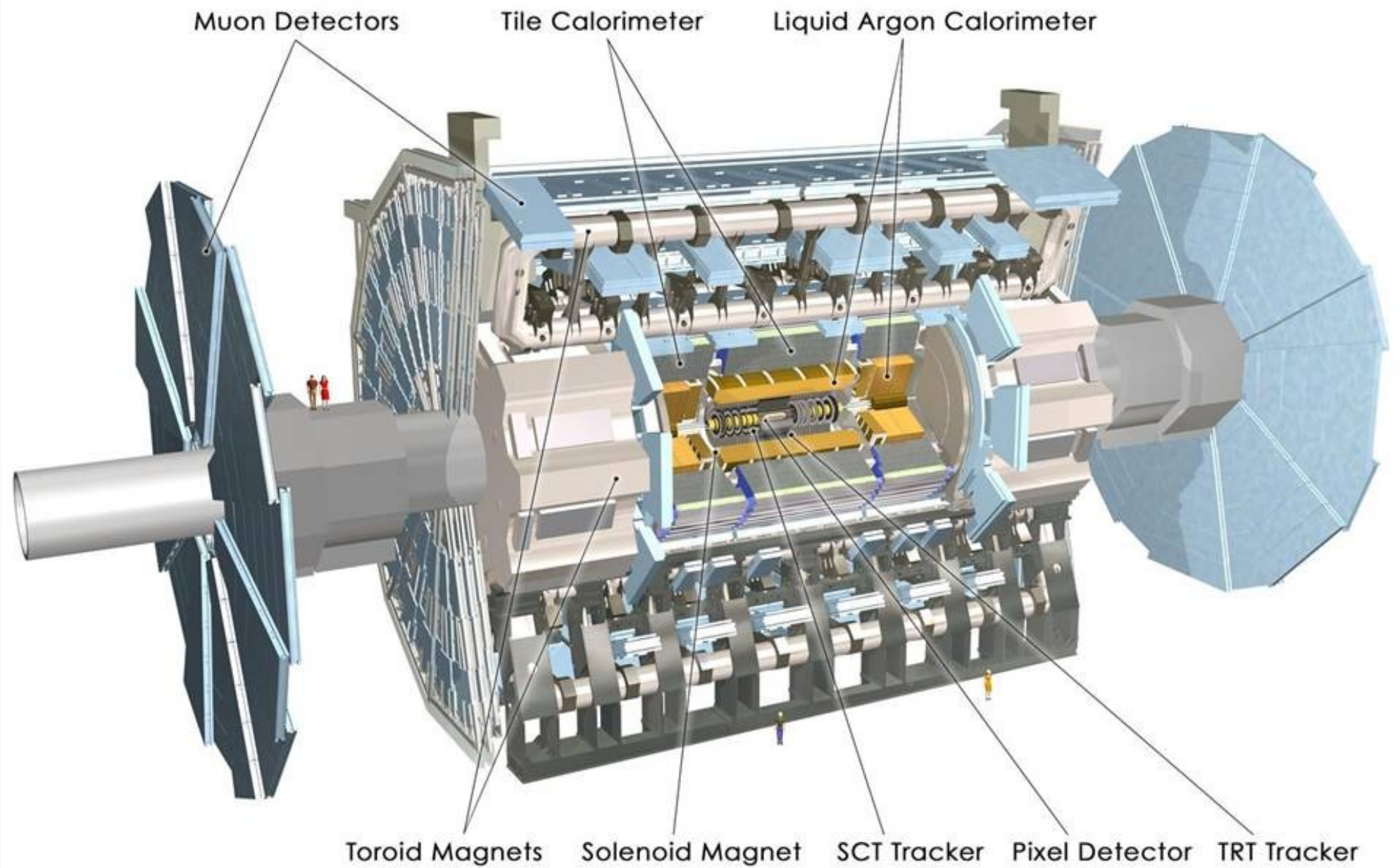


ATLAS Upgrades for High Luminosity

A visualization of a particle detector event, showing a dense spray of blue and green lines radiating from a central point, representing particle tracks. The tracks are overlaid on a grid of white dashed lines. The text is centered over this visualization.

Introduction: ATLAS and the need to upgrade
Phases of ATLAS Upgrades
ATLAS Detector Upgrade Plans

Introduction - ATLAS



Physics goals of sLHC

Main ATLAS Physics goals:

Higgs discovery: Mass and understanding electro-weak symmetry breaking

Unification of forces, gravity, Super SYmmetry, extra dimensions

New forces (W' , Z')

Flavour: why 3 families, neutrino mass, dark matter

Whatever is discovered at the LHC will need a lot of data to understand exactly what has been discovered: characterising the discoveries.

In addition, the sLHC can extend the discovery potential, to higher masses or lower cross-sections.

While the LHC aims at $\sim 300 \text{ fb}^{-1}$ per experiment, the sLHC aims for 3000 fb^{-1} of data, opening up new possibilities for channels limited by statistics at the LHC

There are many measurements where extending the LHC data set is important, including:

1. Higgs couplings
2. Triple gauge-boson couplings
3. Vector boson fusion at $\sim 1 \text{ TeV}$
4. SUSY – discovery or spectroscopy
5. New forces: W' , Z' to higher limits

Why Upgrade?

There are many important results that will benefit from a much bigger data set

Technology improves, and we can build better performing detectors now

Detectors age, especially with accumulated radiation damage, and need replacement: better to plan ahead and replace with the best allowed by technology

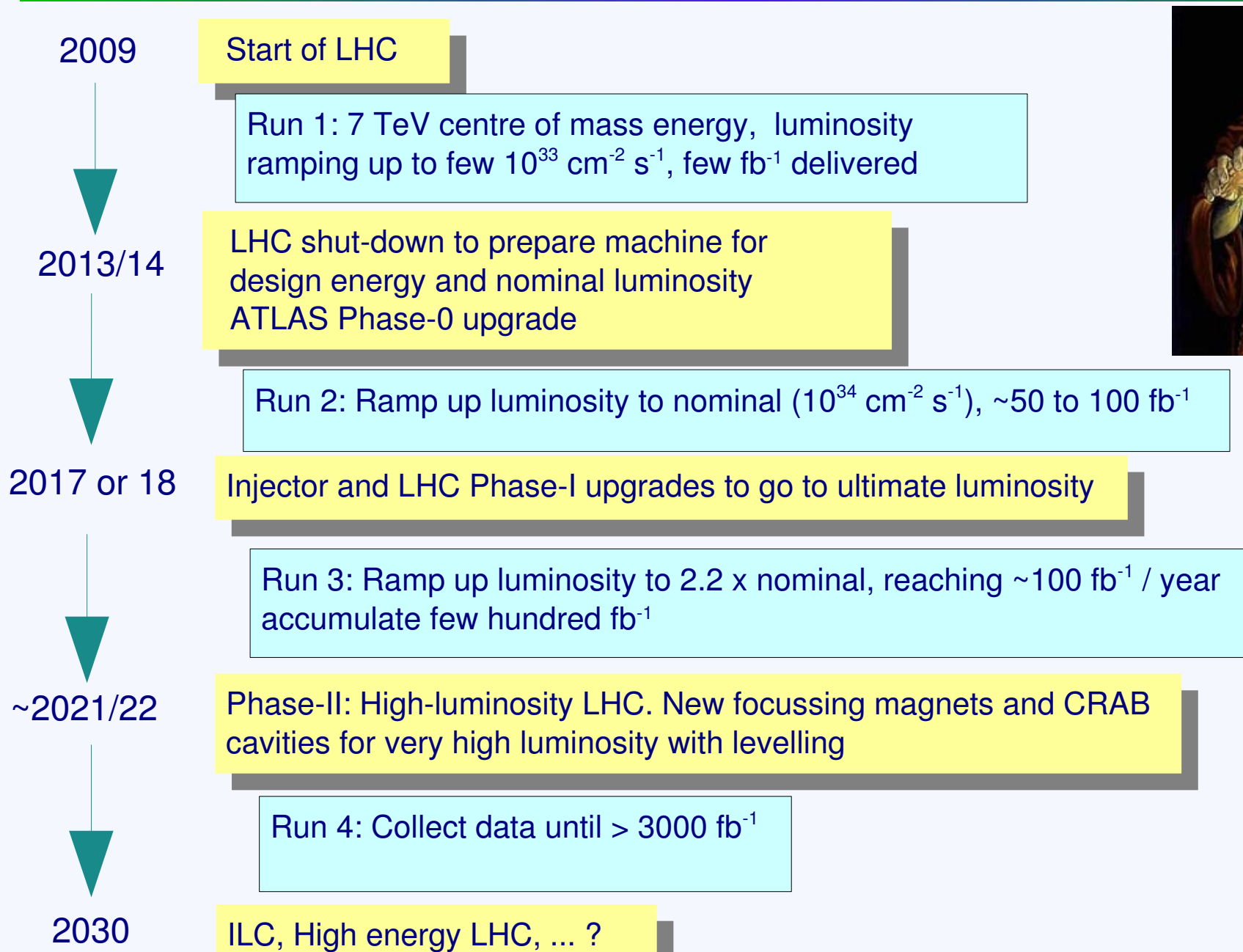
The LHC will improve, in particular delivering higher instantaneous luminosity than ATLAS was designed for: needs higher granularity detectors to maintain performance

It takes a long time to install new detector elements, which has to be done with the LHC off

ATLAS will take maximum advantage of all LHC shut-downs to make the best possible detector

It takes many years to research ideas, design upgrades, and build them, especially new inner trackers, hence the work started several years ago

Summary Possible ATLAS/LHC Upgrades Time-line



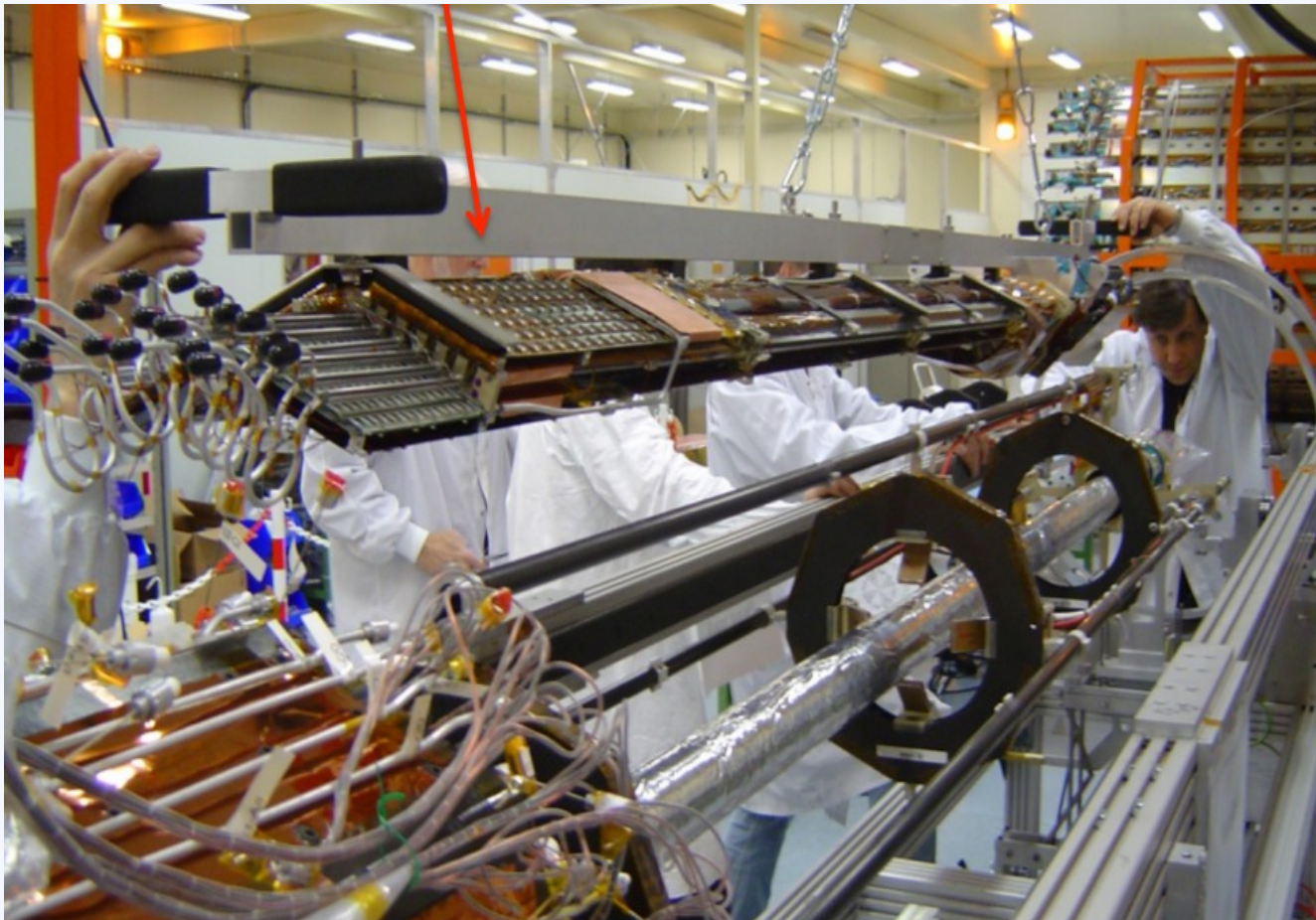
ATLAS Changes for Phase-0, 2013/14 shut-down

Many consolidations, de-staging such as better muon trigger cover, new syphon cooling system, new beam-pipes, repairs, improvements for reliability etc. not covered here

nSQP

New pixel service quarter panels (nSQP):

Possible ageing problem detected for the light-emitting VCSELS used for data transport
Project under way to replace the entire service quarter panels of the pixel detector in 2013
If this has to be done, we have to bring the entire pixel detector to the surface
In that case, it is highly desirable to also install the IBL at the same time



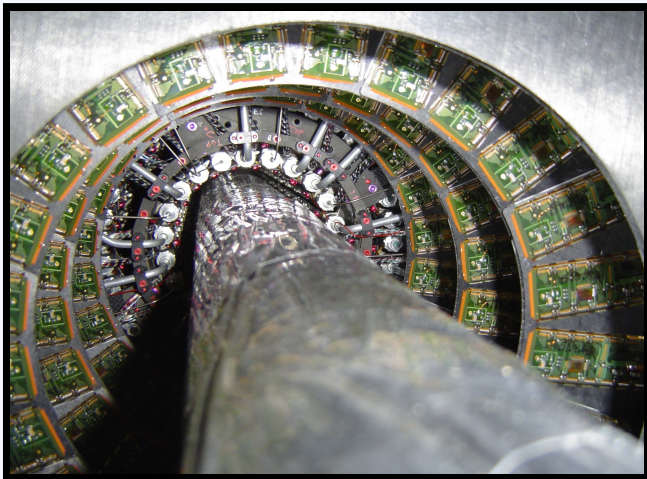
New B-layer (IBL)

The pixel detector very close to the interaction point has a unique role: detecting secondary vertices away from the main interaction point, to identify b-quarks. The inner most layer is the most important one for this and hence is known as the B-layer.

The current ATLAS B-layer will become inefficient after the Phase-I LHC upgrade (max. bandwidth exceeded in front-end chips; radiation damage)

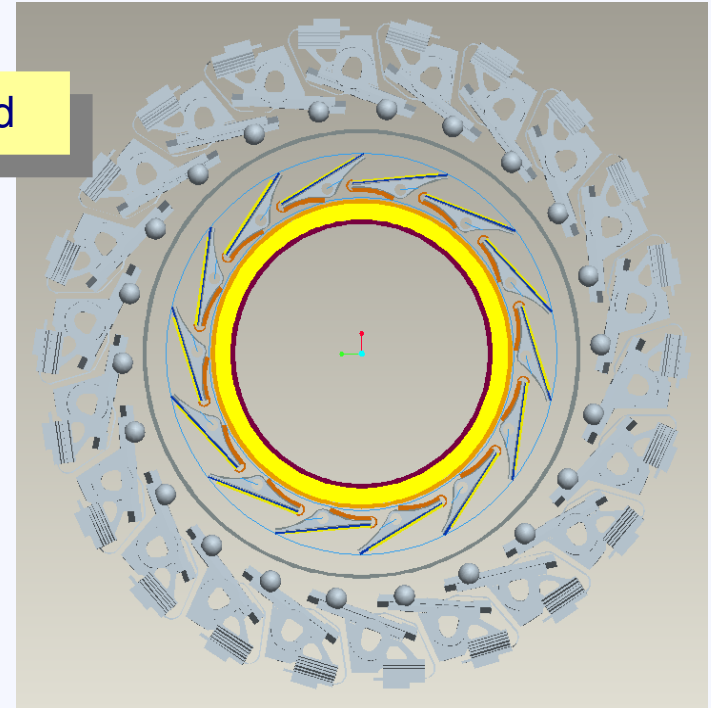
Very difficult to remove the old one and re-insert a new one; instead, insert a completely new layer, "Insertable B-Layer, IBL" inside the current one: 3 layer system becomes a 4 layer one

Requires smaller beam-pipe to make space; 29 mm radius --> 22.5 mm



Current beam-pipe and pixel detector; space is tight!

New layer inside the old



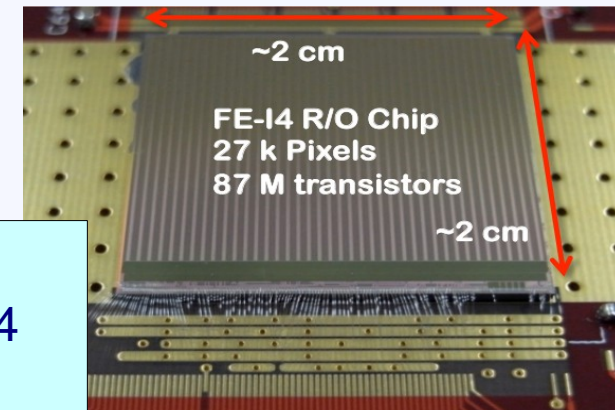
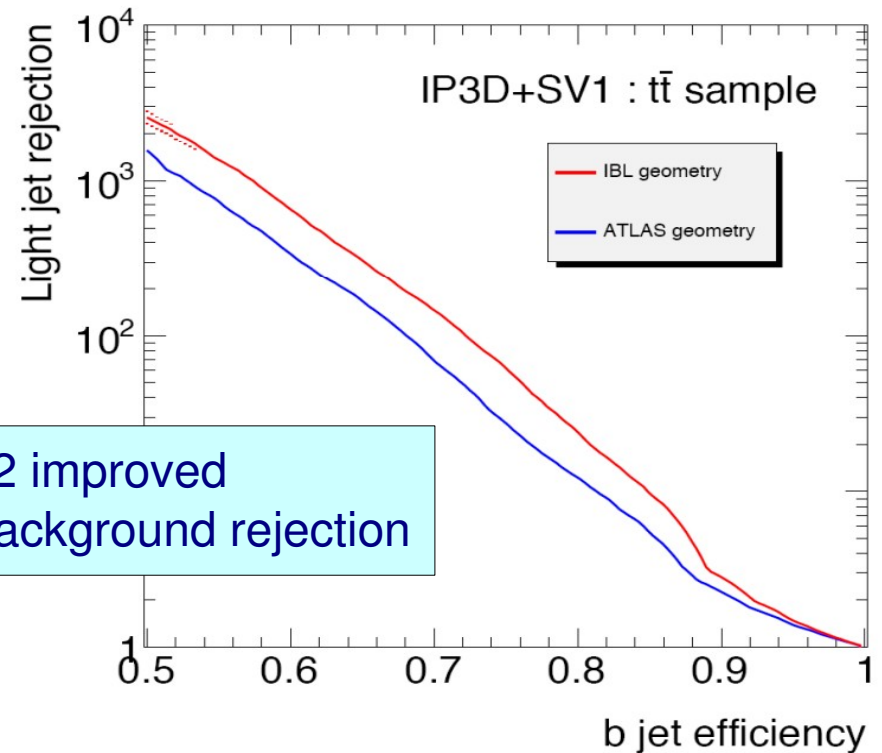
IBL Status

IBL was planned to be ready in 2015, for installation in the 2016 shut-down. Now the LHC will run in 2012 these shut-downs are delayed. There are several **reasons to bring forward the IBL installation into the 2013 shut-down:**

- It improves the physics performance of ATLAS, even at low luminosity
- Less risk/tooling needed to install when the pixel detector is removed for nSQP installation
- Lower radiation environment in 2013 compared to 2017/18
- 2017/18 is a long wait...

ATLAS IBL project will accelerate to install in 2013/14:

-- **very challenging, but looks possible**

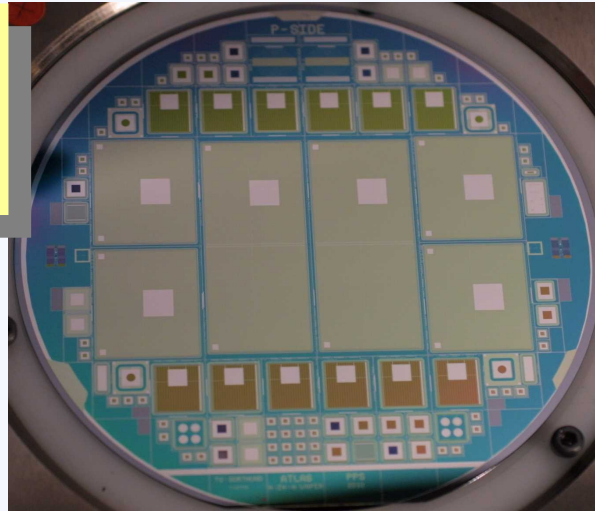


New front-end readout chip FE-I4 delivered and performing very well

IBL Status

Planar silicon sensors delivered

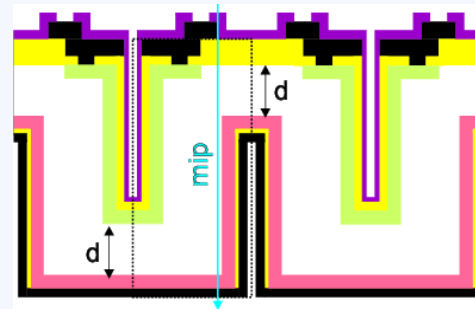
Various thicknesses



Thickness [μm]	Ordered	Received
250	12	18
225	6	11
200	6	10
175	6	11
150	6	8

3D-sensors have chosen double-side 3D to reduce complexity

200 microns guard fences and 230 microns thick
Shown to be **radiation hard** with moderate bias voltage (120-150V at $5 \times 10^{15} \text{ ncm}^{-2}$) and low power dissipation



(Diamond possibility postponed to future upgrades)
Sensor technology to be decided in June 2011

Bump bonding, module manufacture, stave manufacture and module loading all under preparation, and if all goes well it can be installed in 2013

ATLAS Changes for Phase-1, 2017 or 18 shut-down

Conditions and trigger

About 9 months shut-down for installation of new elements

Conditions after:

Peak luminosity increasing to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Total integrated luminosity before Phase-II 3-400 fb^{-1}

Phase-I Task-Force in place to optimise ATLAS Phase-I upgrades

With the delay from 2016 to 2017 or 18, we can do more

Options under study given here; what cannot be done in Phase-I will move into Phase-II

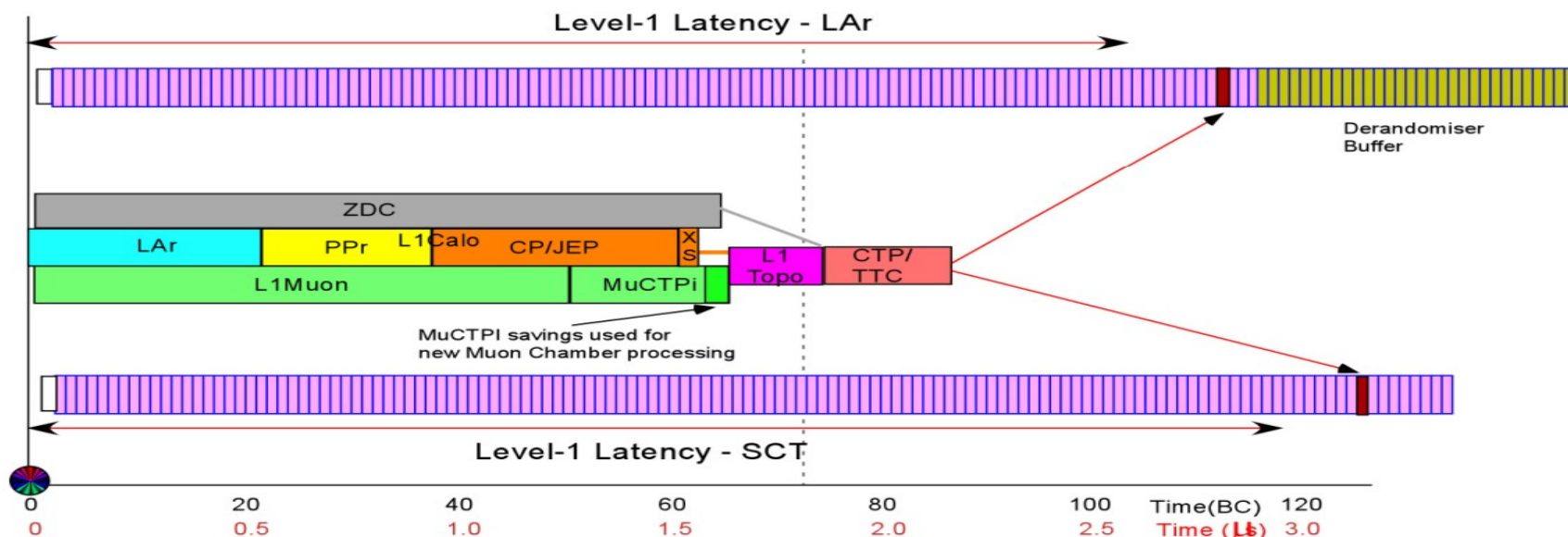
Trigger:

Beef up processors and data links for extra data rate

Bring in “topological” triggers – the ability to look at 2 or more trigger objects at L1

e.g. isolated muon = muon far from any jets

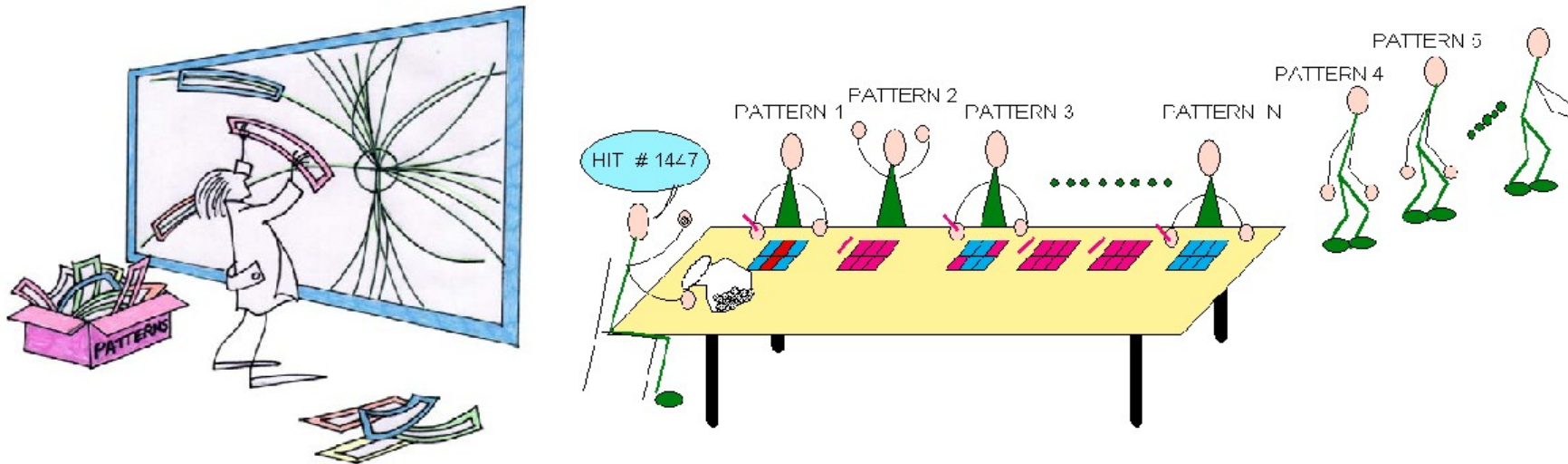
Missing Et significance trigger



Level-2 fast track finder, FTK (before the SD)

Two time-consuming stages in tracking

- **Pattern recognition** – find track candidates with enough Si hits



- **10^9 prestored patterns simultaneously see each silicon hit leaving the detector at full speed.**
- **Track fitting** – precise helix parameter & χ^2 determination
 - **Equations linear in local hit coordinates give near offline resolution:**

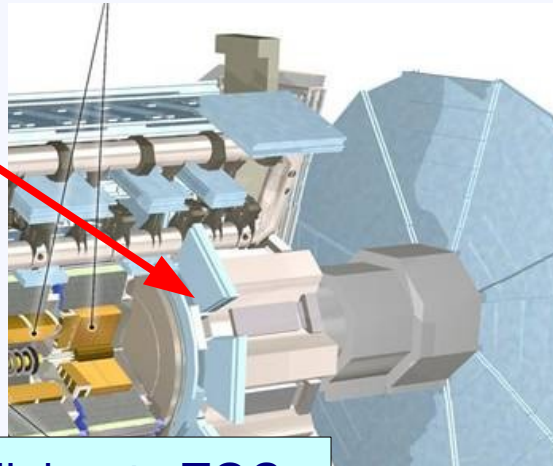
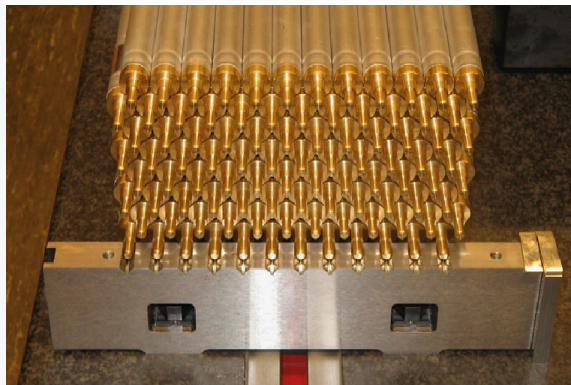
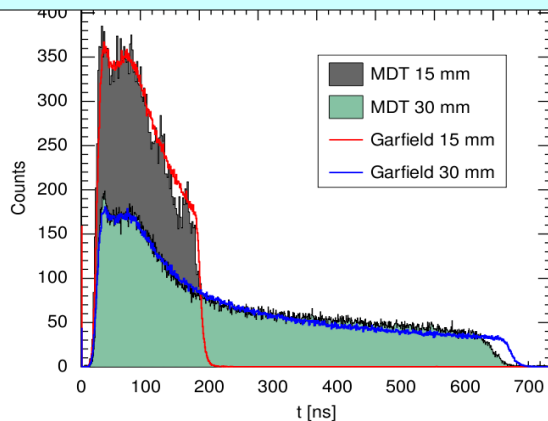
$$p_i = \sum_{j=1}^{14} a_{ij} x_j + b_i \quad a \text{ \& \& } b \text{ are prestored constants; VERY fast in FPGA}$$

Muon Small Wheels

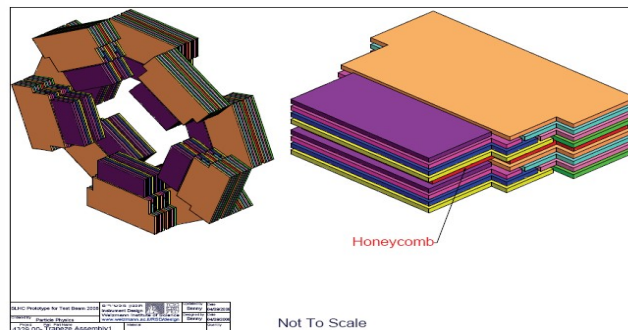
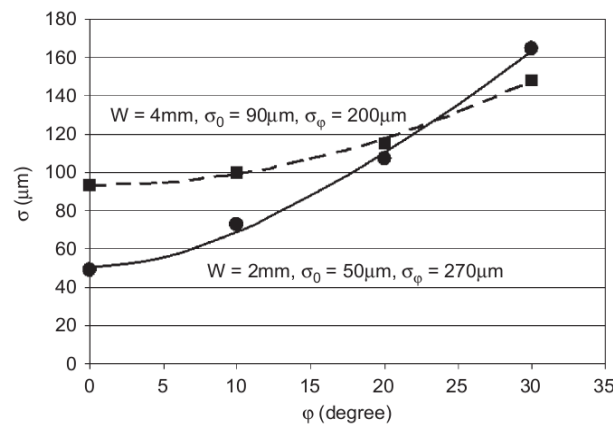
New Muon Small-Wheels

- Sharper trigger in forward region
- More space for shielding with dual purpose thinner chambers

Small diameter drift tubes:
much shorter drift time, high
rate capability



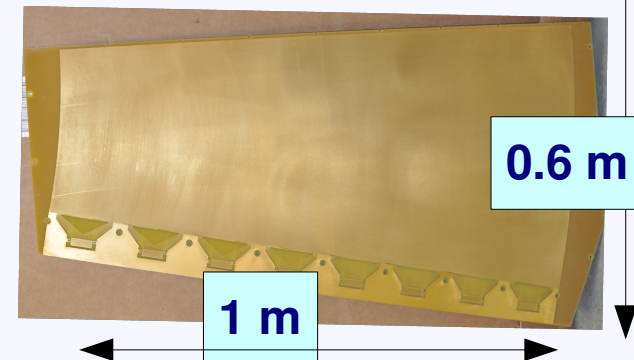
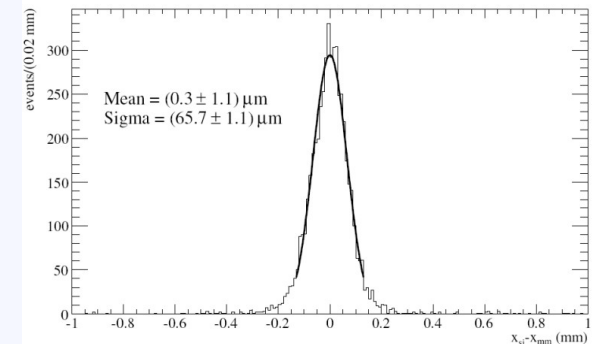
High-rate TGC



Large area micromegas

Strip pitch: 250 μm
Strip width: 150 μm

$$\sigma_{\text{MM}} = (24 \pm 7) \mu\text{m}$$



Warm forward calorimeter

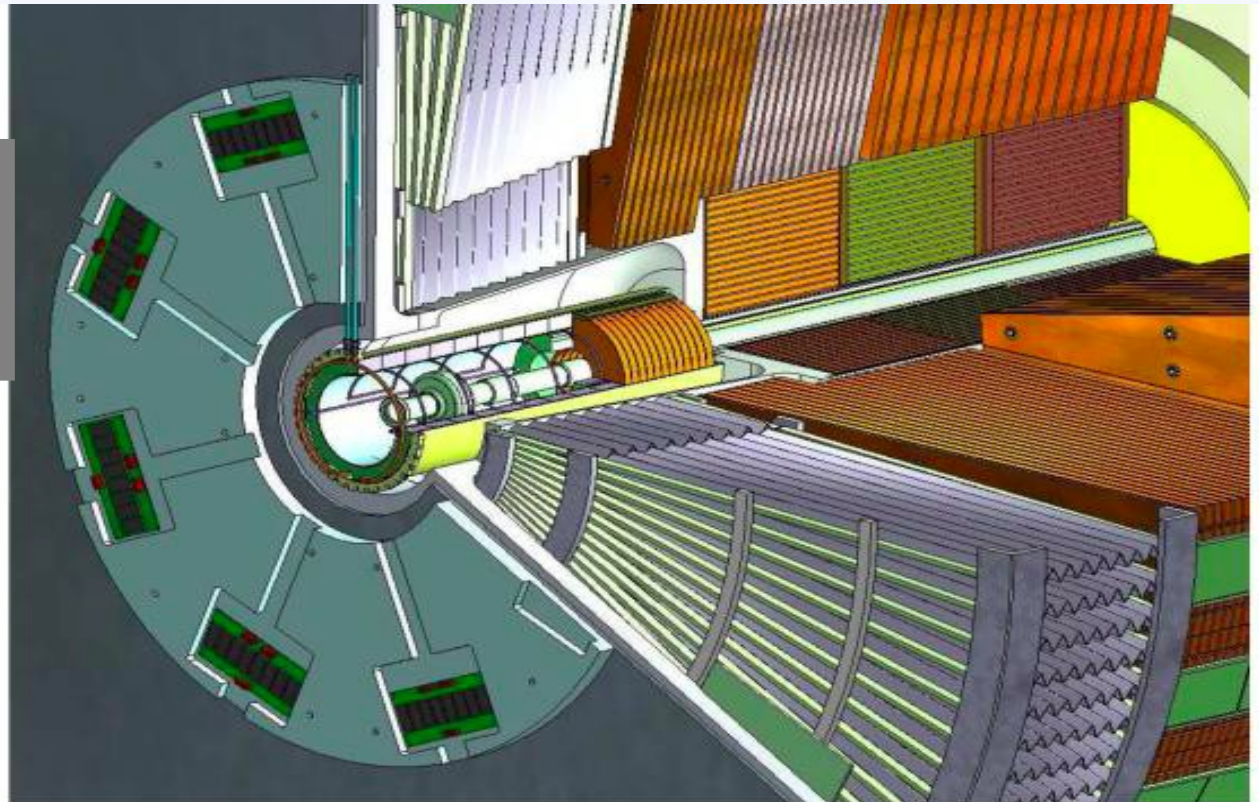
The LAr FCAL extends to pseudorapidity $\eta = 4.9$, with very high particle fluxes

Heating of LAr (boiling?); Ar^+ ion build up and (fluctuating) voltage drop across HV resistors will deteriorate performance; need studies to see how much.

Investigating a miniature warm calorimeter just in front of the current FCAL

It absorbs the e.m. jet component, halving the energy deposit in the FCAL

Cu absorbers, diamond sensors:
very rad-hard, highly segmented
readout. Placed in alcove around
beam-pipe.



ATLAS Changes for Phase-II, ~2021 shutdown

ATLAS Changes for Phase-II, HL-LHC, around 2021

Conditions:

Peak luminosity 5 x nominal with luminosity levelling: 200 interactions per bunch crossing to be disentangled

3000 fb⁻¹ good data on tape: Very big increase in integrated luminosity --> high radiation dose to detectors

18 month shut-down

Most of ATLAS can remain:

Magnets, most of muon and calorimeter systems.

Changes summary:

Trigger and DAQ: significant changes needed

Several new muon chambers needed - to be evaluated with experience

New calorimeter readout for higher granularity trigger information

Changes in LAr End-cap calorimeter

New inner detector

Trigger at sLHC

Need to maintain low thresholds on leptons (~ 20 GeV), missing ET, and forward jet trigger for the physics programme.

Events are ~ 5 x bigger, storage and bandwidth limit us to same final event rate as now (~ 200 events/s - but we are investigating implications of raising this)

So must reject 5x as many events of 5x the size – challenging

Single particle rates at low pT are too high; raise single object thresholds but maintain low thresholds in combination with other features.

Main improvements:

Muon trigger – increase the sharpness of the threshold at higher pT (40 GeV/c)

Calorimetry: read out all data, full granularity, and build trigger off-detector

- allows better particle ID at L1

Longer L1 latency (6 or 12 μ s cf 3 now), allowing more processing for combined objects

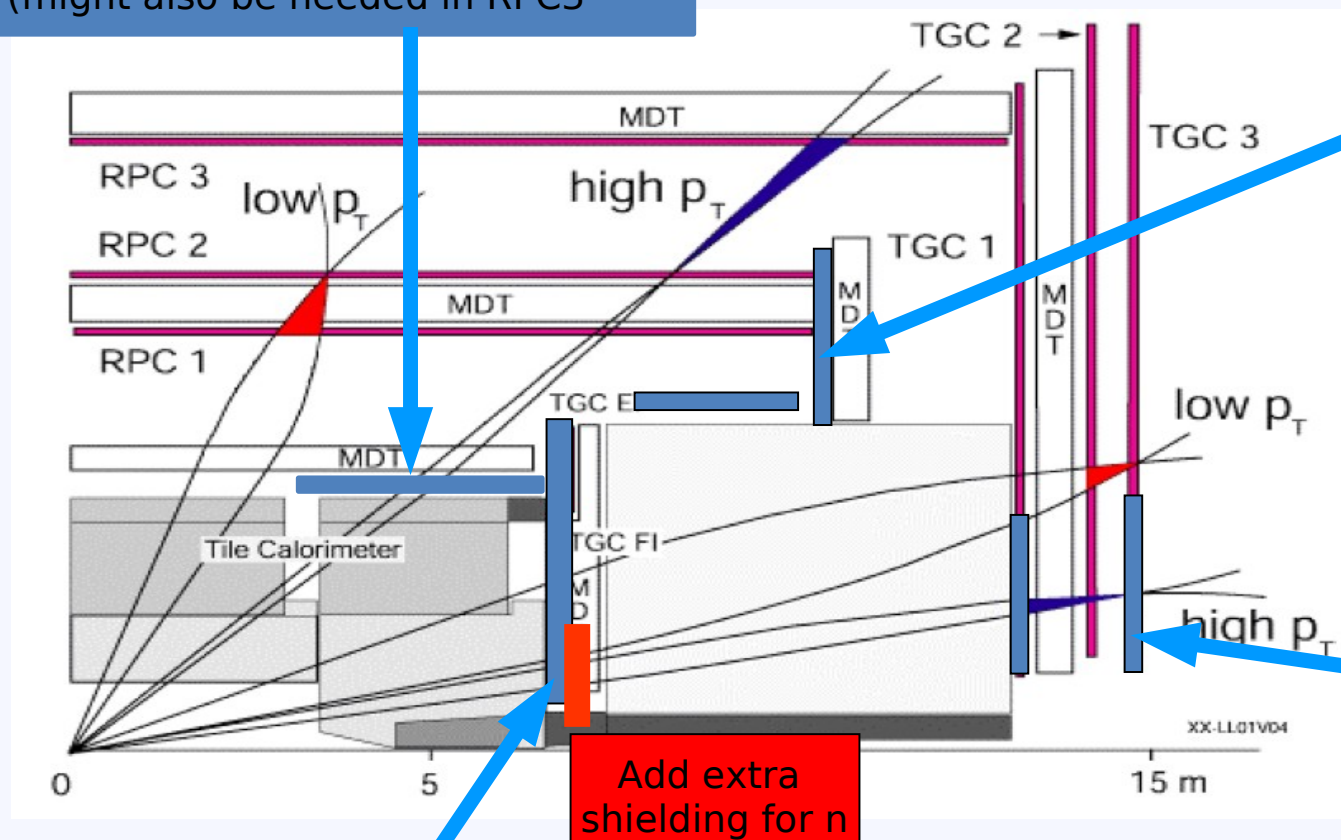
Possible inner-tracker track-trigger at L1

Precise trigger scheme will evolve as the physics priorities and detector capabilities become better known

In addition, data storage and transfer bandwidth need beefing up

MUON Upgrade for sLHC

Add extra doublet with mm resolution
(might also be needed in RPC3)



Might need to add a
Doublet of Trigger ch.
To improve L1 in low
BdL region

Replace very forward
chambers for higher
resolution and rate
capabilities

Add extra
shielding for n

Replace Small-Wheel chambers for
high rate tracking and triggering
Many R&D projects ongoing
Replacement extent depends on
cavern background (large uncertainty)

Other Muon improvements

Studies to bring in MDT trigger with coarse readout (25 ns tdc) **at level-1:**

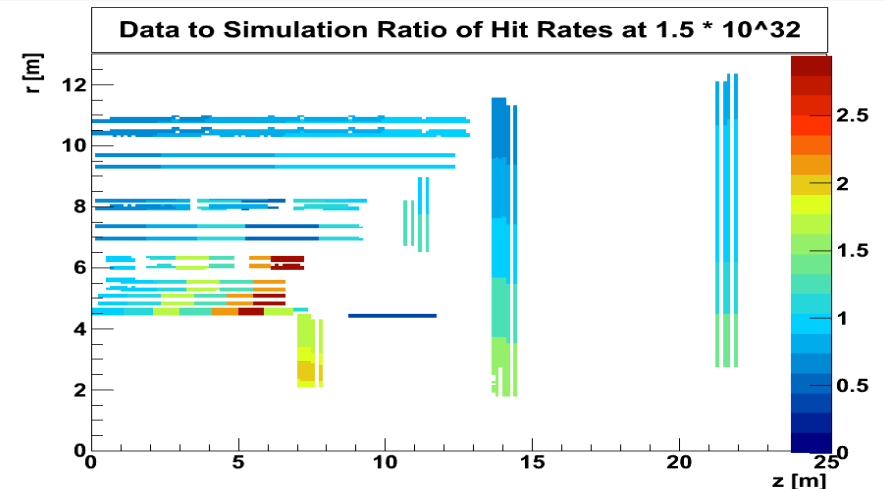
The longer L1 latency at sLHC gives time for this -- Sharpens up trigger a lot

Readout electronics of some muon chambers is inaccessible, and suffers if L1 latency goes beyond current $3\ \mu\text{s}$. We need to develop a means to store the hits off detector until L1 arrives: e.g. use a local muon trigger

Beryllium beam-pipe in place of aluminium (Phase-0) pipe through calorimeters: big reduction in background rate

Data with LHC-on gives measurement of muon hit rates. Scaling up from $10^{32}\ \text{cm}^{-2}\ \text{s}^{-1}$ to nominal can be compared to predictions made long ago of the cavern back-ground. Many uncertainties meant we allowed for a safety factor 5 in the muon design...preliminary results suggest

- (i) For most of the muon system, actual rate is a bit lower
- (ii) For hottest regions, it is 1.6 to 2.4 x higher - hopefully we can confirm soon that most of the muon system will function well



Ratio of actual to predicted muon hit rates, latest simulation and measurement

Calorimeter Upgrades for sLHC

Barrel and Tiles will work well; no changes to detector

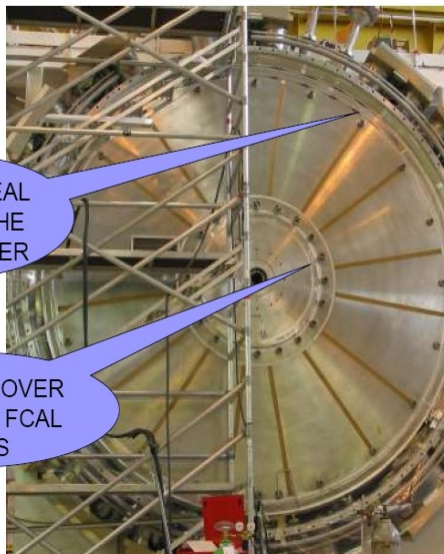
Cold electronics (pre-amps etc. inside end-cap cryostat): will they survive 3000 fb^{-1} ? (Designed for 1000 fb^{-1}). If so, hopefully the miniature warm calorimeter in front of the **FCAL at Phase-I** is enough to fix HV drop, ion build up, and risk of boiling the Ar.

Otherwise, we need to open up the end-cap cryostats – very major task (can fit in 18 months if work is carried out in the pit, but interference with other upgrade work will be challenging)

- Replace cold electronics and FCAL – smaller gaps ($250 \rightarrow 100 \mu\text{m}$)

Plus all data read-out for better trigger (see trigger section)

END CAP WITH WARM COVER REMOVED

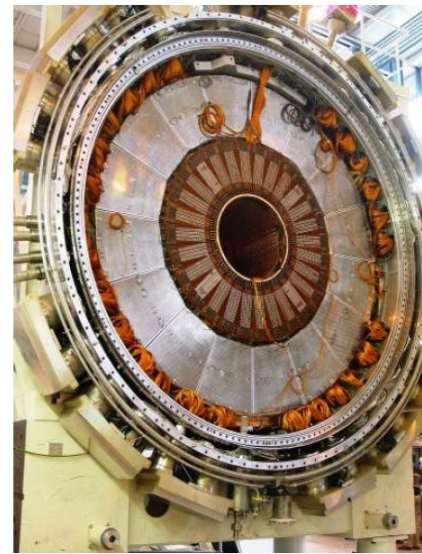


March 8 2011

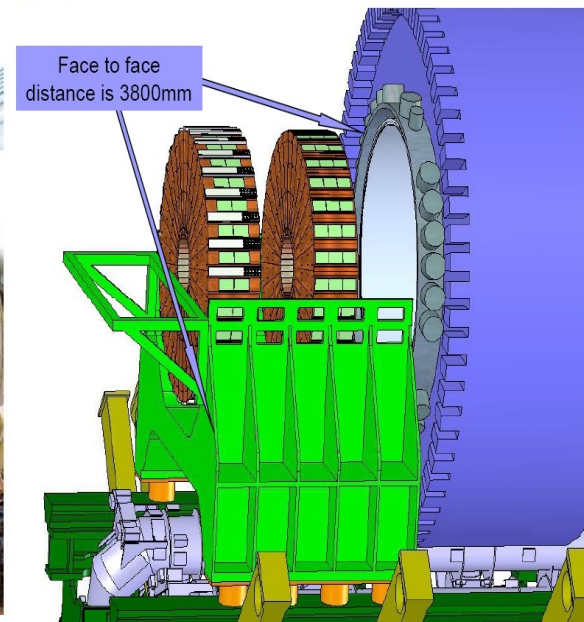
REMOVE COLD COVER TO EXPOSE REAR FACE OF HEC2



Nigel Hessey, Nikhef



sLHC-PP Public Event



Inner Tracker: Completely New

Hit rates in current inner tracker:

Current pixel B-layer becomes noticeably inefficient at $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, significantly so at $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

SCT: some regions cannot readout events above $2.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, due to optical data-link bandwidth

TRT occupancy becomes very high, although it still helps even at $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Radiation damage:

SCT designed for 700 fb^{-1} : above that, progressively worse inefficiency and other problems

Pixel B-layer considerably less

New technology:

New electronics (130 nm and smaller CMOS) allows lower power and smaller chip sizes; for pixel read-out chip, less inactive area

New bump-bonding and chip thinning allows cheaper, thinner pixels

New cooling and carbon support structures can allow lower radiation lengths

Multiplexing, e.g. local powering schemes, and CO₂ cooling allow reduced material budget

Conclude:

ATLAS needs an all new Inner Tracker at Phase-II

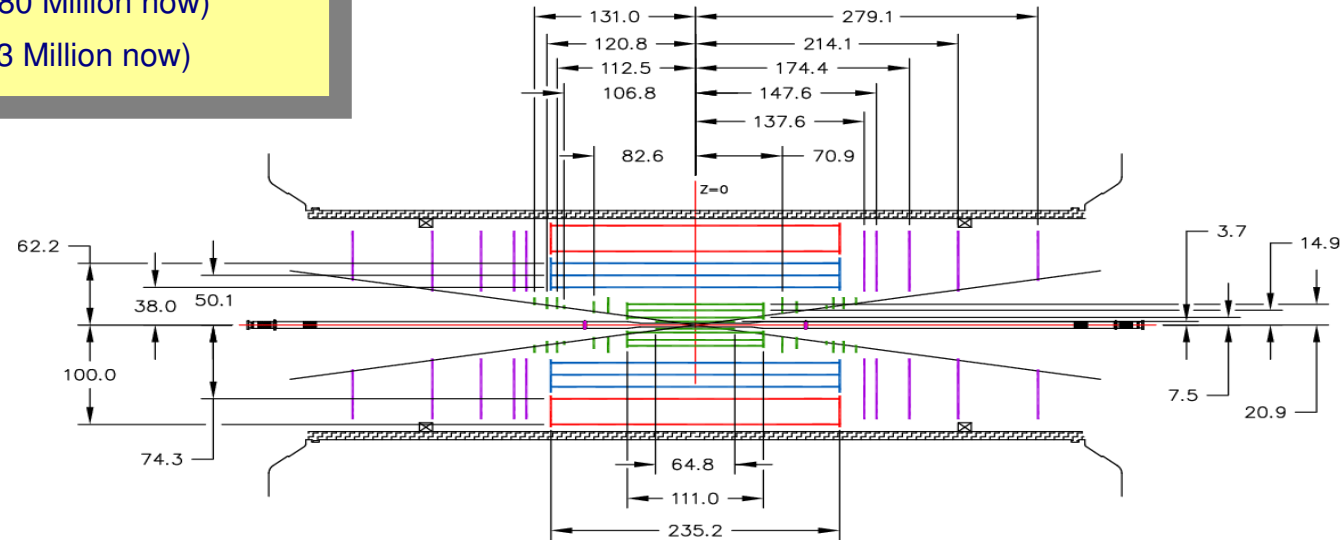
Higher granularity detectors to keep occupancy down

Base-line is an all-silicon tracker: pixels and micro-strips

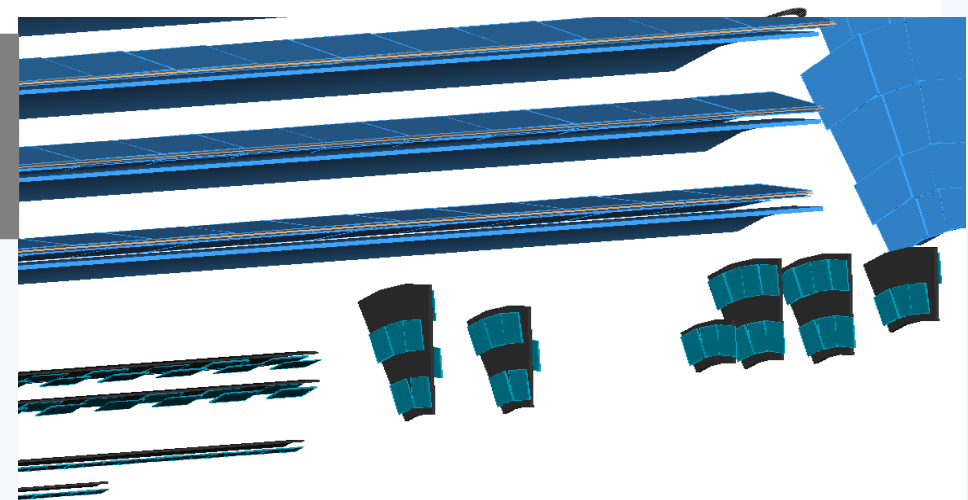
Strawman Layout of New ATLAS Inner Tracker

4 layers of pixels to larger radius than now
3 double-layers of short strips (SCT region)
2 double-layers of long strips (TRT region)
Approx. 400 Million pixels (cf 80 Million now)
Approx. 45 Million strips (cf 6.3 Million now)

4+3+2 (Pixel, SS, LS)
V14-2009



Implemented in Geant, including realistic service material, to study performance and look at optimisations



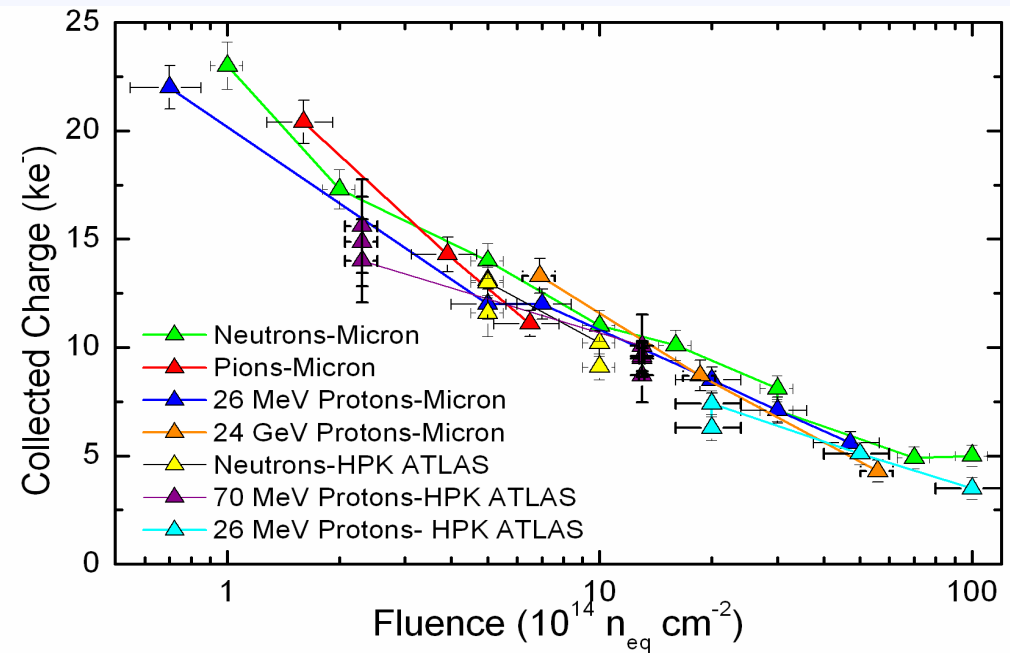
Inner Tracker Sub-committee set up to further improve on this: number of layers, length of barrel, conical end-caps, maintenance

Pixel development and sensor options

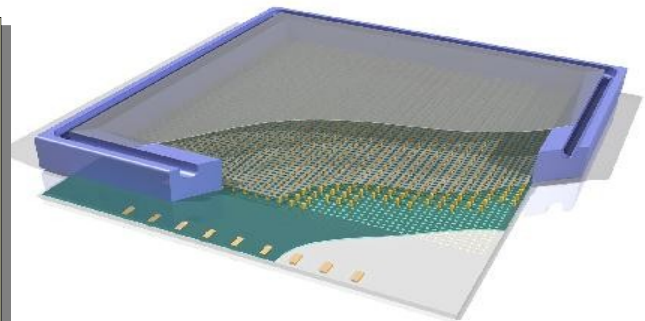
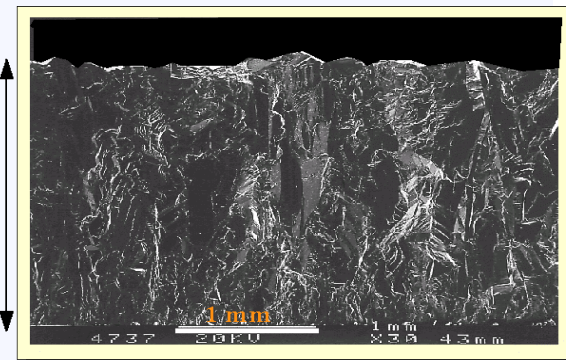
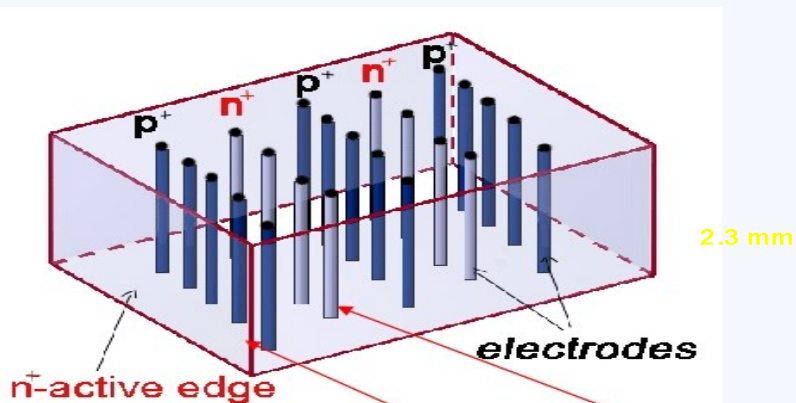
Several silicon sensors investigated for radiation hardness

Sensors from several suppliers show same characteristics

With a high enough bias they give sufficient signal-to-noise at 3000 fb^{-1}



3D, diamond, and Gossip also investigated for b-layer
– may be more rad-hard and other advantages



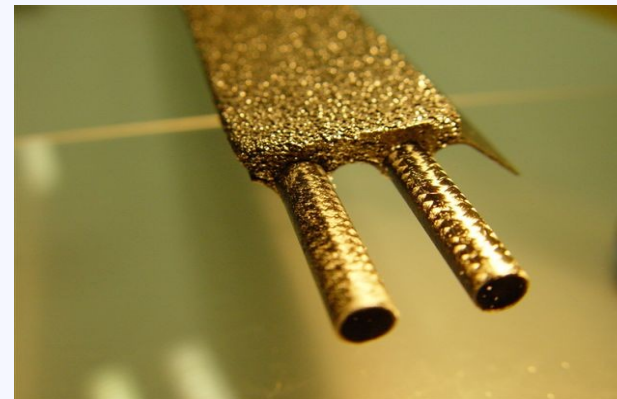
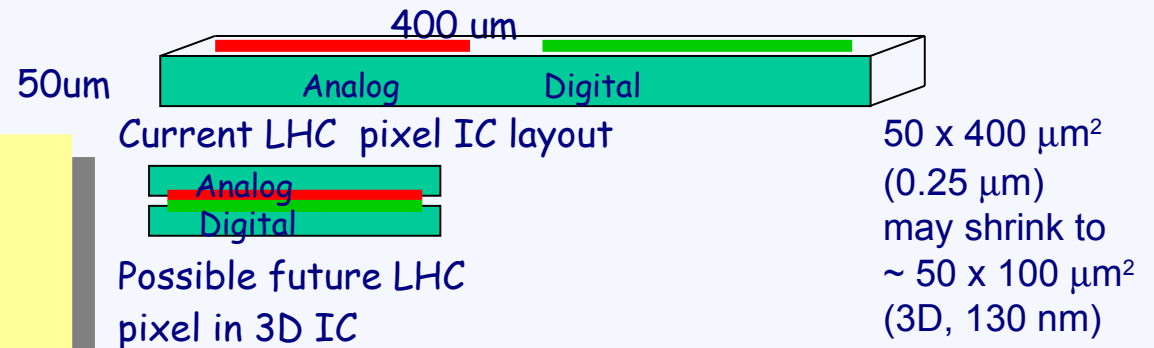
Pixel readout chip and mechanics

Pixel chip FE-I4 developed for IBL can be used for outer layers at Phase-II

B-layer at sLHC needs smaller pixels and more processing/bandwidth

- investigate 3D integration techniques
- smaller feature-size CMOS (65 nm)
- smaller pixels

Investigate new materials for lightweight stable mechanics, with good thermal conduction



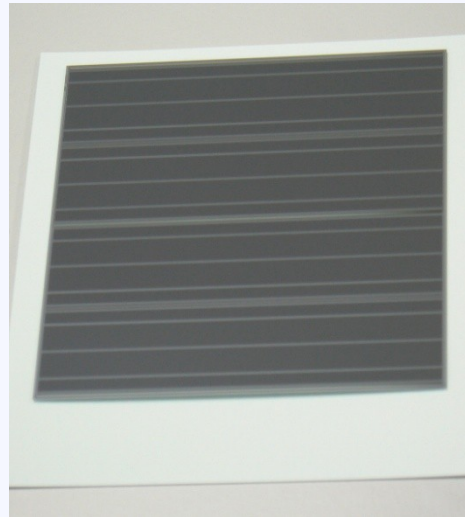
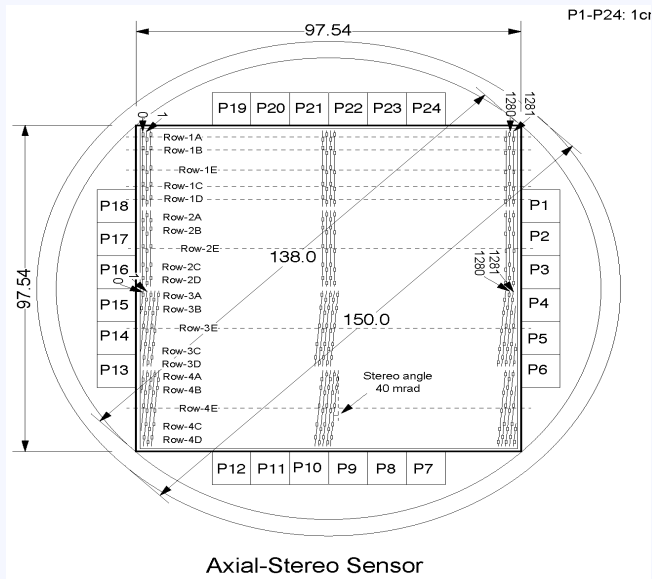
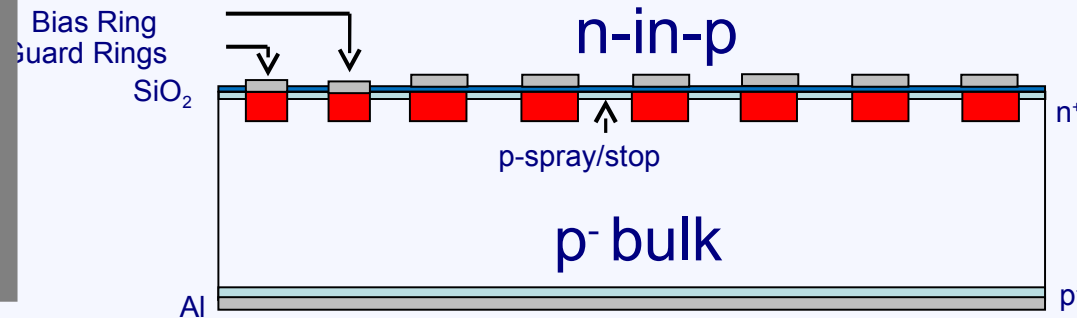
Micro-strips: sensors

Choose n-in-p (cf p-in-n now)

Faster signal collection, cheaper production than n-in-n, does not need full depletion

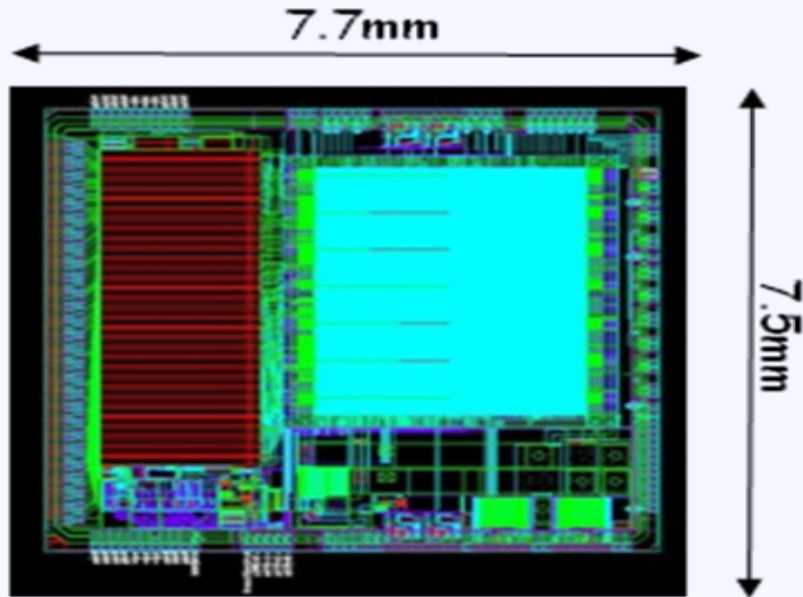
Successful production ATLAS07 sensors at Hamamatsu

- irradiation tests and prototyping made



Neutron irradiation results show S/N worst case is 10:1 in strawman layout after 3000 fb⁻¹ with a safety factor 2

Microstrips: readout-chips



ABCNext prototype chip in 250 nm:

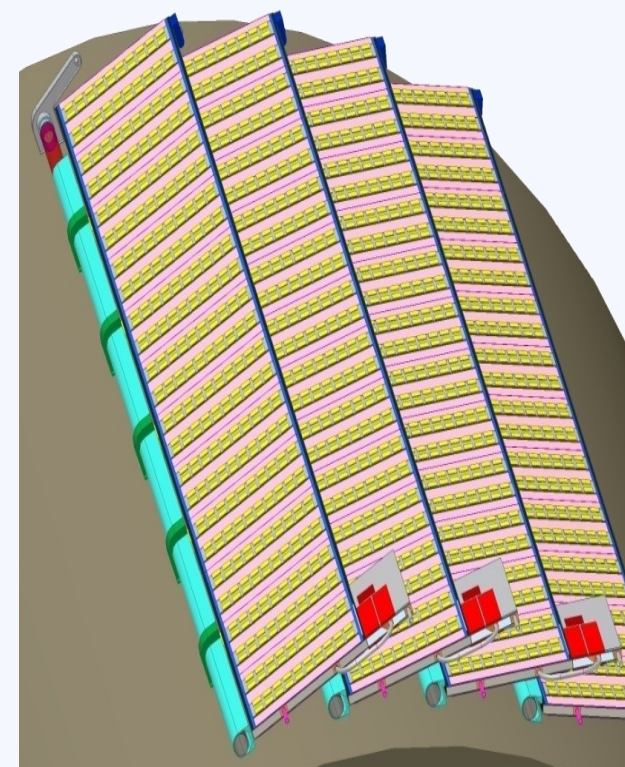
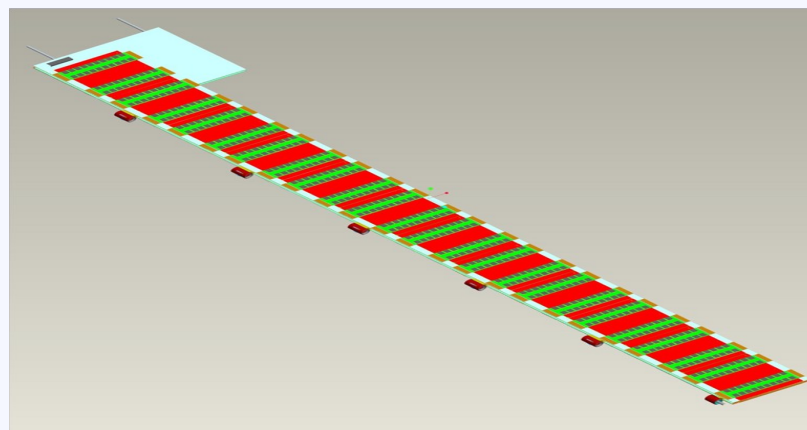
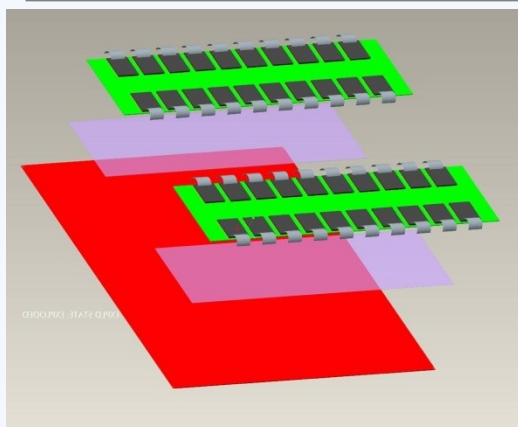
Delivered with very high yield and good performance
Allows early prototyping and try out many ideas on chip

Development of 130 nm version underway:

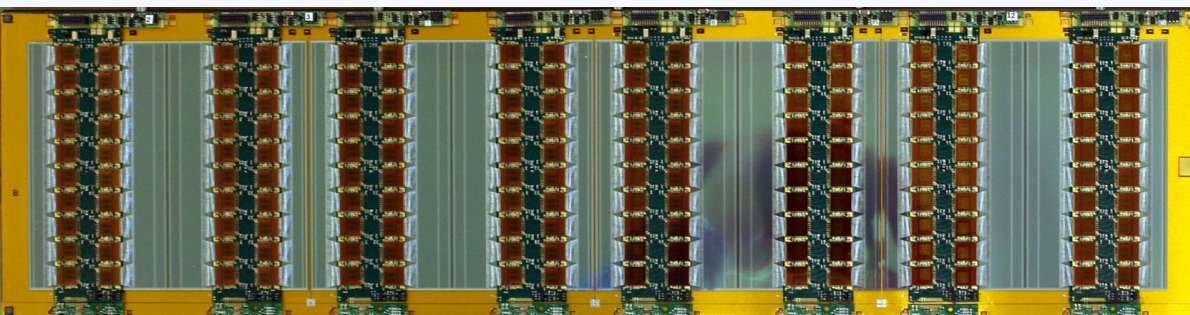
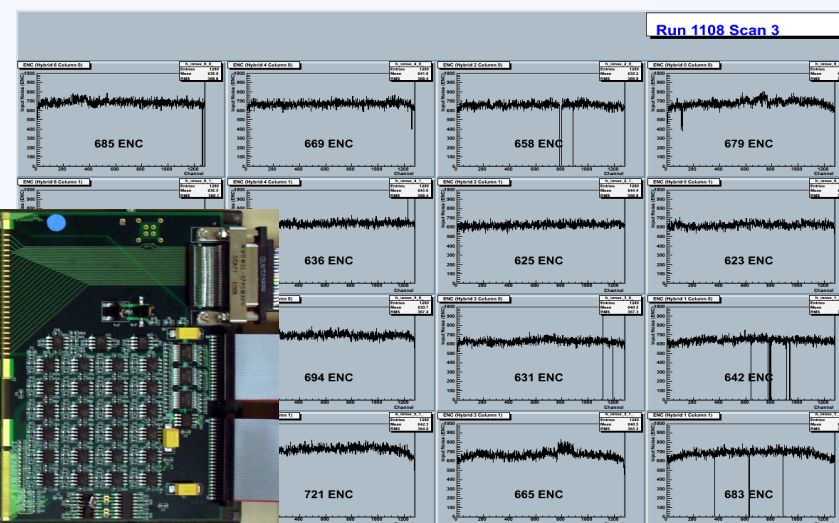
- lower power
- more rad-hard
- 256 channels instead of 128: saves hybrid space and therefore radiation length reduces

Microstrips: Modules and staves

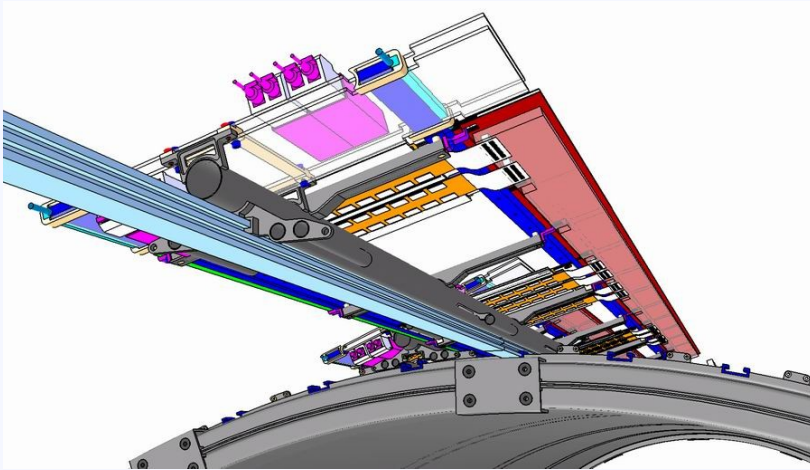
Hybrid with front-end chips glued directly to sensor
Sensor glued to cooled mechanical support - “Stave”
Staves arranged in cylinders
Stave can reduce material and helps assembly schedule by avoiding bottle-neck at module mounting on cylinders



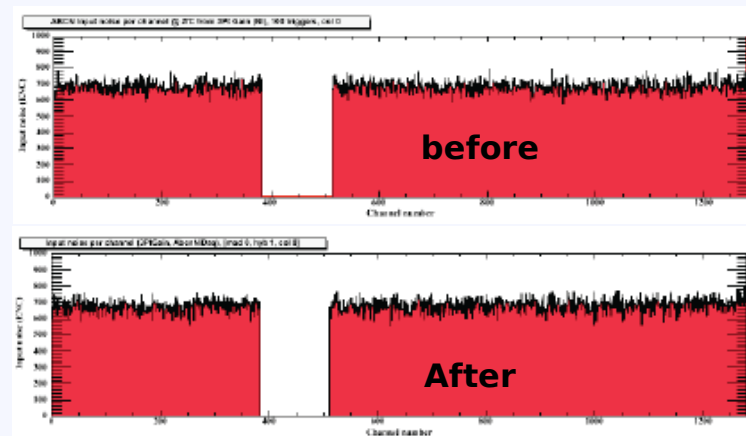
Mini-stave built: very good and uniform front end performance (noise, gain, pedestal, threshold); low dead channel count



Strip Modules R&D



Alternative double-sided modules concept advanced; irradiated modules show no significant noise change



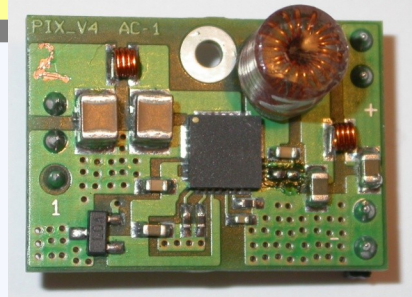
Tracker Power and Cooling – reducing material

A stave needs > 50 A at 2.5 V – heavy cables not acceptable
Look into serial powering and DC-DC: Buck converters, piezo-electric ...

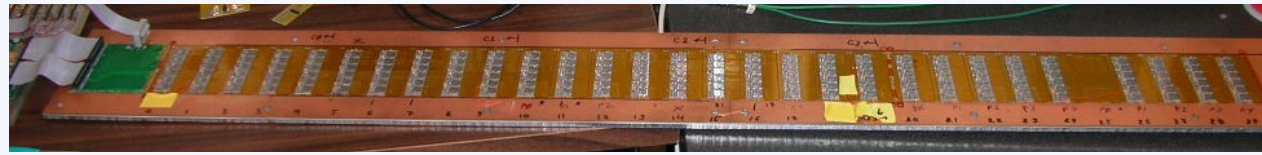
Many issues under investigation (air-core inductors, switching noise, high current capacity...)

Essential R&D, carried out under SLHC-PP project with major advances

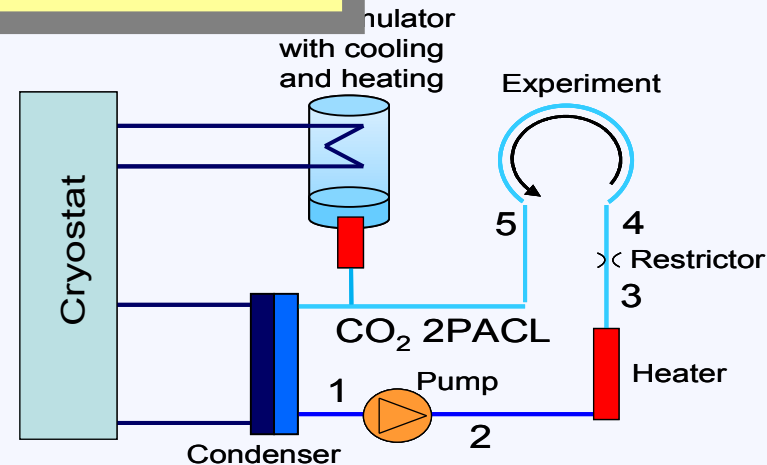
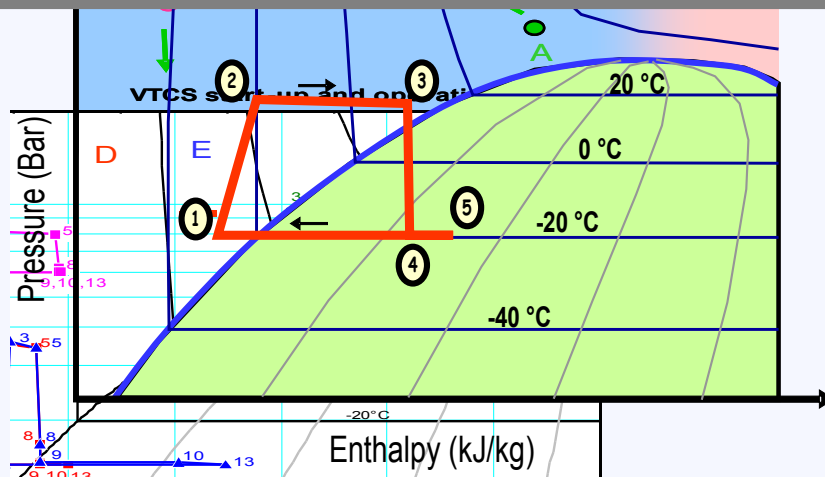
DC-DC converter prototype



30-hybrid stave with serial powering successfully tested (UK+LBNL):
same noise performance as individual powering



Bi-phase CO₂ cooling can reduce mass of cooling system
Rad-hard and demonstrated in LHCb; used for IBL
Small diameter titanium pipes reduce material



Track Trigger at L1

Several ideas for implementing a track trigger at L1.
Wanted: high-PT (~ 20 GeV) leptons.

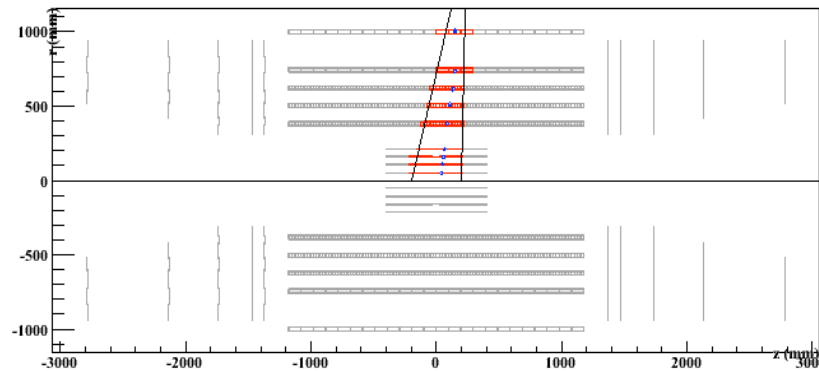
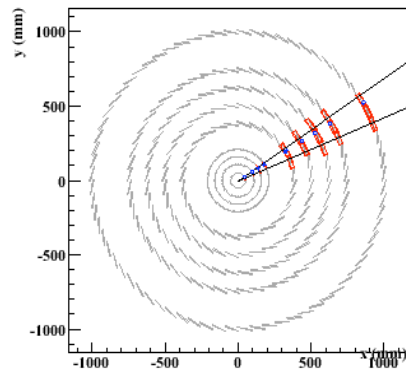
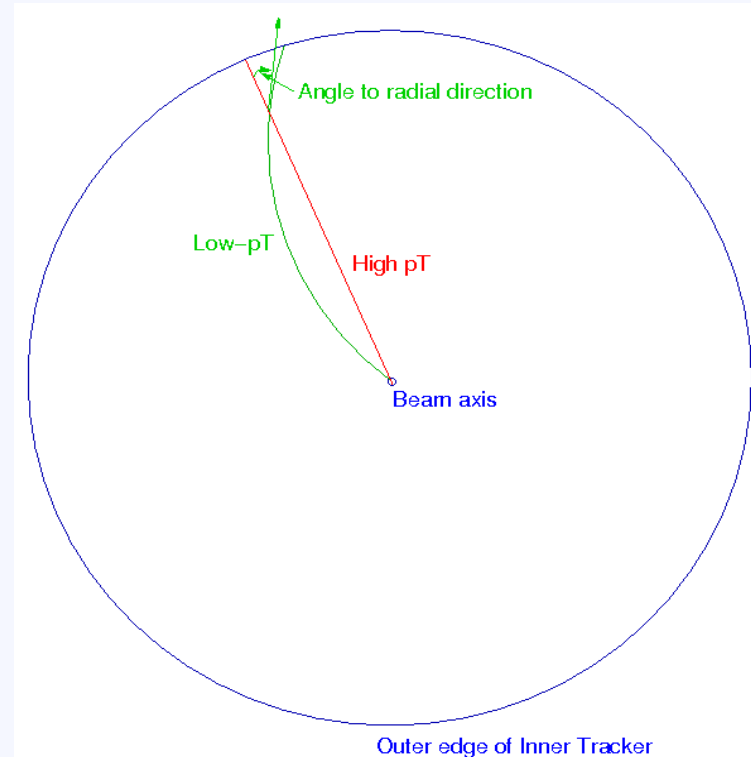
ATLAS EM calo has good identification, allowing a two-stage trigger approach:

Calorimeter or muon system identifies a candidate high-PT lepton and gives region-of-interest

Inner tracker modules in that region are read-out, and hardware track finders confirm presence of track with matching momentum

RoI is a few % of modules so small increase in bandwidth needs \rightarrow very little increase in material

Needs additional data stream in FE chip and a lot more study, but encouraging so far



Alternatively, measure track angle to radial direction at outer edge of inner tracker - look for near radial tracks

Either with paired silicon layers or GasPix detector with 10 mm drift gap

Summary

The LHC is expected to continue operation well beyond 2020 with upgrades to much higher luminosity than nominal

This will provide a rich variety of physics possibilities, with a mixture of SM verification and New Physics

ATLAS has several changes under development to extract as much benefit as possible from this

Already in the 2013-14 shut-down we have new detector elements

Phase-I will need new muon small wheels, possibly warm FCAL, new trigger features, and several improvements elsewhere

Phase-II will require a completely new Inner Tracker, some new muon chambers, major trigger and DAQ improvements and possibly major work on the forward calorimeters.

Work is well under way

This project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under the Grant Agreement n°212114