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Chapter 3

The SCT and the ID evaporative cooling system

Nikhef participated extensively in the design and construction of two ATLAS sub-detectors. For the muon spectrometer all BOL chambers, the muon RODS and parts of the DCS were designed or constructed at Nikhef and in Nijmegen. For the ID, 100 inner SCT end-cap modules were produced and the entire end-cap A was assembled in Amsterdam. In this chapter we go into more details on the SCT and its cooling system which is part of the ID evaporative cooling system.

3.1 The SCT end-cap in detail

We discuss the SCT bottom-up: we will first explain how a silicon detector works. Although the modules in the pixel detector have different schematics, they are based on the same principle. We then go into more details on the components of one SCT end-cap module; the barrel and end-caps differ mostly in the size and orientation of their modules. Finally we elaborate on the layout of the modules on an end-cap disk and the assembling of nine disks into one end-cap. For a more detailed description of the design and functioning of the SCT we refer the reader to [70–73].

3.1.1 Basics of silicon strip detectors

Silicon atoms have four valence electrons. In a lattice, these electrons can become conductive electrons if their energies are raised, be it by thermal excitation or by absorption of energy. This energy raise must exceed a certain minimum: the amount needed to jump the energy band gap between the valence and the conductive band. With one conducting electron, the material also gains another conducting ‘hole’: the deficiency left behind by the electron can be filled up by its neighbors. These shifting electrons can be seen as a positive hole moving in the other direction.

Silicon can be doped with impurities to alter its properties. By adding atoms with five valence electrons the result is n-type silicon: the fifth electron from the impurity can easily jump in the conducting band of the silicon. Impurities with three valence electrons result in p-type material. There the valence electrons of the silicon jump to fill the fourth valence band of the impurity, leaving behind a conducting hole. When a p- and n-type material have a contact surface, charges start moving: the conducting electrons from the n-type material move to the...
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Figure 3.1: Partial cross section of a silicon strip-sensor. The applied potential depletes the bulk region of its ‘free carriers’. The only current measured is the leakage current, caused by electrons freed by thermal energy. Any charged particle passing by releases electrons from the silicon atoms, creating a current in one of the extra-highly doped $p^+$-strips. The $n$-type material inverses over time to $p$-type due to irradiation.

$p$-type side, while holes go in the opposite direction. The resulting charge build-up stops any more charge from moving, creating a depletion zone.

Figure 3.1 shows the schematic cross section of one SCT silicon sensor. The bulk region is $n$-type silicon, which is implanted with extra-highly doped $p$-type strips, so-called $p^+$-type. The inter-strip distance is \( \sim 80\mu m \), while the sensor thickness is \( \sim 300\mu m \). The depletion zone between the $n$- and $p$-type material is increased to cover the whole silicon bulk by applying a positive voltage to the aluminum backplane, the bias voltage $V_{bias}$. To provide good contact, an extra doped $n^+$-type material is implanted between the two.

Once the entire silicon bulk region is depleted, all conducting electrons are taken out of the silicon. Only a very minimal leakage current due to thermal excitations runs through the material. A charged particle traversing the SCT can now be accurately detected: it creates electrons and holes along its path, which drift under the influence of the $V_{bias}$ creating a current in one of the strips. Under influence of the magnetic field present in the ID these drifts are deflected, giving rise to the so-called Lorentz angle.

The current running through the $p^+$-strips does not directly go to the read-out chips. First, the charge builds up inside the strip due to a resistor connected to its far end, that is the side not nearest to the hybrid, see Fig. 3.2. This charge build-up induces another charge in the aluminum strips running parallel to the $p^+$-strips, separated by a SiO$_2$ insulator, see Fig. 3.1. The benefit of this layout is less noise.

**Radiation damage**

The high particle flux through the SCT during LHC operation results in radiation damage to the sensors. Two types of radiation can be distinguished: the ionizing radiation caused by all charged particles, and non-ionizing radiation, caused by all particles, but mainly by hadrons. The effects of this last type are dislocation of atoms and nuclear reactions, introducing impurities and in fact altering the doping of the material. The impurities form traps for the charge carriers, increasing the charge collection time and changing the signal efficiency and timing. The impurities also create intermediate levels in the band gap, thereby increasing the
3.1. The SCT end-cap in detail

Figure 3.2: Components of a SCT end-cap module. See Section 3.1.2 for more details on all components.

leakage current. The ionizing radiation creates trapped holes in the SiO$_2$. The trapped holes are known as surface and oxide damage. This damage causes charge build-ups, increasing the noise and lowering the signal height.

The dislocations in the material cause it to behave more and more $p$-type like. This has great consequences for the depletion voltage. The $n$-type will first become ‘less $n$-doped’, decreasing the depletion voltage. After a certain time this process is however so far that the material really is $p$-type. The junction moves from the $p^+$-type strips to the $n^+$-type, see Fig. 3.1, and an increasing depletion voltage must again be applied to keep the silicon bulk entirely depleted. At the start-up in 2009 the $V_{bias}$ will be 150 V; after ten years, the expected life-time of the SCT, it is expected to have increased up to 450 V.

An efficient cooling is of great importance here. The mentioned dislocations can thermally vibrate back into position, a process called ‘beneficial annealing’. This is however overshadowed by the ‘reverse annealing’: a process less well understood, but probably due to the diffusion of the dislocations or impurities and the creation of acceptors ($p$-type material). This causes the effective doping to increase, be it $n$- or $p$-type. Once a $p$-type material, the reverse annealing speeds up the damage. The annealing can be tempered with decreasing temperature and the SCT will therefore be kept at $-7^\circ$C; any maintenance requiring shutting down the cooling is to be kept to a minimum to prevent more damage.
3.1.2 One SCT end-cap module

Each SCT end-cap consists of nine disks, mounted with modules in an inner, middle and/or outer ring. In Fig. 3.3 we see photographs taken of an end-cap disk with all three layers populated. The three layers have modules of different sizes and shapes, yet all modules are built in a similar way. One hundred inner modules were produced at Nikhef, the rest at different locations. Figure 3.2 shows the components of one end-cap module. Each module has two or four sensors glued back-to-back onto a spine at a 40-mrad stereo angle to provide a two-dimensional position measurement. The modules in the inner ring on a disk have one sensor per side, the modules in the two other rings have two sensors per side, which are bonded together.

There are 768 strips per sensor read out by 6 ABCD chips. In total there are thus twelve ABCD chips per module. For the SCT end-caps the inter-strip distance, also called pitch, varies from 57 to 94 µm. For the barrel there is but one type with a pitch of 80 µm. The ABCD chips are mounted on the copper/Kapton hybrid and each is wire-bonded to 128 strips, also called channels, via the glass fan-ins. A chip converts the strip signals into binary output signal and stores the hits for 132 bunch crossings in a pipeline memory, while awaiting a Level 1 trigger signal, see Section 2.6.1. The chips also contain a charge injection circuitry which can be used for calibration. In contrast to the time-over-threshold signal in the pixel detector, the SCT strips in the end thus result in a hit-or-no-hit signal. The resolution of such a signal is $\text{pitch} / \sqrt{12} \sim 20 \text{ µm}$, if only one strip is hit. When more strips are hit the resolution is smaller, see also Section 3.2.3.

On the hybrid two more chips control the optical link between the module and the off-
detector system. Each module has one \textit{p-i-n} diode\textsuperscript{1}) to receive the Timing, Trigger and Commands (TTC) signals and two VCSELs returning the data from both sides of the modules to the Readout Drivers (RODs). Redundancy links ensure that the TTC can be sent via a neighboring module, and that the data from both sides can be sent through one VCSEL\textsuperscript{2}).

The spine with its side-bars not only gives structure to the module, it also electrically connects the sensor backplanes and the bias voltage, see Section 3.1.1, and serves as thermal conductor to transport the heat generated by the bias current in the sensors to the cooling blocks. The cooling blocks are at the same time the mounting blocks; the fixation of the location washers to these blocks is with a precision that is better than 20 \(\mu\)m in the perpendicular direction of the strips, see [74]. Figure 3.4 depicts the fixation of a module and the heat flows from the module to the cooling circuit.

![Cross section along the spine of an outer module at the hybrid end, with the fixation of the location washer to the cooling block (see also Fig. 3.2). The arrows indicate the heat flows from three ABCD chips and from the sensor. The flow along the cooling block to the cooling circuit is also depicted. The figure is taken from [75].](image)

**3.1.3 End-cap disk and cylinder design**

Figure 3.3 shows photographs of the front (left) and back (right) side of a fully populated disk. Per quadrant the disk has 13 outer, 10 middle and 10 inner modules. One disk is 1.2 cm thick and has an outer radius of 56.7 cm, an inner radius of 26.7 cm and consists of a carbon fiber sandwich with a Korex\textsuperscript{®} honeycomb filling. Various mounting points and holes have been machined on the disk, to facilitate the routing of the cooling circuits, fibers and power

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\textsuperscript{1)}\textit{p}-doped-intrinsic-\textit{n}-doped semiconductor diode.

\textsuperscript{2)}Vertical Cavity Surface Emitting Laser.
tapes over the disk surface. The front and back side are used, to ensure a full coverage of the (x,y)-plane by the modules\textsuperscript{3} and at the same time have space for their associated services.

In Fig. 3.5 a photograph of a part of one disk is shown illustrating the service cables and pipes. The picture was taken before populating the disk with modules; the functioning of the modules was temporarily simulated with dummy hybrids. All the services reach the disk edge where they are routed along the cylindrical support structure, also called ‘the cylinder’. The service components on the disk will now be summarized.

- **The power tapes**, also called ‘wiggly’ tapes, supply the control signal, the high voltage and the low voltage power to each module. Each wiggly tape can supply power for up to three modules.

- **The opto-harnesses** route all the optical fibers to and from the modules. Two fibers per module are used for the transmission of data and one fiber per module is used to send the timing, trigger and control signals. These three lines are connected to each module by an **opto-plugin**, which converts the optical signals into electrical signals. Each opto-harness can be connected to up to six modules.

\textsuperscript{3}In Figure 3.3 we see how the middle modules cover the radial gap where the front-end electronics and services from the outer and inner modules are located.
• DCS sensors, where DCS stands for Detector Control System, are for measuring the temperature and humidity. Up to 30 thermistors are located on one disk and more are attached at various locations throughout the SCT volume.

• Grounding foils are located on the front and back sides of all disks to ensure proper grounding connections to all the applied services. All disk elements are linked up to the support structure (see further down), which is connected to common ATLAS ground.

• The FSI jewels, where FSI stands for Frequency Scanning Interferometry, are present throughout the SCT. A ‘jewel’ is the reflecting element in a grid-line interferometer, with which an accurate measurement of a distance can be made. Each section (barrel or end-cap) is equipped with an FSI grid and is thus monitored for any change in shape.

• The cooling circuits are highly modular allowing one circuit per disk quadrant. The pipes have a Cu-Ni composition and consist of consecutive S-bends to alleviate the stress caused by thermal expansion. Each circuit is divided in up to three different branches, where the mass flow through each branch is regulated by a capillary located on the outside of the end-cap cylinder.\(^4\) The modules in one quadrant of a ring are all cooled by the same branch: one main circuit per quadrant feeds up to three circuits for the modules present on the inner, middle and outer ring.

In Figure 3.6 (left) the schematics of the cooling circuit for the middle modules is given. The right figure shows a photograph of the realization on a disk. As it is the back side, there is but one circuit; the inner and outer modules are mounted on the other side. On a photograph in Fig. 3.8 the capillaries can be seen.

• The cooling blocks - For the outer and middle rings both module ends are cooled, whereas for the inner ring, where the modules consist of only two sensors and are thus

\(^4\)To be exact, the length of the capillary determines the mass flow, see also Section 3.4.2.
shorter, only one cooling contact is implemented. The carbon-carbon\textsuperscript{5)} cooling blocks are soldered to the pipes and mounted on the disk. The blocks have an aluminum threaded pin over which the module is placed and secured, with a controlled layer of thermal grease (20 \(\mu\)m thick) in between. The largest heat production is in the chips on the hybrid, approximately 0.8 W cm\(^{-2}\) per chip. For the blocks located on the hybrid side of the module a 1 mm split therefore separates the block into two parts: a larger part for cooling the hybrid, and a smaller one making contact with the spine for the removal of heat from the sensor. See also Fig. 3.4.

In Table 3.1 the population of all end-cap disks with either inner, middle or outer modules is listed; both end-caps are identical. Disk 8 needs only a short middle, since having a full middle module would not have any optimizing effect on the \(\eta\) coverage. The outer and inner modules face the interaction point, except for disk 9, which was rotated and was mounted with its outer modules facing away from the interaction point to maximize the \(\eta\) coverage.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
Disk & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & Total \\
\hline
\midrule
\midrule
\(|z|\) (mm) & 854 & 934 & 1092 & 1300 & 1400 & 1771 & 2115 & 2505 & 2720 & \\
\hline
Outers & 52 & 52 & 52 & 52 & 52 & 52 & 52 & 52 & 52 & 468 \\
Middles & 40 & 40 & 40 & 40 & 40 & 40 & 40 & - & - & 280 \\
Inners & - & 40 & 40 & 40 & 40 & 40 & 40 & - & - & 200 \\
\hline
Total & 92 & 132 & 132 & 132 & 132 & 132 & 92 & 92 & 52 & 988 \\
\hline
\end{tabular}
\caption{The total population of modules on each disk; each quadrant contains exactly one-fourth of the total. The nominal \(|z|\) position of the center of each SCT end-cap disk is also listed.}
\end{table}

The nine disks are accurately mounted inside a cylindrical support structure, which itself is supported by a front and rear 'wing', see Fig. 3.7. The front wing is closest to the interaction point. These wings are used to place the end-cap on the TRT rails, allowing the SCT and TRT to share a common axis. Apertures are available on the cylinder to allow connections for the fibers and cables to be made at the patch panels at the disk edge. From these so-called patch panel forward 0 (PPF0s) the disk services are routed along the surface of the cylinder to the rear side, where they are again connected to the service lines connecting the end-cap with the systems in the service caverns, see Fig. 2.3. The entire cylinder is grounded with a copper-polyimide ground sheet that covers the outside of the cylinder surface, see Fig. 3.8.

The on-cylinder service lines are fiber ribbons carrying the optical signals, power tapes and the cooling circuits. At the PPF0s the wiggly tapes from the disks connect to Low Mass Tapes (LMTs), 21 mm wide polyimide power tapes with copper traces. These LMTs have been designed very thin to keep the amount of material as low as possible, which however also means that they have a significant resistance and produce considerable heat. LMTs connecting to modules in the same \(\phi\)-segment of the disks are occupying the same surface position on the

\textsuperscript{5)} A form of graphite with high thermal conductivity in one plane (typically \(\sim 100\ W/m-K\)) and poorer conductivity out of the plane (\(\sim 50\ W/m-K\)).
3.1. The SCT end-cap in detail

Figure 3.7: The cylinder support structure. The two wings are used to mount the end-cap on the rails also used by the TRT.

Figure 3.8: Photograph of a part of the end-cap surface with the on-cylinder services. LMT stacks are visible, cooled by two cooling circuits on either side. More cooling circuits and capillaries are present, which connect to the on-disk services through the aperture.
cylinder and are stacked together. When powered, the temperature in the center of a stack of LMTs can rise to 50°C, leading to a significant heat load on the detector.

In order to transport this heat away from the detector, dedicated cooling pipes are placed along side the LMTs, with foils wrapped around the LMTs and the cooling pipes to create sufficient thermal contact between the two components. These pipes are fed from the cooling circuits of disk 7, 8 and 9, which have additional cooling capacity as they contain less module rings. Each set of three LMT stacks has a pipe on either side: one from disk 9 and one from disk 7 or 8. In case of failure of the cooling circuit on one of these disks, the LMTs are still cooled by the cooling circuit from another disk, preventing the loss of a full azimuthal slice of modules.

Separate capillaries carry the coolant to each circuit inlet. The exhausts from the circuits in one disk quadrant merge at the disk edge, such that all inner, middle and outer modules in one disk quadrant rely on a single cooling line outlet. This means that one leaking circuit can cause an entire disk quadrant to be affected. For end-cap C this is unfortunately the case on disk 9: circuit 186 is leaking and the quadrant with positive y and negative x cannot be operated. (Luckily disk 9 only carries outer modules.) Thirteen outer modules are thus non-functional.

3.2 SCT performance

The Inner Detector is designed to measure the transverse momentum of charged particles with precision better than 30% for tracks with $p_T$ up to 500 GeV, requiring a resolution of $\sim 20 \, \mu m$ in the bending plane [70]. For the track reconstruction the hit efficiency is to be $> 99\%$, at least 99% of the channels are to be operational and the noise occupancy per strip in the SCT is required to be less than $5 \times 10^{-4}$. To satisfy this last requirement, the threshold in the ABCD chip above which the signal is interpreted as a hit, needs to be at least 3.3 times higher than the average noise on the strip. With a typical value of the input noise on the silicon strips of $\sim 1500$ electrons, the threshold setting is thus to be $> 0.8$ fC (4950 electrons). The hit efficiency requirement dictates the threshold to be $< 1.3$ fC. For comparison: a charged particle passing through the $\sim 300 \, \mu m$ thick silicon sensor creates approximately $2.5 \times 10^4$ electron-hole pairs, equivalent to a charge deposition of about 4 fC within the silicon.

The performance of the SCT has been monitored all along its production line. First, the individual modules were tested before being sent to the assembly site, i.e. Nikhef for end-cap A. Then during the assembly four main stages of tests can be considered: the end-cap disk (or barrel-layer) assembly, the end-cap cylinder (or entire barrel) assembly, the surface reception tests in building SR1 at CERN and finally the integration in the ATLAS detector in the cavern.

The testing consists of digital and analogue tests: the digital tests check that the redundancy links between modules and the chips bypass links are functional. It also includes a test of the pipeline circuitry. The analogue tests are: the Strobe Delay test, for the correct setting for the delay between the charge injection time and readout time needed for proper calibration, the 3-point-gain and the Response Curve test, see further, and the Trim Range Scan. The latter determines the optimum ‘trim setting’ for each channel, which compensates for the threshold offset each strip can have with respect to the one signal threshold that is set per ABCD chip. In [73] all tests and test results are discussed in detail, here we summarize the results of the tests performed in 2008 after the SCT was integrated in the ATLAS detector in the cavern.

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6) Number of hits on a strip as a result of noise divided by the number of times the signal is read out.
3.2. SCT performance

3.2.1 Noise and dead channels

An important test is the 3-point-gain with which the input noise, the channel gain and the channel efficiency can be determined.\(^7\) As mentioned in Section 3.1.2 the ABCD chips on the modules are equipped with a charge injection circuitry which can be used for calibration. For this calibration pulse a step of 10 mV corresponds to an input charge of 1 fC. These pulses can be used to measure the input noise in the so-called gain test: on each channel increasing values of charge are injected and the number of hits for a given number of triggers is measured over a range of thresholds.

In Fig. 3.9 (left) we see a typical result for one channel of such a scan. A scan of a (hypothetical) perfect channel with no noise would result in a step function: the hit probability drops from 1.0 to 0.0 when the threshold is varied from low to high values (keeping the injected charge fixed). Due to noise on the channel this step function is smeared and the scan produces an S-curve. The threshold at which 50% of the triggers are measured as hits corresponds to the average channel output for that charge, the width of the smeared step function characterises the output noise.

Repeating this scan with pulses with different input charges results in the ‘response curve’, the 50%-response-threshold vs the input charge. The 3-point-gain is simply a response curve of three points. The slope of a linear fit to this is the gain, and the input noise is determined by the output noise at 1 fC divided by the gain. The noise is measured in units of ENC: the Equivalent Noise Charge which is defined as the amount of electrons needed to be delivered to the input to produce the noise. In Table 3.2 an overview of the input noise for the different module groups at the different test stages for end-cap A is given. All values are comparable at each stage of testing. For end-cap C and the barrel the results were similar, see also [76].

With the noise temperature coefficients measured to be $\sim 5$ ENC/$^\circ$C for the outer and middle modules and $\sim 4$ ENC/$^\circ$C for the inner and short-middle modules, the final results in the table are almost within specification: the maximum allowed noise during the initial LHC running is set at 1500 ENC with sensor temperatures $\sim -7^\circ$C. This upper limit is to ensure

\(^7\)The Response Curve test does the same as the 3-point-gain test, with a larger number of injected charges for more accuracy.
Chapter 3. The SCT and the ID evaporative cooling system

that even after radiation damage the noise occupancy does not exceed $5 \times 10^{-4}$. In Fig. 3.9 (right) the noise occupancy is depicted, as measured in the cavern in December 2008 at the end of the cosmic muon run. It is clearly below the specification of $5 \times 10^{-4}$. The results in Table 3.2 are only a few percent too high and should be no reason for concern.

With the noise test defective channels (noisy or dead) can be identified, as well as bonding defects (noise too high or low). After comparing the results from the different test stages it can be concluded that there is no significant increase in the number of bad channels. The fraction of defective channels is 0.2% in the SCT barrel and 0.3% in the SCT end-caps, see [73, 77], safely below the specification of 1%.

<table>
<thead>
<tr>
<th>Test Stage</th>
<th>Outers</th>
<th>Middles</th>
<th>Short Middles</th>
<th>Inners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk assembly</td>
<td>1606 ± 51</td>
<td>1527 ± 44</td>
<td>911 ± 25</td>
<td>1066 ± 31</td>
</tr>
<tr>
<td>Cylinder assembly</td>
<td>1586 ± 52</td>
<td>1519 ± 45</td>
<td>908 ± 25</td>
<td>1057 ± 33</td>
</tr>
<tr>
<td>SR1 reception</td>
<td>1584 ± 77</td>
<td>1534 ± 62</td>
<td>895 ± 38</td>
<td>1055 ± 44</td>
</tr>
<tr>
<td>Cavern integration</td>
<td>1608 ± 83</td>
<td>1559 ± 51</td>
<td>911 ± 26</td>
<td>1072 ± 32</td>
</tr>
</tbody>
</table>

Table 3.2: The mean input noise and spreads (in ENC) of the four module groups for end-cap A during the four main stages of testing. All values have been normalized to a module temperature of $0^\circ C$.

### 3.2.2 Hit Efficiency

The hit efficiency is, in simple words, the fraction of hits recorded in a region of a sensor where a charged particle traversed and a hit can be expected. The hit prediction is calculated in the following way: for a reconstructed track in an event the hit (if there is any) located on the SCT barrel or disk under investigation, i.e. the $i^{\text{th}}$ layer, is removed. A track refit is then performed excluding this hit and from the parameters of the new track an extrapolation to the $i^{\text{th}}$ layer results in the predicted position of a hit on a module.

In order for a hit to be entered into the numerator of the efficiency calculation, it must be found within a certain road width around the predicted hit position. The results presented in this section are obtained with the cosmic run data of fall 2008; as most tracks correspond to low momentum cosmic muons the Multiple Coulomb Scatterings (MCS) of the charged particle traversing the detector can cause significant kinks in its trajectory. (This is not the case for the LHC in general.) In order to neglect the effect of these MCS a value of 2 mm was chosen for the road width.

The result obtained this way for the unbiased hit efficiency is depicted in Fig. 3.10. The horizontal axis is defined as follows: 0.0 is the module side facing the interaction point on the innermost layer of the barrel, or disk of the end-cap; 0.5 is the other side of the same module. 1.0 is again the inner side of the next layer/disk, etc... For this study $5 \times 10^4$ cosmic muon tracks were used, taken end 2008. For the barrel plot the selection cuts reduce the initial $6 \times 10^5$ track/silicon intersections by a factor of 0.47. The left figure thus contains around $3 \times 10^4$ cosmic muons.

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8) Cosmic muons are muons created in the atmosphere by cosmic radiation and can travel all the way down to the ATLAS detector. End 2008 these muons were analyzed for commissioning and calibration purposes.

9) Unbiased here means that the hit was excluded from the track fitting. The same analysis can be done without excluding the hit on the $i^{\text{th}}$ layer, biasing the results.

10) Of which the synchronization of the SCT and TRT read-out timing and the requirement of a $< 40^\circ$ incident angle result in the biggest losses.
entries per layer point. There are however only about $1.7 \cdot 10^4$ entries for the entire end-cap A, as no end-cap triggers were operational yet in the cosmic run of 2008. All tracks are triggered by barrel trigger chambers and the number of entries drops rapidly with the disk number. The results for disk 9 are with approximately 50 entries. Almost all layer hit efficiencies are measured to be within specifications, i.e. greater than 99%. For this data set a preliminary alignment was used, i.e. the barrel was aligned down to the module level, while the end-caps were aligned as a whole to the barrel.

![Figure 3.10: Hit efficiency for each layer of the SCT barrel (left) and each disk of end-cap A (right) from cosmic muon tracks, using a preliminary alignment. Each layer/disk has two sides.](image)

### 3.2.3 Alignment and resolution

As the detected cosmic muons originate in the upper atmosphere, the vertical orientation of the end-cap disks makes a direct alignment using these muons more difficult. Therefore, the end-caps are aligned to the barrel. Figure 3.11 depicts the distribution of the hit residuals in the barrel, defined as the measured hit position minus the expected hit position from the track extrapolation, for the nominal and the preliminary aligned geometry. Compared to the results for a perfect geometry, which are determined from MC results and are shown in the same figure, we can conclude that the alignment is already on a good track.

The SCT detector resolution can be extracted from the width of the SCT hit residual distribution of a given module side after subtracting the track prediction and alignment corrections uncertainties, see [77]. The track uncertainty is however poorly estimated for the case of low momentum particles. Figure 3.12 shows the width of the SCT unbiased residual distribution, for the outer side of the modules in barrel layer 2, as a function of the unbiased track $\chi^2$; this is the track $\chi^2$ minus the contribution of the hit under evaluation. These modules were chosen to maximize statistics and minimize track errors. The figure depicts the distribution obtained for simulated and for real data. The benefit of showing it as a function of the track $\chi^2$ is that when the $\chi^2$ tends to zero the contribution of low momentum tracks, and thus from track uncertainty, is negligible.

A width of $24 \pm 1 \mu m$ is obtained for real data for tracks with an unbiased $\chi^2/\text{ndof}$ of less than 1. This is slightly higher than the $20 \pm 2 \mu m$ obtained for the simulated data, most likely

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11) For the alignment the global $\chi^2$ approach was used, see [78].

12) The total track $\chi^2$ is simply the sum of $\Sigma \left( \frac{\text{residual}}{\sigma} \right)^2$, where the sum runs over all hits $i$. 
caused by the alignment uncertainties which have not been considered. A width of 20 $\mu$m is however lower than the theoretical value of 23 $\mu$m belonging to barrel module strips with a pitch of 80 $\mu$m. These small widths measured are due to the large number of double hits in both the real and simulated data. Approximately one in three of the hits is in fact a double hit, meaning that two neighboring strips are hit. From this one learns that the particle must have passed in between the two, reducing the uncertainty on its exact trajectory. This effectively reduces the resolution of the one-strip hit measurement.

![Figure 3.11: Residual distribution in x (the projection onto the local x coordinate, which is the precision coordinate), integrated over all hits-on-tracks in the SCT barrel for nominal and preliminary aligned geometry. Tracks are required to pass the pixel inner layer.](image1)

![Figure 3.12: Width of the SCT unbiased residuals (taken from [77]) as a function of the unbiased track $\chi^2$ per number of degrees of freedom, for real and simulated cosmic muon data.](image2)
3.3 The ID evaporative cooling system

For both the pixel and the SCT detector a special cooling system has been designed. Being the closest to the interaction point, these two detectors have the highest particle flux, resulting in radiation damage with a continuous degradation of the bulk silicon material and an increase in the device leakage current. To slow down the reverse annealing of the silicon modules, as explained in Section 3.1.1, the temperature must be kept as low as reasonably possible.

The cooling system installed must not only lower the temperature, it must at the same time remove a large heat load. Each of the modules in the detectors is read out through several front-end (FE) chips. With the heat produced at each FE chip \(0.8 \text{ W cm}^{-2}\) all modules together produce a considerable amount of heat: the SCT barrel produces by itself 22 kW, the two SCT end-caps together produce a similar amount and the total heat production of the pixel detector is around 17 kW. Although these values are only expected after years of irradiation, the capacity of the cooling system installed now must be sufficient to remove this heat load. At the start-up of ATLAS the power consumption of the modules will be almost a factor two lower: it increases over time as sensor currents increase due to the radiation damage, see Section 3.1.1. In Table 3.3 we summarize the power loads in different parts of the ID.

<table>
<thead>
<tr>
<th>Number of capillaries per circuit</th>
<th>Number of circuits</th>
<th>Nominal power load per circuit [W]</th>
<th>Subtotal nominal power load [kW]</th>
<th>Nominal mass flow per circuit [g/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCT Barrel</td>
<td>2</td>
<td>44</td>
<td>504</td>
<td>22.2</td>
</tr>
<tr>
<td>SCT EC (3 sectors disk)</td>
<td>3</td>
<td>64</td>
<td>346.5</td>
<td>22.2</td>
</tr>
<tr>
<td>SCT EC (2 sectors disk)</td>
<td>2</td>
<td>8</td>
<td>241.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Pixel Barrel</td>
<td>1</td>
<td>56</td>
<td>220</td>
<td>12.4</td>
</tr>
<tr>
<td>Pixel Discs</td>
<td>1</td>
<td>24</td>
<td>110</td>
<td>2.7</td>
</tr>
<tr>
<td>Pixel service panels</td>
<td>1</td>
<td>8</td>
<td>220</td>
<td>1.8</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>204</td>
<td></td>
<td>63.2</td>
</tr>
</tbody>
</table>

Table 3.3: Basic parameters and cooling capacity of the cooling circuits.

A silicon detector can survive longer at lower temperature, yet with the pixel and SCT detector being at the heart of ATLAS the material restriction and the limited space put severe constraints on the possible cooling achievable. An evaporative cooling system has been chosen, to operate at a coolant temperature of \(-25^\circ\text{C}\). With the total thermal resistance between the modules and the cooling pipes, this amounts to the SCT and pixel modules operating at around \(-7^\circ\text{C}\) and \(0^\circ\text{C}\) respectively. In this section we go into the details of the ID cooling system. We cannot however cover everything and for a more detailed description we refer the reader to [79, 80].

3.3.1 Evaporative and mono-phase cooling systems

An evaporative system has been chosen over a mono-phase system for several reasons: the higher heat transfer coefficient between the cooling fluid and the cooling pipes, the smaller temperature gradient along the long cooling channels, and the smaller pipe size required for
the circuits. An important reason is that extracting heat at a phase change is a more efficient way than using a single phase cooling system, reducing the amount of cooling liquid needed and reducing the sizes of the pipe work.

To give an indication, the specific heat capacity (SHC) of \( \text{C}_3\text{F}_8 \), the refrigerant used in the cooling system, is 0.794 J/(gK), at 1 bar and +25°C. Its latent heat vapourisation (LHV) is 97.0 J/g at 1.7 bar and −25°C. With a heat load of 63 kW the evaporative system thus needs 0.65 kg/s to keep the detector cooled\(^\text{13}\). A mono-phase system would need 7.2 kg/s, assuming we tolerate a 10°C increase in temperature\(^\text{14}\). Not only is such an increase in temperature undesirable, but a factor of ten more coolant would thus be needed.

### 3.3.2 Coolant choice

There are several reasons for choosing \( \text{C}_3\text{F}_8 \) as the coolant for the system. The saturated n-type fluorocarbon refrigerants \( \text{C}_n\text{F}_{2n+2} \) have many properties needed in ATLAS: they have very good stability against radiation, they are non-flammable, non-toxic and electrically insulators.

Different types of fluorocarbons have been considered and in Table 3.4 we list some important properties of two of them. In the end \( \text{C}_3\text{F}_8 \) was chosen for mainly three reasons: firstly, it gives a lower pressure drop in the vapor phase, as we see in Table 3.4, which allows for a reduced size of the return pipe. Secondly, it has a low saturated vapor temperature at the minimum operating temperature of −25°C, which is still above the atmospheric pressure. This means that there can be no air ingress. And thirdly, it shows the highest heat transfer coefficients.

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Latent Heat ([\text{J/g}])</th>
<th>Vapor volume per (\text{cm}^3) of liquid ([\text{cm}^3])</th>
<th>Vapor pressure ([\text{bar}_a])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{C}<em>4\text{F}</em>{10})</td>
<td>101.1</td>
<td>242.6</td>
<td>0.58</td>
</tr>
<tr>
<td>(\text{C}_3\text{F}_8)</td>
<td>97.0</td>
<td>71.4</td>
<td>2.46</td>
</tr>
</tbody>
</table>

Table 3.4: Physical properties of two possible refrigerant candidates, at −15°C.

A system with \(\text{CO}_2\) has also been considered. Such a system has several advantages: the coolant can operate at lower temperatures, there might be less material needed, and \(\text{CO}_2\) is a cheaper material than \(\text{C}_3\text{F}_8\); last but not least, it is environmental-friendlier, see \[81\]. However, due to lack of expertise with such a system and time to develop it, it has not been chosen to be implemented in ATLAS. Especially the higher pressures at which it operates and the exact amount of pipe-work (material) needed for such a system were reasons for concern.

### 3.3.3 Thermal enclosure

For the detectors to be kept at such low temperatures, they must be contained in a dry environment to prevent condensation occurring on the cold structures. The four different parts of the SCT and the pixel, i.e. the pixel, the SCT barrel and the two SCT end-caps, are therefore all individually isolated by a thermal enclosure flushed with dry nitrogen. The TRT itself is

\(^{13}\) This is lower than the total of 1.1 kg/s in Table 3.3: to be sure to have enough cooling capacity at any time, the total flow is almost twice as large. Hence also the need for heaters, see page 76.

\(^{14}\) Here we assume that the SHC is the same at −25°C as it is at +25°C. The boiling point is at −37°C, so the assumption is not too far off.
split in three individual parts, i.e. the barrel and its two end-caps, and these are flushed with 
\( \text{CO}_2 \) as they operate with a gas mixture of \( \text{CO}_2 \), \( \text{O}_2 \) and \( \text{Xe} \). To form a barrier between the 
TRT and the silicon detectors, the gaps in between the sub-detectors are flushed with \( \text{CO}_2 \). See Fig. 3.15 for an overview of the seven systems and [80] for more details.

The enclosures of the seven sub-detectors must ensure thermal neutrality and gas isolation between them, all seven thus have an independent temperature and gas control system. With the limited available space the choice was made for active elements: the pixel and SCT are covered with heating foils to ensure thermal neutrality at the boundary between sub-detectors. During normal operation of ATLAS this means that the outside of the SCT is warmed to the temperature of the TRT, i.e. room temperature; the pixel heater pads can stay off. A second role of the heater pads is keeping the pixel and SCT outer temperatures above the dew point of the cavern, when the detector is open and the cooling is running. This is when the pixel heater pads are also needed.

3.4 Cooling system components

The easiest way to understand how the cooling system works is to go step by step through its pressure-enthalpy (PH-) diagram, see Fig. 3.13(a). The part of the system actually in the ID is between point \( D' \) and point \( F' \). We will start by explaining the process from point \( A \). From there up to point \( D \) the system is located in the USA15 area, see Fig. 2.3. A schematic overview of the lay-out of the cooling system is given in Fig. 3.13(b). The parts going between point \( D \) and \( D' \) and between point \( F' \) and \( A \) correspond to the pipes carrying respectively the fluid and the gas to and from the detector.

3.4.1 Off-detector part

The off-detector part consists first of the main cooling plant with the compressors and the condenser located in USA15, and second of the four distribution racks which are located on the gallery at the sides of the ATLAS cavern (UX15). Each rack serves one quadrant of the detector and controls both the inlet pressure and the back pressure of each of the, on average, 51 individual fluid circuits in a quadrant.

Starting at point \( A \), the gas returns from the back pressure regulator and goes to the compressors. At normal operation of ATLAS a maximum of six compressors, working in parallel, compress the gas from 800 mbar absolute at the main return manifold to 17 bar absolute at their outputs. All but two of these compressors run in an ON or OFF mode; the first two (also on UPS\(^{15}\)) have a by-pass line, making it possible to fine tune the flow rate and thus tuning the pressure at the compressor inlet manifold to a constant value. We note that in 2008 not more than four compressors ran simultaneously; the maximum of six compressors will only be needed at the end of life of the sub-detectors, when the heat production is at its highest. A seventh compressor will also be installed, such that for maintenance one compressor can be turned off with the cooling system still running.

At point \( B \) in the PH-diagram, the fluid is still in a gas form. It is condensed inside a mixed water plate heat exchanger, which has the water circulation inside the heat exchanger regulated to maintain a constant condensation pressure. After the condenser the liquid returns

\(^{15}\) Uninterruptible Power Supply. A system ensuring a continues power supply, even in case of failure of the regular supply.
Figure 3.13: The process of the cooling liquid given in different steps from A to F' in a P-H diagram and in a schematic layout of the system.
3.4. Cooling system components

to the main inlet distribution manifold, passing first through a storage tank and a sub-cooler. This last cooler, also working with mixed water, brings us from point \( C \) to point \( D \) in the PH-diagram.

Leaving the USA15 area the liquid has a long way to go to reach the detector. Along this passage, which is in total more than 100 m long, the pipes are routed for more than 20 m through a tunnel also used to route power cables to UX15. The heat produced by these cables and the environmental temperature in the tunnel is unknown. After the pressure regulators, see next section, but just before the ID, the pipes are again routed along cables. Altogether it has therefore been assumed that, as a worst case, the liquid could warm up to a temperature of 35°C before reaching the ID, bringing us to point \( D' \). By the end of the year 2008 it was clear that the temperature increase is much less and the liquid arrives at the ID not warmer than 25°C: the last part of the routing just before the ID is also together with the returning cold gas pipes, effectively cooling the incoming warmer liquid pipes.

3.4.2 On-detector part

A schematic view of the on-detector part is given in Fig. 3.14. From the distribution racks on the platforms a total of 204 circuits go into the detector. Each circuit starts with one Pressure Regulator (PR) on one of the racks, which sets the inlet pressure. This can be used for small adjustments of the flow rate through the circuit, but its main purpose is to keep the pressure above the saturation point of the fluid; otherwise vapor formation will lead to a significant reduction of the flow through the capillaries and to a reduced cooling capacity.

Each circuit then consists of several components we will discuss shortly and finally returns to the distribution rack where the Back Pressure Regulator (BPR) controls the outlet pressure. This pressure in fact sets the temperature of the outlet cooling fluid, which can be seen in the PH-diagram of Fig. 3.13(a). Setting a higher/lower pressure means that the point in the diagram where the fluid goes from saturated state to gas state will be higher/lower on the phase-transition line and be at a higher/lower temperature. Obtaining a temperature of \(-25^\circ C\) requires therefore an absolute pressure of 1.67 bar for the \( \text{C}_3\text{F}_8 \) cooling fluid.

**Heat exchanger**  
Going from point \( D' \) to point \( D'' \) in the PH-diagram there is a temperature drop of the liquid. This happens in the heat exchanger (HEX) where the incoming warm liquid interacts with the outgoing cold gas. The benefit of this component is that a more efficient use of the available enthalpy can be made, and that the outgoing gas is warmer.

The design of the HEX is sub-detector dependent, mainly driven by the available space. The efficiency of a HEX depends on several factors: the fluid mass flow and speed, the fraction of liquid to vapor in the fluid returning from the detector and the orientation of the HEX. This last factor is of importance as the orientation influences the flow and thus the amount of contact between the incoming and outgoing coolant.

**Capillary**  
After the heat exchanger the coolant passes the capillaries. The purpose of these is to drop the pressure of the fluid, such that it enters the detector structure in a mixed phase of liquid and gas, with a vapor quality\(^{16} \) as low as possible. That is, it must be just in the boiling phase to be as efficient as possible in extracting the heat from the modules.

The flow through the capillaries is the pressure drop we observe in the PH-diagram from point \( D'' \) to point \( E \). Each circuit can have either one, two or three capillaries, depending on

\(^{16}\) A fluid which is pure gas has vapor quality of 1; pure liquid has vapor quality of 0.
the number of branches the circuit splits into. Each capillary is used to set the correct mass flow needed in that specific branch. The required mass flow is branch specific: it depends on the power dissipation along that branch, the efficiency of the circuits HEX and on the vapor quality at the exhaust of the cooling structure. Setting a correct mass flow is achieved by tuning the length and diameter of the capillary. The lengths vary between 1.5m and 6m, the diameters between 0.65mm and 1.00mm; see [79] for all details.

Detector structure Arriving finally at the point where the cooling does what it is designed for, that is taking the heat load from the detector, the fluid goes from point E to point F in the PH-diagram. At point F, this is again after the detector structure, the fluid must not have reached the phase-transition line, since that would imply that it is 100% gas which greatly reduces its cooling capacity.

Heater After the detector structure the fluid passes the HEX again where it absorbs more heat from the incoming liquid. The fluid after the HEX can still be a mixture of liquid and gas, and has a very low temperature. If this were to leave the dry environment of the ID, it would cause condensation along the pipes going back to the distribution racks on the platforms. To prevent this, the coolant is brought to room temperature by a heater, basically an electric coil. This brings it to point F’ in the PH-diagram, where it is at room temperature and completely in a gas state.

If the heat load of the detector should suddenly drop or completely disappear for whatever reason, the heater still has the function of bringing the fluid to room temperature. This means that it must be able to react within a reasonable time to changes in the cooling flow and that its maximum power is equal to or greater than the full heat load of the detector branch.

In Fig. 3.14 we can see the location of several temperature sensors at different points in the cooling circuit. These are used to monitor the whole system; some are used to control
the heater power such that the temperature of the fluid leaving the detector is around 20°C. The temperature of the heater surface is used for the interlock system: if it rises above 55°C, the current is immediately stopped, independent of the power request. When the temperature drops below the limit, the current is resumed. We note that for some circuits the interlock limit is set higher, see Section 3.5.2.

**Change of heater design**  In the beginning of 2007 during the installation of the heaters, two problems were discovered. First, the location of the control sensor on the heater was found to be not-optimal. Secondly, a combination of moisture and wrong glue used for the connectors on the heater resulted in a short-circuit in a limited number of heaters. This ended in one heater partly melting one connector when testing the installation. To prevent this from happening again the heaters were redsigned. It turned out that exactly around the original location of the control thermocouples on the heater the fluid is coldest. This is probably caused by the narrowing of the pipe. In the new design the narrowing was made less severe, and the regulation thermocouple for the control line was placed after the heater, where the fluid has a more homogeneous temperature. In order to still be able to reach the SCT heaters after installation, these were also placed at a different position than originally planned. Figure 3.15 shows the original location where the SCT heaters were supposed to be placed. In the new design they were moved to the end-flanges, just like the pixel heaters.

![Diagram of ID layout](image-url)

**Figure 3.15:** Schematic layout of one quadrant of the ID. The old and new position of the SCT heaters is given. The barrel compartments extend to the other half of the detector: with a mirrored quadrant to the left, we can see the seven different environments. The ‘Was to be TRT wheels’ indicates space reserved for additional TRT wheels. These never were constructed, and the space is now used for the pipe-work needed to the new SCT heaters.
Chapter 3. The SCT and the ID evaporative cooling system

The Back Pressure Regulators The pressure drop observed from F’ to A in the PHzdiagram is the drop over the BPRs which set the pressures at the on-detector side. The pressure of the fluid at the off-detector side of the BPRs is regulated by the operation of the compressors.

For the coolant temperature to be \(-25°C\) in the detector, the pressure at the inlet-side of the compressors is to be around 800 mbar, see Fig. 3.13(a). Turning on cooling circuits however changes this pressure, with more fluid arriving at the compressors. In Fig. 3.16 the Vapor Return Pressure is shown and we observe the pressure rising as circuits are turned on. From 15:00 up to 17:00 a total of 63 loops is turned on. At 15:28 and at 15:42 the pressure suddenly drops: at both times an extra compressor is turned on. The pressure drop is a consequence of the sucking-effect of the extra compressor. The fact that we do not measure 800 mbar after the turn on of a compressor, is because in 2008 the cooling system was operated at higher temperatures than in final operation.

![Figure 3.16: Vapor return pressure during turn on of circuits. At 15:28 and at 15:42 the effect is visible of two compressors turning on.](image)

Problems with the compressors

On May 1st 2008 a serious failure of the cooling plant occurred, shutting it down for three months. It turned out that three compressors were badly damaged due to slipping of the internal magnetic couplings. Fig. 3.17(a) shows a schematic of one compressor. An electric motor drives the compressor through a magnetic coupling; this type of compressor was chosen because the magnetic coupling makes it possible to have a good isolation of the $C_3F_8$ gas, reducing leaks and possible contaminations. Due to a still unknown reason the coupling started to slip. The magnet driving the compression came to a halt, while the magnet driven by the electric motor kept turning, creating electric currents heating up the magnets. The system almost certainly ran for more than twelve hours in this condition and came to a halt when the magnets broke to pieces due to the heat.

The manufacturer repaired the compressors and also installed sensors on all compressors counting the number of rotations of the cranks to make sure these run at 1450 RPM; the cranks drive the compression and are magnetically coupled to the electro motor running at 1450 RPM, see again Fig. 3.17(a). The interior damage from the May 1st incident was however such that small parts of the debris might have been transported into the cooling pipes. After investigation only the pipes outside the detector in the USA15 pump room were found to be contaminated, filters protected the pipes further downstream. When taken apart for cleaning the debris was found to be mostly from another part of the compressors: apparently the pistons eroded much
3.5 Operating the cooling

Once the cooling plant is operational there are basically three controls to be set:

- The PR which is set for groups of circuits. In total there are 18 PRs to be set.
- The BPR which in fact controls the temperature of the cooling fluid in the detector. The BPR is set for 40 groups of circuits.
- The power of the heater of each of the 204 circuits. This is automatically regulated by a standard PLC\(^{17}\), which uses the temperature sensors downstream of the heater as a control input.

The operation of the system is straightforward once it is in normal run mode. The PR and BPR are at a certain fixed point, only the heater-power in fact is to be controlled and this is done by the PLC, which is based on a PID algorithm.

**PID algorithm** A Proportional-Integral-Derivative (PID) algorithm is used to control a certain parameter, such as the temperature of the cooling fluid, by measuring it and changing

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\(^{17}\)Programmable Logic Controller
the setting of the heater current to reach a certain operational point. It does so by calculating the needed correction based on three different measurements of the coolant temperature: the absolute offset (the Proportional value), the integrated offset over time (the Integral value) and the rate at which the offset is changing (the Derivative value). The correction is a weighted sum of the three values and must be tuned to achieve a smooth transit to the set-point.

In our case, each circuit temperature is to be controlled by adjusting the power of the heater. Parameters to be fine-tuned are the proportional weights of the three measurement values and the set-point. A set of parameters can easily lead to (too big) overshoots. For example, if the temperature is too low, the power request will heat the fluid, but with such an amount that the temperature may become too high. If a wrong set of parameters is chosen, these overshoots will never get smaller, or worse, they will get bigger. The trick is to find that set of parameters which stabilizes the temperature as smooth as possible.

Most of the heaters have now been fine-tuned, however some still have problems with regulation. These problems are not immediately caused by wrong PID parameters and have to be dealt with in other ways. We go more into details on this in section 3.5.2.

### 3.5.1 Turning on and off the circuits

The cooling process shown in Fig. 3.13(a) operates during a standard stable run. The turning on and off of the circuits are however processes causing large temperature fluctuations themselves. Once LHC and ATLAS are operational and running normally, the cooling system will be turned on and off only once a year. In 2008 we were still in the commissioning phase. We will now discuss the turn on and off process of the circuits and with it the problems that were encountered during that time.

In Table 3.5 the different states a circuit can be in are given. As we mentioned, only the BPR, the PR and the heater-power are to be controlled.

#### Turning on

Turning on a circuit is a matter of setting the BPR and PR to the desired set-points and of opening the PR valve. We can go directly from any state, be it the LOCKED, OFF or STANDBY state, to the ON state. We note that only when a circuit is in ON state can the pixel or SCT modules on that circuit be powered. Whenever the state changes from ON to something else, the modules are also immediately powered off.

<table>
<thead>
<tr>
<th>State</th>
<th>PR valve</th>
<th>BPR valve</th>
<th>Heaters</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>Open &amp; pressure set</td>
<td>Open &amp; regulating to set-point</td>
<td>On &amp; controlled by PLC</td>
</tr>
<tr>
<td>STANDBY</td>
<td>Closed</td>
<td>Open &amp; regulating to set-point</td>
<td>On &amp; controlled by PLC</td>
</tr>
<tr>
<td>OFF</td>
<td>Closed</td>
<td>Open &amp; line is sucked vacuum</td>
<td>Off</td>
</tr>
<tr>
<td>LOCKED</td>
<td>Closed</td>
<td>Open &amp; line is sucked vacuum</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.5: Different states of the cooling circuits.
Figure 3.18: Heater sensors for a well-behaving loop (#126); at 17:28 the circuit is set to ON. The power request is adjusted to the fluctuations of the exhaust temperature, until a stable state is reached. See text for more details.

Turning off

When going to STANDBY, the PR valve of a circuit is closed. The coolant flow comes to a halt and the pressure at the on-detector side of the PR will slowly drop until it reaches the same value as at the BPR. The pipes are thus kept full, and the PLC can still run a current through the heater.

This is the reason that the intermediate STANDBY state is needed when shutting down: if

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18 Throughout this section the heater current is given in percentages of its nominal 100%. The PLC regulates the current by turning on/off a power source of 110 V.
Figure 3.19: Heater sensors for a well-behaving loop (#126); at 11:30 the circuit is set to STANDBY. The power request is adjusted to the fluctuations of the exhaust temperature, until a stable state is reached. See text for more details.

In these three states, the ON, STANDBY and OFF state, the heater is still on and its power is under control of the PLC. It is only when the circuit has stabilized again, visible by steady temperatures and no power over the heater, that the circuit is set to LOCKED: the heater is secured in an off-state. Figure 3.19 depicts the heater sensors during a standard turn to STANDBY. At 11:30 the circuit is put into STANDBY and with this command the PLC also sets the current to 1%. This is however too extreme and the exhaust liquid temperature drops more than 22°C. The heater current is resumed until 11:32 when the exhaust liquid temperature shoots over the 20°C and the heater temperature itself goes up to 40°C. This last value is still below the interlock level of 55°C. The heater current fluctuates until 11:35, and these fluctuations are immediately seen in the temperatures. At 11:35 the current stops as the exhaust temperature gets too high and these start dropping again. The exhaust temperature goes to 12.5°C at 11:42, not low enough to resume the heater current, and then stabilizes around 15°C.
3.5. Operating the cooling

3.5.2 Loops with problematic heater control

The turn on and shut down shown in Fig. 3.18 and 3.19 are both of circuit 126, a loop with no problems. Some circuits have turned out to be difficult to regulate. Due to different geometries of the circuits the flow through the 204 heaters is not always the same and the orientation of the heaters turns out to have a significant impact. During the first operation of the pixel cooling circuits in April 2008 it was seen that the pixel heaters were unstable (for approximately 30 loops) in the bottom half of the detector. For the SCT a similar problem exists for some circuits in the bottom half of the detector. All in all, we can distinguish two different problems we will discuss here.

Temperature regulation problem - temperature readout at the wrong location

It turns out that for some circuits the position of the control temperature sensor is too close to the heater itself. At that location, the mixture is not homogeneous enough and the temperature is not a correct measurement of the fluid’s overall temperature. The control sensor for several pixel heaters is placed in the bend of the circuit, which happens to be a cold spot due to the dynamics of the flow. In Fig. 3.20 we see consequently how the temperature cannot be stabilized: at 21:35 the circuit is turned on. The exhaust temperature stays below 20°C, while the heater temperature almost goes up to 70°C. The exhaust temperature however stays low, simply because the sensor is reading at a cold spot, and at the same time the current

\[\text{Exhaust Liquid Temp} \leq 20°C, \quad \text{Heater Surface Temp.} \geq 70°C.\]

For these pixel circuits the interlock limit has been changed: the temperature limit is set to 80°C.

Figure 3.20: Heater sensors for a problematic loop (#50) with temperature readout at the wrong location; at 21:35 the circuit is turned ON, but no stable setting is found. At 22:09 the circuit is set to STANDBY. See text for more details.
and heater temperature keep rising. At 22:09 the loop is turned to STANDBY again. For circuits with these problems a different method is now in use for regulation of the heaters: the temperature is read out further downstream by the so-called C31 sensors (50 to 100 cm downstream), which give a more correct measurement of the liquid temperature, see also Fig. 3.14.

In the SCT there are no circuits with a similar design as the bended ones in the pixel detector. Still, some circuits do have the drawback that the position of the control sensor directly after the heater is not perfect, i.e. even after the re-designing, see section 3.4.2. Especially the circuits again in the bottom part of the SCT have this problem. For these the control has not been moved to the C31 sensors: a stable regulation is recovered by lowering the control temperature to 17°C and by setting the PR to lower values, thus reducing the mass flow. For two SCT barrel circuits this does not recover the regulation, as these also suffer from the next problem we will discuss.

**Temperature regulation problem - Interlock problem**

When the heater is on, a current runs through a coil which runs around the fluid pipe. In Fig. 3.21 a schematic is drawn which shows how this creates a front somewhere along the heater where the liquid/gas mixture goes to a 100% pure gas. The gas after this front is heated even further by the current and being now in a single phase, its temperature rises.

For many circuits this single phase heating creates a problem. If the control sensor measuring the heater body temperature is behind the phase front, its readout can easily trigger the interlock and stop the current. Figure 3.22 shows the heater sensors for a circuit which has been turned on, but cannot find a stable current. First, just before 21:40 the loop is turned to ON. At 21:45 a stable exhaust temperature seems to be found, but the power request does go up slowly to 60%, probably to compensate for the small fluctuations of the exhaust temperature just below the 20°C. The heater temperature however is very high and at 22:14 hits the 55°C, thus triggering the interlock; this briefly cuts the current at 22:14, until the temperature is below 55°C again. The power request at the same time goes up due to the current being cut and not providing enough heat. After this, the current fluctuates due to the interlock being hit all the time, and with it the temperatures. The power request keeps rising until at 22:45 it reached 90%. To prevent this from getting even worse, the loop is turned to STANDBY manually.

There are several solutions to this problem: first, the limit for the heater body temperature can be raised such that the interlock is not fired. The heater will find a stable point, but the drawback is that this means running the system with several very hot heaters in the detector.

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**Figure 3.21:** Schematic of a heater. The coil lines are given by the arrows, the front between liquid/gas mixture and 100% gas is shown by the dotted line.
Figure 3.22: Heater sensors for a problematic circuit (#149) hitting the surface temperature interlock when turned on. No stable run can be found and the circuit is turned to STANDBY at 22:45. See text for more details.

Another solution is turning on the modules on that circuit immediately when the cooling circuit is turned on. The heat load of the modules means that the heater power request does not have to be too high and a stable running of the circuit can be found, as can be seen in Fig. 3.23. At 23:00 the coolant flow starts and the temperatures drops, the modules are turned on at this same time. The power request goes up and overshoots, just as we observed in Fig. 3.18. In this overshoot the heater temperature hits the 55°C limit twice at 23:06 and 23:07 and the current is cut at those times. This does not cause any problem. A few minutes later the exhaust temperature is at a stable value and the heater is still safely below the interlock limit. Around 23:40 when it is clear that it stays stable, the loop is turned to STANDBY again.

Although this last problem has made the operation of the cooling more difficult during the commissioning phase in 2008, it is believed to be temporary. (Approximately 5 loops are still affected by this problem.) In the commissioning phase the cooling was operated at a back-pressure set to around 3 bar. This ‘warm’ running was chosen as a safe way to test the system. During normal operation of ATLAS, the back-pressure will be lowered to around 1.3 bar and the system will be much colder. This will solve the interlock problem: during tests on several
heaters it was found that the front as visualized in Fig. 3.21 moves to the left or right when
the back-pressure is raised or lowered respectively. With the interlock sensor on the mixture
side of the front, the problem disappears.

Figure 3.23: Heater sensors for the same circuit as in Fig. 3.22. The difference is that at 23:00
the modules are also turned on. At 23:40 the circuit is again turned to standby.