Development of the CMS Phase-1 Pixel Online Monitoring System and the Evolution of Pixel Leakage Current

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On behalf of CMS Pixel Collaboration

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Introduction

- **Pixel monitoring system**

- **Cooling schematics & Temperature**

- **Leakage current & correlation with temperature**

- **Prediction on pixel leakage current**

- Pixel detector is the inner detector of silicon tracker
- Shortest distance: **2.9 cm** to the beam pipe

- LHC: proton-proton collision in 13 TeV
- CMS :Integrated luminosity ~ 120 fb^{-1} (2017 ~ 2018)

CMS Phase-1 pixel detector

LHC

inner side

-z end

+z end

outer side
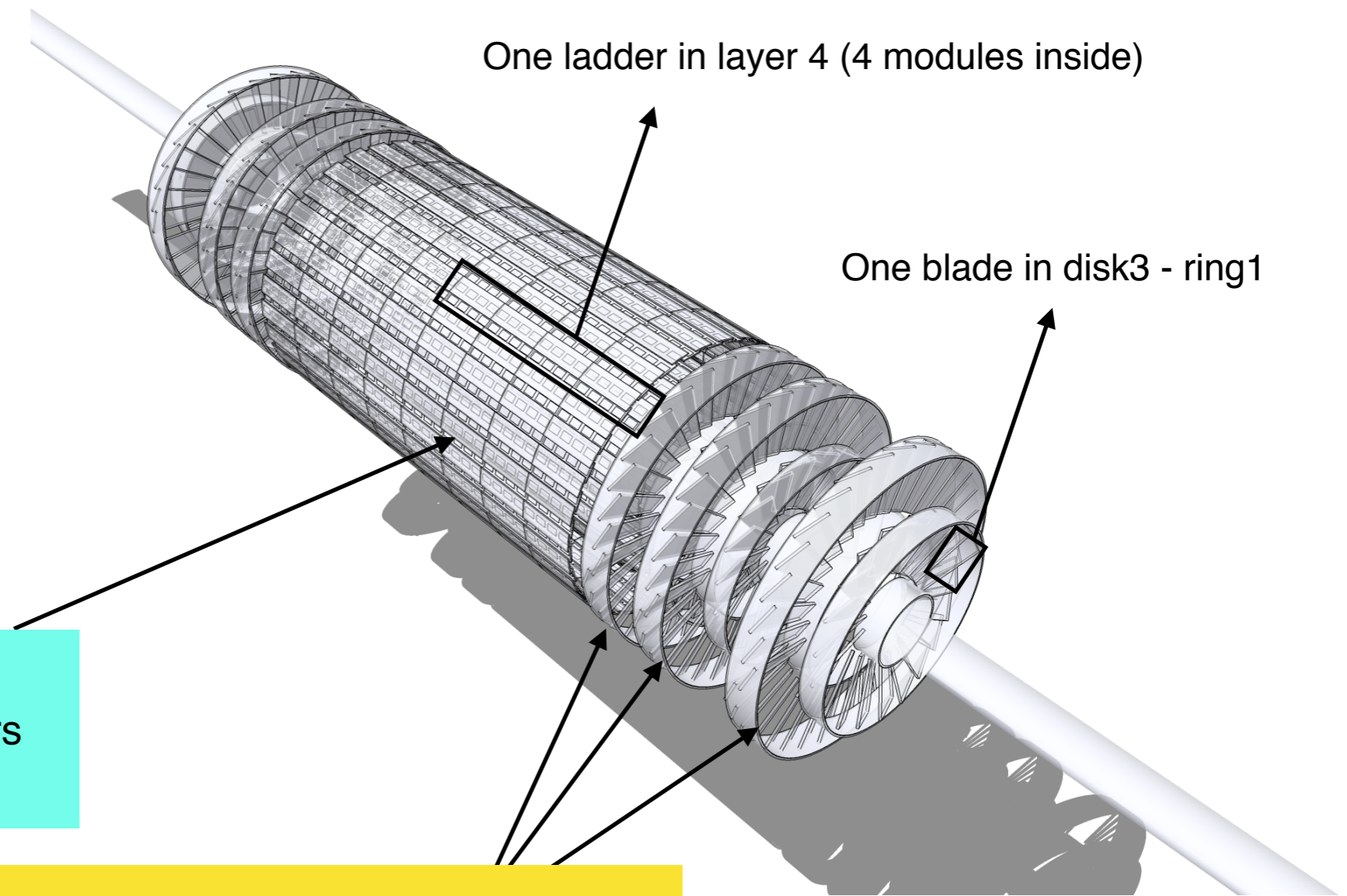
y
x
z
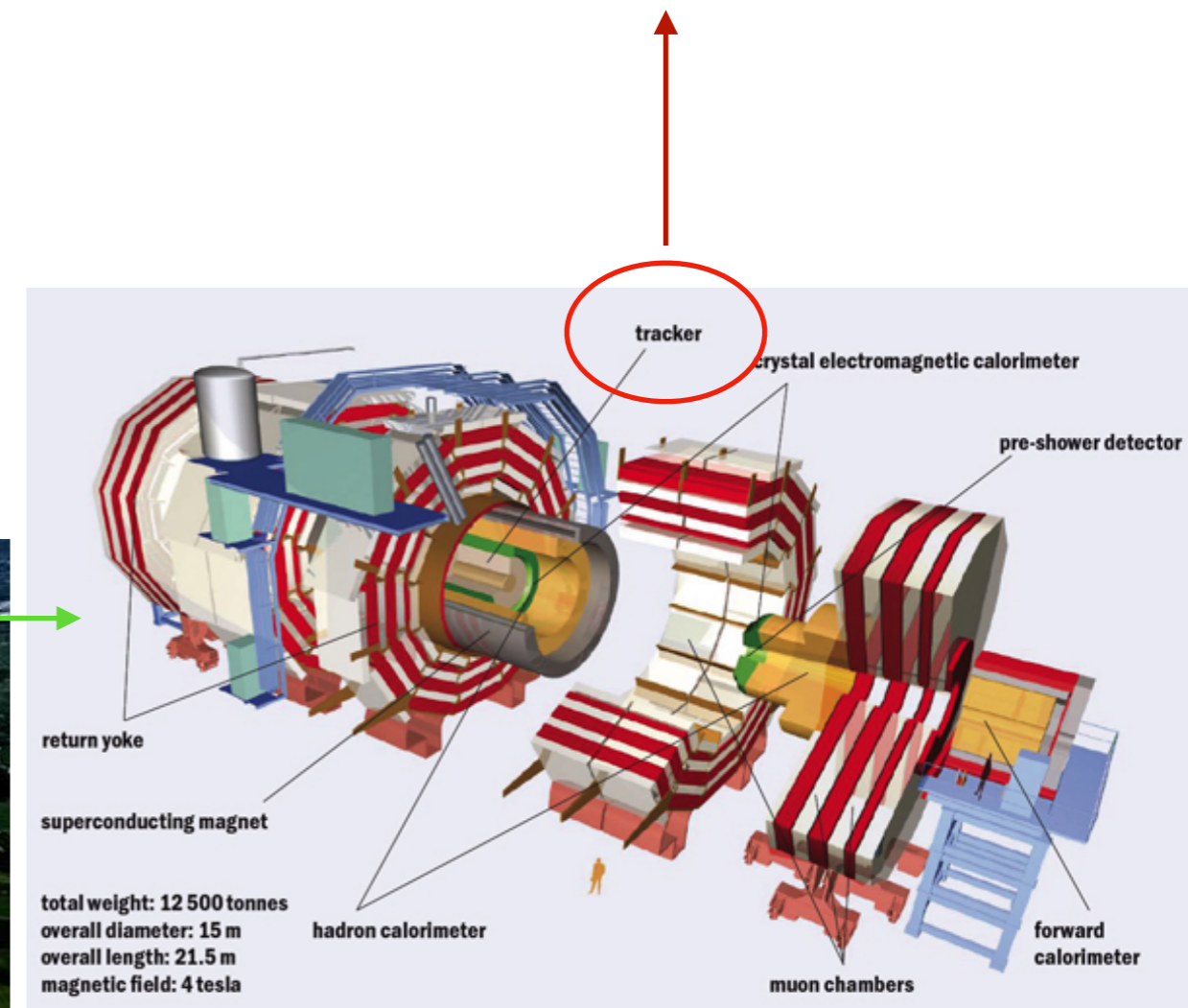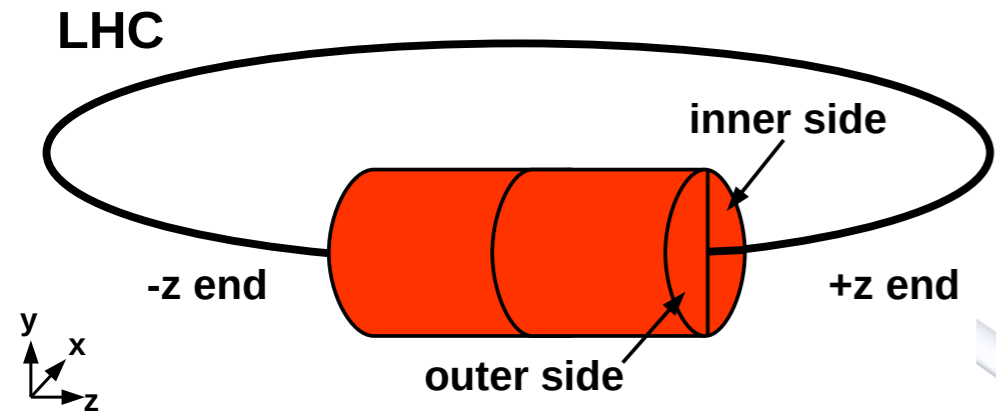
- LHC coordinates: four half cylinders:
  - Inner side +z end (BpI)
  - Inner side -z end (BmI)
  - Outer side +z end (BpO)
  - Outer side -z end (BmO)

One ladder in layer 4 (4 modules inside)

One blade in disk3 - ring1

- Pixel barrel:
  - 4 concentric layers
  - Array of ladders

- Pixel endcap:
  - 3 disks with 2 concentric rings
  - Array of blades (modules in each blade panel)

124 million pixels in total

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Pixel detector

Online Monitoring Development

Motivation of Pixel Online Monitoring Development

CMS Pixel Online Monitoring   Views ▼   DAQ monitor   Issues DB   Data quality ▼   Radiation damage ▼   Masked channels   CASTOR DCDCs   Tools ▼   PixDB ▼   Help ▼   Links ▼

○ **A webpage for monitoring the following parameters online/offline:**

- Environment variables:
  - Dew point
  - Air pressure
  - Air temperature
  - Humidity
  - …

- Detector variables:
  - Power supply voltage
  - Current in power supply group
  - Module temperatures
  - Cooling flow status
  - …

- CMS detector run property:
  - Instantaneous / integrated luminosity
  - Detector run status
  - Data acquisition status
  - Data quality monitoring
  - …

○ **Function of online monitoring system:**

- ○ **Correlate these information to have a good overview of the detector status**
- ○ **Centralize the above information**
- ○ **Have an easily accessible user interface**

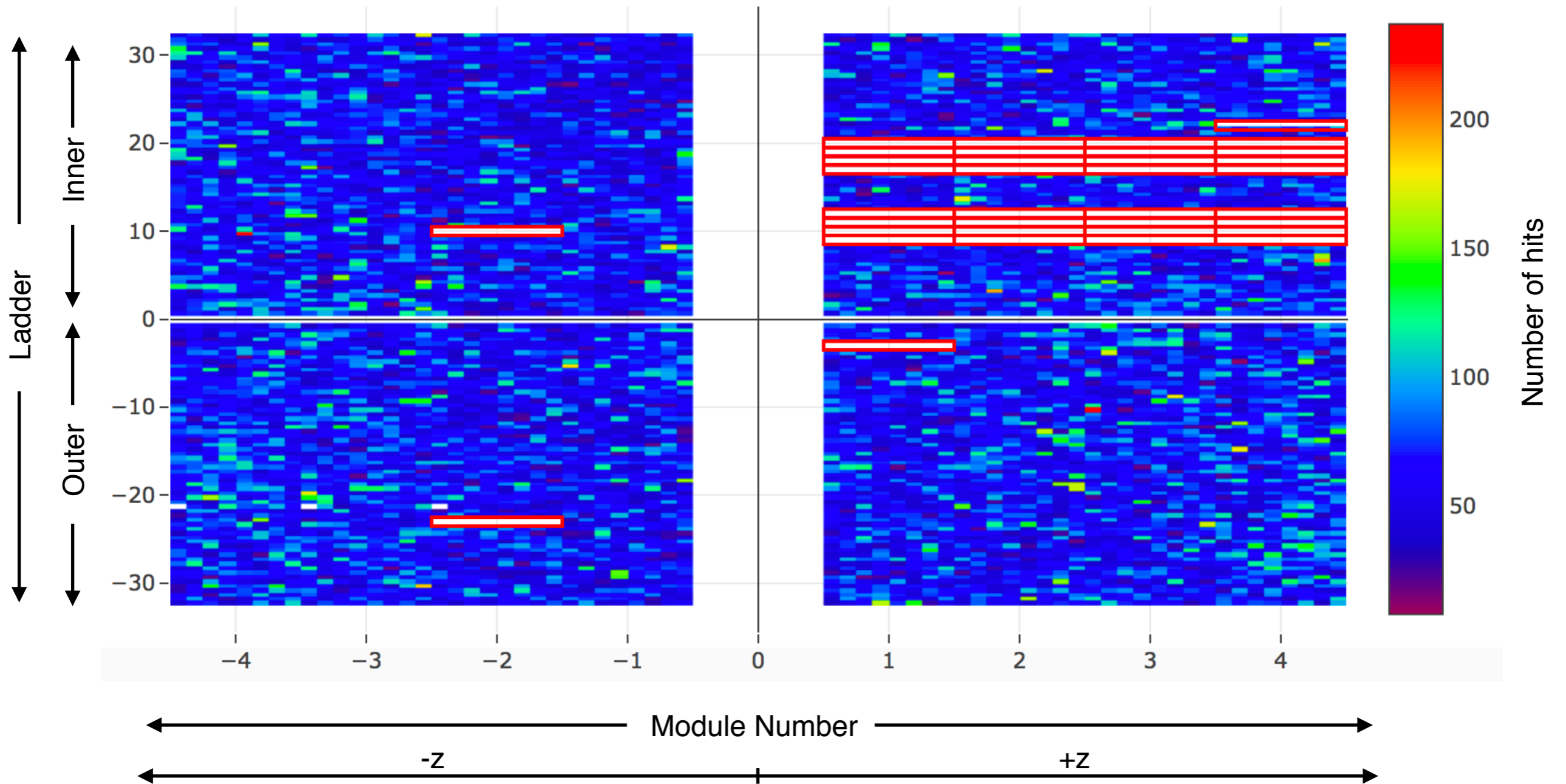# View of online quantity in the monitoring system
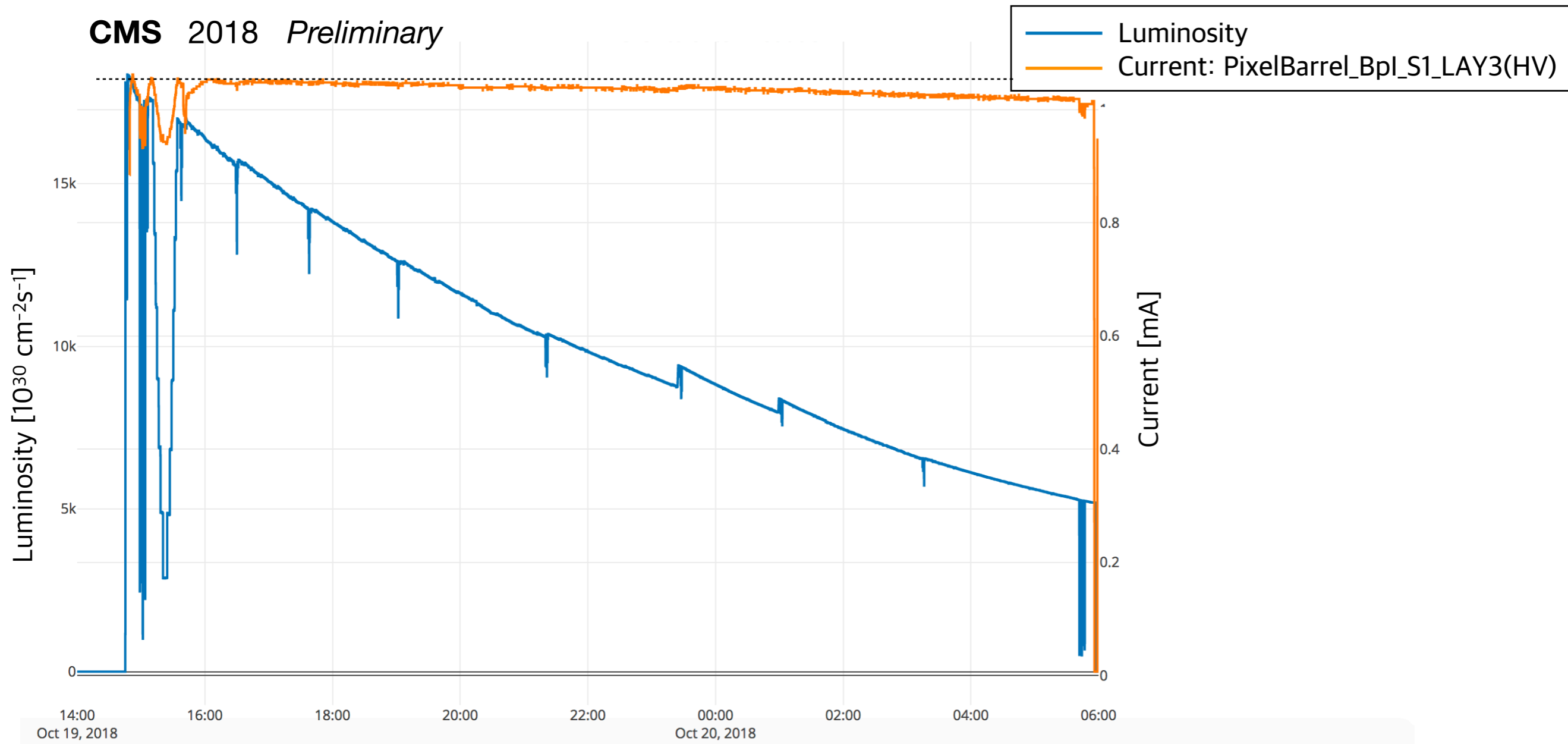
- During an LHC fill:

  - Instantaneous luminosity & leakage current (one power sector in layer 3 of Pixel Barrel)

- **The monitoring system correlates the instantaneous luminosity and the leakage current at the same time**
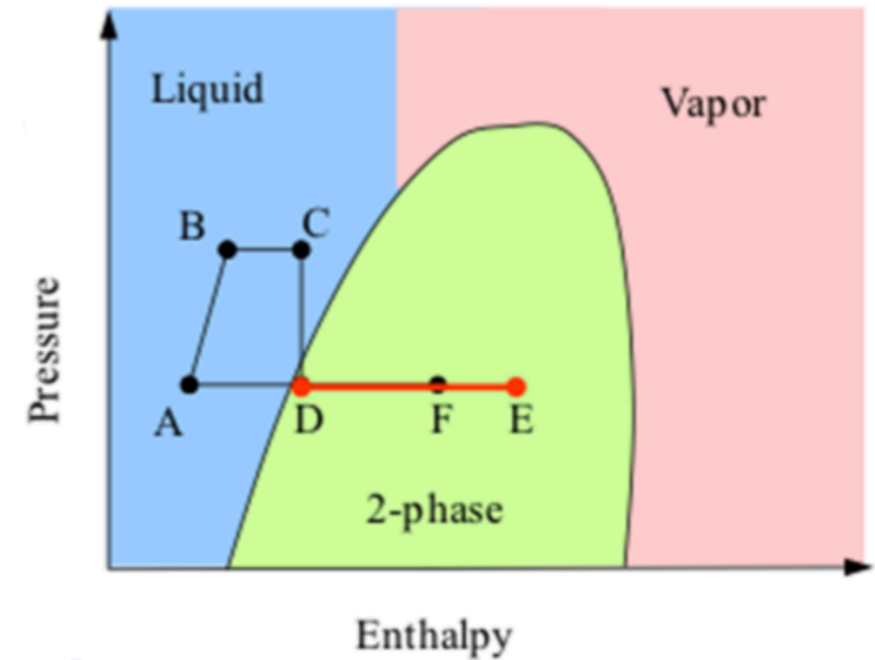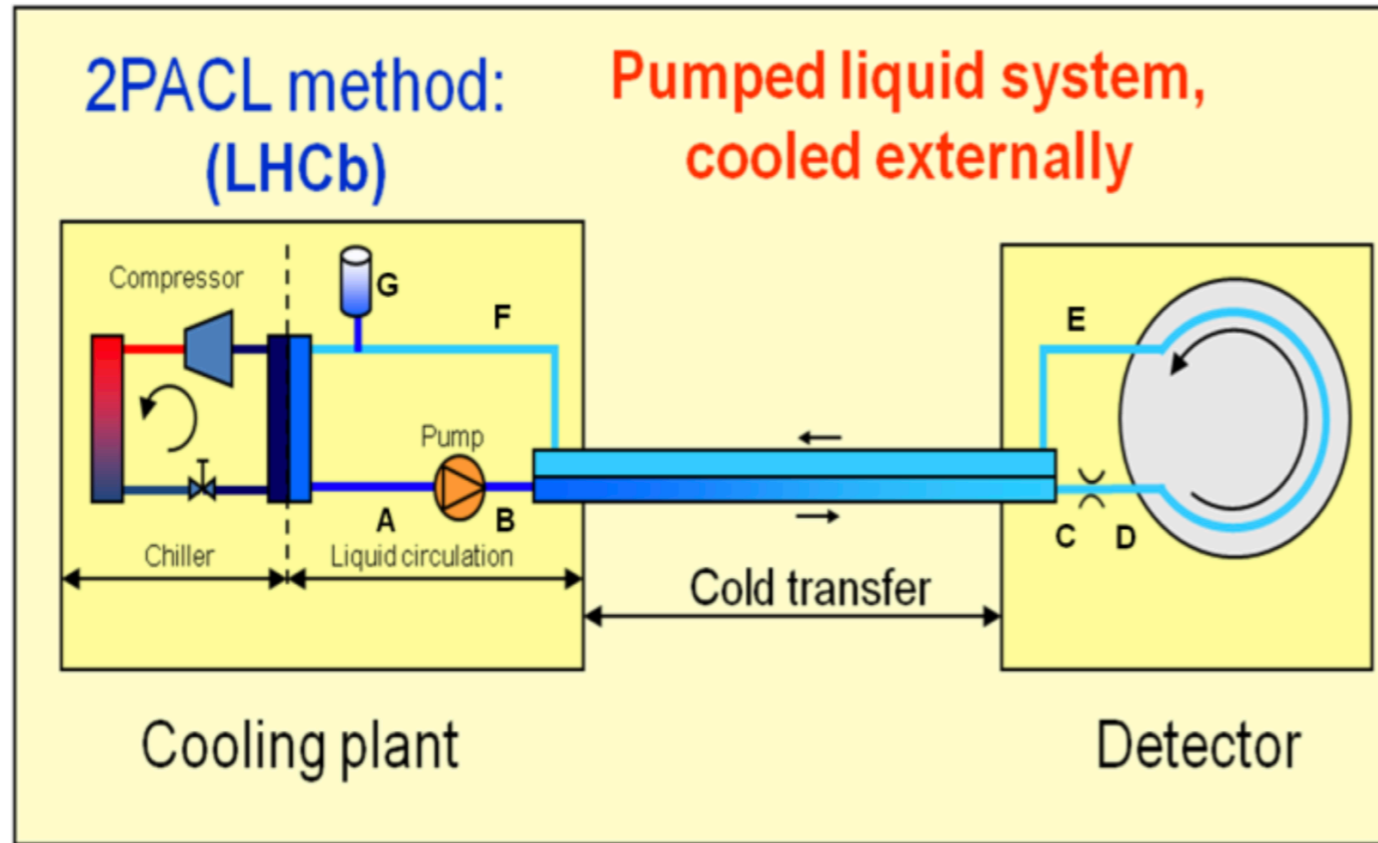
Pixel module occupancy

- Each module has 16 readout chips
- In the plot, one bin corresponds to one readout chip (ROC)
- The monitoring system has **a database** recording the **problems associated to the detector occupancy**
  - Red marked rectangles

Pixel detector

Cooling schematics & temperature distribution

Pixel detector cooling loop schematics & flow

2PACL method: (LHCb)

Pumped liquid system, cooled externally

Compressor
Chiller
Pump
Liquid circulation
Cold transfer
Cooling plant
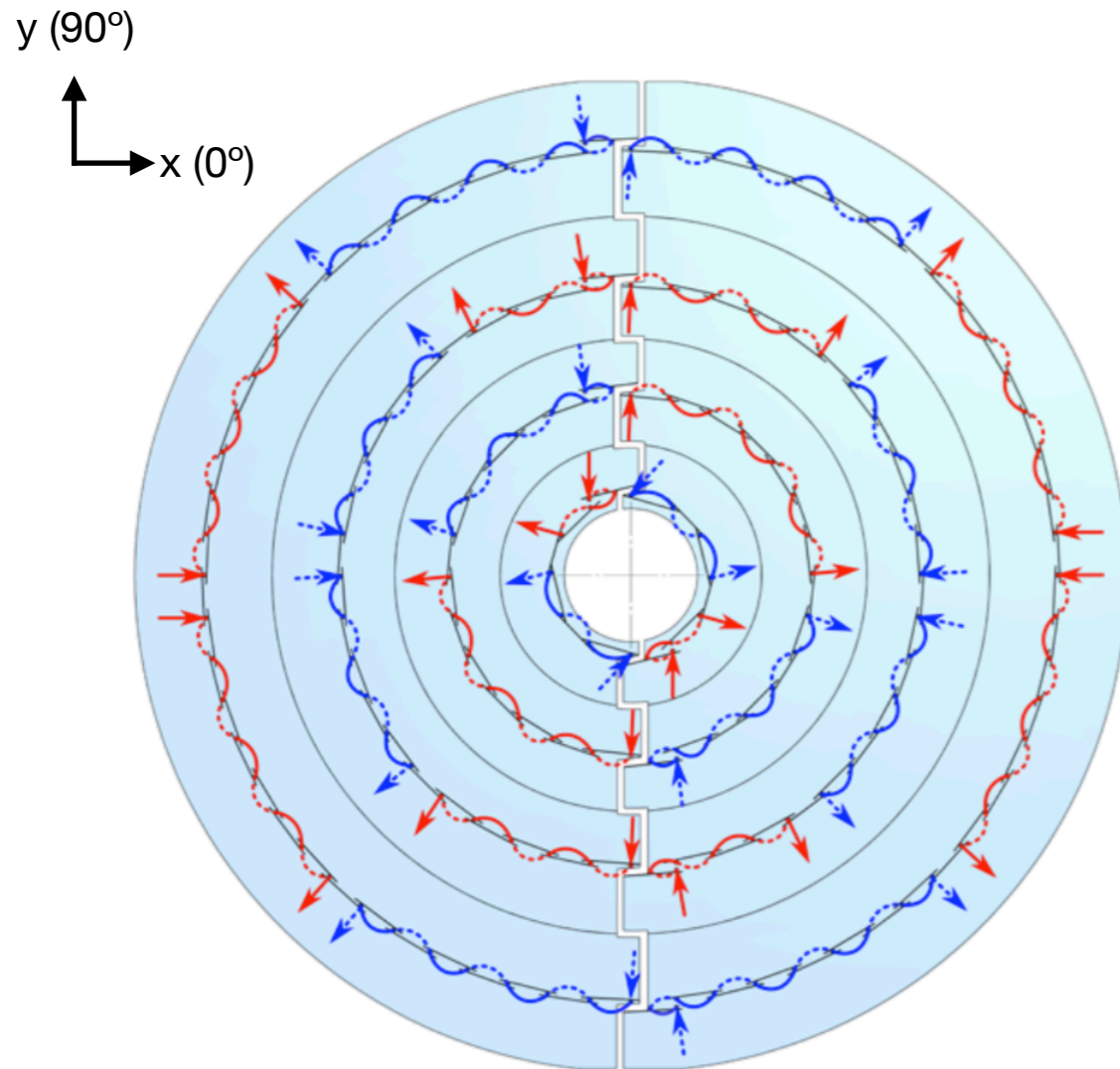Detector

Liquid
Vapor
Pressure
Enthalpy
2-phase

- 2-phase accumulator controller (2PACL):

  - **Point A**: CO_2 flow liquified by chiller

  - **Point B**: increase liquid pressure by pump

  - **Point B ~ C**: thermal exchange

  - **Point C ~ D**: decrease the pressure

  - **Point D**: reach 2-phase state at **inlet**

  - **Point D ~ E**: evaporation (absorbing heat in the detector)

    - **cooling becomes more efficient**

    - **temperature drops**

  - **Point E ~ F**: liquid/vapor mixture return to cooling plant from **outlet**
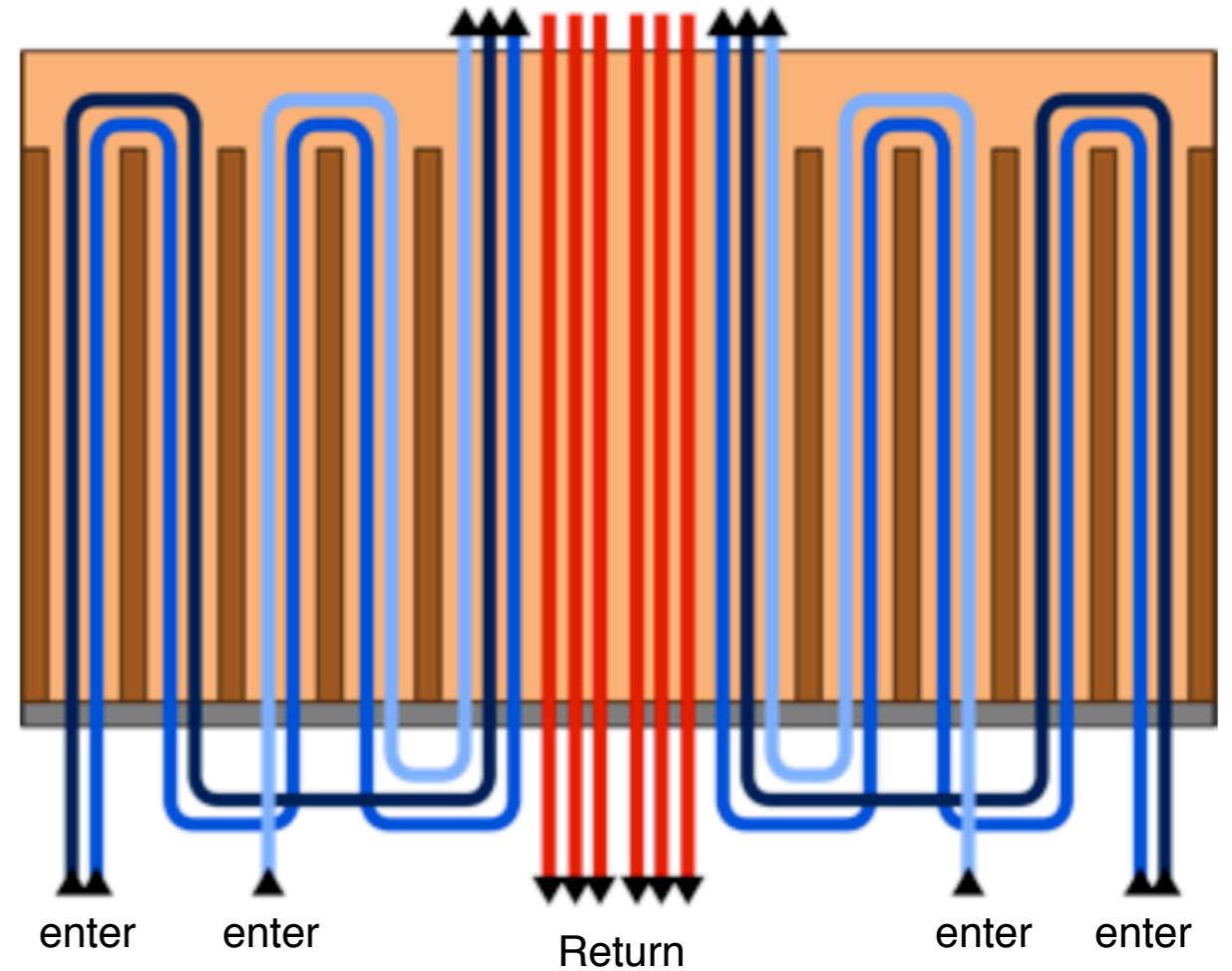
  - **Point G**: accumulator vessel

- CO_2 cooling flow was used since 2017 for the Phase-1 pixel detector

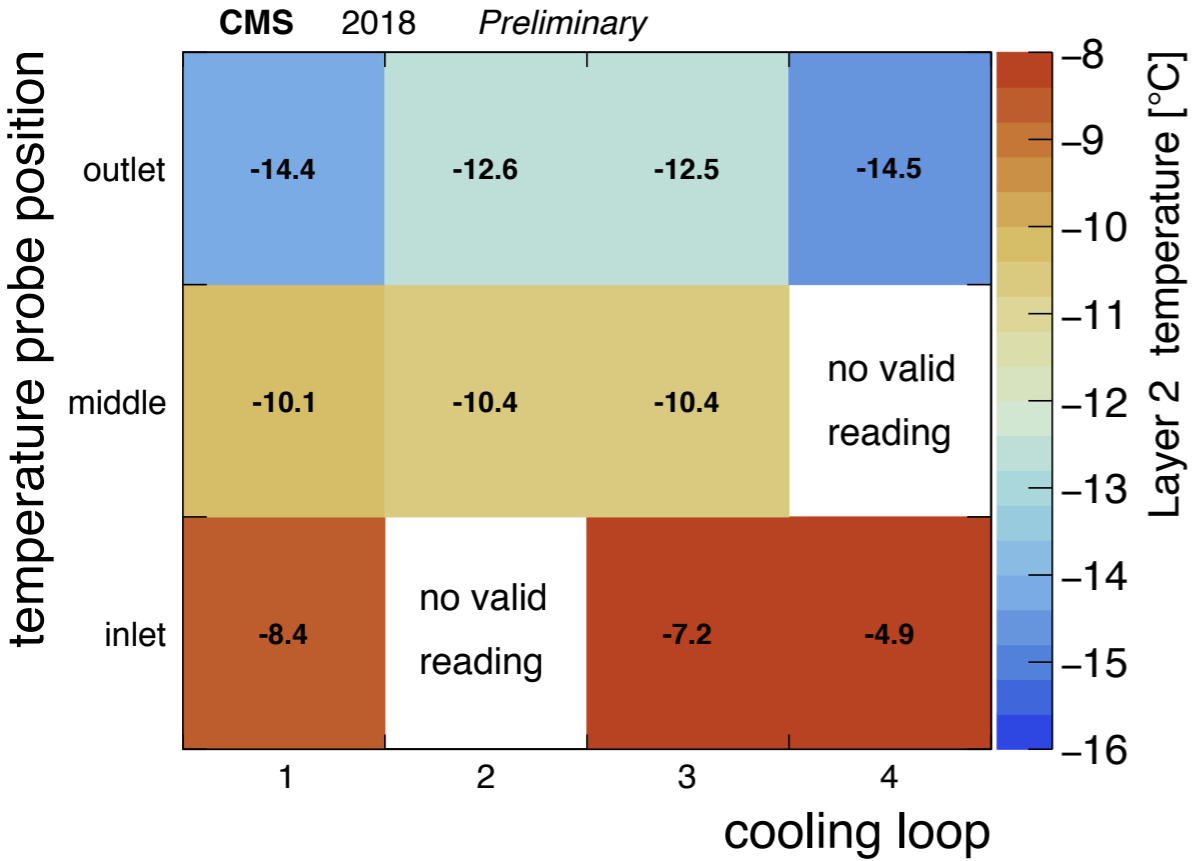# Pixel barrel cooling loop schematics & flow

x-y plane section

y (90°)

x (0°)

View along z on the supply line

(Pre-heating of pixel detector)

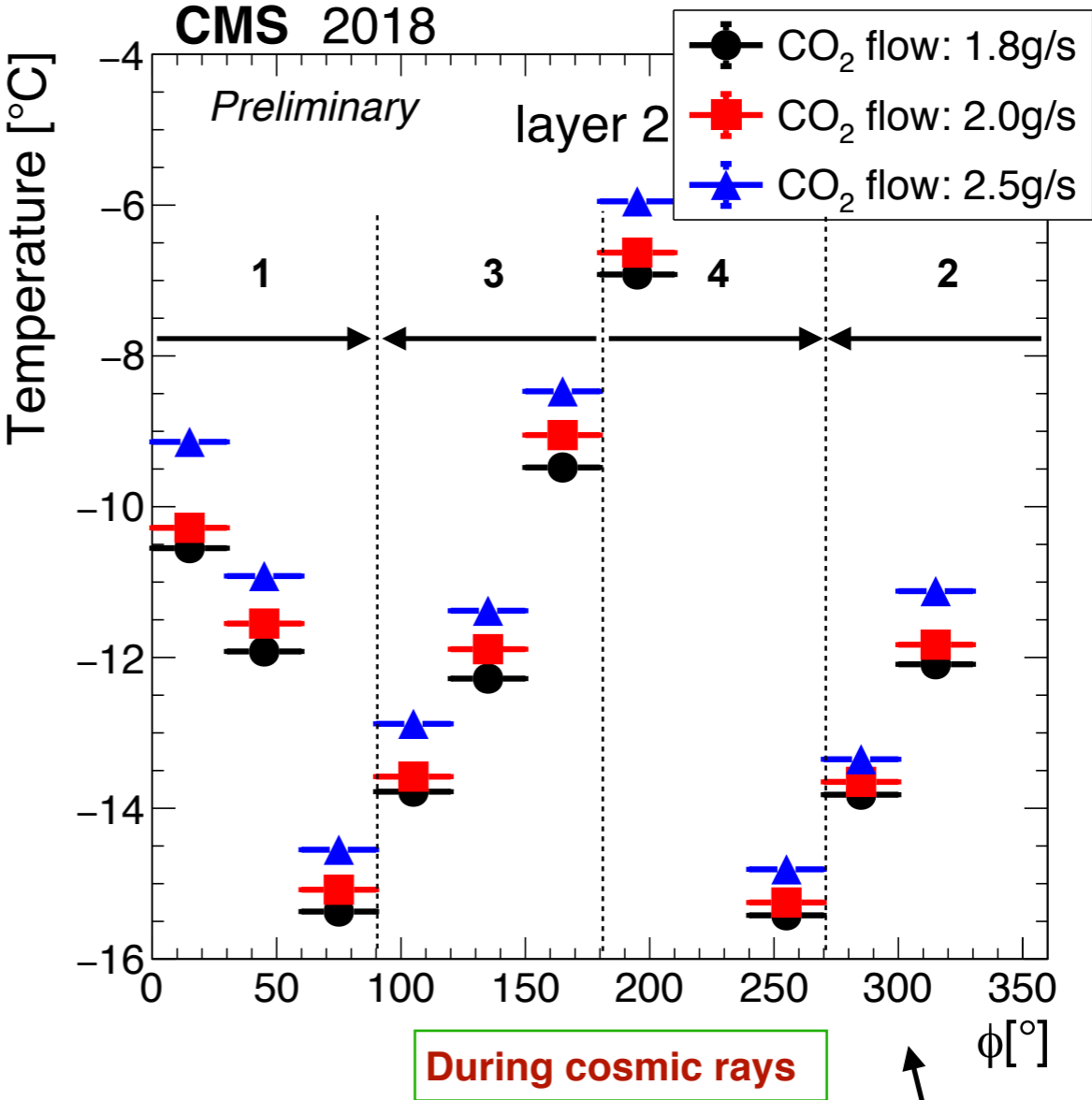enter   enter   Return   enter   enter

- Each loop cools down the full barrel length over a given azimuthal (ϕ) range
- Arrows: direction of CO_2 flows

Average temperature accuracy:
± 0.5 degree celsius

Pixel barrel temperature (layer 2)
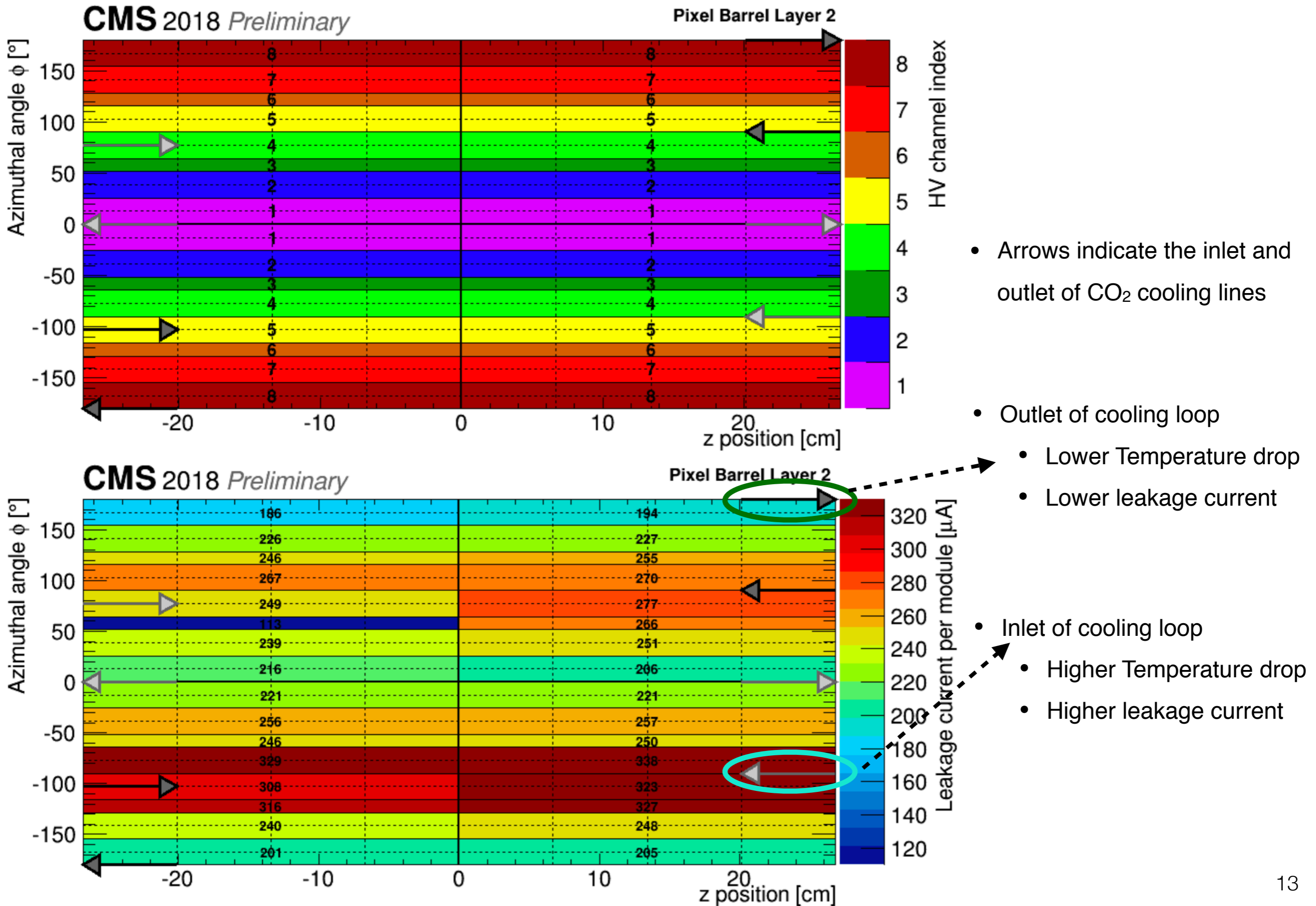

- As a result of CO_2 flow feature (slide 9), temperature gradient: inlet > middle > outlet
- Temperature measured during p-p collisions is higher than the measured temperature in cosmic rays

- Decreased CO_2 flow leads to a better heat exchange more sufficiently, resulting in more efficient cooling:
 - lower temperature, less temperature spread

Assignment of power groups & leakage current distribution

Map of power sectors & leakage current (pixel barrel layer 2)

- Arrows indicate the inlet and outlet of CO_2 cooling lines

- Outlet of cooling loop
  - Lower Temperature drop
  - Lower leakage current

- Inlet of cooling loop
  - Higher Temperature drop
  - Higher leakage current

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Pixel barrel leakage current w.r.t azimuthal coordinate

- Gray arrows: CO_2 cooling direction
- Dashed lines: inlet or outlet
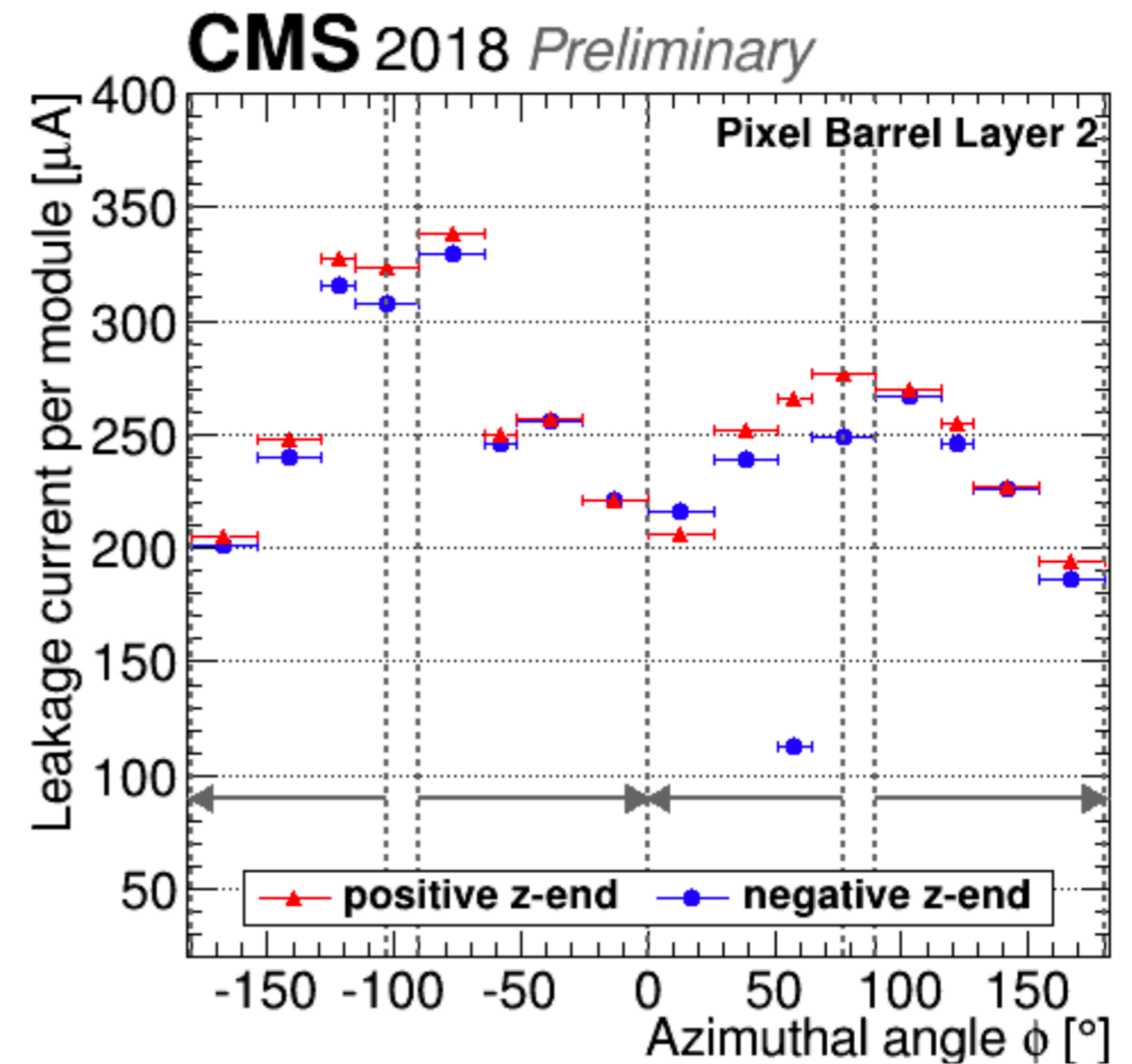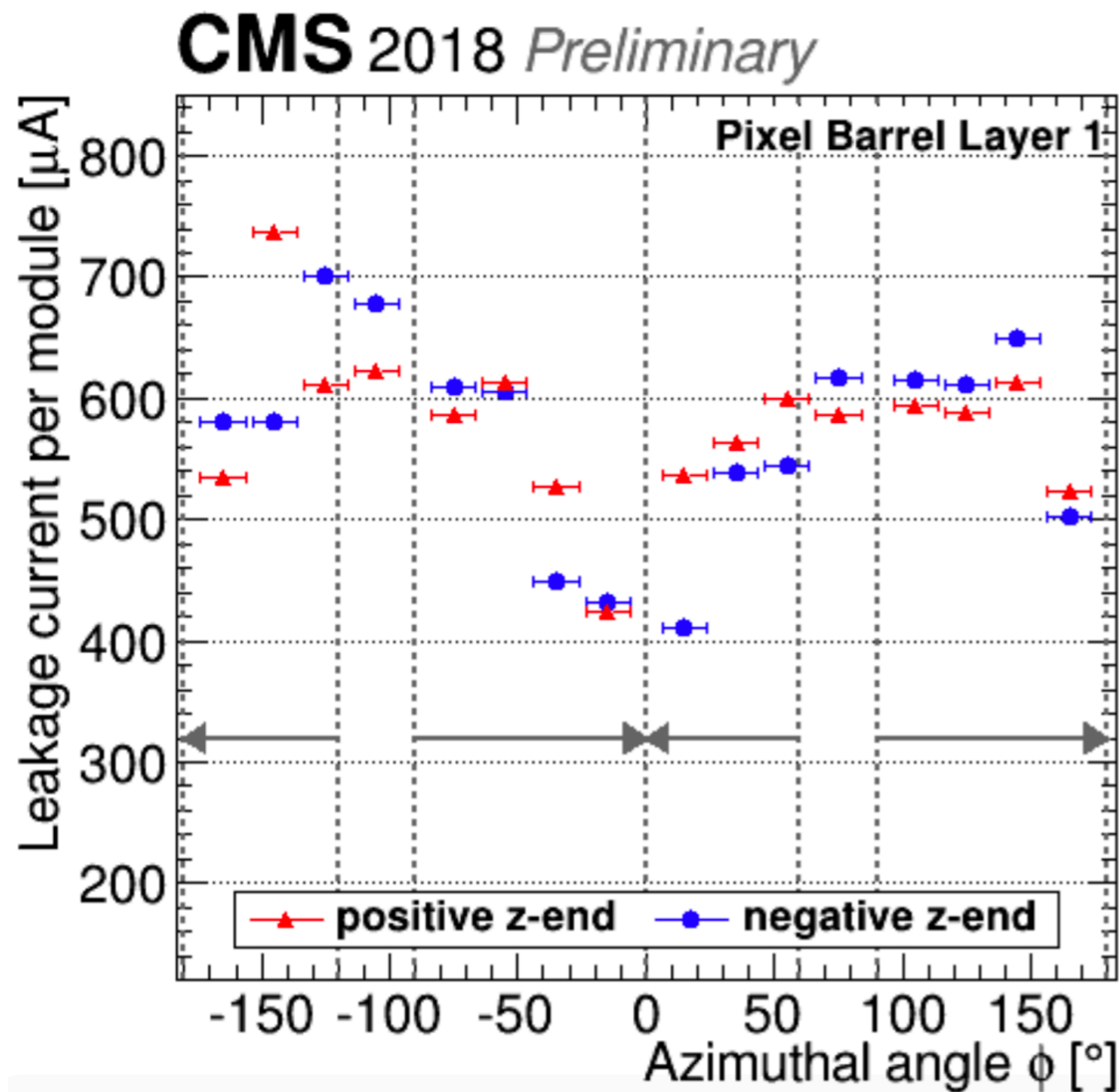
- Temperature (inlet) > Temperature (outlet)
- Leakage current (inlet) > leakage current (outlet) — correlated with temperature gradient
- Layer 1 is closer to the beam pipe than layer 2, so higher leakage current (more accumulated radiation dose)
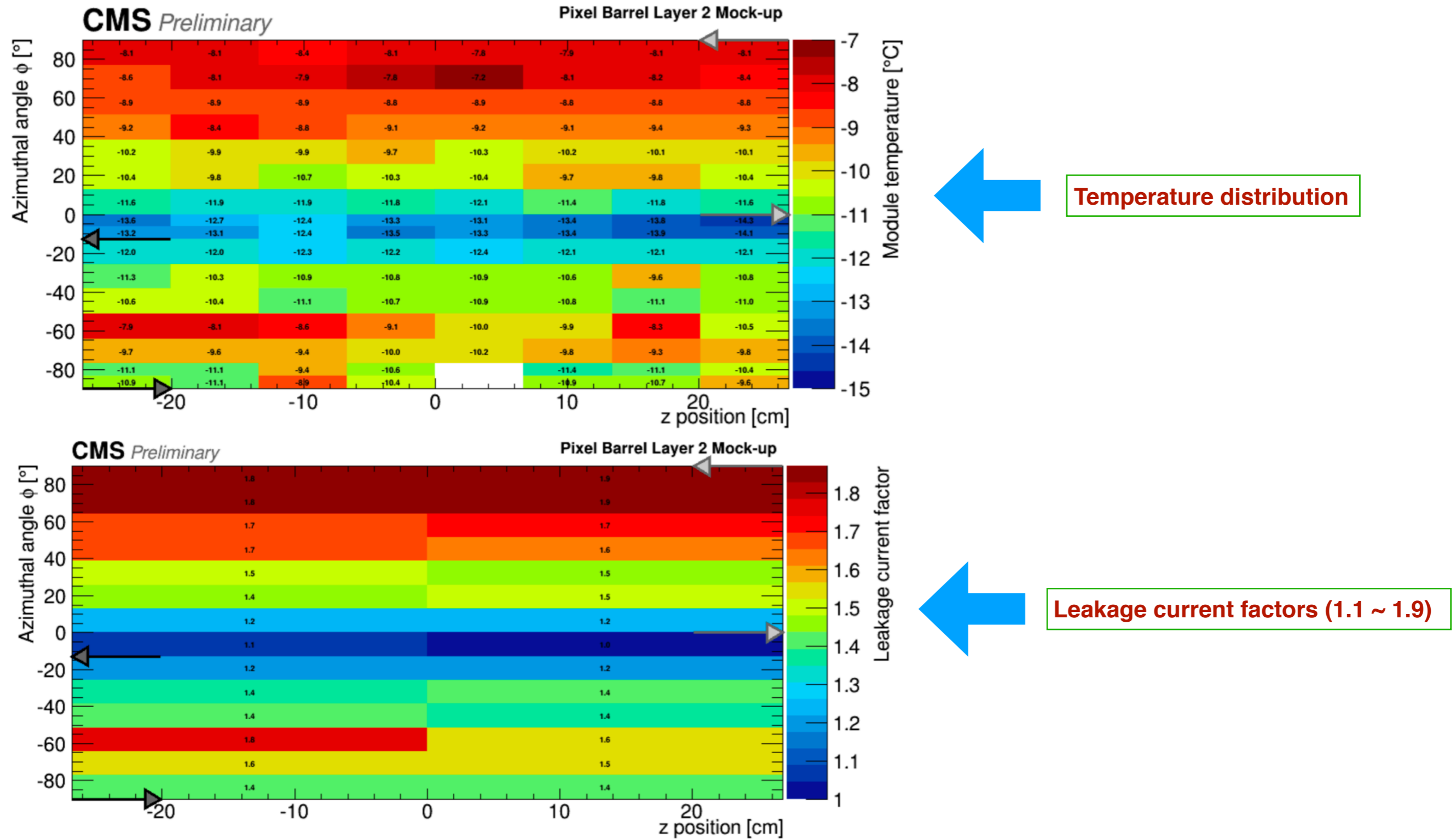
Correlation of leakage current & temperature

- We can improve the temperature estimates by use of a thermal mockup

Thermal Mockup

- Motivation:
  - Emulate the temperature distribution along pixel barrel layer 2
  - Estimate temperature spread in the real detector
  - Better model the correlation between pixel leakage current and temperature
- Setup: simulate the second layer of real pixel barrel detector
  - Same as a half shell of layer 2
  - Same cooling loop as the real detector
  - Same silicon sensors as the real detector
  - Every module has a heater instead of readout chip
  - Each module has a temperature probe — precise measurement of temperature

Module

Cooling pipe
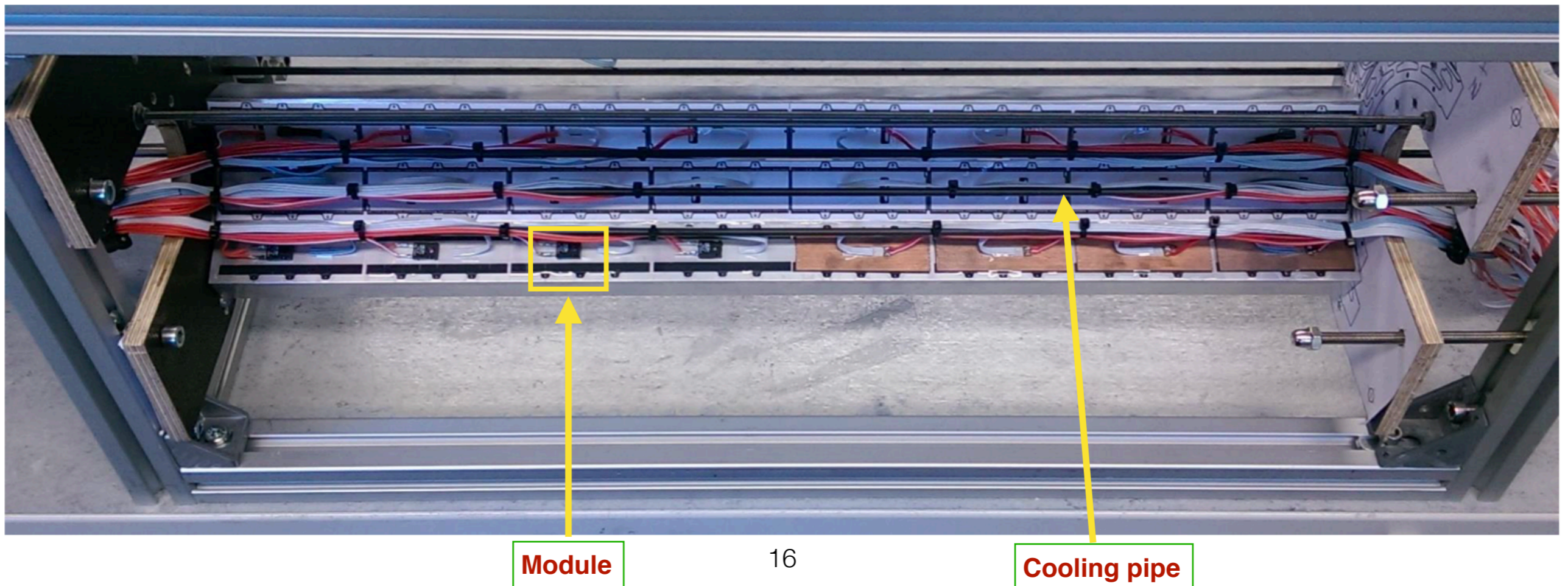
Leakage current & temperature dependence (thermal mockup)

- We expect to have a spread of temperature of factor 2, which matches with the above plot

- Formula relating leakage current & temperature:

$$\text{leakage current factor} = \frac{I}{I_0} = \frac{1}{N_{\text{modules}}} \sum_i \frac{T_i^2}{T_0^2} \exp\left[-\frac{\Delta E}{2\,k_B}\left(\frac{1}{T_i} - \frac{1}{T_0}\right)\right]$$

- Good agreement with the measured leakage currents in the real detector — We understand the cooling in the detector

Pixel module leakage current evolution

Pixel barrel module leakage current evolution (measurement)

CMS Barrel Pixel Detector Leakage Current May 2017 - Oct 2018
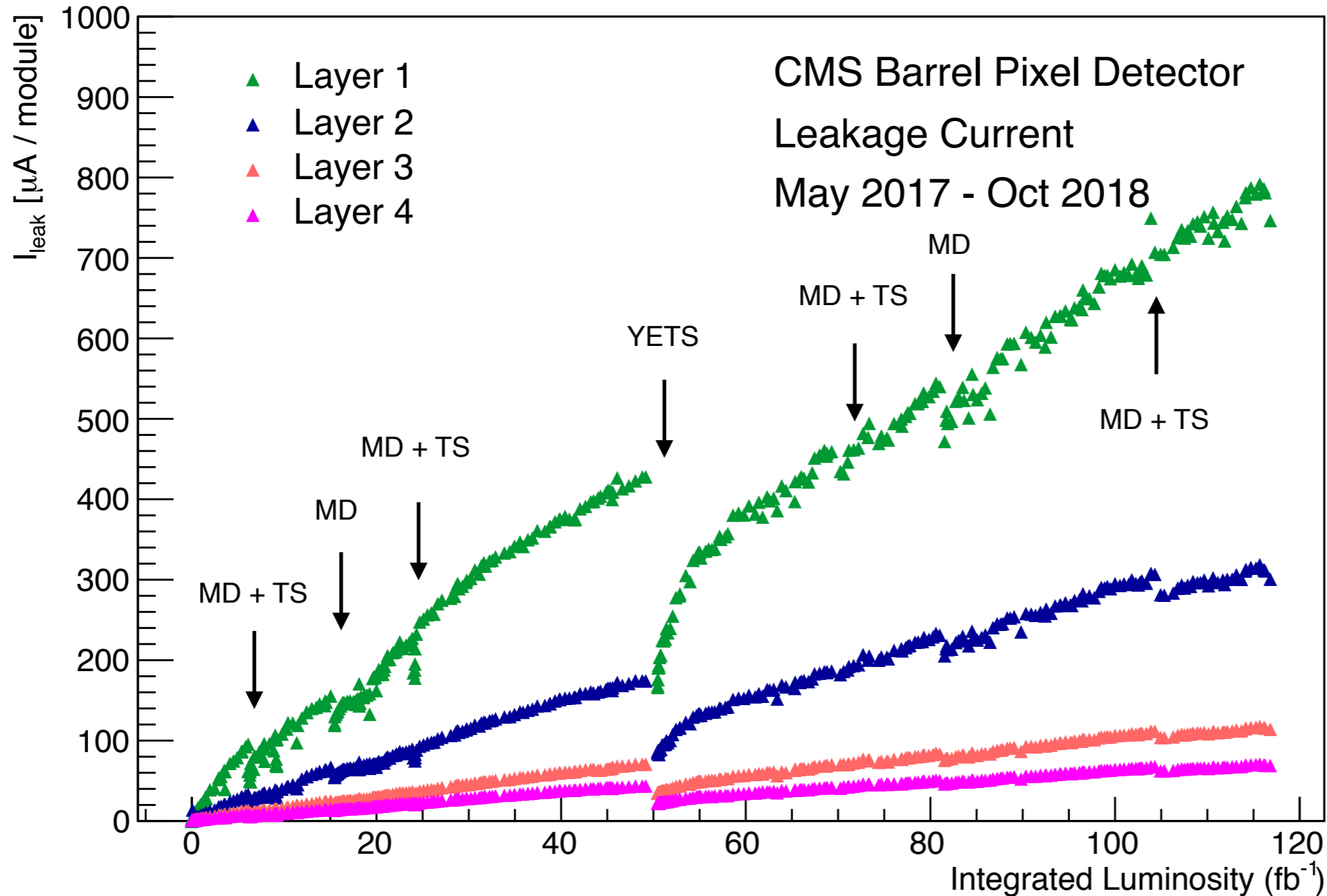
During p-p collisions

- MD: Machine development
- TS: Technical stop
- YETS: Year-End technical stop

- Leakage current increased gradually due to accumulated radiation dose through the year

- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (layer 1 > layer 2 > layer 3 > layer 4)

- Leakage current drop during MD/TS/YETS: annealing or changed high voltage settings

Pixel endcap module leakage current evolution (measurement)
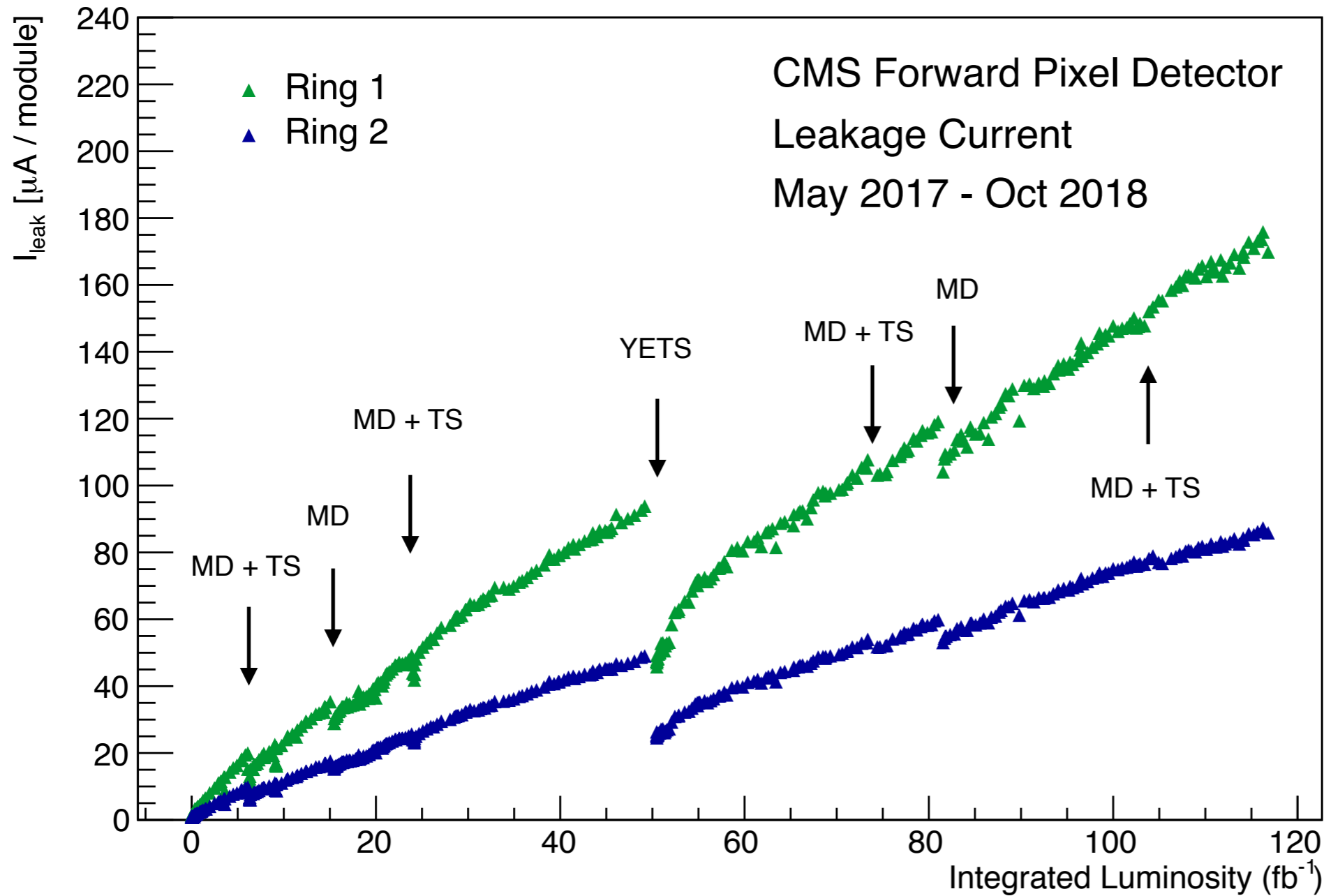
- Leakage current increased gradually due to accumulated radiation dose through the year

- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (ring 1 > ring 2)

- Leakage current drop during MD/TS/YETS: annealing or changed high voltage settings
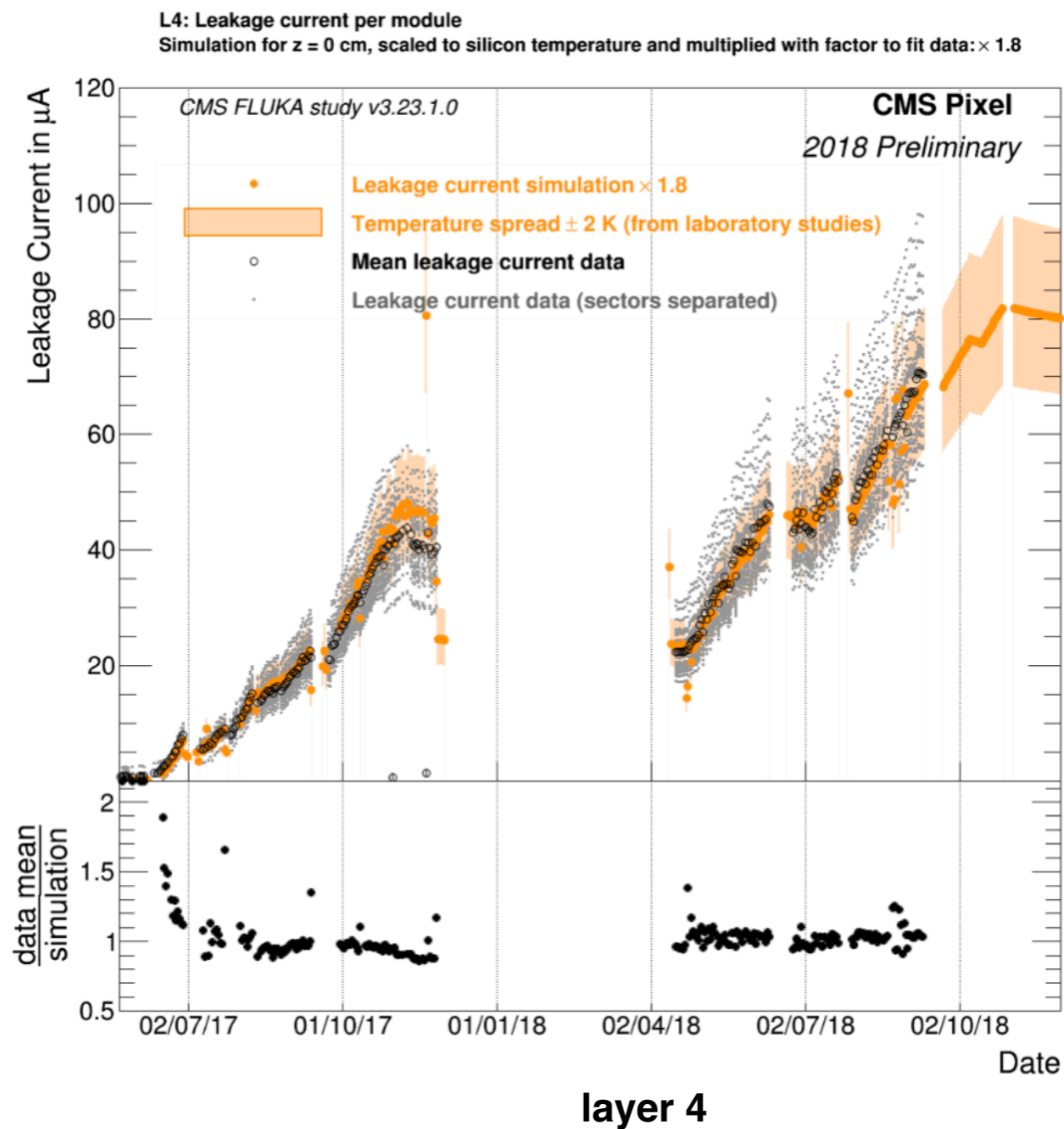
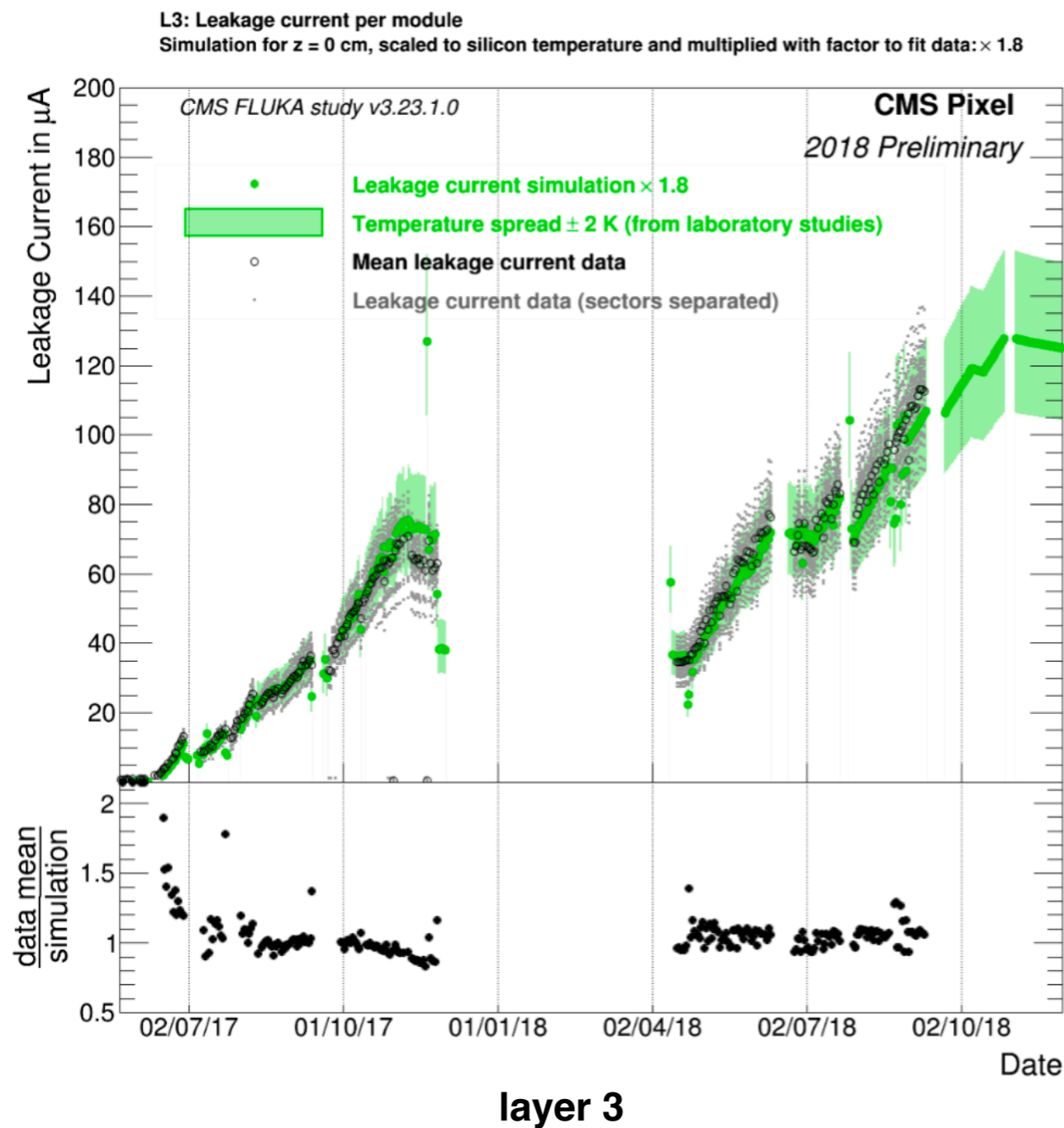# Pixel module leakage current simulation

- The expected leakage current in each pixel barrel layer is calculated based on the temperature and irradiation history

- Empirical radiation damage model is used by including the parameters: fluence, temperature, time, sensor volume

- **Reference: DESY-THESIS-1999-040 (Hamburg model)**

Pixel barrel leakage current simulation
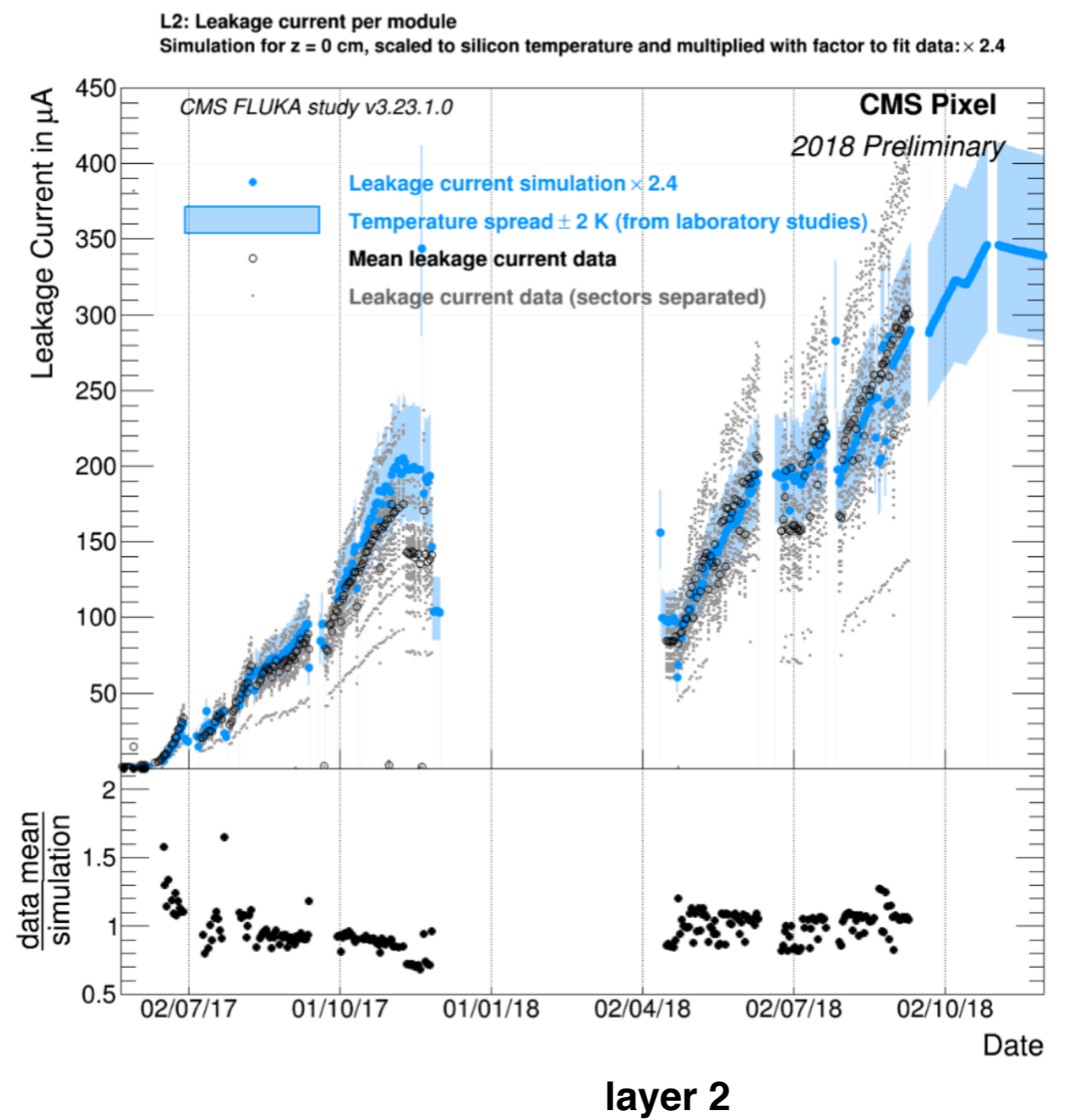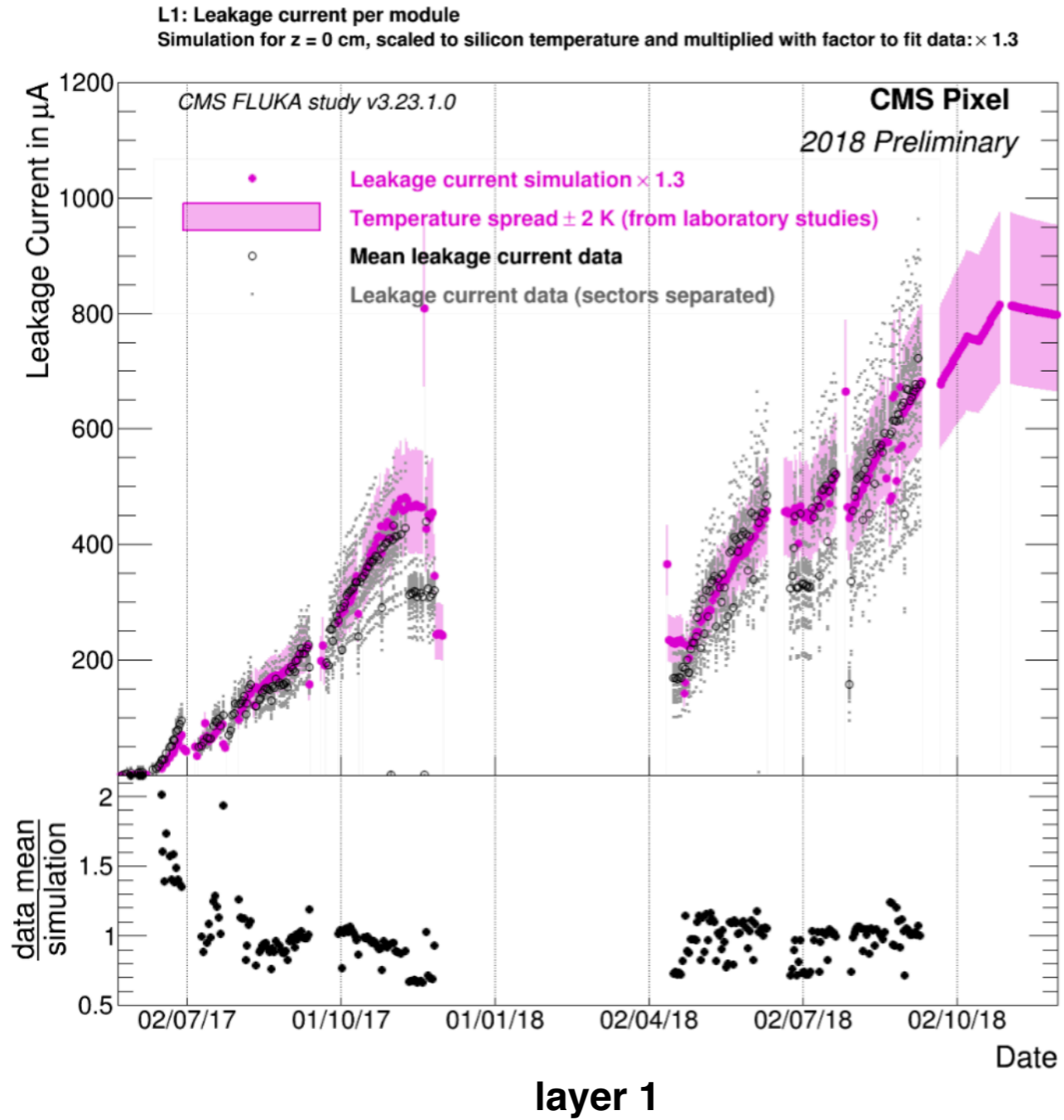
layer 1

layer 2

- Good agreement between measurement and simulation on module leakage current evolution

Pixel barrel leakage current simulation

layer 3

layer 4

- Good agreement between measurement and simulation on module leakage current evolution
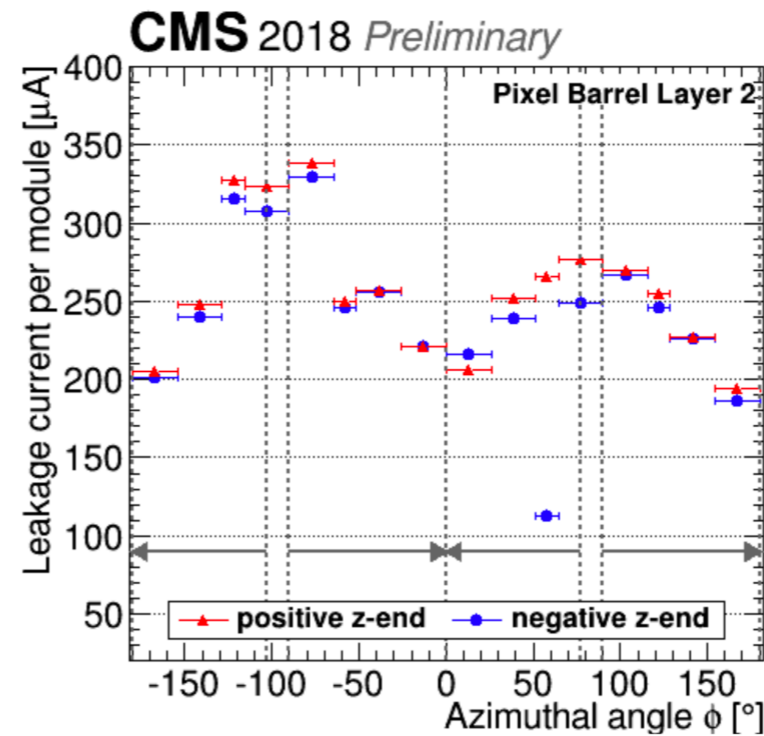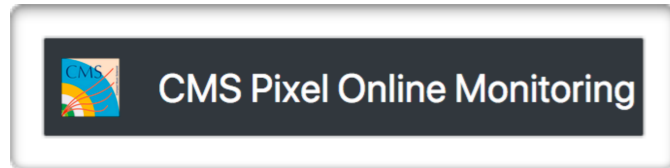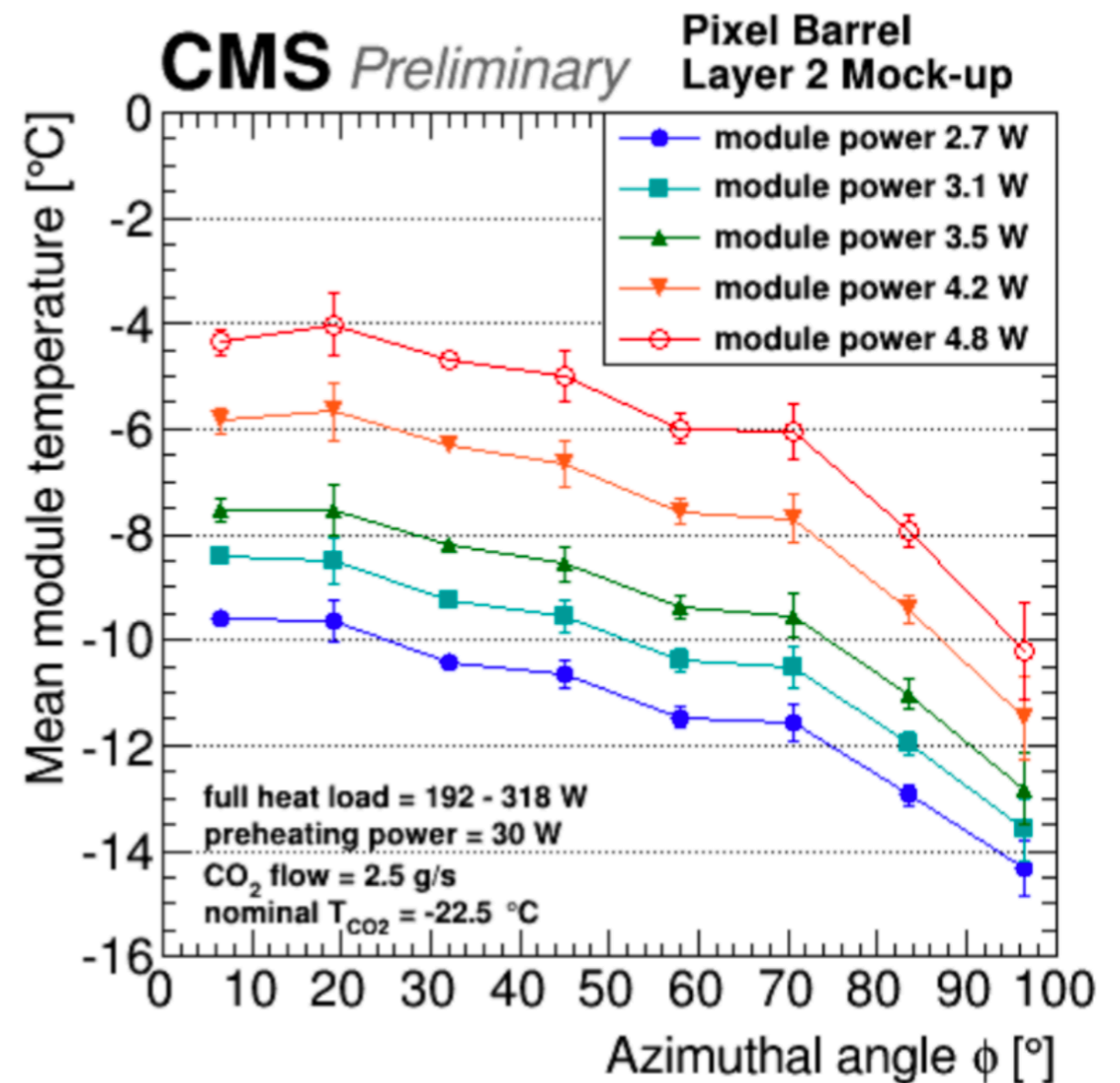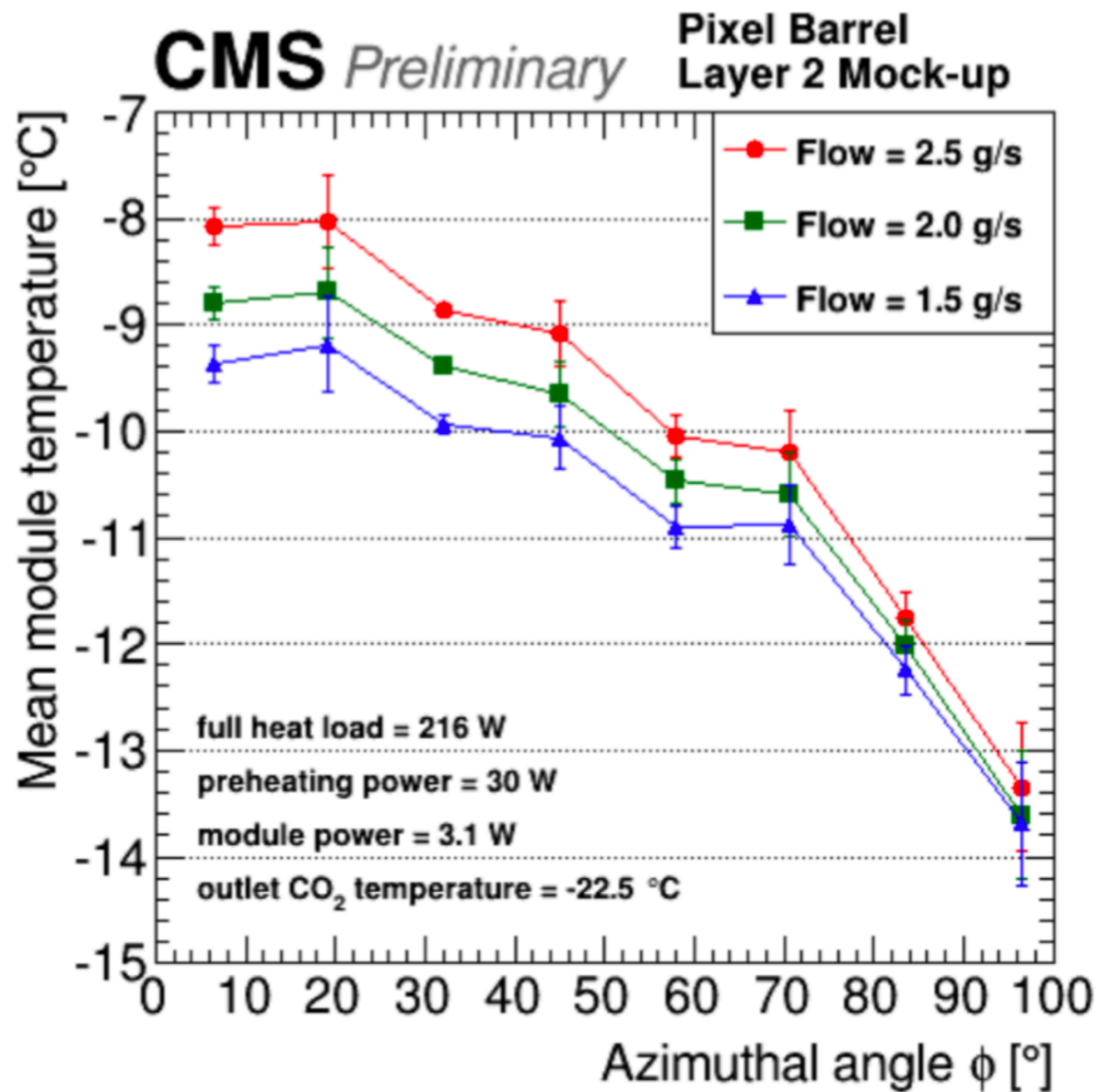
Conclusion

- We have developed an awesome monitoring system for CMS Phase-1 pixel detector

- We have achieved a good understanding on the cooling of the pixel detector

- The study on the correlation between pixel leakage current and temperature has been successful

- We have realized a precise prediction on the module leakage current evolution

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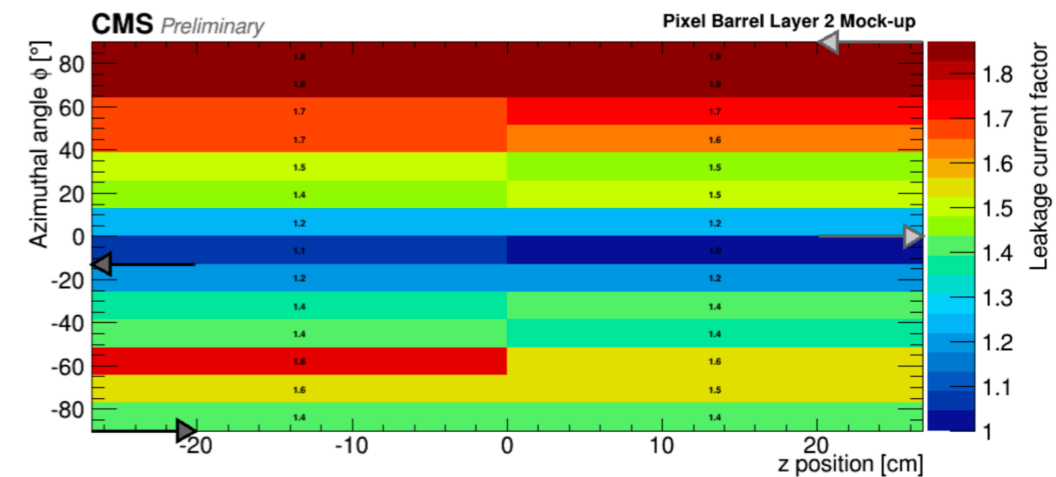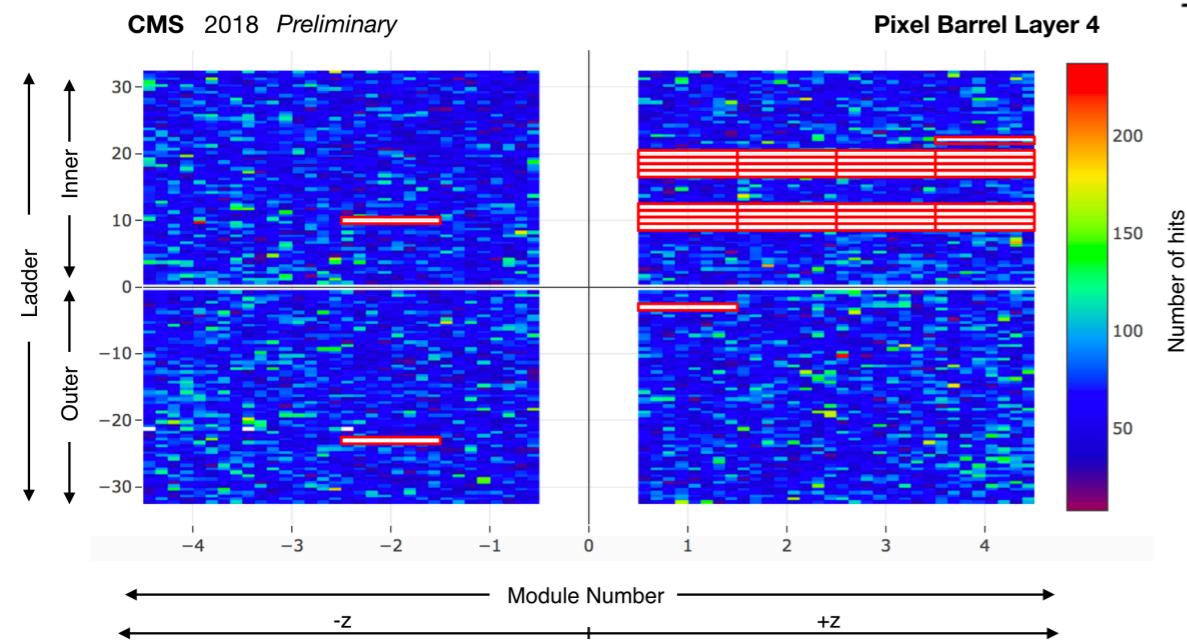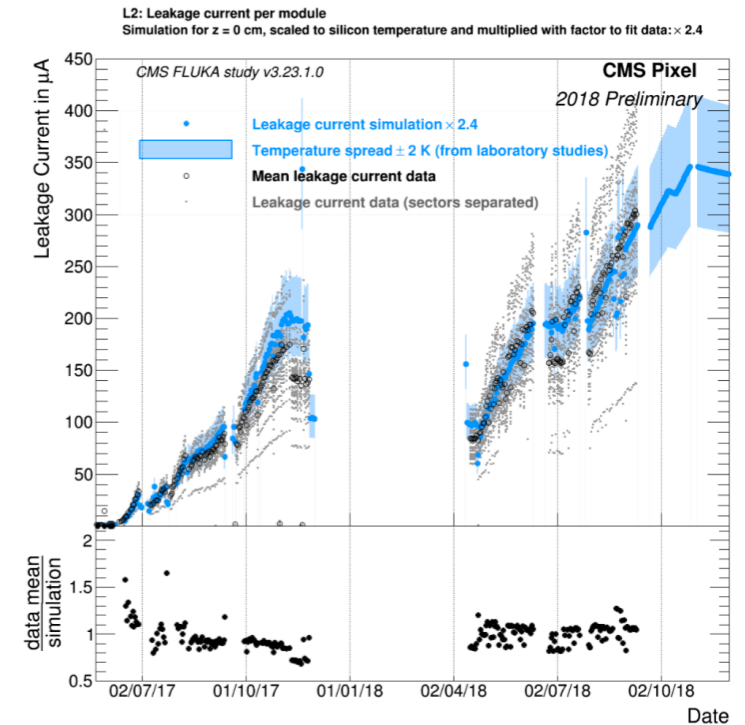
Thanks for your attention!

Backup

Temperature & cooling flow dependence (thermal mockup)

Left plot: CMS *Preliminary* — Pixel Barrel Layer 2 Mock-up
Mean module temperature [°C] vs Azimuthal angle ϕ [°]

Legend:
- Flow = 2.5 g/s
- Flow = 2.0 g/s
- Flow = 1.5 g/s

full heat load = 216 W
preheating power = 30 W
module power = 3.1 W
outlet CO_2 temperature = -22.5 °C

Right plot: CMS *Preliminary* — Pixel Barrel Layer 2 Mock-up
Mean module temperature [°C] vs Azimuthal angle ϕ [°]

Legend:
- module power 2.7 W
- module power 3.1 W
- module power 3.5 W
- module power 4.2 W
- module power 4.8 W

full heat load = 192 - 318 W
preheating power = 30 W
CO_2 flow = 2.5 g/s
nominal T_{CO2} = -22.5 °C

- The effect observed is due to the properties of the CO_2 in 2-phase state

- The temperature at the return point (ϕ = 90°) stays nearly constant, the differences (spreads) depending the full heat load

- CO_2 mass flow reduction can decrease the temperature and leakage current in the detector

- A significant higher module power also affects the temperature

Silicon module temperature estimation

1. Measurements from carbon fibre (near cooling loop):
Taking the average of all sensors and average over a day.
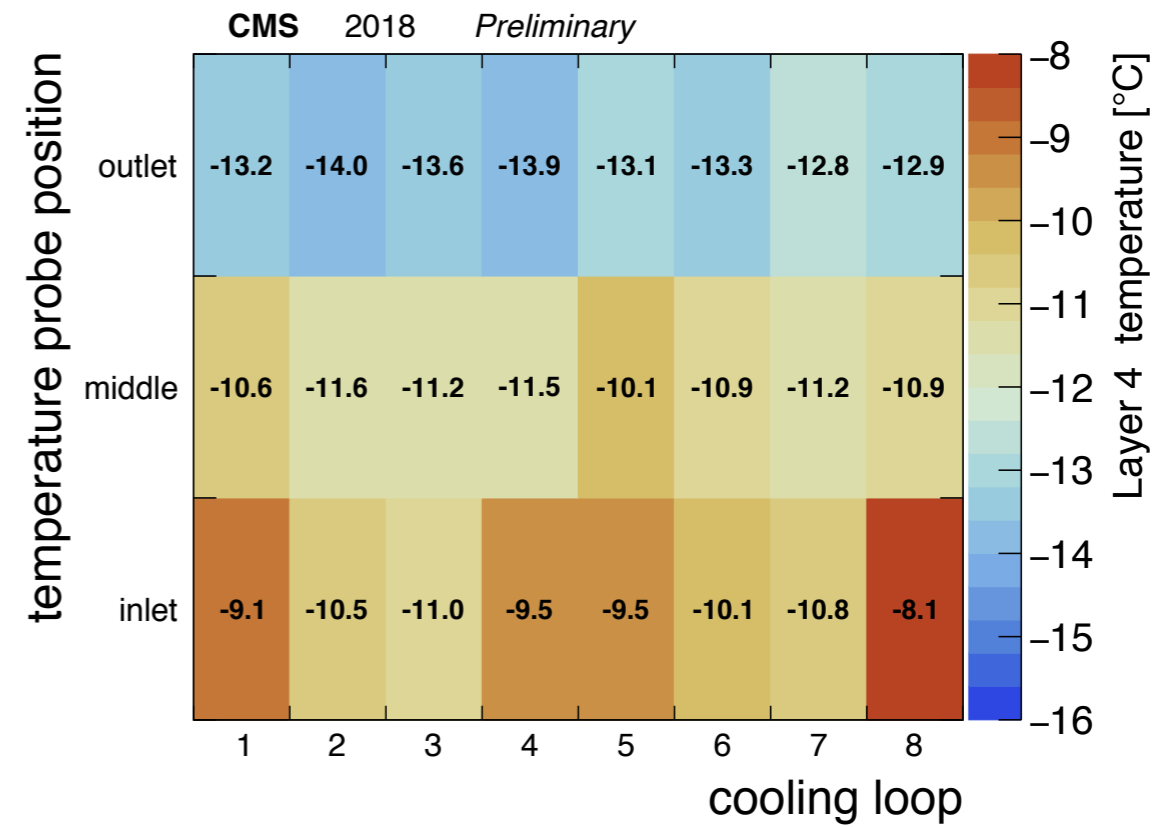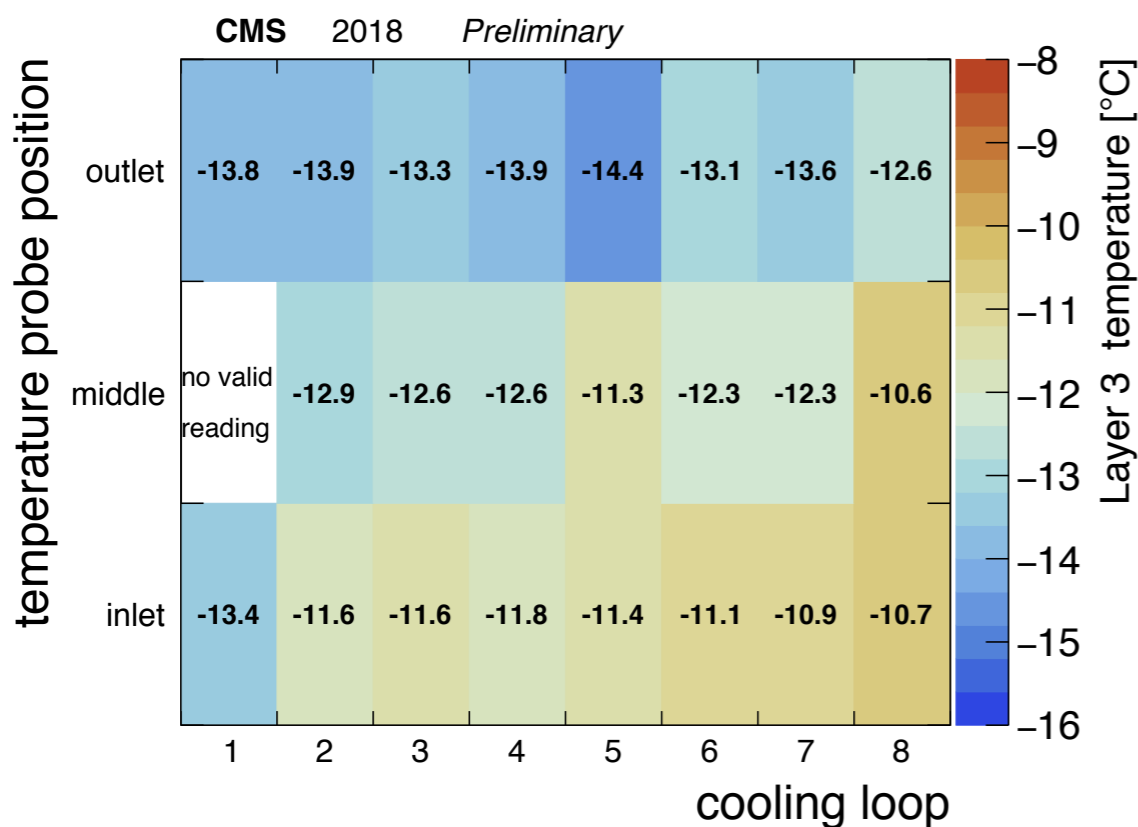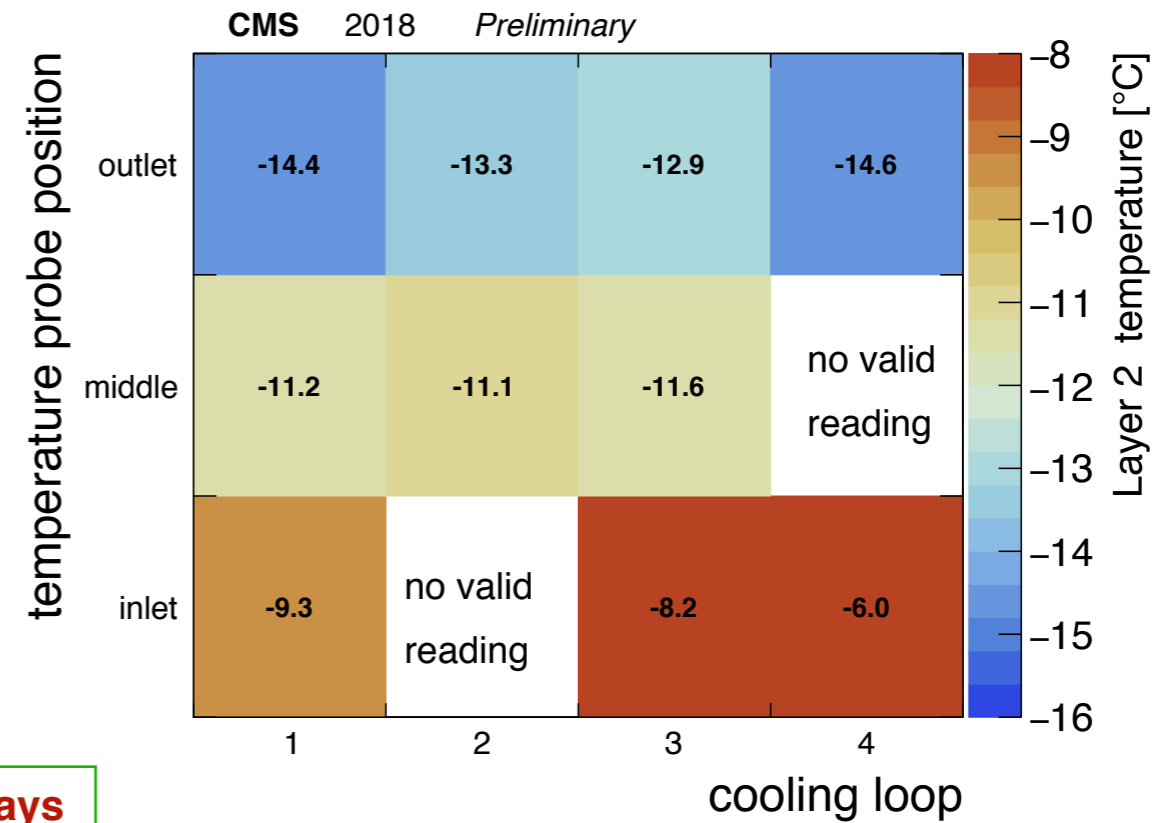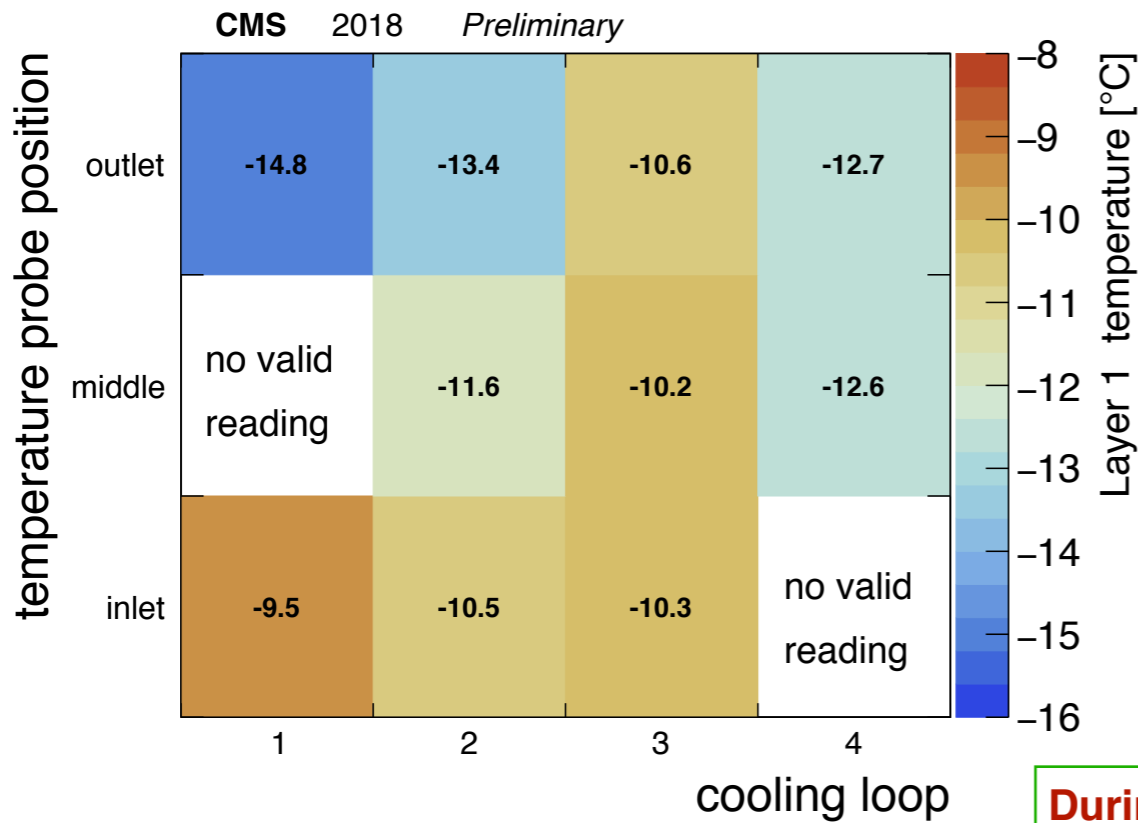Temperature is around -11.5 °C when low voltage is on.

2. Actual silicon temperature is higher than measurements
near cooling loop when module power (low voltage) is on.
Estimation from mock-up layer 2 in laboratory:
+ 2-3 K offset to carbon fibre measurements.

	L1	L2	L3	L4
1. Avg. carbon fibre temperature per day	fluctuating around -11.5 °C			
2. Estimated offset	+3 K	+3 K	+3 K	+4 K
Silicon temperature	**-8.5 °C**	**-8.5°C**	**-8.5°C**	**-7.5°C**

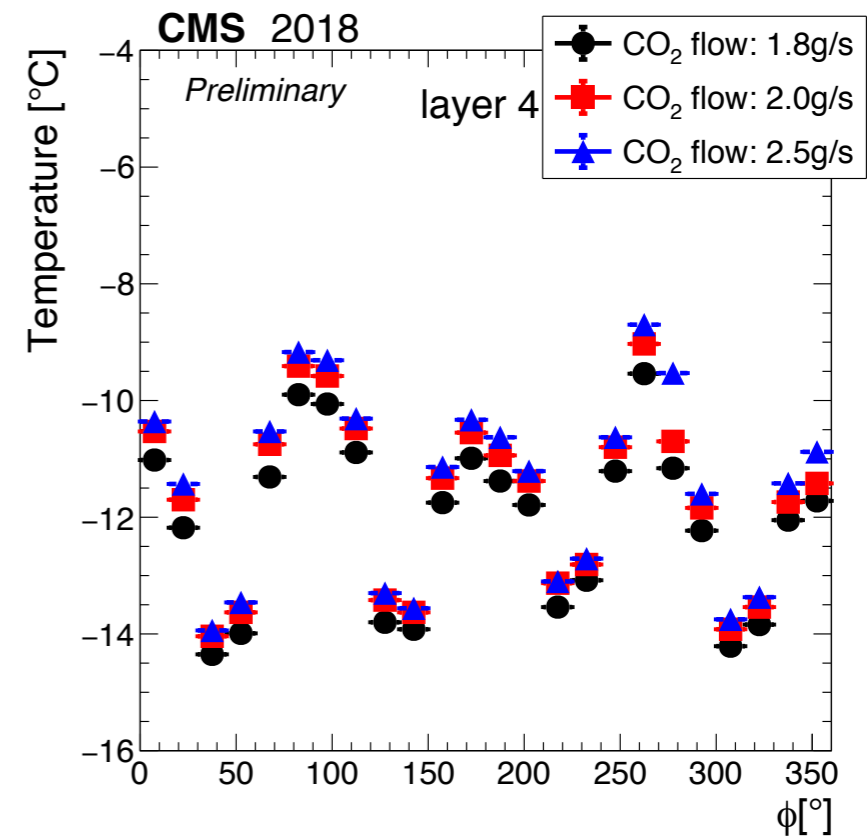Layer 4:
Warmed by the
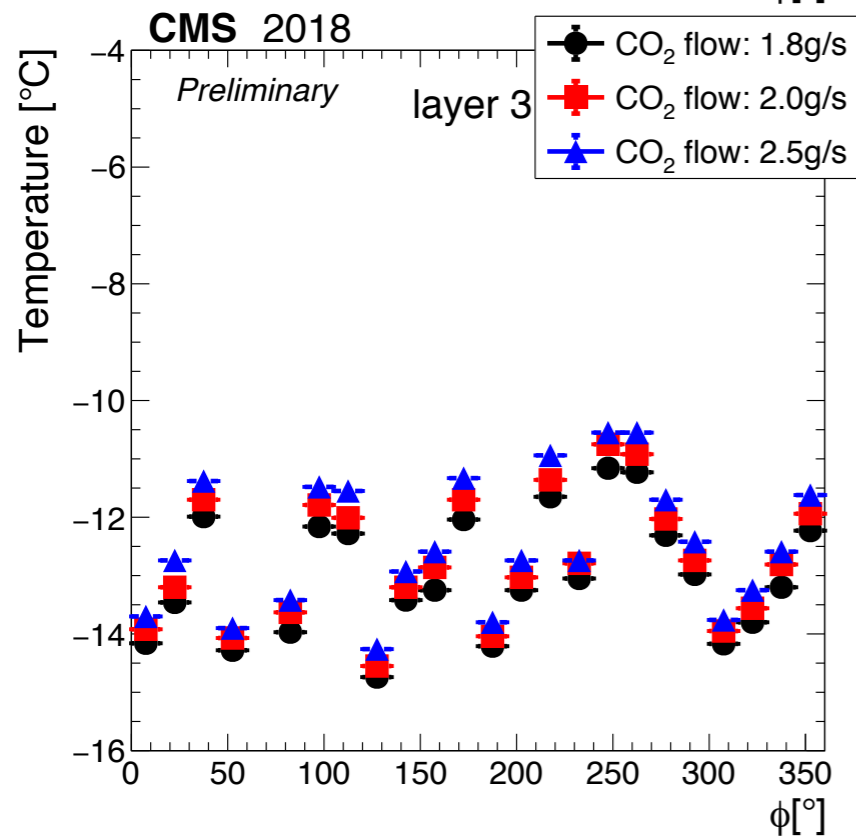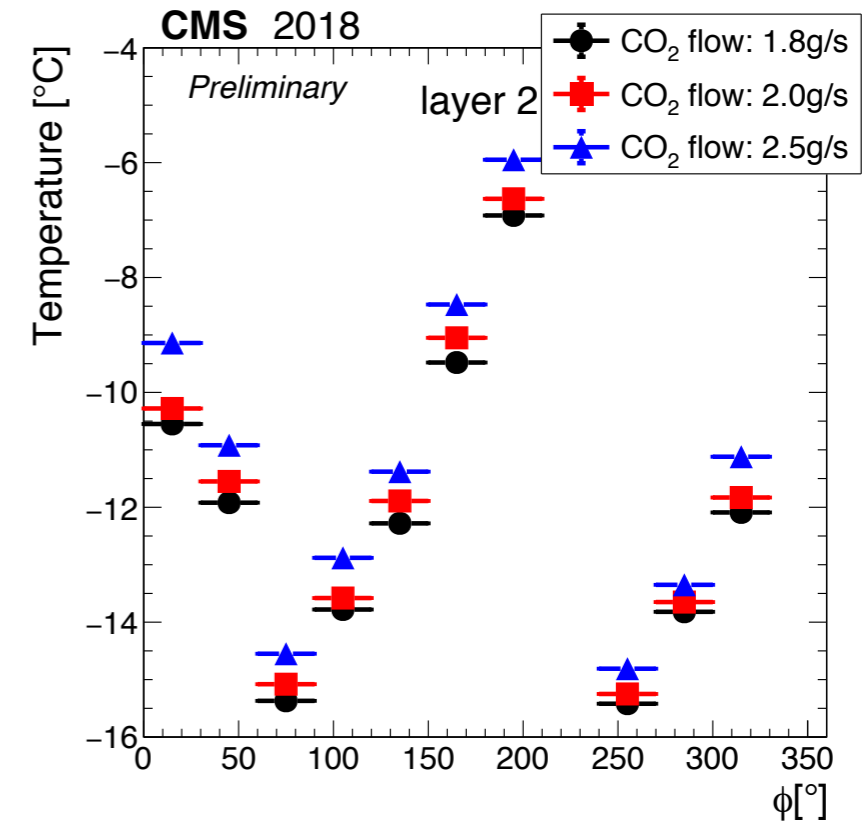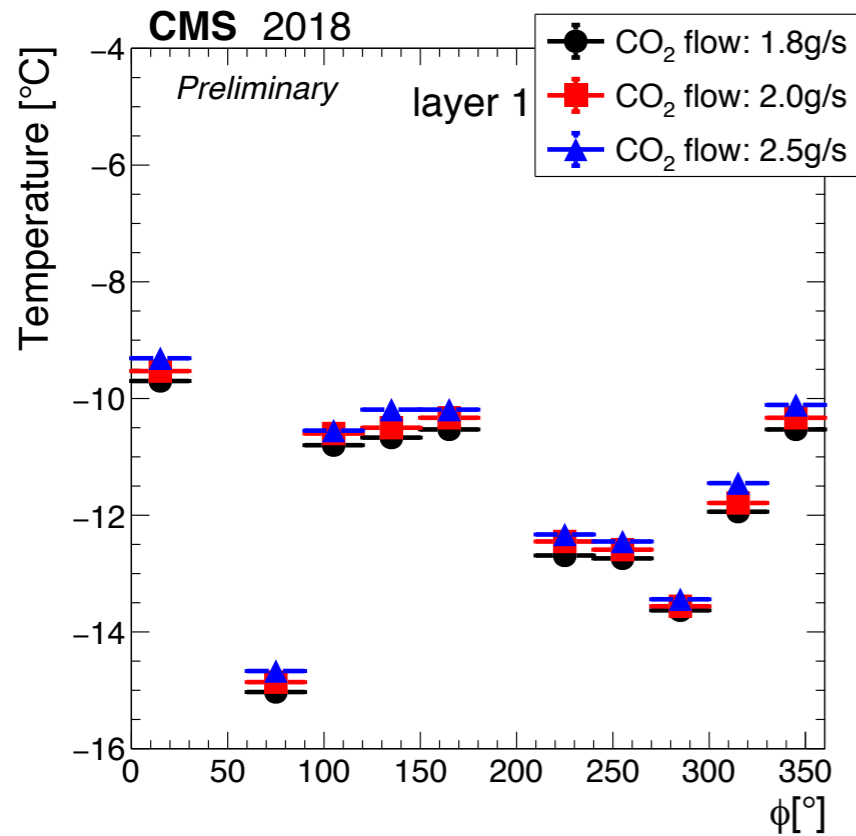adjacent strip tracker,
assuming +1 K

Layer 1: Better thermal contact (no base strips),
but also higher digital activity.
We estimate that these effects cancel each other out.

Pixel barrel temperature gradient along each cooling loop

CMS 2018 *Preliminary* — Layer 1 temperature [°C]

temperature probe position	cooling loop 1	cooling loop 2	cooling loop 3	cooling loop 4
outlet	-14.8	-13.4	-10.6	-12.7
middle	no valid reading	-11.6	-10.2	-12.6
inlet	-9.5	-10.5	-10.3	no valid reading

CMS 2018 *Preliminary* — Layer 2 temperature [°C]

temperature probe position	cooling loop 1	cooling loop 2	cooling loop 3	cooling loop 4
outlet	-14.4	-13.3	-12.9	-14.6
middle	-11.2	-11.1	-11.6	no valid reading
inlet	-9.3	no valid reading	-8.2	-6.0

During cosmic rays

CMS 2018 *Preliminary* — Layer 3 temperature [°C]

temperature probe position	cooling loop 1	cooling loop 2	cooling loop 3	cooling loop 4	cooling loop 5	cooling loop 6	cooling loop 7	cooling loop 8
outlet	-13.8	-13.9	-13.3	-13.9	-14.4	-13.1	-13.6	-12.6
middle	no valid reading	-12.9	-12.6	-12.6	-11.3	-12.3	-12.3	-10.6
inlet	-13.4	-11.6	-11.6	-11.8	-11.4	-11.1	-10.9	-10.7

CMS 2018 *Preliminary* — Layer 4 temperature [°C]

temperature probe position	cooling loop 1	cooling loop 2	cooling loop 3	cooling loop 4	cooling loop 5	cooling loop 6	cooling loop 7	cooling loop 8
outlet	-13.2	-14.0	-13.6	-13.9	-13.1	-13.3	-12.8	-12.9
middle	-10.6	-11.6	-11.2	-11.5	-10.1	-10.9	-11.2	-10.9
inlet	-9.1	-10.5	-11.0	-9.5	-9.5	-10.1	-10.8	-8.1

- Each cooling loop has three temperature probes, which are located respectively at the beginning (inlet), middle, end (outlet) positions

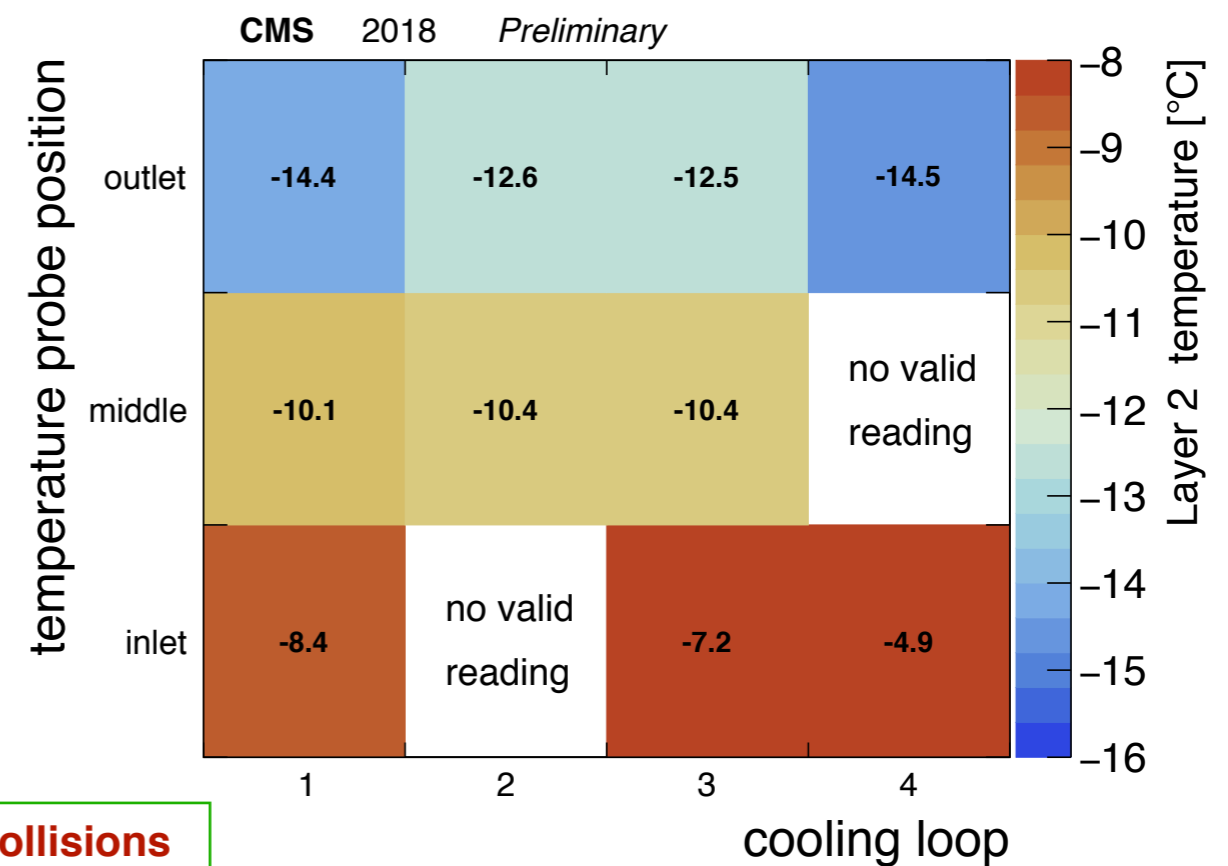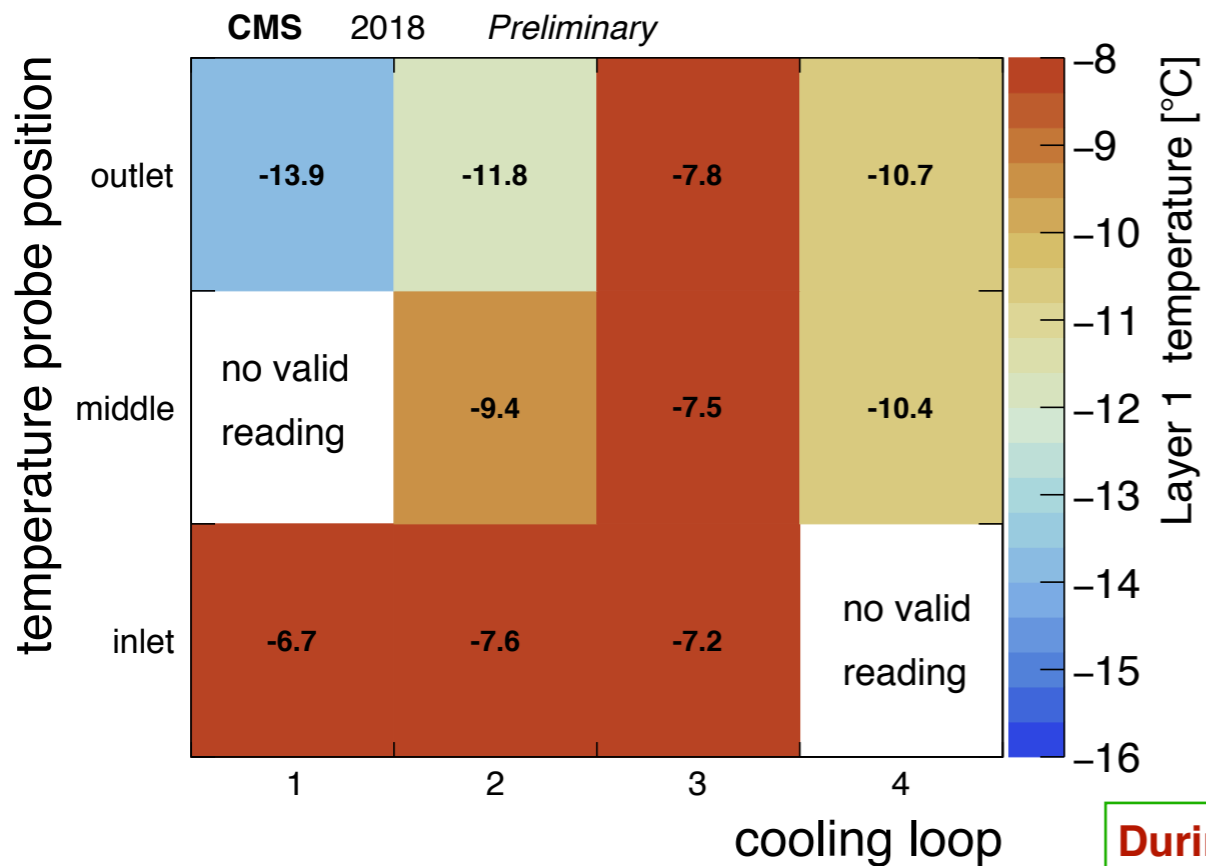- As expected for CO_2 cooling, the temperature at the outlet is lower than at the inlet
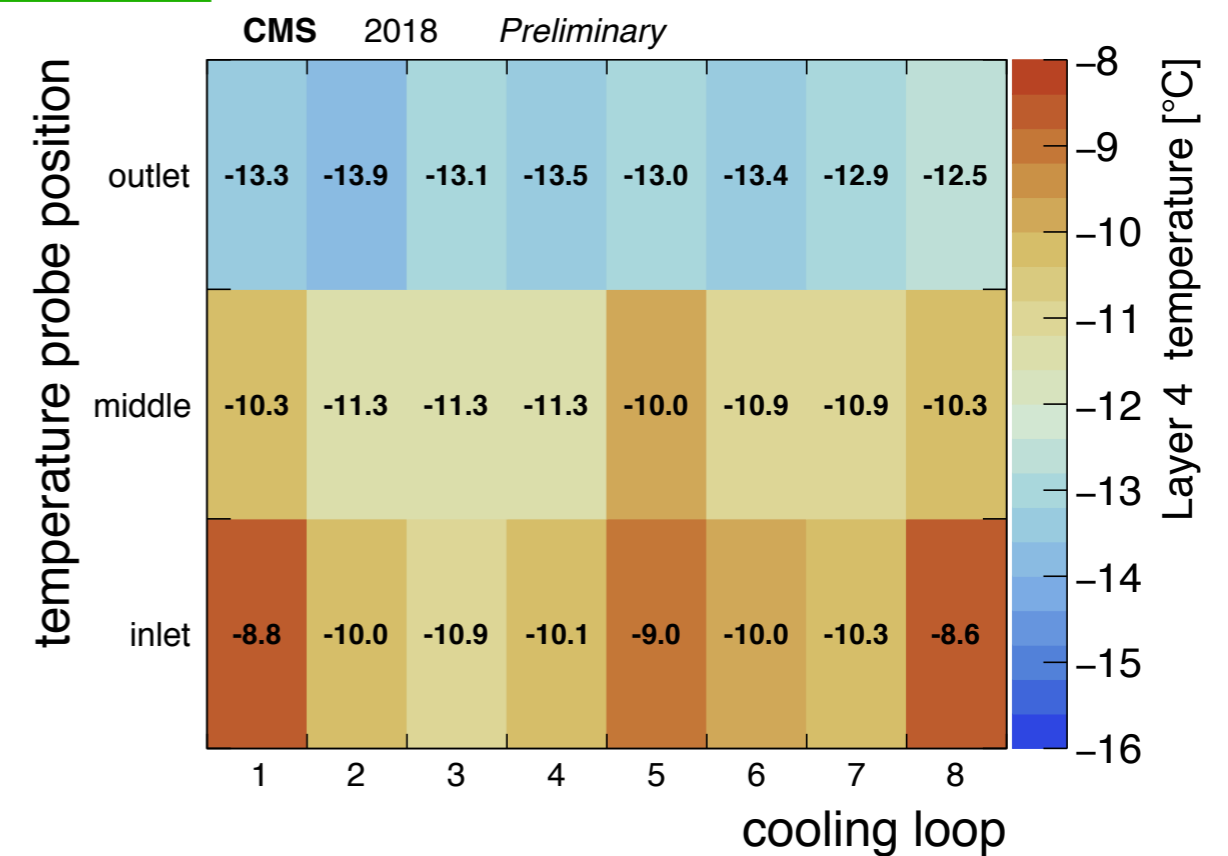
29
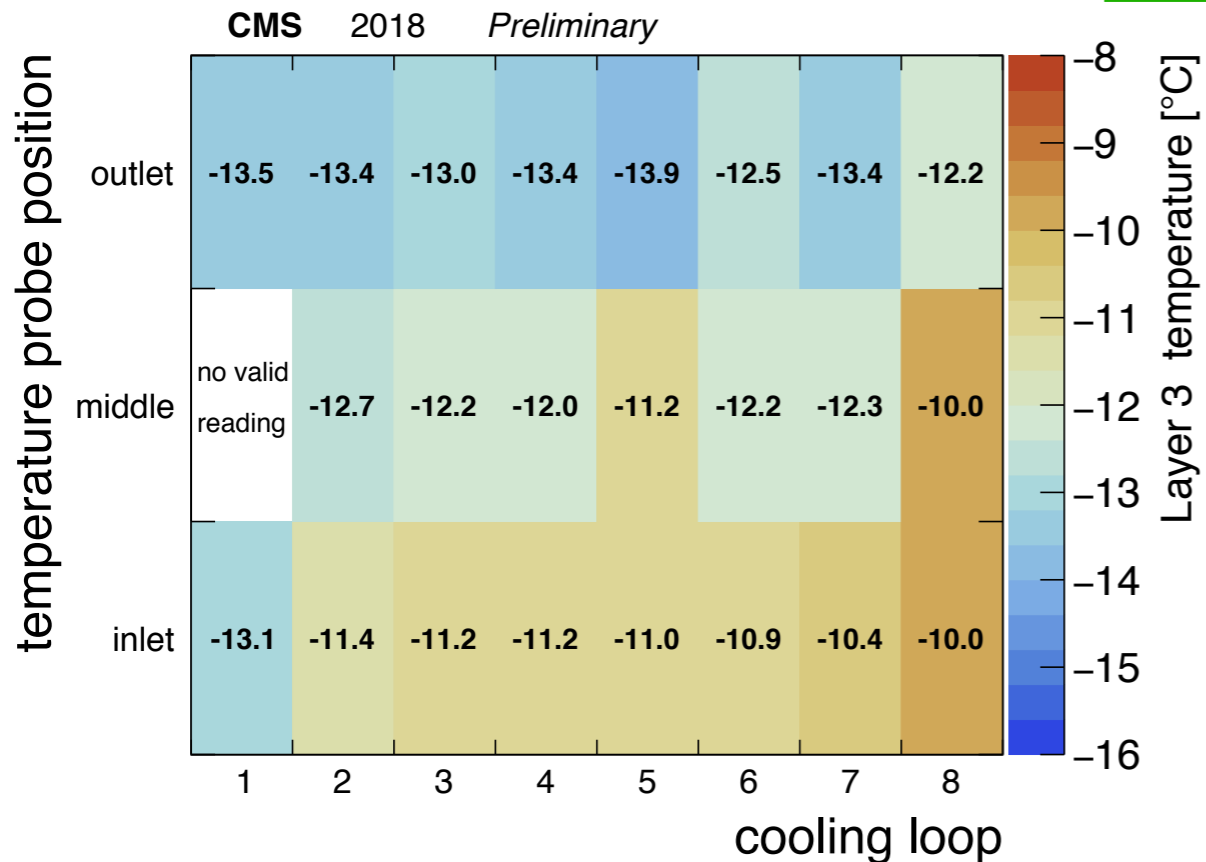
Pixel barrel temperature w.r.t azimuthal coordinate

- As a result of the 2-phase state of CO_2 cooling flow, decreased CO_2 flow leads to its absorbing heat more sufficiently, resulting in more efficient cooling, lower temperature, less temperature spread (explanations in slide 9)

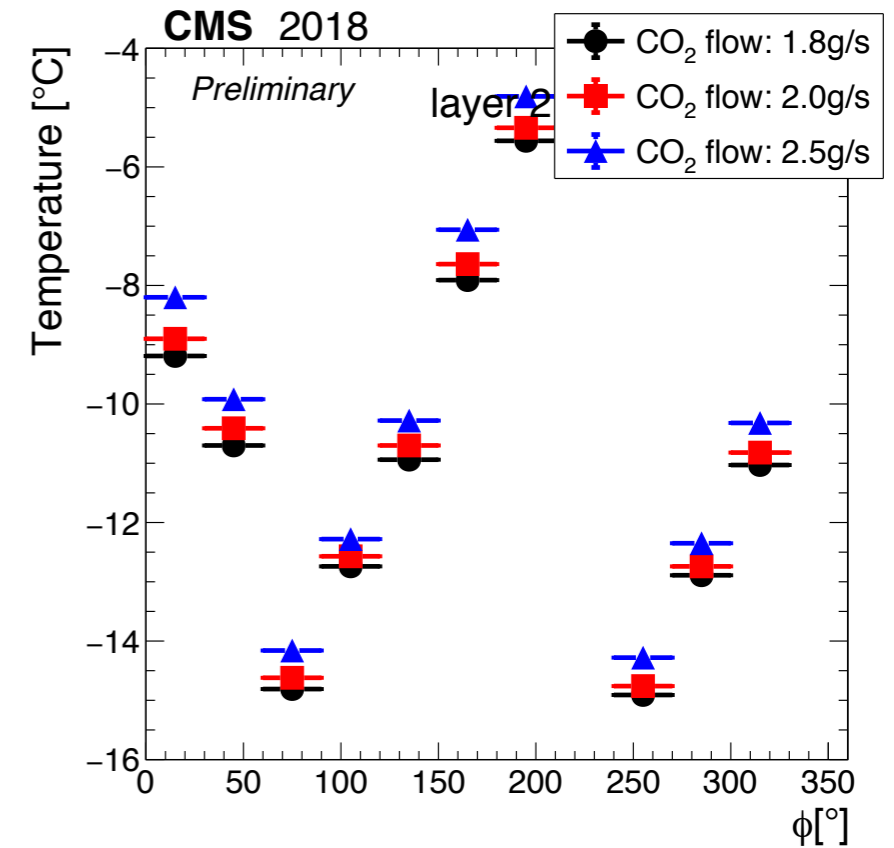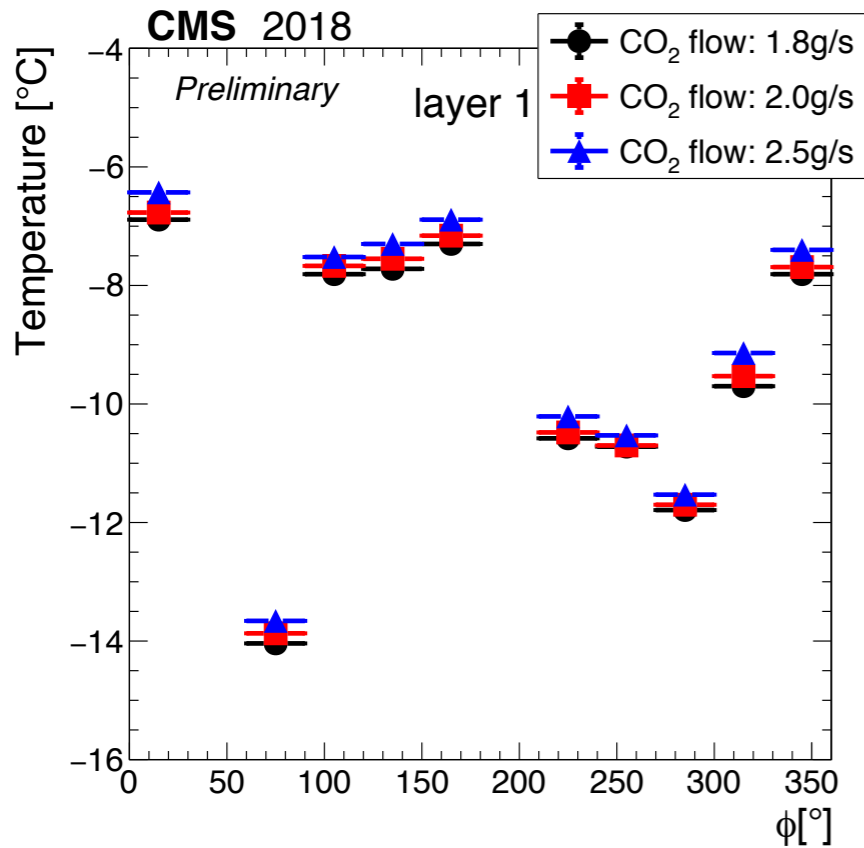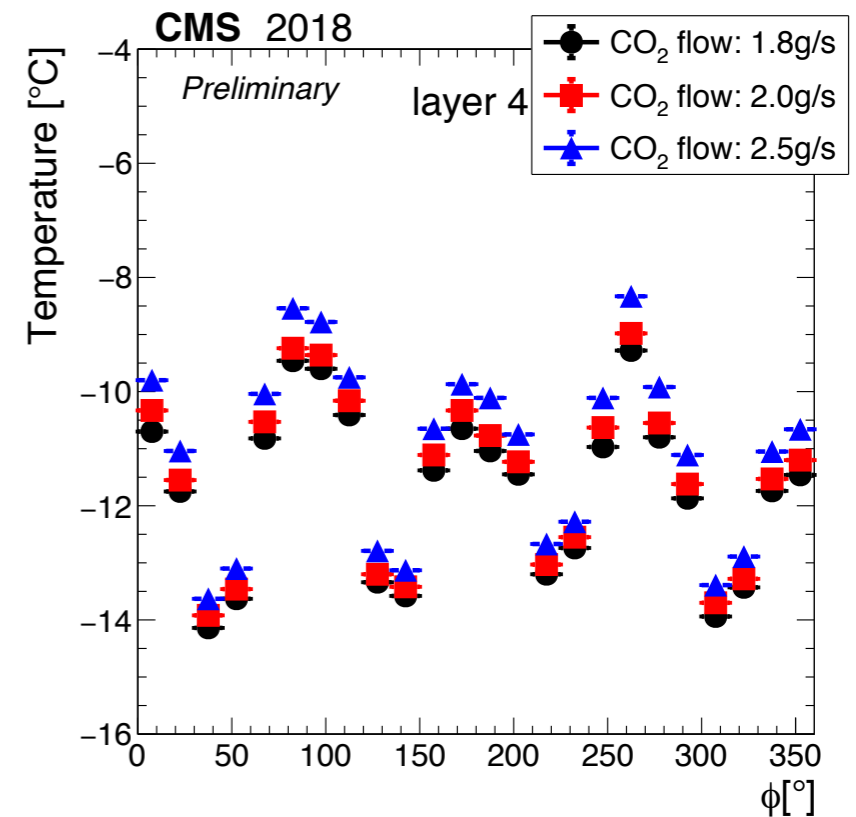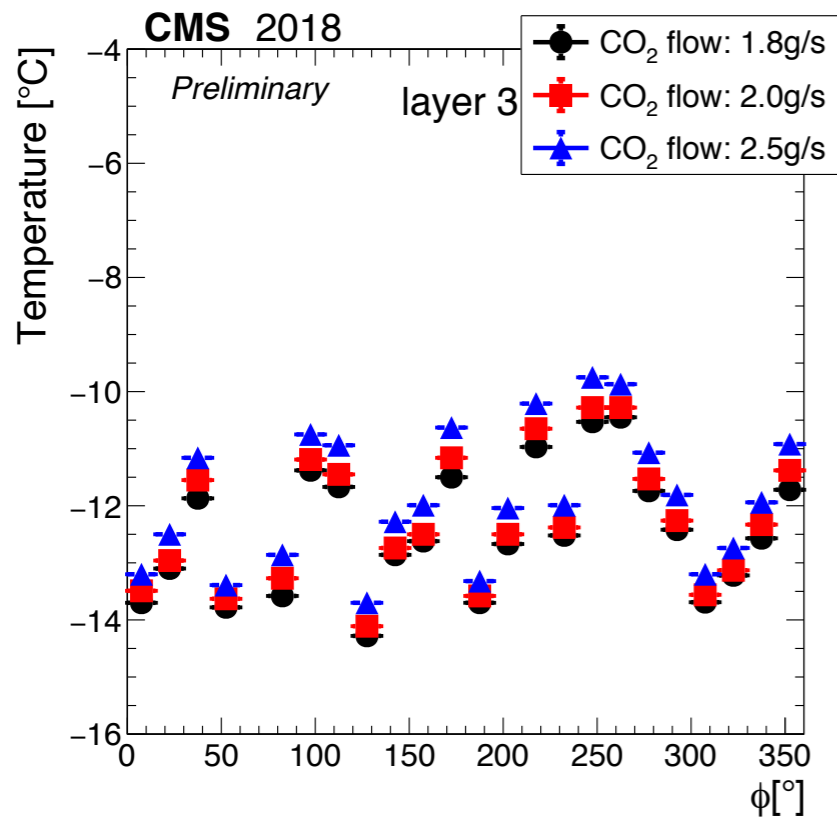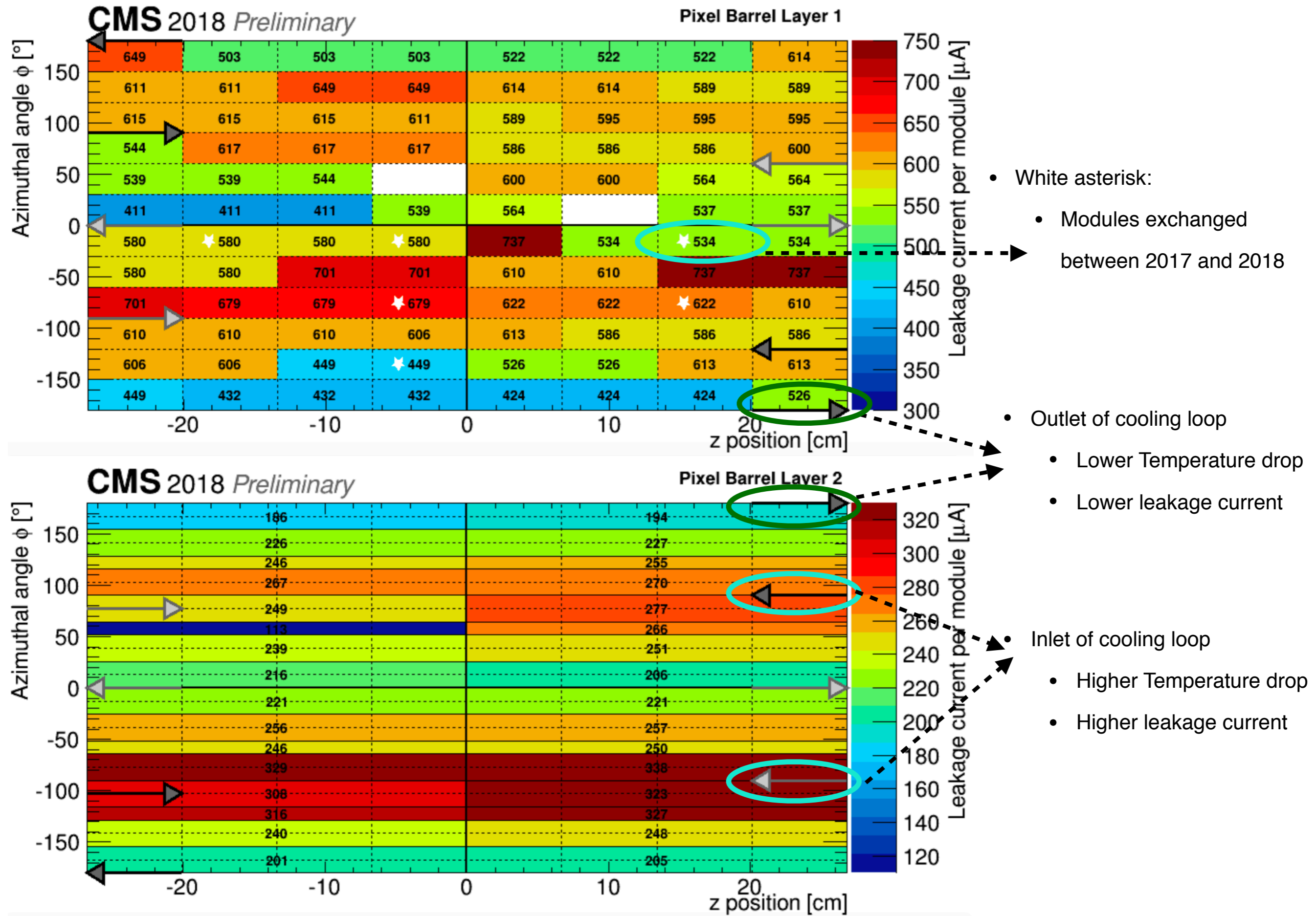# Pixel barrel temperature gradient along each cooling loop

- Each cooling loop has three temperature probes, which are located respectively at the beginning (inlet), middle, end (outlet) positions
- As expected for CO_2 cooling, the temperature at the outlet is lower than at the inlet

Pixel barrel temperature w.r.t azimuthal coordinate

- As a result of the 2-phase state of CO_2 cooling flow, decreased CO_2 flow leads to its absorbing heat more sufficiently, resulting in more efficient cooling, lower temperature, less temperature spread (explanations in slide 9)

Map of pixel barrel power sectors

- Each layer has 8 power sectors

- Arrows indicate the inlet and outlet of CO_2 cooling lines
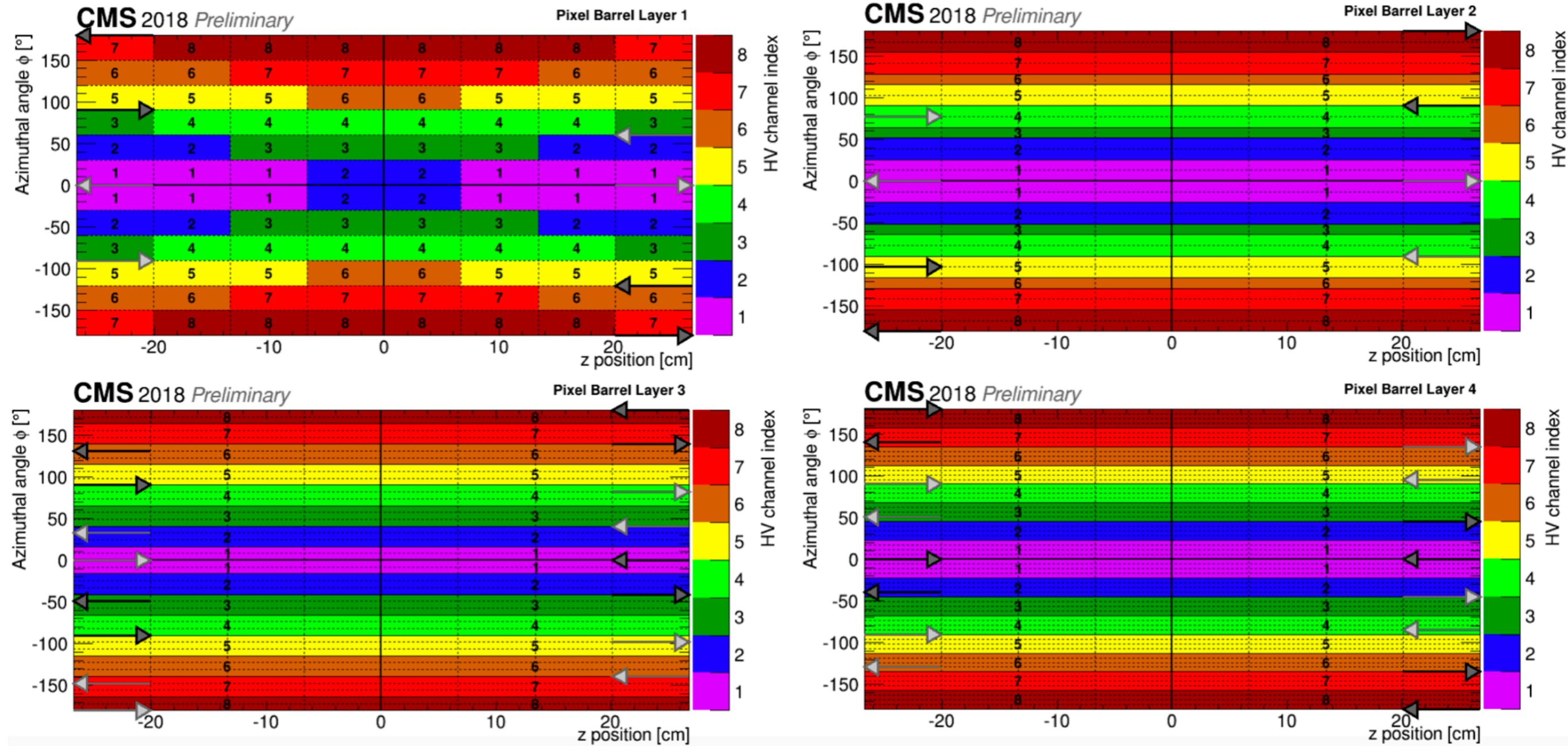
Pixel barrel leakage current distribution (average per sector)

- White asterisk:
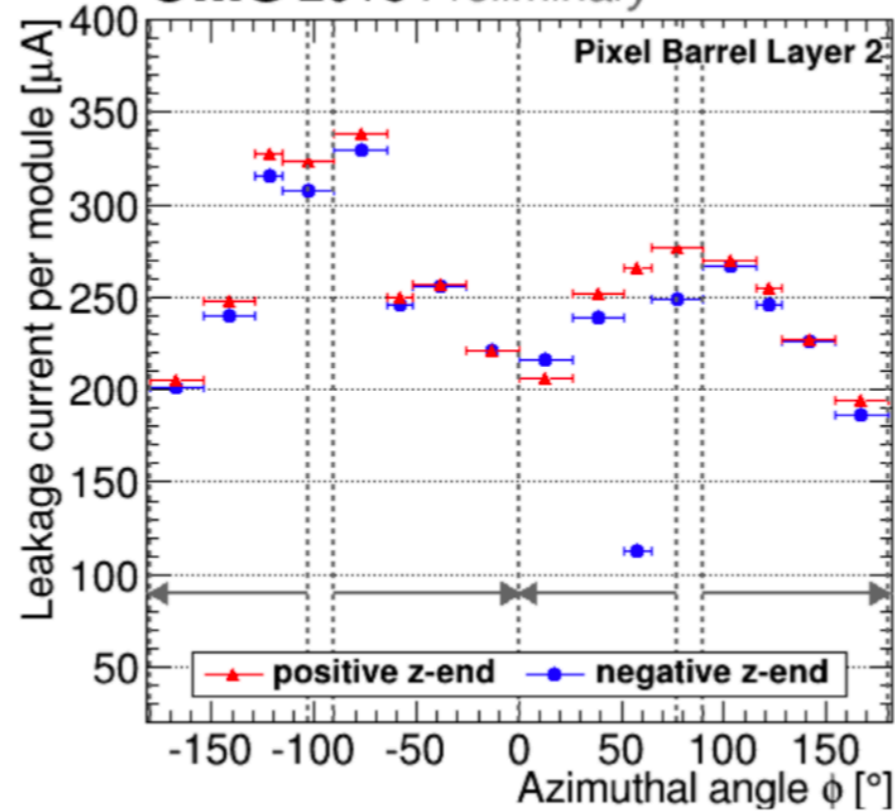 - Modules exchanged between 2017 and 2018

- Outlet of cooling loop
  - Lower Temperature drop
  - Lower leakage current

- Inlet of cooling loop
  - Higher Temperature drop
  - Higher leakage current

Pixel barrel leakage current distribution (average per sector)
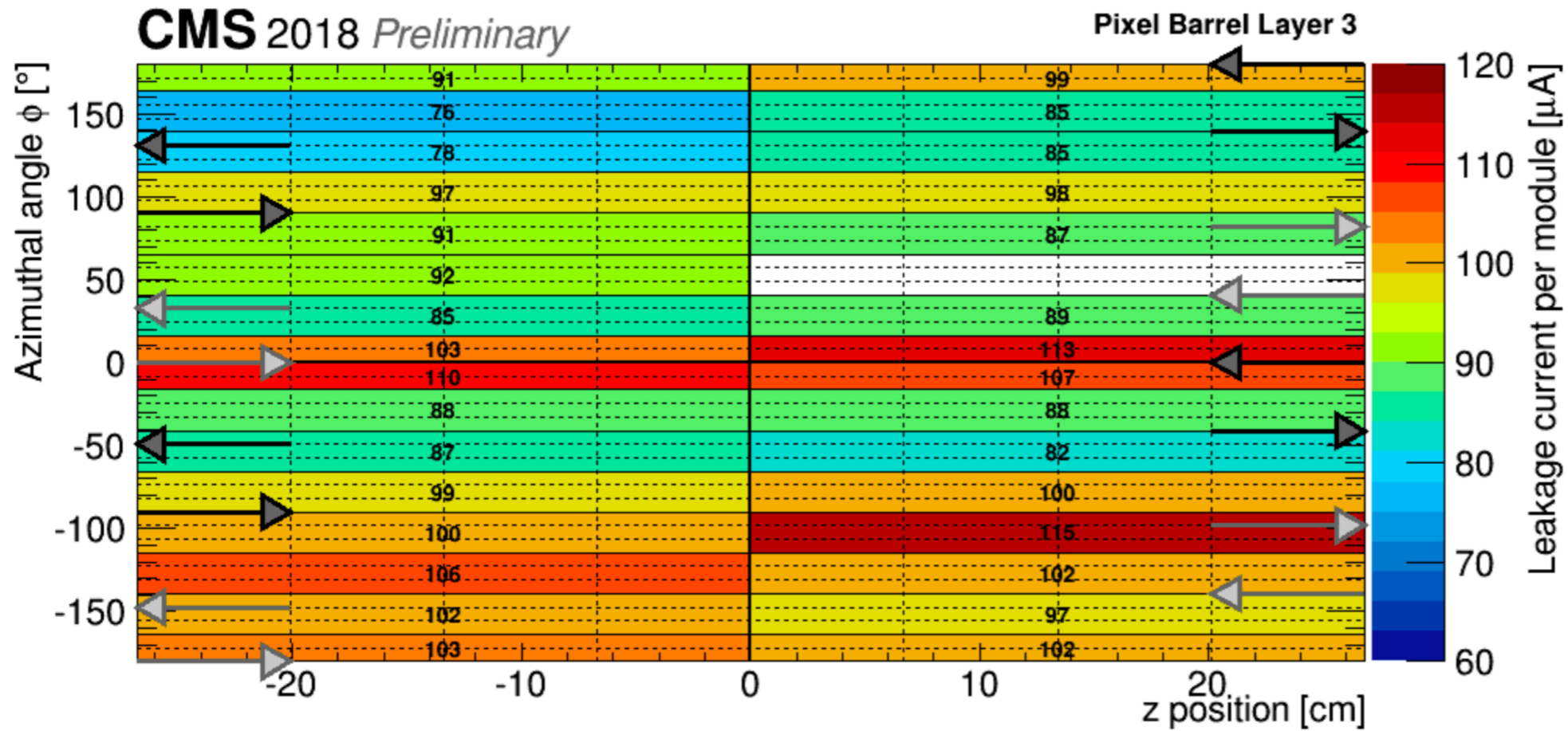
- Layer 3/4 are more distant from beams than layer 1/2 —> lower leakage current
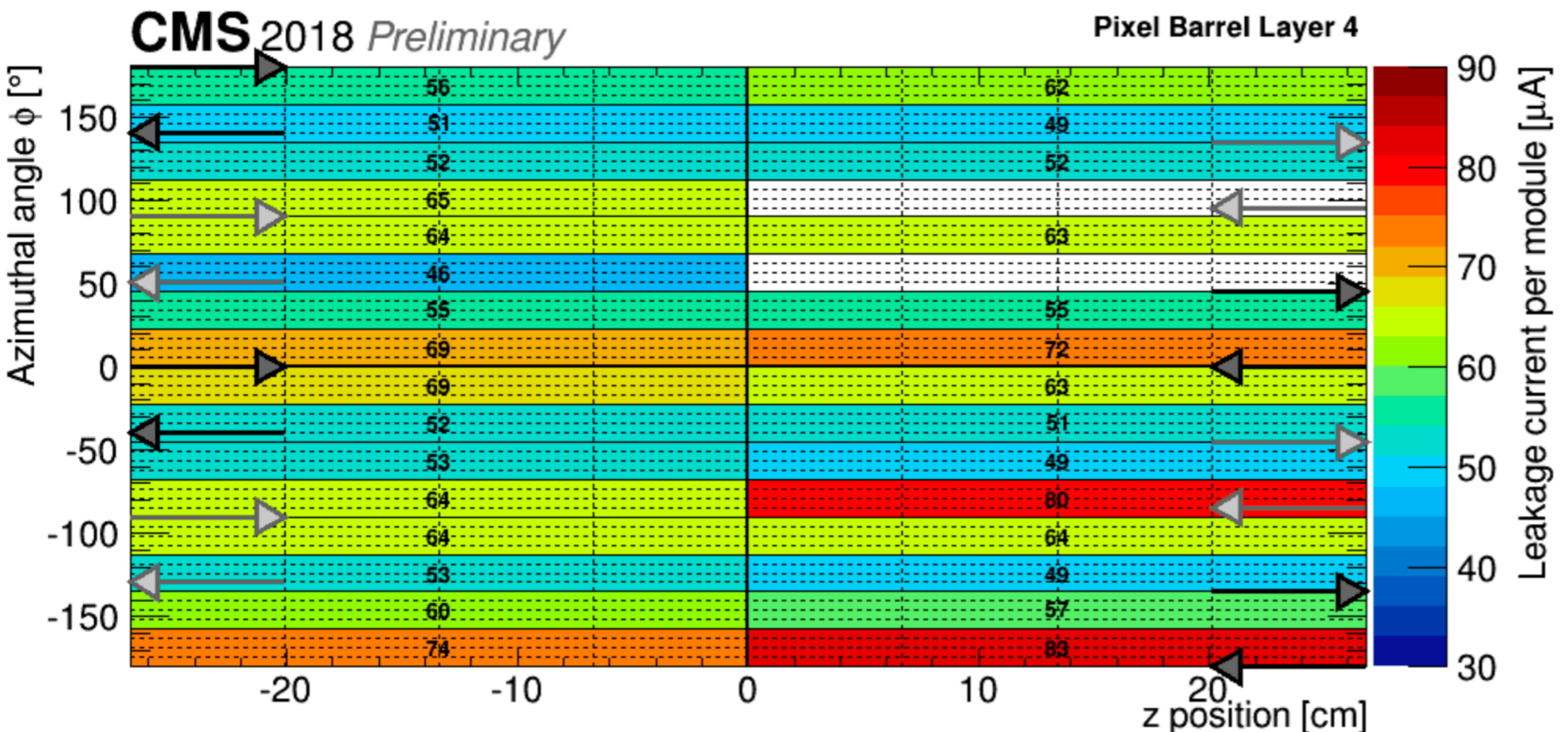
- Outlet of cooling loop
  - Lower Temperature drop
  - Lower leakage current

- Inlet of cooling loop
  - Higher Temperature drop
  - Higher leakage current

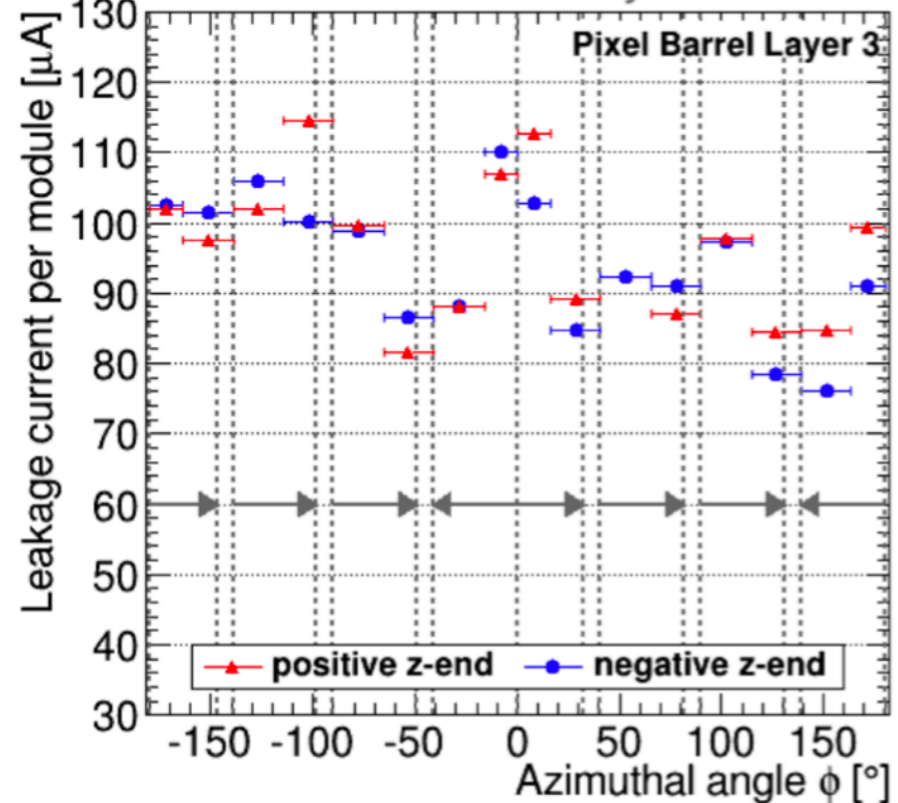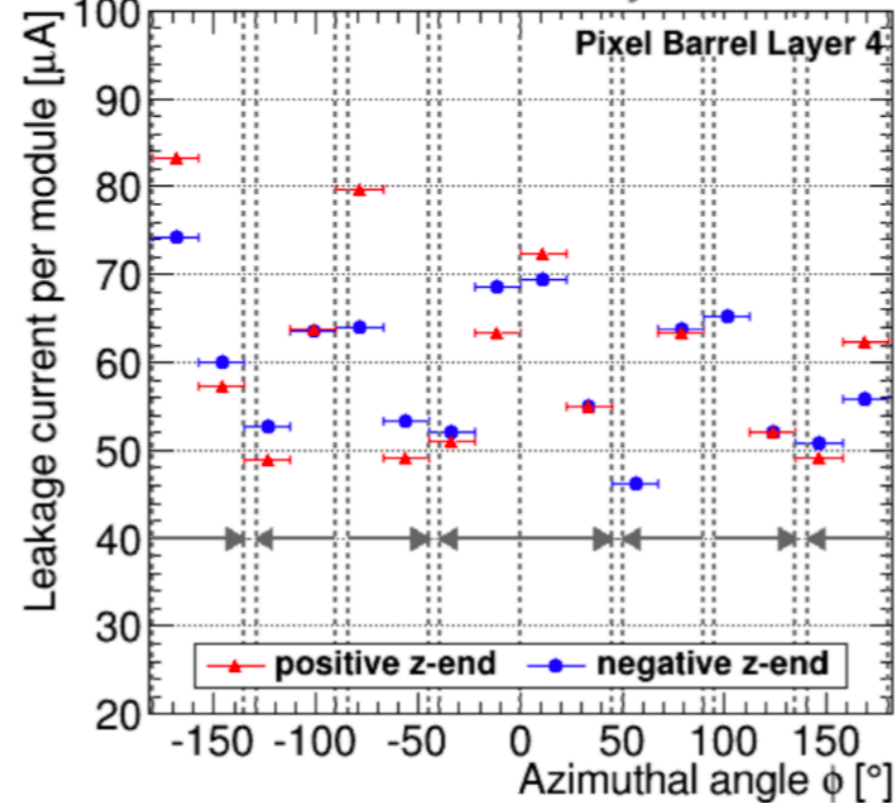# Pixel barrel leakage current w.r.t azimuthal coordinate
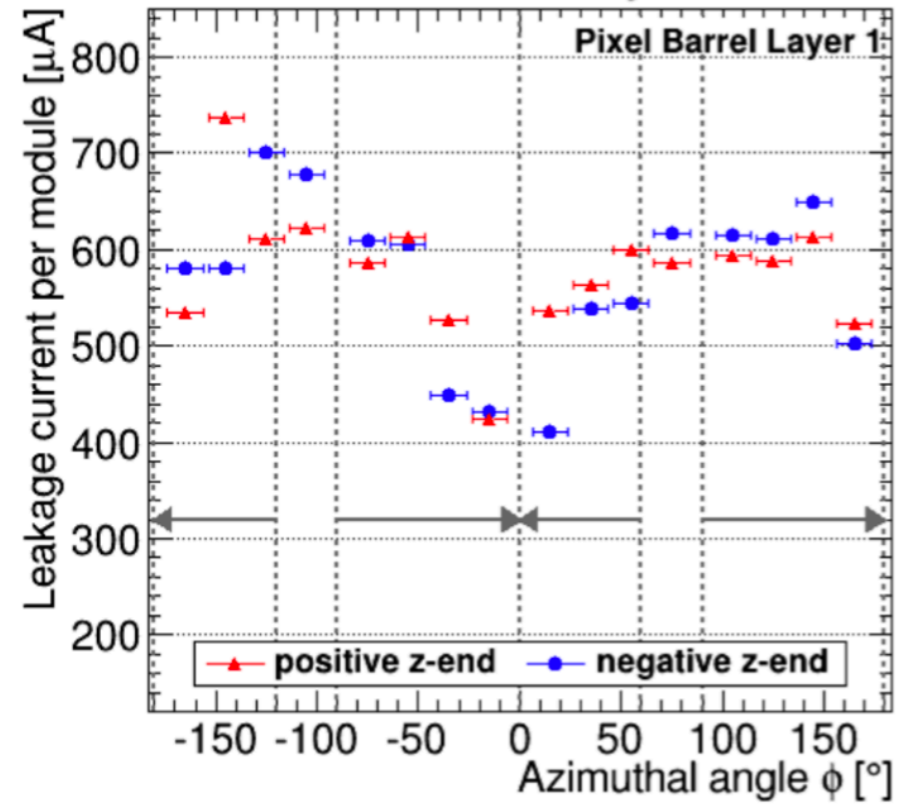
- Gray arrows: CO_2 cooling direction
- Dashed lines: inlet or outlet

- Outlet of cooling loop
  - Lower Temperature drop
  - Lower leakage current

- Inlet of cooling loop
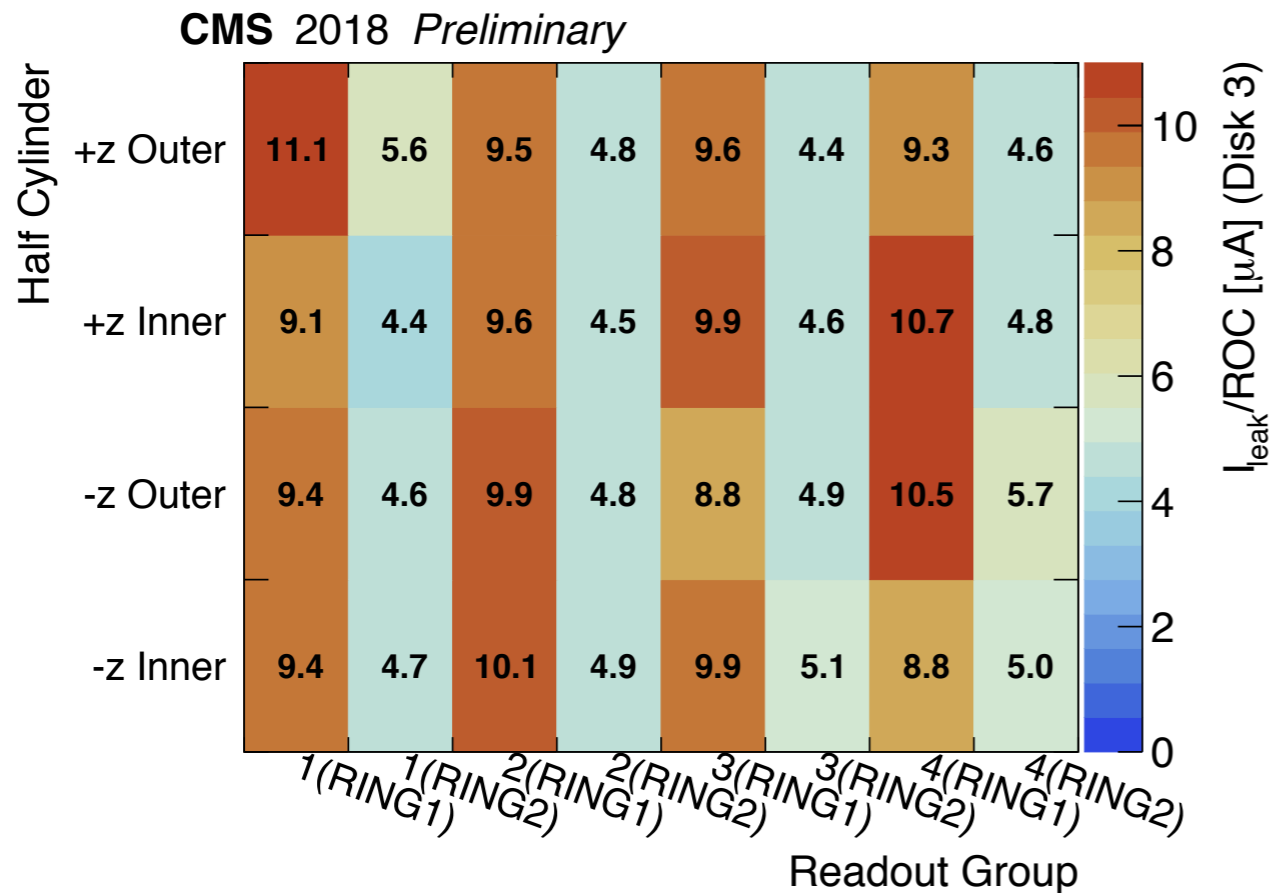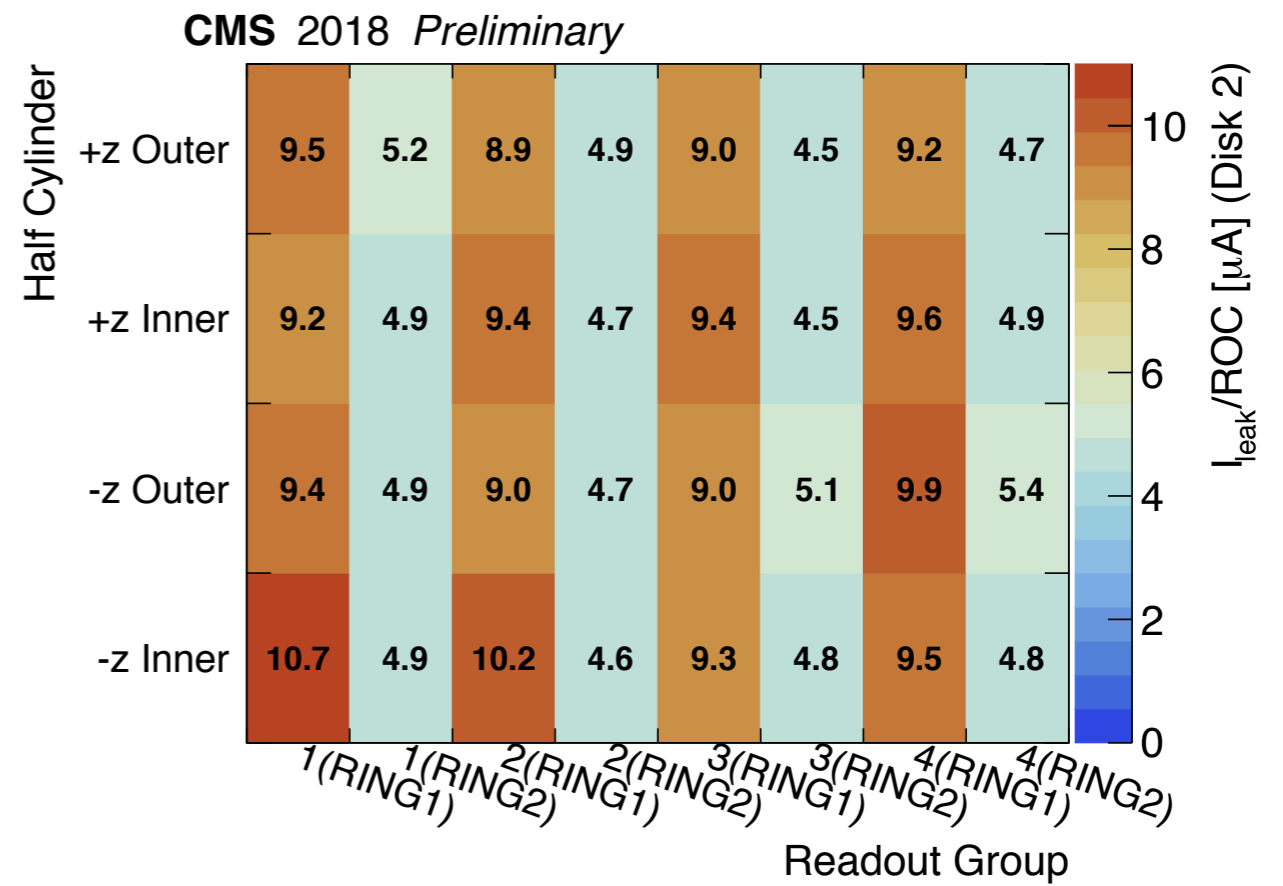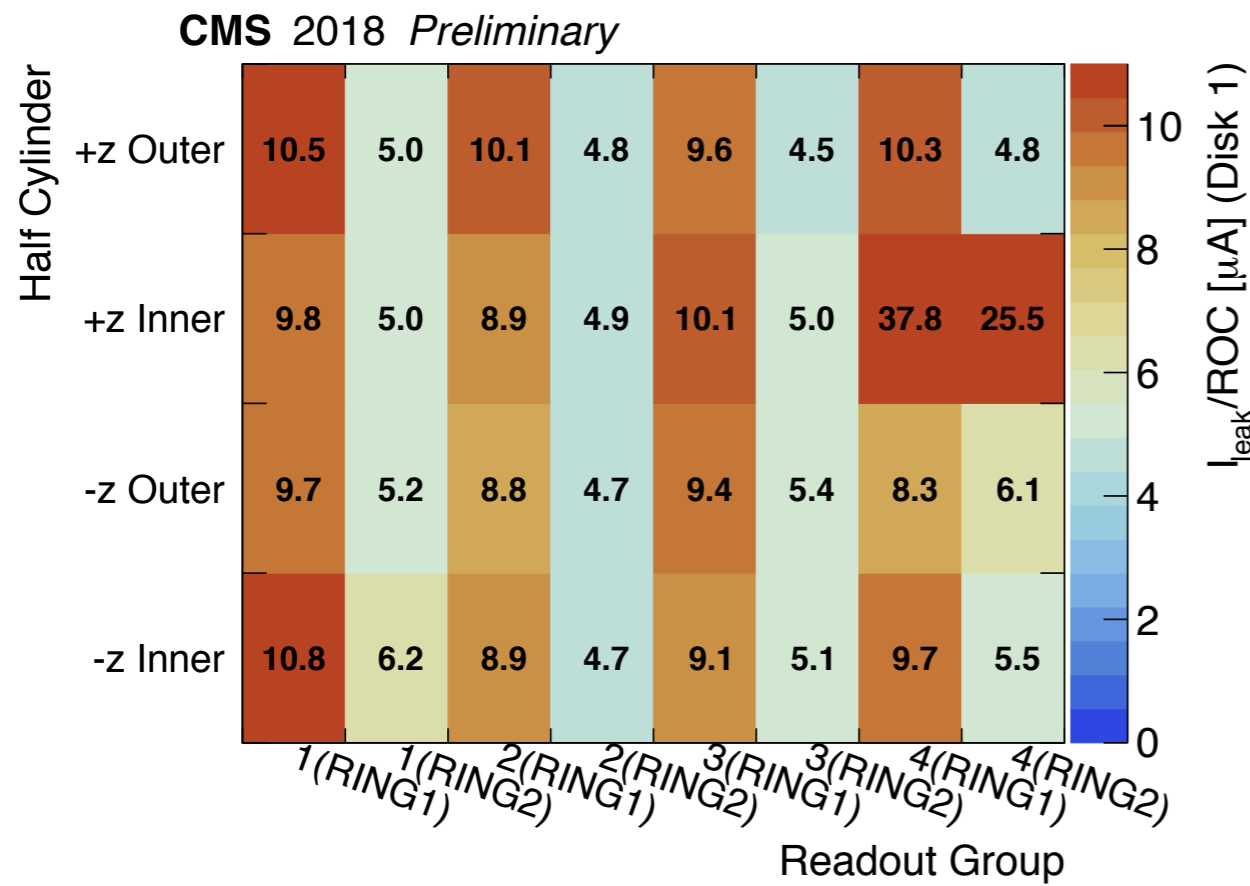 - Higher Temperature drop
  - Higher leakage current

Pixel endcap leakage current distribution

Pixel barrel module leakage current evolution
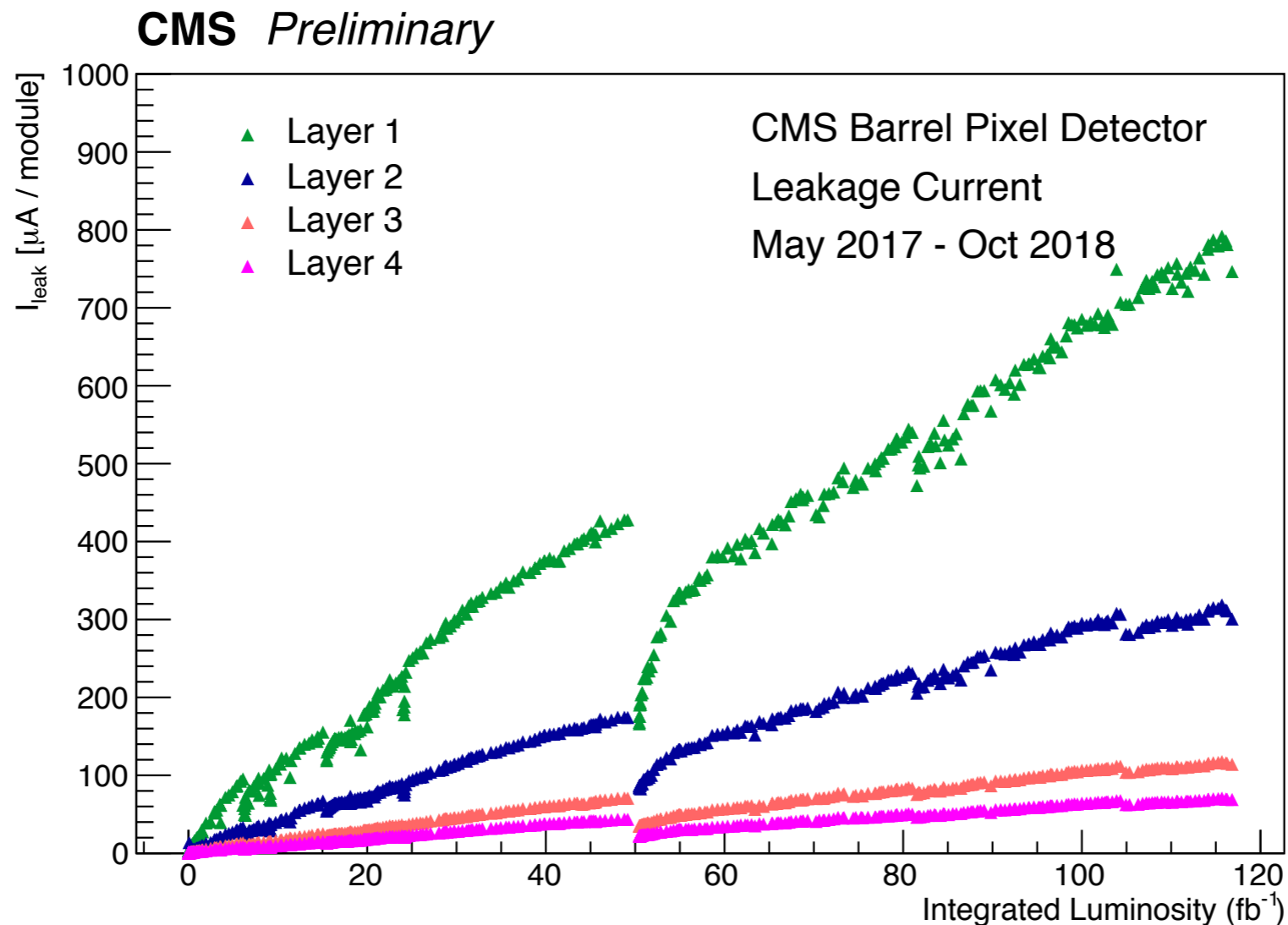
- LHC fills from beginning of 2017 until end of October in 2018 data-taking are employed (proton-proton collisions)
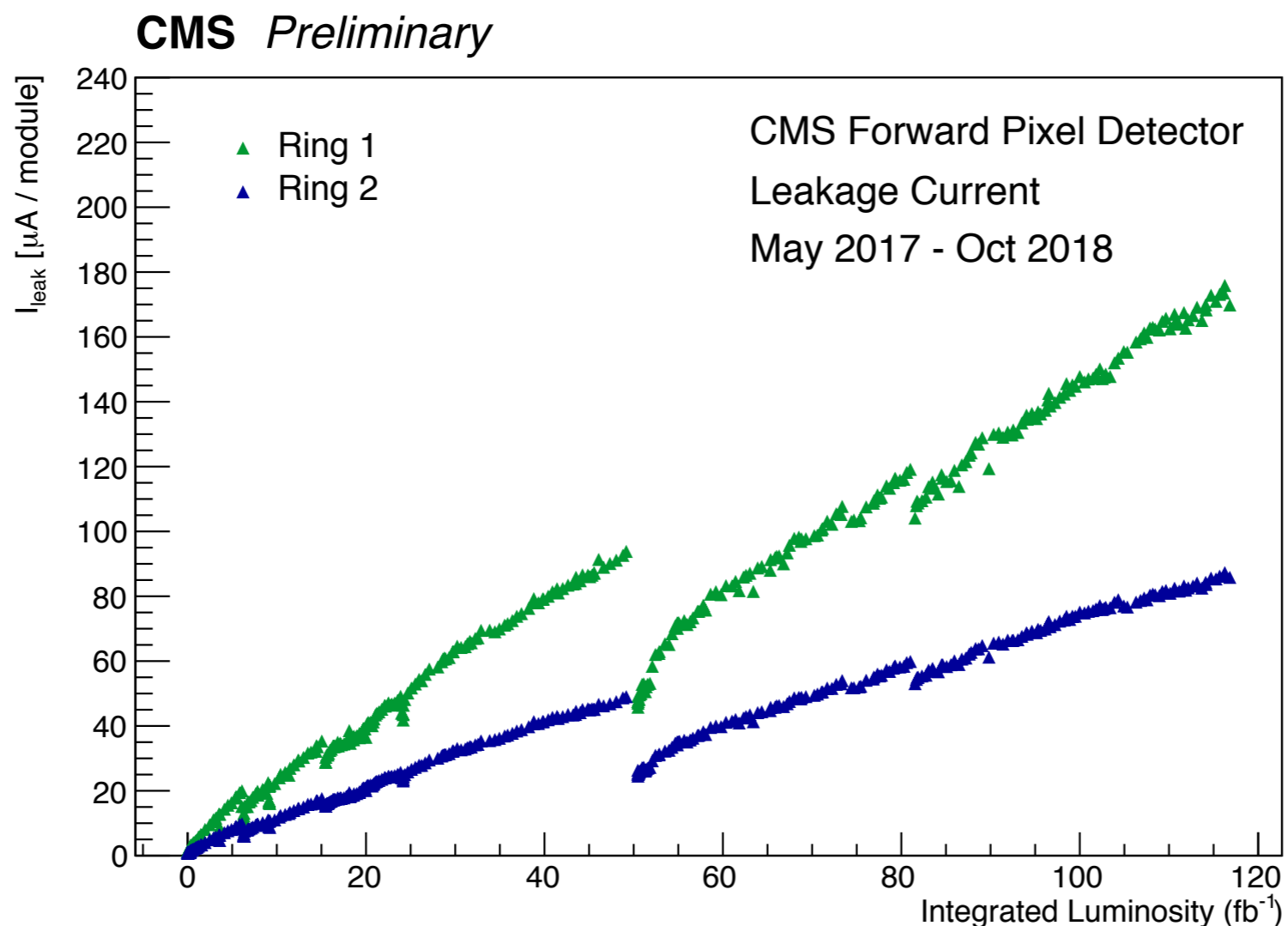
- Currents measured within 20 minutes from Stable Beam declaration

- Average current per pixel module measured from power groups (**no temperature correction**)

- Leakage current increased gradually due to accumulated radiation dose through the year

- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (layer 1 > layer 2 > layer 3 > layer 4)

- There are some drops of leakage current from the global trend because of:
  - Annealing during Machine development or technical stop period
  - Power supply replacement
  - HV setting change

Pixel endcap module leakage current evolution

- LHC fills from beginning of 2017 until end of October in 2018 data-taking are employed (proton-proton collisions)

- Currents measured within 20 minutes from Stable Beam declaration

- Average current per pixel module measured from power groups (**no temperature correction**)

- **Note: The 4th power group giving much higher current in disk 1 (seen in slide 25) is removed from the average**

- Leakage current increased gradually due to accumulated radiation dose through the year

- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (ring 1 > ring 2)

- There are some drops of leakage current from the global trend because of:
  - Annealing during Machine development or technical stop period
  - Power supply replacement
  - HV setting change