The use of a 90 metre thermosiphon cooling plant and associated custom ultrasonic instrumentation in the cooling of the ATLAS inner silicon tracker.

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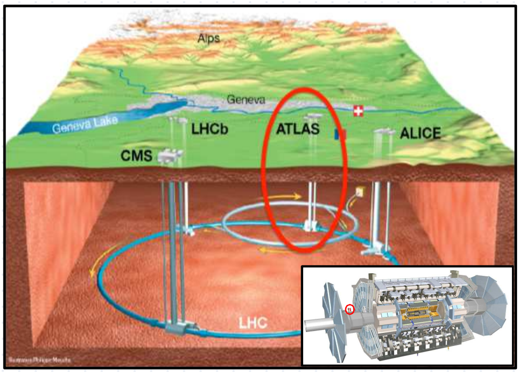
INTRODUCTION

The inner tracker of the ATLAS experiment at the CERN Large Hadron Collider contains silicon microstrip and pixel detectors, evaporatively cooled with C_3F_8 and CO_2.

The present compressor-driven C_3F_8 recirculator is being replaced with a new 60kW thermosiphon exploiting the 92 metre depth of the ATLAS cavern to generate a liquid hydrostatic column of sufficient pressure to circulate C_3F_8 through the tracker with no moving parts in the primary coolant loop. Vapour returns to the surface condenser; - the lowest pressure part of the system.

The thermosiphon has a cooling capacity of 60 kW and circulates C_3F_8 at a high mass flow of up to 1.2 kg/second. The thermosiphon is integrated into the CERN UNICOS system and the ATLAS detector control system (DCS).

Custom ultrasonic instrumentation is extensively used in the thermosiphon and silicon tracker cooling control systems.



The ATLAS Experiment at the CERN Large Hadron Collider

Custom ultrasonic ("sonar") instruments are used to:

- measure very high thermosiphon C_3F_8 coolant vapour flow,
- analyse binary gas mixtures
- detect leaks of coolant into the nitrogen-purged anti-humidity envelopes surrounding the silicon tracker sub-detectors.

Ultrasound pulses are transmitted in opposite directions in flowing gas. Transit time differences are used to calculate the flow rate while averages are simultaneously used to calculate sound velocity, which - at a given temperature and pressure - is a function of the molar concentration of the two gases.

Gas composition is computed from comparisons of real time sound velocity measurements with a prediction database, using algorithms running in Siemens SIMATIC WinCC under Linux.

5 instruments are integrated into the ATLAS DCS, with communication to a Dell Poweredge R610 SCADA computer via TCP/IP Modbus over Ethernet.

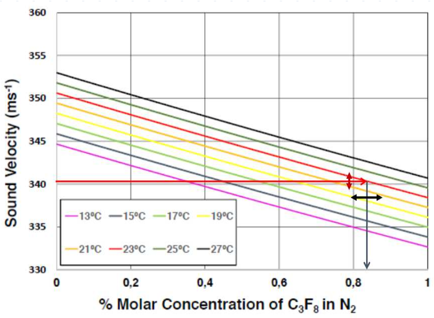
ULTRASONIC BINARY GAS ANALYSIS

Molar composition is determined by comparison of continuous real-time measurement of sound velocity, ***c***, with a velocity-composition look-up table based on prior measurements in calibration mixtures and/or theoretical predictions made with an appropriate equation of state.

$$c = \sqrt{\frac{\gamma RT}{M}} \qquad \gamma_m = \frac{C_{pm}}{C_{vm}} = \frac{\sum_i w_i Cp_i}{\sum_i w_i Cv_i} \qquad c = \sqrt{\frac{\frac{\sum_i w_i Cp_i}{\sum_i w_i Cv_i} RT}{\sum_i w_i M_i}}$$

$$M = \sum_i w_i M_i$$

R is the molar gas constant (8.314 J·mol⁻¹·K⁻¹),
T is the absolute temperature (K)
M is the molar mass (kg·mol⁻¹)



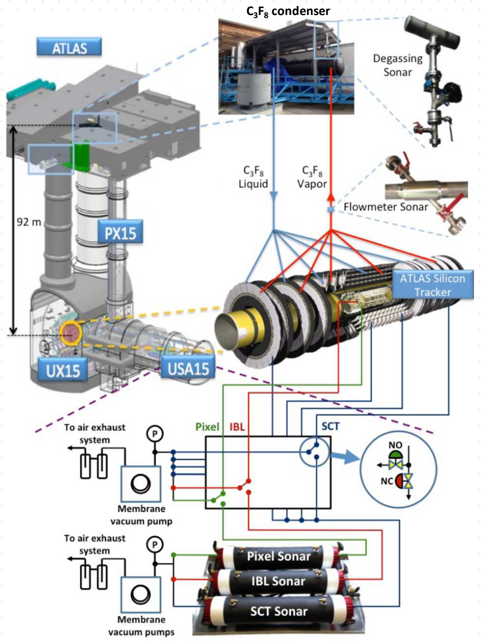
Comparison between measured sound velocity data and theoretical predictions (NIST-REFPROP) in molar C_3F_8/N_2 mixtures of thermodynamic interest for the ATLAS pixel and SCT sub-detectors

Contributions to 0.025 ms^{-1} overall sound velocity meas. error δc:

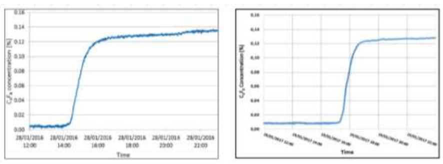
- ±0.1°C temperature uncertainty in gas ($\delta c = \pm 0.02\ ms^{-1}$);
- ±1 mbar pressure uncertainty ($\delta c = \pm 0.003\ ms^{-1}$);
- ±0.1 mm transducer spacing uncertainty ($\delta c = \pm 0.002\ ms^{-1}$);
- ±100 ns transit time uncertainty ($\delta c = \pm 0.002\ ms^{-1}$).

Precision of mixture determination given by $\delta(mix) = \delta c/m$,
m is local slope of sound velocity/concentration curve ($ms^{-1}\%^{-1}$)

➔ C_3F_8 in N_2: $\delta c = \pm 0.025\ ms^{-1}$ yields $\delta(mix) = \pm 2.10^{-5}$, in the C_3F_8 range 0-1%, where $m = \sim -12.27\ ms^{-1}\%^{-1}$.



Layout of the 92m thermosiphon C_3F_8 coolant recirculator which cools most of the ATLAS silicon tracker. Also shown: ultrasonic isntruments forming part of the thermospihon control system and the automated sampling system for continuous ultrasonic monitoring of C_3F_8 coolant leaks into the N_2 volumes of the ATLAS pixel & SCT trackers, and for CO_2 coolant leaks into the N_2 volume of the IBL pixel detector.

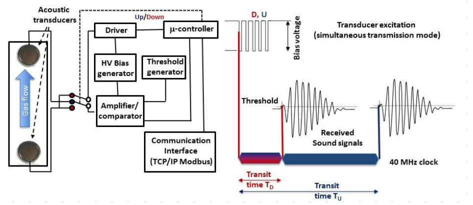


C_3F_8 concentration increase seen in the N_2 - purged anti-humidity volume of the ATLAS pixel detector on cooling system restart January 2016 and January 2017. Leaking circuits identified.

CUSTOM ULTRASONIC INSTRUMENTATION AND READOUT ARCHITECTURE

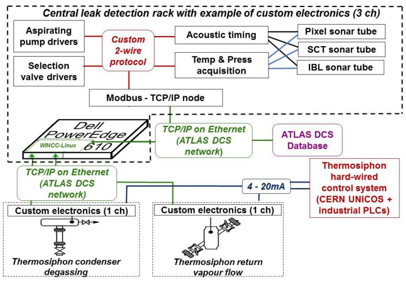
Custom electronics based on dsPIC33F µ–controllers & SensComp 600 50kHz capacitive transducers:

- Transducers sensitized with +300 V bias & energized by (300➔0V) square wave pulse transitions;
- Receive chain: differential & programmable gain amplifiers followed by comparator. implemented in the µ–controller;
- 40 MHz transit time clocks, generated in µ–controller, started in synchronism with the edge of the first transmitted sound pulses & stopped by first above-threshold sound pulses in each direction.



Driver/amplifier circuit adapted to the Senscomp Model 600 50kHz ultrasonic trasnsducer

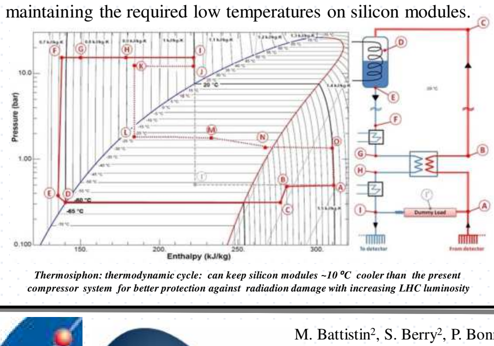
- 5 instruments currently integrated into the ATLAS DCS



Readout architecture using 2-wire custom inernal communication protocol and long distance transmission visa TCP/IP Modbus on Ethernet.

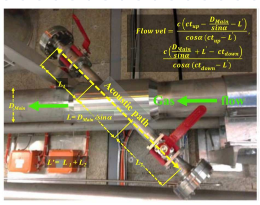
RECENT THERMOSIPHON OPERATION

- Thermosiphon tested for the first time with the ATLAS SCT and pixel detectors in April 2017;
- Demonstrated "cold swaps" between present compressor (➔"back-up") system and new thermosiphon (➔"baseline"), maintaining the required low temperatures on silicon modules.

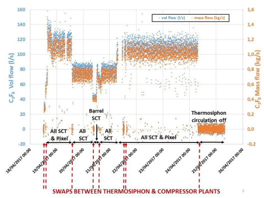


Thermosiphon: thermodynamic cycle: can keep silicon modules ~10 ºC cooler than the present compressor system for better protection against radiadion damage with increasing LHC luminosity

- Combined ultrasonic flowmeter/gas mixture analyzer with 45º angled acoustic tube installed in vapour return to the surface condenser; operating at C_3F_8 mass flows up to 1.2 kgs^{-1}, for cooling capacity equivalent to the SCT & pixel detector combined power dissipation of 60 kW. Resolution ± 0.05 kgs^{-1}.

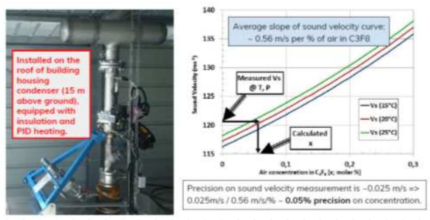


Detail of the high flow 45° angled flowmeter Total acoustic path length ~ 72cm, acoustic path in moving gas ~ 19 cm



Volume & mass flow measured in recent thermosiphon Trials with the ATLAS SCT & pixel detector cooling systems Testing cold swapping between the old compressor and new thermosiphon external C_3F_8 circulation plants

- The thermosiphon condenser operates below atmospheric pressure. An ultrasonic instrument monitors air ingress and can trigger the venting of accumulated air using a 4-20mA signal proportional to air concentration in the gas phase above the liquid C_3F_8 in the condenser. Expected resolution ~ 9.10^{-4}.



View and shematic of the ultrasonic instrument for the monitoring and elimination of ingressed air in the condenser of the ATLAS thermosiphon fluorocarbon coolant recirculator

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