Operational experience on the CMS silicon strip detector

Ivan Shvetsov on behalf of the CMS collaboration

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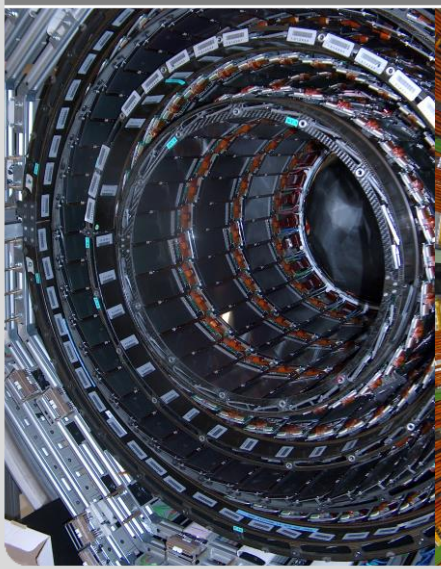
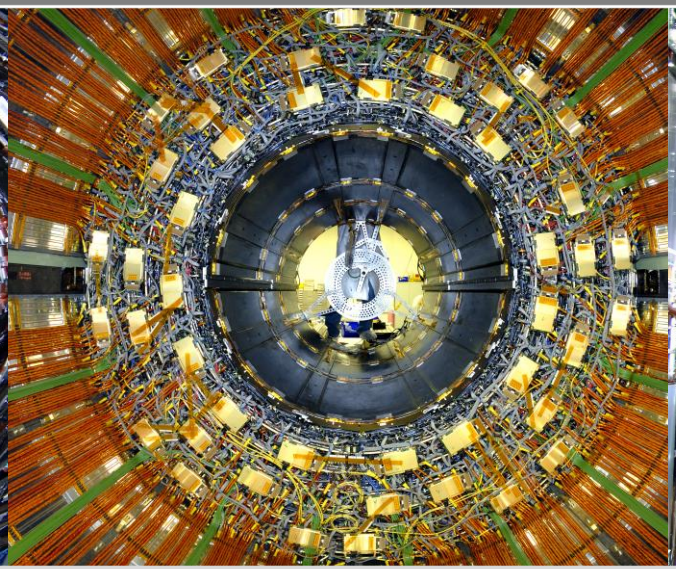
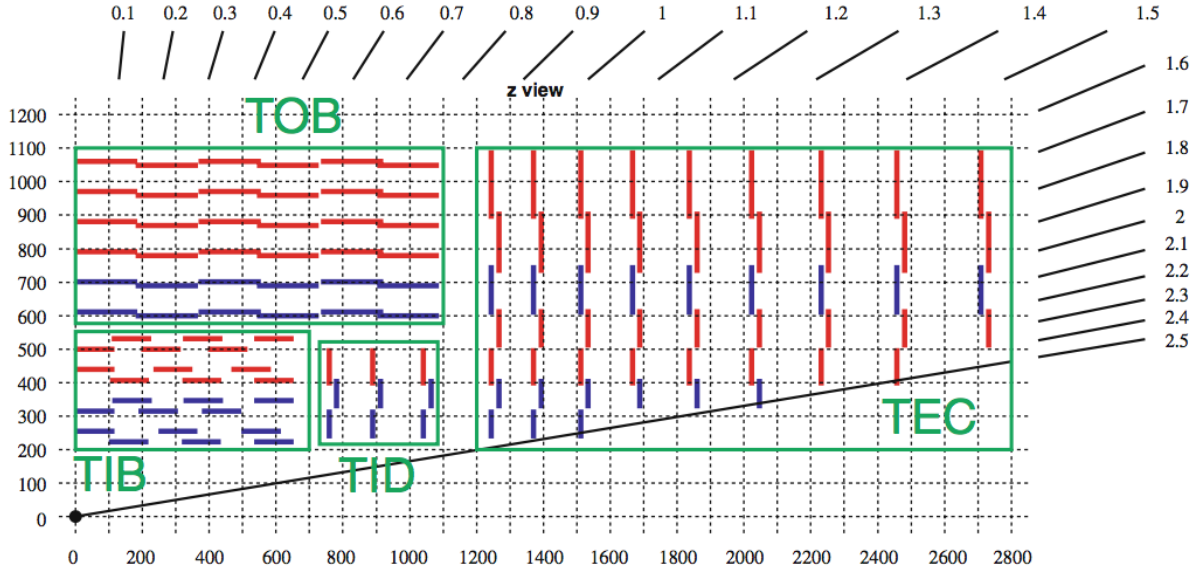
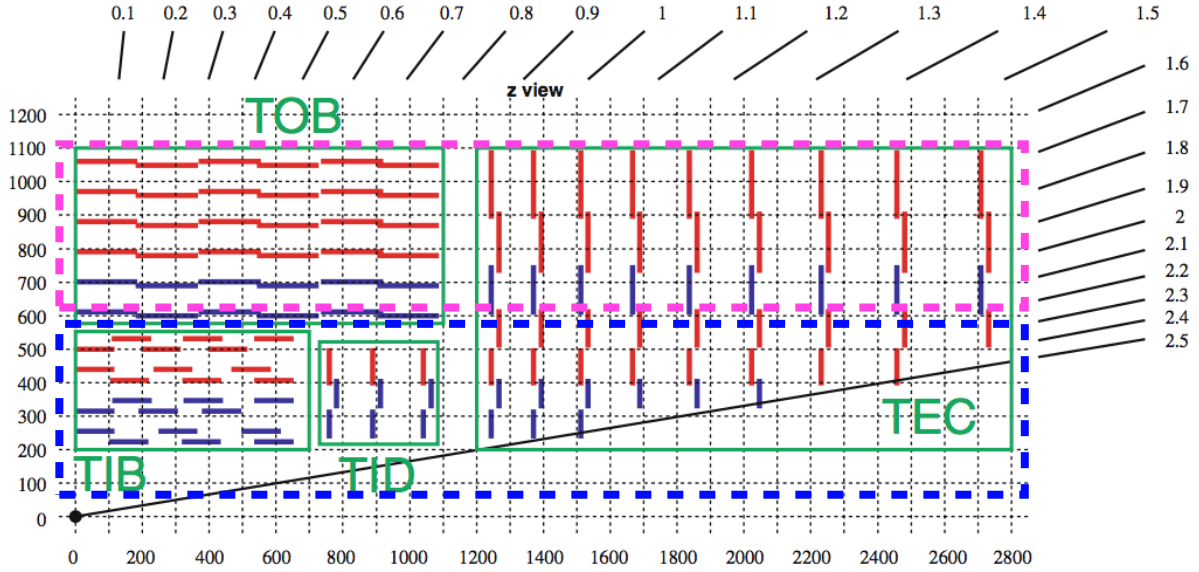




CMS Strip Tracker



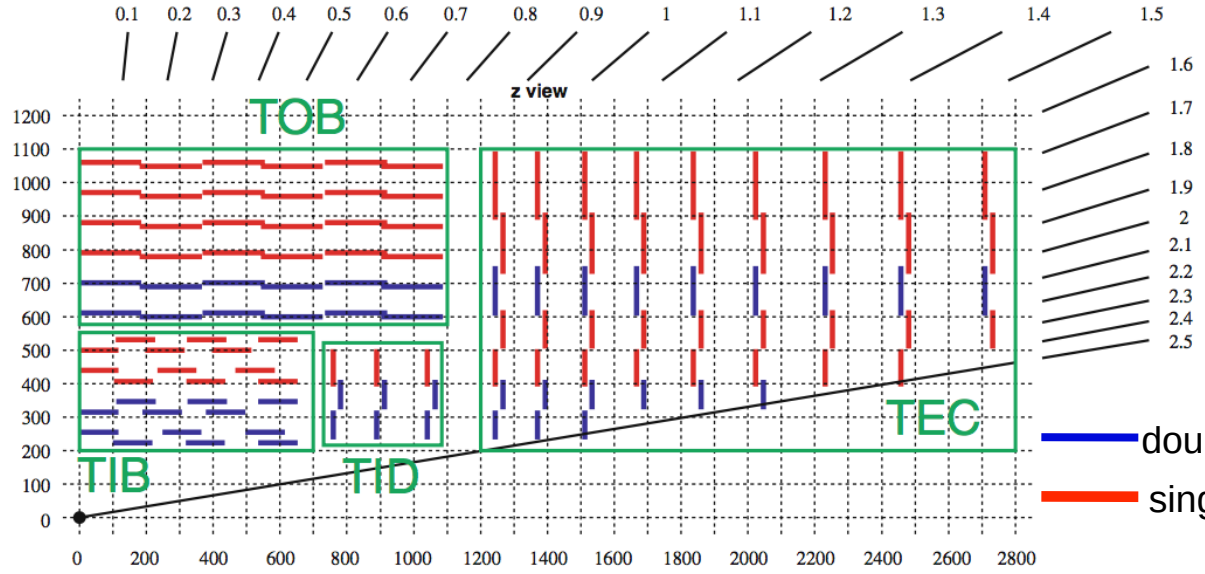
- 9.3 million strips, 198 m^2 active silicon area, 15148 modules
- 5 m long, 2.5 m diameter
- 10 layers in the barrel region, 4 inner barrel layers (TIB) and 6 outer barrel layers (TOB)
- 3 inner disks (TID) and 9 endcap disks (TEC)
- **p-in-n** sensors

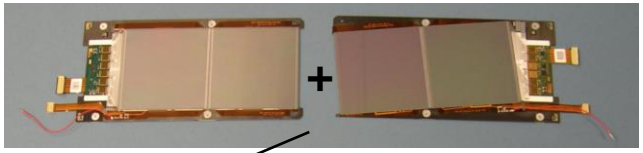
CMS Strip Tracker



- 9.3 million strips, 198 m^2 active silicon area, 15148 modules
- 5 m long, 2.5 m diameter
- 10 layers in the barrel region, 4 inner barrel layers (TIB) and 6 outer barrel layers (TOB)
- 3 inner disks (TID) and 9 endcap disks (TEC)
- 320 µm Si in inner layers (TIB, TID, TEC ring 1-4)
- 500 µm Si in outer layers (TOB, TEC ring 5-7)

CMS Strip Tracker





double sided

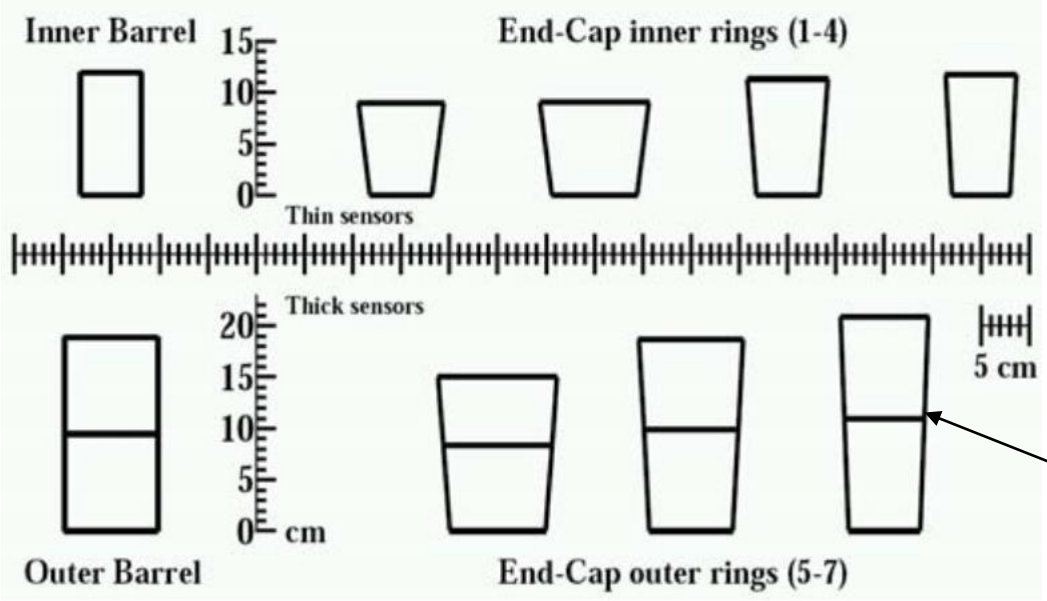
single sided

- 9.3 million strips, 198 m^2 active silicon area, 15148 modules
- 5 m long, 2.5 m diameter
- 10 layers in the barrel region, 4 inner barrel layers (TIB) and 6 outer barrel layers (TOB)
- 3 inner disks (TID) and 9 endcap disks (TEC)
- Double sided modules (2 modules with stereo angle of 100 mrad) in 4 layers (3 rings) in barrel (endcap)

Modules

320 µm

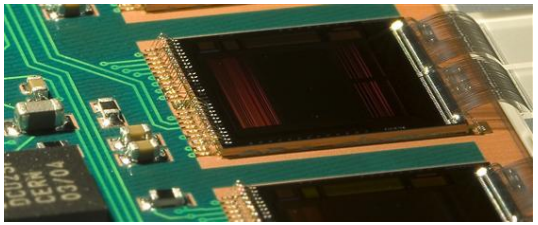
500 µm



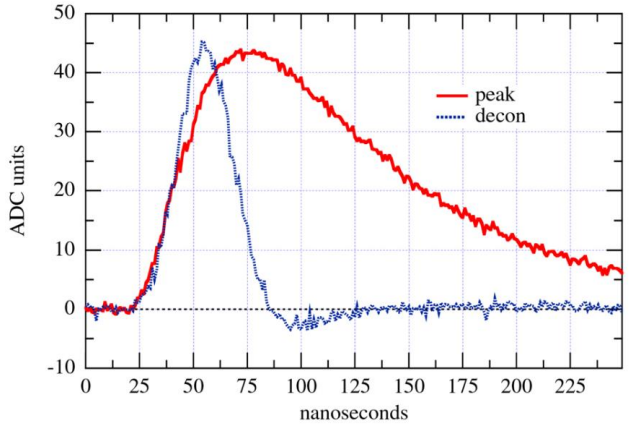
daisy chained

- Longer strips in outer layers/rings
- Longer strips → thicker sensor to keep high signal to noise

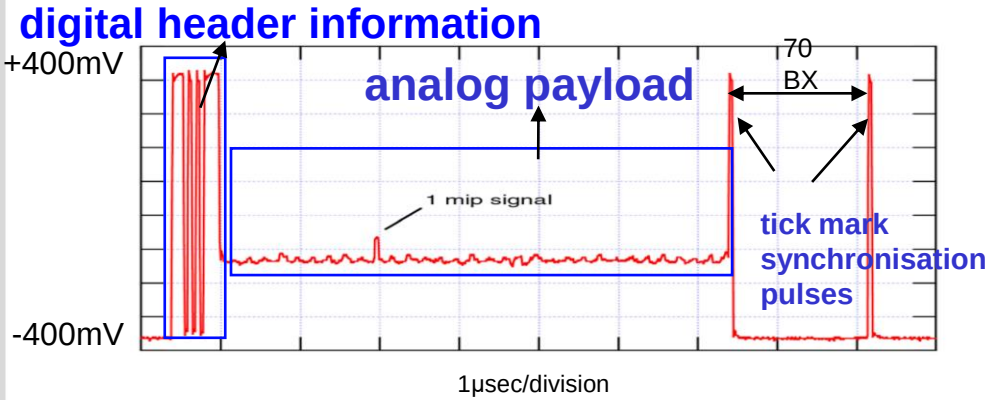
Tracker Analog readout

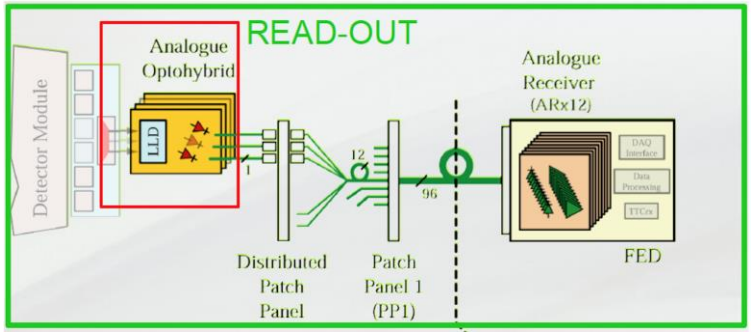


- Tracker readout is analog (signal height information)
- APV25 chip can be read out in 2 modes:
  - peak mode (single sample from shaper)
  - deconvolution mode (3 sample weighted average, shorter pulse)
- Signal from APV25 is converted to optical on the analog-opto-Hybrid (AOH):
  - linear laser drivers
  - edge emitting photodiodes
- Laser driver has four gain stages: equalize readout gain and compensate the radiation damage

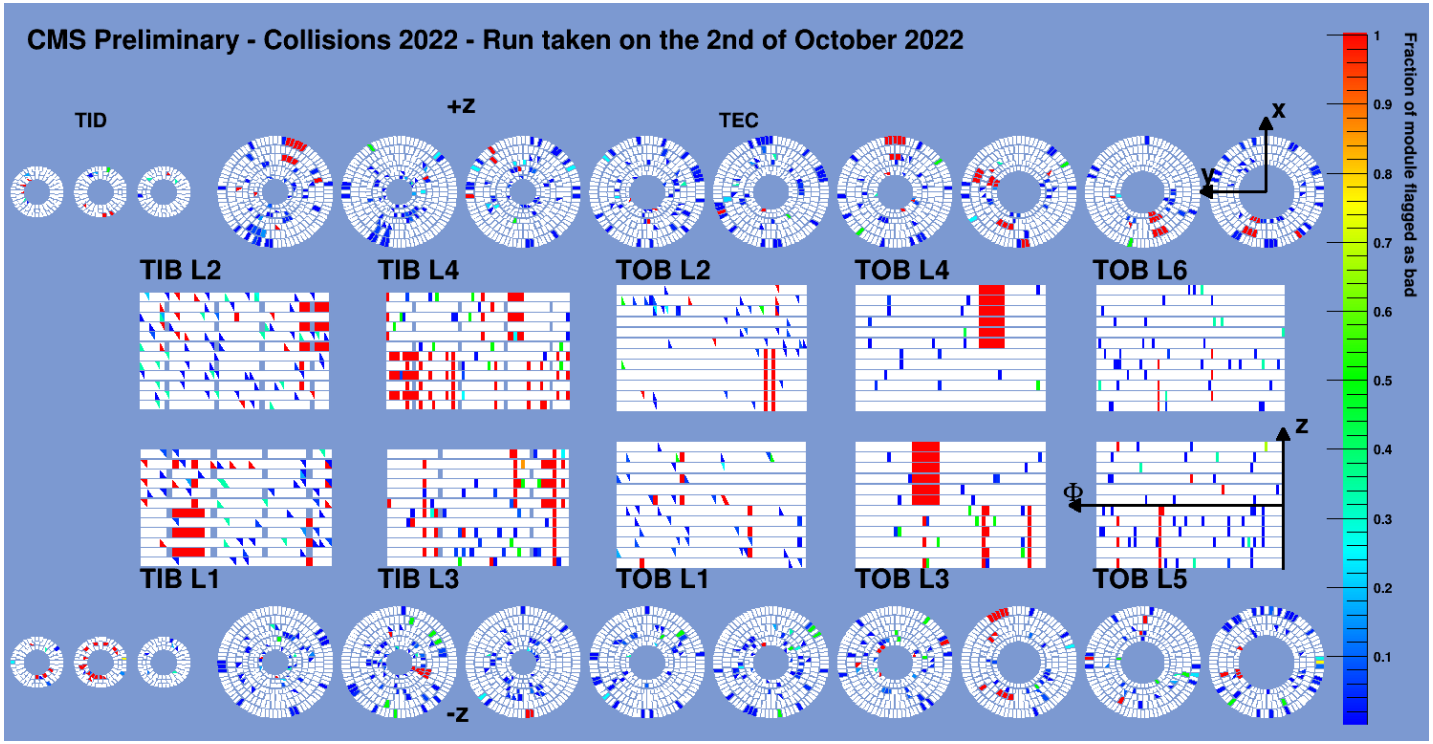


1 BX = 25 ns





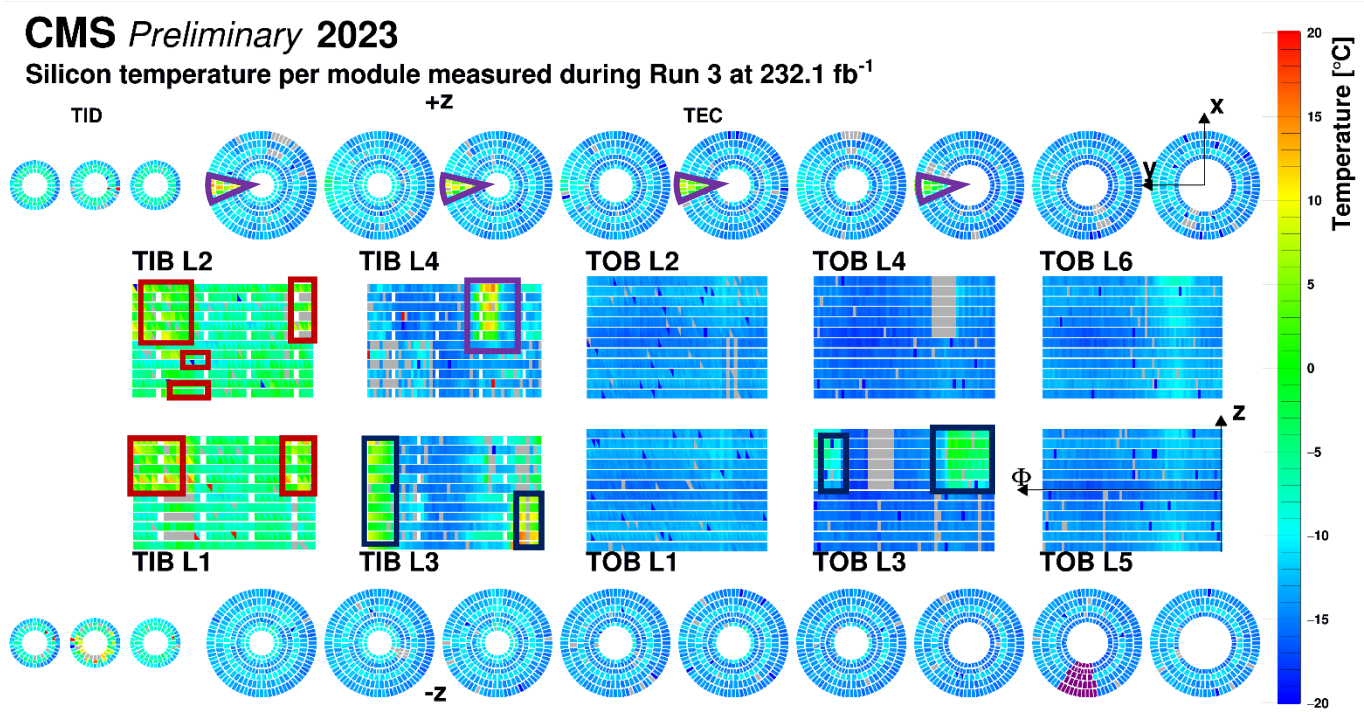
Detector status in LHC Run 2



- Fraction of active channels about 96% is stable over years
- Components excluded from data-taking: 4 control rings, power groups, individually switched off modules

Silicon temperature

- 2 cooling loops were closed in the beginning of 2022
- Detector is currently operated at -22℃ (since June 2023)
- Grey regions = modules excluded from data-taking
- Purple regions = modules with DCU data missing



Closed (leaky) cooling loops

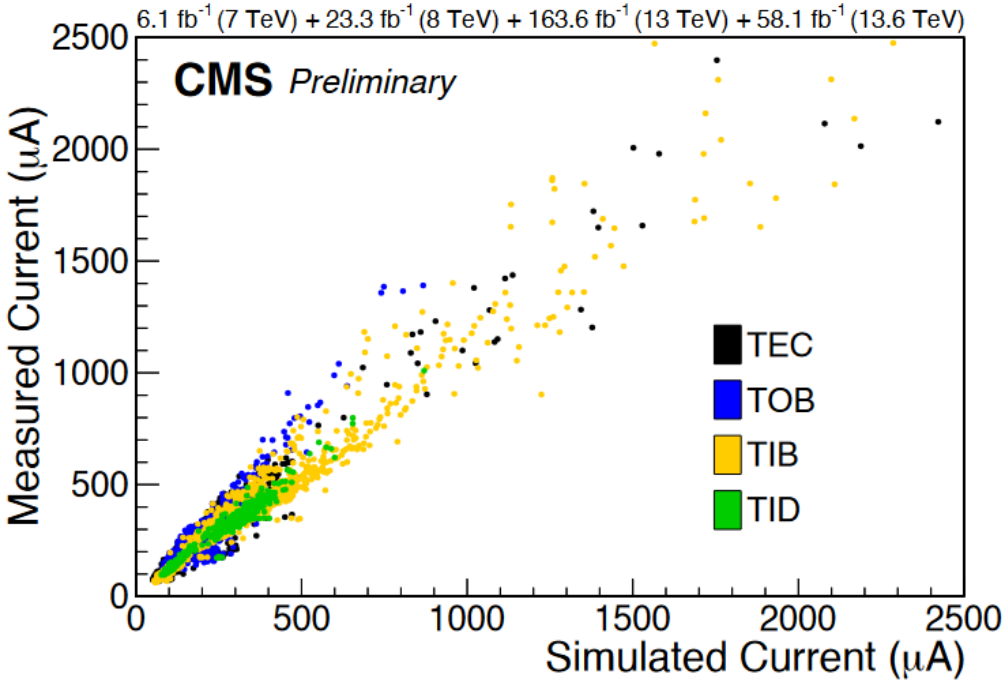
Degraded cooling contacts

Loops closed in 2022

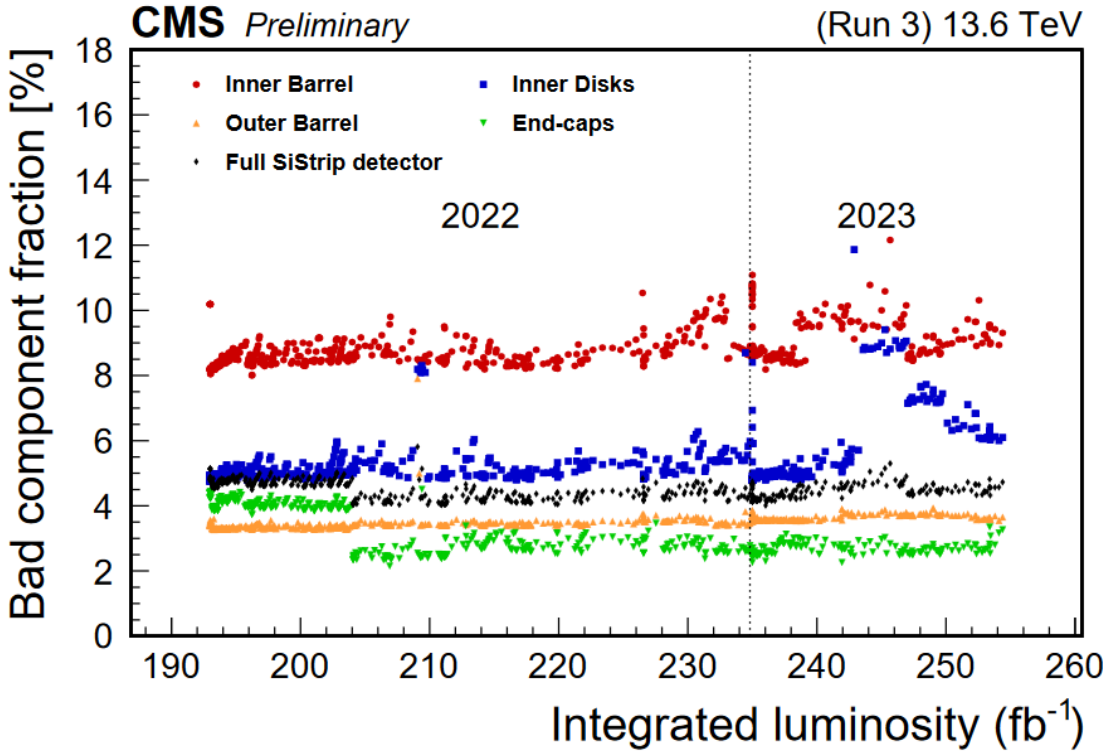
Change of operational temperature

- Operational temperature change from -20 ℃ to -22 ℃ in 2023
- Driven by increase of leakage current in modules with degraded cooling contact in TIB L1

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



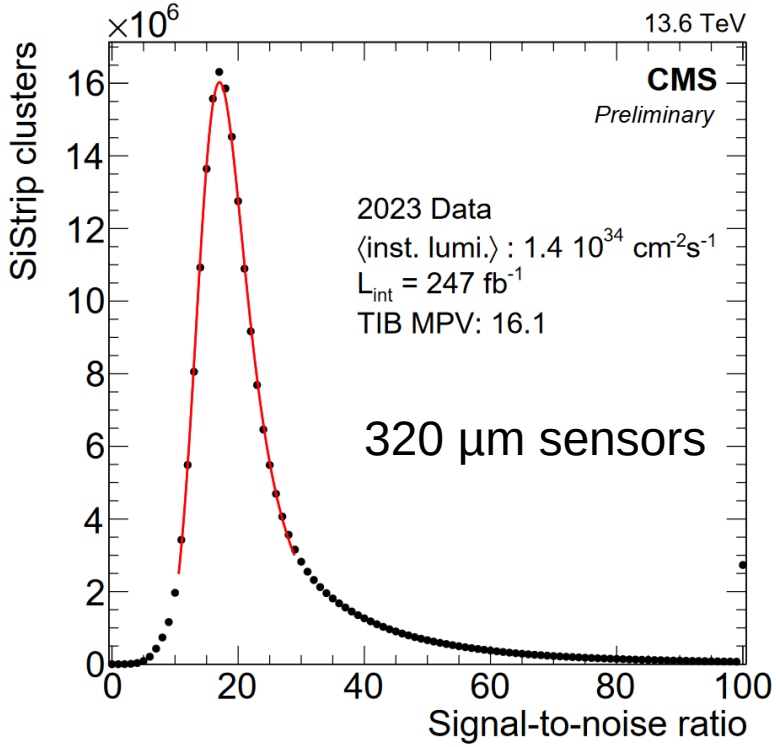
Evolution of “bad” components during run 3

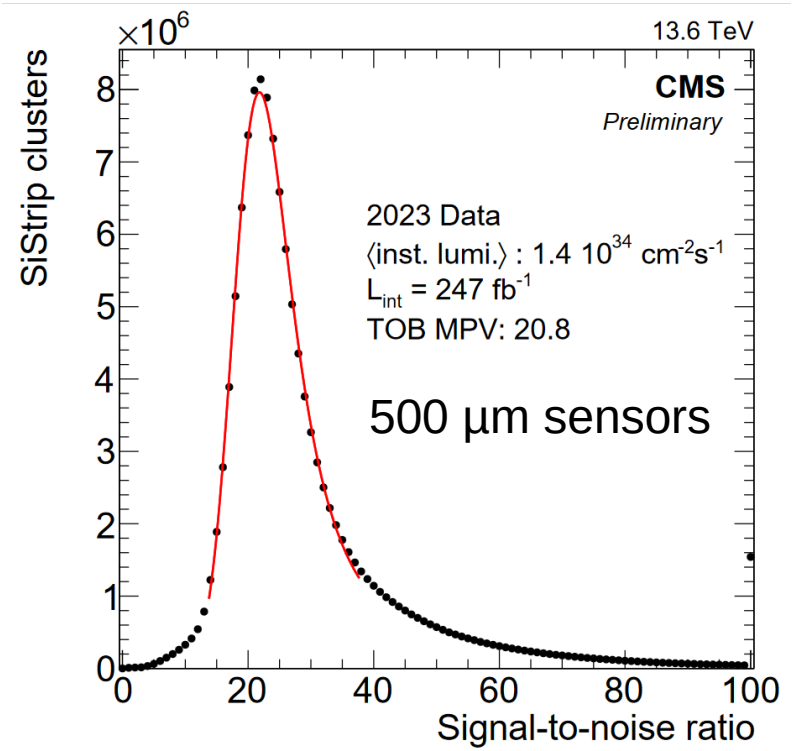


Fraction of components marked bad for reconstruction

- Fraction of active channels about 96% is stable over years
- Components excluded from data-taking: 4 control rings, power groups, individually switched off modules
- The drop in TEC is related to recovery of uncooled modules

Signal to noise performance

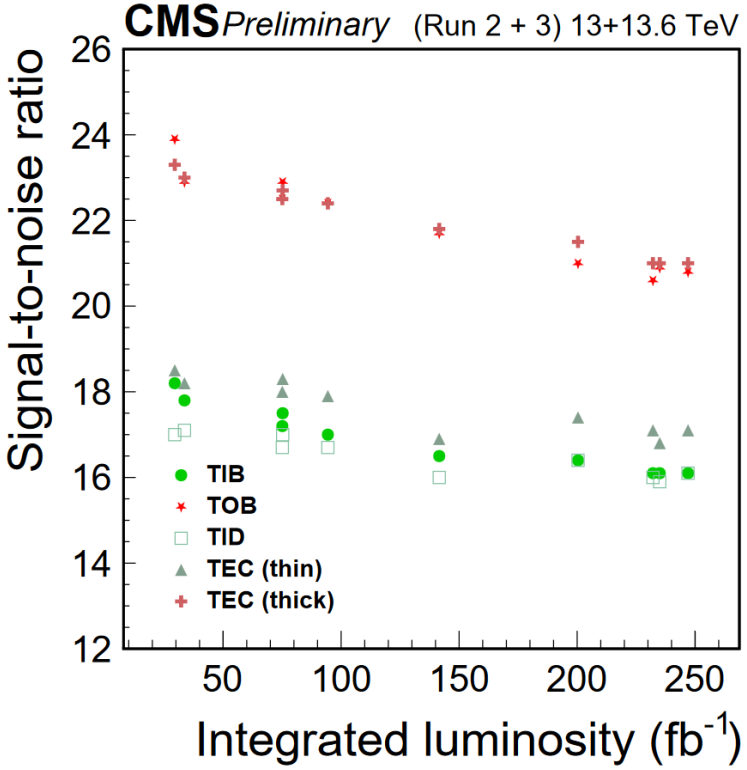


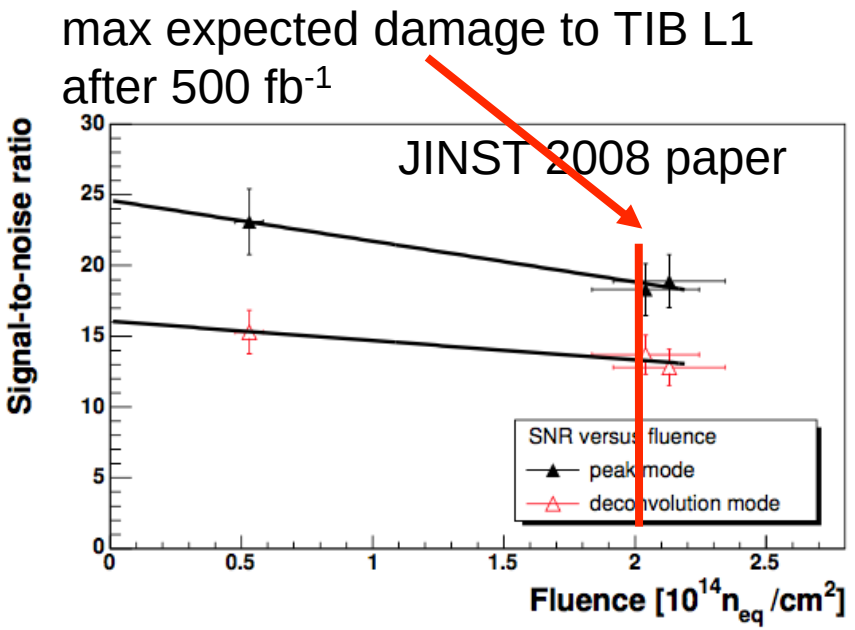


- high signal to noise

Signal to noise performance

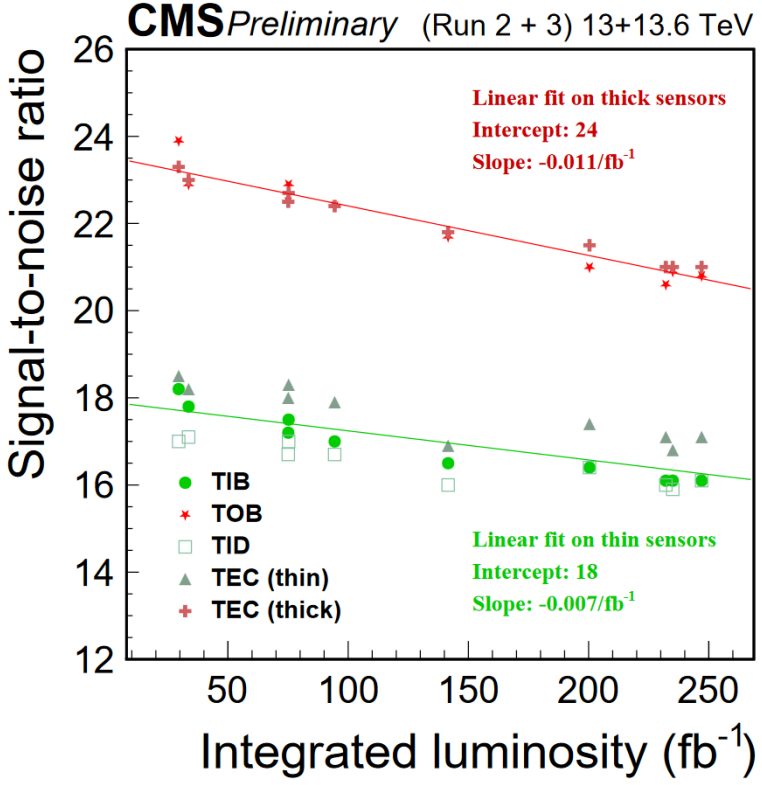
- Expected decrease of signal to noise with irradiation
- Signal to noise is not expected be an issue at the end of life (~ 500 fb^{-1})

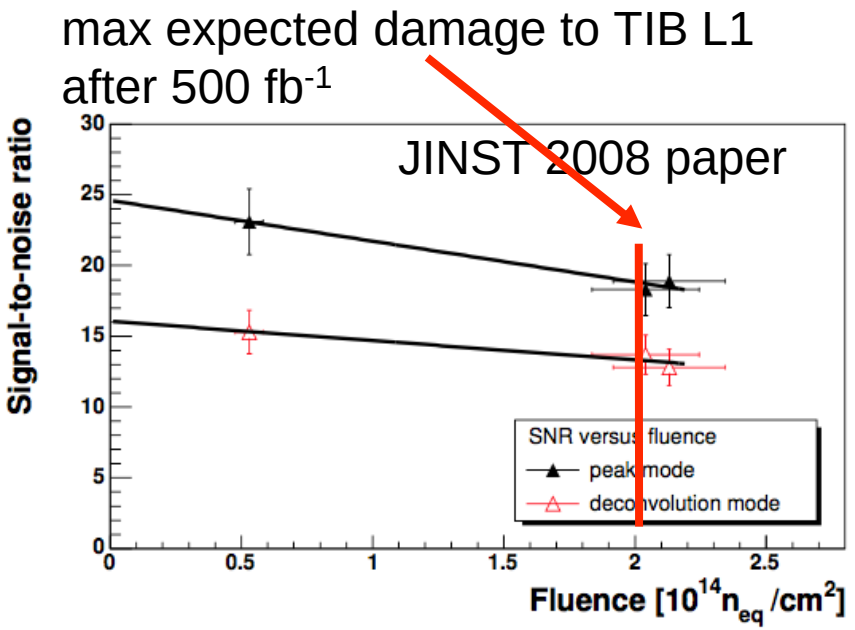




Signal to noise performance

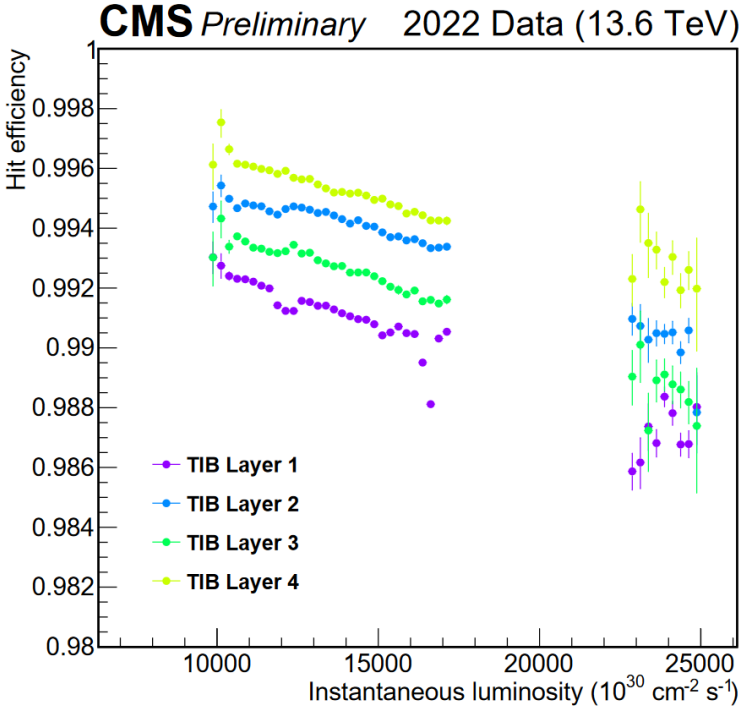
- Expected decrease of signal to noise with integrated luminosity
- Signal to noise is not expected be an issue at the end of life (~ 500 fb^{-1})

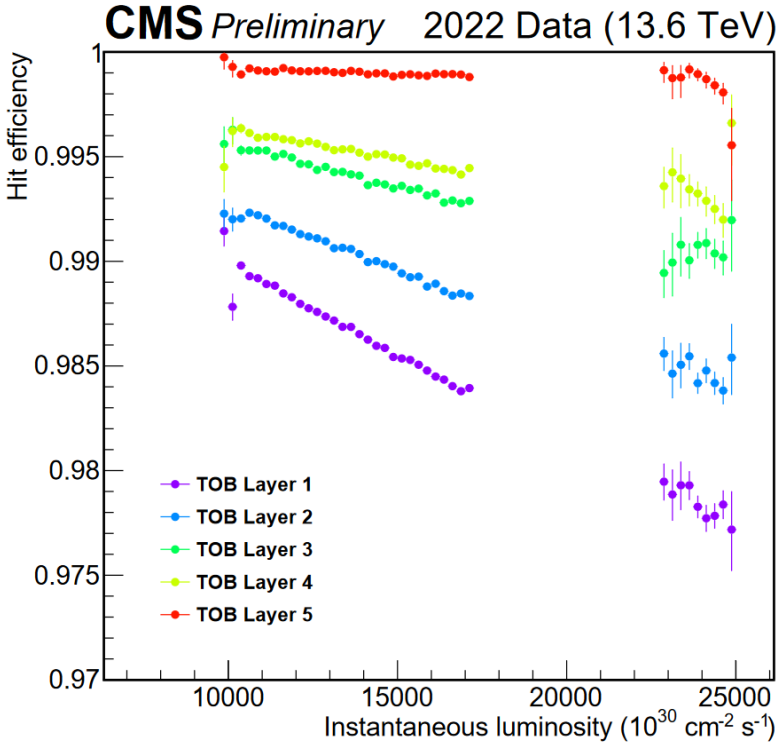




Hit efficiency

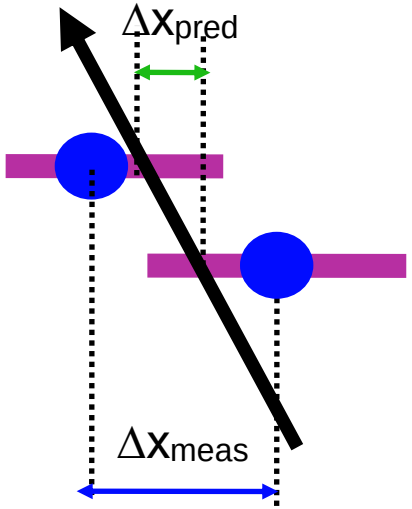
- Hit efficiency > 98 %
- Linear as a function of instantaneous luminosity
- Measured with standard fill with luminosity below 1.8e34 Hz/cm^2 and high luminosity fill with luminosity over 1.8e34 Hz/cm^2

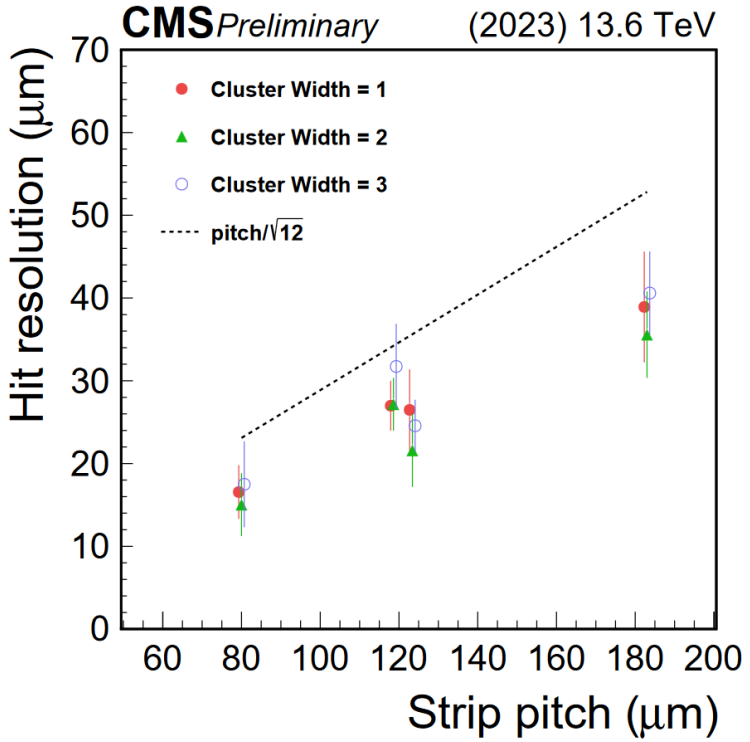




Single hit resolution

- Pair method: hit resolution is computed by using hits from overlapping modules in the same layer





$$\sigma_{hit} = \frac{\sqrt{\sigma(_{meas-pred})^2 - \sigma^2_{meas}}}{\sqrt{2}}$$

- Expected scaling with the pitch size can be seen

Radiation effects

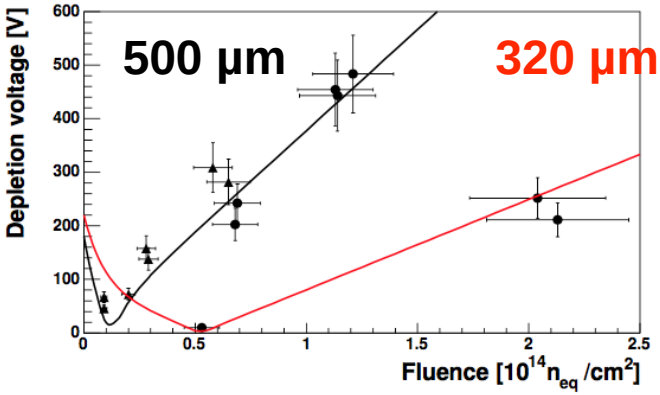
Radiation effects

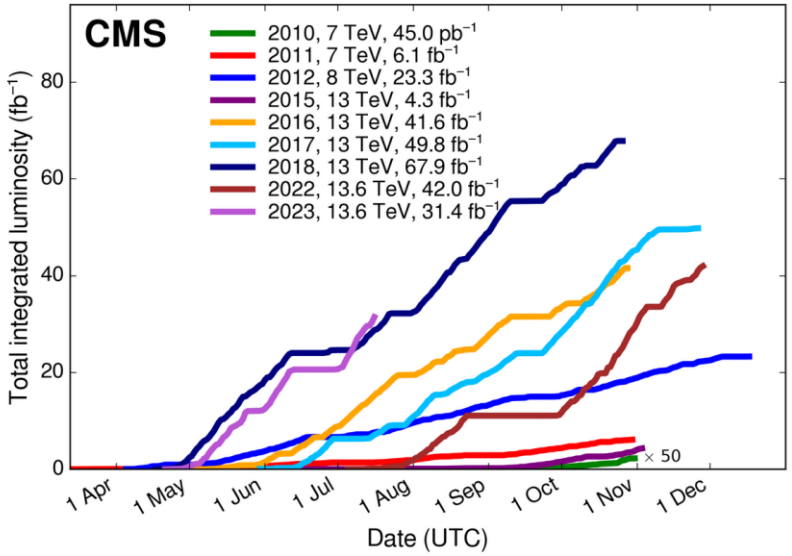
- About 266 fb^{-1} delivered by the end of 2023
- Regular measurement of radiation related quantities done
- Leakage current (I_{leak}) is measured using power supply and with detector control units on the module level
- Full depletion voltage:
  - bias scan on full detector

  (twice per year)
  - once per month on

  representative power groups

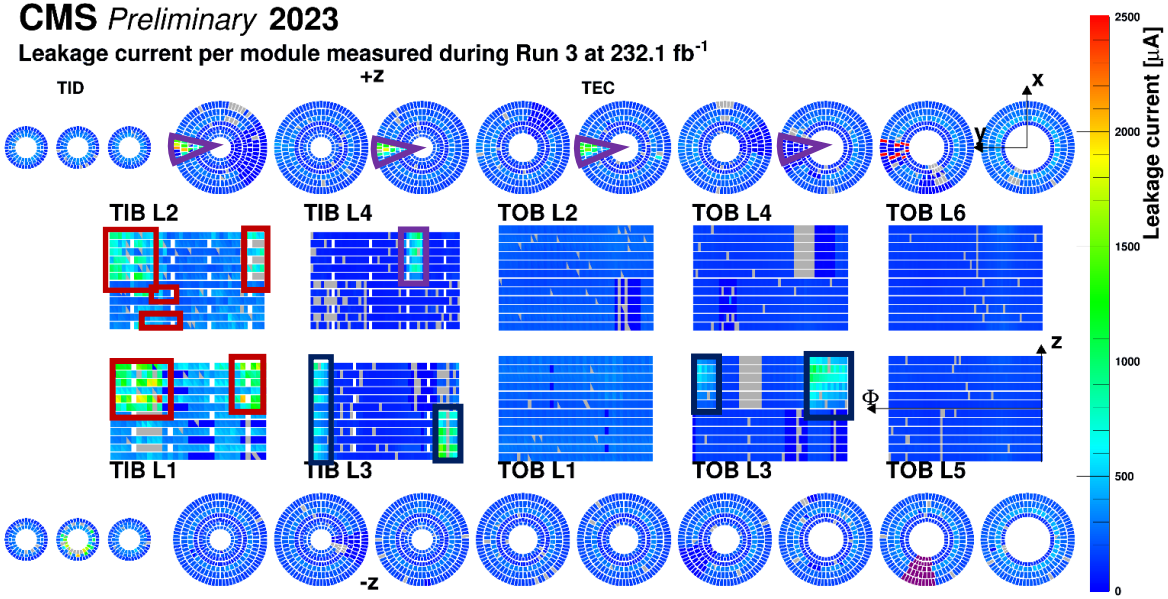
JINST 2008 paper





Leakage current

- Modules in uncooled regions have quite high leakage current, with few modules in TIB L1 exceeding 2 mA (power supply limit of 12 mA for group of 6 modules)
- Most of the tracker is far away from reaching power supply limit



leakage current

Closed (leaky) cooling loops

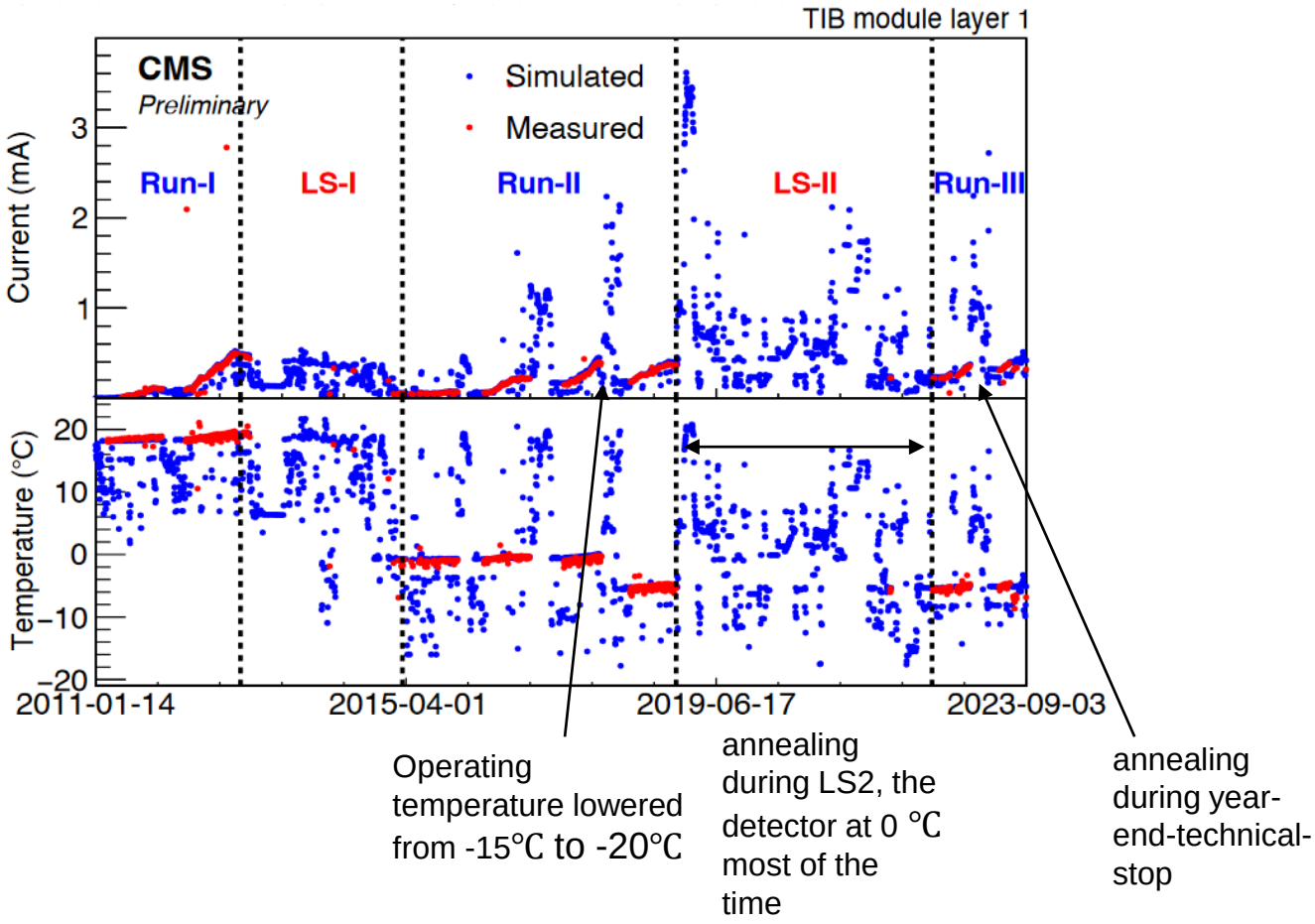
Degraded cooling contacts

Loops closed in 2022

- empty regions correspond to problem with slow local control readout

Evolution of leakage current in TIB layer 1

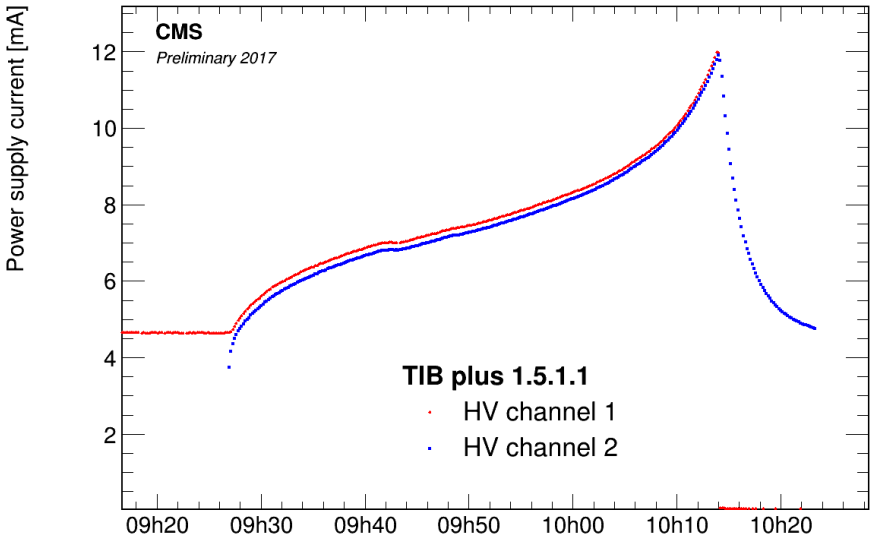
- The leakage current is well below 1 mA



Thermal runaways

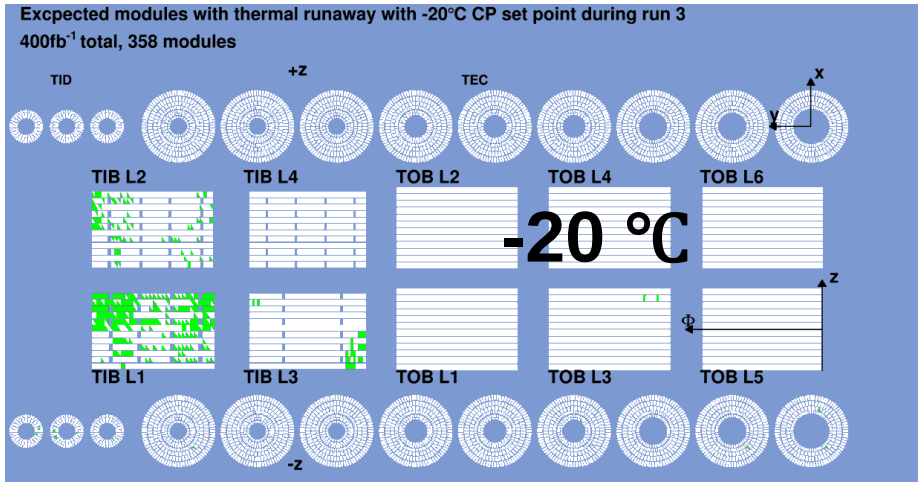
- Few thermal runaways were observed in 2023
- Two ways to attack the problem:
  - switching off half of stereo modules
  - reducing bias from 300 V to 200 V

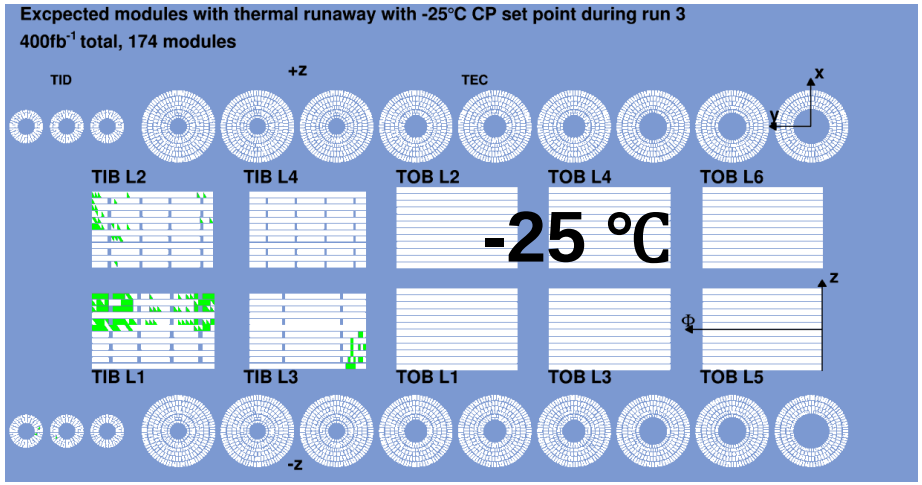
grouping of modules in double sided layer



Number of expected thermal runaways

- Expected modules with thermal runaway by the end of Run 3 (400 fb^{-1})

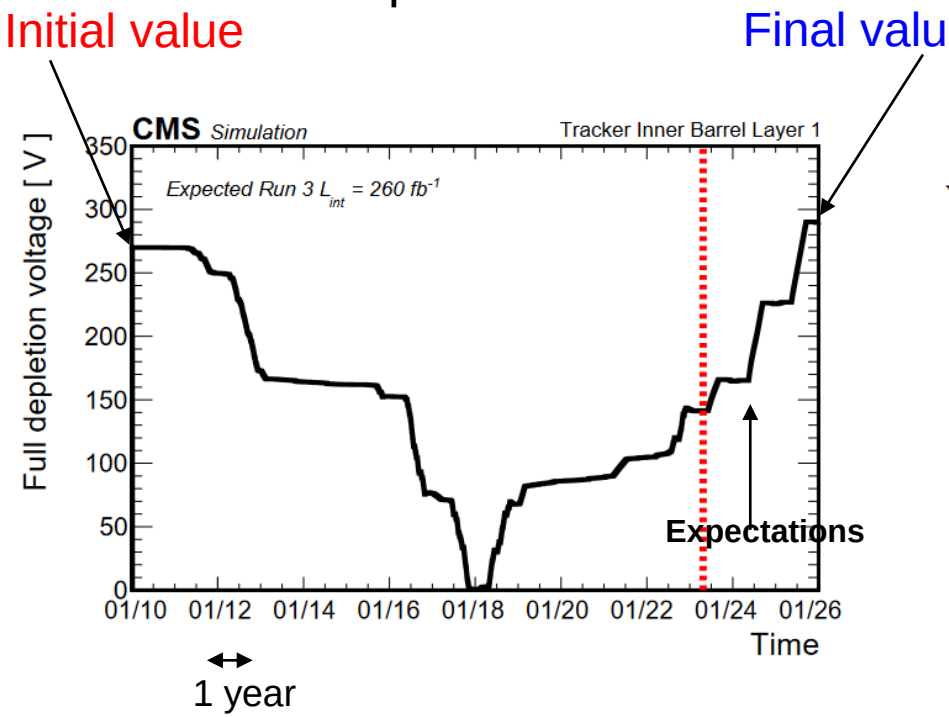


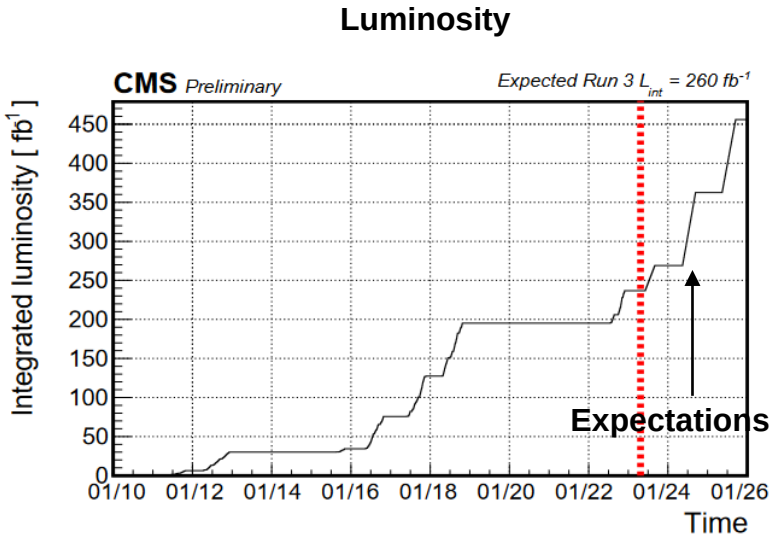


- Changing temperature from -20℃ to -25℃ reduces the number of thermal runaways by a factor of 2
- Temperature eventually will be lowered to -25 ℃
- Given that leak of cooling plants is strongly temperature dependent, this will be postponed if possible

Full depletion voltage

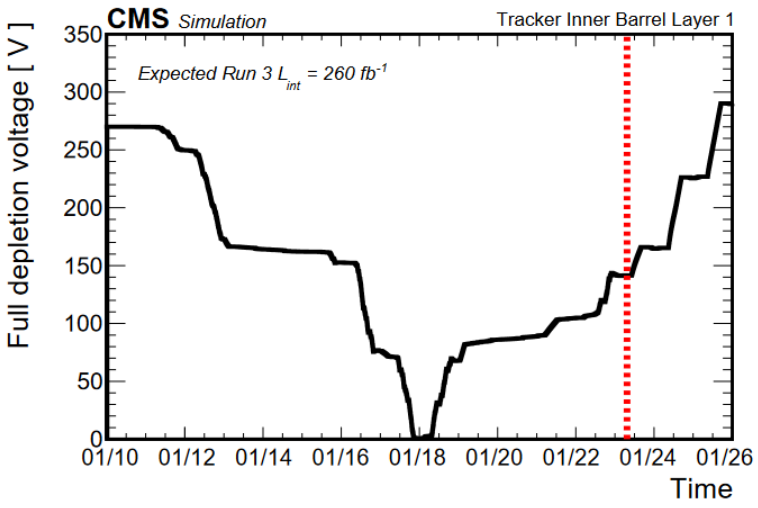
- The prediction of the full depletion voltage is presented for the lifetime of the detector
- Inner layers have passed type inversion:
  - measurements not very sensitive for voltages close to inversion point
  - TIB L1 is predicted to be around 100 V

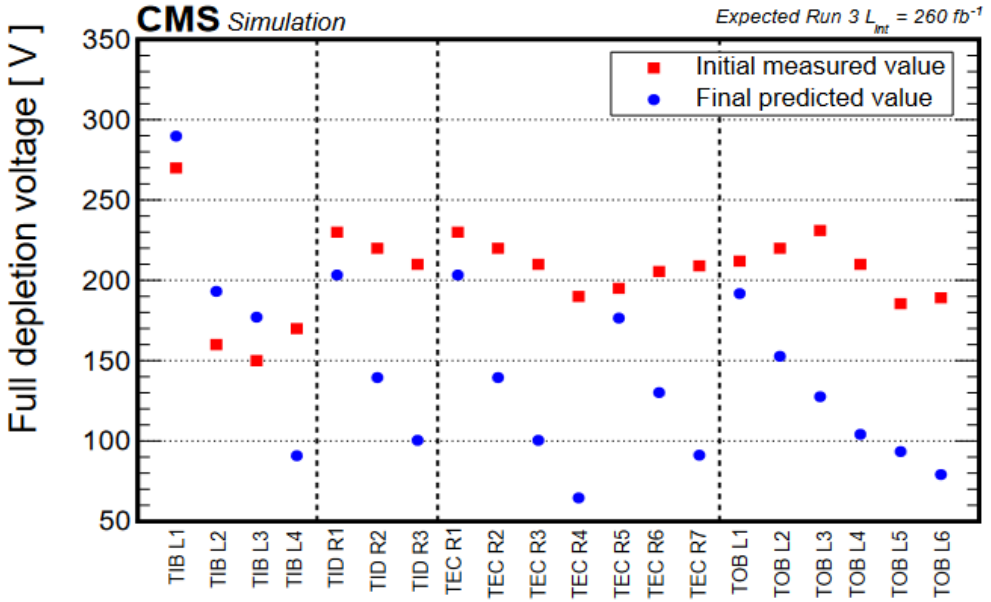




Full depletion voltage

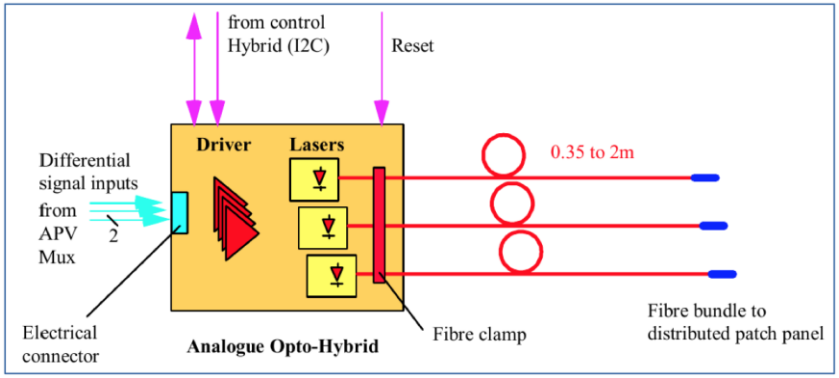
- Summary of expected full depletion voltage by the end of Run 3 compared to initial value from lab measurements
- TIB L1 will approach 300 V
- Currently majority of the detector is operated at 300V
- 600 V is the limit of the power system



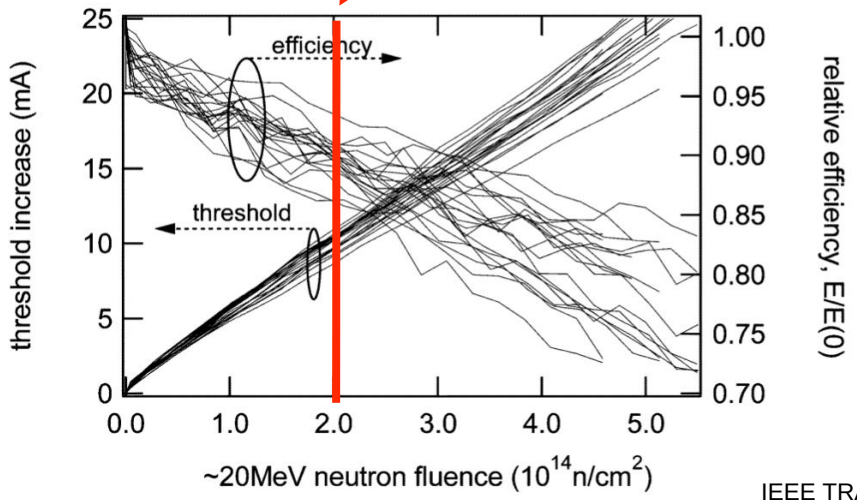


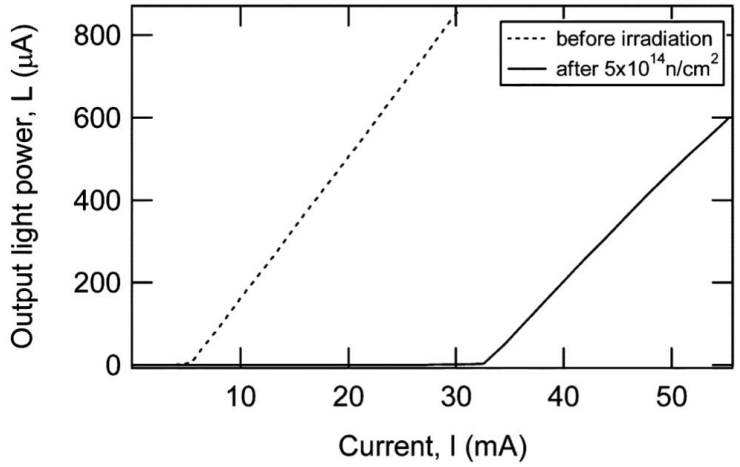
Radiation effects in the optical readout

- Laser drivers and photodiodes are aging due to irradiation, causing:
  - threshold increase
  - loss of efficiency



max expected damage to TIB L1 after 500 fb^{-1}





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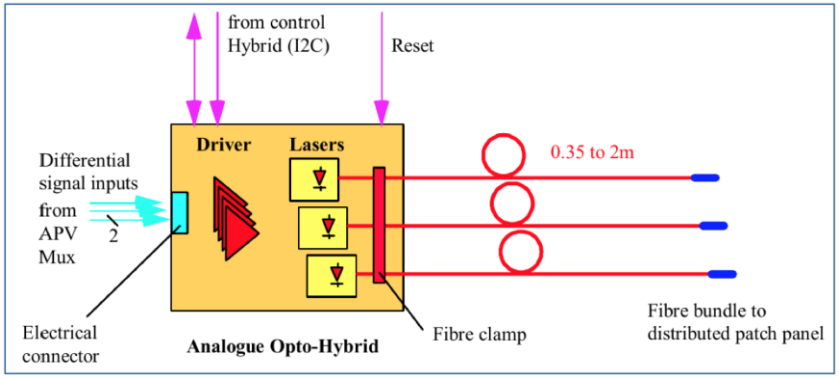
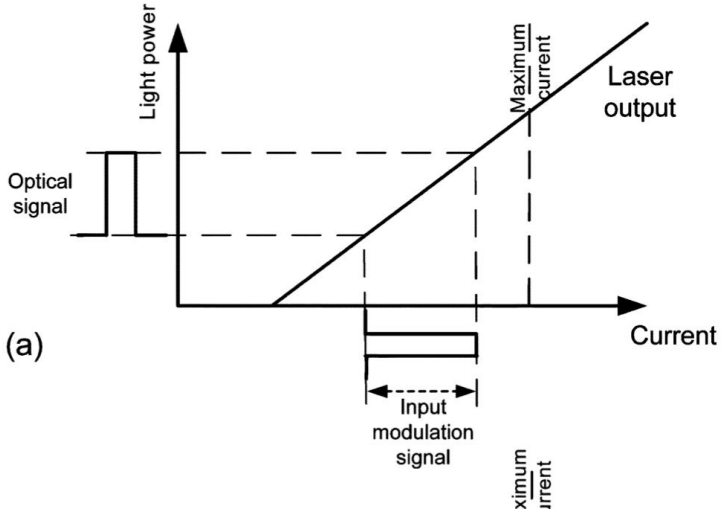


normally working laser driver



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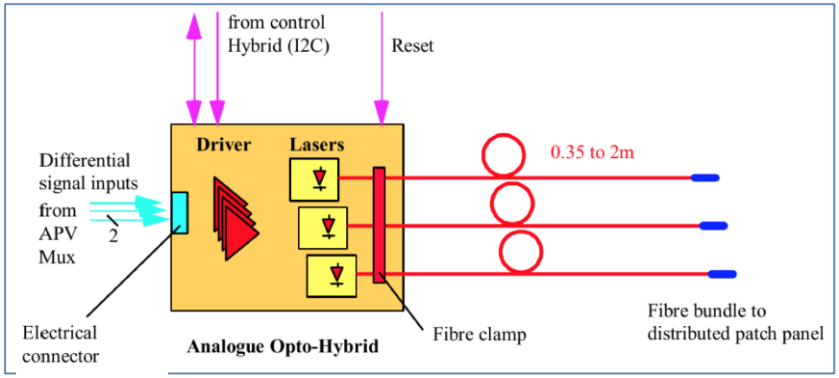
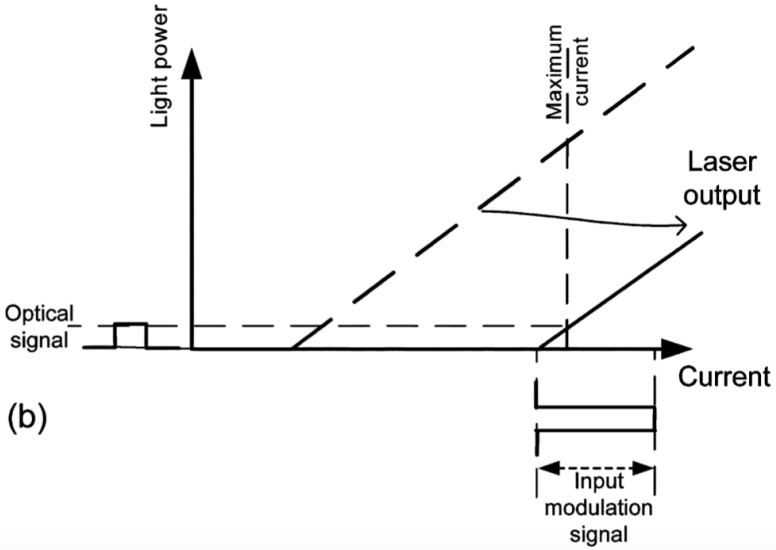


threshold increase



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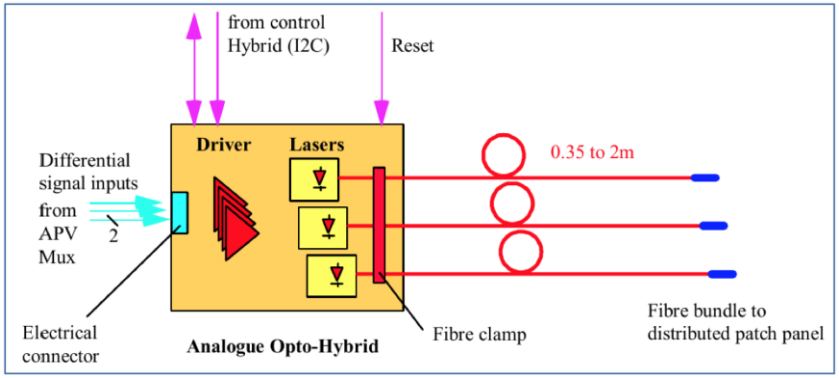
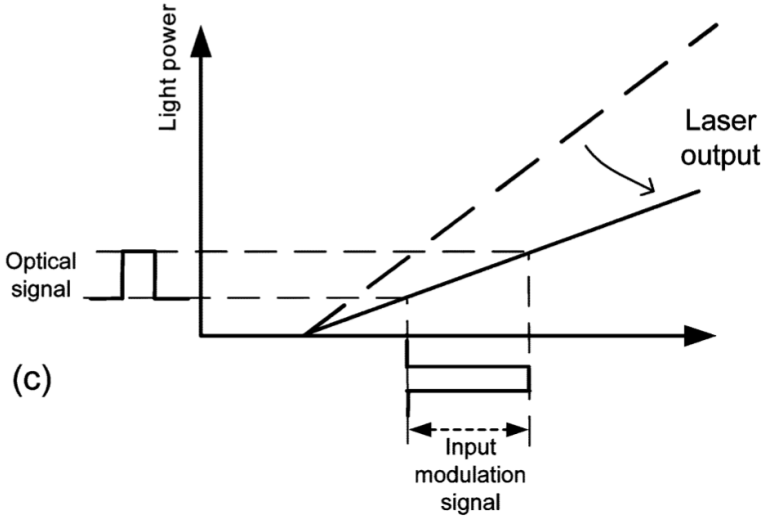


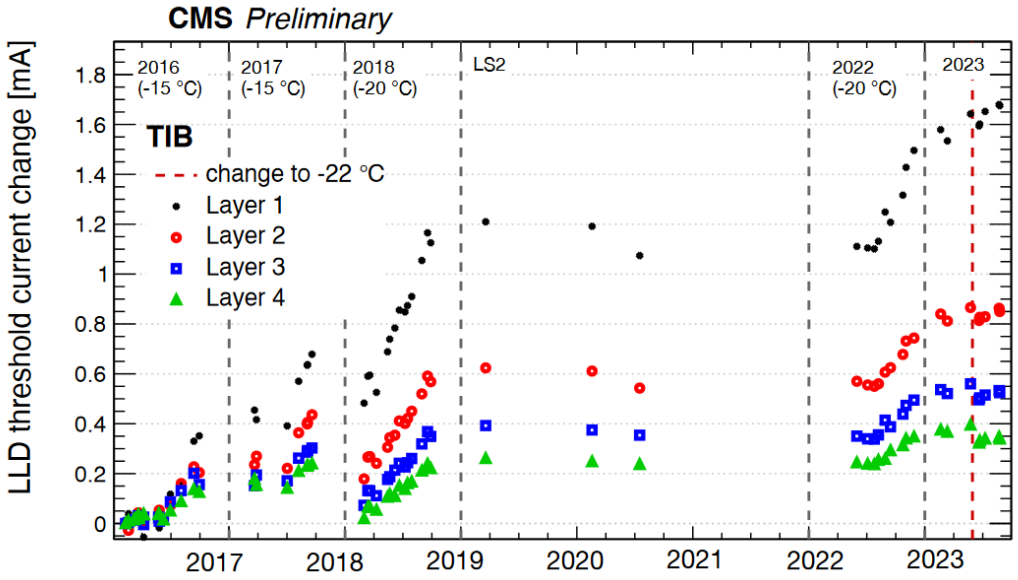
loss of efficiency



AOH performance with irradiation

- Absolute threshold increase in mA
- Average threshold current at the time of reference runs around 3 mA
- Maximum allowable threshold current 22.5 mA
- Increase during high luminosity periods and annealing during off-beam periods
- Decrease after changing coolant temperature from -15 ℃ to -20 ℃
- Clear dependence on radius

Inner Barrel



Summary and outlook

- CMS Strips tracker performing well after almost 15 years of operation
- No major degradation of detector components in the last years
- Signal to noise, hit efficiency and hit resolution are very good
- Operation temperature changed from -20 ℃ to -22 ℃ in 2023 helped to decrease leakage currents in uncooled regions and regions with degraded cooling
- Radiation effects are increasing in line with delivered luminosity
  - Monitoring various effects (leakage current, full depletion voltage)
  - TIB L1 passed the inversion point and has a full depletion voltage around 100 V now
- Strip Tracker is expected to continue delivering high quality tracks to CMS until end of its life at the start of LS3

BACKUP SLIDES

Sensors types

Module type	Pitch [μm]	Strip length [mm]	S/N Peak mode	S/N Dec. mode
IB1	80	116.9	25.8 ± 1.3	18.3 ± 0.5
IB2	120	116.9	29.5 ± 1.4	20.3 ± 0.6
OB1	122	183.2	36	25
OB2	183	183.2	38	27
W1TEC	81–112	85.2	33.1 ± 0.7	21.9 ± 0.6
W2	113–143	88.2	31.7 ± 0.5	20.7 ± 0.4
W3	123–158	110.7	29.2 ± 0.6	20.0 ± 0.4
W4	113–139	115.2	28.6 ± 0.5	19.2 ± 0.3
W5	126–156	144.4	42.2 ± 1.1	24.1 ± 1.1
W6	163–205	181.0	37.8 ± 0.6	23.0 ± 0.4
W7	140–172	201.8	35.5 ± 1.0	20.3 ± 1.1

Simulations

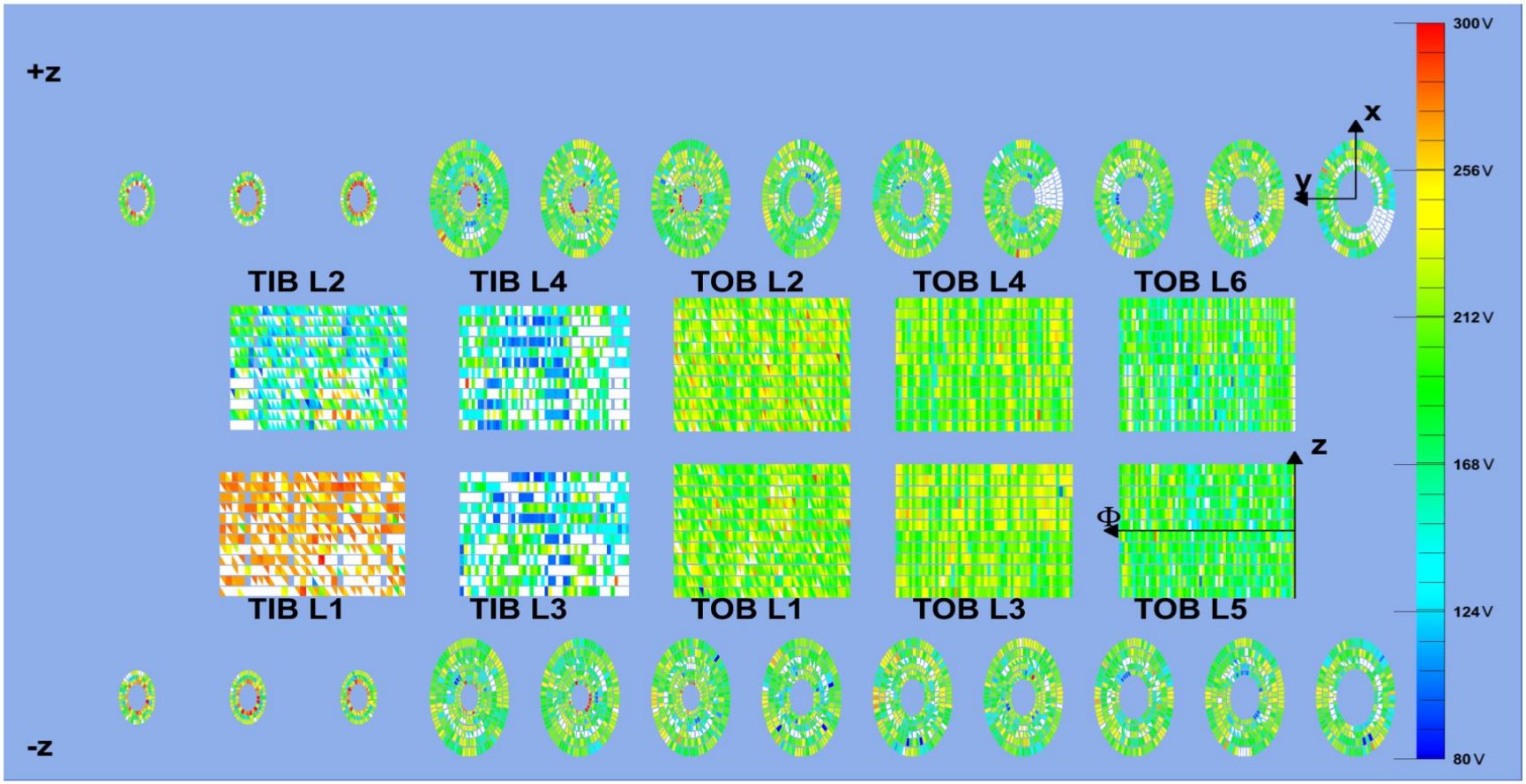
- Simulations are done based
  - temperature measurements per module
  - particle flux simulations with FLUKA

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

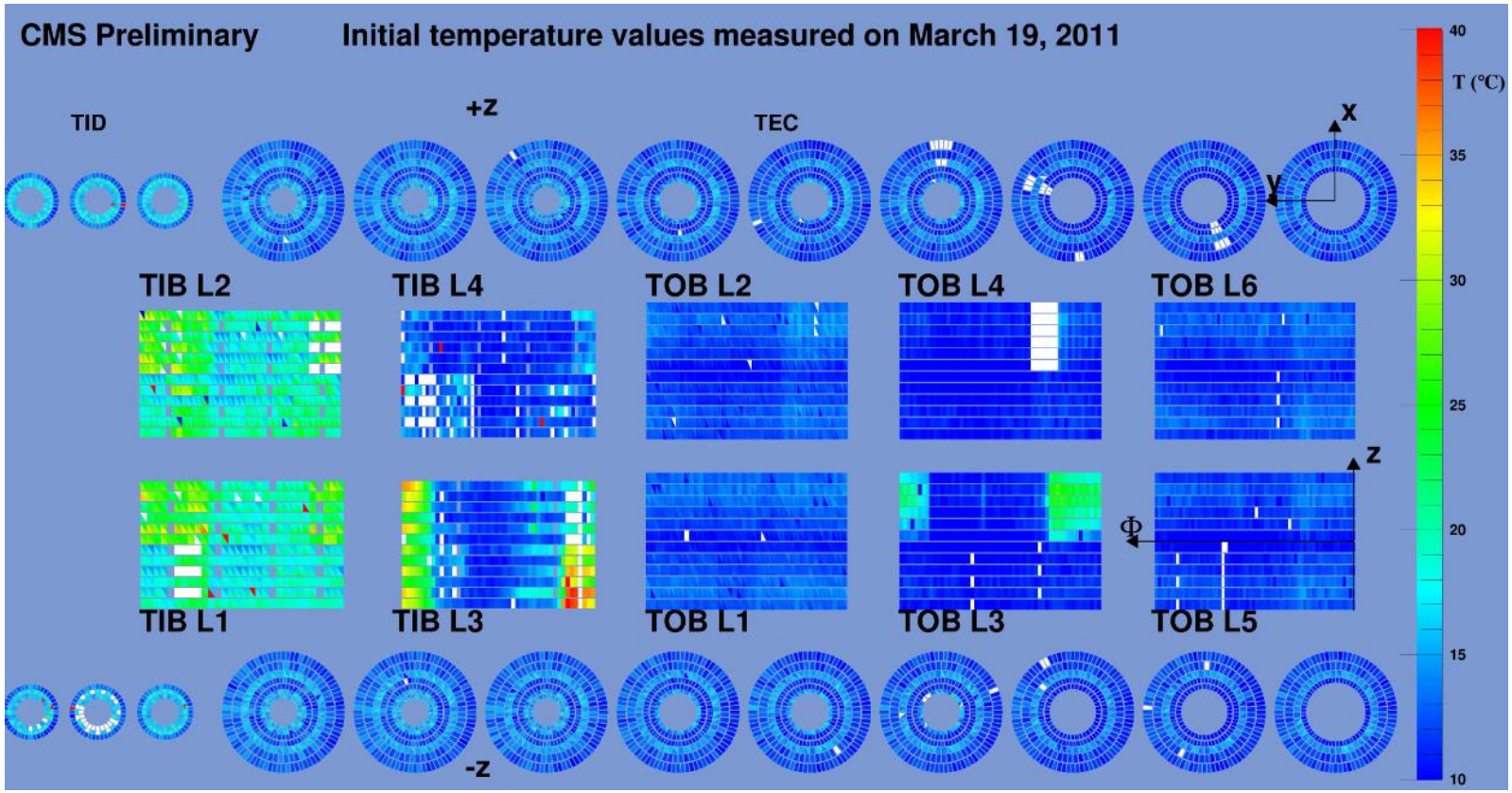
$$\alpha(t, T) = \alpha_0(T) + \alpha_I \exp\left(\frac{-t}{\tau_I(T)}\right) - \beta \ln \frac{t}{t_0}$$

Intial Vfd

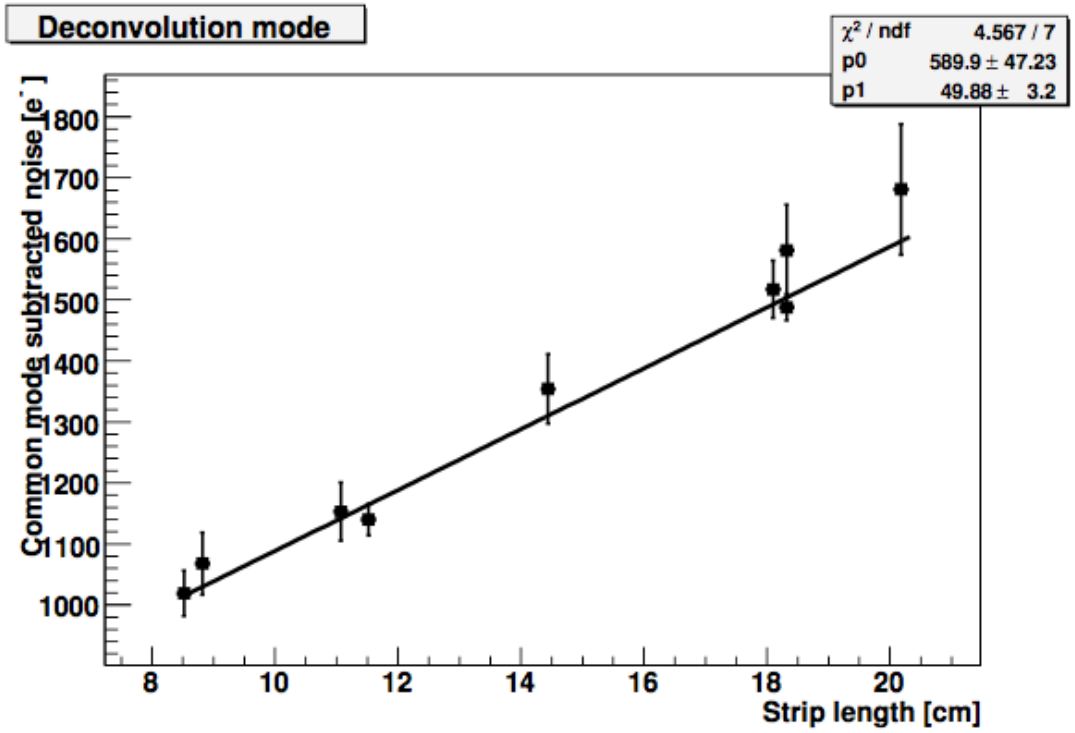
- Christian Barth thesis



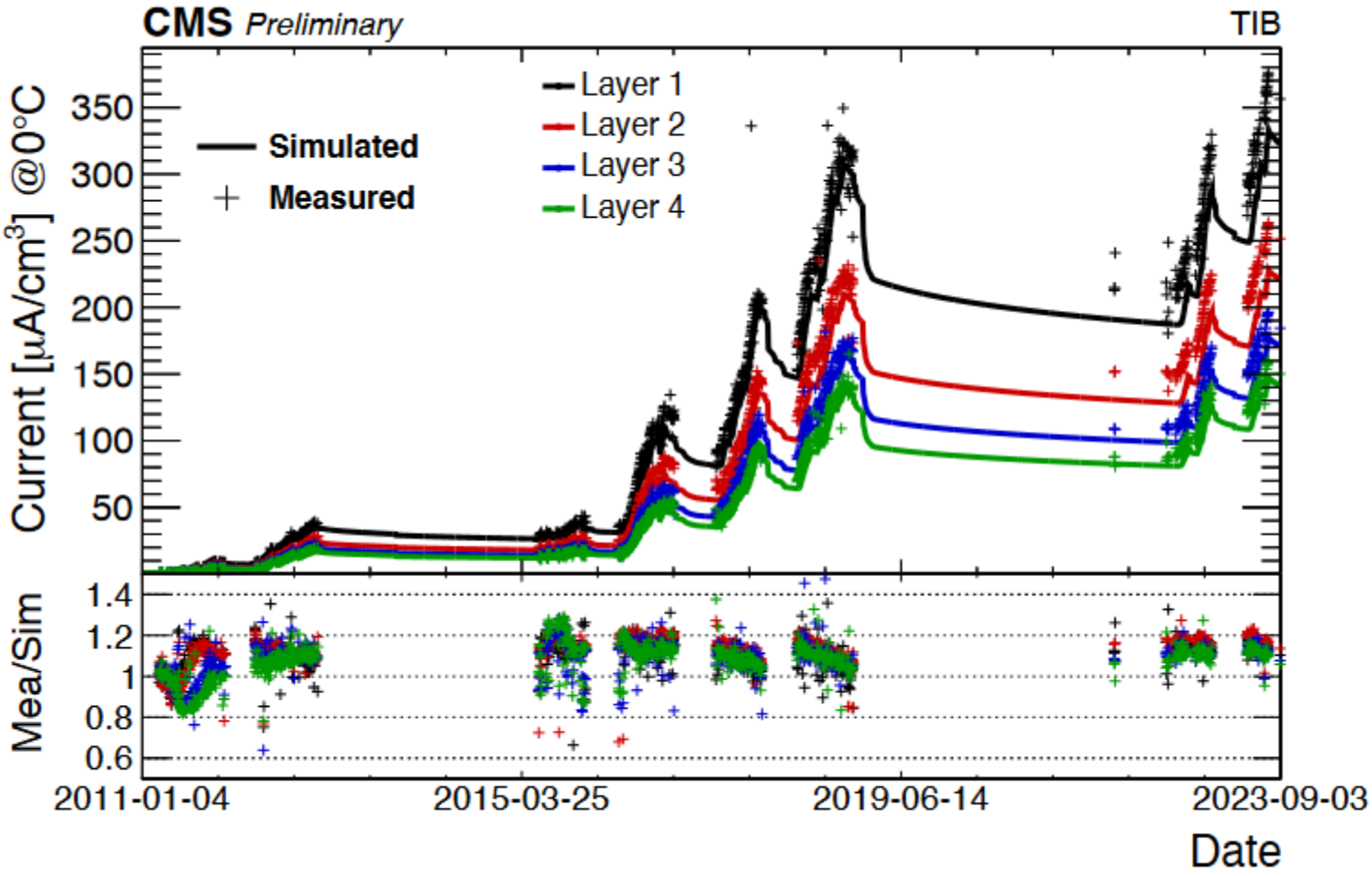
Initial temperature map



JINST 2008 paper

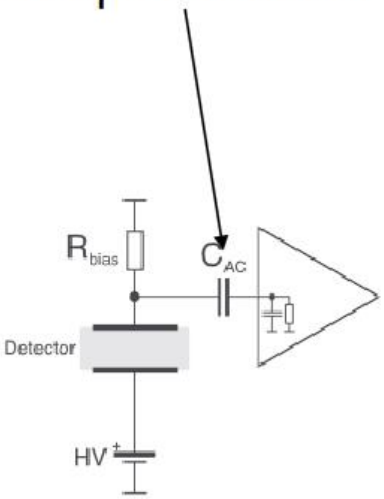


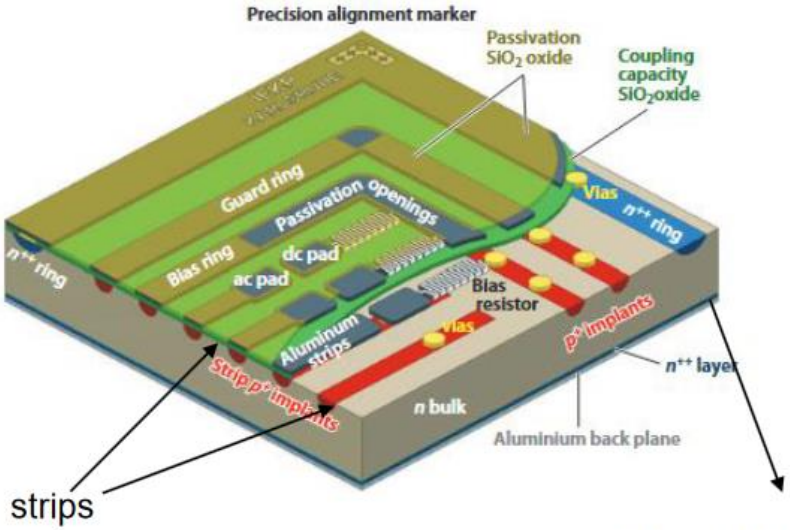
Average leakage current



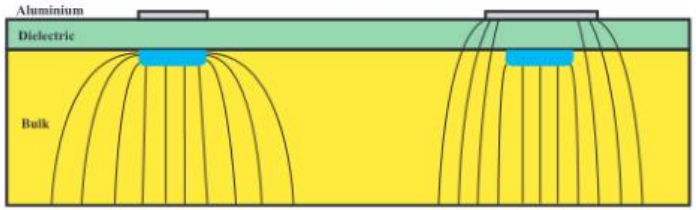
Sensors

- p-type strips in n-type bulk material
- AC coupled readout



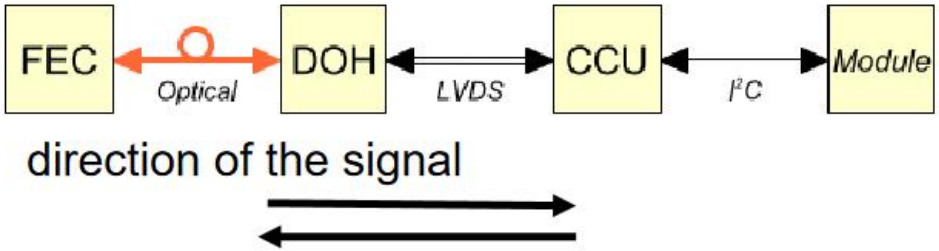


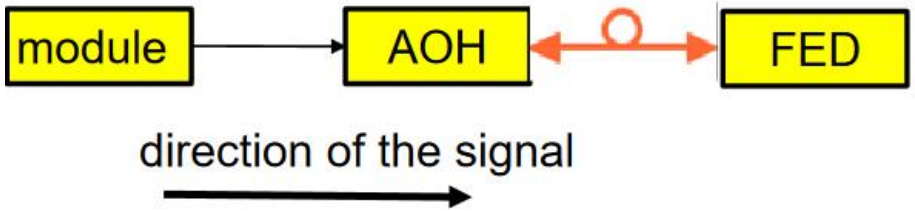
Connected to HV (high voltage)

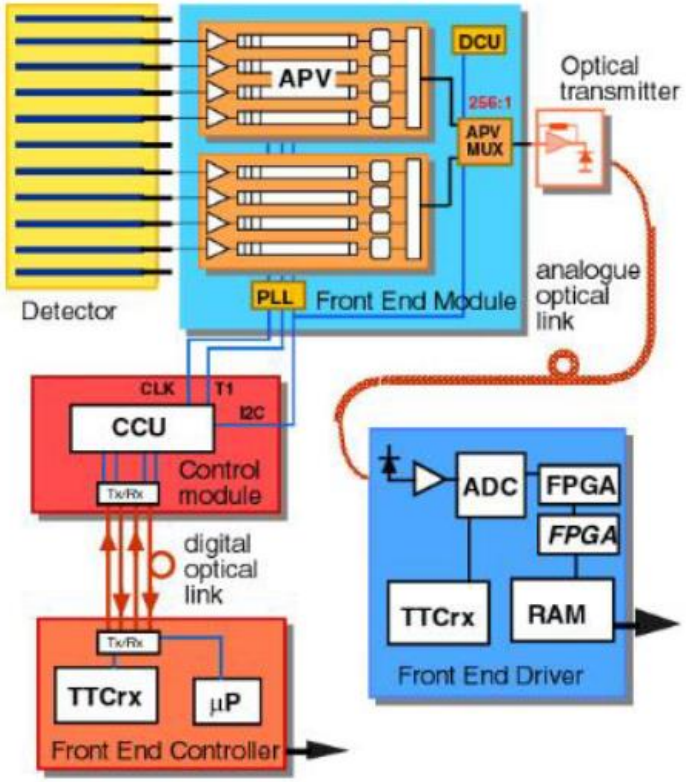


Metal overhang improving the HV stability

Readout scheme







HIP probability