The ATLAS IBL CO$_2$ Cooling System

International Workshop on Semiconductor Pixel Detectors for Particles and Imaging (Pixel 2016)

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On behalf of the ATLAS collaboration

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ATLAS IBL: A new 1st layer around a reduced beam pipe

IBL an extra pixel layer

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W/unit)</th>
<th>Power (W/stave)</th>
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<tr>
<td>FEI4 chip</td>
<td>1.12</td>
<td>35.84</td>
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<td>Pixel sensor (after irradiation)</td>
<td>0.68</td>
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<td><strong>Total for 14 staves</strong></td>
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Cooling temperature required: $<-35^\circ C$
The IBL cooling loops

- Vacuum insulated concentric tubes (flex lines) (7x1.6x0.3mm inlet inside 4x0.5mm outlet)
- Splitter box (Concentric split and vacuum termination)
- Connection tube bundle 14x 3x0.5mm
- Beam pipe

Evaporator tubes in staves 1.5mm

1 round trip = 1 loop = 31m

- PP1 connectors
- Radial bundle to splitter box
- IBL connectors
- Electrical break
- Splitter box in IDEP
- Manifold box in S5

PP1 connectors

Vacuum insulated transfer line

Manifold box

Junction box

Solenoid magnet

Inner detector (TRT+SCT+Pixel)

Electromagnetic calorimeter (LAR)

Hadronic calorimeter (Tile)

Muon area sector 5

Flex line routing in IDEP

7 miniature vacuum insulated flexible cooling lines (<18mm)
IBL has **2 redundant CO\textsubscript{2} systems**, in case of failure it swaps transparent to the other system. **Detector is minimal affected** (small temperature fluctuation)
The cooling system is commissioned over a by-pass dummy load (3kW) and with the detector attached. The cooling system is very stable (<<1°C) over a large temperature range (from room temperature down to -35°C).
The beam pipe bake-out was a crucial event for the IBL cooling.

- The beam-pipe was heated in steps to 230°C, the cooling system prevented the IBL for overheating.
- A 2 fault redundant operation of the cooling was established:
  - 2 systems operated in parallel
  - System back-up by a bottle battery blow system
- Results and observations:
  - Maximum recorded sensor temperature was -8°C @ 230°C beam pipe
  - Due to twice the flow (2 systems in parallel) => ca. 4x pressure drop, most staves stayed single phase for long time.
- No serious issues during bake-out, system run without problems

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IBL Cooling temperatures at bake-out

- Stave01 Inlet
- Stave01 Outlet
- Stave01 Modules
- Stave05 Inlet
- Stave05 Outlet
- Stave05 Modules
- Stave07 Inlet
- Stave07 Outlet
- Stave07 Modules

Temperatures when liquid

Temperatures when boiling

- Cooling temperatures (°C)
- Beam pipe temperature (°C)

IBL-cooling blow off test with 3kW heating

- FT901 Blow system flow
- FT106 IBL-A flow
- FT306 IBL-B flow
- TT116 Junction box liquid
- TT136 Junction box return (2phase)
- TT117 Heater

Flow (g/s), Temperature (°C)

Failure of plant B

Failure of plant A

Cooling temperature remains stable

Blow

Delivered flow

Sys. A

Sys. B

25 minutes of stable 3kW cooling using blow system (3kW Test was stopped to save CO2)

Stave 14 behavior

Liquid cooling

Partly boiling

Full boiling
The IBL cooling heat loads

- The cooling system has to cope with several heat loads:
  - Detector electronics power
  - Ambient heat leak in the detector
  - Ambient heat leak of the system
- The detector power now is about ~30 Watt/stave (420 W total)
- The total absorbed heat load can be measured when both in and outlet of the plant are in liquid phase (occasionally present)
- The ambient heat leak in the detector, is the same order as the electrical power
- Total load for the cooling system (detector + ambient)
  - Current operation: 1.5 kW at low temperature
  - Expected EOL: 2 kW at low temperature
  - Tests have been done with 3kW dummy load

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End of commissioning steady state tests and comparison with simulations (Dec. 2014)

IBL temperatures for set point -30°C; Measured data and CoBra simulation results

Temperature (°C)

Distance from Junction Box (m)

IBL position (m)

Inlet:
- Cable temperature: -13.6±0.8 °C / -11.2±0.9 °C
- Cable board temperature: -16.5±0.3 °C / -10.3±0.3 °C

Outlet:
- Cable temp.: -13.6±1.4 °C / -11.3±1.6 °C
- Cable board temp.: -16.5±0.4 °C / -10.4±0.5 °C

Heat Loads:
- Ambient (CoBra): 446.6 W / 579.6 W
- Ambient (Measured): NaN W / NaN W
- Modules: 0 W / 355.4 W

Miscellaneous:
- Pressure drop: 5.3 Bar / 5.5 Bar
- Mass flow: 18.1 g/s / 17.9 g/s
- Ambient temp.: -16.5 °C / -10.3 °C
- Exit vapor quality: 0.08 - / 0.17 -

Set point = -30°C
Ambient heat load from previous slide included in simulations
Steady state tests (Dec. 2014)
Overview of different set point temperatures

First modules show a larger and more irregular temperature offset (boiling onset issue)

Gradients due to stave conduction relatively constant

Gradients increase with colder cooling temperature

Module 1 det off
Module 1 det on
Module 2 det off
Module 2 det on
Module 3 det off
Module 3 det on
Module det 4 off
Module det 4 on
Module det 5 off
Module det 5 on
Module det 6 off
Module det 6 on
Module det 7 off
Module det 7 on
Module det 8 off
Module det 8 on
JB return det off
JB return det on
MB return det off
MB return det on
CP outlet det off
CP outlet det on
CP inlet det off
CP inlet det on
MB liquid det off
MB liquid det on
JB liquid det off
JB liquid det on

Data of previous slide
The cooling system is stable within 0.2 °C (<0.05 °C RMS), Detector modules within a few degrees due to power fluctuations.

Cooling pipe measured stability during M9 run

** Please note that the shown temperatures in 2015 show values which are not yet corrected with the calibration constants defined in April 2015. As a consequence cooling pipe sensors shown are ~1.5°C too high, Module temperatures ~0.5°C
Operational experience since LS1 (1.5 years of operation)

- The IBL CO₂ cooling system had an excellent track record: 0% downtime during physics
- Only limited interventions were needed, of which most were done during safe periods (TS, MD)
- 2 incidents during detector operation
  - 1 hardware failure with a successful back-up procedure
  - 1 DSS interlock due to a threshold conflict in the stepper introduced for long term high temperature operation, interlock occurred during a controlled intervention
- We are getting positive feedback of the system operation and reliability by ATLAS
- Very good cooperation between the operator team (ATLAS+EN-CV) and development team (EP-DT)

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<th>Software modification</th>
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07/09/2016 B. Verlaat
• Sometimes the boiling is not triggered, and a reduced cooling performance is observed (bad heat transfer)
• We are trying to understand what causes this phenomena and how we can improve it
• The non-boiling issue is annoying for the alignment due to stave bowing.
• A test set-up containing a real size stave pair including flex lines and its orientation is made in SR1 to investigate the phenomena
1st results from SR1 show the superheated liquid in the inlet tube
Flow reduction looks promising
Flow reduction needs a modification in the manifold to avoid manifold evaporation
  - Will be tried in SR1
• The IBL CO$_2$ cooling system was successfully commissioned in 2014.

• The cooling system has been fully operational since LS1 for 1.5 years and has performed very reliable with 0% downtime for ATLAS physics.

• The cooling system wide operational temperature range has proven to be very convenient to solve the LV-current issue.

• The high temperature stability of the cooling is very advantage for the stave bowing issue.

• The boiling onset issue is studied in a real size cooling loop mock-up in SR1.

• The IBL cooling method and operational experience has proven to be a good baseline for the ITk cooling.