Readout Electronics Tests and Integration of the ATLAS Semiconductor Tracker

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On behalf of the ATLAS SCT Collaboration

12th Workshop on Electronics for LHC and Future Experiments
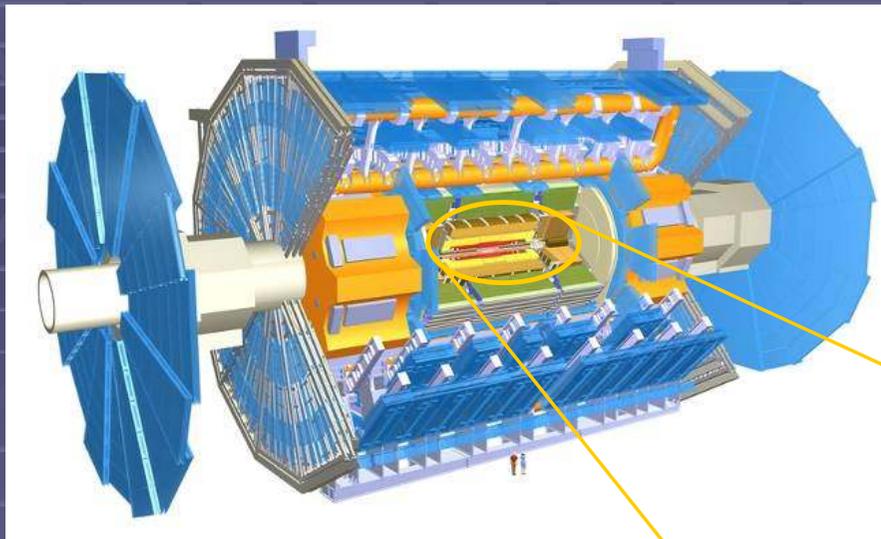**25–29 September 2006, Valencia, Spain**

Outline

- Introduction: ATLAS → Inner Detector
- SCT / ID integration
  - end-cap assembly: modules to disks / disks to support cylinders
  - barrel assembly: modules to cylinders / cylinders insertion to barrel
  - barrel ID integration: SCT + TRT
- SCT readout tests
  - SCT readout system description
  - defective channels
  - noise measurements
  - test with cosmic rays
- SCT status
  - barrel ID installation
  - end-cap preparation for integration with TRT
- Conclusions

*Thanks to Pepe Bernabeu and other colleagues whose work is presented here*

ATLAS: A Toroidal LHC ApparatuS

- **Inner Detector (tracker):**
  - 2T- superconducting solenoid magnet
  - rapidity coverage: $|\eta| < 2.5$
  - **Transition Radiation Tracker (TRT)**
    straw drift tubes - outer part
  - **SemiConductor Tracker (SCT)**
    silicon strip detector - middle part
 - Pixel detector
    silicon pixel detector - inner part

- **Muon Spectrometer:**
  - large superconducting air-core toroid magnet
  - combines precision and trigger chambers
  - excellent muon momentum resolution
- **Calorimetry:**
  - hadron calorimeter for jets and missing transverse energy
  - electromagnetic calorimeter for electron and photon identification
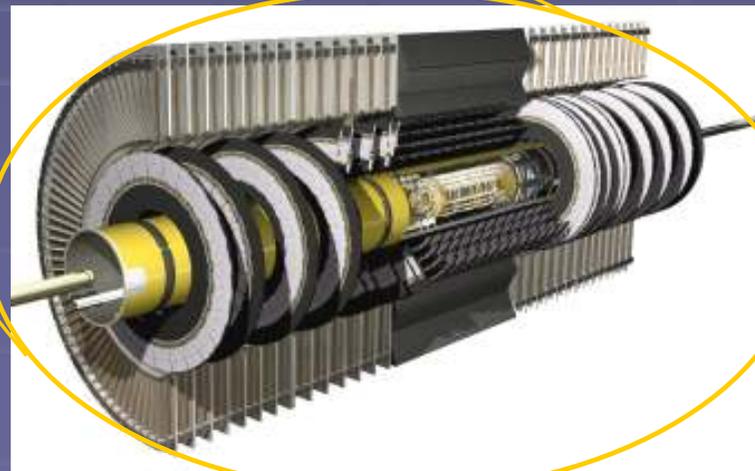
Inner Detector

~ 6 m long, 1.1 m radius

Beam pipe

TRT

Pixels

**SCT**
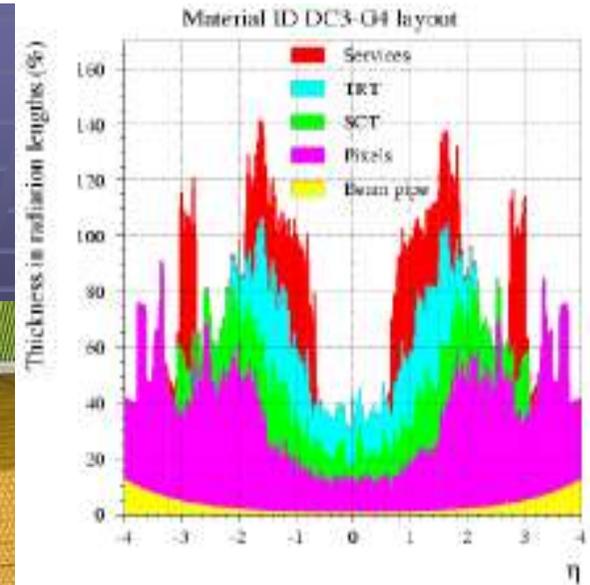
Semi-Conductor Tracker (SCT)

- Double-sided module build-up of 2 pairs of sensors (768 *p*-in-*n* strips; single sided; 285 μm thick)

- Sensors glued back-to-back at a 40-mrad stereo angle to measure second coordinate

- 4 barrel layers
  - barrel radii: 300, 371, 443 and 514 mm; length 1530 mm
  - in total **2112** modules (4 layers: 384, 480, 576, 672 modules)
- 2 × 9 forward disks
  - disk distance from z = 0: 835 - 2788 mm
  - radii: 259-560 mm
  - in total **1976** modules (3 rings: 40, 40, 52 modules each)

6.3·10⁶ channels
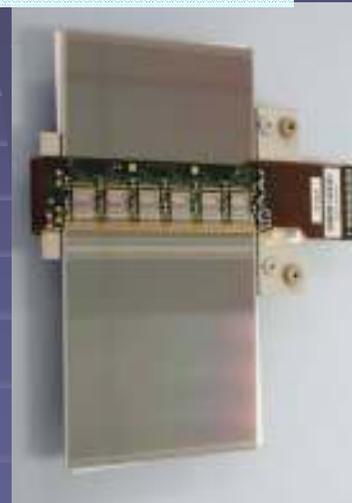
End-cap module (long middle)

Barrel module

1.04 m

5.6 m

1.53 m
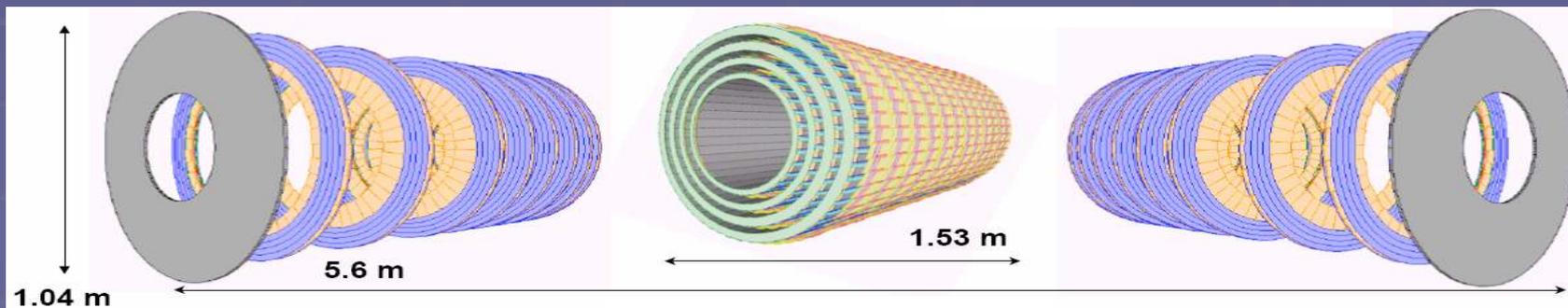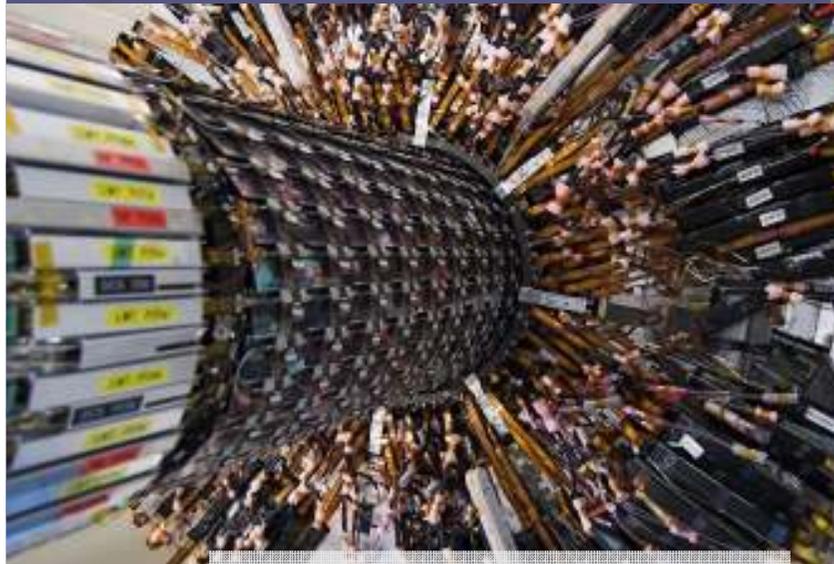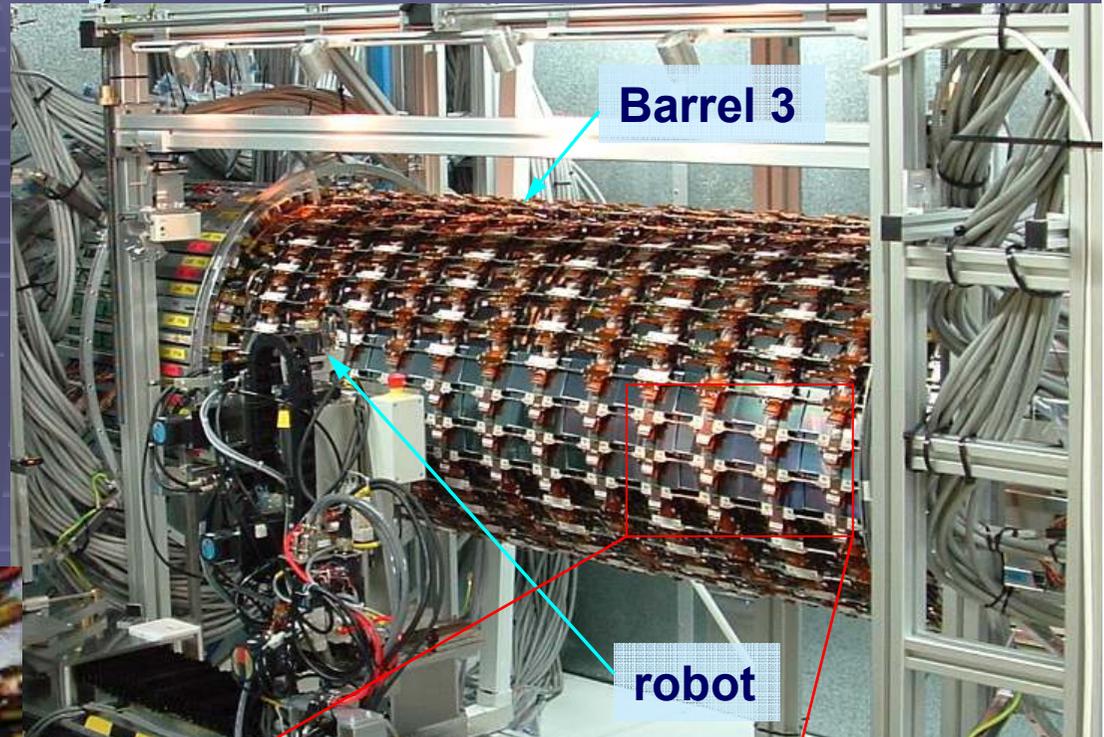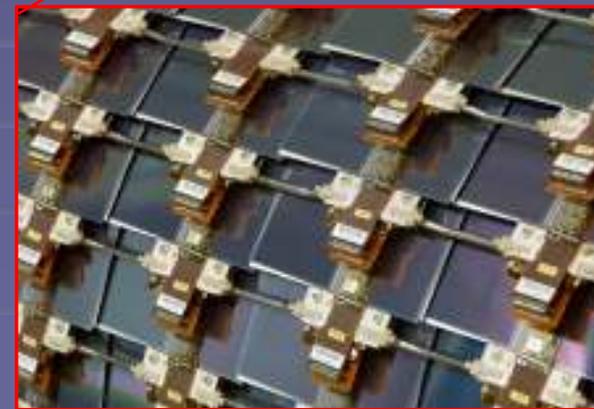
SCT barrel assembly

- 4 SCT barrels assembled in Oxford
- Transferred to CERN and tested
- Integrated into one SCT barrel at CERN

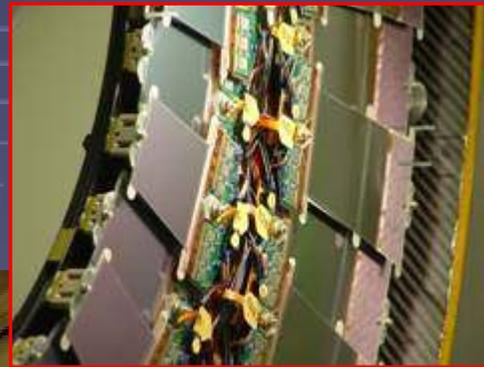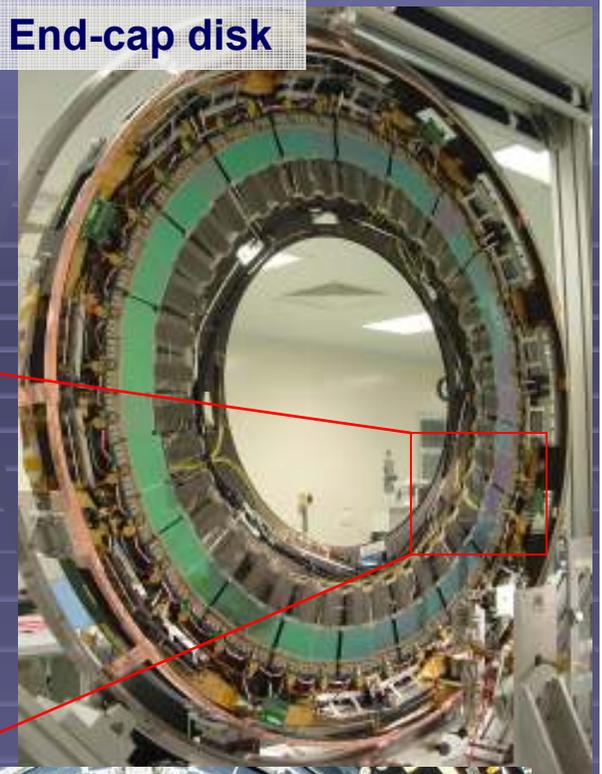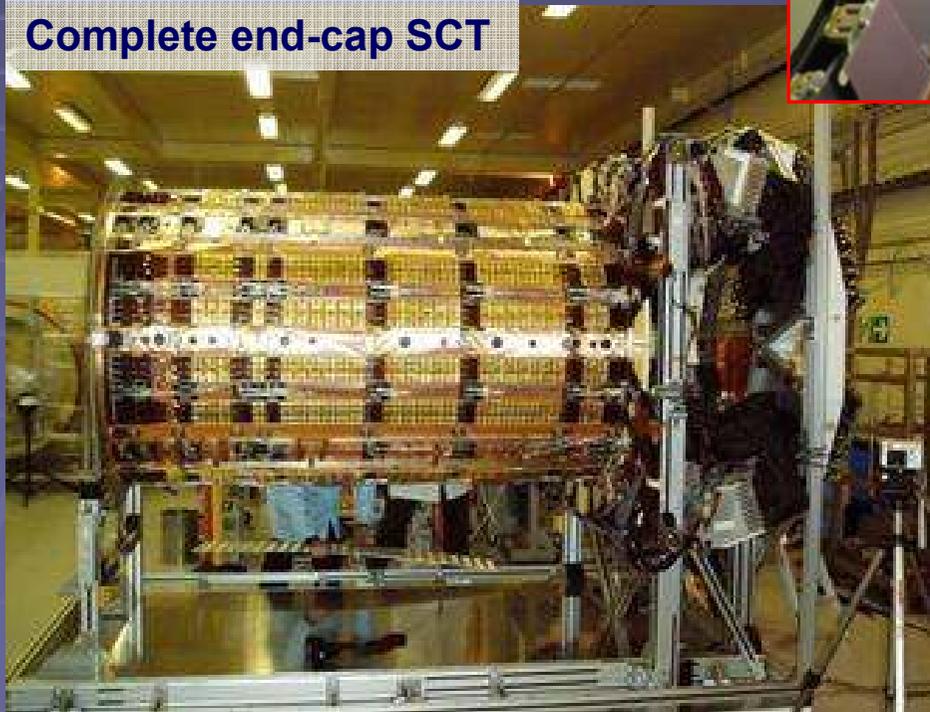**Barrel 3**

robot

Barrel 3 insertion into B4

SCT end-caps assembly

- 2 SCT end-cap assembled in Liverpool (EC-C) and NIKHEF (EC-A)
- 9 discs each
- Transferred to CERN and tested

End-cap disk

Complete end-cap SCT

End-cap SCT seen from inside

SCT and TRT barrel integration

Barrel SCT being inserted inside the barrel TRT

Barrel ID: SCT + TRT

- Barrel SCT insertion into barrel TRT (February 2006)
- The Pixel sub-system will be installed independently from the rest of the Inner Detector

SCT readout electronics I

- Handled by ASICs realised in the radiation-hard DMILL technology (ABCD3TA)
- 128-channel analog front-end consisting of amplifiers and comparators
- Digital readout circuit through a 132-cell pipeline
- Operating at the LHC bunch crossing frequency (40 MHz)
- Utilises the "binary" scheme
  - silicon detector signals are amplified and then compared with a threshold
  - only the result of this comparison (hit or no-hit logic) enters the input register and the digital pipeline
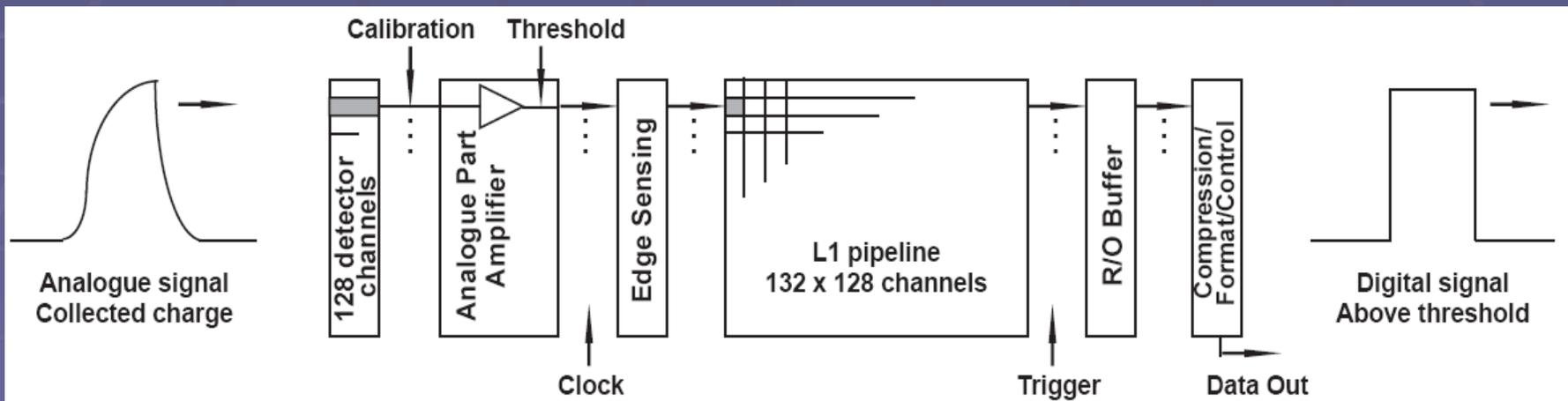
SCT readout electronics II

- Internal 4-bit trim DAC controls the comparator offset channel by channel
  - The channel-to-channel matching, although acceptable for the non-irradiated chips, is expected to deteriorate significantly in the lifetime of the experiment
  - 4 selectable ranges
- Contains a dedicated internal charge injection circuit to calibrate the performance of the analog part
  - calibration pulses are issued with variable amplitude and delay (Strobe Delay) relative to the clock
- Two data links per module (1 link = 6×128 channels)
- Data and TTC (Timing, Trigger and Control) signal between front-end and off-detector electronics are transmitted via optical fibres

Electronics testing method

- Binary front-end chip → occupancy vs. threshold → "S-curves"
- From S-curves are derived:
  - median point *(Vt50)*: signal height (response)
  - width *(σ)*: output noise
- Vt50 measured for various values of injected charge → Vt50 vs. change → Response Curve (RC)
- Trim DACs adjust the offset channel by channel: trim all channels to give same response at 1 fC

before trimming

after trimming

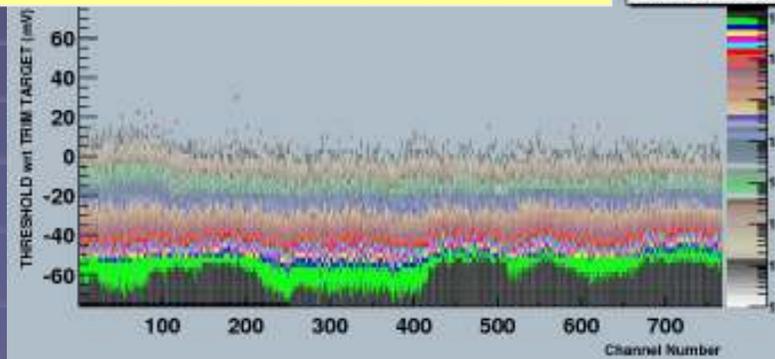*median point @ 2 fC vs. channel number*
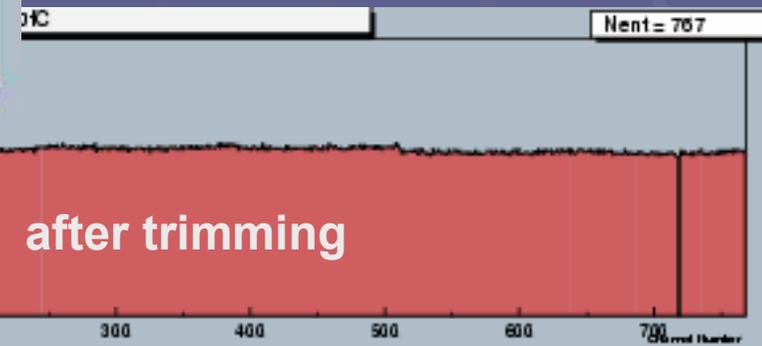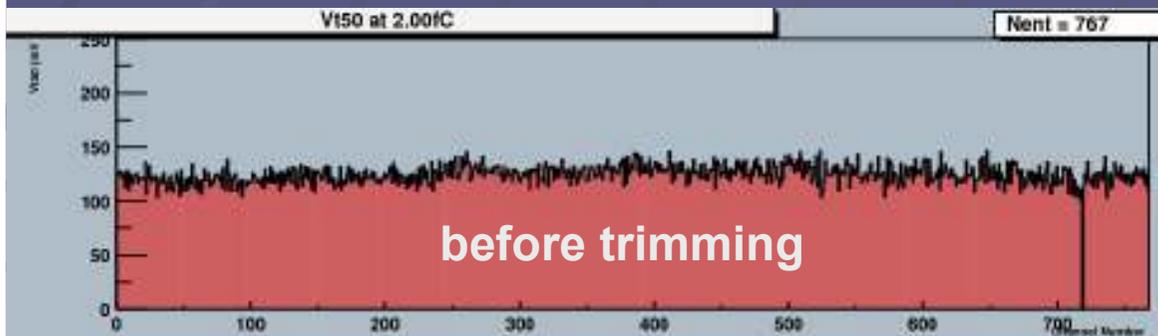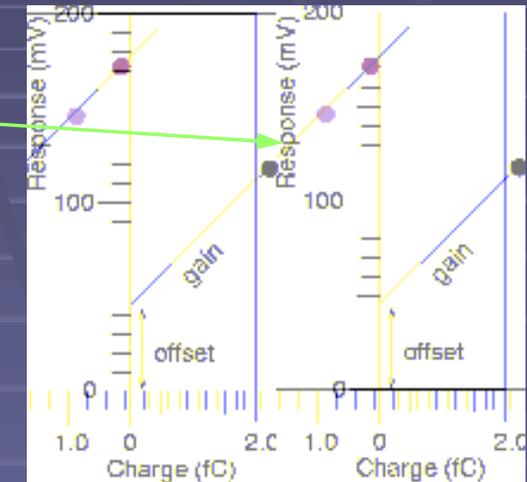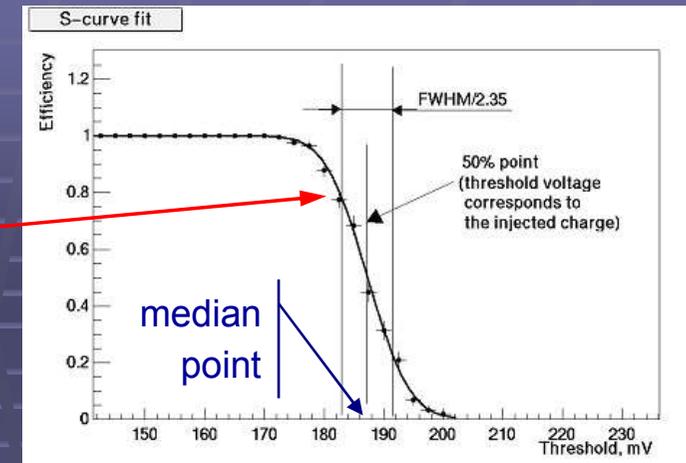
Noise measurements

- Measured noise is due to:
    - front-end noise (fixed for given ASIC and detector)
    - additional noise: common mode, feedback etc.
- Noise Occupancy *(NO)* is measured by threshold scans with no injection charge after trimming
- NO ≡ occupancy @ 1-fC threshold – Specification: NO < 5×10^{-4} per strip

occupancy vs. channel and threshold   log(occupancy) vs. threshold
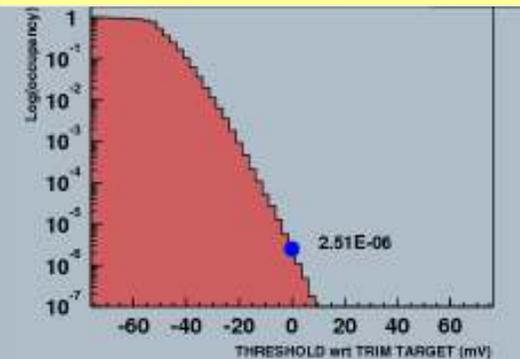
- Equivalent Noise Charge (ENC): input charge giving signal equal to effective output noise (in electrons)
- ENC derived from:
    - threshold scan with injection charge (output noise / gain)
    - NO: straight line fit to a log(occupancy) vs. THR^2 plot

$$NO = \frac{1}{2}\,\mathrm{erfc}\!\left(\frac{THR}{\sqrt{2}\,ENC}\right)$$

Testing: when and why…

- Modules are tested after:
  - Production (@ module assembly sites)
  - Macro-assembly (on disks / cylinders)
  - Reception at CERN
  - Insertion into TRT, during tests with cosmics

- Check that module performance does not change at different stages
- Development of "final running" software through all these stages
- Learn how to recover errors on modules

Typical test sequence

- Basic tests
    - establish communication
    - optimise optical settings
- Digital tests
    - verify communication
    - do trigger counters work?
- Analogue tests
    - measure gain, offset, noise
    - measure noise occupancy
    - look for time structure
    - detect excess noise possibly related to high frequency, synchronous triggers
- Check module supply and sensor currents

Barrel: defective channel

Barrel	Total nr. channels	Not bonded	Dead	Not reachable	Partly bonded	Noisy	Other	Total Defects
B3	589824	180	357	384	91	460	11	1483 (2.5‰)
B4	737280	55	245	256	16	242	27	841 (1.1‰)
B5	884736	173	770	256	97	492	30	1818 (2.1‰)
B6	1032192	385	2513	640	197	1936	49	5720 (5.5‰)
Total	**3244032**	793	3885	1536	401	3130	117	**9862 (3‰)**

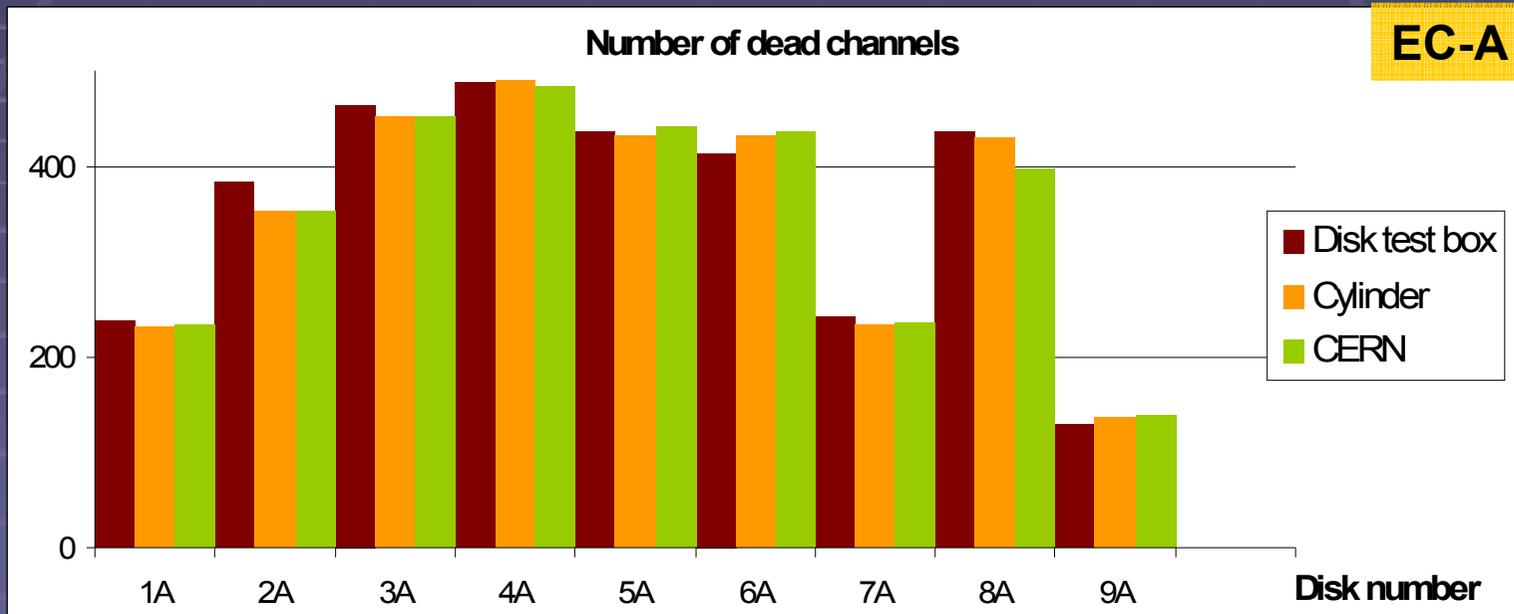
Number of Bad Readout Channels/module
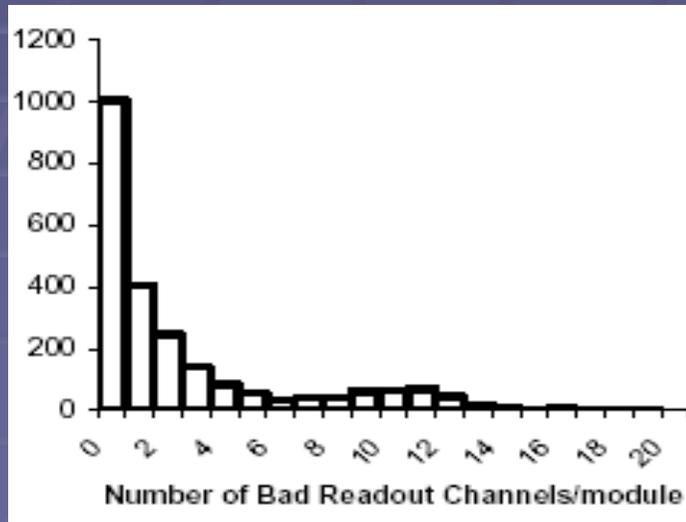
99.8% working channels!

End-cap: dead channels

- Number of dead channels remains constant and at the **0.2%** level (typical value for both end-caps)

Number of dead channels — EC-A

Legend: Disk test box, Cylinder, CERN

#modules	92	132	132	132	132	132	92	92	52

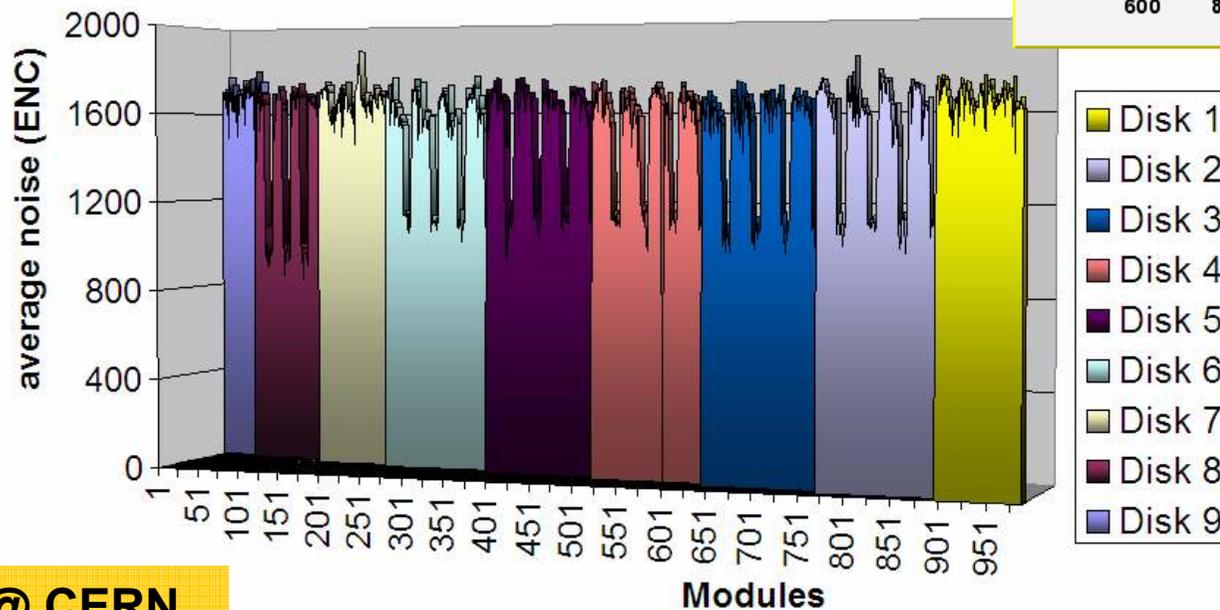Disk number: 1A, 2A, 3A, 4A, 5A, 6A, 7A, 8A, 9A

- EC-A: Performance was found to be the same as before shipping
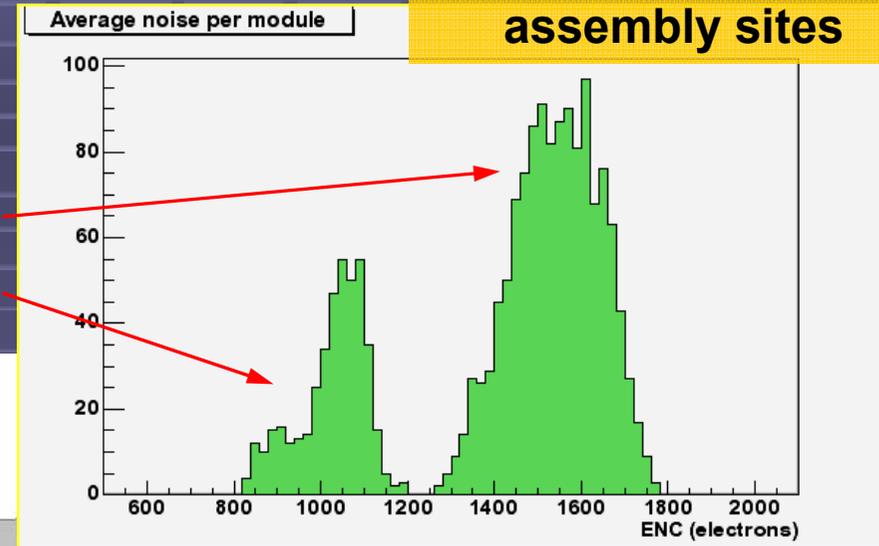 - noise, gain, pipeline
  - high voltage behaviour

End-cap A: noise measurements

- Modulation due to different type of modules ↔ strip length
  - Outer & long middle → high noise
  - Short middle & inner → low noise

9 out of 9 disks tested (988 modules)

Average noise per module

@ CERN

- ENC noise @ CERN at the same level as after production

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LECC '06 Valencia

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ID barrel cosmics test: SCT+TRT combined

View from outside towards Side A
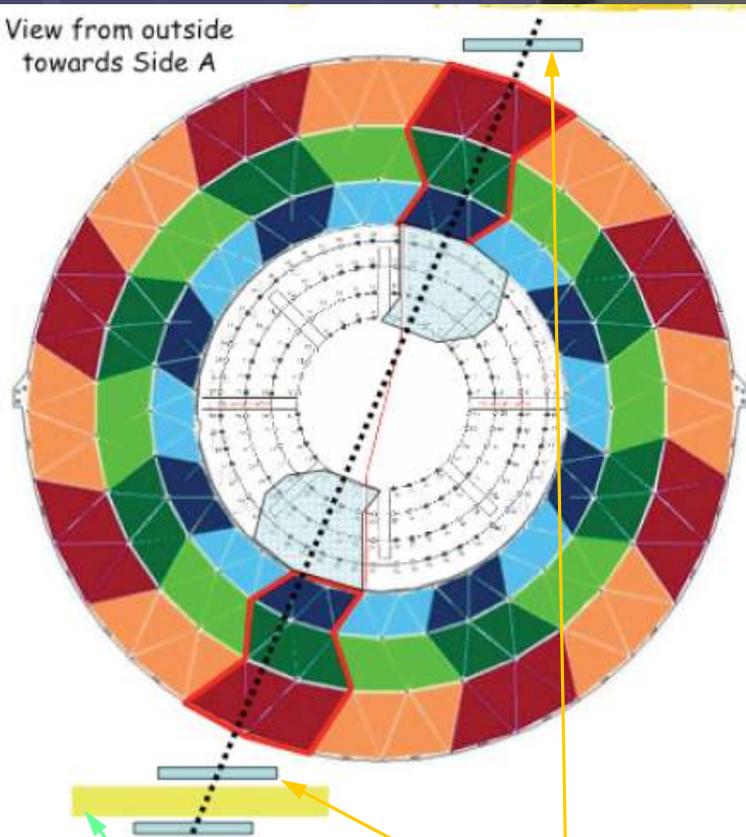
20cm concrete   scintillators

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- First commissioning phase for the Inner Detector at SR1
- Aim: verify their good operation before installation in the pit
- SCT: 468 of 2112 modules (1/4):
  - 5616 ABCD chips
  - 718848 channels
  - 12 RODs
- TRT (1/8):
  - 2 x ~6600 channels
  - 9 RODs (no electronics in bottom -z)
- 3 sets of scintillators
- Operational and running experience on:
  - DCS (cooling, T, P, …)
  - DAQ (calibration, timing, …)
  - Monitoring (event display)
- Next measurements presented refer to this setup…

Noise stability I
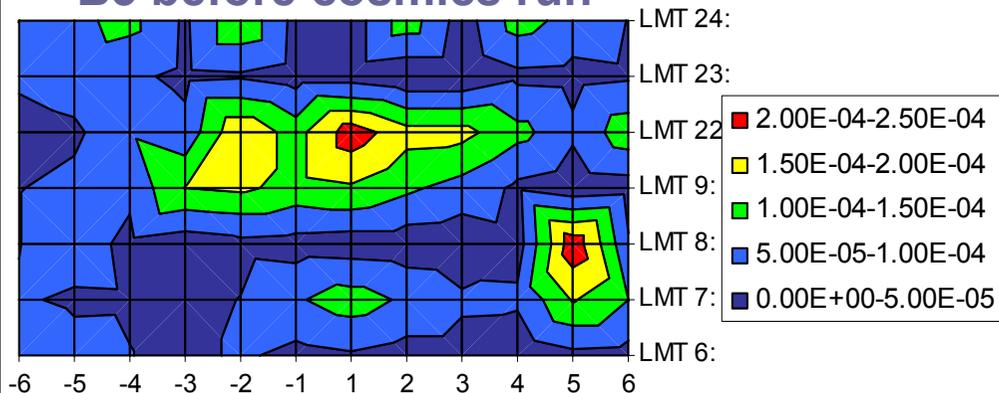
B3 standalone

B3 with other barrels
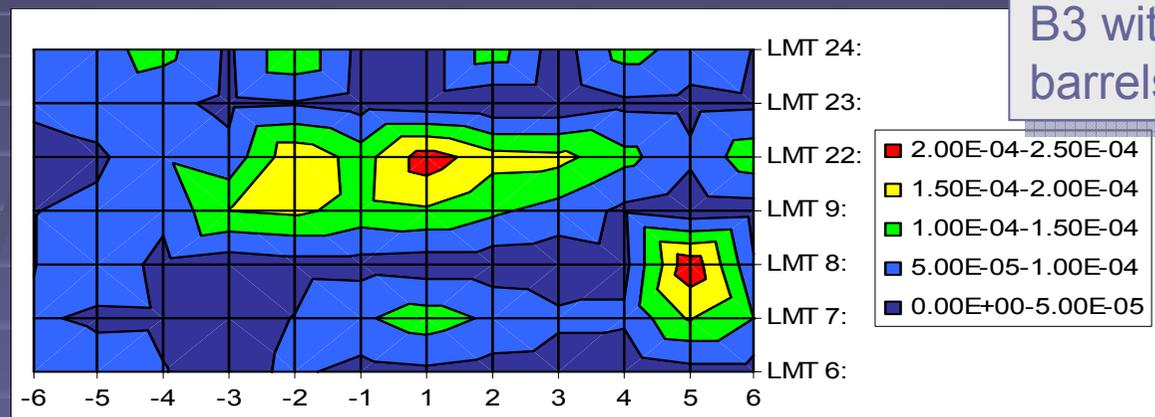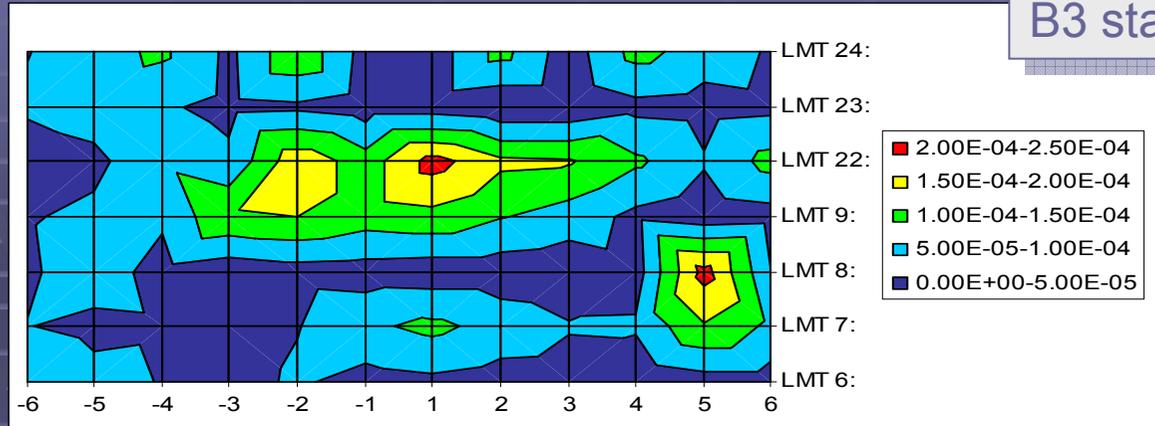
- Noise occupancy
  - a little higher for single barrel test than macro-assembly
  - also a little higher for all barrels than for single barrel tests
- ENC input noise (from 3-point gain) after temp corrections
  - ~40-50 electrons greater than macro-assembly
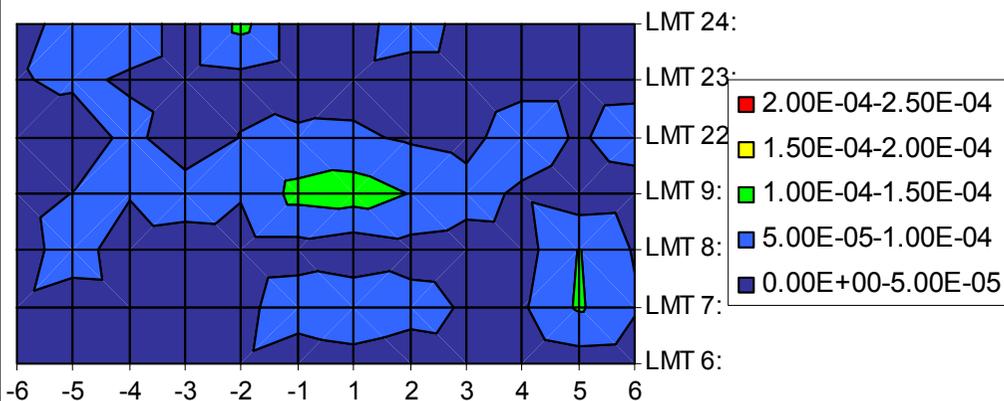 - ENC input noise within 5 electrons of module assembly values

Noise stability II

B3 before cosmics run

Legend:
- 2.00E-04-2.50E-04 (red)
- 1.50E-04-2.00E-04 (yellow)
- 1.00E-04-1.50E-04 (green)
- 5.00E-05-1.00E-04 (blue)
- 0.00E+00-5.00E-05 (dark blue)

B3 after cosmics run

Legend:
- 2.00E-04-2.50E-04 (red)
- 1.50E-04-2.00E-04 (yellow)
- 1.00E-04-1.50E-04 (green)
- 5.00E-05-1.00E-04 (blue)
- 0.00E+00-5.00E-05 (dark blue)

- Dependence on trigger rate
  - in physics mode the pulser rate varies:
    - 5 Hz
    - 50 Hz
    - 500 Hz
    - 5 kHz
    - 50 kHz
  - no evidence of increase in noise occupancy
    - events sizes the same
    - plots look very similar

- Long runs exist to check overall stability in time
- Calibration runs show expected decrease in NO after long period on bias
  - also seen in physics-mode runs
 - consistent with single barrel tests

Threshold configuration

- Started running with thresholds as set from production database (: module assembly)
    - not good – wide variety of thresholds
- Once problem identified, two different thresholds used:
    - "Trim target" → uncorrected 1-fC threshold
    - "Response Curve 1 fC" → includes ~10% wafer-by-wafer correction for variations in ABCD calibration capacitor

	Trim target	RC
Mean	$6.8 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$
RMS	$5.5 \cdot 10^{-5}$	$3.7 \cdot 10^{-5}$

- Mean & RMS noise occupancy decreases when using "Response Curve 1 fC " threshold

Data from calibration runs

Run 2968: with new RC fits

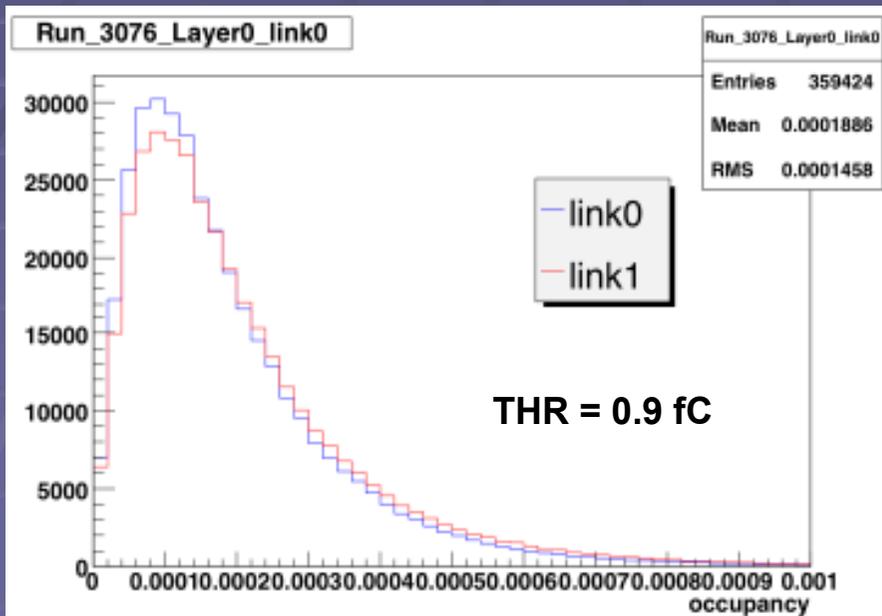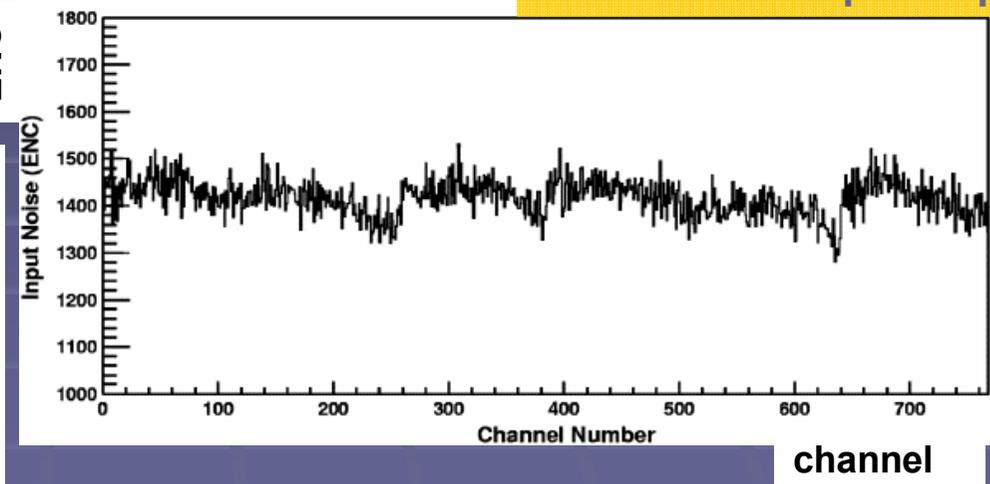Run 2808: old configuration
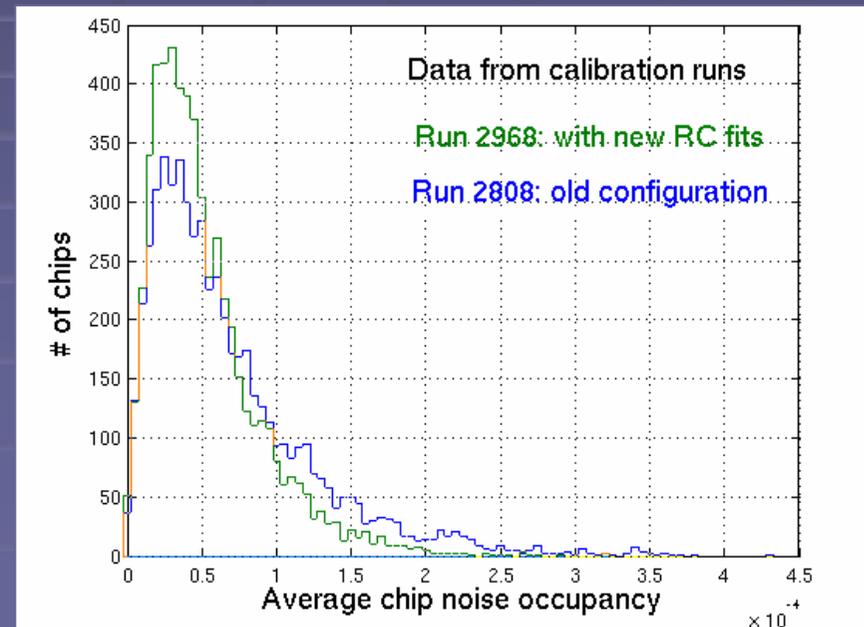
Noise occupancy per strip

- Usual noise behaviour across module
    - noise occupancy higher towards centre of chips
    - link 1 (inner) noisier than link 0 (outer) → $NO_1/NO_0 \approx +7\%$
    - both as they have been observed in module tests

	Link0 (outer)	Link1 (inner)
Mean	$1.9 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$
RMS	$1.5 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$

ENC averaged over all modules in φ and η

Run_3076_Layer0_link0

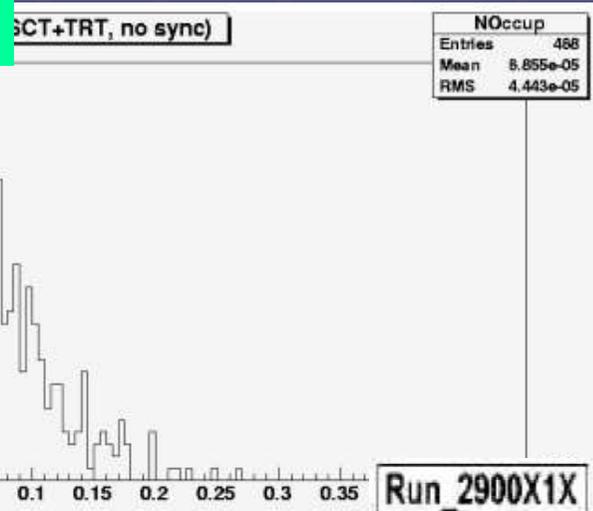| Run_3076_Layer0_link0	
Entries	359424
Mean	0.0001886
RMS	0.0001458

link0
link1

THR = 0.9 fC

- ENC with new RC 1-fC threshold configuration
- with `trim target', dispersion is quite large: NO variation by factor 2
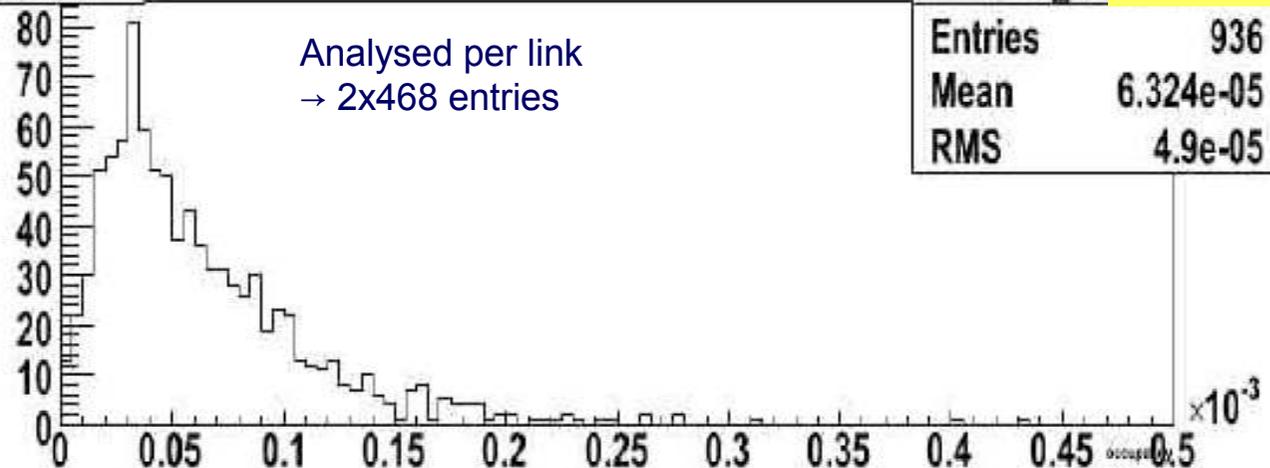
Online / offline comparison

SCT+TRT, no sync)

NOccup	
Entries	468
Mean	8.855e-05
RMS	4.443e-05

Noise Occupancy at 1fC = 6.85·10⁻⁵

Run_2900X1X

Analysed per link
→ 2x468 entries

Run_29		**Offline**
Entries	936	
Mean	6.324e-05	
RMS	4.9e-05	

- **Online:** calibration scans, ROD and TIM triggered
- **Offline:** physics mode scans + offline analysis, triggered from pulser
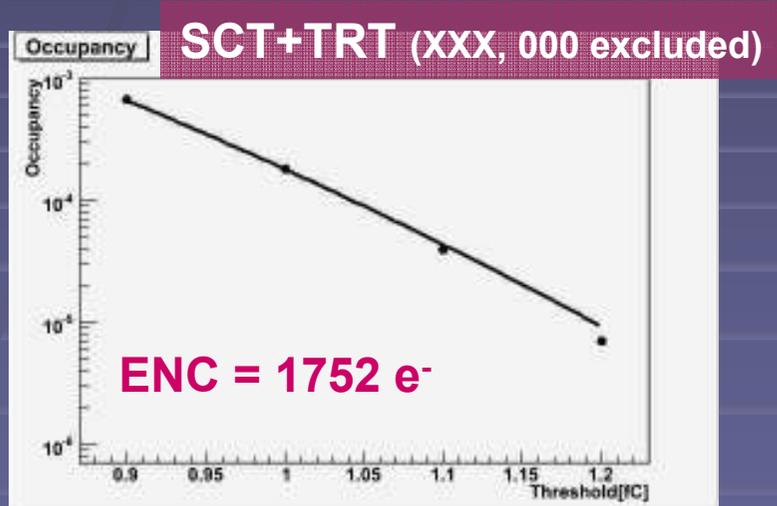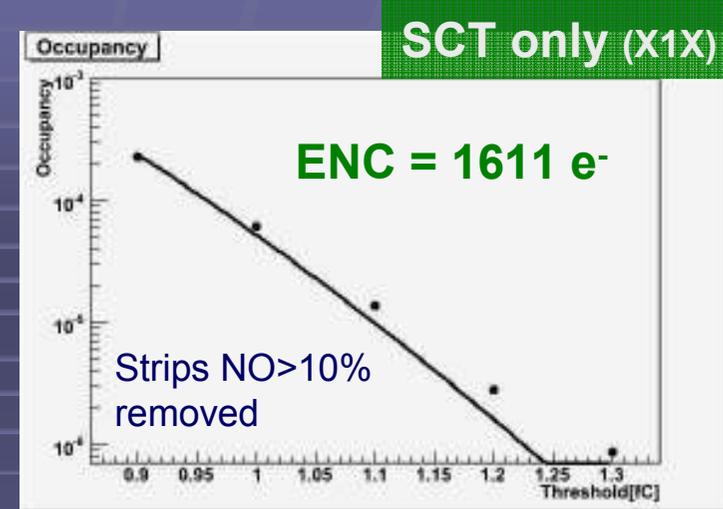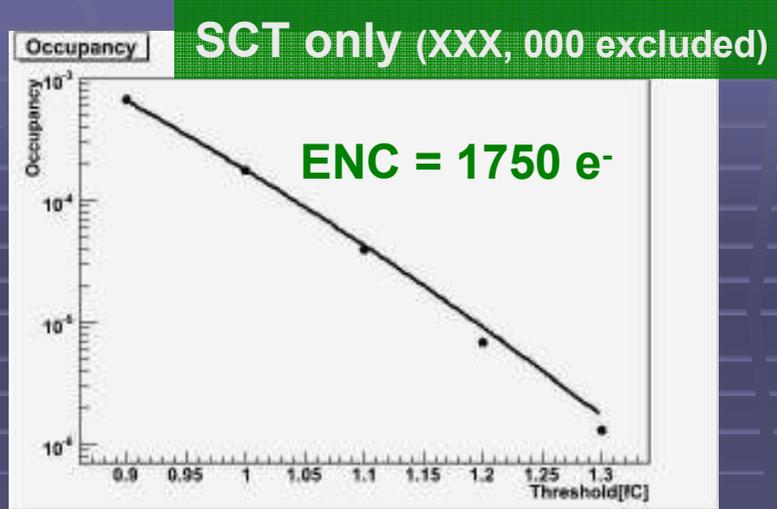
- Shape, mean and variance roughly agree between online / offline, except some noisy modules in offline *(7 modules with NO>3x10⁻⁴)*

Noise with / without TRT
Occupancy vs. threshold

- Different time-bin patterns:
  - XXX: test mode
  - X1X: normal data taking
- Points → measurements
- Curves → NO derived from indicated ENC
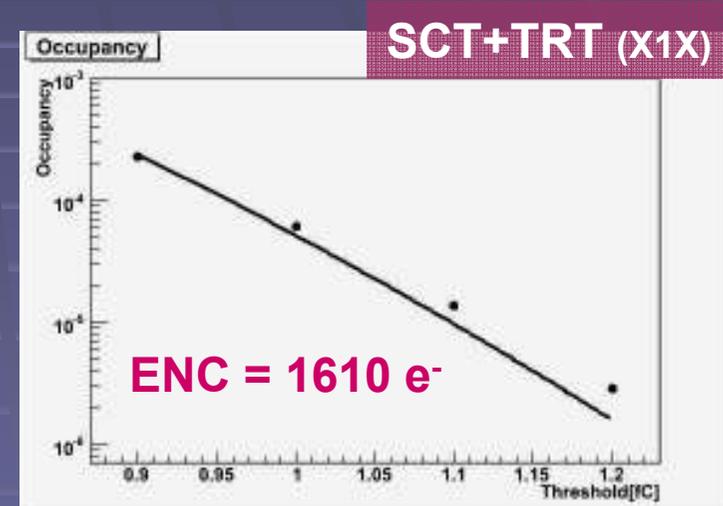
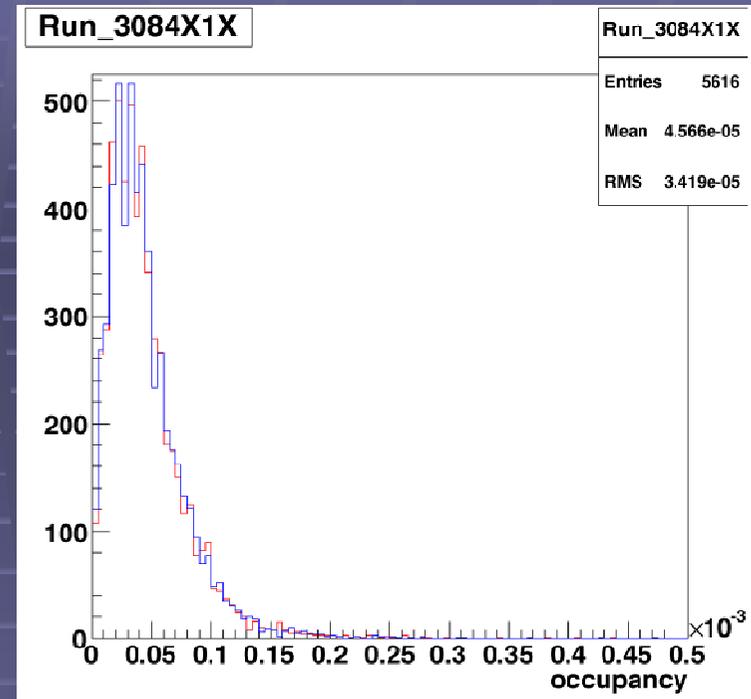$$NO = \frac{1}{2}\mathrm{erfc}\left(\frac{THR}{\sqrt{2}ENC}\right)$$

Grounding schemes

Cosmics setup:

#chips = (252+216)×12 = 5616

| Shorting	`out'	`in'
Mean	4.57×10^{-5}	4.57×10^{-5}
RMS	3.42×10^{-5}	3.39×10^{-5}

- Two grounding schemes tested:
  - `out' → SCT and TRT both triggered from pulser at ~50Hz
  - `in' → same as `out' but with power supply DC shorting cards in
- No significant change in the noise occupancy when grounding scheme is changed
  - grounding scheme in surface building *(SR1)* is not "final"
  - final scheme only available in the final detector position

Barrel ID installation
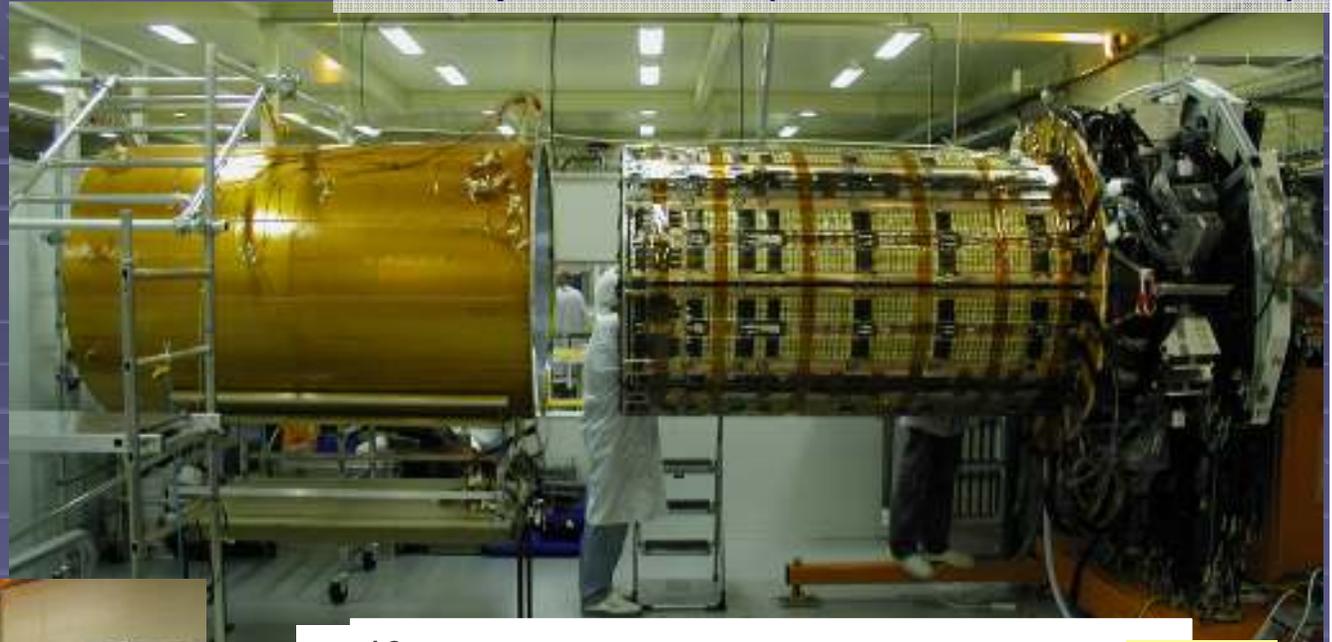
Barrel ID inside LAr cryostat
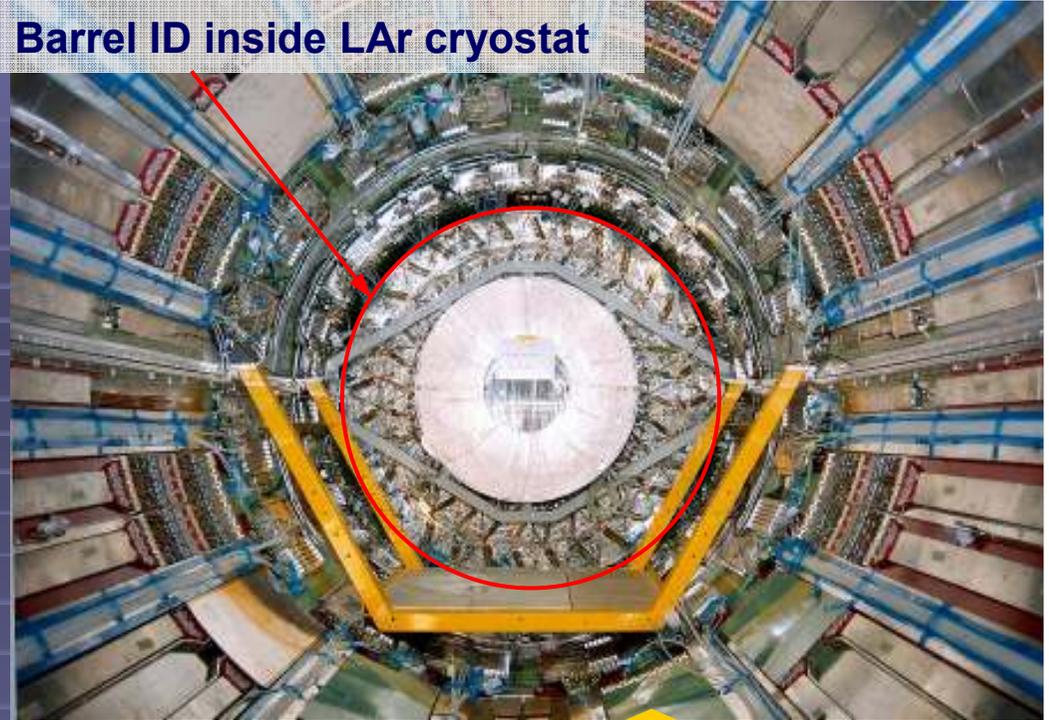
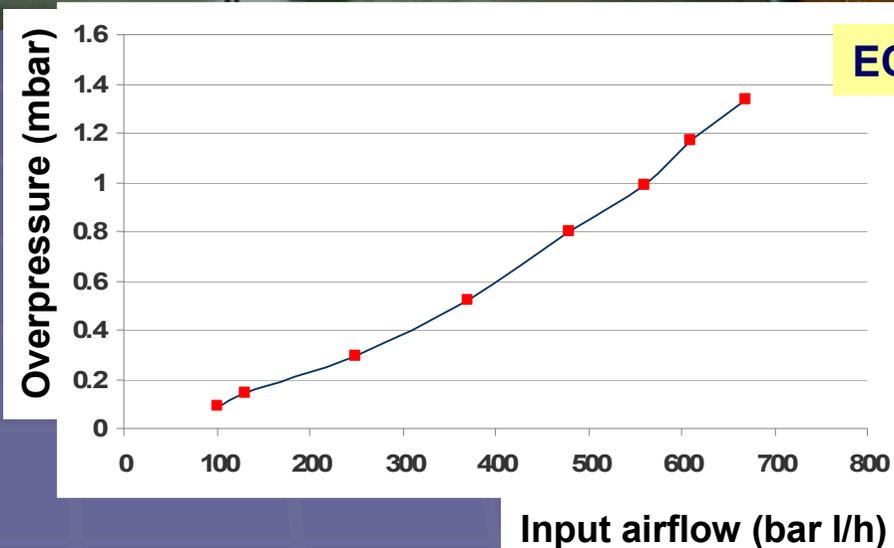- SCT+TRT barrel insertion into the cryostat (August 2006)

End-cap SCT status

- End-cap C in preparation for insertion into TRT end-cap C (on Sept 28th)
- Cosmics test with ID end-cap C will follow in November

End-cap A

EC-C

Overpressure (mbar) vs Input airflow (bar l/h)

Conclusions

- ATLAS SCT is progressing well toward integration and installation
- Repeated tests in various stages have demonstrated stability and good performance
- Dead channels: < 0.2 %
- Noise:
  - No change w.r.t. to measurements during module production / macro-assembly
  - No pick-up noise while TRT is read out
- Cosmics test allowed to get experience with the overall operational and running conditions (DAQ, DCS, monitoring, …)
- Barrel ID (SCT + TRT) successfully installed in ATLAS
- SCT end-caps are being prepared for integration with TRT