Recent Modifications and tests of the SCT & Pixel Evaporative Cooling System for the Atlas Inner Detector

Prepared by G. Hallewell and V. Vacek

With special thanks to: C. Bayer, H. Burckhart, D. Cragg, R. English, B. Hallgren, K. Langedrag, M. Merkel and M. Bosteels team
and
S. Stapnes & G. Tappern, witnesses and observers

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AGENDA:

(1) *Postmortem of Dec '99 Input Liquid/Exhaust Vapour Counter-Current Heat Exchanger Test* **– Some Comments**
(2) Modifications to Lab Circulator to study New Flexible Supply/Exhaust Configuration
(3) Status of Tests in May 2000 & Current results & Additional tests
(4) *Phase (2) Circulator Plans and Status* **– Some Comments**

(1) Postmortem of Dec '99 Input Liquid/Exhaust Vapour Counter-Current Heat Exchanger Test

Are heat exchangers needed? If so, what type?…Should we use the exit vapor (*and more dangerously? any unevaporated liquid*…) to sub-cool the input liquid ?

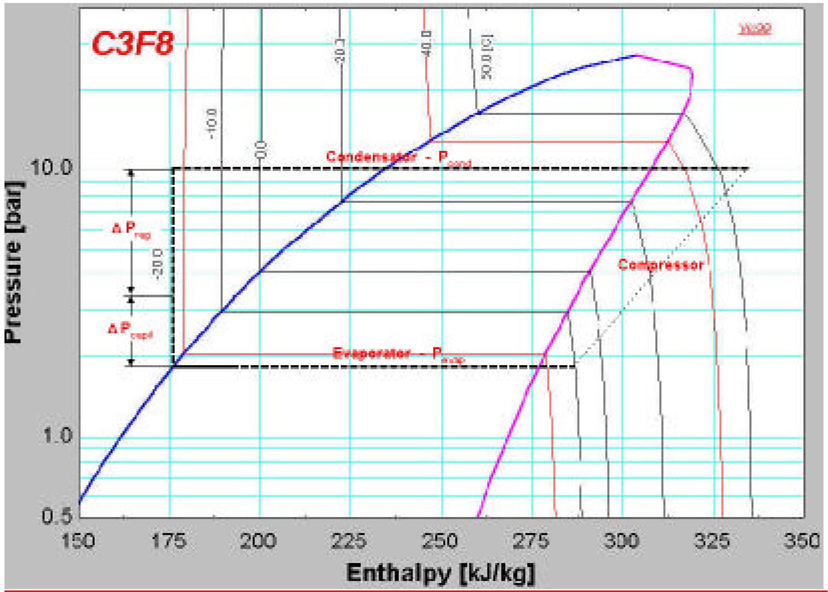
RISK OF A POSITIVE FEEDBACK (FLOOD) SITUATION?

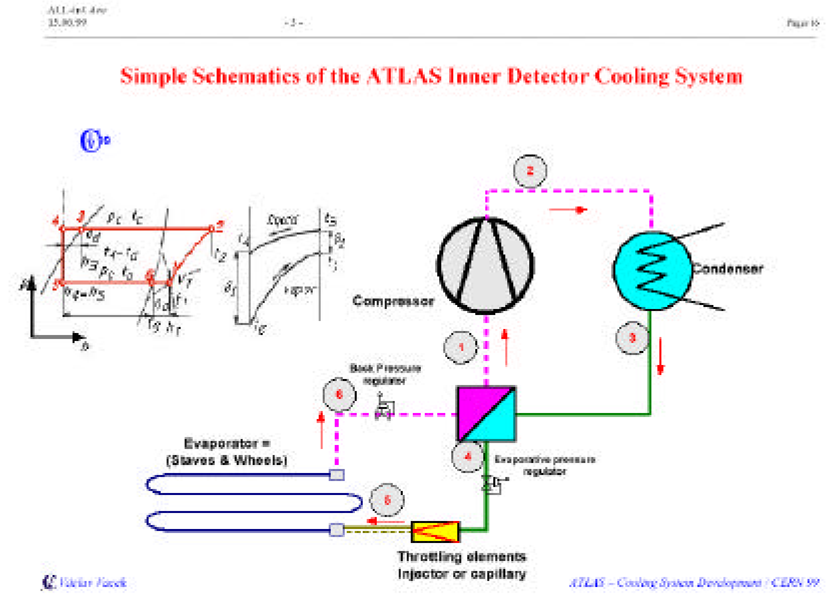
Role of a(ny) heat exchanger should be to minimize the mass flow of coolant necessary to evacuate a given heat dissipation, by optimizing the arrival condition of the liquid coolant.

LIMITATIONS TO RESPECT IN OUR EVAPORATIVE SYSTEM

(1) We have a fixed orifice reducing element that is not accessible;

(2) The pressure of liquid upstream of this (P_{EVAP}) cannot drop below the saturated liquid pressure (P_{SL}) at the liquid temperature, or boiling will occur (saturated liquid line crossed in cycle diagram);➔ ➔



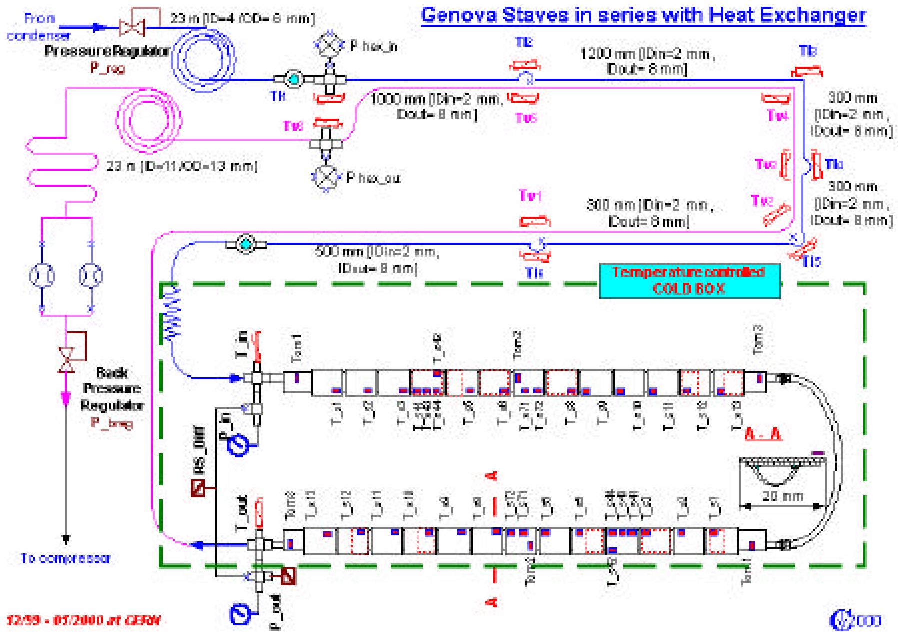


(3) Above the S.L.L. a range of pressure ((P_{COND}) - (P_{EVAP})) is available for the linear regulation of mass flow rate (There is an advantage to having the lowest liquid temperature that is reasonable, upstream of the orifice since this extends this linear range); ➔ ➔

(4) The evaporative circuit behaves like an enthalpy potential divider. If too much enthalpy (heat take up potential) is available for the heat to be evacuated from the evaporator (stave), it will be used up elsewhere (i.e.) downstream in the exhaust tubing at a rate (length) depending on insulation level and additional heat sources. Boiling liquid in exhaust line, but << %X0 all liquid.

Reaction time in an evaporative cooling system depends on the time to adjust enthalpy *(rather than mass flow)* to a varying heat load…

- **At a given mass flow, an exhaust vapor ➔ supply liquid HeX alone can (depending on its efficiency) cause a *positive feedback* in enthalpy availability (seen in the HeX tested by Olcese and Vacek➔).**



•

This excess enthalpy is mainly available in the form of extra liquid that cannot be evaporated in the evaporator stave at its given power dissipation (rather than sensible heat of any cold, already evaporated vapor).

- **Reducing the mass flow by variation of the pressure upstream of the orifice will take a long time to give a visual effect on temperatures on the stave since, even in the absence of any new liquid at all, it will take time to evaporate the excess liquid that has built up.**
-

ORIGIN OF A LONG TIME CONSTANT EFFECT OBSERVED…

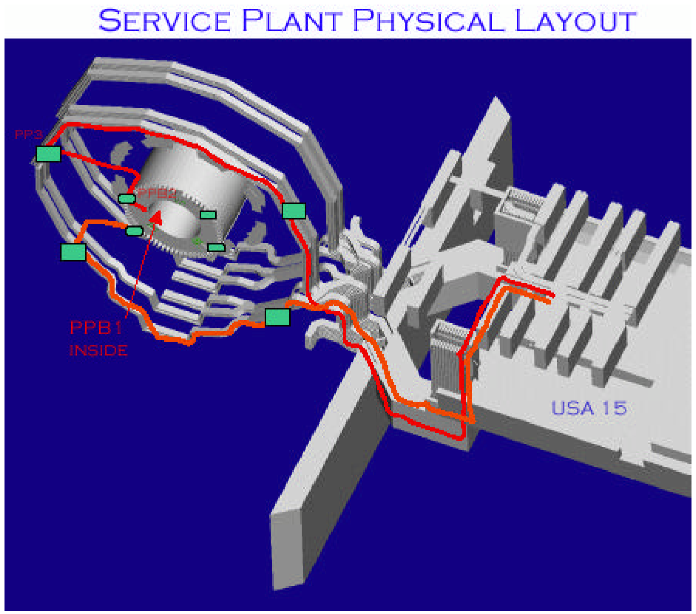
THIS HEAT EXCHANGER WAS REPLACED BY MORE FLEXIBLE ARRANGEMENT

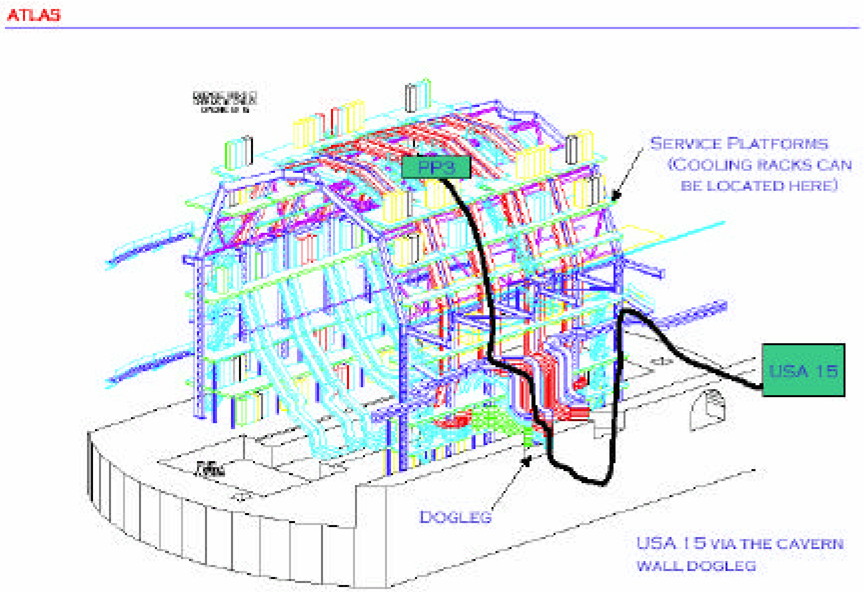
- **Aim of the modifications – to bring design of the cooling circuit closer to the final arrangement within the ATLAS detector**

(2) Modifications to Lab Circulator to study New Flexible Supply/Exhaust Configuration

<u>Foreseen Implementation of the Cooling Circuit</u>

<u>*Aim of the modifications*</u> – to bring design of the cooling circuit closer to the final arrangement within the ATLAS detector

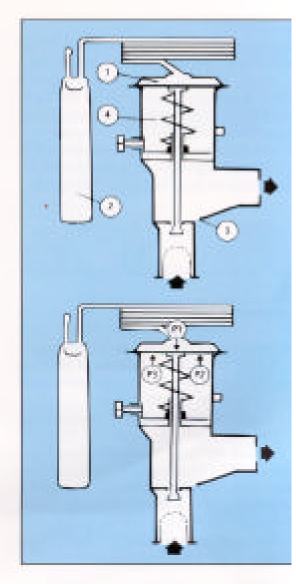


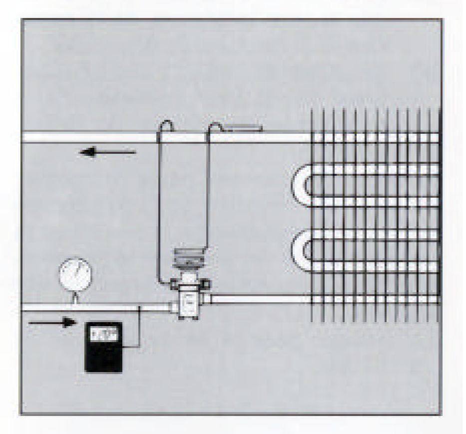


Comparison with Industrial Practice

In an industrial system, a thermostatic valve is often used to regulate mass flow. Three parts…

(a) Valve body with membrane and connected stem tip





**(b) Vapor pressure bulb containing the same fluid as the process fluid, and connected to (a) through a capillary.
The bulb is clamped to the exhaust tube of the evaporator**

(c) Injectors or varying sizes that are variable over a certain range by pressure from the stem tip of (1)HOWEVER… IN COMMERCIAL SYSTEMS, SUB-COOL/SUPER HEAT HeXs ARE *OUTBOARD, NOT INBOARD* OF THE REGULATION VALVE AND BULB (WHICH ADJUSTS (DECOUPLES) MASS FLOW FOR A GIVEN SUB-COOLING)

Range of Options of Liquid Delivery & Vapour Exhaust Configurations to Test (➔ ➔ May 2000)

Varying between:

- **variable mass flow over the full range of circuit power dissipation;**

Cold liquid delivery preferable:
➔ ➔ *Evaporation temperature for maximum effect:*
a few additional cooling lines per bundle may be required to keep liquid cold right to point of use…

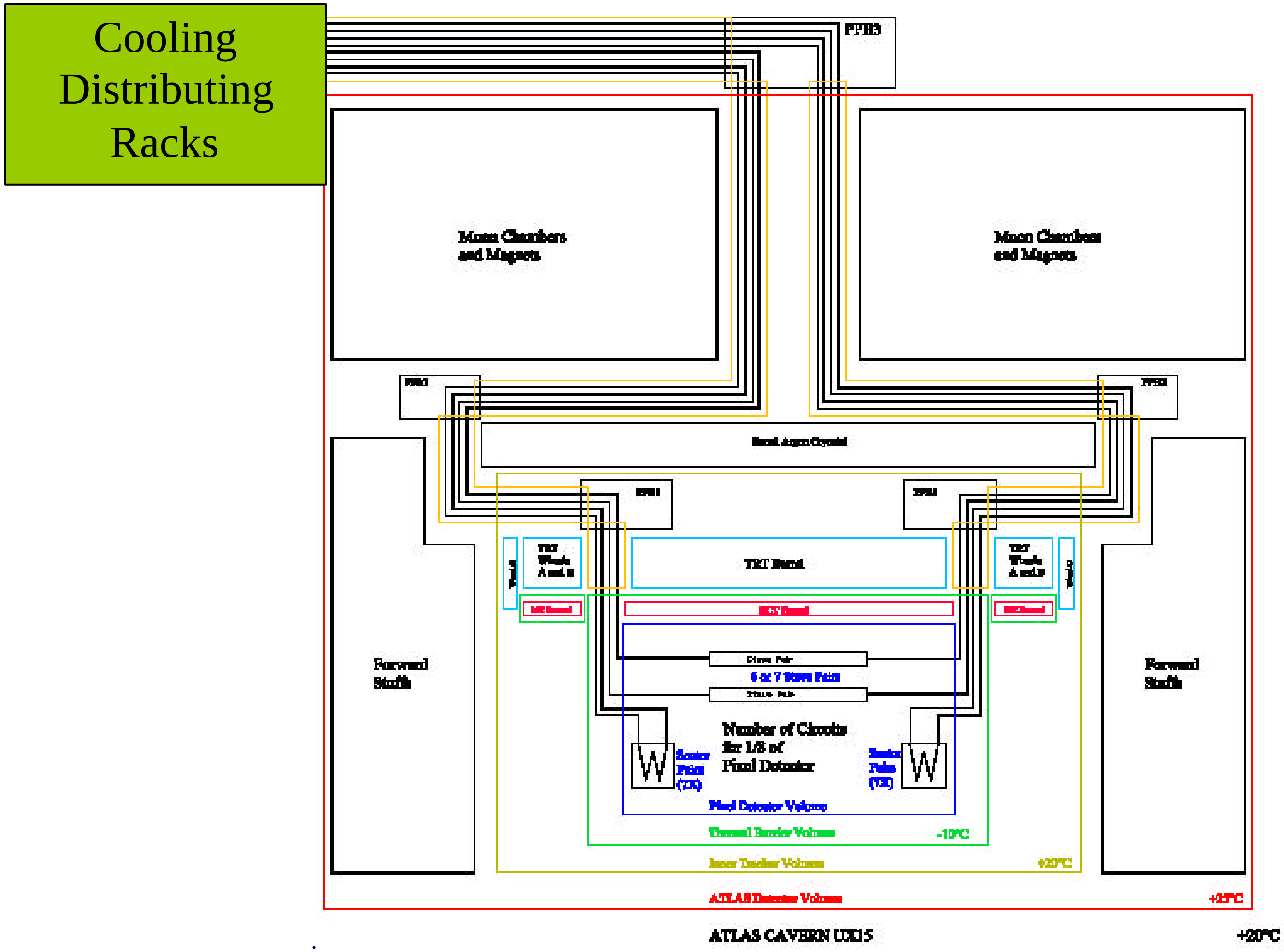
And:

- **fixed flow: exhaust heater attached to each circuit exhaust line;**
- **Exhaust heater power ³ circuit dissipation + sensible heat;**

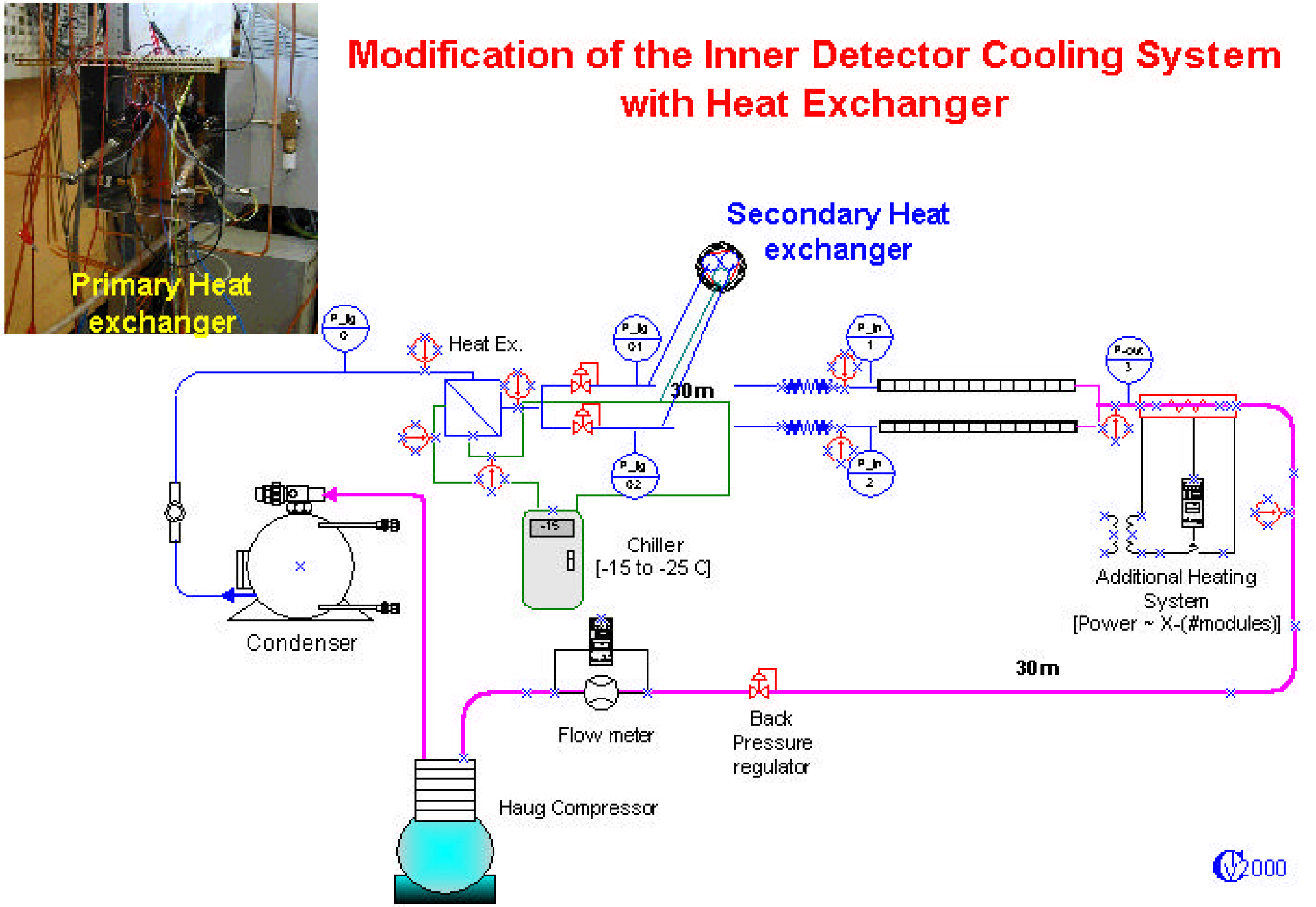
➔➔Investigate tuning mass flow and/or heater power to number of powered modules on circuit ➔➔

New heater has been manufactured [heating elements soldered on the cooper tube] with better thermal contact and section of the tube with the heater was “separated” by stainless steeel swagelok connectors from rest of the exhaust tube.

Approximate tube routines:



Current Cooling System Setup

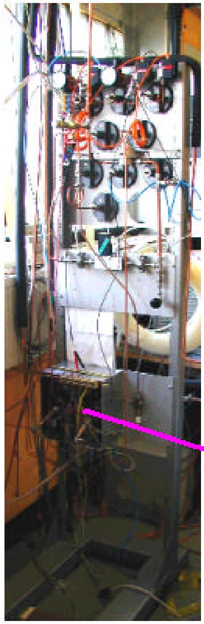


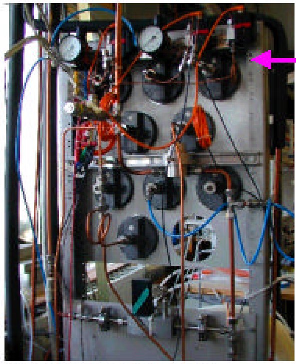
HeX Geometry Tested

- **Chilled liquid HeX (to –25 C) cooling of liquid upstream of flow regulator valve, with coolant tracer tube with C_3F_8 tube under same overall insulation jacket**
- ***FLOW REGULATORS ATTACHED TO PARALLEL PLATE HeX CONTINUATION BUNDLE COOLING TUBE (l=25 m) INSTALLED ➔ ➔***

Present status of the installation in the lab – part one

Rack with control devices



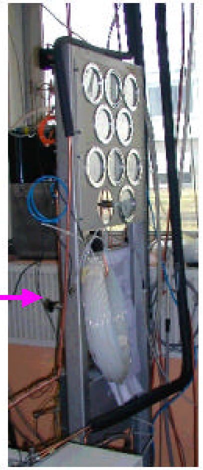


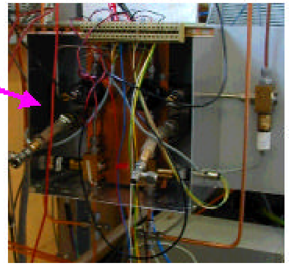
LEFT:

Pressure gauges, back-pressure regulator, mass flow-regulators and vapor mass flow-meter

RIGHT:

Front view of the panel

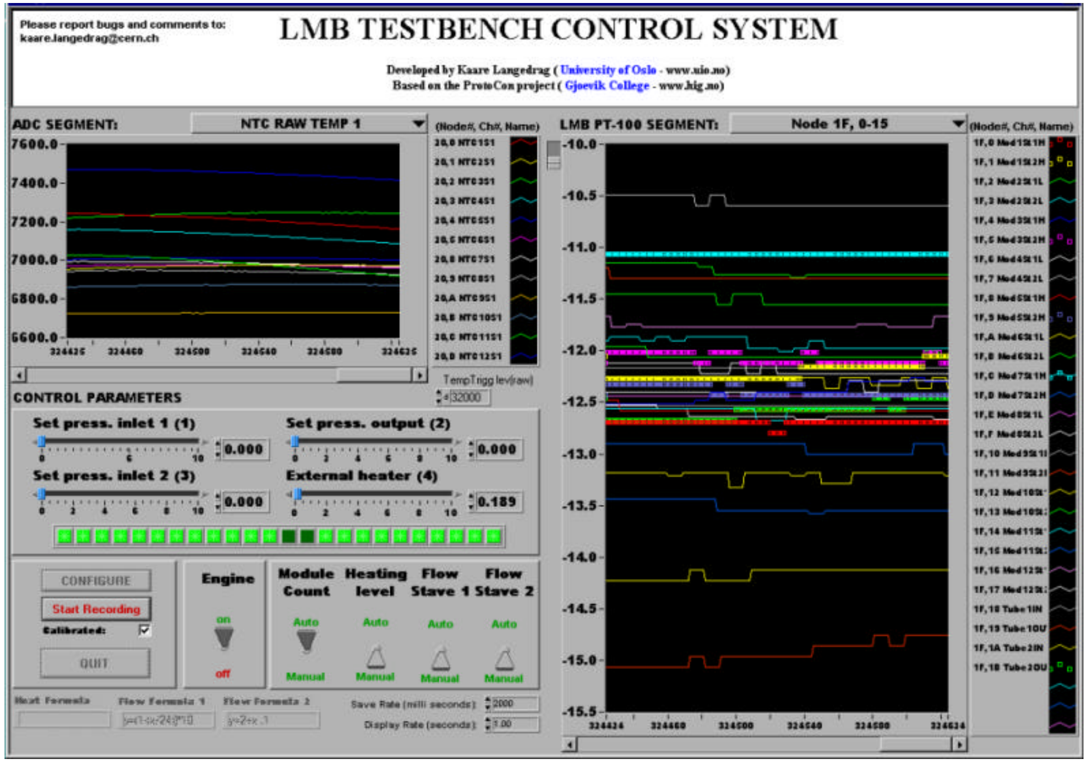




Detailed view of the C3F8 pre-cooler with pressure regulators and electronic pressure sensors

Implemented Control System

BridgeView Software (CanBus, LMB DAQ) commissioned (K. Langedrag, Oslo) to vary flow regulator output pressures via: $P_{(ORUP1,2)} = P_{(SV)} + m_{1,2} * (n_{modules1,2})$ ➔➔



$N_{modules1,2}$ counted via "module OK" bits from Wuppertal Power Interlock Box (BIT = module on and Temp Correct)

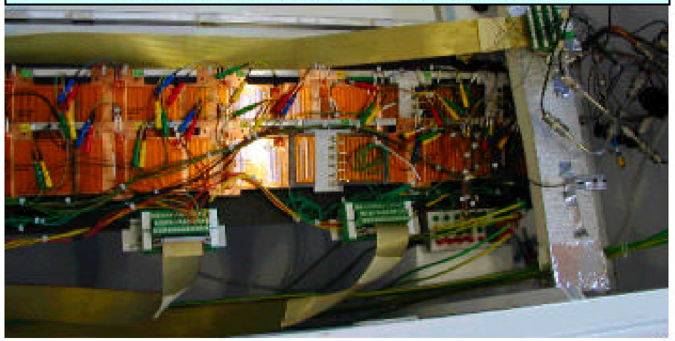
Installed Test Structures and DAQ/Control System

Present status of the installation in the lab – part two

LMB and WAGO based CanBus DAQ System that enables monitoring of the temperatures and basic control parameters of the Cooling system

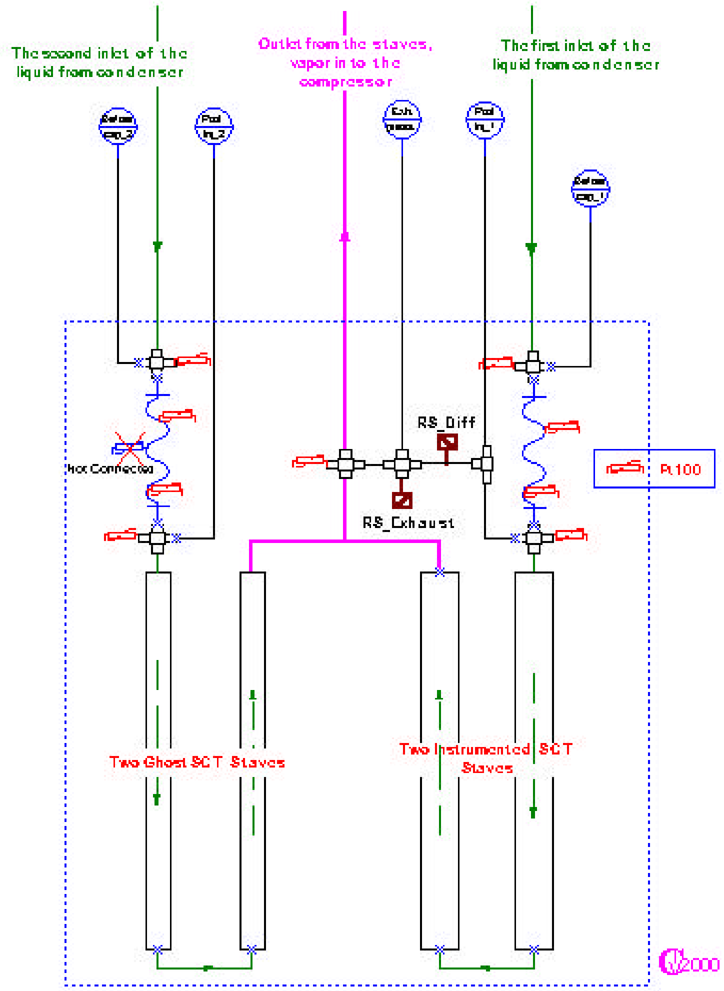
2 SCT thermal model staves and 2 "parallel ghost" SCT staves placed in the temperature controlled box

Detail of the manifolding into the staves, temperature sensors and heater wiring



(3) Tests in May 2000 & Current results & Additional tests to come

Situation in the Temperature Controled box



Various tests were performed with 50 cm heater [the only dimensional specs we obtained] attached to the exhaust tube of the setup. They included runs:

With pre-cooling:

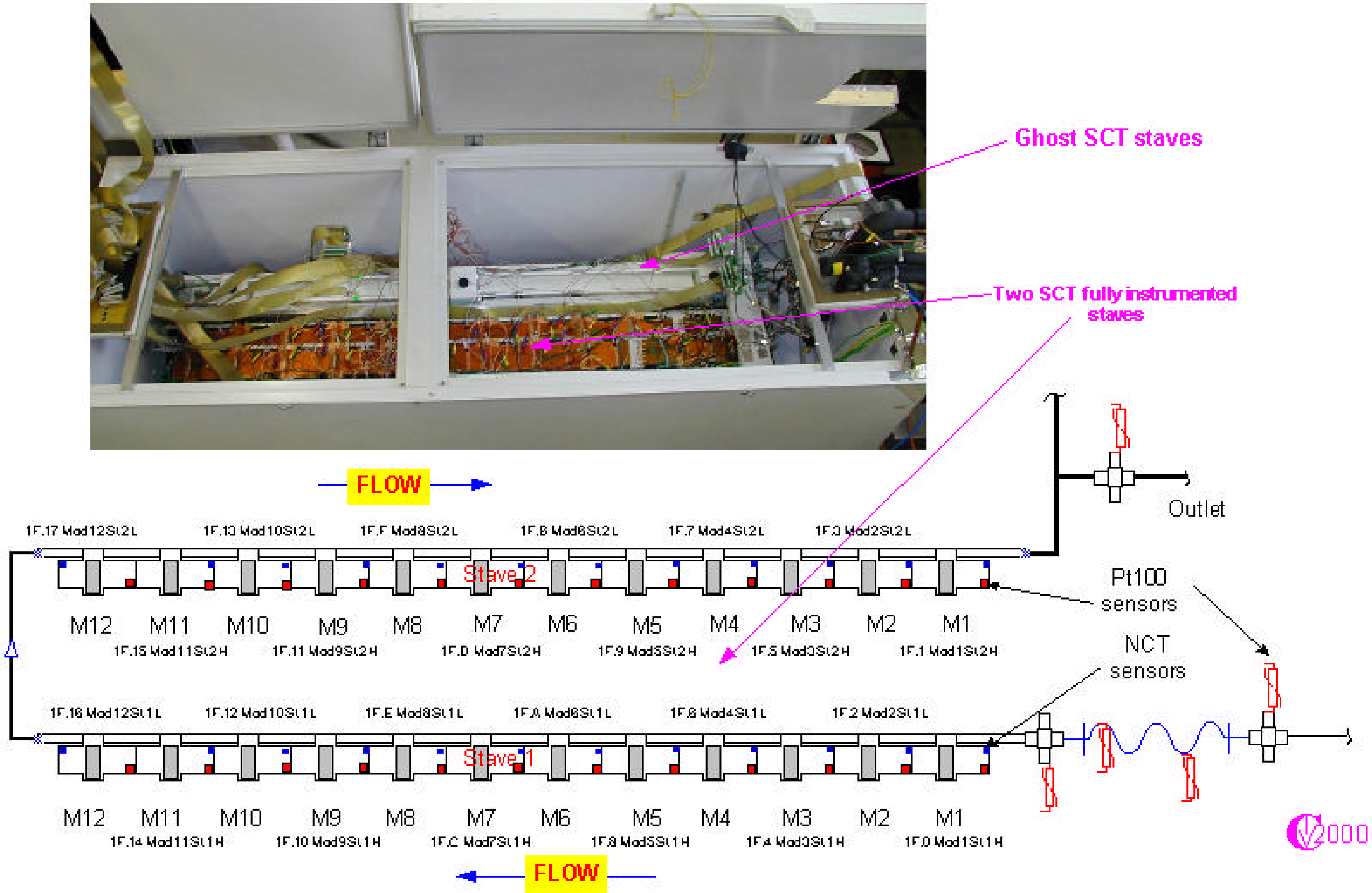
- **Start-up** procedure and **shut-down** procedure
- **Steady state runs** with flow regulation and power on the external heater ranging from 100W to 150W {with surface of the heater temperature PID control [20-25 °C]} while power introduced into modules was set to: 100%, 50% and 10% of the nominal power or one module; plus accidental switching of the modules "on" and "off"
- **Standby runs** were investigated
- **Fixed flow** runs with external heater power variation were tested

Without pre-cooling:

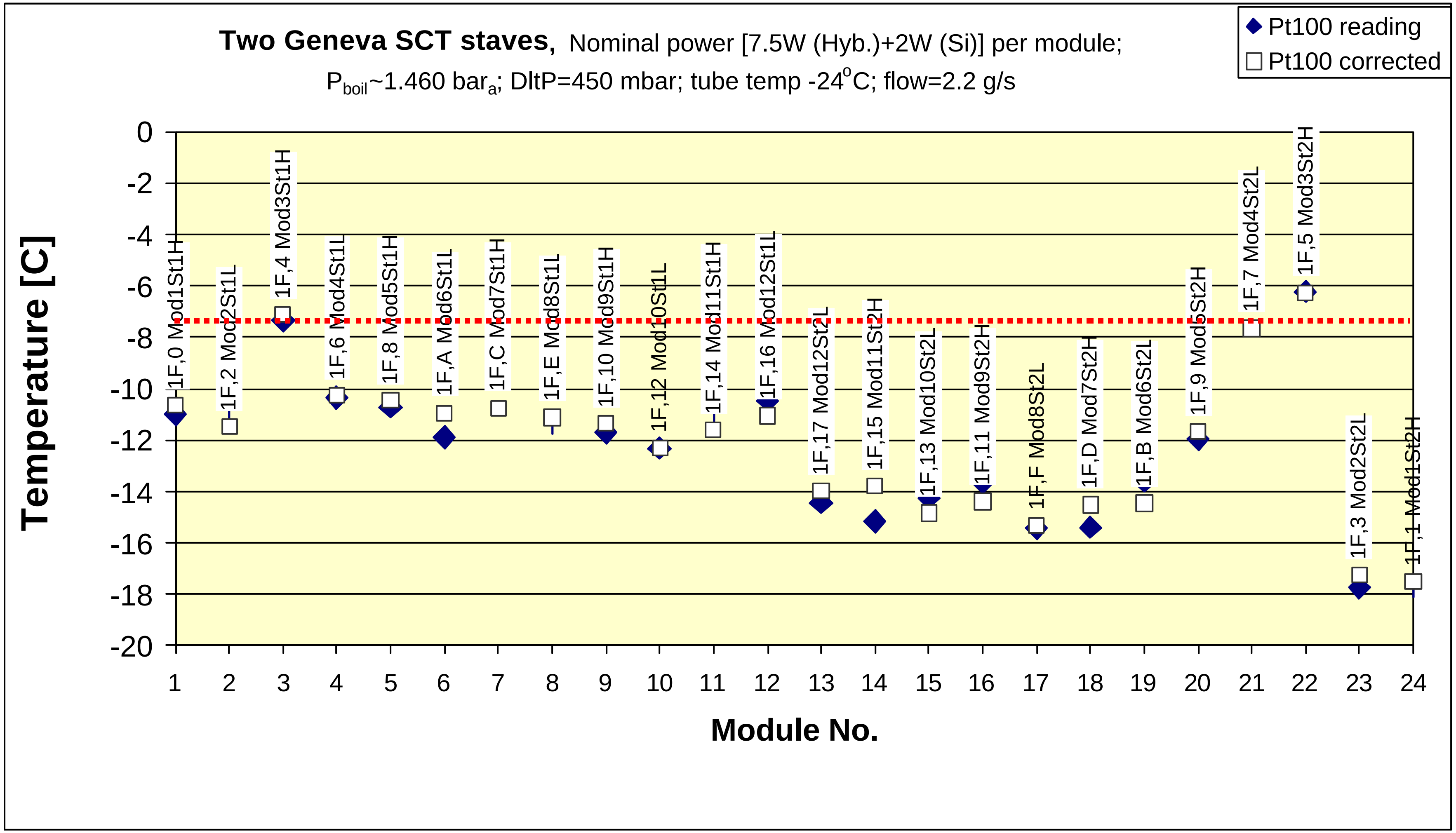
- **Start-up** procedure and **shut-down** procedure
- **Steady state runs** 100%, 50% less of the nominal power

One Half of Stave Quartet Heated and Cooled ➔

Map of NTC and Pt100 Sensors



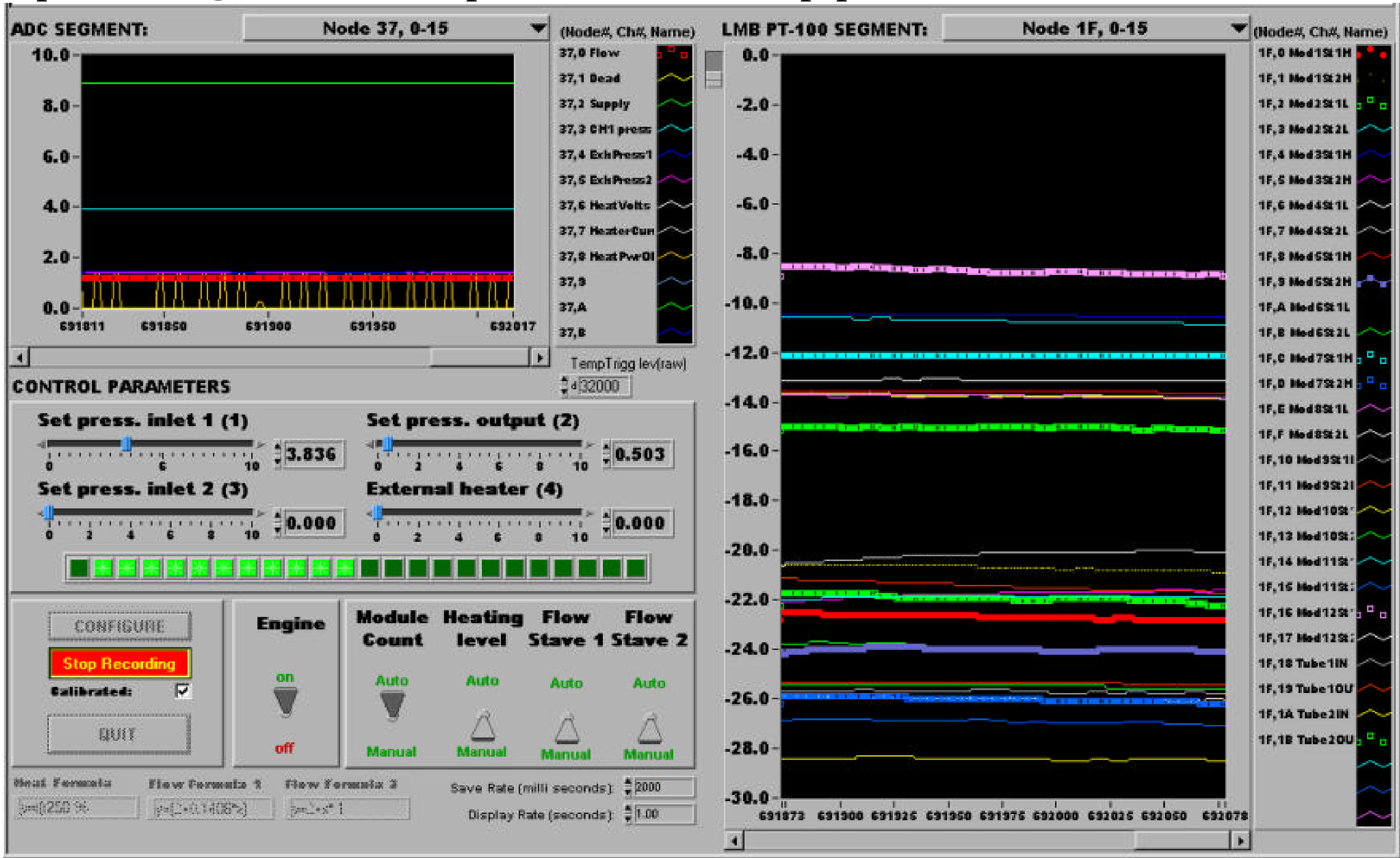
Typical SCT stave temperature profile at steady state conditions

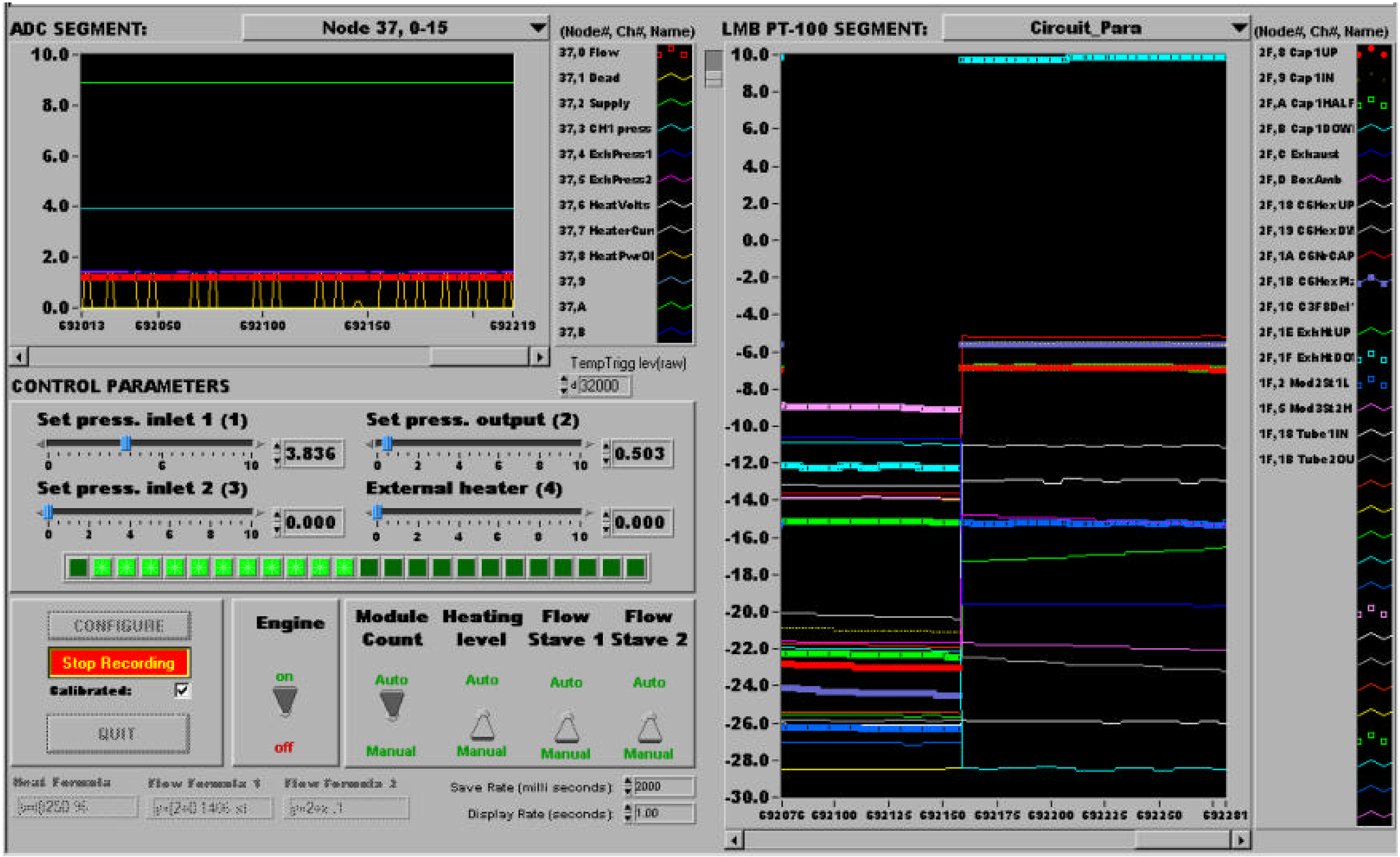


Short summary of the test runs:

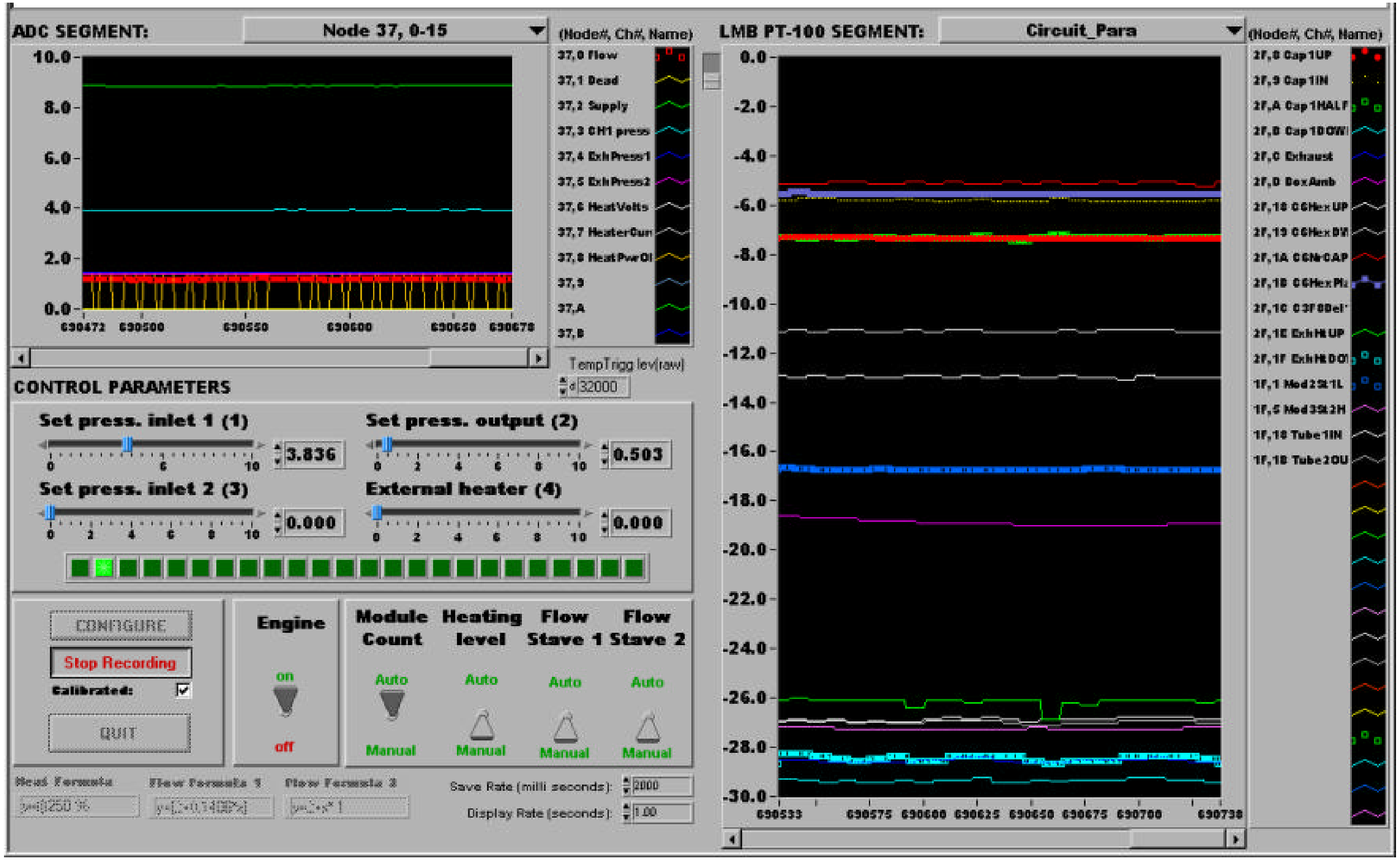
- With pre-cooling and refrigerant flow regulation

1. For 50%, 100% power; External heater & 100 W and PID for the heater surface temperature @ +20°C; temperature of return pipe ≤ 10°C;




ADC SEGMENT:
Node 37, 0-15
(Node#, Ch#, Name)
37,0 Flow
37,1 Dead
37,2 Supply
37,3 CH1 press
37,4 ExhPress1
37,5 ExhPress2
37,6 HeatVolts
37,7 HeaterCurr
37,8 HeatPwrOI
37,9
37,A
37,B
LMB PT-100 SEGMENT:
Circuit_Para
(Node#, Ch#, Name)
2F,8 Cap1UP
2F,9 Cap1IN
2F,A Cap1HALF
2F,B Cap1DOWN
2F,C Exhaust
2F,D BoxAmb
2F,18 C6HexUP
2F,19 C6HexDW
2F,1A C6HxCAP
2F,1B C6HexMi
2F,1C C3F8Del
2F,1E ExhHtUP
2F,1F ExhHtDO
1F,2 Mod2St1L
1F,5 Mod3St2H
1F,18 Tube1IN
1F,1B Tube2OU
TempTrigg lev(raw)
32000
CONTROL PARAMETERS
Set press. inlet 1 (1)
3.836
Set press. output (2)
0.503
Set press. inlet 2 (3)
0.000
External heater (4)
0.000
CONFIGURE
Stop Recording
Calibrated:
QUIT
Engine
on
off
Module Count
Heating level
Flow Stave 1
Flow Stave 2
Auto
Manual
Heat Formula
Flow Formula 1
Flow Formula 2
Save Rate (milli seconds)
2000
Display Rate (seconds)
1.00

2. Standby /one module "ON"; External heater & 100 W and PID for the heater surface temperature @ +20°C; temperature of return pipe slowly cools down to -27°C [but does not cause any problem to the stability of the cooling system]



3. Standby /one module "ON"; External heater has to be set permanently [no PID] to 100÷150 W to hold return pipe @ ≈ 0°C (still very slowly raising); temperature of the heater goes up to 60°C (still raising when test was stopped)

Stave temperatures under control and within the SPECS [all modules below -7°C]

Other Typical Circuit Parameters

Condenser: P_{cond} = 8÷9 bar_g t_{cond} ≅30°C

Compressor $P_{bufferSET}$ =1100 torr P_{buffer} = 1200÷1300 torr

$P_{exhaust}$ = P_{evap} = 0.45 bar_g

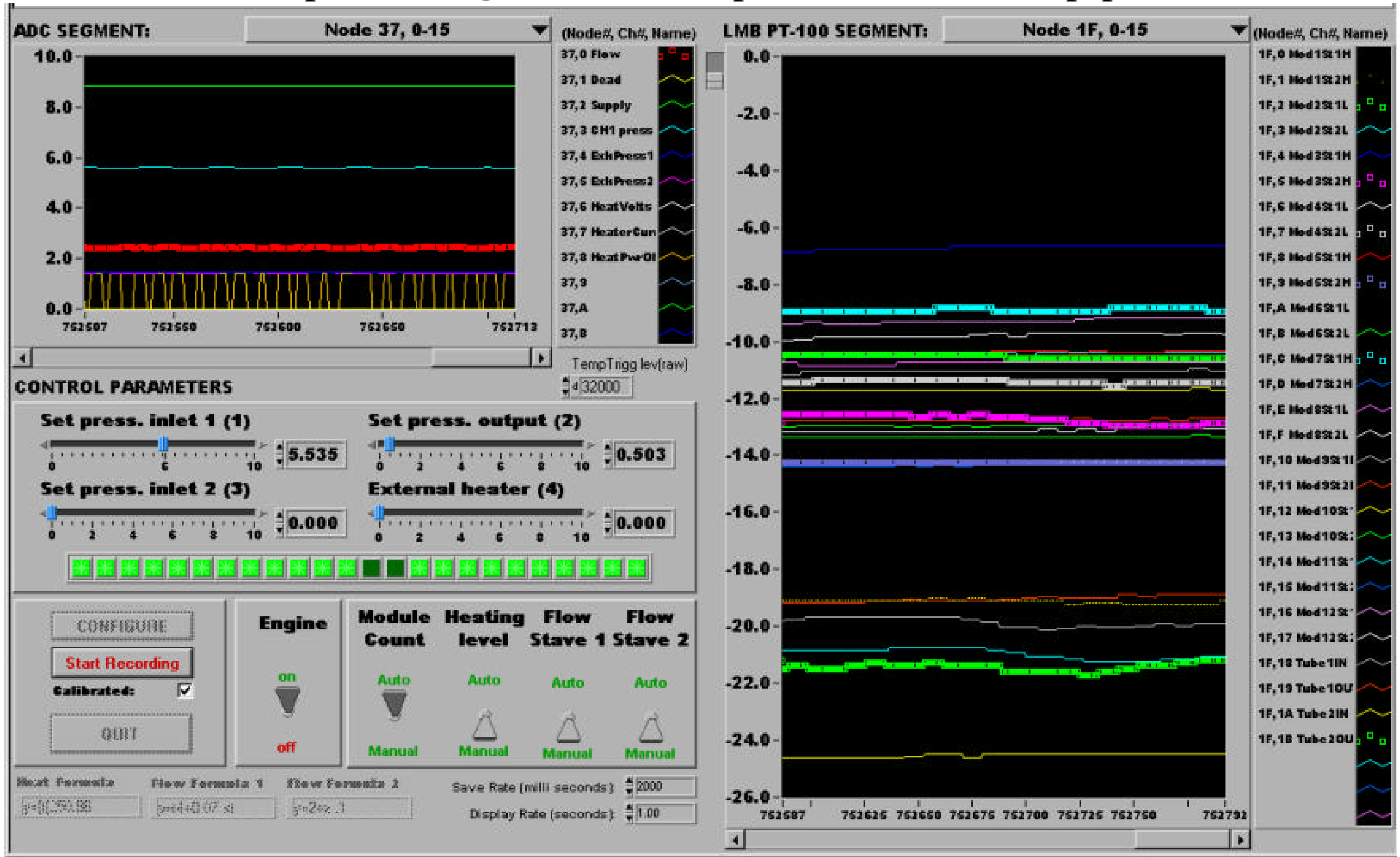
Pre-cooling t_{SET} ≅ - 29°C t_{out} ≅ - 14.6 °C Flow = 54 l/h

Pressure drops over staves:

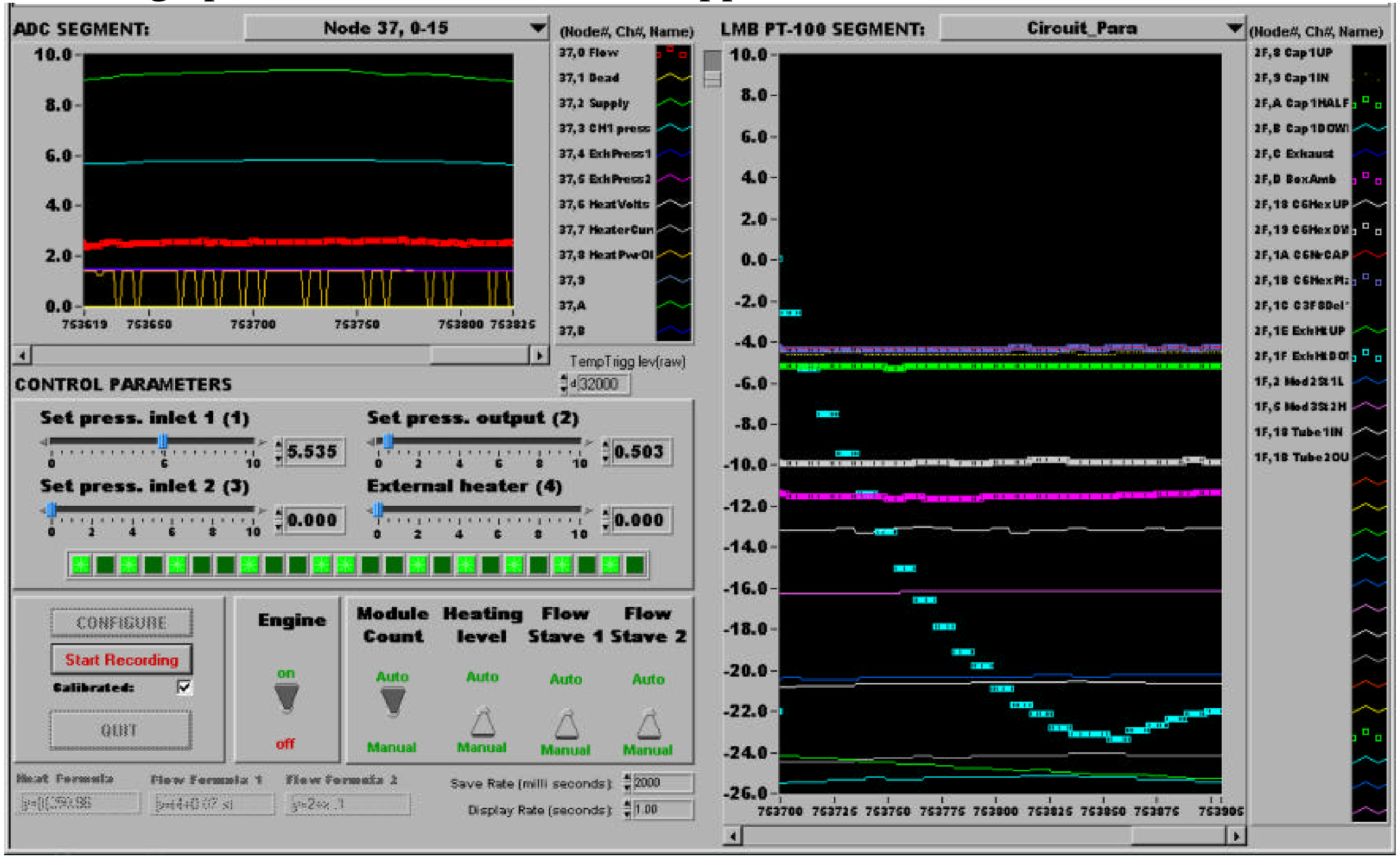
Standby ΔP = 0.08 bar or less Steady runs ΔP = (0.3÷0.35) bar

- With pre-cooling; fixed flow of refrigerant (adequate to the 100% power dissipation in the staves, approximately 2.2 g/s)

1. 100% power dissipation in the staves; External heater & 100 W and PID for the heater surface temperature @ +20°C; temperature of return pipe ≅ 10°C;



2. 50% power dissipation in the staves; External heater has to be set permanently [no PID] to 150 W to get return pipe temperature to ≅ 10°C; temperature of the heater increasing up to 40°C when test was stopped



3. Standby /one module “ON”; External heater power has been gradually increased up to 300 W; temperature of return pipe $\cong$ - 25 °C; run was stopped when surface temperature of the heater, raising continuously, reached 80°C.

Stave temperatures within the SPECS [all modules below -7°C]

Other Typical Circuit Parameters

Condenser: P_{cond} = 8.5 bar_g $t_{cond} \cong$29°C

Compressor $P_{bufferSET}$ =1060 torr P_{buffer} = 1280 torr

$P_{exhaust}$ = P_{evap} = 0.45 bar_g

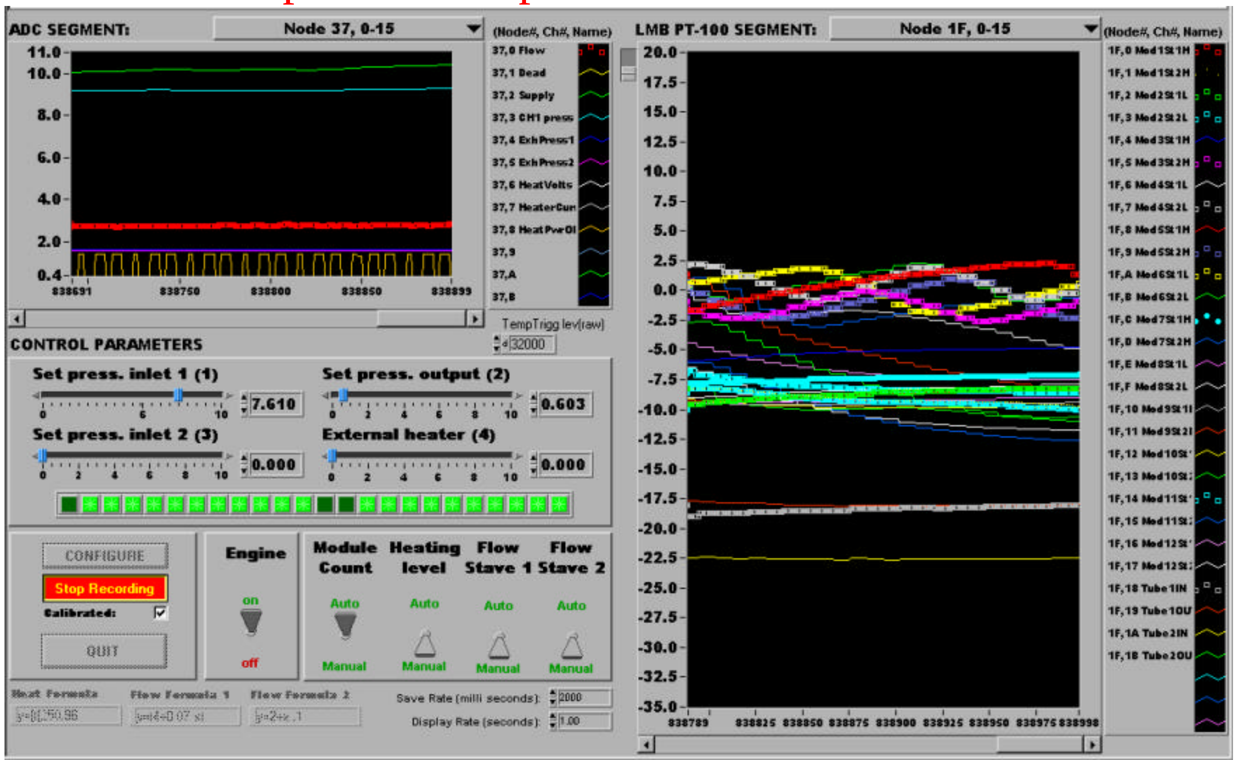
Pre-cooling $t_{SET} \cong$ - 29°C $t_{out} \cong$ - 14.3 °C Flow = 53 l/h

Pressure drops over staves:

Steady runs 100% ΔP = 0.4 bar Steady runs 50% ΔP = 0.29 bar

- No pre-cooling [refrigerant @ 22°C];

1. 100% power dissipation in the staves; External heater & 100 W and PID for the heater surface temperature @ +20°C; flow of refrigerant close to the limit of the compressor capacity @ 2.6 g/s at needed pressure and temperature conditions; significant increase in pressure drop across the staves ≈ 0.46 bar



Problematic to cool down all modules [LMB acts on more then half of modules]

General observation:

- No change of pressure in the staves [i.e. evaporative pressure] has been observed even if cool "liquid/mist" [i.e. wet vapor with quality factor less then 1] fills return pipe. It indicates a proper and reliable behavior of the dome-loaded back pressure regulator

- Unless a surface temperature of the heater is controlled its surface temperature will continuously rise [max. value achieved was 90 °C, then we stopped heating]

Status of new Pixel Engineering Structures & Test Timescale

- **Evaporator Control System Tests to Continue**

➔ May-June

- **CPPM back up stave available mid May (?) for tests.**
- **Pixel C-C Baseline Staves with Final Hydraulic Diameter**
- **NEW SCT disk sector cannot be tested before June**
- **4 Pixel disk sectors prototype announced for middle of June – via videoconference with LBL on May 4, 2000**

Pixel Local Support FDR 6/2000…
Not enough circulator time and manpower available for tests on final diameter pixel staves at CERN (?)

"Demonstrator Phase II" of C_3F_8 Evaporative Cooling Project Plans and Status.

- **AIM :**
  - **Simulate representative part of SCT&Pixel silicon…**

    Thermally

    (include optimum scalable power compressor),

    In cooling channel (manifolds) count,

    With Final Controls &DAQ electronics,

    With Realistic Thermal Screens,

    tube lengths, Height Differences

    and Heat Exchangers

One eighth (~6 kW dissipation)

6 SCT barrel manifolds and 16 pixel staves in 17 circuits represent similar power (5 kW) & cooling circuit count (14) to outermost SCT layer ➔

Thermal structures

6 Barrel SCT 4 folds in fabrication

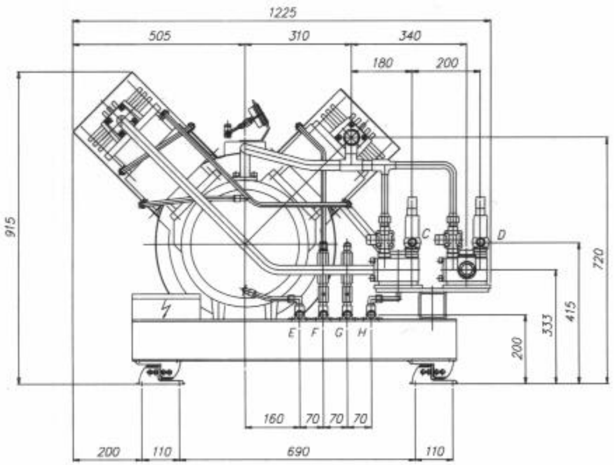
(modular block construction, with new D_H tube)

16 aluminum pixel staves already fabricated

Other components :

Compressor : Haug 3 cylinder hermetic, oil-less: ➔ ➔ **80m³hr⁻¹**

$80 m^3 hr^{-1}$ C_3F_8 pump speed at 1 => 10 bar (abs) ratio



(i) **TECHNICAL SPEC WITH CERN PURCHASING ➔Easter 2000**
(needs ID community approval: ONLY: no CERN money),

(ii) **Market survey for remaining series published by May(CERN money)**

First Compressor Delivery Required Aug/Sept 2000

[No compressor has been purchased by ID community up to now – all were landed to us !!!]

25 dome-loaded flow & 17 dome-loaded back-pressure
(boiling temperature) regulators
(Part of final count already ordered, (Vespel, PEEK seats)

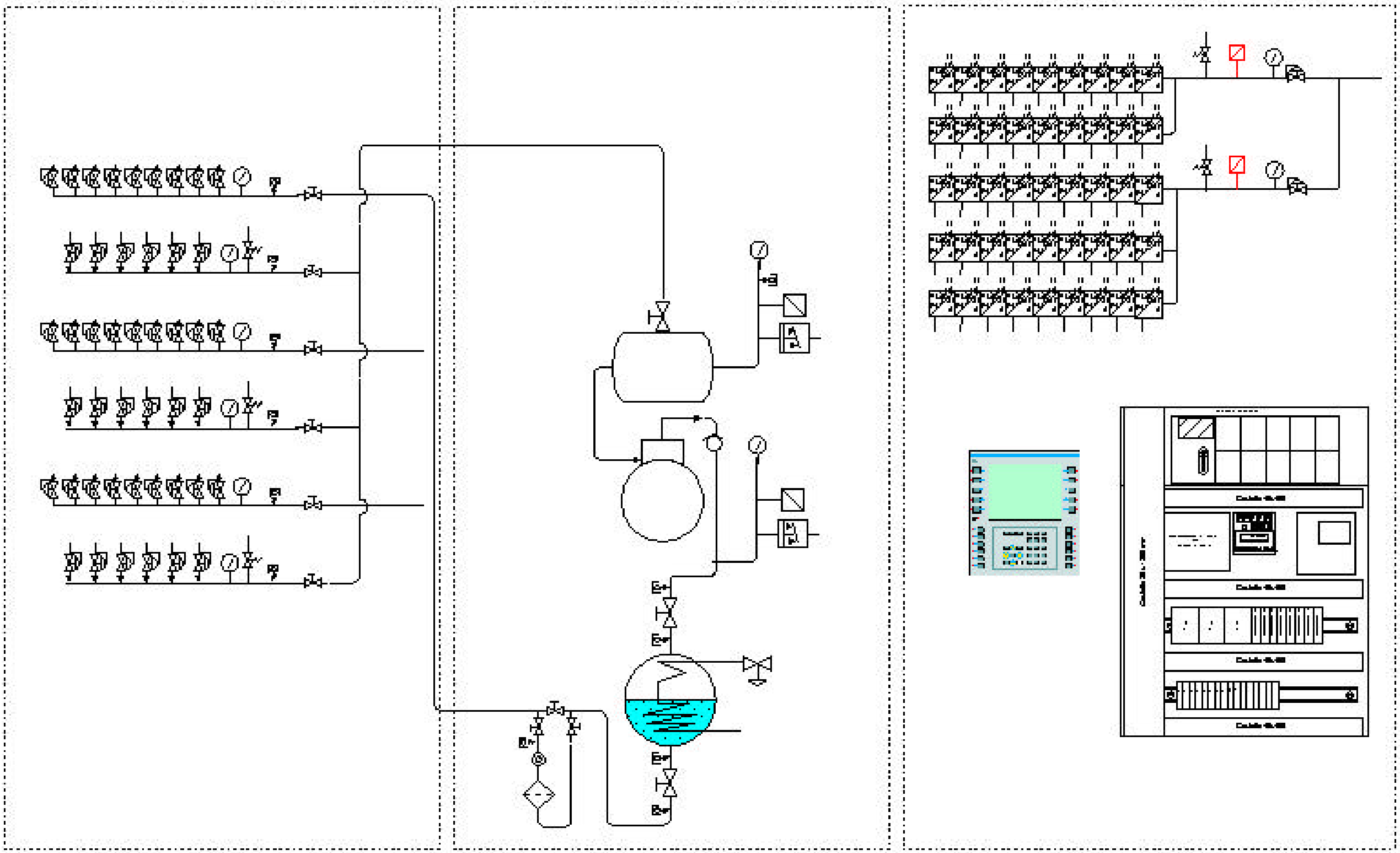
~ 500 channel PT1000 sensor & analog input acquisition (delivered)
42 V➔P air converters and DACs

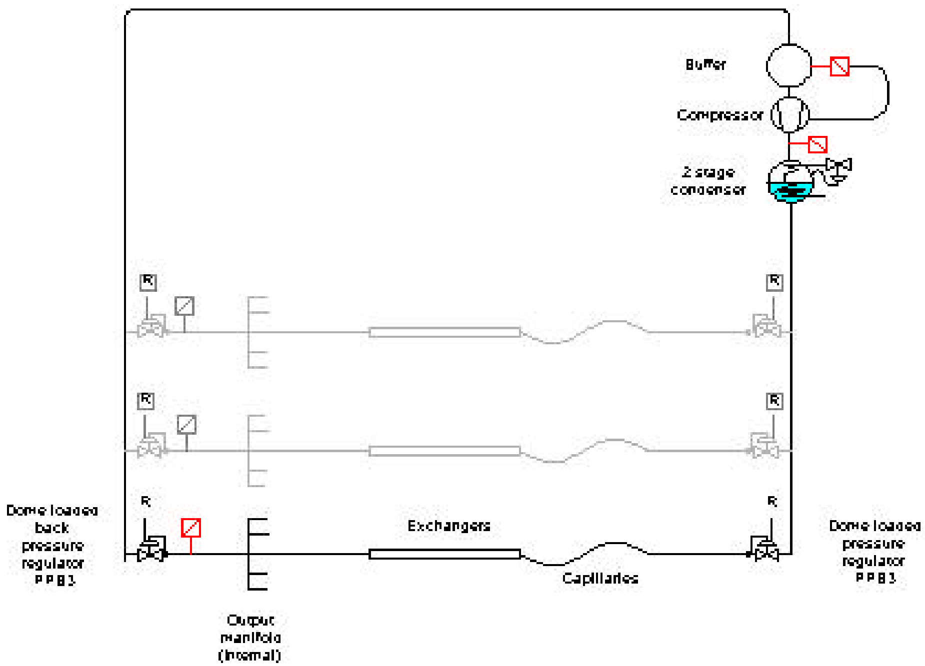
Modularity of Circuits and Analog flow elements in Phase (2) Demonstrator.

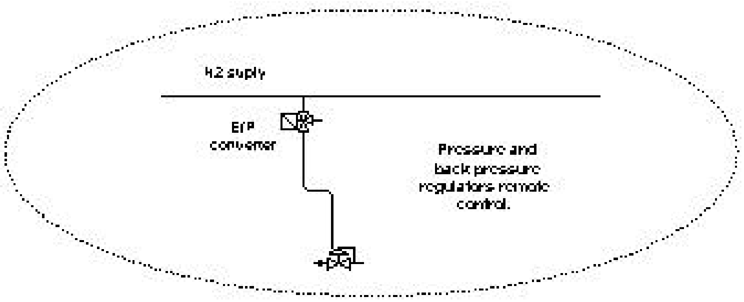
Cooling Circuits and Analog Flow Elements for SCT+Pixel Evaporative Cooling Demonstrator

Layer	No. elements	elements/ cool circuit	Staves / 8	Supplies (regs) / circuit	Exhausts (b.p. regs / circuit	Phase 2 No. circuits	Power /cct (W)	Phase 2 No. regs	Phase 2 No. b.p. regs
SCT 4	56	4	7	2	1	2	480	4	2
SCT 3	48	4	6	2	1	2	480	4	2
SCT 2	40	4	5	2	1	1	480	2	1
SCT 1	32	4	4	2	1	1	480	2	1
Pixel 2	56	2	7	1	1	4	208	4	4
Pixel 1	42	2	6	1	1	3	208	3	3
B layer	18	1	2	1	1	2	144	2	2
SCT disk/4	2	2	-	2	1	2	160	2	1
Pixel disk/6	2	2	-	2	1	2	96	2	1
TOTALS						19	5136	25	17
COMPARISON: TOTAL FOR SCT 4						14	6720	28	14

Positioning of Evaporative Cooling Recirculator Components in Final Installation




Buffer
Compressor
2 stage condenser
R
R
R
R
R
R
Dome loaded back pressure regulator PPB3
Exchangers
Capillaries
Dome loaded pressure regulator PPB3
Output manifold (internal)


N2 suply
E/P converter
Pressure and back pressure regulators remote control.

Demonstrator Time scale and Planning

ITEM	Time to Completion
Circulator Definition & Technical Specification	**→ end 1999 COMPLETE**
Market Survey of Components & Purchases	**Jan →May 00**

WAS ON HOLD PENDING TESTS OF HEAT EXCHANGER AND CONTROL SYSTEM :

SIGNIFICANT RISK OF MISSING MILESTONES
IF COMPRESOR ORDER DELAYED (13 WEEK DELIVERY A.R.O.)

Component Delivery (mainly smaller controls Components & DAQ)**	**→ end May 00** **DAQ DELIVERED** **REGULATOR PURCHASE** **DISCUSSION WITH LBL**

ITEM	**Time to Completion**
Circulator Fabrication & Installation in B175	**July ➔ Sep 00**
Detailed Tests	**Oct 00 ➔ Feb 01**

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NOTE:

** **Compressor identified (~ CHF 70K) has sufficient power for SCT outer layer and can be integrated into final parallel compressor set-up for SCT and Pixels in USA15 ➔ ➔ Detailed INFO for market survey handed already to S. Stapnes**

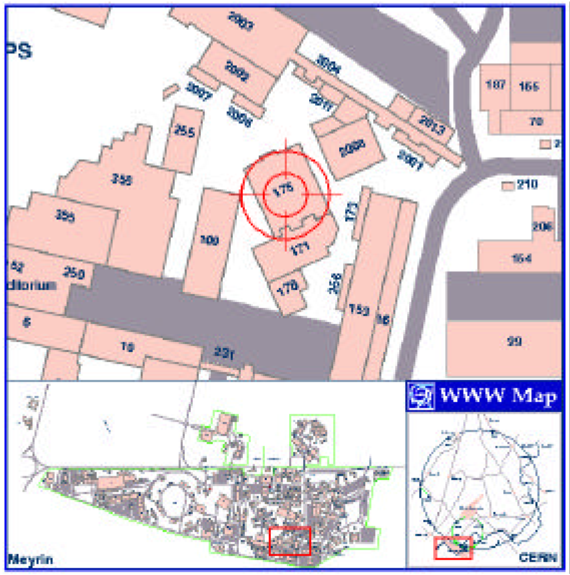
****This compressor will be first used at the first SCT assembly site, starting mid 2001.**

Cannot delay its procurement too long…

Cooling Demonstrator Test Location

Building 175 ;

(agreed 30/9/99, space clearing started 2/2000,
chilled water plant sizing started)



Could share supports with services mock-up
(inc. Simulated cryostat bore, Magnet crack)

(saving up to 1 M.Y. F.T.E. :CHF 90K) & implement active coolant tubing thermal environment, inc. Cryostat wall heating

Summary and very near future work

- Majority of requested measurements of the cooling system behavior were completed and reliability of the system was verified

- Tests with exhaust heater [*Ni-Cr heater was implemented for higher power , better heat sinking to exhaust tube*] PID driven @ 100W to 150 W AND C_3F_8 mass flow variation showed practicality of varying on-stave cooling over full dynamic range AND keeping exhaust tube temperature close to the dew point temperature.

- More requirements for heater power are coming from standby conditions (more then 100 W needed). However, no change observed in cooling system technological parameters, even if the return pipe is cold [≈ -27°C]

- Test with fixed high flow and/or no pre-cooling show that these conditions require higher mass flow [i.e. high pressure drop over the staves] and higher input pressure. Under these condition we get also low temperatures of the return pipe [i.e. more power would be needed for external heater]

Action list for next weeks:

• Cooling circuit modification:

- Replacement of pressure regulators for "real" dome-loaded ones [Order placed, delivery foreseen in the middle of May]
- Preparation of the new return pipe to test active insulation and new heater [approx. 2.5 m long with kapton heating elements – delivery of the heating element expected at the end of May from Italian manufacturer]

Note Vic's suggestion: It would be more desirable and efficient to use extended inner surface of the "heated" part of the exhaust tube then to play with the "length" of the heater

- Implement transparent section of the return pipe into the return line to study flow pattern and check the quality factor of the refrigerant [is the mist flow in the return pipe really problem ???]
- Some additional measurements and conclusions expected during the second week of June

• Structure measurements:

- Backup pixel stave needs to be measured as soon as possible [prototype expected to arrive next week from CPPM]; structure will be placed above the existing SCT structure and Prague DAQ system will be modified for the measurements

- Four pixel disk sector announced for thermal test at CERN; delivery of the prototypes is set for middle of June; sectors have two different hydraulic diameters : dh=2.4 mm and 3.3 mm and are to be tested in parallel arrangements and also in series. It will require a lot of extra work

- SCT disk sector also expected for measurements in June