Development of a custom on-line ultrasonic vapour analyzer and flow meter for the ATLAS inner detector, with application to Cherenkov and gaseous charged particle detectors

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ABSTRACT: Precision sound velocity measurements can simultaneously determine binary gas composition and flow. We have developed an analyzer with custom microcontroller-based electronics, currently used in the ATLAS Detector Control System, with numerous potential applications. Three instruments monitor C_3F_8 and CO_2 coolant leak rates into the nitrogen envelopes of the ATLAS silicon microstrip and Pixel detectors. Two further instruments will aid operation of the new thermosiphon coolant recirculator: one of these will monitor air leaks into the low pressure condenser while the other will measure return vapour flow along with C_3F_8/C_2F_6 blend composition, should blend operation be necessary to protect the ATLAS silicon tracker under increasing LHC luminosity. We describe these instruments and their electronics.

Contents

1 Introduction

We describe a microcontroller-based combined ultrasonic gas mixture analyzer and flow meter for continuous real-time composition analysis of binary gas mixtures. Five instruments of this type will be used within the ATLAS Detector Control System (DCS) for flowmetry, coolant composition determination, and leak detection in the evaporative cooling systems of the ATLAS silicon tracker [1, 2].

The instrument exploits the phenomenon whereby the sound velocity in a binary gas mixture at known temperature and pressure is a unique function of the molar concentration of the two components of differing molecular weight. The combined flow measurement and mixture analysis algorithm is implemented together with the user interface in WINCC-OA® [3] running on a Dell Poweredge R610 under Linux. Measurements of temperature, pressure, and sound transit times in opposite directions are used with a velocity-composition database for on-line determination of binary gas mixtures. The database is created from prior measurements in calibration mixtures or from theoretical derivations made with an appropriate equation of state.

Figure 1 illustrates the connection architecture of the five ultrasonic instruments being incorporated into the ATLAS DCS. One analyzer has been used since January 2010 to monitor C_3F_8 coolant leaks into the N_2 envelope of the Pixel detector. Individual leaking circuits have been identified through C_3F_8 concentration changes of $< 5 \cdot 10^{-5}$. Similar analyzers will monitor the N_2 envelopes of the silicon microstrip tracker and the new Pixel B layer, respectively for C_3F_8 and CO_2 coolant leaks.

The compressor-based C_3F_8 evaporative cooling system of the ATLAS silicon tracker will be replaced with a thermosiphon [2] exploiting the hydrostatics of the 92 m shaft to the experimental cavern. At 60 kW dissipation $1.2 \, \text{kg} \cdot \text{s}^{-1}$ ($0.4 \, \text{m}^3 \cdot \text{s}^{-1}$) of vapour will return to the surface-level condenser. The flow will be calculated from sound transit time differences in opposite directions angled at $45°$ to the stream. Although the thermosiphon will initially operate with C_3F_8, the coolant may be changed to a blend containing 20–25% C_2F_6 to better protect the silicon against thermal runaway under increasing LHC luminosity [4]. The same instrument will be able to measure C_2F_6/C_3F_8 blend composition with a precision of $\sim 3 \cdot 10^{-3}$ [5]. Another instrument will monitor possible air ingress to the condenser, which will operate below atmospheric pressure. When air concentration

exceeds a predetermined threshold it will be automatically vented via a vacuum system to maintain condenser performance.

Although ultrasonic binary vapour analysis was first used for the N_2/C_5F_{12} radiator of the SLD Cherenkov Ring Imaging Detector [6] and subsequently adopted in all major RICH detectors, including DELPHI, COMPASS, and LHCb, none of these applications exploited simultaneous flowmetry and vapour analysis in the same instrument. The instrument described here has many applications where knowledge of binary gas composition and flow are required.
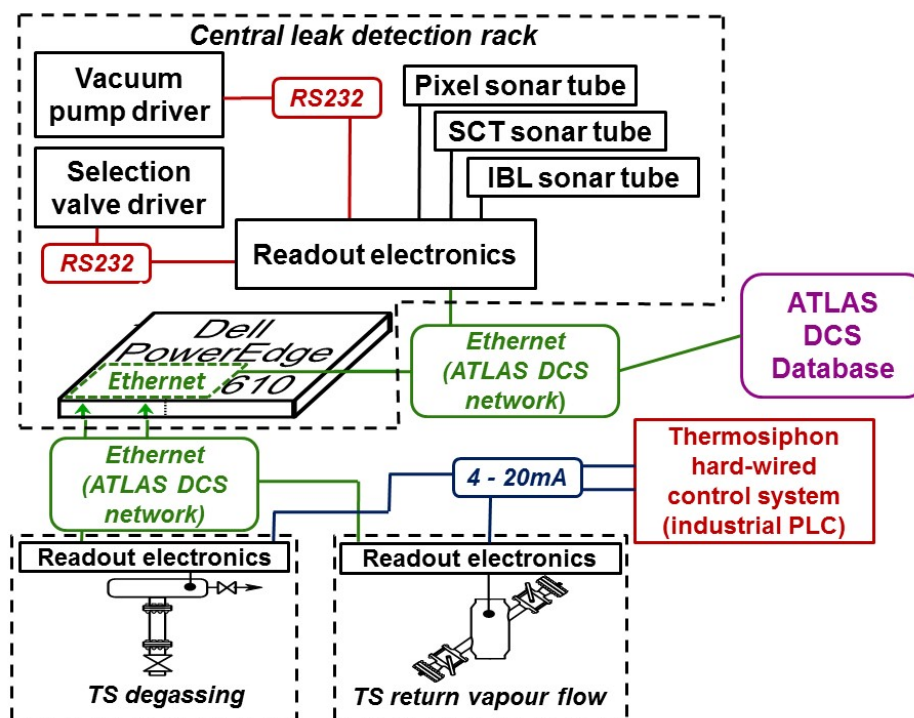

Figure 1. Connection architecture of the five ultrasonic instruments being incorporated into the ATLAS Detector Control System.

2 Principle of operation of the electronics

Figure 2 illustrates the major elements of the electronics, which is based on Analog Devices ADuC and Microchip® dsPIC33F microcontrollers and communicates using the MBED LPC1768 platform [7] via MODBUS TCP/IP over Ethernet. Custom timing electronics — internally implemented in the dsPIC33F microcontroller — generates 50 kHz ultrasound 'chirps' and synchronously starts a 40 MHz transit time clock, which is stopped by the first pulse crossing the user definable threshold (figure 3). The microcontroller also provides two 4–20 mA DAC signals proportional to transit time for use in external hardwired control systems. Analog inputs from NTC thermistors and pressure sensors are read in by the ADuC microcontroller.

Figure 4 illustrates the amplification and biasing scheme, which is adapted to the SensComp Model 600 instrument-grade 50 kHz capacitive-foil ultrasonic transducer [8] operated as

a transceiver. The DC bias voltage of around +300 V is provided by inexpensive custom DC-DC converters. When transmitting, the transducer foil is excited by down-going (300 V → 0 V) square wave pulses generated from LV precursors in the dsPIC33F microcontroller. For reception, the LV signal induced on the floating metal can of the transducer is DC-coupled to a signal chain containing a differential amplifier followed by a combined 4:1 analog multiplexer and linear programmable gain amplifier (Microchip MCP6S26). The following comparator is implemented in the dsPIC33F microcontroller. This new configuration replaces a previous version, where the foil signal was AC-coupled to the first amplification stage, and allows shorter transit times to be measured through elimination of the waiting time associated with the discharge of a HV DC blocking capacitor.
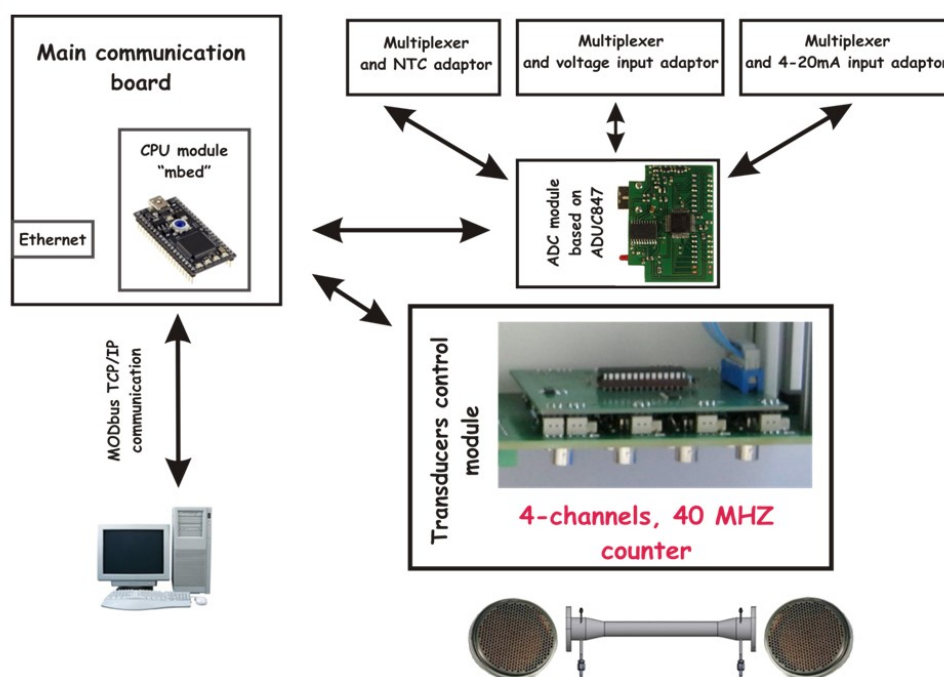
Figure 2. Main elements and connectivity of the bidirectional time-of-flight measuring electronics.

Transit times in both directions are needed to compute the gas flow rate, while the average of the sound velocities in the two directions (or a unidirectional measurement in quasi-static gas) is used together with temperature and pressure to compute the binary gas composition by comparison with stored *sound velocity vs. concentration* look-up tables.

Various modes for pulse injection in the opposite directions can be selected in the dsPIC33F microcontroller. Pulse injection can be simultaneous, alternate after a 'blanking' delay, or alternate triggered by the reception of above-threshold pulses.

Presently, mixture calculations are made using *sound velocity vs. concentration* look-up tables stored in the supervisory computer. In future versions of the instrument these calculations may be made in an on-board microcontroller to allow full standalone operation.

Bidirectional transit times, vapour temperature and pressure measurements are buffered, averaged, time-stamped, and pipelined by a FIFO memory implemented in the dsPIC33F microcon-
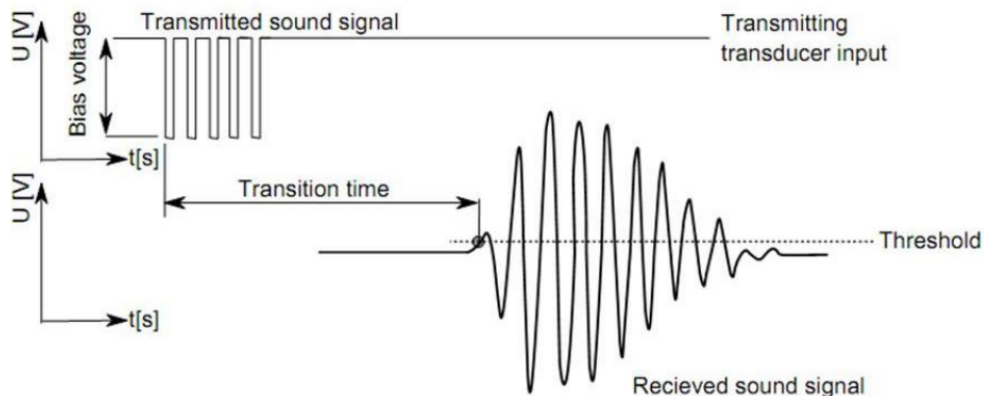
Figure 3. Principle of measurement of transit time between the first transmitted sound pulse and the first over-threshold detected pulse.
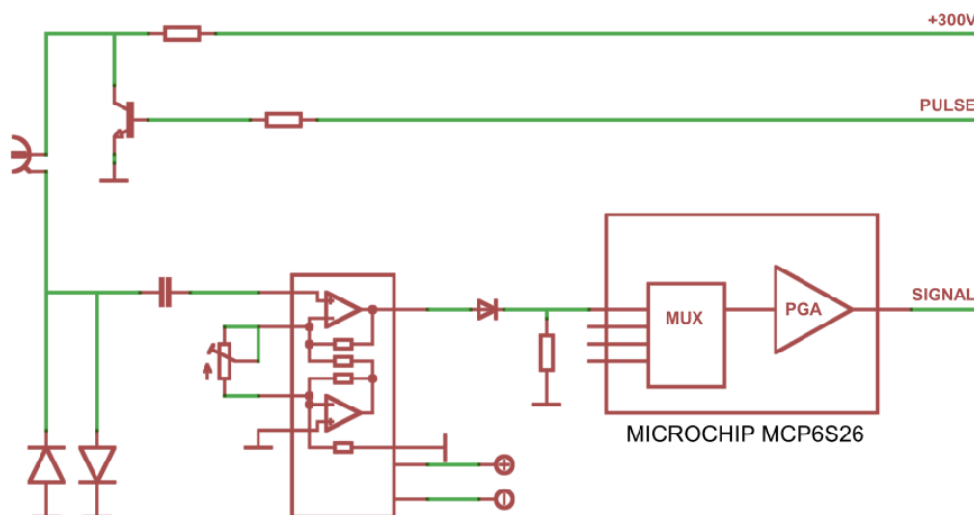

Figure 4. Ultrasonic transducer bias and amplification chain.

troller for transmission over Ethernet. For transit time measurements the FIFO buffer depth is 16, presently with median finding, while for temperature and pressure measurements the buffer depth is 4 with arithmetic mean averaging.

3   Results from various implementations of the instrument

The instrument has been implemented in several geometries, starting with a small "pinched axial" flow meter/analyzer [5] which has demonstrated a linearity of 2% of full scale for flows up to 230 litres per minute with simultaneous measurements of the C_2F_6 concentration in C_2F_6/C_3F_8 blends to a precision of $\sim 0.3\%$.

A second instrument has been used for more than a year to detect low levels of C_3F_8 coolant leaking into the N_2 environmental gas surrounding the ATLAS silicon Pixel detector. Figure 5 illustrates an 18-month continuous log of the C_3F_8 contamination of the Pixel detector envelope.

Fluctuations of the measured C_3F_8 contamination are correlated with the development of leaks in some of the 88 individual cooling circuits that were identified by progressive turn-on or turn-off. A reduction in sound velocity of $\sim 0.86\,\mathrm{m \cdot s^{-1}}$ from that of pure nitrogen is typically observed when all 88 circuits are operating.

The precision of the instrument for measurements of sound velocity is estimated to be better than $0.05\,\mathrm{m \cdot s^{-1}}$. Contributions to this uncertainty, $\boldsymbol{\delta c}$, are due to:

- $\pm 0.2°C$ temperature stability in the sonar tube (equivalent to $\pm 0.044\,\mathrm{m \cdot s^{-1}}$);

- ± 4 mbar pressure stability ($\pm 0.012\,\mathrm{m \cdot s^{-1}}$);

- ± 0.1 mm transducer inter-foil measurement uncertainty ($\pm 0.018\,\mathrm{m \cdot s^{-1}}$);

- ± 100 ns electronic transit time measurement uncertainty ($0.002\,\mathrm{m \cdot s^{-1}}$).

The precision of mixture determination, $\boldsymbol{\delta(mix)}$, at any concentration of the N_2 and C_3F_8 components is given by;

$$\partial \left(mix \right) = \frac{\partial c}{m} \tag{3.1}$$

where m is the local slope of the *sound velocity vs. concentration* curve ($\mathrm{m \cdot s^{-1} \cdot [\%C_3F_8]^{-1}}$).

The average gradient of the *sound velocity vs. concentration* curve is $-12.55\,\mathrm{m \cdot s^{-1} \cdot [\%C_3F_8]^{-1}}$ for C_3F_8 concentrations in the range 0%–0.5% in N_2. The intrinsic sound velocity measurement uncertainty of $\pm 0.05\,\mathrm{m \cdot s^{-1}}$ yields, via eq. (3.1) a corresponding mixture uncertainty of $\pm 0.004\%$.

The gas extraction and sampling system (figure 6) also allows measurement of C_3F_8 leak rates into the N_2 gas envelope of the silicon microstrip (SCT) tracker, and CO_2 coolant leaks from the new "Insertable B-Layer" Pixel detector (IBL) into its external N_2 envelope.

Gas is continuously aspirated from six points (Pixel: 1; SCT: 4; IBL: 1) of the sub-detector environmental gas envelopes, and is sent for sequential analysis — via a matrix of normally-open (NO) and normally-closed (NC) pneumatic valves — in three ultrasonic instruments (see also figure 1). The entire sequence of operations is supervised by the WINCC–OA control system.

Gas exiting the three tubes is vented to the air extraction system for return to the surface. Injection points for automated periodic recalibration of the analysis tubes with pure nitrogen are also incorporated.

In the case of the ATLAS IBL, the smaller difference in molecular weight between CO_2 and N_2 results in a shallower slope to the *sound velocity vs. concentration* curve. For example, in the (0%–0.1%) molar range, of most interest in leak detection, the slope is $-1.12\,\mathrm{m \cdot s^{-1} \cdot [\%CO_2]^{-1}}$. This slope, taken in combination with a $\boldsymbol{\delta c}$ of $\pm 0.05\,\mathrm{m \cdot s^{-1}}$ would result in a mixture resolution of $\pm 4.4 \cdot 10^{-4}$. Efforts are underway to improve the precision of temperature control: the biggest contributor to the sound velocity uncertainty.

Initiated by the plans to replace the present underground compressor-driven C_3F_8 circulation plant with a thermosiphon [2], two additional instruments have been constructed.

The first of these (figure 7) will monitor and eliminate air leaking into the surface condenser, which operates below atmospheric pressure. Although the difference in molecular weight between C_3F_8 and air (respectively 188 and 29 units) is very large, this instrument operates well
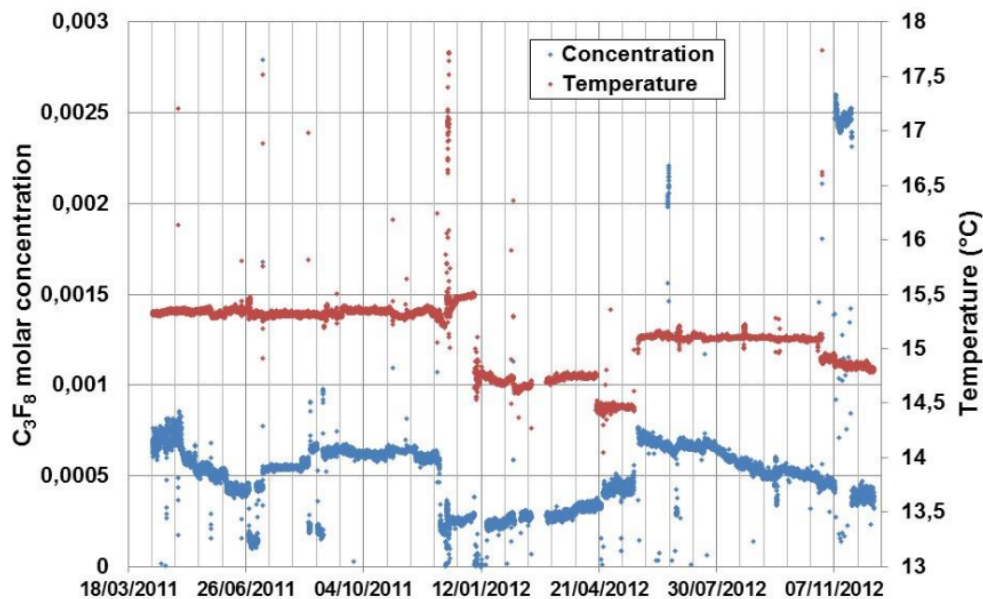
Figure 5. Long duration (18 month) log of C_3F_8 leak contamination in the N_2 environmental gas surrounding the ATLAS Pixel detector.
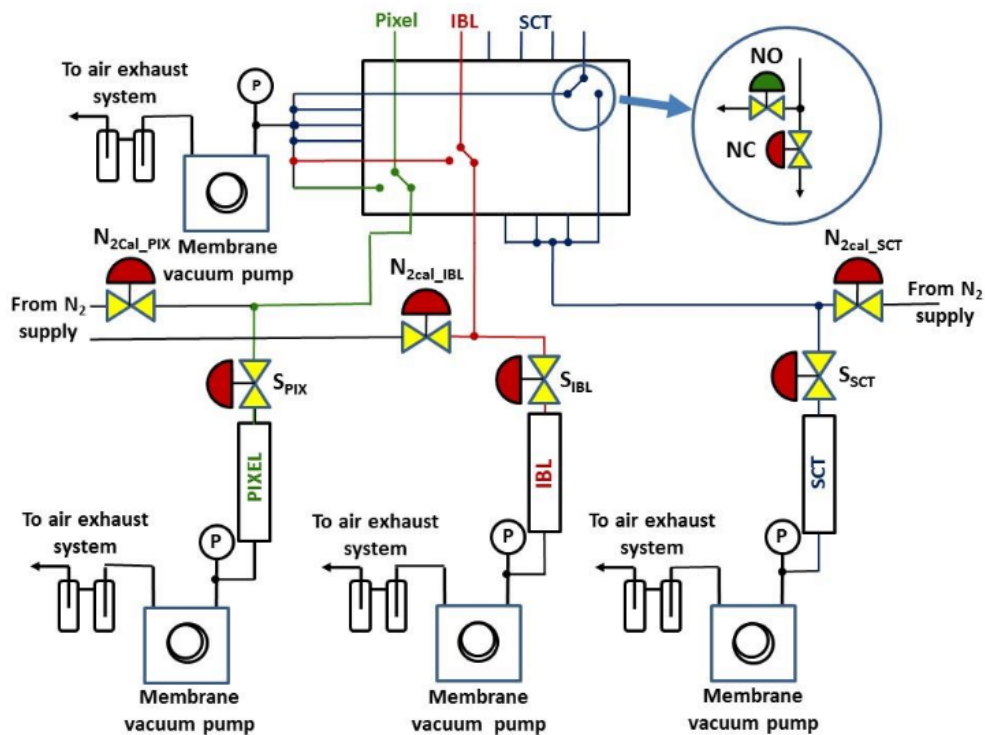

Figure 6. Automated sampling system for continuous ultrasonic monitoring of C_3F_8 coolant leaks into the N_2 volumes surrounding the ATLAS silicon Pixel and SCT trackers, and for CO_2 coolant leaks into the N_2 volume surrounding the new IBL Pixel detector.

in a mode where a light contaminant leaks into a heavy carrier. The slope for the corresponding end of the *sound velocity vs. concentration* curve is shallower, e.g., in the (0%–10%) molar range, of most interest in this application, the slope of the *sound velocity vs. concentration* curve is $0.53\,\text{m}\cdot\text{s}^{-1}\cdot[\%\,\text{air}]^{-1}$. This slope, taken in combination with the sound velocity measurement error of $\pm0.05\,\text{m}\cdot\text{s}^{-1}$, results in a mixture resolution of $\pm9.4\cdot10^{-4}$.
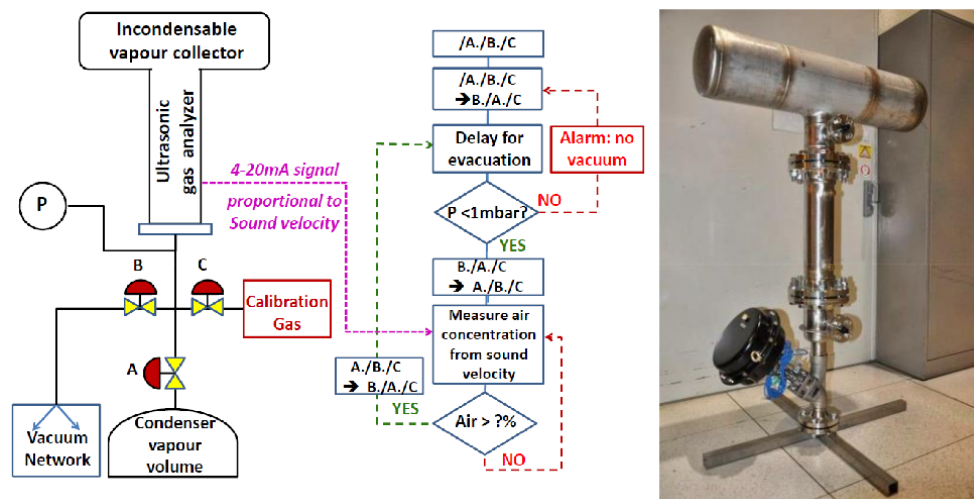

Figure 7. Operating schematic and photograph of the ultrasonic instrument for the monitoring and elimination of ingressed air in the condenser of the ATLAS thermosiphon fluorocarbon coolant recirculator.

The second instrument is a combined ultrasonic gas mixture analyzer and flow meter (figure 8) which has been installed in the 133 mm diameter C_3F_8 coolant vapour return tube from the silicon tracker to the surface condenser, in which very high flow rates of around $1.2\,\text{kg}\cdot\text{s}^{-1}$ ($>400\,\text{l}\cdot\text{s}^{-1}$) are expected. Computational fluid dynamics studies [5] showed that only an angled crossing geometry, with the transducers not impinging on the gas flow, was suitable. The flow meter has been built with a 45° crossing angle and calibrated in air against a commercial anemometer (Amprobe model TMA10A: $25\,\text{m}\cdot\text{s}^{-1}$ full-scale (FS) with intrinsic accuracy $\pm2\%$ FS). The *rms* accuracy of the ultrasonic flow meter is equivalent to $\pm2\%$ of the full-scale flow, of $10\,\text{m}\cdot\text{s}^{-1}$, achievable with the available air supply. Tests of this instrument with fluorocarbons will be made as soon as the closed thermosiphon circulation system becomes available.

4 Conclusions and future applications

We have developed a combined, real-time flow meter and binary gas analyzer with custom electronics and dedicated SCADA software running under WINC-OA [3] (a CERN standard). First, a small "pinched axial" flow meter/analyzer has demonstrated a linearity of 2% of full scale for flows up to $230\,\text{l}\cdot\text{min}^{-1}$ with simultaneous measurements of C_2F_6/C_3F_8 blend molar ratios to a precision of $\sim0.3\%$. Another instrument, in continuous operation over more than 18 months, has demonstrated a sensitivity of $<4\cdot10^{-5}$ to C_3F_8 leaks into the N_2 envelope of the ATLAS Pixel detector. The sampling system also includes analyzers for C_3F_8 leaks from the SCT detector and CO_2 leaks from the IBL detector.
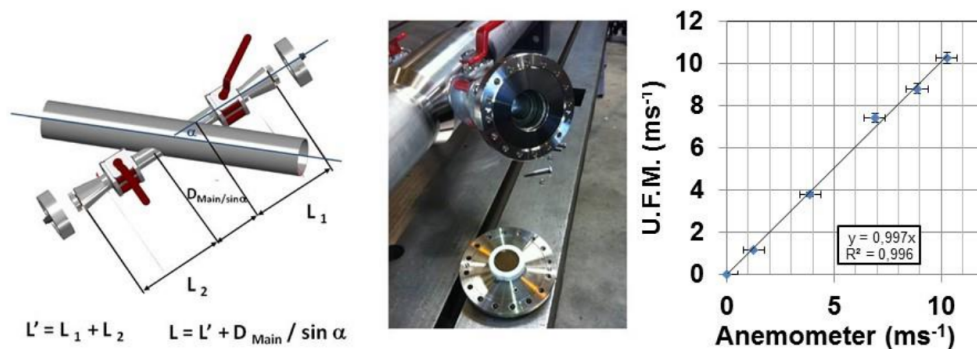
Figure 8. Constructional details, ultrasonic transducer mounting, and air calibration of the high-flow angled flow meter of the ATLAS thermosiphon.

Lastly, two other instruments have been developed for the new ATLAS thermosiphon recirculator. One will detect and eliminate ingressed air from the surface condenser, which will operate below atmospheric pressure. The second instrument, with a sound path angled at $45°$ to the gas flow, will measure fluorocarbon flows back to the condenser which can be as high as $0.4\,\mathrm{m^3s^{-1}}$ when the SCT and Pixel detectors operate at their full dissipation of $60\,\mathrm{kW}$. Tests in air have demonstrated a flow measurement precision of $\pm 2\%$ of full scale up to $10\,\mathrm{m\cdot s^{-1}}$ and the instrument will soon be tested with fluorocarbons.

The instruments described in this work have many potential applications where continuous binary gas analysis is required in real-time; these include the analysis and flowmetry of hydrocarbon mixtures, vapour mixtures for semi-conductor manufacturing, and anaesthesia.

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