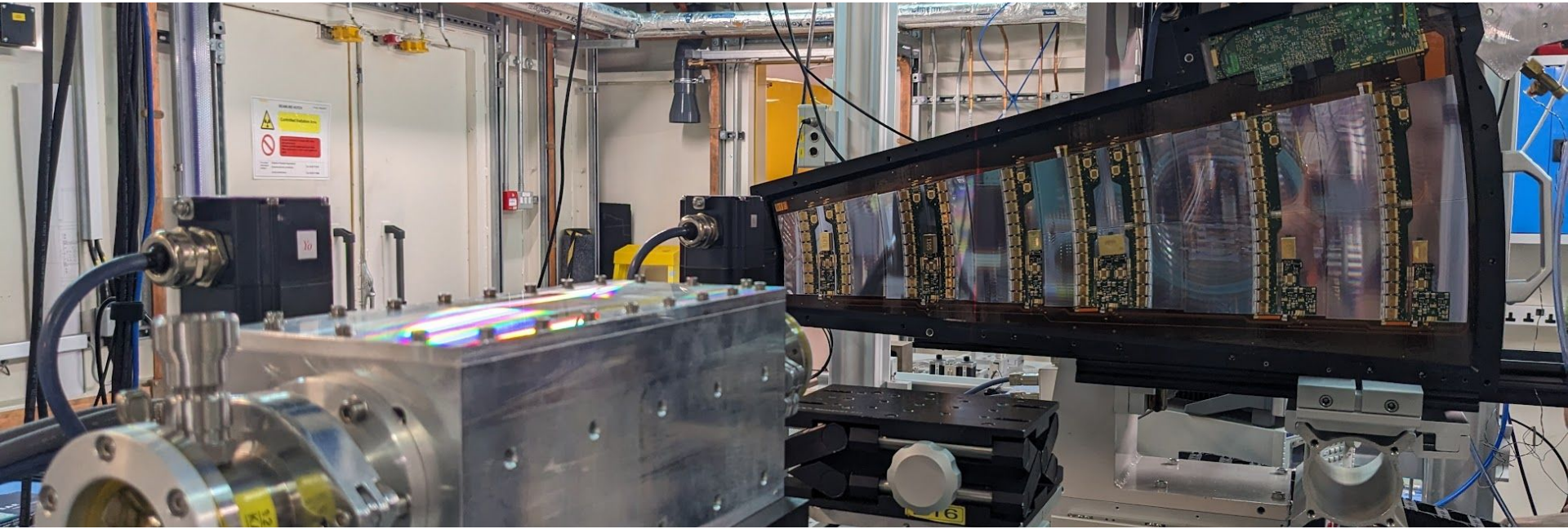
Studying electrical petals for the ATLAS Inner Tracker Upgrade using a micro-focused X-ray beam



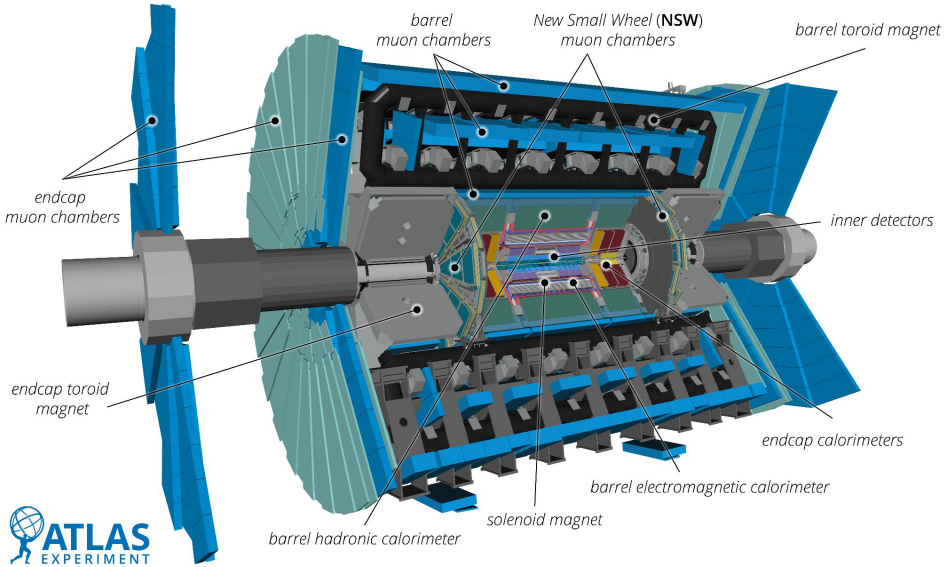
CAP Congress 2026
UOttawa / Carleton, June 23, 2026

Matthew Basso (TRIUMF)

https://indico.global/event/15553/contributions/145991/

Introduction

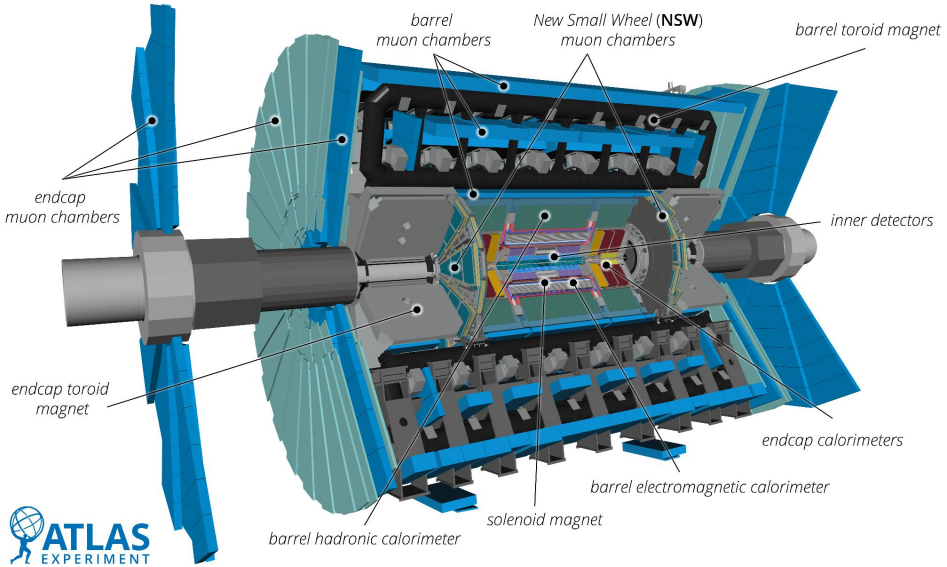
- ATLAS: general purpose particle detector at the Large Hadron Collider (LHC)



ATLAS-PHOTO-2022-055

Introduction

- ATLAS: general purpose particle detector at the Large Hadron Collider (LHC)
- High-Luminosity LHC (HL-LHC) → **6–10 times** the collision rate of the LHC Run 2
  - LHC has collected **500 fb^{-1} of data**

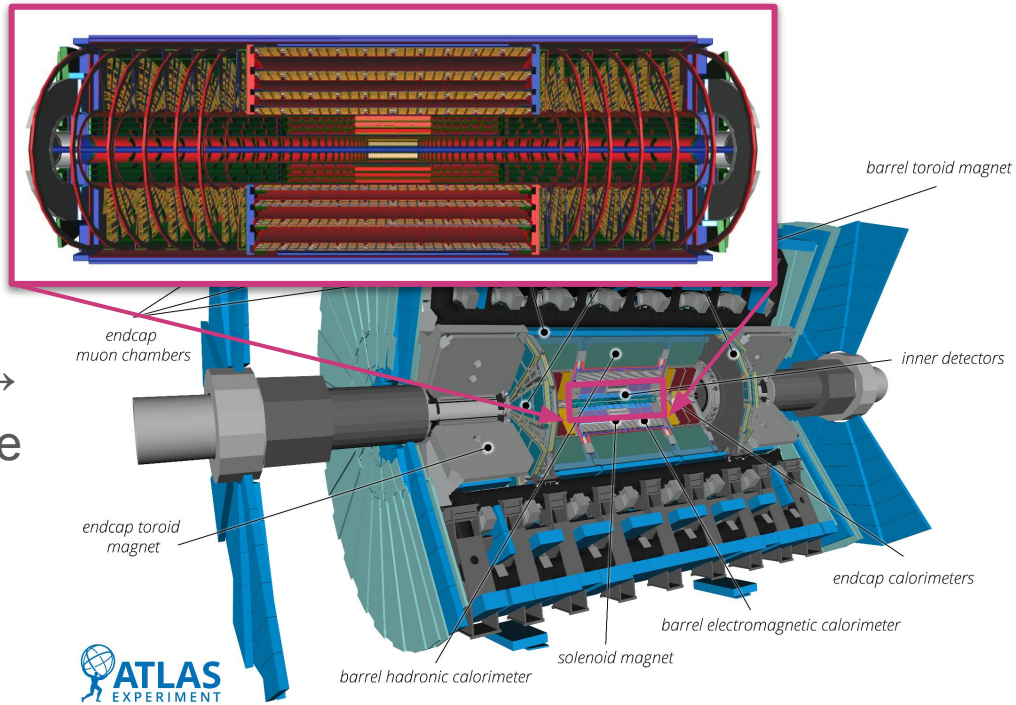


ATLAS-PHOTO-2022-055

Introduction

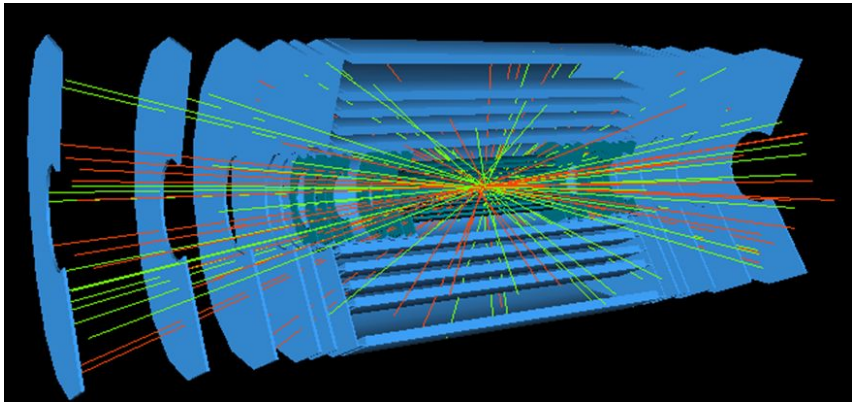
- ATLAS: general purpose particle detector at the Large Hadron Collider (LHC)
- High-Luminosity LHC (HL-LHC) → **6–10 times** the collision rate of the LHC Run 2
  - LHC has collected **500 fb^{-1} of data**
- To accommodate the complex collision environment, ATLAS is replacing its inner detector with the all-silicon **Inner Tracker (ITk)**

The ITk ITK-2023-001



ATLAS-PHOTO-2022-055

The collision environment in the ITk is complex!



23 collisions per bunch crossing (LHC Run 2)

ATL-UPGRADE-PROC-2012-003

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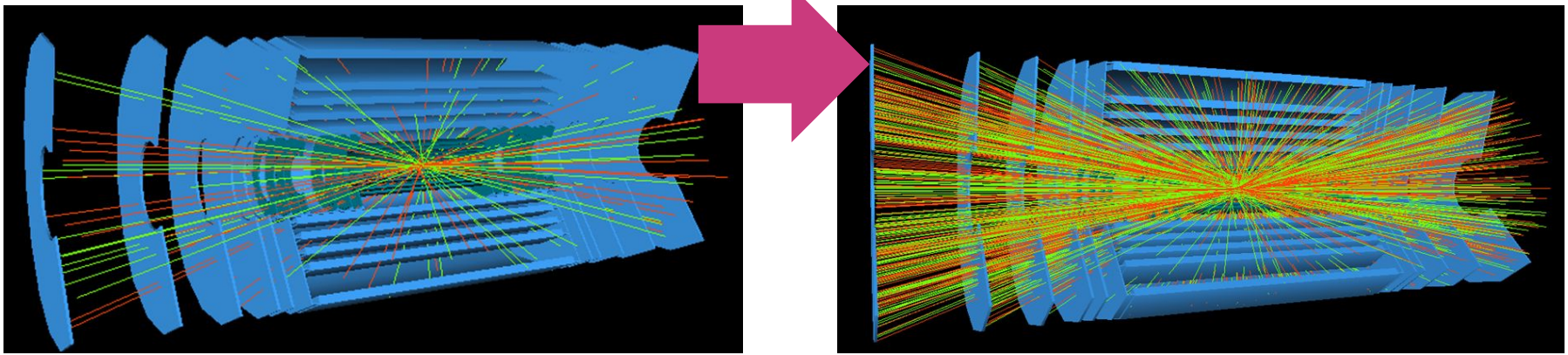


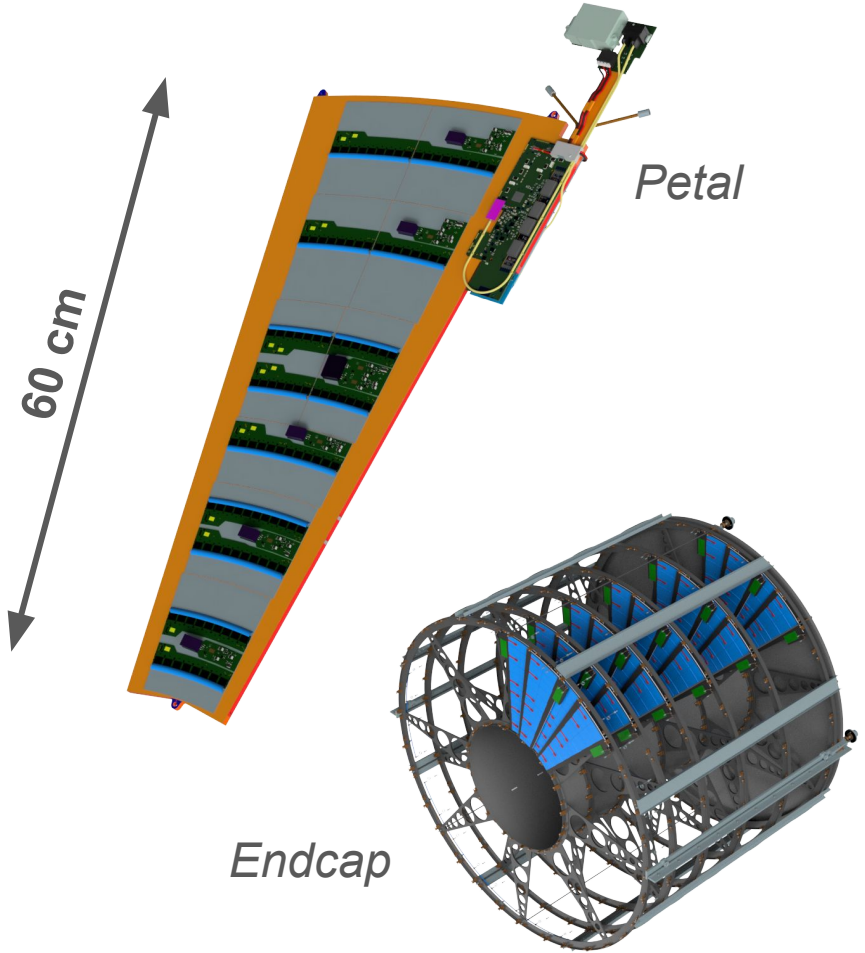
23 collisions per bunch crossing (LHC Run 2)

230 collisions per bunch crossing (HL-LHC)

ATL-UPGRADE-PROC-2012-003

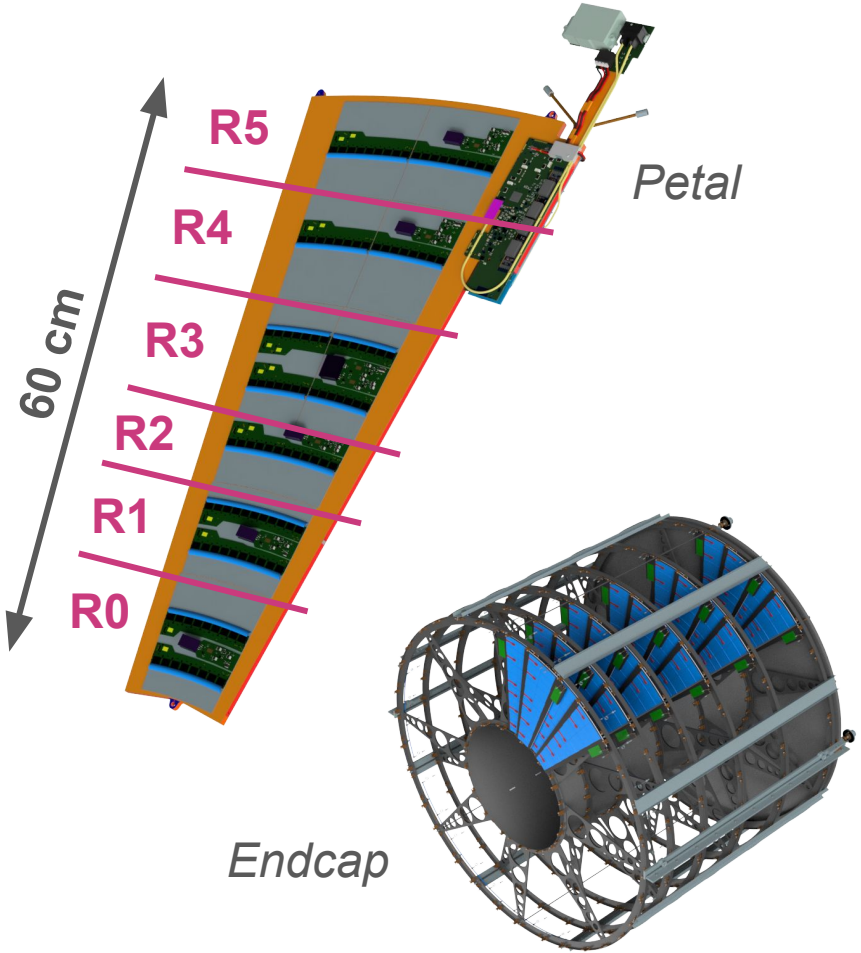
All about petals

- In Vancouver, we build and test **petals**, which comprise the ITk **endcaps**



All about petals

- In Vancouver, we build and test **petals**, which comprise the ITk **endcaps**
  - Each petal is **double-sided** with six strip sensor modules (labelled R0–R5) per side → O(50K) channels/petal



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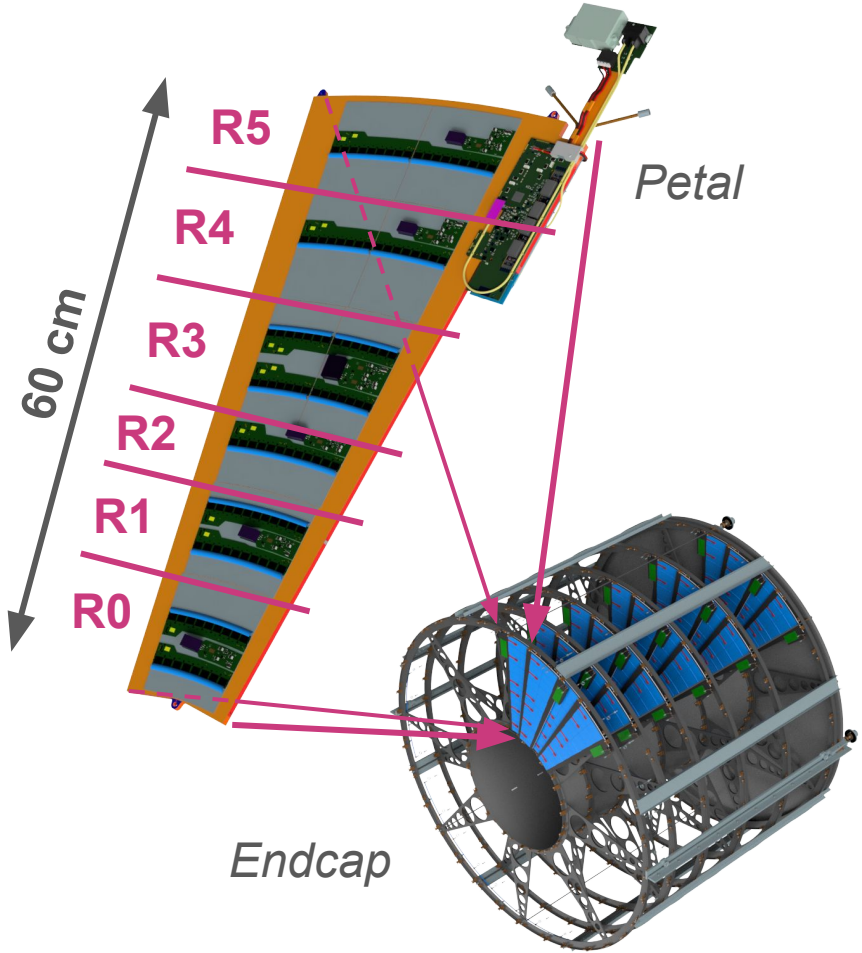
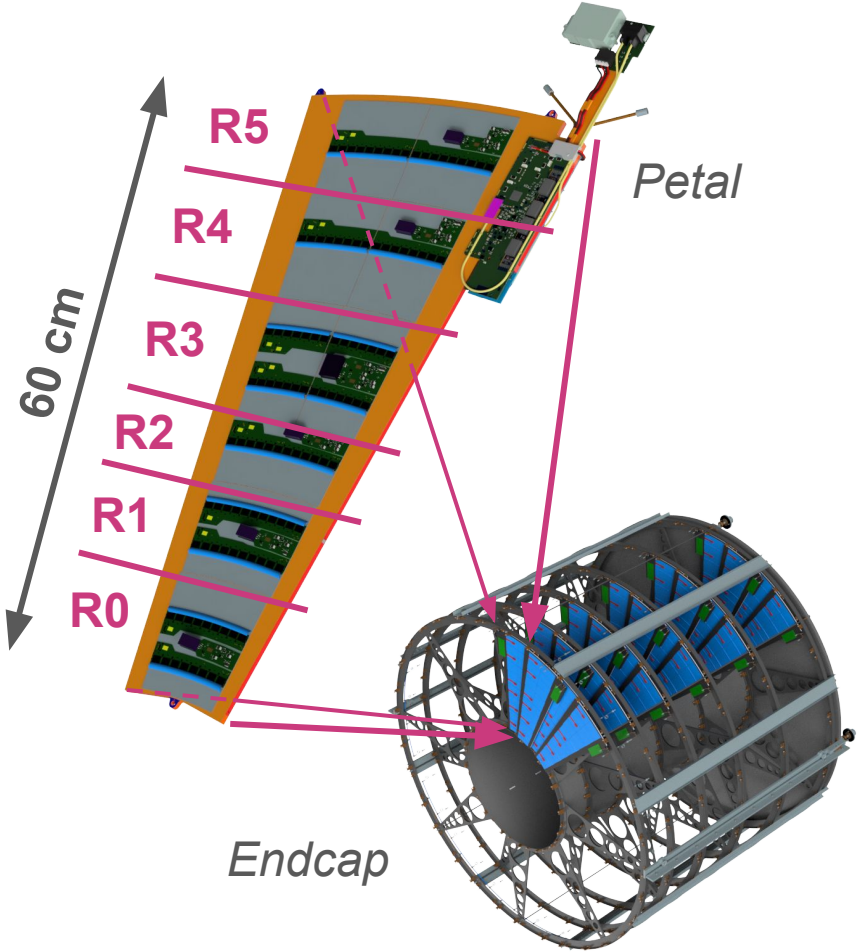
  - 32 petals/disk, six disks/endcap



All about petals

- In Vancouver, we build and test **petals**, which comprise the ITk **endcaps**
  - Each petal is **double-sided** with six strip sensor modules (labelled R0–R5) per side → O(50K) channels/petal
  - 32 petals/disk, six disks/endcap
- **Mechanical properties** of a petal's construction are tied to its **physics performance** → important to verify!
  - Typically done using a coordinate measuring machine (CMM)



Mechanical properties → physics performance

- Rotation of the modules on the petal affects the detector's **intrinsic resolution**

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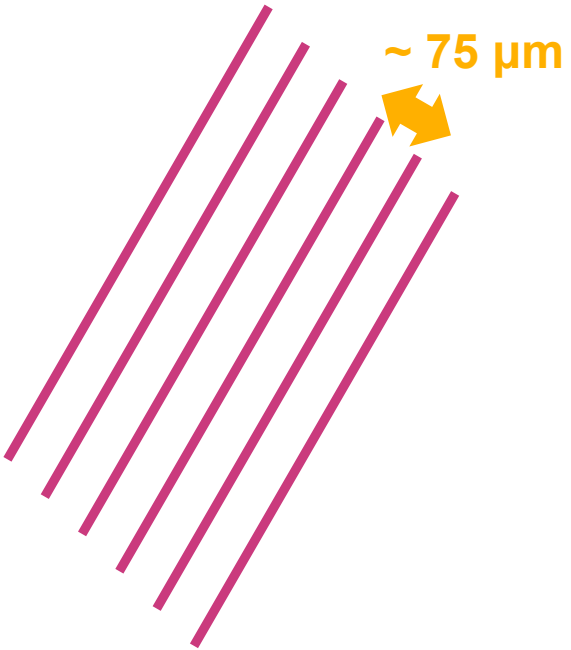
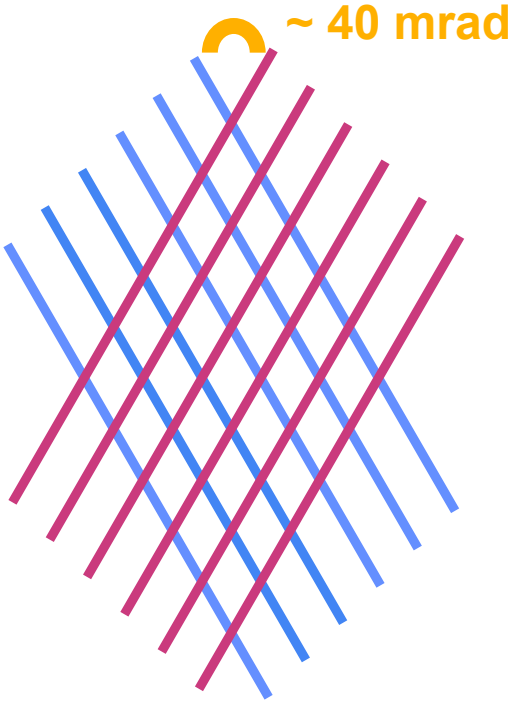
- Sensors are segmented into vertical **strips** (channels) with a pitch of **~ 75 μm**

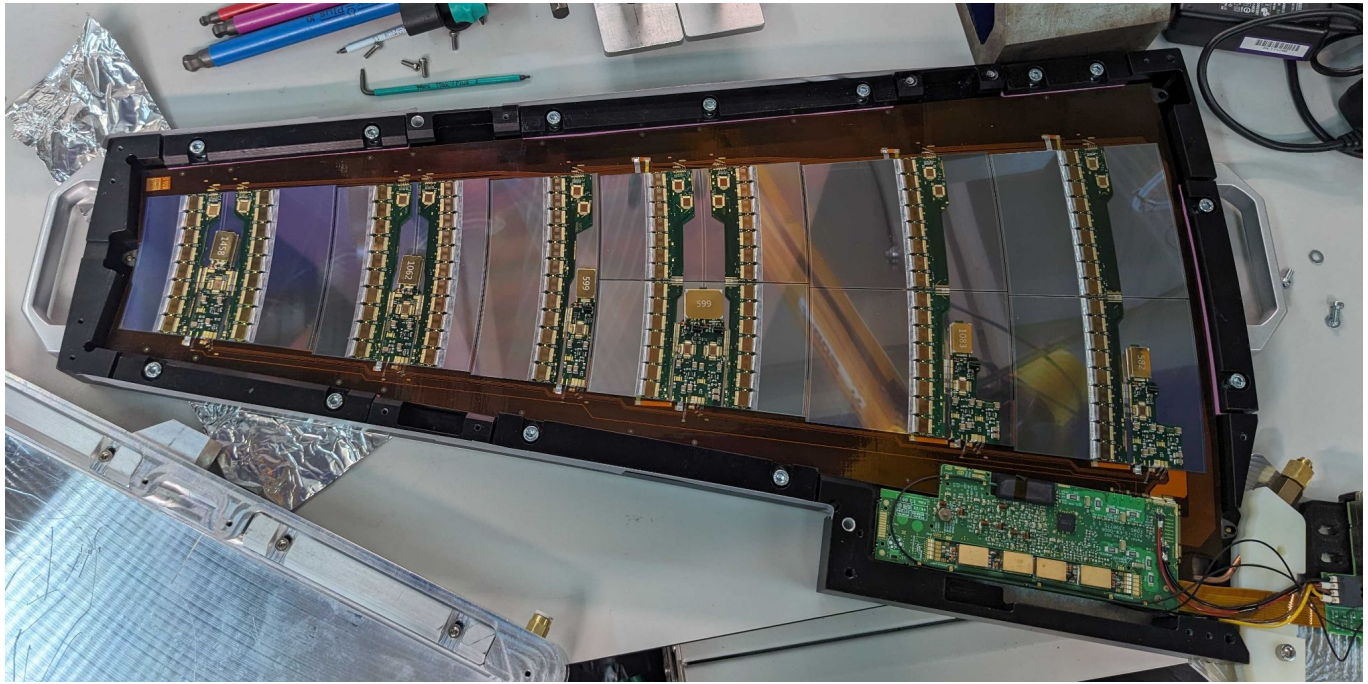


Mechanical properties → physics performance

- Rotation of the modules on the petal affects the detector's **intrinsic resolution**
- Sensors are segmented into vertical **strips** (channels) with a pitch of **~ 75 µm**
- Sensors on the **front** and **back** sides of the petal are rotated by a **~ 40 mrad stereo angle** w.r.t. each other → provides a measurement orthogonal to the pitch



Picture of a completed petal



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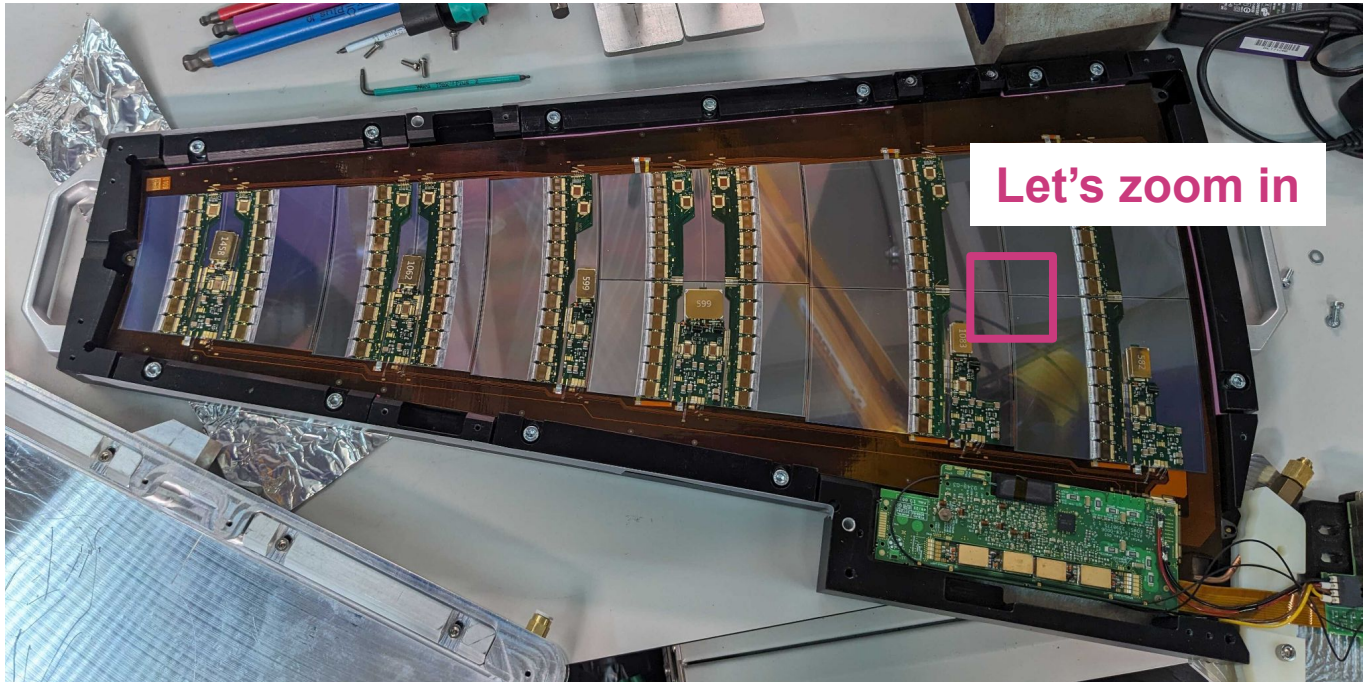
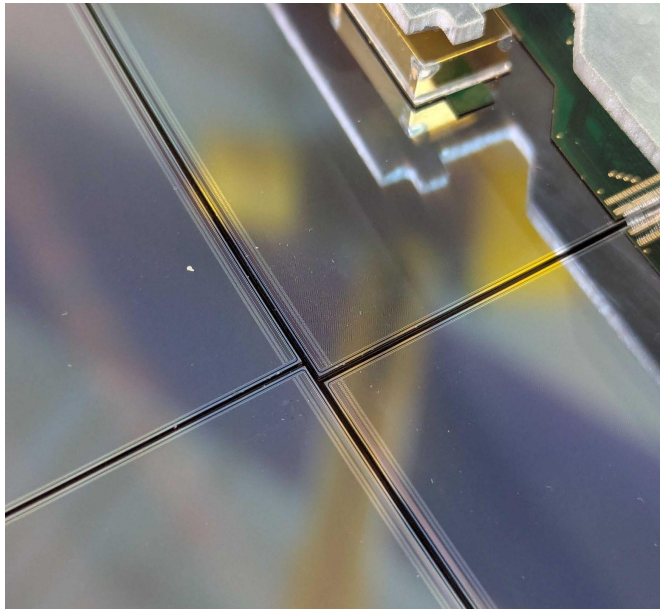
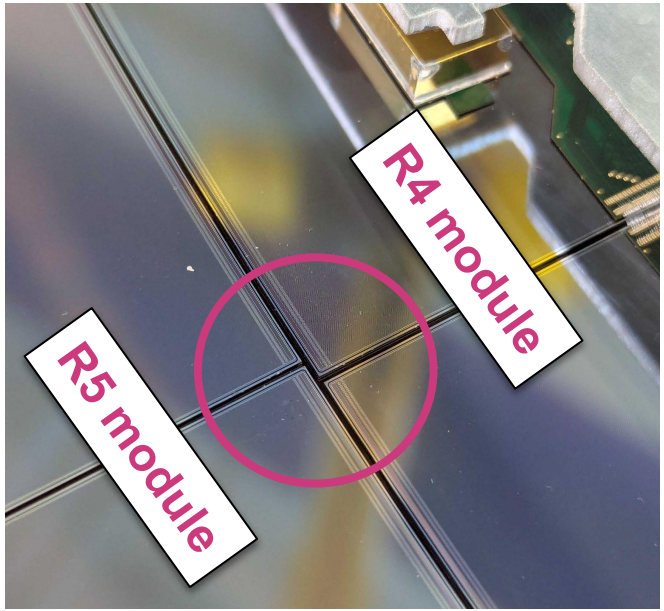


Mechanical properties → physics performance



- Alignment of the modules on the petal affects the detector's **hermeticity** → at least one side of the petal is expected to measure incident radiation

Mechanical properties → physics performance

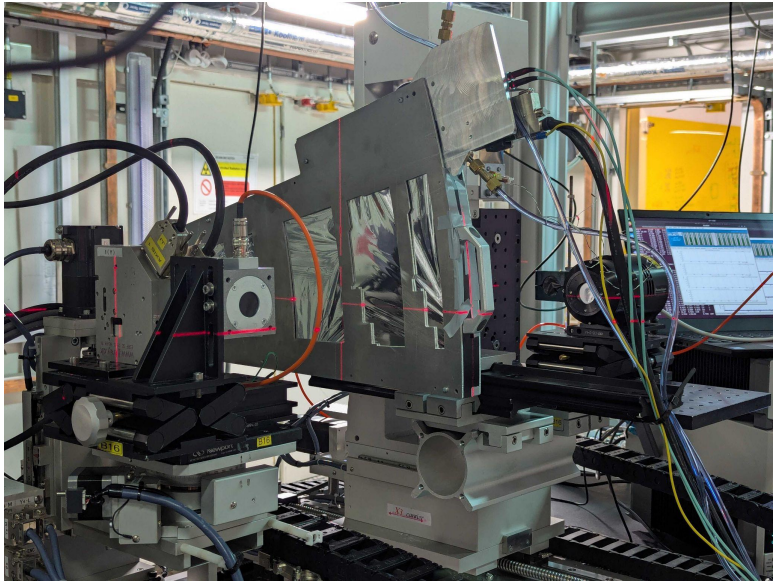


- Alignment of the modules on the petal affects the detector's **hermeticity** → at least one side of the petal is expected to measure incident radiation
- **Tolerances are tight!** On the left, the gaps at this corner are all O(0.1) mm

While CMMs measure these mechanical properties for each side of a petal independently, ***X-ray beams*** *can be used to measure them* ***simultaneously***

Diamond Light Source

- Took a petal to the Diamond Light Source in Didcot, UK
  - Electron synchrotron providing a 15 keV X-ray beam with a 2 μm × 3 μm area → **capable of resolving individual strips**



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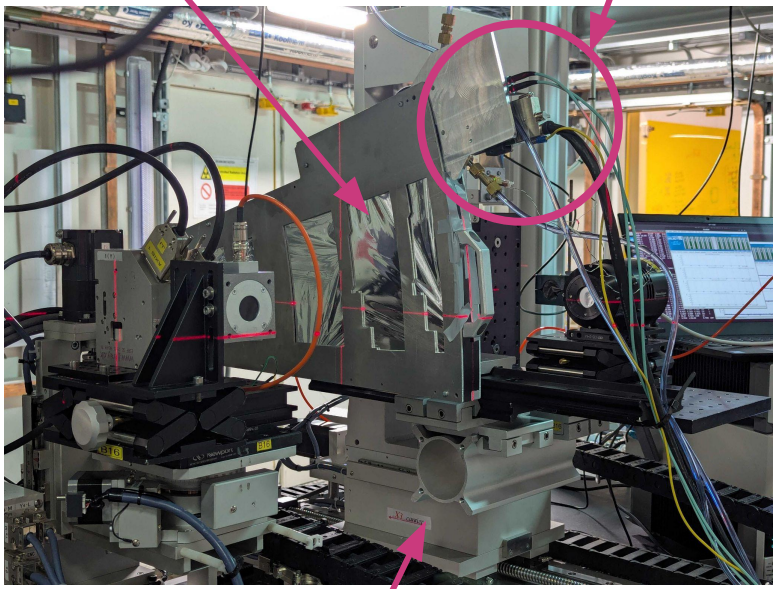

Diamond Light Source

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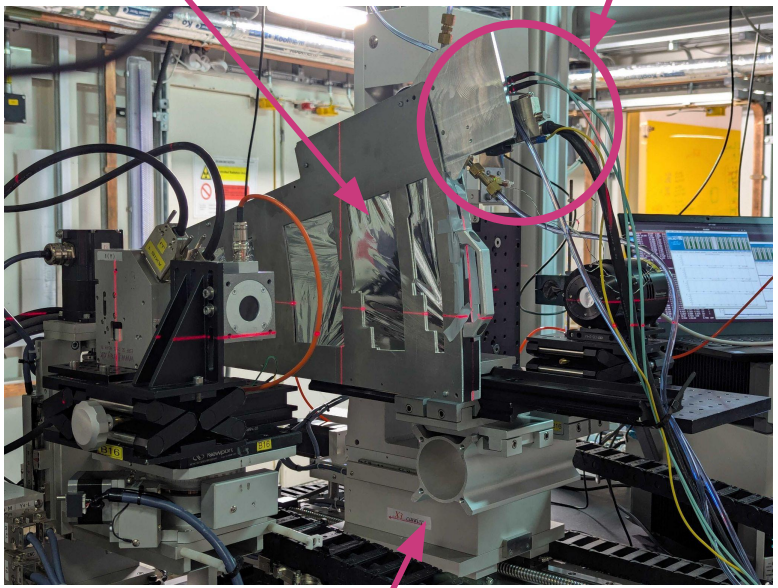
  - Electron synchrotron providing a 15 keV X-ray beam with a 2 μm × 3 μm area → **capable of resolving individual strips**
- Beam is rastered across a 2D grid of positions via a mechanical stage and the petal is read out at each position → **2D snapshot of the petal's active area**
  - Step size is either 10 or 25 μm, tradeoff between fine details and time

Light-tight, thin aluminum windows

Power, readout, and cooling

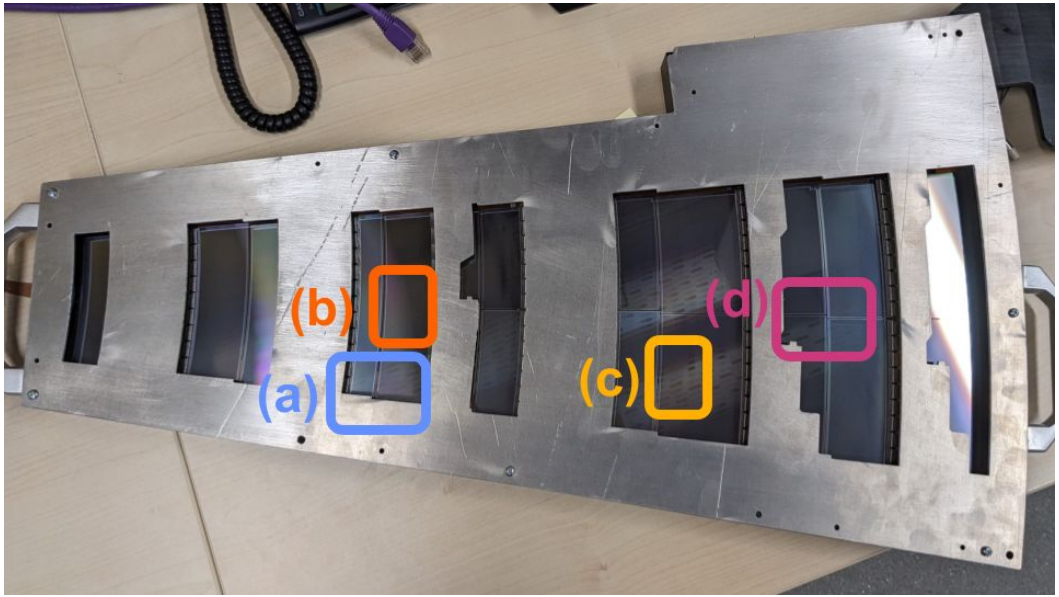


Mechanical stage

Which regions did we study?

(a) R1/R2 corner region
(b) R2 centre region
(c) R4 centre region
(d) R4/R5 corner region

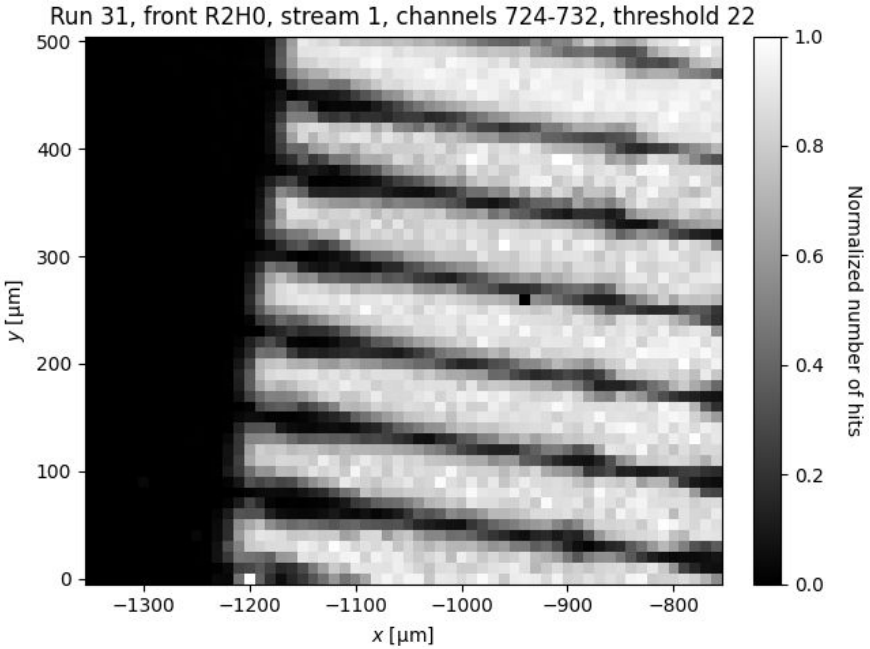
In some regions, multiple 2D scans were performed to capture all the relevant features (full details in Backup)



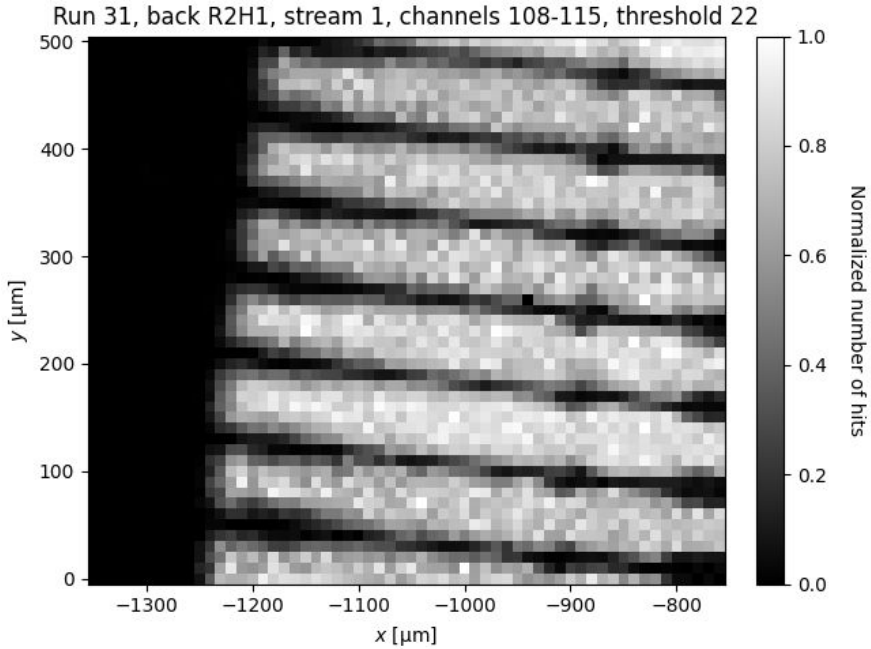
Measuring the stereo angle

Results for the R2 centre region

Each channel is normalized to its maximum number of hits



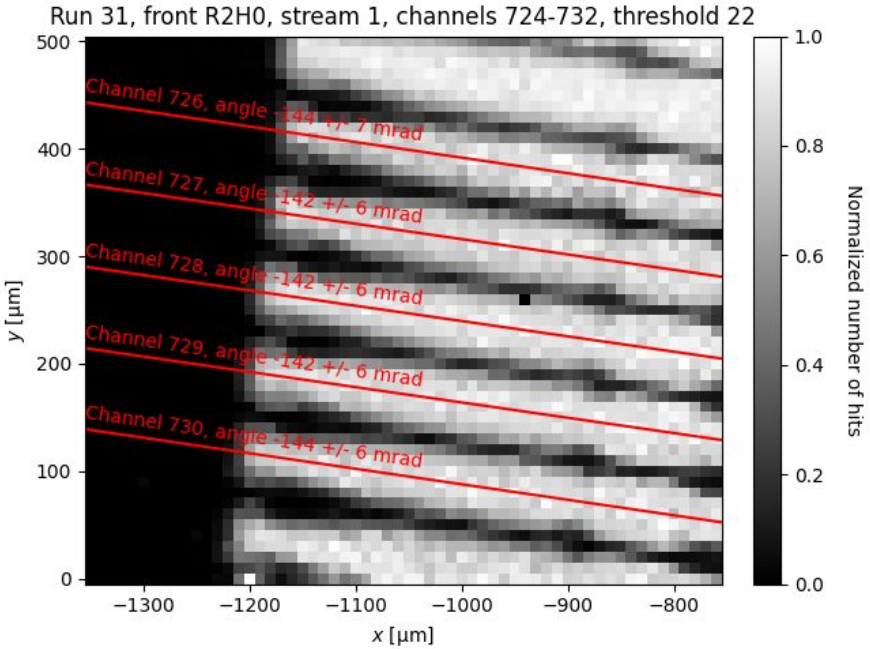
Beam-facing side



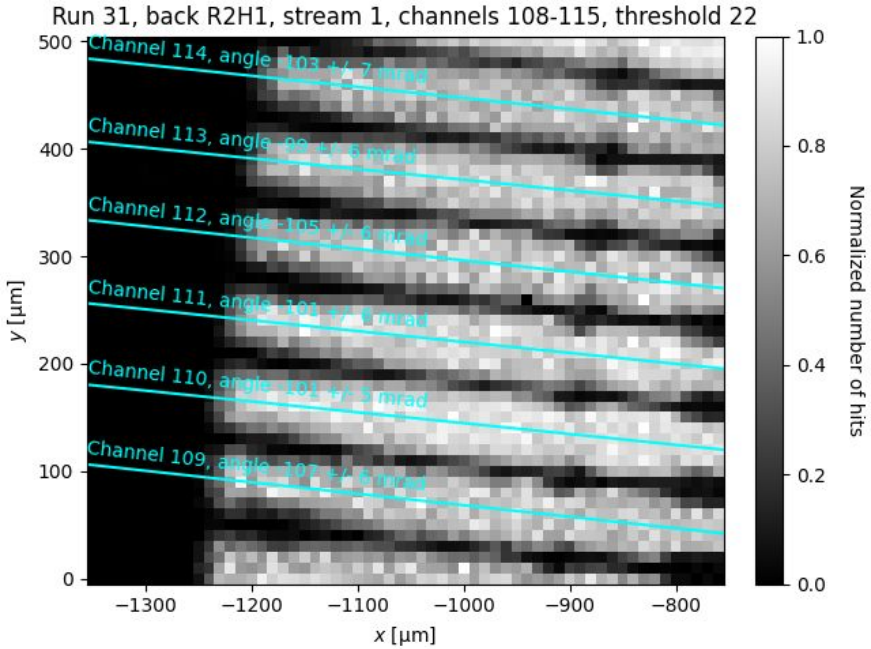
Beam-away side

Extracting the stereo angle

Weighted least squares fit to each (visible) strip



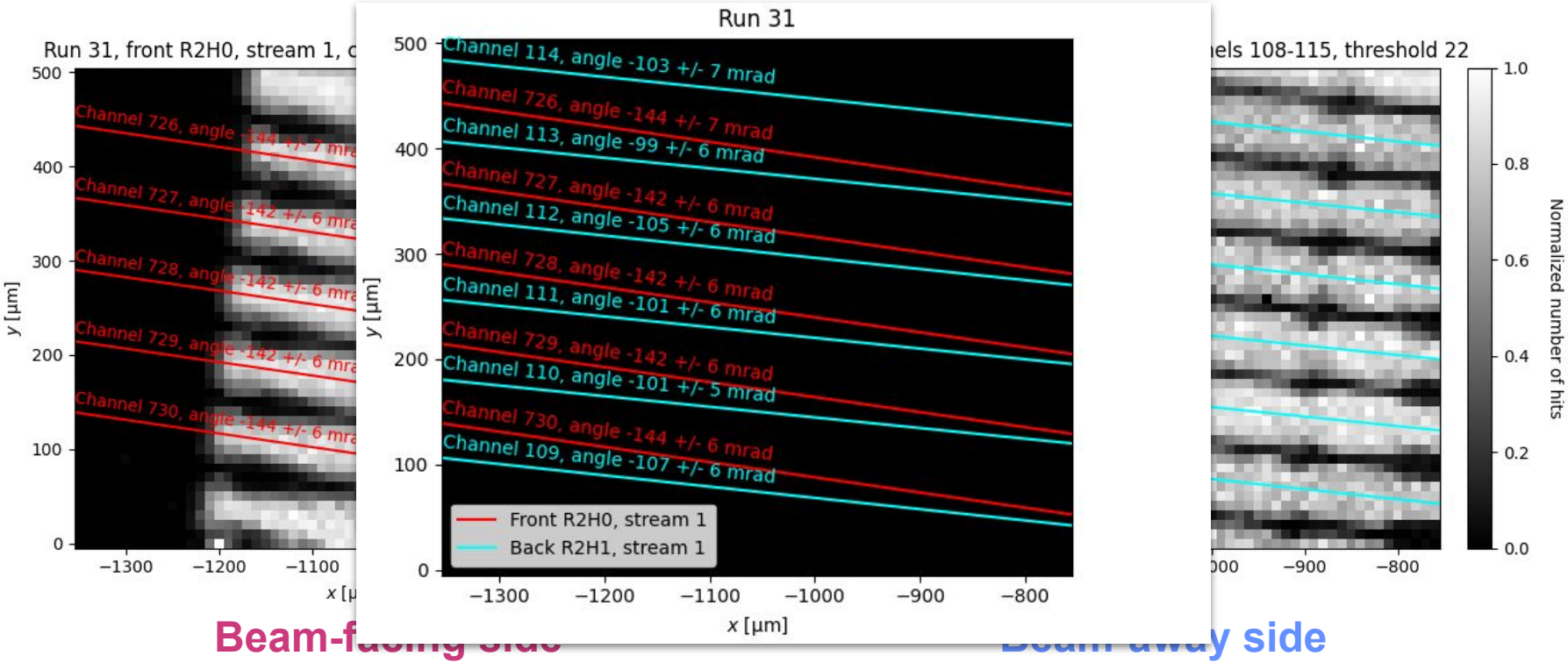
Beam-facing side



Beam-away side

Extracting the stereo angle

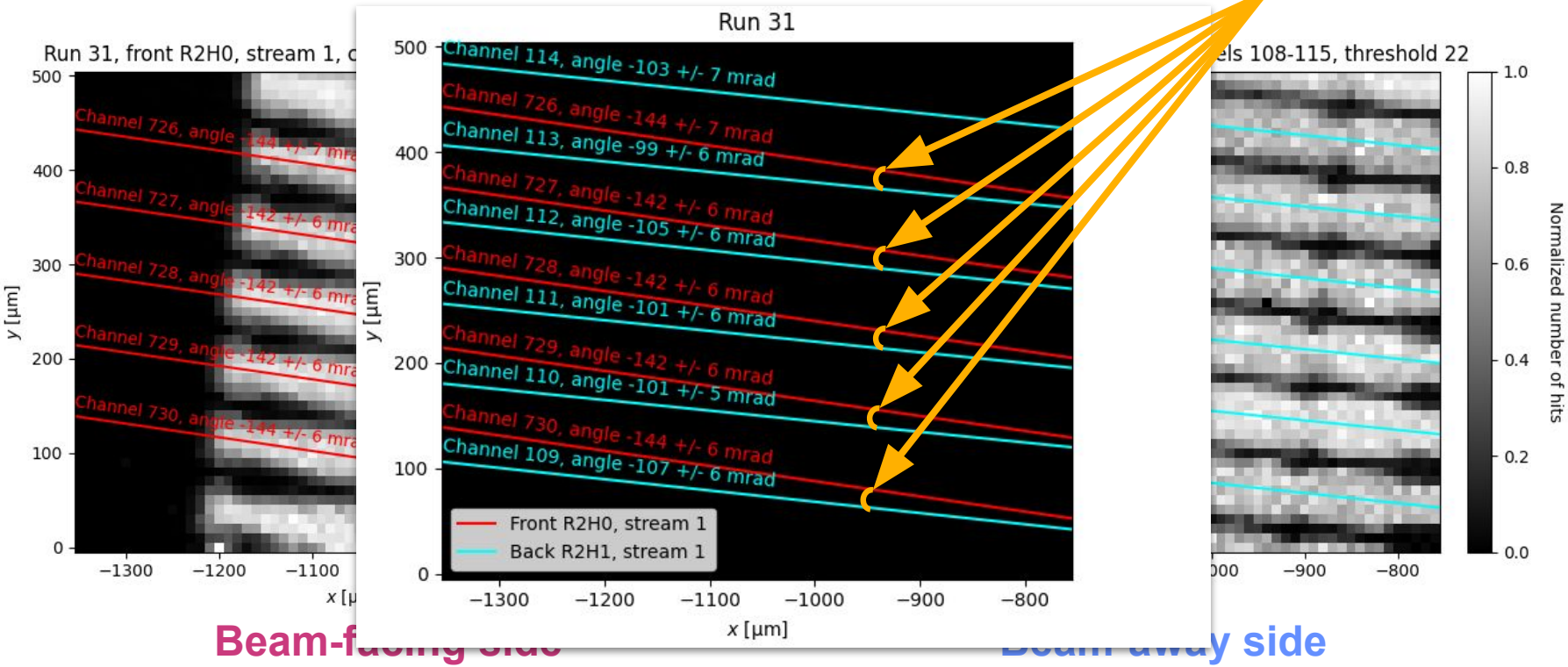
Overlaying the fits for each side



Beam-facing side

Beam-away side

Extracting the stereo angle



Stereo angle results

- **Excellent agreement** between measured/expected for all scans of all regions (calculation of expected described in Backup)
  - **Only one case with 1.5σ deviation** → possibly due to a misrotation or bowing of either sensor beyond tolerance due to exposure to temperatures < −35 °C, **but acceptable**

Run number	Region of interest	Module type		No. of strip pairs	Stereo angle [mrad]			
		Beam-facing	Beam-away		Minimum	Maximum	Average	Expected
31	R2 centre region	R2	R2	5	37 ± 9	45 ± 9	40 ± 4	42.3
41	R4 centre region	R4M0	R4M1	6	38.1 ± 1.3	42.0 ± 2.2	39.4 ± 2.0	42.0
51	R4/5 corner region	R4M0	R4M1	10	32 ± 5	39 ± 6	35 ± 4	37.5
		R4M1	R4M1	11	29.8 ± 3.2	39.3 ± 3.5	34 ± 5	37.6
		R5M0	R5M1	14	37 ± 4	44 ± 5	39.4 ± 3.0	42.3
		R5M1	R5M1	11	44 ± 5	50 ± 5	46.8 ± 2.9	42.4
58	R1/2 corner region	R1	R1	9	31.8 ± 1.9	41.7 ± 1.5	38 ± 5	37.2
		R2	R2	9	41.3 ± 2.3	44.1 ± 2.3	42.1 ± 1.4	42.2

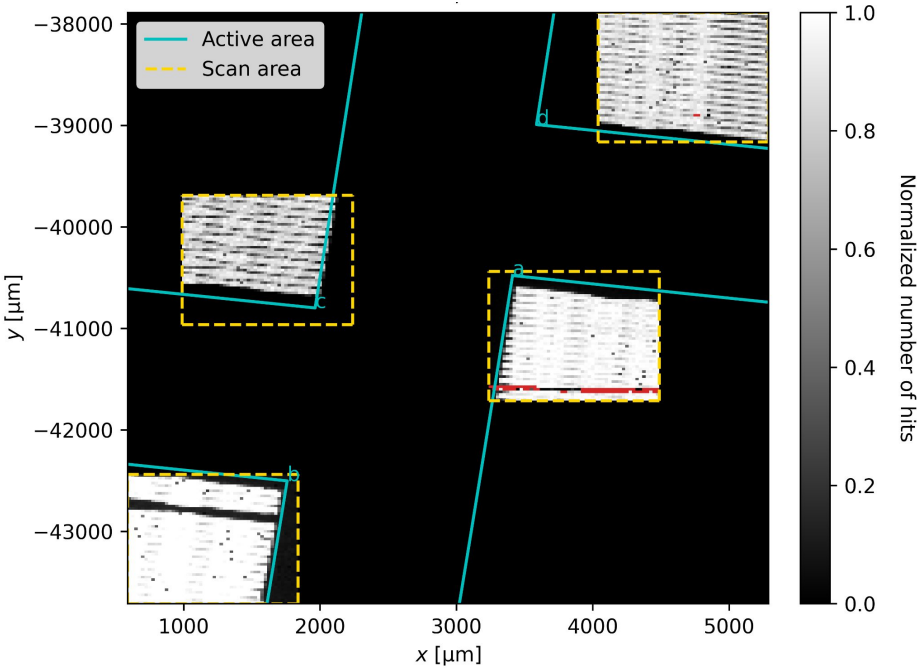
Measuring the hermeticity

Measuring the alignment and hermeticity

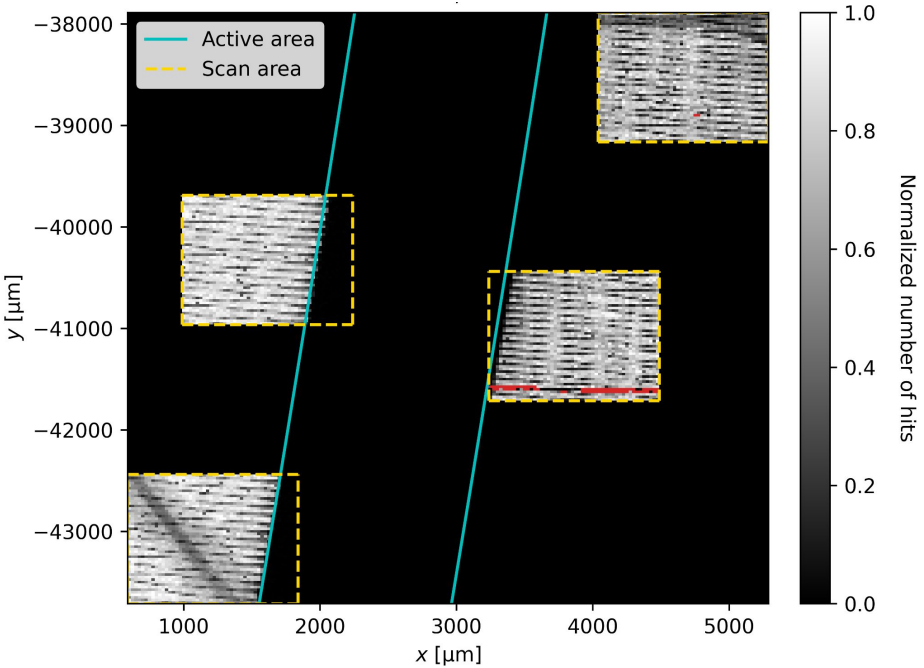
- Alignment can be extracted by fitting the edge of each sensor
  - As before, this relies on the parameterization of the strip positions within the reference frame of each sensor (Backup)
- Tolerance on the placement accuracy of the sensor corners on the petal is ~ 50 μm
- We expect overlap in the active areas of the front and back of the petal ***except*** in gap regions where neither side is expected to measure any hits

R4/R5 corner region: all scans stitched together

Beam-facing side



Beam-away side



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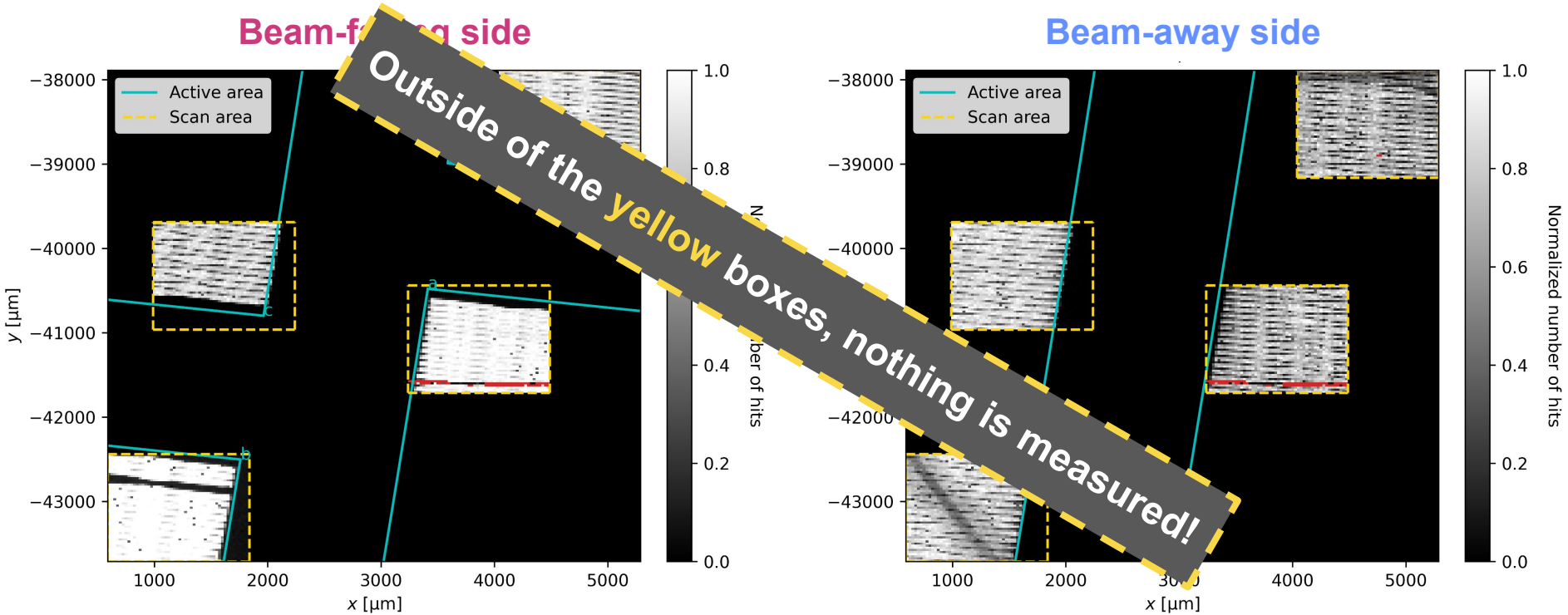
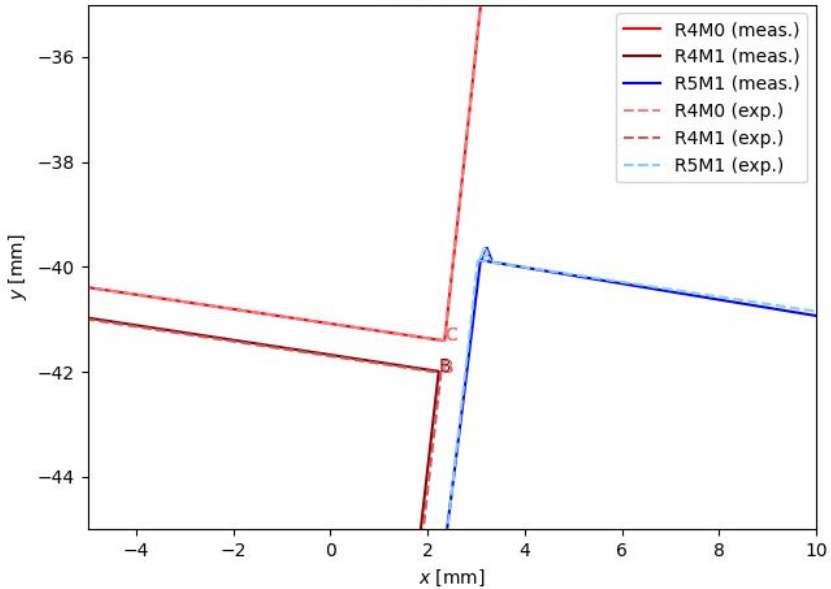
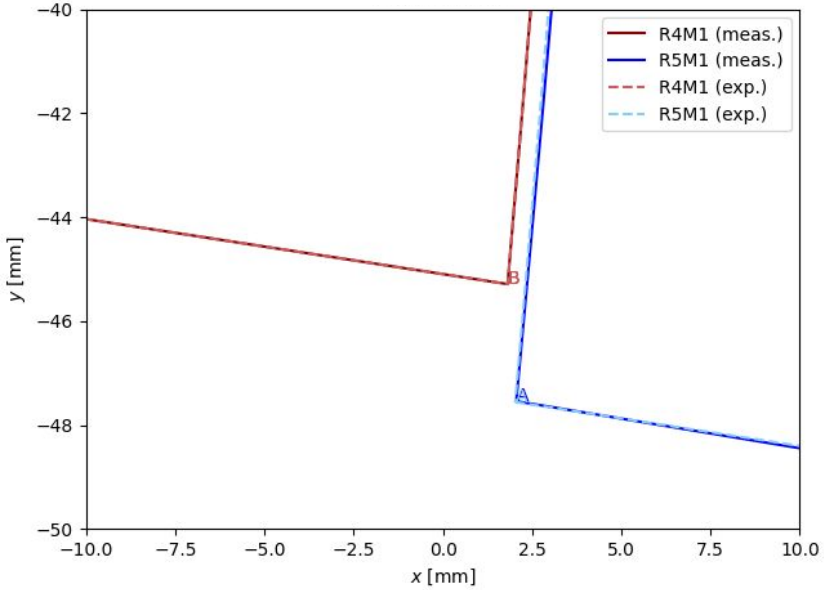


R4/R5 corner region: checking the alignment

Beam-facing side



Beam-away side



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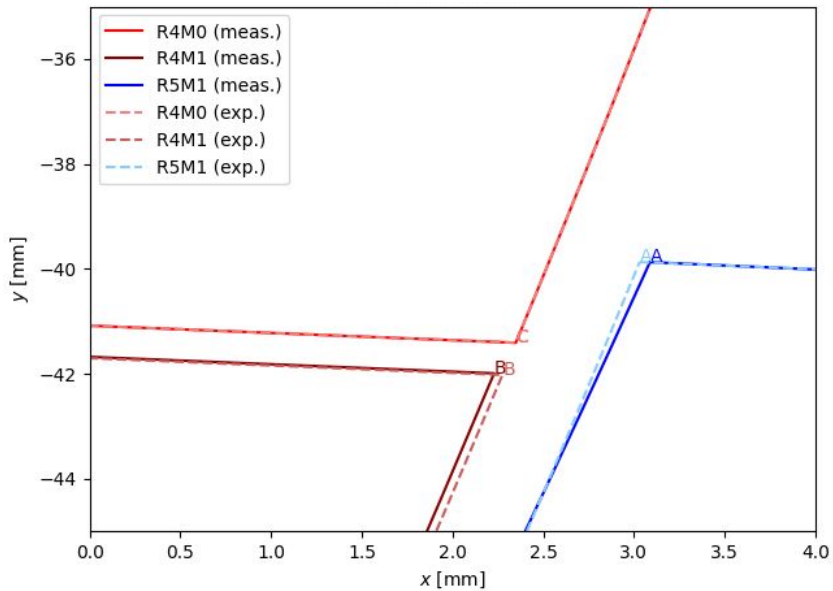
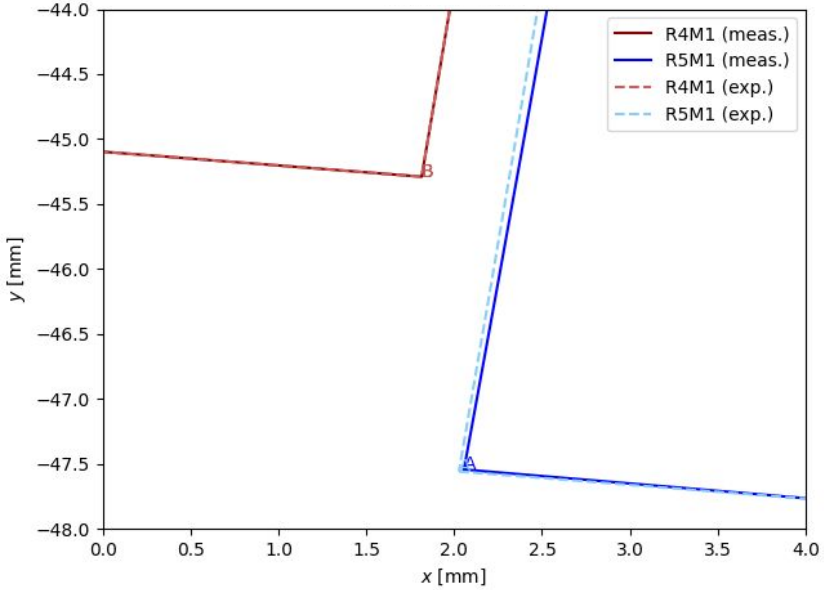


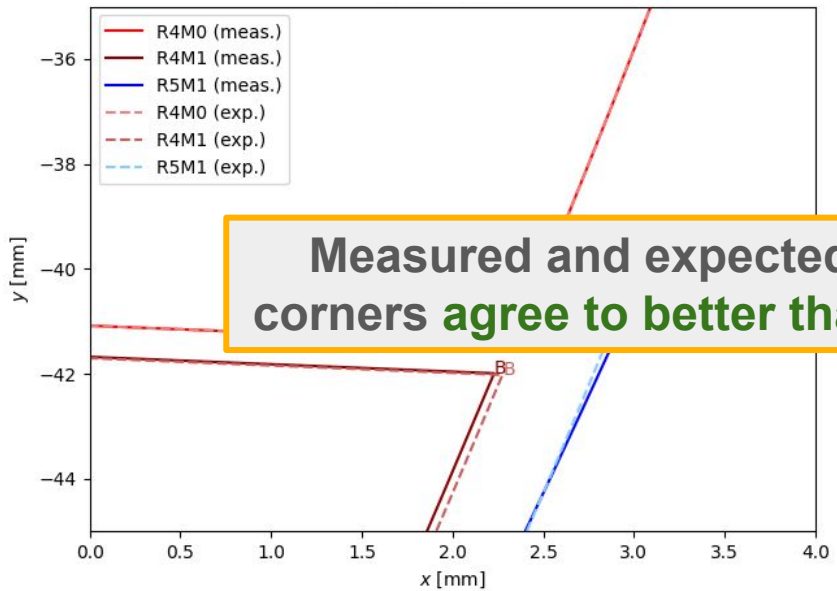
Beam-away side



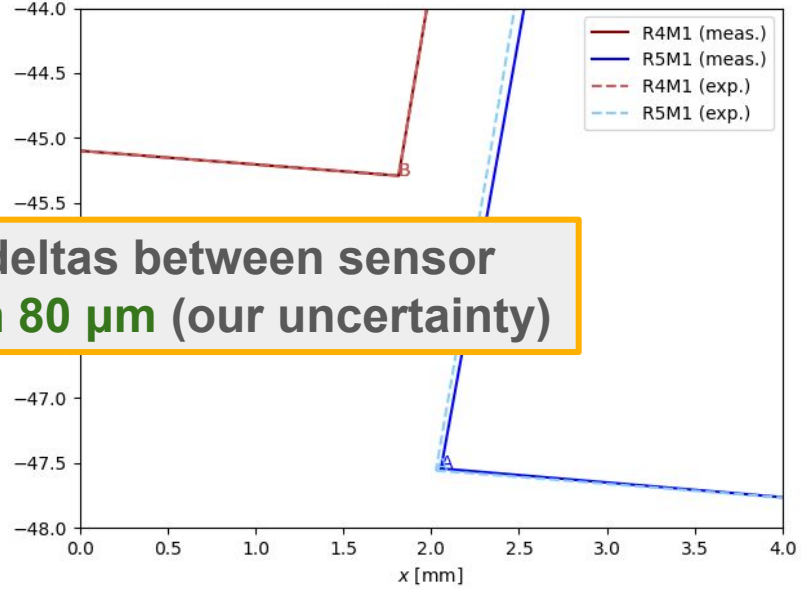
Zooming in 🔍

R4/R5 corner region: checking the alignment

Beam-facing side



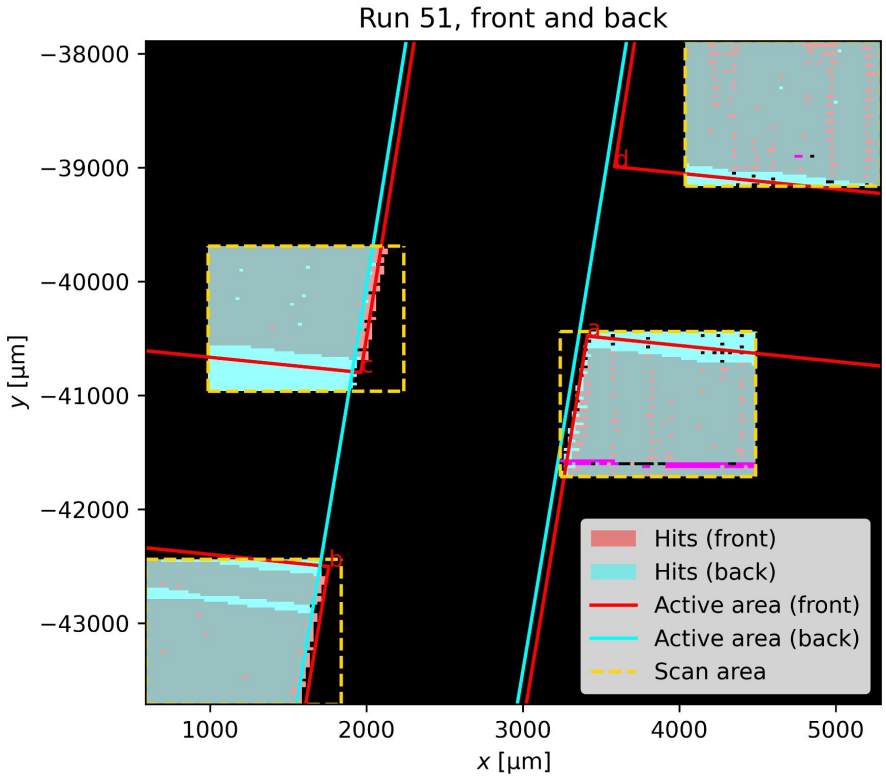
Beam-away side



Measured and expected deltas between sensor corners **agree to better than 80 μm** (our uncertainty)

Zooming in 🔍

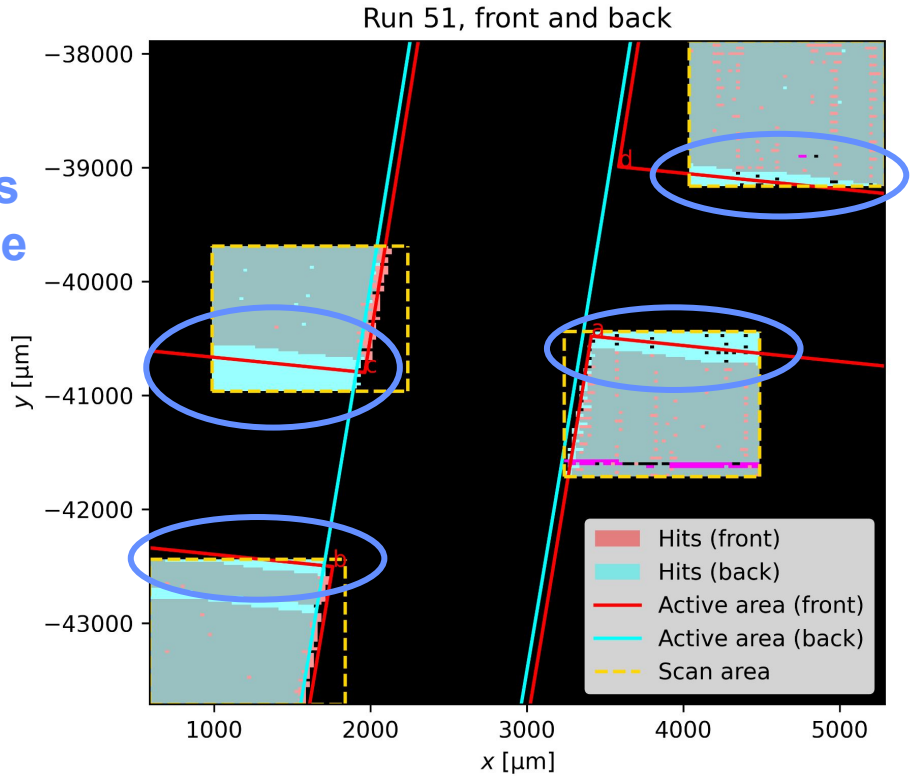
R4/R5 corner region: checking the hermeticity



Digitizing hits (set to 1 if N_{hits} exceeds 10% of maximum, otherwise 0) and overlying both sides

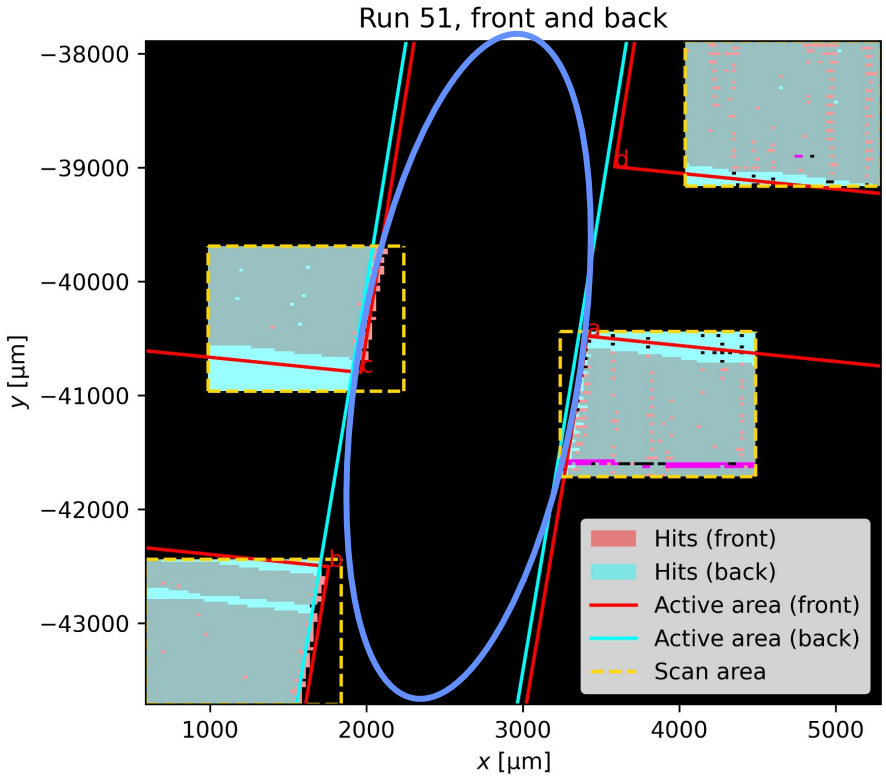
R4/R5 corner region: checking the hermeticity

Back side measures hits where front side does not ✅



R4/R5 corner region: checking the hermeticity

Gap region where neither side measures hits ✅



Wrapping it up

Summary

- Studied an ITk petal using an X-ray beam at the Diamond Light Source → **first time the alignment of a petal has been checked in a beam test!**
- Measurements of the **stereo angle** and **hermeticity** exhibit **excellent agreement** with their expectations, confirming the fidelity of the petal's build
  - Emily Filmer provided more info on how we assemble petals in her talk from yesterday
- Demonstrated the ability to reliably operate a petal for **>90 hours** in a beam
  - Serves as a blueprint for future beam tests of petals and other large-scale ITk subdetectors

Thank you for listening! Any questions?

In the news!

Diamond's B16 validates crucial ATLAS detector component

Nov 17, 2025

The team from Triumf with B16 staff. L-R: Vishal Dhamgaye, Emily Filmer, Matthew Basso, Bruce Gallop, Dennis Sperlich, Luise Poley and Kawal Sawhney.

Backup

Detailed scan info for each region measured

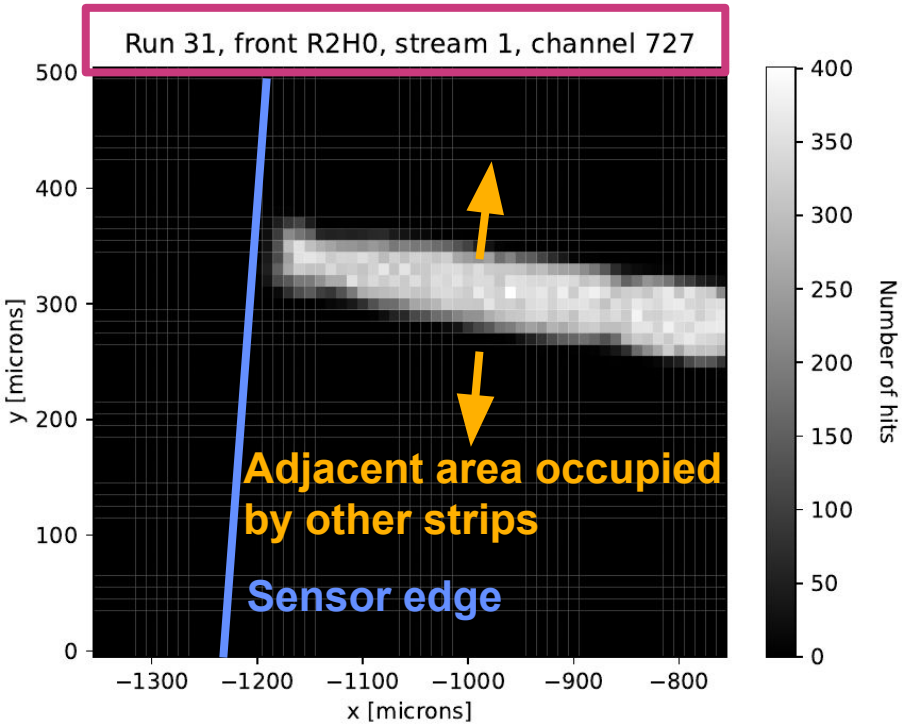
Table 1: Scan information for each measurement of interest. The run numbers are arbitrary but are kept for posterity. For each run, the starting position ("Start"), stopping position ("Stop"), and step size ("Step") for both the x and y scans are specified as well as wait time per point and the runtime. For some runs, multiple scans were required to capture the important features in the region of interest. The frame of reference is always the same within a run but may vary between runs.

Run number	Region of interest	x scan [µm]			y scan [µm]			Wait time [s]	Runtime [hh:mm]
		Start	Stop	Step	Start	Stop	Step		
31	R2 centre region	−1350	−750	10	0	500	10	15	13:06
41	R4 centre region	−350	650	10	−300	300	10	12	21:36
51	R4/5 corner region	600	1850	25	−43700	−42450	25	13	09:52
		1000	2250	25	−40950	−39700	25		09:52
		4050	5300	25	−39150	−37900	25		09:52
		3250	4500	25	−41700	−40450	25		09:52
58	R1/2 corner region	−6537.5	−4762.5	25	41547.5	42422.5	25	15	11:15
		−2537.5	−762.5	25	40147.5	40897.5	25		09:41

Example: R2 centre region

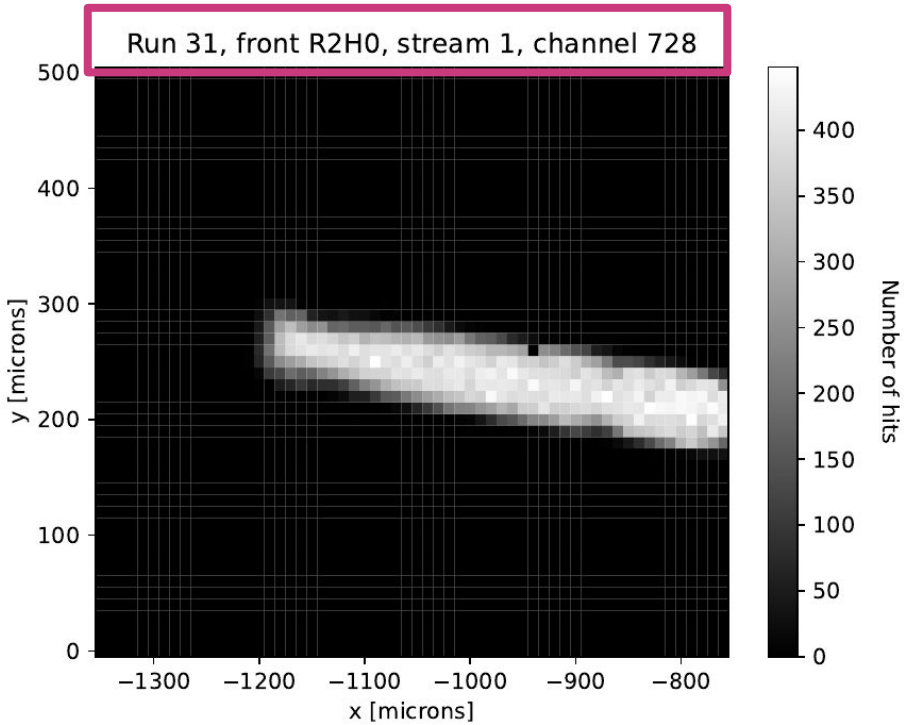
This is a map of the **end of a single strip**, showing the number of hits reported by that strip for each position of the beam → identifies the **position** and **extent** of the strip

Step size is 10 microns



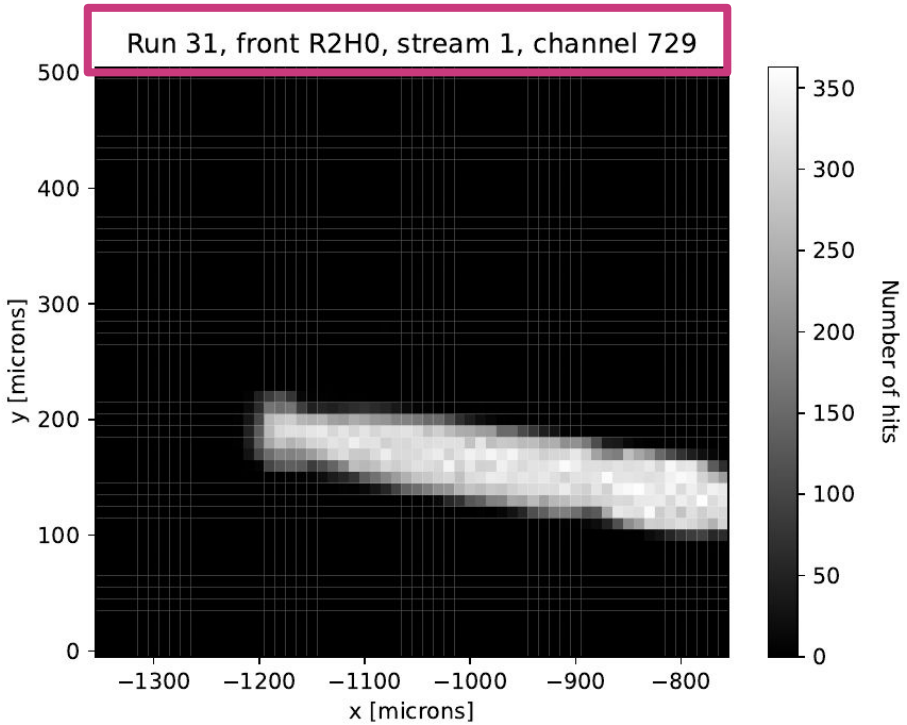
Example: R2 centre region

Step size is 10 microns

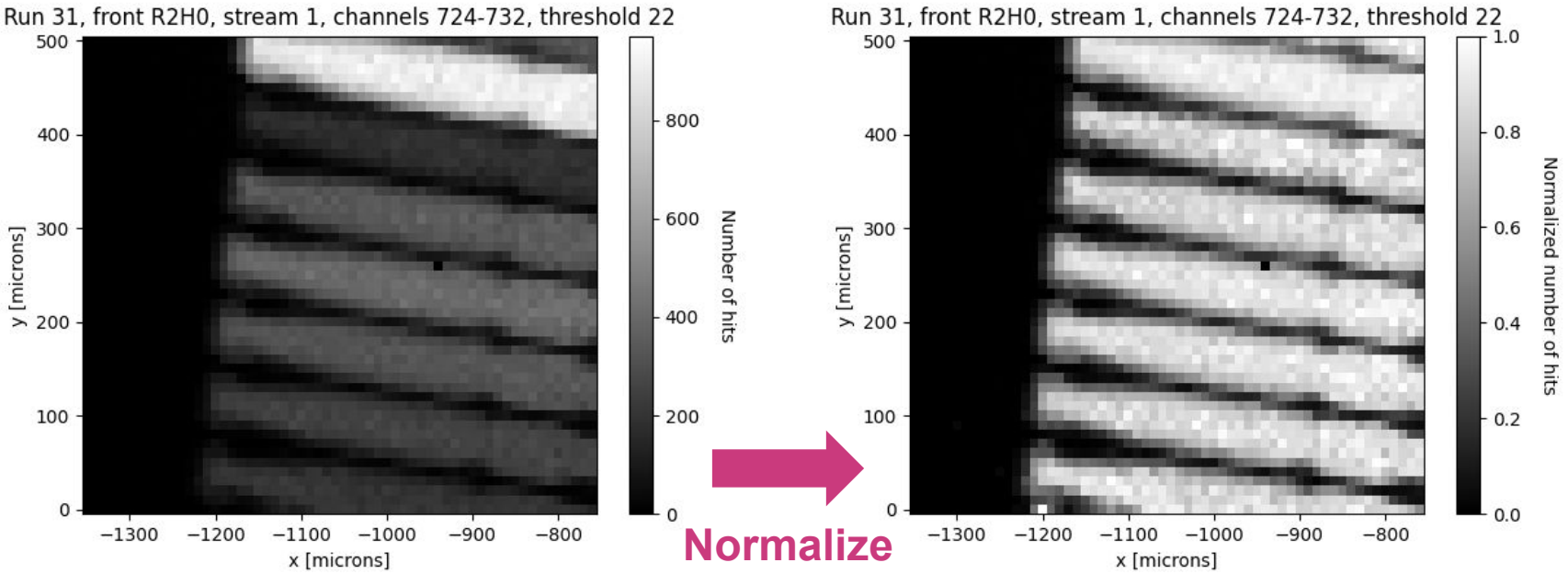


Example: R2 centre region

Step size is 10 microns



Example: R2 centre region

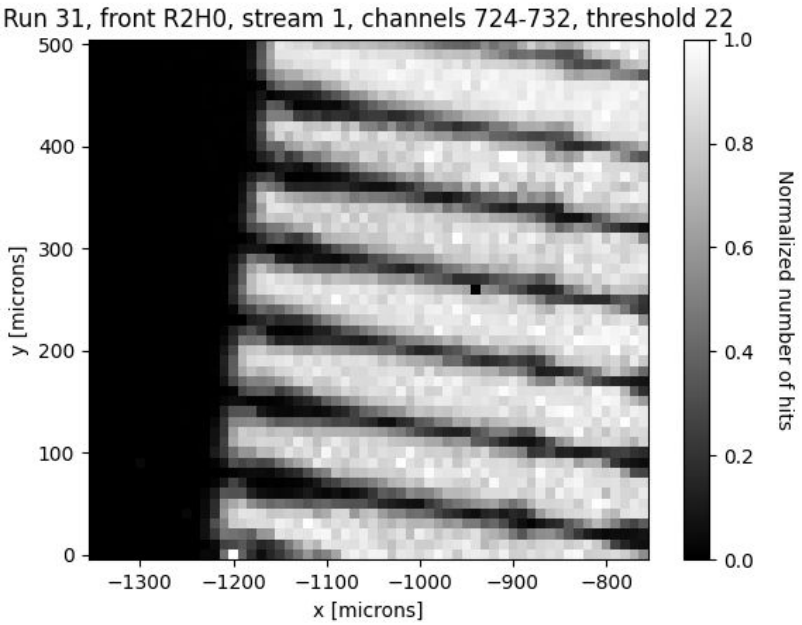


Overlaying each channel

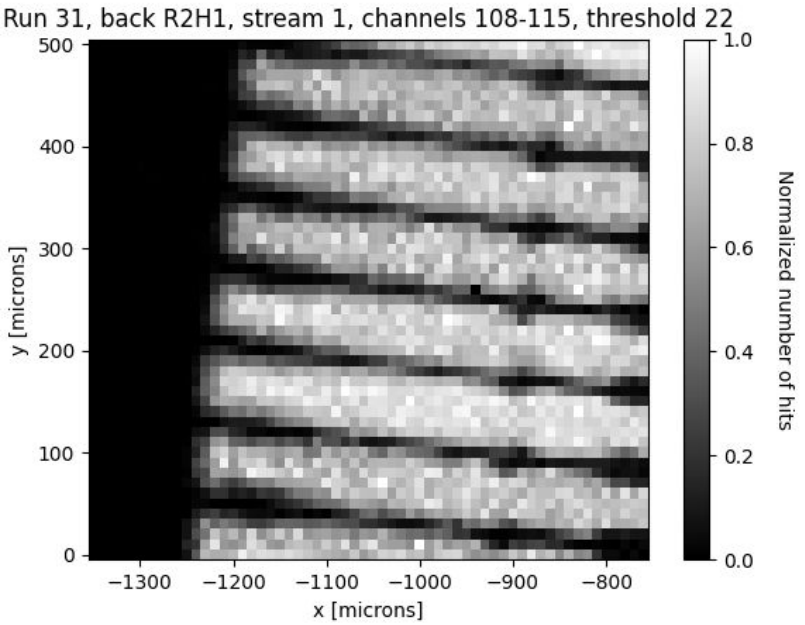
Each channel is *independently* normalized to its maximum

Example: R2 centre region

Beam-away side has fewer hits than beam-facing side, due to photon absorption in the material

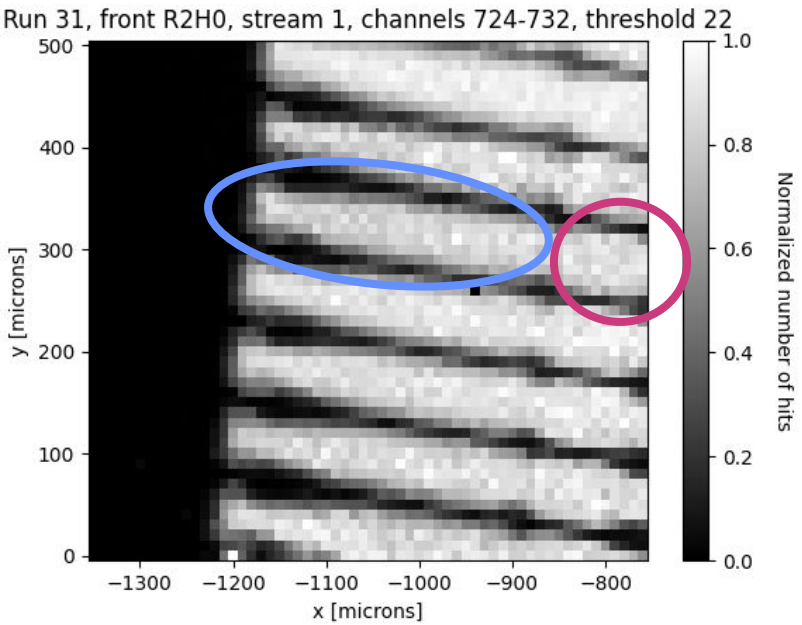


Beam-facing side



Beam-away side

Comparing the scan to a picture of a sensor



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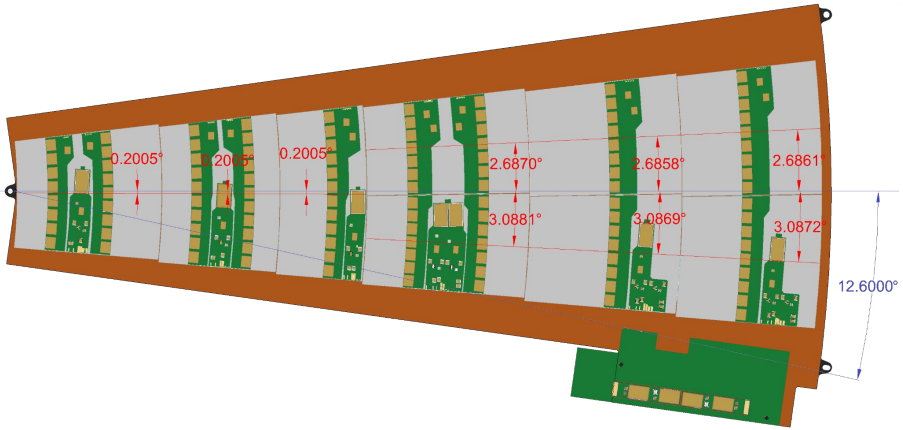
Not the same sensor! Red corresponds to AC pads and blue corresponds to bias resistors

Calculating the expected value for the stereo angle

- Expected stereo angle calculated using the expected placement of each sensor on the petal and the formulation of the strip positions within the reference frame of each sensor (JINST 18 (2023) T03008)



A Formulation of the strips of the endcap sensors

In the geometry of Fig. 3a, the coordinates of i-th strip at a radius r are defined by

$$x(i,r) = -r'\sin(\varphi_i' + \varphi_s) + R\sin(\varphi_s)$$
$$y(i,r) = r'\cos(\varphi_i' + \varphi_s) - R\cos(\varphi_s) \quad \text{(A.1)}$$

where

$$\varphi_i' = (-1)(i - N/2 + 0.5)\varphi_p$$
$$b = -2(2R\sin(\varphi_s/2))\sin(\varphi_s/2 + \varphi_i')$$
$$c = (2R\sin(\varphi_s/2))^2 - r^2 \quad \text{(A.2)}$$
$$r' = (-b + \sqrt{b^2 - 4c})/2\,.$$

with N being total number of strips, i-th strip in clock-wise counting, φ_p angular pitch, φ_s rotation angle, and R radius of the wafer center of the sensor Ow. The basic parameters such as N, φ_p, φ_s, and R are summarized for each endcap sensor in Table 2. The coordinates of the ends of strips are calculated at the boundaries, r_i, $r1$, $r2$, $r3$, and r_o, of the rows of each endcap sensor.