Radiation effects in the CMS phase 1 pixel detector

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Photo courtesy of Erik Butz

Universität Hamburg
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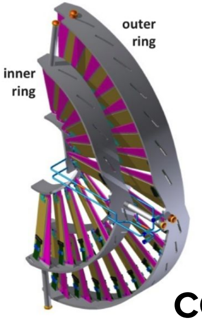
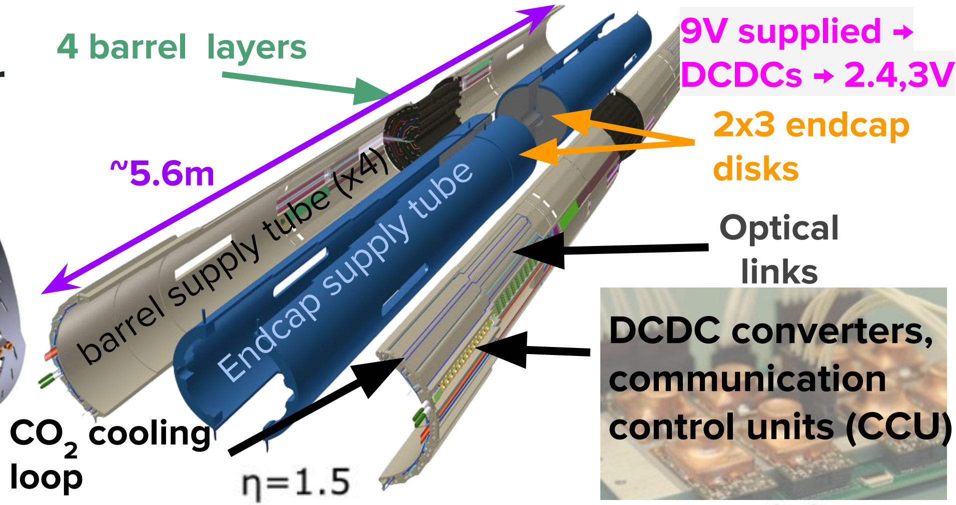
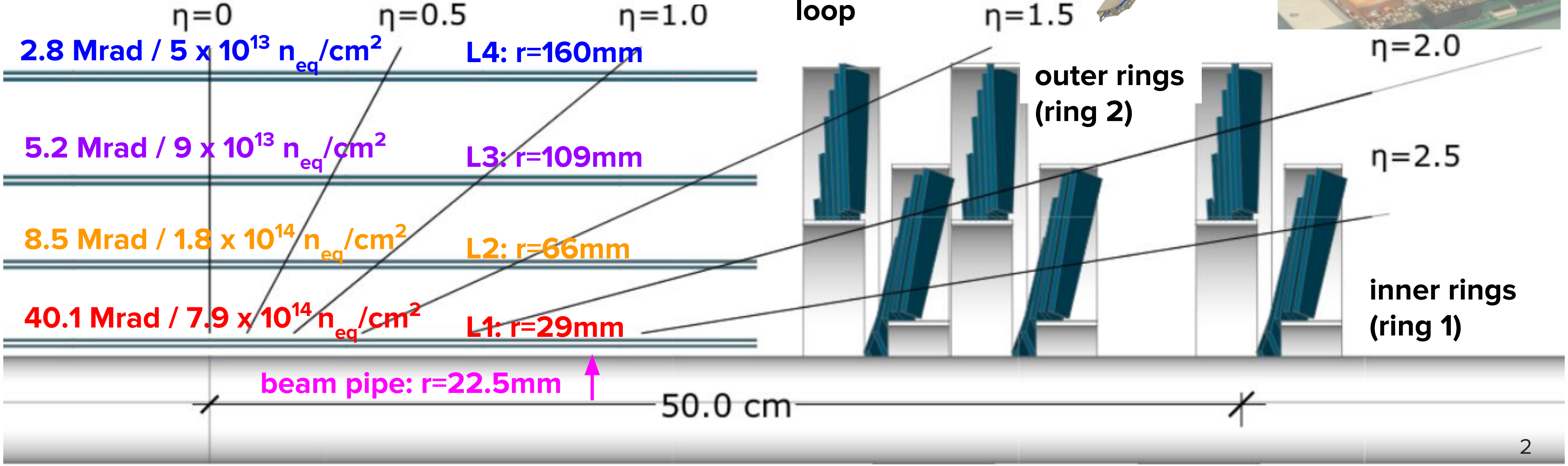
CMS phase 1 pixel detector

- 4 hit coverage and high-rate capability
- Turbine-like structure for endcap disks for optimal resolution
- CO_2 cooling for reduced material
- DCDC converters to keep same powering services ➔ 9V supplied
- Uniform module design throughout





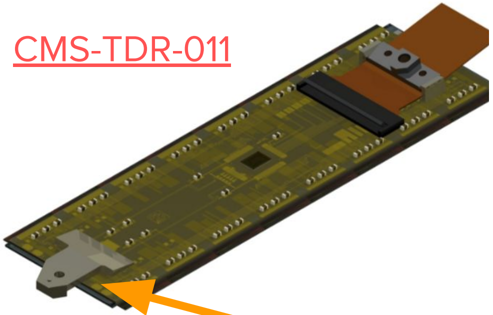


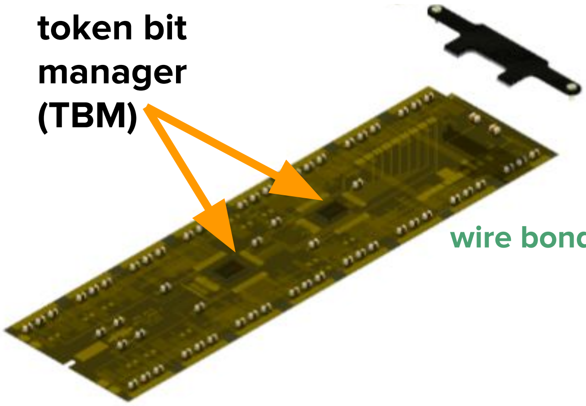
Fluences as of today, from FLUKA 3.23.1.0

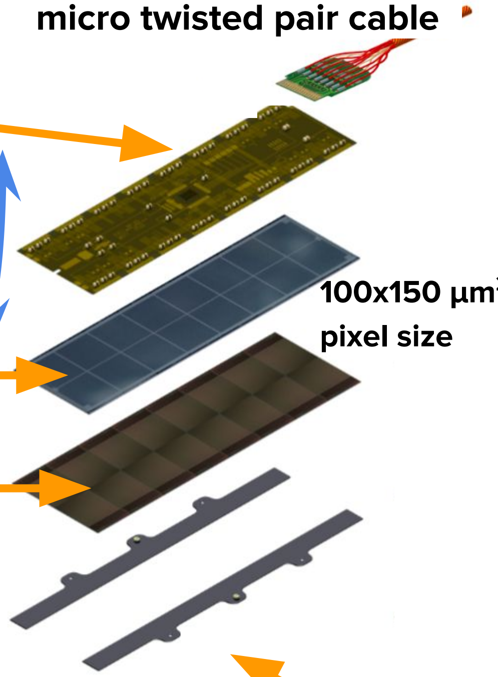
Module design

Readout chips (ROCs): 80x52pixels, 250nm CMOS ASIC, pulse height **digital** readout

CMS-TDR-011







Endcap disks 1-3

- 672 modules
- 40-100 MHz/cm^2
- PSI46dig: column drain
- 2 TBM readout channels
- Functions up to 150 Mrad

Barrel layer 1

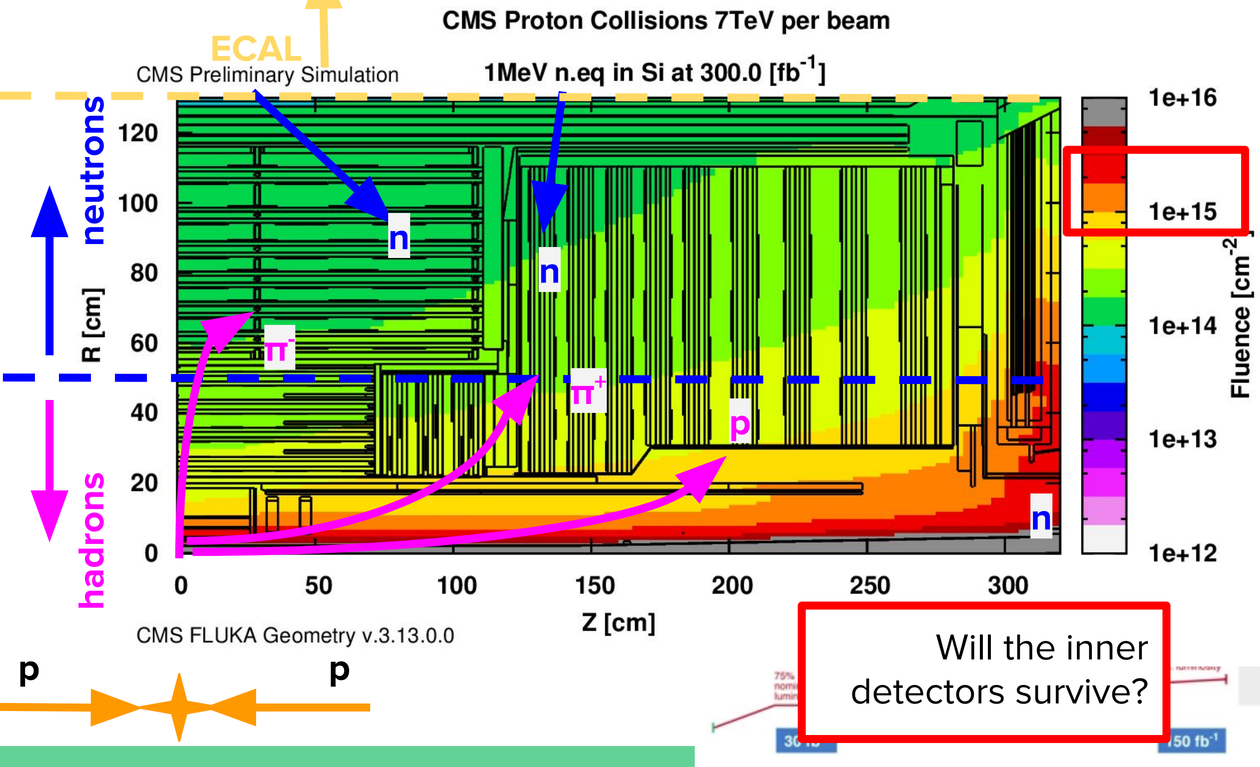
- 96 modules
- 580 MHz/cm^2
- PROC600: dynamic cluster column drain
- 8 TBM readout channels
- Functions up to 480 Mrad

Barrel layer 2-4

- 1088 modules
- 40-100 MHz/cm^2
- PSI46dig: column drain
- 2 TBM readout channels (L3,L4) / 4 TBM readout channels (L2)
- Functions up to 150 Mrad

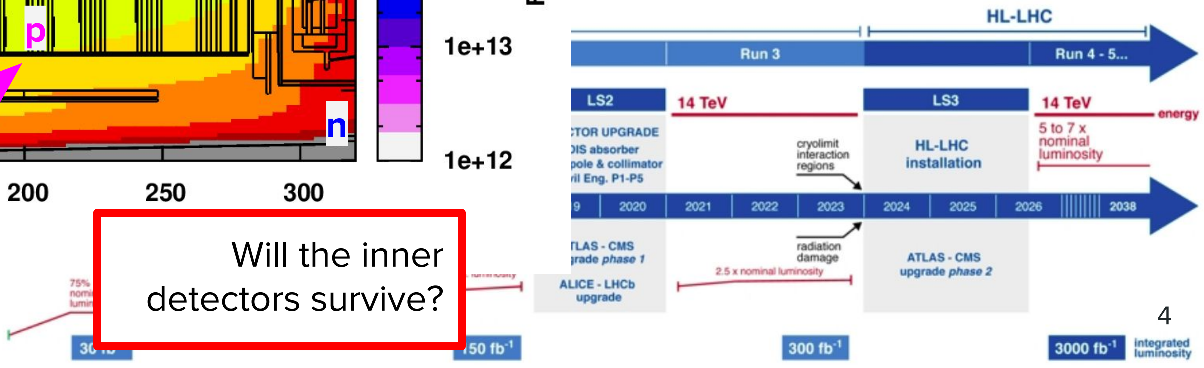
LHC: a challenging environment

2017+2018: 118 fb^{-1}
2018: 68 fb^{-1}



Radiation effects are challenging for operations and performance:

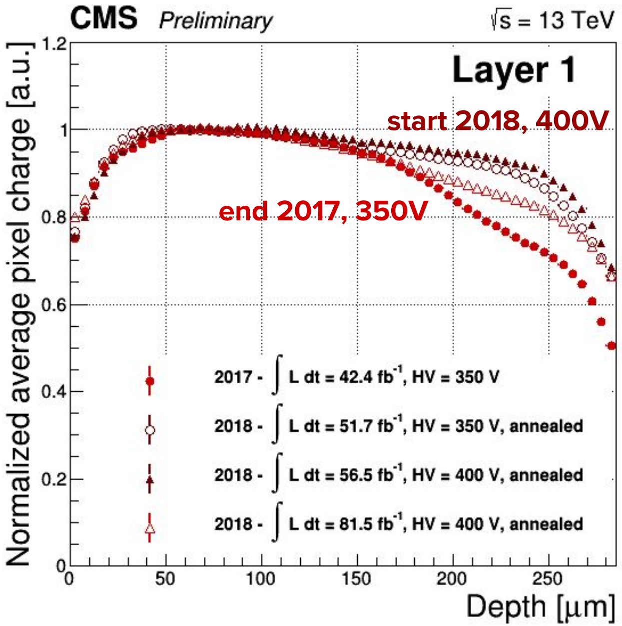
- Damage and single event upsets (SEUs) in electronics
  → false signals, chip damage
- Bulk defects cause change of space charge distribution
  → bias voltage increase
- Increasing leakage currents and heat dissipation
- Charge trapping in sensor:
  → decreasing charge collection efficiency



Will the inner detectors survive?

Impact on performance and data

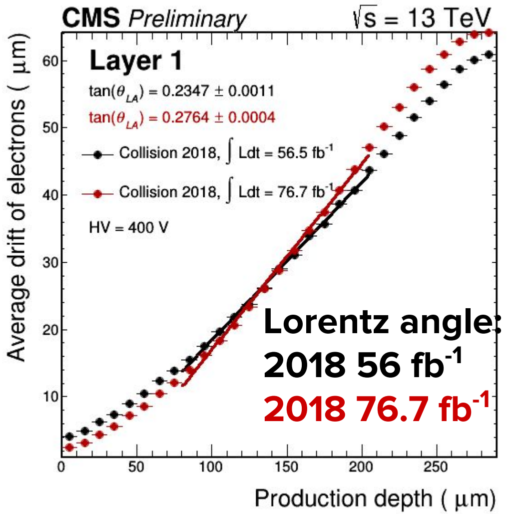
- Radiation effects clearly seen in Lorentz angle evolution and pixel charge profile
- Effects can be reduced by increasing bias voltage and performing annealing
- Decrease in charge collection efficiency taken into account in simulation using PixelAV and TCAD.

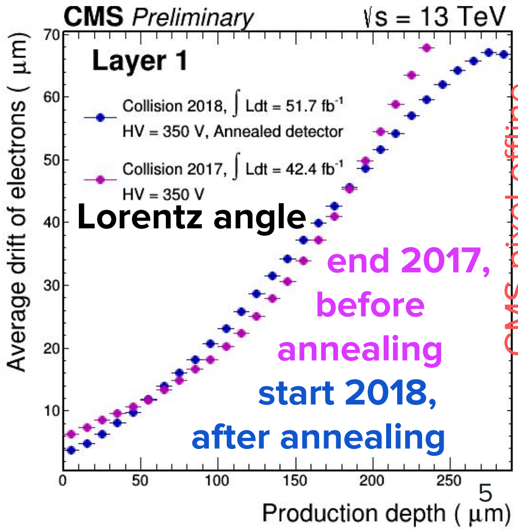


Normalized average pixel charge vs sensor depth:

- flat for unirradiated sensors
- increase for 350 → 400V and annealing
- decrease with further irradiation

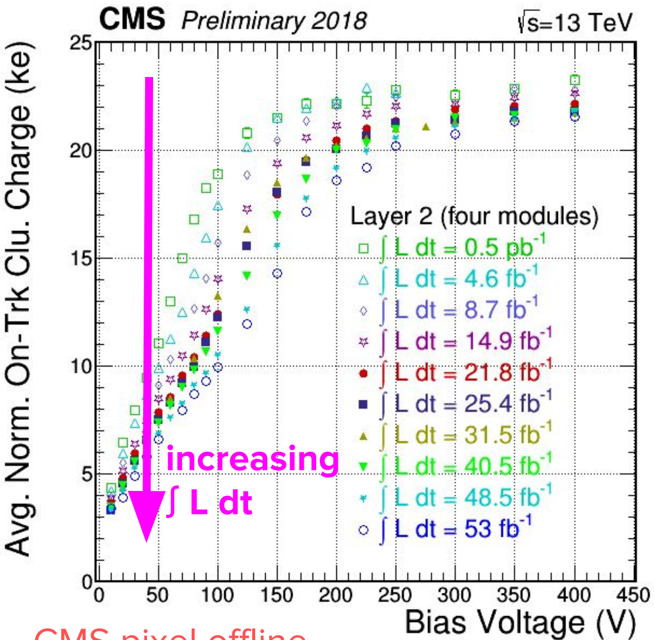
Thresholds:
Endcaps: 1500 e^-
L2-4 1200e^-
L1: 2100e^-
Relatively constant over time



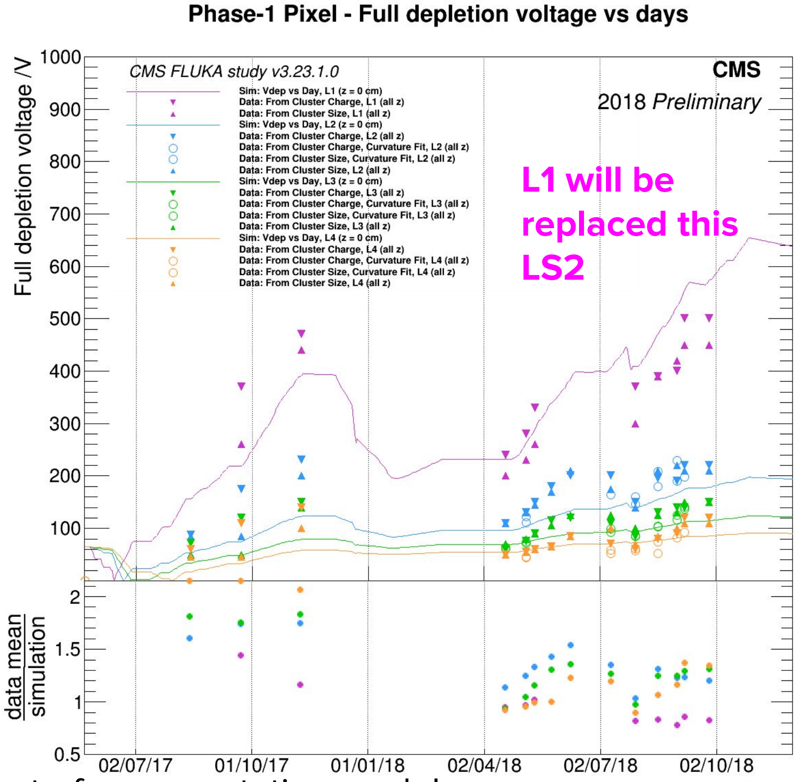


CMS pixel offline

Radiation effects on depletion voltage



CMS pixel offline



Run 3 depletion voltages expected to be within power supply limit of 800V.

Operational voltages at end of run 2:
L1: 450V
L2: 300V
L3-L4: 250V
Ring 1: 350V
Ring 2: 300V

Regular sensor bias voltage scans on subset of representative modules

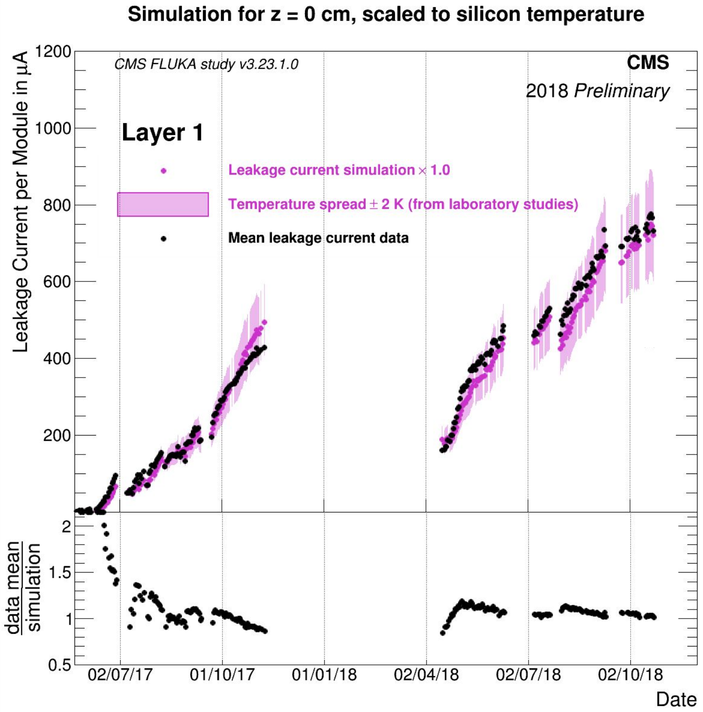
Simulation with effective space charge Hamburg model (E_{eff}=1.21 eV), fluence from DPMJet + FLUKA 3.23.1.0

Hamburg model parameters from Michael Moll

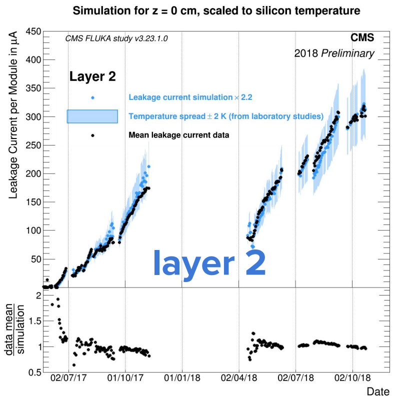
CMS pixel operations

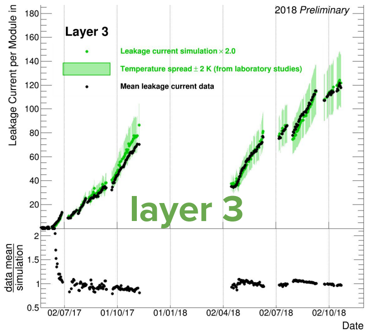
Leakage currents

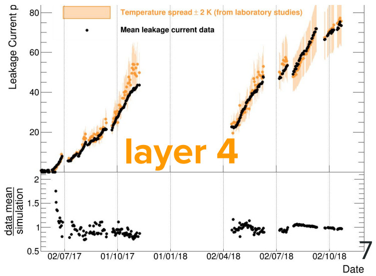
- Leakage currents in L2-4 underestimated by about a factor of 2
- Main uncertainties from temperature modeling and particle generator + FLUKA ➜ work on improvements in modeling foreseen
- Prediction for run 3: safely below the operational limit of the power supplies of 20mA.



[CMS pixel operations]

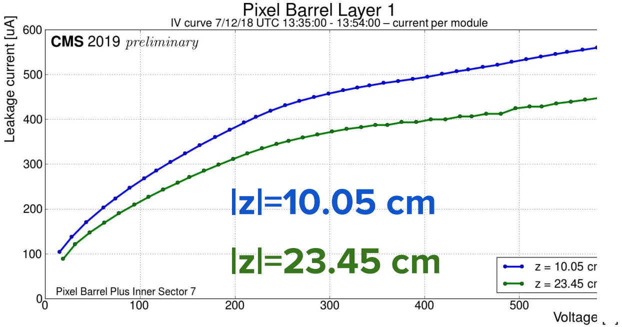


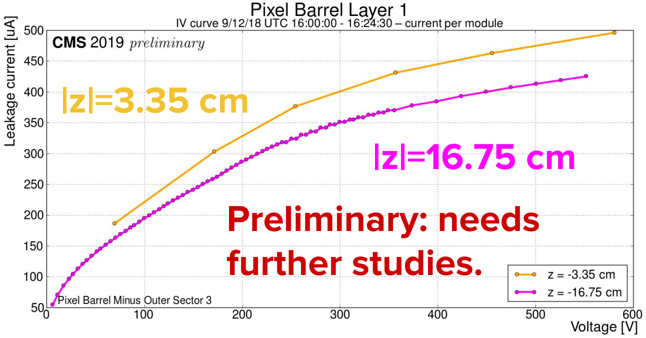




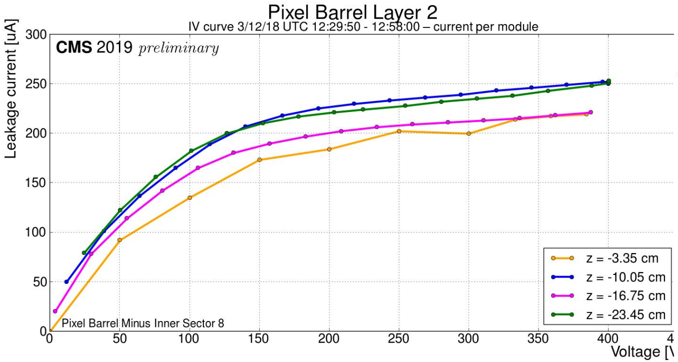
Leakage currents vs z

Leakage current seems consistently higher for lower z. [ATLAS sees a similar effect.]

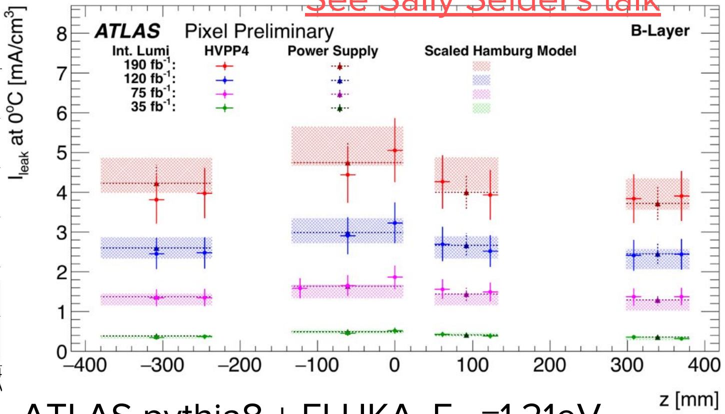




No effect seen on layers other than innermost:



[See Sally Seidel's talk]

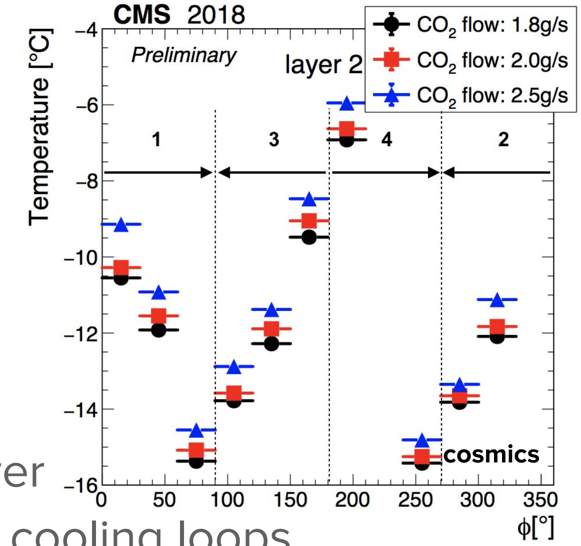


ATLAS pythia8 + FLUKA, E_{eff}=1.21eV

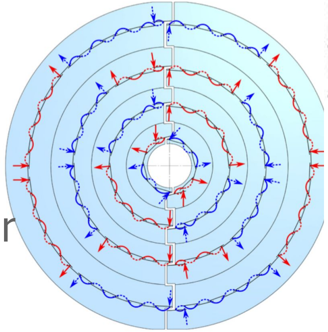
CO_2 cooling

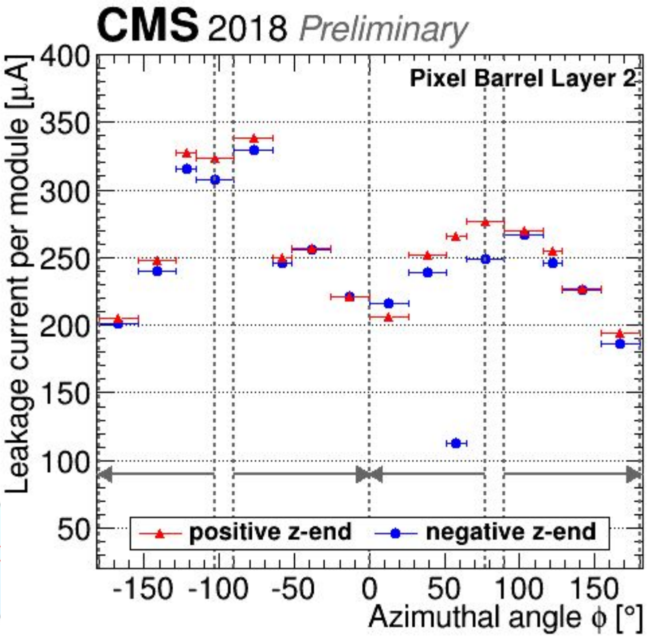
Important to understand detector temperatures for radiation effects:

- ✓ -22°C, option to go lower
- ✓ 1.7mm ø stainless steel cooling loops
- ✓ wall thickness 50µm
- ✓ very lightweight
- ✖ gradient of 4-5K along cooling loop
- ✖ efficient cooling but **no efficient heating** which can be problematic for targeted **annealing or safety**



Increasing the flow did decrease some gradient but still a **non-negligible pressure drop** along cooling loop: under investigation





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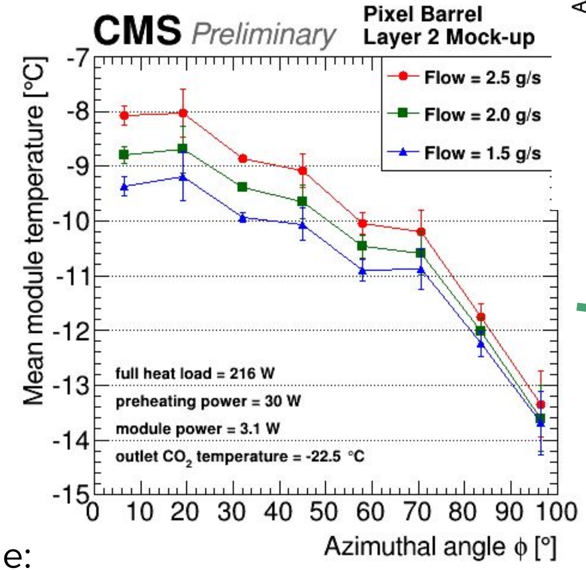
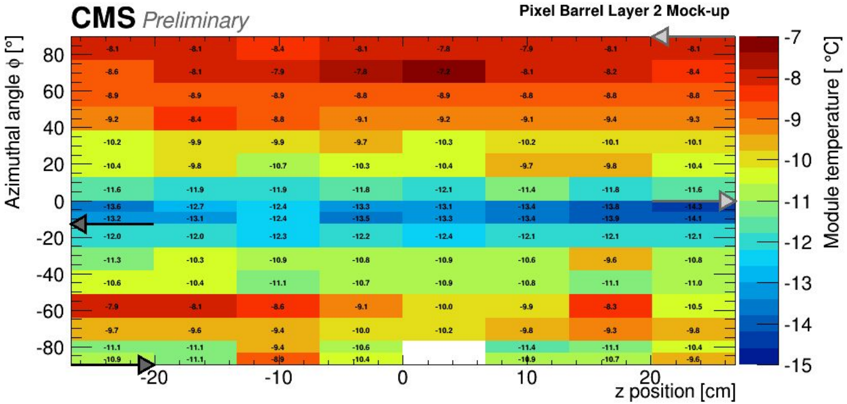
CMS pixel operations

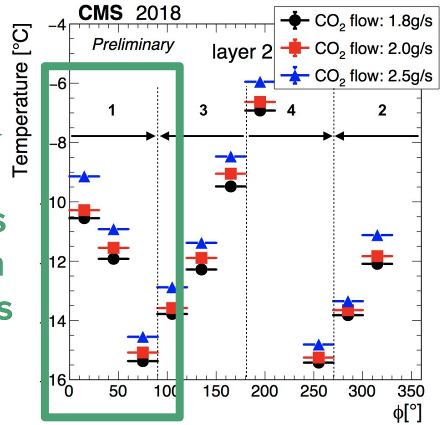
Temperature studies with a mockup of layer 2

Realistic layer 2 half-shell mechanics and CO_2 cooling with adjustable heat load on pseudo-modules with temperature sensors





Mockup results agree well with detector results



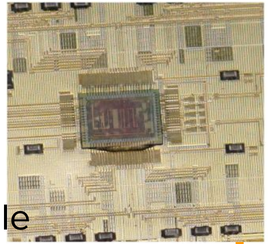
CMS pixel operations

Thermal mockup indispensable:

- ➡ temperature modeling is a large uncertainty for simulation
- ➡ few temperature sensors in the detector

Radiation effects in electronics

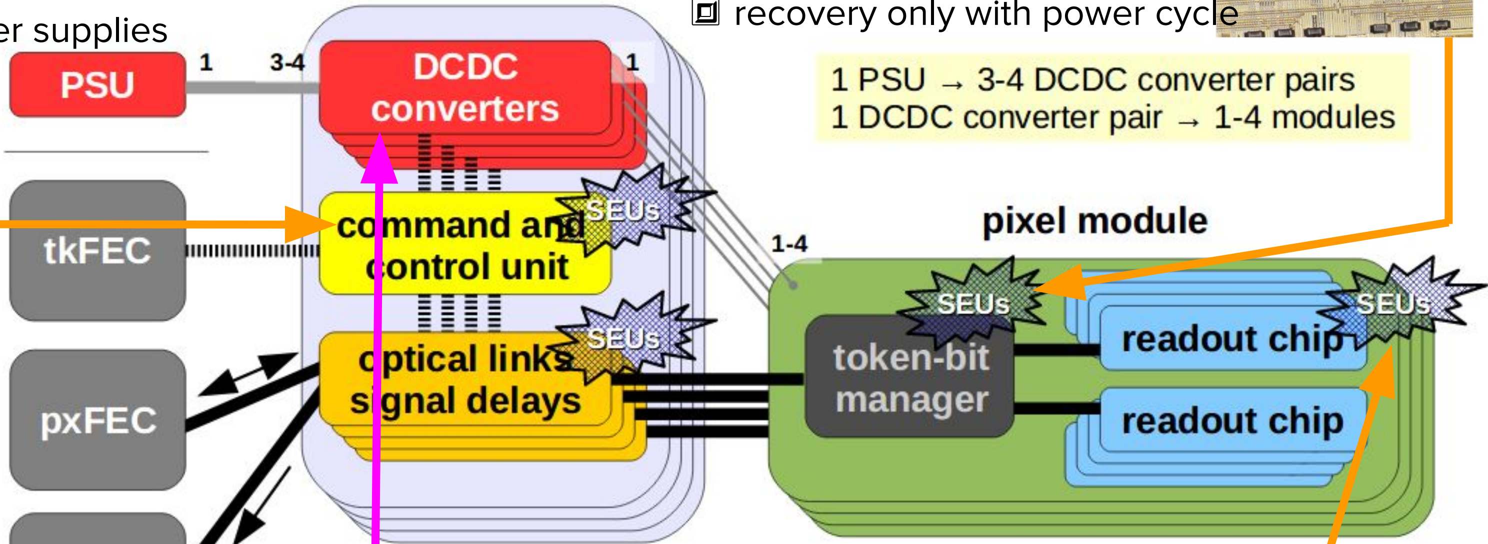
TBM
- 30/fb^{-1} in L1 transistor in TBM flipflop sets TBM to 'no readout' mode: "**stuck TBMs**"
- recovery only with power cycle



Power supplies

CCU misbehavior:
- 1/300pb^{-1} reset portcard → reprogram
- 1/month reset DCDCs

[From Klaas Padeken]



Front end controllers/drivers

Irradiated DCDCs stop functioning in disabled state (not an SEU)
- 63/1216 at end of 2017 stopped functioning
- 333/1216 in 2017 found to have high current

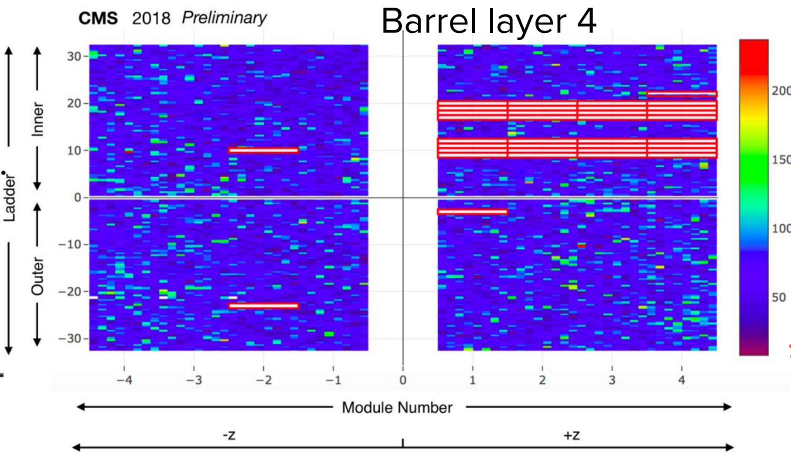
[From Benedikt Vormwald]

ROC: solved by reprogramming

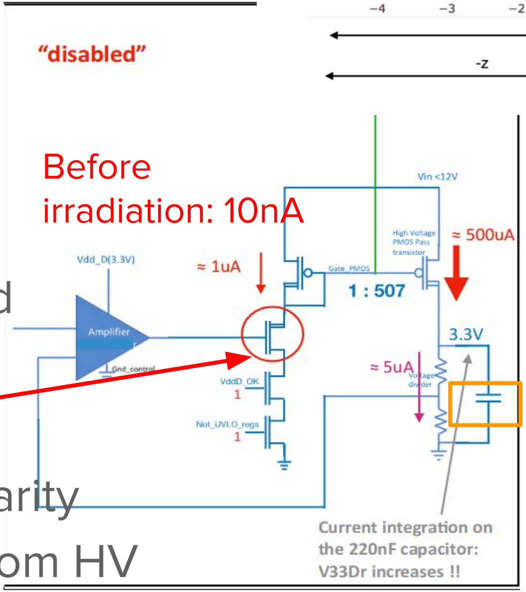
Compensation for chip radiation effects in offline reconstruction

DCDCs

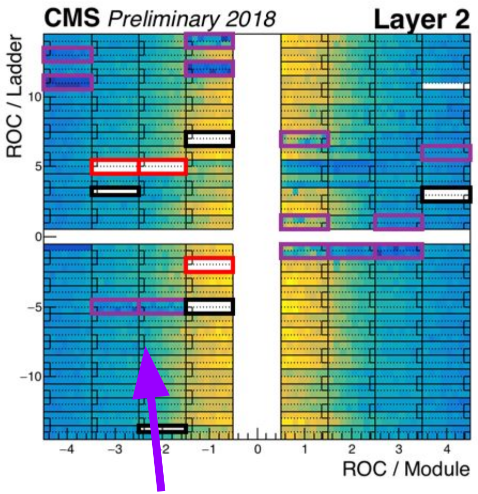
Disconnected DCDCs: for safety switched off entire power supply (LV and HV).
No DCDC broke in 2018!



- SEU in transistor in TBM flipflop sets TBM to ‘no readout’ mode ➔ powercycle TBM
- Powercycled with DCDCs (lowest amount of modules) in 2017
- Increased leakage current in DCDCs after irradiation causes charging up of capacitor in disabled state ← design mistake in layout around one transistor:
- High and low voltage group granularity not the same: damaged modules from HV on where DCDCs were broken ➔ LV off.



From Federico Faccio

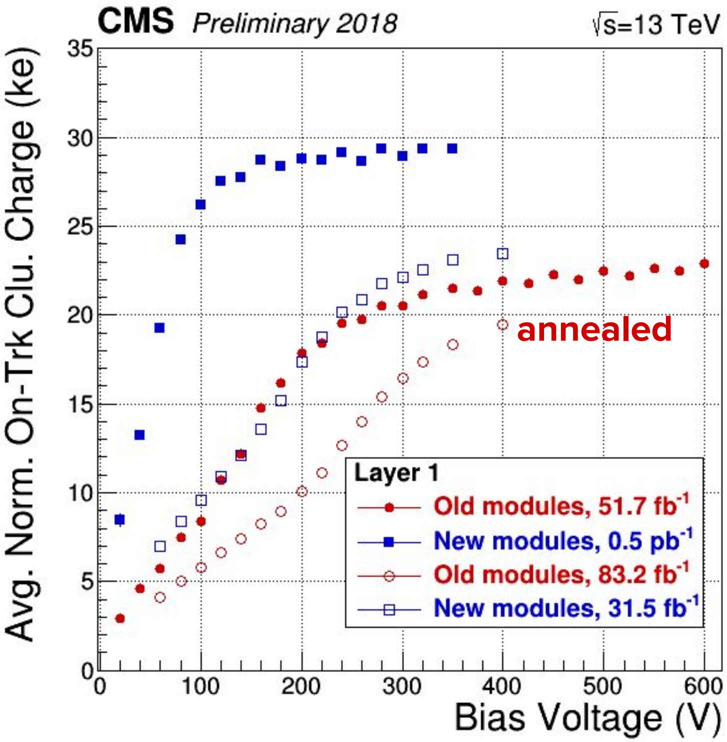


Damaged modules behind failed DCDCs in 2017

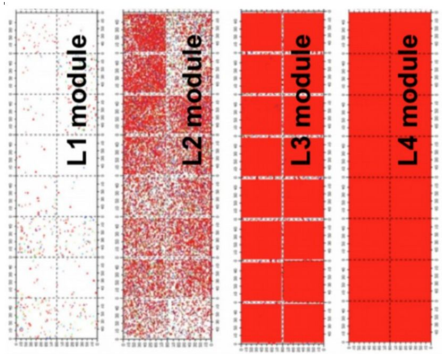
CMS pixel operations

CMS pixel offline

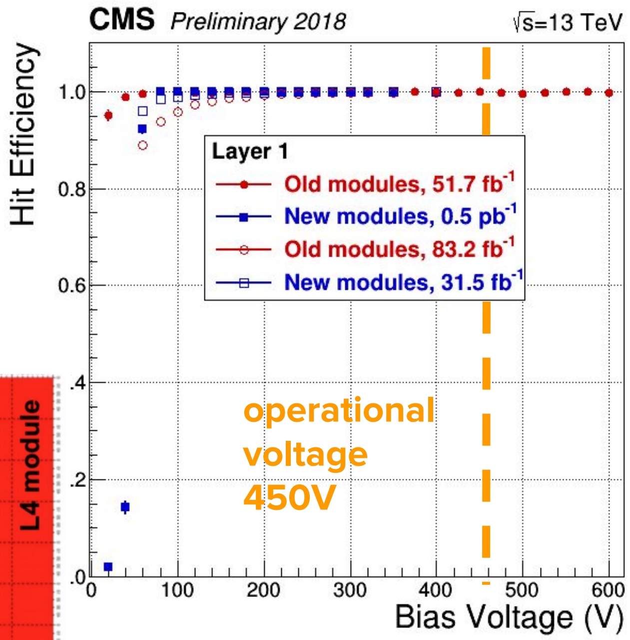
Radiation effects: on-track cluster charge



In long shutdown 2017-2018: replaced 6 of 8 layer 1 modules damaged by high voltage leakage current



No impact on hit efficiency!

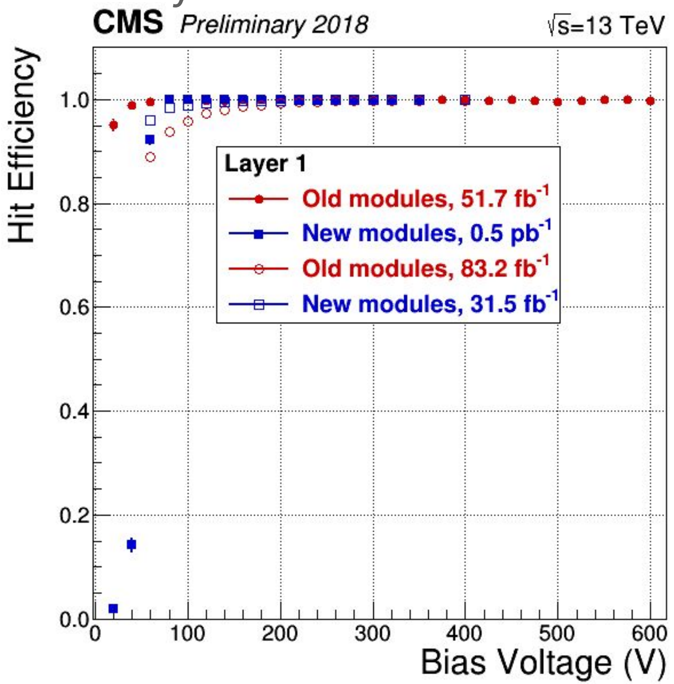


CMS pixel offline

Summary and lessons learned

CMS pixel offline

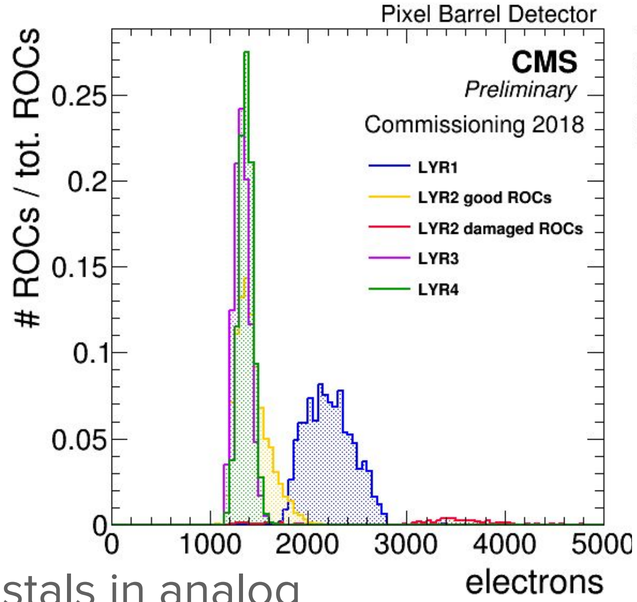
- Successful commissioning of CMS pixel detector since start of 2017
- Despite many challenges, pixel detector performed very well in 2017 and 2018
- Good to have test setups to study:
  - CO_2 cooling with adjustable heat load for understanding
    - module temperatures
    - radiation effects
- HV and LV granularity: Ideally the same
- Monitoring temperatures, chip properties important for studying radiation effects



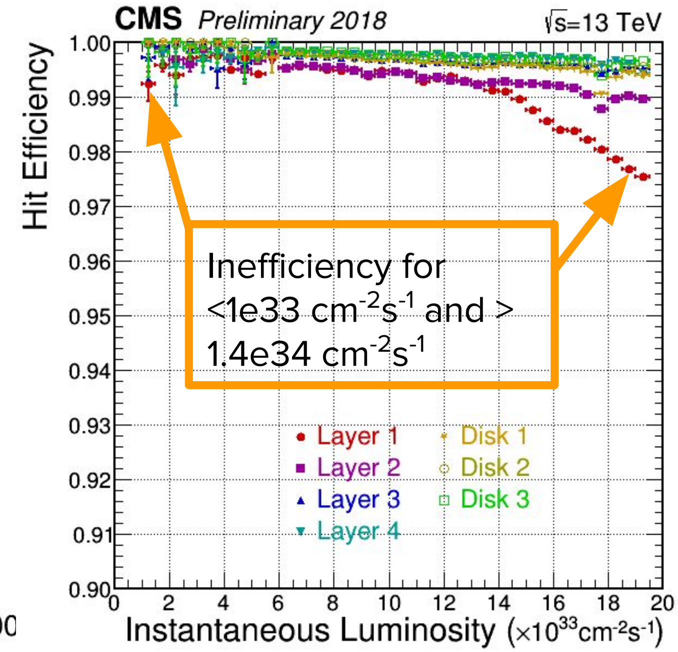
Spares

Inner layer chip: crosstalk, inefficiency, timing

- Layer 1 timing very different from layer 2
- High thresholds resulting from crosstalk and large timewalk
- Inefficiency at high and low rates
- Distribution of pedestals in analog pulse height large, ~80 ADC units



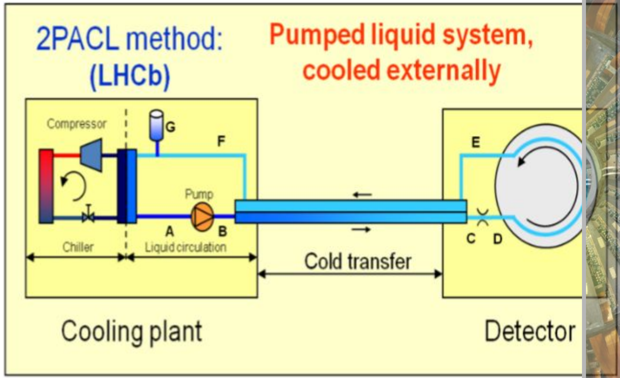
CMS pixel operations



CMS pixel offline

All solved/addressed in next L1 chip version.

CO_2 cooling



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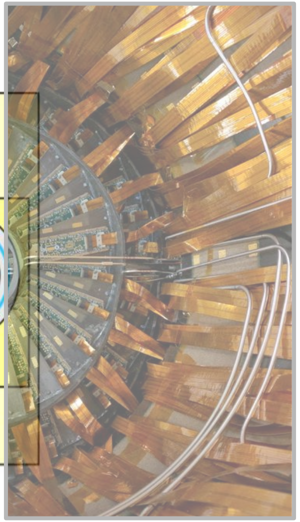
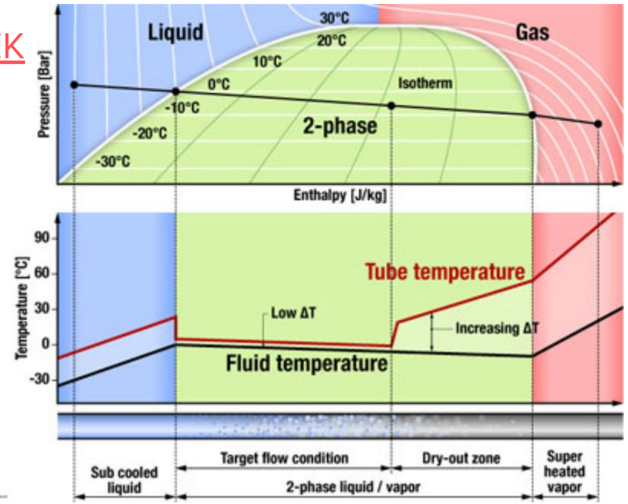
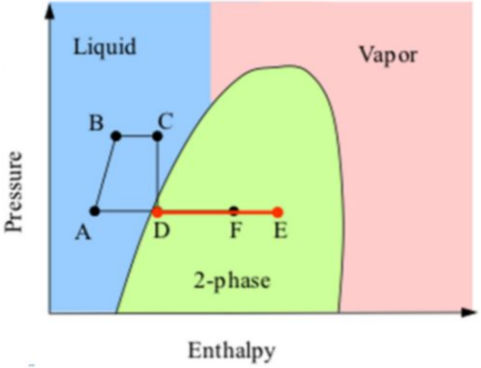


From KEK

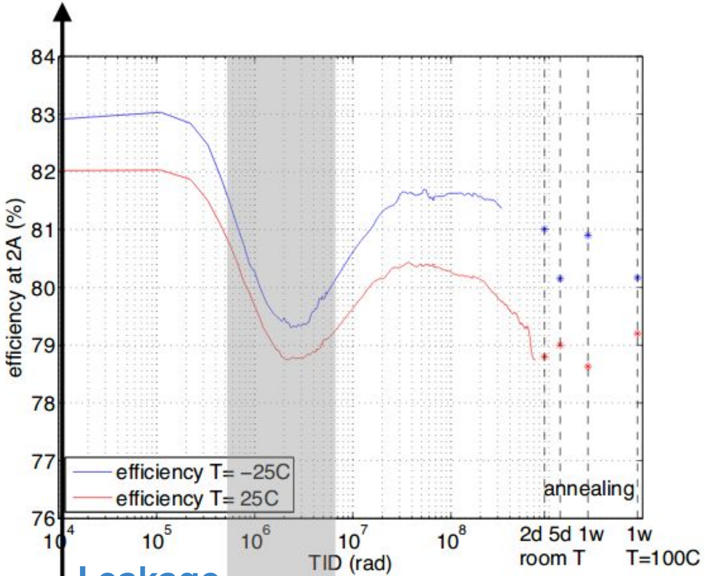


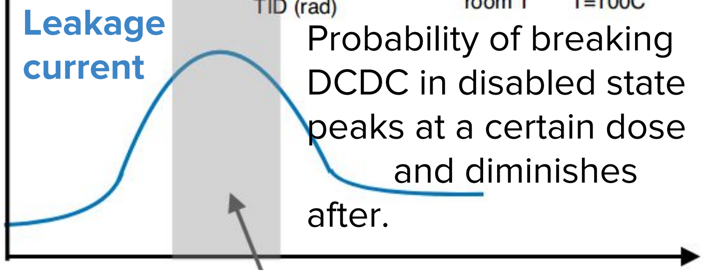


A→B: CO_2 pressure is increased for transfer to the experiment
B→C: temperature increases from heat exchange with returning CO_2
C→D: pressure inside the detector is reduced to reach onset of evaporation
D→E: heat from the detector is absorbed
E→F: CO_2 liquid/vapor mixture condensates on incoming colder CO_2 pipe
F→G: CO_2 is cooled with main chiller
G: temperature in detector is regulated with pressure in accumulator:
D-G low impedance system with ~constant pressure back to D

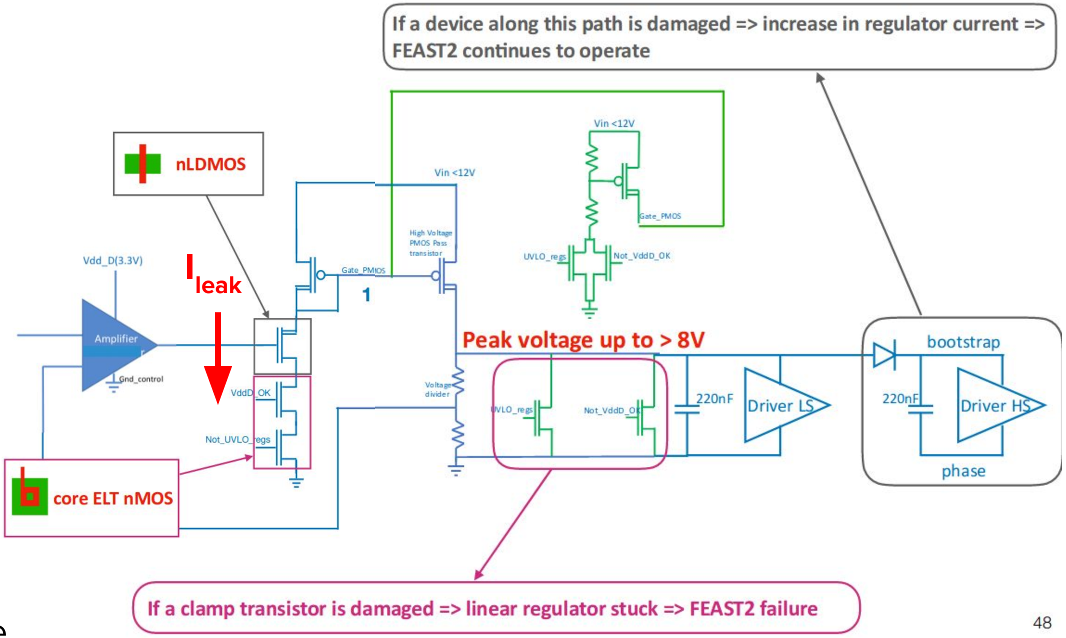
DCDC malfunctioning

Enclosed layout (ELT) vs linear transistors → can 'cut' leakage current path by adding ELT in series





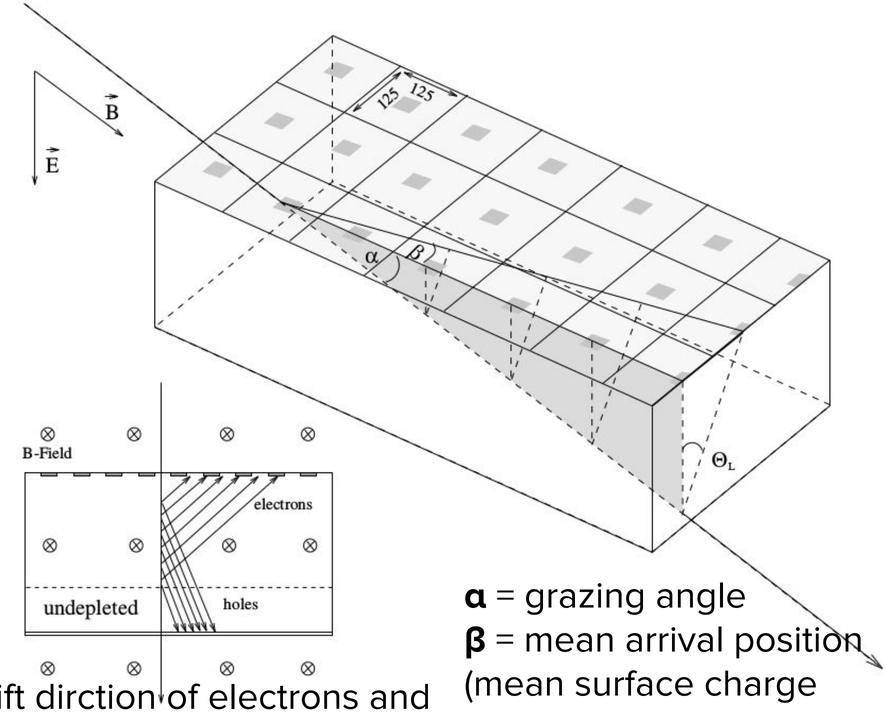
Probability of breaking DCDC in disabled state peaks at a certain dose and diminishes after.



Capacitor charges up in disabled state and causes spikes beyond 3.3V

From Federico Faccio

Cluster charge vs depth: grazing angle method



Drift dirction of electrons and holes from different depths
[From Henrich and Kaufmann]

α = grazing angle
β = mean arrival position (mean surface charge deflection)
Θ_L = arctan(tan(β)/tan(α)) = Lorentz angle

- Ionizing particles arriving at shallow angle create pixel “signal street”
- Each pixel in the street has a charge from part of the track ➡ from a certain depth segment
- Compute drift and depth from track and pixel position and α, β
- Project 3D histogram of drift, depth, and charge along drift path to obtain charge vs depth.