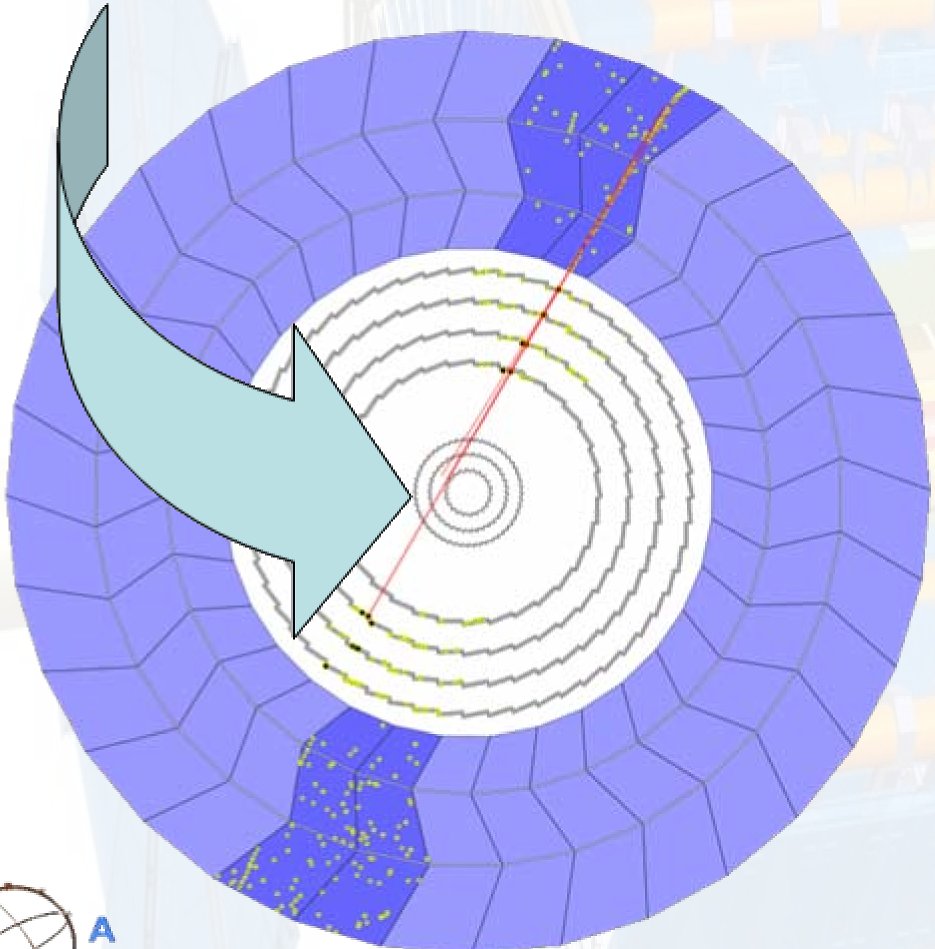
Commissioning of the ATLAS Pixel Detector with Cosmic Data and Status of the ATLAS detector at the LHC



- Overview
  - LHC and ATLAS
  - Pixel Detector
- Commissioning
  - Pixel Opto-heaters
  - Slow Controls
- Readout
- Calibration
- Cosmic Runs
- ATLAS readiness summary

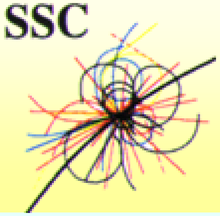
Evgeny Galyaev
On behalf of the ATLAS Pixel Collaboration

Introduction and the Talk Outline

1976: Born in Protvino, Russia

1992/93: Trip to the US - the SSC

SSC



First chance to see a HEP project of such an unprecedented scale!...

1993/99: Moscow State University

1996/99: MSU/IHEP Institute

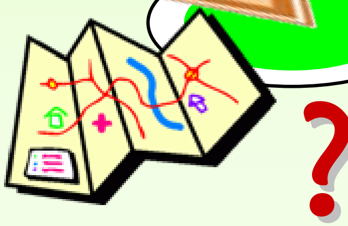
1999/06: University of Notre Dame

- Fiber Tracker
- PhD work
- b-tagging

2001/06: Working at Fermilab

2006/09: Joined ATLAS at CERN

- Pixel Detector installation, commissioning
- Building the pixel opto-heater system
- Inner Detector work: new heater electronics



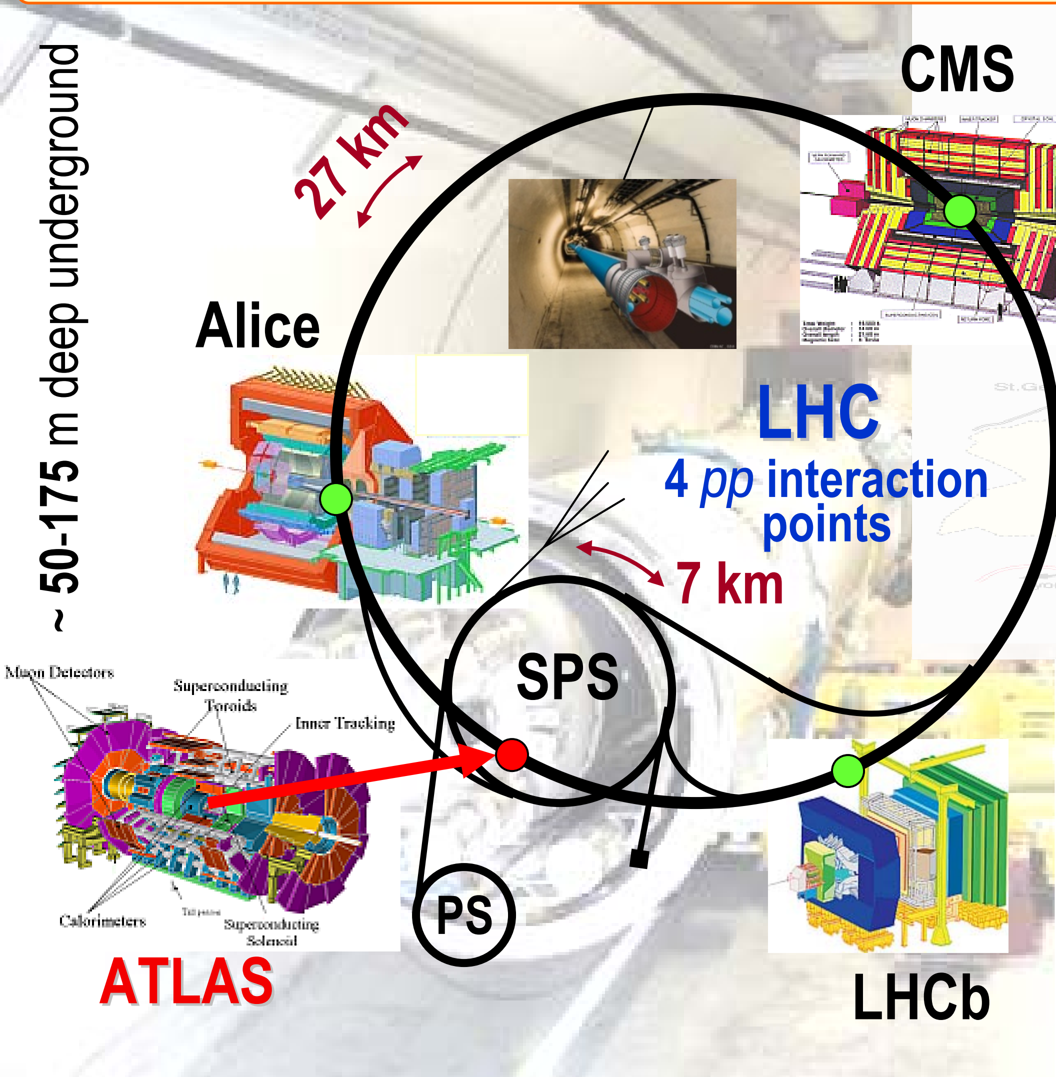
In this talk:

LHC and ATLAS:	Pixel Detector:	Pixel Detector Operation:
General overview	Commissioning	Calibration Procedures
ATLAS Pixel Detector	Pixel Opto-heaters	Status and Cosmic Run Results

Large Hadron Collider (LHC)

November 15, 2006: Research Scientist at UTD; December 6: Landed in Geneva…

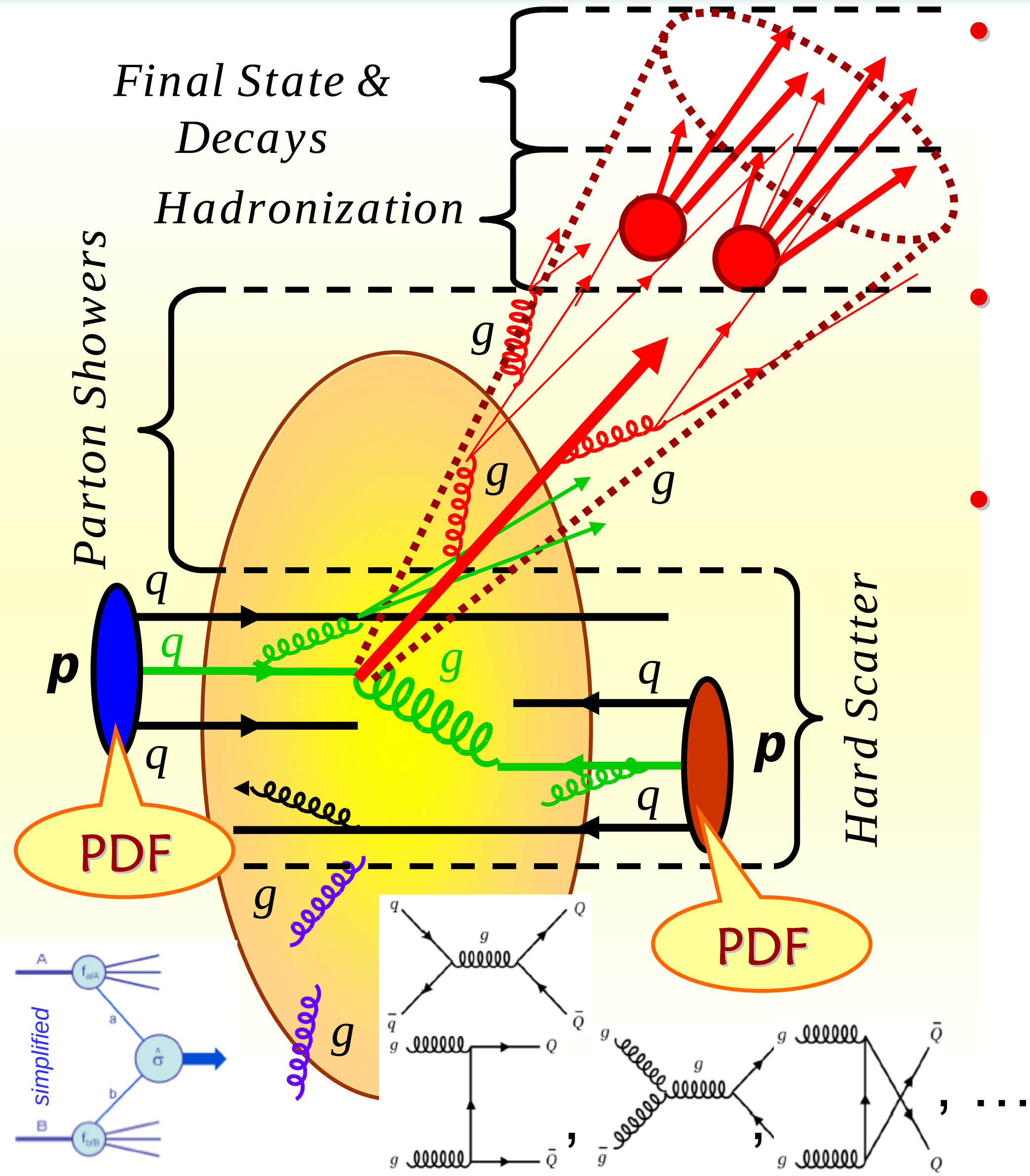
MOTIVATION: To find Higgs Boson and discover New Physics beyond Standard Model



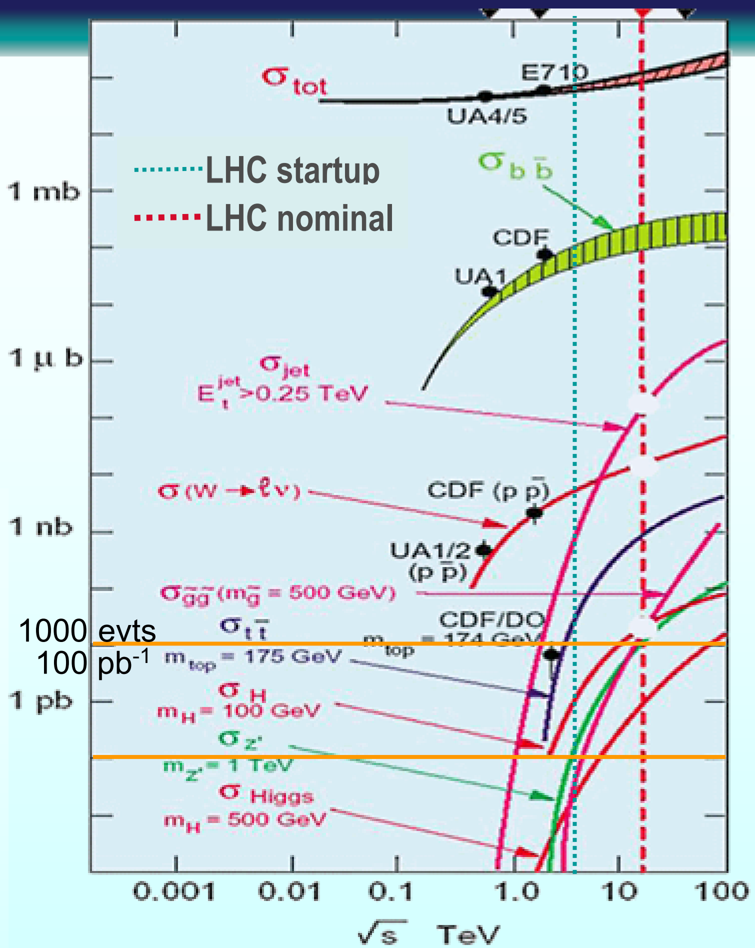
- 1232 dipoles, 858 quadrupoles;
- Dipole field 8.3T at 1.9°K;
- 96 tons of liquid *He*;
- 2808 proton bunches
- 25 ns bunch crossings
- ~1.15×10^{11} protons / bunch
- 40M collisions / second!
- 350MJ stored energy / beam

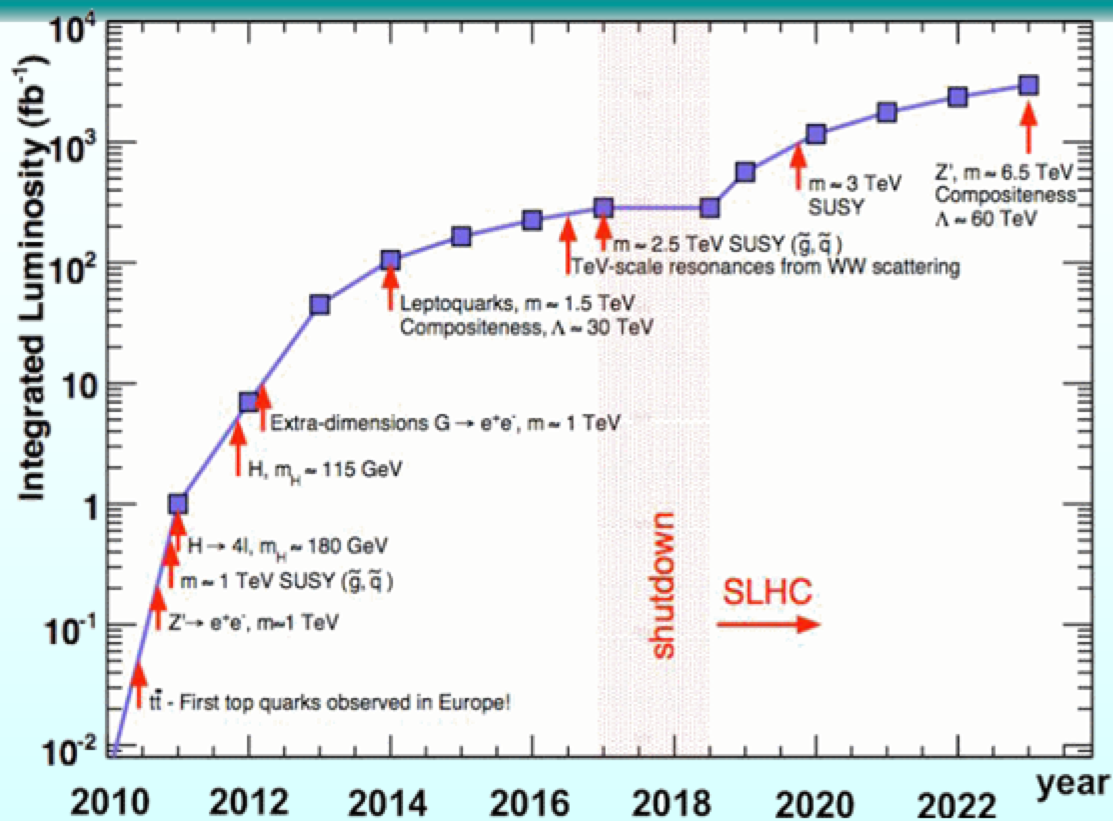
37 kgs worth of cheese fondue!

Machine	Beams	Energy	Luminosity
LHC	p p	14 *TeV*	10^{34} $cm^{-2}s^{-1}$
LHC	Pb Pb	5.5 *TeV*	10^{27} $cm^{-2}s^{-1}$
Tevatron	p $\bar{p}$	2.0 *TeV*	10^{32} $cm^{-2}s^{-1}$
LEP	$e^+ e^-$	200 *GeV*	10^{32} $cm^{-2}s^{-1}$



- LHC - The discovery machine:
  - Probe deep into the *terascale*;
  - *pp* collisions: the abundance of possibilities!
- LHC's assets:
  - High *CM* energy;
  - High integrated luminosity;
- Physics goals:
  - Cover the SM topics well:
    - *W, Z, Jets, Top, QCD…*
    - Precision measurements
  - The Higgs Boson m_H **= 0.1~1 TeV**;
  - The new Physics:
    - Supersymmetry?
    - Extra Dimensions?
    - Leptoquarks?
    - Compositeness?
    - **…the unexpected?**





Despite a rather conservative start…

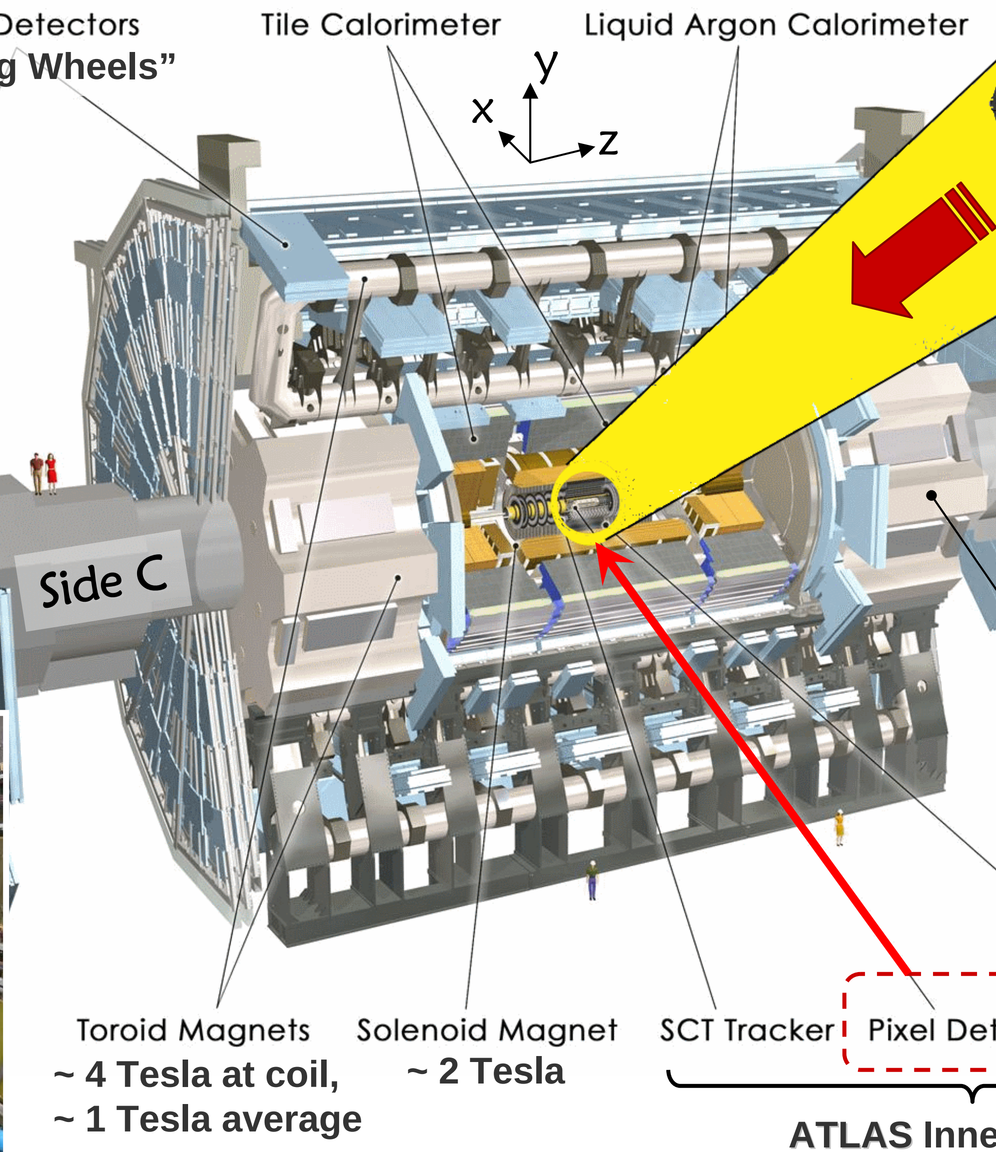
- ➢ *High probability of discoveries!*
- ➢ *Understand and improve the detector performance*
- ➢ *Fine tuning of the MC:*
  - Refine the PDF's
  - Tuning: min-bias, UI, tt, WZ+jets, etc.

Tentative parameters for the first LHC run:

- Startup date……late Fall '2009
- CM energy……..3.5 ~ 4.5 TeV/beam
- Instantaneous $\mathscr{L}$ = 10^{31} ~ 10^{32} cm^{-2}s^{-1}
- Integrated luminosity = 20 ~ 100 pb^{-1}

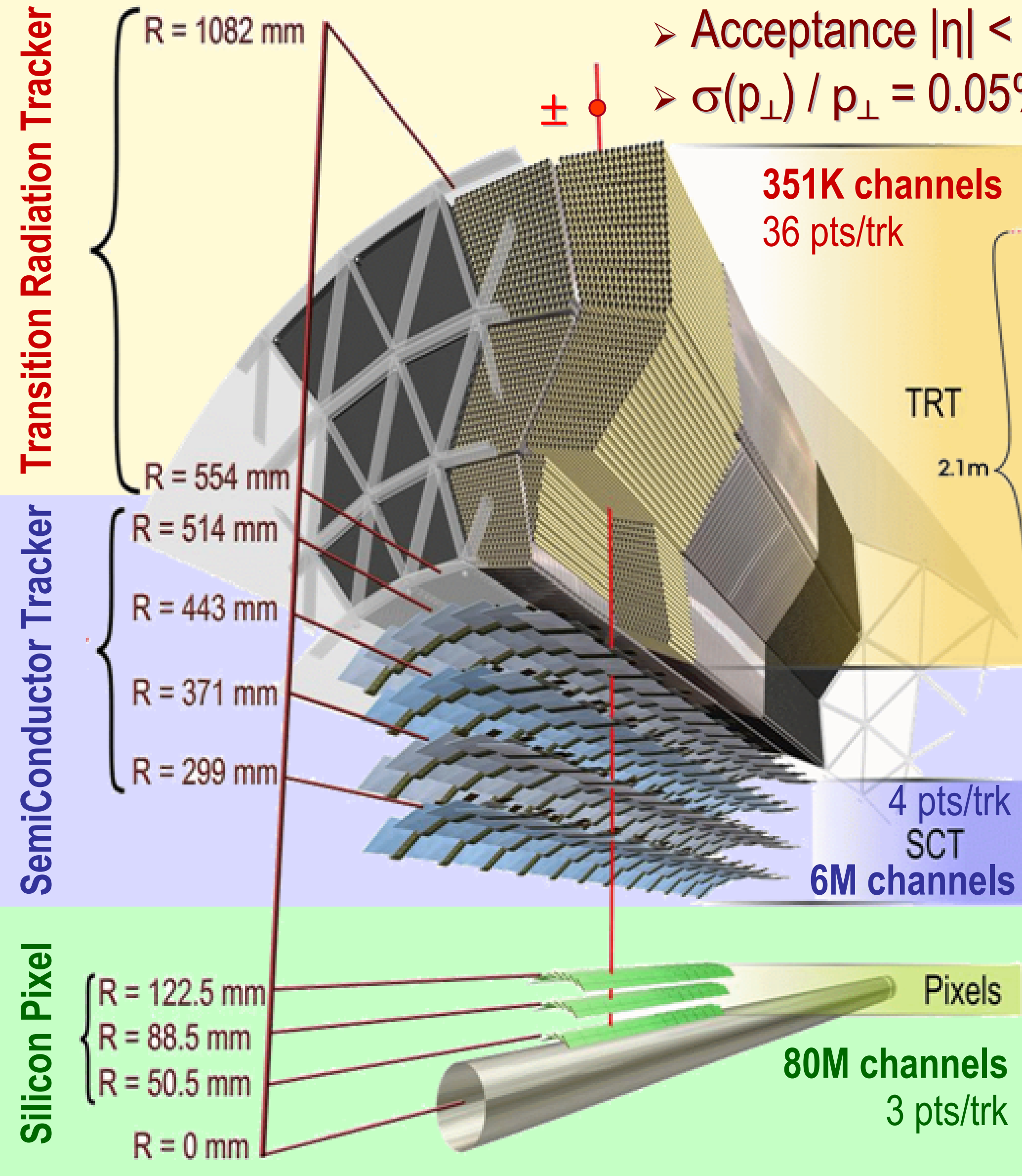
ATLAS: A Toroidal LHC Apparatus

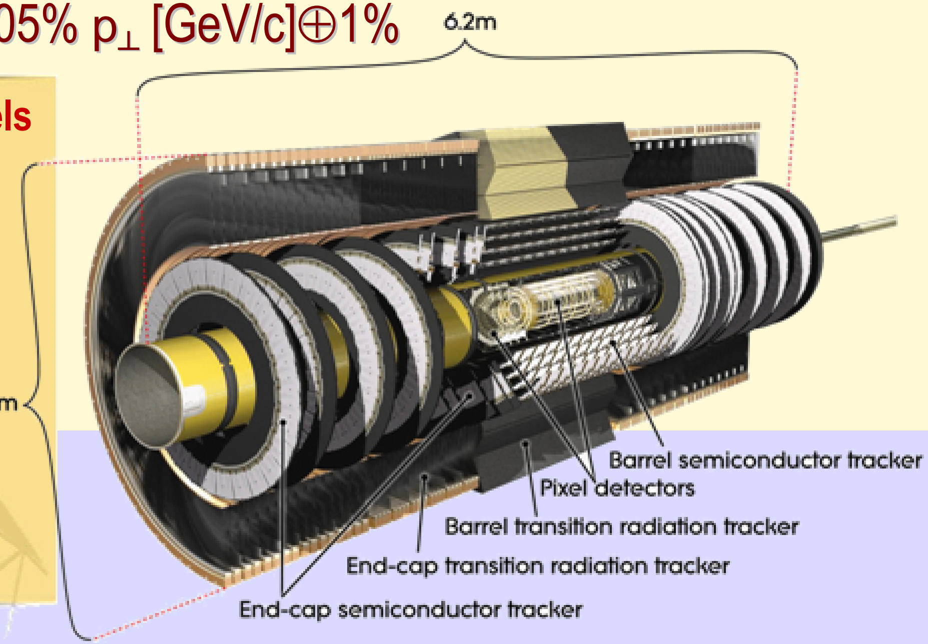
- 44m long
- 22m high
- 7K tons heavy

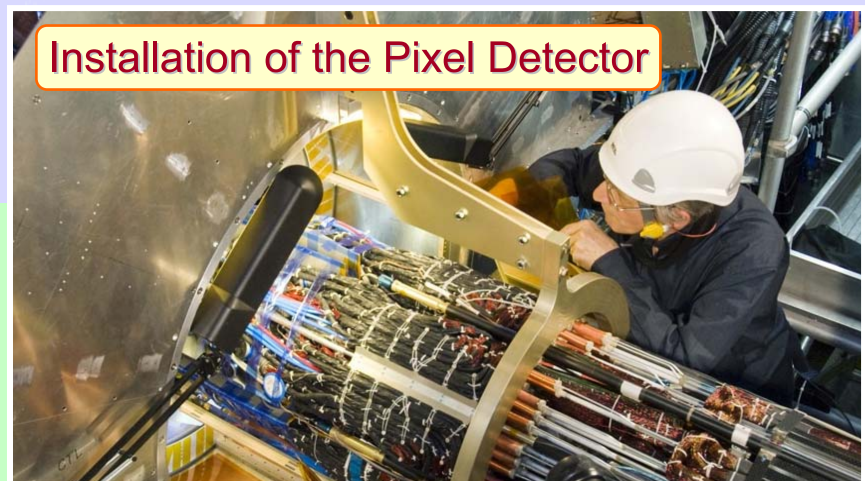


ATLAS Inner Detector

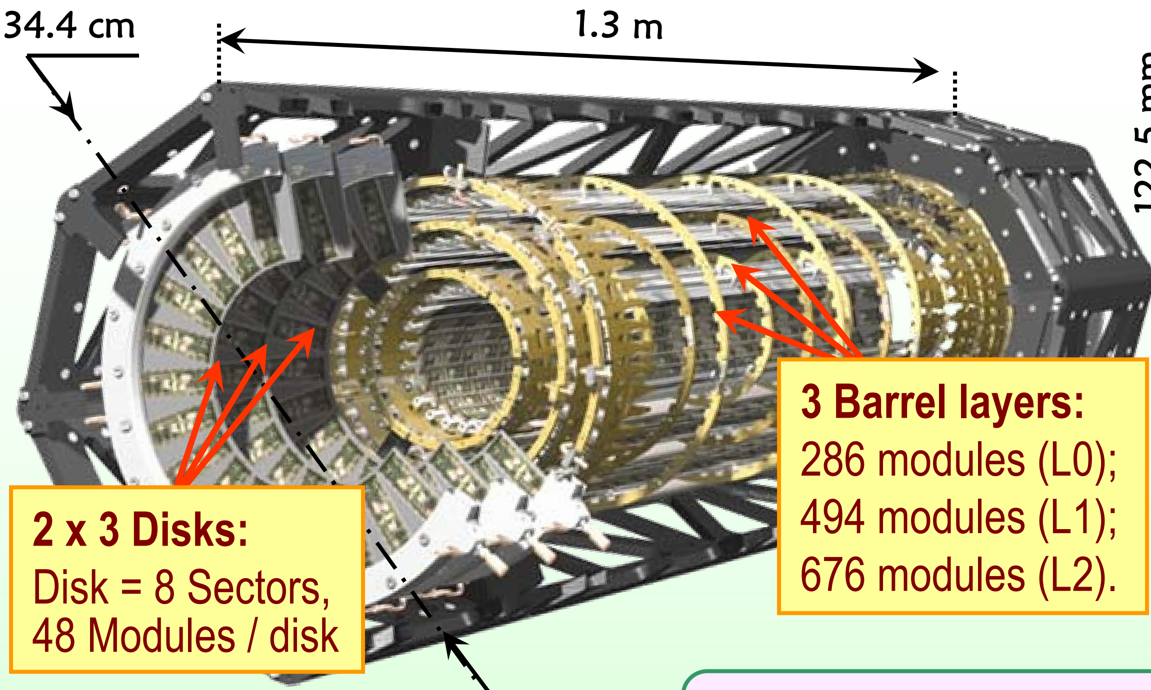
- Acceptance |η| < 2.5 (|η| < 2 for the TRT)
- $\sigma(p_\perp) / p_\perp = 0.05\%\ p_\perp\ [GeV/c] \oplus 1\%$





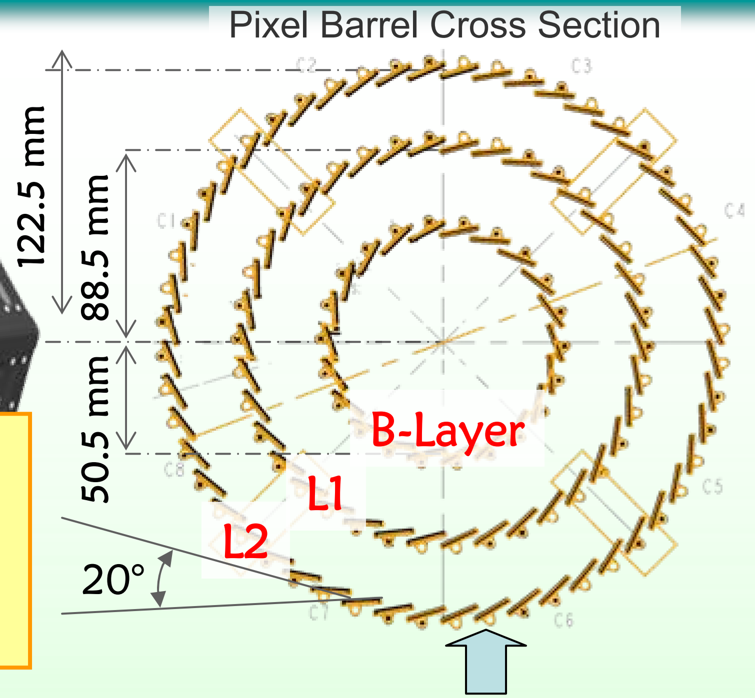


ATLAS Pixel Detector

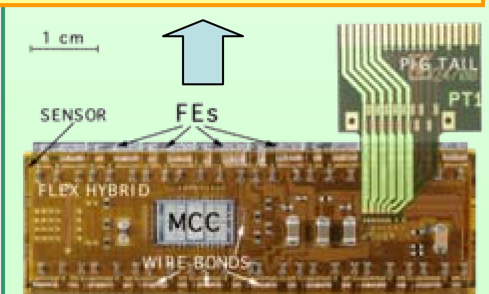


2 x 3 Disks:
Disk = 8 Sectors,
48 Modules / disk

3 Barrel layers:
286 modules (L0);
494 modules (L1);
676 modules (L2).



Staves with 13 Modules



Pixel Module
= 46080 channels

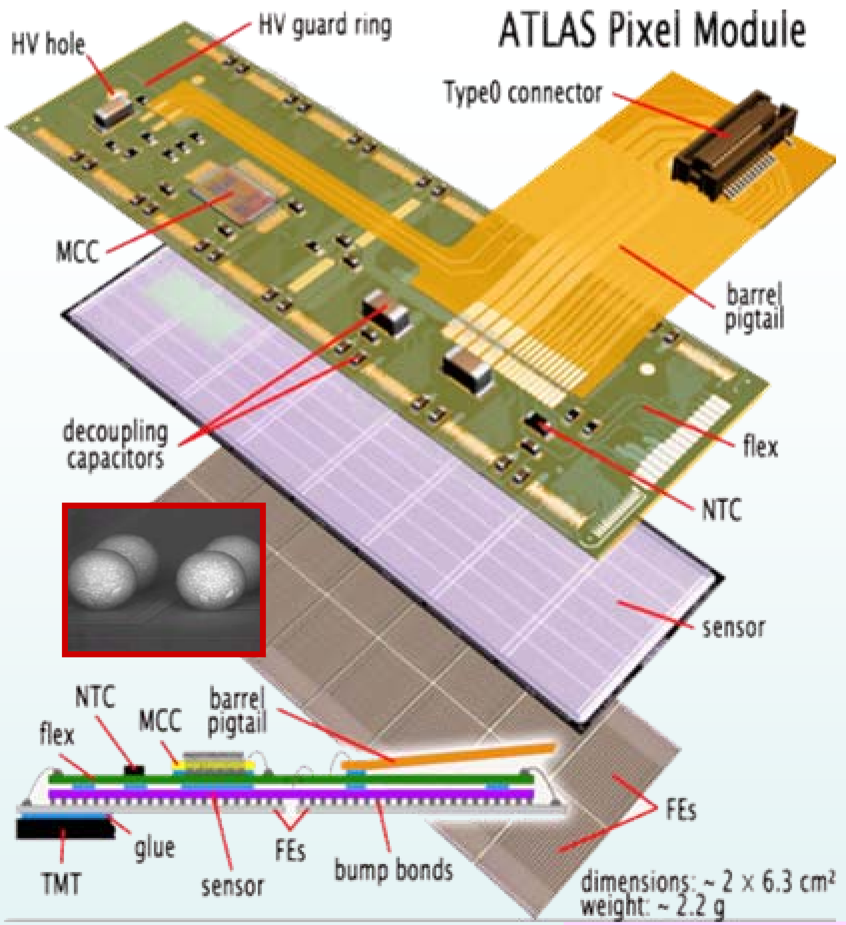
Construction

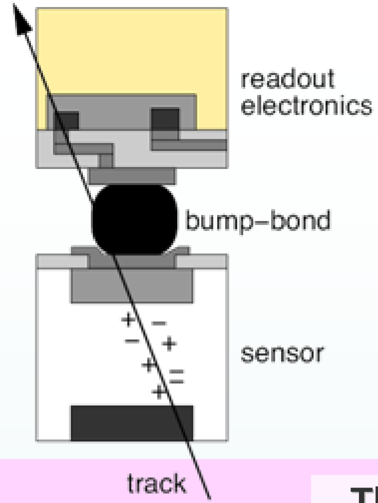
- Package weight ~ 4.5 kg
- Active sensor area ~ 1.7 m^2
- Bi-phase C_3F_8 cooling
- 500 kGy or 10^{15} n_{eq}/cm^2 radiation hardness: 5 yrs/L0

Performance

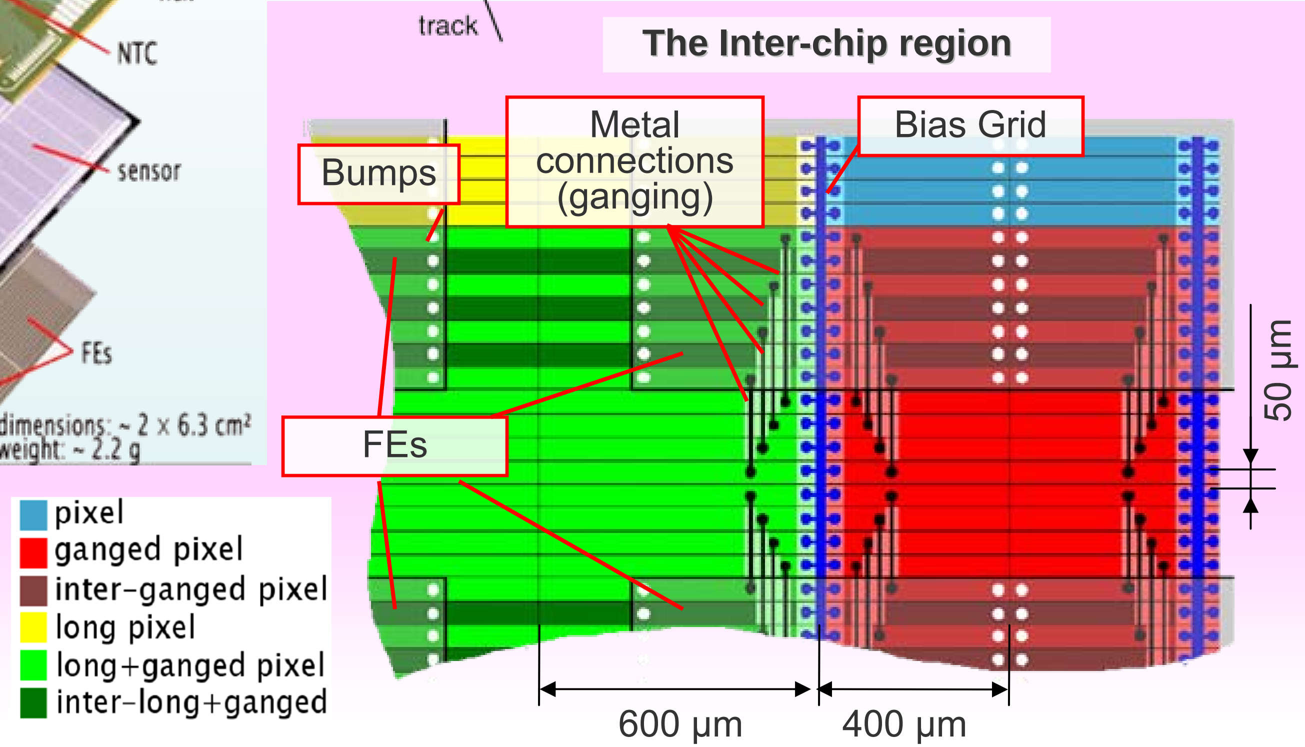
- 1744 pixel modules
- Total of ~ 80M channels
- 3-Hit Tracks
- $|\eta| \leq 2.5$
- Spatial resolution: 15 μm in R-ϕ, 115 μm in Z

ATLAS Pixel Module





- Sensor = 47232 pixels
- n^+-in-n DOFZ
- Bias 150-600 V
- 2 x 8 readout FE chips
- 18 x 160 cells each



- Charge-sensitive preamps in cells
- Local threshold generators in cells

Extremely tight schedule was met successfully

2007	
June 22-27	Installation ★
★ Pixel detector is disconnected, with no access to it	
2008	
February - April	Initial connection, connectivity tests and pixel detector sign-off
May - August	Environmental systems commissioning, Final integration in ATLAS DCS
July	Beampipe bakeout: successful, on-time
	Pixels are on the beampipe, cooled!
August	First pass calibration (communication links)
End of August	All cooling loops on
September 19th	LHC accident in sectors 3-4
	Running with Cosmics is top priority
September 14th to November	Combined cosmic data taking: continuous calibration adjustments, modules recovery

Signal Readout / Main Tuning Points

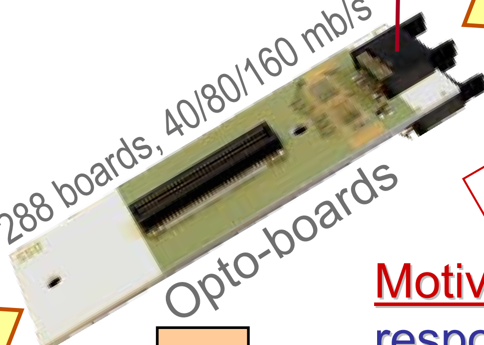
1. Opto-Link Tuning

<u>Goal:</u> Reliable communication between the modules and off-detector Back-Of-Crate readout cards via the optical links.

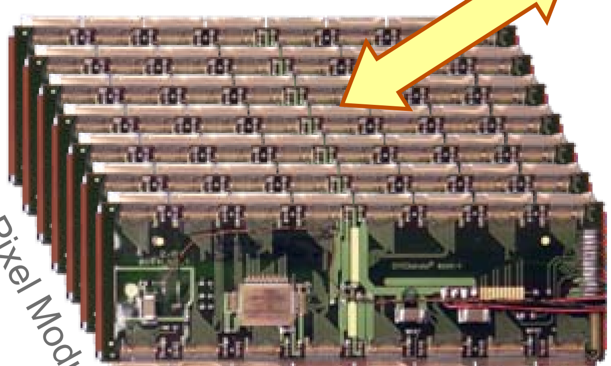
- Find optimal conditions for modules
- There are 6 or 7 modules on each link ⇒ not an easy task!

OFF-DETECTOR READOUT

Optical communication links: commercial laser arrays (VCSELs) and receiving PIN diodes at both ends



Data readout: Data-push
Receiving: Cell control logic signals: Thresh, ToT, test charge…



ON-DETECTOR

Significant technical challenge appeared in course of system tests in fall of 2006!

My 'entry point'

2. Module Tuning

<u>Motivation</u>: Initial homogenous detector response; account for degradation due to irradiation in the future.

Threshold – level to tell signal from noise

Time-Over-Threshold – ToT, indirect measurement of the deposited charge from the above-threshold signal amplitude

For every pixel cell

Pixel Opto-Board Heaters (I)

December 2006: UTD joins work ATLAS…

- Initial hardware involvement: **ATLAS Pixel Detector**
- **Problem:** Many Optical Data Links *do not work right when cold!*

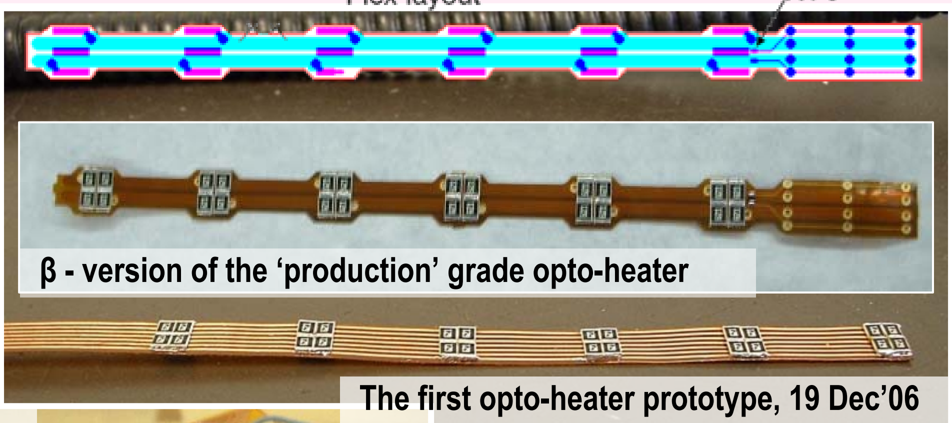
- Slow turn-ons
- Low optical power
- No laser output…

Only 7 months left to detector insertion!..

Absolutiely **CRUCIAL** to have the opto-links operating stably and reliably!

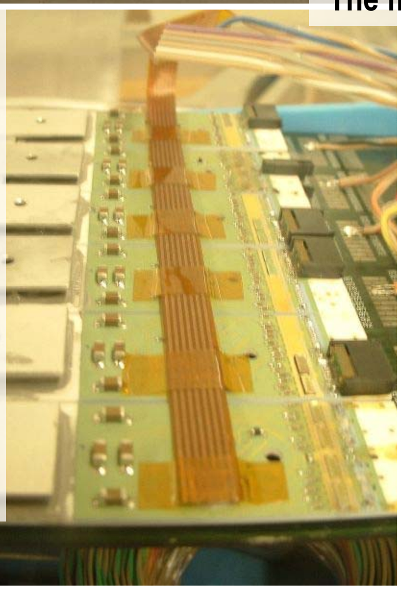
Solution: The idea of the opto-heaters:

- A system of tiny, regulating heater elements on the opto-boards
- 6 groups of resistors and an NTC sensor placed on a flex strip
- ~105Ω @ 48V, pulse-regulated
- 48 opto-heaters in total required



β - version of the 'production' grade opto-heater

The first opto-heater prototype, 19 Dec'06



Prototype attached to opto-boards

I became the one responsible for:

- Initial prototyping/engineering
- Feasibility studies
- Reliability/operation studies

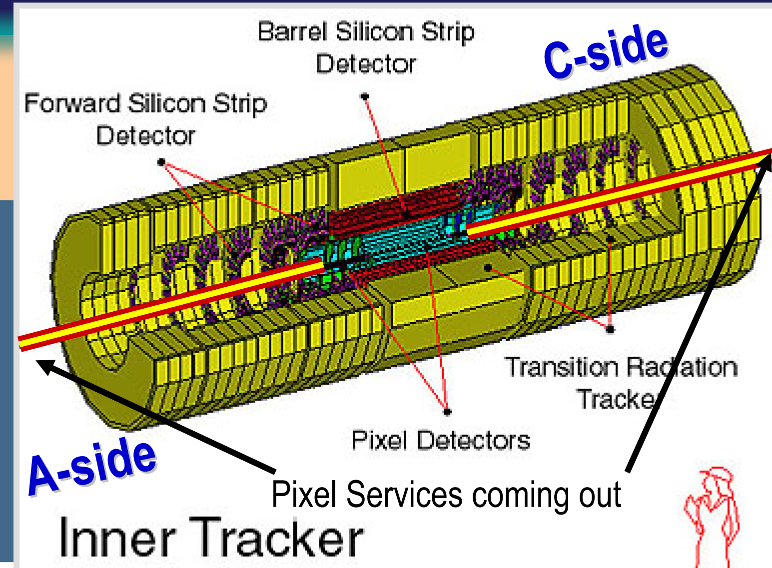
Lots of prototyping work, assembly of test set-ups, testing, obtaining/reporting the results..

- Production/on-detector instrumentation
- Assembly and testing of the control system
- Final deployment and integration to ATLAS DCS

Connections
Electronics
Firmware
Software

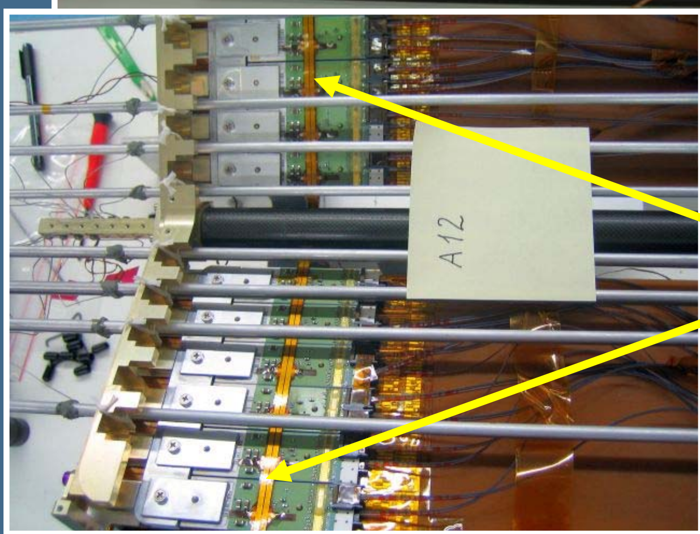
Pixel Opto-Board Heaters (II)

Connections of pixel detector are routed outside the inner tracking volume via the 'Service Panels' by which all electrical, optical, cooling services are facilitated.



Below: Pixel Services assembly area at CERN, 2007

6 Opto-boards are attached to each Service-Panel

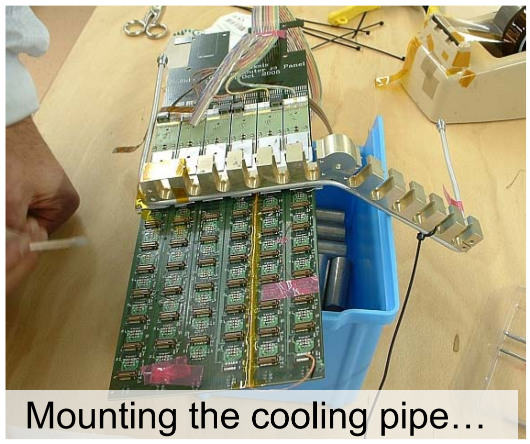


Heater Strips

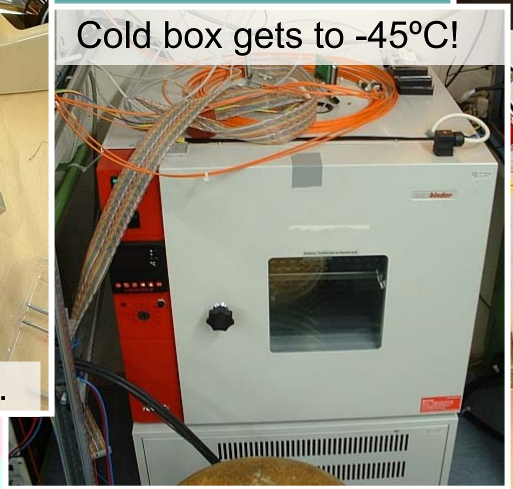
There are INNER and OUTER Service Panels which were assembled into 'octants' from the outside and the inside, then the 'quadrants'…

Pixel Opto-Board Heaters (III)

Lots of work with prototyping and testing!...



Mounting the cooling pipe…

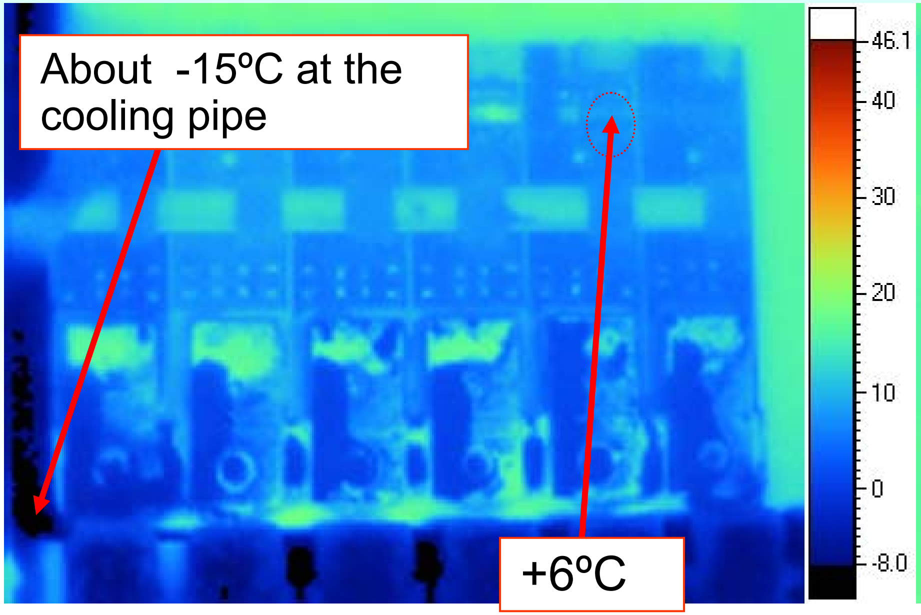


Cold box gets to -45ºC!

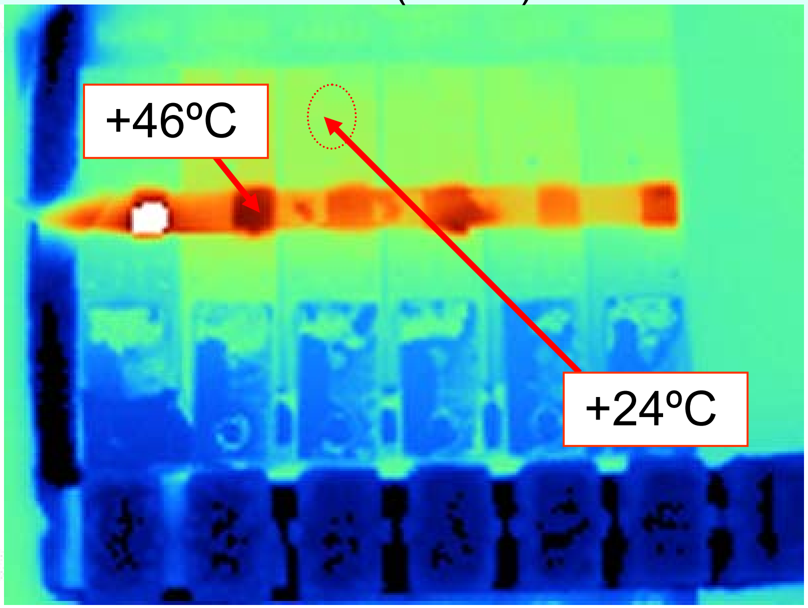
One of tests being assembled…

…Just to illustrate the effect of the heater strip:

Pic.1: Heater is OFF



Pic. 2 Heater is ON (~16W)

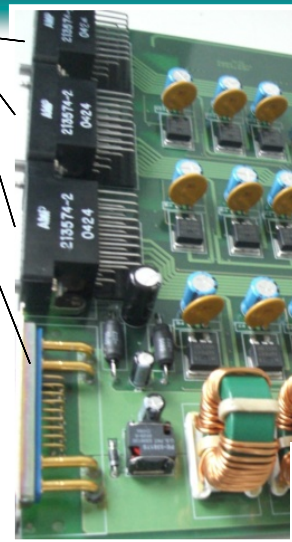


Opto-Board Heaters: Electronics

Switching Cards

“AMP” connectors lead to cavern and connect to heaters.

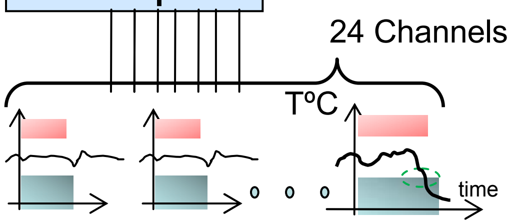
Power from, and Data to crate BP



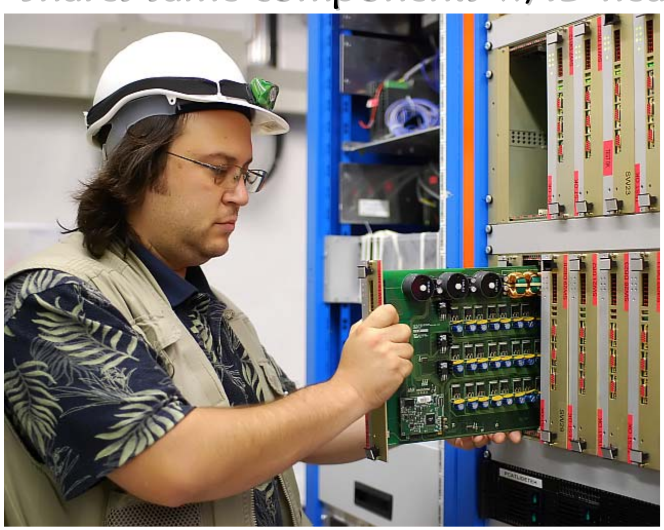
ELMB microcontroller:
Control algorithm embedded
3*8 pairs = Current and temperature measurements

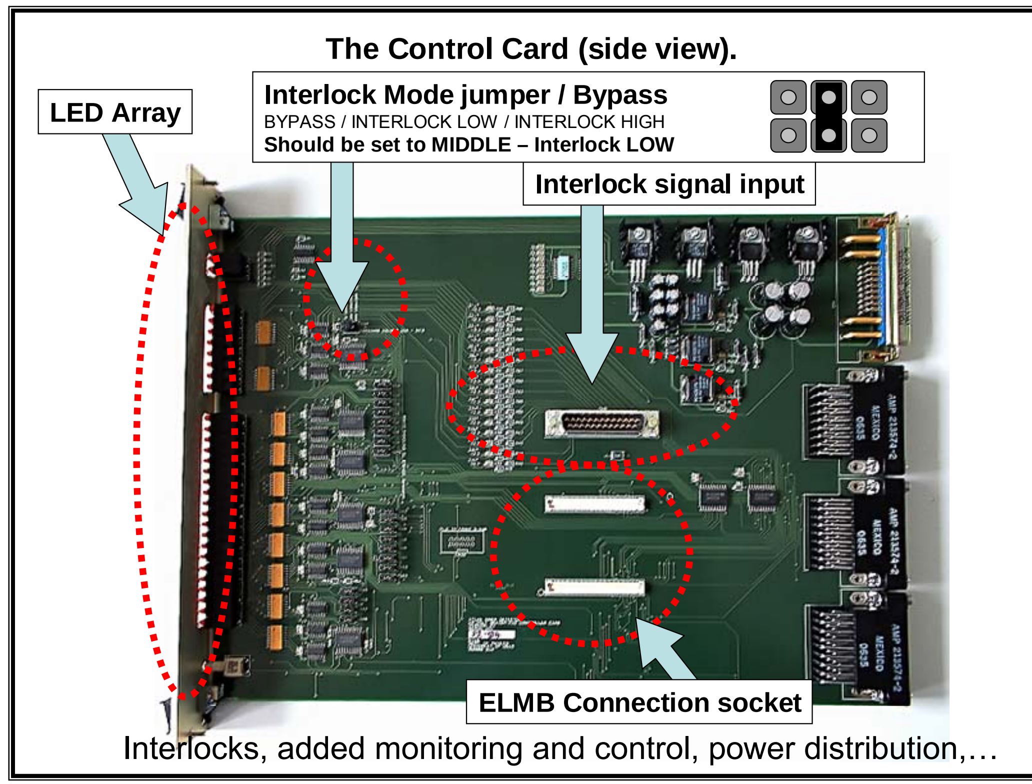
Switches:
24 x Switches 48V, 1.6A per channel, frequency set by the microcontroller program

ELMB inputs



- Crate-based system
- CAN: multi-master broadcast serial bus
- Shares same components w/ID heaters





Pixel Opto-Board Heaters (V)

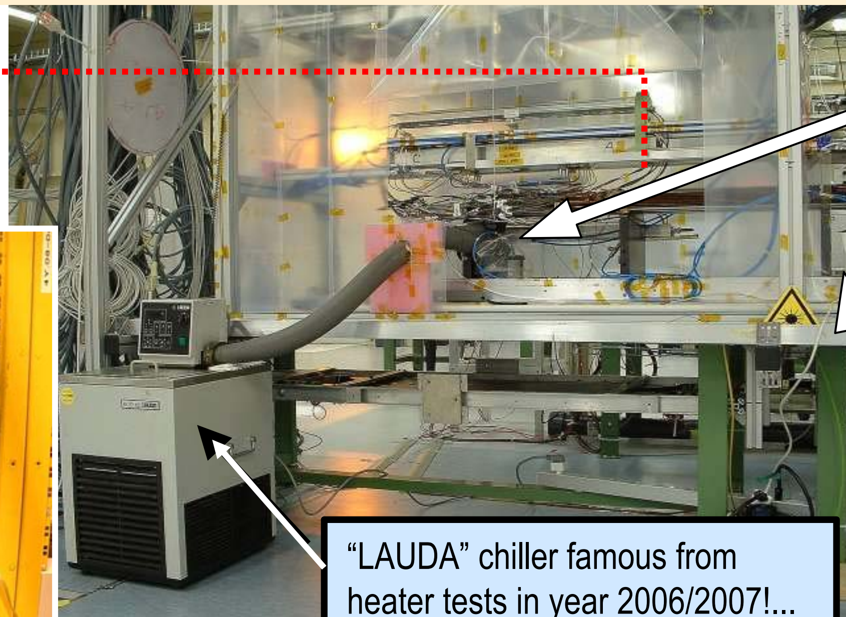
- Test “ToothPix” has everything: modules, opto-links, electronics, cooling
- My task was to integrate and attempt to run the opto-heater system
- No possibility to work on real detector, but need to have many answers!

Test of pixel detector readout chain is set-up in above-ground lab next to ATLAS cavern: the SR-1

Had to pull a 42m long cable

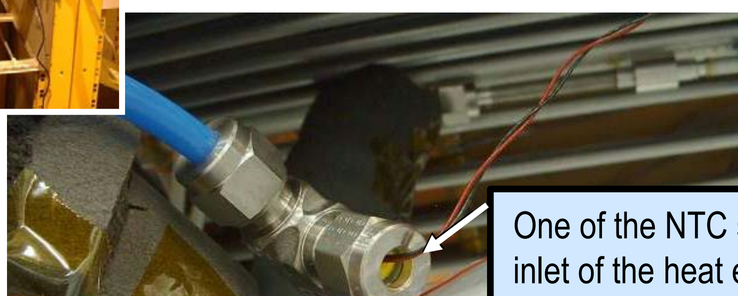
Opto-heater control crate

Electronics:
-Switching Cards
-Controller
-CAN interface
-5V, 24V, 48V power supplies



“LAUDA” chiller famous from heater tests in year 2006/2007!...

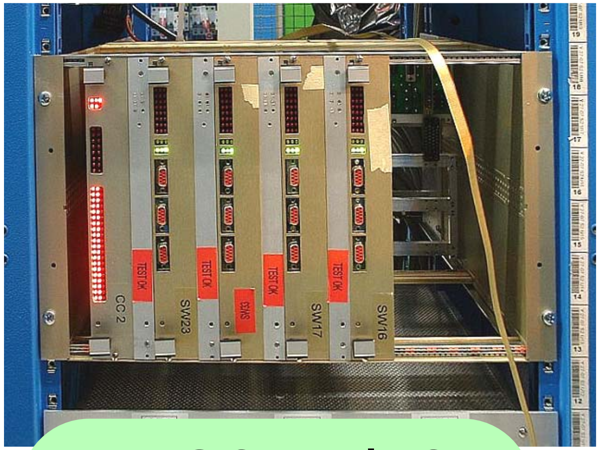
Above: A former tin can, now heat exchanger!
Below: Quite literally, a tea kettle has found its place in the experiment!

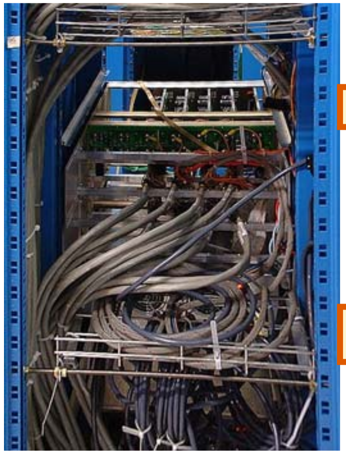


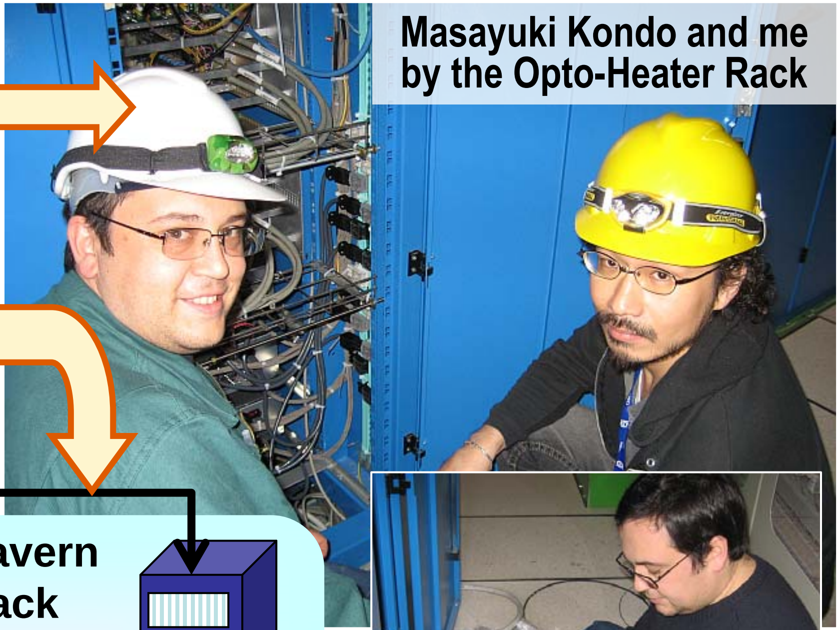
One of the NTC sensor in the inlet of the heat exchanger

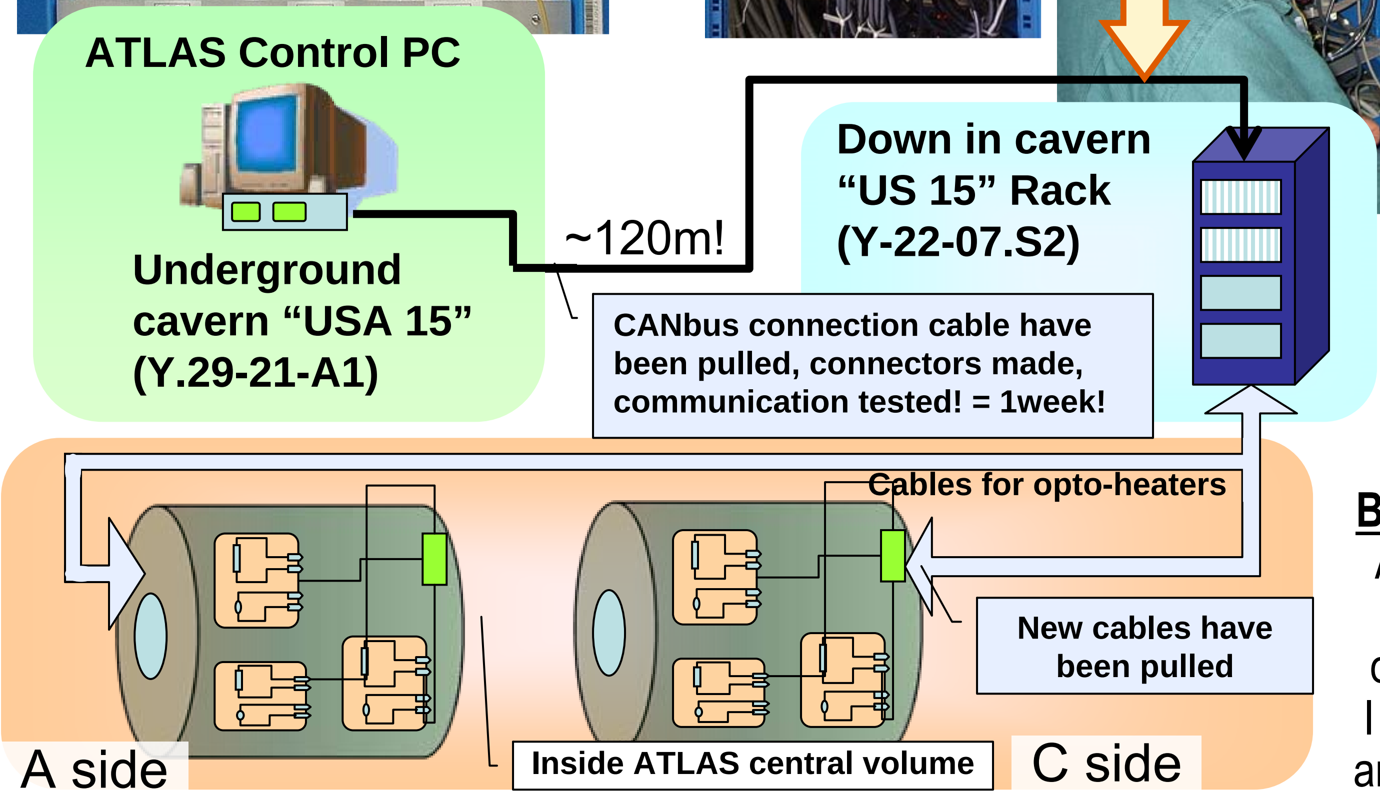
Mission accomplished: test results have proven functionality of the opto-heaters while having no impact on the readout chain & data quality.

ATLAS Pixels: Commissioning — Opto-Board Heaters: Deployment



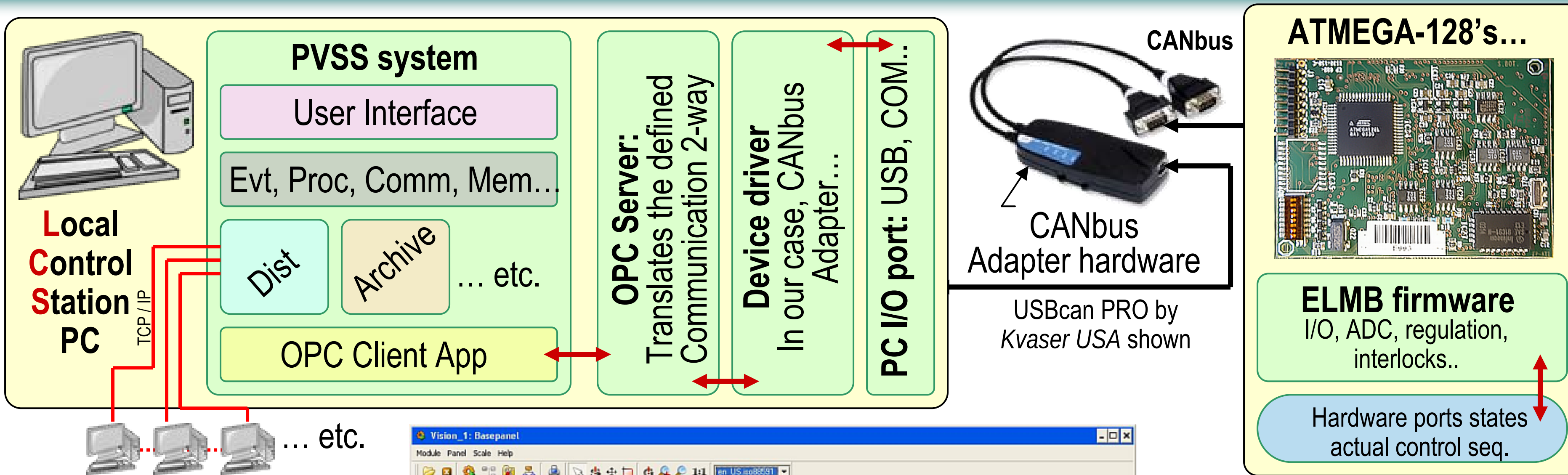






<u>BIG problem</u> was discovered:
A short of one NTC sensor to ground, making control of one of 48 heaters impossible. I have researched it and tried, and finally **<u>was able to fix it!!!</u>**

Opto-Board Heaters: the Control Interface

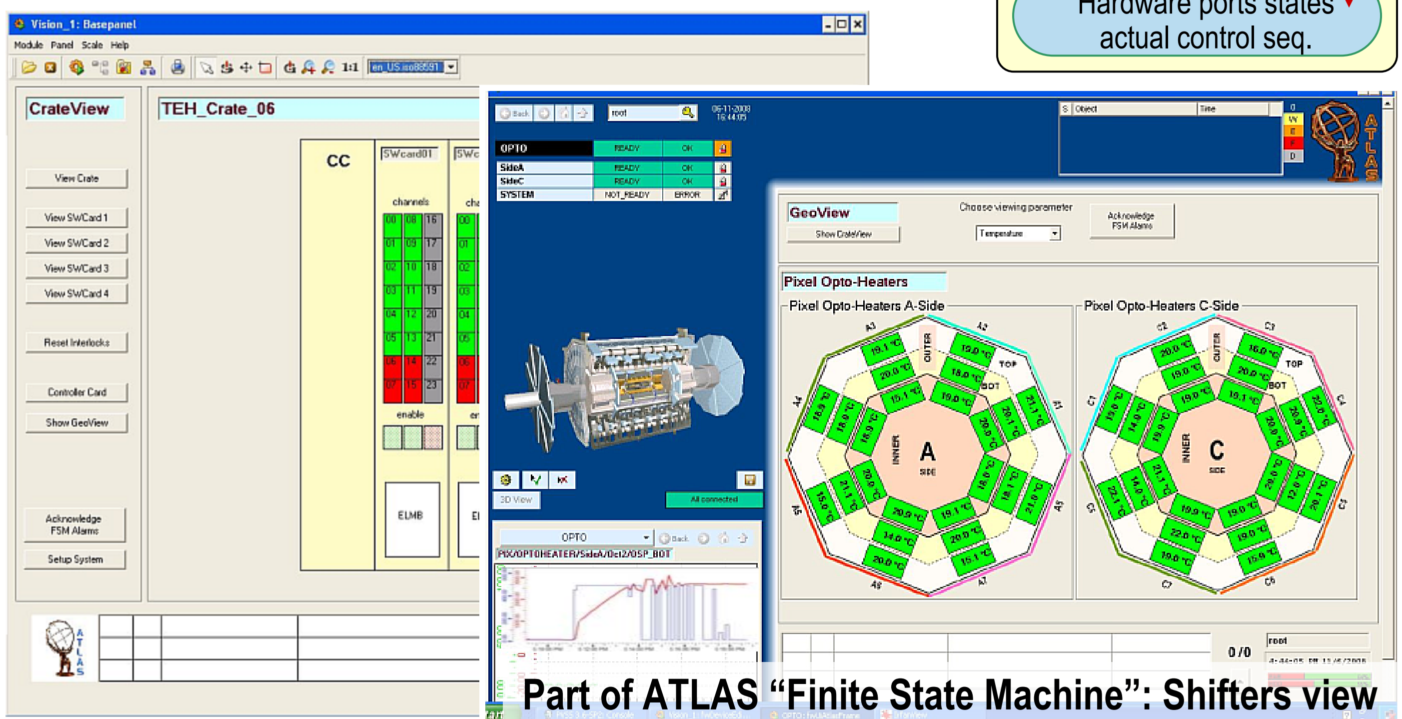


PVSS II

Austrian software company **ETM**

- Used for all detector 'slow controls' at CERN
- SCADA system
- C++ -like syntax and functionality
- **Highly scalable**
- OPC standards

Expert GUI runs on the LCS

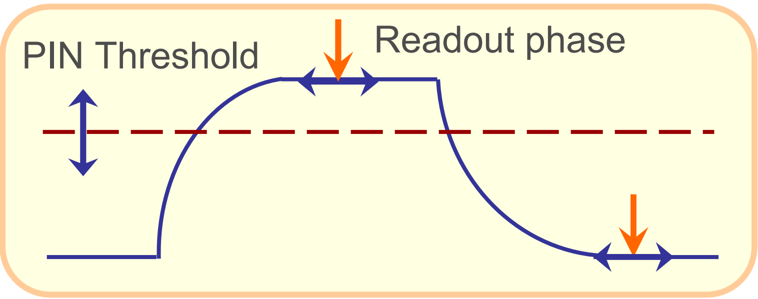


Part of ATLAS "Finite State Machine": Shifters view

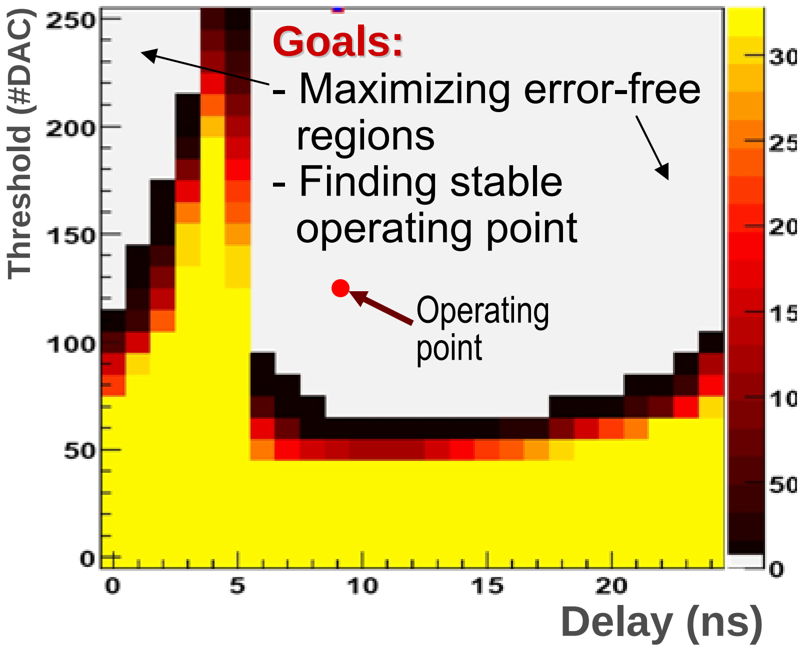
Back to pixel detector calibration!

- The optical communication uplink is tuned by adjusting
  - The power of the on-detector lasers
    - Power of VCSEL lasers is temperature-dependent
    - One laser power setting / opto-board (6/7 channels)
  - The delay of the off-detector sampling clock
  - The PiN current thresh of the off-detector receiver diode

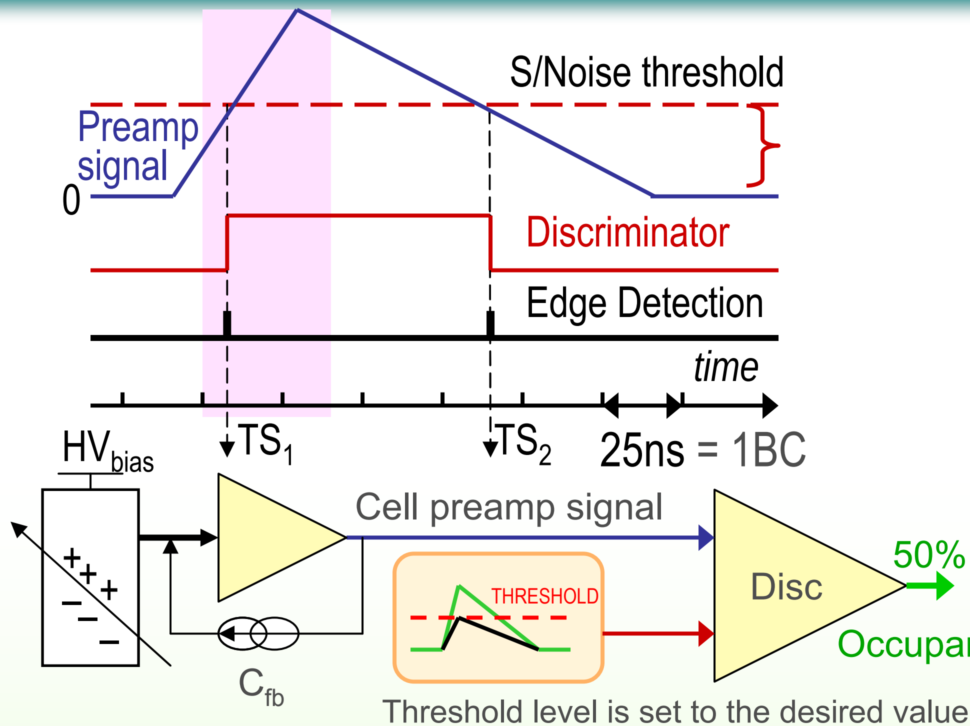
Opto-heaters have been delivered!

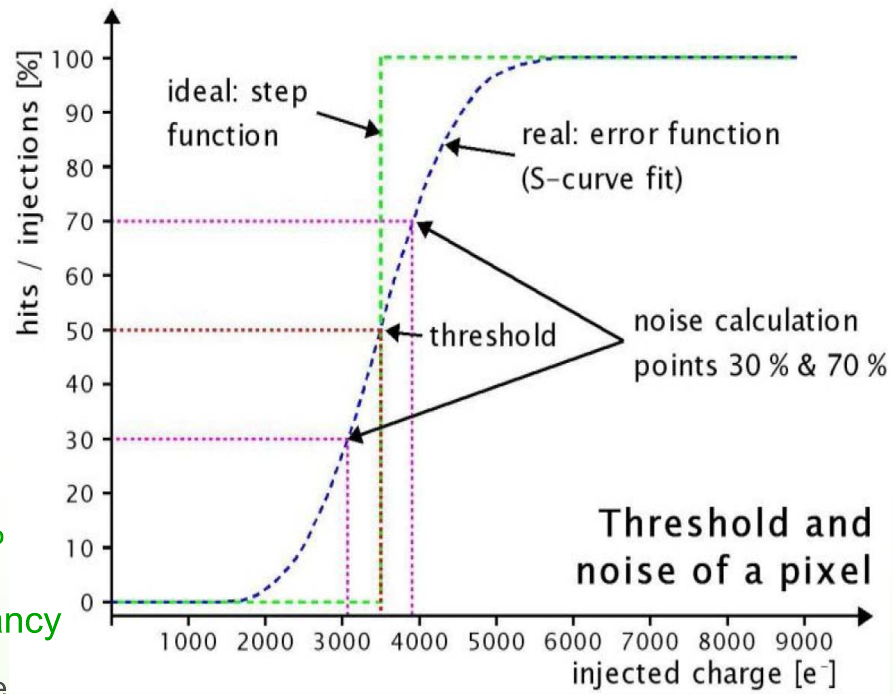


- Modules cannot be operated without good optical tuning
- Scanning 2-D parameter space
- Common stable operating point for 6/7 links has to be found
- Tuning takes ~15 min (all links)



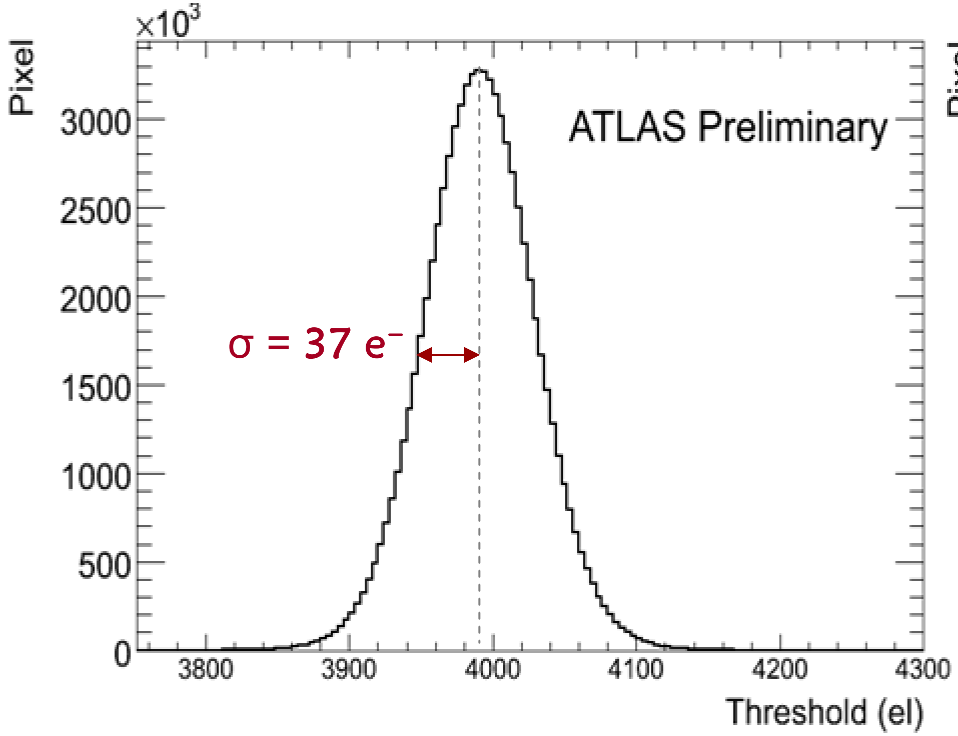
Error rate when sending a 20 MHz clock 0-1-0-1 pattern

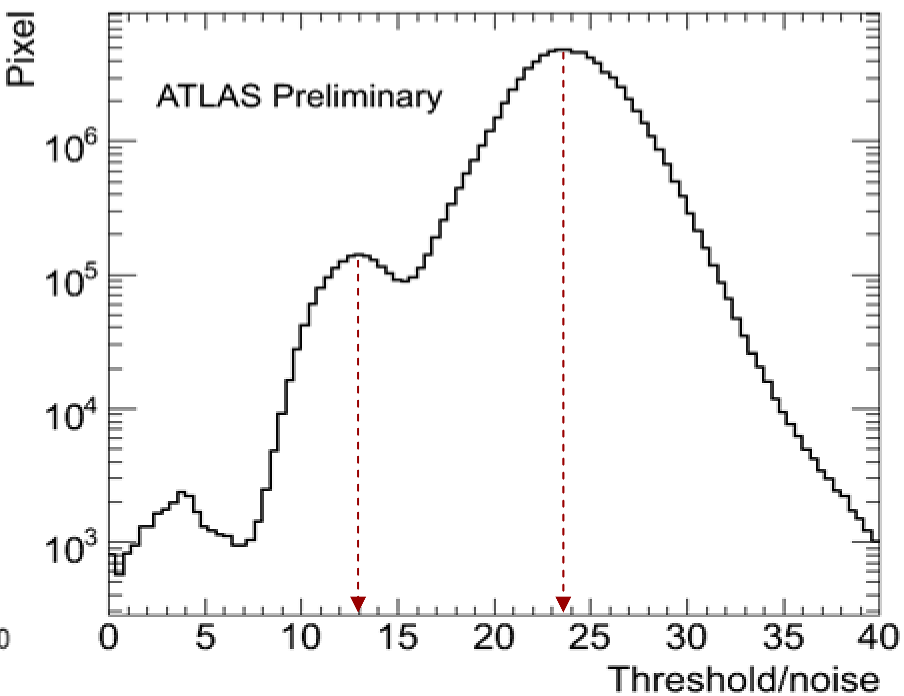




- Threshold is adjusted on pixel cell level
  - Varying charge injections in the preamp of each pixel cell via integrated in-cell calibration circuitry;
  - Fit error function to number of events vs. charge;
  - 1.5 hrs to tune the entire detector.
- September 2008 cosmic runs ⇒ initial production tuning
- November 2008 cosmic runs ⇒ fully tuned configuration

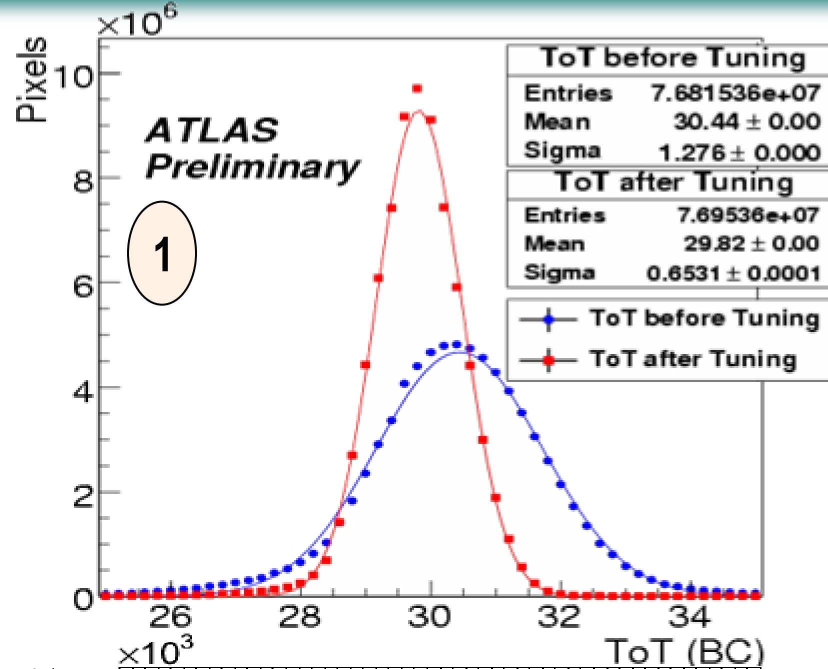
- Thresholds are tuned to 4000 e^- in November 2008
- Dispersion is only ~ 37 e^-
  - Threshold over noise is ~ 24 for most pixels
  - Threshold over noise is ~ 13 for those few special inter-chip pixels…
- New calibration has been just done in late August 2009
  - New plots are not ready yet…

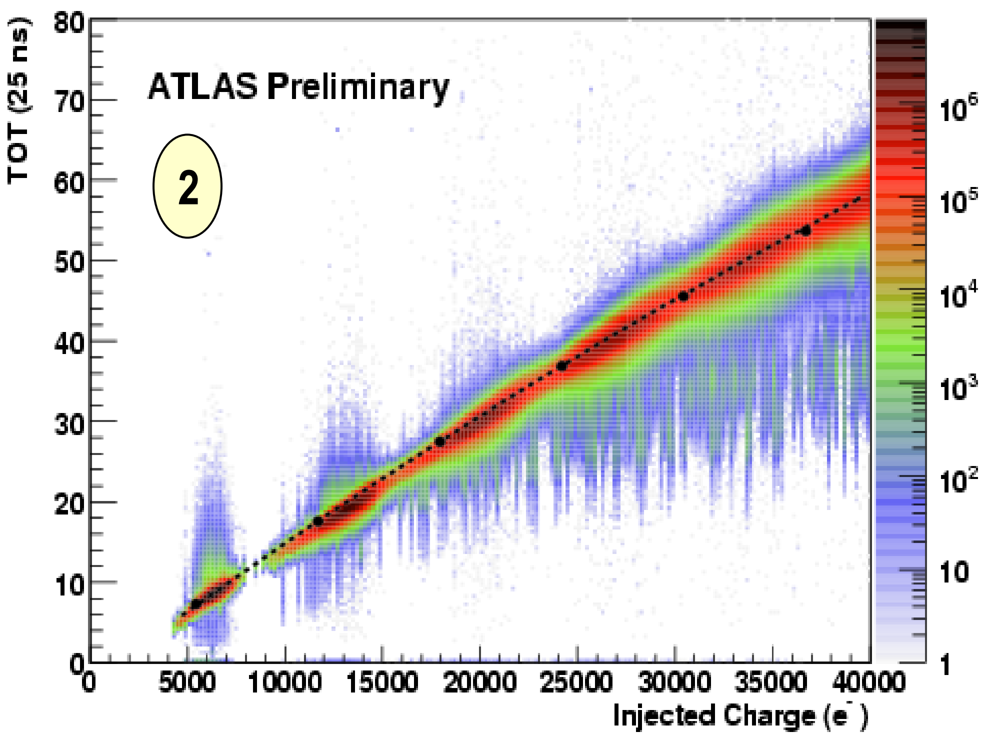


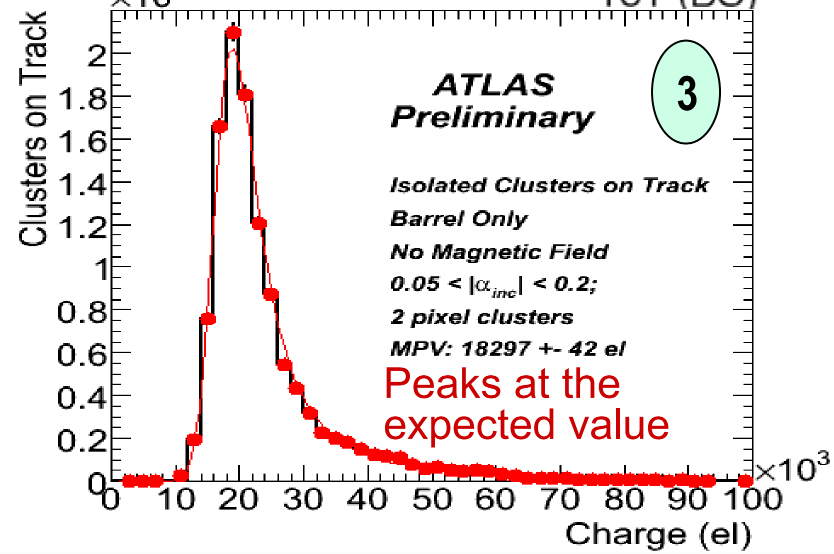


ToT (Time over Threshold) Tuning

- Adjust the preamplifier feedback current on FE's until a M.I.P. (20ke$^-$) corresponds to a Time-over-Threshold value of 30 BC's
- Uniform response improves accuracy for the cluster position determination
- Extract full ToT vs. charge calibration curve for each FE to use off-line

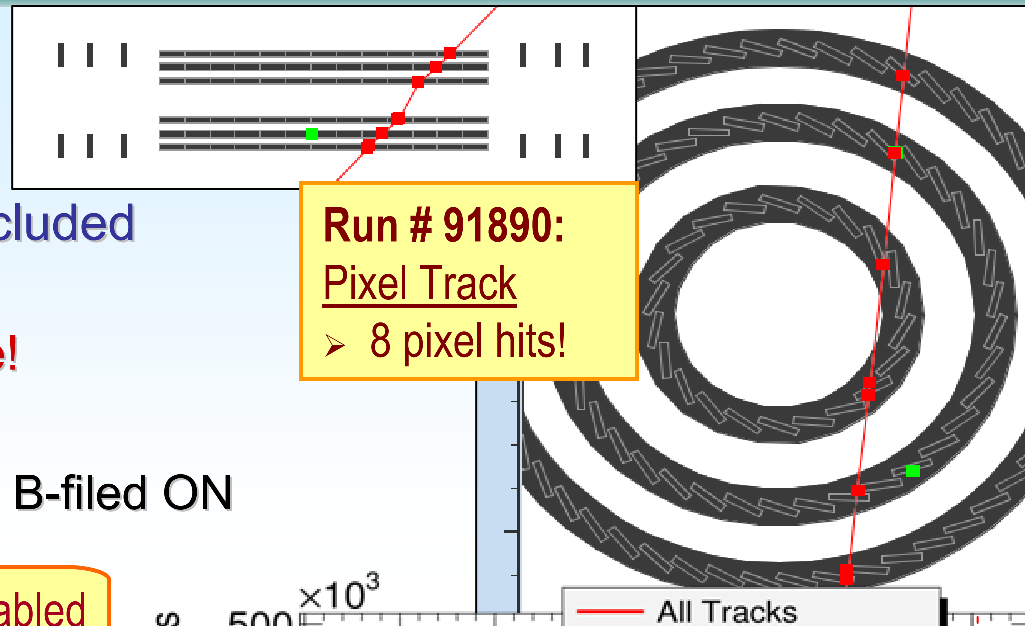


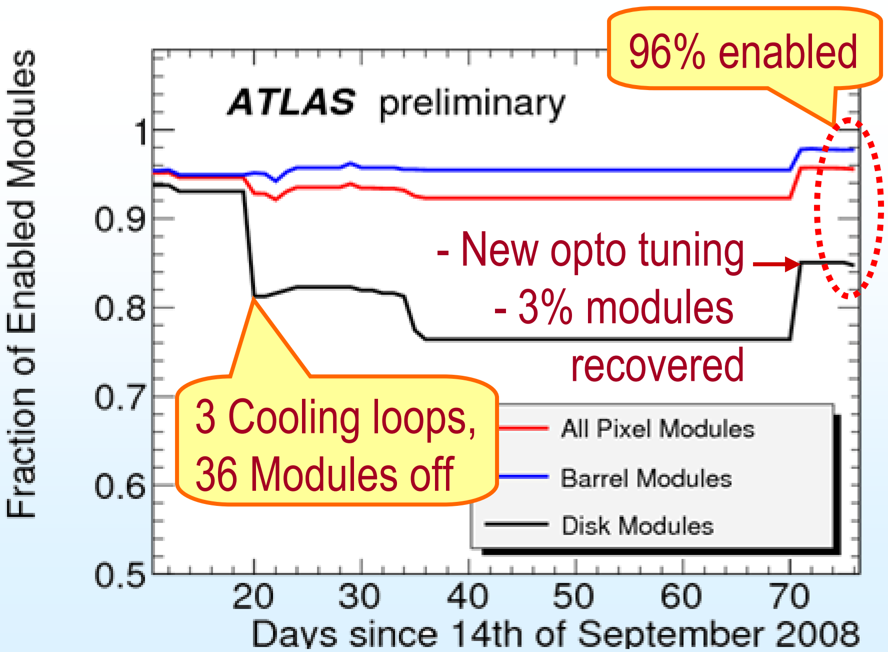


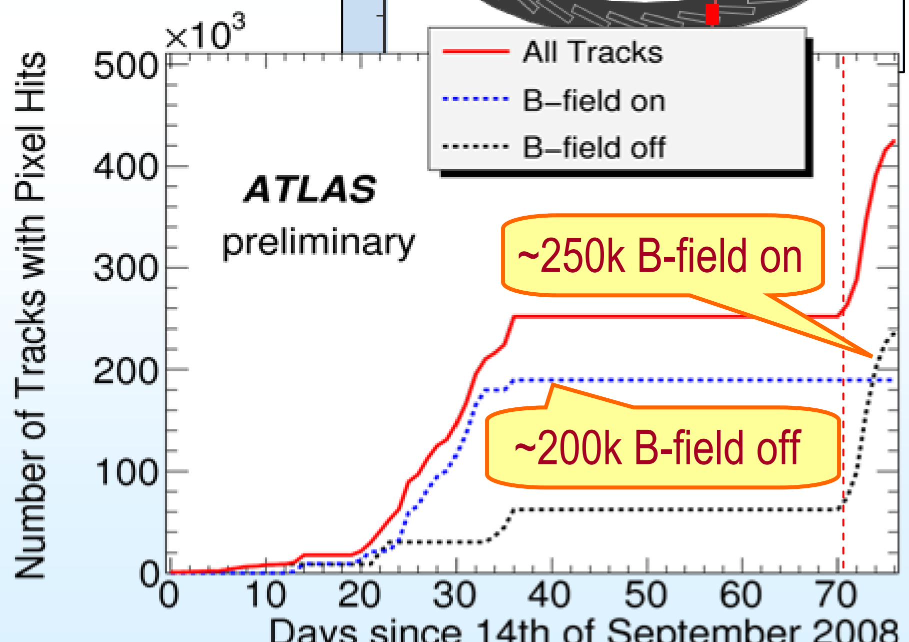


Cosmic Data Taking: Fall 2008

- Sept 14th, 2008: First tracks!
  - Trigger used: muon triggers
- Some modules were initially excluded
  - Improved optical tuning ⇒ most modules now are on-line!
- During cosmic data taking:
  - 2/3 time B-field OFF, 1/3 time B-filed ON

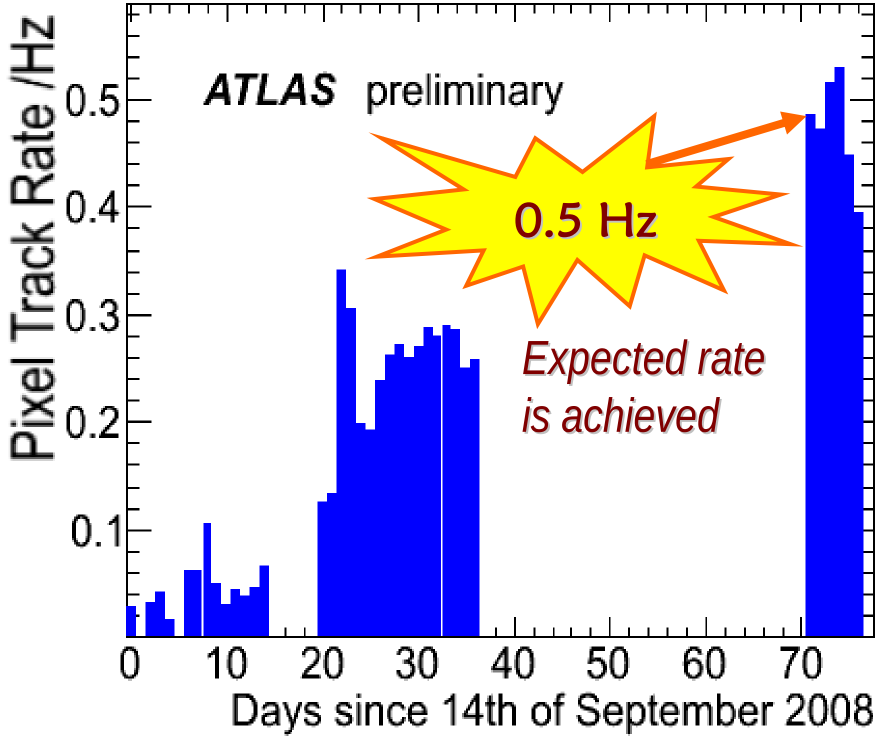


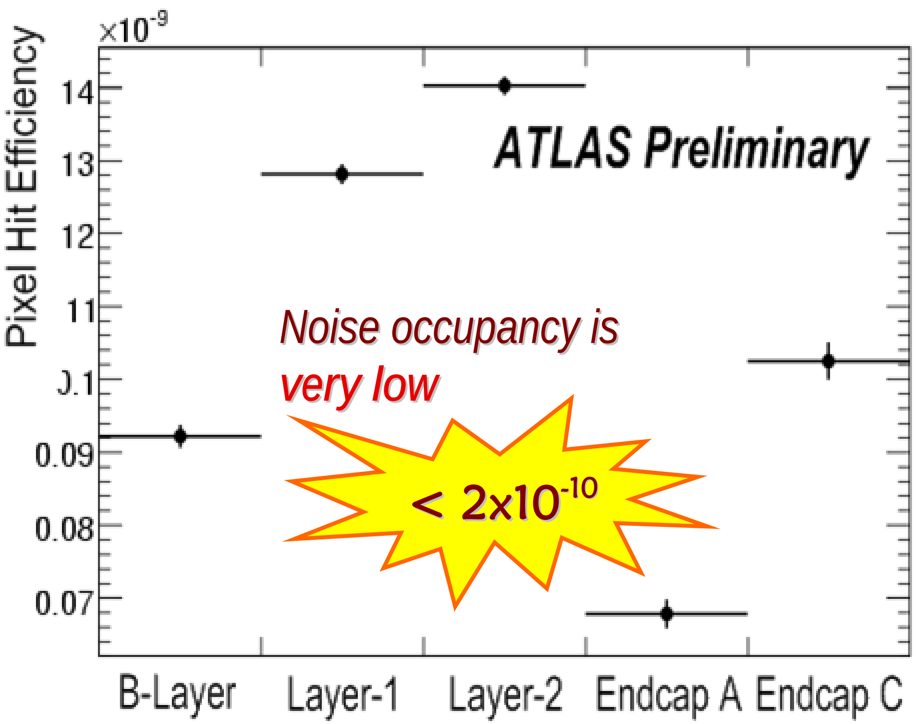




- improvements to muon trigger timing
- commissioning of HLT & TRT L1 triggers

➔ increased pixel track rate to ~0.5Hz (expected from sim.)

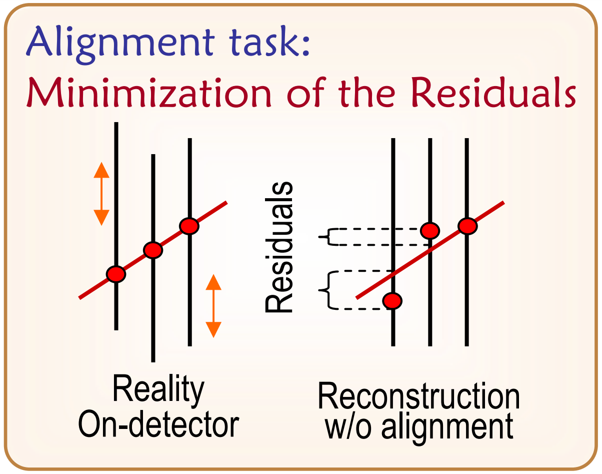


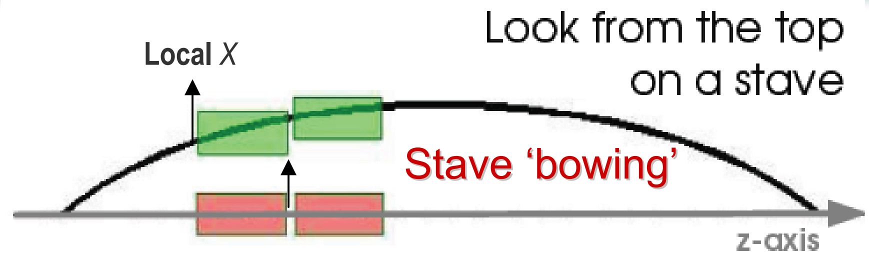


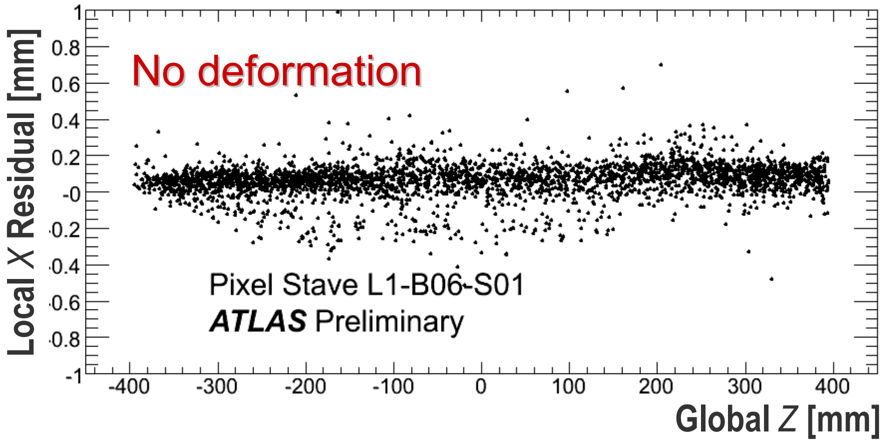
Noise: $< 2\times10^{-10}$ pixel / crossing

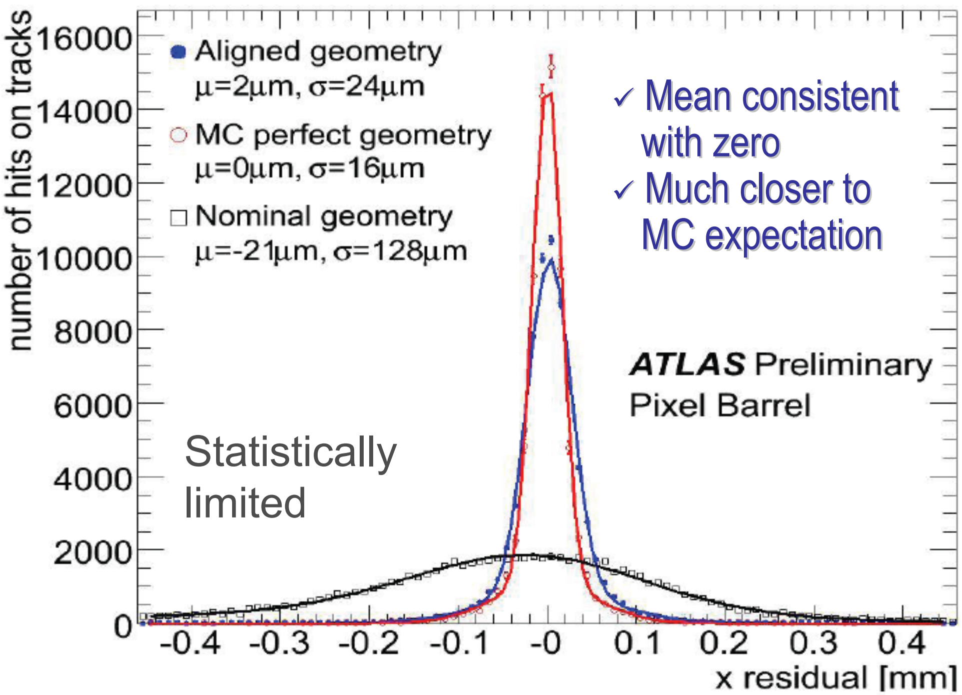
0.3-0.7 noise hits in full detector per crossing!

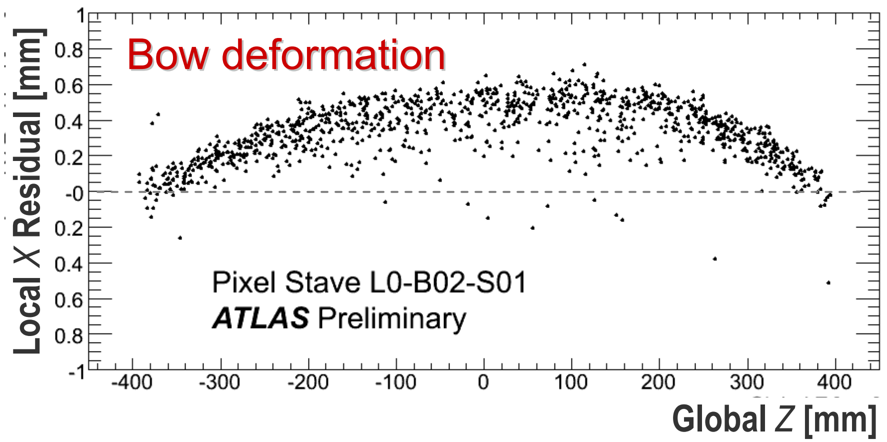
Alignment with Cosmic Data



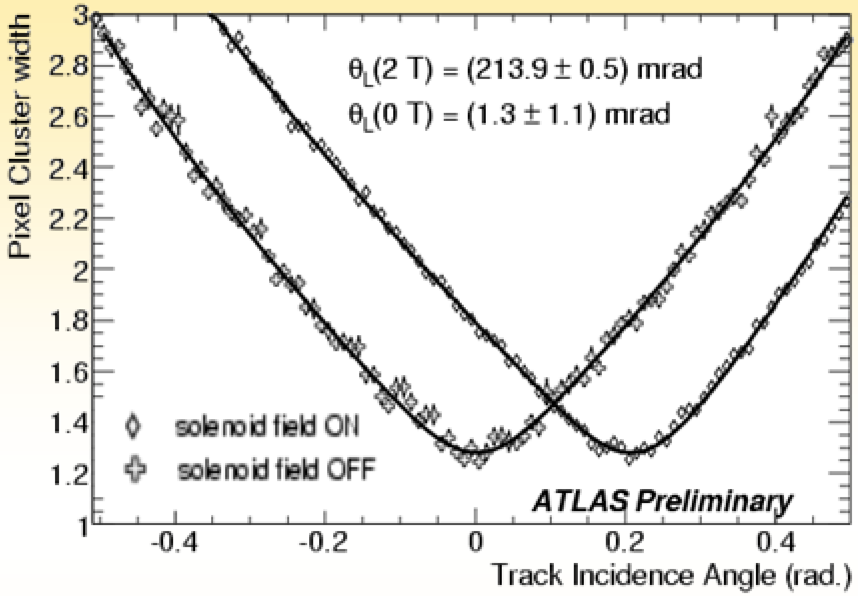








Lorentz angle: 214 ± 0.5 mrad (expect ~224 mrad)

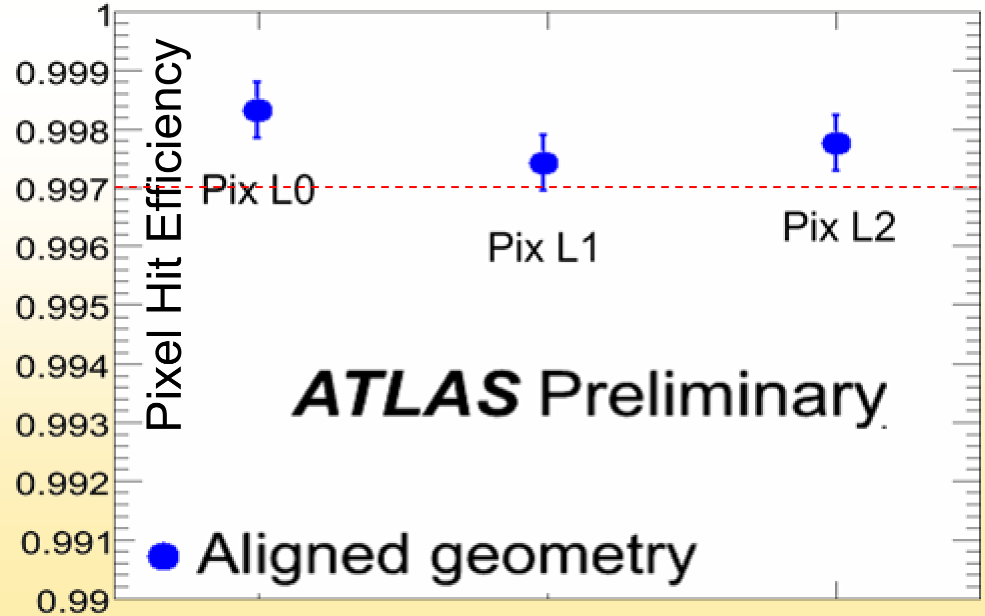


- Quantifies the electron drift in the sensor due to the B-field.
- Measured by fitting the cluster size vs. the incidence angle.
- Data measurement agrees with the expectation to within 5%.
- Angle with the B-field OFF is consistent with zero.

- Improvements with alignment
- Hit efficiency in barrel layers

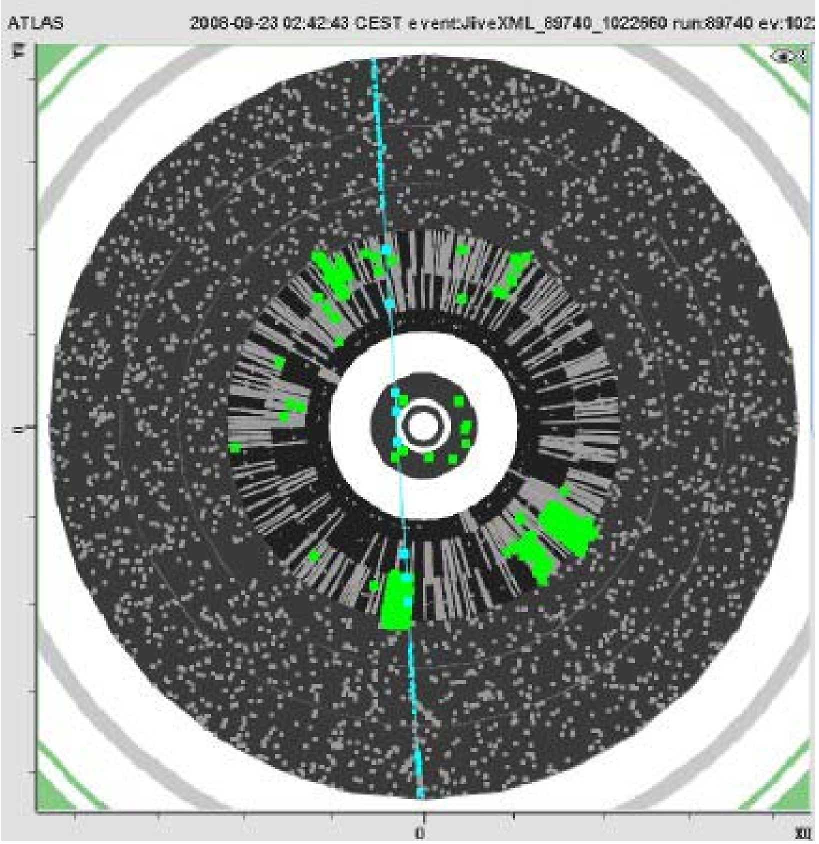
\> 99.7%

Alignment: Hit Efficiency (Barrel Layers)

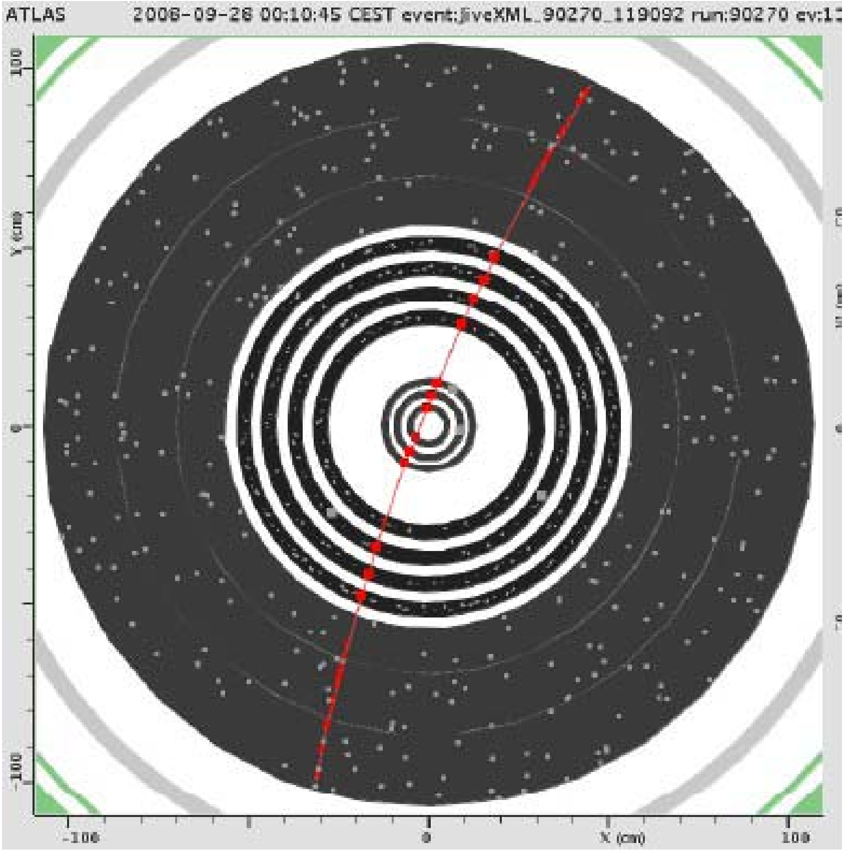


- Noise mask is created off-line and applied on-line
- Noisy, "hot" pixels are defined having ≥ 10^{-5} hits / event
- ~ 5K pixels are being masked ⇒ only 0.006% of all pixels

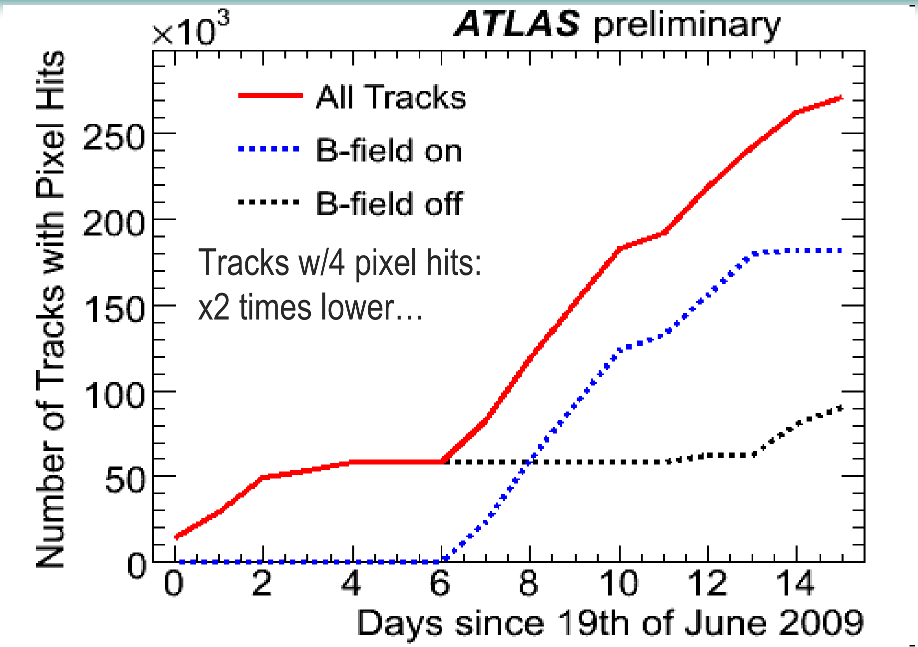
w/o the noise mask

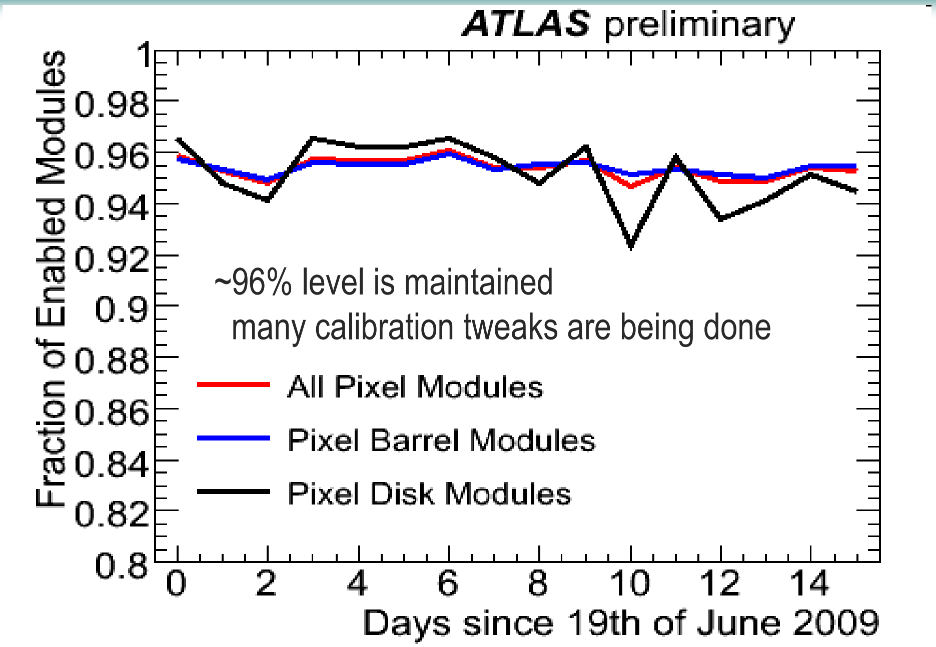


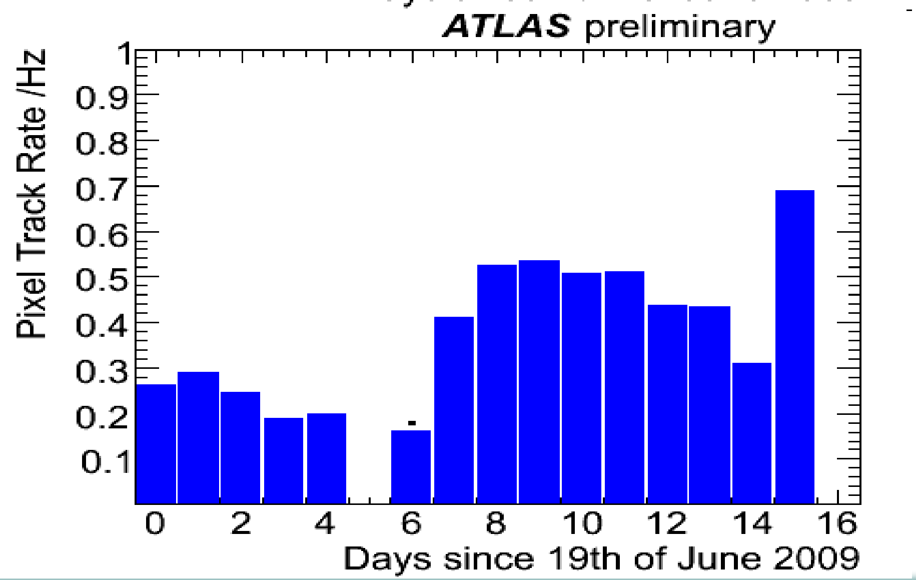
with the noise mask

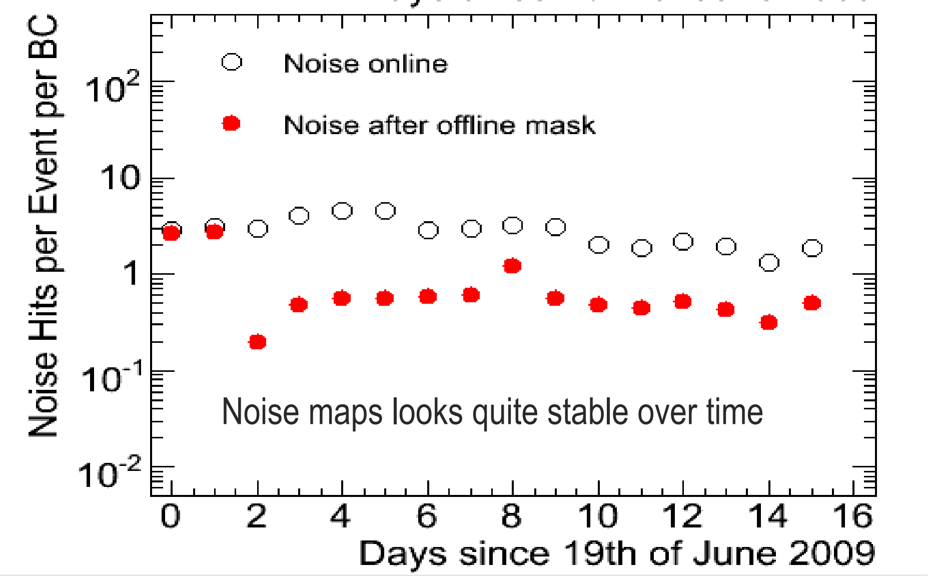


The Most Recent Updates



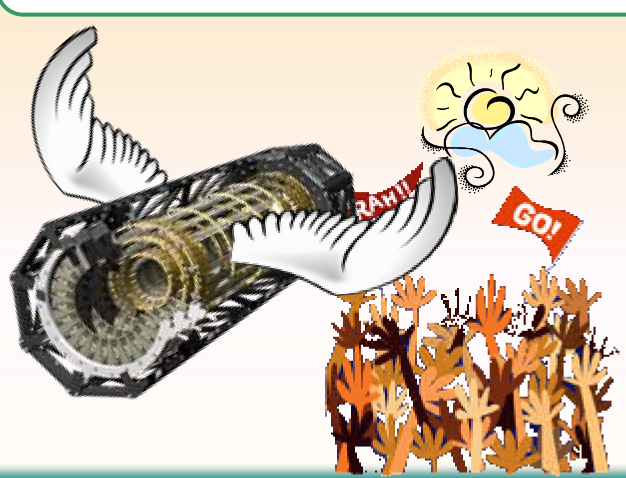






Summary for the Pixel Detector

- Extremely tight commissioning schedule was successfully met.
- All of the commissioning challenges were successfully resolved.
- 96% of all modules are included in data taking.
- 2% were disabled due to problematic cooling loops (all in the disks):
  - ⇒ Year 2009: all cooling loops are operating;
  - ⇒ June 2009: Modules on these loops are qualified, tuned, and operate!
- Hit efficiency in the enabled modules (barrel layers) is above 99.7%.
- Noise occupancy is $< 10^{-10} \Rightarrow$ Well below one noise hit per event.
- Resolution after recent alignment with available cosmics ~24 μm.
- Pixel detector performs very well.



ATLAS pixel detector is ready to take collision data in 2009/2010!

My Activities While on ATLAS

5 UTD Physics interest
- Quarkonia / exotics

ATLAS Pixel Detector

4 Running Pixel Detector
- Detector operations
- Calibration: opto-links etc.

Inner Detector Heater Pads ⟷ **Pixel Opto-Heaters**

Systems share the same electronics so it was decided to keep a high degree of unification

The main goal was set to get the subsystem that UTD had started to support, up and working, and do whatever it takes to get ATLAS operational on schedule.

Documentation

1 Hardware Tasks
- Installation and testing
- Troubleshooting
- Functionality improvements and mods
- New heater hardware electronics development

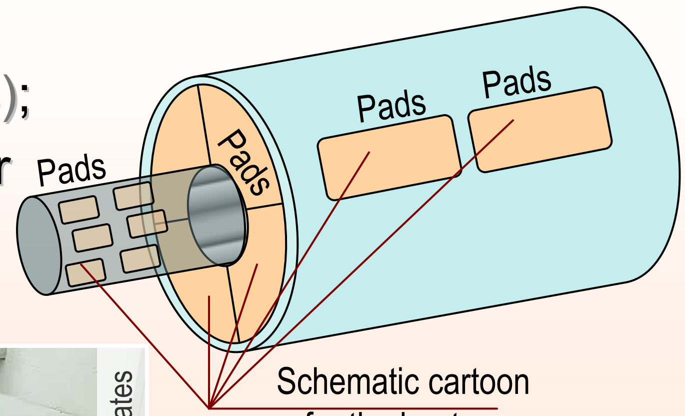
2 Firmware (front end)
- Develop the ELMB code
- Further PID mods, two choices / regimes
- Implementing hardware functionality features
- Troubleshooting
- FSM features
- New development

3 Software / GUI / FSM
- PVSS project installation
- PVSS development
- Maintenance/debugging
- Finite State Machine
- Troubleshooting (additional scripts, DP's)
- Integration into Pixel DCS $\rightarrow$ ATLAS DCS

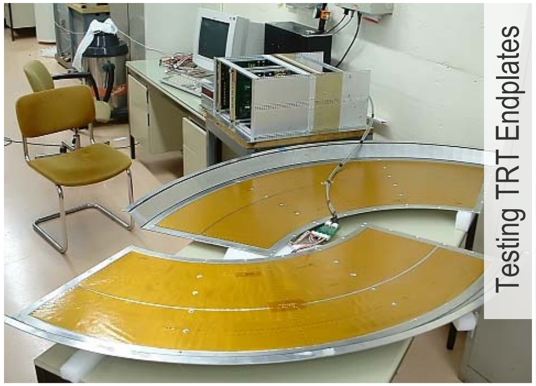
Inner Detector Heater Pads

- Purpose and general scope:
  - About 270 auxiliary heat sources glued to various components of the ID (~480 channels);
  - Independently driven, heaters compensate for undesired aggressive cooling in target areas;
  - Maintain thermal neutrality between sub-detectors boundaries;
  - Prevent condensation.

Thermal Enclosure Heaters (TEH)



Schematic cartoon for the heaters



Testing TRT Endplates

SCT endcap

- More detail on heater pads:
  - Sized from 0.04 to 0.64 m^2;
  - Various shapes, some quite complex;
  - Copper on Kapton, 5-8 μm thick;
  - Sensors: NTCs attached to pads.

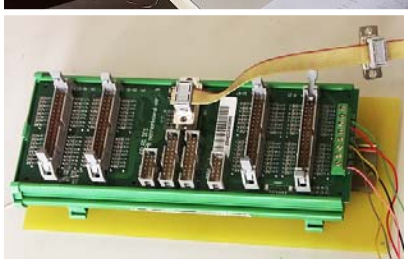
4 configurations of pads:

Sorted by 'complexity'

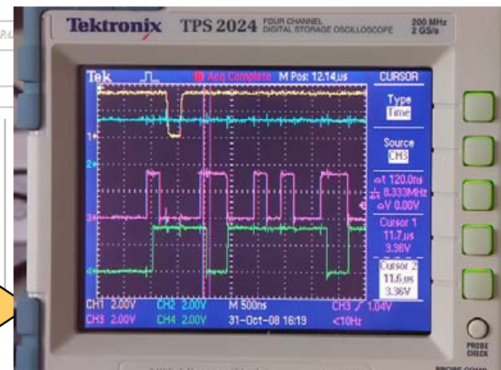
$1^{NTC}/1^{HE}$	$1^{NTC}/2^{HE}$	$2^{NTC}/2^{HE}$	$2^{NTC}/4^{HE}$
Scheme D	Scheme A	Scheme C	Scheme B

- Time frame: July 2008 – present time;
- All of the designs have been made, passed the Safety Review at CERN in 2008!
- PCB boards (switching and controller cards), crate mechanics, backplanes… all have been developed and prototyped!
- New electronics design philosophy: all logic is in ALTERA 10K10 FPGAs
- One of my main challenge was making the ELMBs talk to FPGAs
- PVSS-based testing programs
- Just passed the final expert peer review at CERN!

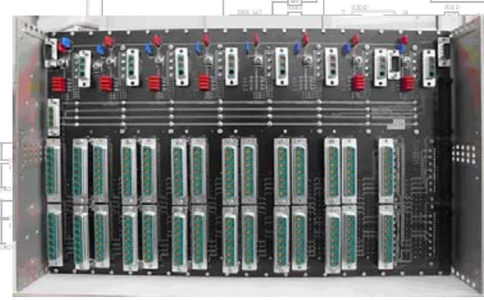
I was the one putting together the technical writeup



A small ELMB test stand was put together, and…

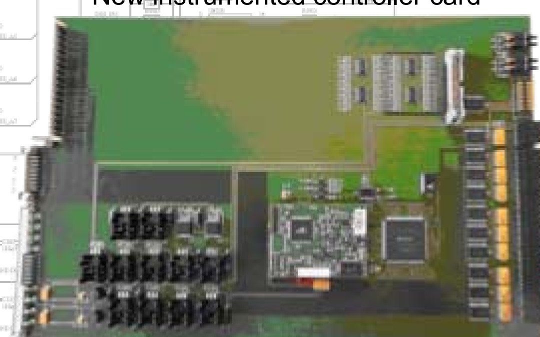


… this is the correct WRITE cycle to the FPGA visible on the scope!



New instrumented switching card

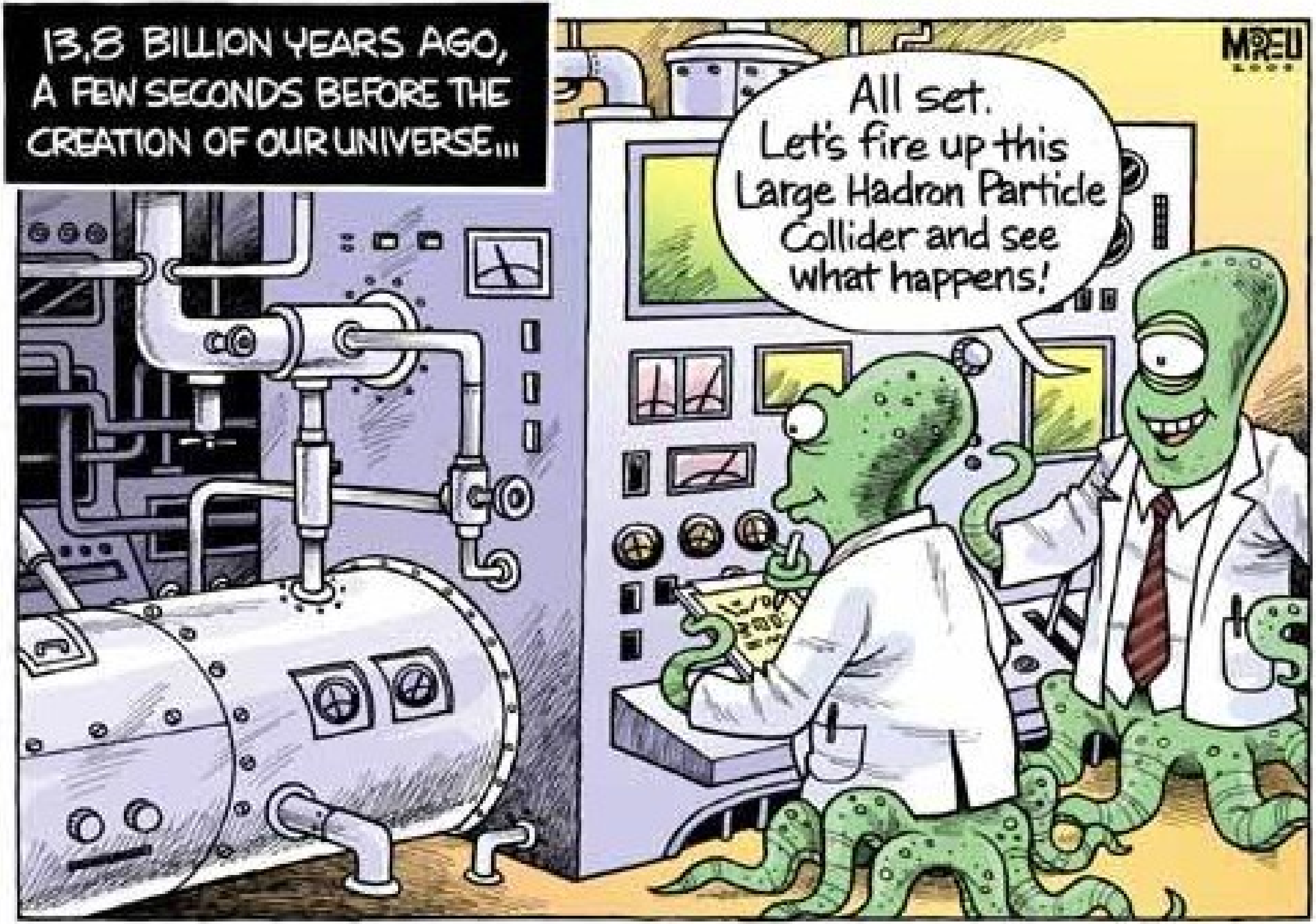
New instrumented controller card



Ready to Take Physics!

- **Inner Detector**
  - Pixel Detector
    - ✓ ~ 98.5% channels good
    - ✓ Hit efficiency 99.7%
    - ✓ Noise occupancy ~10^{-10}
  - Silicon Strip Tracker
    - ✓ > 99% modules good
    - ✓ Hit efficiency > 99.5%
    - ✓ Noise occupancy: 4.4×10^{-5} (BRL), 5×10^{-5} (EC)
  - Transition Radiation Tracker
    - ✓ e-π separation: 0.5 < E < 150 GeV
    - ✓ > 98% of 52K channels operational
  - Services and cooling
    - ✓ Leaky loops fixed
    - ✓ Upgraded cooling plant
    - ✓ Uptime efficiency ~ 96%
    - ✓ New opto-heater system
    - ✓ New ID TEH electronics is coming
- **Calorimetry**
  - LAr
    - ✓ 99.98% operational
    - ✓ Noisy channels ~ 0.003%
    - ✓ Calibration systems OK
  - Tile Calorimeter
    - ✓ 99.6% operational
    - ✓ Calibration systems OK
  - L1 Calorimeter trigger
    - ✓ Dead channels < 0.4% (+0.3% to be recovered) of 7200 analogue channels
    - ✓ Channel to channel noise suppression allows $E_{\perp}$= 1GeV cut (aim is 0.5 GeV)
- **Muon Spectrometer**
  - Precision chambers
    - ✓ Resolution 35-40μm;
    - ✓ MDTs (BRL/EC):
      - 99.3% good, 0.5% recoverable;
    - ✓ CSC ('small wheel'): 98.5% good;
    - ✓ Optical alignment system (12232 ch.):
      - 99.7% (BRL), 99% (EC) good.
  - Trigger chambers
    - ✓ Resolution 5-10mm;
    - ✓ Time res. < 25ns;
    - ✓ RPC (BRL): 96% good;
    - ✓ TGC (EC):
      - 99.8% good;
      - Noisy ch. < 0.02%
  - Muon System stand alone resolution: $\Delta P_{\perp}/P_{\perp}$ < 10% (up to 1 TeV)

Thank you for your attention!



Notes

BACKUP SLIDES

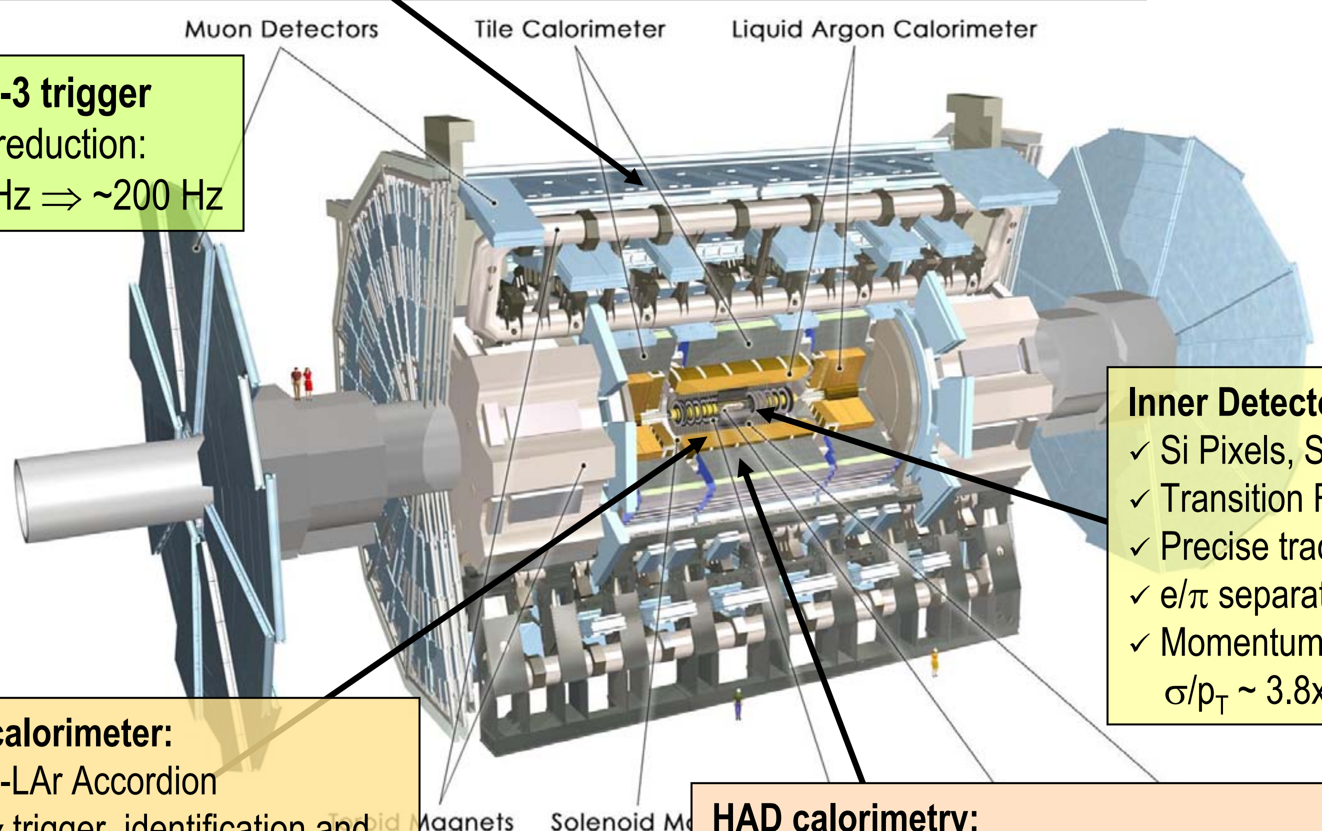
FOLLOW

ATLAS in More Detail

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

A giant indeed:
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

Level-3 trigger
Rate reduction:
40 MHz ⇒ ~200 Hz



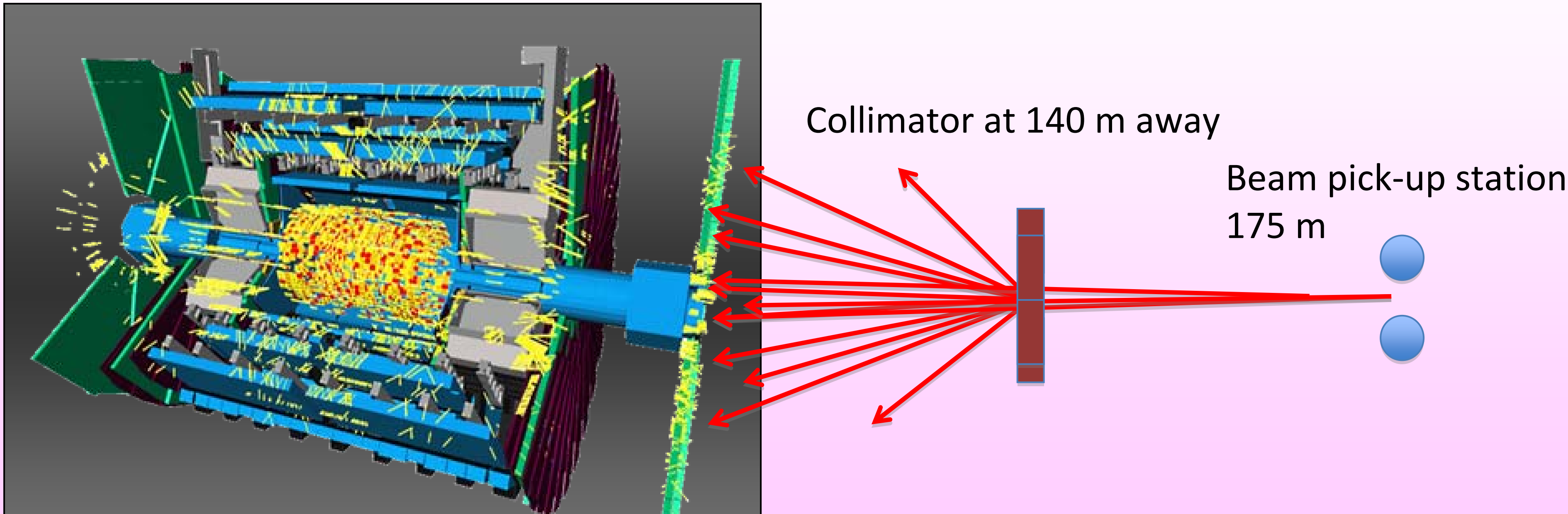
Inner Detector ($|\eta|<2.5$, B=2T):
- ✓ Si Pixels, Si strips
- ✓ Transition Radiation detector (straws)
- ✓ Precise tracking and vertexing
- ✓ e/π separation
- ✓ Momentum resolution:
  $\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\mathrm{GeV}) \oplus 0.015$

EM calorimeter:
- ✓ Pb-LAr Accordion
- ✓ e/γ trigger, identification and measurement
- ✓ E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

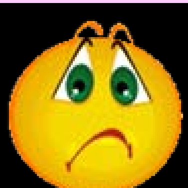
HAD calorimetry:
($|\eta|<5$): segmentation, nearly 4-π hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

ATLAS: Commissioning — 9/10/08 - Startup of the LHC

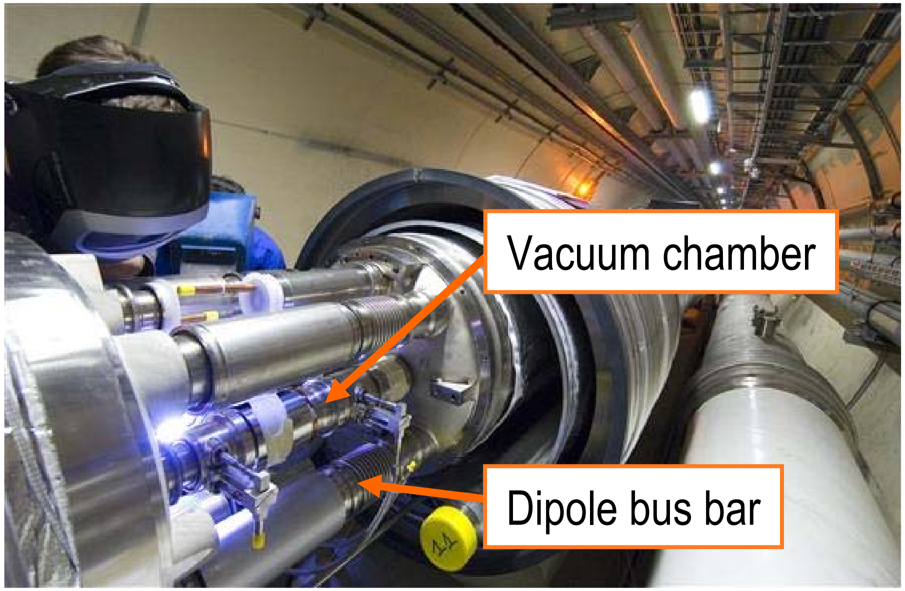
After almost 20 years of hard work on R&D, construction, and commissioning of the LHC, first beam with energy 450 GeV passes through the LHC tunnel.



First beam splash event seen in ATLAS

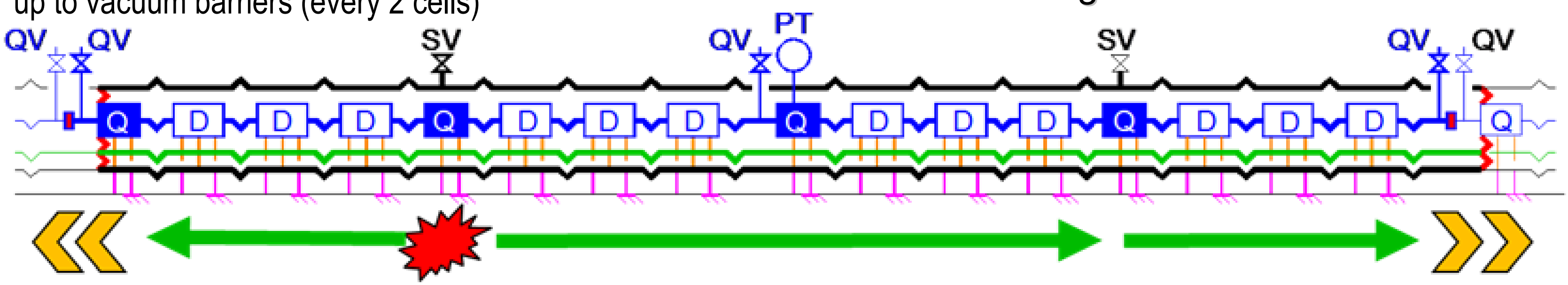


September 19th: Operational accident in the LHC sectors 3-4 disables accelerator operation. Cosmic data becomes the primary source for detector operation and calibration procedures.



He pressure wave travels along magnet inside insulation vacuum up to vacuum barriers (every 2 cells)

- Last commissioning step Sector 3-4: ramp to 9.3 kA (5.5 TeV)
- An electrical fault developed @ 8.7 kA in the dipole bus bar Q24.R34
  - R_{splice} in the interconnect of ~ 220 nΩ vs. 0.35 nΩ
- An electrical arc developed which punctured the *He* enclosure
  - Secondary arcs developed along the circuit
  - ~ 400 MJ / 600MJ were dissipated into the magnet coldmass and in electrical arcs.



- Cold-mass
- Vacuum vessel
- Line E
- Cold support post
- Warm Jack
- Compensator/Bellows
- Vacuum barrier

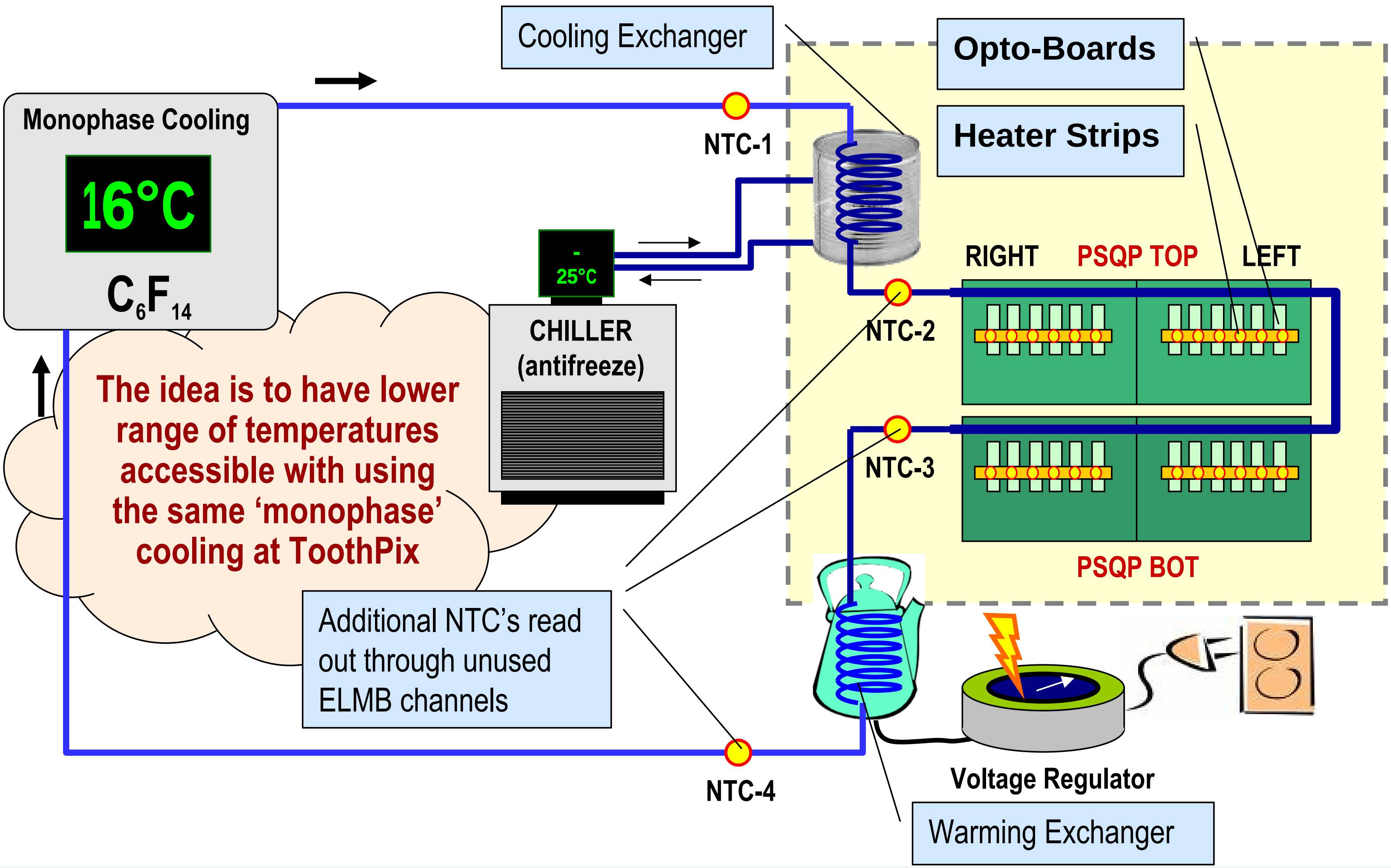
- **Self actuating relief valves:**
  - 2 kg He/s vs.~ 20 kg He/s
- **Large forces exerted on vacuum barriers:**
  - 1.5 bar vs. ~ 8 bar
  - Resulted in ~ 50 cm displacements of the magnets!

- Tons of liquid *He* were released into the insulation vacuum
  - Pressure wave along the magnets in the insulation vacuum → collateral damage

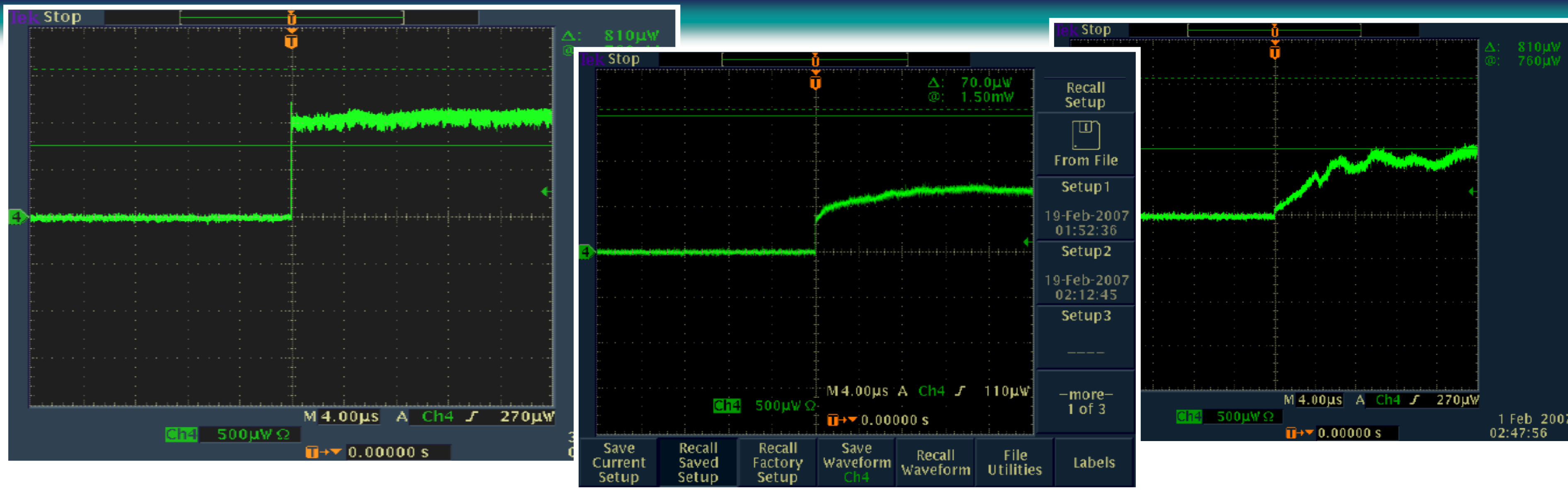
Based on: Mike Harrison

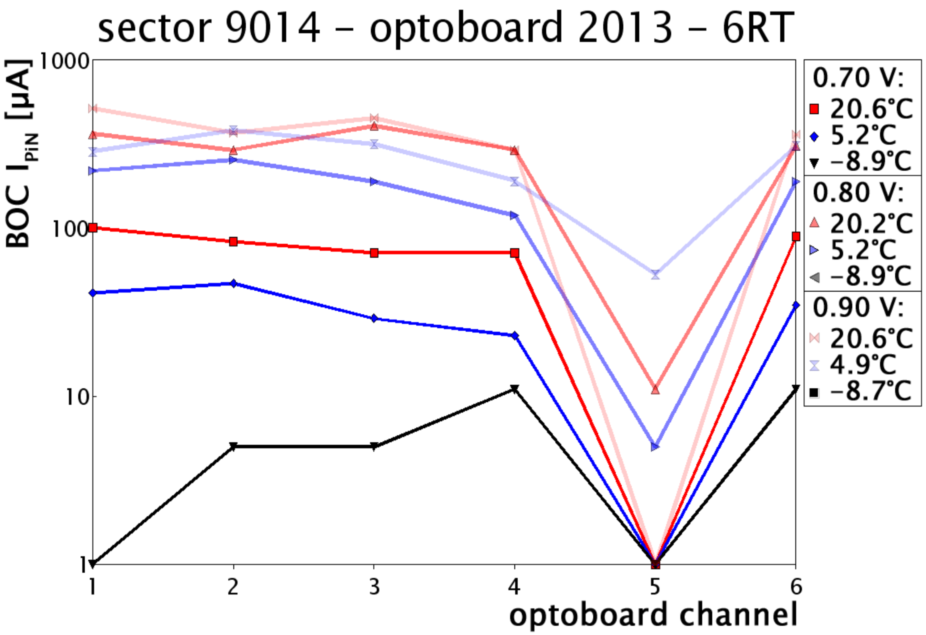
Pixel Opto-Board Heaters (IV)

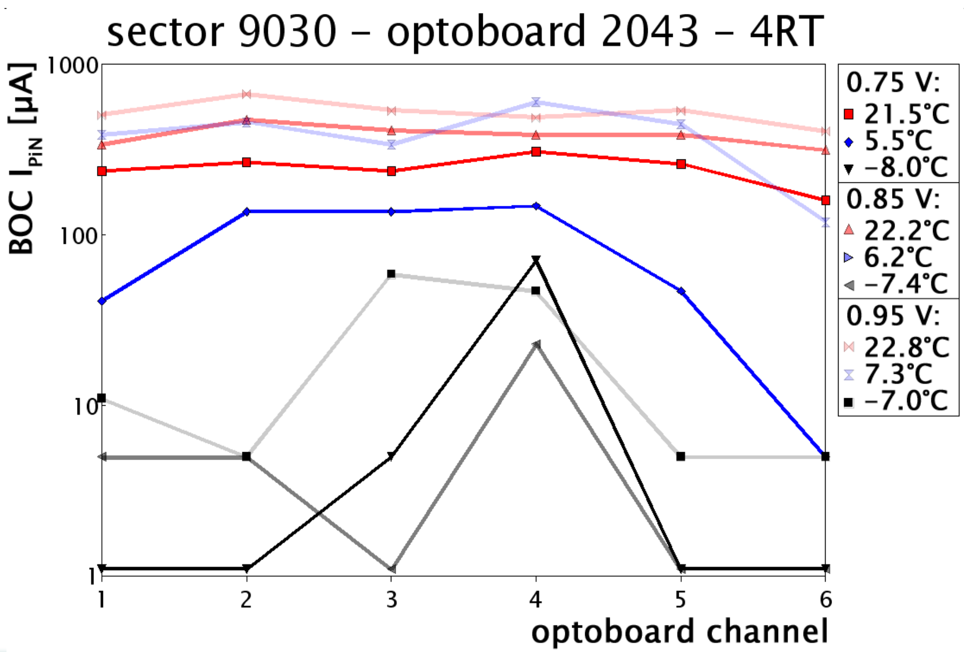
Schematic plan on how to test the opto-heaters as part of Pixel detector:



Opto-board Problems: Slow Turn-On







- It's been an exciting journey so far!
  - Consider a blessing my opportunities to work on three HEP experiments, two of which are of such grand scale as DØ and ATLAS!...
- Lots of hands-on experience is already gained
  - Barely scratching the surface, determined to dig deeper!
  - Both detector R&D and commissioning, and Physics algorithms and analysis are very exciting to me.
- Looking forward to expand and broaden my expertise
  - Not only pushing the energy frontier is of importance but a broad view of the field, providing missing evidence and much needed explanations to the physics effects observed;
  - Neutrino physics may be an excellent aim for my future efforts.
- Looking forward to developing original research ideas
- Value educational impact of physics research
  - Would like to be able to contribute;
  - Enjoy my teaching experience, desire for more to come in the future.