ATLAS Upgrades for the High-Luminosity Large Hadron Collider

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2023 CAP Congress

The Upgrade of the LHC

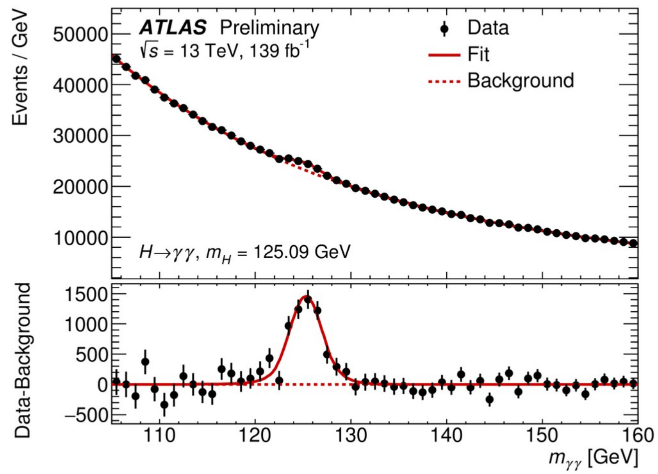
Large Hadron Collider: discovery of Higgs boson (2012)

- Ongoing searches for
  - supersymmetric particles
  - dark matter candidates
- Several Upgrade Phases
- Planned extension for Phase-II: the LHC High Luminosity Upgrade (luminosity increase x 10)

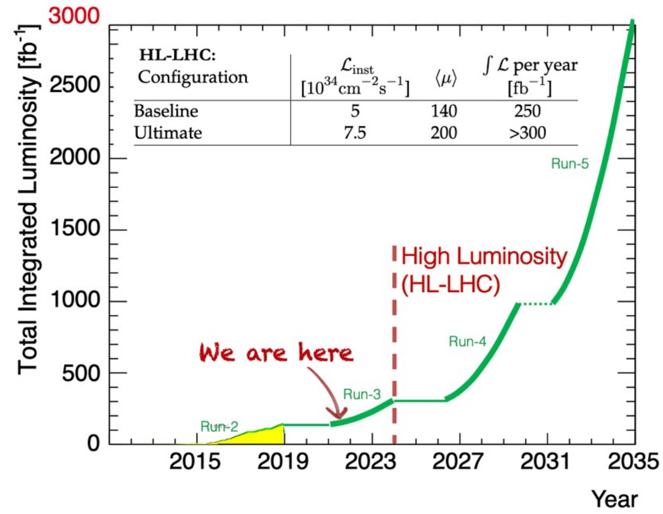
  → Searches for rare processes, e.g. Higgs self-coupling

  → access to new physics sector

  → Use of the LHC's full discovery potential



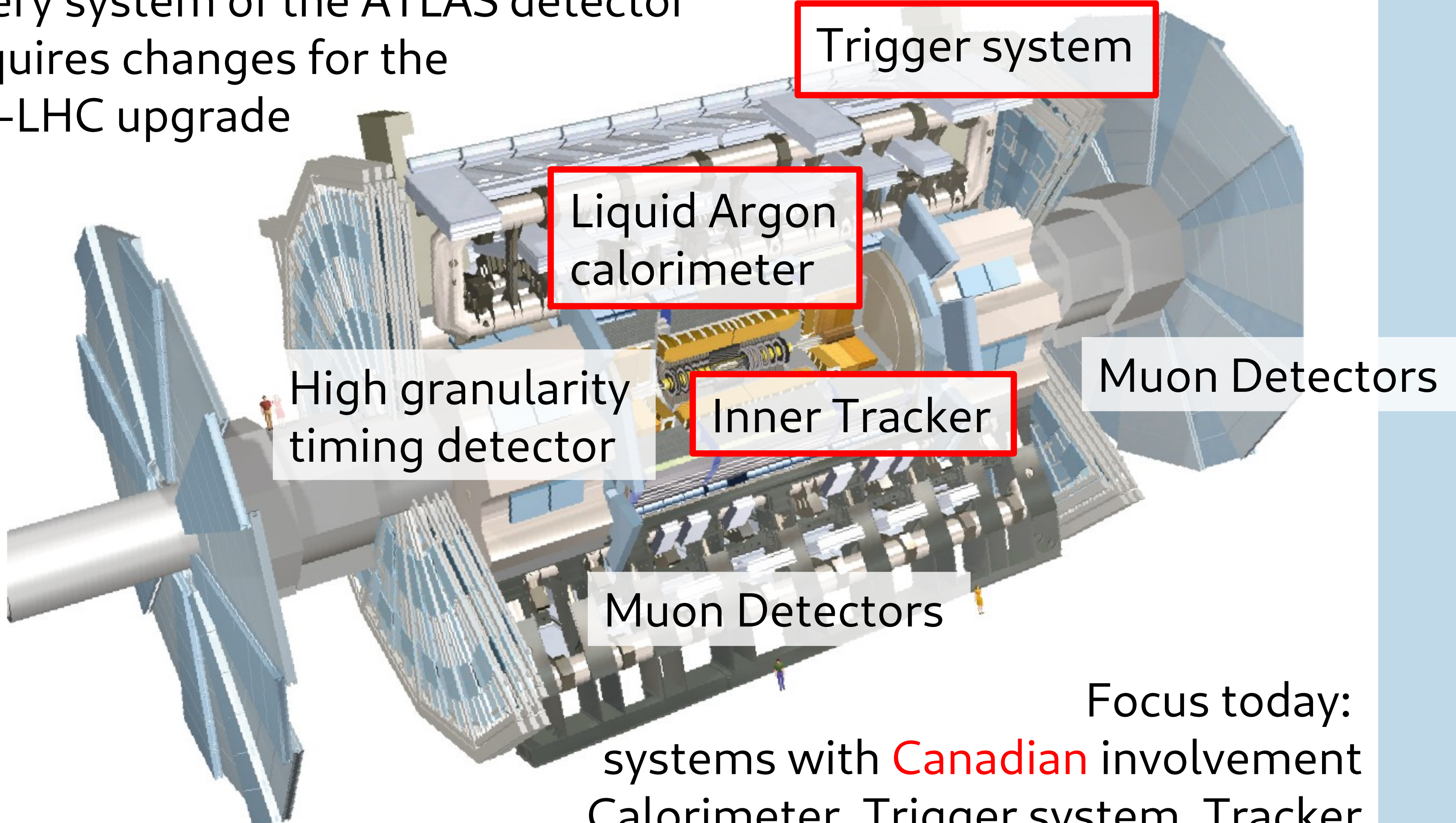
ATLAS Physics Briefing: Exploring the Higgs boson discovery channels - ATLAS releases full Run 2 measurements of Higgs boson properties



ATLAS public physics results: SUSY June 2021 Summary Plot Update

Upgrades of the ATLAS Detector

Every system of the ATLAS detector requires changes for the HL-LHC upgrade



Focus today:
systems with Canadian involvement
Calorimeter, Trigger system, Tracker

The Liquid Argon Calorimeter*

Liquid Argon Calorimeter:

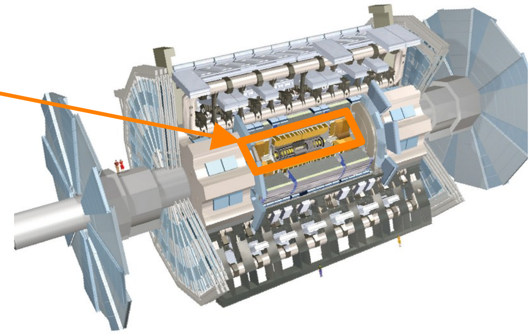
Several layers of calorimeter cells with high granularity for high resolution energy reconstruction

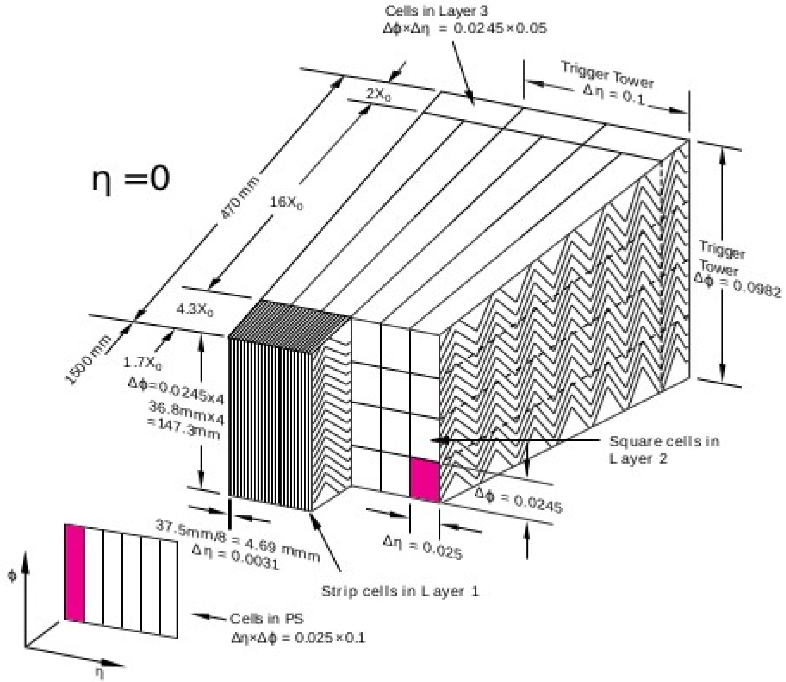
During collision event reconstruction, the full granularity of the detector of the detector is used for highly resolved energy reconstruction

However, the trigger system could not handle the amount of data …

… initially

The part of the detector used to find photons, (anti)-electrons and charged particles





*the granularity we were looking for was here all along!

The Liquid Argon Calorimeter

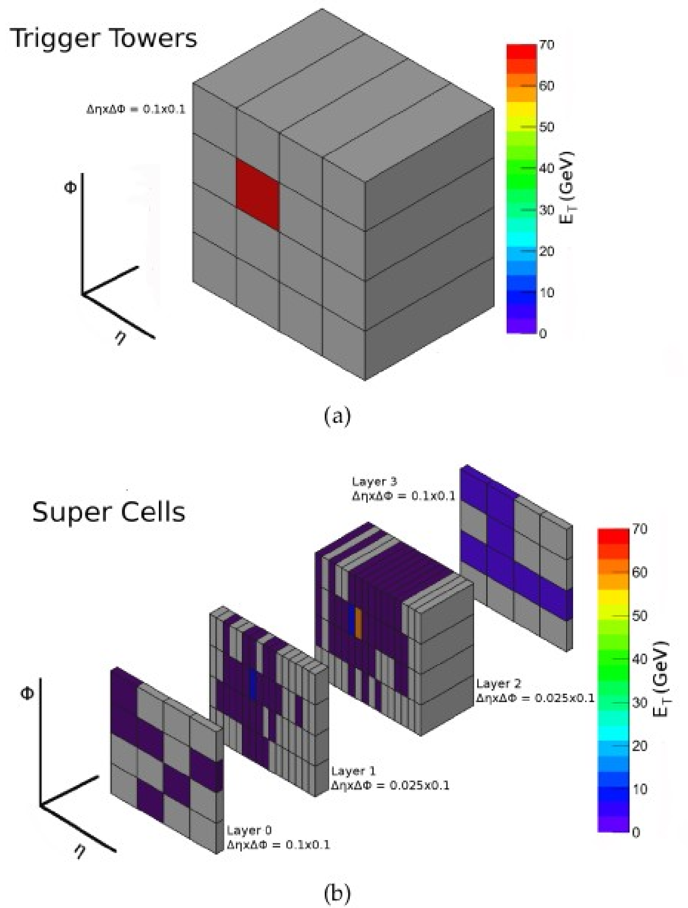
Original trigger information: combined trigger towers

Since the Phase-I Upgrade: triggering on super cells

Phase-II Upgrade:

- Use signals from individual cells for better triggering
- Move from analogue detector signal to digital
- Lots of options for machine learning and better signal processing

Next stop: trigger upgrades!



The trigger/DAQ system upgrade

Collision rate at the HL-LHC:

40 MHz

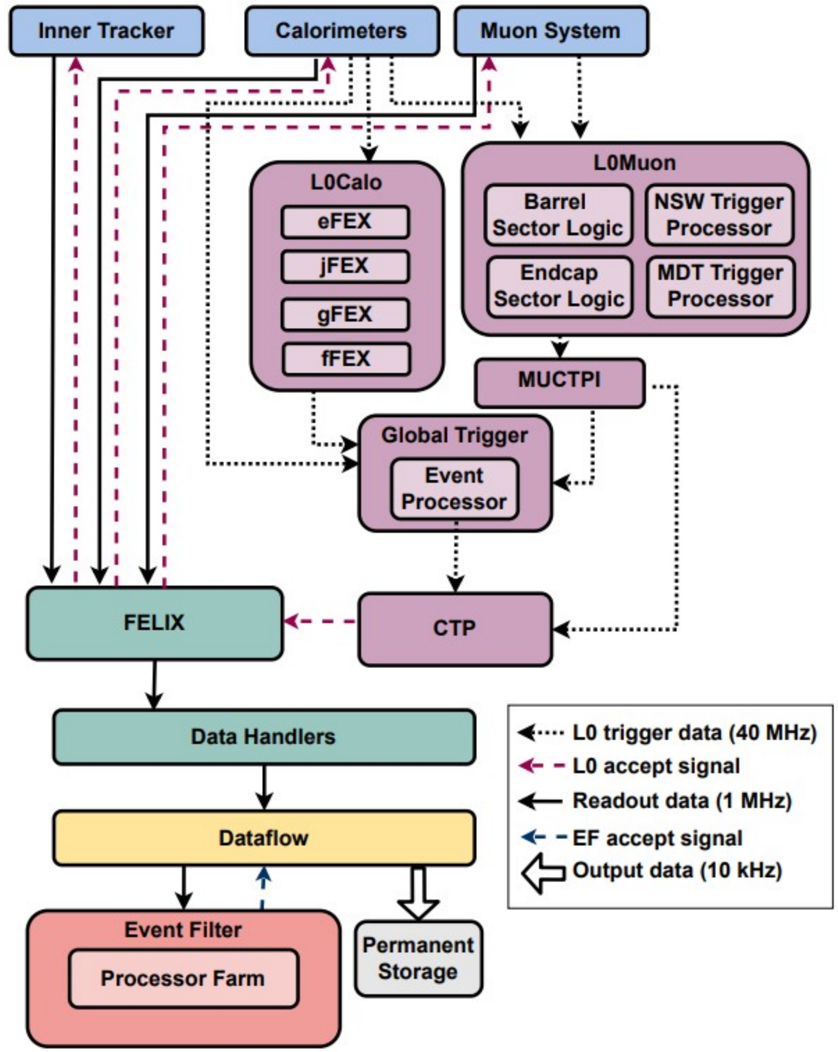
Data that can be stored and analysed later:

10 kHz*

How does that work?

Trigger experts will point to this diagram, because it explains everything

(about how triggering decisions are made for the ATLAS detector during the HL-LHC)



*this may seem wasteful, but a large fraction of collisions actually doesn't involve any interesting processes and doesn't need to be saved, so the job of the trigger system is to make sure that all the **interesting** events are moved to storage

The trigger/DAQ system upgrade

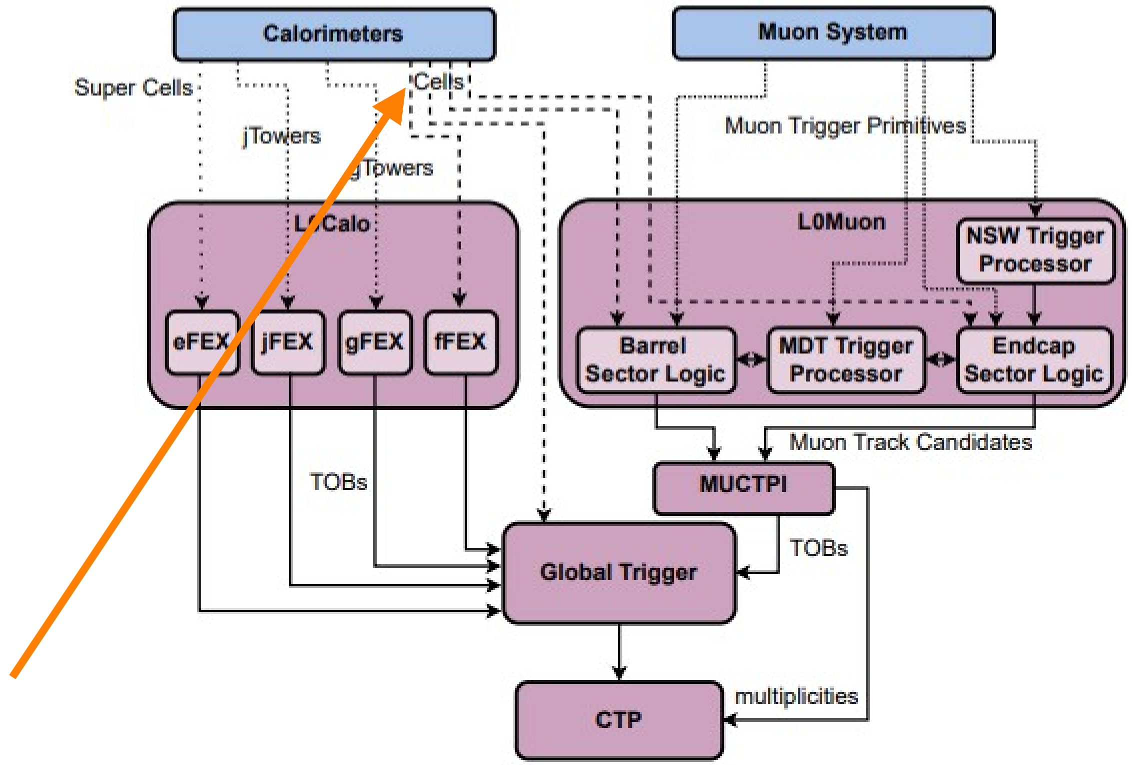
The important part:

The Global Trigger

Takes information from calorimeters and muon systems (40 MHz rate)

Now not only from towers (initially) and super cells (Phase-I), but also single cells (60 TB/s)

To inform decision about which event data to read out, process and store



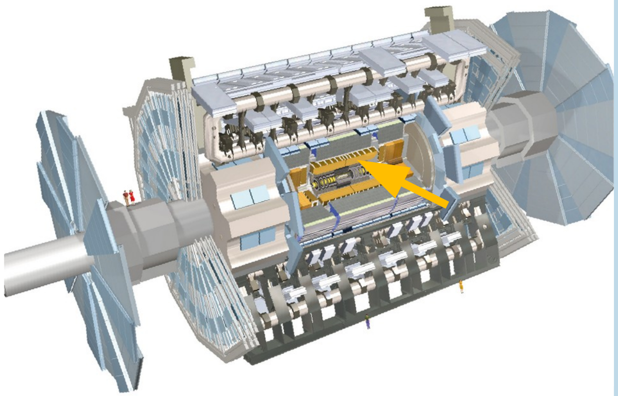
The calorimeter cell granularity always existed, but with the Phase-II Upgrade, it can be used for a better trigger

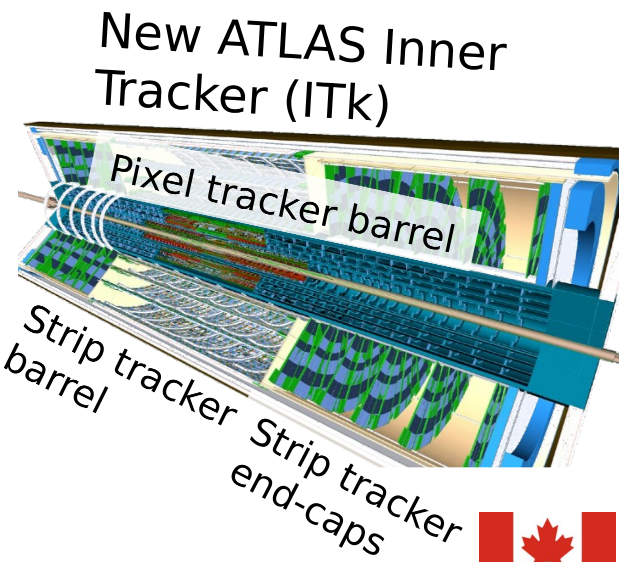
The ITk strip tracker*

ATLAS Inner Detector will have to be replaced

- Too much radiation damage
- Insufficient spatial resolution

- Construction of the new, all-silicon ATLAS Inner Tracker
  - More readout channels
  - Better spatial resolution
  - Higher radiation tolerance
  - In existing detector volume**

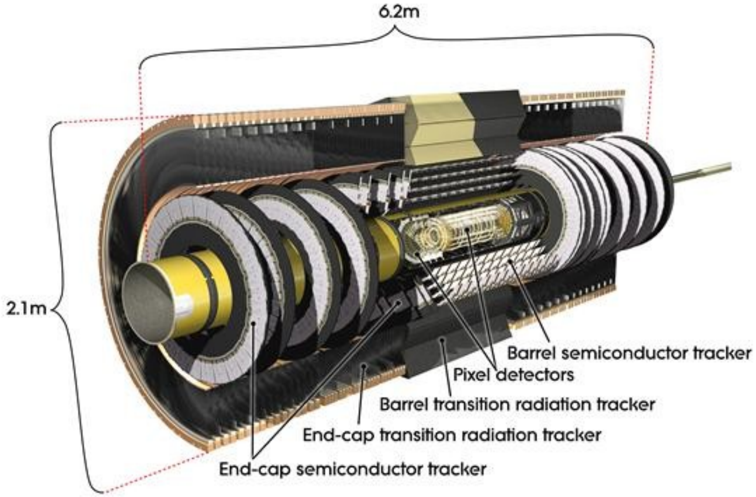


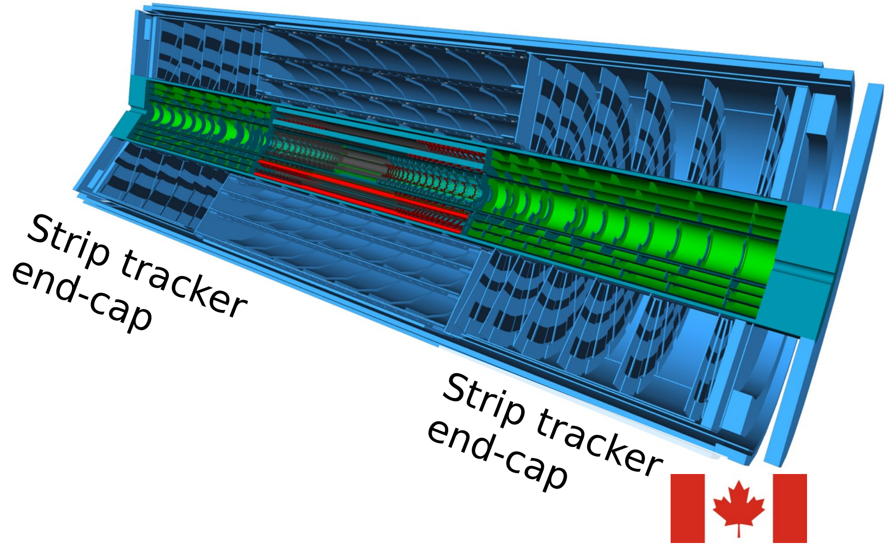


*out with the old, in with the new

**also: using the existing cables, which has surprisingly far-reaching implications

ITk strip tracker





Inner Detector: SCT

4088 sensors

6 million channels

60 m^2 of silicon

Dose: up to 3.8 MRad

Fluence: up to $2 \cdot 10^{14}$ n_{eq}/cm^2

Inner Tracker: strip tracker*

17,888 sensors

60 million channels

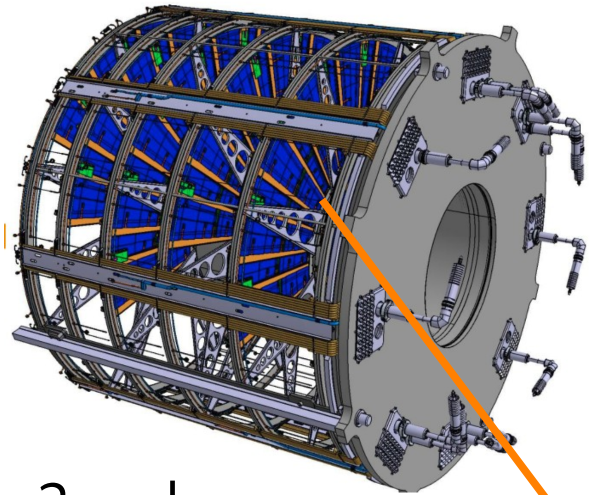
165 m^2 of silicon

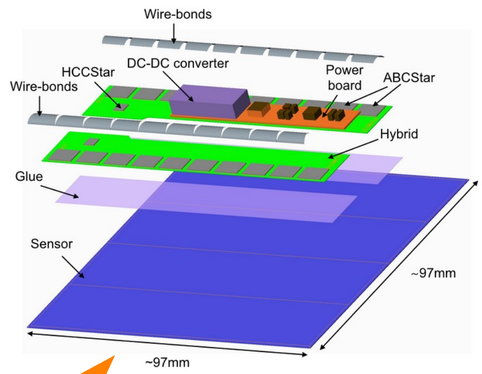
Dose: up to 50 MRad

Fluence: up to $1.2 \cdot 10^{15}$ n_{eq}/cm^2

*bigger, better, faster, stronger

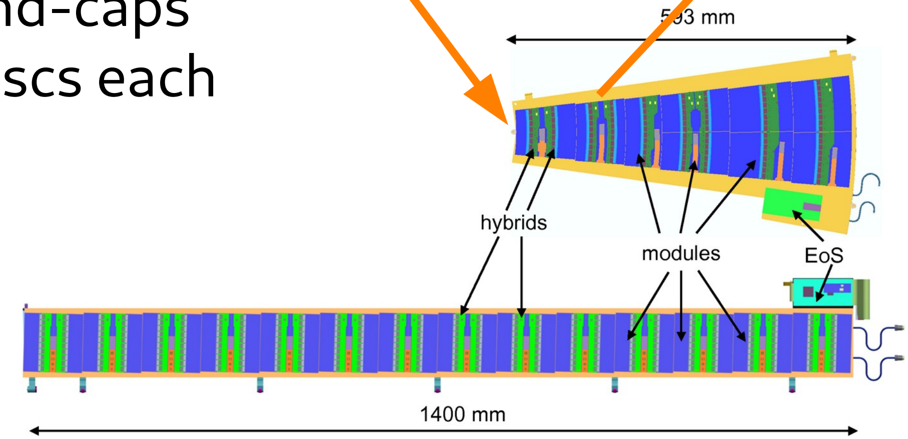
The ITk strip tracker (end-cap)





6 end-cap module types
4608 modules total
(¼ built in Canada)

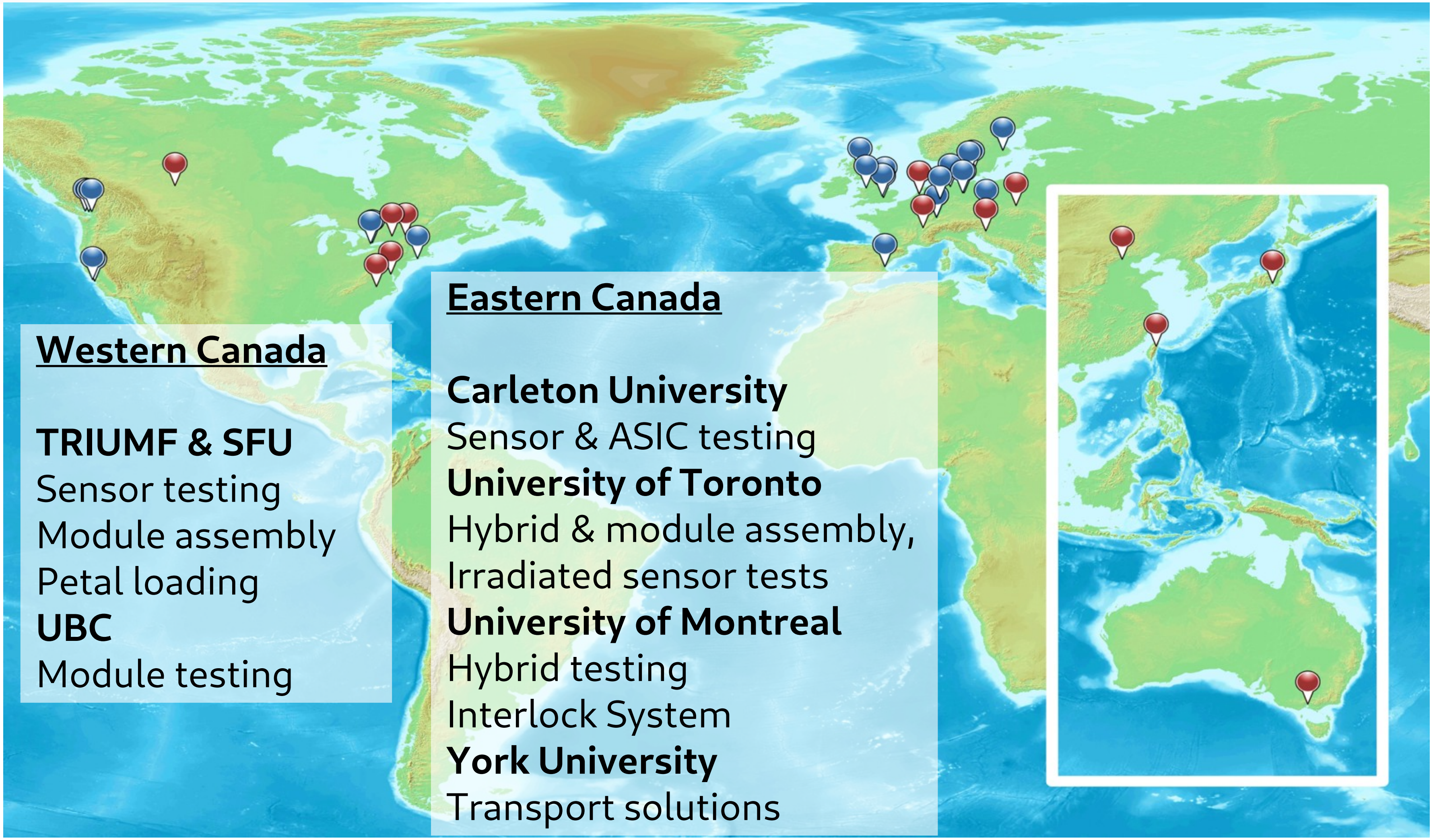
2 end-caps
6 discs each



32 petals per disc
(12 modules per petal)

384 petals total
(¼ built in Canada)

The ITk strip tracker (globally)



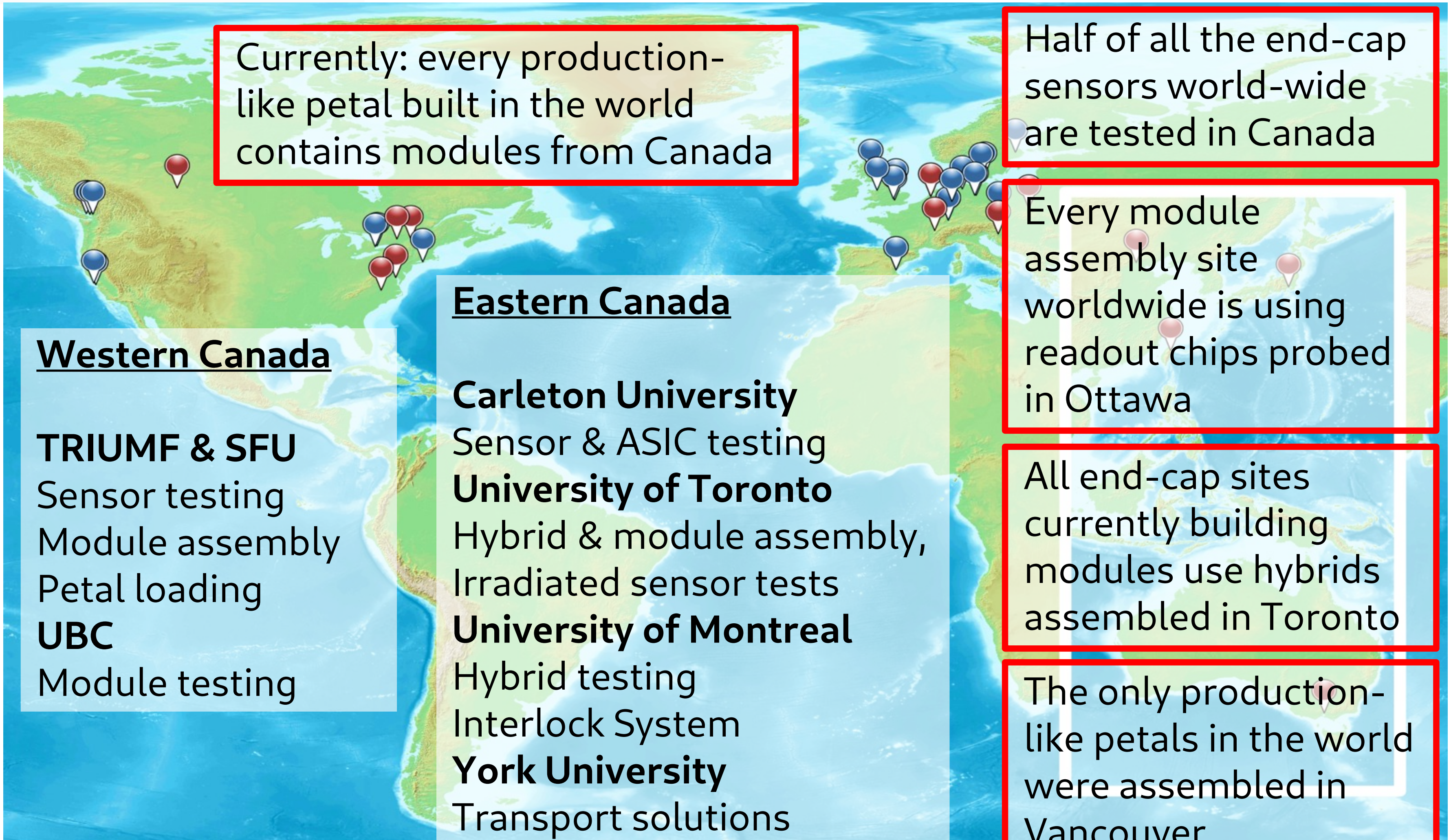
Western Canada

TRIUMF & SFU
Sensor testing
Module assembly
Petal loading
UBC
Module testing

Eastern Canada

Carleton University
Sensor & ASIC testing
University of Toronto
Hybrid & module assembly,
Irradiated sensor tests
University of Montreal
Hybrid testing
Interlock System
York University
Transport solutions

The ITk strip tracker (globally)



Currently: every production-like petal built in the world contains modules from Canada

Half of all the end-cap sensors world-wide are tested in Canada

Western Canada

TRIUMF & SFU
Sensor testing
Module assembly
Petal loading
UBC
Module testing

Eastern Canada

Carleton University
Sensor & ASIC testing
University of Toronto
Hybrid & module assembly,
Irradiated sensor tests
University of Montreal
Hybrid testing
Interlock System
York University
Transport solutions

Every module assembly site worldwide is using readout chips probed in Ottawa

All end-cap sites currently building modules use hybrids assembled in Toronto

The only production-like petals in the world were assembled in Vancouver

Canada in the international project:

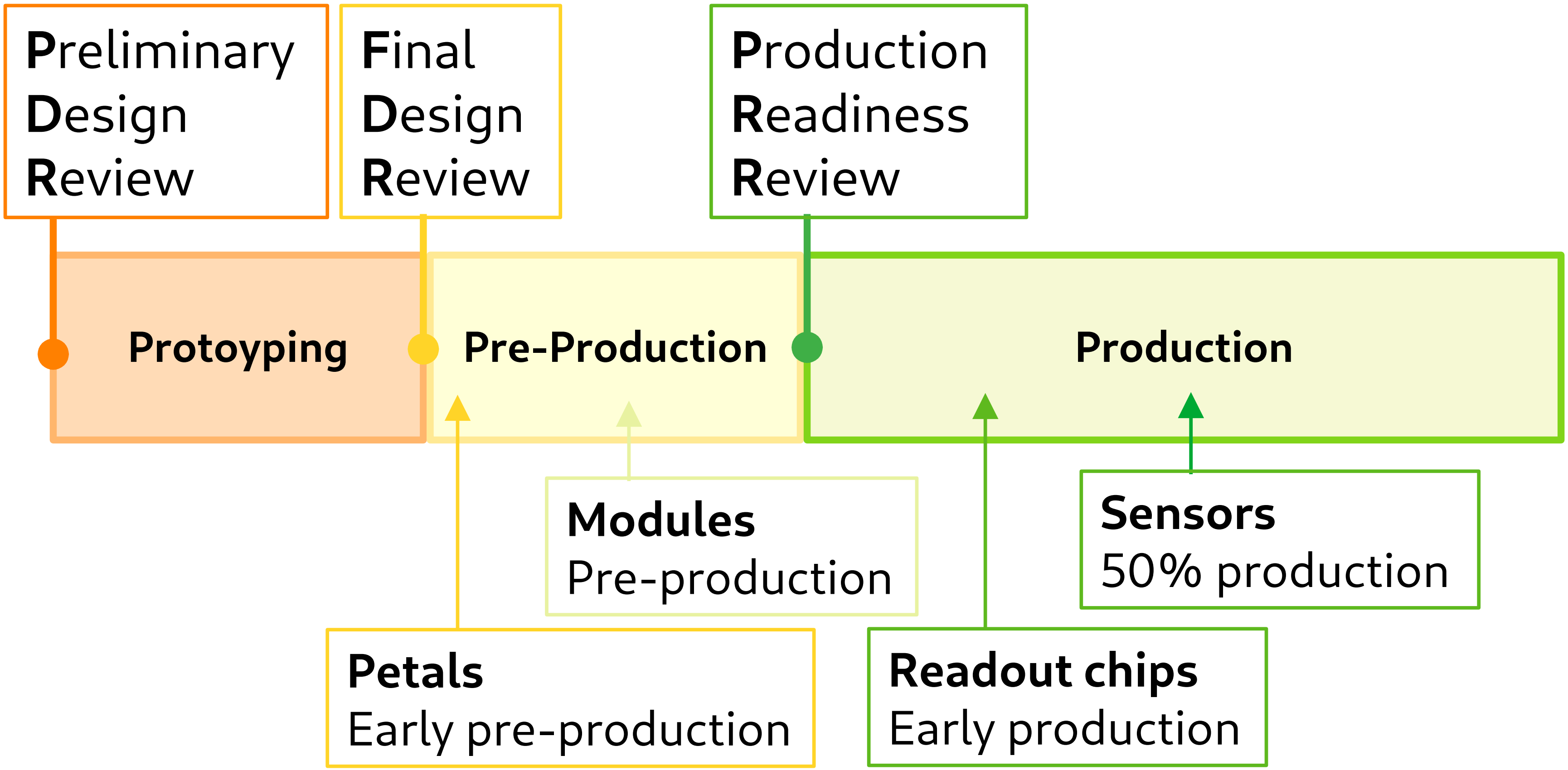
Deputy ITk project leader: Thomas Koffas (Carleton)

Testbeam activity coordinator: John Keller (Carleton)

Module activity coordinator: Luise Poley (TRIUMF/SFU)

Petal loading coordinator: Bernd Stelzer (SFU/TRIUMF)

2023 - Where we are now



Modules: the year of 2022

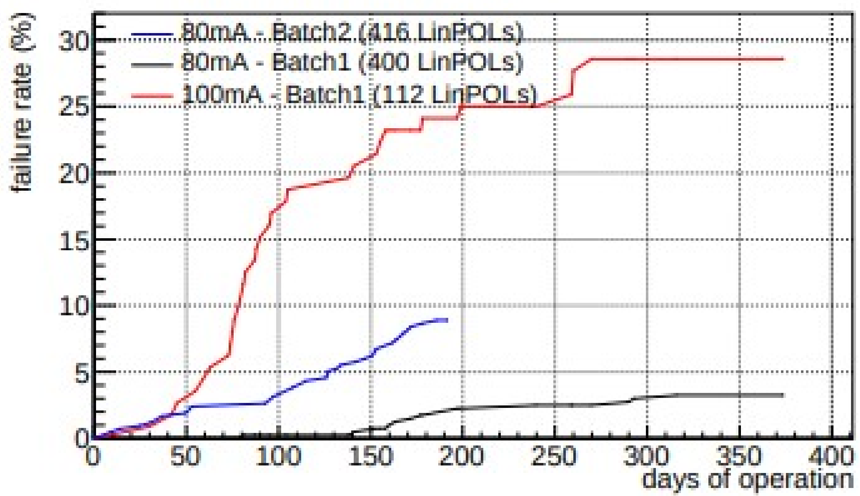
2022 was supposed to be the year of the module PRR

Instead: a series of problems each individually representing major delays, compounding each other

1) Chip reliability problems
premature deaths of linPOLs in reliability tests
2) Death by irradiation
sudden module deaths after irradiation
3) Split module noise
excess noise in R4 and R5 modules
4) Cold Noise
noisy module channels at -40 degrees
5) Glue selection
default module glue unavailable

Reliability problems

- LinPOL is a linear regulator used to power part of a module
- Spec load limit of linPOL (80 mA) close to actual load
- Early tests showed large numbers of failures (later attributed to SMD mixup)
- Alarming number of failures at 80 mA in second batch with correct population, attributed to lack of cooling by designers
- After discussion with designers: start of third batch with cooling, no failures
- Problem solved

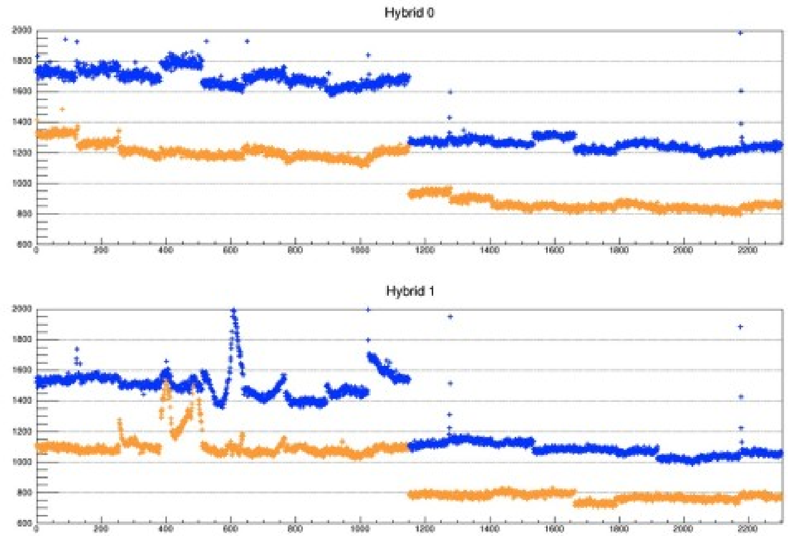


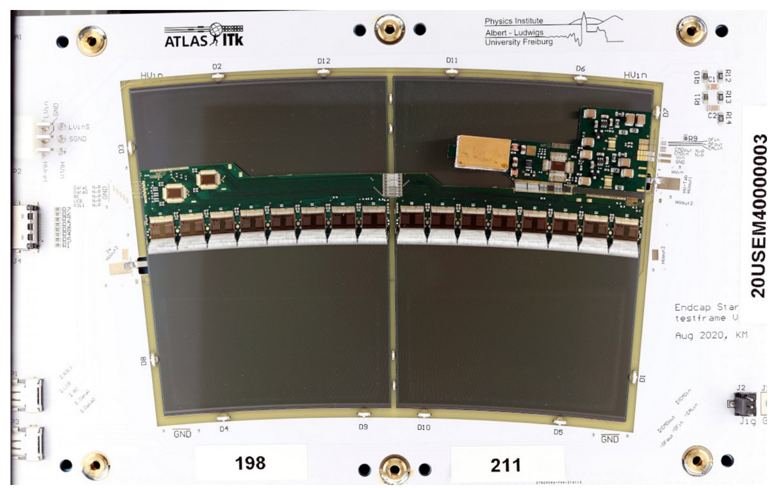
Batch	load	#linpols	#days	#failed (%)
Batch1	80 mA	400	374	13 (3.2%)
	100 mA	112	374	32 (28.6%)
Batch2	60 mA	48	192	0 (0%)
	70 mA	48	192	0 (0%)
	80 mA	416	192	37 (8.9%)
Batch3	60 mA	344	0	-
	70 mA	344	0	-
	80 mA	336	0	-

240 days without any failures!

Excessive noise of split end-cap modules

- Most end-cap module types were first built in 2022*
- Excessive noise observed on first R4 + R5 modules**
- Four months to find issue (filter on powerboard)
- Re-design and reordering of powerboards
- Additional delay: changed design rules at manufacturer (extra round of re-design needed)
- New powerboards only available in early 2023
- Noise performance of new powerboards is in spec!





*a necessity due to limited funds during prototyping and high cost of sensor mask design

**the only place building this module type at the time was Vancouver, therefore most of the investigation was done here

(although the final fix was made in Germany)

Cold Noise

Discovery in May 2022:

When cooling down modules, clusters of extremely noisy channels appear in certain locations on modules

A year-long investigation followed

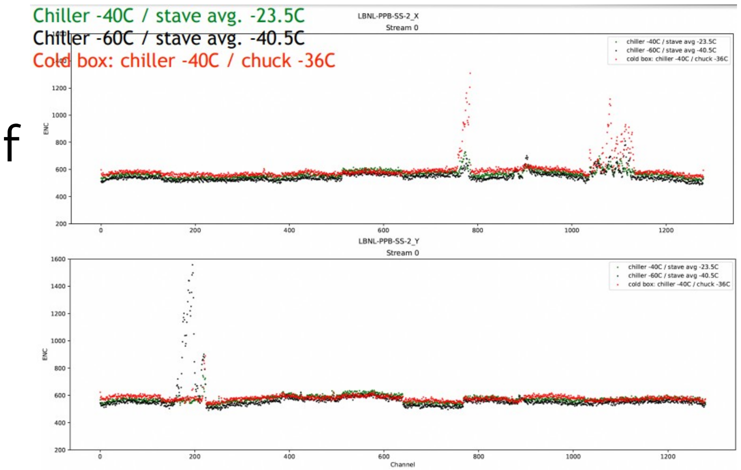
→ Identified that Cold Noise only occurs when powerboard is present and powered

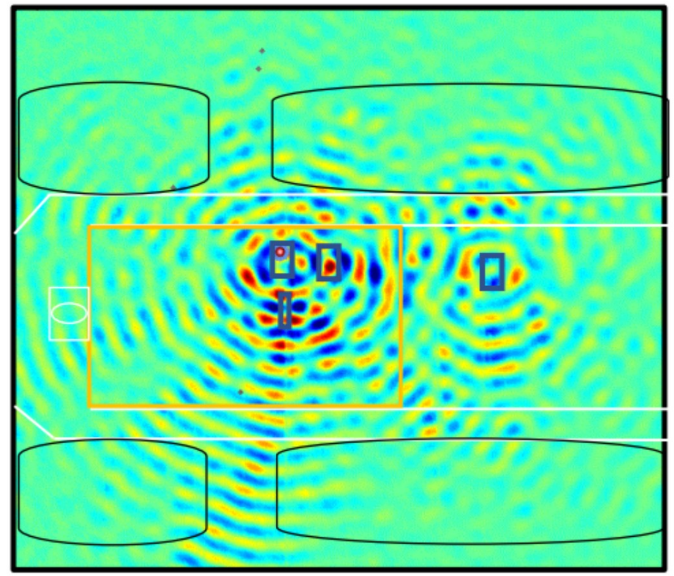
→ found that more load leads to more Cold Noise

→ Found that cause of Cold Noise are vibrations on powerboard

→ Found that capacitors vibrating on powerboards cause Cold Noise*

Good news: does not affect the end-cap





*how exactly a vibrating sensor leads to noise in our readout chips and why only when cold has not been fully understood yet, but everyone agrees that if you intentionally tried to build a system that was able to produce, transmit and detect vibrations, it would be almost impossible to fine-tune the system to be as efficient as ours accidentally is

Finding a new glue for production

Default glue no longer being produced

Investigation into alternatives:

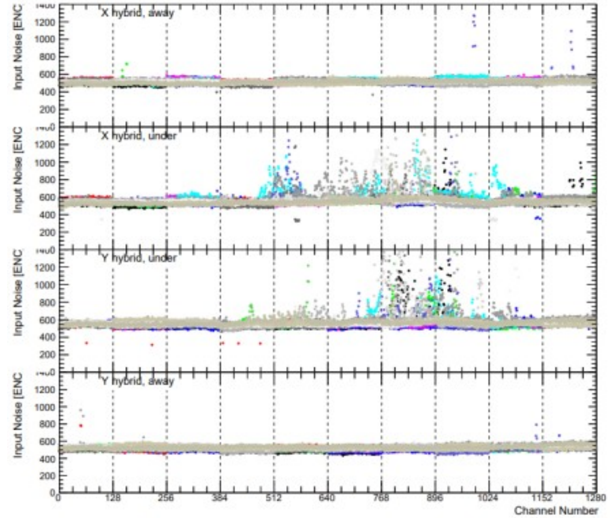
Chemical analysis

Sensor tests before/after gluing and irradiation

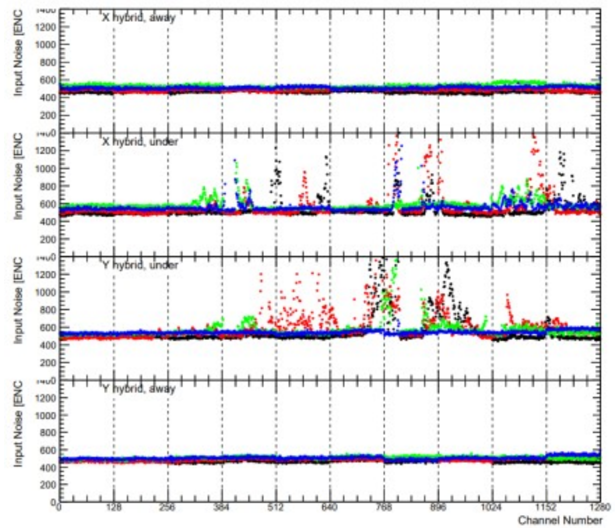
Shear tests pre/post irradiation

Differential scanning calorimetry

Glue dispensing and mixing



Initially: did not expect correlation between cold noise/glue choice (mechanism still unclear), both investigations separate and in parallel

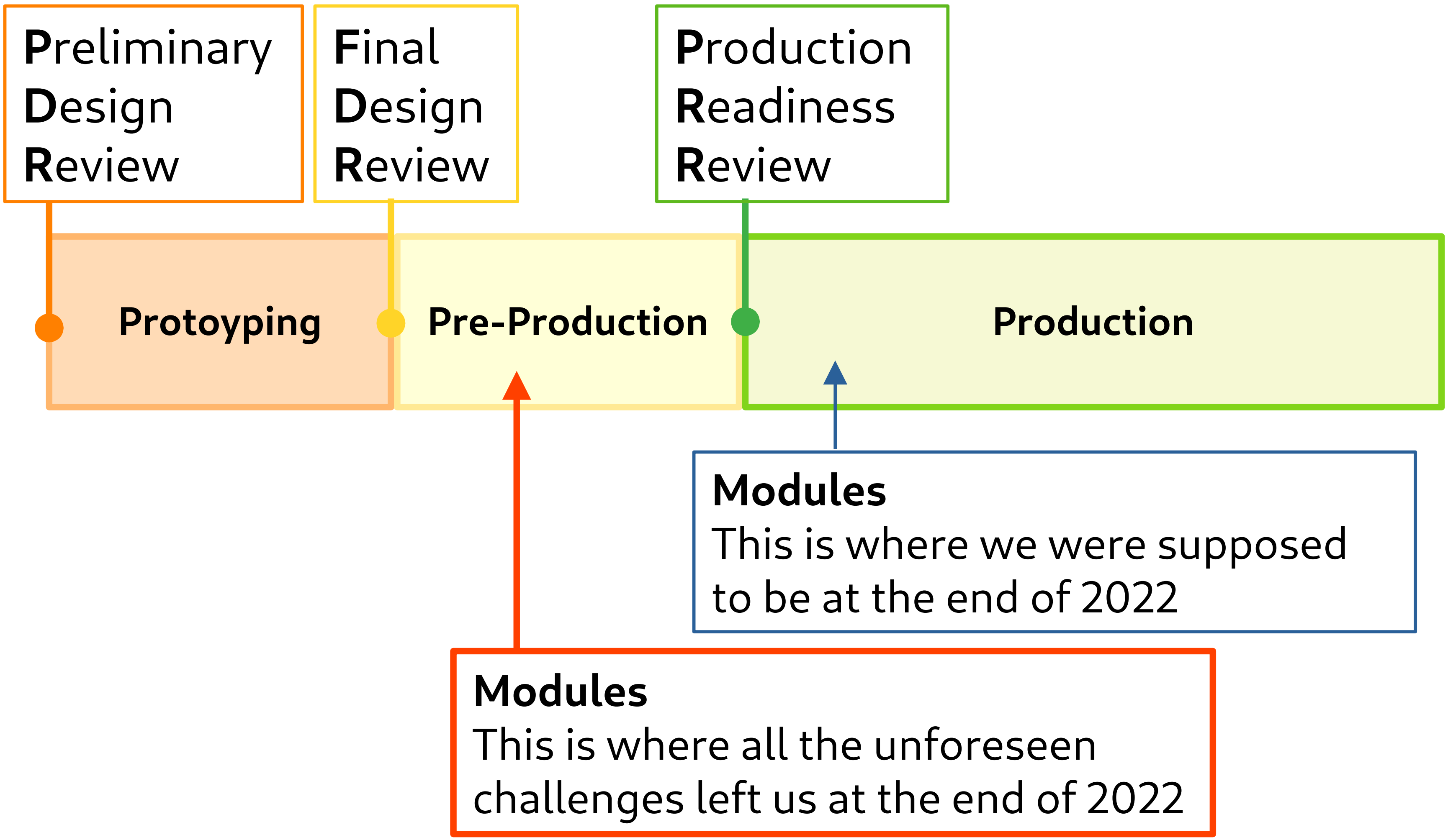


Then: discovered that glue affects degree of cold noise on modules for unknown reasons

Selection of the glue showing best cold noise performance

Two good candidates remaining

Its' been quite a year

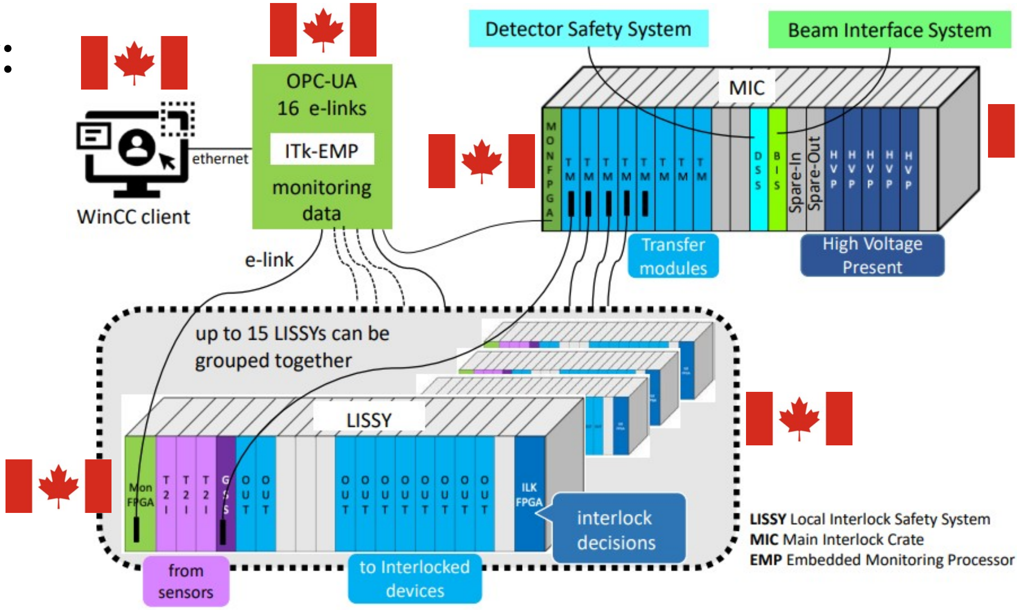


Interlock system*

Major threats to detector:

- Overheating (whole detector or individual units)
- High humidity (crossing dew point)
- Failure in cooling system
- Unstable beam
- Smoke

→ Interfaces with sensors and detector controls



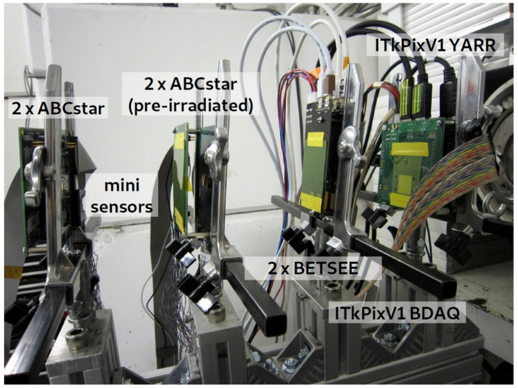
But also:

Interlocks on individual sub-systems (e.g. to turn off individual modules in case of high current or temperature), linked to individual detector units

*because anything can kill a sensor or module

Towards the future

A lot of effort is being dedicated, infrastructure built and expertise developed for the upgrade(s) of the ATLAS detector in Canada

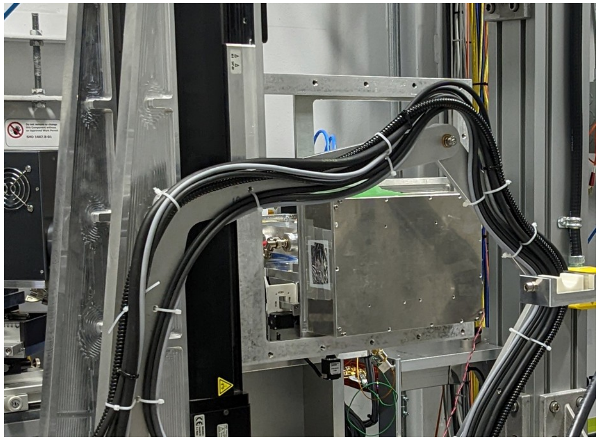


- Cleanrooms at several institutes
- Assembly and testing infrastructure set up
- Industry collaborations for assembly and testing
- Development of advanced methods using existing infrastructure in Canada (particle beams, beam lines at Canadian Lightsource)

Putting us in the perfect position to participate in the construction of a detector for the next collider experiment

→ readout chips, sensor development, beam tests, precision assembly, readout tests …

Whatever the next collider will be!



BACKUP