SiPM characteristics after very high Radiation at low Temperature for the SLHC CMS PHASE II upgrade

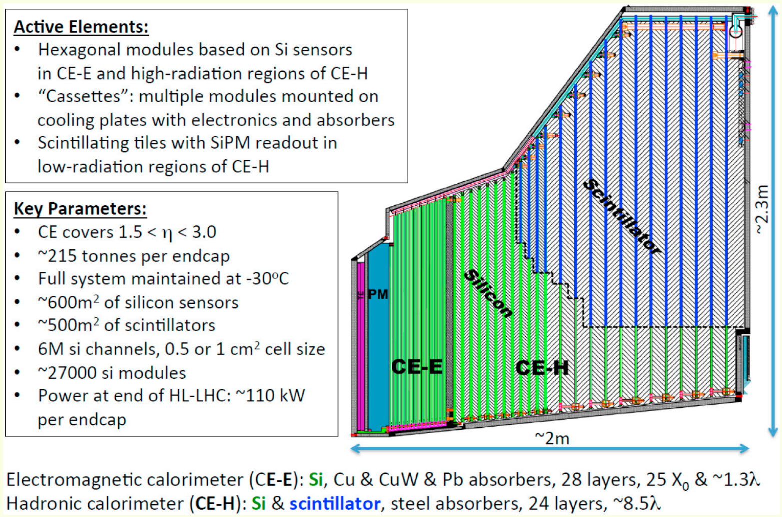
A. Heering, Y. Musienko * , M. Wayne (Notre Dame)
A. Karneyeu, Yu. Andreev (INR Moscow)

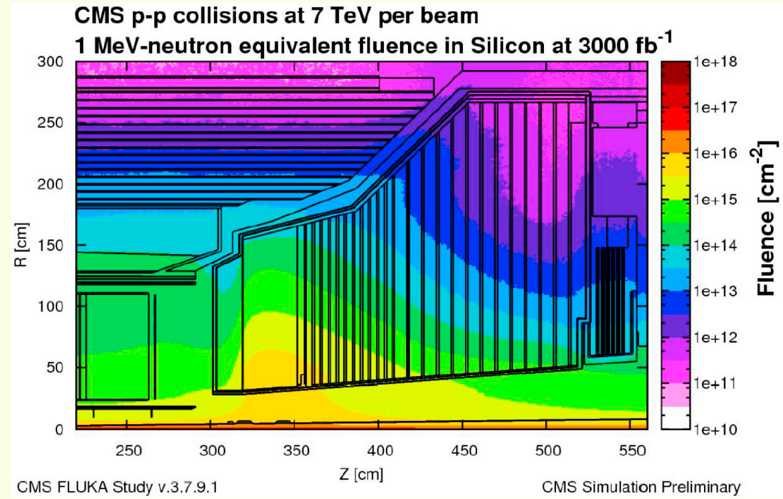
* On leave from INR(Moscow)

Outline

- 2 future CMS sub detectors which are planning on using SiPMs
- General experience from last > 10 years of R&D on raddam on SiPMs
- Results of latest Wafer run with FBK on thin epitaxial layer substrate
- Main effects of raddam at very high doses > 5E13 n/cm2 1 Mev eq

CMS - CEH EndCap for Phase II

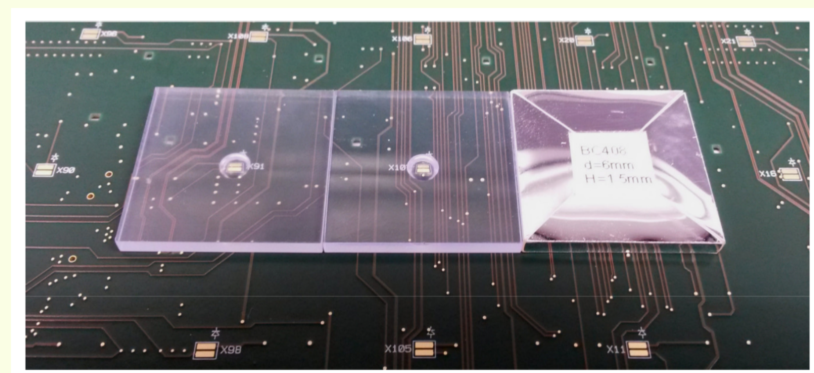




1 Mev eq Neutron fluence up to 8E13 n/cm2

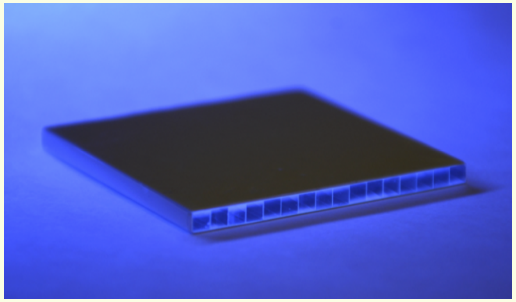
We expect a signal of ~ 40 p.e/MIP

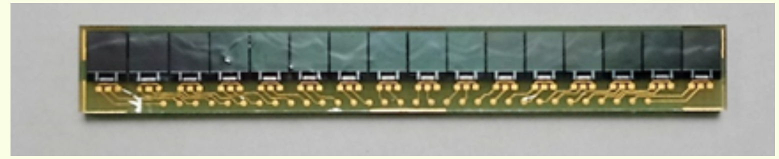
Signal to Noise is very important for calibration



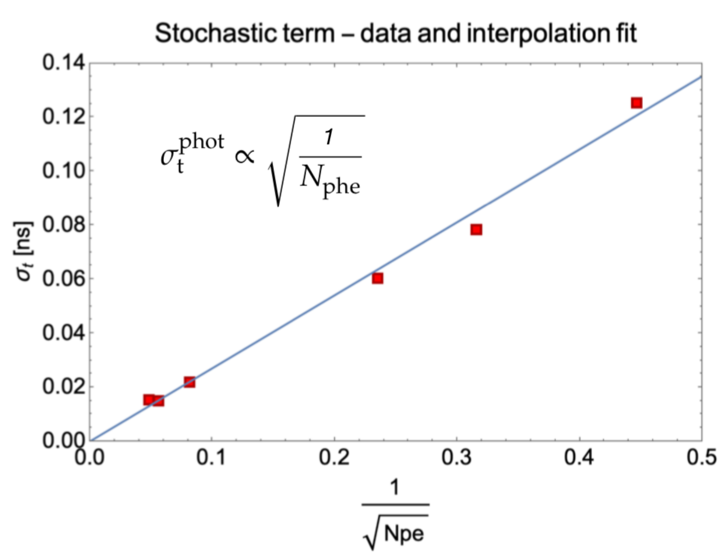
SiPM-on-Tile in the biggest part of CE for high granularity to compliment CE-E

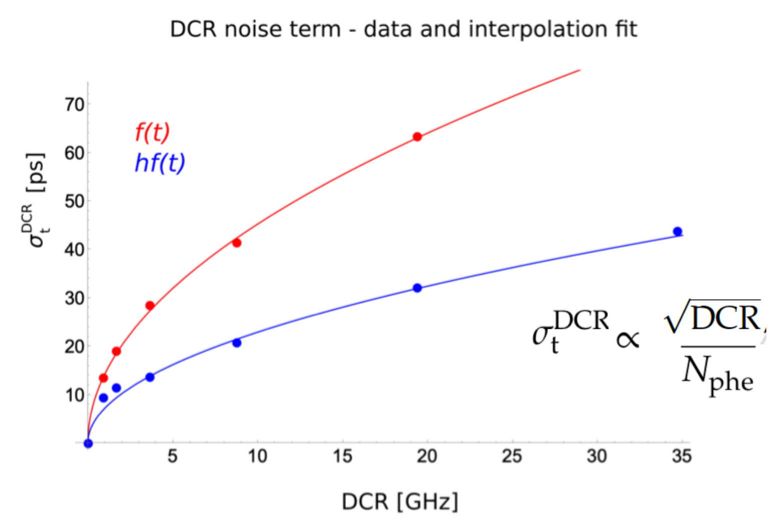
CMS - Barrel Timing Layer for Phase II





SiPM array to readout LYSO array (2 sides)



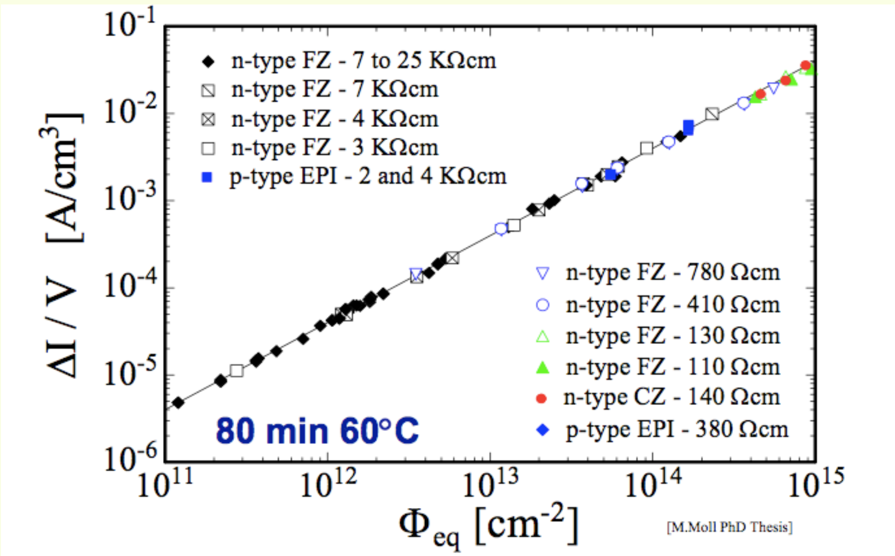


Bench measurement of the timing dependance of the N_{phe} and DCR using an LED with a pulse of 390 p.e. and time spread of 350 ps rms.
At 2E14 n/cm2 eq. the DCR is expected to rise to 40-60 GHz even at an operating temperature inside the tracker tube of -30C. The DCR noise term will quickly be the dominating factor in the timing resolution.

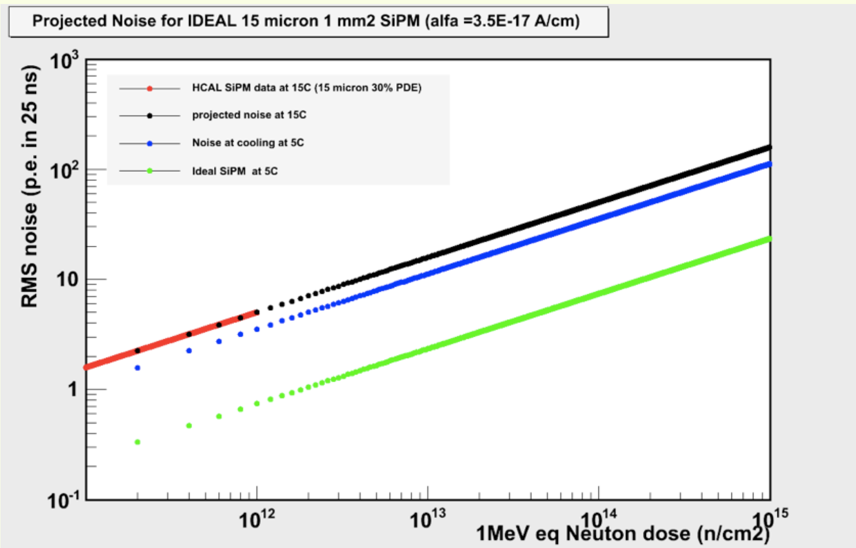
DCR or Noise increase in SiPMs due to rad

Leakage current increase in Si-PIN diodes
for 1 MeV equivalent dose

slope= 3.5E-17 A/cm



Measurements show ~4X more noise

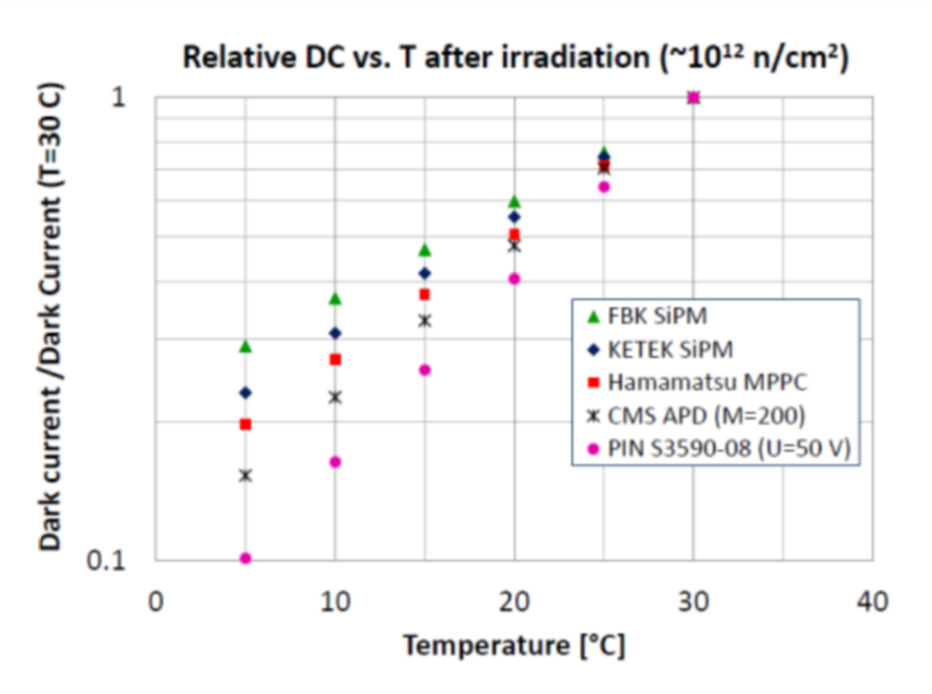


We expect the dark count rate:
Dark Count = 1/q * V * Φ * slope * G.F. * $P_{(V)}$

V= cell size * d_{epi} (few microns in case of SiPM)

The dark noise generation rate in APDs/ SiPMs is dominated by high electric field effects mainly by tunneling via radiation-induced defects or traps in Si

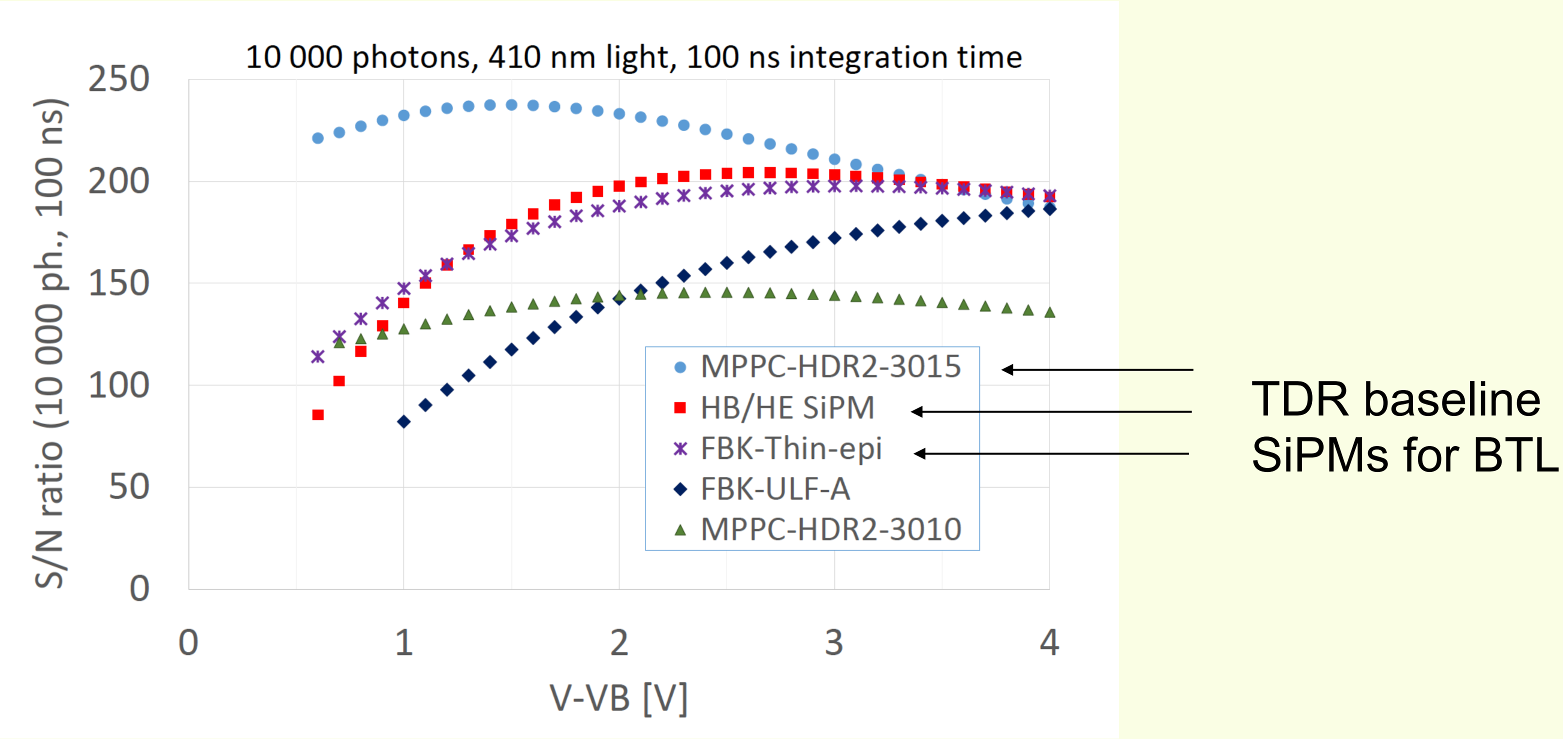
Efield Tunneling effects vs Temp and irrad



Before Irradiation:
Primary dark count rate is due to the thermal generation of carriers; 1/T (reduction of 2.4 x every 10C)

After irradiation we find that temperature reduction coefficient drops to as low as 1.6 / 10C depending on the internal electric field structure of the SiPM
General trend is that SiPMs with higher Vbr have larger reduction with T

2018 HPK and FBK SiPMs after 2.1E14 n/cm²



In 2018 we chose the best 3 SiPMs with the best performance vs irradiation for the BTL as a TDR baseline. All cell sizes are 15x15 micron to avoid saturation due to high DCR. This also reduces the recovery time

FBK wafer split for optimization

Wafer n.	Substrate	Technology	DI dose	Meas Vbr (RT)
1	Thin Epi	Low Field	1	
2	Thin Epi	Low Field	1	38.0
3	Thin Epi	Low Field	2	
4	Thin Epi	Low Field	2	35.2
5	Thin Epi	Low Field	2	
6	Thin Epi	Low Field	3	
7	Thin Epi	Low Field	3	33.0
8	Thin Epi	Low Field	4	
9	Thin Epi	Low Field	4	32.0
10	Thin Epi	Low Field	4	

DI dose

} smaller

} TDR Thin epi

} larger

} largest

In addition each wafer has 2 different micro cell versions
one aggressive for better FF

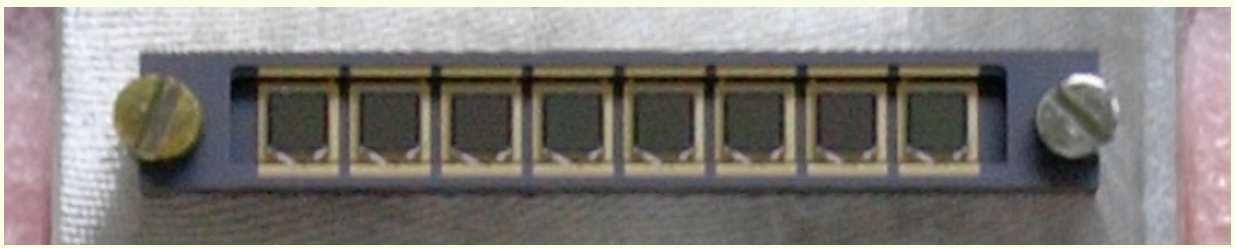
15 micron STD : 51.2 %
15 micron HFF : 60.1 %

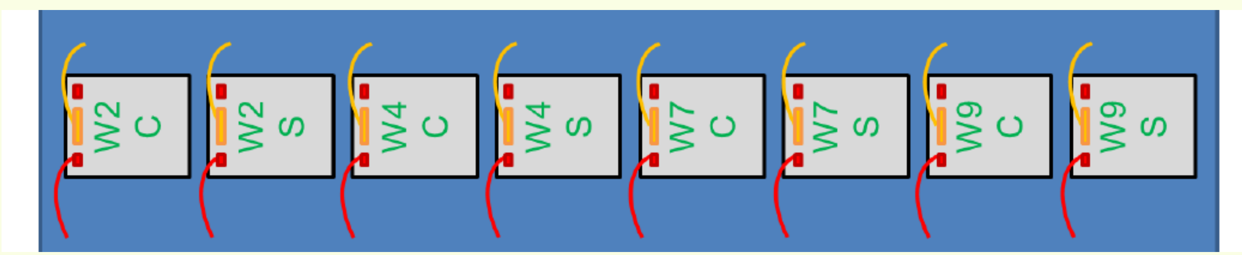
Irradiation in ceramic Package of the wafers

We packaged the 8 different Types in a 8ch ceramic package

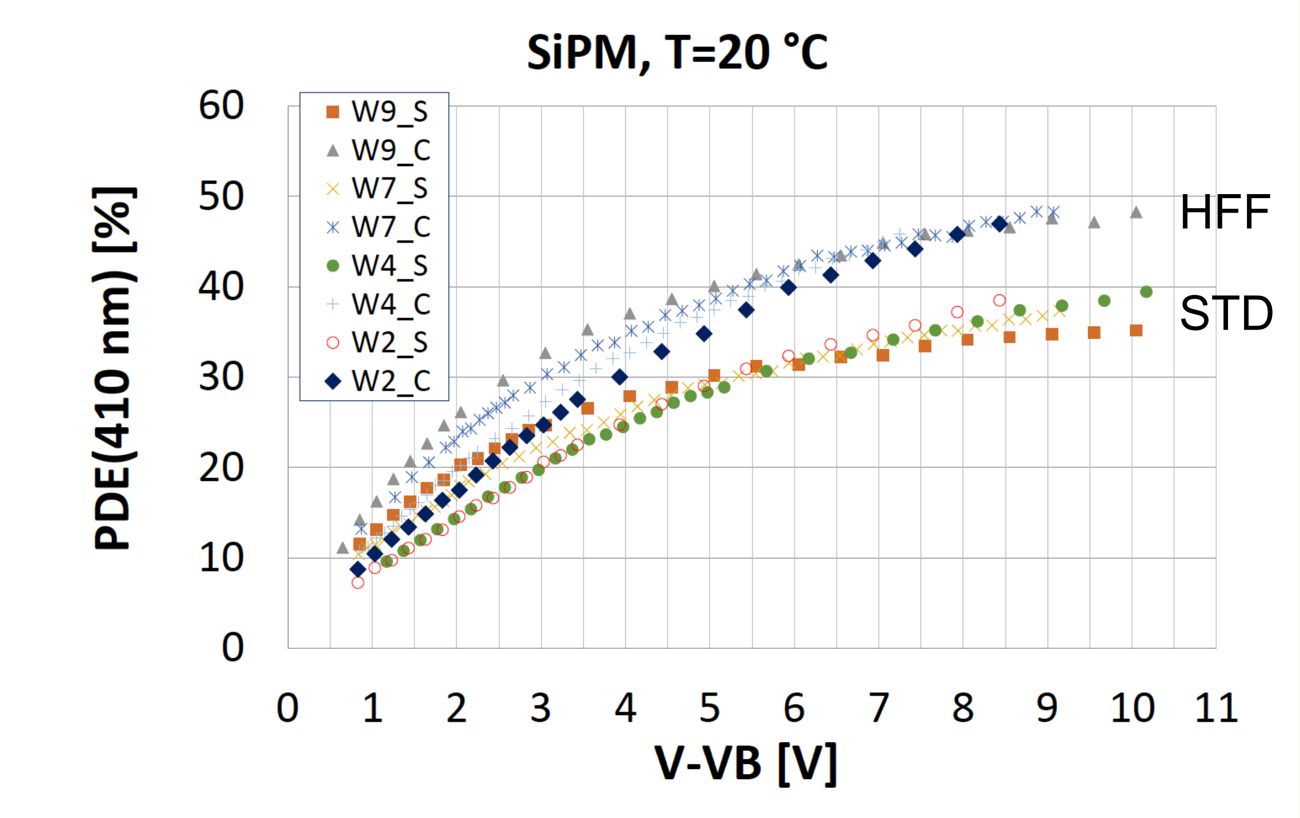
3 of these arrays were sent to JSI for passive irradiation
for a total dose of 1E13, 2E14 and 4E14

For direct comparison we also included 3 HPK 3x3 mm HDR2 for each dose



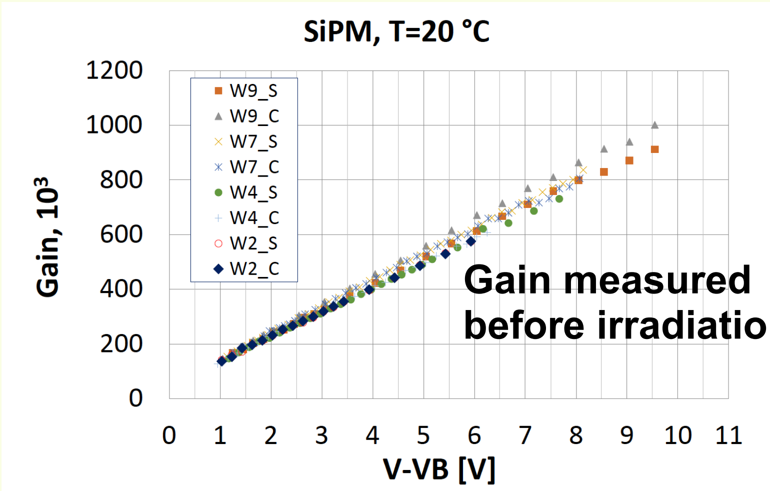


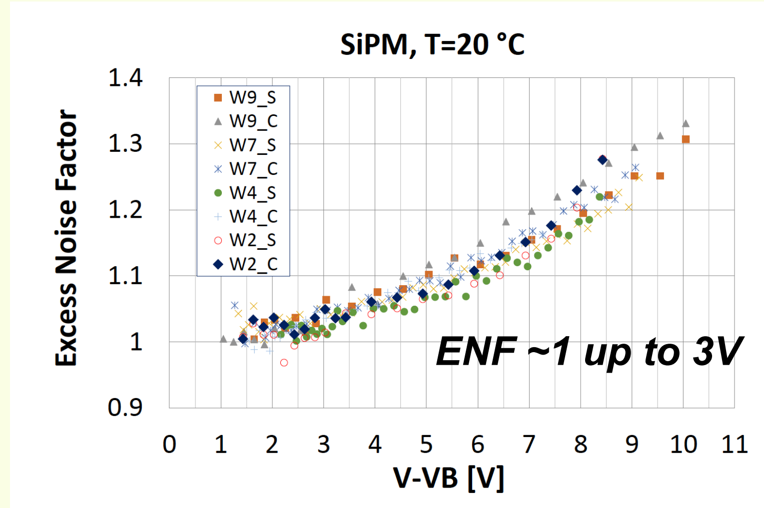
Measured PDE before irradiation



Average number of photons in LED pulse is measured using XP2020 calibrated: PMT (QE(410 nm)=25.0 %, ENF=1.15), and waveforms recorded by DSO

Approach of measurement of irradiated SiPM



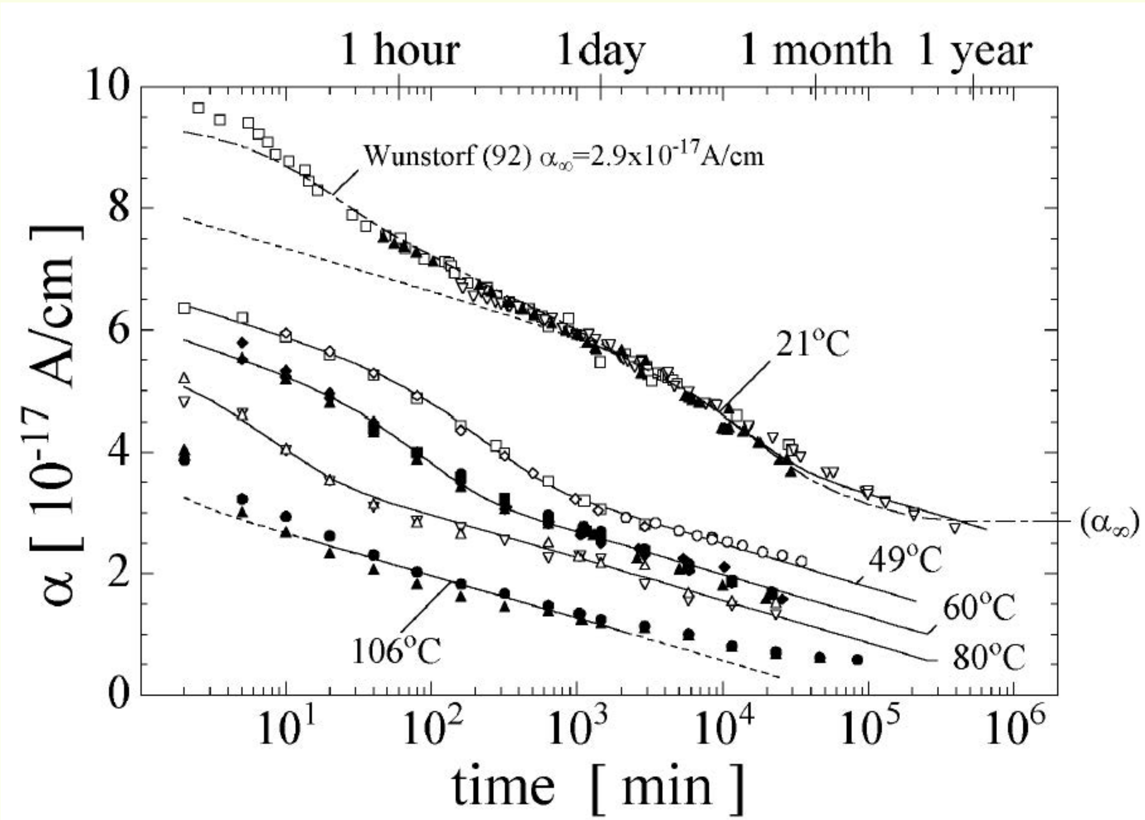


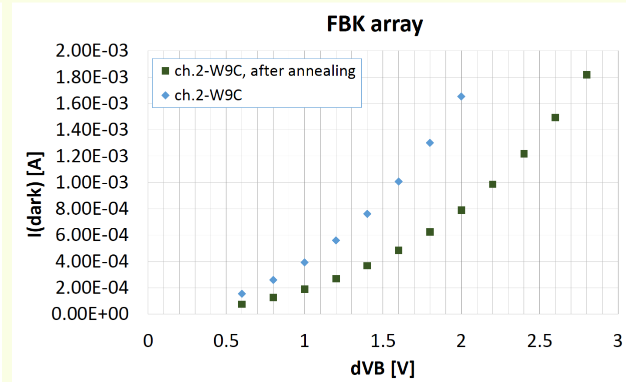
To measure S/N after irradiation we use constant light illumination from 405 nm LED source (calibrated uniform over the 8ch):

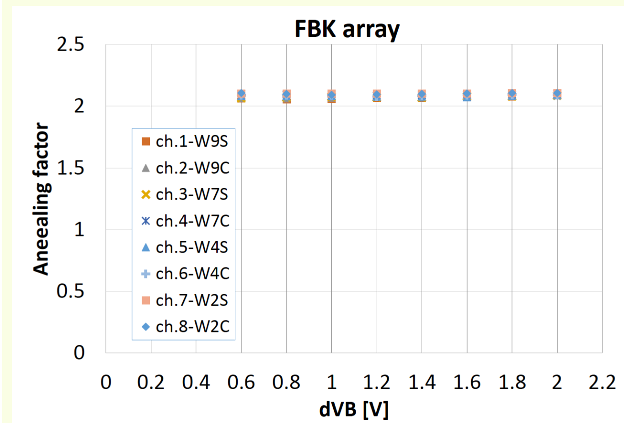
I (total) = I(ph) + I(dark) =(I'ph + I'dark)* Gain*ENF with ENF ~1
I'ph and I'dark are the primary generated currents (before amplification)
I(total) and I(dark) are measured simultaneously (LED On and LED off)

Phcurrent= I'ph/1.6E-19
DCR = I'dark/1.6E-19
S/N = Phcurrent/DCR

Silicon Annealing vs temperature



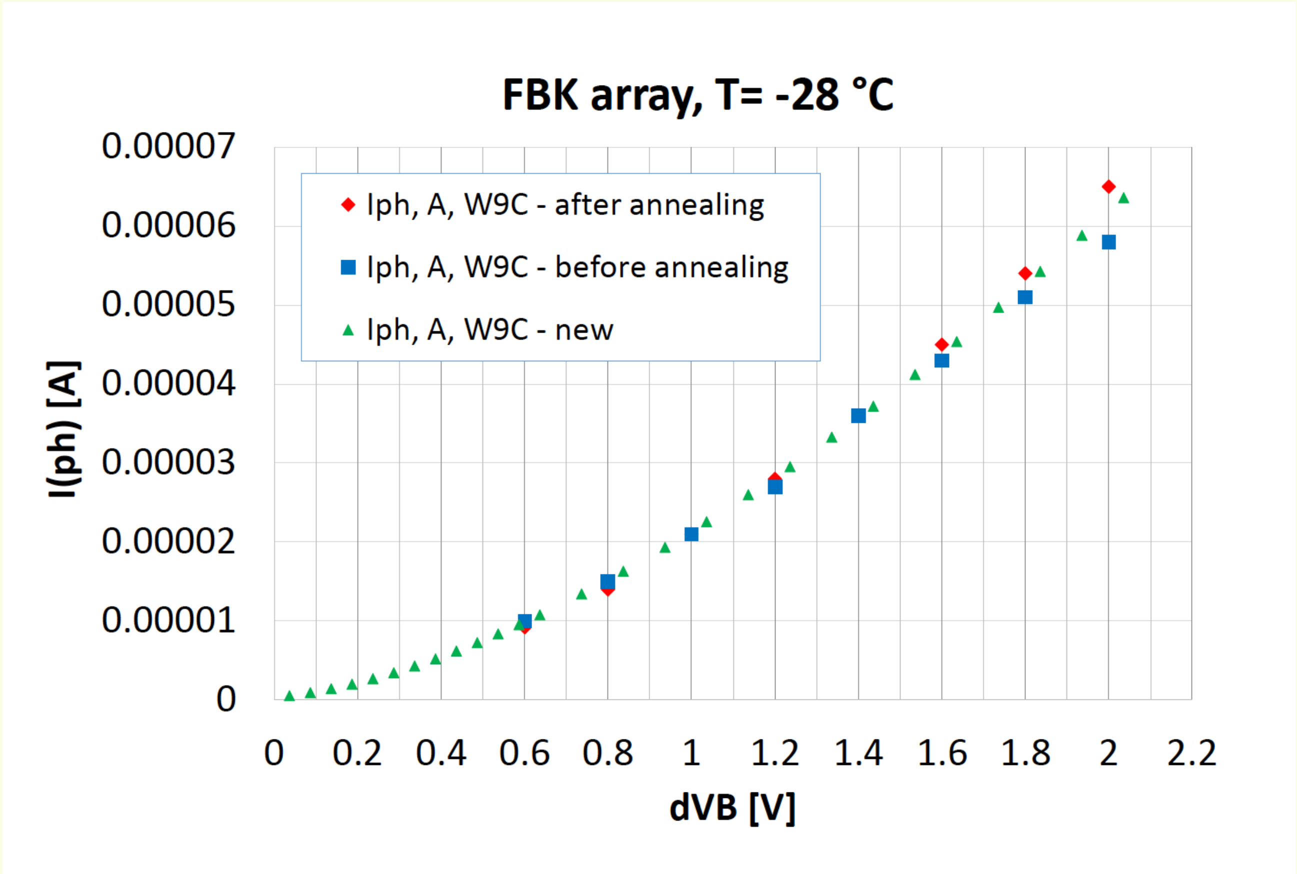




- We use 60C for 80 min to simulate RT annealing

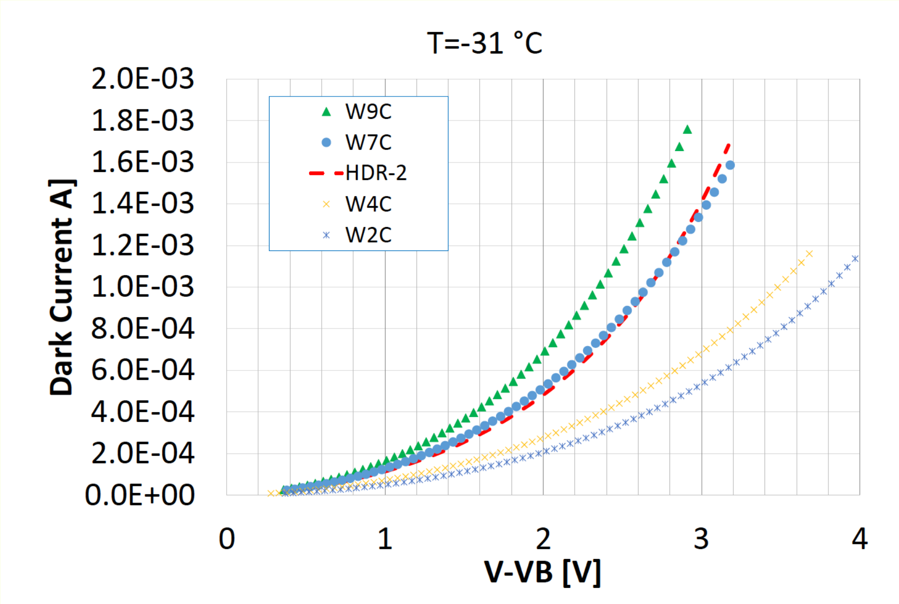
I(ph) measured before and after irradiation

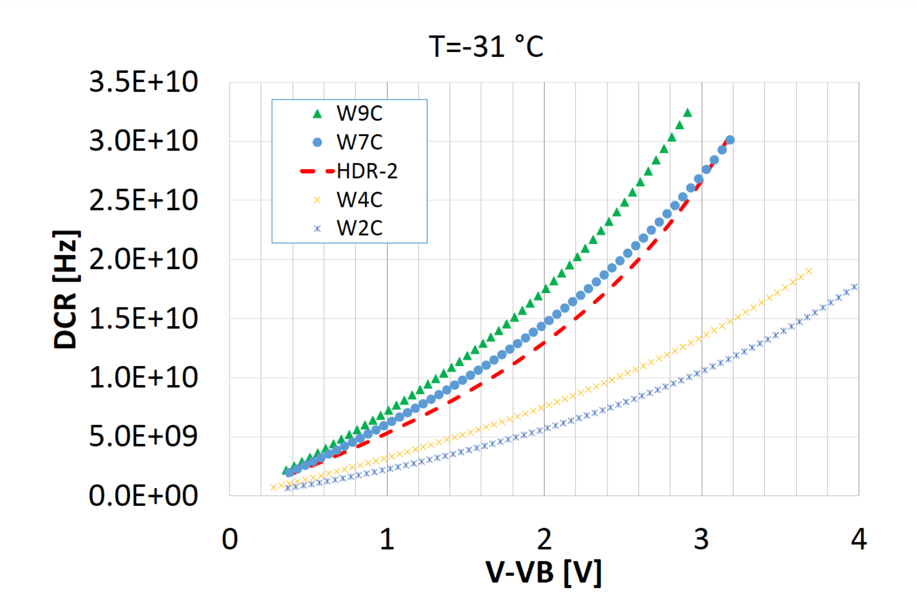
Dose = 1.4E13 n/cm eq.



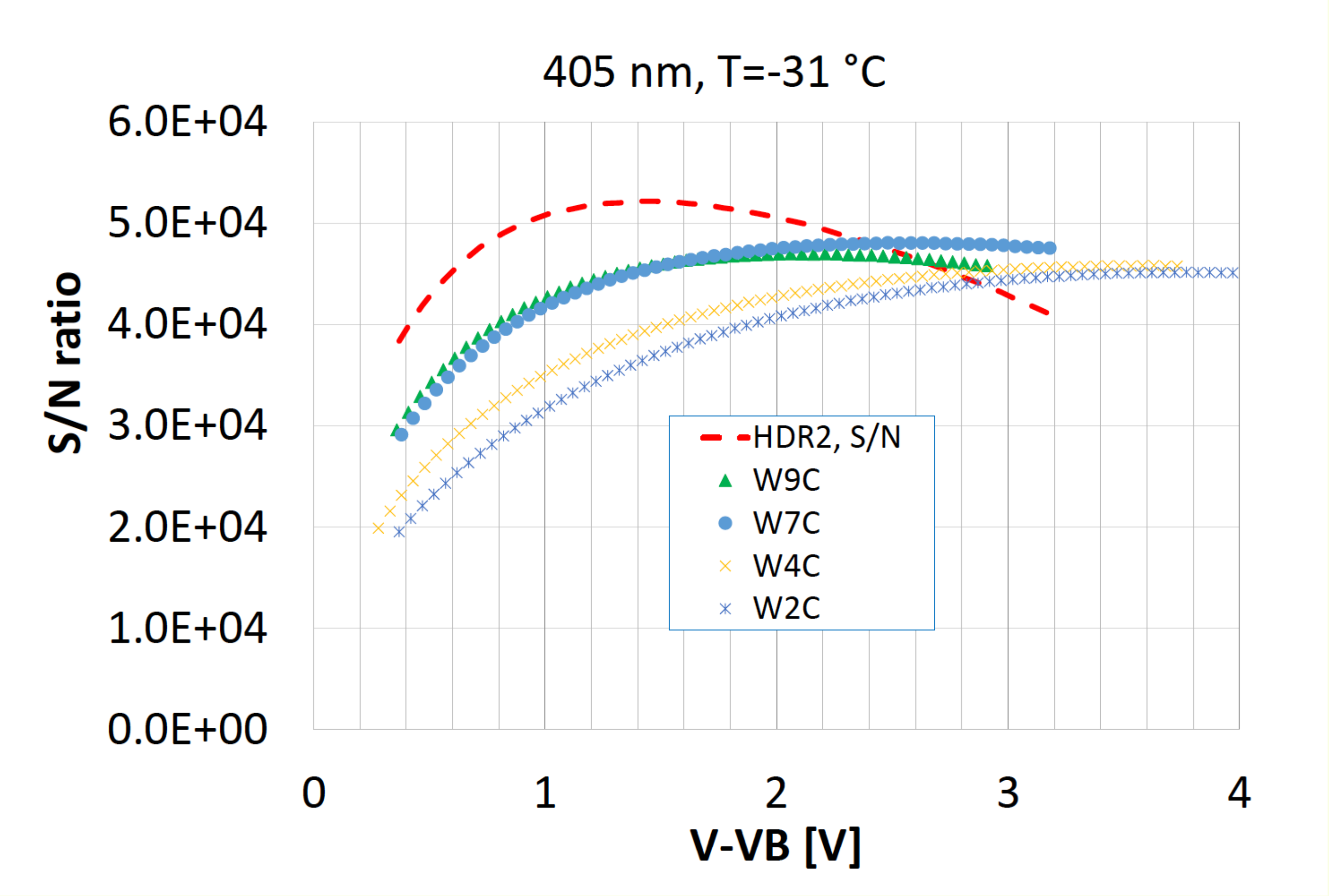
I(ph) is unchanged after irradiation and annealing:
Hence PDE,Gain and ENF are unchanged at this dose

DCR after irradiation of 1.4E13 n/cm²





Currents reach 2 mA at 3V over voltage
which starts to cause self heating of the SiPM



405 nm, T=-31 °C
S/N ratio
6.0E+04
5.0E+04
4.0E+04
3.0E+04
2.0E+04
1.0E+04
0.0E+00
0
1
2
3
4
V-VB [V]
HDR2, S/N
W9C
W7C
W4C
W2C

Previously measured Vbr shift with rad

Using the CERN IRRAD 24 GeV proton beam we irradiated a 8 ch Array with 10 micron HPK S12572 SiPMs

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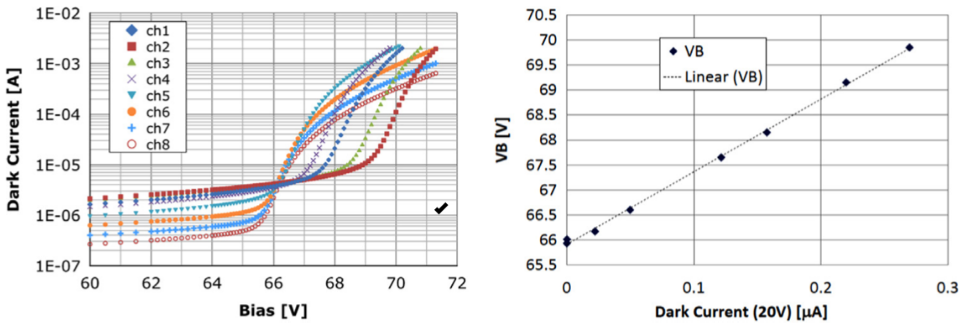


Fig. 3. 10 μm cell HPK 8 channel array with ø 2.8 mm SiPMs with a maximum dose of 2.2×10^{14} n/cm^2 in channel 2. (a) Dark current vs. bias voltage. (b) Bias voltage shift vs. dark current at gain 1.

5x5 mm2

Beam, p

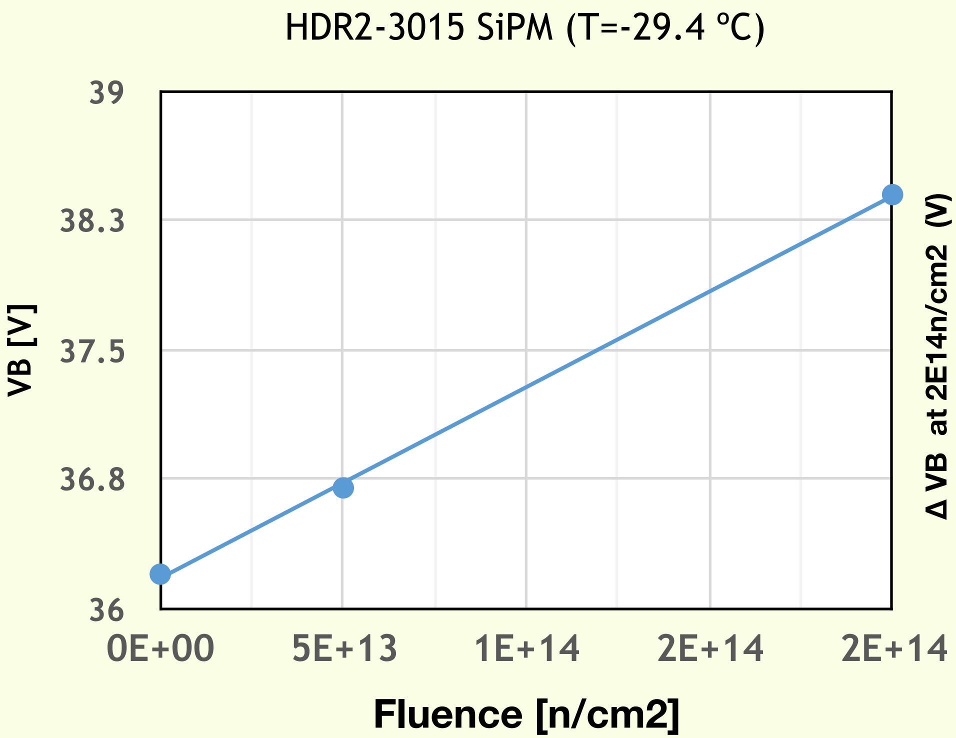
Ch.2 – irradiated with 24 GeV protons (~2.2E14 n/cm^2)

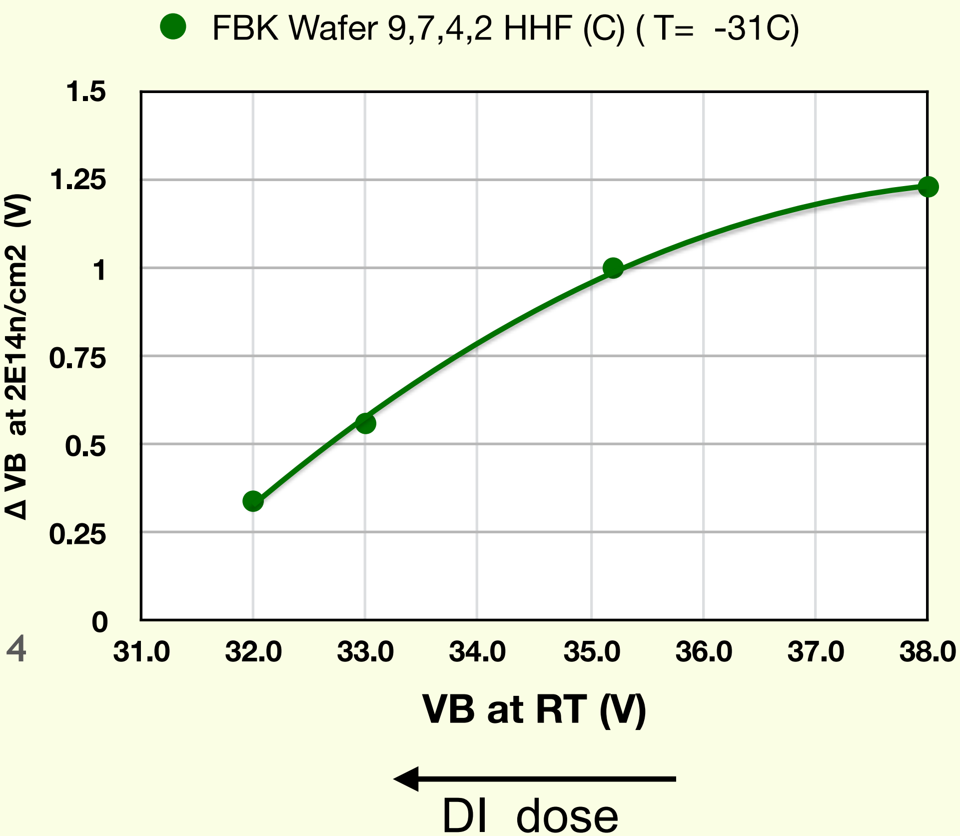
Ch.8 – irradiated with 24 GeV protons (~7.5E12 n/cm^2)

Due to Change of the doping concentration:
VB shift with fluence reaches 4 V at 2.2E14 n/cm2

Vbr = 66 V at zero dose

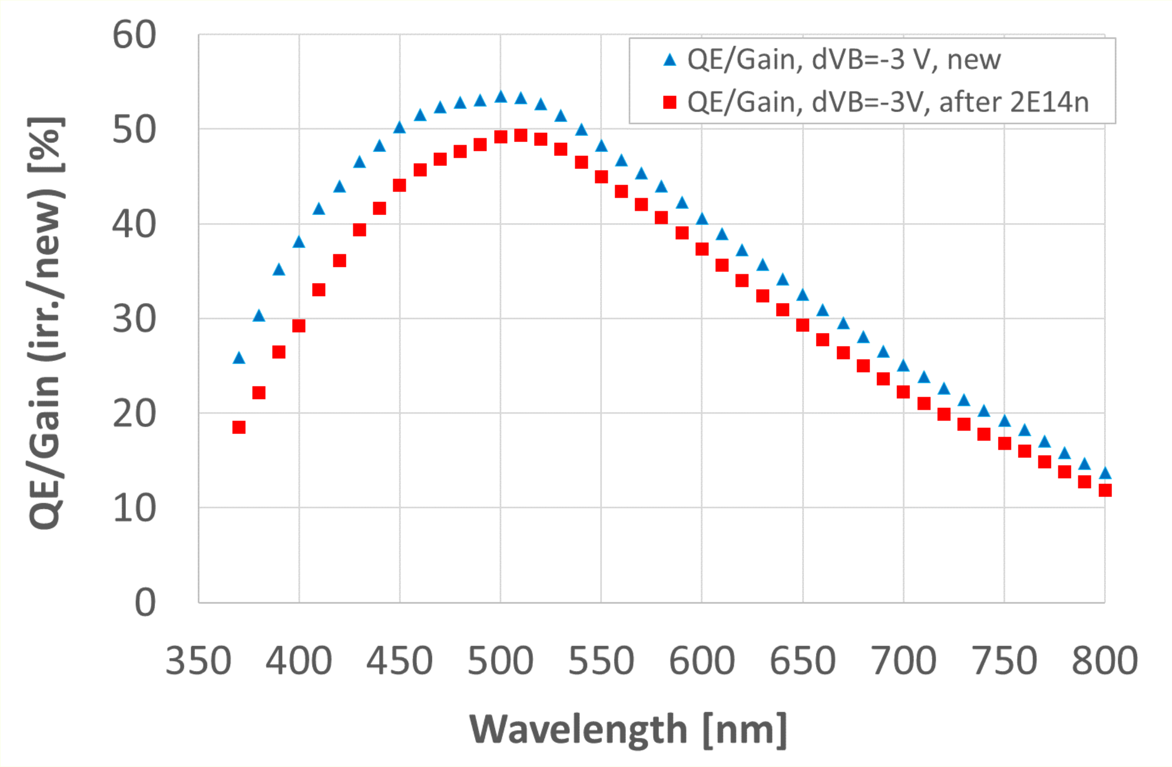
Measured Breakdown voltage shift at 2E14





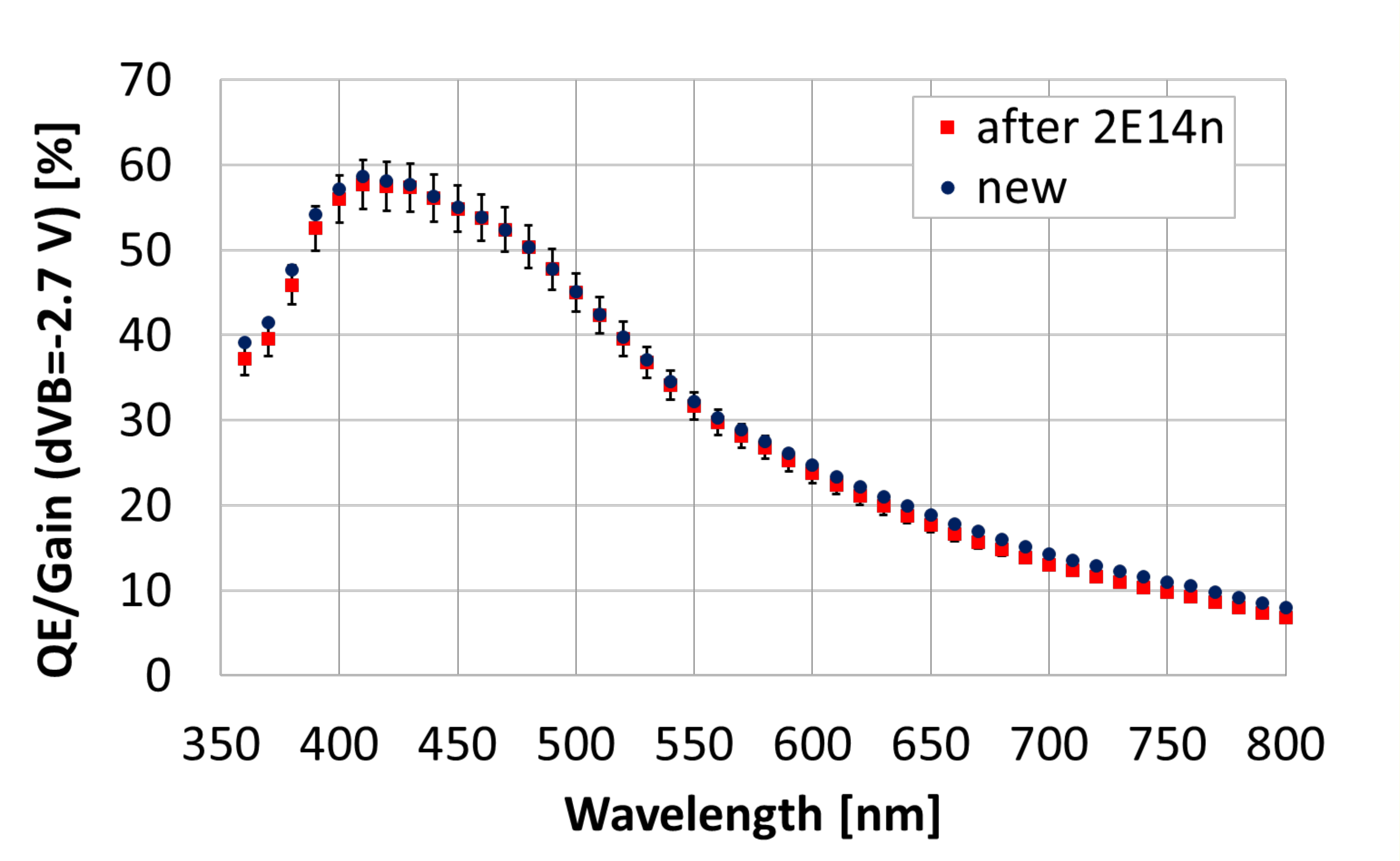
HPK HDR2 after 2E14

Other EFFECT we found at 2E14 is QE loss



This could be a combination of ; Recombination of e-h in top p+ layer and Browning of protective resin used (under investigation)

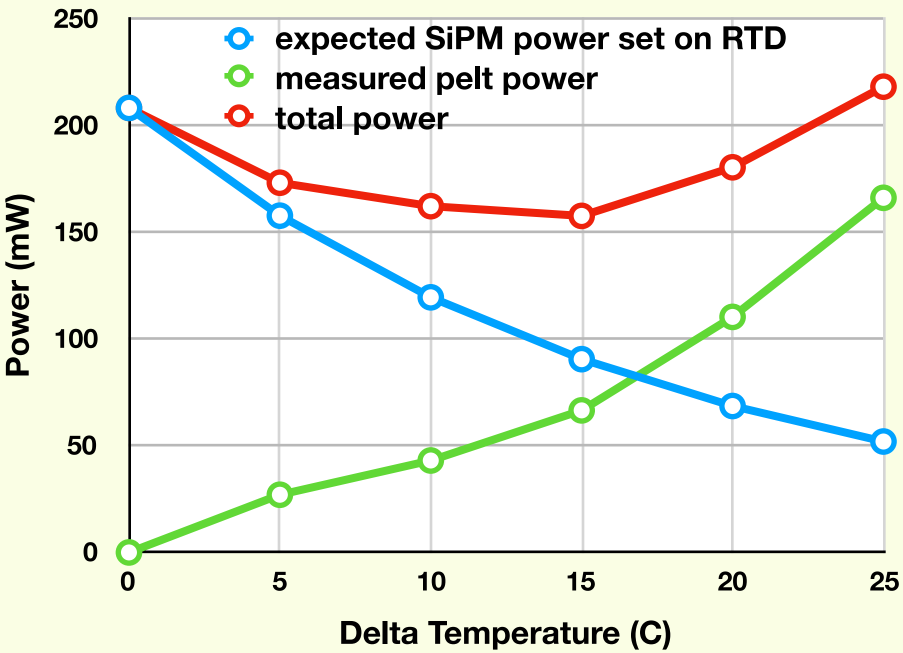
FBK thin epi after 2E14



FBK with thinner top p+ layer

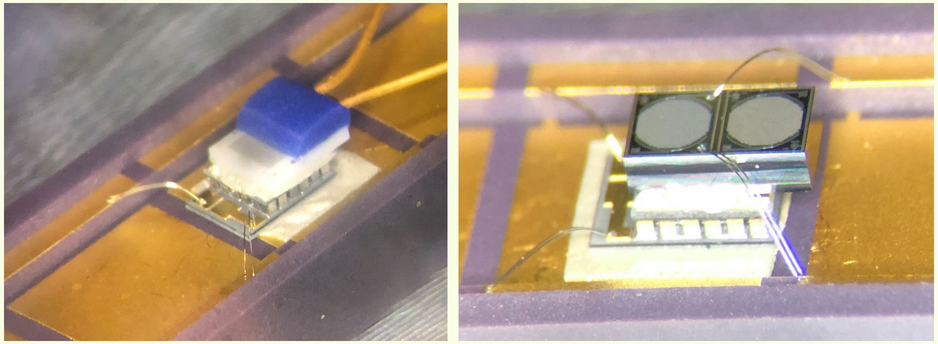
R&D on the use of mini peltiers

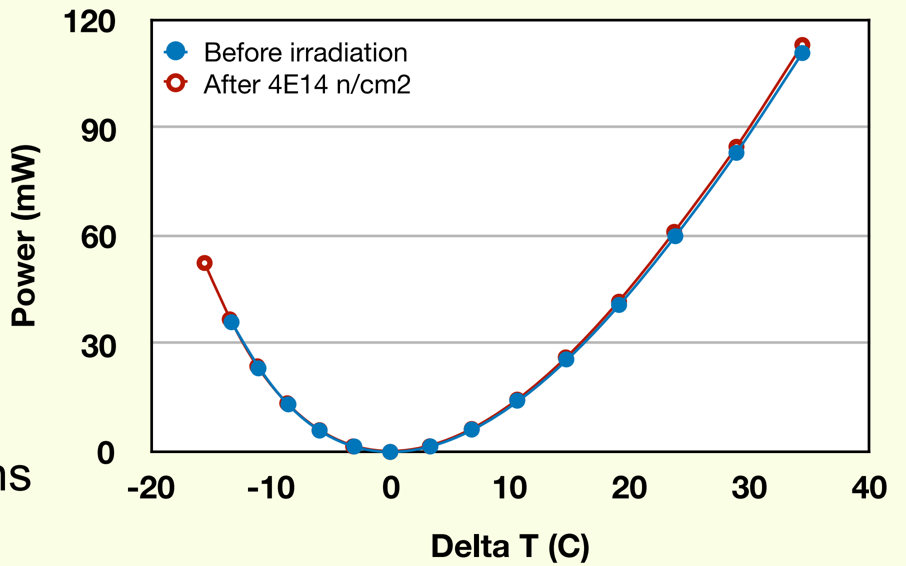
power consumption vs ΔT



phonønic

2x2x0.8 mm^3





Advantage of the use of mini peltiers:

- ΔT of -20C without extra power
- Annealing at +60C during LHC shutdowns

Summary

After successful replacement of HPDs with SiPMs in the CMS HCAL in the last 6 years with a neutron dose of max 2E12 n/cm2

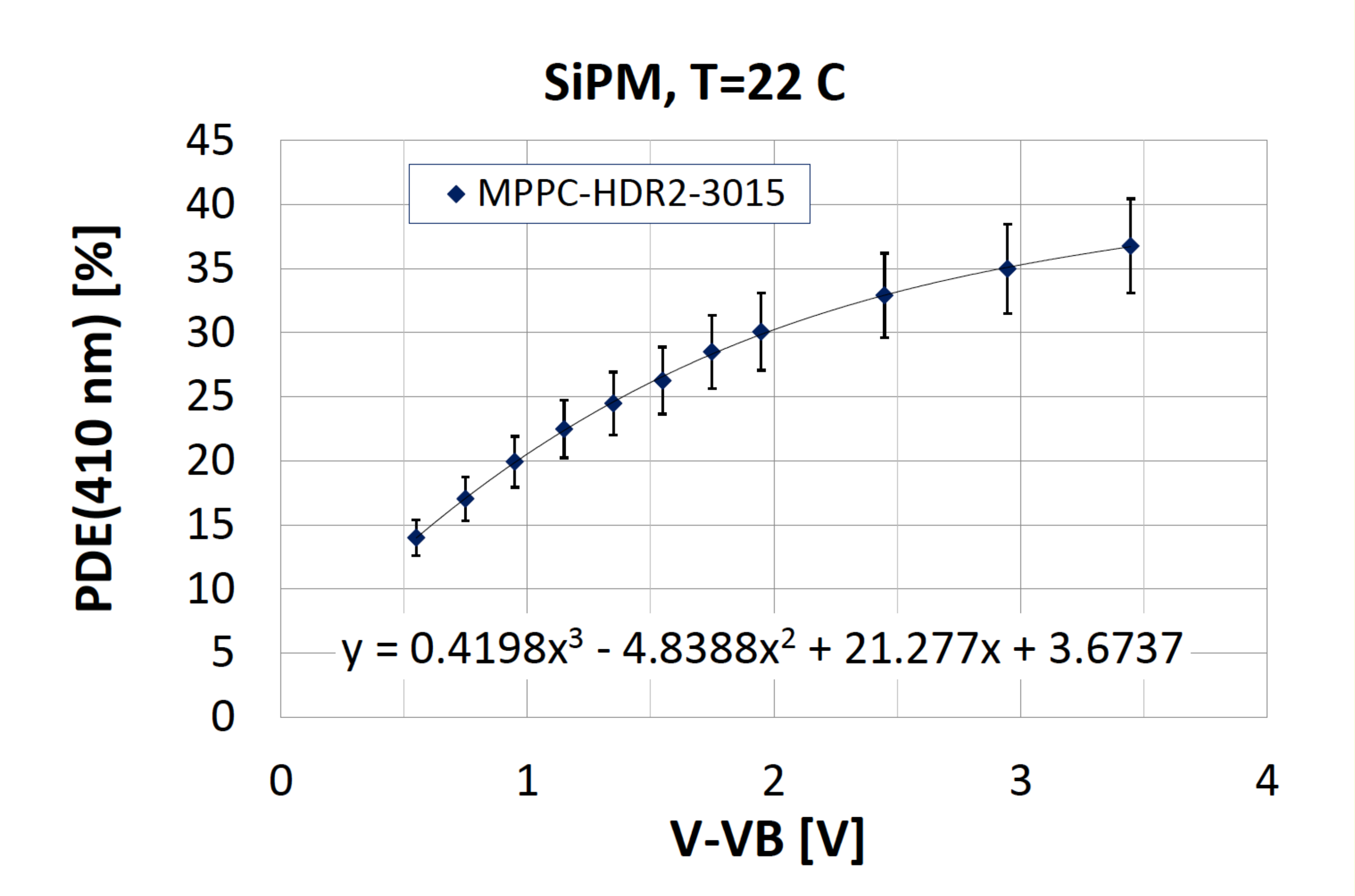
We now plan to also use them in two more sub-detectors in CMS:
HGCAL and BTL.
This bring significant new challenges due to the large fluence of 2E14 n/cm2 1MeV eq.
(Even though we will operate at -30C)

- Large DCR linear with the fluence
- Breakdown voltage shift due to change in doing concentration
- Self heating of the SiPMs due to the large gain
- Loss of PDE in front p+ layer and/or the protective resins used

We like to thank FBK and Hamamatsu for the commitment to this project and the progress made in the last years to improve the SiPMs for these projects

R&D will continue…..

Backup


SiPM, T=22 C
MPPC-HDR2-3015
y = 0.4198x³ - 4.8388x² + 21.277x + 3.6737
PDE(410 nm) [%]
V-VB [V]
0
5
10
15
20
25
30
35
40
45
0
1
2
3
4