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The Compact Muon Solenoid Experiment

CMS Performance Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

25 May 2021

Measurement and modelling of the leakage current and depletion voltage in Phase-1 Forward Pixel

CMS Collaboration

Abstract

This Detector Performance Summary shows a comparison between the modelling and measurement of the leakage current and depletion voltage in Phase-1 Forward Pixel.

LEAKAGE CURRENT AND DEPLETION VOLTAGE PLOTS. FORWARD PIXEL

cms-tracker-runcoord@cern.ch

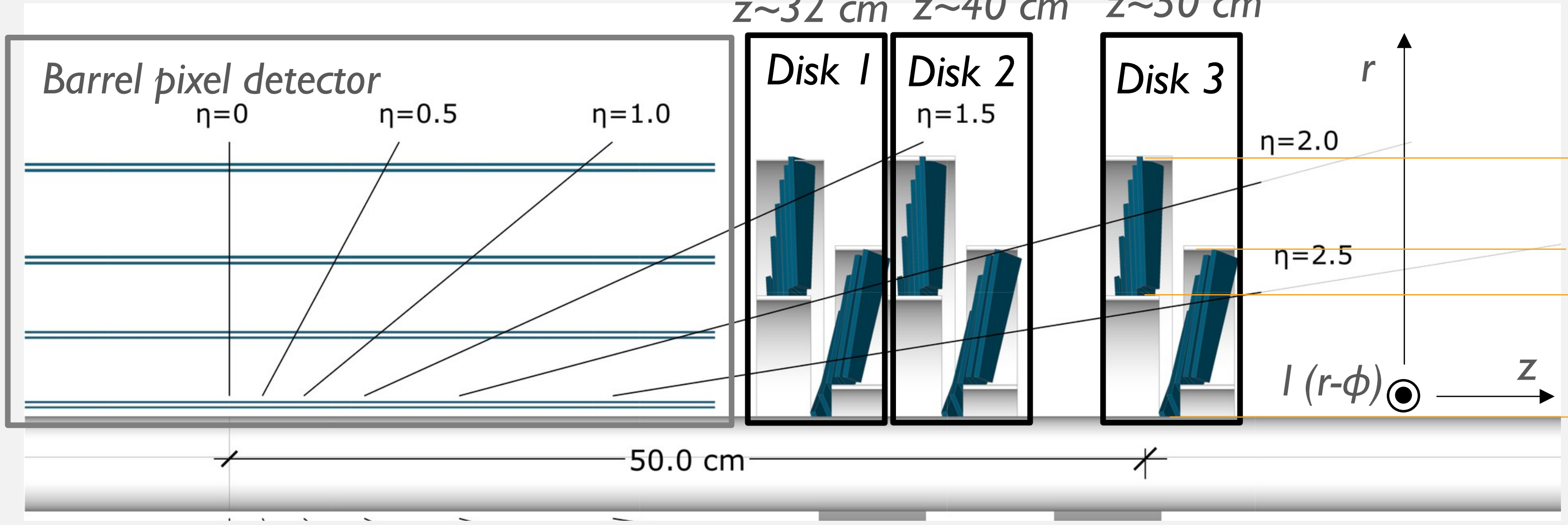
INTRODUCTION

- The pixel detector is the innermost part of the CMS
- Two parts: barrel and forward
- The forward pixel detector is divided by disks and rings (picture below), which are sets of modules – n+-in-n sensors with dimensions 6.42x1.68x0.0285 (Δr, Δl, Δz) cm^3
- Since the pixel detector is the innermost part of the detector, the monitoring of the radiation damage in it is important.
- Macroscopic physics effect of the radiation damage is change in the leakage current and the full depletion voltage.

Disk 1: z~32 cm

Disk 2: z~40 cm

Disk 3: z~50 cm

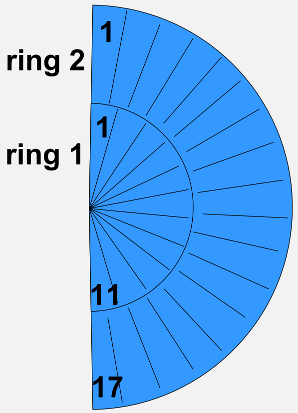


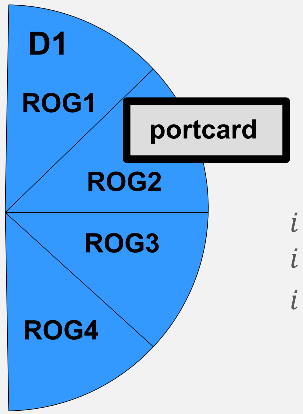
Ring 2: r ~ 9.5 to 16 cm

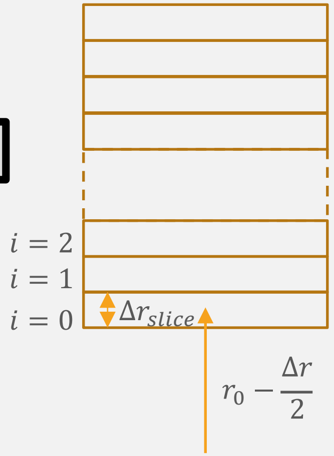
Ring1: r ~ 4.5 to 11 cm

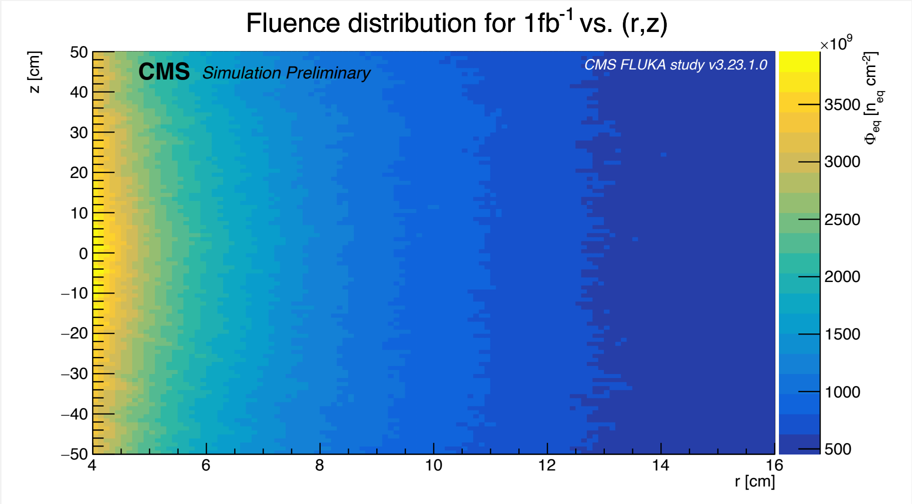
RADIATION DAMAGE SIMULATION: FPIX CASE

- Temperature reading from a sensor is the temperature measured on the High-Density Interconnect (HDI) of the corresponding module.
- A set of modules (read-out group, ROG) of a half disk is connected to a corresponding portcard.
- Leakage current reading from a portcard is the sum of the currents of all the modules of the corresponding ROG. Number of modules per ROG vary.
- The temperature reading assigned to a portcard/ROG is the temperature of one of the modules of the corresponding ROG. This temperature is assigned to all of the modules of the ROG.
- **Leakage current:** Average fluence for the module with volume V: $\frac{1}{V}\int \Phi_{eq}(r,z)dV \rightarrow \frac{1}{N}\sum_i \Phi_{eq,i}$, where N is the number of slices.
- **Depletion voltage:** 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









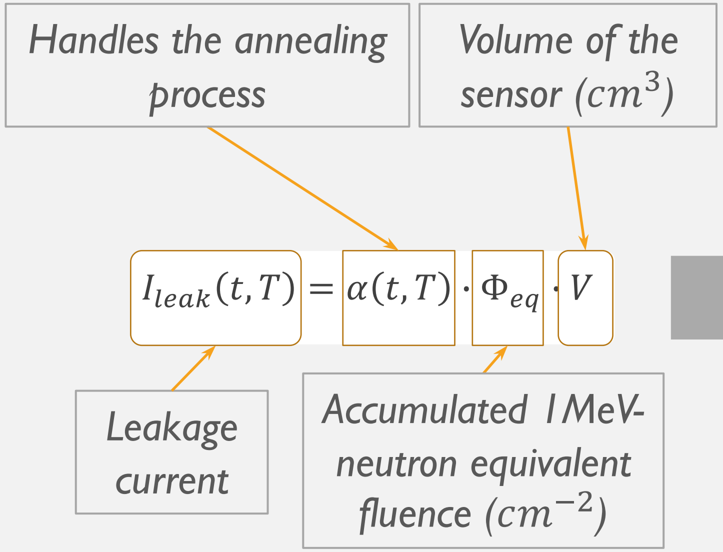
Final fluence of the innermost slice of the module for Run 2 (10^{14} n_{eq}/cm^2)

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

Final average fluence for Run 2 (10^{14} n_{eq}/cm^2)

Ring\Disk	Disk 1	Disk 2	Disk 3
Ring 1	1.71	1.62	1.56
Ring 2	0.81	0.78	0.76

SIMULATION OF THE LEAKAGE CURRENT



Handles the annealing process

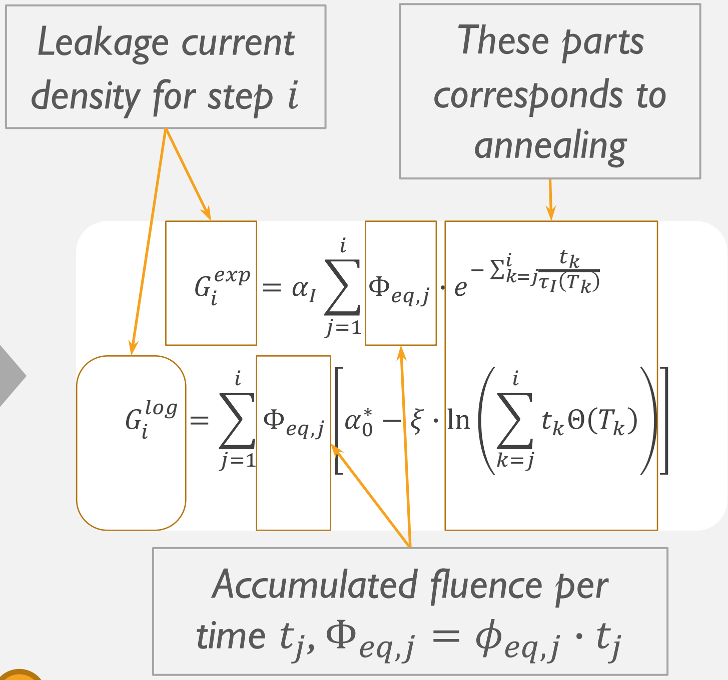
Volume of the sensor (cm^3)

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

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).

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

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

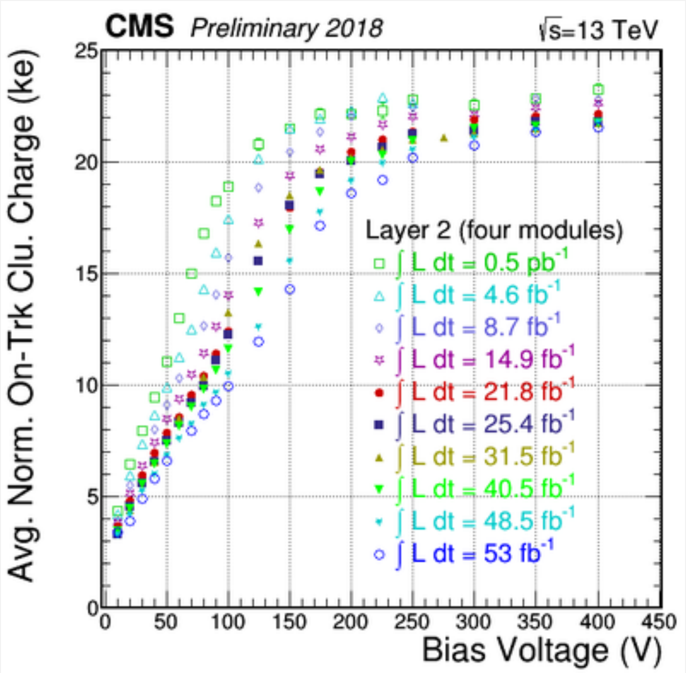
③ Leakage current for each step is calculated by multiplying the current density by volume of the sensor. The last equation is used to scale the simulated (measured) leakage current from the temperature T_{ref} it is simulated (performing the measurement) at to the specified temperature T. $E_g = 1.21\ eV$, 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
- $\boldsymbol{V_{depl} = \frac{e \cdot d^2}{2\epsilon_r \epsilon_0} \cdot \left| N_{eff}\left(t,T;\phi_{eq}(r_0 - \Delta r/2)\right)\right|}$ - 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:** $N_r^{a,2}(t,T;\phi_{eq}) = \boldsymbol{g_Y} \frac{\phi_{eq}}{k_Y}\left(k_Y t + e^{-k_Y t} - 1\right) + N_0^{nd}\left(1 - e^{-k_Y t}\right)$
- **Dopant 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**: $N_r^{a,1}(t,T;\phi_{eq}) = \frac{\boldsymbol{g_A}\phi_{eq}}{k_A}\left(1 - e^{-k_A t}\right) + N_0^{a,1} \cdot e^{-k_A t}$
- At the end we can **express $\boldsymbol{N_{eff}}$** as a function of **g parameters and fit $\mathbf{g_C}$ parameter**, with $g_Y = 7 \cdot 10^{-2}\ cm^{-1}$, $g_A = 1.4 \cdot 10^{-2}\ cm^{-1}$ fixed.
- In addition, **we test logarithmic dependence of constant damage rate $\boldsymbol{N_c^{a}(t;\phi_{eq})}$** on fluence: $N_c^{a}(t;\phi_{eq}) = g_C \ln(\phi_{eq}(t)t)$.
- Depletion voltage data is determined from the cluster charge vs bias voltage data.

We define the depletion voltage as the value of the bias voltage at which charge saturation is obtained.



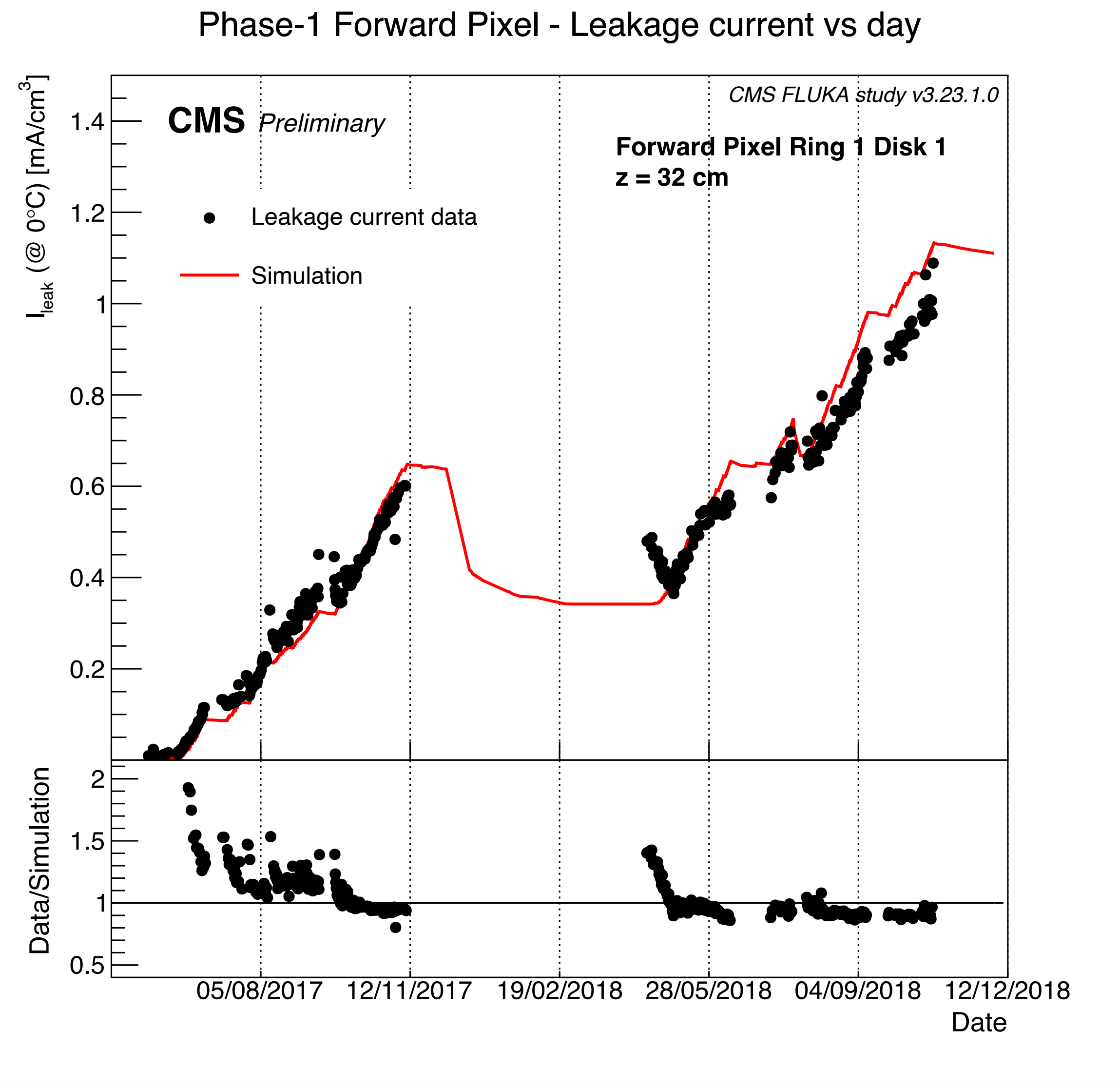
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlotsOctober2018#Bias_Voltage_Scans

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	$8.6173303 \cdot 10^{-5}\ [eV\ K^{-1}]$

LEAKAGE CURRENT PLOTS

LEAKAGE CURRENT: RING 1, DISK 1

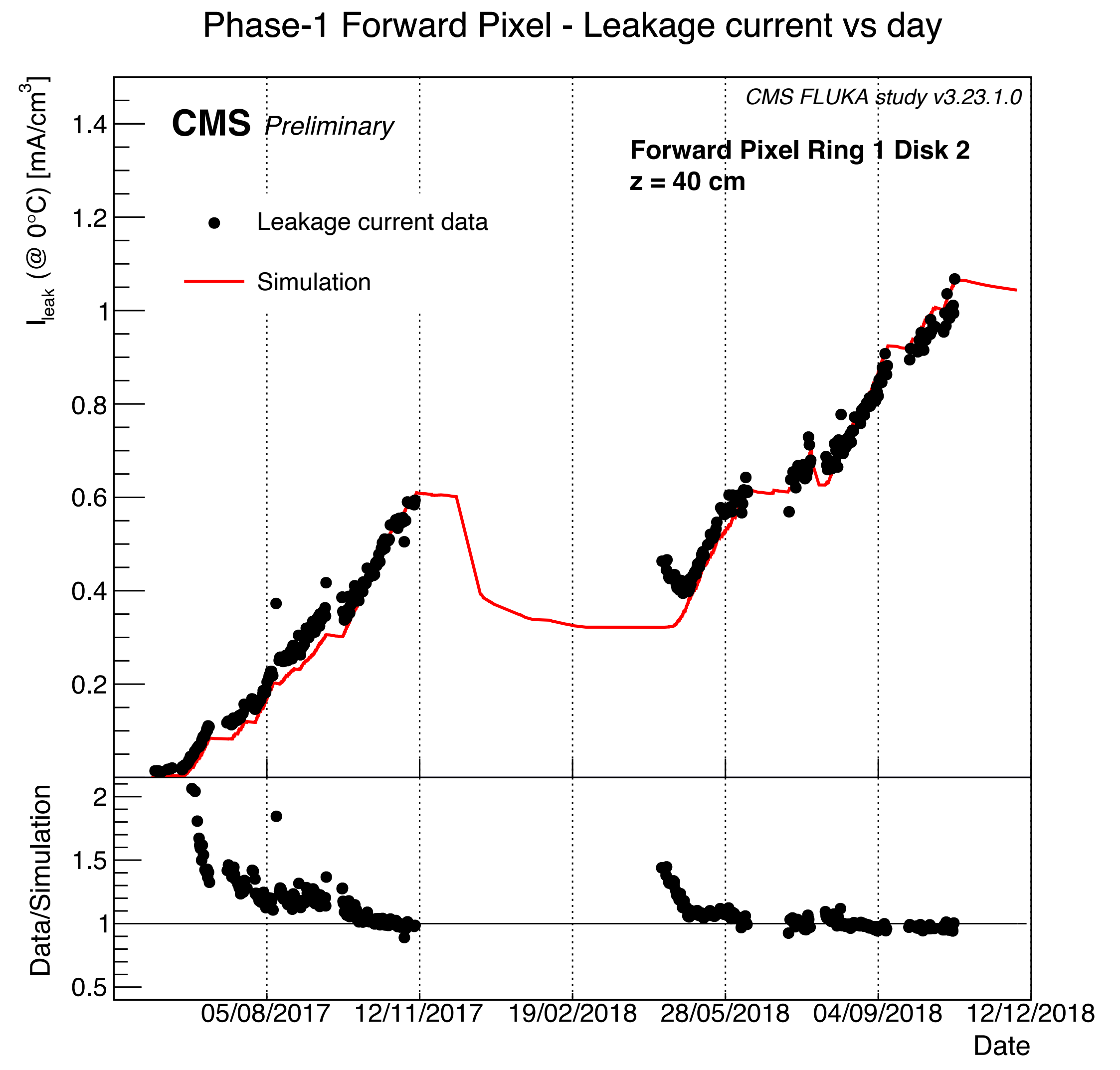


The expected leakage current in each of the forward pixel disks is calculated based on the full temperature and irradiation history using the empirical radiation damage model $I(\Phi, t, T) = I0 + \alpha(t,T)\cdot\Phi\cdot V$. Radiation-induced increase of leakage current depends on fluence Φ, time t, temperature T, volume V. The α-parameter set for the radiation damage model used comes from M. Moll, Radiation Damage in Silicon Particle Detectors, Universität Hamburg, DESY-THESIS-1999-040, 1999 https://mmoll.web.cern.ch/mmoll/thesis/.

For the simulation, a FLUKA fluence simulation (v3.23.1.0) was used with high granular resolution and detector geometry as input. Actual temperature history is taken from the database where on-module temperature sensor measurements for each readout group (ROG) are stored: only one module temperature per ROG is read out and the temperature of the other modules belonging to the same ROG is assumed to be the same. The low luminosity periods at the start of the data taking 2017 and 2018 have a large difference between prediction and measurements. This is probably due to temperature effects that are not fully taken into account yet. No rescaling factors are applied. The integrated luminosity for 2017 is 50 fb^{-1} and for 2018 is 70 fb^{-1}.

The leakage current data is from the CMS forward pixel detector, averaged over all the modules in the ROG, and rescaled to T=0^{o}C.

LEAKAGE CURRENT: RING 1, DISK 2



The expected leakage current in each of the forward pixel disks is calculated based on the full temperature and irradiation history using the empirical radiation damage model $I(\Phi, t, T) = I0 + \alpha(t,T)\cdot\Phi\cdot V$. Radiation-induced increase of leakage current depends on fluence Φ, time t, temperature T, volume V. The α-parameter set for the radiation damage model used comes from M. Moll, Radiation Damage in Silicon Particle Detectors, Universität Hamburg, DESY-THESIS-1999-040, 1999 https://mmoll.web.cern.ch/mmoll/thesis/.

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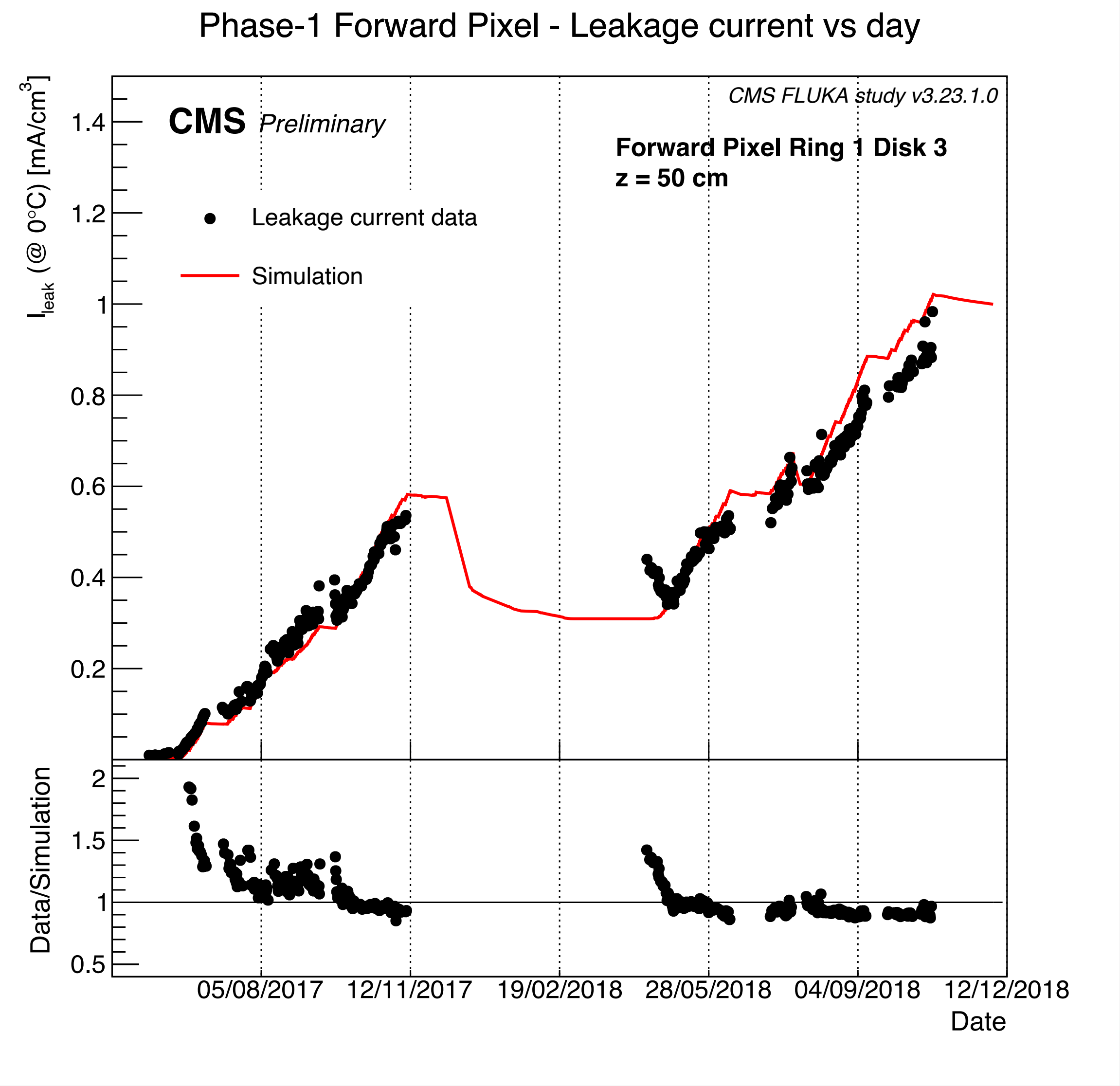
The leakage current data is from the CMS forward pixel detector, averaged over all the modules in the ROG, and rescaled to T=0°C.

LEAKAGE CURRENT: RING 1, DISK 3



The expected leakage current in each of the forward pixel disks is calculated based on the full temperature and irradiation history using the empirical radiation damage model $I(\Phi, t, T) = I0 + \alpha(t,T)\cdot\Phi\cdot V$. Radiation-induced increase of leakage current depends on fluence Φ, time t, temperature T, volume V. The α-parameter set for the radiation damage model used comes from M. Moll, Radiation Damage in Silicon Particle Detectors, Universität Hamburg, DESY-THESIS-1999-040, 1999 https://mmoll.web.cern.ch/mmoll/thesis/.

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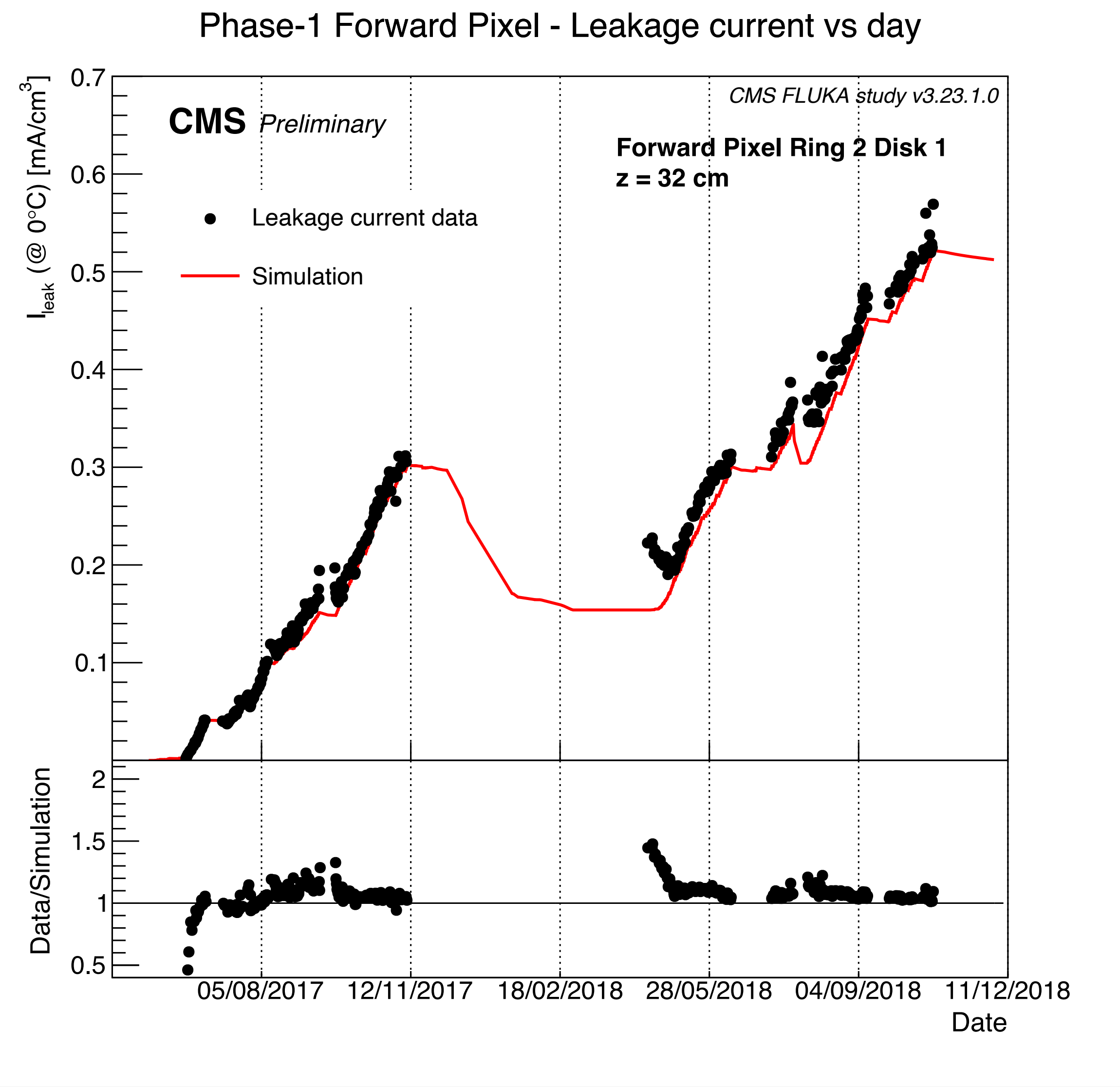
The leakage current data is from the CMS forward pixel detector, averaged over all the modules in the ROG, and rescaled to T=0°C.

LEAKAGE CURRENT: RING 2, DISK 1



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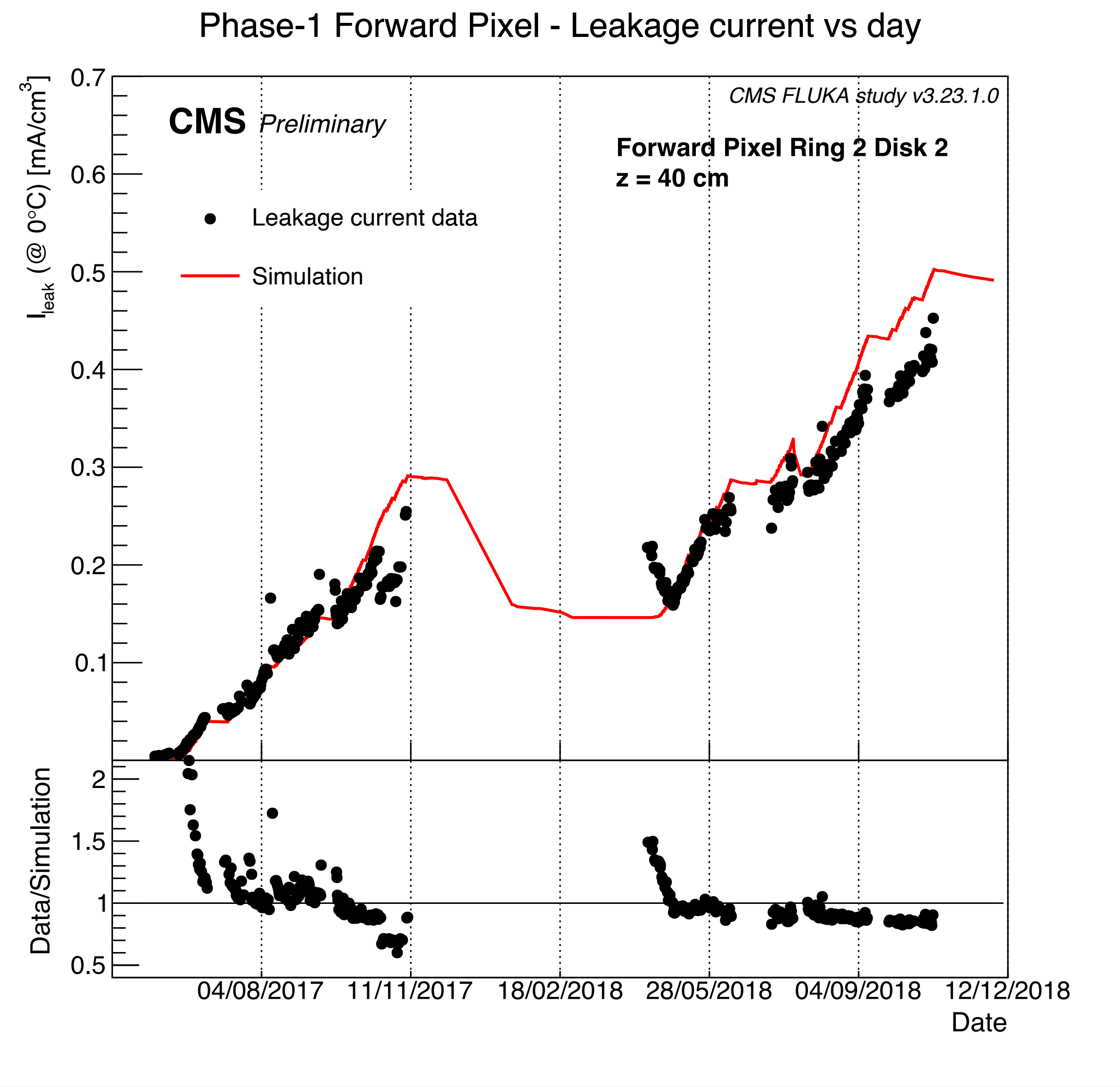
The leakage current data is from the CMS forward pixel detector, averaged over all the modules in the ROG, and rescaled to T=0°C.

LEAKAGE CURRENT: RING 2, DISK 2



The expected leakage current in each of the forward pixel disks is calculated based on the full temperature and irradiation history using the empirical radiation damage model $I(\Phi, t, T) = I0 + \alpha(t,T)\cdot\Phi\cdot V$. Radiation-induced increase of leakage current depends on fluence Φ, time t, temperature T, volume V. The α-parameter set for the radiation damage model used comes from M. Moll, Radiation Damage in Silicon Particle Detectors, Universität Hamburg, DESY-THESIS-1999-040, 1999 https://mmoll.web.cern.ch/mmoll/thesis/.

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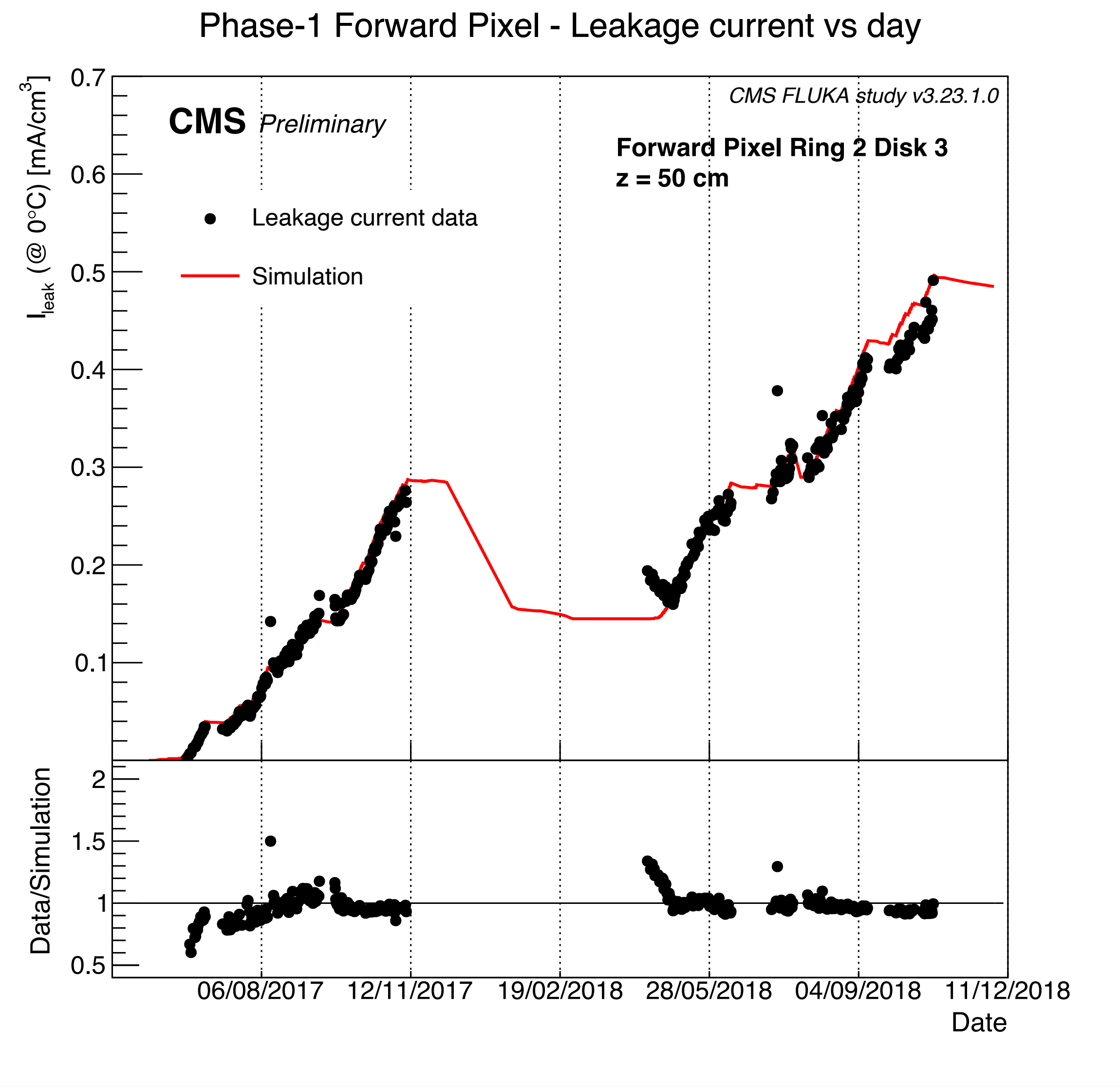
The leakage current data is from the CMS forward pixel detector, averaged over all the modules in the ROG, and rescaled to T=0°C.

LEAKAGE CURRENT: RING 2, DISK 3



The expected leakage current in each of the forward pixel disks is calculated based on the full temperature and irradiation history using the empirical radiation damage model I(Φ, t, T) = I0 + α(t,T)·Φ·V. Radiation-induced increase of leakage current depends on fluence Φ, time t, temperature T, volume V. The α-parameter set for the radiation damage model used comes from M. Moll, Radiation Damage in Silicon Particle Detectors, Universität Hamburg, DESY-THESIS-1999-040, 1999 https://mmoll.web.cern.ch/mmoll/thesis/.

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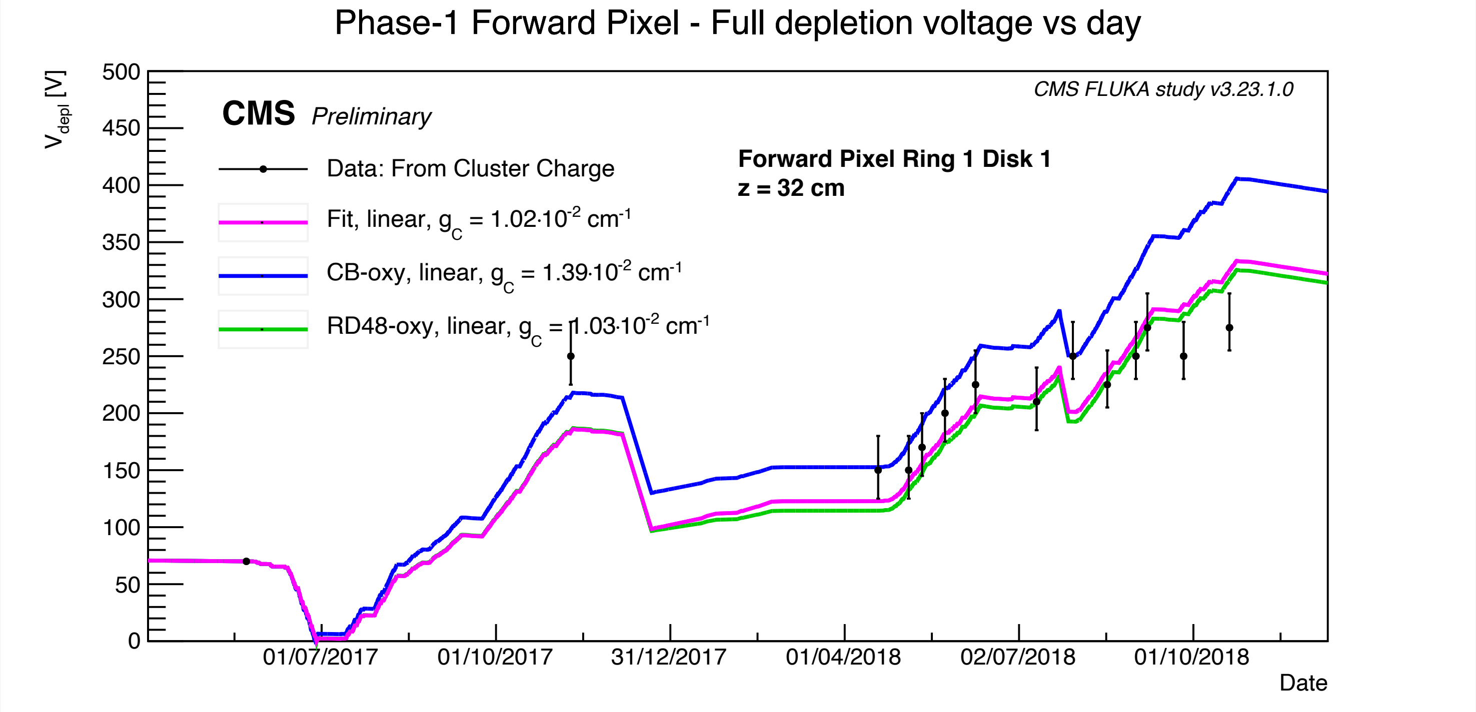
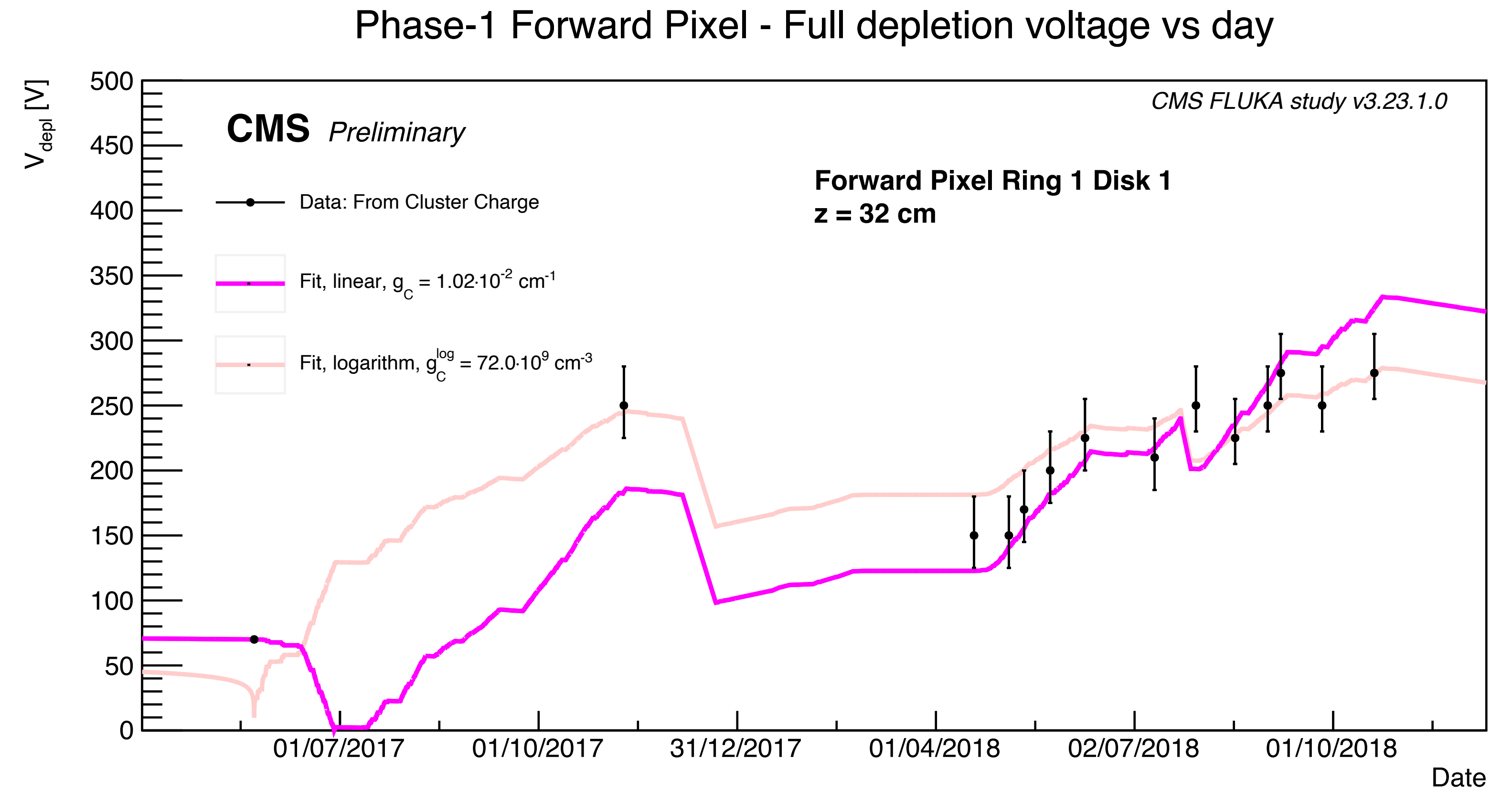
DEPLETION VOLTAGE

DEPLETION VOLTAGE. DISK 1, RING 1



Based on the full temperature and irradiation history the expected full depletion voltages of the forward pixel tracker disks are simulated using the Hamburg model (M. Moll, Radiation Damage in Silicon Particle Detectors, Universität Hamburg, DESY-THESIS-1999-040, 1999) for radiation damage. Warm periods during various technical stops lead to a change of depletion voltage due to annealing. Simulation input: FLUKA fluence simulation (v3.23.1.0) with high granular resolution and detector geometry where the different impact of charged and neutral particles on oxygenated silicon are taken into account. The Hamburg model is fitted to 2018 data leaving the g_C parameter as a free parameter. The g_Y parameter is fixed to 7×10^{-2} cm^{-1} and g_A to 1.4×10^{-2} cm^{-1}. The resulting prediction is compared to the Hamburg model using two sets of Hamburg parameters for oxygenated Si (DOFZ): CB-oxy and RD48-oxy. Actual temperature history is taken from the database where on-module temperature sensor measurements for each readout group (ROG) are stored: only one module temperature per ROG is read out and the temperature of the other modules belonging to the same ROG is assumed to be the same. Data points are taken from bias voltage scans and are defined to be the point of saturation of the charge collection. The integrated luminosity for 2017 is 50 fb^{-1} and for 2018 is 70 fb^{-1}.

DEPLETION VOLTAGE. LOGARITHM-LINEAR COMPARISON. DISK 1, RING 1



Phase-1 Forward Pixel - Full depletion voltage vs day

Linear model:

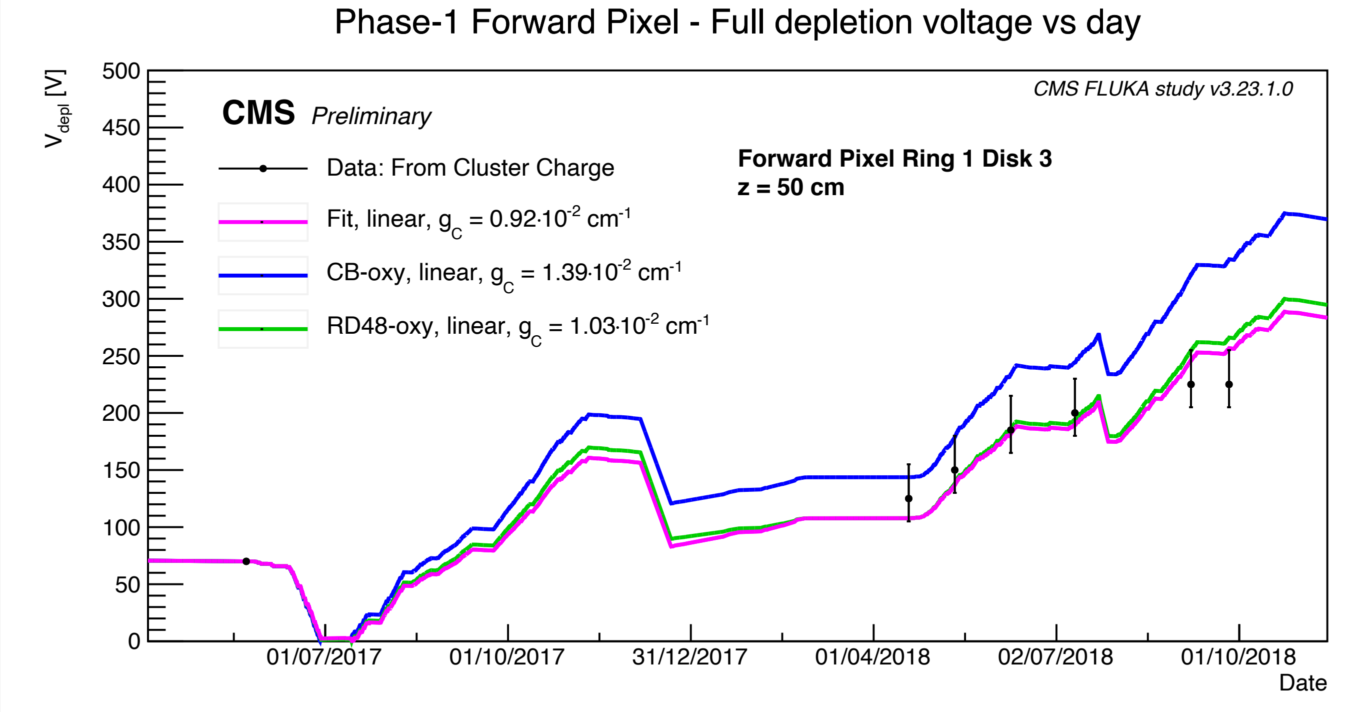
$$N_C = g_C \Phi_{eq}$$

Logarithmic model:

$$N_C = g_C^{log} \ln(\Phi_{eq})$$

Comparison of the fit to the data following the Hamburg model, with a linear dependence of the effective doping concentration on the received fluence in the stable damage term, with an alternative empirical formulation where the stable damage term has a logarithmic dependence on the fluence.

DEPLETION VOLTAGE. DISK 3, RING 1



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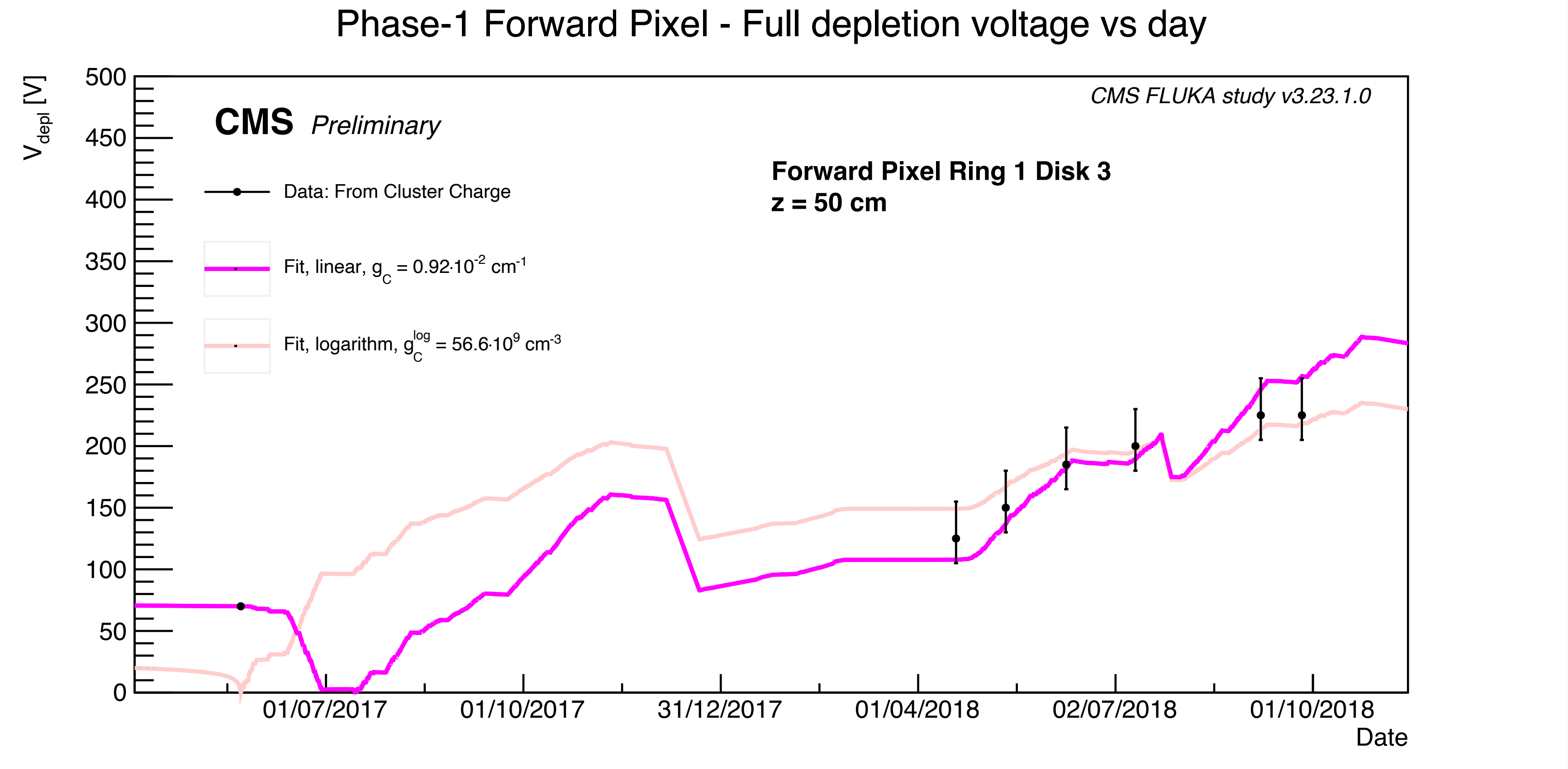
DEPLETION VOLTAGE. LOGARITHM-LINEAR COMPARISON. DISK 3, RING 1



Linear model:

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Logarithmic model:

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Comparison of the fit to the data following the Hamburg model, with a linear dependence of the effective doping concentration on the received fluence in the stable damage term, with an alternative empirical formulation where the stable damage term has a logarithmic dependence on the fluence.