Influence of the photoelectric effect occurring at the PMT first dynode on the RED-100 detector performance

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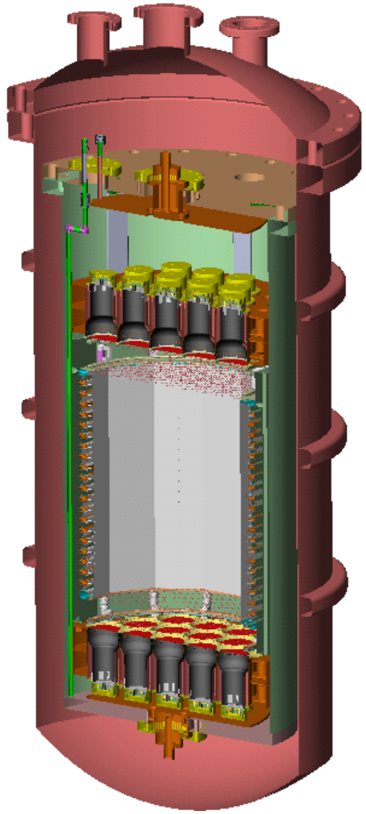
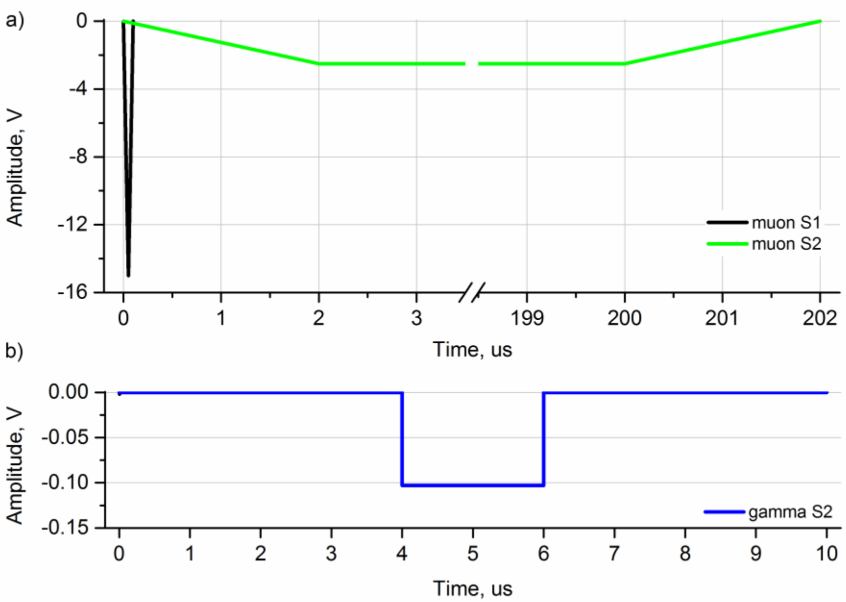
The RED-100 detector

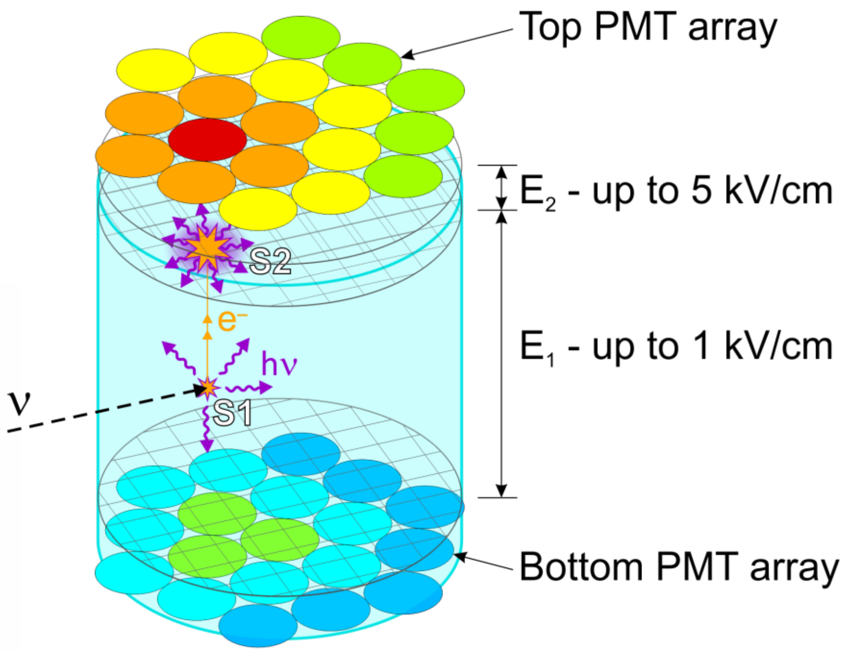


- Two-phase xenon emission detector to search for **coherent elastic neutrino-nucleus scattering (CEvNS)**;
- **~250 kg of Xe**, ~100 kg in fiducial volume (for the "wall-less" regime);
- Sensitivity to **~1 keV** recoil energies;
- 38 (32) **Hamamatsu R11410-20** low-background 3" PMTs;
- To be exposed at a **shallow-depth experimental site** at the Kalinin Nuclear Power Plant (Russia)**.**

Two-phase emission technology

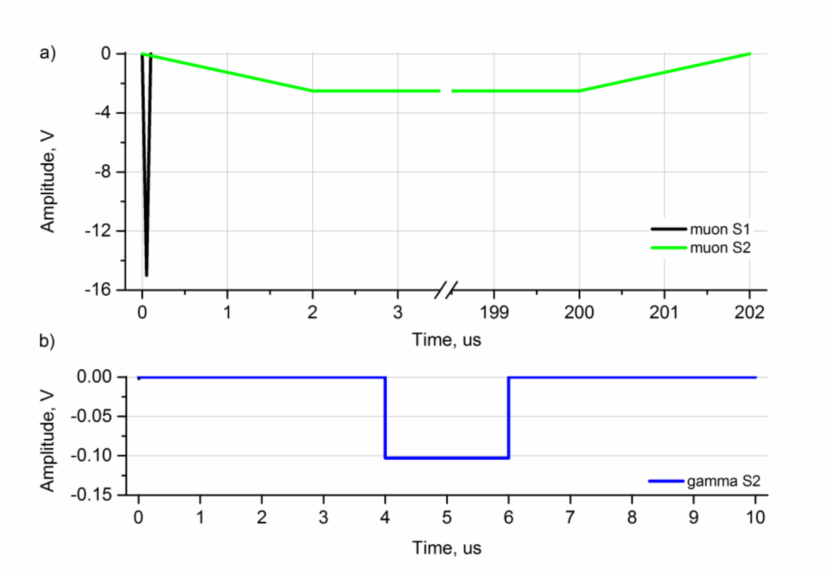
Useful events are expected to have single photoelectron amplitude (at a single PMT). Waveforms of the expected signals from calibration gammas and cosmogenic muons are presented below for $9*10^5$ PMT gain (2 mV/s.pe):

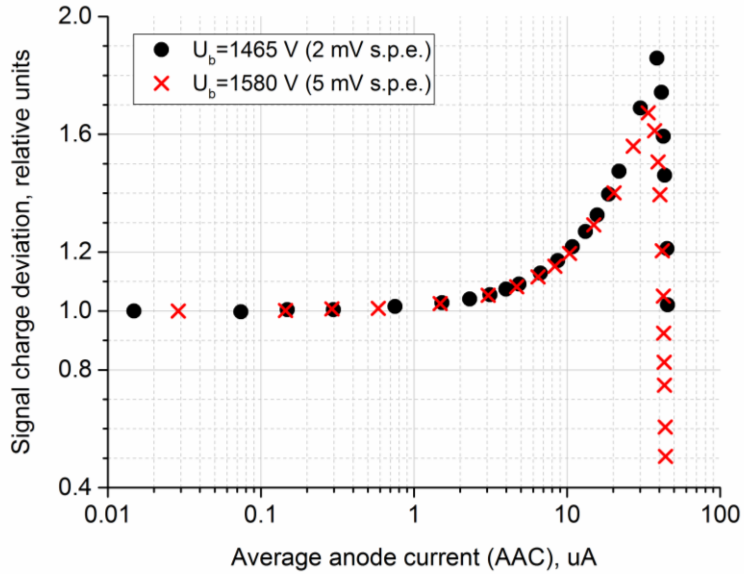




↑ Particle detection principle

Expected detector load

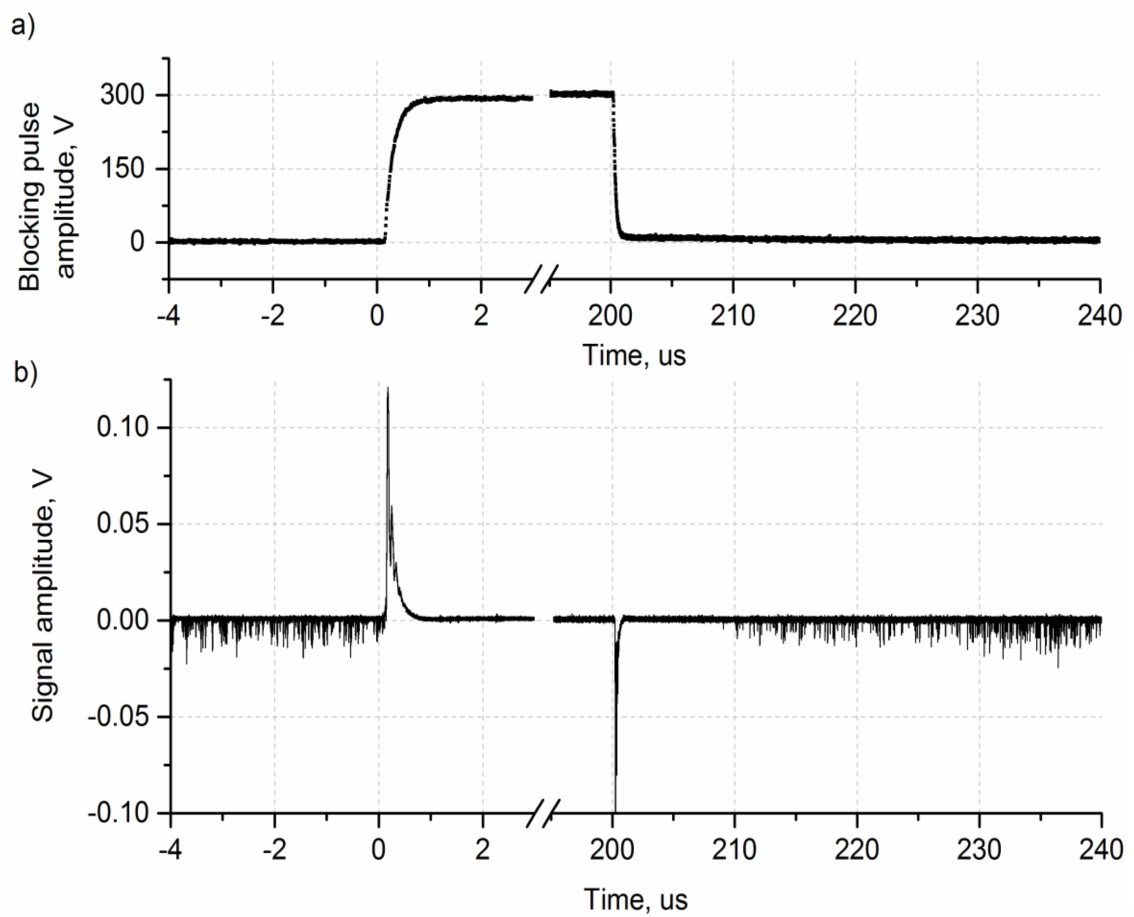




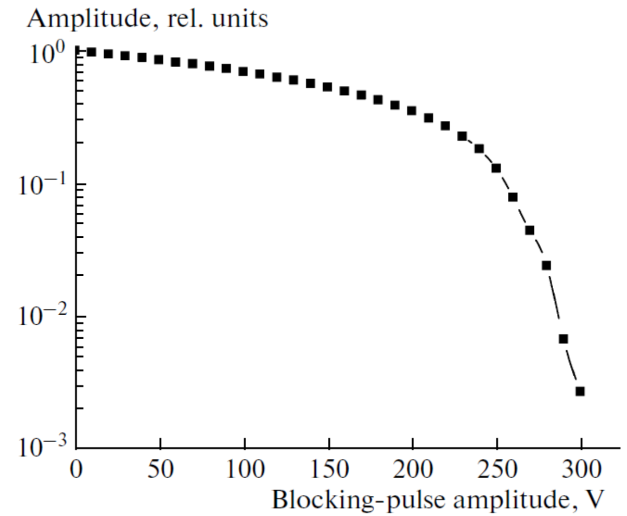
Signal type	Gamma S2	Muon S1	Muon S2
Average charge detected by each PMT, p.e.	$1.8*10^4$	$6.3*10^4$	$4.3*10^7$
Impact to the expected AAC per PMT, μA	~0.41	≲0.14	~98

Average anode current (AAC) of a PMT in RED-100 does not exceed the **1 uA** limit if muon S2 signals are blocked → **1% gain stability**.

Active PMT base



Positive pulses of ~350 V are supplied to the photocathodes of all PMTs less than in 1 us to block out muon S2 signals.



Photoelectric effect at the first dynode

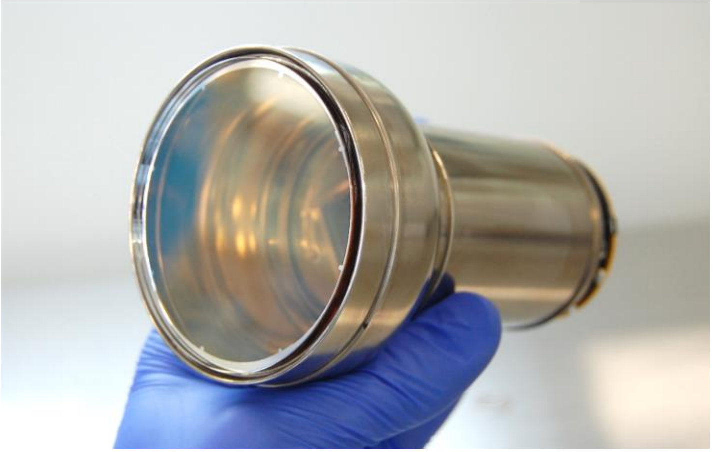
Hamamatsu R11410-20 is equipped with large *(450 mm^2)* first dynode (D1) open to the incoming light;

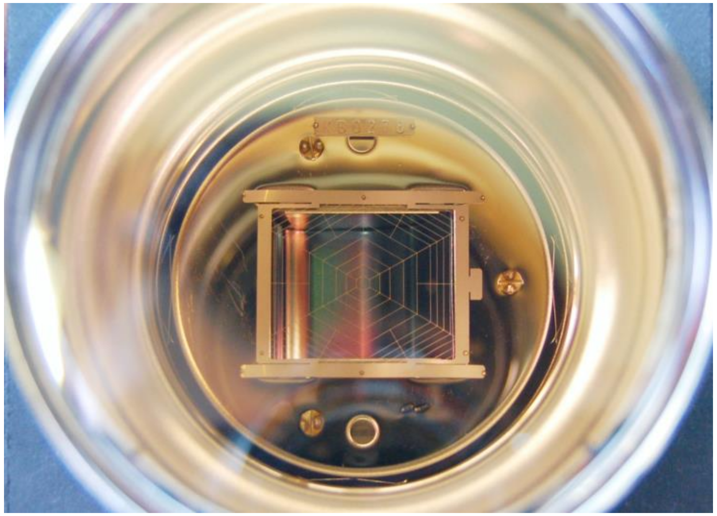
D1 is coated with *K-Cs-Sb* substance with low work function for the best SPE resolution of the PMT;

↓

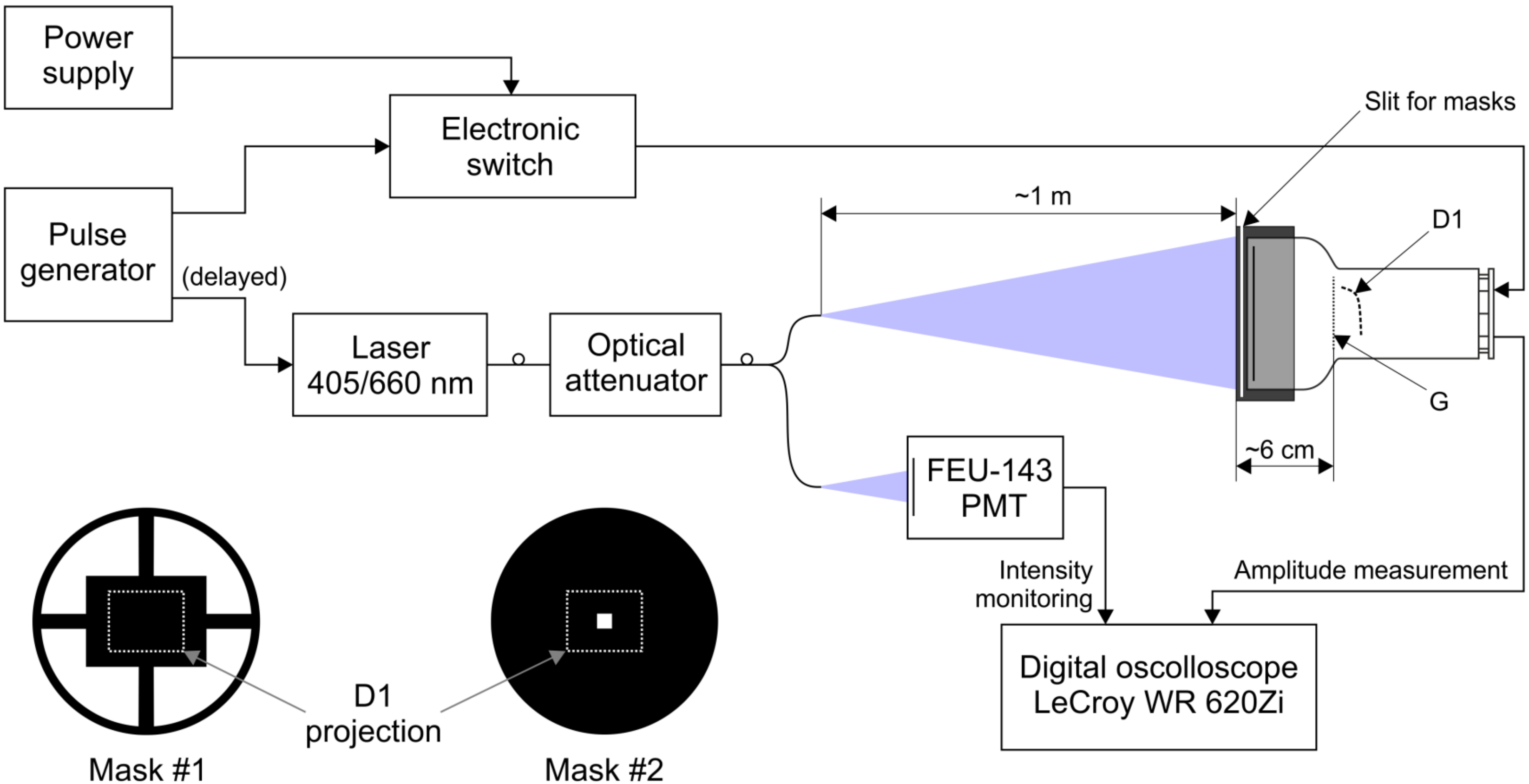
Some of the incoming VUV photons hit the D1 and induce a photoelectric effect → signal generation at the PMT anode even when the photocathode-D1 gap is entirely blocked out.

Do muon S2 signals produce enough electrons at D1 to affect the RED-100 photodetection system stability?

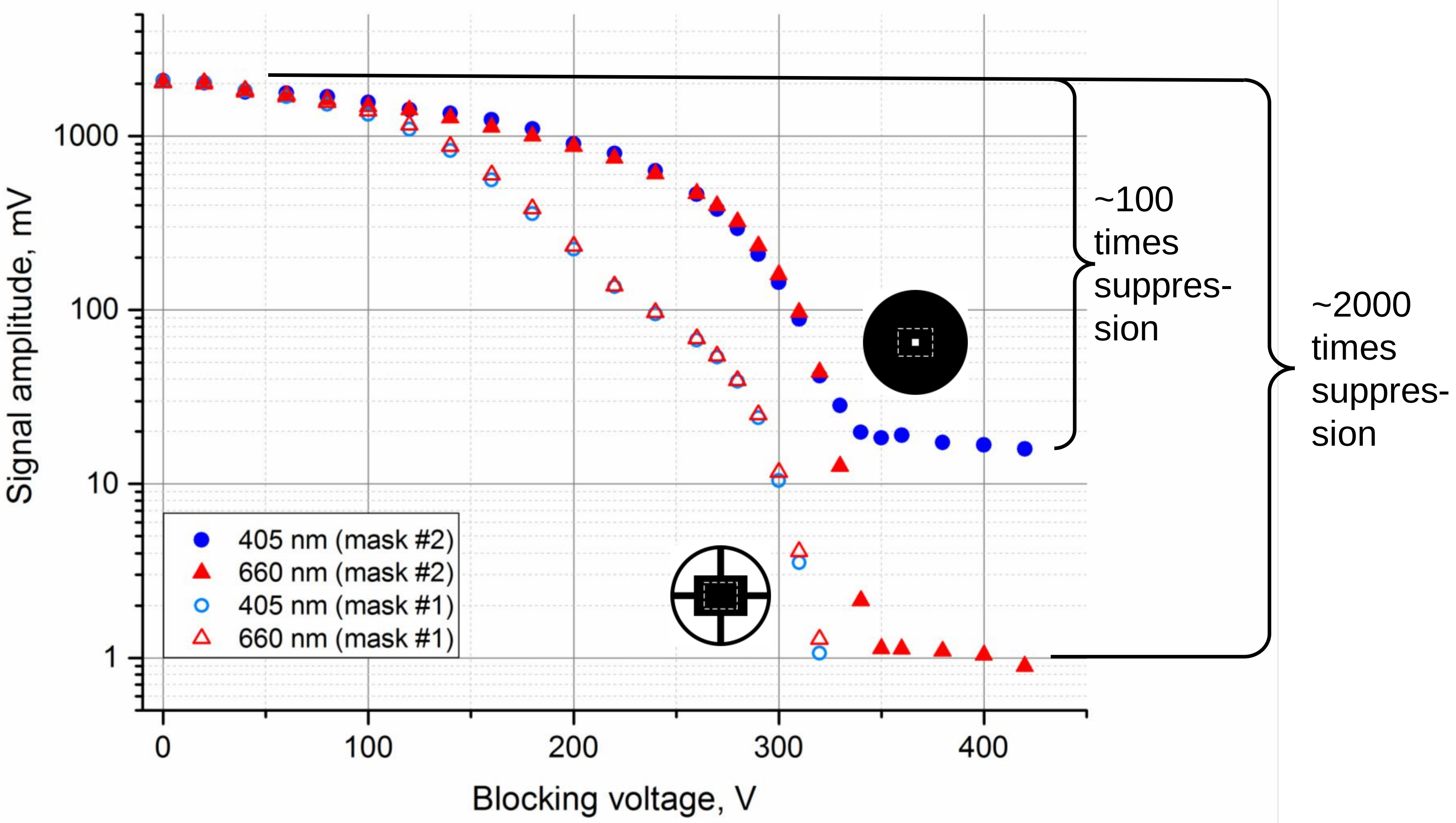




Photoelectric effect at D1: experimental setup for the visible light



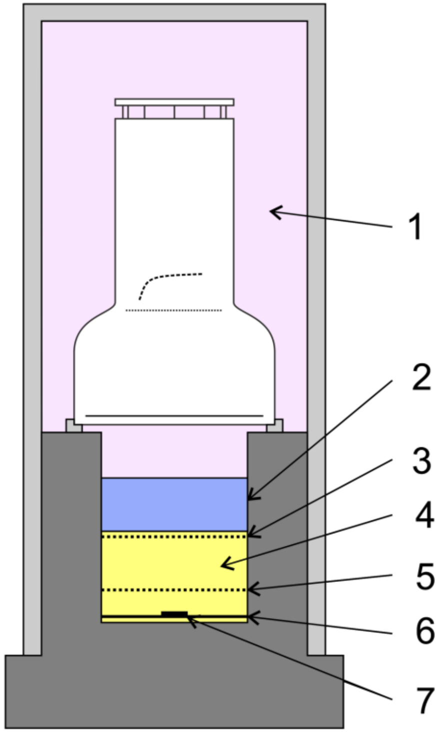
Photoelectric effect at D1: the results for the visible light



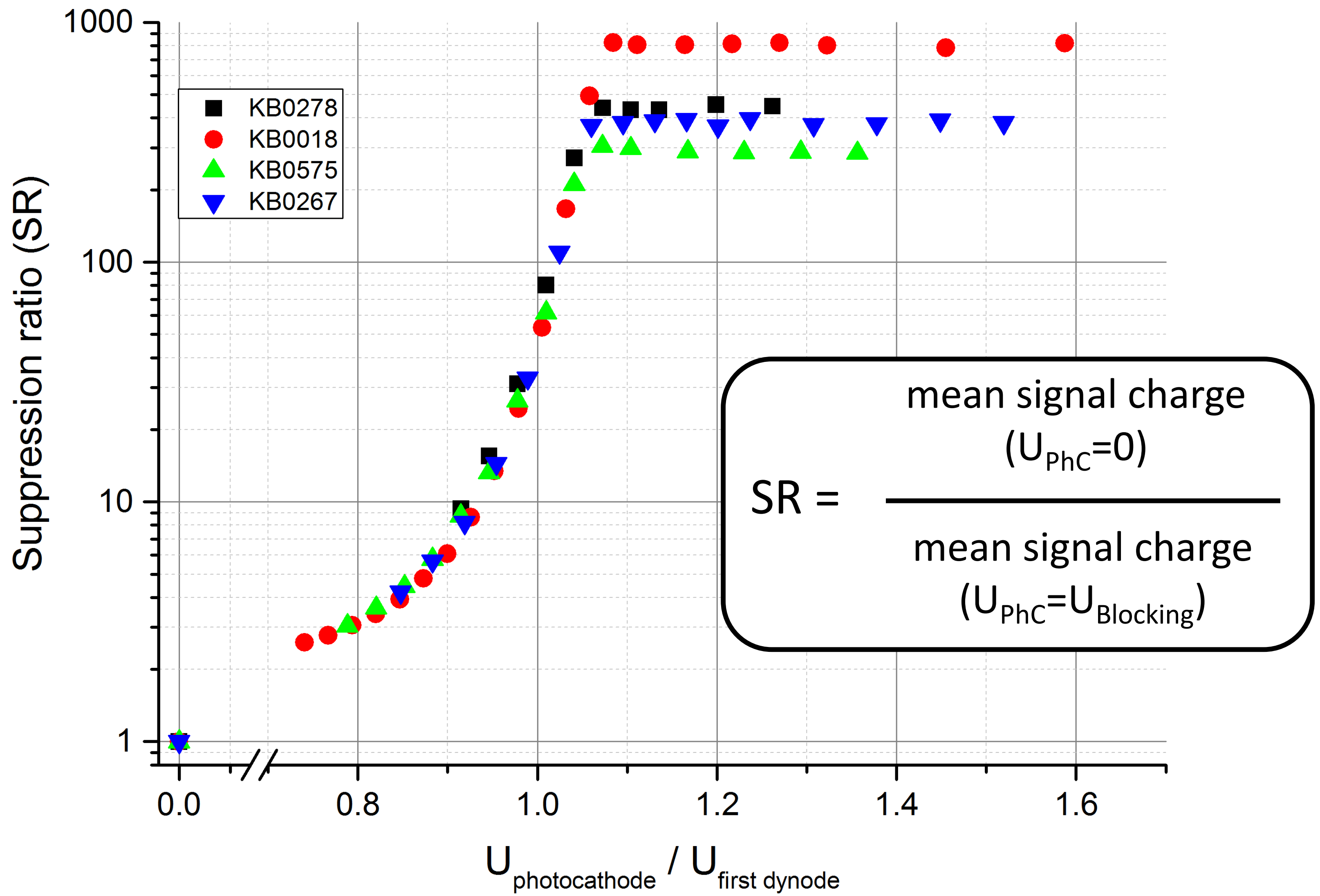
Photoelectric effect at D1: VUV light experimental setup

The previous test is not sufficient to estimate the quantitative effect for the RED-100 conditions: all photons are focused at the D1 and are of a very different wavelength.

Experimental setup to simulate the PMT illumination conditions in the RED-100 detector:



1 – argon gas;
2 – fused silica window (2 cm-thick);
3 – anode grid (+4 kV);
4 – xenon gas (6 bar pressure);
5 – grounded grid;
6 – cathode grid (-1 kV);
7 – ^{239}Pu alpha source.


Suppression ratio (SR)
1000
100
10
1
0.0
0.8
1.0
1.2
1.4
1.6
U photocathode / U first dynode
KB0278
KB0018
KB0575
KB0267
SR =
mean signal charge
(U PhC=0)
mean signal charge
(U PhC=U Blocking)

Photoelectric effect at D1: results for the VUV light

PMT ID	Best peak-to-valley [8]	Gain at 1500 V, $*10^6$	Q.E. at 175 nm, %	SR	Estimated muon S2 signal amplitude after suppression, mV	Estimated muon S2 signals impact to the PMT AAC, µA
KB0018	1,9	2,5	34,0	810	3	0,12
KB0019	2,1	2,5	28,1	379	7	0,26
KB0022	2,2	2,8	32,5	433	6	0,23
KB0024	2,3	3,2	37,3	510	5	0,19
KB0049	3,3	6,0	34,0	530	5	0,18
KB0267	2,9	13,9	33,4	385	7	0,25
KB0274	3,9	7,0	34,7	345	7	0,28
KB0278	2,7	5,3	32,8	441	6	0,22
KB0279	3,5	6,2	38,2	542	5	0,18
KB0575	3,8	5,2	30,4	292	9	0,34
KB0580	3,0	3,8	33,4	327	8	0,30
KB0584	3,5	9,1	31,7	413	6	0,24
KB0586	3,6	6,9	32,3	322	8	0,30

Estimation of the average Q.E. of the first dynodes of the tested PMTs

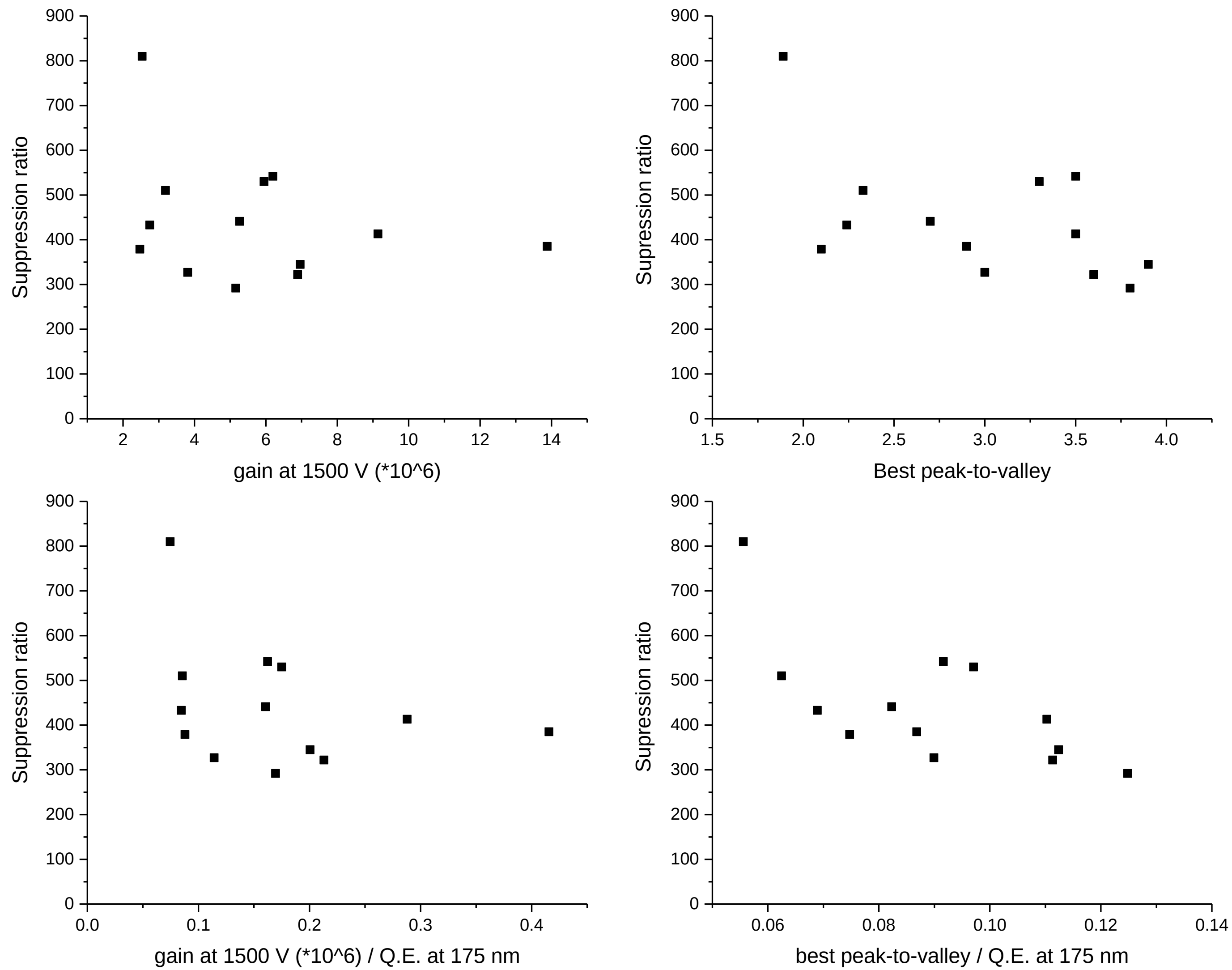
Due to the possible variation of the collection efficiency across the D1 area, this calculation represents only the lower limit of D1 Q.E. for 175 nm light:

$$\boldsymbol{Q_{D1}} \geq \frac{Q_{PhC} * G_{(PhC-D1)gap}}{(SR-1)*(1-Q_{PhC})*\frac{S_{D1}}{S_{PhC}}} = \mathbf{10,6\%}$$

$\mathbf{Q_{D1}}$ – quantum efficiency of the first dynode;
$\mathbf{Q_{PhC}}$ – average quantum efficiency of the photocathode for the tested PMTs (*0,33*);
$\mathbf{G_{(PhC\text{-}D1)\ gap}}$ – gain of the first interdynode gap (~*13*);

SR – average suppression ratio of the tested PMTs when the PhC is biased to the potential higher, than the one at the D1 (*440*);
$\mathbf{S_{D1}}$ – first dynode projection area to the photocathode (*450 mm²*);
$\mathbf{S_{PhC}}$ – photocathode area (*3215 mm²*).

No clear dependence of the measured SR values on the PMT gain or SPE characteristics was found:

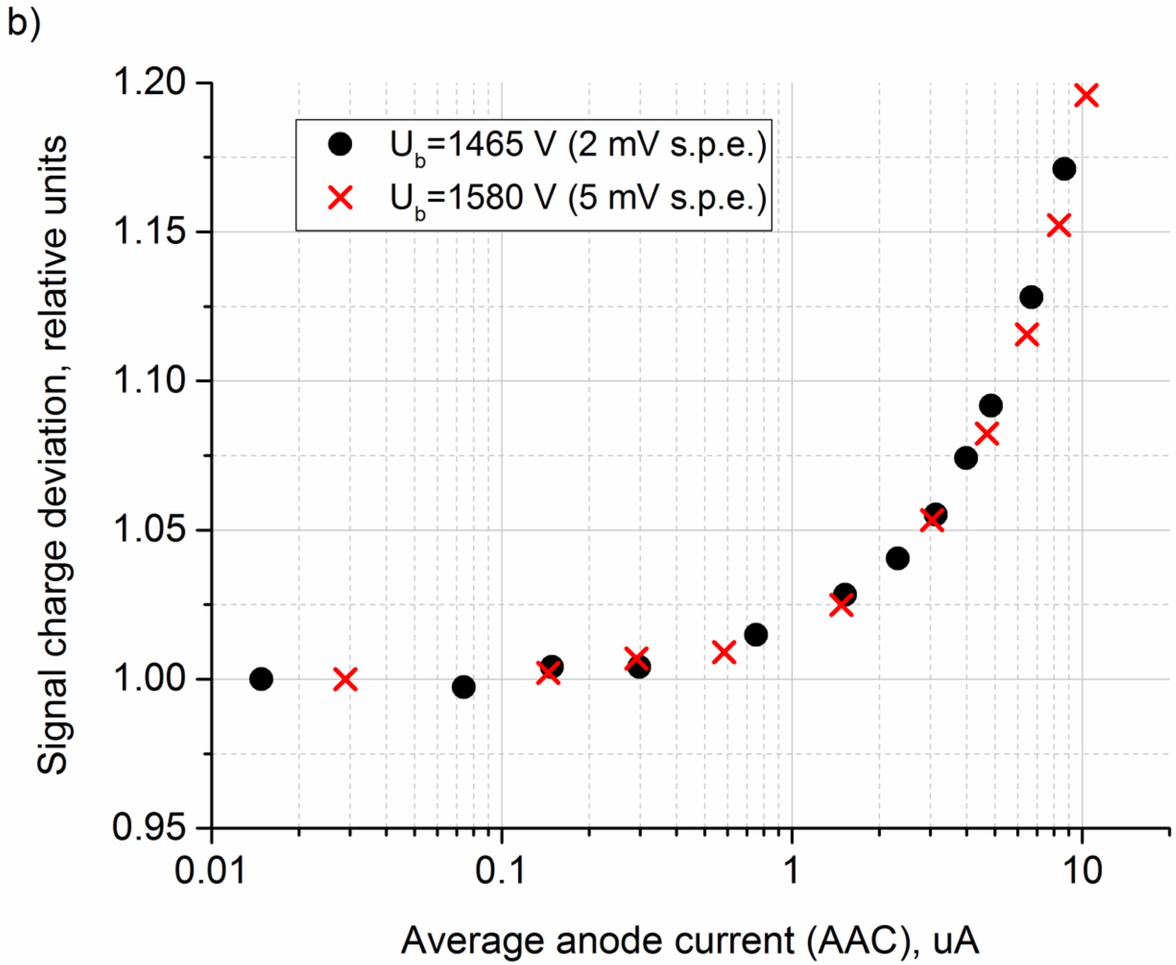


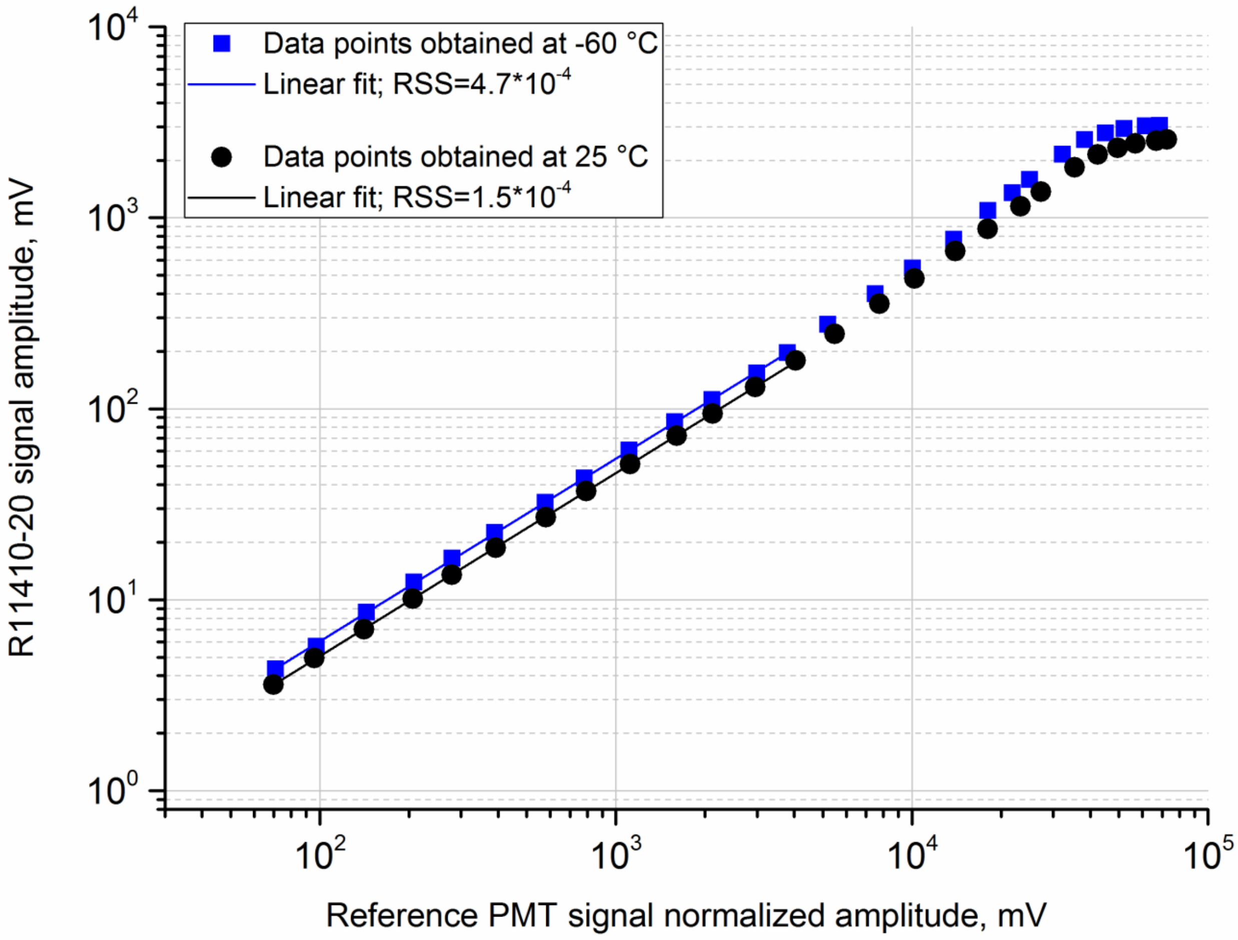
Conclusion

- Cosmogenic muons pose significant difficulties for a stable RED-100 detector operation at a shallow-depth experimental site;
- Most of these difficulties are solved with the dedicated active base system, which blocks the photocathodes sensitivity upon a special trigger;
- Those muon S2 signal photons hitting the PMT first dynode would generate detectable signals at the PMT anode – it could be used for the free electron lifetime monitoring basing on the cosmogenic muon signals waveforms;
- Impact of those signals generated at the D1 to the average PMT anode current is significant, but nor critical for the PMT gain stability: variation of up to 2% is expected;
- Quantum efficiency of the first dynode in Hamamatsu R11410-20 PMT averaged over 13 tested pieces is ≥10.6%.

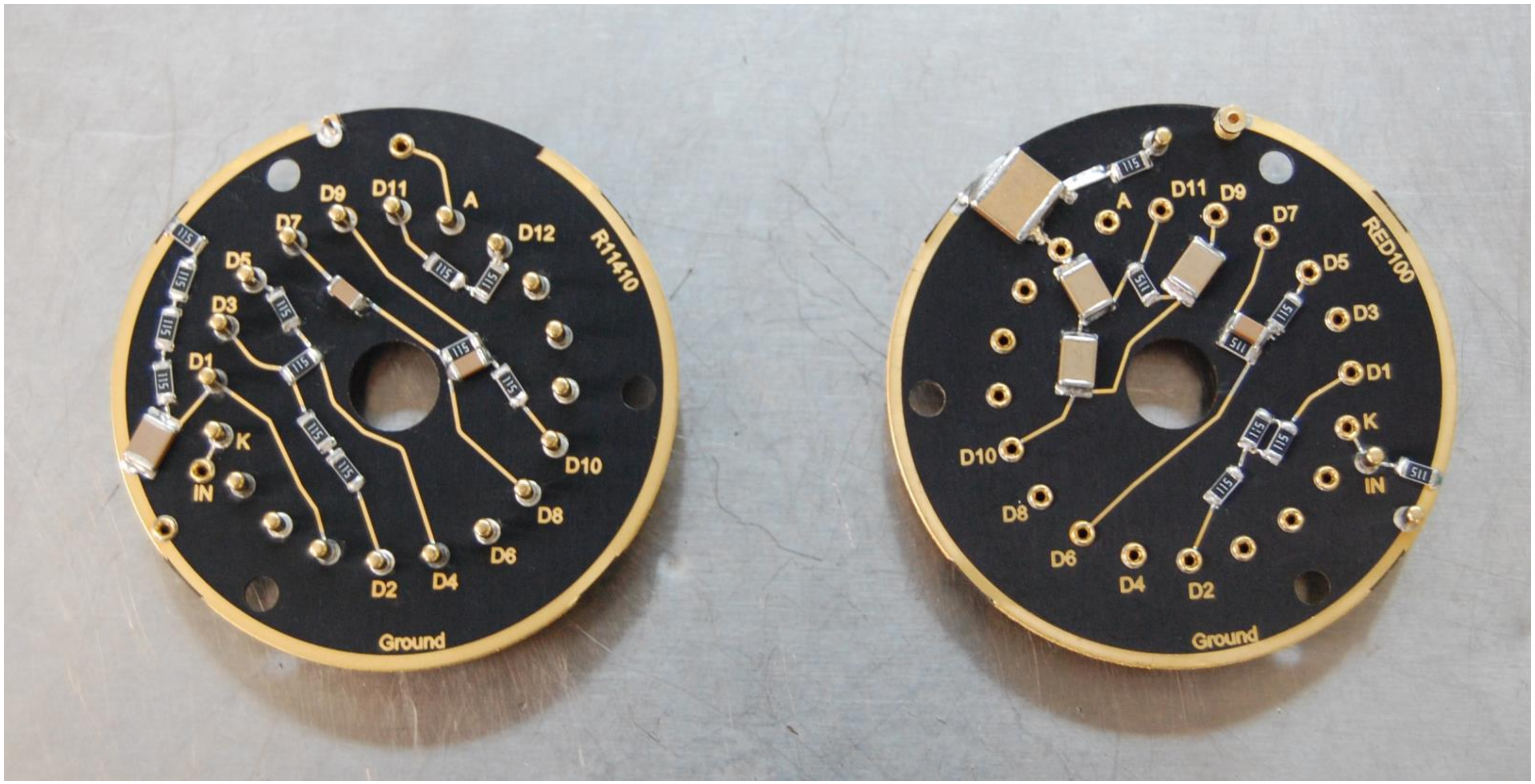
Thank you for your attention!

Back-up slides

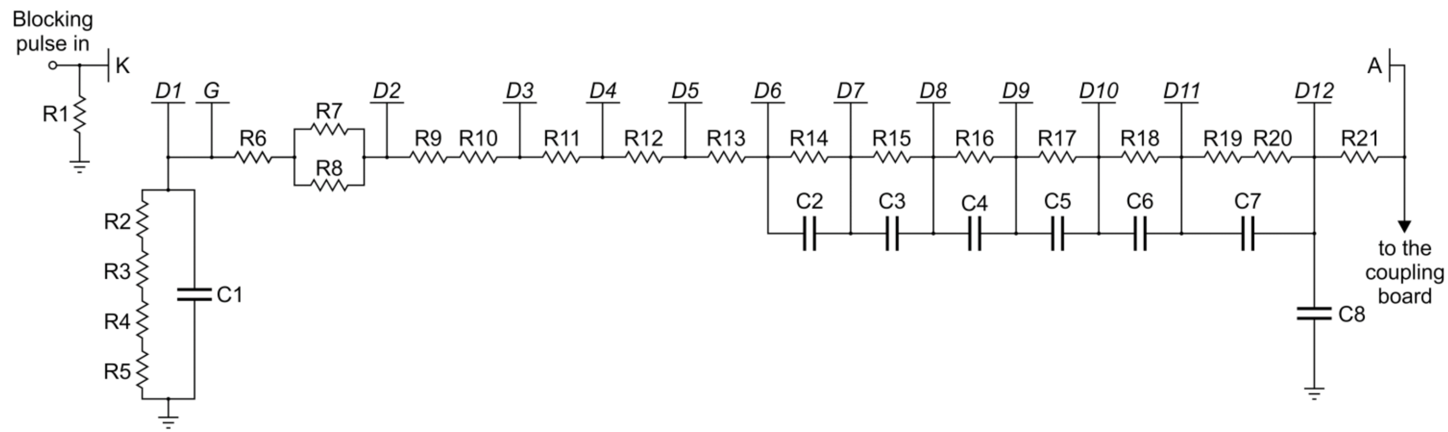

b)
1.20
1.15
1.10
1.05
1.00
0.95
0.01
0.1
1
10
Signal charge deviation, relative units
Average anode current (AAC), uA
U_b=1465 V (2 mV s.p.e.)
U_b=1580 V (5 mV s.p.e.)



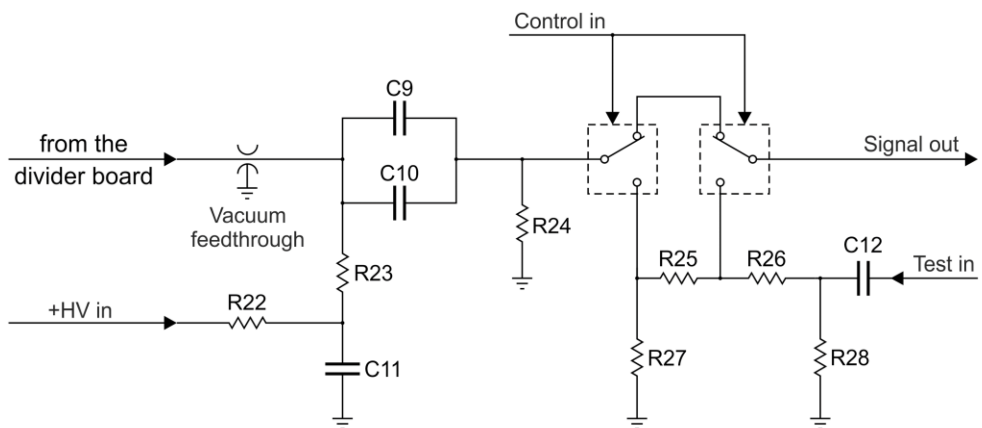
Data points obtained at -60 °C
Linear fit; RSS=4.7*10^-4
Data points obtained at 25 °C
Linear fit; RSS=1.5*10^-4
R11410-20 signal amplitude, mV
Reference PMT signal normalized amplitude, mV
10^0
10^1
10^2
10^3
10^4
10^5

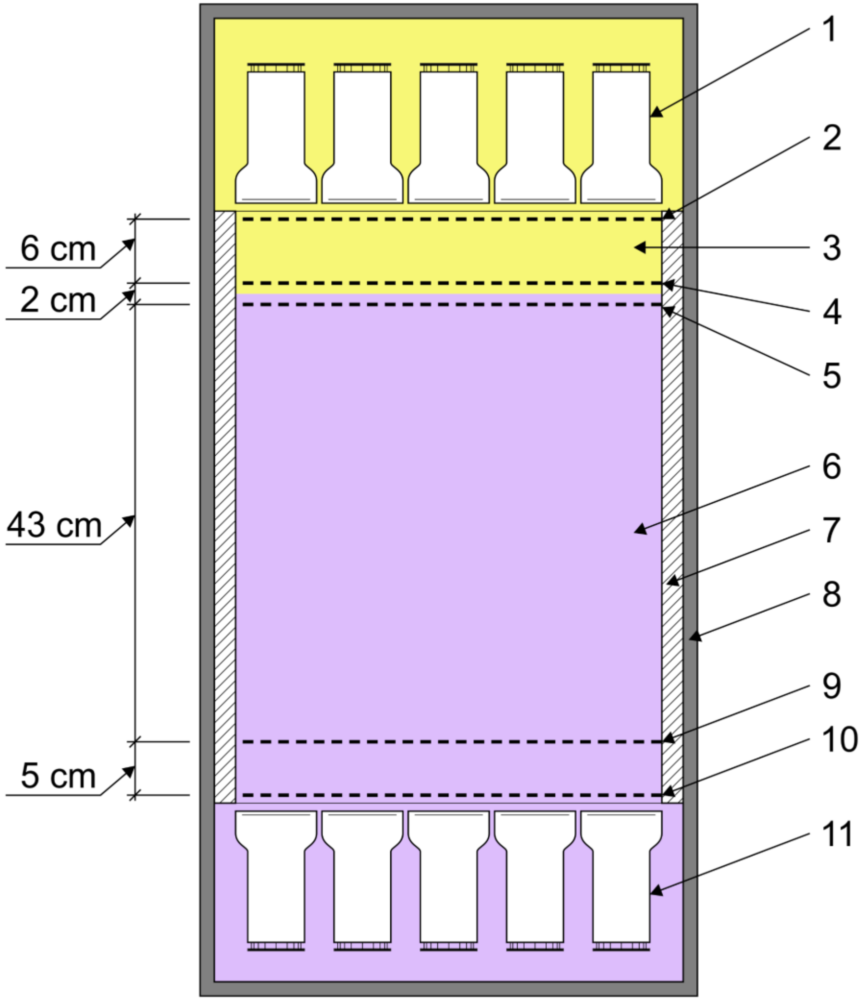

D9
D11
A
D7
D12
R11410
D5
D3
D1
K
IN
D10
D8
D2
D4
D6
Ground
A
D11
D9
D7
RED100
D5
D3
D1
K
IN
D10
D8
D6
D4
D2
Ground

a)


Blocking pulse in
K
R1
D1
G
R6
R7
R8
D2
R9
R10
D3
R11
D4
R12
D5
R13
D6
R14
D7
R15
D8
R16
D9
R17
D10
R18
D11
R19
R20
D12
R21
A
to the coupling board
R2
R3
R4
R5
C1
C2
C3
C4
C5
C6
C7
C8

b)


Control in
from the divider board
Vacuum feedthrough
C9
C10
R23
+HV in
R22
C11
R24
Signal out
R25
R26
C12
Test in
R27
R28



1
2
3
4
5
6
7
8
9
10
11
6 cm
2 cm
43 cm
5 cm