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A Versatile Evaporative Cooling System Designed for Use in an Elementary Particle Detector

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Abstract An evaporative cooling system developed for operation and qualification testing of silicon pixel and microstrip detectors for the inner tracking detector of the CERN ATLAS spectrometer is described. Silicon detector substrates must be continuously operated between 0 and −7°C in the high radiation environment near the circulating beams at the CERN Large Hadron Collider (LHC). This requirement imposes unusual constraints on the cooling system and has led to the choice of perfluoro-*n*-propane (C_3F_8) refrigerant, which combines good chemical stability under ionizing radiation with high dielectric strength and nonflammability. Since the silicon detectors must also be of extremely light construction to minimize undesirable physics background, coolant tubes are of thin (200 μm) aluminum wall, while evaporative operation allows a very low circulating coolant mass-flow (1–3 $g \cdot s^{-1}$/100 W to evacuate). The assembled detector arrays will undergo qualification tests at room temperature before installation in the ATLAS spectrometer. The cooling system is "dual-fuel," and can also be operated with perfluoro-*n*-butane (C_4F_{10}) refrigerant, offering a reduced evaporation pressure (1.9 bar) compared to that of C_3F_8 (6.5 bar at 15°C).

Keywords ATLAS detector · Cooling circuit · Experimental results · Flow control system · Fluoroinert refrigerant · Inner detector structures

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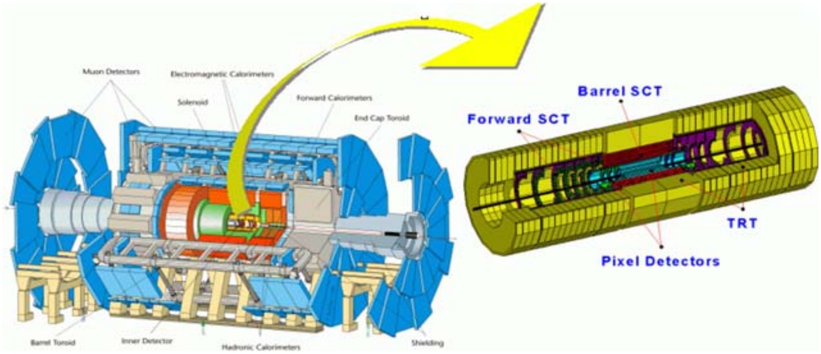

Fig. 1 General view of the ATLAS spectrometer inner tracking detector, showing positions of the silicon pixel and microstrip (SCT) detectors

1 Introduction

Figure 1 illustrates the elements of the silicon pixel and microstrip (SCT) detectors, located at the heart of the inner tracking detector of the 12,000 tonne ATLAS toroidal magnetic spectrometer, which will come into operation at the CERN Large Hadron Collider (LHC) in 2007.

The ATLAS pixel and micro-strip detectors are divided into around 320 linear and disk-like arrays of sensor tiles with a total silicon area in excess of 20 m^2 [1,2]. The linear arrays ("staves") have lengths varying between 0.8 and 1.6 m with up to 13 sensors tiled along them. The total dissipation of the semiconductor tracking detectors will be $\sim$60 kW. The evaporative cooling system must have a high modularity to minimize fraction of the detector out of service in the event of a local fault. More than 200 parallel channels (with an adjustable flow rate in the limited range and controlled evaporating temperature) will be supplied from a central compressor station comprising up to seven parallel compressors.

The safeguarding of the sensitive and expensive semiconductor detectors and electronics in the difficult high radiation environment imposes new and nonstandard constraints on the cooling system. The coolant should be electrically nonconducting and chemically inert in the event of a leak. The temperature gradient along the cooling channels should be minimized using a cooling fluid that is noncorrosive, nontoxic and nonflammable. Also, the circuit should operate with oil-free circulation. This has led to the choice of saturated fluorocarbon ($C_nF_{(2n+2)}$) refrigerants, which combine high dielectric strength with good chemical stability under ionizing radiation and compatibility with the materials used in the construction of the ATLAS inner tracking detector.

In addition to these concerns, the total amount of structural material must be minimized to reduce background from secondary particles. Coolant is evaporated inside the structures to be cooled, to allow a very low circulating coolant mass flow (1–3 $g \cdot s^{-1}$/100 W to evacuate). The coolant tubing is of thin aluminum wall, and it is not possible to locally fit flow control valves or regulators on the cooled structures as is normal practice on evaporators in industrial cooling applications.

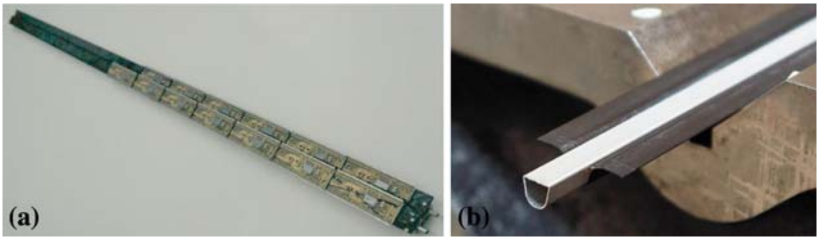

Fig. 2 (**a**) Pair of ATLAS pixel detector "staves" showing detector substrates bonded onto 80-cm-length carbon–carbon support and thermal drain structures, and (**b**) "D"-shaped 200-μm-wall aluminum cooling tube of a pixel "stave" in its carbon-fiber "Ω"-channel before bonding to the carbon–carbon support

Figure 2a and b illustrate the mechanical structure of part of the ATLAS pixel detector. Silicon pixel tiles are glued to a support and thermal drain structure machined from carbon–carbon. Heat enters the flat side of a 'D'-shaped aluminum tube (200 μm wall; $D_H = 3.6$ mm) held in contact with the rear of the carbon–carbon support by an 'Ω'-shaped carbon-fiber extrusion. The difference in the coefficient of thermal expansion of the tube and support is accommodated by a sliding thermal grease contact between the two.

Although the silicon detector substrates must be continuously operated between 0 and −7°C (depending on their proximity to the circulating high-intensity proton beams) for a 10-year operational lifetime at the LHC, thermal impedances in the support structures channeling heat from the detector tiles to the cooling fluid dictate an in-tube fluid evaporation temperature of about −25°C. The evaporation of the C_3F_8 refrigerant (saturated vapor pressure of 1.8 bar at −25°C) was convenient in this regard.

The assembled detector arrays will undergo qualification testing before installation in the ATLAS spectrometer. These tests will be made at room temperature, avoiding the need for a second large low-temperature nitrogen envelope of the type used in the final installation. A second evaporation temperature close to +15°C was needed to keep all surfaces above the dew point in the test chamber. With this in mind, we adapted the circulator for "dual-fuel," operation. Replacing the C_3F_8 in the condenser with C_4F_{10} reduces strain on the thin aluminum wall tubing during this test phase, allowing the same evaporation temperature at 1.9 bar, as needed to be obtained with C_3F_8 at 6.5 bar.

The operation of this cooling system has been verified using the two fluids. Section 2 describes the cooling system and its control elements, while Sect. 3 illustrates thermal measurements on a preproduction ATLAS pixel structure.

2 "Dual-Fuel" Evaporative Cooling Test System

2.1 Main Elements of the Cooling System

The evaporative cooling system [3–5], shown in Fig. 3, is based on an oil-free piston compressor[1] and has a maximum cooling capacity of ∼250 W. Perfluoro-*n*-propane

[1] SOGX 50-D4 dry piston compressor (3.6 $m^3 \cdot h^{-1}$ air, $P_{in(out)} = 1(9)$ bar); Mfr: Fritz Haug AG, CH-9015, Saint Gallen, Switzerland.

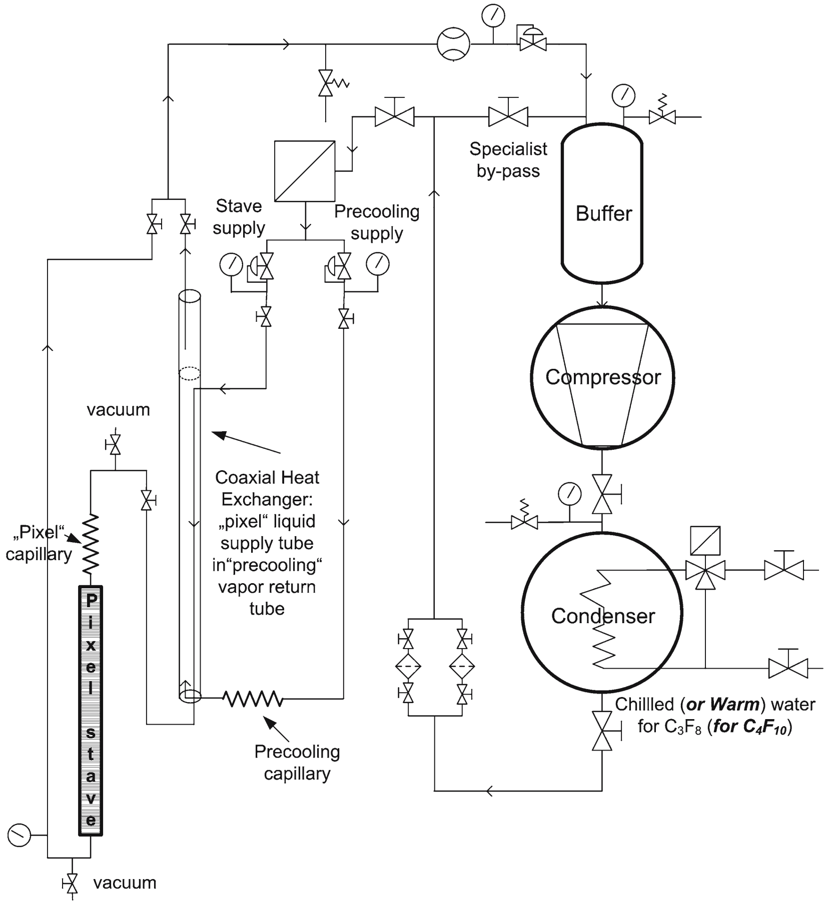

Fig. 3 "Dual-fuel" evaporative cooling test system

(C_3F_8)[2] or perfluoro-*n*-butane (C_4F_{10})[3] circulates from a condenser[4]—which also serves as a storage tank when the system is shut down—to a pixel structure undergoing thermal test (the evaporator) and back to the compressor via an aspiration buffer maintained at a pressure of 1 bar. The total round-trip tube length of 50 m corresponds to the length of the coolant flow path in the ATLAS detector [1,2].

Several properties of the two refrigerants are shown in Table 1 and were studied extensively for our purpose [6–8]. Evaporative cooling allows for a very low circulating coolant mass flow and liquid refrigerant delivery to the detector through capillaries with inner diameters (ID's) as small as 0.6 mm.

[2] Suppliers 3M, Ausimont S.p.A., 15047 Spinetta Marengo, Italy; Astor Co., 197198 St. Petersburg, Russia.

[3] Mfr.: 3-M Corp. Specialty Chemicals Division, St. Paul, MN, USA; PFG 5040, grade >99% purity.

[4] Model NK 17-100/6P; Mfr: WAEKA AG, CH-5507, Melingen, Switzerland.

Table 1 Selected refrigerant properties (−15°C)

Fluid formula	Latent heat ($kJ \cdot kg^{-1}$)	Liquid–gas expansion factor at −15°C	s.v.p at −15°C (bar)	s.v.t. at 2 bar (°C)
C_3F_8	97	71.4	2.46	−21
C_4F_{10}	101.1	242.6	0.58	+16

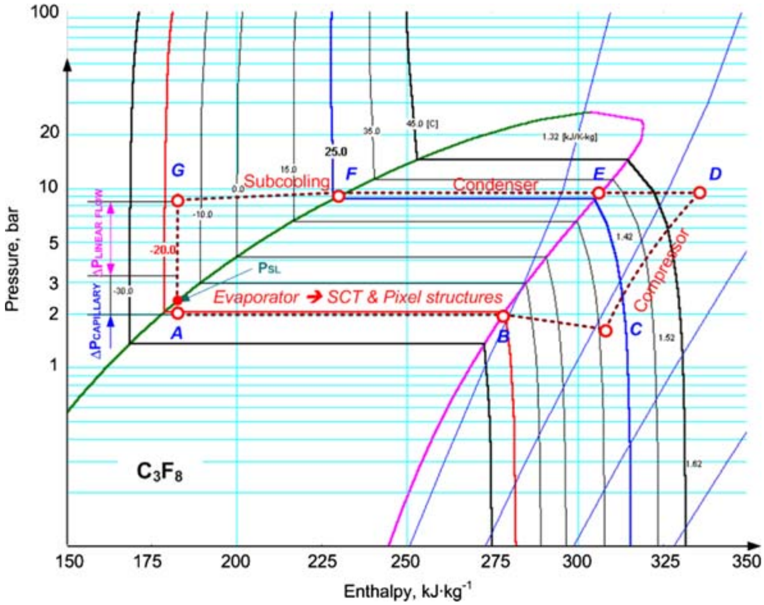

Fig. 4 Simplified pressure–enthalpy-phase diagram for C_3F_8 circulation

Figures 4 and 5 illustrate the pressure–enthalpy diagrams for the two fluids. The flow of liquid to the pixel structure is set using a dome-loaded flow regulator,[5] which is piloted via a voltage-to-pressure ('V2P') driver.[6] The flow of coolant to the pixel structure can be set to a fixed value or varied according to the refrigeration power required (Sect. 2.4).

The evaporation pressure (and temperature) in the pixel structure is set via a dome-loaded back-pressure regulator.[7] A second cooling circuit, using an identical flow regulator, may be used to increase the available enthalpy of the fluorocarbon refrigerant. Liquid coolant sent to the pixel structure through a copper tube with OD/ID of 6 mm/4 mm is cooled by evaporation of the same fluid in a coaxial counter-flow

[5] Model 44-2211-242-1099; Mfr: Tescom Industrial Controls Division, Elk River, MN 55330, USA, Gain = 1, offset = 0.

[6] Model PS111110-A; Mfr: Hoerbiger Origa GmbH, D-70794 Filderstadt, Germany; Input 0-8 VDC, output 1-9 bar.

[7] Tescom Model 26-2310-28-205, Gain = 1, offset = 0.

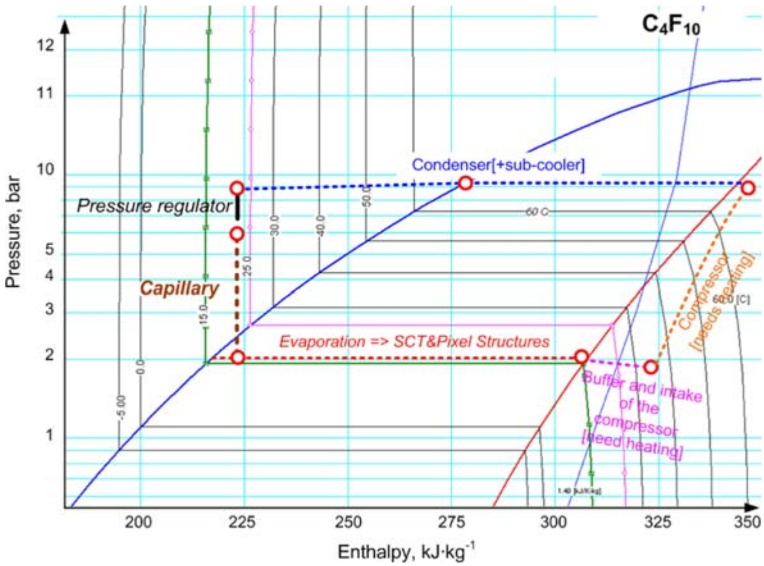

Fig. 5 Simplified pressure–enthalpy-phase diagram for C_4F_{10} circulation

heat exchanger whose outer envelope is an insulated copper tube with OD/ID of 14 mm/12 mm. The tube diameters are chosen to correspond to those in the ATLAS installation where space for services is very limited. The length of the precooling heat exchanger is around 25 m:—almost the entire length of the supply side—and the evaporation pressure (temperature) is maintained at the same value as the pixel circuit through sharing the same back-pressure regulator.

2.2 Condenser Pressure Control

The condenser is the highest pressure point in the circulator. Its pressure is maintained at 8.5 bar by a three-way water valve[8] receiving its drive signal from an industrial PID controller[9] monitoring the condenser pressure via an electronic pressure sensor. A 10°C chilled water supply is used with C_3F_8. With C_4F_{10} a hot water source at 55°C is used.

2.3 Compressor Aspiration Pressure Control

The compressor aspiration buffer is the lowest pressure point in the circulator. Its pressure is maintained at 1 bar by variation of the three-phase frequency sent to

[8] Sauter Automation Model B6R equipped with AVR32 W32S servomotor.

[9] Model G9FTE-R*E1R-88-N; Mfr: RKC Instrument Co., 16-6 Kugahara, 5-Chome Ohta-Ku, Tokyo, Japan.

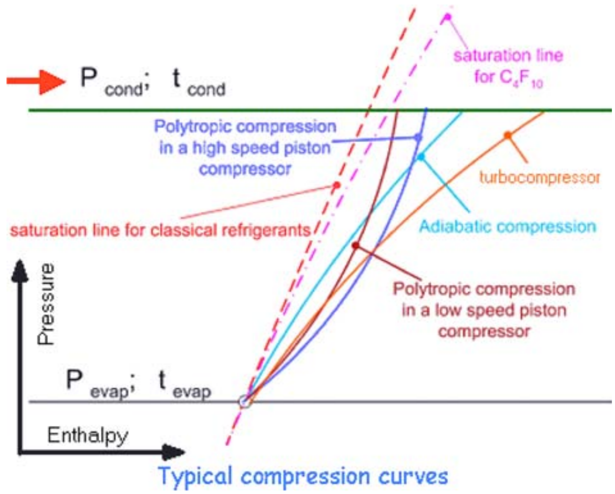

Fig. 6 Typical compression curves

the compressor motor. A motor speed controller[10] receiving its drive signal from an industrial PID controller[11] monitors the aspiration buffer pressure via an electronic pressure sensor. The buffer is heated for operation with C_4F_{10} to prevent condensation. The crankcase of the compressor is maintained at 50°C to prevent condensation and possible resultant damage to the compressor. The estimates of the temperature ranges were made with respect to the typical compression curve shown in Fig. 6 applicable to our low-speed piston compressor.

2.4 Flow Control

Refrigerant mass flow through the "pixel" and "pre-cooling" loops depends on the pressure set on the dome-loaded flow regulators. Figure 3 also illustrates the flow control principle; the maximum pressure range available for linear mass flow control is the pressure difference between the condensation and desired evaporation isotherms minus the pressure drops in the supply tubing and capillary. This range depends approximately linearly on the degree of sub-cooling.

Mass flow can be decreased by reducing the analog compressed air signal on the regulator dome down to a "zero cooling" limit at which the capillary pressure falls below the saturated liquid pressure. Note: the requirement of minimal material near the silicon detectors means that the flow regulators must be placed about 30 m upstream of the capillaries.

Mass flow can be set to fixed values or varied dynamically according to the thermal load on the cooling channel. In the latter case, feedback from a temperature sensor in

[10] Model CIMR-XCAC41P5, (400 V 3-phase, 3.7 kVA); Mfr: Yaskawa Co., 1-16-1 Kaigan, Minato-Ku, Tokyo 105-6891, Japan.

[11] RKC Model G9FTE-R*E1R-88-N.

the exhaust tubing is used to vary the voltage sent to the V2P driver (which in turn varies the analog air signal) via a PID algorithm stored in a commercial controller[12] or written into a microcontroller chip[13] [4,5]. The PID control loop varies the mass flow to maintain the temperature on the exhaust sensor a few degrees above the isotherm temperature at the chosen evaporation pressure. In this way, the cooling power is adapted to the number of silicon detector tiles that might be powered on a particular cooling circuit, with minimum injection of un-evaporated coolant into the exhaust tubing.

2.5 Evaporation Pressure Control

The desired evaporation isotherm is selected by applying the corresponding pressure to the dome of the back-pressure regulator. Since the requirement of minimal material near the silicon detectors requires that the back-pressure regulator be placed about 30 m downstream of the evaporators, the pressure applied to the dome of the backpressure regulator must correspondingly be reduced to allow for the pressure drop in the exhaust tubing.

3 Results from Cooling Evaluation

Figure 7 illustrates some typical cooling runs with C_3F_8: in (a) with an evaporation temperature around −25°C and in (b) at a slightly higher temperature with the evaporation pressure set to 2 bar.

The data in Fig. 8 represent a half-day continuous run with C_4F_{10} on an ATLAS pixel "stave" (l = 0.8 m). The cooling system behavior was stable and smooth. The system was capable of auto-correction under changing power load (stepping power from zero up to a maximum dissipation of 37 W and back down). We made several cycles of this type. With in-tube evaporation pressures between 1.8 and 1.9 bar, the temperatures of the pixel substrates varied between 14°C (zero power) and 20°C (37 W dissipation). The hottest substrate did not exceed 22°C.

4 Future Developments

An evaporative system based on a 22 kW rated compressor[14] is currently under construction for the final testing of silicon pixel and microstrip detectors before their installation in the ATLAS spectrometer. This system can test a maximum of one third of the ATLAS silicon at a time. The installation was originally designed to the standard specification; silicon operational below −7°C with C_3F_8 evaporation at the −25°C isotherm. In this mode, however, it would be necessary to surround the silicon

[12] RKC Model HA901.

[13] AT90S8515; Mfr: ATMEL Corp, San Jose, CA 95131, USA, programmed from C via GNU toolkit.

[14] Haug QTOGV125LM; $80\,m^3 \cdot h^{-1}$ C_3F_8 vapor; $P_{in(out)}$ 1 (10) bar.

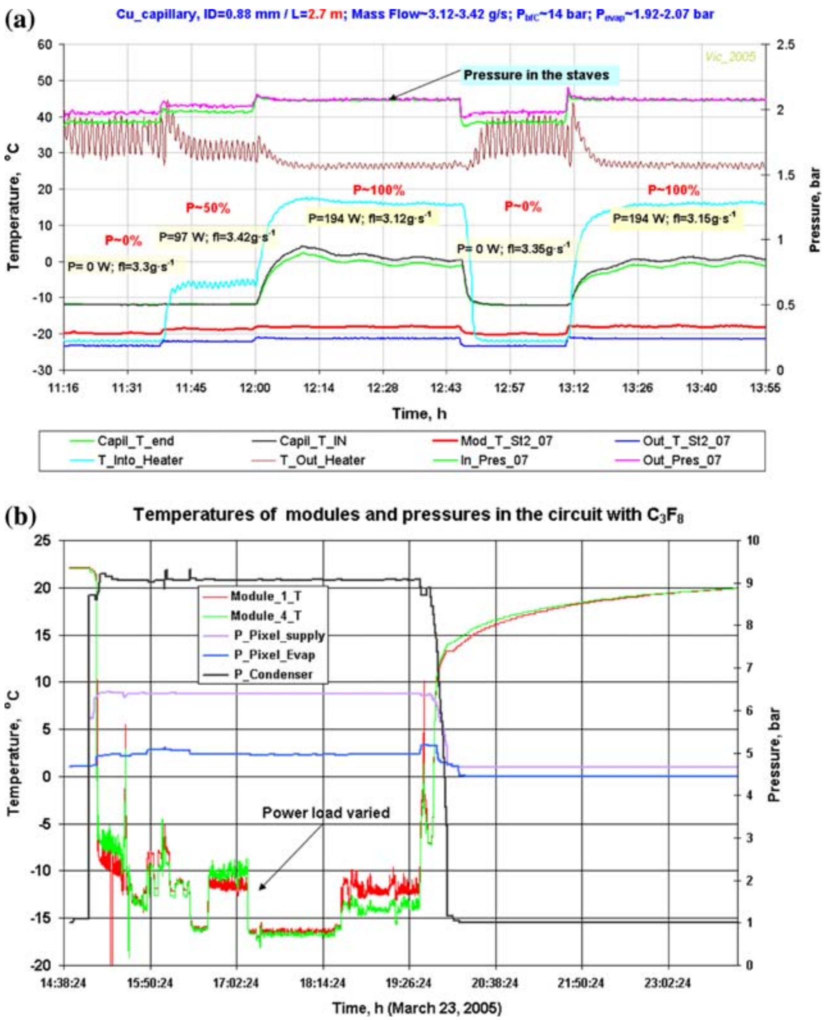

Fig. 7 Some typical runs with C_3F_8: (**a**) two staves in series and (**b**) single stave; performed with pixel structures

detectors in an atmosphere with a dew point of −35°C or lower, held in a complex gas-tight enclosure pierced with numerous cables and coolant tubes.

A "warm test" mode with an evaporation temperature between 14 and 18°C could dispense with this enclosure and maintain the sensitive silicon components above the dew point in normal laboratory conditions. Since evaporative cooling with C_3F_8 at these temperatures would subject the fragile cooling tubes to pressures around 7 bar, we proposed the use of C_4F_{10}. When the pressure drops in the cooling circuit were recalculated for C_4F_{10}, it was found that the refrigerant change would move the circuit parameters to the required temperature regions for the "warm test" mode, where the pressure would be around 1.8 bar, with no changes to the hardware.

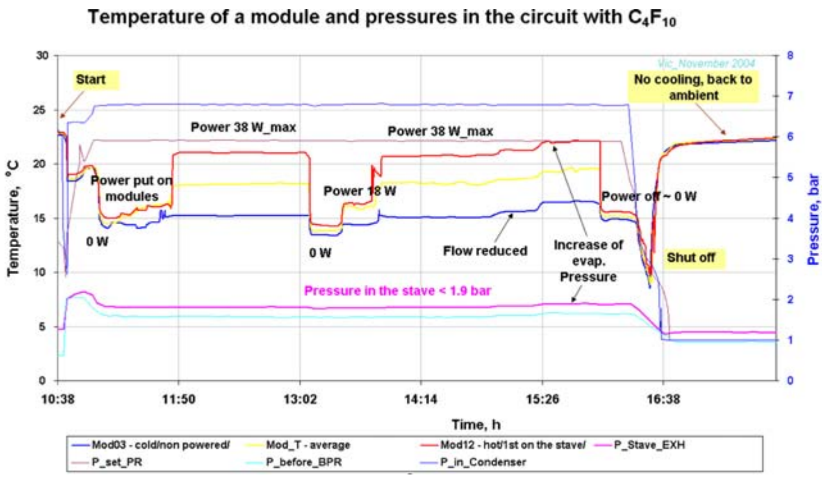

Fig. 8 Record of the run with C_4F_{10}

5 Conclusion

A simple evaporative cooling recirculator has been constructed using tube dimensions and length characteristics of the final installation in the ATLAS inner tracker. The system is “dual fuel,” allowing changeover between C_3F_8 (‘cold’ evaporation on the −25°C isotherm) and C_4F_{10} (room temperature evaporation on the 15°C isotherm) with only an increase in condenser temperature from 10 to 55°C and the heating of the compressor aspiration buffer.

All the circuit hardware remained unchanged. A detailed study was made of the pressure drops in the supply lines and degree of subcooling enhanced via passive subcooling, due to the advantageous ambient temperature for C_4F_{10} use. The study confirmed that the same control elements (valves and even capillaries) could be used. The only minor inconveniences in the changeover were the exchange of the process fluid and the corresponding changes to the various process set points.

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References

1. ATLAS Inner Detector Technical Design Report CERN/LHCC/97-16, 30.04.1997
2. ATLAS Pixel Detector Technical Design Report CERN/LHCC/98-13, 31.05.1998
3. E. Anderssen, D.L. Bintinger, S. Berry, P. Bonneau, M. Bosteels, P. Bouvier, D. Cragg, R. English, J. Godlewski, B. Górski, S. Grohmann, G.D. Hallewell, T. Hayler, S. Ilie, T. Jones, J. Kadlec, S. Lindsay, W. Miller, T.O. Niinikoski, M. Olcese, J. Olszowska, B. Payne, A. Pilling, E. Perrin, H. Sandaker, J.F. Seytre, J. Thadome, V. Vacek, in *Proceedings of the 5th Workshop on Electronics for LHC Experiments, Technical Design Report CERN 99-09 CERN/LHCC/99-33*, Snowmass, CO, USA (1999), p. 421

4. C. Bayer, S. Berry, P. Bonneau, M. Bosteels, H. Burckhart, D. Cragg, R. English, G. Hallewell, S. Ilie, S. Kersten, P. Kind, K. Langedrag, S. Lindsay, M. Merkel, S. Stapnes, J. Thadome, V. Vacek, in *Proceedings of the 6th Workshop on Electronics for LHC Experiments*, Crackow, Poland (2000), CERN 2000-101 CERN/LHCC/2000-041
5. C. Bayer, S. Berry, P. Bonneau, M. Bosteels, H. Burckhart, D. Cragg, R. English, G. Hallewell, B. Hallgren, S. Ilie, S. Kersten, P. Kind, K. Langedrag, S. Lindsay, M. Merkel, S. Stapnes, J. Thadome, V.Vacek, *2000 IEEE Nuclear Science Symposium Conference Record*, vol. 2. Lyon, France (2000), p. 10/1–5, ISBN: 0-7803-6503-8
6. V. Vacek, G. Hallewell, S. Lindsay, Fluid Phase Equilib. **185**, 305 (2001)
7. M. Lísal, W. R. Smith, M. Bureš, V. Vacek, J. Navrátil, Mol. Phys. **15**, 2487 (2002)
8. V. Vacek, G. Hallewell, in *CTU Reports, Proceedings of Workshop 2002*, vol. 6, Part A. CTU in Prague (2002), p. 150, ISBN 80-01-02511-X