Building the new ATLAS tracking detector …

and some of the side quests we encountered in the process

July 28th
TRIUMF Science Week 2025

Luise Poley

ITk, end-cap and Canada

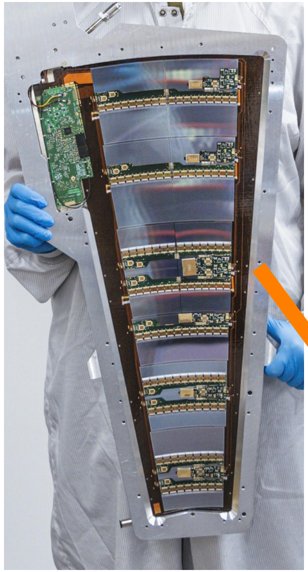
In 2030, the Large Hadron Collider will be upgraded (higher particle collision rates)

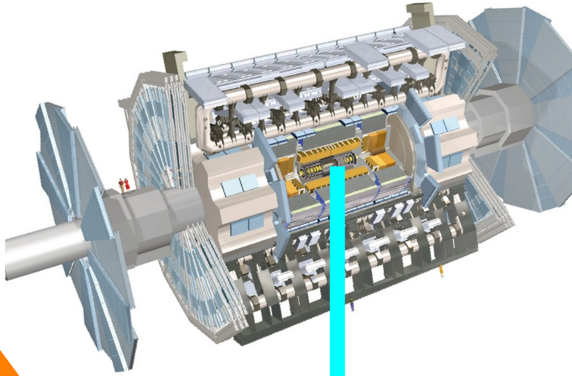
ATLAS Detector is upgraded as well

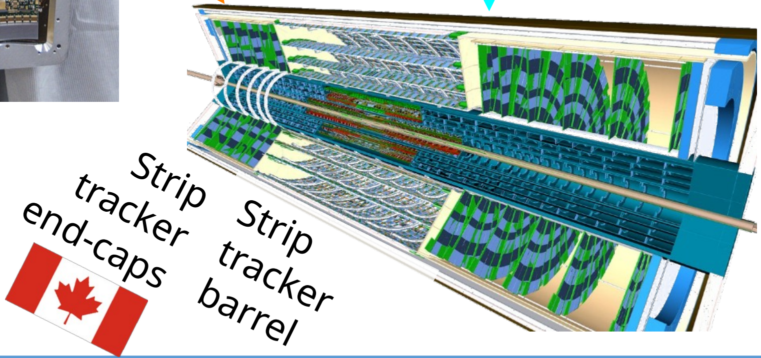
ATLAS Inner Detector will be replaced
→ Too much radiation damage
→ Insufficient spatial resolution

Construction of the new
ATLAS Inner Tracker
→ More readout channels
→ Better spatial resolution
→ Higher radiation tolerance
→ In existing detector volume

Canada is building ¼ of all end-cap modules and petals!







The long path to a detector

Planned Phases in our international project

Prototyping (parts that mostly look like final modules)
Pre-Production (5% of production)

Production (384 petals)

The long path to a detector

Actual phases in our international project

Prototyping (parts that ~~mostly~~ vaguely look like final modules)
Pre-Production A (almost the finished modules, but not quite usable)
Pre-Production B (4% of production, okay to use in detector)

Production (remaining 368 petals)

The long path to a detector

Actual phases in our international project

Prototyping (parts that ~~mostly~~ vaguely look like final modules)
Pre-Production A (almost the finished modules, but not quite usable)
Pre-Production B (4% of production, ~~okay to use in detector~~, just a few final tweaks)
Pre-Production C (okay, these ones can really go into the detector)

Production (remaining 368 petals)

The long path to a detector

Phases in our international project

Prototyping (parts that vaguely look like final modules)
Pre-Production A (almost the finished modules, but not quite usable)
Pre-Production B (technically ready for installation, just a few final bits …)
Pre-Production C (okay, ~~these ones can really go into the detector,~~ this time we really thought we could use these)

Pre-Series (16 petals) **and Production** (remaining 368 petals)

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Frequently asked questions

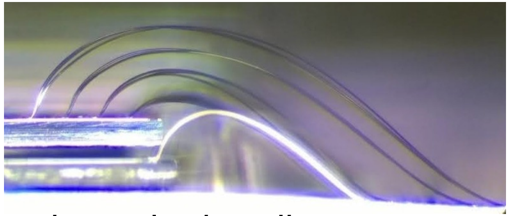
Question 1 (usually from outside ATLAS):

"But the technology you use [130 nm chips, planar silicon sensors] is quite old and pretty well known – why is that still so difficult?"

Yes, the technology we use has been around for a while,
But we are pushing it to new limits because

a) we use a lot of the technology very differently from industry, e.g. with a whole lot of radiation
b) we need it to work reliably for ten years without repairs (have I mentionted the irradiation?)

My favourite example: Module wire bonding (four rows on top of each other, each wire has a diameter of 25 µm)



When wire bonding machine manufacturers see this, they usually pale and ask it if is too late to change the design

(yes, it is)

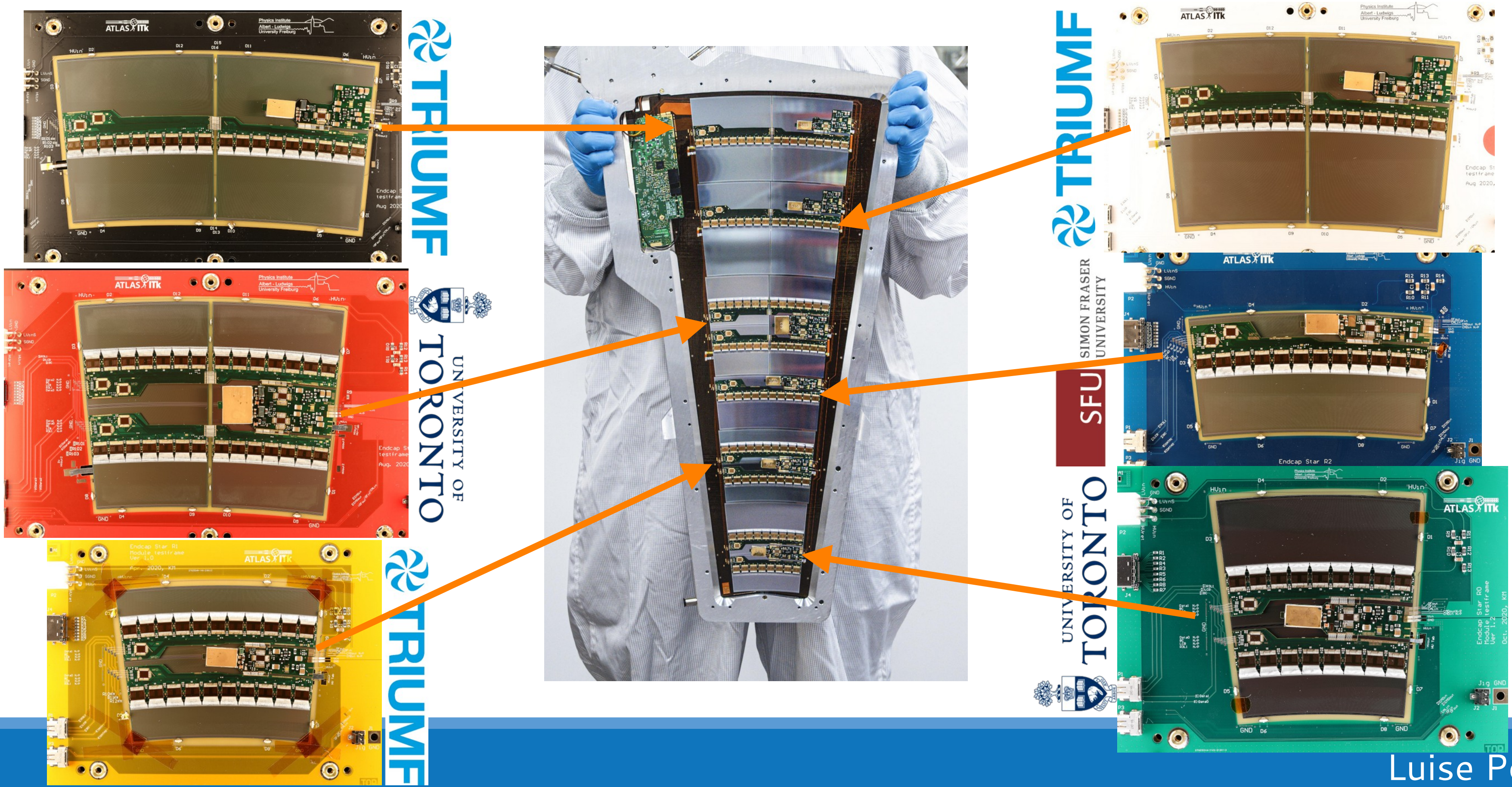
Learning from experience?

Question 2 (usually from within ATLAS)
"But surely you have learned from the previous detector?"

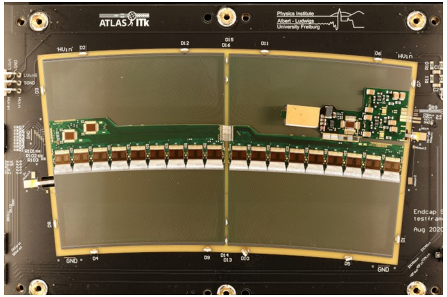
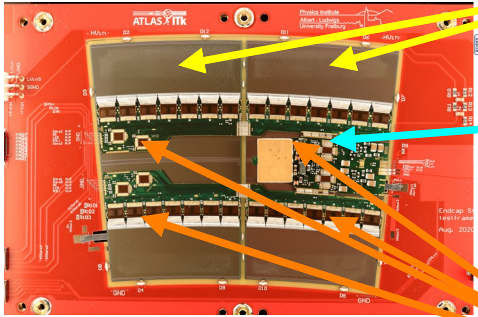
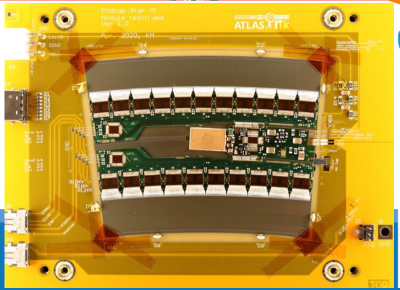
	ATLAS (our detector)	**CMS** (the other one)
Currently	Modules: Very complex, few types Support: Simple	Modules: Simple, many types Support: Complicated
Future	Modules: "Simple*", many types Support: Complicated	Modules: Very complex, few types Support: Simple

Follow-up Question (3) (usually from every reasonable person)
"Why would you BOTH do that??"
-> Because everyone remembers the previous production phase + problems

End-cap modules



End-cap modules

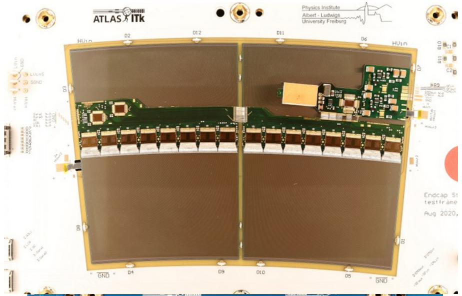
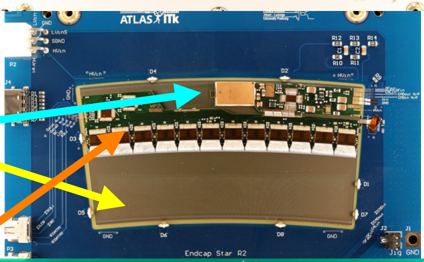
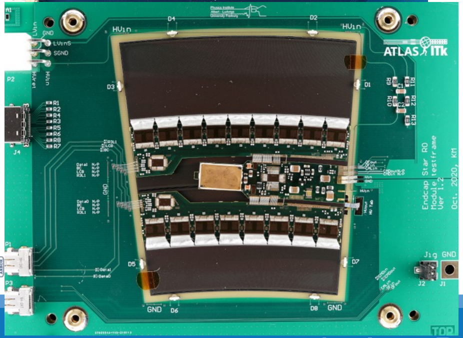




All modules have the same components, just in different shapes and quantities

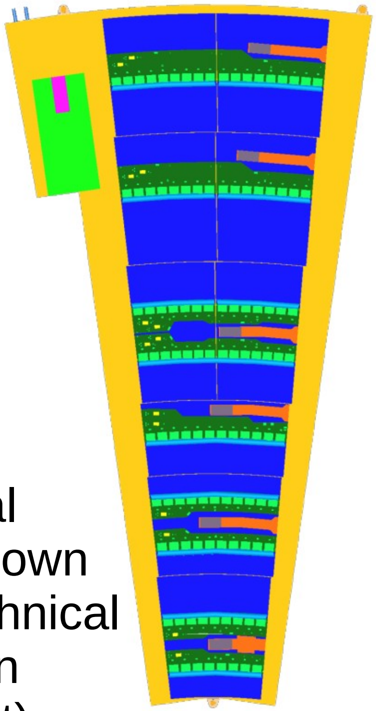
Sensor(s)

Powerboard (voltage reduction and control), glued directly to sensor

Hybrids with readout chips glued directly to sensors

Using ~~old~~ established technology



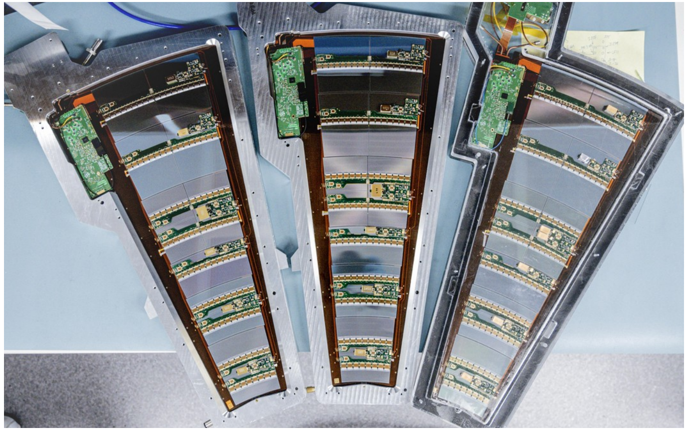
A petal (as shown in Technical Design Report)

We thought using established technology would help us avoid unforeseen problems
(we were wrong)

A few examples of later problems

- Chip radiation hardness
- **Sensor breakdown**
- Strange Noise from gluing parts directly to sensor
- Delivery issues
- **Mechanical problems**
- **Cold Noise**
- High Voltage contact

And many more!



Petals (as they will be installed in the detector)

Why so many problems (!?!)

All **individual** components are made following industry standards and quality control
(and they encountered plenty of difficulties!)

Problems happen at the interfaces, during assembly, handling, integration – and irradiation

That is challenging, but it also provides opportunities to learn new and exciting things for future detectors and spin-off technologies

So we do our best to understand these problems
- for our detector (all ten years)
- for the next detector
- for possible other applications

Sensors
Electrical tests,
mechanical tests,
visual inspection,
irradiation

Printed circuit boards (PCBs)
Electrical tests,
long-term tests,
delamination tests,
mechanical tests,
visual inspection,
irradiation

Sensors + PCBs
Gluing PCBs onto sensor:
early breakdown,
glue spilling,
strange noise problems ...

Selected Challenges

- **Early Sensor Breakdown**
- Cold Noise on Modules
- Cracking petals

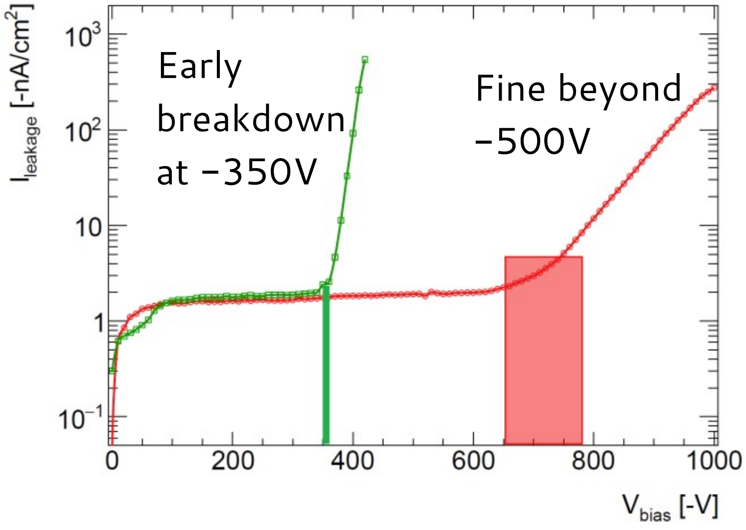
Sensors and early breakdown

Perhaps the least applied and maybe most relevant for next detector: early sensor breakdown

Sensors in detector are operated at −350 V initially, −500 V at end of life (for sufficient signal collection)

Requires sensor current to be < 10 mA at −500 V in initial tests

Ongoing and persistent problem: some sensors can’t be used all the way up to the required bias voltage



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How did we end up here?

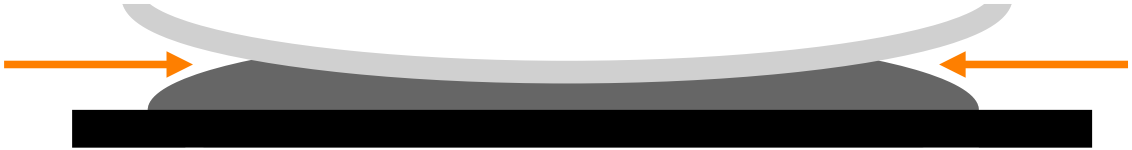
ATLAS07 sensors

Excellent electrical performance (low leakage current, high breakdown voltage)

Problem: shape (bowl shaped sensors with a height difference of 0.2 mm, exceeding allowed range)

Concern:

When mounting modules with a large bend, glue coverage under sensor may be insufficient support



Question for manufacturer:

could you make sensors less bent?

How did we end up here?

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ATLAS12 sensors

Shape much improved (flatness now within specifications)

New problem: early sensor breakdowns (nominal operating voltage: −500 V, breakdowns as low as at −100 V)

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Shape much improved (flatness now within specifications)

New problem: early sensor breakdowns (nominal operating voltage: −500 V, breakdowns as low as at −100 V)

Feedback to manufacturer

It looks like these sensors have early breakdown when exposed to humidity

Would it be possible to make the sensors also less humidity sensitive, please?

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ATLAS12 sensors

Shape much improved (flatness now within specifications)

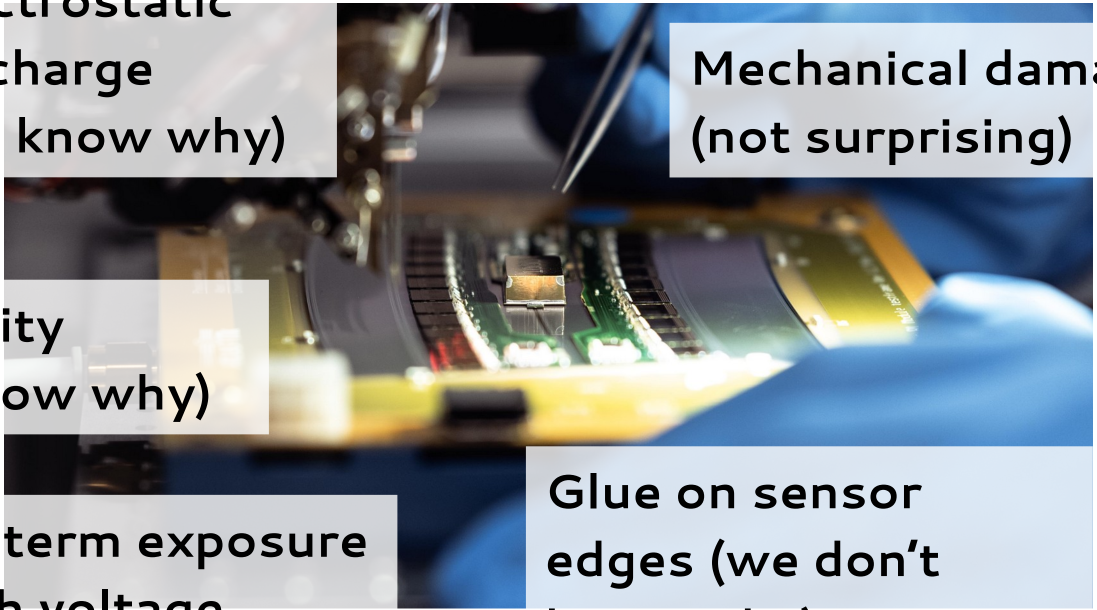
New problem: early sensor breakdowns (nominal operating voltage: −500 V, breakdowns as low as at −100 V)

ATLAS18 sensors

Production version of sensors much improved compared to previous versions, but still humidity sensitive (dry storage and drying required)

Ongoing issue with early sensor breakdown

Known causes for breakdown



Electrostatic discharge
(we know why)

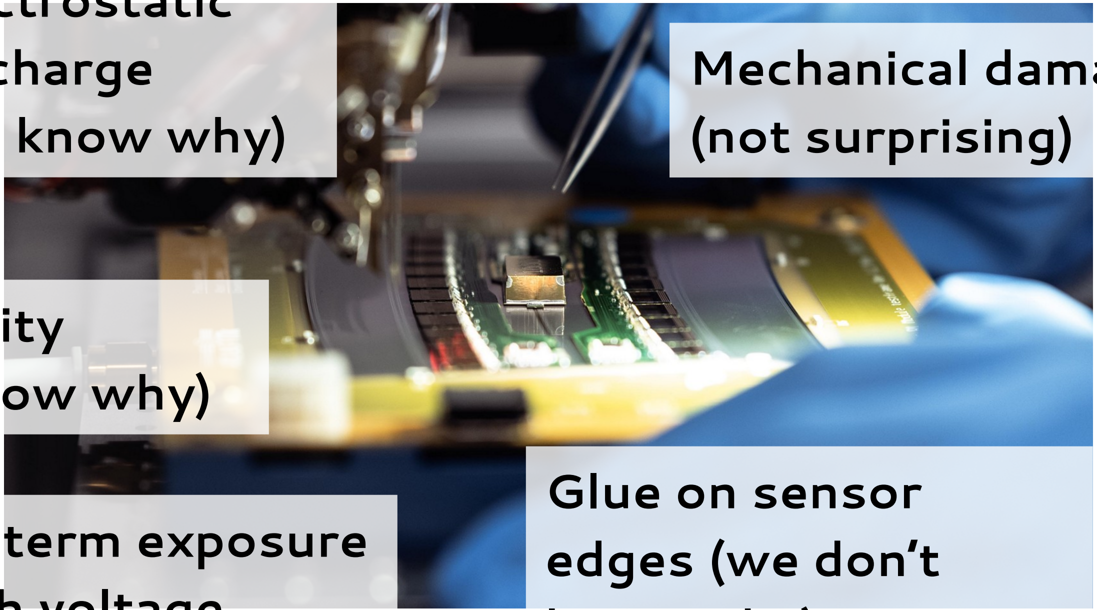
Mechanical damage
(not surprising)

Humidity
(we know why)

Long-term exposure to high voltage
(we may know why)

Glue on sensor edges (we don't know why)

Known causes for breakdown



Electrostatic discharge (we know why)

Mechanical damage (not surprising)

Humidity (we know why)

Long-term exposure to high voltage (we may know why)

Glue on sensor edges (we don't know why)

In summary:

It's very easy to avoid sensor breakdown:

Don't ship them, handle them, assemble them, expose them to ambient air or test them

Less easy to avoid it **and** build modules

Selected Challenges

- Early Sensor Breakdown
- **Cold Noise on Modules**
- Cracking petals

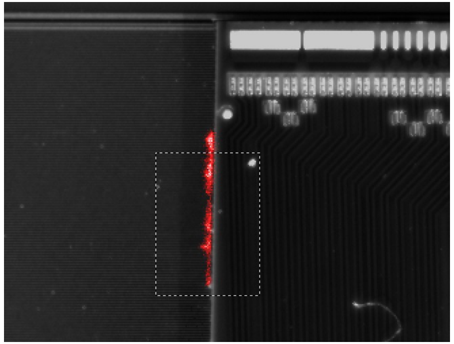
ATLAS ITk work, but also R&D

<u>Why does glue on sensors cause breakdown?</u>
Undergraduate student research topic
(paper in preparation)

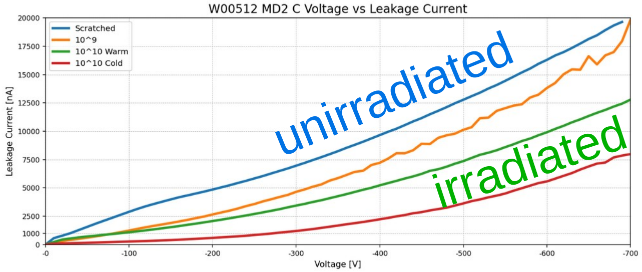
<u>Early breakdown on modules and what causes it</u>
Graduate student topic together with SFU Engineering Department

- Visualising breakdown location
- Systematic studies of mechanism

<u>Improvement with radiation</u>
Fundamental question why sensors with early breakdown improve with radiation
Multi-year iterative irradiation study ongoing with DLS and CLS



Identifying the location of a sensor breakdown using hot spot imaging



Cold Noise – against all odds

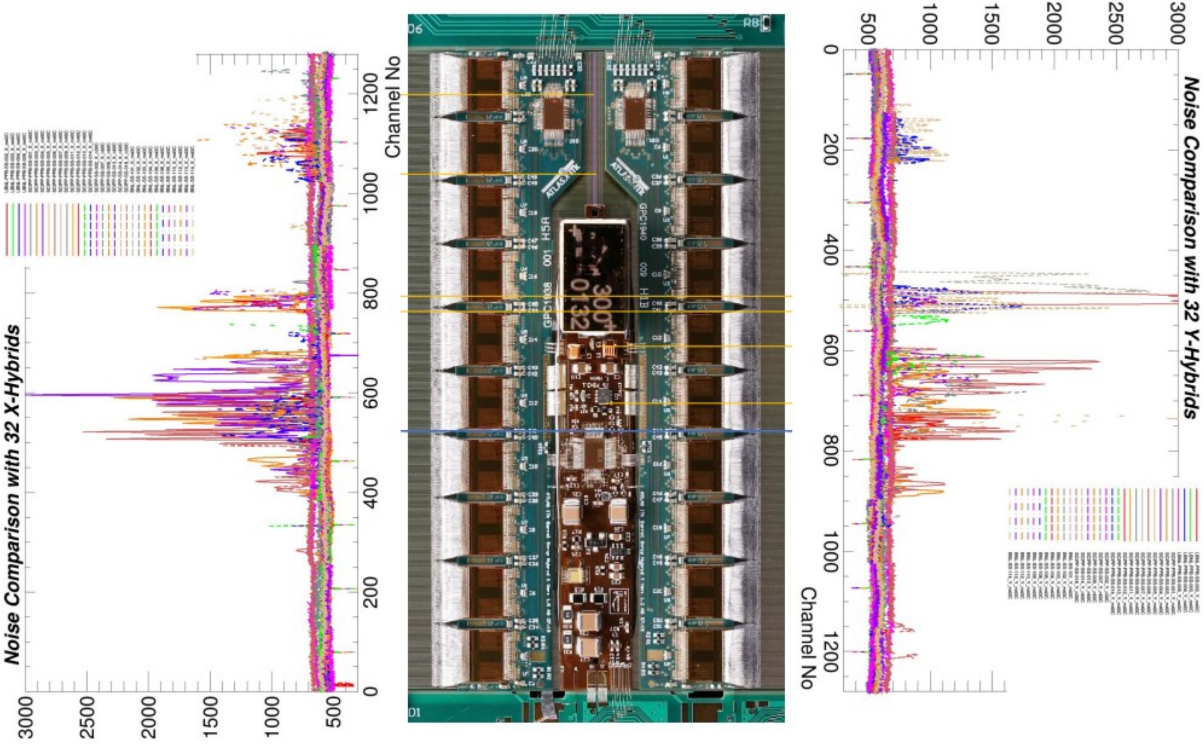
Cold Noise

Excessive noise peaks which only occur at cold (operating) temperatures

Only on certain modules and types

Only in certain areas

Only for certain glue



Cold Noise – where we are

A fascinating case of individual components all within specifications,
Producing modules which do not comply with specifications

Complex interaction of individual parts (vibrating capacitors on circuit boards, vibrations travelling through sensor and glue layers and somehow couple back into readout)

Solved by using a different glue in 2022 …

"If you *tried* to design a system like this, which produces a Cold Noise like signal, it would be almost **impossible** to line up all the parts to be in that tiny corner of the phase space."

A relieved colleague from CMS

Cold Noise – where we are

A fascinating case of individual components all within specifications,
Producing modules which do not comply with specifications

Complex interaction of individual parts (vibrating capacitors on circuit boards, vibrations travelling through sensor and glue layers and somehow couple back into readout)

Solved by using a different glue in 2022 …
resurfaced in 2025 (barrel modules only, only in one place)

Important lessons to be learned about interfaces of materials, complex interactions and quality control of complex systems

Now a graduate student research topic

"If you *tried* to design a system like this, which produces a Cold Noise like signal, it would be almost **impossible** to line up all the parts to be in that tiny corner of the phase space."

A relieved colleague from CMS

Selected Challenges

- Early Sensor Breakdown
- Cold Noise on Modules
- **Cracking petals**

The catastrophe: cracking

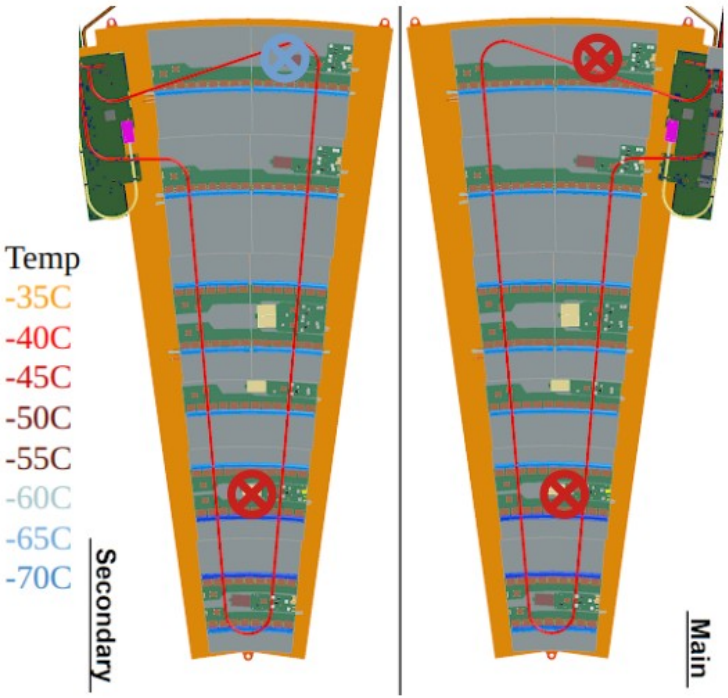
Discovered in 2023:
due to mismatched components properties, barrel modules on supports crack at −35 °C (petals less and only from −45 °C)

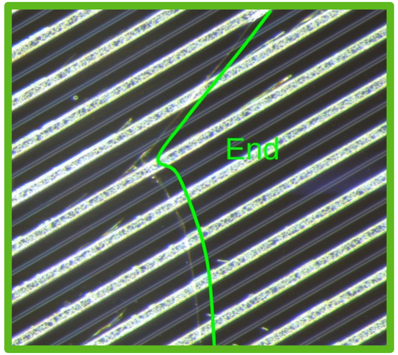
(temperatures down to −55 °C theoretically possible in case of catastrophic failures)

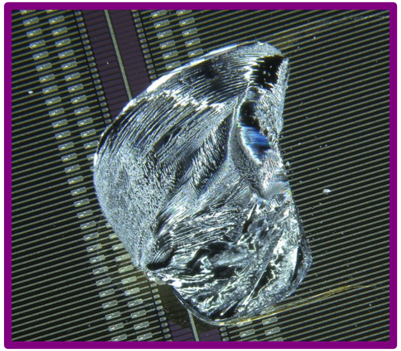
Two year investigation, design changes needed, major delays

How did this happen?

First petal tested very cold







What happened?

Thermo-mechanical simulation in 2016 predicted maximum stress of 120 MPa
Mechanical measurements found that sensors don't crack before 350 MPa
We *should* have been fine.

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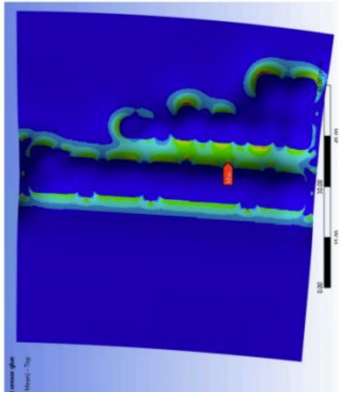
Mechanical measurements found that sensors don’t crack before 350 MPa
We *should* have been fine.

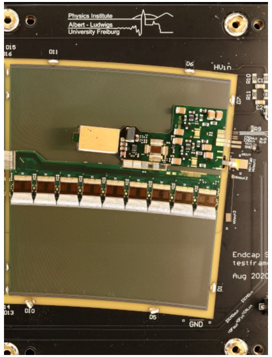
Refined simulation in 2023/2024 with much better knowledge:
maximum stress on sensors is up to 250 MPa
Details still to be understood

Meanwhile: mitigation strategies have been implemented,
major production delays

For production and for future detectors,
continuing the investigation into what we missed

Two publications in preparation:
- development of a mitigation strategy, mostly in Vancouver
- the fascinating behaviour of glues at cold temperatures





Crises are opportunities

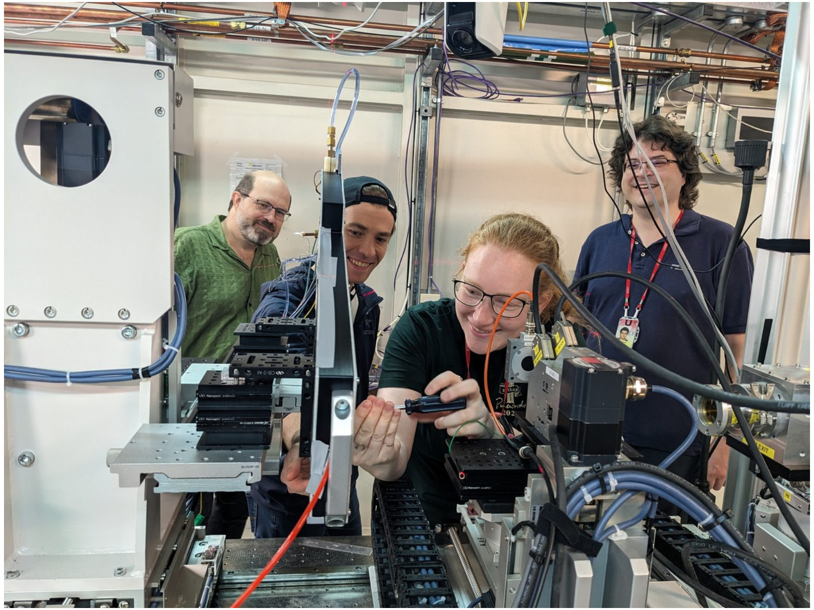
For about ten years of R&D for the ITk, unexpected challenges have required design changes (and caused delays)

Looking back, several of these could have been addressed earlier if early warning signs had been followed up on by the project on time

We are learning!

We are now treating strange and unexpected observations as learning opportunities which are worth investigating by our students and postdocs

... and publishing



A few selected examples

Papers in progress:

- The discovery and mitigation of Cold Noise on ITk strip tracker modules
- Thermal reliability of electrical petals for the end-cap detector of the ATLAS Inner Tacker Upgrade
- Investigations into the quantitative impact of contamination and surface damage on the leakage current of silicon strip sensors
- Thermo-mechanical characterisation of SE4445 silicone gel for use in particle tracking detectors

Published:

- Quality concerns caused by quality control – deformation of silicon strip detector modules in thermal cycling tests (2025)
- Threshold bounce – occupancy-dependent modulation of the discriminating threshold in silicon detectors (2024)
- Hot spot visual evaluation of breakdown locations in ATLAS18 ITk strip sensors and test structure (2024)
- Curing early breakdown in silicon strip sensors with radiation (2024)
- Analysis of humidity sensitivity of silicon strip sensors for ATLAS upgrade tracker, pre- and post-irradiation (2023)
- A starry byte — proton beam measurements of single event upsets and other radiation effects in abcstar asic versions 0 and 1 for the itk strip tracker (2022)
- Magnetic triggering — time-resolved characterisation of silicon strip modules in the presence of switching DC-DC converters (2021)

Backup

Why so many problems

R&D phase:
Construction of a few R0 modules (no other types)

Preliminary Design Review (sign-off on Prototyping)

Protoyping:
Construction of more R0 modules (no other types)

Final Design Review (sign-off on Pre-Production)

The first time all module types were built!

End-cap modules require six sensor types, 13 flex shapes and four types of powerboards

Money required to prototype all components only released during Final Design Review

First modules with final components built at beginning of pre-production

We will get there

So far, every problem we have encountered has been solved

Students have majorly contributed to solving them:
Whenever problems occur, they are an excellent opportunity for students!

Over the past few years, our students have worked on

- Investigating early breakdown on sensors and modules
- Cold Noise analysis
- Investigating deformation of modules in thermal cycling
- Investigating mitigation of cracking on petals

Most of these have resulted in publications written by students!

In the end, we will have a working detector!