Radiation damage of SiPM in neutron fields

N.Zamyatin, JINR, Dubna

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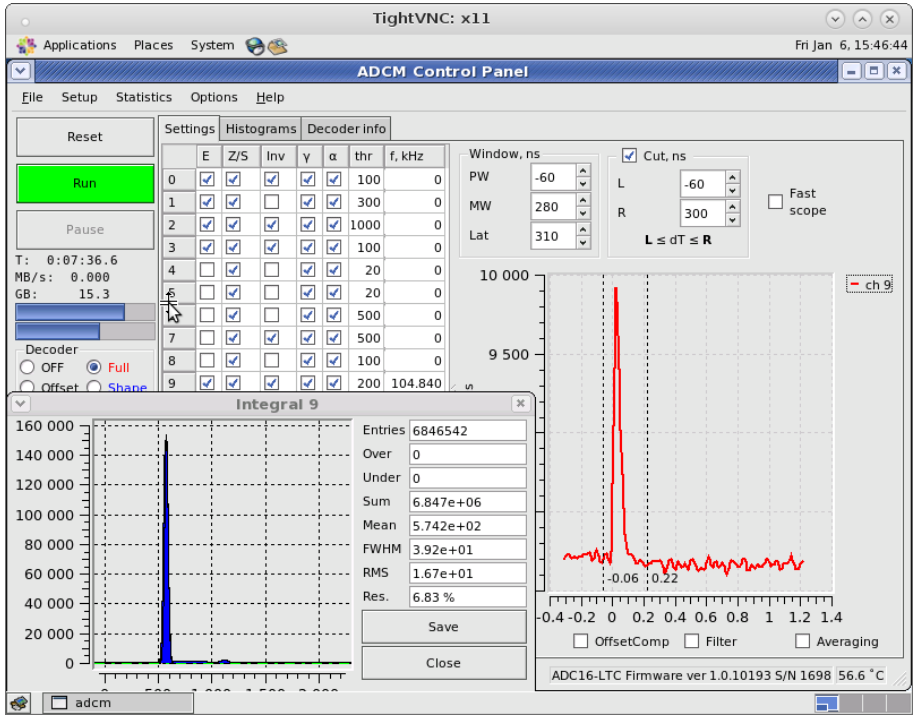
Negative effects at radiation damage of SiPM

- I_d – dark current SiPM increase
- F_d – dark count SiPM increase
- σ_N – noise SiPM increase
- U_{br} and U_{op} – break down and operation voltage SiPM increase
- Crosstalk and after pulse - increase
- Power dissipation SiPM increase ($P_{SiPM} = I_d \times U_{op}$)
- C_{pixel} - not change ($C_{pixel} = \varepsilon_0 \varepsilon_{Si} S_{pixel} / d_{epi}$)
- M_{SiPM} – not change ($M_{SiPM} = C_{pixel} \times U_{ov}$)

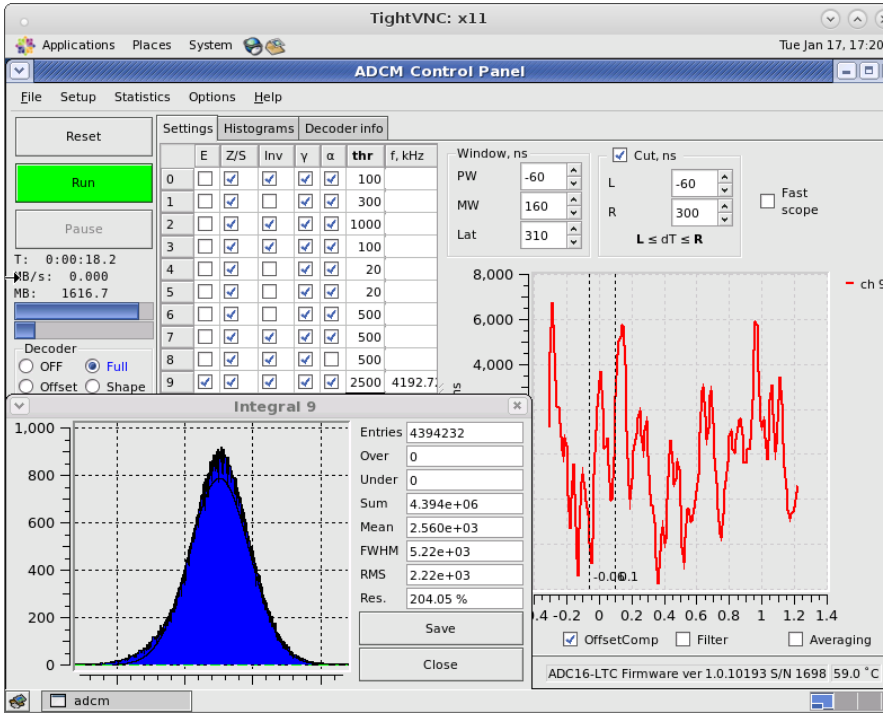
Evolution of the SiPM noise after irradiation by fast neutrons:

(A) – Spectra and shape pulse of the noise for *non irradiated* SiPM (S13360-1325CS) at +25°, Vov=5V, thr=0.5 pix, t_s= 25 ns.

(B) – Spectra and shape pulses of the noise for *irradiated* $\Phi=5{,}4\times10^{12}$ см$^{-2}$ SiPM (S13360-1325CS) at -22°, Vov=3V, *threshold*=3×σ_0, t_s= 25 ns

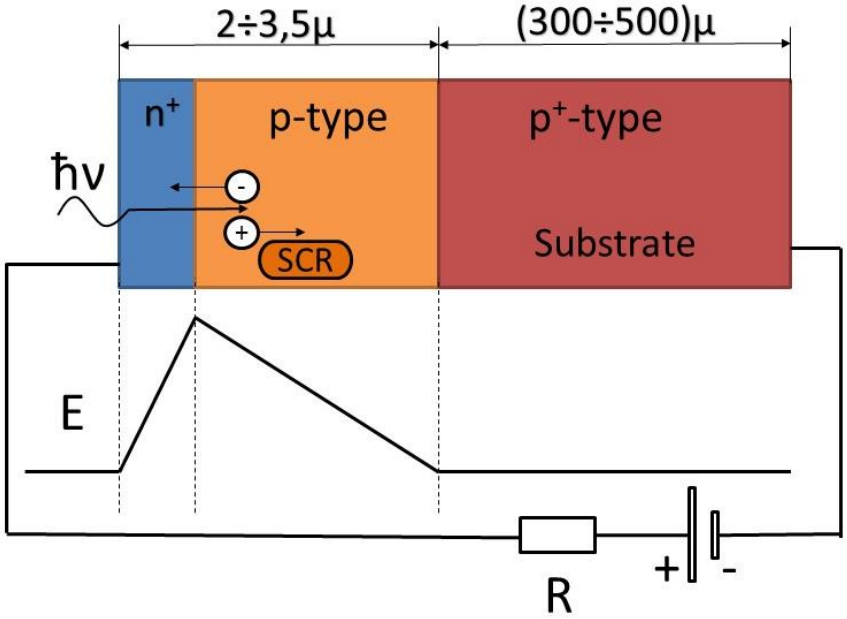


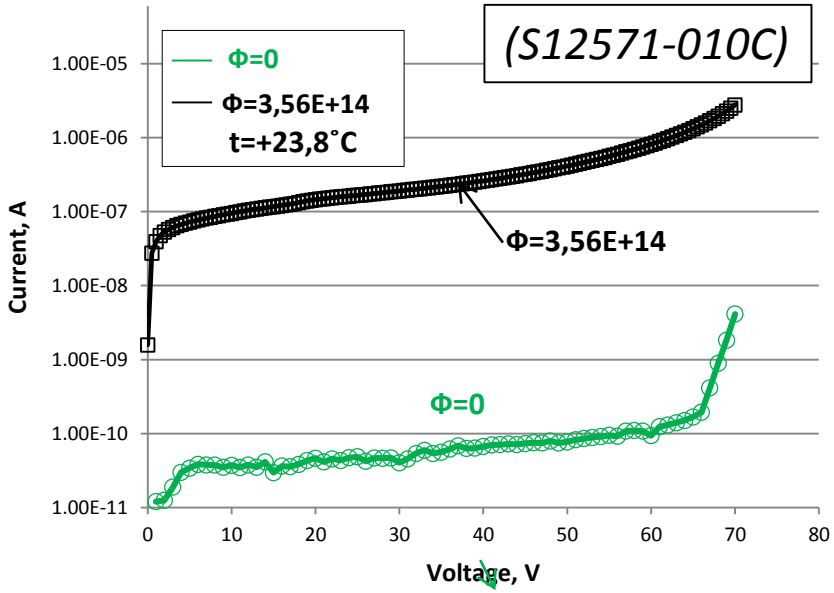
(A)



(B)

Which part of SiPM dedicated of the value dark current?





Dark current SiPM increasing in space-charge region (SCR) at Uop<Ubr (M=1)

$I_d = \alpha \cdot \Phi \cdot V$, where:

α – current constant of damage (5×10^{-17} A/cm, at +20 C, En=1MeV),

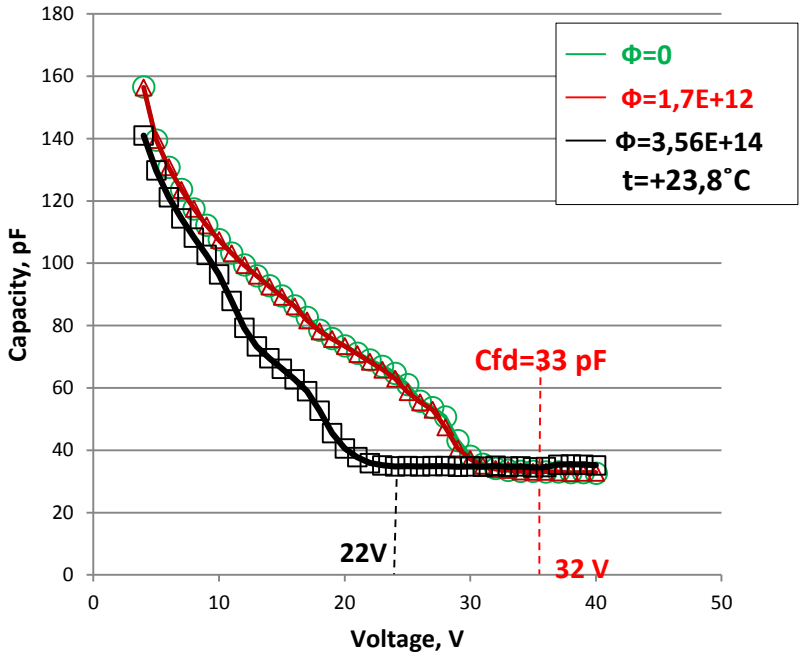
Φ – fluence, V – volume of SCR detectors.

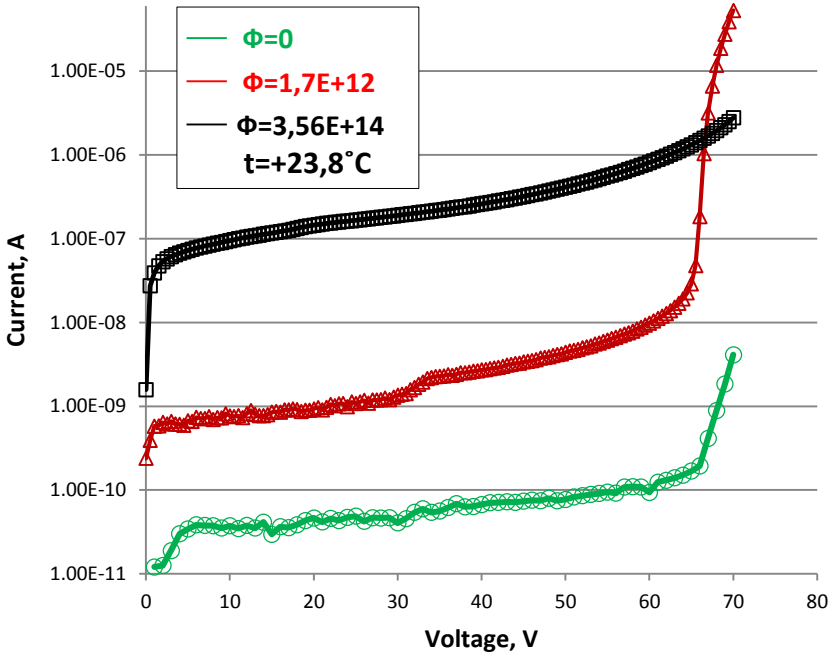
Calculated Id:

$V_{(S12571-010C)} = 3{,}5 \times 10^{-6}\,cm^3$, $\alpha_{(+23{,}8^\circ C)} = 8 \times 10^{-17}\,A/cm$, $\Phi = 3{,}56 \times 10^{14}\,cm^{-2}$ => $Id = 1 \times 10^{-7}\,A$

Radiation damage of SCR for SiPM (S12571-010C)

(high resistivity epitaxial layer of SiPM)





Cfd=33pF/1mm² value of capacitance corresponded to thickness of SCR d= 3,5 mkm and value of pixel capacitance = 33pF:10000 pixel = **3,3fF/pixel**

$$C_{pixel} = \frac{\varepsilon_0 \varepsilon_{Si} \times S_{pixel}}{d}$$

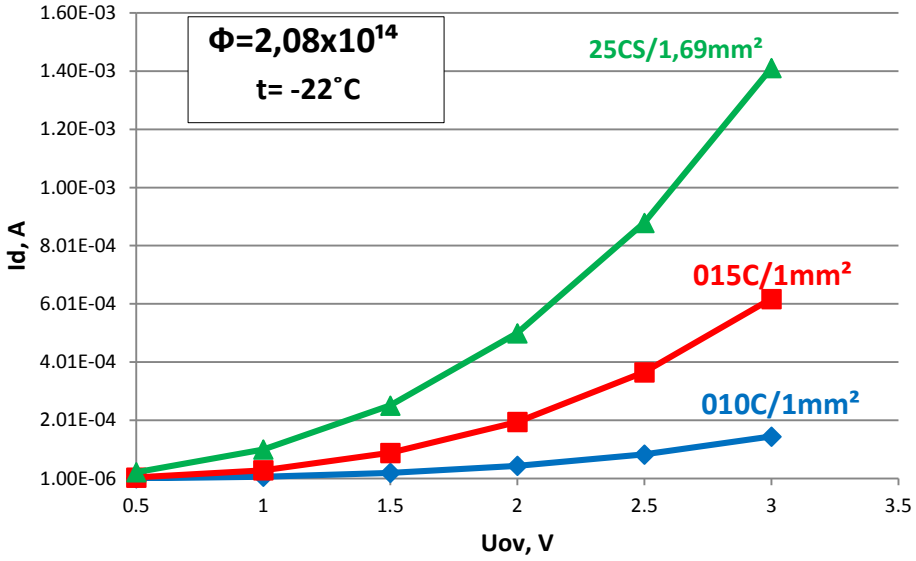
$\varepsilon_0\ \varepsilon_{Si}=10^{-12}$F/cm, $S_{pixel}=10^{-6}$ cm², $d_{pixel}=3{,}5\times10^{-4}$cm

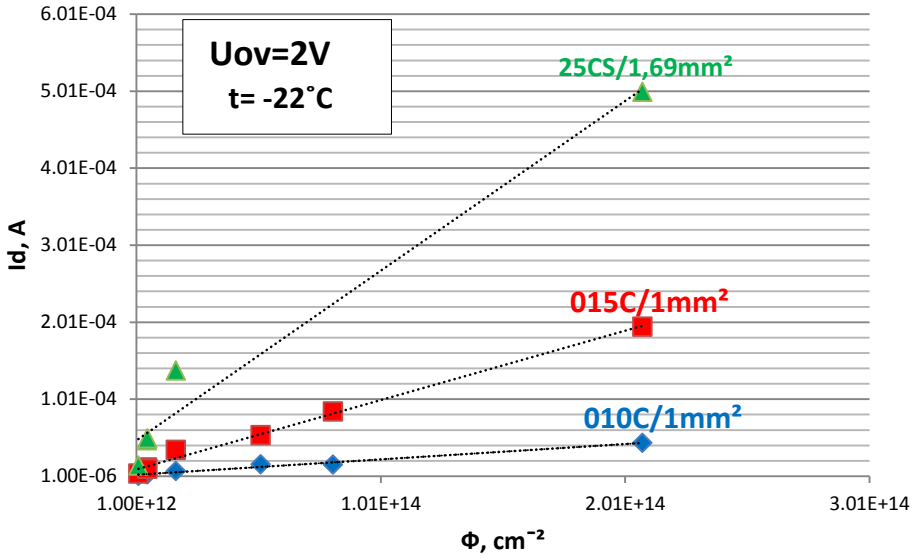
U=40 V		I_2/I_1
I_2, A	1,45E-07	155,52
I_1, A	9,32E-10	

		Φ_2/Φ_1
Φ_2, cm^{-2}	3,56E+14	209,4
Φ_1,cm^{-2}	1,70E+12	

Compare of the damage by fast neutrons for different types SiPM (HPK)

(*S12571-010C, S12571-015C, S13360-1325CS*) vs ***Uov*** and ***Φ*** at t=-22˚C

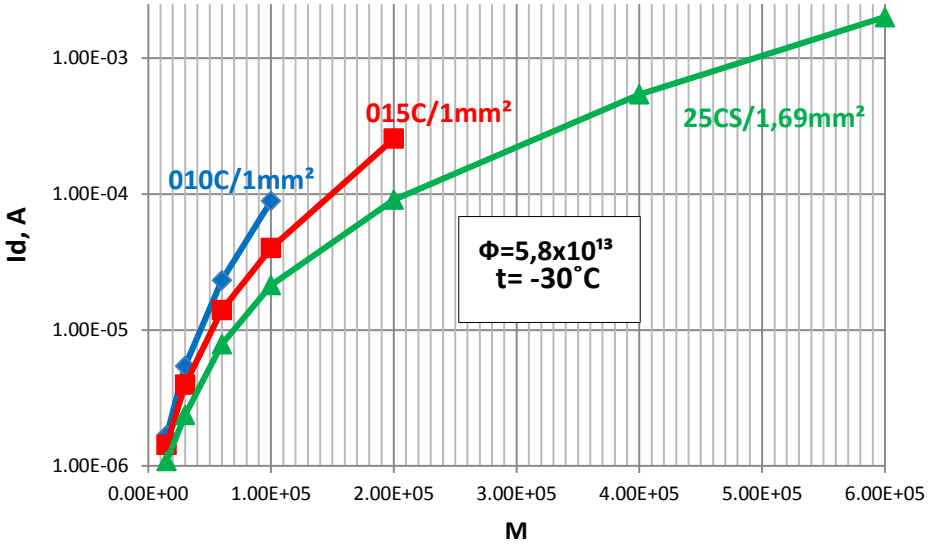


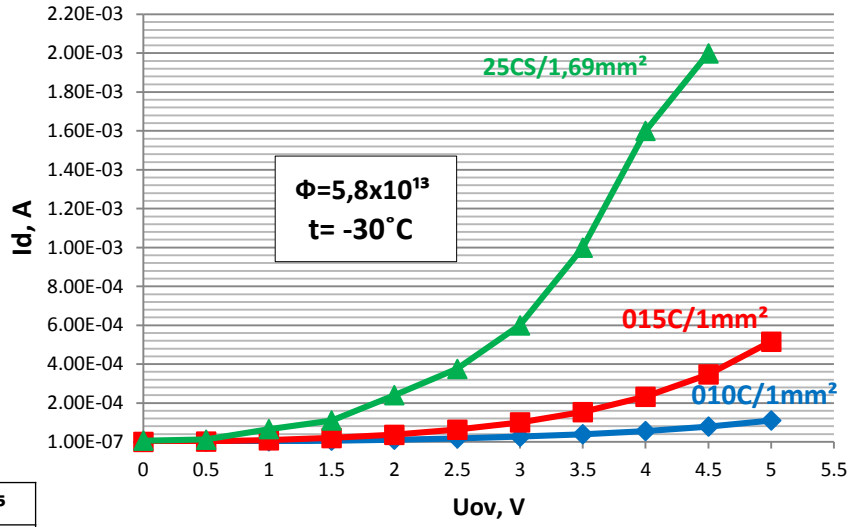


Uov, V	Id(010C), A	Id(015C), A	Id(25CS), A
0,5	1,42E-06	4,32E-06	2,24E-05
1	7,01E-06	2,90E-05	1,00E-04
1,5	2,03E-05	8,87E-05	2,52E-04
2	4,44E-05	1,95E-04	5,00E-04
2,5	8,34E-05	3,66E-04	8,80E-04
3	1,45E-04	6,18E-04	1,41E-03

Uov=2V	010C	015C	CS25
Φ, cm⁻²	Id, A	Id, A	Id, A
1,70x10¹²	1,24E-06	4,50E-06	1,47E-05
5,3x10¹²	3,62E-06	1,20E-05	4,75E-05
5,4x10¹²	3,58E-06	1,06E-05	5,02E-05
1,7x10¹³	7,74E-06	3,50E-05	1,38E-04
5,18x10¹³	1,63E-05	5,40E-05	
8,14x10¹³	1,58E-05	8,50E-05	
2,08x10¹⁴	4,44E-05	1,95E-04	5,00E-04

Compare of the damage after irradiation Φ=5,8x10¹³cm⁻² for different types SiPM vs ***Uov*** and ***M*** at t= -30˚C





M	1,5x10⁴	3x10⁴	6x10⁴	10⁵	2x10⁵	4x10⁵	6x10⁵
Uov,V	0,7	1,41	2,82	4,7			
Uop, V	64,08	64,79	66,2	68,08			
Id(010C)	5,4x10⁻⁶	1,69x10⁻⁶	2,32x10⁻⁵	8,9x10⁻⁵			
Uov,V	0,31	0,62	1,24	2,05	4,11		
Uop, V	62,42	62,73	63,35	64,16	66,22		
Id(015C)	1,4x10⁻⁶	3,96x10⁻⁶	1,4x10⁻⁵	4,01x10⁻⁵	2,5x10⁻⁴		
Uov,V	0,11	0,22	0,44	0,73	1,45	2,91	4,36
Uop, V	49,56	49,67	49,89	50,18	50,9	52,36	53,81
Id(025CS)	1,09x10⁻⁶	2,37x10⁻⁶	7,85x10⁻⁶	2,14x10⁻⁵	9,09x10⁻⁵	5,4x10⁻⁴	2x10⁻³

Uov, V	0	1	2	3	4	5
Uop, V	63,38	64,38	65,38	66,38	67,38	68,38
Id (010C)	2,38x10⁻⁷	3,06x10⁻⁶	1,11x10⁻⁵	2,7x10⁻⁵	5,6x10⁻⁵	1,1x10⁻⁴
Uop, V	62,11	63,11	64,11	65,11	66,11	67,11
Id (015C)	3,3x10⁻⁷	9,01x10⁻⁶	3,7x10⁻⁵	10⁻⁴	2,33x10⁻⁴	5,16x10⁻⁴
Uop, V	49,45	50,45	51,45	52,45	53,45	54,45
Id (25CS)	6,2x10⁻⁶	6,6x10⁻⁵	2,4x10⁻⁴	6x10⁻⁴	1,6x10⁻³	

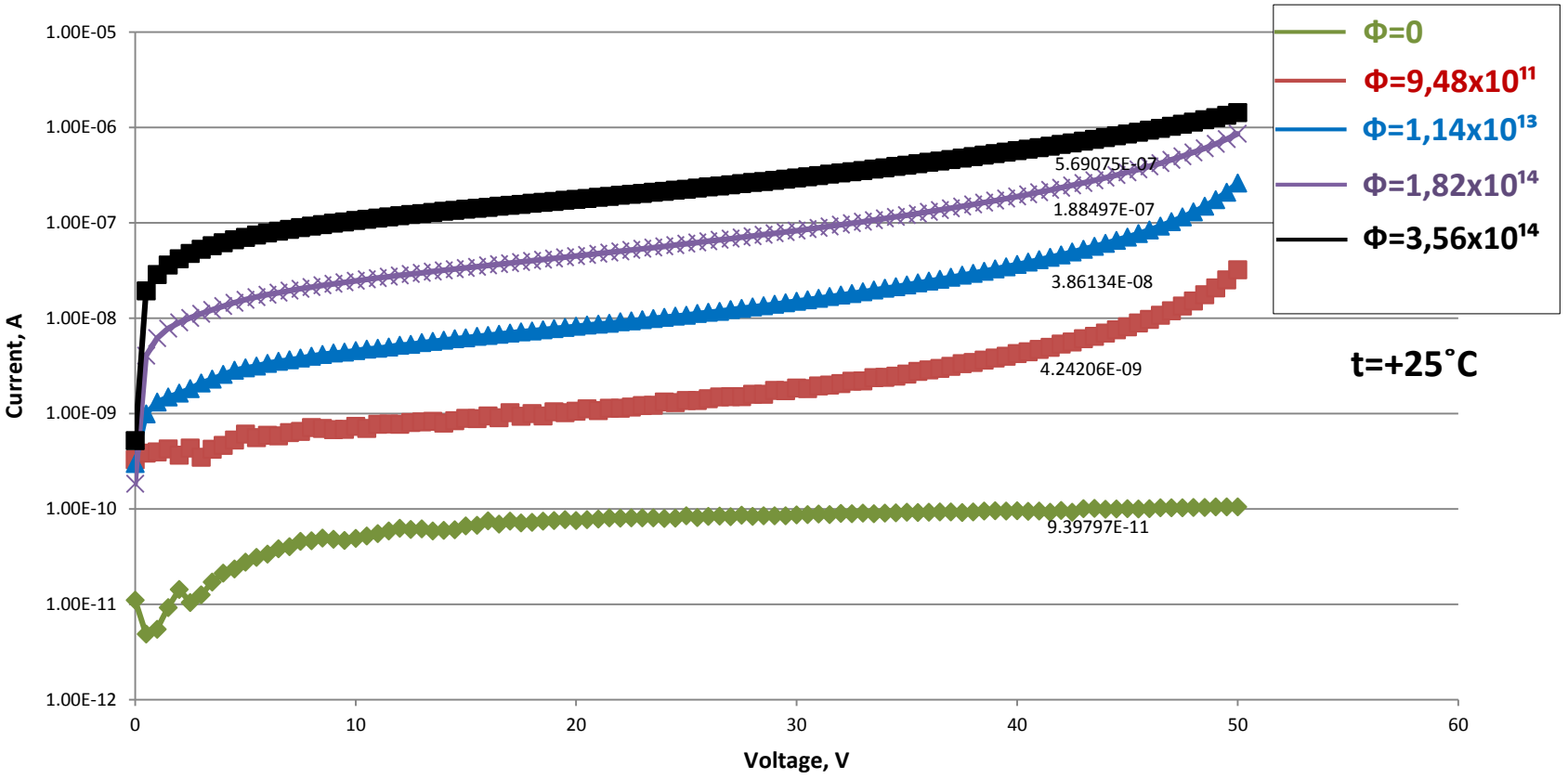
Conclusion

- At irradiation by fast neutrons of silicon always form in crystal volume structural defects
- Radiating defects form in the forbidden zone of silicon energy levels so called “the deep level”
- Thermal current of SiPM at Uop<Ubr (M=1) after irradiation by fast neutrons can be calculated
- Deep levels is source of thermal current in region SCR, which magnification (M>>1) up to high value of dark current at Uop>Ubr (Geiger-mode)
- Radiation hardness of Silicon Photo Multiplier impossible to increase, because α_I - current damage constant independent from type of Si crystals (CzSi, CzMSi, FZ-Si, Epi-Si).
- Dark current of pixel can be decrease only decrease thickness of SCR *(decrease PDE)* and decrease area of pixel *(decrease M)*
- Research and development of semiconductors of PM on crystals with bigger value forbidden gap (ΔE= 5.5÷1.46 eV - SiC, C, GaAs, CdTe et all) can be increase radiation hardness in compare with Si

Back up

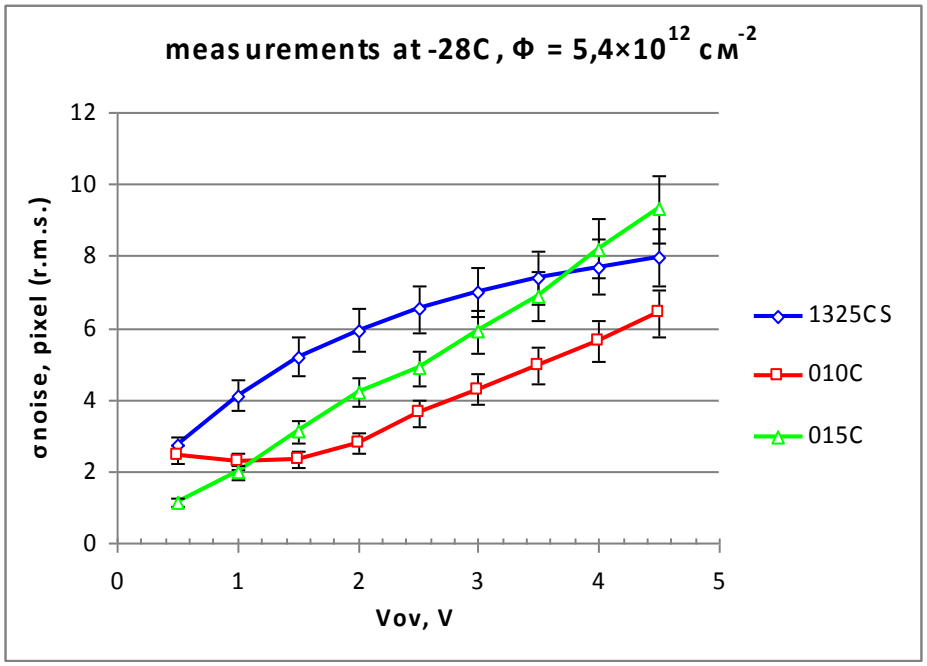
Dark current SiPM (S13360-1325CS) at four point fluence

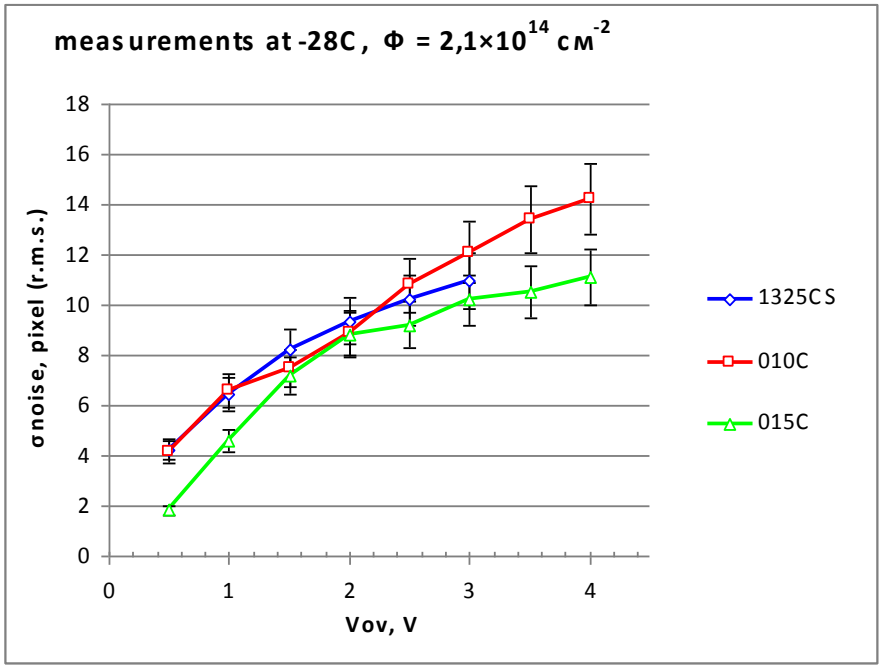
t=+25˚C



Noise *(r.m.s. pixel)* **vs Vov for irradiated SiPMs** *(three types)* **at -28°**

σ,(r.m.s. *pixel*) **= (σ,**(r.m.s. *ch.ADC*)**×1ch.ADC,**(*e/ch.ADC*)**)/M,**(*e*/r.m.s.*pixel*)

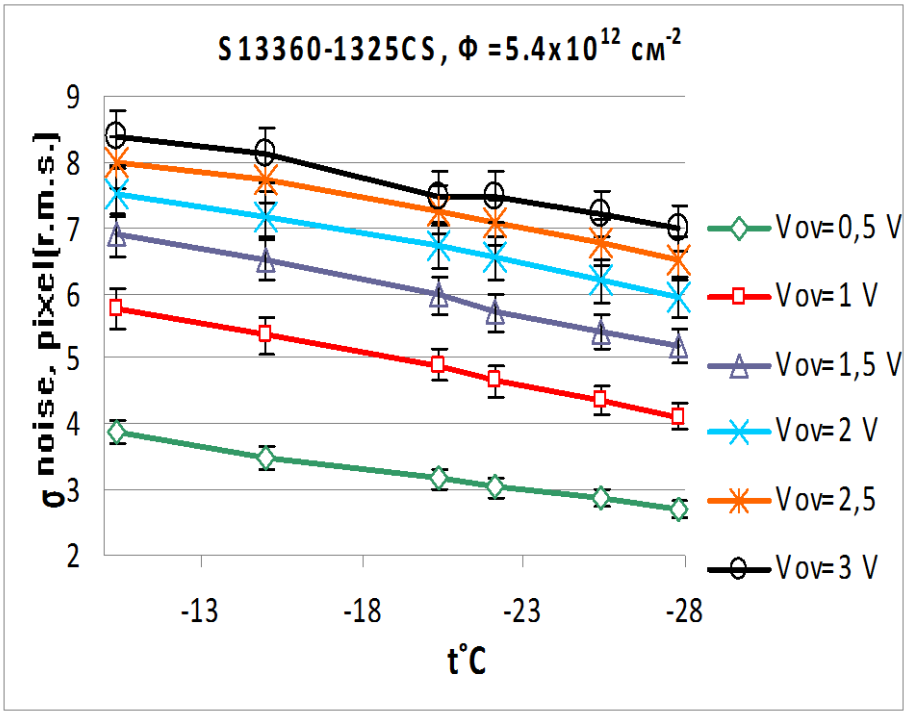


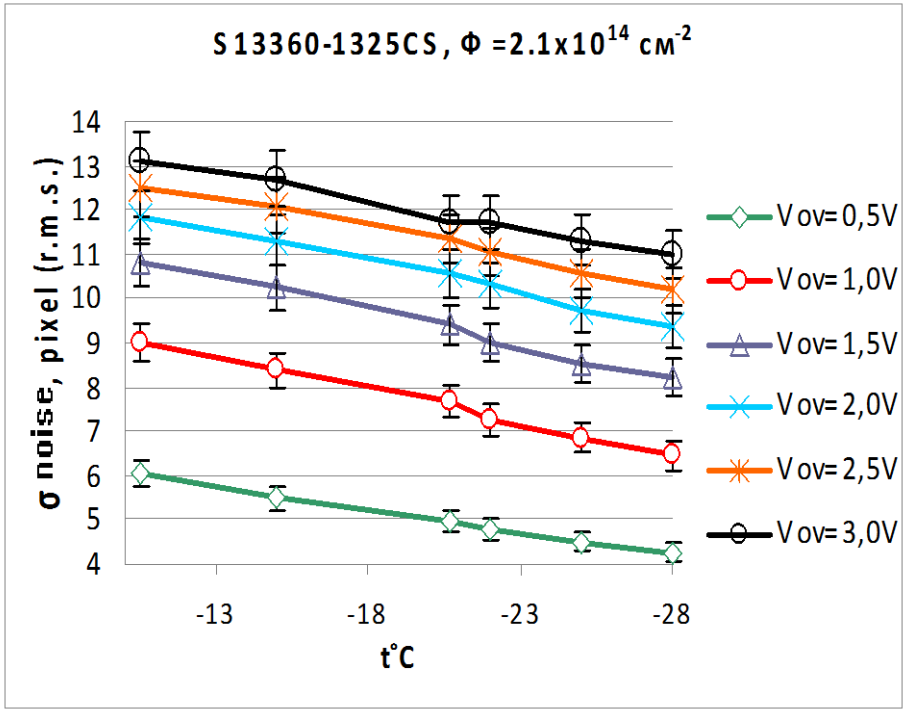


(A) – Φ=5,4×10^{12}см$^{-2}$

(B) – Φ=2,1×10^{14}см$^{-2}$

Noise SiPM *(type S13360-1325CS)* vs temperature at different value V*ov* after irradiation

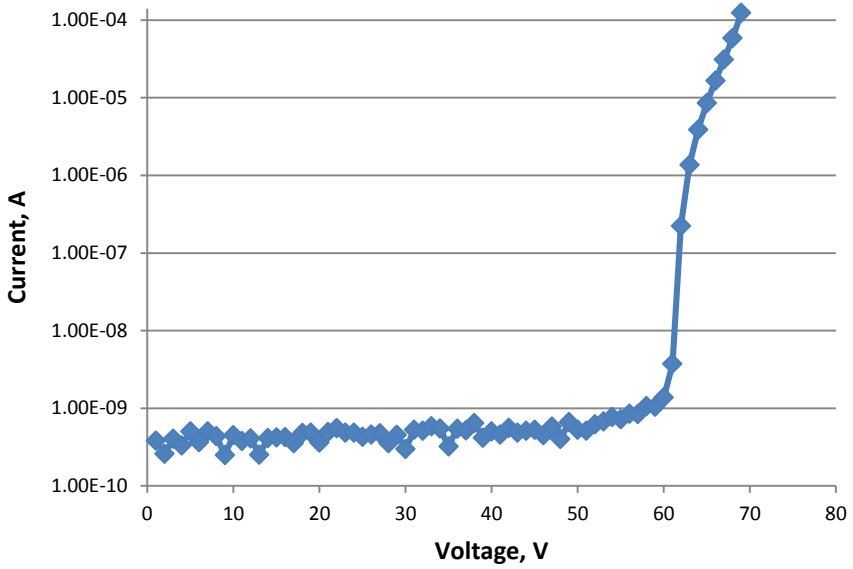




(A) - 5,4×10^{12} cm^{-2}

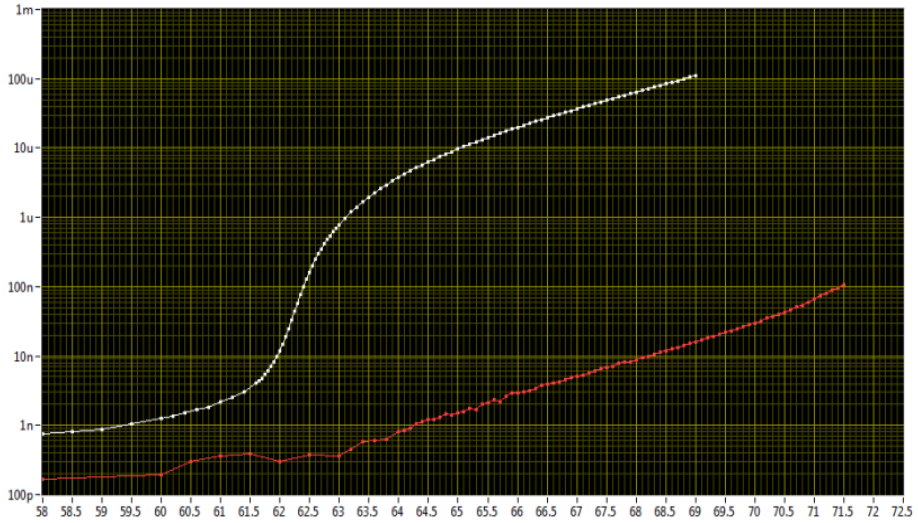
(B) - 2,1×10^{14} cm^{-2}

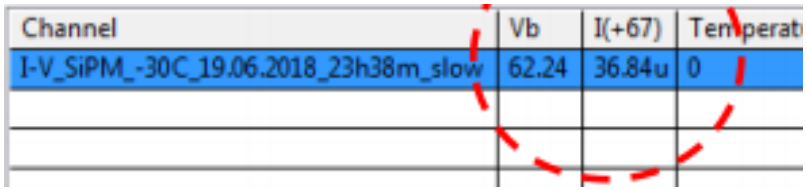
Dark current SiPM (S12571-015C) at the same value of fluence irradiation and measurements in JINR and CERN



SiPM type S12571-015C after irradiation (IBR-2, JINR)
Φ=1,7*10¹², measure at t=-30˚C

Id=31 мА, Uop=67 V, (Uov=4,76 V), t=-30˚C





Y. Musienko, CERN, 2018

Id=36,84 мА, Uop=67 V, (Uov=4,76 V), t=-30˚C