Characterisation of radiation-damaged SiPMs

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1. **Aims**
2. **SiPMs + measurements**
3. **Results**
   - **3.1 C-V: Electrical parameters and doping profile**
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   - **3.3 PH_{dark}: DCR**
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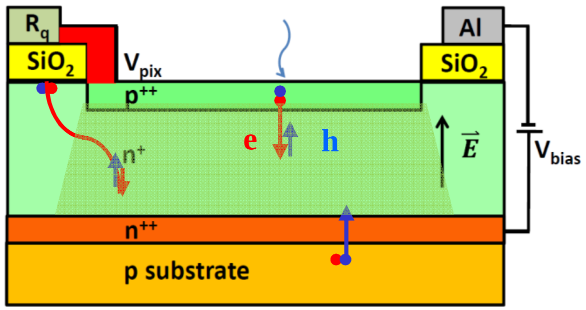
Aims + SiPMs investigated

Aim: Develop and test methods to characterise hadron-damaged SiPMs

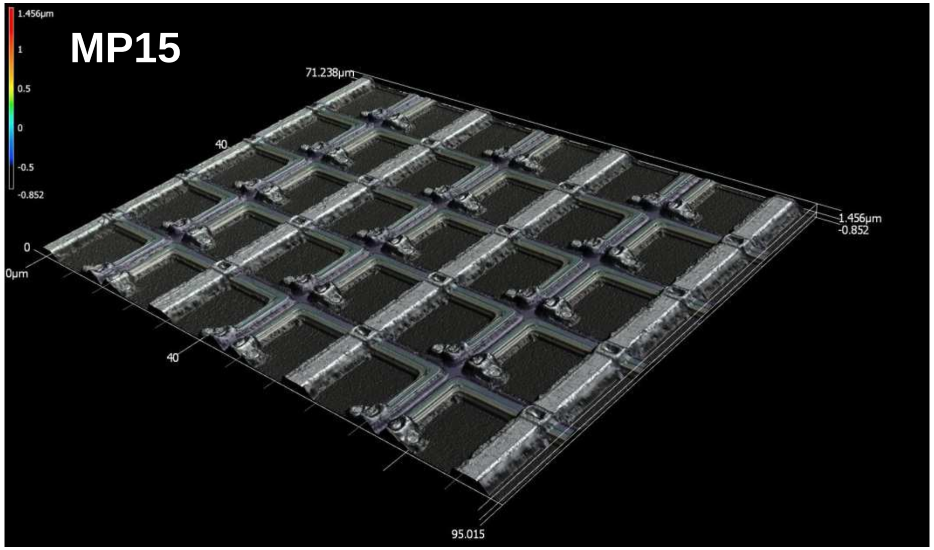
- → Demonstrate them on a specific SiPM → which is the best method?
- → Which parameters change with fluence? → physics of damage → Improvements?
- → Quantify optimal operating conditions + pulse shaping for a given task

SiPM: KETEK MP15*) with 4384 pixels 15x15 μm²

n-irradiated at JSI (reactor) to 10^9, 10^{11}, $5{\cdot}10^{11}$, 10^{12}, $5{\cdot}10^{12}$, 10^{13}, $5{\cdot}10^{13}$, $5{\cdot}10^{14}$ cm^{-2}



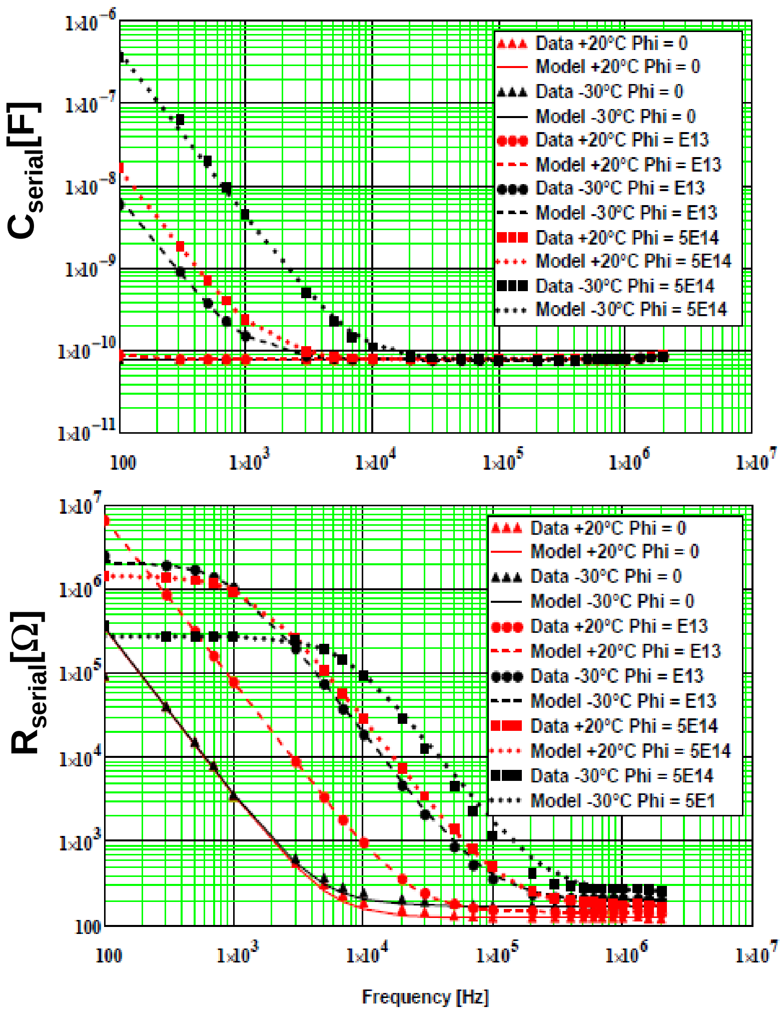
- Depth ampli-region ~ 1μm
- $V_{bd} \approx 27.5$ V at 20°C
- $V_{off} \approx V_{bd} - 850$ mV
- R_q poly-Si



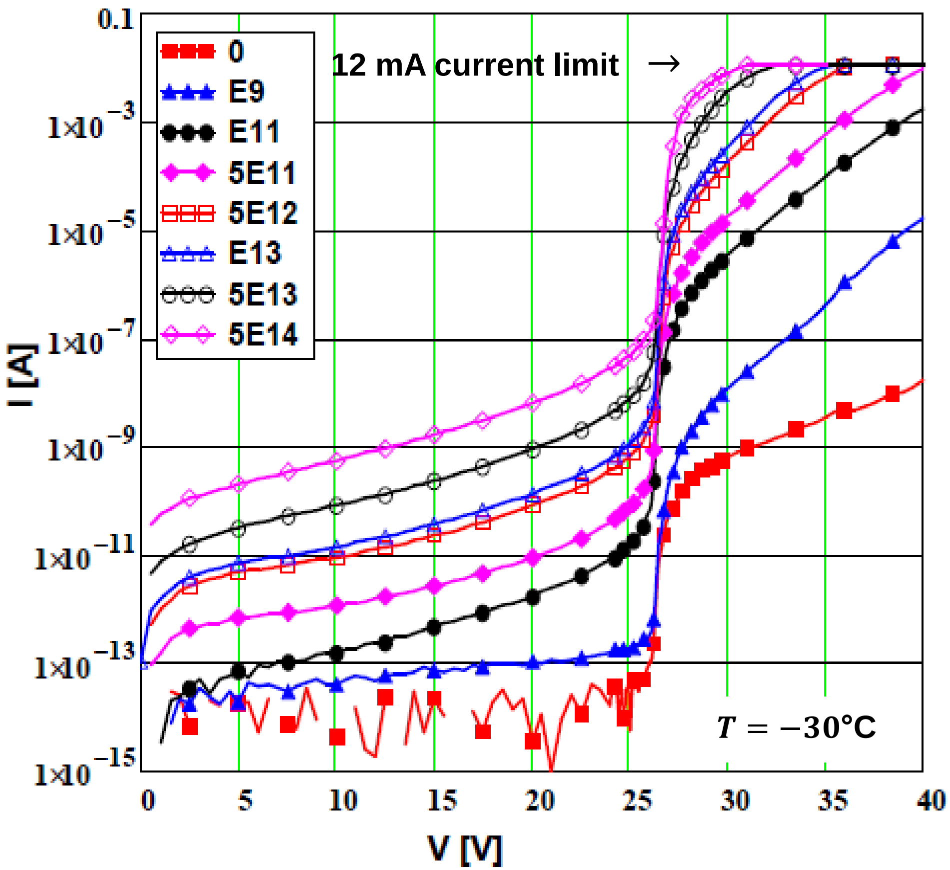
*) SiPM well studied @ UHH
(RK. et al., NIM-A 854 (2016) 70)

Measurements

C/G-V: V = 0…26.5V, f = 100 Hz…2 MHz
T = -30°C and +20 °C



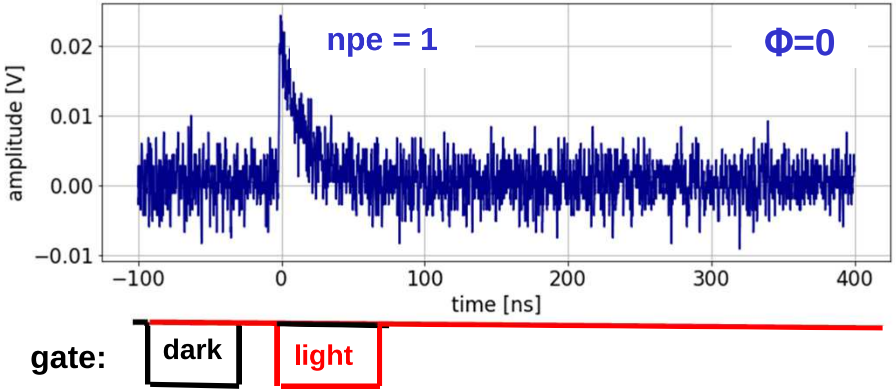
I_{dark}: V = -2…+35 (40) V,
T = -30°C and +20 °C

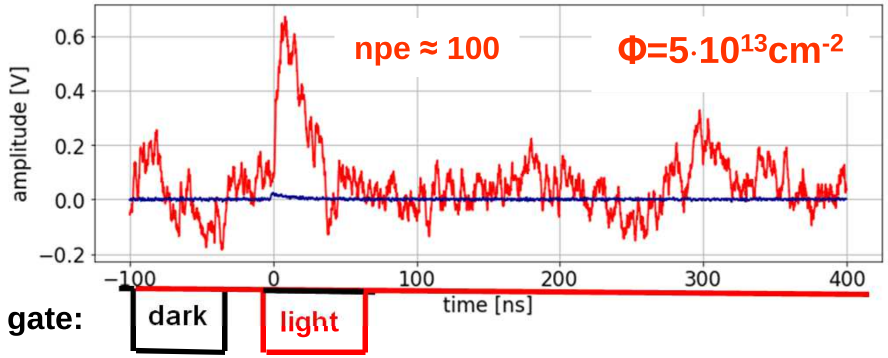


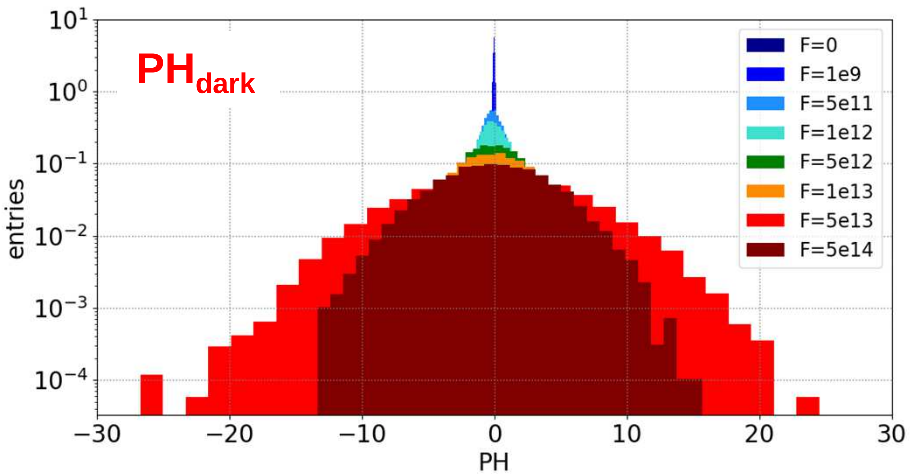
***I_{dark}* used in analysis**

Measurements

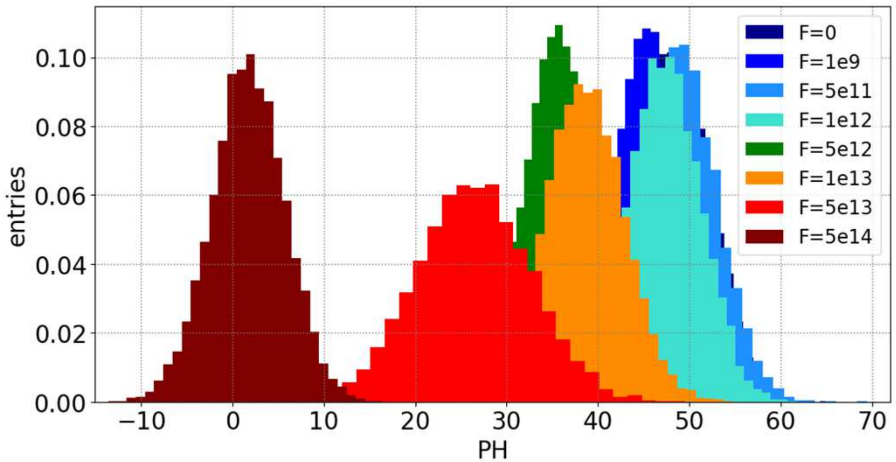
Current transients: V = 27.7…30.5V, T = -30°C → PH_{dark} and PH_{light}-spectra
for $t_{gate} = 15 \ldots 75$ ns







$$Var_{light} = Var_{light}^{meas} - Var_{dark}$$



Var_{dark} **used in analysis**

$Mean_{light}$ + Var_{light} **used in analysis**

Parameters and formulae for analysis

C_{pix} … pixel capacitance
R_q… quenching resistance
C_q … quenching capacitance
V_{bd} … breakdown voltage
V_{off} … Geiger turnoff voltage

pulse shape (slow comp.): $\tau = C_{pix} \cdot R_q$

$$Gain \approx (C_{pix} + C_q) \cdot (V - V_{off}) \cdot f_{gate}$$

(f_{gate} … fraction of signal in gate)

DCR … dark count rate

$$I_{dark} = DCR \cdot EQF \cdot Gain(f_{gate} = 1)$$

EQF … excess charge factor $EQF = \frac{Mean}{Mean_{Poisson}}$

ENF … excess noise factor $ENF = \frac{Var/Mean^2}{Var_{Poisson}/Mean^2{}_{Poisson}}$

PDE … photon detection efficiency
μ … no. photons initiating Geiger discharge

$$\mu = Mean_{Poisson} = Var_{Poisson}$$

$$Mean = \mu \cdot Gain \cdot EQF$$

$$Var = \mu \cdot Gain^2 \cdot EQF^2 \cdot ENF$$

→ 3 ways to obtain μ +

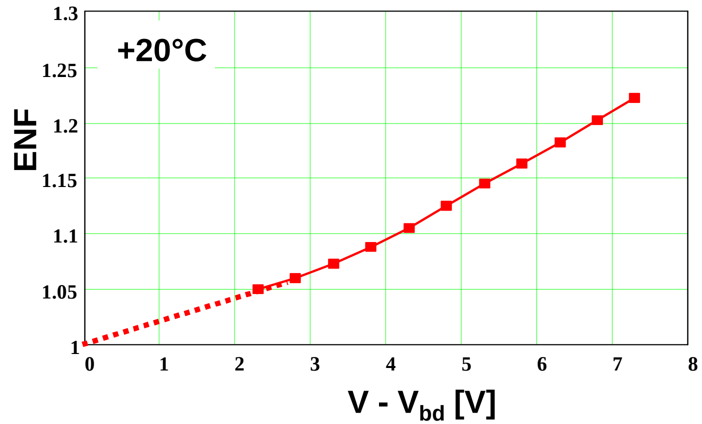
$$\rightarrow Gain = \frac{Var}{Mean \cdot EQF \cdot ESF}$$

N.B: valid if no saturation effects !

$V_{bd} - V_{off} \approx 850$ mV from high statistics Φ=0 data at +20°C
→ assume $V_{bd} - V_{off}$ does not depend on Φ, T

EQF and ENF determined from high statistics Φ=0 data at +20°C → for most cases a small correction

find: EQF ≈ ENF



V_{bd} versus V_{off}

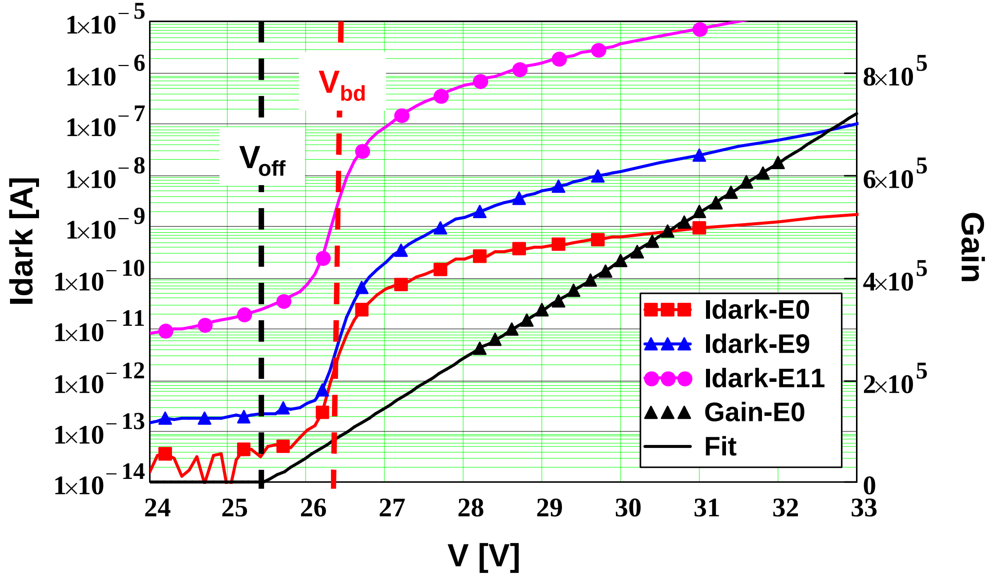
From PH-fits: $Gain(V)$ → find $Gain(V)$ =d$Gain$/d$V\cdot(V - V_{off})$ → with d$Gain$/dV=const

→ straight line describes $Gain(V)$ → V_{off} from extrapolation to $Gain = 1$ ($f_{gate} = 1$)

→ for $t_{gate} = 75$ ns (compatible results for other t_{gate} values):

d$Gain$/dV $= 9.75\cdot10^{4}$ V^{-1} (compare to: $C_{pix}/q_0 = 17.8$ fF/$1.6\cdot10^{-19}$C = $11.1\cdot10^{4}$ V^{-1} ≈ ok)

$V_{off} = V_{bd} - 850$ mV



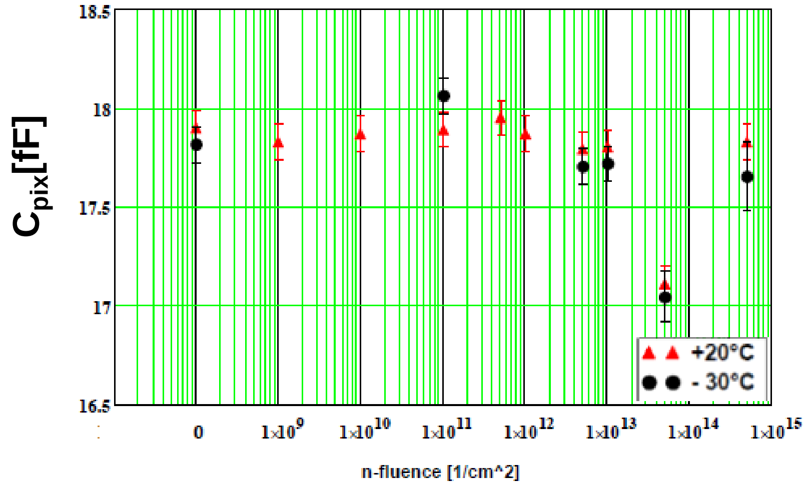
Difference: $V_{bd} - V_{off} \approx 850$ mV to be taken into account for analysis

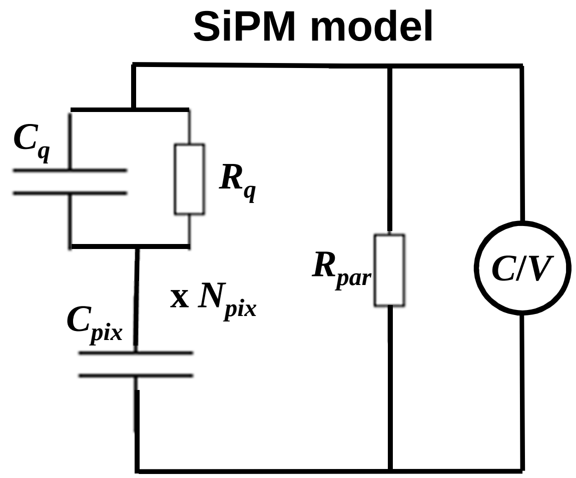
for further analysis assume no dependence of $V_{bd} - V_{off}$ on Φ

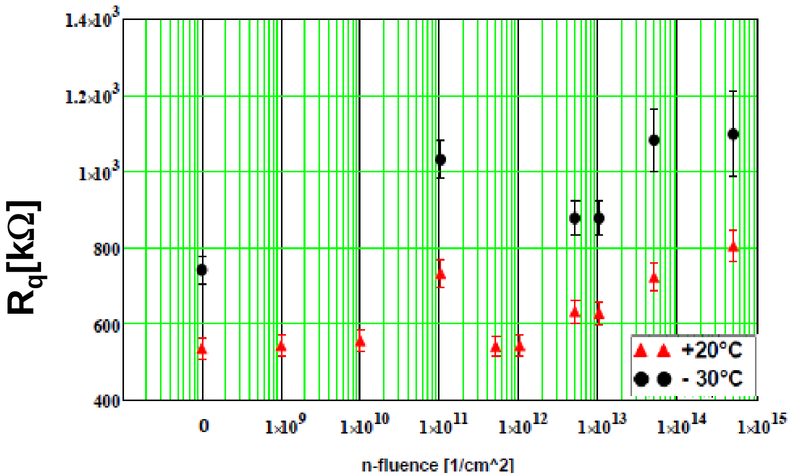
d$Gain$/dV ≈ compatible with C_{pix}/q_0

C-V measurements and C_{pix}, R_q, C_q

Dependence of C_{pix} and R_q on T and Φ (neutron fluence):







- **Upper limit C_q< 5 fF (~1 fF-pulse shape)**
- **Significant differences for SiPM samples**

C_{pix} not influenced by T and Φ

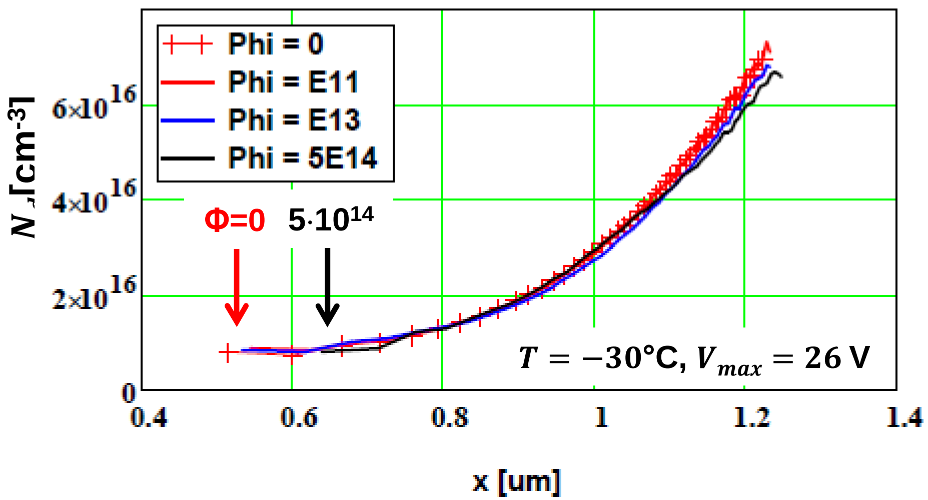
R_q increases with decreasing T (poly-Si)

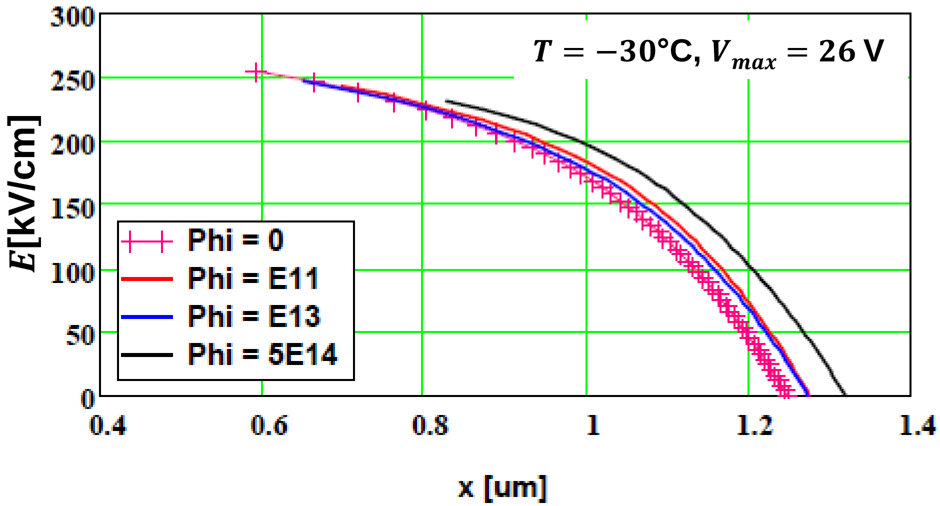
R_q appears to increase for $\Phi > 10^{13}$ cm^{-2}

C-V measurements: Doping and E-field

Doping profile $N_d(x)$ and E-field $E(x)$ assuming 1-D abrupt p$^+$n-junction:

$$x(V) = \frac{\varepsilon_0\,\varepsilon_{Si}\,A}{C(V)} \quad N_d(x) = \frac{2}{q_0\,\varepsilon_0\,\varepsilon_{Si}\,A^2}\cdot\frac{1}{\mathrm{d}(1/C^2)/\mathrm{d}V} \quad E(x) = \int_{x_{max}}^{x}\frac{q_0\,N_d(x)}{\varepsilon_0\,\varepsilon_{Si}}\,\mathrm{d}x \quad A = N_{pix}\cdot pitch^2$$

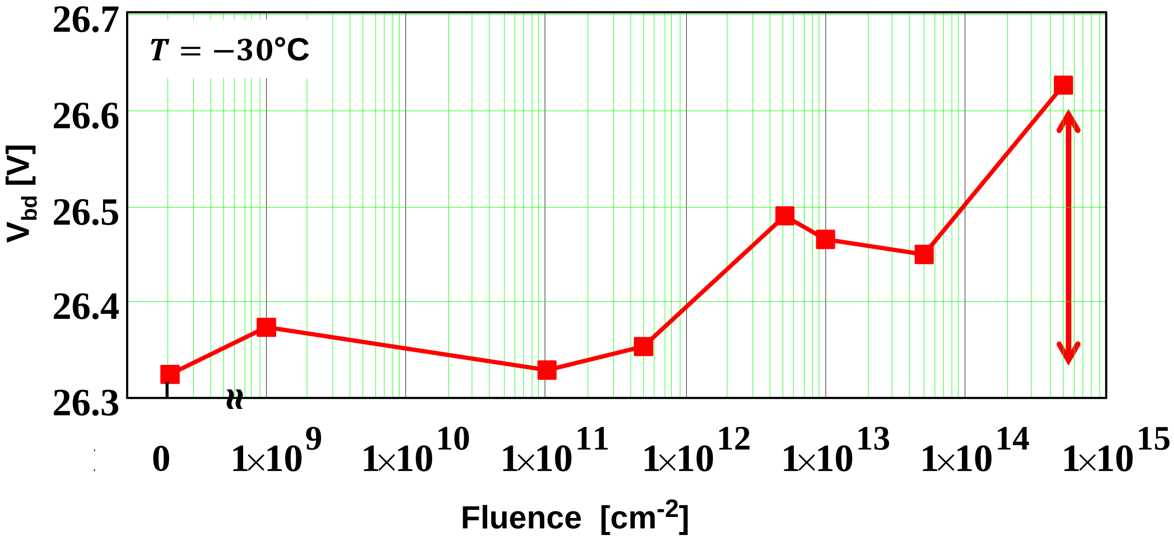




Minor decrease of N_d for $\Phi = 5{\cdot}10^{14}$ cm^{-2}
(expected from radiation-induced donor removal)

Breakdown voltage V_{bd}

V_{bd} using max(ILD) with $ILD = (\mathrm{d}\ln|I|/\mathrm{d}V)^{-1}$



Only at +20°C I_{dark} measured for all SiPMs for $\Phi = 0$ → variations observed

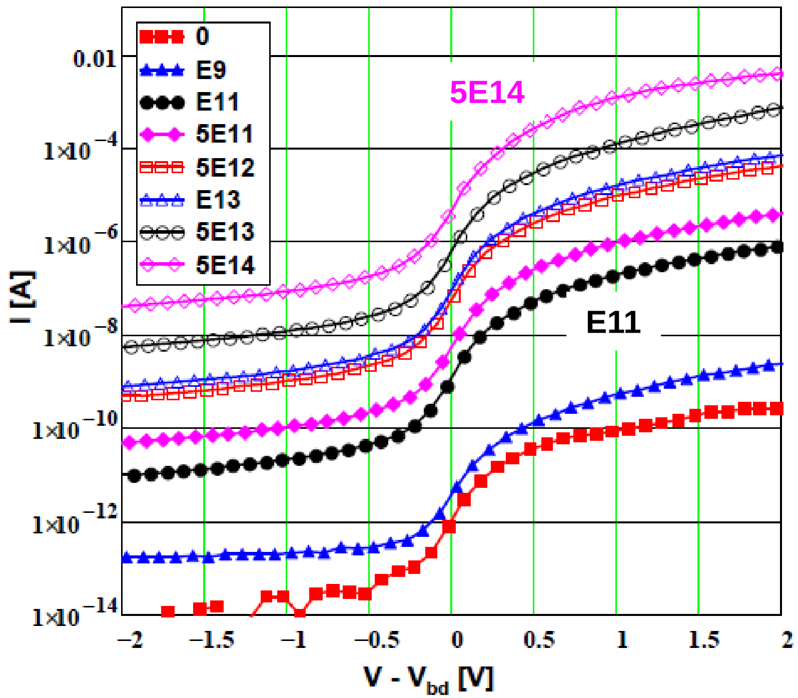
→ difference $V_{bd}(\Phi) - V_{bd}(\Phi = 0)$ significant only at $5 \cdot 10^{14}$ cm^{-2}

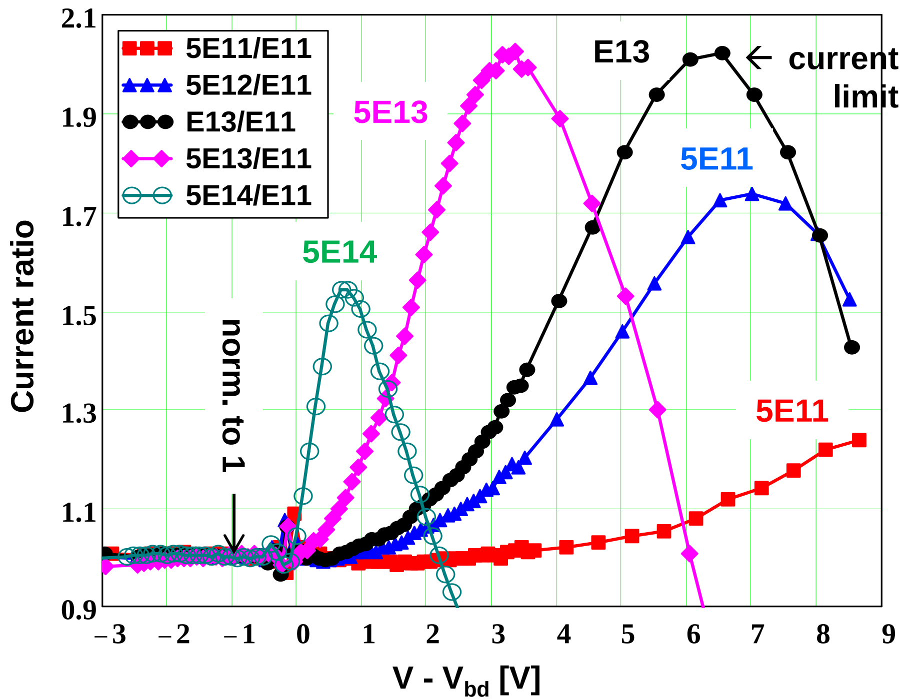
V_{bd} ≈ const. up to ≈$5 \cdot 10^{13}$ cm^{-2}

Increase by ≈ 300 mV at $5 \cdot 10^{14}$ cm^{-2}

Dark current vs. fluence and voltage

Does $I_{dark}(V - V_{bd})$ scale with Φ? → $R_{dark} = I_{dark}(\Phi)/I_{dark}(10^{11})$ vs. $V - V_{bd}$





→ $V < V_{bd}$ → R_{dark} ≈const; for $V > V_{bd}$ increase by factor up to 2 with V

Model: $I_{dark} = DCR{\cdot}(C_{pix}{\cdot}(V - V_{off})){\cdot}EQF$ → x2 by EQF and gain implausible →

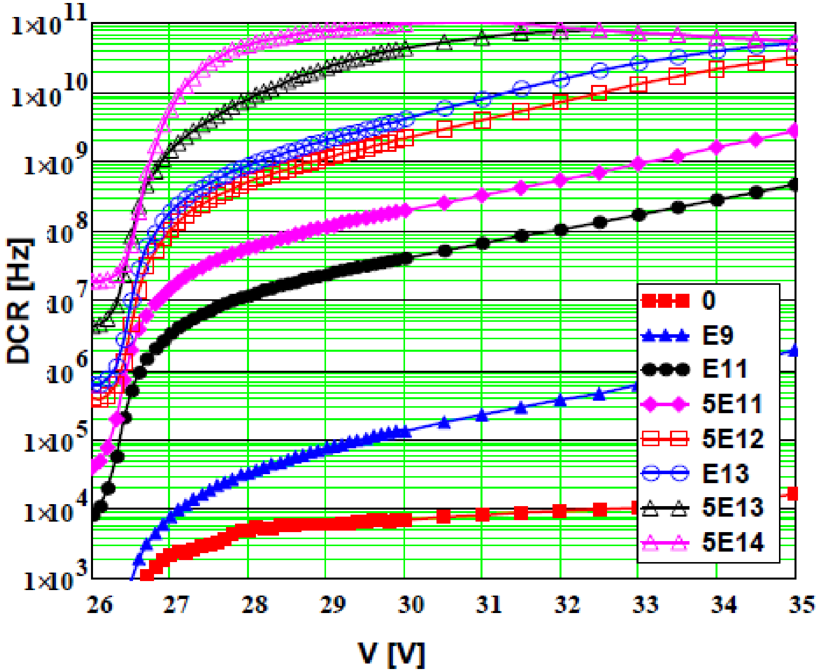
assume change due to DCR → "trap assisted high-field generation"?

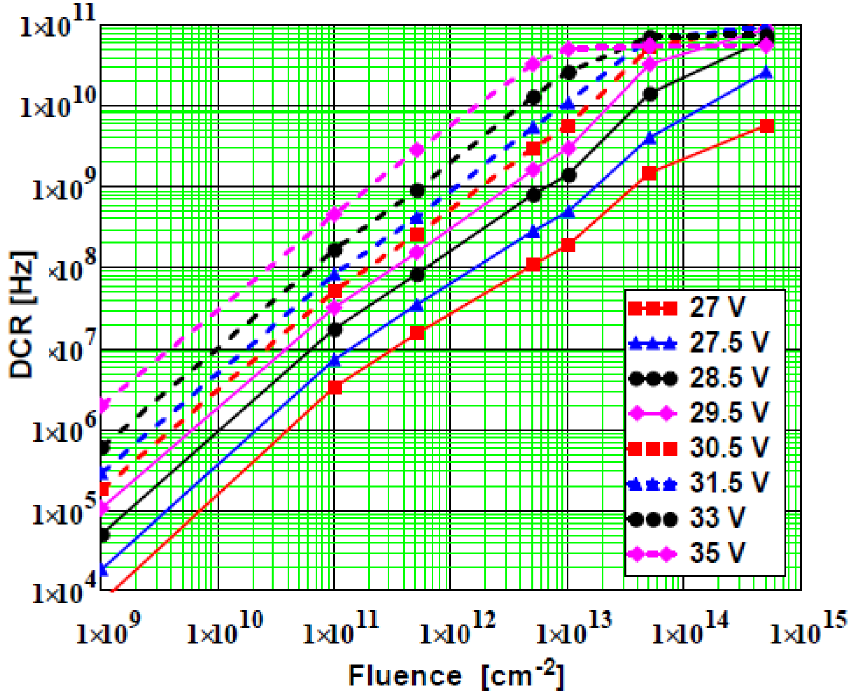
$I_{dark}(\Phi)/I_{dark}(10^{11})$ increases with $V - V_{bd}$: higher Φ → faster increase

DCR vs. fluence and voltage

Model: $I_{dark} = DCR \cdot (C_{pix} \cdot (V - V_{off})) \cdot EQF$ **assume** $C_{pix} = 18$ **fF**

($V_{bd} - V_{off} = 850$ **mV and** ESF **from** $\Phi = 0$ **data)**





Comment: Estimate fraction of busy pixels (occupancy) $\approx (DCR \cdot \tau)/N_{pix} \approx 0.5$ for $DCR = 10^{11}$ s^{-1}, $\tau = 20$ ns, $N_{pix} = 4384$

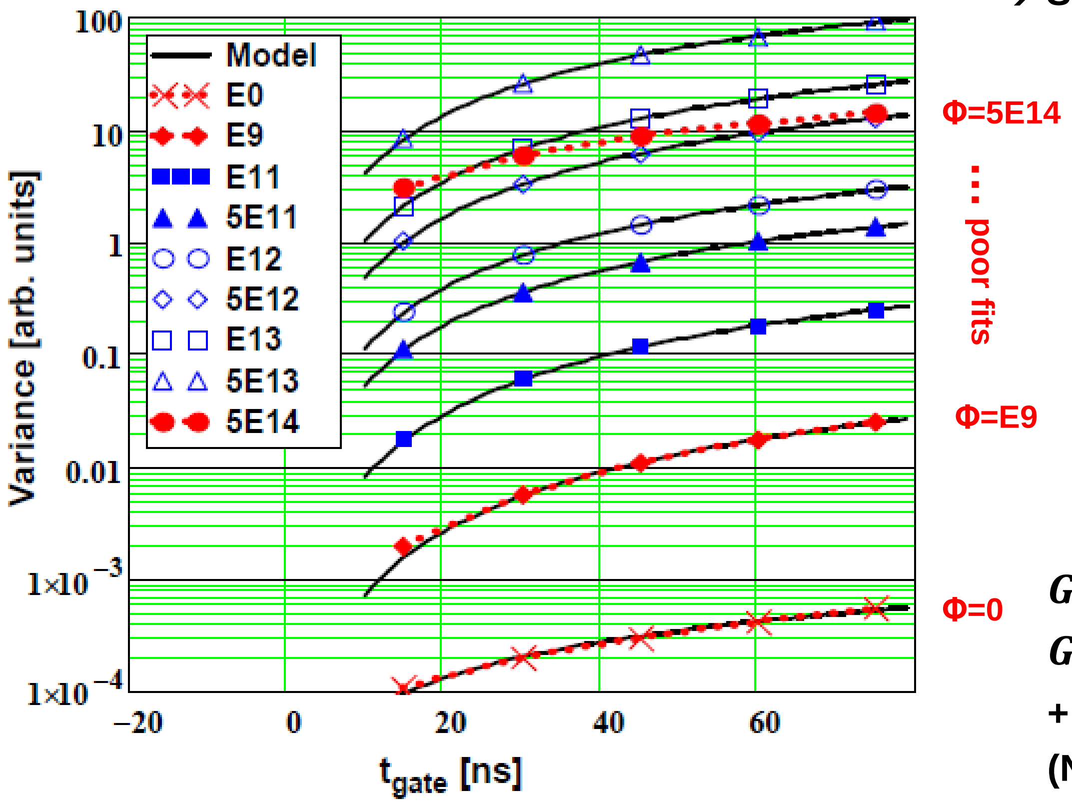
$I_{dark}(\Phi, V)$ allows estimation of $DCR(\Phi, V)$

→ V-dependence of DCR very different after irradiation!

→ Exponential increase for $V - V_{bd} > 2$ V + saturation at high Φ

PH$_{dark}$ – irradiated SiPM

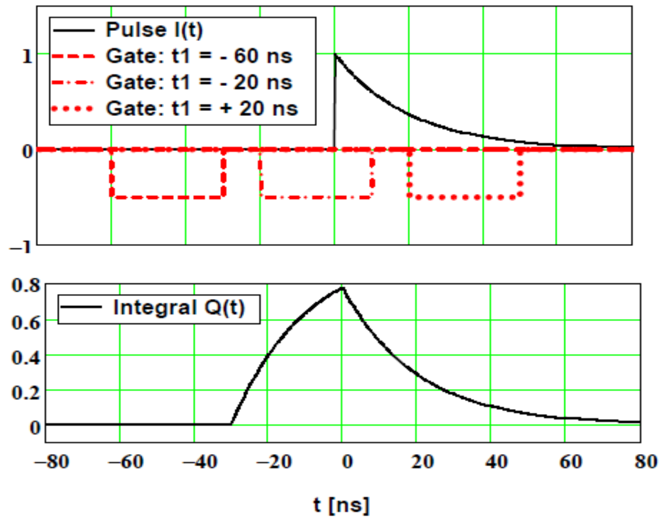
$Var_{dark}(t_{gate})$ vs. Φ at -30°C:



1 pulse $(e^{-t/\tau})/\tau$ per sec in random gate t_{gate}:

$$var_1 = t_{gate} - \tau(1 - e^{-t_{gate}/\tau})$$

→ Solid curves, which describe data ($\tau \approx$ 20 ns)



$Gain$ =1 no CN (corr. noise): $var_1 \cdot DCR$

$Gain \neq 1$ no CN: $Gain^2 \cdot var_1 \cdot DCR$

+ CN: $Var = ENF \cdot EQF^2 \cdot Gain^2 \cdot var_1 \cdot \mathrm{DCR}$

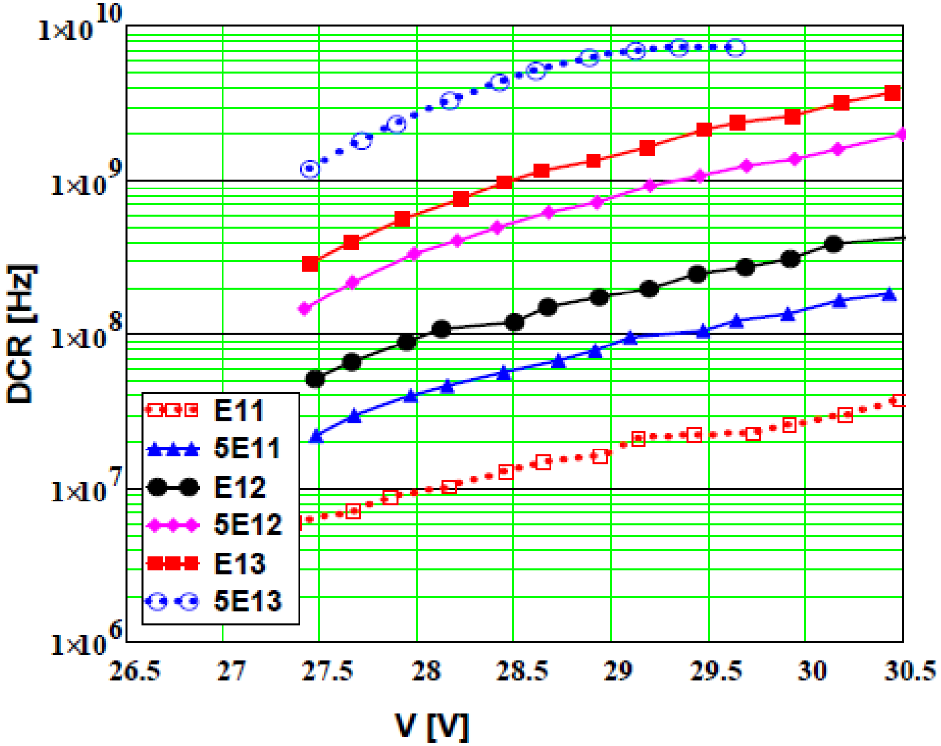
(N.B. only valid in absence of saturation)

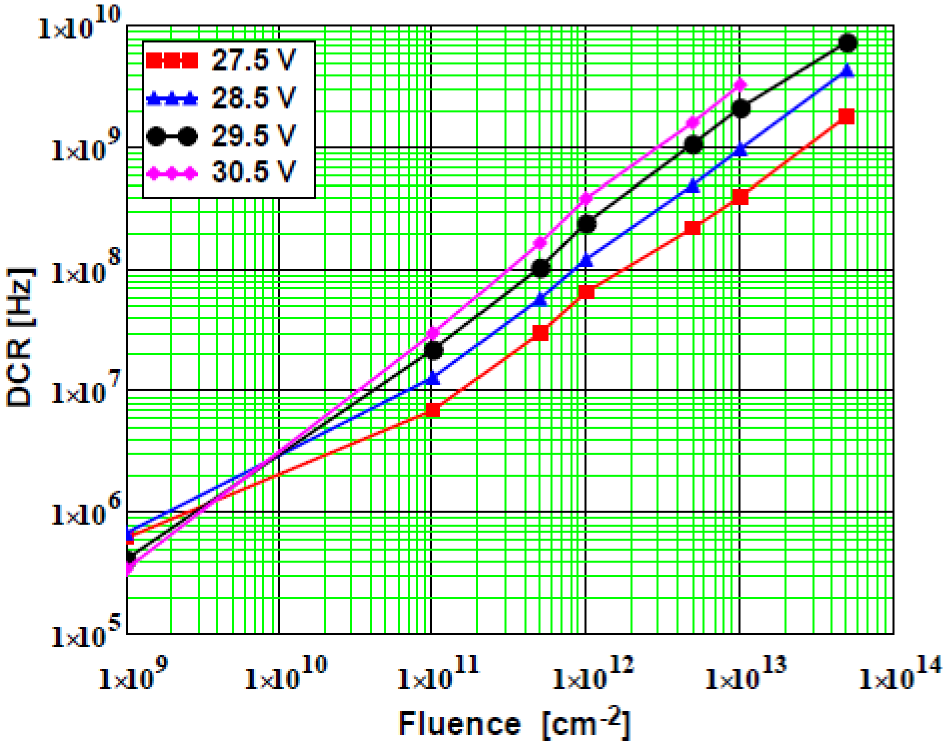
t_{gate} – dependence of Var → described by model for $10^{11} < \Phi < 5 \cdot 10^{12}$ cm^{-2}

Var allows to estimate τ and DCR (if no strong saturation effects)

PH_{dark} – irradiated SiPM – DCR

$$Var = ENF \cdot EQF^2 \cdot Gain^2 \cdot var_1 \cdot \mathrm{DCR} \;\rightarrow\; DCR = \frac{Var}{ENF \cdot EQF^2 \cdot Gain^2 \cdot \left(t_{gate} - \tau\left(1 - e^{-t_{gate}/\tau}\right)\right)}$$





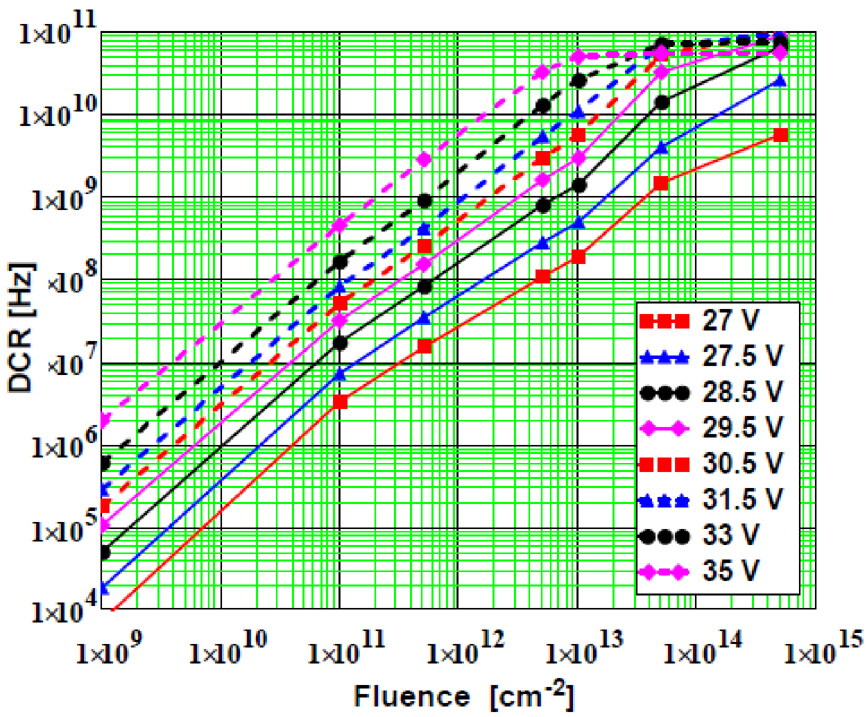
DCR-results agree within ≈ 30 % with results from I_{dark}

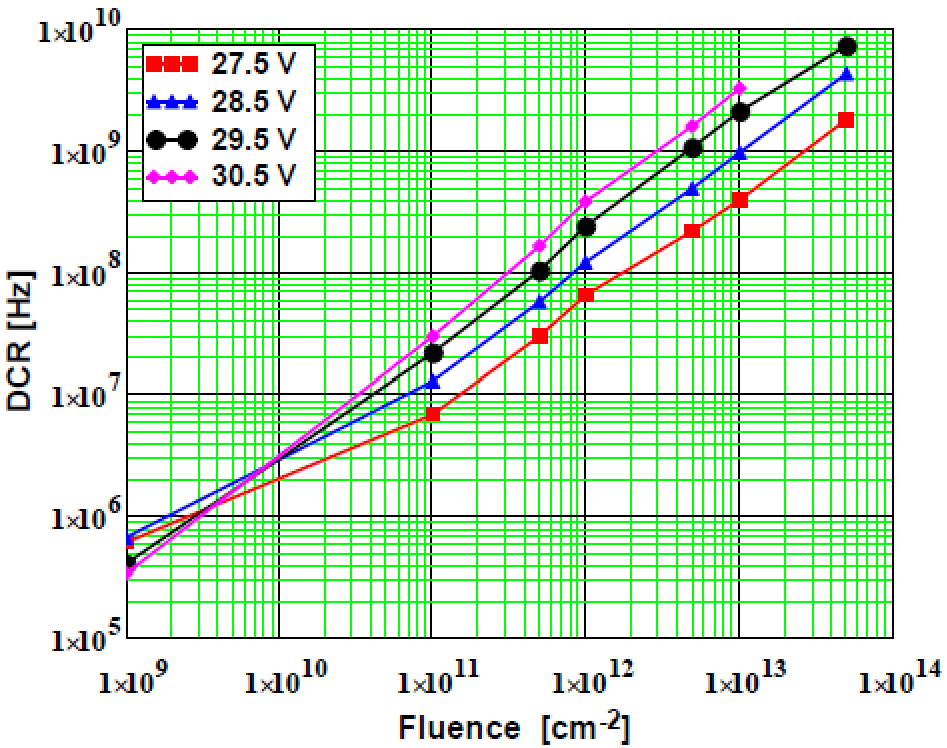
Var-method more complicated and range of validity limited

Differences may help to better understand rad.damage effects on SiPMs ???

Comparison of Var and I_{dark} method

Comparison:





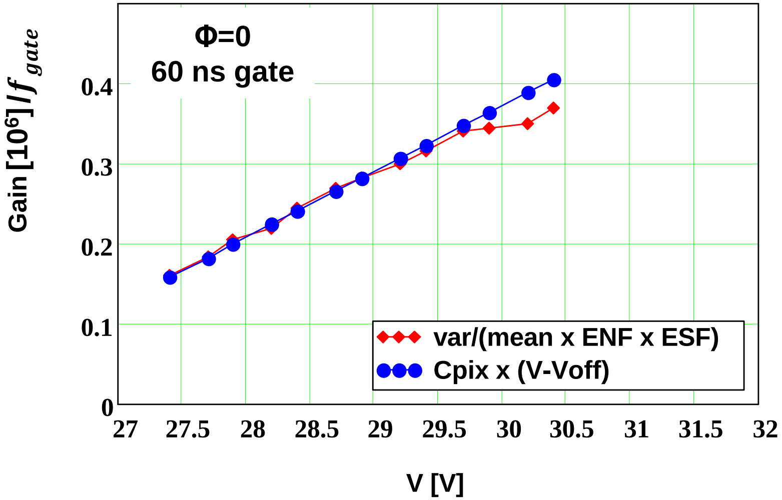
Typical agreement O(30%), however also larger differences →

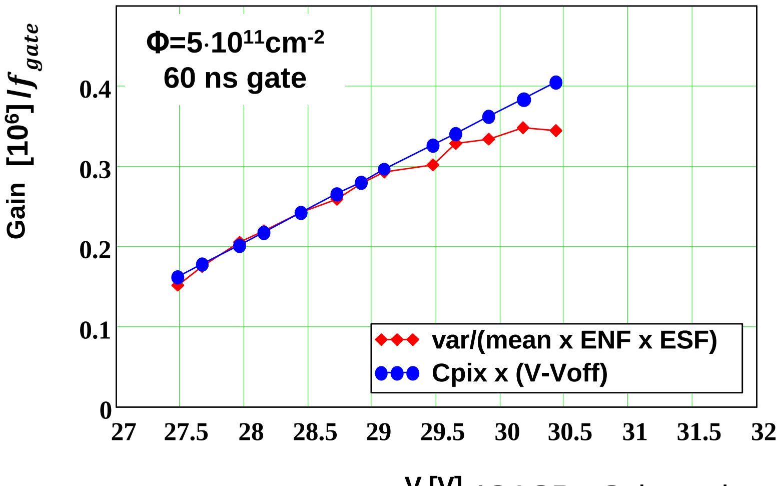
Detailed comparison + understanding of differences still to be done

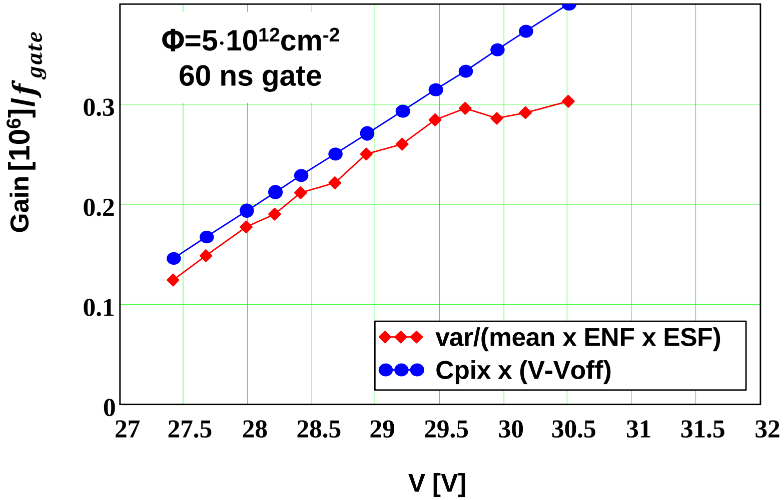
PH$_{light}$: *Gain* determination

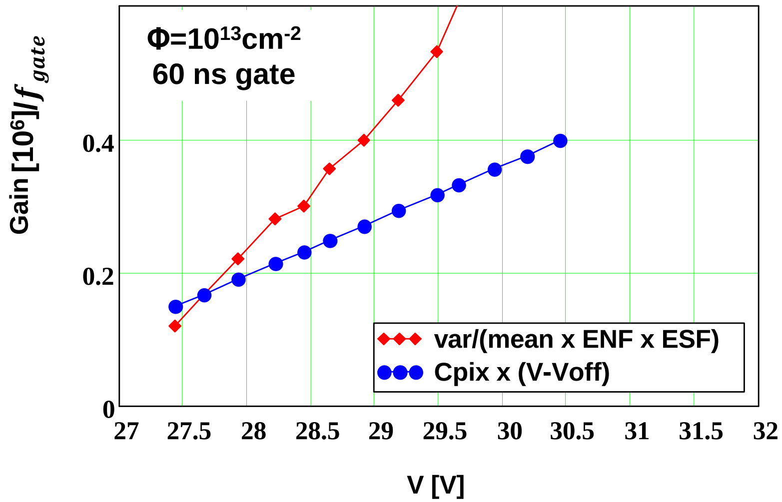
Can we determine *Gain* ?

$$Gain = \frac{Var}{Mean} \cdot \frac{1}{ENF \cdot EQF}$$









Yes, up to ~10^{12} cm^{-2};

No for higher fluences – saturation!

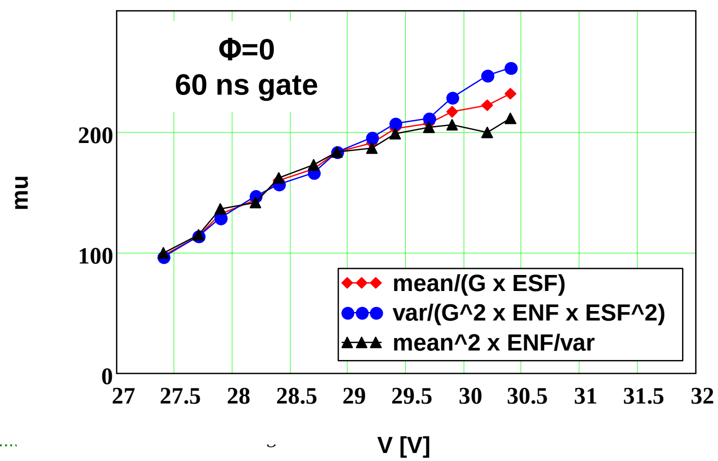
PH_{light}: μ-determination

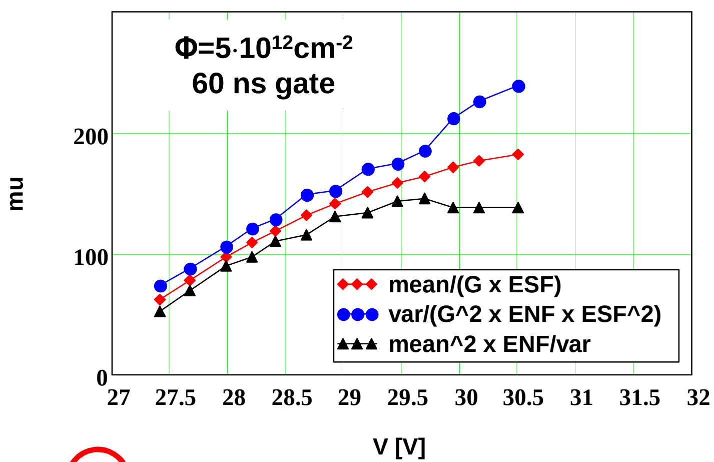
Can we determine μ ?

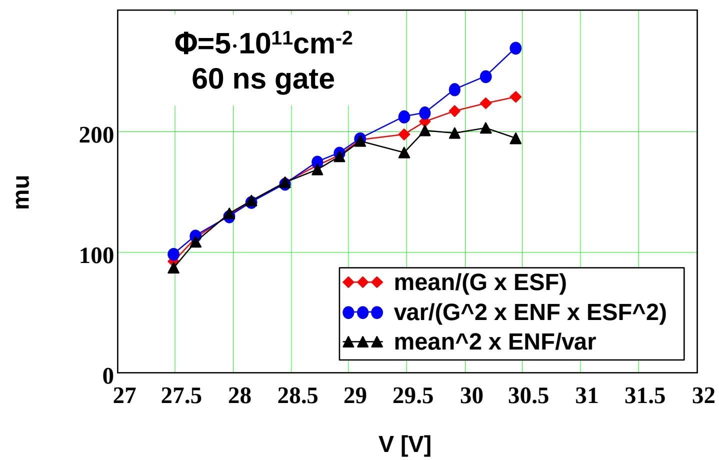
(μ = no. of photons initiating a Geiger discharge)

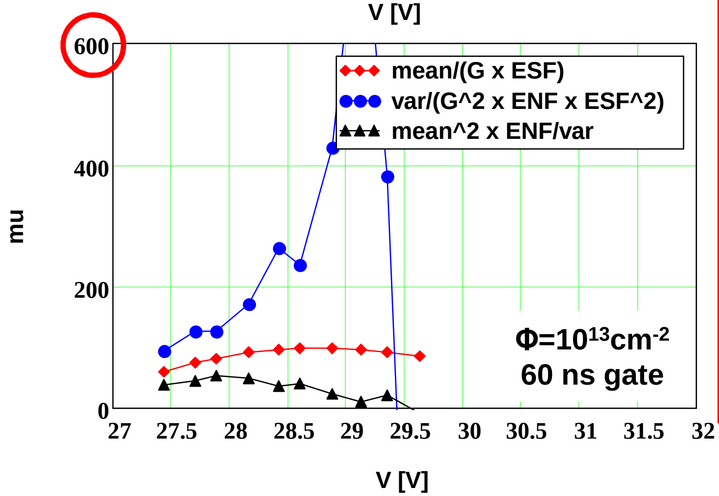
Yes, $V < 29.5$ V + up to ~10^{12} cm^{-2};
No for higher fluences – saturation!

Most reliable: $\frac{Mean}{Gain \cdot EQF}$









3 ways to determine μ

$$\mu = \frac{Mean}{Gain \cdot EQF}$$

$$\mu = \frac{Var}{Gain^2 \cdot ENF \cdot EQF^2}$$

$$\mu = \frac{Mean^2 \cdot ENF}{Var}$$

with $Gain \approx$

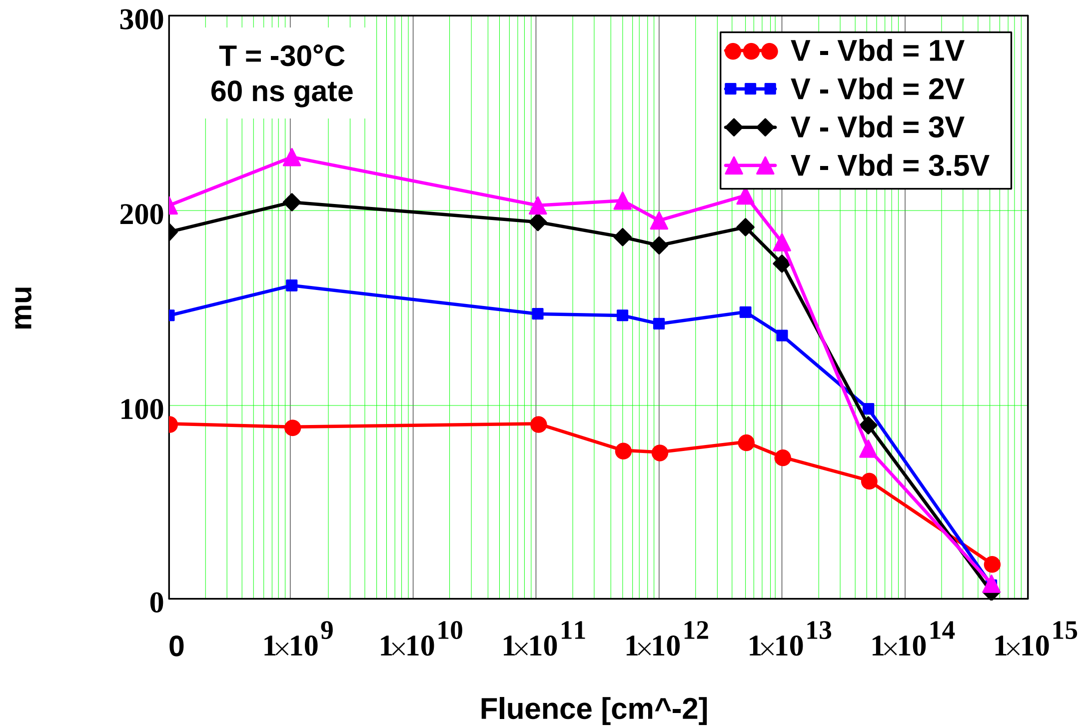
$$C_{pix} \cdot (V - V_{off}) \cdot f_{gate}$$

PH_{light}: μ (∝ PDE) photo-detection

$$\mu = \frac{Mean}{Gain \cdot EQF}$$

$$\mu = \frac{Var}{Gain^2 \cdot ENF \cdot EQF^2}$$

$$\mu = \frac{Mean^2 \cdot ENF}{Var}$$



$\Phi < 10^{13}$: PDE essentially unaffected by irradiation

$\Phi = 10^{13} - 5{\cdot}10^{13}$: irradiation affects PDE (low $V - V_{bd}$ still ok)

$\Phi = 5{\cdot}10^{14}$: SiPM not a useful photo-detector „all pixels occupied“

(→ „t_{gate}“ optimisation under way)

Conclusions + next steps

1. C-V, I_{dark}, PH_{dark}, PH_{light} measured at -30°C for Φ = 0 … $5{\cdot}10^{14}$ n/cm²
2. Formulae presented, which relate SiPM parameters to measured quantities
3. C_{pix} and R_q little affected by Φ
4. I_{dark} → DCR → increase with V and Φ → high DC pixel occupancy for $\Phi > 10^{13}$
   → expect a significant PDE reduction
5. PH_{dark} → DCR from variance → ~consistent with DCR from I_{dark}
6. PH_{light} → different methods indicate Gain not affected by Φ
7. PH_{light} → approximate V- and Φ-dependence of „relative“ PDE (μ) →
   for $\Phi=5{\cdot}10^{14}$ cm $^{-2}$ and –30°C SiPM investigated not a useful photo-detector

Next steps:

1. DCR-“PDE“ as a function of (Φ, V, t_{gate}) + noise vs. threshold as function of (Φ, V, t_{gate})
2. Optimisation of pulse-shaping → how much can one gain?
3. Include fast component from C_q in analysis
4. Implement saturation effects due to dark counts + photons
5. Implement what we learn in Schwetzingen

Most methods of SiPM characterisation fail after high Φ irradiation
??? Can we find + agree on the most suitable methods ???