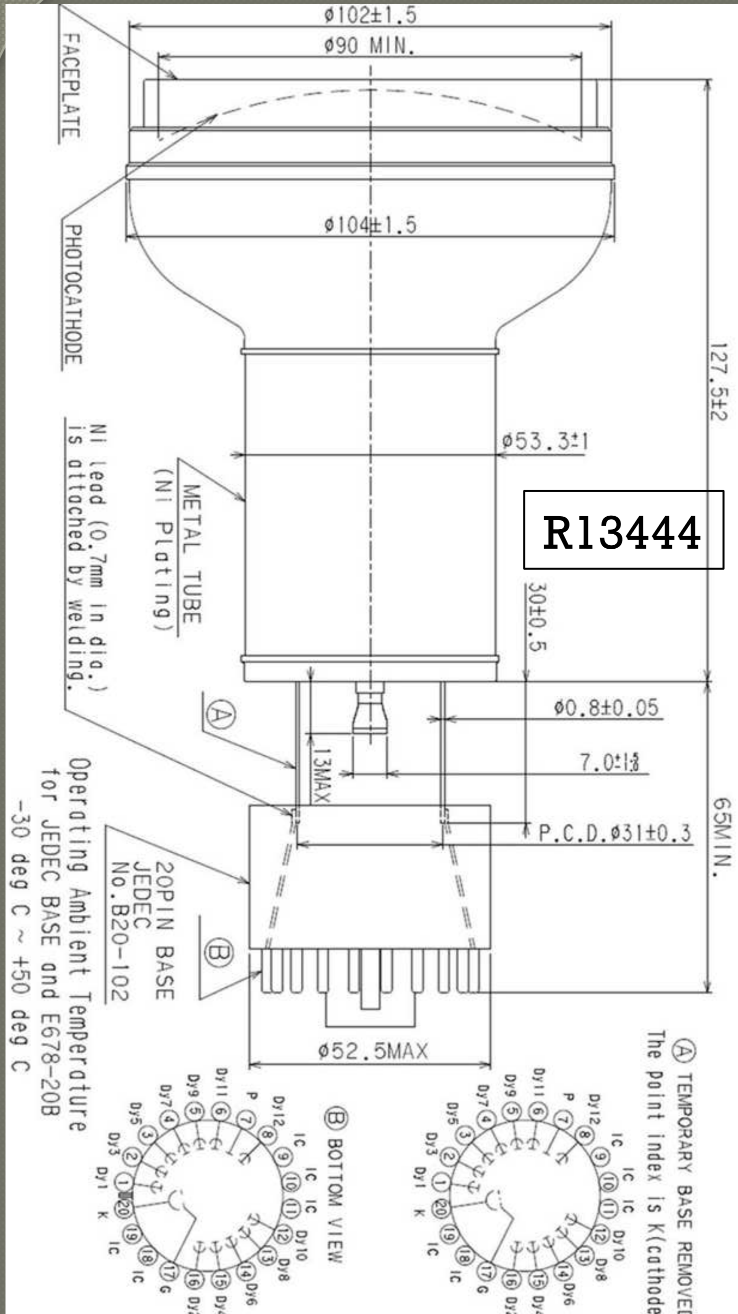
a postcard from Hamburg

Started a Ph.D. @ Desy in August

Where do we stand?

- We have setup a multipurpose facility to test PMTs, crystals, DAQ, PSD, …
  - Currently rearranged in radon box
  - can host two parallel setups
  - see also Simone's talk

- (1 faulty +) 2 working PMTs with very uneven performances:
  - 1 excellent
  - 1 pretty bad in both noise and signal
  - production of R11065-20 keeps being problematic…



Proposed 4'' PMT

- in April Hamamatsu proposed us a new 4'' SBA PMT with planar-concave window
  - better collection efficiency
  - smaller transit time spread
- 90mm diameter effective area:
  - perfect match with RMD full size crystals
  - no reflection on sides: better pulse shape
- pricy: ~13k€ >2x price of 3''
- INFN funded buying 2 PMTs in 2017 but:
  - now Hamamatsu says the production process will be revised
  - Not happy to accept orders for 3'' or 4'' PMTs
  - 10.5 months delivery time!

Improving voltage dividers

Low Background Voltage Dividers

Ultra-thin (300μm) ultra-pure pyralux substrate:

- 4-5 times less radioactive than cirlex
- high purity components
- test HV+ and HV-
- 10+10 delivered by CMT
- completed screening with HPGe
- will be tested in the dry test facility

	Cirlex	Pyralux	Cuflon
^{226}Ra	10.2±1.2	2.6±0.2	1.4±0.4
^{228}Th	2.1±0.7	0.5±0.2	1.2±0.4
^{40}K	23±7	4±1	140±20
^{137}Cs	<0.86	<0.10	<0.36

substrate sheets measured with HPGe (mBq/kg)

CMT CIRCUITI STAMPATI

[thanks to M. D'Incecco]

Screening with HPGe

		naked PCBs (pyralux)	PCB with HV– components	PCB with HV+ components
^{232}Th	^{228}Ra	<48μBq	(0.14±0.04)mBq	(0.68±0.08)mBq
	^{228}Th	<39μBq	(0.14±0.03)mBq	(0.57±0.05)mBq
^{238}U	^{226}Ra	<34μBq	(2.0±1.0)mBq	(22.7±0.8)mBq
	^{234}Th	<0.86mBq	<1.6mBq	<3.6mBq
	^{234m}Pa	<1.4mBq	<2.5mBq	<3.8mBq
	^{235}U	<23μBq	<45μBq	<84μBq
	^{40}K	<0.47mBq	(0.5±0.2)mBq	<0.78mBq
	^{137}Cs	<6.9μBq	<20μBq	<49μBq
	^{60}Co		<50μBq	<93μBq
All activities per piece, measured on 10 pieces for ~10d in HPGe				

Data M. Laubenstein (2017)

we picked a bad decoupling capacitor…

Comparison with PoP bases

- Same as DarkSide-50 (?)
- Cirlex PCB (800μm) was also under threshold
- Components contribution from:
  - 5x 4.7nF capacitors
  - 26x mixed R resistors
  - supposedly the same as used in HV— prototype
- Soldering tin not included
  - could be relevant

		naked PCBs (cirlex)	DS50 HV— components
^{232}Th	^{228}Ra	<17μBq	(0.12±0.02)mBq
	^{228}Th	<11μBq	(0.13±0.02)mBq
^{238}U	^{226}Ra	(34±5)μBq	(0.41±0.02)mBq
	^{234}Th	<0.16mBq	(0.6±0.2)mBq
	^{234m}Pa	<0.26mBq	(1.1±0.4)mBq
	^{235}U	<10μBq	(23±1)μBq
	^{40}K	<51μBq	[0.16-0.33]mBq
	^{137}Cs	<4.0μBq	<8μBq
	^{60}Co	<1.6μBq	<11μBq
	^{210}Pb		(1.1±0.2)mBq

Data M. Laubenstein (2011)

Side-by-side

		pyralux PCBs (naked)	cirlex PCBs (naked)	pyralux PCB with HV–components	DS50 HV–components (no PCB)
^{232}Th	^{228}Ra	<48μBq	<17μBq	(0.14±0.04)mBq	(0.12±0.02)mBq
	^{228}Th	<39μBq	<11μBq	(0.14±0.03)mBq	(0.13±0.02)mBq
^{238}U	^{226}Ra	<34μBq	(34±5)μBq	(2.0±1.0)mBq	(0.41±0.02)mBq
	^{234}Th	<0.86mBq	<0.16mBq	<1.6mBq	(0.6±0.2)mBq
	^{234m}Pa	<1.4mBq	<0.26mBq	<2.5mBq	(1.1±0.4)mBq
	^{235}U	<23μBq	<10μBq	<45μBq	(23±1)μBq
	^{40}K	<0.47mBq	<51μBq	(0.5±0.2)mBq	[0.16-0.33]mBq
	^{137}Cs	<6.9μBq	<4.0μBq	<20μBq	<8μBq
	^{60}Co		<1.6μBq	<50μBq	<11μBq
	^{210}Pb				(1.1±0.2)mBq
					all activities per PCB

Impact on backgrounds

All numbers in 10^{-3} cpd/kg/keV

	HV– (no veto)	HV+ (no veto)	HV– (veto)	HV+ (veto)
^{238}U	3.36±0.08	38.0±0.8	1.20±0.04	13.5±0.5
^{232}Th	0.267±0.005	1.19±0.02	0.091±0.003	0.40±0.01
^{40}K	0.182±0.009	0.29±0.01	0.166±0.008	0.26±0.01
^{60}Co	0.048±0.006	0.089±0.003	0.0032±0.0004	0.0059±0.0007
Total	**3.86±0.08**	**39.5±0.8**	**1.46±0.05**	**14.2±0.5**

Cmp background from PMTs:
1.2×10^{-2} cpd/kg/keV (veto)

good

bad
look for better capacitor

thanks to Paolo&Giulia for simulations

Conclusions on voltage dividers

- Although pyralux is supposed to be 4-5 times less radioactive and was made with lower thickness (300μm vs. 800μm), we can't appreciate the difference with HPGe.
- Background is dominated by components.
- Contribution to background: ~1.5×10^{-3} cpd/kg/keV, tolerable.
- HV+ requires selecting a low radioactivity HV capacitor.
- Functionality test in dry setup soon.