ATLAS
SCT End-cap

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This Talk

- ATLAS
- Inner Detector
- SCT
- End-cap
  - Silicon Modules
  - Disks
  - Support Structures & Thermal Enclosures
  - Assembling the End-caps
  - Integration at CERN
  - Status
- Tracking in the Inner Detector
- Status
- Conclusions

Focus is Engineering for the SCT End-cap – JINST 3 P05002 (2008)
ATLAS

Goals

- Understand the “mass mechanism”: Higgs, Technicolour ...
- Investigate physics beyond the Standard Model: SUSY, Extra Dimensions (Black Holes), Additional Symmetries, etc.
- Investigate the Standard Model at 14 TeV: QCD, etc.
- Improve measurements of the Standard Model parameters: $M_W$, $m_{\text{top}}$, B-sector, etc.

Measurements at LHC:

- $\sqrt{s} = 14$ TeV
- Design Lumi = $10^{34}$ cm$^{-2}$s$^{-1}$
\[ \eta = -\log(\tan\theta/2) \]

\[ \eta = 2.5 \leftrightarrow \theta = 9^\circ \]

Radius = 1150 mm   Length = 2700 mm

B = 2T Solenoid – non-uniform at ends

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ATLAS SCT End-cap  5
**TRT**

**Straw Tracker** – continuous tracking

**Transition Radiation** detected by Xe – distinguish electrons and pions

**Barrel:**
- Effectively 36 layers of straws
- Embedded in “mats” of polypropylene fibres

**End-cap:**
- Stacks of 16 15 µm polypropylene foils, each separated by 200 µm

Total num straws = 400,000
50 μm × 400 μm Pixels
- Bump-bonded chips
- 1744 Modules
- 82M channels

**Barrel:**
- 3 barrels at R = 5, 9, 12 cm

**End-cap:**
- 2 × 3 disks
SemiConductor Tracker (SCT)

**Barrel:**
- 4 cylinders
- 2112 Modules

**End-cap:**
- 2 × 9 disks
- 1976 Modules

**Typical Module:**
- 2 × 6 cm × 6 cm axial strips
- 2 × 6 cm × 6 cm stereo strips (40 mrad)
- Strips ~80 μm wide
- 6M channels
SCT End-cap
Requirements

- Provide 4 space-points within $|\eta| < 2.5$
- Modules placed on Disks to 70 (Inner) or 220 (Outer) $\mu$m
- Disks placed in Cylinder to 100 (x-y) and 1000 (z) $\mu$m
- Aligned to O(1) $\mu$m; stable to O(1) $\mu$m/hour
- Modules kept at $-7^\circ$C – each End-cap generates 10 kW heat
- End-cap to be kept dry; dew-point O($-30^\circ$C
- Withstand hadron fluences of $2\times10^{14}$ cm$^{-2}$ 1 MeV neutron equiv
- Minimise magnetic materials (Fe,Ni)
- Minimise potential activation (Ag)
- Minimise electrical noise pick-up from ext sources and emission
- Comply with fire-safety requirements
- Reduce mass (radiation & interaction lengths)
- Tolerate Solenoid quench
- 6 × 128 channels on each side
- Thermal pyrolytic graphite (TPG) spine provides rigidity & cooling path
- Cooling at hybrid and “second point” (opposite end)
- Build precision: $O(10)$ µm; 5 µm in most important params; measured to $O(2)$ µm
- Expected measurement precision: 17 µm × 580 µm – confirmed in Test Beam
- Modules are “key-stone” – phi-strips are radial
- 3 different radii: Outer, Middle, Inner (shorter)
- Disk 8 has “Short Middles”
- Total of 4 different types

- Stereo alternates orientation (same in Barrel): uφ, φv, uφ, φv, ...
- Achieved by rotating Modules by ±20 mrad
Disks

- Support Modules
- Support Module Services

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180 µm CFRP facesheets: 3 plies at 0, ±60°
8.3 mm Korex® honeycombe core
Korex: aramid fibres with phenolic resin; low moisture absorption

1st natural frequency: 22 Hz
Out of plane distortions expected to be less than 40 µm
Services on Front of Disk

- Outer Module
- Inner Module
- OptoHarness
- Tape aperture
Services on Rear of Disk

FSI Jewel

Tape PPF0

Opto PPF0

Cooling Circuit

Middle Module
On-Disk Cooling Circuits

- Modules generate up to 10 W → 10 kW per End-cap
- Must be kept at −7°C to reduce radiation damage to silicon
- Stable temperature essential to reduce thermal motion

- Use evaporative cooling (latent heat): C₃F₈

- Tried Al pipes – corrosion problems
- Use CuNi (70:30) 3.7 mm OD, 70 µm wall-thickness
  Good corrosion properties; easy to solder
- “Wiggly” design for stress relief
- Difficult to bend with bend radius of 4×diameter
- Watch holes in wall (from inclusions) → careful QA
- Modules bolted to Pin on Cooling Blocks
- Cooling Blocks made of Carbon-Carbon: 100 W/m/K in good direction
- PEEK insulation between detector and hybrid portion of Block
- Gold-plated to avoid grease absorption
Power Tapes

Supply
- LV digital & analogue power for detector
- HV for detector
- Power for Opto-electronics
- Control lines

- LV power (higher current): copper-clad aluminium twisted pair
- Rest: Cu traces on Polyimide tape (Aluminium too fragile)

- Due to complex design (modularity) 21 flavours of tape required
OptoHarnesses

Optical fibres for
- **Data** from Modules
- **Timing/Trigger/Control** info to Modules

250 µm fibres clad in 0.9 mm OD furcation tubing

Contained in 12-way ribbons for upto 6 Modules
Frequency Scanning Interferometry provides real-time alignment info (Interfere light from measured length with light from reference length; scanning frequency allows absolute determination of length)

Precision $O(1)$ $\mu$m in length

Installed only in SCT

Measures movement … due to thermal & humidity effects, gravitational sag, etc

Delicate emitter/receiver fibres in holders & reflectors on Disks
Took 2 years to assemble 9 UK Disks

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ATLAS SCT End-cap 23
Module Mounting

- By hand, with tooling (Barrel used robot)
- Thermal grease applied in controlled amount to Cooling Blocks
- Modules held to Block by washer & nut

Date

% Done

10 months

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ATLAS SCT End-cap 24
Testing

Extensive testing of
- Disks with Services
- Modules
- Modules on Disks

Metrology:
- Require Cooling Block Pins' position to 37, 60, 190 µm for Inner, Middle, Outer Modules (for sufficient overlap)
- Measure with CMM to 10 µm
- Global rotations, but Pin-Pin position in spec for all but one Pin
- 8000 “problematic” strips – 0.26% of total, cf spec of 1%
- Mean of 4 out 1536 strips per module
- 80% of these are “dead”; 20% noisy or unbonded
Finished Disks

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ATLAS SCT End-cap 27
CFRP composites similar design to Disks: Faceskins & Korex honeycomb
Cost 2/3 M$ and consumed several years
Support Cylinder

- 9 mm thick
- **Inserts** accurate to 250 µm to position Disks
Front & Rear Supports

Front: 9 mm thick

Rear: 25 mm thick
Front & Rear Supports rest on TRT rails
Supported kinematically by “Mechanisms”
FEA & Tests

37,000 element model

Effect of gravity & CTE

- CTE $1.4 \times 10^{-6} \, ^\circ\text{C} \ldots 30 \, ^\circ\text{C} \text{ over } 2 \, \text{m} \rightarrow 80 \, \mu\text{m} \quad \text{CME} = 1.0 \times 10^{-4}$
- 1st mode 6 Hz; 2nd mode 24 Hz
- Taking a conservative vibration spectrum, expect deviations of 3 (40) $\mu$m perpendicular (parallel) to axis
- Test sample panels to > 2.5 MPa
- Load structure to $\times 1.5$ working load; measure deflections of 0.74 and 0.87 mm, cf predictions of 0.63 mm

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Thermal Enclosures

- Contain SCT environmental gas ($\text{N}_2$) … external gas is $\text{CO}_2$
- Moisture barrier
- Thermal barrier … TRT is at 22.5 °C
- Prevent formation of condensation/ice on outside of SCT
- Faraday shield
Outer Thermal Enclosure

- **Sandwich**: aluminised polyimide / 8 mm foam / Cu-polyimide
- Use **Araldite 2011**
- Much **prototyping**
Inner Thermal Enclosure

- CFRP laminate cylinder / 5 mm foam / Cu-polyimide
- Includes gas channels with 0.3 mm holes for gas purge

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ATLAS SCT End-cap 36
Membranes

- Gas seals
- Complete Faraday shield

- Connect all Cu-Kapton foils with solder
Heater Pads

- Critical component: To ensure keep outside above dew-point and in case moist air gets into Inner Detector, cover outside with heater pads
- 8 µm thick Cu tracks sandwiched between polyimide
- 150 W/m² or 300 W/m²
- Double tracks for redundancy
- Integral thermocouples
- Switch power (rise/fall time O(1) ms)
Above ignores Module heating / cooling ~ $O(10)$ kW per End-cap
Net inward flux ~ 200 W – so small perturbation for Module cooling
Assembling the End-caps

Took place in
- Liverpool
- Nikhef

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ATLAS SCT End-cap 40
Disk Insertion

Disk “grabbed” at inner radius
- Located with **microscopes** longitudinally to 200 \( \mu \text{m} \)
- Located with **telescopes** transversely to \(~100 \mu \text{m}\)
- **Cylinder pre-loaded** to compensate for subsequent additions of Disks & Services
- Each Disk held by **12 pins** around circumference
Services

- Power Tapes
- Purge gas return pipes
- Module Cooling delivery capillaries
- OTE support rail
- Module Cooling return pipe
- Disk Fixings

+ Optical Fibres

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ATLAS SCT End-cap 43
Significant heat load
Expect temp rise of 50°C at worst
Wrap in 150 μm Al foil, including dedicated (spare) cooling pipes
Compress with Cu-Be spring
Transportation from Liverpool

- Temperature & humidity controlled, air-sprung lorry
- Serious test run with dummy load
- Carefully monitored
- Insured for 9 MSF

Largest internal acceleration \(~1.2\) g
Integration at CERN

- Lots of checks and re-laying of Services at CERN
- Add Rear Support and mount on cantilever beam
Add Thermal Enclosures
- TRT on rails and slid over the SCT on cantilever beam
- Add Front Support
- Align on TRT Rails
- Seal Thermal Enclosure & dry out
- Electrical tests
Insert into ATLAS

- Use **Contact Sensor** to work out when in place (up to Barrel)
- Both End-caps make contact 5 mm before nominal – one End-cap 3 mm **too long**
Services & Patch Panels (PPF1)

- **Service lengths** carefully calculated to avoid deficit/excess
- **Cable trays** added
- **Patch panels** at end of Ecal Cryostat

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ATLAS SCT End-cap 50
Cooling System

- $\text{C}_3\text{F}_8$ liquid enters SCT at room temp
- Leaves as vapour/liquid at around $-20 \, ^\circ\text{C}$
- Heat Exchanger to heat/cooling entering/leaving $\text{C}_3\text{F}_8$
- Heat Exchangers occupy space foreseen for cancelled TRT C-wheels
- Must boil off excess fluid, else will cause condensation on un-insulated pipes
- Heaters have been cause of many problems
Grounding & Shielding

- Can be a make-or-break factor
- Careful consideration:
  - Module, Disk, End-cap, Services, Cable Trays, ID, ATLAS
- Solid connections ($< 0.2 \, \Omega$) & insulation ($> 1 \, \text{M}\Omega$)
- Avoid apertures $> 1 \, \text{cm} \times 10 \, \text{cm}$ where possible
- Use Alochrome 1200 & Fingerstock
- Make measurements before/after insertion into TRT & ATLAS
Mass

- **Target** for error is 1% – more critical at lower radii (tracking volume)
- Very careful bottom-up estimates of component masses
- **Disk** (without Modules) correct to 1.4%
- Mass supported by Front & Rear Supports is 178 kg, cf initial design estimate of 168 kg
- Difference between two **End-caps** (some +’s and –‘s) is < 1 kg
- Attempt to **weigh** SCT (inside TRT) was inconclusive

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td>24</td>
</tr>
<tr>
<td>Disks</td>
<td>33</td>
</tr>
<tr>
<td>Support Cylinder, Services &amp; OTE</td>
<td>57</td>
</tr>
<tr>
<td>Other Support Structures</td>
<td>23</td>
</tr>
<tr>
<td>Rest of Services</td>
<td>88</td>
</tr>
<tr>
<td>PPF1 Patch Panels</td>
<td>35</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>259</strong></td>
</tr>
</tbody>
</table>
Radiation Lengths

Disk

Cylinder & Services

Other Services etc

Total (except PPF1)

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ATLAS SCT End-cap 54
RAL Contributions

Barrel:
- 600 Modules
- On-Cylinder Cooling Circuits
- Services → Cylinders
- Thermal Enclosure design & manufacture
- Mass

End-cap:
- On-Disk Cooling Circuits
- Services → 9 Disks
- Support Structures design & procurement
- Thermal Enclosure design
- UK Transportation & Insurance
- Off-Disk Cooling Circuits, Services routing & Patch Panels
- Mass
Tracking Performance
**Track Parameter Resolutions**

**Momentum resolution**

\[ p_T \times \sigma(1/p_T) \]

**Impact parameter resolution**

\[ \sigma(d_0) \]

**Barrel:**

\[ \sigma(1/p_T) = 0.34 \times (1\oplus44 \text{ GeV}/p_T) \text{ TeV}^{-1} \]

\[ \sigma(d_0) = 10 \times (1\oplus14 \text{ GeV}/p_T) \mu\text{m} \]

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ATLAS SCT End-cap 57
Reconstruction Efficiency

Tracks in b-jet from ttbar events, as function of distance from core of jet

Tracks in Min Bias events
Vertex Reconstruction

Z vertex resolution
40 \mu m (ttbar), 70 \mu m (Higgs)

Radial resolution for K_s decays

B-tagging in ttbar events
Electrons & Conversion Photons

J/ψ mass resolution in Barrel (left) & End-cap (right)

Pion rejection in TRT

Conversion identification

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ATLAS SCT End-cap 60
Status
ATLAS was ready for Collisions on Sunday, but ... 😞
I am not aware of any serious problems with any of subdetectors

Inner Detector

TRT
- Some dead HV cards

Pixels
- 11 (4) dead (problematic) modules
- 36 modules unusable on Disks due to problems with 3 cooling loops
- Currently, can operate 95% of Pixels – hope to recover even more

SCT
- Leak rates of N$_2$ exceed spec, but are tolerable: dry-out achieved, so operate with lower overpressure (Barrel SCT has large leak rate)
- One Module Cooling Circuit on Disk 9 has large leak of C$_3$F$_8$ and is inoperable – loss of 13 Modules ... not terrible
- One Module Cooling Circuit on Disk 1 has Heater problem and is currently inoperable – loss of 23 Modules ... not great
## SCT Summary

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>End-cap A</th>
<th>End-cap C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Num Modules</td>
<td>2112</td>
<td>988</td>
<td>988</td>
</tr>
<tr>
<td>Modules not functional</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Dead Strips (%)</td>
<td>0</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>Modules not cooled (2008)</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Chips lost</td>
<td>13</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Functional channels (%)</td>
<td>99.6</td>
<td>99.7</td>
<td>96.0</td>
</tr>
</tbody>
</table>
Inner Detector Commissioning

Huge amount of testing, more recently with:

- **Cosmics** – very useful for Alignment
- **Beam “splash”** – very useful for timing:
  “Unique opportunity to time whole the detector at once in one event! This saves may be months of work.”
- **Beam-gas** – nice for Software Reconstruction, but not many events
Cosmics

SCT & Pix Barrels

SCT End-cap

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Single Beam

Beam-gas in SCT

Interaction in Beam-pipe

Beam-gas in TRT

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Conclusions

Two ATLAS SCT End-caps have been constructed, meeting almost all of the specs.

The project has taken ~15 years, with ~6 years required for Construction and Assembly.

~200 people have worked on the End-caps.

The insured value of the hardware was 9 MCHF for each End-cap.

Apart from one two Cooling Circuit problems, the End-caps are close to fully functional.

The ATLAS Inner Detector is ready to receive LHC collisions and the Software is in place to reconstruct the First Data.
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