PhotoDET 2012

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Study on large area photomultipliers with superbialkali photocathode

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Large area photomultipliers

Features:

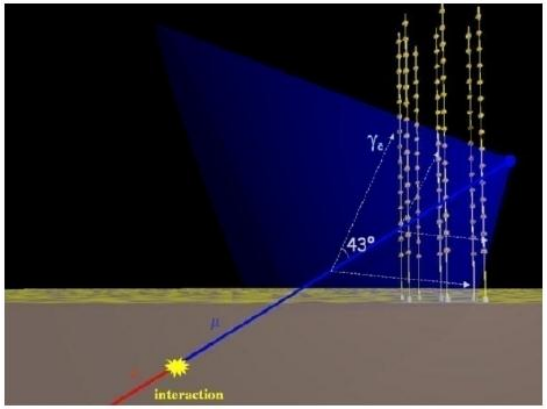
- Large detection area (8”, 10”, …)
- High sensitivity photons
- Fast time response
- Low dark count

Cosmic Ray Detection

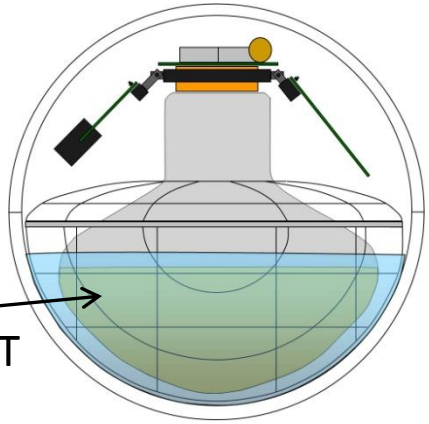
Application:

- Astroparticle experiments
- Neutrino detection

Underwater neutrino detection



Optical Module in NEMO KM3NeT



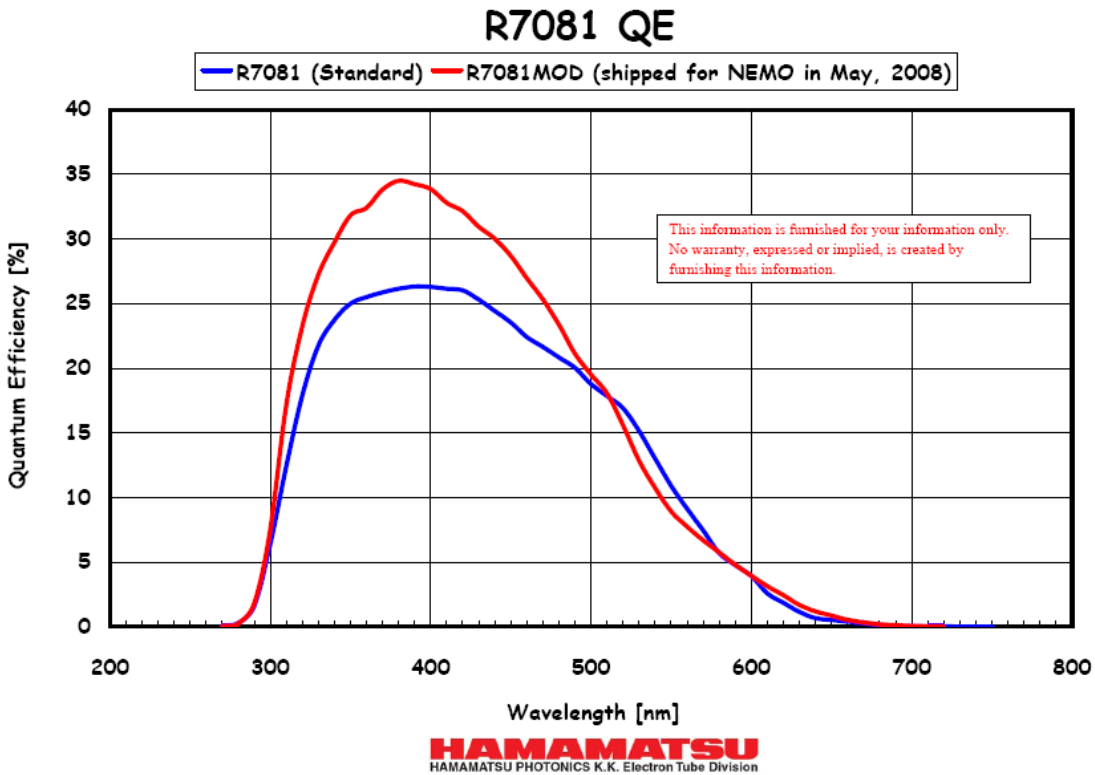
10” PMT

Super bialkali photocathode

Common specifications for standard PMT

- Photocathode material: Bialkali
- Spectral response: 300 nm to 650 nm
- Quantum efficiency (QE) : 25% at peak

Hamamatsu has realized super Bialkali (SBA) large area PMT with QE ≈ 35% at peak



Standard and SBA PMTs have the same mechanical design and internal structures. Differences only on photocathodes

Quantum efficiency of a super bialkali PMT (red line) and a standard (blue line)

(Hamamatsu internal communication)

Comparison for 10 inch. PMTs

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Performances of 4 SBA PMTs with 10 inch photocathode were measured and compared with those measured on a batch of 72 standard PMTs (R7081).

Main measurement conditions:

- **Attenuated laser source (s.p.e. conditions, 410nm, 60 ps width, 15 KHz)**
- **Whole photocathode illuminated**
- **All PMTs at the same gain condition (5×10^7)**
- **All PMTs powered by ISEG active base PH7081 sel.**

Measurements performed :

- **increase of the quantum efficiency of the SBA PMTs with respect to standard PMTs**
- **super bialkali secondary effects:**
  - **dark count rate**
  - **time and charge resolutions**
  - **fraction of spurious pulses**

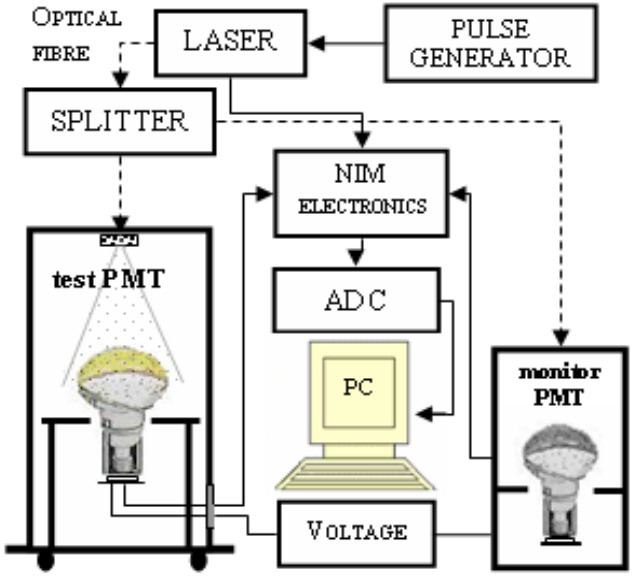
The SBA quantum efficiency increase

The quantum efficiency increase with respect to standard PMT was measured :

<u>increase in photon detection efficiency (PDE) =</u>

<u>n° of PMT detected events / nn° of emitted laser pulses</u>

The PDE was measured for SBA PMTs and compared to standard PMTs



Sketch of the testing facility

	increase in detection efficiency [%]	QE calculated for SBA PMT * [%]
SBA PMT 1	37.7	34.4
SBA PMT 2	32.1	33
SBA PMT 3	39.7	35
SBA PMT 4	36.1	34

* Considering a standard QE of 25

Results complies with the QE of 35% declared by Hamamatsu

Overall characteristics of the SBA PMTs

- Dark count rate (threshold 1/3 s.p.e)
- Transit Time Spread (threshold 1/3 s.p.e.) acquired by TAC FAST (25 ps per channel)
- P/V ratio and sigma charge resolution, acquired by QDC Silena (0.17 pC per channel)

	Volt @gain 5E7 [V]	DC rate [Hz]	P/V	RES sigma [%]	TTS FWHM [ns]
Average 72 std. PMTs	1655	1388	3.5	32	2.8
SBA PMT 1	1760	4805	2.8	27	2.8
SBA PMT 2	1678	2003	2.5	41	3.1
SBA PMT 3	1760	3265	3.0	33	2.7
SBA PMT 4	1696	1598	3.4	28	2.6

Resume of the overall characteristics of the 4 SBA PMTs with respect to standard

The SBA Time and Charge characteristics were similar than standard

The SBA dark count rate is higher than standard PMTs (SBA mean value = 2900 Hz)

Spurious pulses definition and typical time distributions

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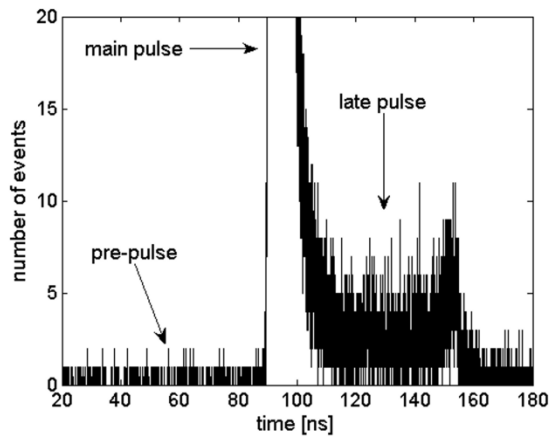
Spurious pulses are noise pulses time-correlated with the main PMT response

-**Pre-pulses (P.P.),** appear 10-80 ns before the main pulse. Due to direct photo-effect on the first dynode.

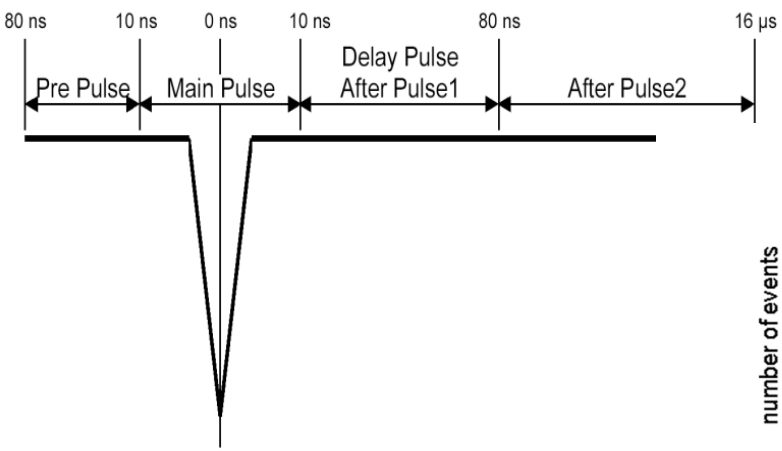
- Late pulse (L.P.), appear 10-80 ns after the main pulse, in the place of it. Due to photoelectron backscattering on the first dynode.

-**Type 1 after pulse (AP1),** appear 10-80 ns after the main pulse. Due to luminous reaction on the electrodes.

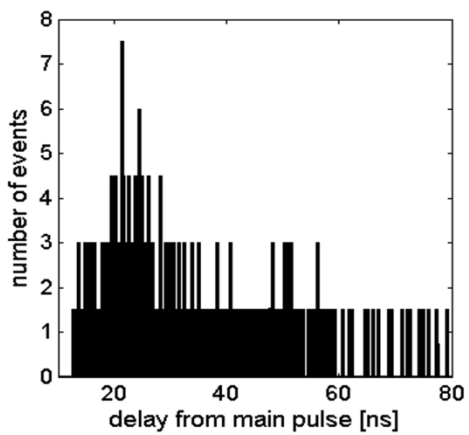
- Type 2 after pulse (AP2), arrive in the 80ns-16us after the main. Due to the ionization of the residual gas in the PMT.

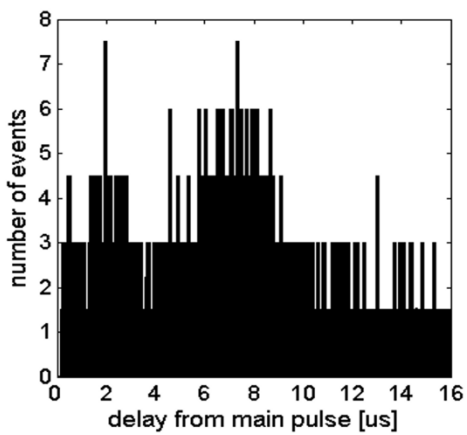


Time distributions of pre- and late pulses



Arrival time of spurious pulses with respect to main pulses





Time distributions of the AP1 and AP2

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The fractions of the spurious pulses

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The ratio of the number of spurious pulses divided by the number of the Main pulses was measured for each SBA PMT

	Pre P. [%]	Late P. [%]	After P.1 [%]	After P.2 [%]
Average 72 STD PMT	0.02	5.4	1.1	4.4
SBA PMT 1	0.03	5.8	1.9	15.2
SBA PMT 2	0.02	6.4	1.2	8.4
SBA PMT 3	0.01	5.7	1.6	11.3
SBA PMT 4	0.01	5.8	1.3	8.7

Resume of the SBA fraction of spurious pulses compared with standard

Comparison with standard PMTs :

The fractions of pre- and late pulse were not worse

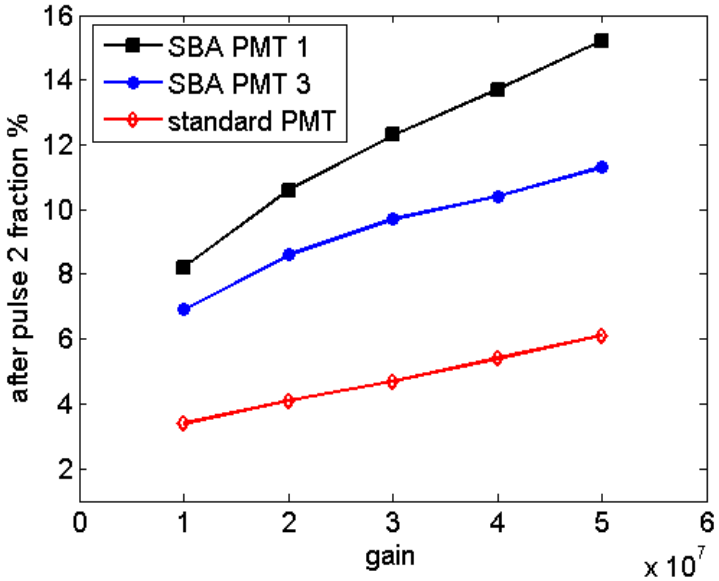
The fraction of type 1 after pulses was slightly increased

The fraction of type 2 after pulses was considerably increased (almost three times greater than STD)

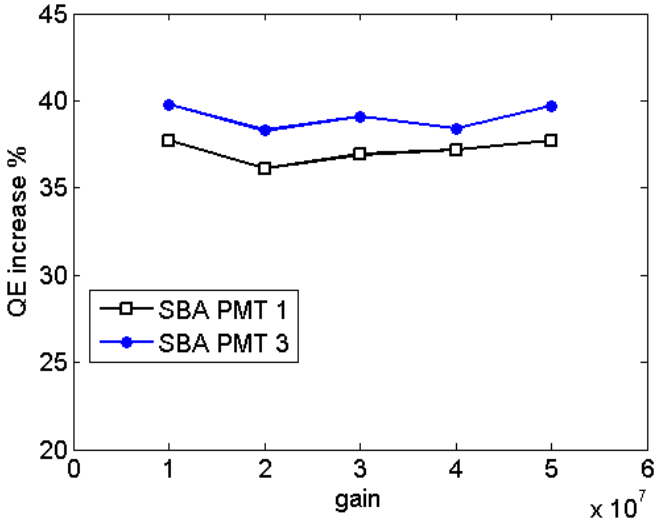
This effect is confirmed by published studies on other Super Bialkali PMTs

Type 2 after pulse as function of gain

The fraction of the type 2 after pulses was studied as function of the gain, decreasing the HV Voltage



Fraction of the after pulse type 2 as function of the gain



As expected, the increase of the QE with respect to standard PMTs did not vary with the gain

The fraction of type 2 after pulses decreases almost linearly with the gain decreasing

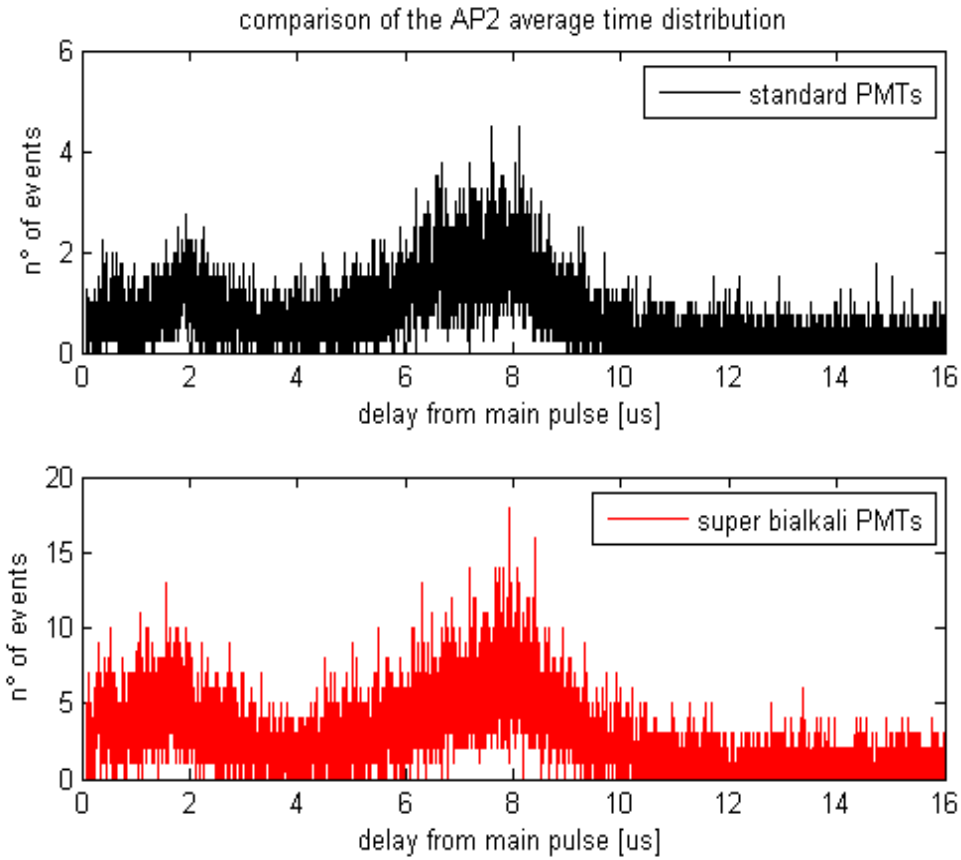
This trend was also measured in standard PMTs, and was confirmed by other studies

Use of the SBA PMT with a low gain to reduce After Pulses fraction

Type 2 after pulse time distribution

The delay time of after pulse 2 from main pulse is correlated to the atomic mass of residual gas → information about impurity inside the PMT

The mean time distribution of the SBA PMTs was compared to the mean distribution of the standard PMTs



- **The shapes of the distributions were the same**
- **The fractions of events within the two peaks with respect to the number of total events did not vary**

The super bialkali PMT production did not introduce other types of impurity with respect to the standard PMT

SBA photocathode uniformity measurements

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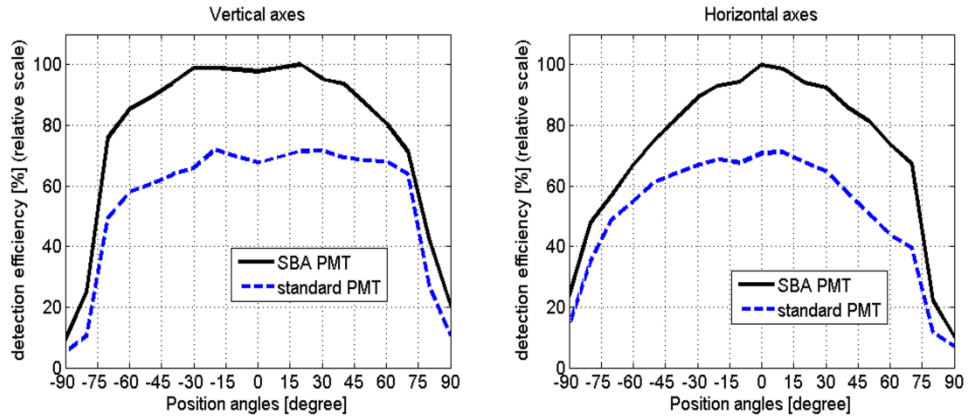
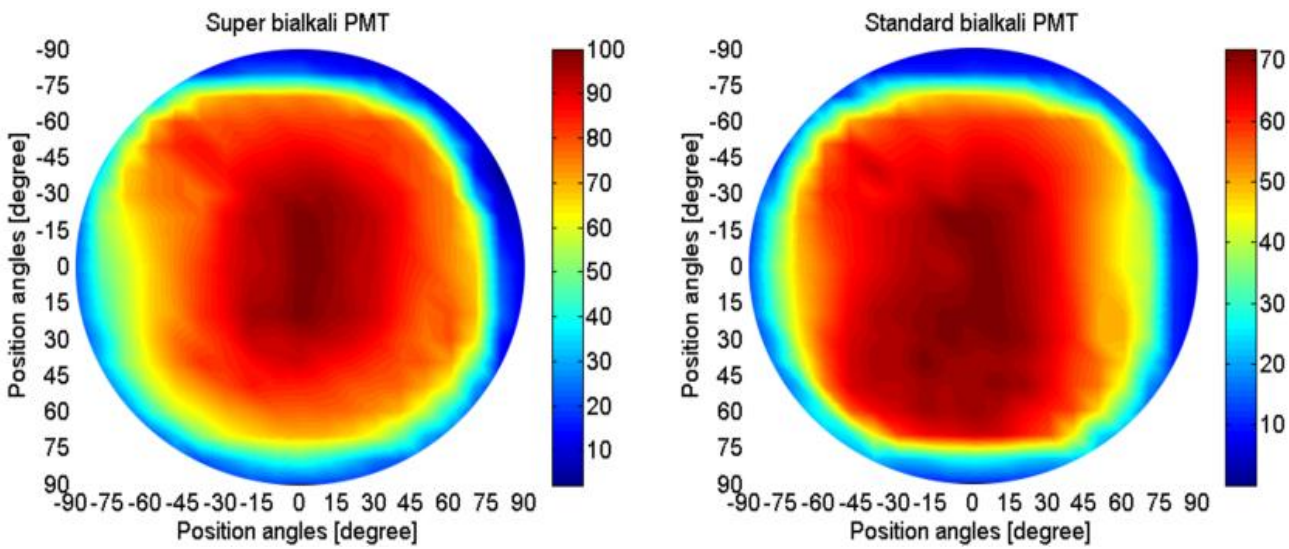
The uniformity of the photon detection efficiency was measured on a 10” SBA PMT and compared to that of the standard 10” PMT by scanning the photocathode surface:

- **324 points uniformly distributed on the photocathode**
- **410 nm Laser Source pulsed in s.p.e. condition**
- **5mm light spot diameter, normal to PMT surface**



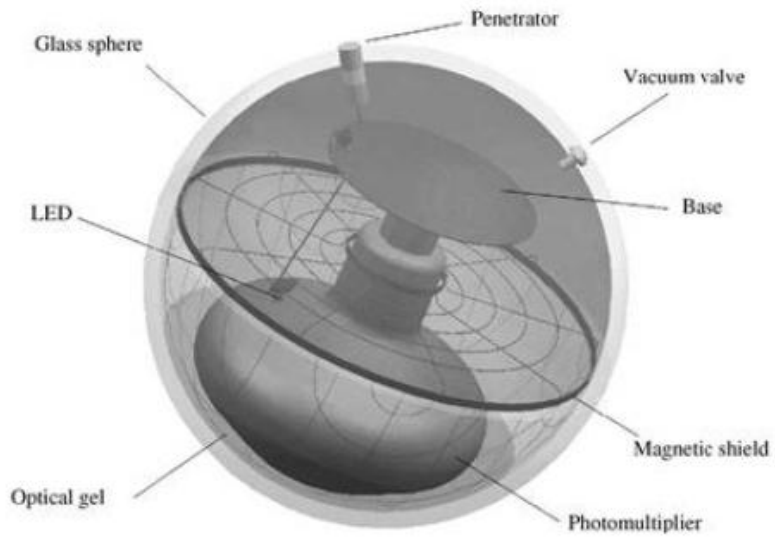


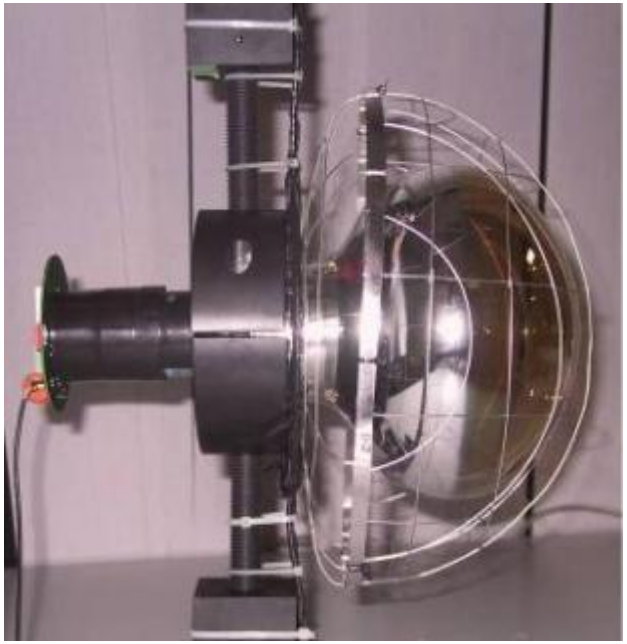
Maps of the local measurements of the detection efficiency

The SBA photocathode uniformity was not worse than that of the standard PMT

Terrestrial Magnetic Field Effects

Earth's magnetic field influences the performances of PMTs which vary their orientations. To reduce that effect the PMT could be surronded with a magnetic shield





The influence of the Earth's magnetic field on three Hamamatsu large area PMTs was studied

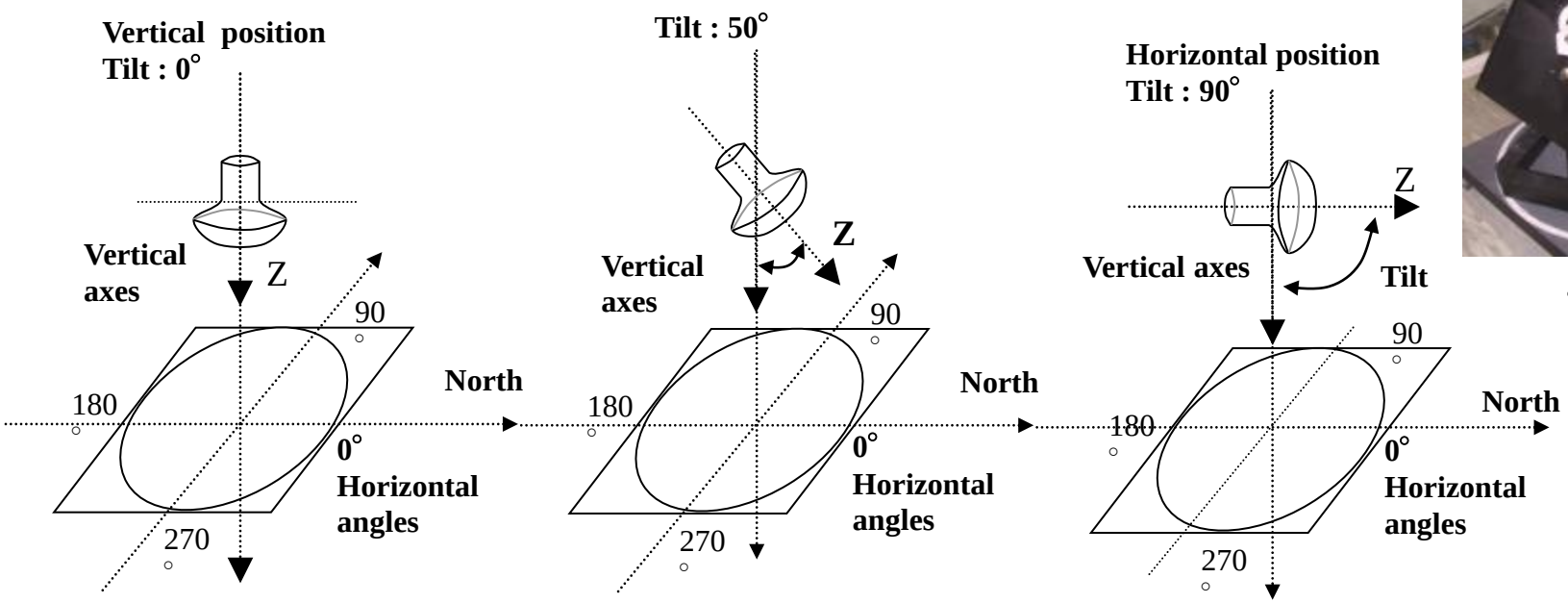
R7081 (10" STD):
10 inch. photocathode
Standard bialkali photocathode
(QE ≈ 25% @ 400nm)

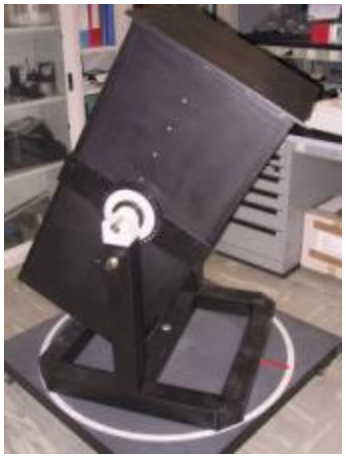
R5912 (8" STD):
8 inch. photocathode
Standard bialkali photocathode
(QE ≈ 25% @ 400nm)

R5912 HQE (8" HQE):
8 inch. photocathode
Super bialkali photocathode
(QE ≈ 32% @ 400nm)

Measurements

Every one of the three PMTs was measured in 3 inclinations:
-vertical downwards **(Tilt = 0°)** ; 50° downwards **(Tilt = 50°);** horizontal **(Tilt = 90°)**
-the PMT under test was rotated **360°** around its vertical axis in **30°** steps





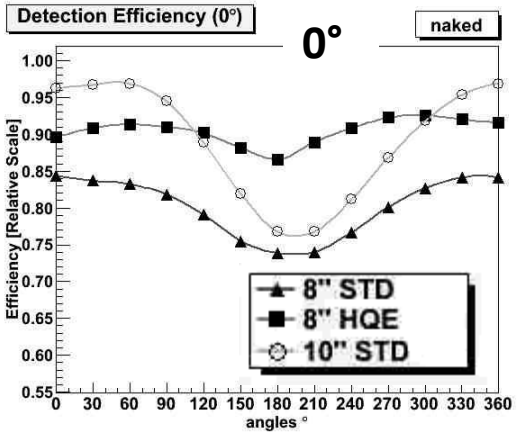
Testing box

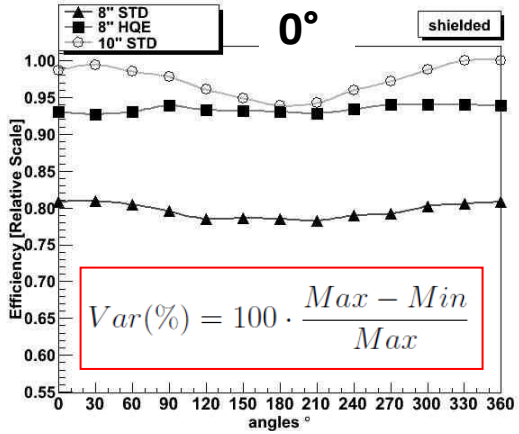
- Detection Efficiency , Gain , P/V ratio, Charge Resolution , TT (relative), **TTS** (FWHM)
- **Faction of spurious pulses** (Pre pulses, delayed pulses, Type 1 and 2 after pulses)

All measurements were made on **naked PMTs** and repeated with a **mu-metal magnetic shield**

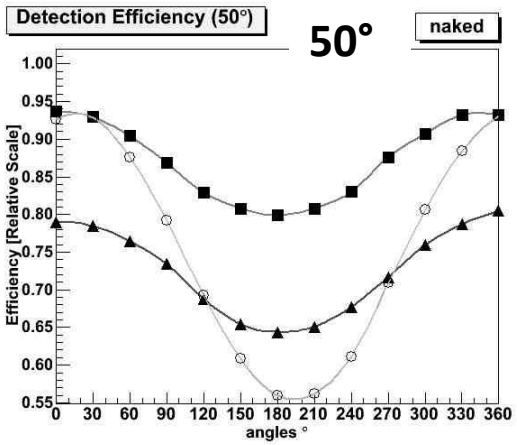
Results didn't show differences between standard and super bialkali photocathode PMT

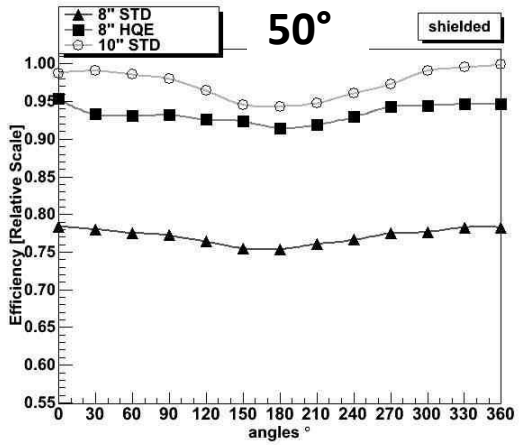
Detection efficiency

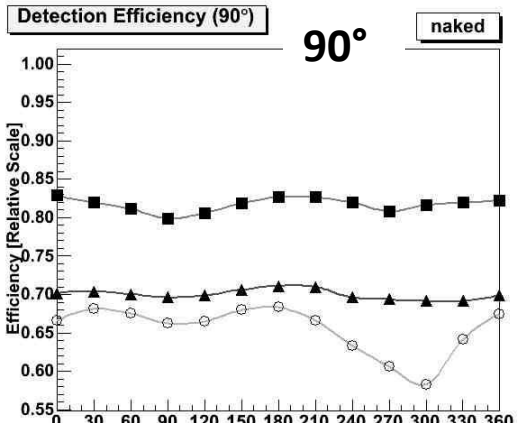


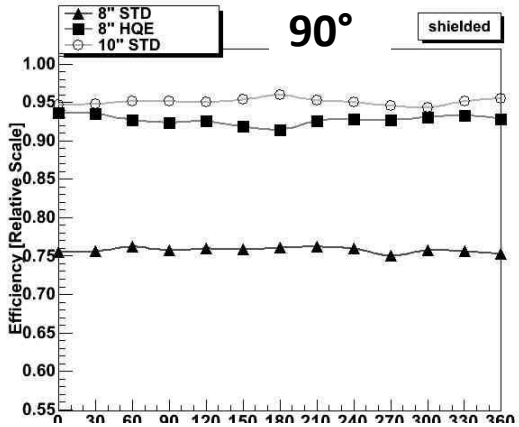


$$Var(\%) = 100 \cdot \frac{Max - Min}{Max}$$









NAKED

SHIELDED

Efficiency		naked			shield		
Tilt		8" STD	8" HQE	10" STD	8" STD	8" HQE	10" STD
0°	Ave	0.80	0.91	0.89	0.80	0.93	0.97
	$Var_{\%}$	12.47	6.49	20.76	3.29	1.35	6.13
50°	Ave	0.73	0.87	0.76	0.77	0.93	0.97
	$Var_{\%}$	19.97	14.69	39.88	3.84	4.12	5.56
90°	Ave	0.70	0.82	0.66	0.76	0.93	0.95
	$Var_{\%}$	2.76	3.63	14.72	1.52	2.35	1.69

- the 8” PMTs have the same trend
- different average values for the two 8” were due to different Quantum Efficiency
- The increased QE in the HQE 8” PMT compensates the smaller detection area with respect to the standard 10”

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Ageing Characterization

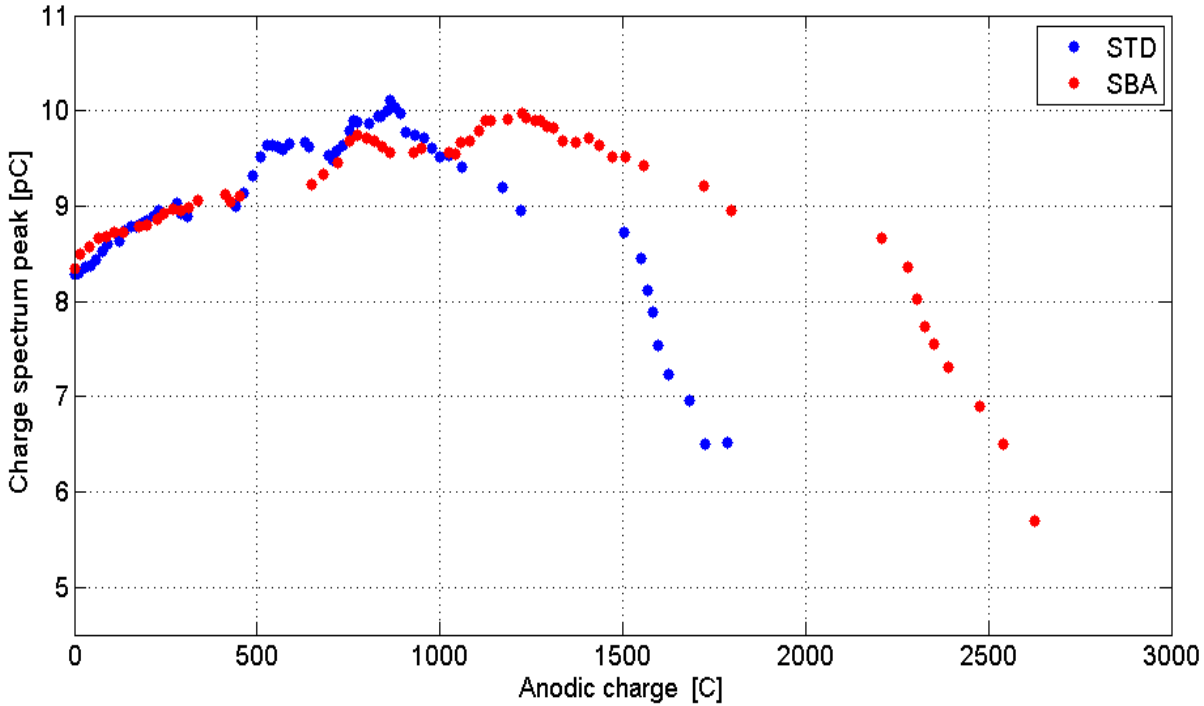
Measures of the parameters variations with operating time for 2 Hamamatsu R7081 10”
- Standard Bi-alkali photocathode (STD)
- Super-bialkali photocathode (SBA)

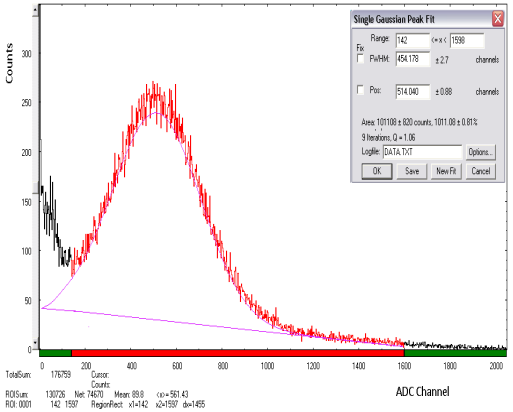
PMTs at the same start gain condition G ≈ 5 E 7
Two alternate measurement phases:
-**Ageing (continuosly)**
LED ON (about 3pe @ 1 MHz) 400 nm (switched 50/50) to illuminate the PMTs uniformly
PicoLog recording of the anode DC current for each PMT

-**Measurements of PMT parameters (once a week)**
LED OFF
Pulsed Laser at s.p.e. condition (410 nm, 60 ps width, 10 KHz)
charge spectrum (Gain)
Transit Time spectrum (TTS)
Spurious pulses (Pre pulses, delayed, type 1 and 2 after pulses)

- The ageing process was stopped (after 3 years) when the total charge arrived up to about 1800 C for STD PMT and 2600 C for SBA PMT
- The measuring time (3 years) is equivalent to an operating time of about 45 years @ 1 pe @ 200 KHz

Results: Gain

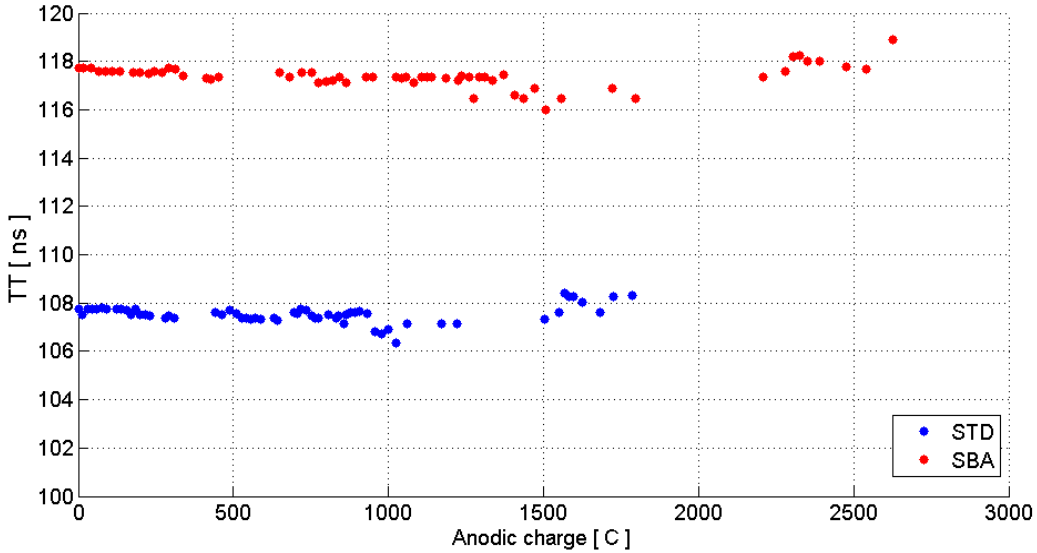




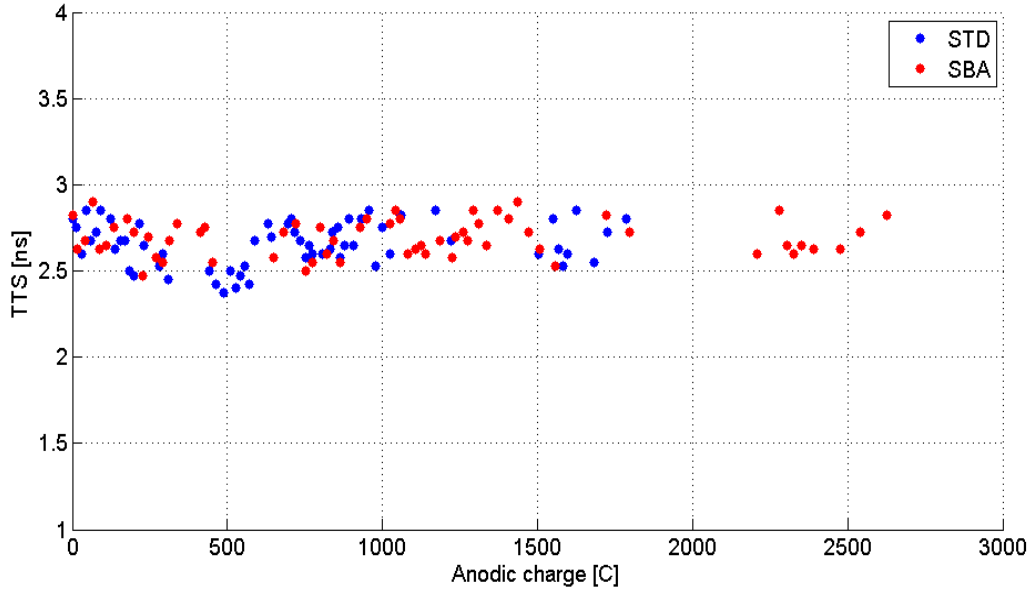
Analized Charge spectrum

- **A gain first phase of up-drift with an increase of about 20 %**
- **A gain final phase of down drift with a diminuition up to 40% from the max value**
- **Due to the increased QE the SBA PMT accumulated more charge than standard (STD)**

Results: TT and TTS

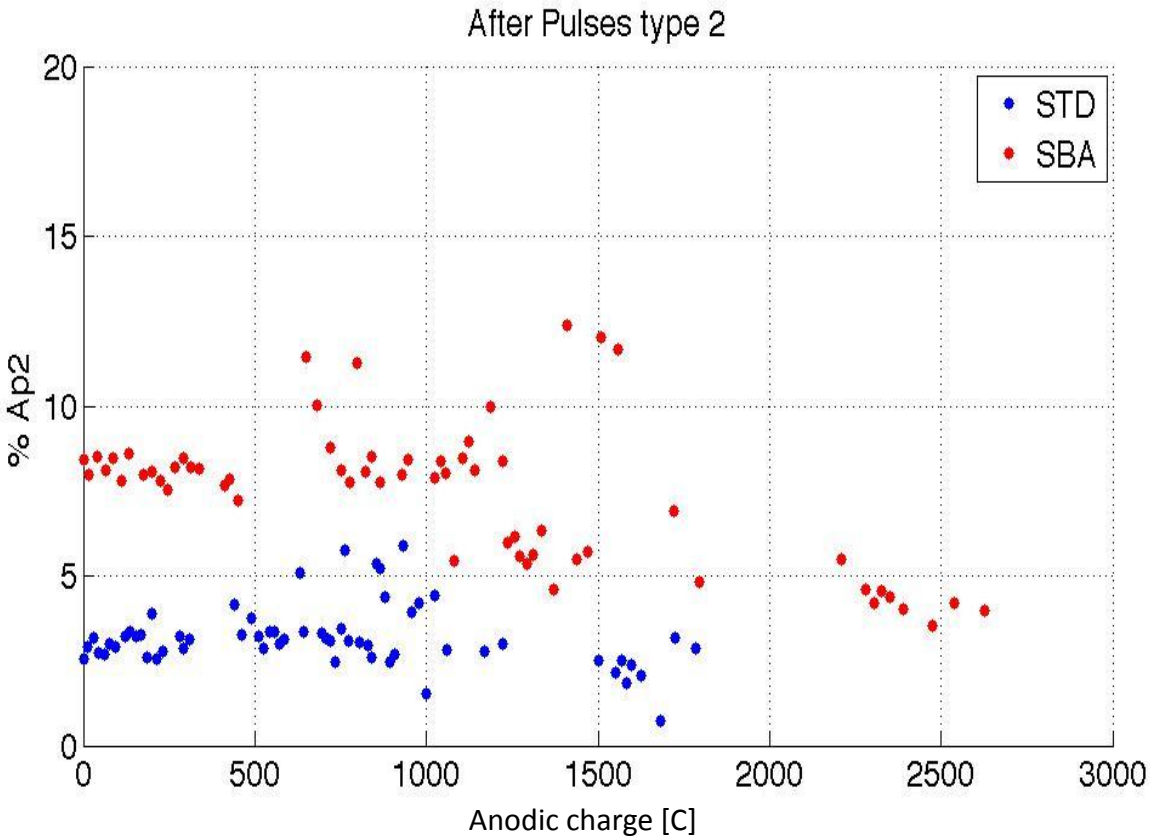


Not considerable variations in Transit Time (relative) during operating time



Not considerable variations in Transit Time Spread

Results: Fraction of spurious pulses



Not considerable variations during operating time for pre pulses, delayed pulses and type 1 after pulses

- **Not considerable variations for a lot of the operating time for type 2 after pulses**
- **Decrease in type 2 after pulse for SBA PMT after 1700 C**

Conclusions

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Performances of large area (8”, 10”) PMTs with super bialkali photocathode were measured and compared with standard bialkali PMTs :

- **The quantum efficiency measured ranges in 33% - 35% (@ 410 nm)**
- **The time and charge resolutions were not worse than that of the standard PMT**
- **The dark count rate was higher than standard (almost twice)**
- **The fraction of type 2 after pulse was almost 3 times greater than that of the standard**
- **The fraction of type 2 after pulse decreased with gain decreasing**
- **The quantum efficiency improvement did not vary with the gain**

→Use PMT with low gain to reduce after pulse

- **The super bialkali photocathode did not introduce other types of impurity inside the PMT with respect to standard**
- **The SBA photocathode uniformity was not worse than that of the standard PMT**
- **None differences on influence of the Earth’s magnetic field**
- **None differences on aging effects for long operating time (45 years of 1 p.e. at 200 KHz)**

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Thank you

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Additional slides

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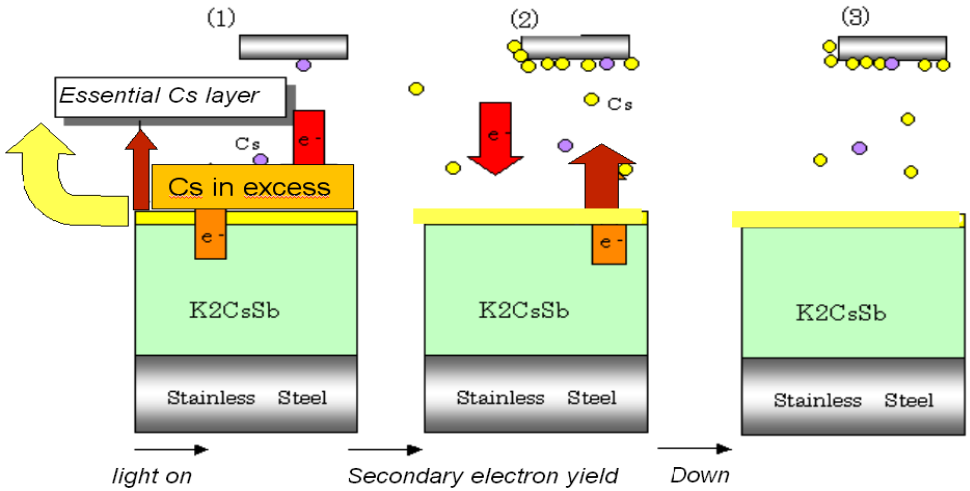
Ageing model : Up-drift and down-drift

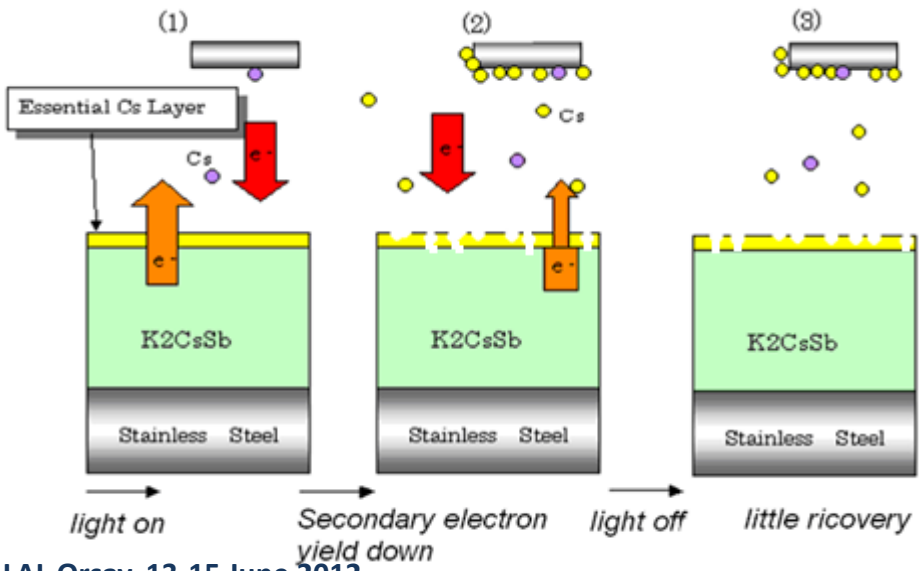
Up-drift



Progressive sputtering by secondary electrons of excess caesium layer :

- Gain increase
- Evaporation of caesium ions in vacuum

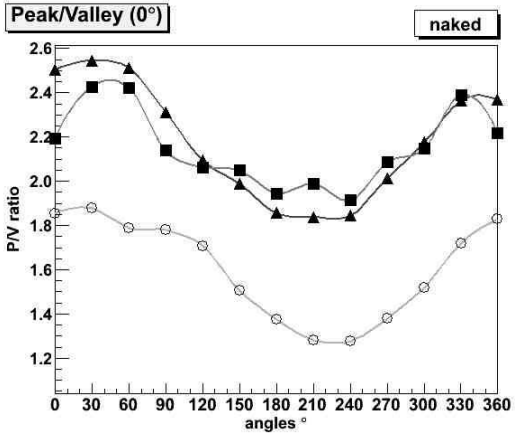
Down-drift

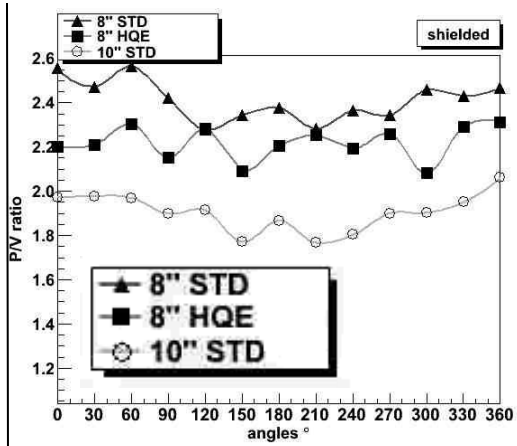


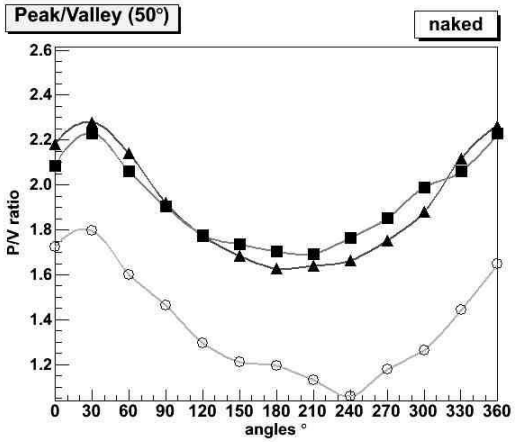
Once the excess caesium layer is removed, sputtering continues on the essential layer and on dynode surface:

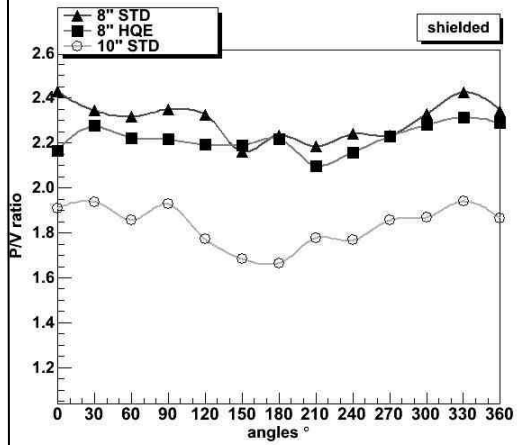
- Gain decrease
- Evaporation of caesium ions in vacuum

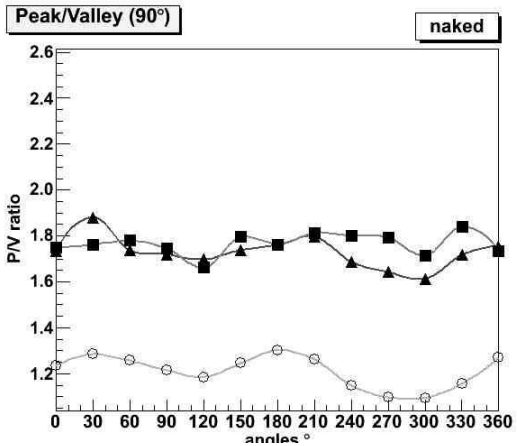
Peak to Valley ratio

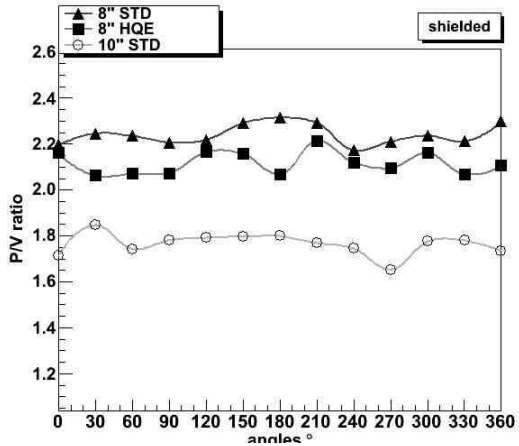












NAKED

SHIELDED

P/V ratio		naked			shielded		
Tilt		8" STD	8" HQE	10" STD	8" STD	8" HQE	10" STD
0°	Ave	2.19	2.15	1.61	2.41	2.22	1.90
	$Var_{\%}$	27.78	21.21	31.93	11.15	9.87	14.22
50°	Ave	1.92	1.93	1.39	2.30	2.22	1.83
	$Var_{\%}$	28.61	24.16	41.00	10.99	9.25	14.13
90°	Ave	1.73	1.77	1.21	2.24	2.12	1.76
	$Var_{\%}$	14.25	9.58	15.96	6.14	6.87	10.46

- Considerable variations for all the un-shielded PMTs
- Great reductions in variation by using the magnetic shield
- Not considerable differences between the two 8” PMTs

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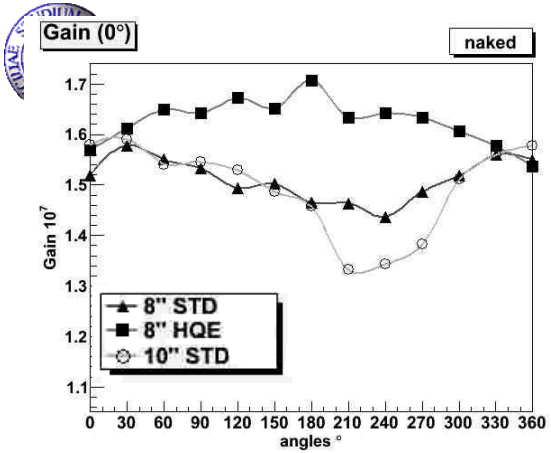
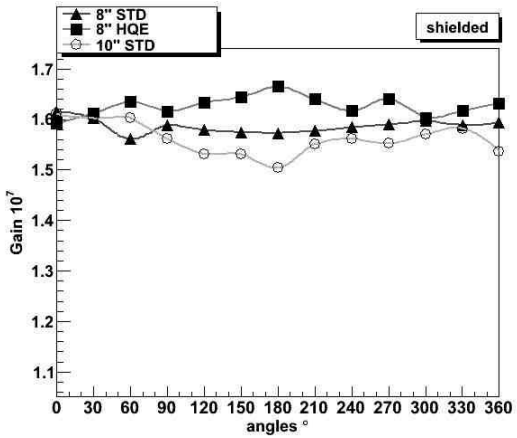
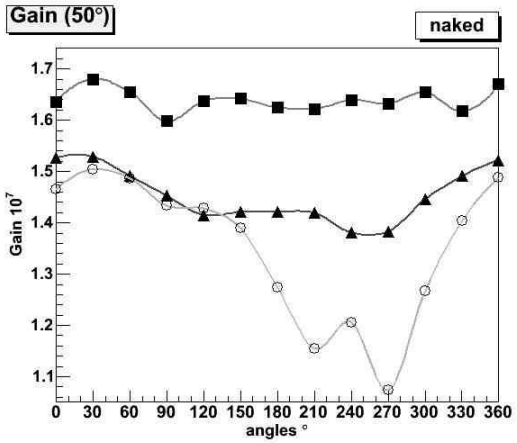
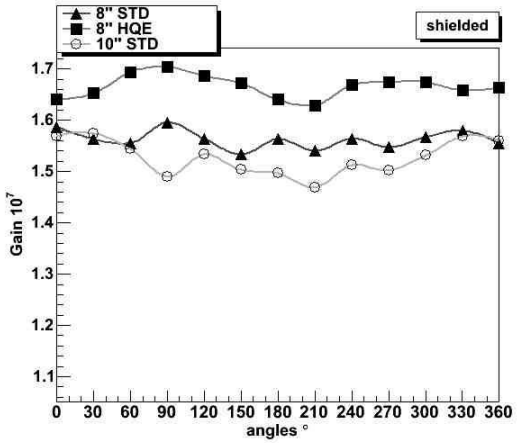
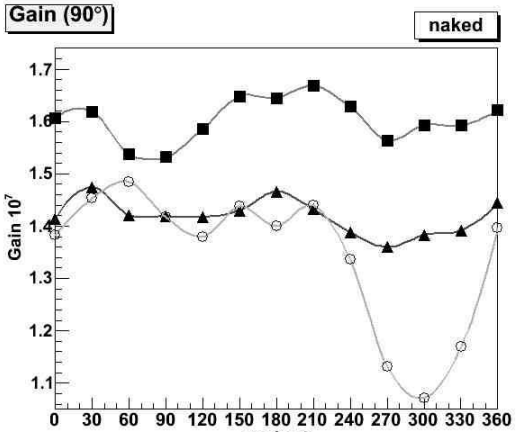
Gain

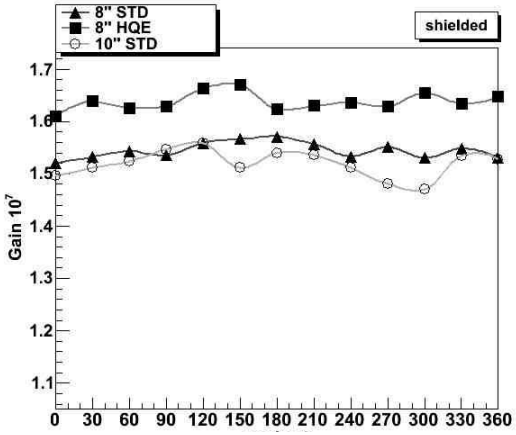












NAKED

SHIELDED

Gain [1xE 7]		naked			shielded		
Tilt		8" STD	8" HQE	10" STD	8" STD	8" HQE	10" STD
0°	Ave	1.51	1.63	1.50	1.59	1.63	1.56
	$Var_{\%}$	8.94	9.96	16.28	3.34	4.38	6.64
50°	Ave	1.45	1.64	1.35	1.56	1.67	1.53
	$Var_{\%}$	9.68	4.88	28.59	3.89	4.40	6.67
90°	Ave	1.42	1.60	1.35	1.54	1.64	1.52
	$Var_{\%}$	7.73	8.15	27.81	3.25	3.65	5.65

- Greatest gain variation was less than 10% for both the naked 8”
- Considerable variations in the 10” PMT naked, up to 29%
- The shield reduces variations in both the 8” PMTs, with variations less than 4.4 %
- The shield reduces strongly the variations in the 10” PMT, with variation less than 7%