Karlsruhe Institute of Technology

CMS pixel and strip tracker radiation damage

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RD50 Workshop, CERN, Geneva

ETP – Institut für Experimentelle Teilchenphysik AG Müller

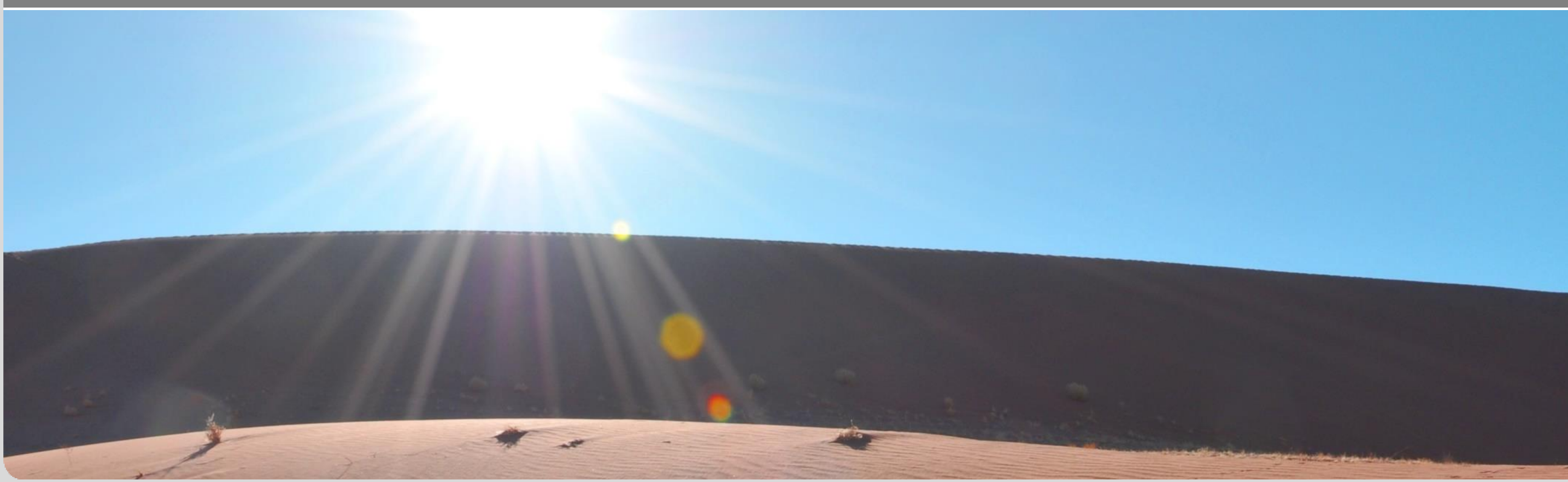
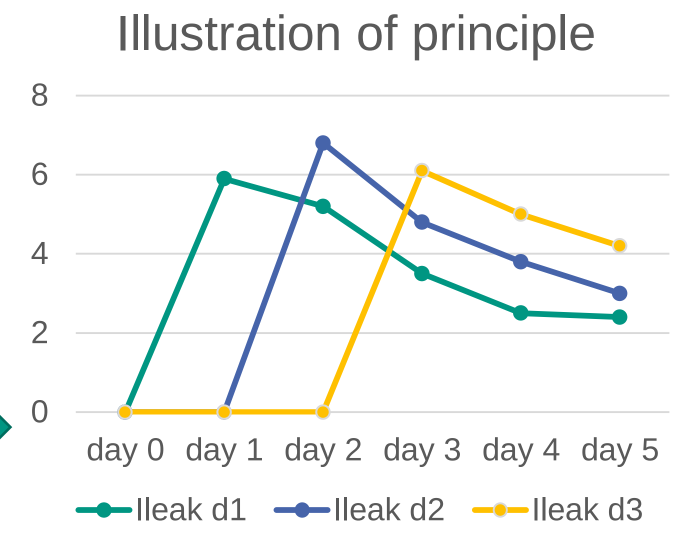


Illustration of principle: Radiation damage simulation

Full **irradiation** history

Radiation damage model:
Leakage current or depletion voltage
- α or Hamburg parameters
- FLUKA fluence predictions*
- Sensor position and geometry
- Thermal contacts*

Full **temperature** history*



Compute the full annealing scenario for the fluence induced radiation damage (including self-heating) **at each day**.

Superimpose to obtain the leakage current or depletion voltage evolutions.

* these parameters introduce significant uncertainties

CMS STRIP TRACKER

Strip tracker map – sensor temperature

- Temperature history is known precisely
- Wide spread in temperatures across the tracker

Cooling set points:
+4 °C before LS1
-15 °C until YETS 17/18
-20 °C since.

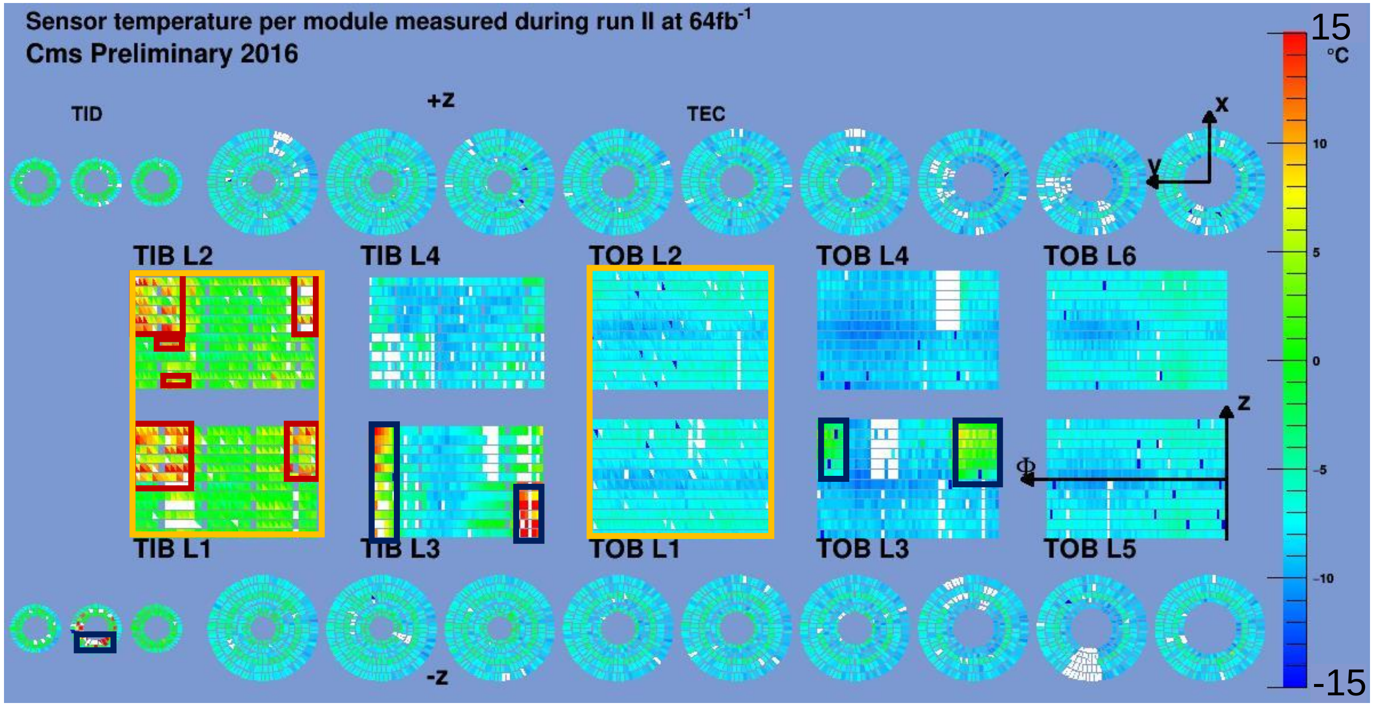
Sensor temperature per module, cooling set point -15 °C

Closed (leaky) cooling loops

Degraded cooling contacts

Double sensor stereo modules

Rings 1, 2 & 5 in all discs have stereo modules



Measurement of the strip tracker thermal contacts $\frac{dT}{dP}$

- Thermal contact = change of temperature with sensor power
- Bias scans :
  - Vary high voltage stepwise → different leakage currents in silicon volume

→ Extract thermal coupling **for each individual module** by correlating power and temperature

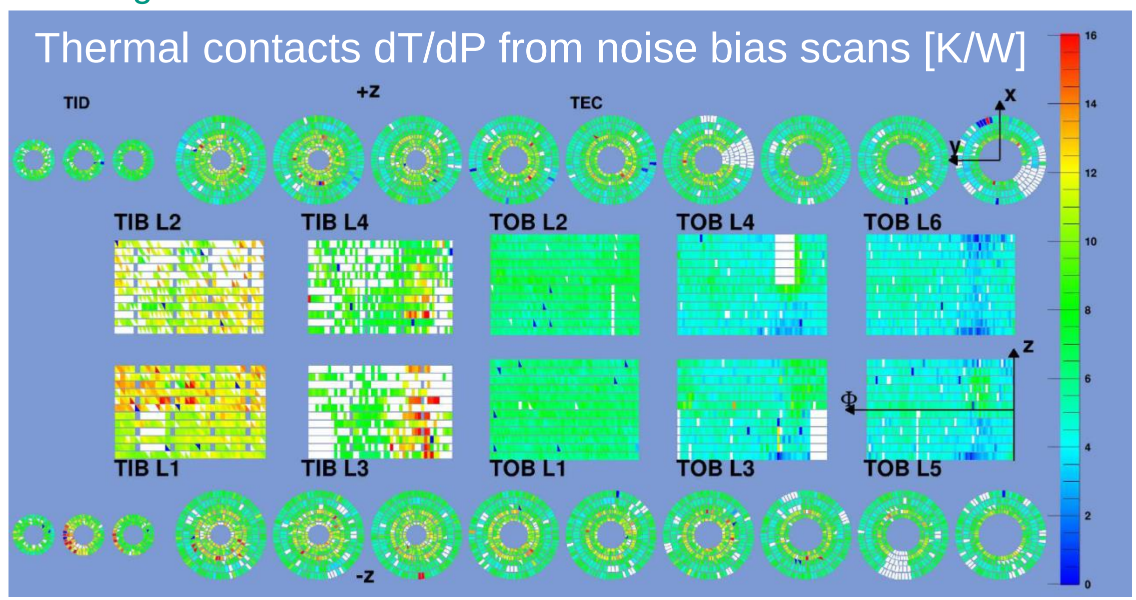
$$V_{bias} \cdot I_{leak} = P = \frac{dP}{dT} T_{sil}$$

Set values

Detector Control Unit (DCU) ASICs readings

DCU readings

Large values near uncooled loops or in regions with degraded cooling contact



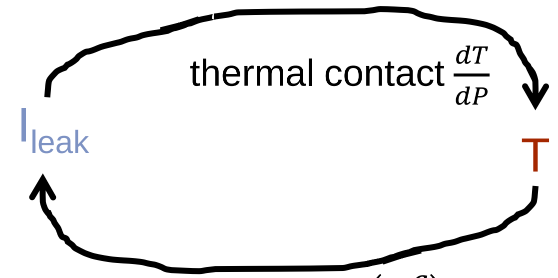
Self-heating effect through thermal contact dT/dP

- dT/dP
  - *Cooling power* **lowers** temperature
  - Increased sensor power (leakage current) **raises** temperature
- $I_{leak} \sim T^2 \exp\left(\frac{-c}{T}\right)$: Leakage current increases with temperature
- **Initially:** *Radiation* raises leakage current

What happens if the temperature value doesn't converge...?
See next slide!

Implementation in strip tracker simulation

- Calculate irradiation-induced leakage current increase and following **"self-heating"**



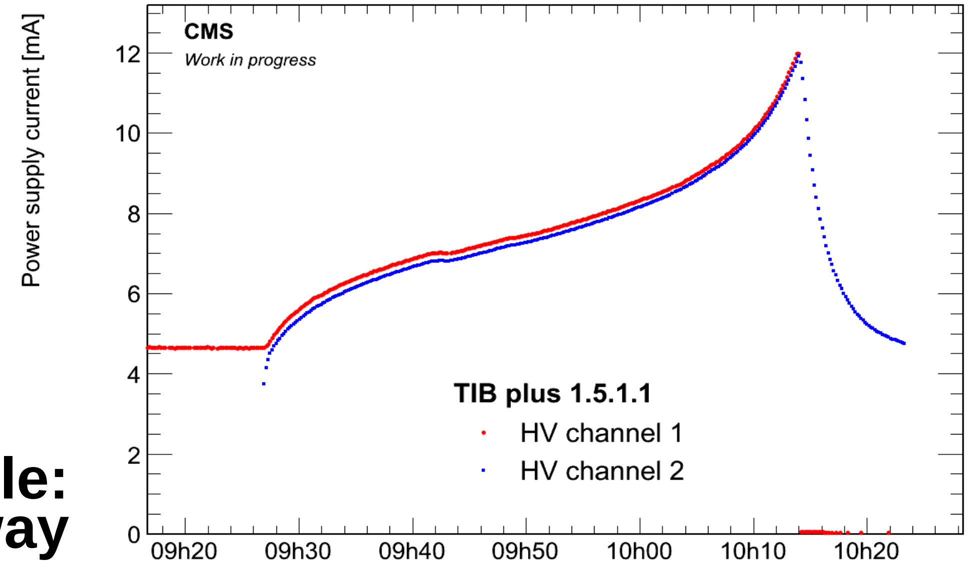
$I_{leak} \sim T^2 \exp\left(\frac{-c}{T}\right)$

... Temperature converges?

Sim: Exit loop when leakage current delta smaller than a lower threshold. → **no thermal runaway.**

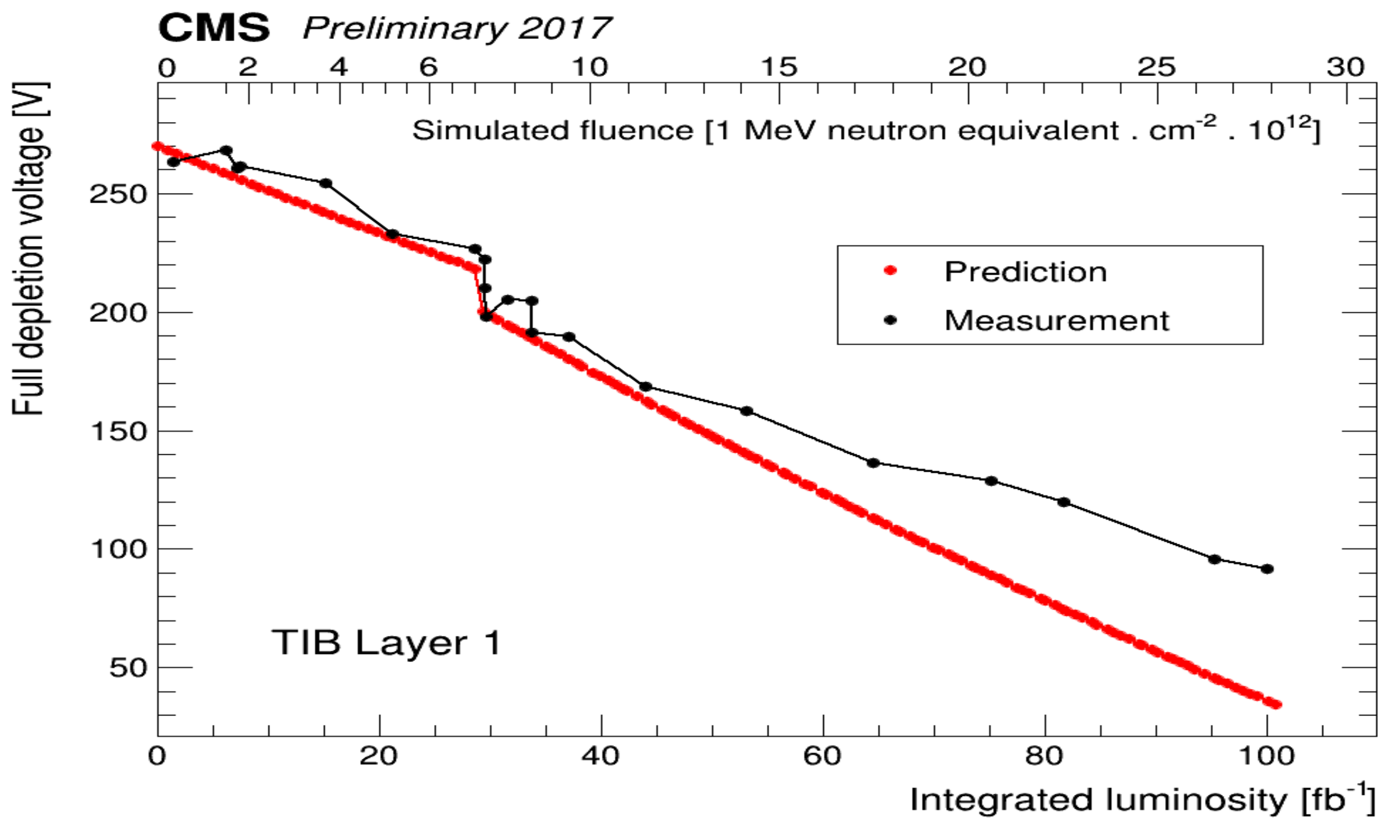
... Temperature and leakage current keep rising? → **Thermal runaway**

A real-life example: Thermal runaway



Observation of a thermal runaway in 2017, cooling at -15°C

Reminder: Depletion voltage simulation and data



- Good agreement in the beginning
- Shows expected deviation near type-inversion

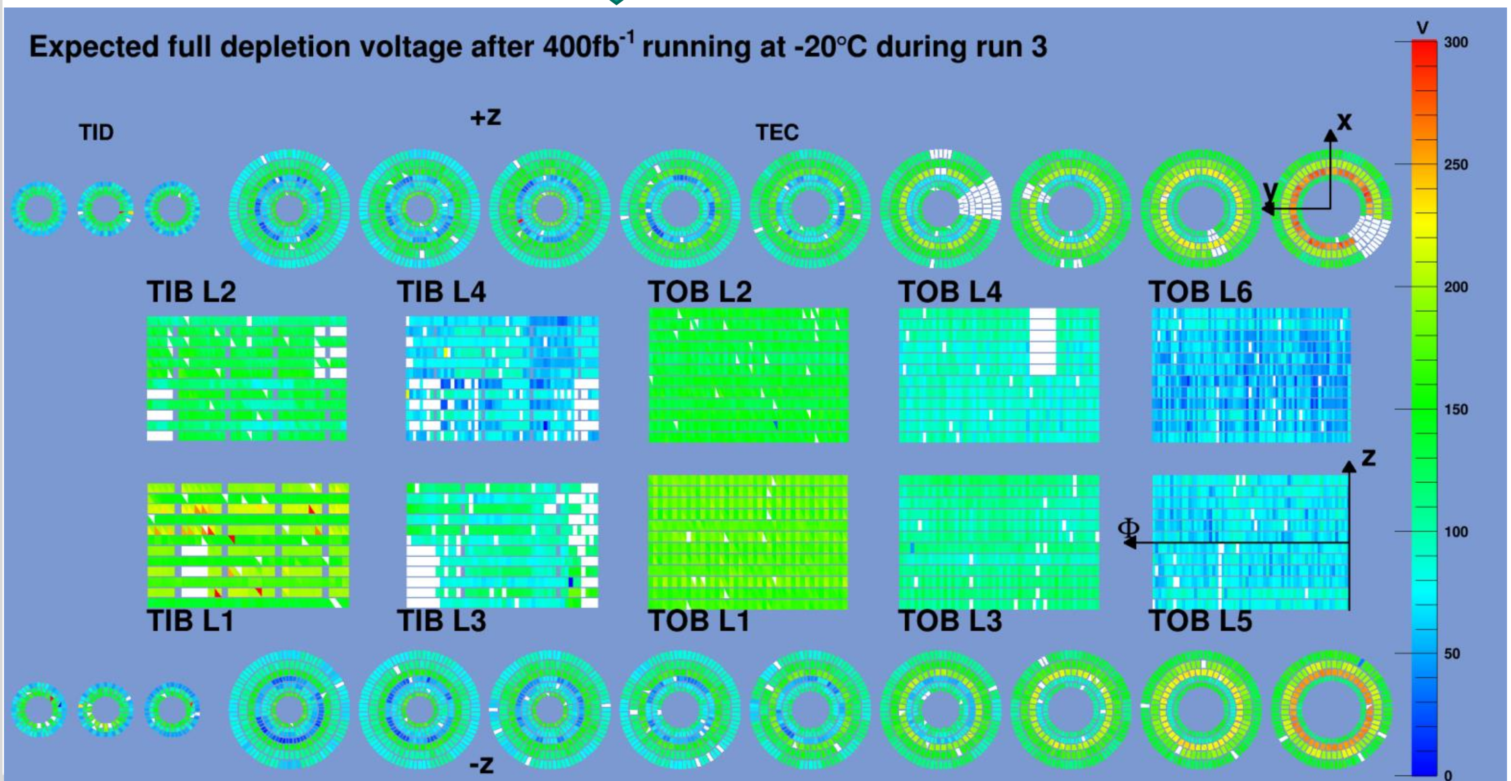
Simulation: Depletion voltage

after 400 fb^{-1} with cooling at -20 °C during run 3

Full irradiation history + realistic future scenario + FLUKA fluence

Thermal contacts + Full temperature history + realistic future scenario ← assuming 120 days at RT and otherwise temperatures **below 0 °C for LS2 and all YETS**

→ Hamburg model*



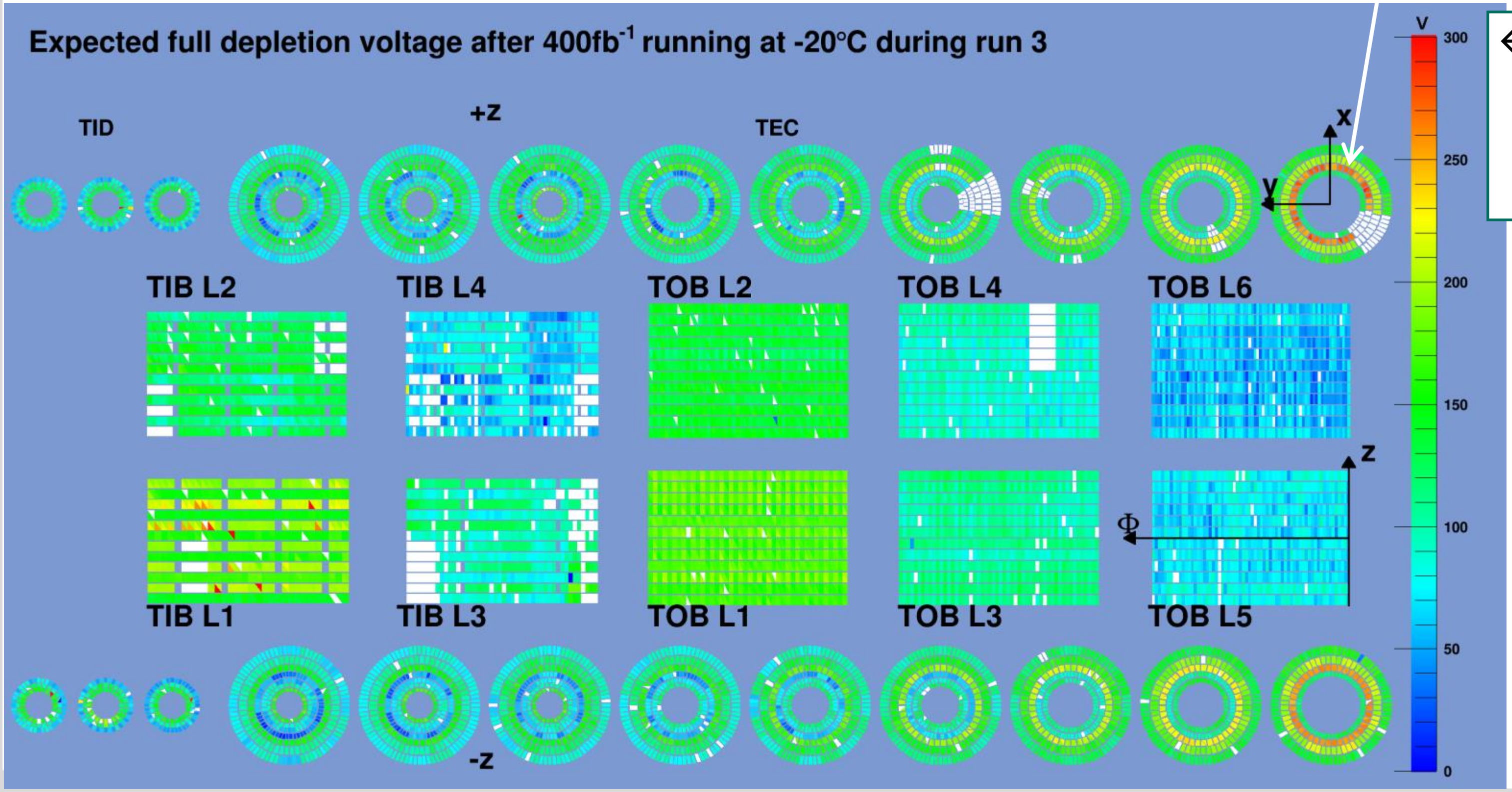
* Hamburg model: M. Moll, Radiation Damage in Silicon Particle Detectors, Universität Hamburg, DESY-THESIS-1999-040, 1999 https://mmoll.web.cern.ch/mmoll/thesis/

Simulation: Depletion voltage
after 400 fb^{-1} with cooling at -20 °C during run 3

Range of depletion voltages arises from differences in:

- Sensor thickness: $V_{dep} \sim d^2$
- Temperature (uncooled parts/ degraded cooling contacts)
- Initial depletion voltage
- Radiation exposure
  - radial distance from IP
  - Increased radiation in forward region due to neutron backscattering

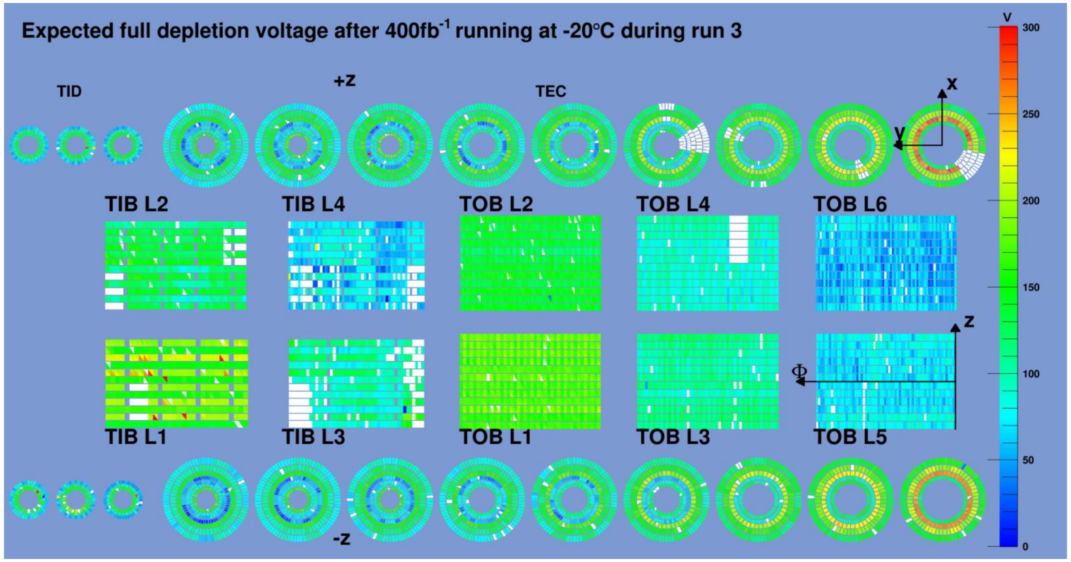
... e.g. **Ring 5 Disk 9** featuring stereo modules has a much higher depletion voltage since:
- sensor thickness is 500 μm,
- it is at medium radius
- it is near to the calorimeter



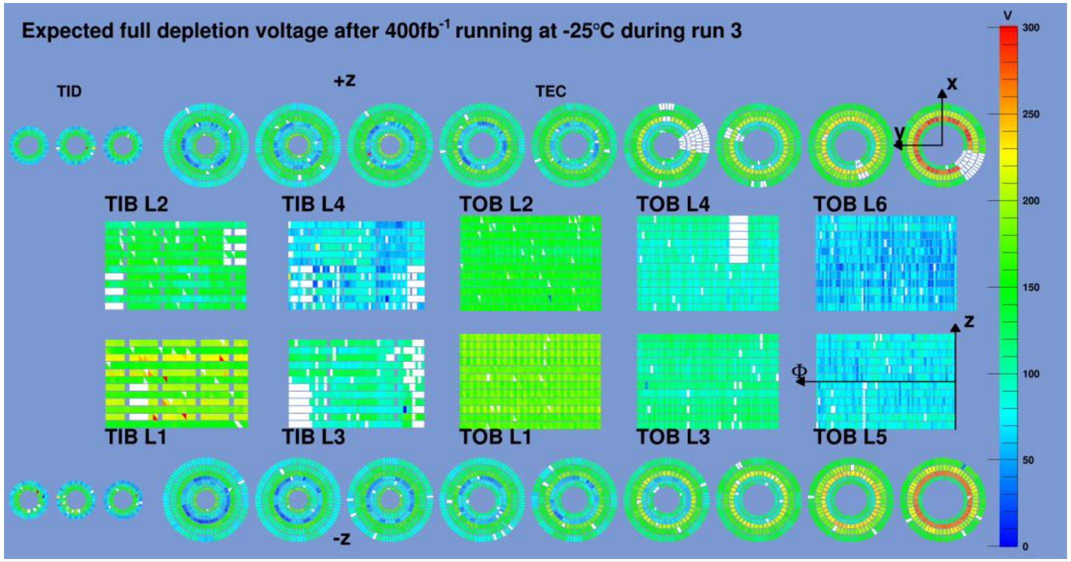
← Depletion voltage is expected to stay **below 300 V.**
Well below power supply limit at 600 V.

Simulation: Impact on depletion voltage
Cooling at -20 °C and -25 °C during run 3

cooling set point -20 °C

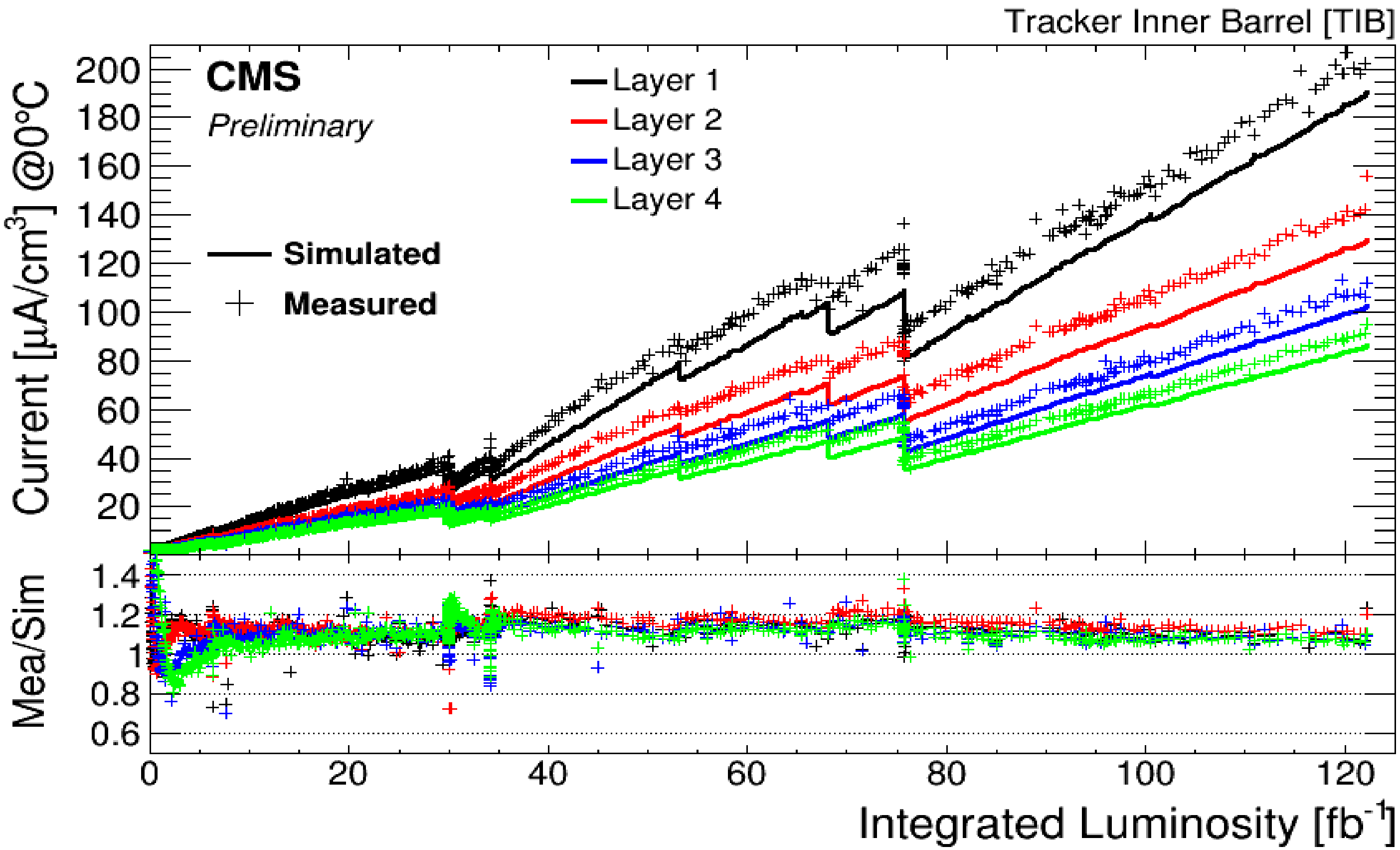


Change of operational temperature from -20 °C to -25 °C has little impact on the depletion voltage



cooling set point -25 °C

Reminder: Leakage current simulation and data



- Agreement is good for leakage current, **~20% underestimation**
- Relative discrepancies are fairly stable in time

Simulation: Leakage current per HV channel

after 400 fb^{-1} with cooling at -20 °C during run 3

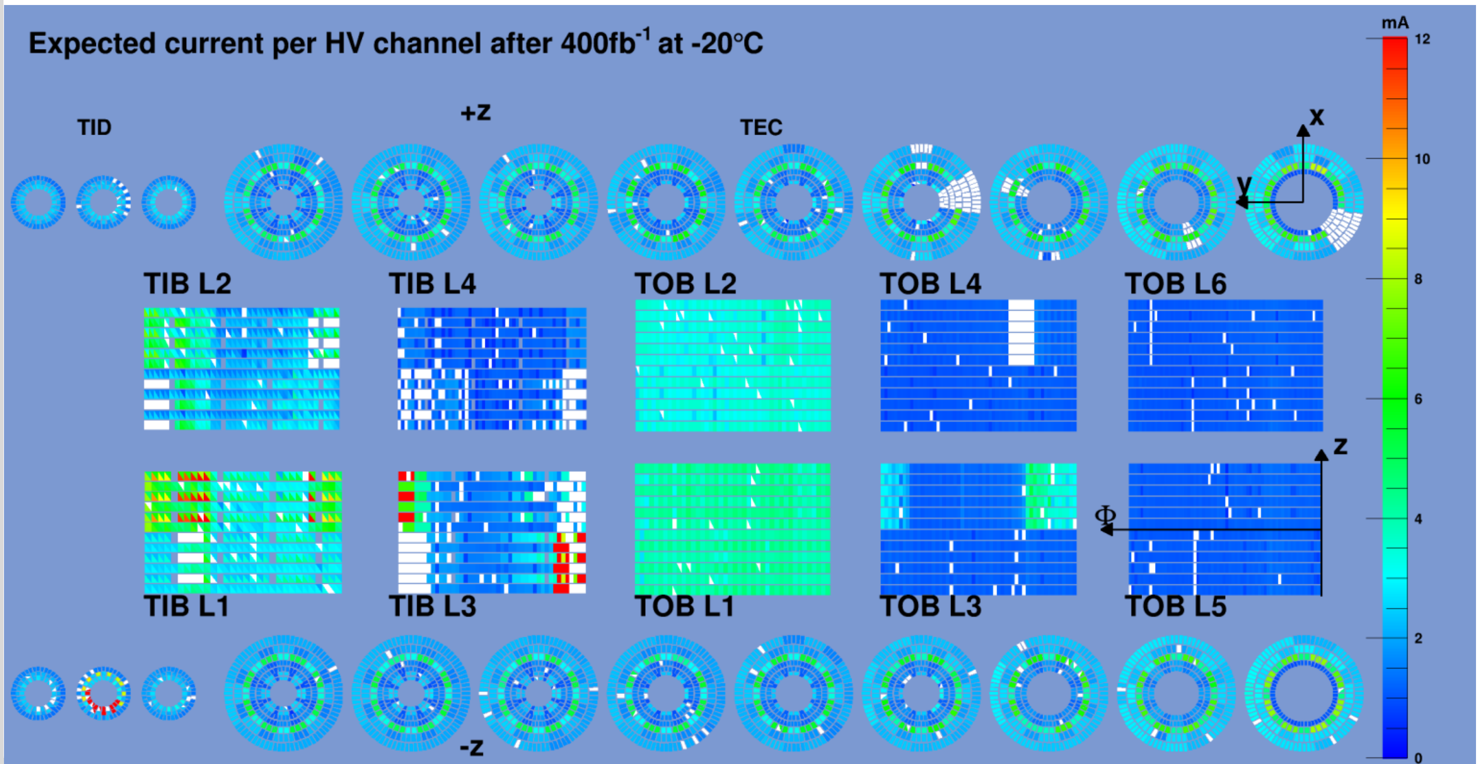
Full irradiation history + realistic future scenario

\+ FLUKA fluence

Thermal contacts + Full temperature history + realistic future scenario ← assuming 120 days at RT and otherwise temperatures **below 0 °C for LS2 and all YETS**

$I(\Phi, t, T) = I_0 + \alpha(t,T)\Phi V$

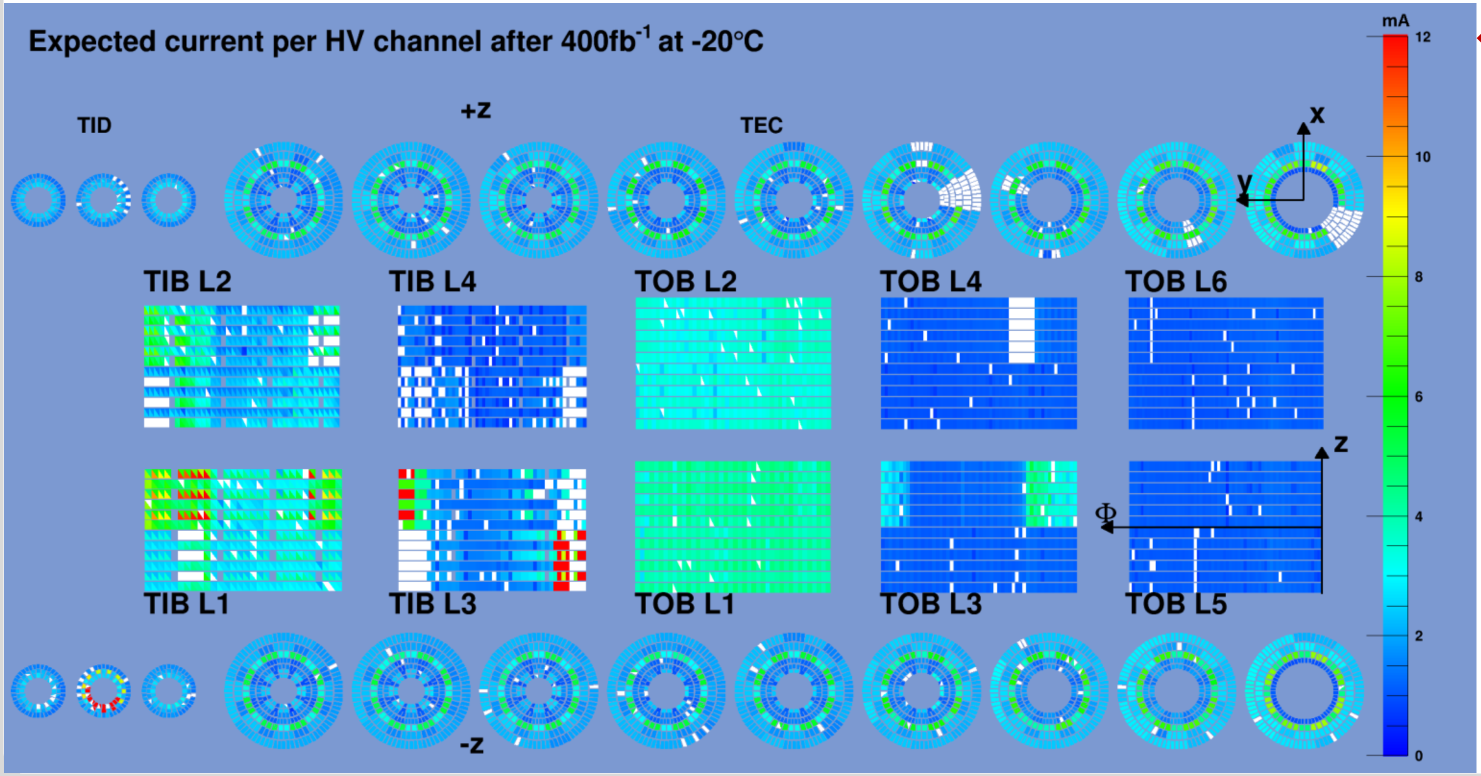
Leakage current model



Simulation: Leakage current per HV channel
after 400 fb^{-1} with cooling at -20 °C during run 3

Range of leakage currents arises from differences in:

- Temperature
- Sensor volume
- Radiation exposure

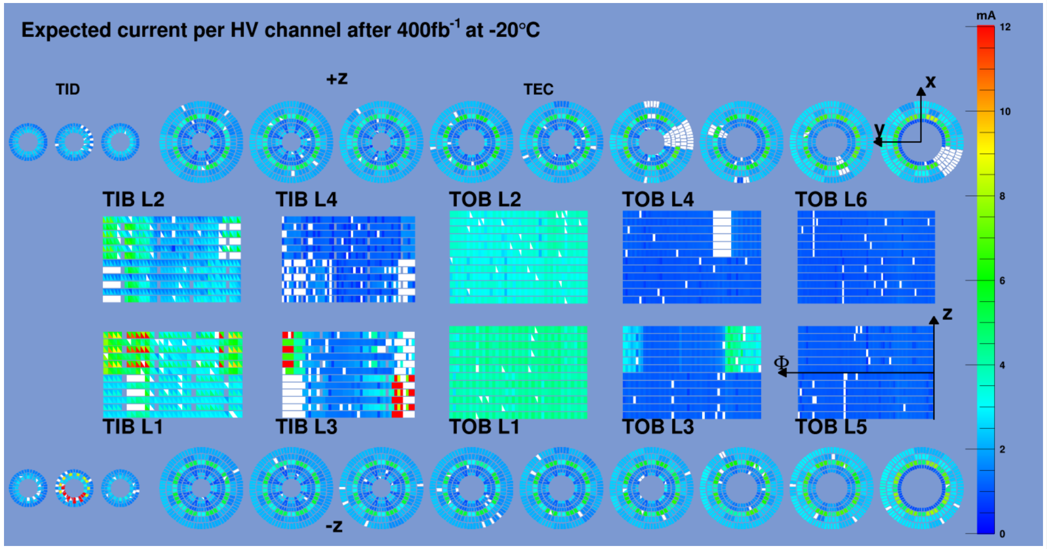


← Current limit of the power supply system as it is now: 12 mA per HV channel

Present ssimulation **underestimates the leakage current by ~20%** compared with data

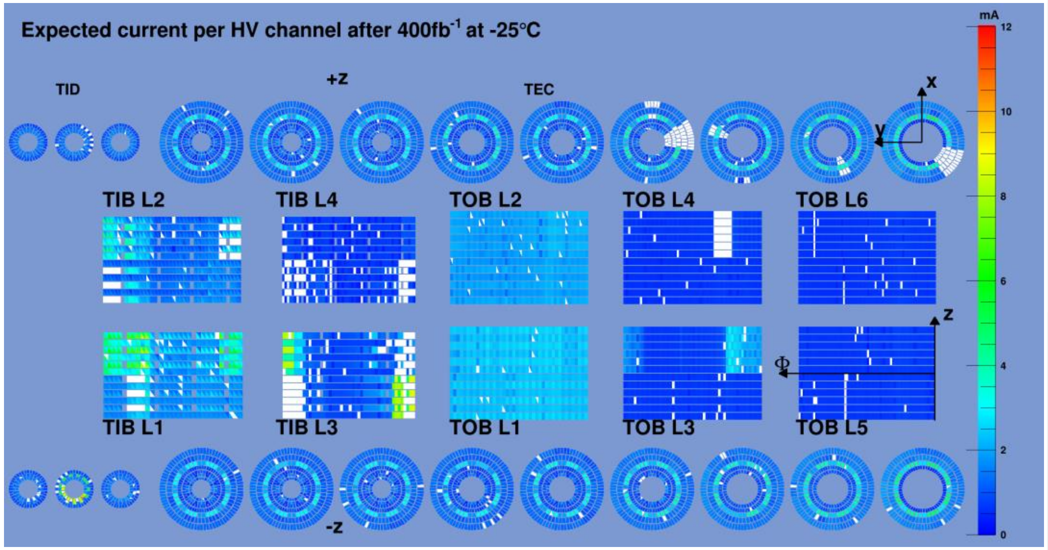
Warmer modules' HV channels would reach critical values with cooling set point at -20°C

Simulation: Impact on leakage current per HV channel Cooling at -20 °C and -25 °C during run 3



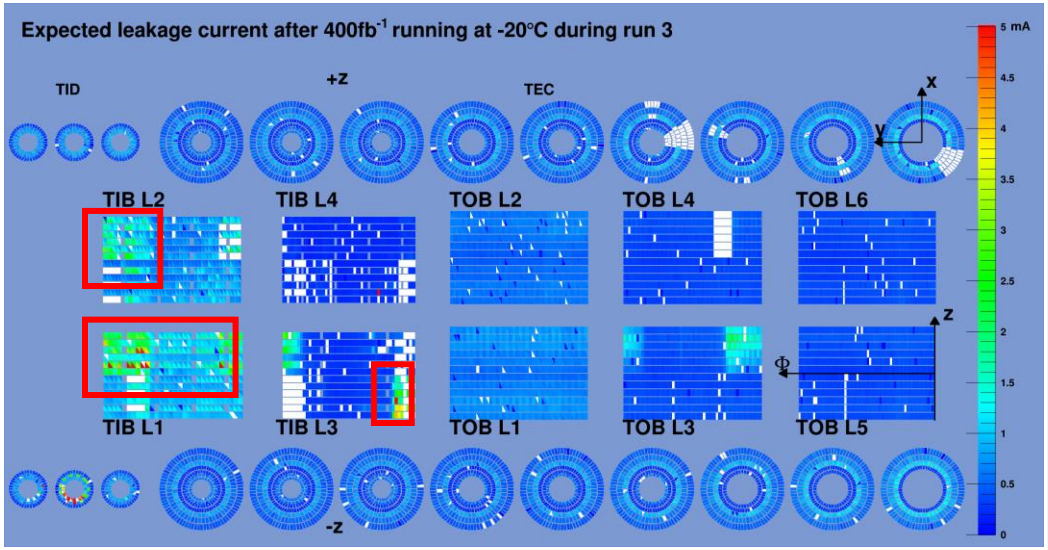
cooling set point -20 °C

By setting the cooling to -25 °C, reaching the power supply limit 12 mA can be avoided.



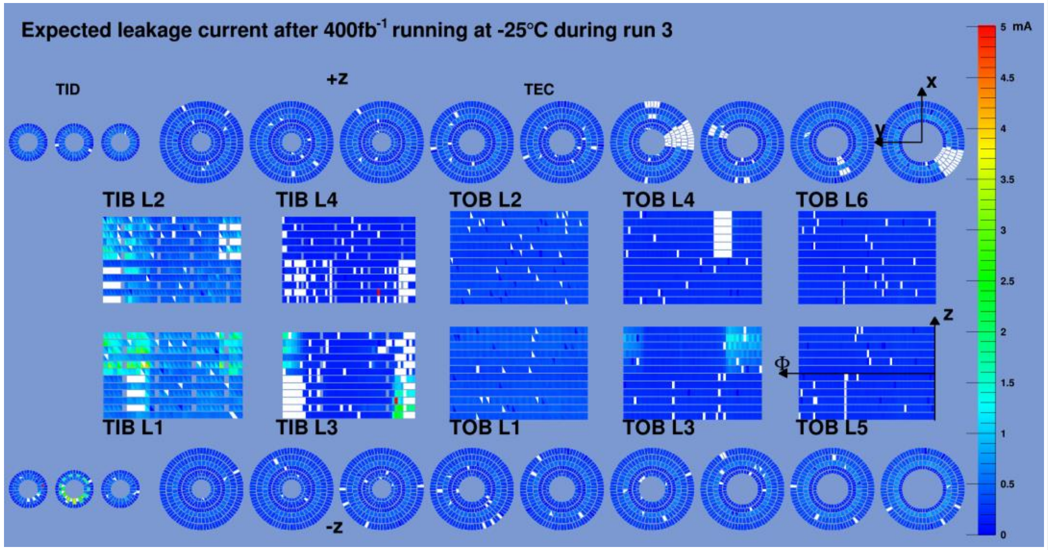
cooling set point -25 °C

Simulation: Impact on leakage current per module
Cooling at -20 °C and -25 °C during run 3



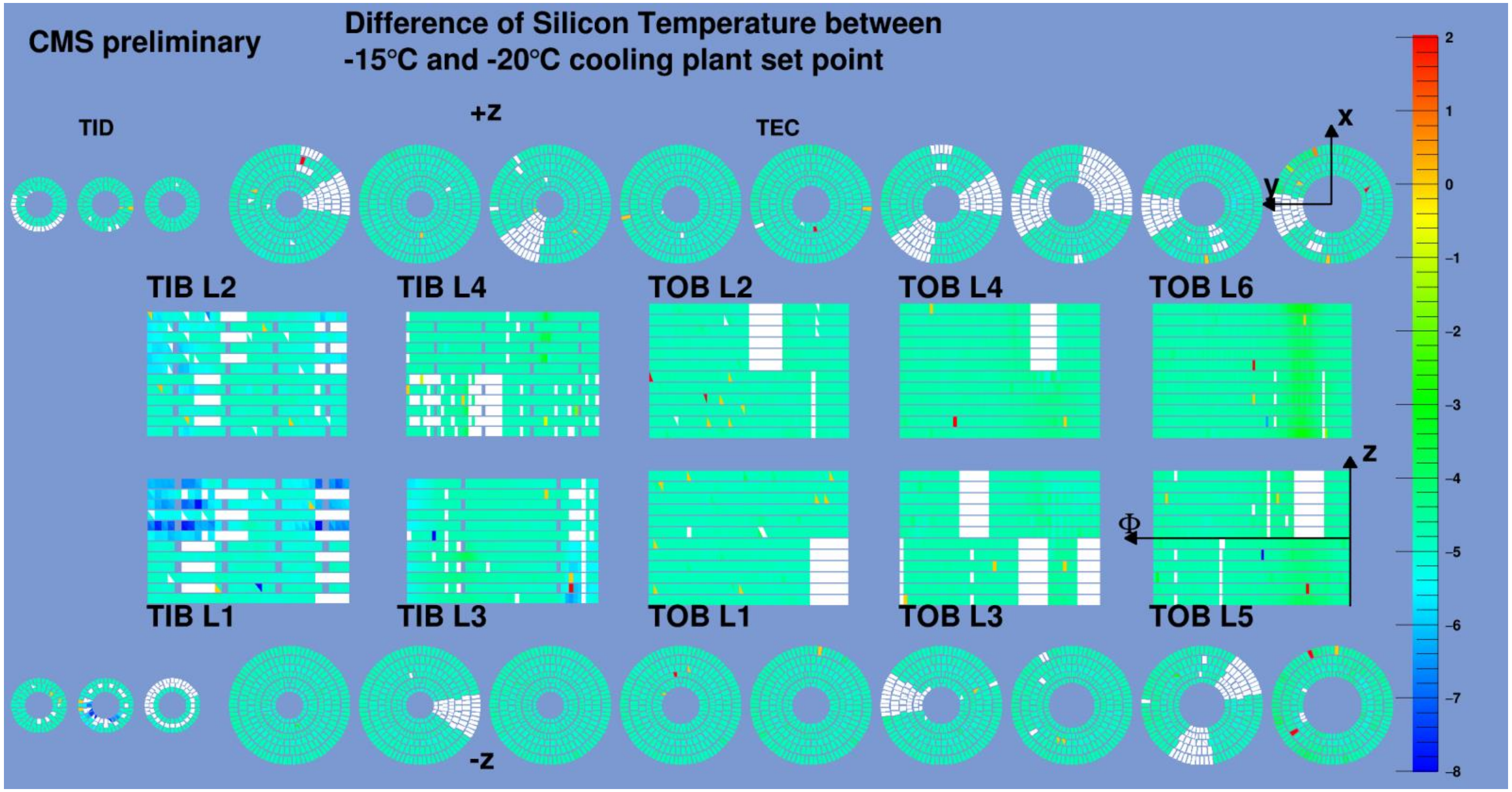
cooling set point -20 °C

With cooling at -20 °C the leakage current of the warmer modules approaches critical values with **risk of thermal runaways**.
By lowering the cooling set point to -25 °C this can be ameliorated.



cooling set point -25 °C

Data: Difference of Silicon temperature going from cooling plant set point -15°C to -20°C



- Modules with degraded cooling contact or no direct cooling: eg. TIB L1, L3
- Enhanced drop in temperature in those regions thanks to enhanced drop in leakage currents: **Reduced self-heating.**

$$I_{leak} \sim T^2 \exp\left(\frac{-c}{T}\right)$$

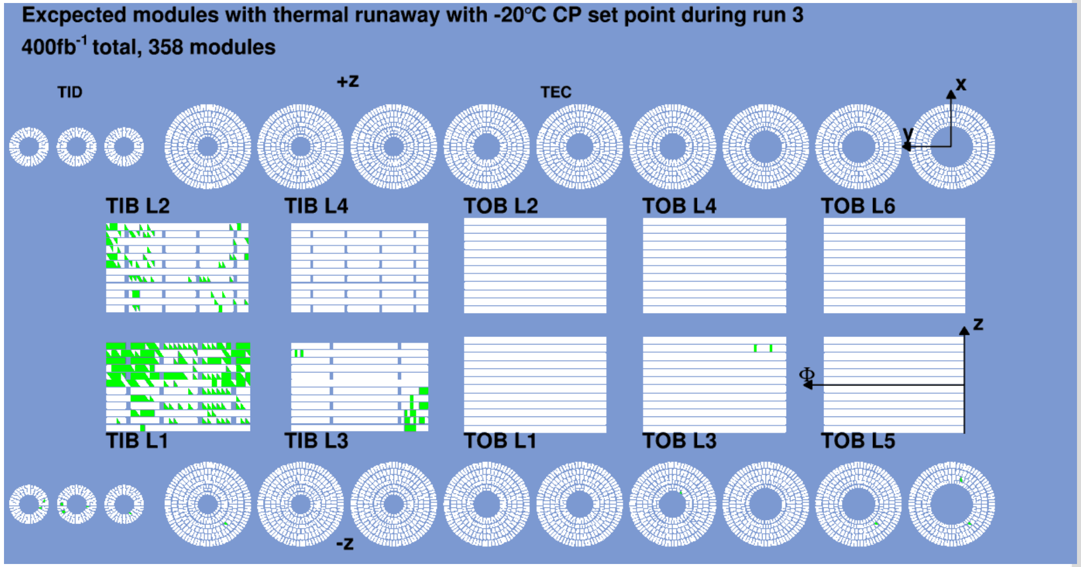
Simulation: Number of thermal runaways

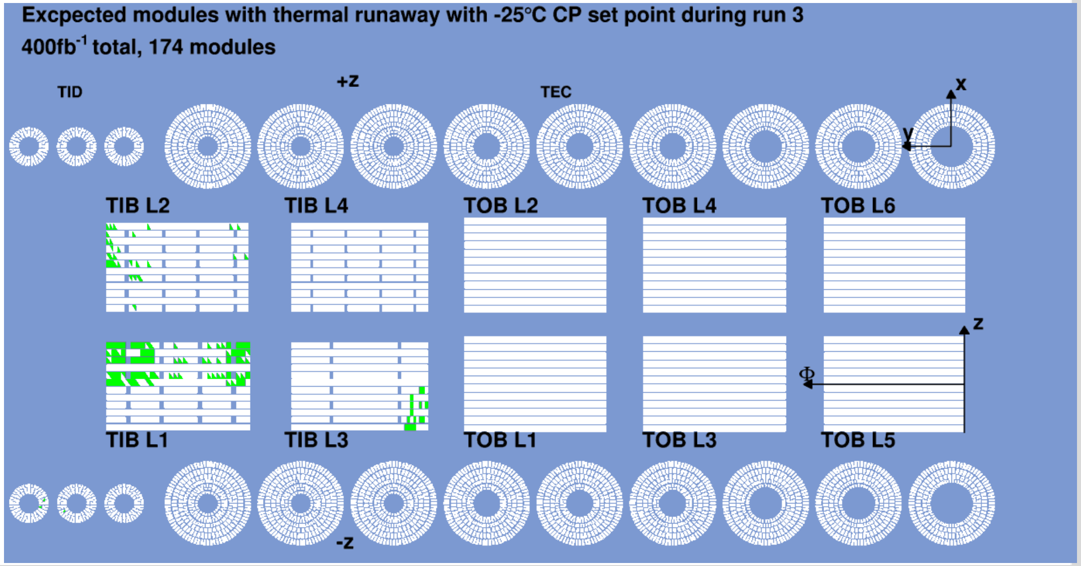
cooling set point -20 °C

- **Number of thermal runaways is reduced by decreasing the cooling set point,** thanks to enhanced drop in temperature and therefore leakage current for "warmer" modules.

For this scenario the number of expected thermal runaways is approximately halved (from 358 to 174 modules) at 400 fb^{-1}

cooling set point -25 °C





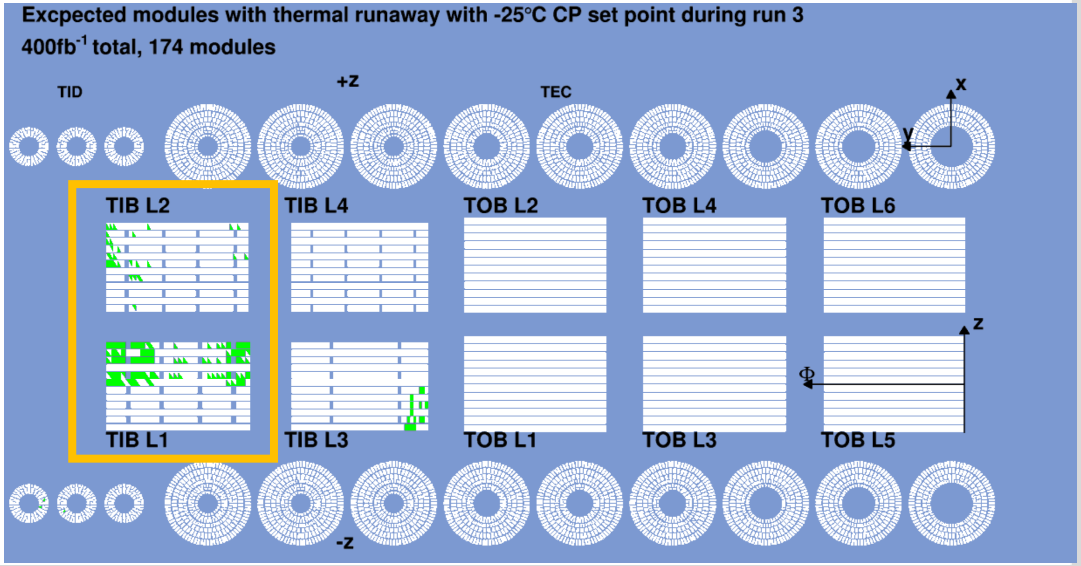
Simulation: Number of thermal runaways

Mostly stereo-layers will be affected by thermal runaways.

The number of runaway modules can be further reduced by ***switching off the stereo part*** - thereby reducing temperature.

→ The already installed pixel layer 4 at higher radius will **mitigate any tracking degradation** substantially.

cooling set point -25 °C



CMS PIXEL TRACKER

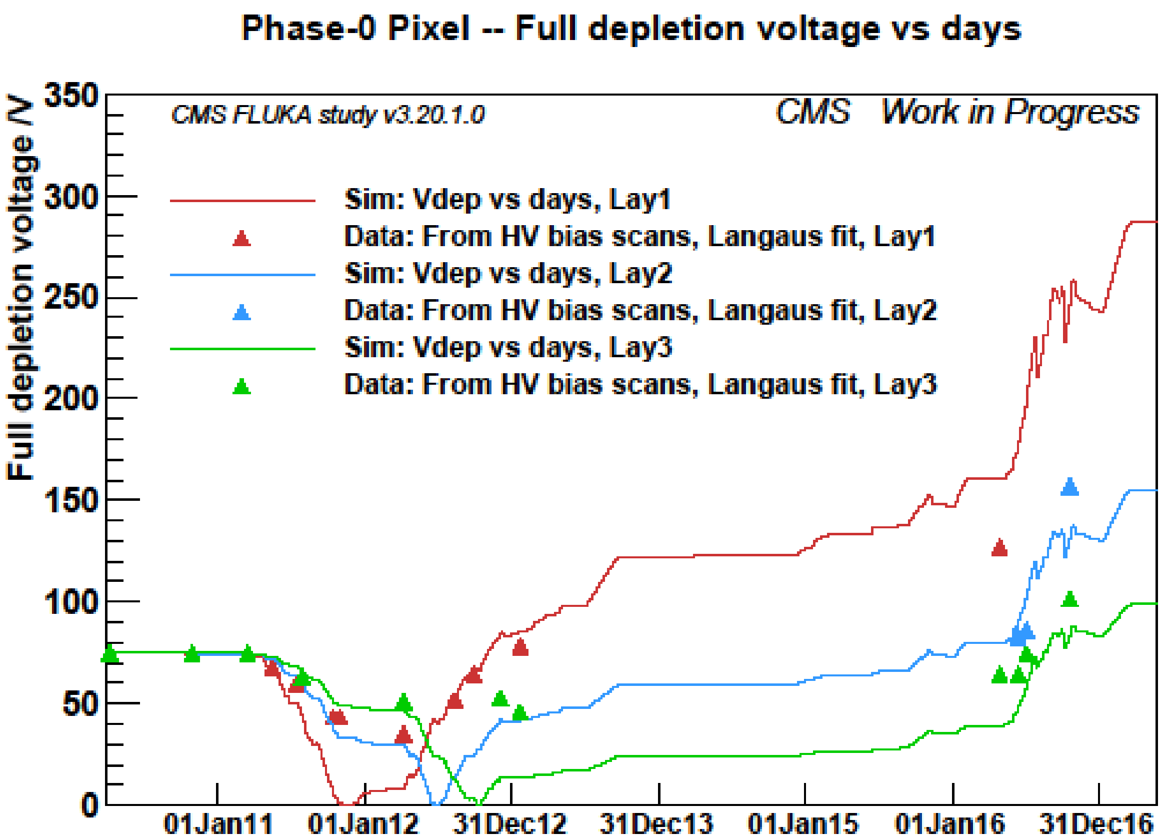
Simulation input

- **FLUKA fluence** simulation*:
  - Pixel: oxygenated Silicon (DOFZ) → **different impact of charged and neutral particles** scored to 1MeVneq
  - High spacial resolution
- Hamburg model: **Hamburg parameter set***
  for oxygenated Si from RD48 3rd status report
  http://rd48.web.cern.ch/RD48/status-reports/rd48-3rd-status-report.pdf
- **Actual temperature history** from database*
  - Silicon temp. > measurement
    whenever LV on → added an offset
- **Depletion voltage data points*** for comparison: from HV bias scans

* All of these parameters introduce significant uncertainties.

Pixel Phase-0: Depletion voltage simulation Work in progress

- Based on the **full temperature- and irradiation history** the expected full depletion voltages of the pixel tracker modules are simulated using the **Hamburg model*** for radiation damage
- The various plateaus in the simulation mirror long shutdown 1 and different technical stops of the LHC



→ Considering the high sensitivity to input data, the simulation matches the data well

Phase-1 (since 2017): Depletion voltage simulation

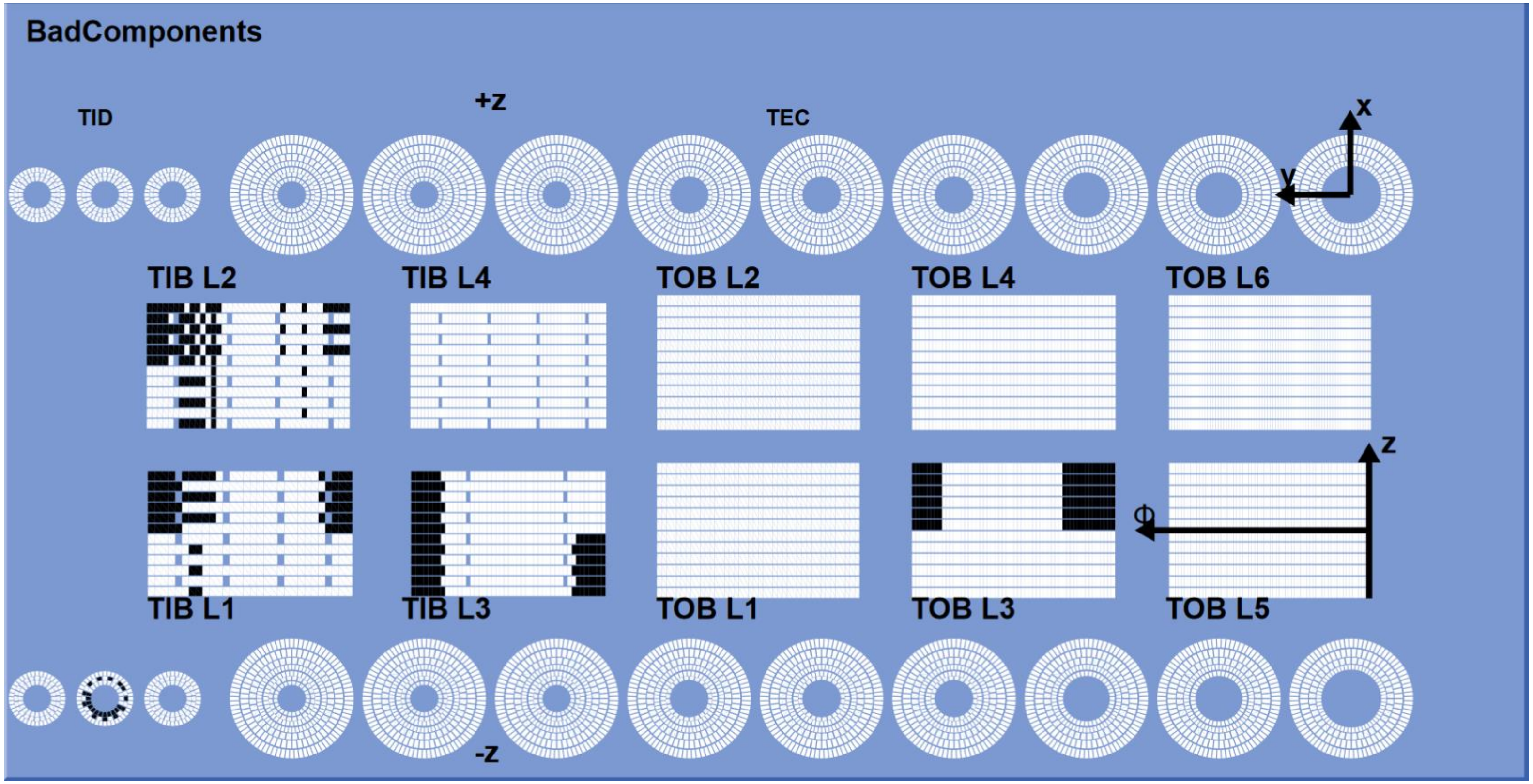
- Same approach as Phase-0
  - Add realistic 2018 temperature and irradiation scenarios
  - Different layer radii and slightly different overall geometry
  - Inner layer: Fluence is quite different even for inner and outer modules

- Work in progress, not yet ready to show
  - Simulation is quite sensitive to input parameters
    - Need to gain a better understanding of the input parameters first
  - Data from the first bias scan in 2018 coming soon

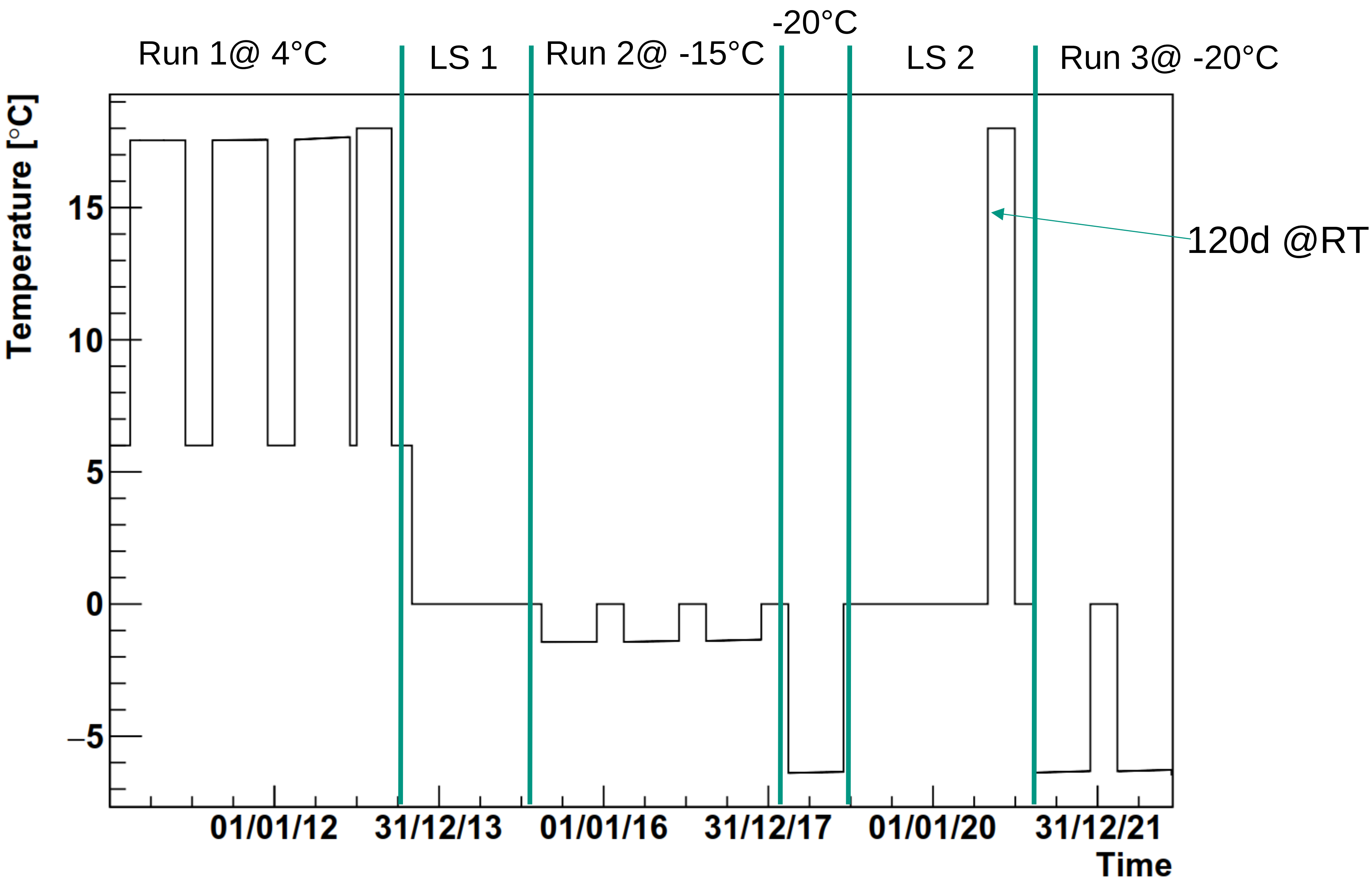
BACK-UP

After run 3:
Worst case scenario for degraded components

- From Update TDR
- https://cds.cern.ch/record/1481838/files/CMS-TDR-011.pdf
- Accounts for the thermal runaway scenarios (Slide 18)

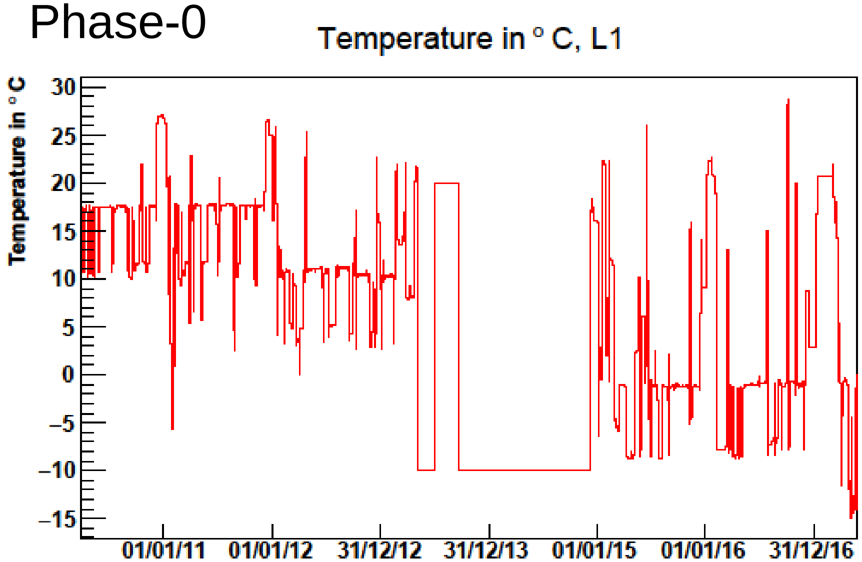


Example temperature scenario for strip tracker simulation

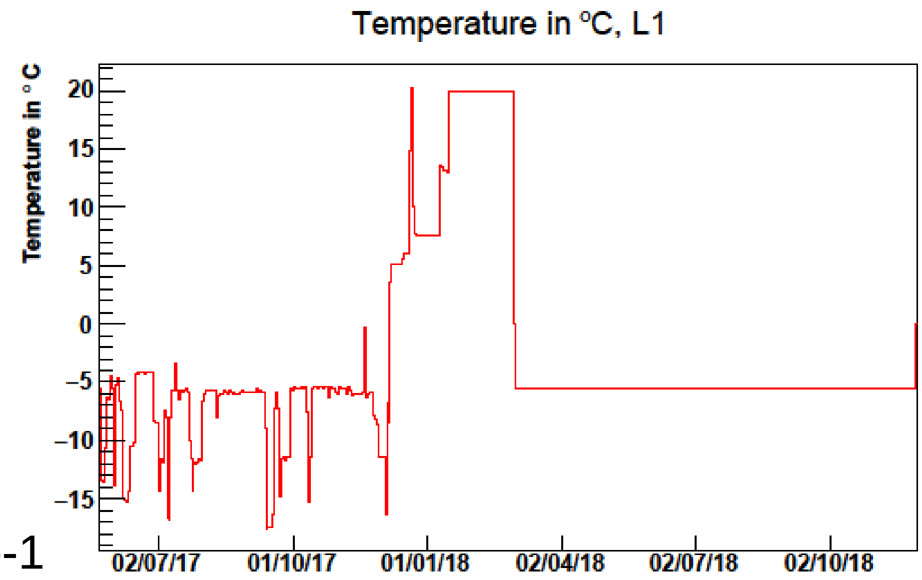


Simulation input: Sensor temperatures

Phase-0

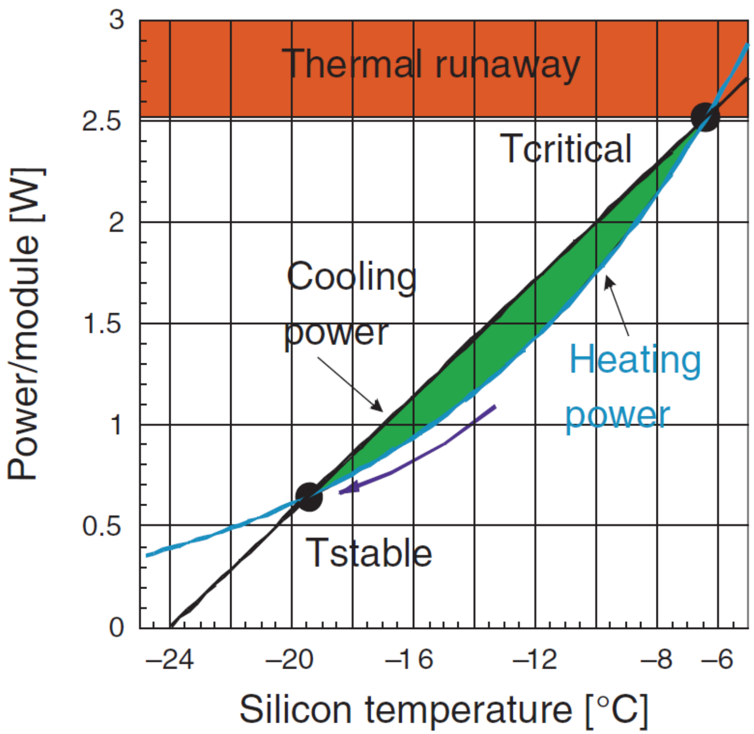


Expect that
Silicon temperature > measurement data if detector (tracker low voltage) is on.
→ Added temperature offset
whenever LV = on.



Phase-1

Thermal runaway



F. Hartmann, Evolution of Silicon Sensor Technology in Particle Physics, 2nd Edition, Springer 2017