Commissioning of the ATLAS Silicon Tracker

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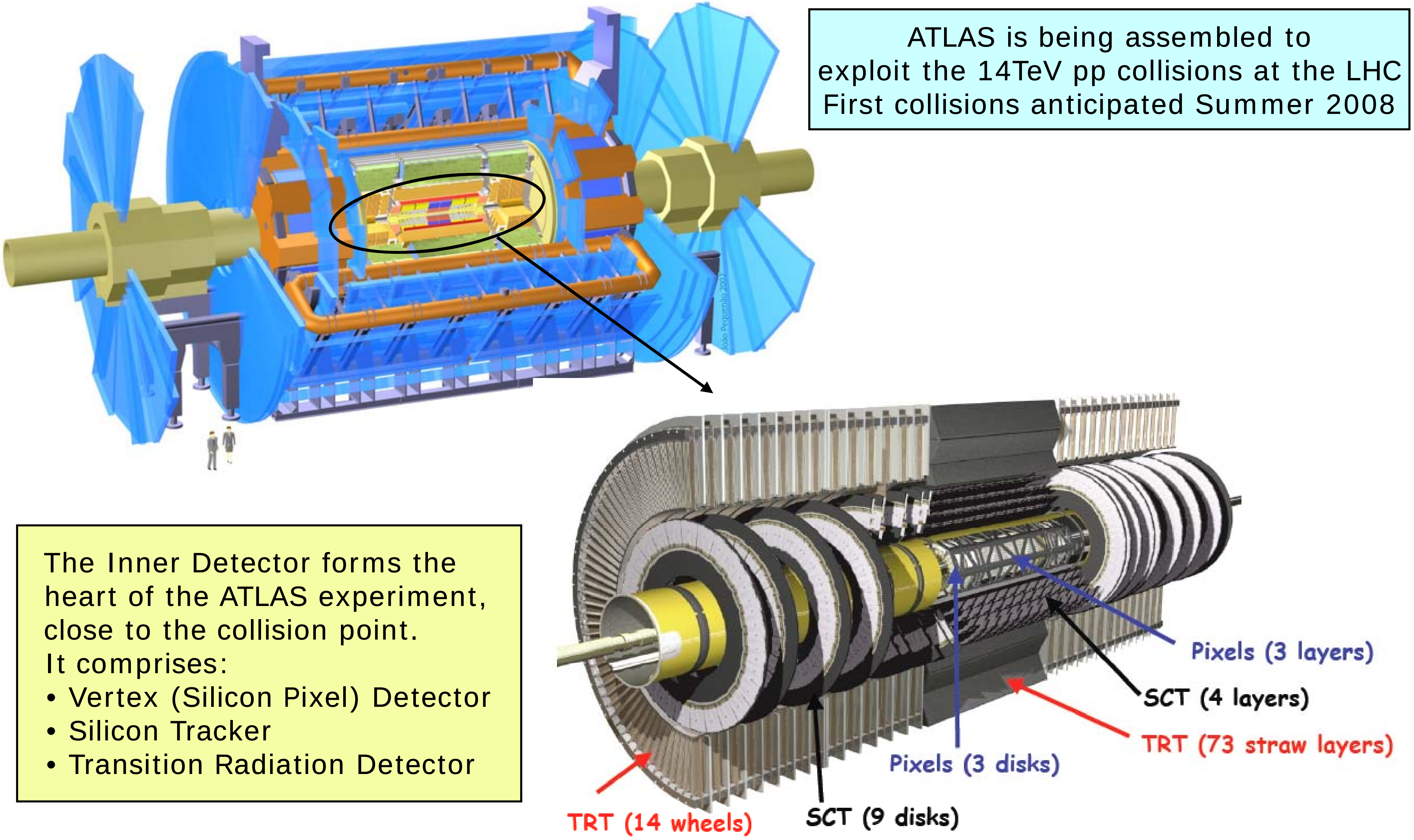
On behalf of the SCT Collaboration

- Overview of the ATLAS Silicon Tracker
- Assembly and Commissioning Milestones
- Current Status
  - Connectivity Tests
  - Electrical and Tracking Performance
- Summary & Outlook

16th International Workshop on Vertex detectors
September 23-28, 2007, Lake Placid, NY, USA

The ATLAS Inner Detector

ATLAS is being assembled to
exploit the 14TeV pp collisions at the LHC
First collisions anticipated Summer 2008

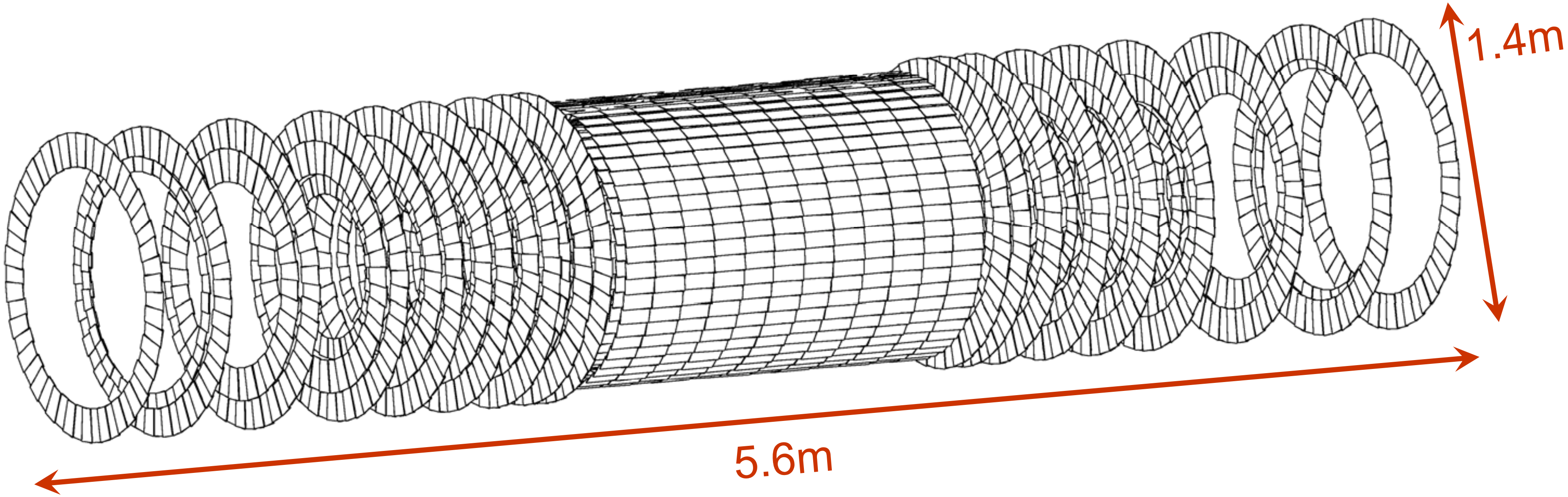


The Inner Detector forms the heart of the ATLAS experiment, close to the collision point.
It comprises:

- Vertex (Silicon Pixel) Detector
- Silicon Tracker
- Transition Radiation Detector

The Silicon Tracker (SCT)

- 61 m^2 of silicon with 6.2 million readout channels
- 4088 silicon modules arranged to form 4 Barrels and 18 Disks (9 each end)
- Barrels : 2112 modules (1 type) giving coverage $|\eta| < 1.1$ to 1.4
- Endcaps : 1976 modules (4 types) with coverage 1.1 to $1.4 < |\eta| < 2.5$
- $30\text{cm} < R < 52\text{cm}$
- Space point resolution $r\phi \sim 16\mu m$ / $Z \sim 580\mu m$

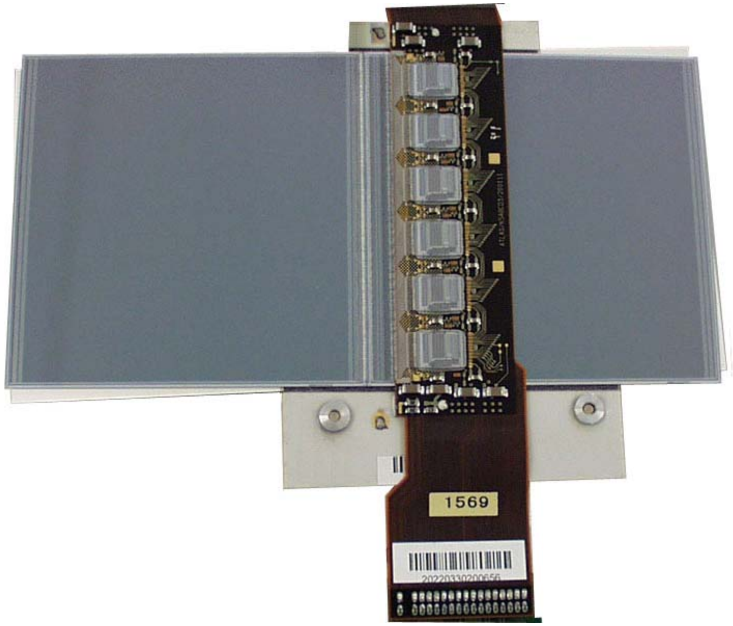


- Radiation hard: tested to 2×10^{14} 1-MeV neutron equivalent /cm^2
- Lightweight: 3% X0 per layer
- Global collaboration by 32 institutes

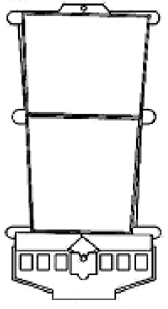
The Silicon Modules

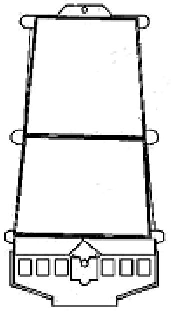
The barrels and endcaps had completely independent assembly & commissioning paths

- Back-to-back sensors, glued to highly thermally conductive substrates for mechanical/thermal stability
- 40mrad stereo angle between sensors
- 1536 channels (768 on each side)
- Binary readout
- Optical communication
- 5.6W/module (rising to ~10W after 10 years LHC)
- up to 500V sensor bias
- Cooled to -8^{o}C to limit sensor radiation damage



- 2112 barrel modules
- one shape
- assembled at 4 SCT sites

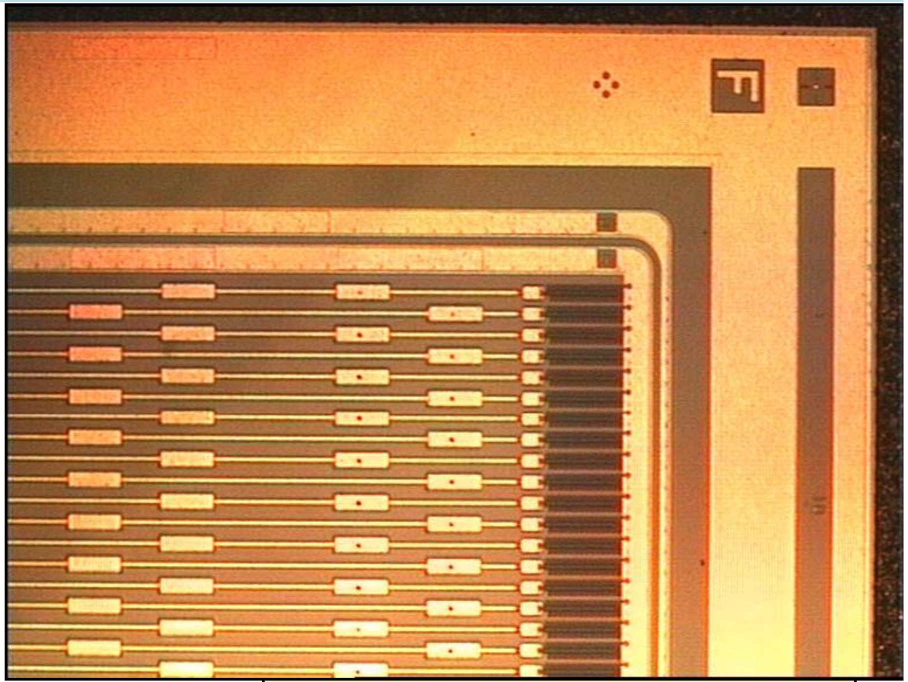

Outer module


Middle module

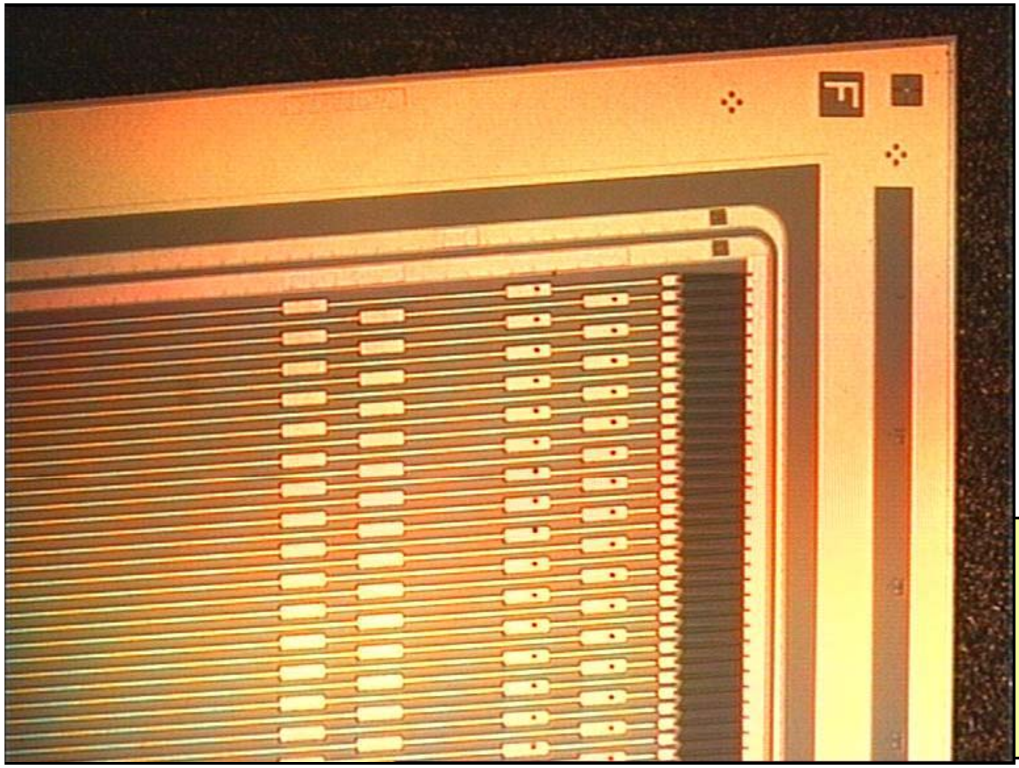
- 1976 endcap modules
- 3 shapes
- assembled at 7 SCT sites

The Sensors

- Single sided p-on-n
- <111> substrate
- 768+2 AC-coupled strips
- Polysilicon (1.5MΩ) Bias
- 285μm thick

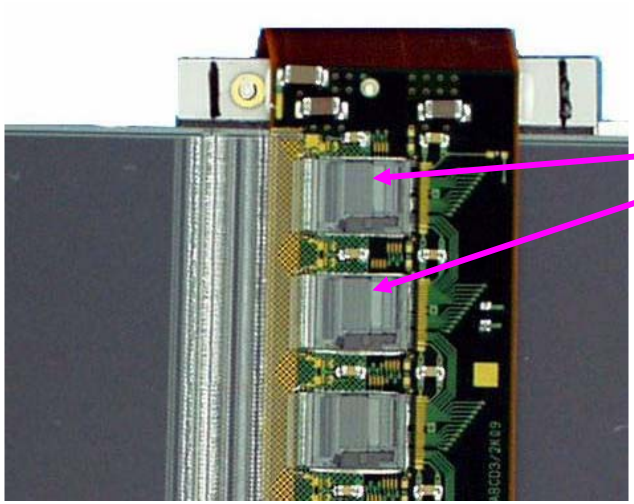


- 8448 barrel sensors
- 64.0 x 63.6mm
- 80μm strip pitch
- all supplied by Hamamatsu

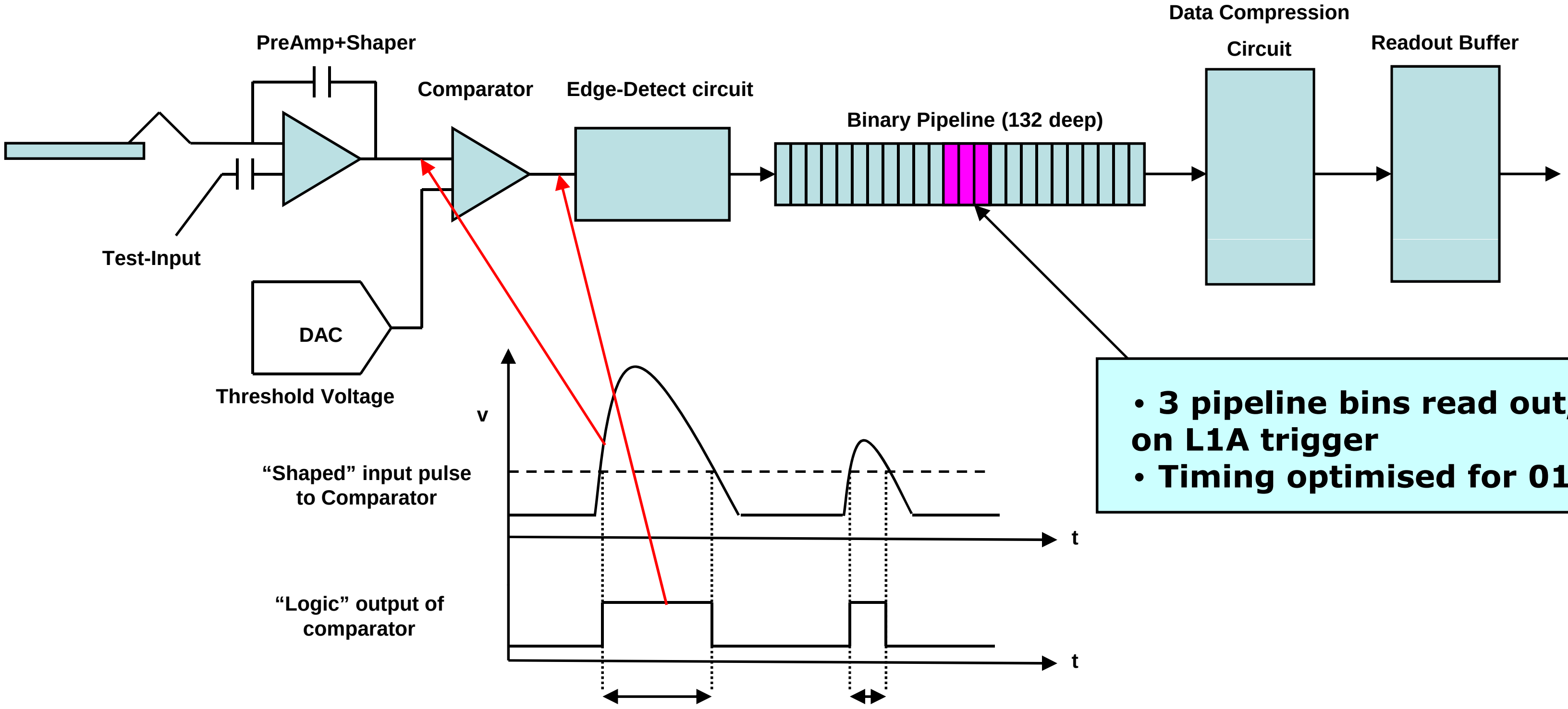


- 6944 wedge sensors
- 56.9-90.4μm strip pitch
- Two suppliers
  - 82.8% Hamamatsu
  - 17.2% CiS

The ASICs (ABCD chips)



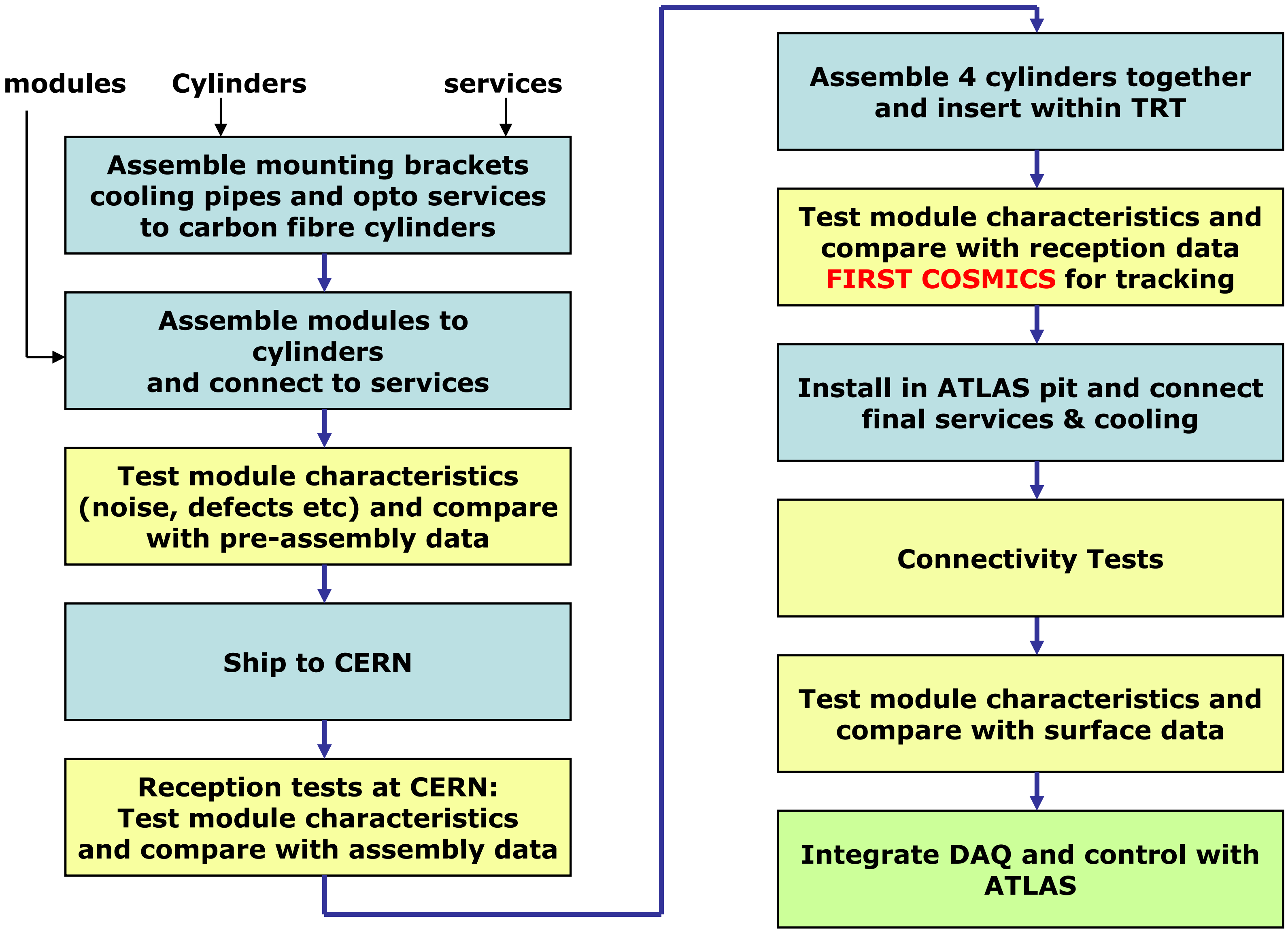
- 128 channel ASIC with binary architecture
- Radiation-hard DMILL technology
- 12 chips per module (6 each side)
- glued to hybrid (Cu/polyimide flex circuit)
- 40MHz (25ns) clock
- 20ns front end shaping time



- **3 pipeline bins read out, centered on L1A trigger**
- **Timing optimised for 01X**

Assembly & Commissioning Path

In parallel with development and gaining experience on: Detector Control, DAQ and Cooling



modules

Cylinders

services

Assemble mounting brackets cooling pipes and opto services to carbon fibre cylinders

Assemble modules to cylinders and connect to services

Test module characteristics (noise, defects etc) and compare with pre-assembly data

Ship to CERN

Reception tests at CERN: Test module characteristics and compare with assembly data

Assemble 4 cylinders together and insert within TRT

Test module characteristics and compare with reception data FIRST COSMICS for tracking

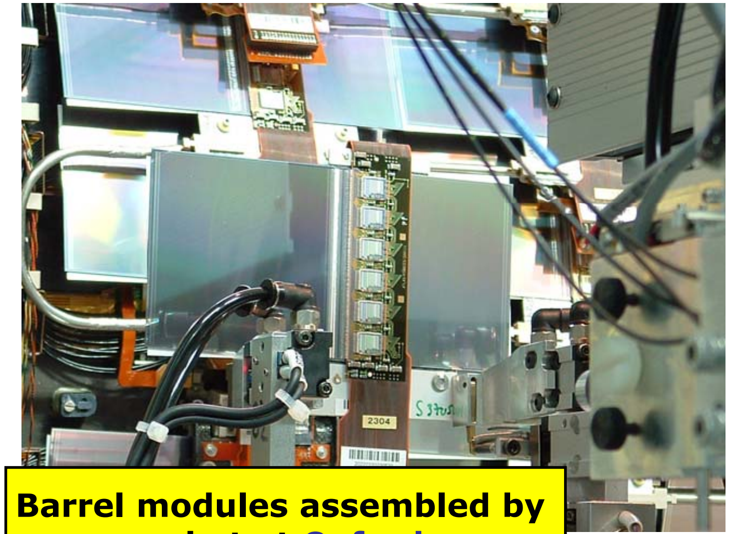
Install in ATLAS pit and connect final services & cooling

Connectivity Tests

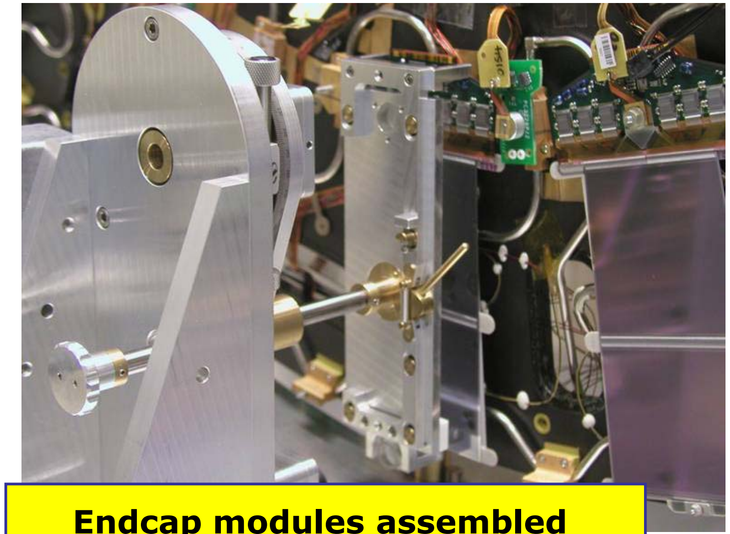
Test module characteristics and compare with surface data

Integrate DAQ and control with ATLAS

Assembly of modules to barrels & disks

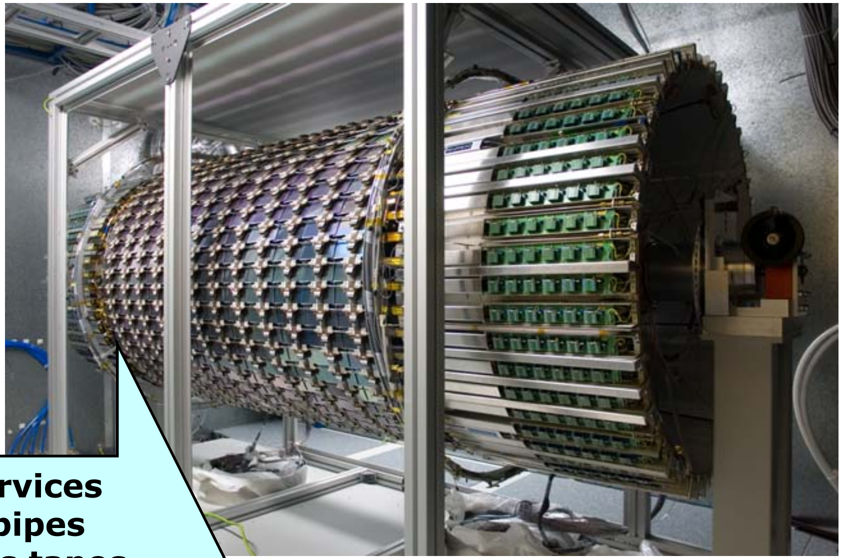


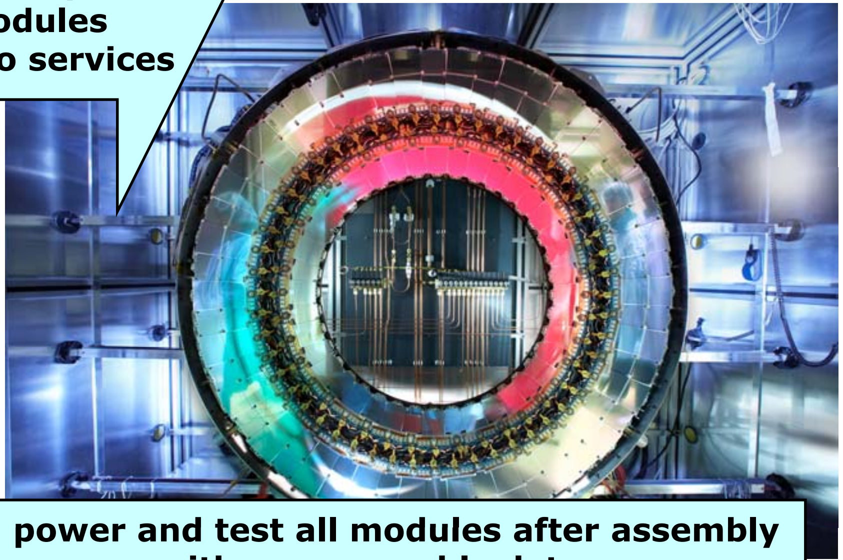
Barrel modules assembled by robot at Oxford



Endcap modules assembled manually at NIKHEF and Liverpool

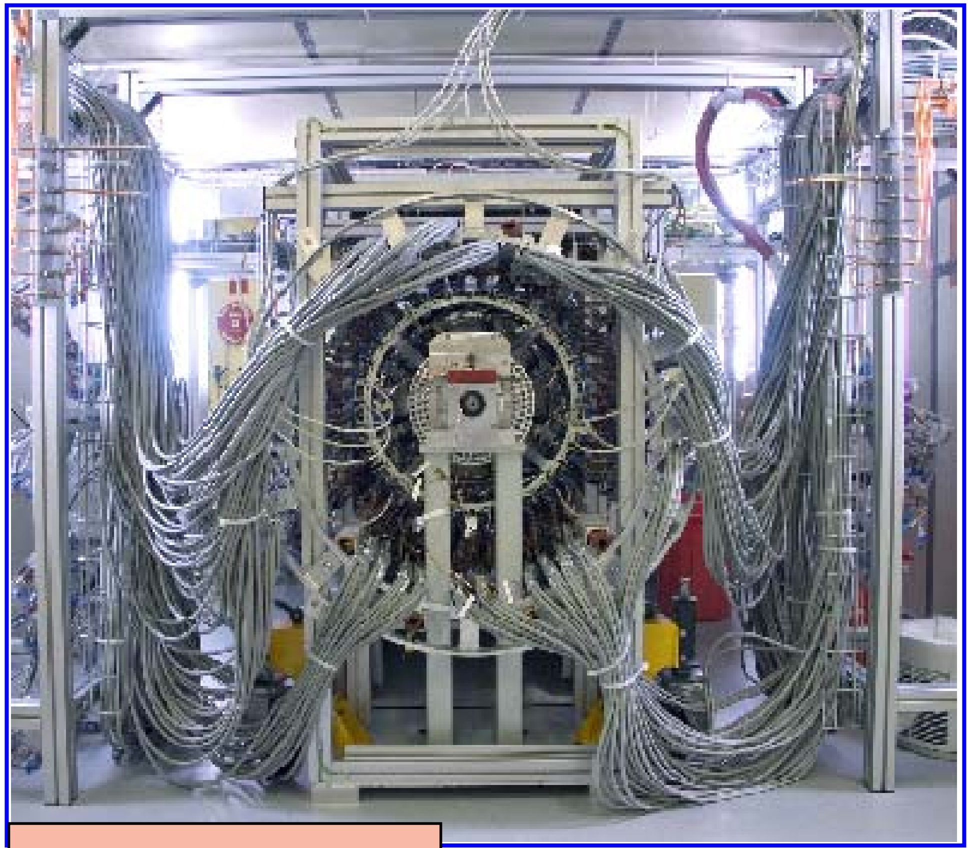
- **mount services**
  - **cooling pipes**
  - **low mass tapes**
- **mount modules**
- **connect to services**





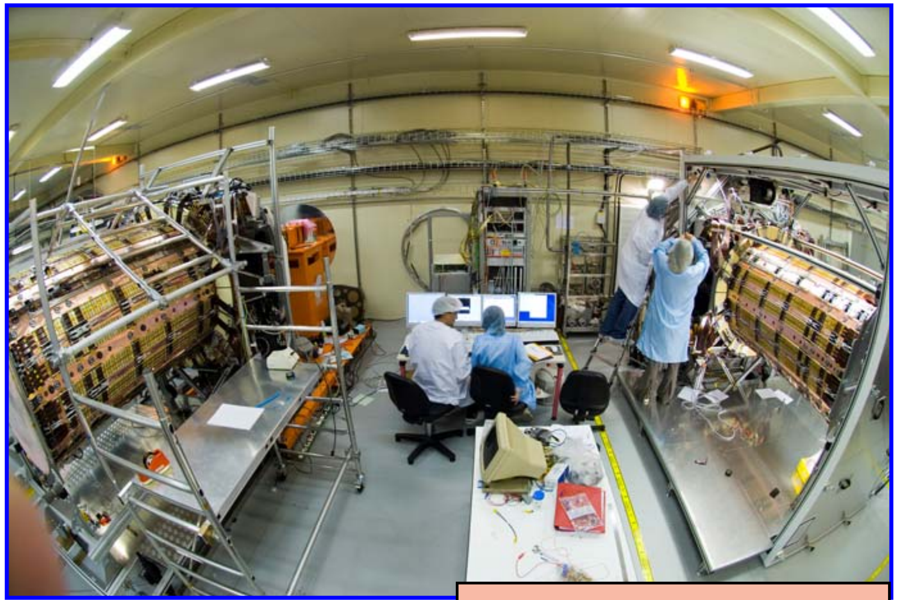
Cool, power and test all modules after assembly and compare with pre-assembly data

Reception Testing at CERN



April-August 2005

First tests under realistic conditions
- Complete barrel/disk cooled
- Simultaneous readout of all modules
- Using final supply hardware, DAQ & DCS

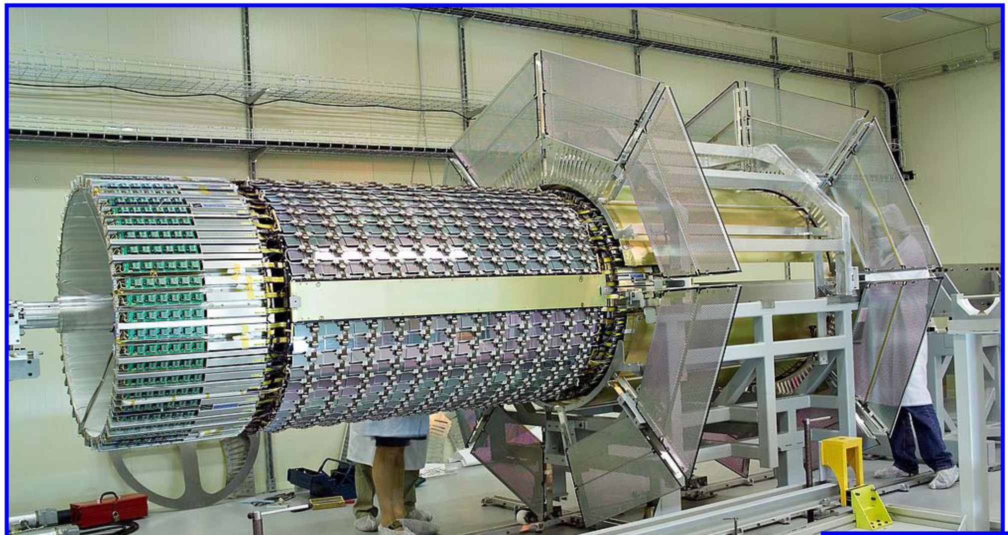


End Caps from February 2006

- Stability & uniformity of cooling and module temperatures
- Stability of power supplies and optical communication
- Digital functionality, response and noise from all modules

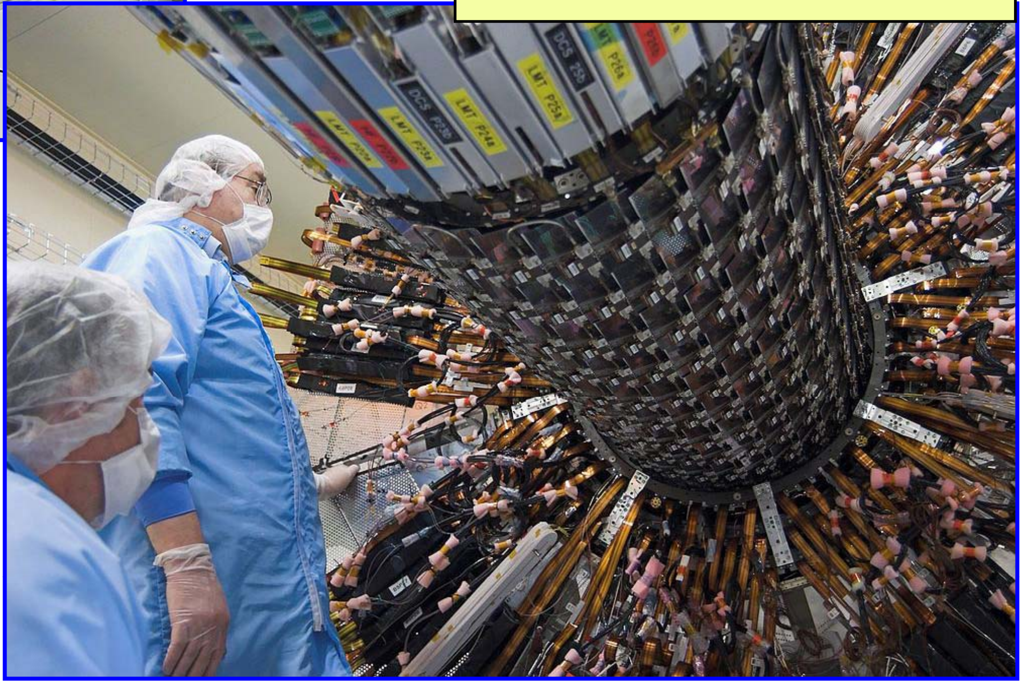
4-Barrel Assembly at CERN

Sep-Dec 2005

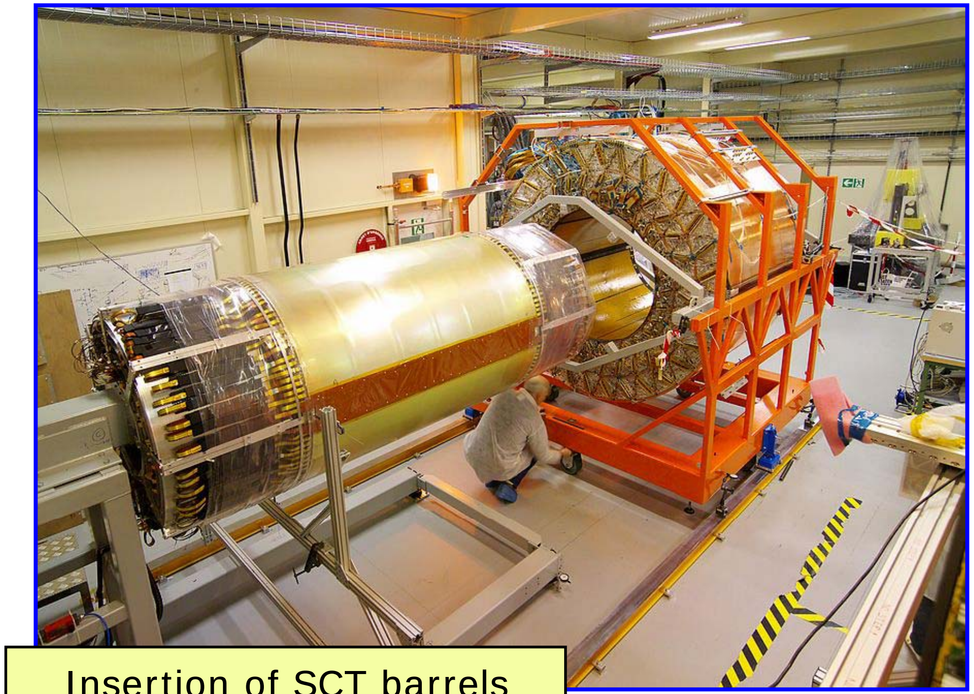


First barrel (barrel 6) start of insertion into thermal enclosure

Final barrel (barrel 3) insertion within barrel 4



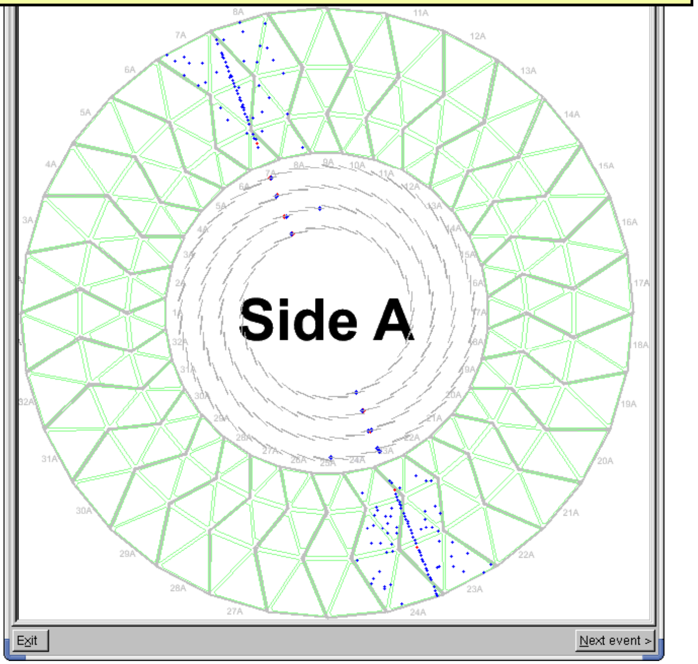
Barrel Insertion in TRT and First Combined Tests



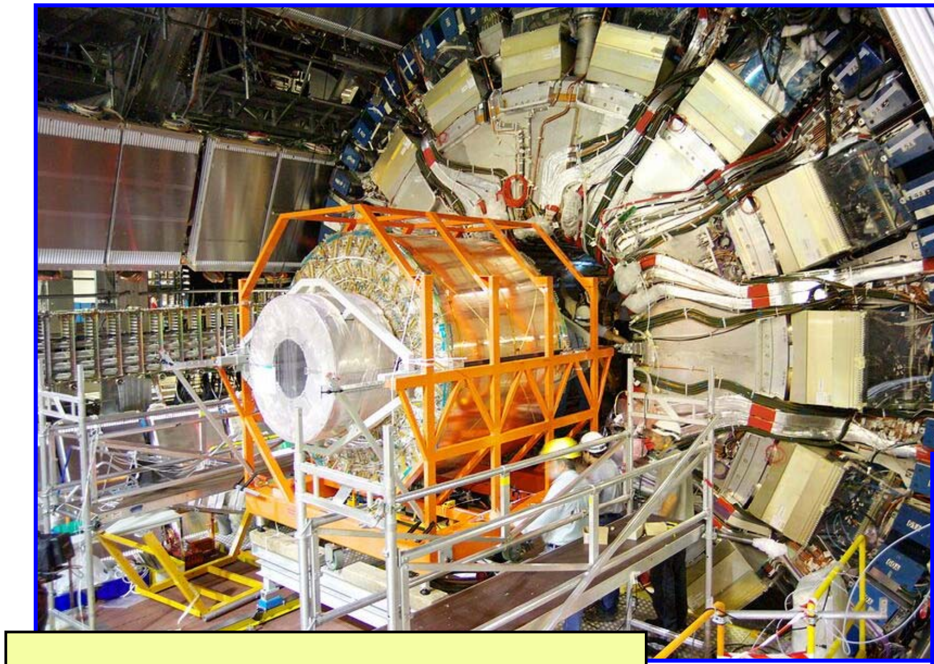
Insertion of SCT barrels
within the TRT
(Feb 2006)

- TRT performance with SCT powered
- Synchronous runs for X-talk studies
- SCT/TRT grounding schemes
- Time in for first cosmics

First cosmics in SCT and TRT
(May 2006)



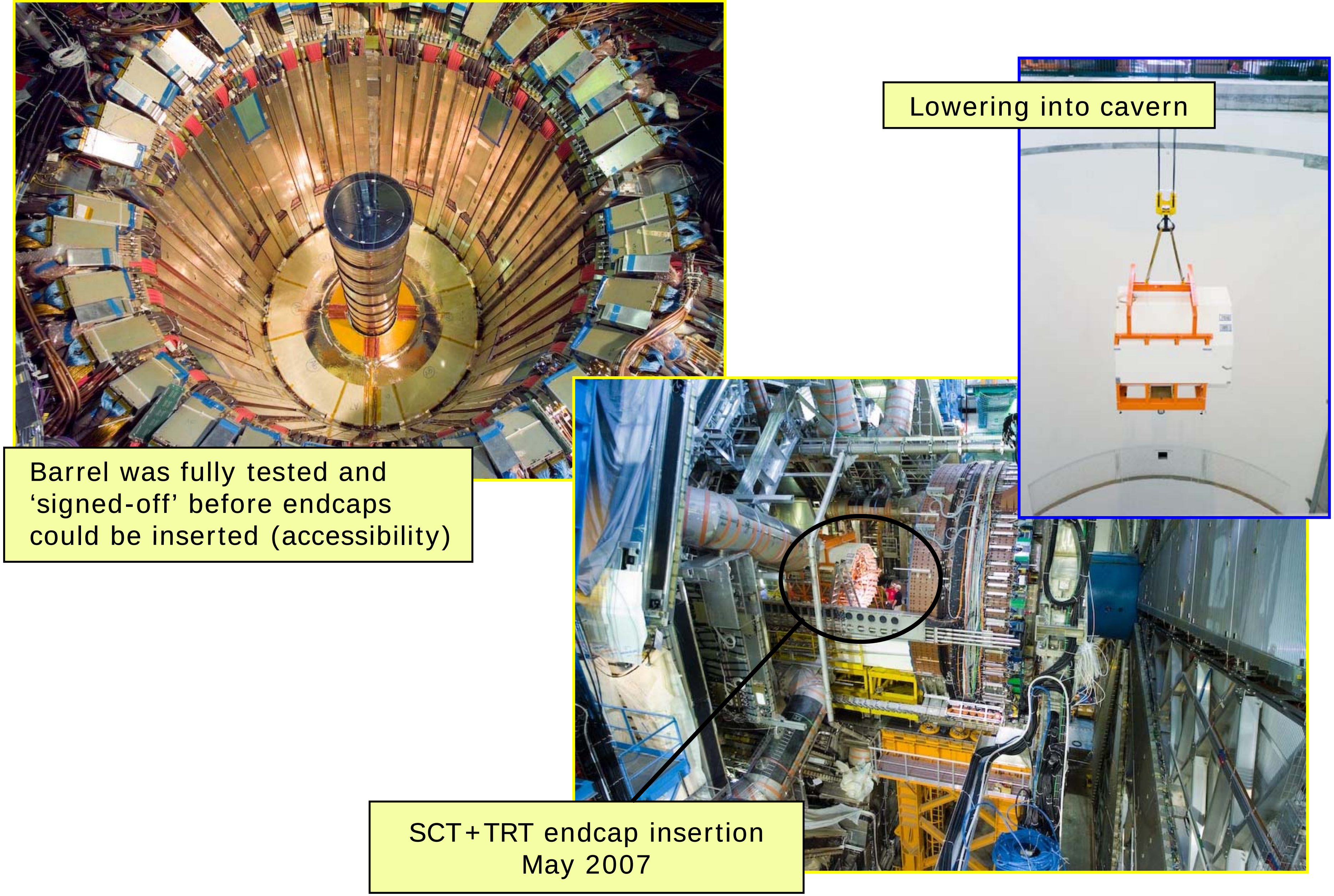
Barrel Installation in ATLAS cavern



SCT+TRT Barrel installation
August 2006

Connectivity tests
Jan/Feb 2007

Endcap Installation in ATLAS cavern



Lowering into cavern

Barrel was fully tested and ‘signed-off’ before endcaps could be inserted (accessibility)

SCT+TRT endcap insertion
May 2007

Final Services

- DCS system
- control/monitor power supplies, temperatures, cooling plant, crate infrastructure
- 88 power supply crates
  - each containing 4-channel LV and 8-channel HV cards
  - **power supply cables for 4088 modules**

- Interlock system
  - inhibit power supply operation in cases of cooling failure

- DAQ system
- 250K lines of c++ and java code
- Infrastructure comprises:
  - 8 9-U ROD crates
  - 90 ReadOut Driver (ROD) cards
  - 90 Back of Crate (BOC) cards
    (each BOC providing optical control/data communication to 48 modules --
    ~12000 fibres (354 TX ribbons and 708 RX ribbons)
  - 8 RCCs (Readout Crate Controllers) running API to front end
  - 8 TTC Interface Modules – interface to ATLAS timing/trigger system
  - 9 servers dedicated to DAQ and online monitoring/calibration

- Cooling System
  - Evaporative system using C3F8
  - Compressors shared with pixel system
  - Back pressure regulator to control temperatures

Current Status - Commissioning

Barrels

- Jan-Feb 07 - All optical and electrical connections verified
  - minor issues resolved (mapping errors or cleaning fiber joints or electrical repairs)
  - some minor losses due to broken fibres or ESD damage, all recovered by redundancy
  - one module lost due to HV connection

- March 07 – Electrical Tests
  - Gain, noise etc measurements on all modules
  - first running with final system (DAQ, DCS, cooling)
  - terminated prematurely due to component failure in cooling circuit

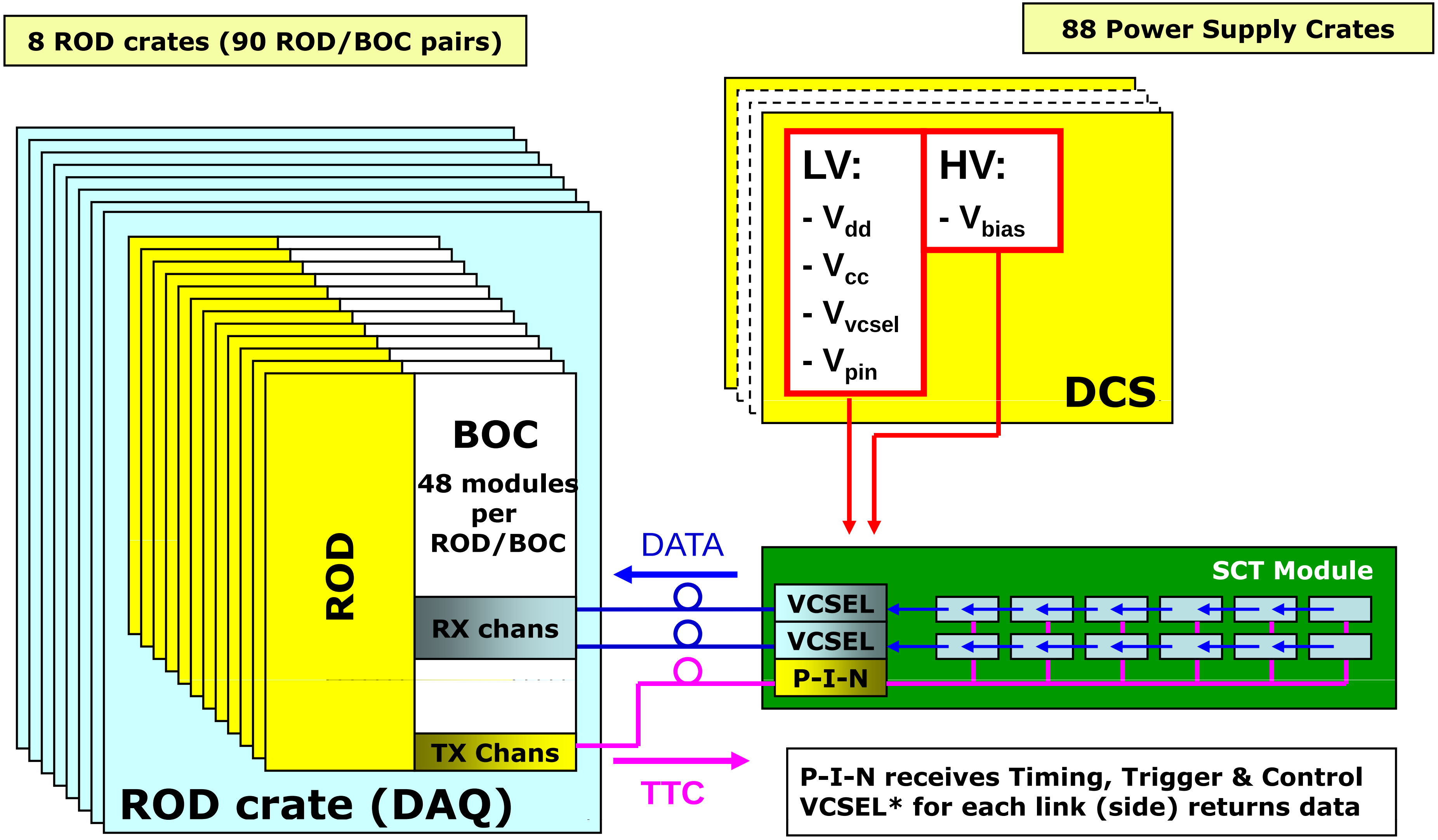
- April 07
  - Barrels 'signed off' (loss of physical access)

End Caps

- Installed May '07

- From July '07 to present
  - optical and electrical connection tests
  - performed without cooling using 'Dicing With Death' procedure
    (brief periods of powering, switching off when temperature exceeds ~30^{o}C)

Optical Communication & Power Supplies

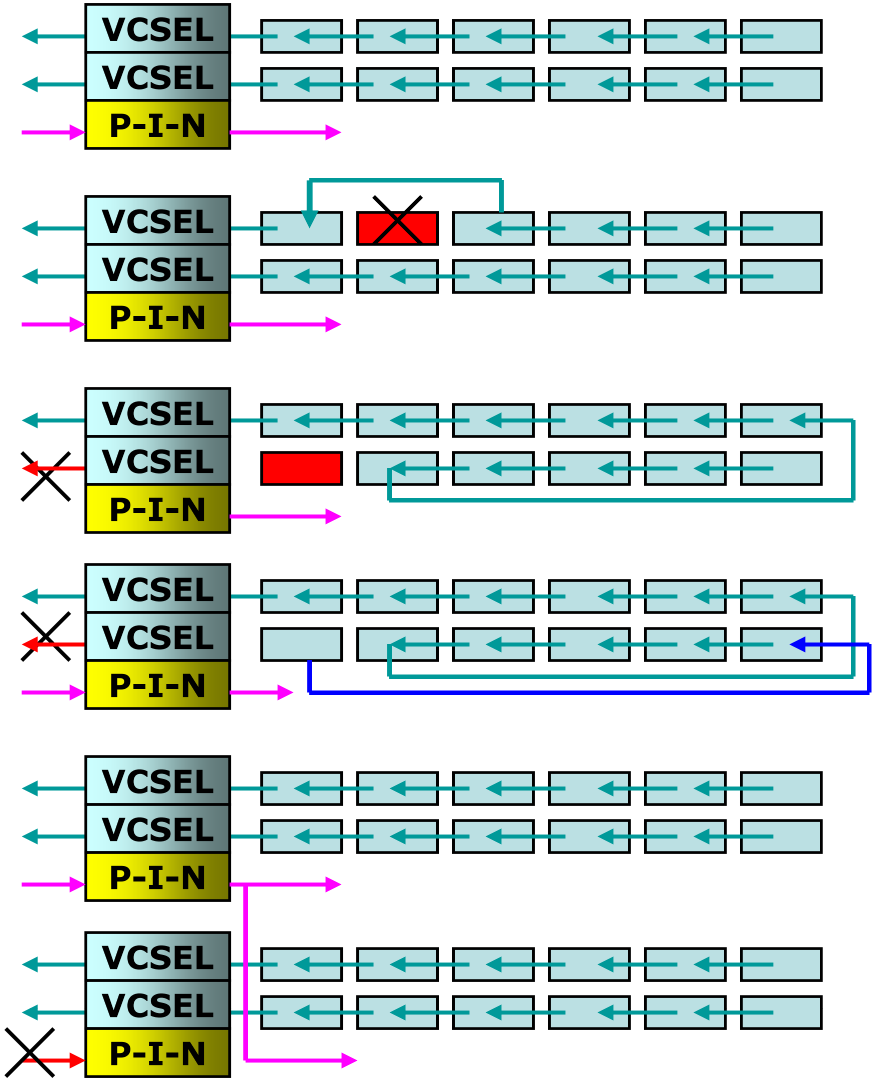


P-I-N receives Timing, Trigger & Control
VCSEL* for each link (side) returns data

* VCSEL=Vertical Cavity Surface Emitting Laser

Redundancy Schemes

Essential to build in redundancy in case of component failure or fibre breakages



Standard setup
All chips and fibres ok

Dead chip bypassed
All fibres ok

Broken RX fibre from standard module
or dead VCSEL
Master chip of second link bypassed

Broken RX fibre to modified module
or dead VCSEL
All chips read out

Broken TX fibre or dead PIN
Clock and control from neighbouring module

Barrel Defects after Connectivity & Electrical Testing

Optical Link Defects/Issues

Some modules have very low I-pin

24 defective data links
- 9 newly identified after final installation in cavern
- total of 13 non-readable ASICs (out of 25344)

6 defective TTC lines
- 2 newly identified after barrels installation
- no losses due to use of redundant clock from neighbouring module

Defective Channels (Electrical characterisation)

Sample based on 2095 modules

7619 DEAD channels

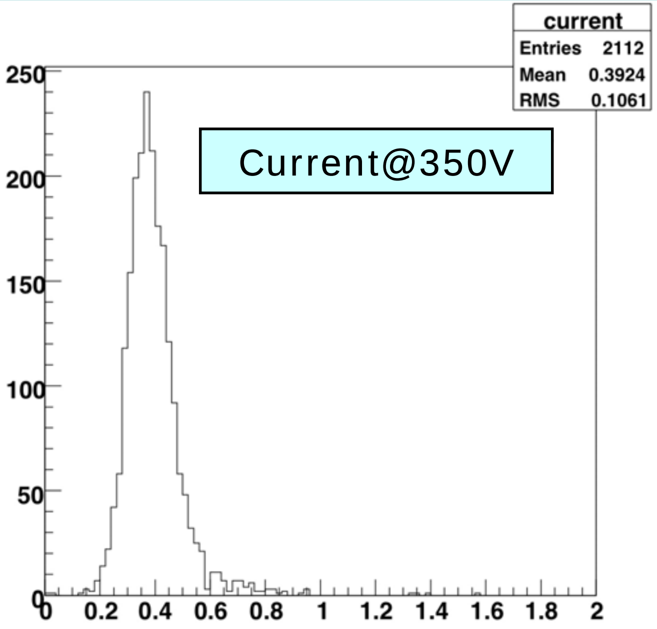
784 UNBONDED channels

1536 channels lost due to single module HV problem

7 STUCKON channels

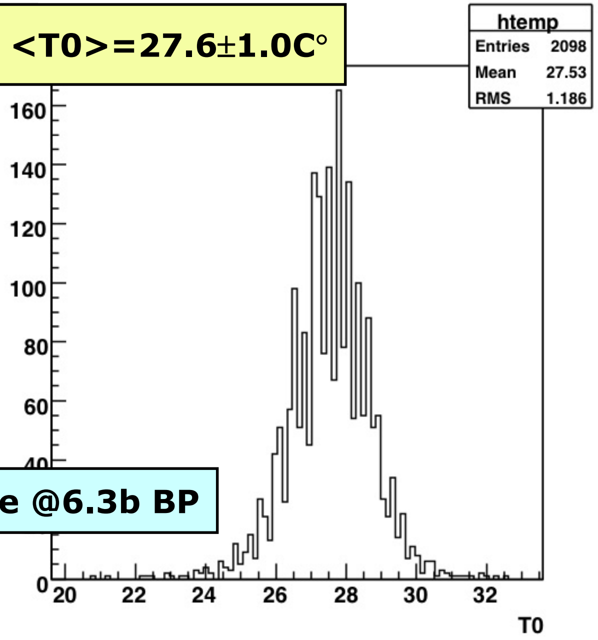
Total non-working channels: 9946 (0.031% of total)

Module Leakage Currents & Temperature Uniformity



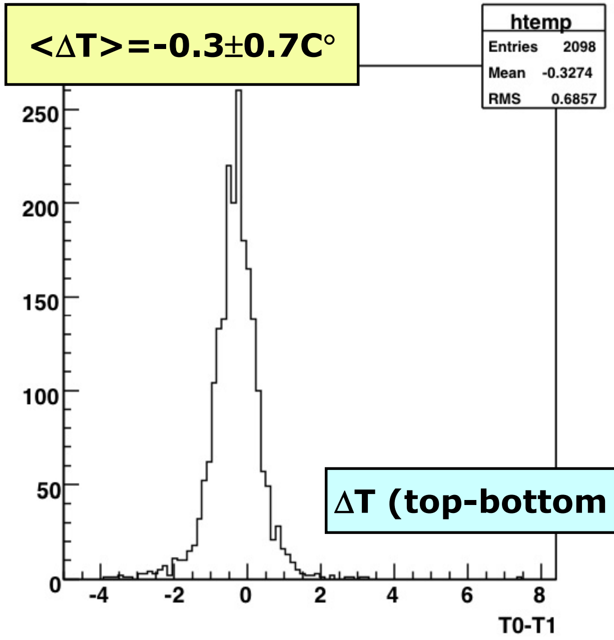
Current@350V

- <I>=390nA @ 350V and 25^{o}C
- One module to 300V only due to abnormal current (~4µA)
- One module lost due to no HV connection



<T0>=27.6±1.0C°

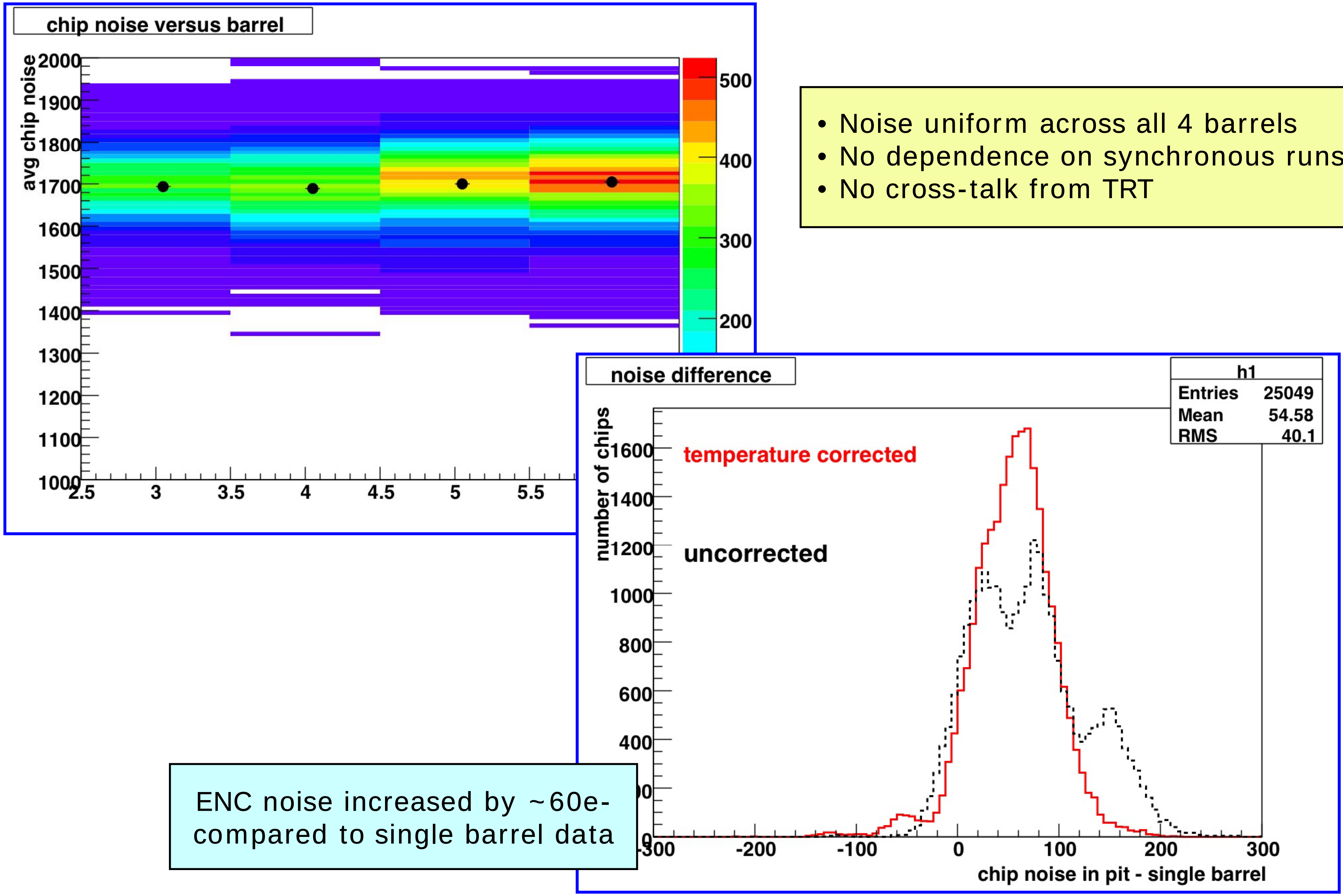
Temperature @6.3b BP



<ΔT>=-0.3±0.7C°

ΔT (top-bottom of hybrid)

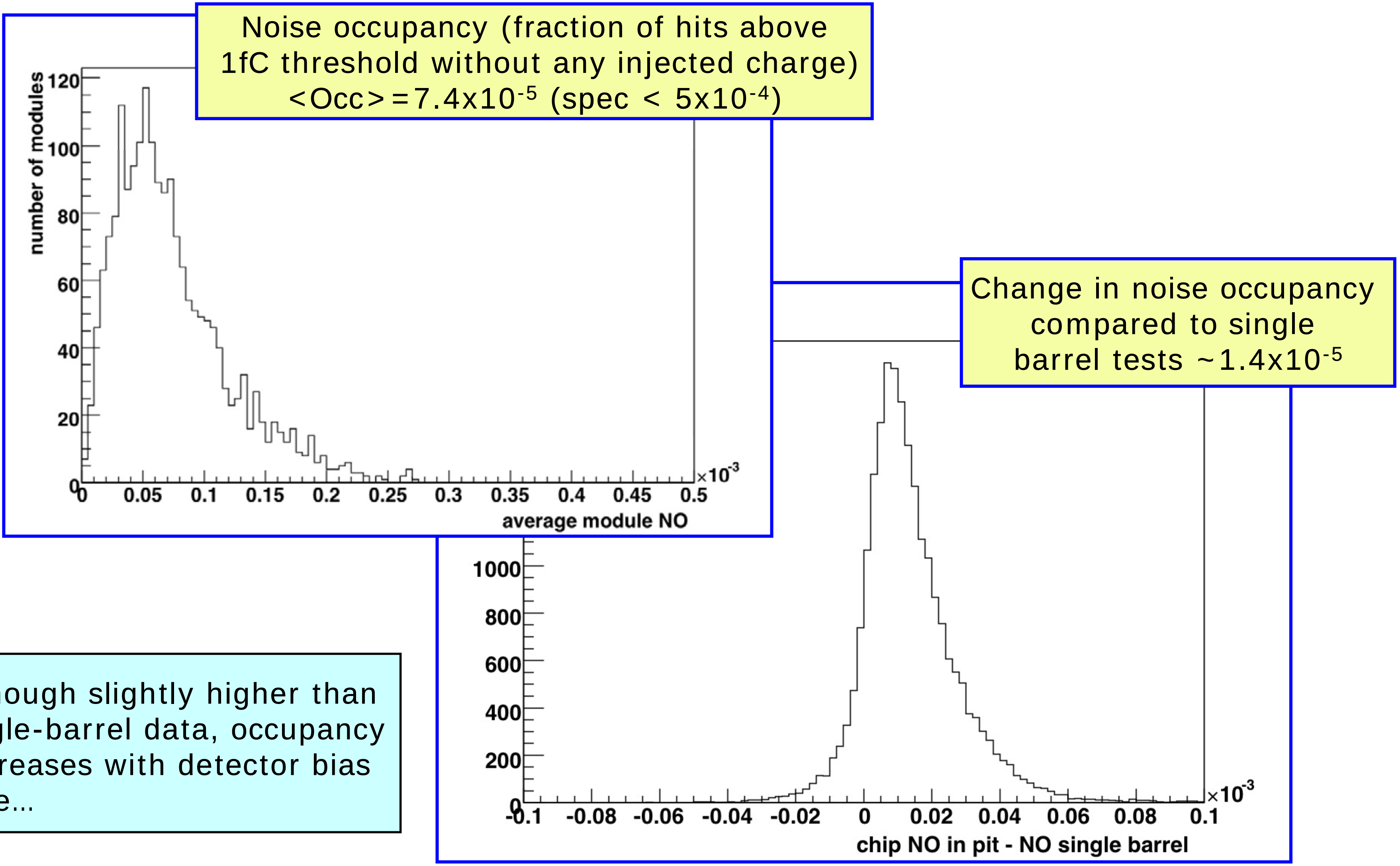
Barrel Noise Measurements



- Noise uniform across all 4 barrels
- No dependence on synchronous runs
- No cross-talk from TRT

ENC noise increased by ~60e- compared to single barrel data

Noise Occupancy



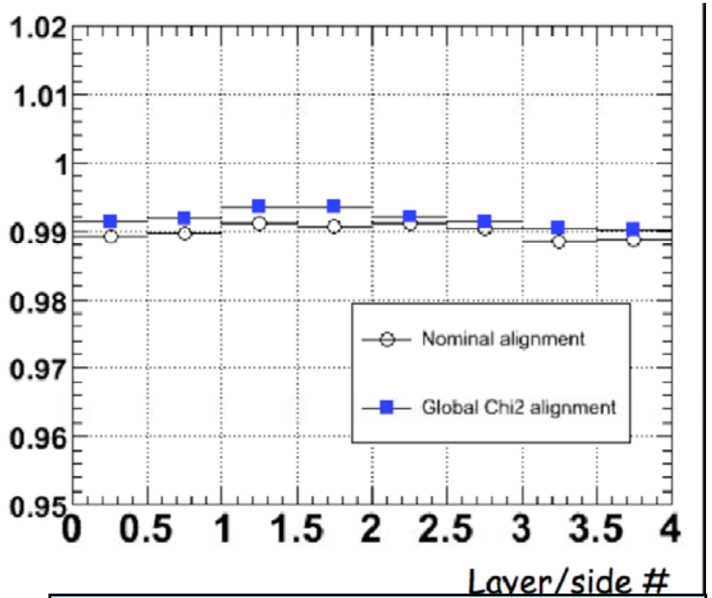
Noise occupancy (fraction of hits above 1fC threshold without any injected charge) $\langle Occ \rangle = 7.4\times10^{-5}$ (spec $< 5\times10^{-4}$)

Change in noise occupancy compared to single barrel tests $\sim 1.4\times10^{-5}$

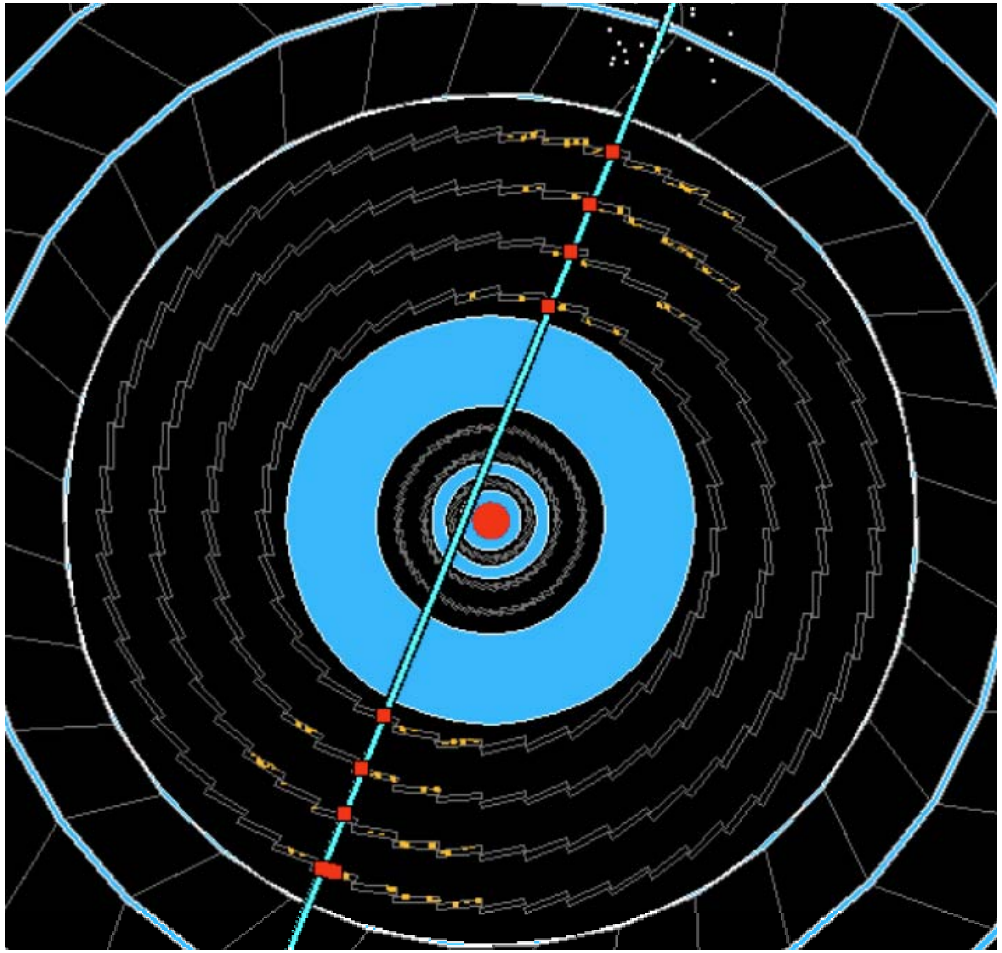
Although slightly higher than single-barrel data, occupancy decreases with detector bias time…

Tracking

~9 million triggers taken in ‘physics’ mode, including ~450K cosmics triggers



SCT Hit Efficiency after alignment >99%



Expect to time in for cosmics a fraction of the SCT during the ATLAS “Milestone-5” Technical Run start 23/10/07

Summary

- The SCT barrels and both endcaps are now installed in their final positions within the ATLAS experiment
  - for the barrels, all optical and electrical connections have been verified (all modules operational apart from one without HV)
  - for the endcaps, connectivity tests complete this month (all modules look to be operational)

- No significant deterioration in module electrical performance observed at any stage of the assembly and installation program
  - final barrel data indicate 99.97% working channels, only ~60e$^-$ shift in noise compared to pre-installation data

- Successful demonstration of tracking with cosmics for both barrels and endcaps
  - on the surface, pre-installation in ATLAS

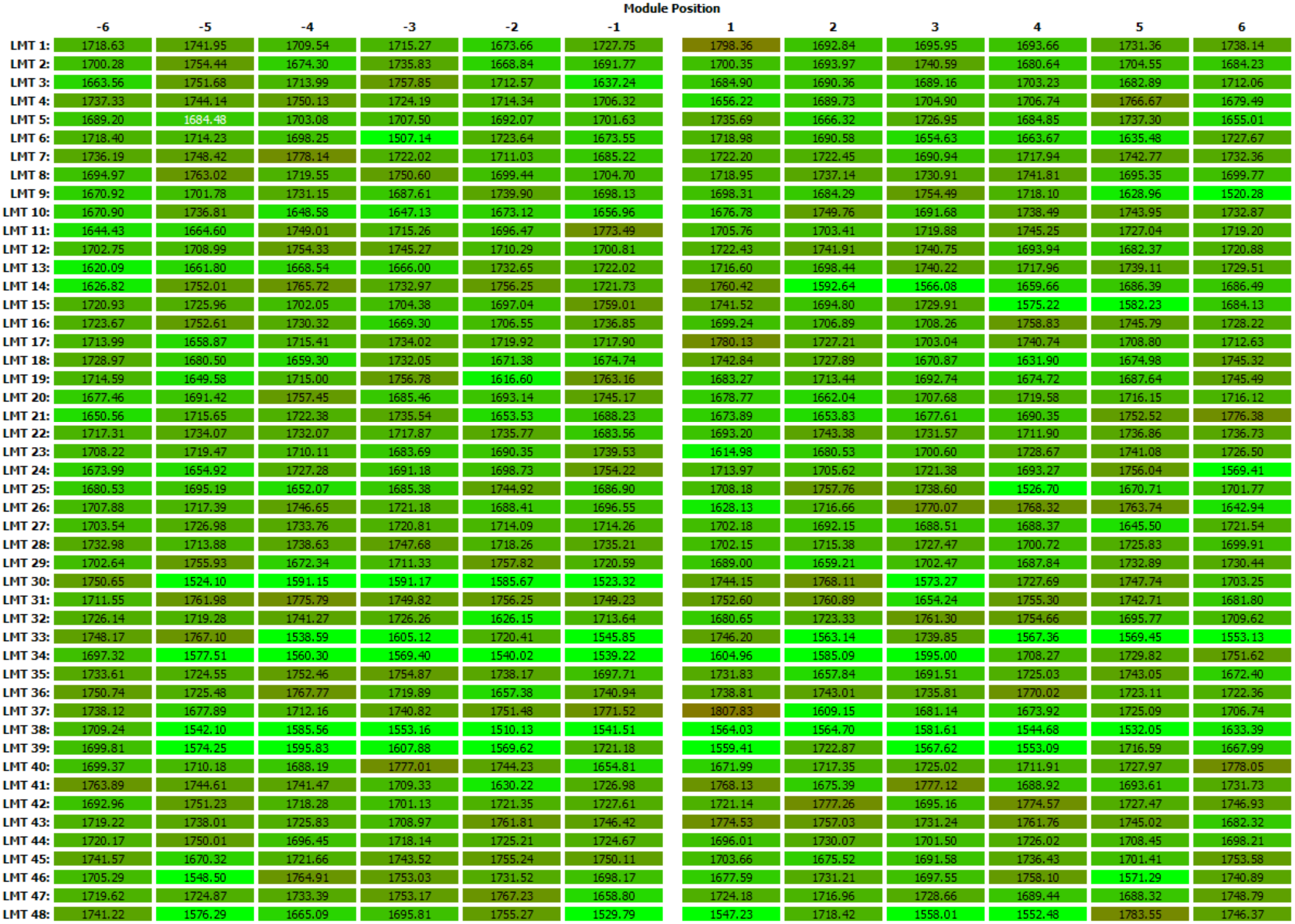
- The lack of cooling is a significant setback to the commissioning schedule
  - cannot operate the SCT with cooling
  - have not been able to participate in ATLAS cosmics runs
  - final electrical performance has been verified for the barrels only
  - some cooling expected to be implemented in time for a fraction of the SCT to participate in the M5 Technical Run in October 07

- In the meantime, integration of SCT services (DAQ, DCS) into ATLAS is well advanced

We expect to be ready for the first LHC Collisions in Summer 08!!

Backup slides

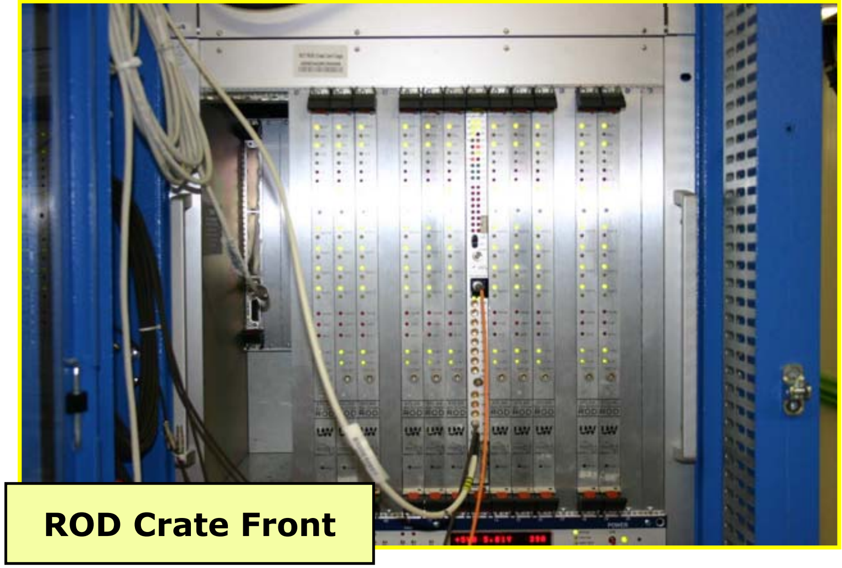
Barrel 5 Module Average ENC Noise



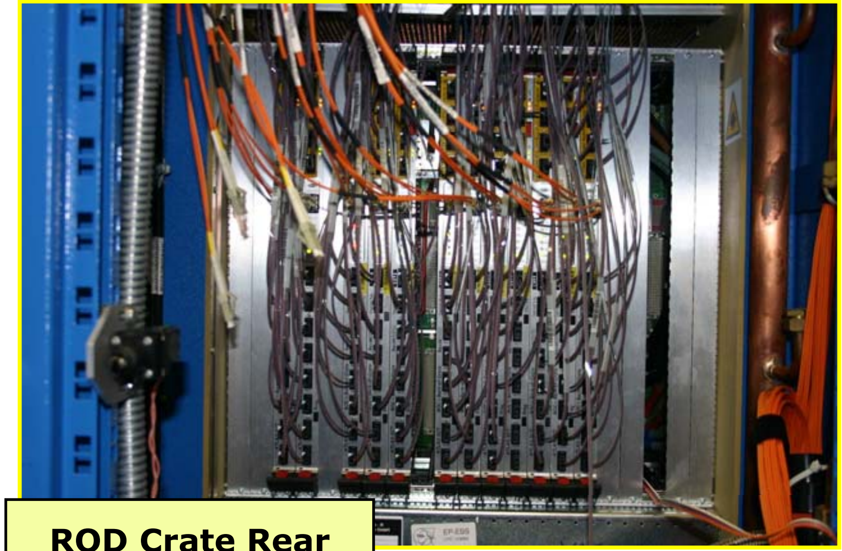
Module Position

	-6	-5	-4	-3	-2	-1	1	2	3	4	5	6
LMT 1:	1718.63	1741.95	1709.54	1715.27	1673.66	1727.75	1798.36	1692.84	1695.95	1693.66	1731.36	1738.14
LMT 2:	1700.28	1754.44	1674.30	1735.83	1668.84	1691.77	1700.35	1693.97	1740.59	1680.64	1704.55	1684.23
LMT 3:	1663.56	1751.68	1713.99	1757.85	1712.57	1637.24	1684.90	1690.36	1689.16	1703.23	1682.89	1712.06
LMT 4:	1737.33	1744.14	1750.13	1724.19	1714.34	1706.32	1656.22	1689.73	1704.90	1706.74	1766.67	1679.49
LMT 5:	1689.20	1684.48	1703.08	1707.50	1692.07	1701.63	1735.69	1666.32	1726.95	1684.85	1737.30	1655.01
LMT 6:	1718.40	1714.23	1698.25	1507.14	1723.64	1673.55	1718.98	1690.58	1654.63	1663.67	1635.48	1727.67
LMT 7:	1736.19	1748.42	1778.14	1722.02	1711.03	1685.22	1722.20	1722.45	1690.94	1717.94	1742.77	1732.36
LMT 8:	1694.97	1763.02	1719.55	1750.60	1699.44	1704.70	1718.95	1737.14	1730.91	1741.81	1695.35	1699.77
LMT 9:	1670.92	1701.78	1731.15	1687.61	1739.90	1698.13	1698.31	1684.29	1754.49	1718.10	1628.96	1520.28
LMT 10:	1670.90	1736.81	1648.58	1647.13	1673.12	1656.96	1676.78	1749.76	1691.68	1738.49	1743.95	1732.87
LMT 11:	1644.43	1664.60	1749.01	1715.26	1696.47	1773.49	1705.76	1703.41	1719.88	1745.25	1727.04	1719.20
LMT 12:	1702.75	1708.99	1754.33	1745.27	1710.29	1700.81	1722.43	1741.91	1740.75	1693.94	1682.37	1720.88
LMT 13:	1620.09	1661.80	1668.54	1666.00	1732.65	1722.02	1716.60	1698.44	1740.22	1717.96	1739.11	1729.51
LMT 14:	1626.82	1752.01	1765.72	1732.97	1756.25	1721.73	1760.42	1592.64	1566.08	1659.66	1686.39	1686.49
LMT 15:	1720.93	1725.96	1702.05	1704.38	1697.04	1759.01	1741.52	1694.80	1729.91	1575.22	1582.23	1684.13
LMT 16:	1723.67	1752.61	1730.32	1669.30	1706.55	1736.85	1699.24	1706.89	1708.26	1758.83	1745.79	1728.22
LMT 17:	1713.99	1658.87	1715.41	1734.02	1719.92	1717.90	1780.13	1727.21	1703.04	1740.74	1708.80	1712.63
LMT 18:	1728.97	1680.50	1659.30	1732.05	1671.38	1674.74	1742.84	1727.89	1670.87	1631.90	1674.98	1745.32
LMT 19:	1714.59	1649.58	1715.00	1756.78	1616.60	1763.16	1683.27	1713.44	1692.74	1674.72	1687.64	1745.49
LMT 20:	1677.46	1691.42	1757.45	1685.46	1693.14	1745.17	1678.77	1662.04	1707.68	1719.58	1716.15	1716.12
LMT 21:	1650.56	1715.65	1722.38	1735.54	1653.53	1688.23	1673.89	1653.83	1677.61	1690.35	1752.52	1776.38
LMT 22:	1717.31	1734.07	1732.07	1717.87	1735.77	1683.56	1693.20	1743.38	1731.57	1711.90	1736.86	1736.73
LMT 23:	1708.22	1719.47	1710.11	1683.69	1690.35	1739.53	1614.98	1680.53	1700.60	1728.67	1741.08	1726.50
LMT 24:	1673.99	1654.92	1727.28	1691.18	1698.73	1754.22	1713.97	1705.62	1721.38	1693.27	1756.04	1569.41
LMT 25:	1680.53	1695.19	1652.07	1685.38	1744.92	1686.90	1708.18	1757.76	1738.60	1526.70	1670.71	1701.77
LMT 26:	1707.88	1717.39	1746.65	1721.18	1688.41	1696.55	1628.13	1716.66	1770.07	1768.32	1763.74	1642.94
LMT 27:	1703.54	1726.98	1733.76	1720.81	1714.09	1714.26	1702.18	1692.15	1688.51	1688.37	1645.50	1721.54
LMT 28:	1732.98	1713.88	1738.63	1747.68	1718.26	1735.21	1702.15	1715.38	1727.47	1700.72	1725.83	1699.91
LMT 29:	1702.64	1755.93	1672.34	1711.33	1757.82	1720.59	1689.00	1659.21	1702.47	1687.84	1732.89	1730.44
LMT 30:	1750.65	1524.10	1591.15	1591.17	1585.67	1523.32	1744.15	1768.11	1573.27	1727.69	1747.74	1703.25
LMT 31:	1711.55	1761.98	1775.79	1749.82	1756.25	1749.23	1752.60	1760.89	1654.24	1755.30	1742.71	1681.80
LMT 32:	1726.14	1719.28	1741.27	1726.26	1626.15	1713.64	1680.65	1723.33	1761.30	1754.66	1695.77	1709.62
LMT 33:	1748.17	1767.10	1538.59	1605.12	1720.41	1545.85	1746.20	1563.14	1739.85	1567.36	1569.45	1553.13
LMT 34:	1697.32	1577.51	1560.30	1569.40	1540.02	1539.22	1604.96	1585.09	1595.00	1708.27	1729.82	1751.62
LMT 35:	1733.61	1724.55	1752.46	1754.87	1738.17	1697.71	1731.83	1657.84	1691.51	1725.03	1743.05	1672.40
LMT 36:	1750.74	1725.48	1767.77	1719.89	1657.38	1740.94	1738.81	1743.01	1735.81	1770.02	1723.11	1722.36
LMT 37:	1738.12	1677.89	1712.16	1740.82	1751.48	1771.52	1807.83	1609.15	1681.14	1673.92	1725.09	1706.74
LMT 38:	1709.24	1542.10	1585.56	1553.16	1510.13	1541.51	1564.03	1564.70	1581.61	1544.68	1532.05	1633.39
LMT 39:	1699.81	1574.25	1595.83	1607.88	1569.62	1721.18	1559.41	1722.87	1567.62	1553.09	1716.59	1667.99
LMT 40:	1699.37	1710.18	1688.19	1777.01	1744.23	1654.81	1671.99	1717.35	1725.02	1711.91	1727.97	1778.05
LMT 41:	1763.89	1744.61	1741.47	1709.33	1630.22	1726.98	1768.13	1675.39	1777.12	1688.92	1693.61	1731.73
LMT 42:	1692.96	1751.23	1718.28	1701.13	1721.35	1727.61	1721.14	1777.26	1695.16	1774.57	1727.47	1746.93
LMT 43:	1719.22	1738.01	1725.83	1708.97	1761.81	1746.42	1774.53	1757.03	1731.24	1761.76	1745.02	1682.32
LMT 44:	1720.17	1750.01	1696.45	1718.14	1725.21	1724.67	1696.01	1730.07	1701.50	1726.02	1708.45	1698.21
LMT 45:	1741.57	1670.32	1721.66	1743.52	1755.24	1750.11	1703.66	1675.52	1691.58	1736.43	1701.41	1753.58
LMT 46:	1705.29	1548.50	1764.91	1753.03	1731.52	1698.17	1677.59	1731.21	1697.55	1758.10	1571.29	1740.89
LMT 47:	1719.62	1724.87	1733.39	1753.17	1767.23	1658.80	1724.18	1716.96	1728.66	1689.44	1688.32	1748.79
LMT 48:	1741.22	1576.29	1665.09	1695.81	1755.27	1529.79	1547.23	1718.42	1558.01	1552.48	1783.55	1746.37

ROD and Power Supply Crates



ROD Crate Front

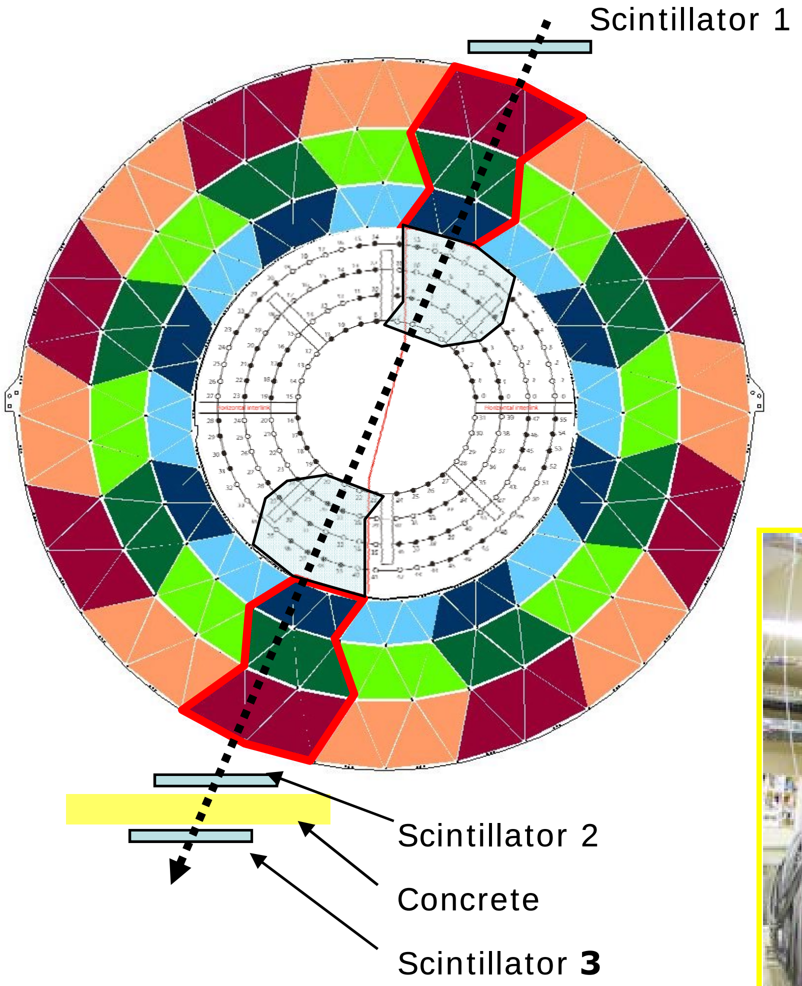


ROD Crate Rear

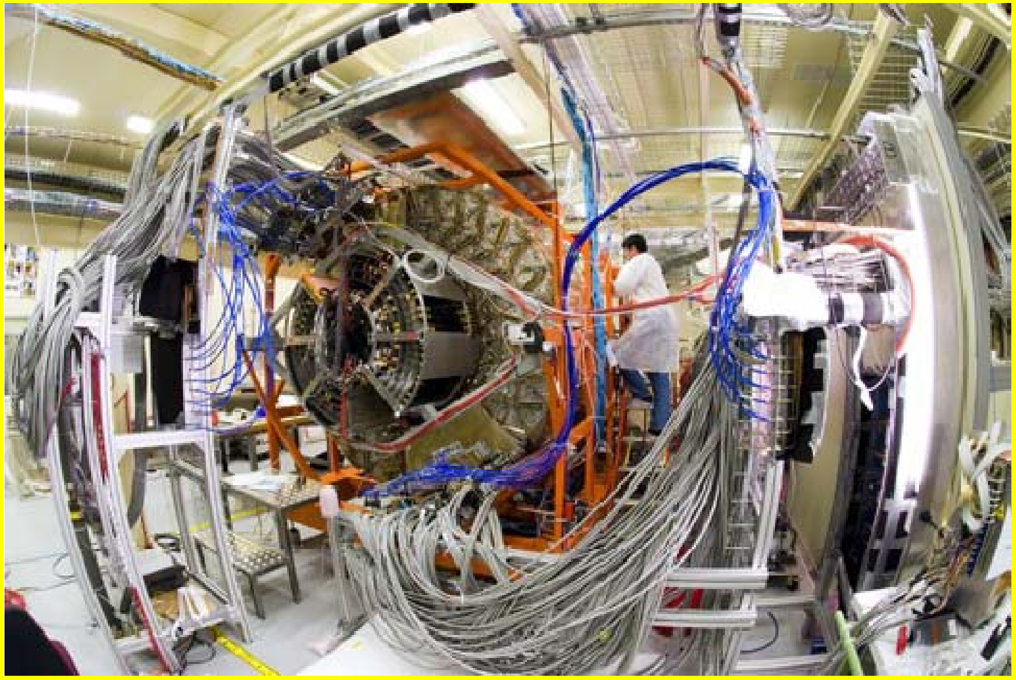
Power Supply Crates

PS Crate Rear

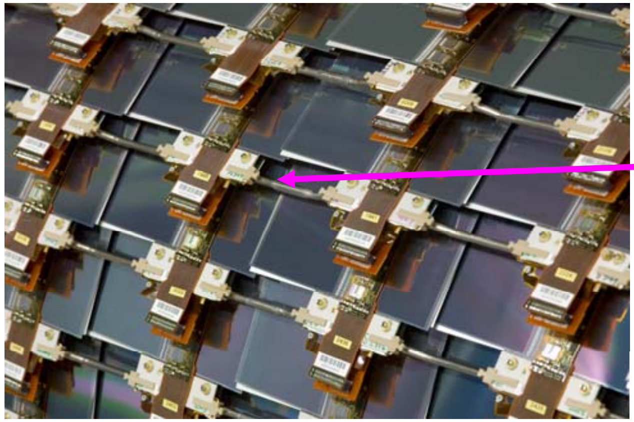
First Cosmics in SCT/TRT combined tests



¼ of SCT and 1/8 of TRT were cabled for combined tests.
Cross-talk & grounding studies.
First timing in for cosmics (using coincidence in scintillators above and below the barrels)



SCT Cooling Problem



The SCT is cooled by an evaporative cooling system using C3F8

- evaporation within cooling loops attached to hybrids ensures uniform and stable temperature
- removes up to ~40kW of heat
- compressors shared with pixel subdetector
- evaporation temperature defined by back pressure regulators

As the C3F8 exits the SCT cooling circuits, any remaining liquid must be boiled off with heaters to prevent the possibility of evaporation in the return lines and any subsequent condensation.

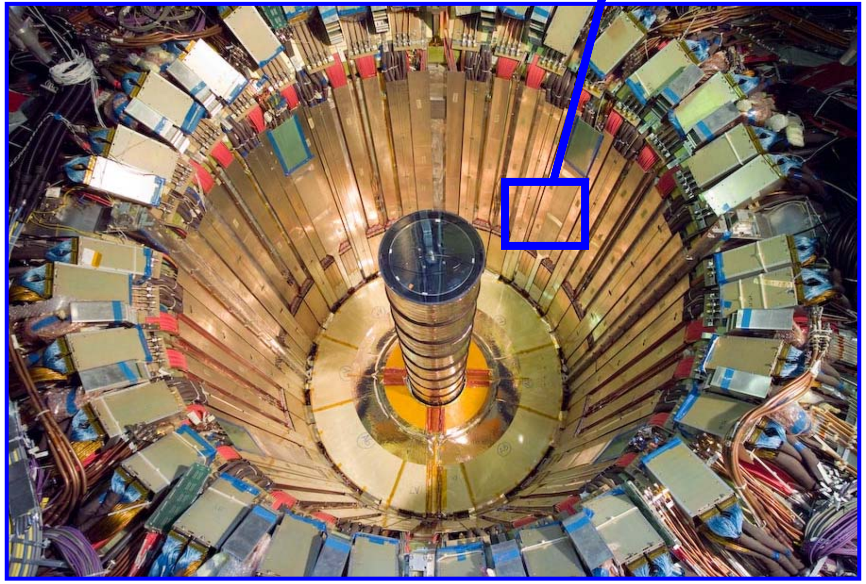
A short in one heater connector developed during barrel testing in Feb 07, resulting in extreme temperatures. All heaters were examined and any non-conformities in manufacturing tolerance and vulnerability to moisture were corrected.

Another heater connector, which had been well within specification, shorted in May 07 after several days of successful operation.

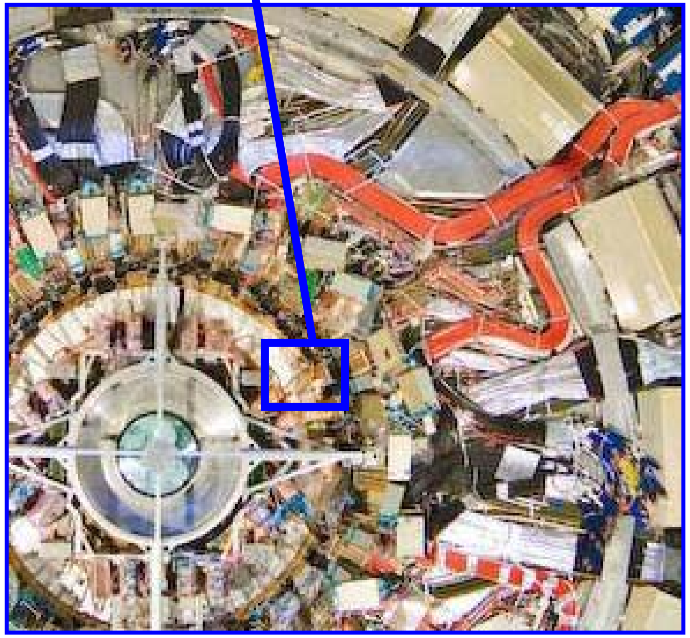
Following this incident all cooling operations were suspended indefinately and all testing had to proceed without cooling...

SCT Cooling Status – what now?

All heaters were removed from their positions in the inner surface of the cryostat
- otherwise the installation of the SCT endcaps (and the rest of ATLAS!) would have to be suspended



New ‘far-heater’ solution to be implemented on the outside of the cryostat



Restart of cooling plant with ‘far-heater’ solution is expected before the next ATLAS combined technical run in mid-October

Until that time, no cooling is possible, which impacts significantly on the SCT commissioning

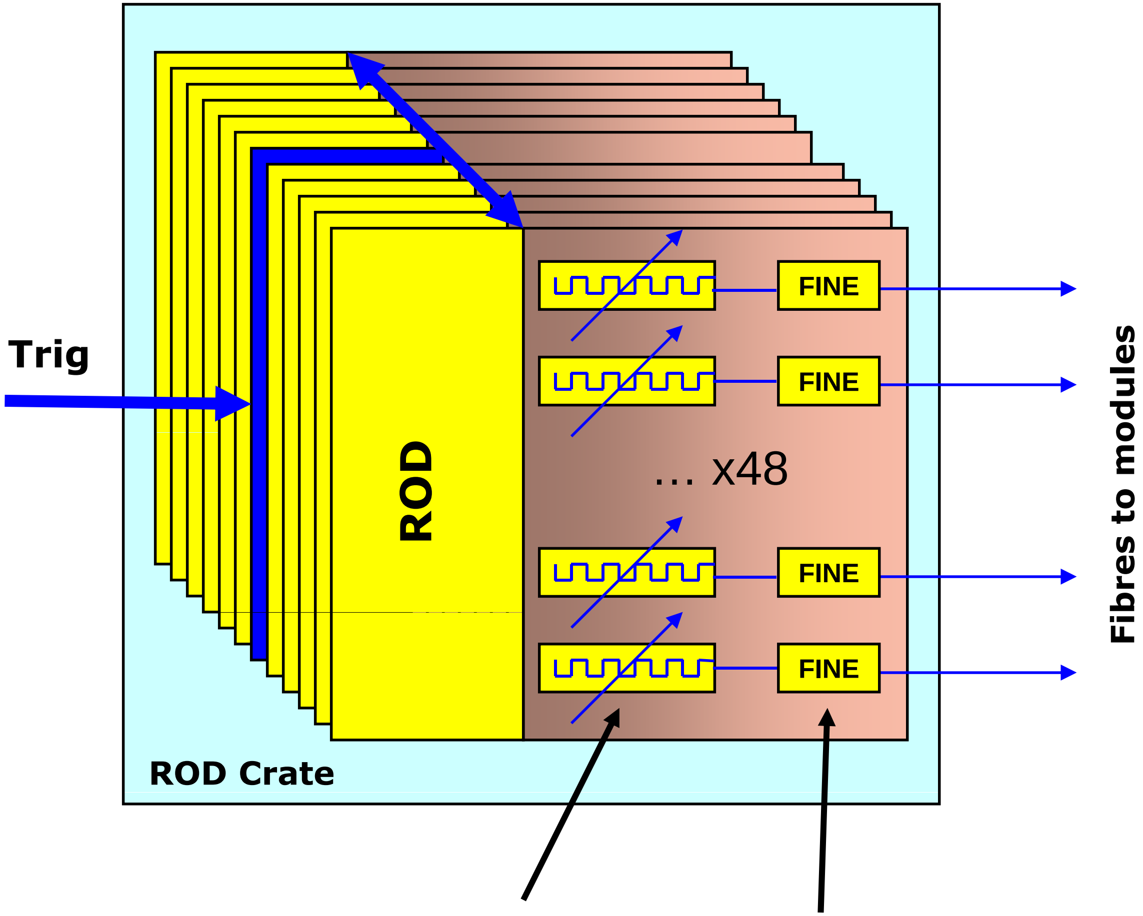
Timing in for Cosmics & Physics

1. Synchronise individual modules (4088 independent delays)

Before attempting to time in for cosmics we must ensure all modules are exactly synchronised (ie signal from the track falls in the same 25ns clock cycle and same phase relative to clock cycle).

The fibre length (and hence TX propogation delay) from BOC to module varies for each module (from 380 to 446ns, depending on fibre ribbon lengths in cavern and on the detectors).

The clock and control data is therefore individual delayed for each module.

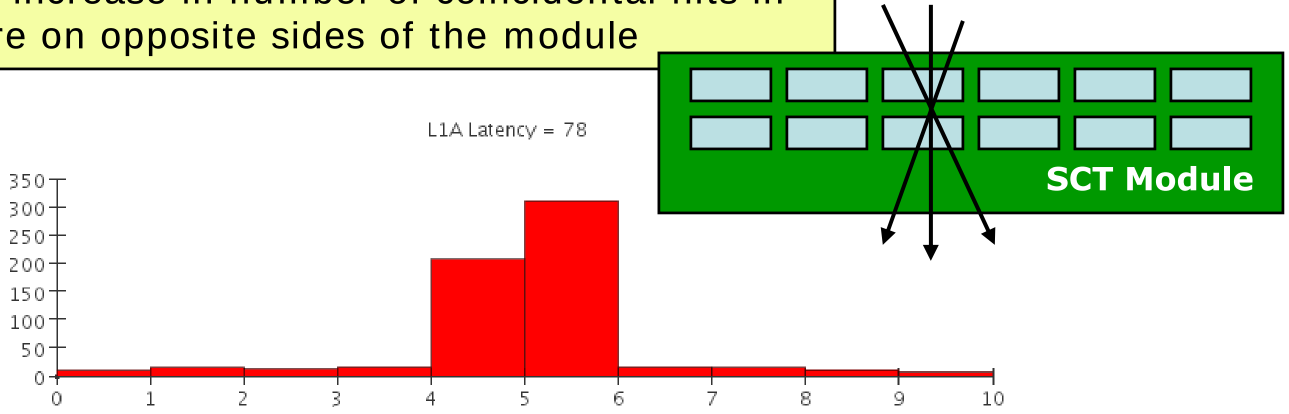


BOC coarse delay
Up to 32 clock cycles

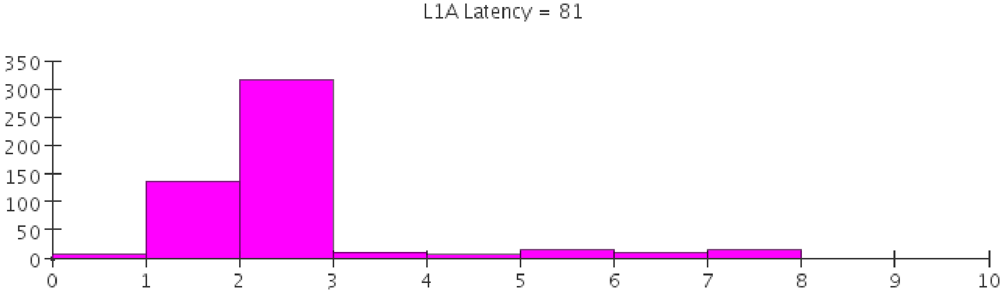
BOC fine delay up to
35ns in 280ps steps

Timing in [2]

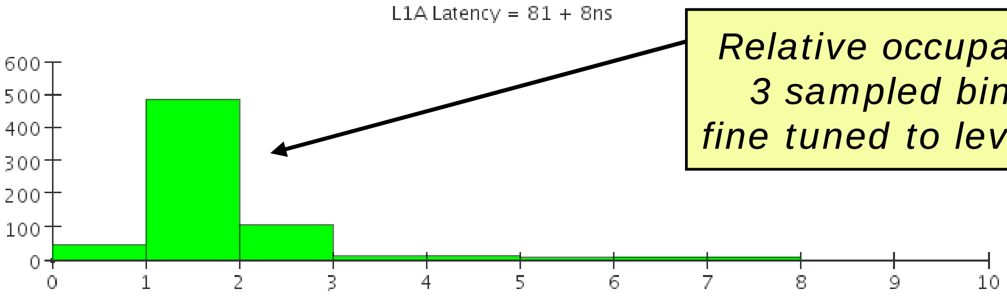
2. Apply global TX delay offset on top of the 4088 individual delays, and scan offset to look for increase in number of coincidental hits in The chips which are on opposite sides of the module



Offset 1



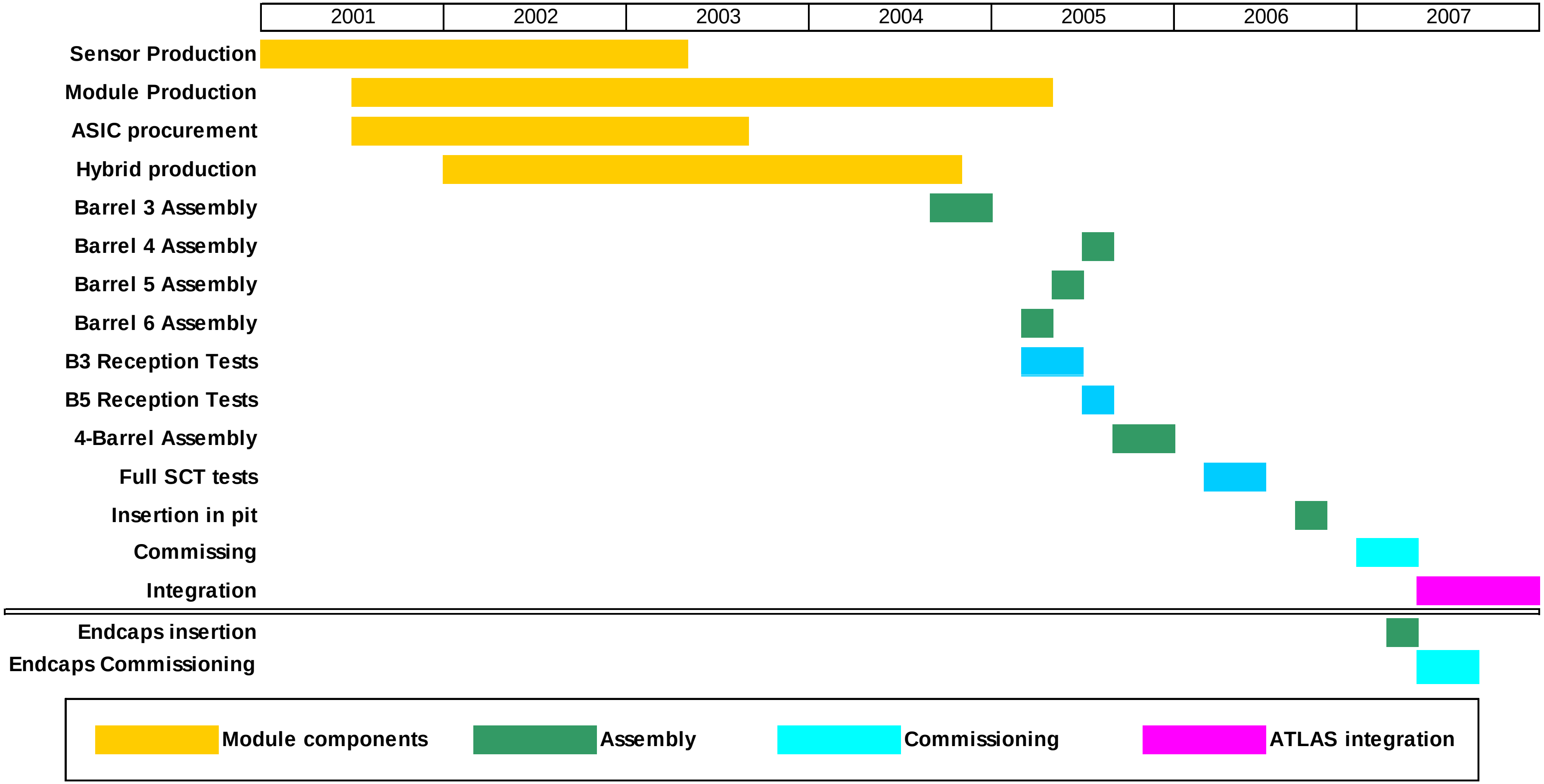
Offset 1 + 3 clocks



Offset 1 + 3 clocks + 8ns

Relative occupancy of the 3 sampled bins can be fine tuned to level of 280ps

Assembly & Commissioning Schedule



Optical Tests without Cooling

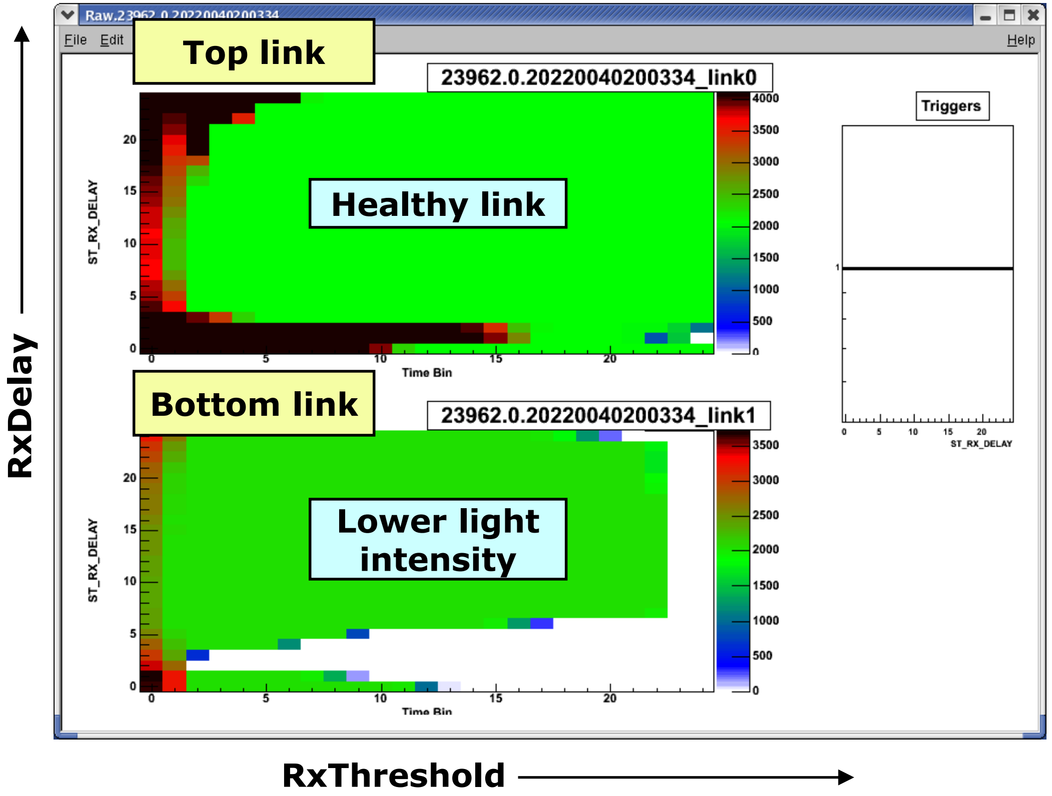
Fortunately all connectivity tests (optical and electrical) can be performed without cooling

“Dicing With Death”

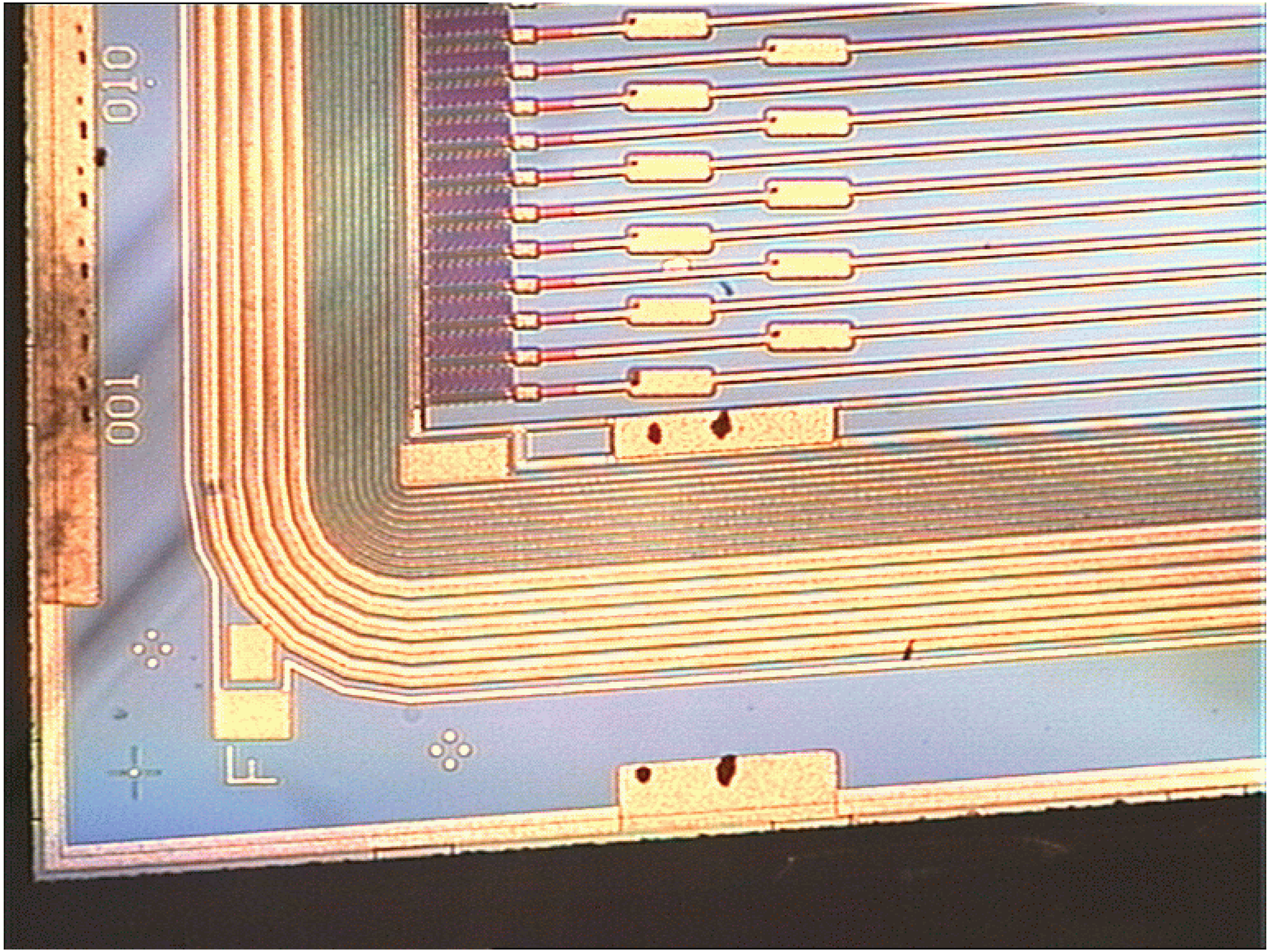
- Switch on
- Test and switch off within ~15secs
- Usually Tmodule < 30°C
- Interlock switches off module if T>35°C

Tests:

- Check for I-pin (TX)
- Check mapping
- Perform fast optical RX tuning with DAQ takes ~few seconds

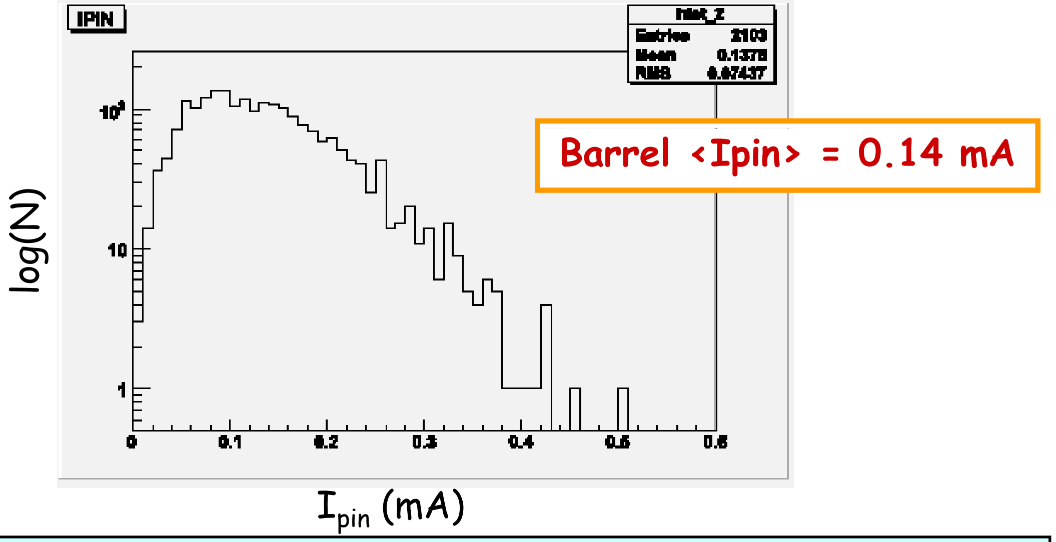


CiS Wedge Sensors



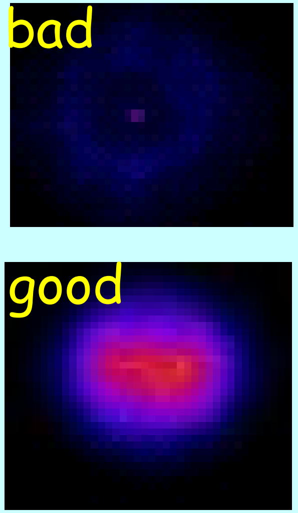
Low I-Pin

Current induced by light from BOC with V_{pin}=6 Volt



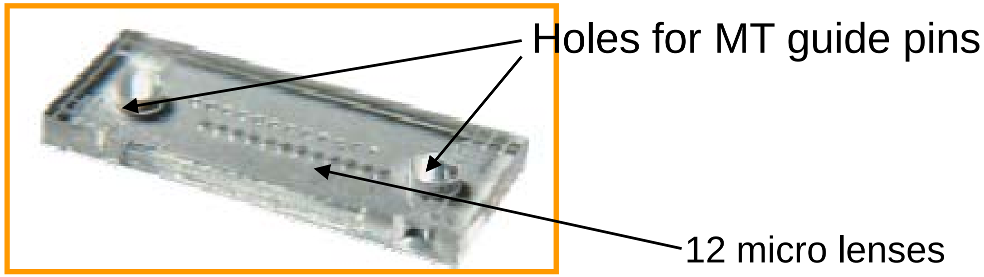
Barrel <Ipin> = 0.14 mA

- All modules tested so far see the clock, but a few channels are very close to the threshold (0.02mA)
- Threshold for operation will deteriorate with irradiation
- Current situation not sustainable in the long term



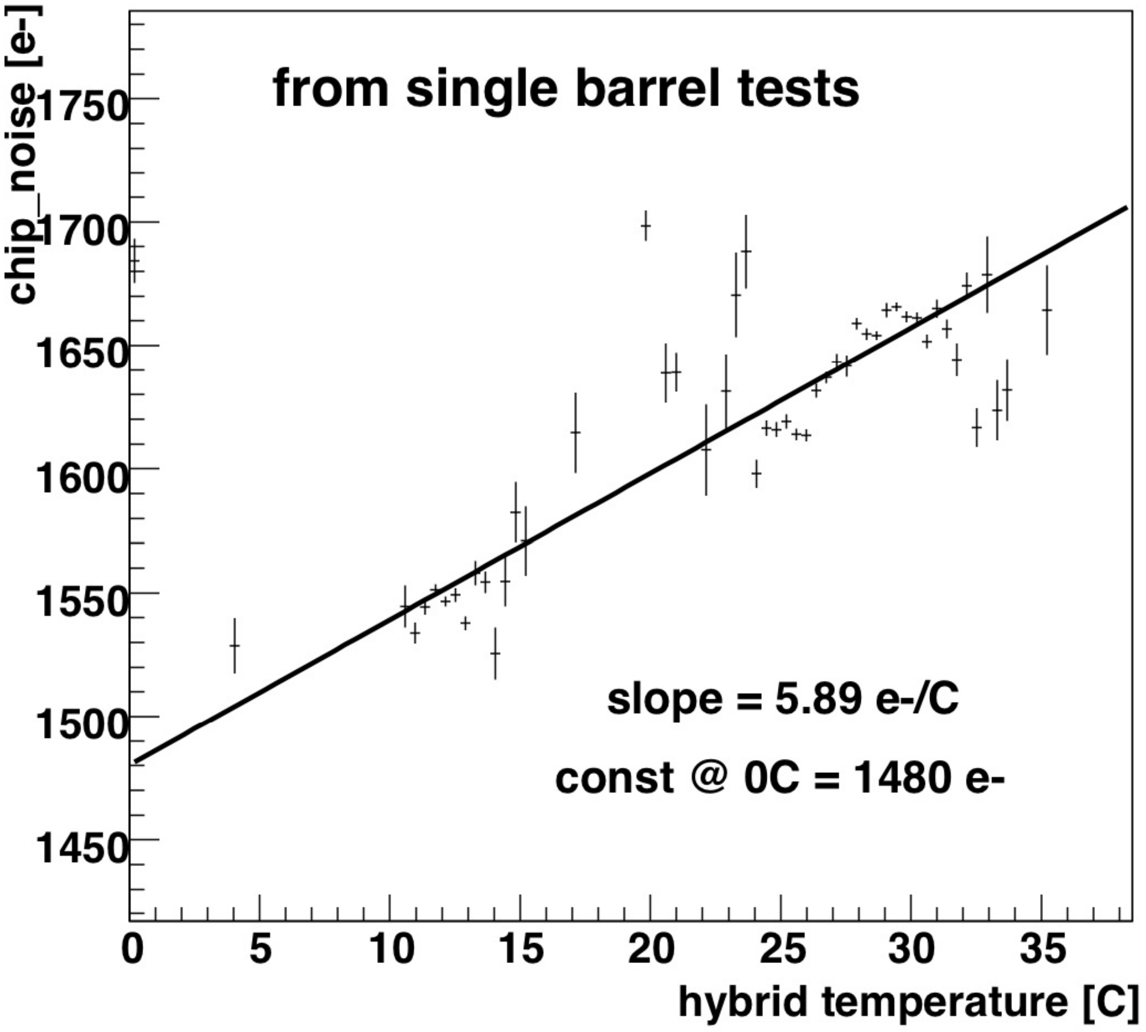
Light from poor TXs typically less focussed

Studies are ongoing, including investigating use of micro-lenses but replacement of TXs in long term is not excluded



Noise vs Temperature

Extracted from single barrel tests, at Oxford assembly site and CERN reception



BackPlane Resistance Problem[1]

- Problem first identifed in April 2006 during acceptance tests at CERN

- High bias resistance is likely to originate from silver-loaded electrically conducting epoxy joint that connects the sensor backplane
  - Barrels use ‘Eotite p-1023’
  - Endcaps use ‘Tra-Duct’

- Forward bias resistance of a 4-wafer module should be ~11.6 kΩ
  - source current at 10mA or 100mA, measure V and determine R
    - at 10µA, ‘normally’ expect R~35kΩ
    - at 100µA R~16-20kΩ
    - at 1mA R~12kΩ

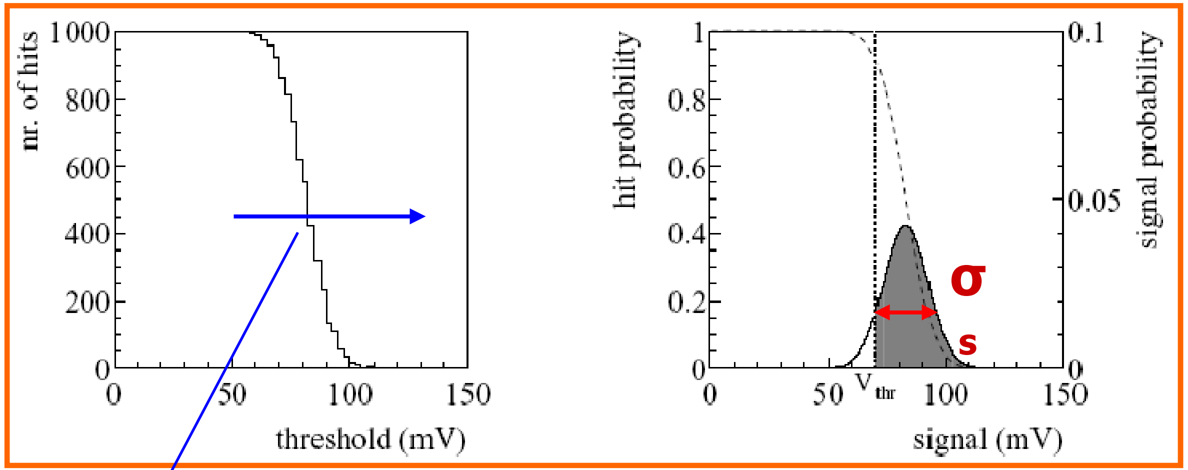
- Found that on ~5% of endcap modules and ~18% of barrel modules, R > 60kΩ at 10µA

BackPlane Resistance Problem[2]

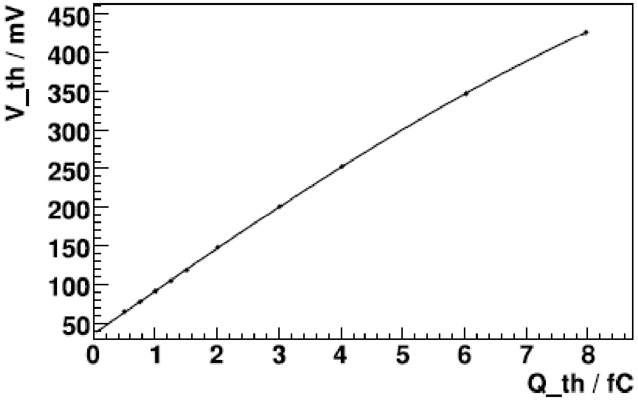
- No bias connections have been lost
- No evidence that environment issues are to blame
  - different histories for different barrels/endcaps
- No evidence that situation is deteriorating
  - no new modules with problem since April 06
- ~40% of modules are ‘cured’ by forward biassing to 100μA
- ~30% of those modules ‘cured’ in early 2006 remain cured today
- Module performance unaffected in early days of operation
- After irradiation, with high current, will we see ‘self-curing’?
- The cause, and ‘cure’, are not yet understood

Binary Analysis

- ***Analogue performance*** *is evaluated by looking at the* ***S-curve*** *for each channel:*
    - *Inject known charge and read-out number of hits as a function of threshold*
    - *Gaussian noise distribution is the derivative of the threshold scan*



Determine shift in response (50% occupancy point) as a function of increasing injected charge to generate response curve:



Input chip Noise = σ_s / Gain

Where Gain = Δ(response)/Δ(input charge)