RADIATION EFFECTS IN THE CMS PHASE-1 PIXEL DETECTOR

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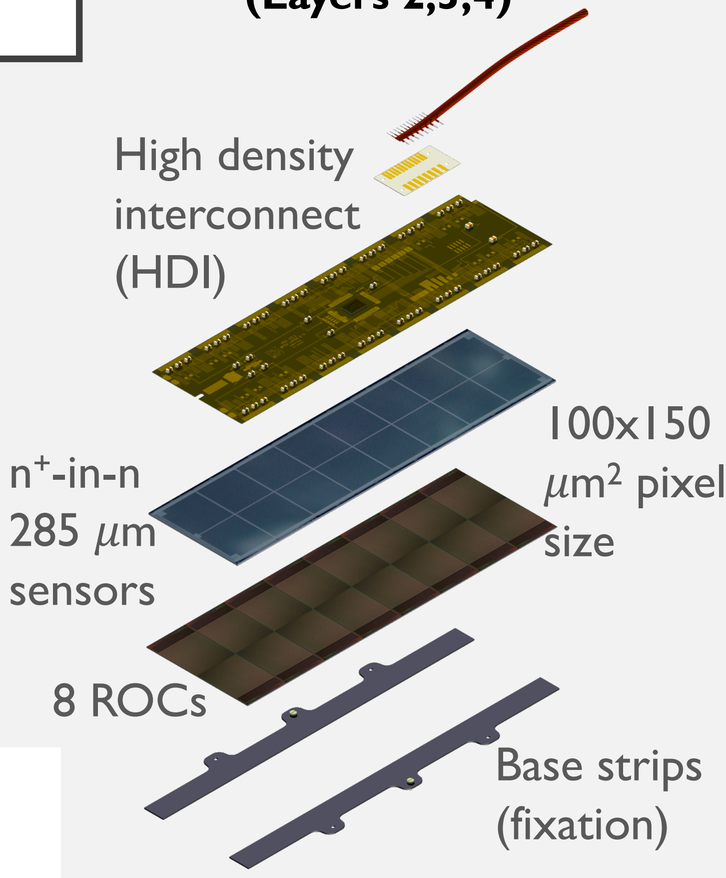
TREDI2020: 15th "Trento" Workshop on Advanced Silicon Radiation Detectors

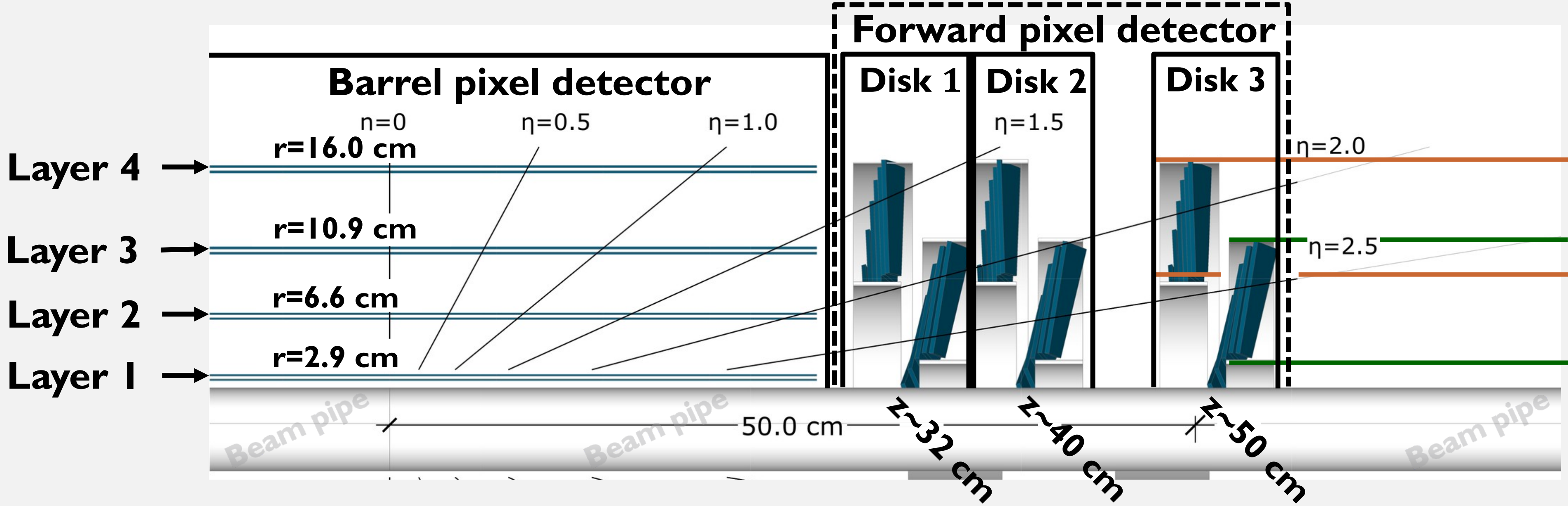
INTRODUCTION

CMS PIXEL DETECTOR

- **CMS Pixel detector** consists of two main parts: **Barrel Pixel** and **Forward Pixel**
- An **upgraded Pixel** detector was **installed in 2017 and operated** (up to now) **until the end of 2018**:
  - Barrel Pixel (**BPix**): four layers, 4 hit coverage and high-rate capability
  - Forward Pixel (**FPix**): 2 rings x 3 disks, turbine-like structure for forward disks for optimal resolution
  - CO_2 cooling
- **Leakage current and depletion voltage** studies are done **for 2017-2018 years** of operation for full CMS **pixel detector**

Module structure (Layers 2,3,4)





LEAKAGE CURRENT

- **Leakage current change for BPix** is simulated using the following expression:

$$\Delta I_{leak}\left(t,T;\Phi_{eq}\right) = \alpha(t,T)\;\Phi_{eq}(r,z)\;V$$

  - $\boldsymbol{V}$ is the **volume** of the sensor module
  - $\boldsymbol{\Phi_{eq}}$ is **1-MeV neutron equivalent fluence** of all the particles, calculated using FLUKA. $\Phi_{eq}{\sim}r^{-1.5}$ and almost flat vs z
  - $\boldsymbol{\alpha(t,T)} = \alpha_0 + \alpha_I \exp\left(-\frac{t}{\tau_I(T)}\right) - \beta \ln\left(t\,\Theta(\mathrm{T})\right)$ is **a current related damage rate**

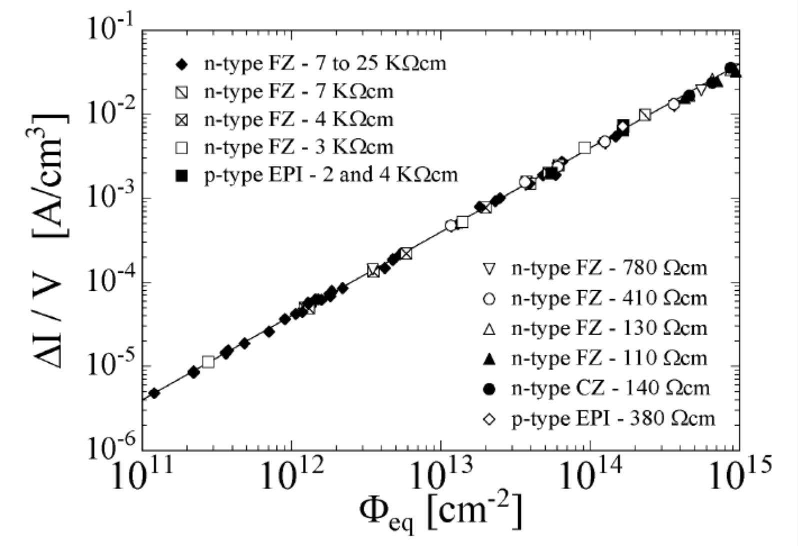
- For **FPix**, we need to **integrate over** the module **volume** (modules cover wide radius range):

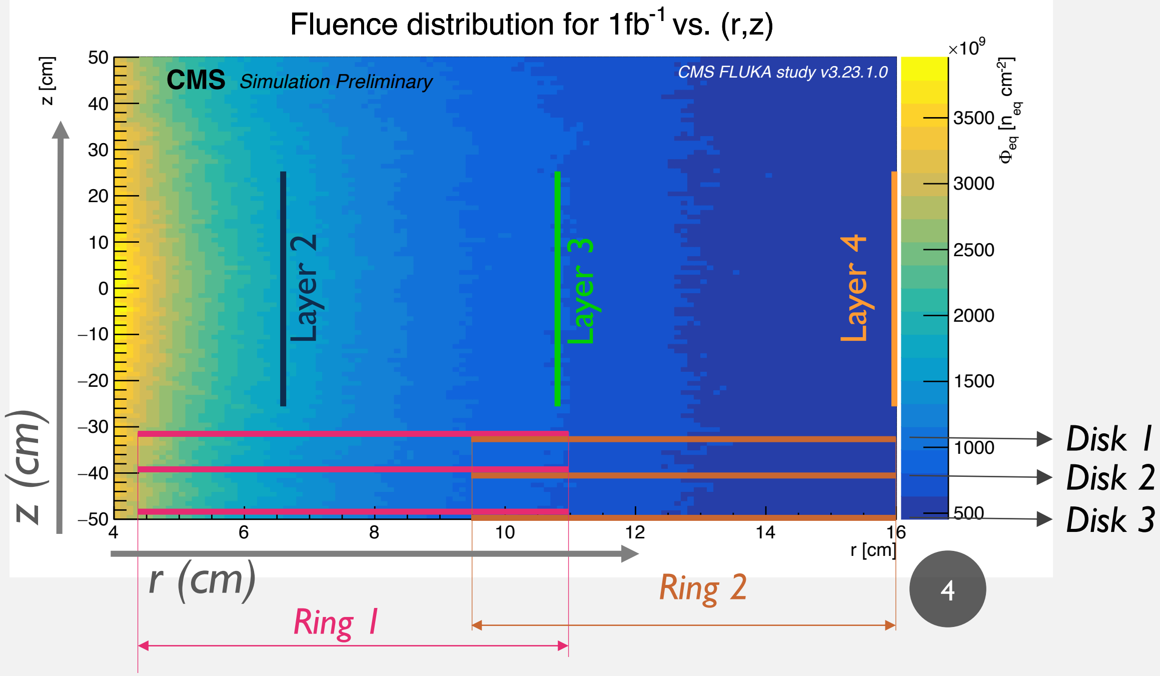
$$\Delta I_{leak}\left(t,T;\Phi_{eq}\right) = \alpha(t,T)\int \Phi_{eq}(r,z)dV = \alpha < \Phi_{eq} > V,$$

$< \Phi_{eq} >$ is the average fluence over a module volume.

- **Leakage current** at the end is **scaled to** a reference temperature $\boldsymbol{T_{ref}}$ using:

$$I_{leak}\left(T_{ref}\right) = I_{leak}(T)\cdot\left(\frac{T_{ref}}{T}\right)^2 \exp\left(-\frac{E_g^*}{2k_B}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)$$





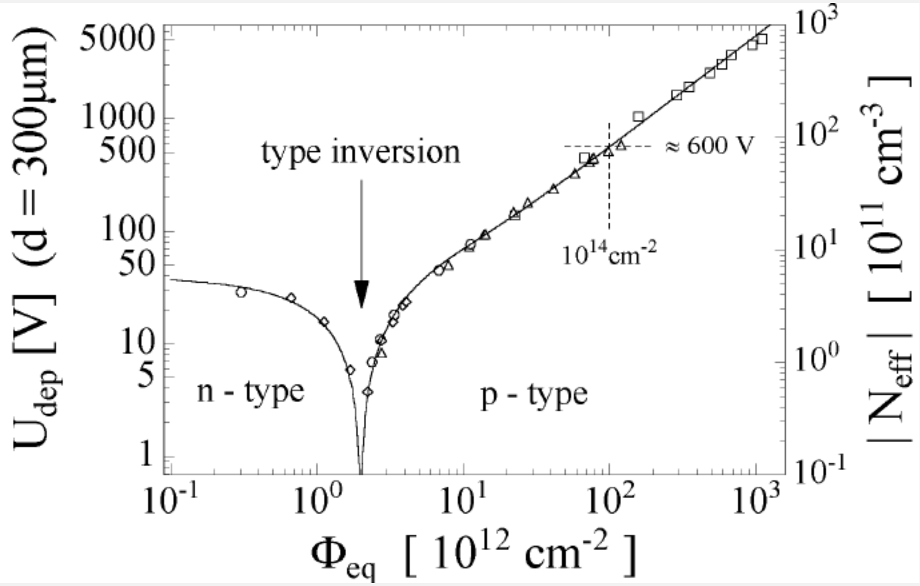
M. Moll, Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties, Ph.D. thesis, Hamburg U. (1999)

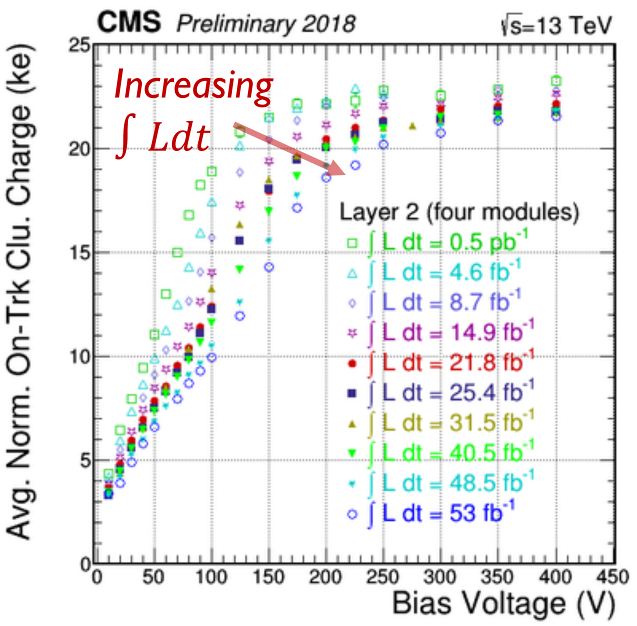
DEPLETION VOLTAGE

- Number of effective doping concentration:

$$N_{eff} = N_c^{dr} + N_c^a + N_r^{a,1} + N_r^{a,2}$$

  - $N_c^{dr}(t;\Phi_{eq})$ **– initial donor removal**
  - $N_c^a(\Phi_{eq}) = g_C\Phi_{eq}$ **– constant damage**
  - $N_r^{a,1}(t,T;\Phi_{eq}) \sim g_A$ **– beneficial annealing**
  - $N_r^{a,2}(t,T;\Phi_{eq}) \sim g_Y$ **– reverse annealing**
- **Two parameter sets** are considered (oxygenated silicon): **RD48-oxy** and **CB-oxy**
- **Fit** of the **depletion voltage** data for **FPix** is performed **to find** optimal value of g_C constant (g_A and g_Y fixed)
- In addition**, log-dependence** of the **constant damage** rate was tested for **FPix** using $N_c^a(\Phi_{eq}) = g_C^{log}\ln(\Phi_{eq})$ as an empiric model
- **Depletion voltage data** is determined **from the cluster charge** (for BPix also from **cluster size**) **vs bias voltage** data
- In order to **fully deplete a sensor**, the **fluence of the innermost part** (r~4.5 for ring 1, r~9.5 cm for ring 2) **of the module** is taken in the depletion voltage simulation



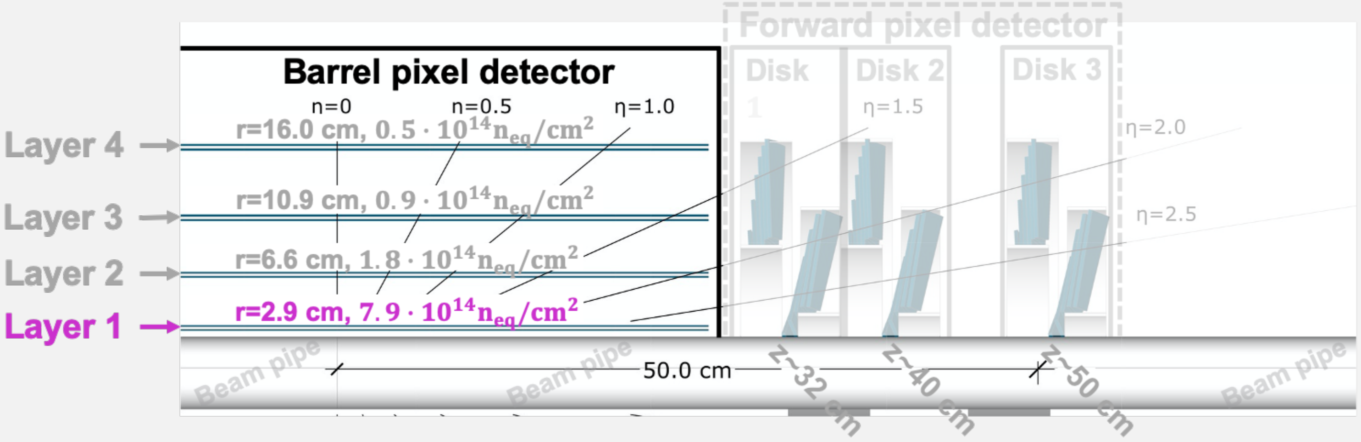


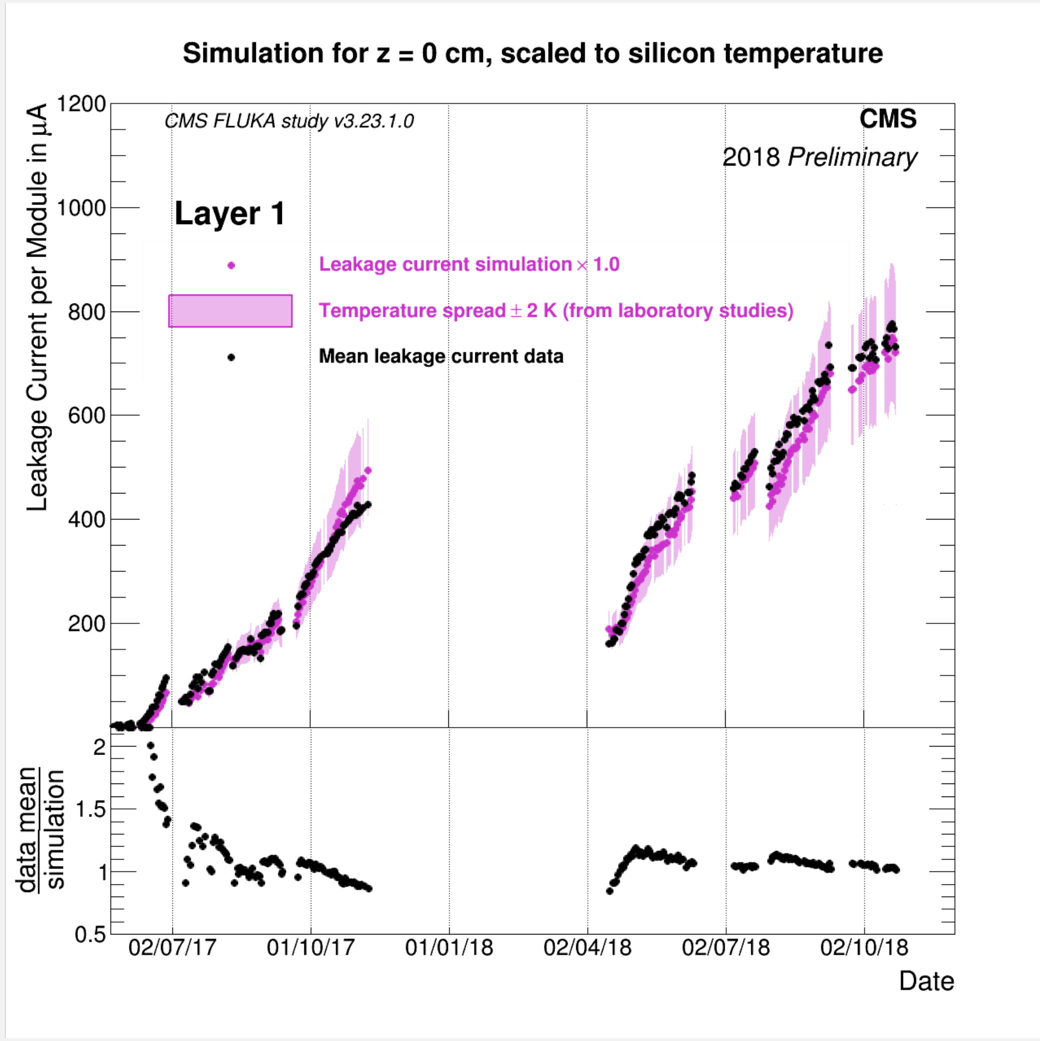
M. Moll, Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties, Ph.D. thesis, Hamburg U. (1999)

BARREL PIXEL RESULTS

LEAKAGE CURRENT RESULTS: BARREL PIXEL, LAYER 1

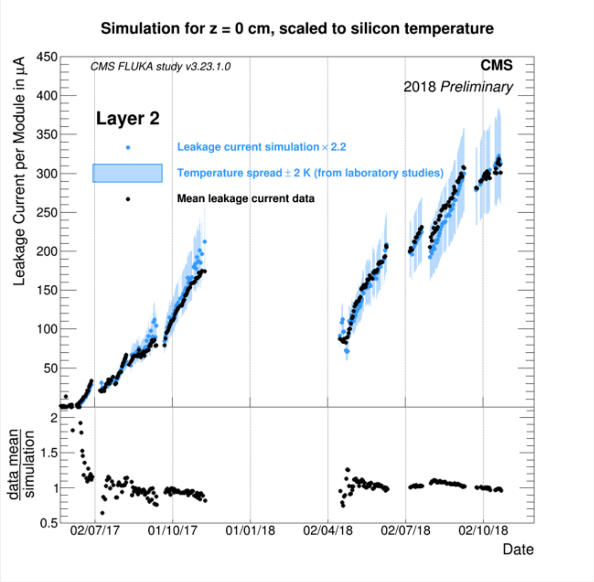
- Simulated leakage current per module scaled to measured temperature
- Satisfactory agreement for Layer 1
- **Temperature** is measured **on top of CO_2 cooling pipe**:
  - added +3℃ during operation as a correction of module temperature

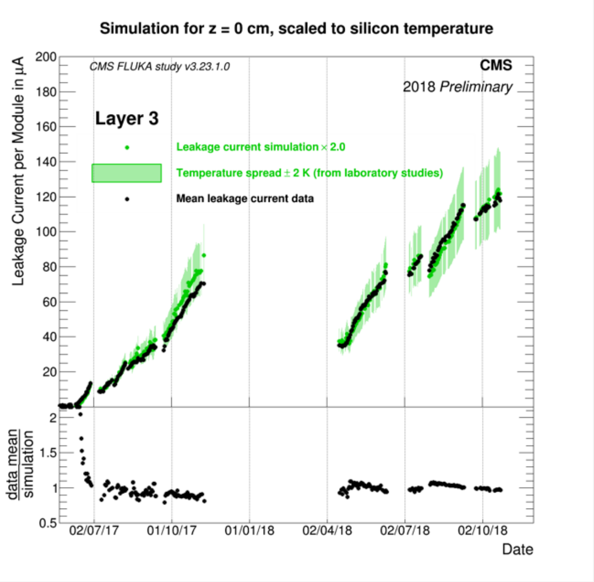


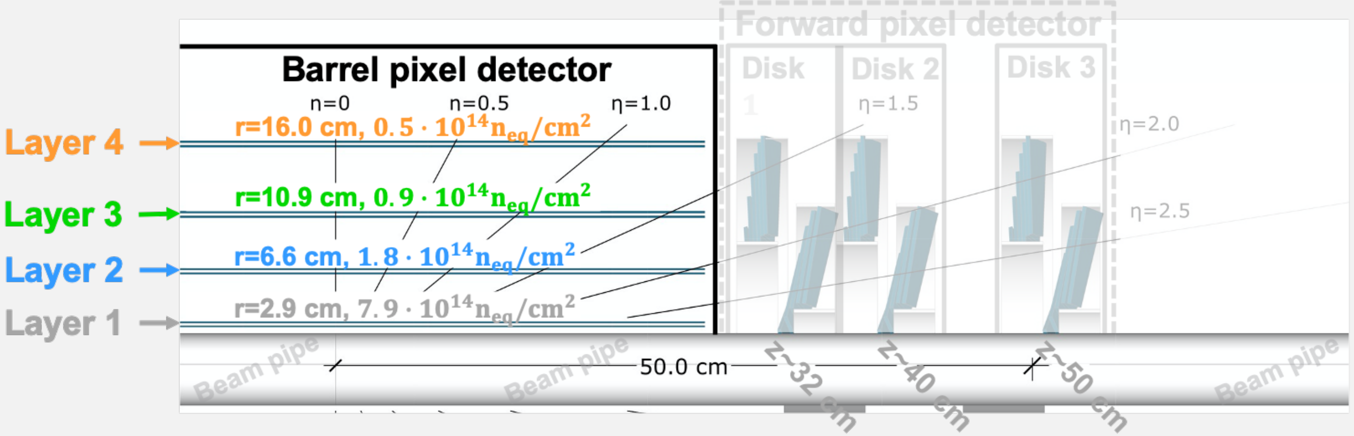


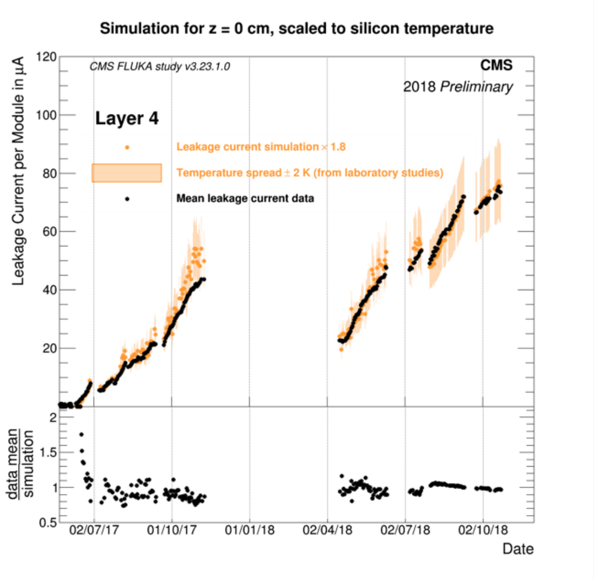
LEAKAGE CURRENT RESULTS: BARREL PIXEL, LAYERS 2,3,4

- Simulated leakage current per module scaled to measured temperature
- Underestimation by about a factor of 2 for Layer 2, 3 and 4. Scale factor is needed.
- **Temperature** is measured **on top of CO_2 cooling pipe**:
  - added +3℃ (+4℃ for layer 4) during operation as a correction of module temperature
- Discrepancy in Layer 2, 3 and 4 might be caused by temperature mismodeling







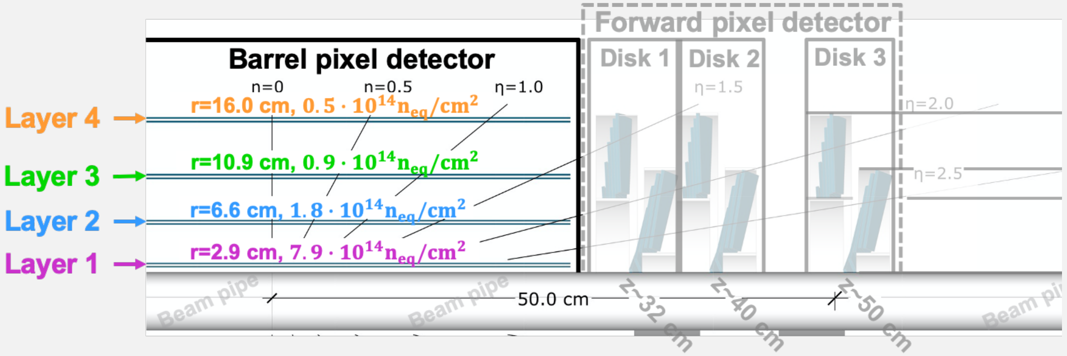


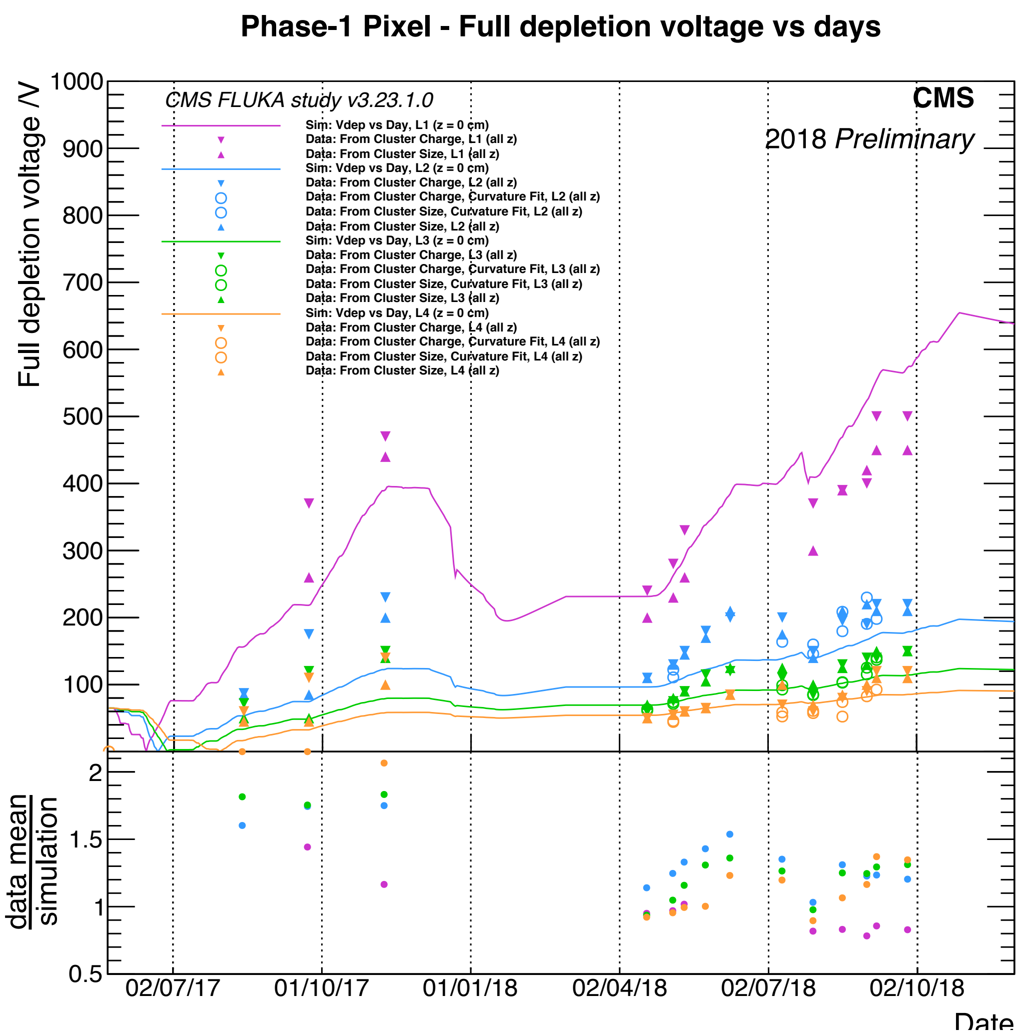
DEPLETION VOLTAGE RESULTS: BARREL PIXEL

- Use N_{eff} as calculated from the Hamburg model. CB-oxy parameter set is considered for the simulation
- Full depletion Voltage:

$$V_{depl} = |N_{eff}| \frac{qd^2}{2\epsilon\epsilon_0}$$

- Data obtained from HV scan during operation:
  - Avg. cluster charge and size are determined as a function of bias voltage
  - The full depletion voltage is estimated from the kink in the respective distributions
- Layer 1 to be replaced during LS2. Layer 2 depletion voltage to be expected at 650 V at the end of Run 3



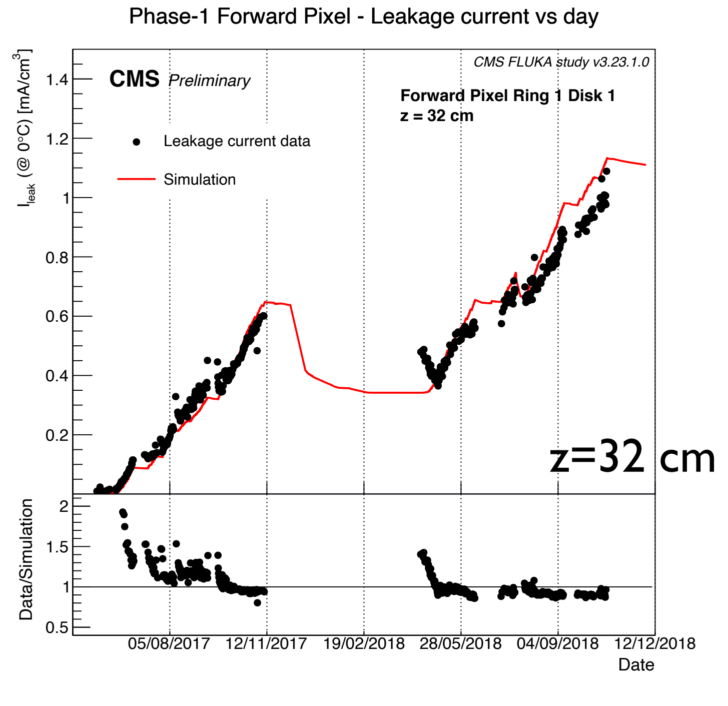


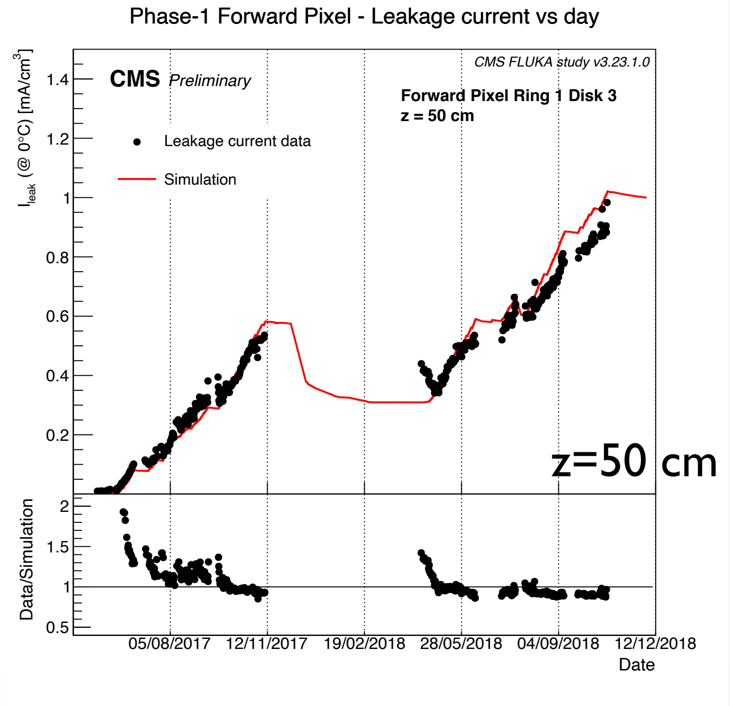
NEW!

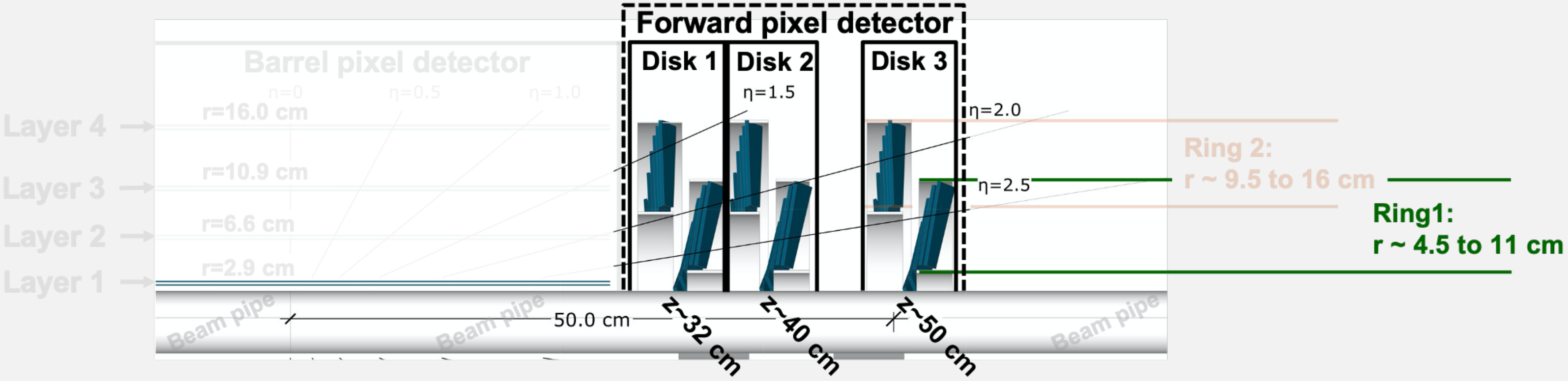
FORWARD PIXEL RESULTS

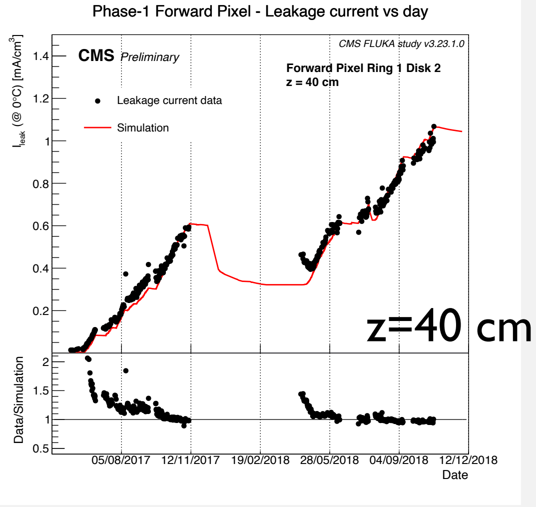
LEAKAGE CURRENT RESULTS: FORWARD PIXEL, RING 1

- Leakage current per volume scaled to 0°C
- Good agreement between data and simulation for Ring 1:
  - No scale factor required
  - **Temperature** reading on module, T-sensor **on top of the HDI**
- FLUKA prediction reliable in full z range
- Discrepancy at the start of run periods in 2017 and 2018 probably due to temperature underestimation





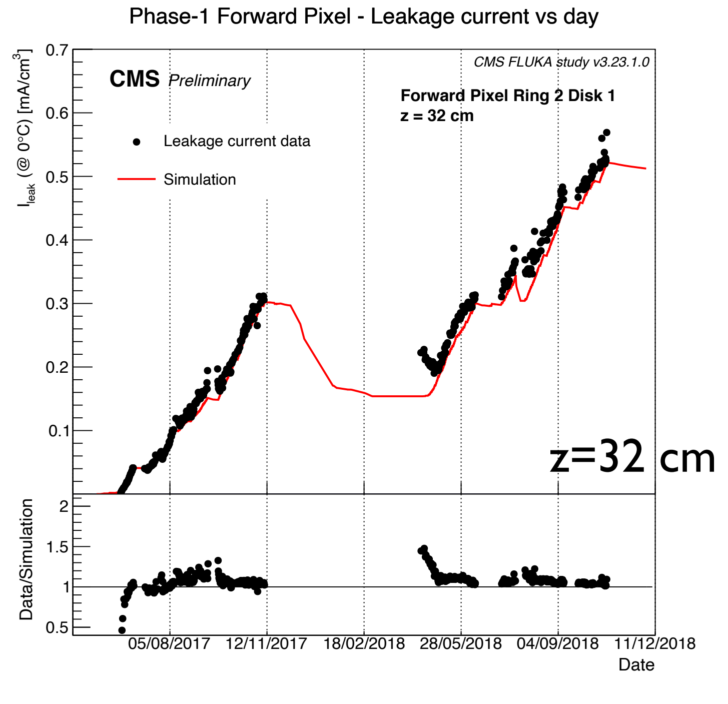


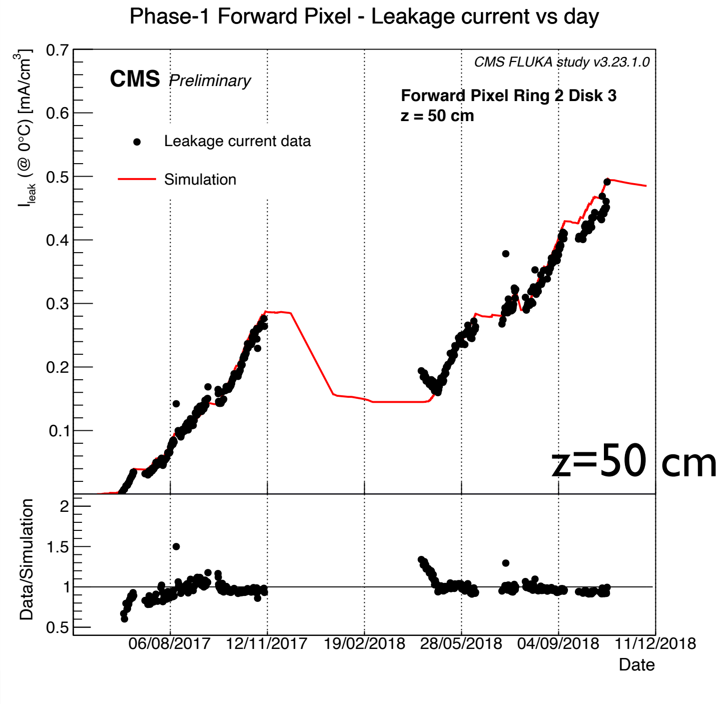


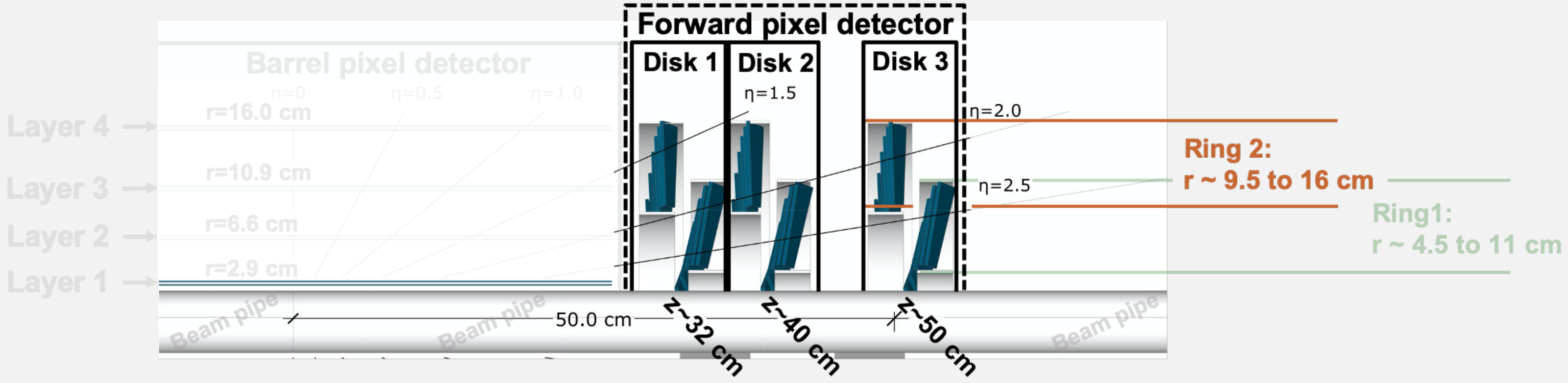
Φ_{eq}\Disk	**Disk 1**	**Disk 2**	**Disk 3**
Final fluence (L_{int}=120 fb^{-1})	$1.71 \cdot 10^{14}\, n_{eq}/cm^3$	$1.62 \cdot 10^{14}\, n_{eq}/cm^3$	$1.56 \cdot 10^{14}\, n_{eq}/cm^3$

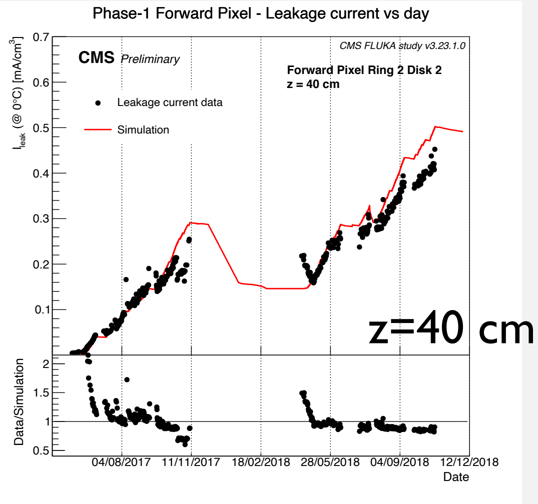
LEAKAGE CURRENT RESULTS: FORWARD PIXEL, RING 2

- Leakage current per volume scaled to 0℃
- Good agreement between data and simulation for Ring 2:
  - No scale factor required
  - **Temperature** reading on module, T-sensor **on top of the HDI**
- FLUKA prediction reliable in full z range
- Discrepancy at the start of run periods in 2017 and 2018 probably due to temperature underestimation



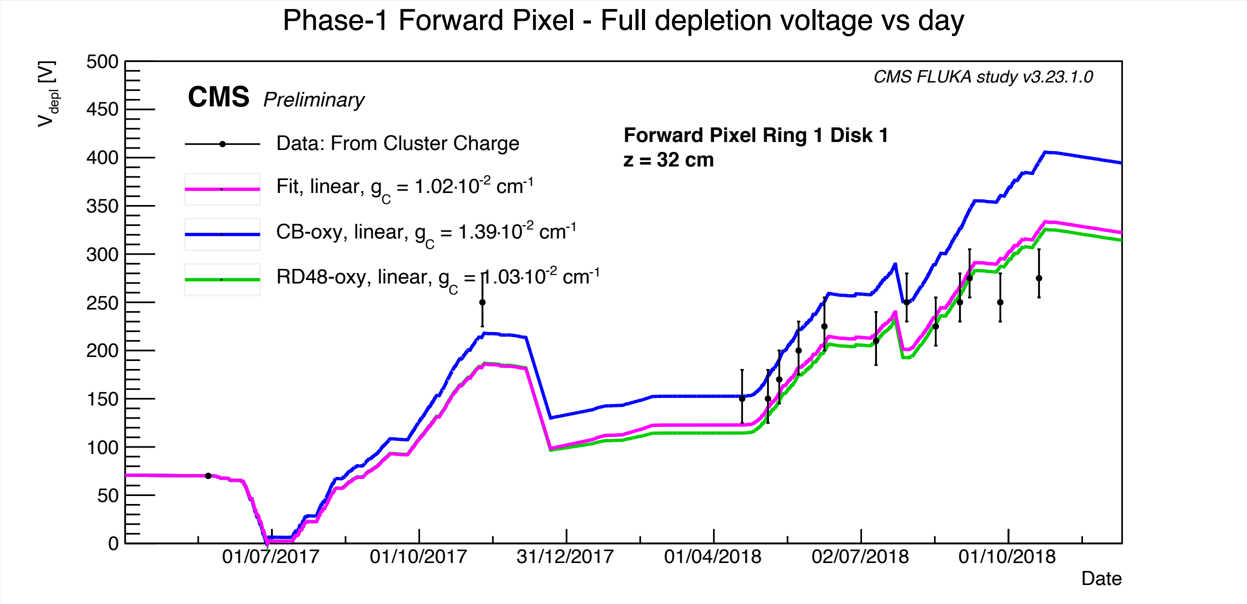


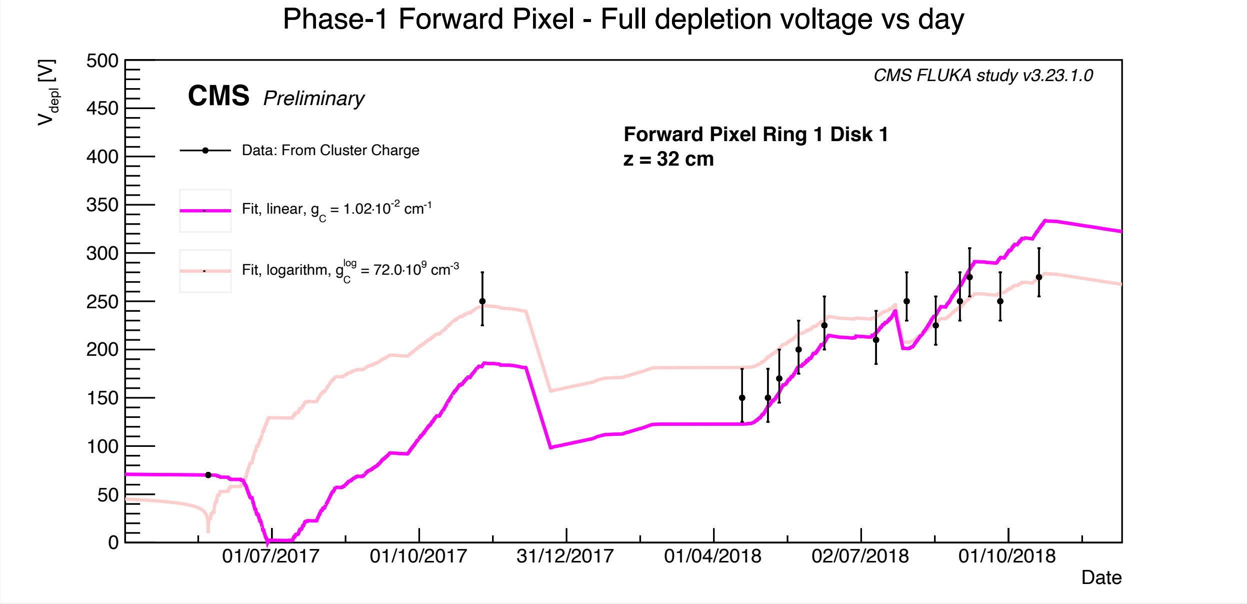




Φ_{eq}\Disk	Disk 1	Disk 2	Disk 3
Final fluence (L_{int}=120 fb^{-1})	$0.81 \cdot 10^{14}\, n_{eq}/cm^3$	$0.78 \cdot 10^{14}\, n_{eq}/cm^3$	$0.76 \cdot 10^{14}\, n_{eq}/cm^3$

DEPLETION VOLTAGE: RING 1, DISK 1



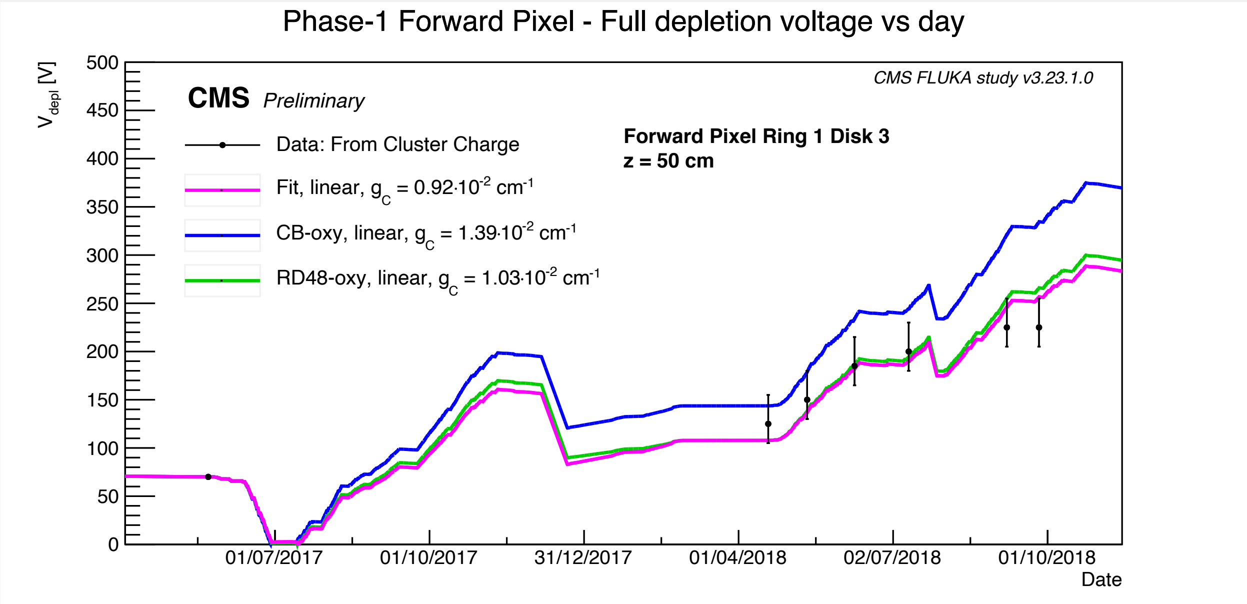


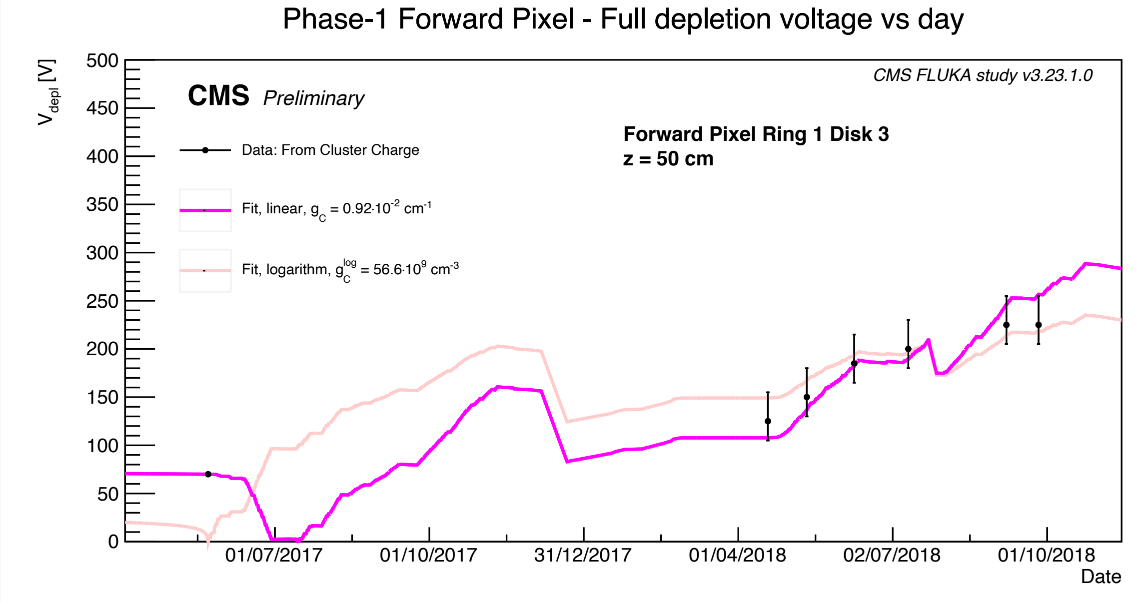
- Depletion voltage results for Ring 1, Disk 1.
- Fit g_C parameter, assuming linear model, with g_A= 1.4x10^{-2} cm^{-1}, and g_Y=7x10^{-2} cm^{-1} fixed
- Data is obtained from the average cluster charge distribution vs. bias voltage – kink of the distribution
- Fit is done only for 2018 data points
- Logarithmic model for N_C tested – try to find an effective empiric model
- Final fluence assumed for the innermost slice of Ring 1, Disk 1: $3.32 \cdot 10^{14}\ n_{eq}/cm^2$

Final fluence of the innermost slice of the module for Run 2 (10^{14} n_{eq}/cm^2), L_{int}=120 fb^{-1}

Ring\Disk	Disk 1	Disk 2	Disk 3
Ring 1	3.32	2.99	2.92
Ring 2	1.15	1.11	1.09

DEPLETION VOLTAGE: RING 1, DISK 3





- Depletion voltage results for Ring 1, Disk 3.
- Fit g_C parameter, assuming linear model, with $g_A = 1.4\text{x}10^{-2}$ cm^{-1}, and $g_Y = 7\text{x}10^{-2}$ cm^{-1} fixed
- Data is obtained from the average cluster charge distribution vs. bias voltage – kink of the distribution
- Fit is done only for 2018 data points
- Logarithmic model for N_C tested – try to find an effective empiric model
- Final fluence assumed for the innermost slice of Ring 1, Disk 3: $2.92 \cdot 10^{14}\, n_{eq}/cm^2$

Final fluence of the innermost slice of the module for Run 2 (10^{14} n_{eq}/cm^2), L_{int}=120 fb^{-1}

Ring\Disk	Disk 1	Disk 2	Disk 3
Ring 1	3.32	2.99	2.92
Ring 2	1.15	1.11	1.09

CONCLUSIONS

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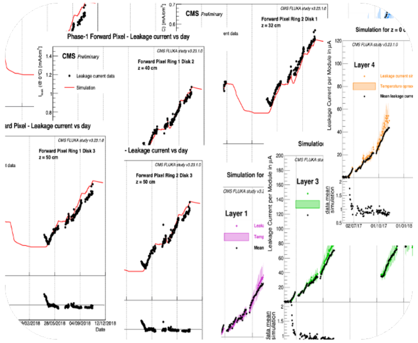
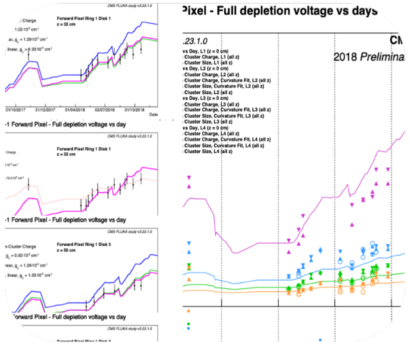


Leakage current studies:

- Good agreement for Layer 1, scale factor of ~2 is needed for Layer 2-4
- Good agreement for FPix (no need for scale factors, better knowledge of the temperature)

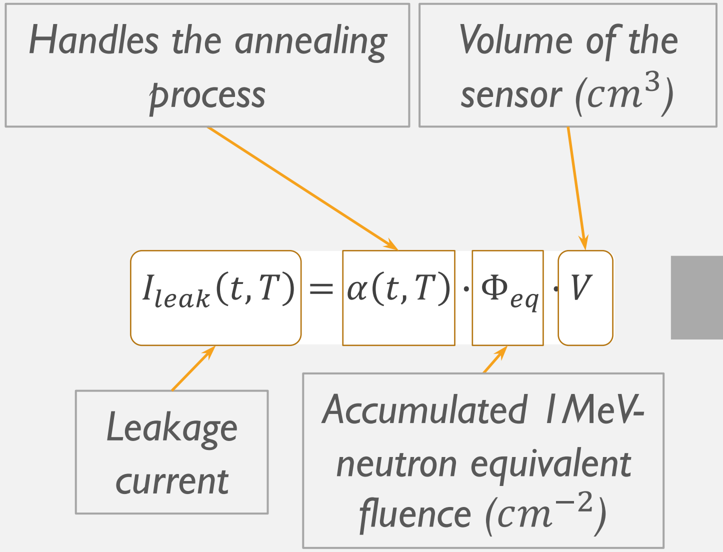


Depletion voltage studies:

- BPix: underestimation for Layers 2-4, underestimation in 2017 and overestimation at the end of 2018 for Layer 1
- FPix: fit results for g_C parameter is close to "-oxy" models.
- Logarithmic dependence of N_C on fluence was tested. Better agreement in 2017 and at the end 2018 data.

BACK UP

SIMULATION OF THE LEAKAGE CURRENT



Handles the annealing process

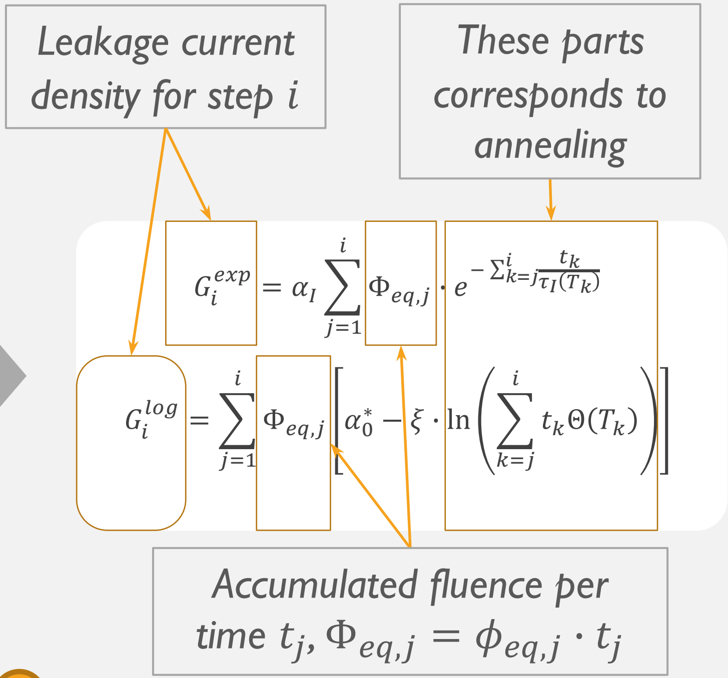
Volume of the sensor (cm^3)

$$I_{leak}(t,T) = \alpha(t,T) \cdot \Phi_{eq} \cdot V$$

Leakage current

Accumulated 1MeV-neutron equivalent fluence (cm^{-2})

① Leakage current depends on the accumulated fluence, $\alpha(t,T)$ function responsible for the annealing and volume of the sensor



Leakage current density for step i

These parts corresponds to annealing

$$G_i^{exp} = \alpha_I \sum_{j=1}^{i} \Phi_{eq,j} \cdot e^{-\sum_{k=j}^{i} \frac{t_k}{\tau_I(T_k)}}$$

$$G_i^{log} = \sum_{j=1}^{i} \Phi_{eq,j} \left[\alpha_0^* - \xi \cdot \ln\left(\sum_{k=j}^{i} t_k \Theta(T_k) \right) \right]$$

Accumulated fluence per time t_j, $\Phi_{eq,j} = \phi_{eq,j} \cdot t_j$

② Dividing whole run period by N chunks, we define leakage current density $G_i (= G_i^{exp} + G_i^{log})$ for step i, using accumulated fluence and temperature information from previous steps $k (= 1 \text{ to } i)$ of duration t_k (might be different for different steps).

$$I_{leak}^{i} = \left(G_i^{exp} + G_i^{log}\right) \cdot V$$

$$I_{leak}(T) = I_{leak}(T_{ref}) \cdot \left(\frac{T}{T_{ref}}\right)^2 \exp\left(-\frac{E_g^*}{2k_B}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$$

③ Leakage current for each step is calculated by multiplying the current density by volume of the sensor. The last equation is used to scale the simulated (measured) leakage current from the temperature T_{ref} it is simulated (performing the measurement) at to the specified temperature T. $E_g^* = 1.21\ eV$, k_B is the Boltzmann constant.

M. Moll, Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties, Ph.D. thesis, Hamburg U. (1999)

DEPLETION VOLTAGE: SIM AND DATA

- $N_{eff}(t,T;\phi_{eq}) = \boldsymbol{N_c^{dr}(t;\phi_{eq})} + \boldsymbol{N_c^{a}(t;\phi_{eq})} + \boldsymbol{N_r^{a,1}(t,T;\phi_{eq})} + \boldsymbol{N_r^{a,2}(t,T;\phi_{eq})}$ - number of effective doping concentration
- $\boldsymbol{V_{depl}} = \boldsymbol{\frac{e\cdot d^2}{2\epsilon_r\epsilon_0}} \cdot \boldsymbol{\left|N_{eff}\left(t,T;\phi_{eq}(r_0 - \Delta r/2)\right)\right|}$ - depletion voltage as a function of effective doping concentration. $\boldsymbol{\phi_{eq}(r_0 - \Delta r/2)}$ **is a fluence/time** (flux) for the **nearest slice of a FPix module**.
- **Reverse annealing:** $N_r^{a,2}(t,T;\phi_{eq}) = \boldsymbol{g_Y}\frac{\phi_{eq}}{k_Y}\left(k_Y t + e^{-k_Y t} - 1\right) + N_0^{nd}\left(1 - e^{-k_Y t}\right)$
- **Initial donor removal**: $N_c^{dr}(t;\phi_{eq}) = N_{eff}^{0,nr} + N_{c,0}\cdot\left(1 - e^{-c\phi_{eq}(t)t}\right)$
- **Constant damage**: $N_c^{a}(t;\phi_{eq}) = \boldsymbol{g_C}\phi_{eq}(t)t$
- **Beneficial annealing**: $N_r^{a,1}(t,T;\phi_{eq}) = \frac{g_A\phi_{eq}}{k_A}\left(1 - e^{-k_A t}\right) + N_0^{a,1}\cdot e^{-k_A t}$

FUNCTIONS AND CONSTANTS

Function, relation or constant	Expression
Time/temperature scaling function	$\Theta(T; T_{ref}) = \exp\left(-\frac{E_I^*}{k_B}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$
Arrhenius law	$\frac{1}{\tau_I} = k_{0I} \cdot \exp\left(-\frac{E_I}{k_B T}\right)$
α_I	$(1.23 \pm 0.06) \cdot 10^{-17}\ [A\ cm^{-1}]$
k_{0I}	$\left(1.23^{+5.3}_{-1.0}\right) \cdot 10^{13}\ [s^{-1}]$
E_I	$1.11 \pm 0.05\ [eV]$
α_0^*	$7.07 \cdot 10^{-17}\ [A\ cm^{-1}]$
ξ	$3.07 \cdot 10^{-18}\ [A\ cm^{-1}]$
E_I^*	$1.30 \pm 0.14\ [eV]$
E_g^*	$1.21\ [eV]$
k_B	$8.6173303 \cdot 10^{-5}\ [eV\ K^{-1}]$

PARAMETER SETS

Parameter set name	**Constants ($10^{-2}\ cm^{-1}$)**						**References**
	Neutrons			**Protons**			
	g_A	g_Y	g_C	g_A	g_Y	g_C	
RD48-oxy	1.4	4.8	2.0	1.4	7.4	0.5	The ROSE Collaboration, R&D on Silicon for future Experiments. 3rd RD48 Status Report. CERN/LHCC 2000-009, LEB Status Report/RD48. 1999.
CB-oxy	1.4	5.7	1.6	1.4	4.8	0.5	M. Moll. Hamburg model parameter sheet. Personal communication (C. Barth, T. Rohe). November 3, 2017.