Dynamic (on demand) variation of liquid phase flow of (any) evaporative coolant in new systems

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Centre de Physique des Particules de Marseille, France;

Thermosyphon workshop, CERN, July 6, 2009

Advantages of dynamic flow variation

- **Delivers only as much liquid as is instantaneously needed;**

  does not need to know the instantaneous demand from the silicon detector cooling circuit – works to eliminate unevaporated liquid in the exhaust (though this can also be made available if desired)

- **Eliminates the need for a heater in the exhaust to vaporize any remaining liquid;**

  (in the present system heaters are required to operate reliably in any orientation in stratified liquid-vapor and biphase coolant mixtures)

- **Coupled with cold delivery using precooling from *separate* circuits operating the same coolant, enthalpy can be maximized without a local *(ID volume)* heat exchanger per circuit as at present;**

- **Not based on particularly new principles;**

  replaces the on-evaporator vapour pressure bulb flow control system with an electronic system for an environment where VPB's cannot be installed

PRE-HISTORY…

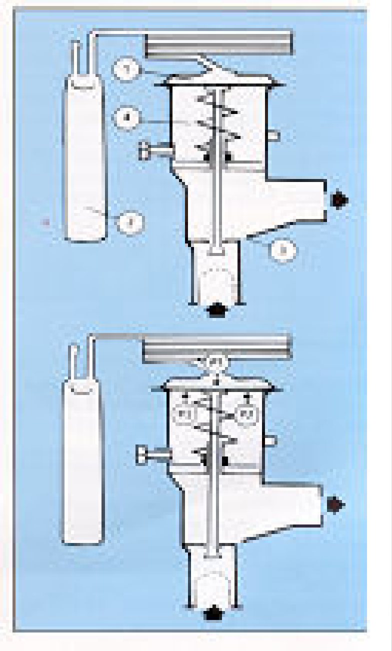
From conceptual design of pixel services workshop: Dec 7, 2001

Comparison with Industrial Practice

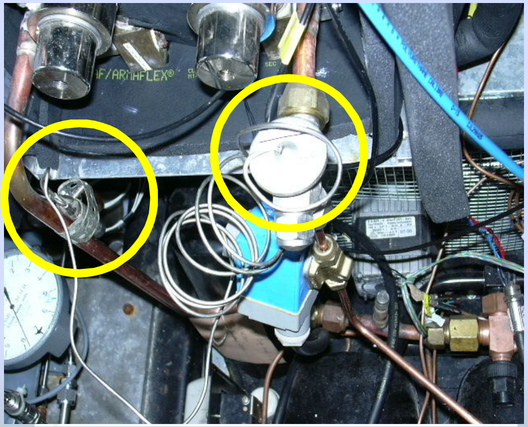
Industrial refrigeration, thermostatic valves regulate coolant mass flow.

HOWEVER, valve is the only detent, and is mounted directly on the evaporator

(1) Valve body with membrane and connected stem tip



(2) Injectors of varying sizes, variable over certain pressure range by pressure on stem tip (1)



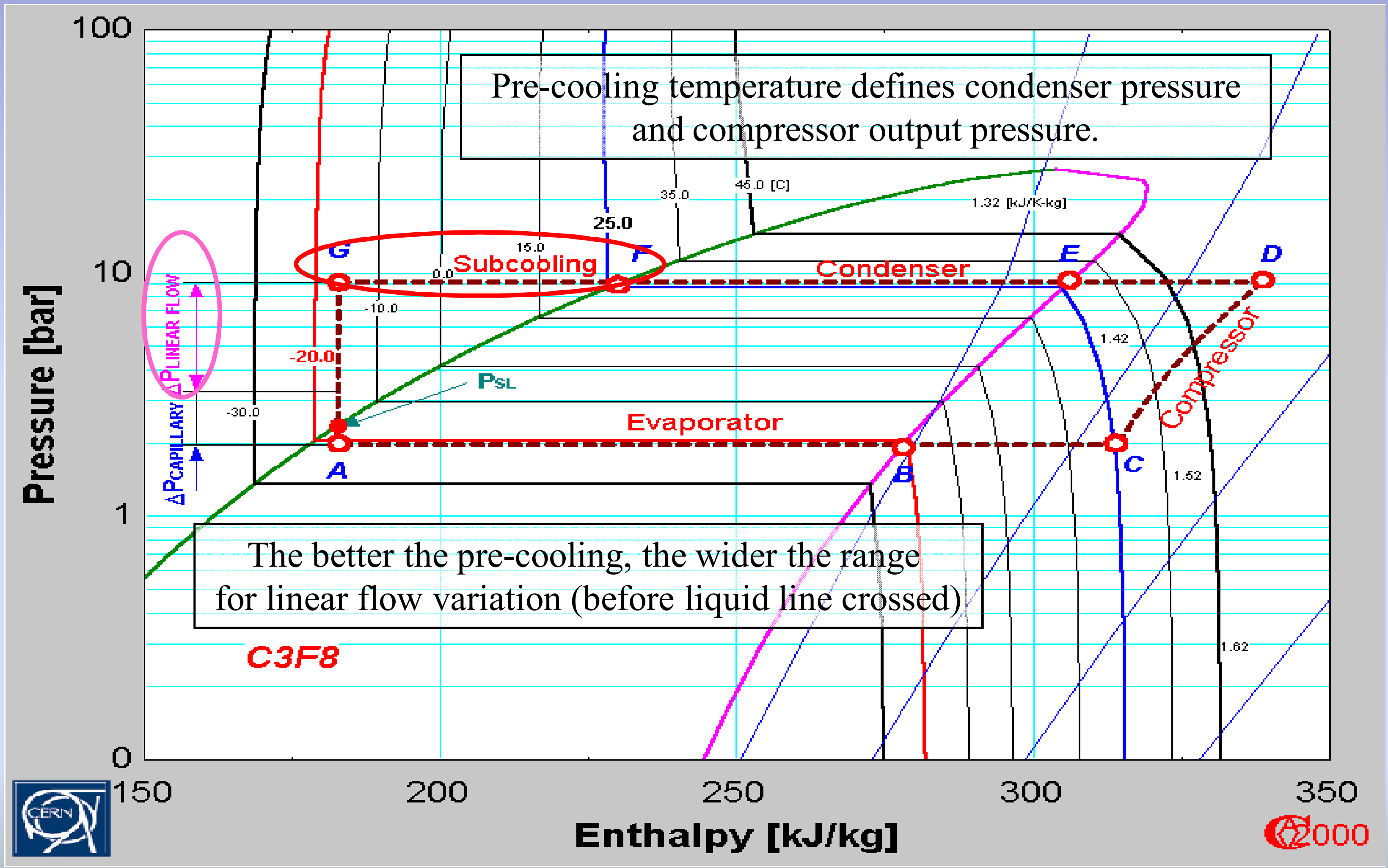
(3) Vapour pressure bulb containing same process fluid as cooling circuit, clamped to evaporator exhaust tube and acting on stem tip (1) to vary flow rate, avoiding unevaporated liquid in downstream tubing

In our application, radiation length concerns preclude the placement of vapour pressure bulbs (VPBs) and dome loaded throttle valves on the evaporators (SCT & pixel structures): capillaries also preferred for innermost delivery tubes

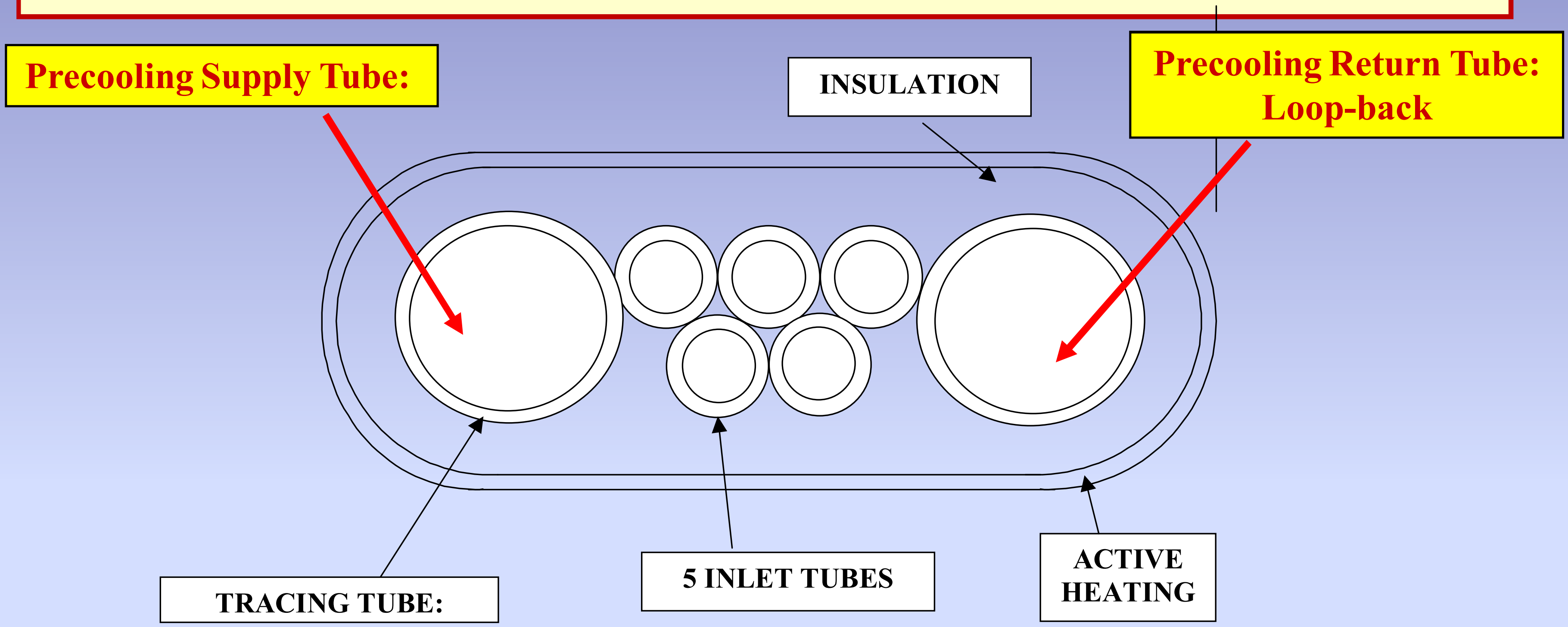
Simply moving VPBs and throttle valves to the service platforms does not help: the entire supply and return tubing through the magnet would be redefined as the evaporator and would operate at – 27ºC in the present system

Correct solution is to use a dome-loaded pressure regulator on the service platforms and a low mass measurement of post-evaporator temperature (PT100, NTC thermistor etc) with combined electro-pneumatic feedback to pressure regulator. This was demonstrated in 2000 but not taken up.

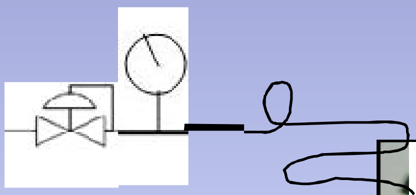
C_3F_8 Cycle indicating the wide variation of flow possible in combination with optimized pre-cooling



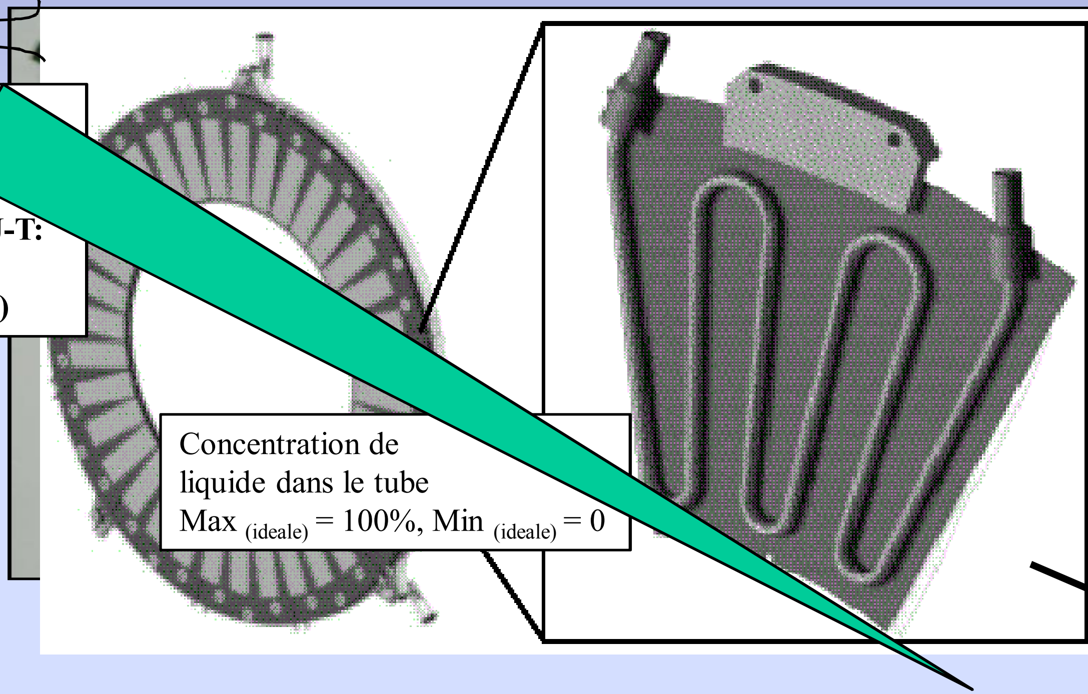
Example of ligquid supply multi - tube bundle sized for passing through ATLAS magnet to ID volume (Andy Nichols, RAL, 2000-2001)



Principe « on-detector » de refroidissement (toutes fluides)

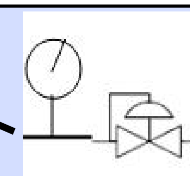


Dispositif de livraison liqui
Réglage de debit par déte
amont d'un restriction
(qui provoque l'expansion J-T:
capillaire sert aussi comme
tube fin de livraison liquide)



Concentration de
liquide dans le tube
Max $_{(ideale)}$ = 100%, Min $_{(ideale)}$ = 0

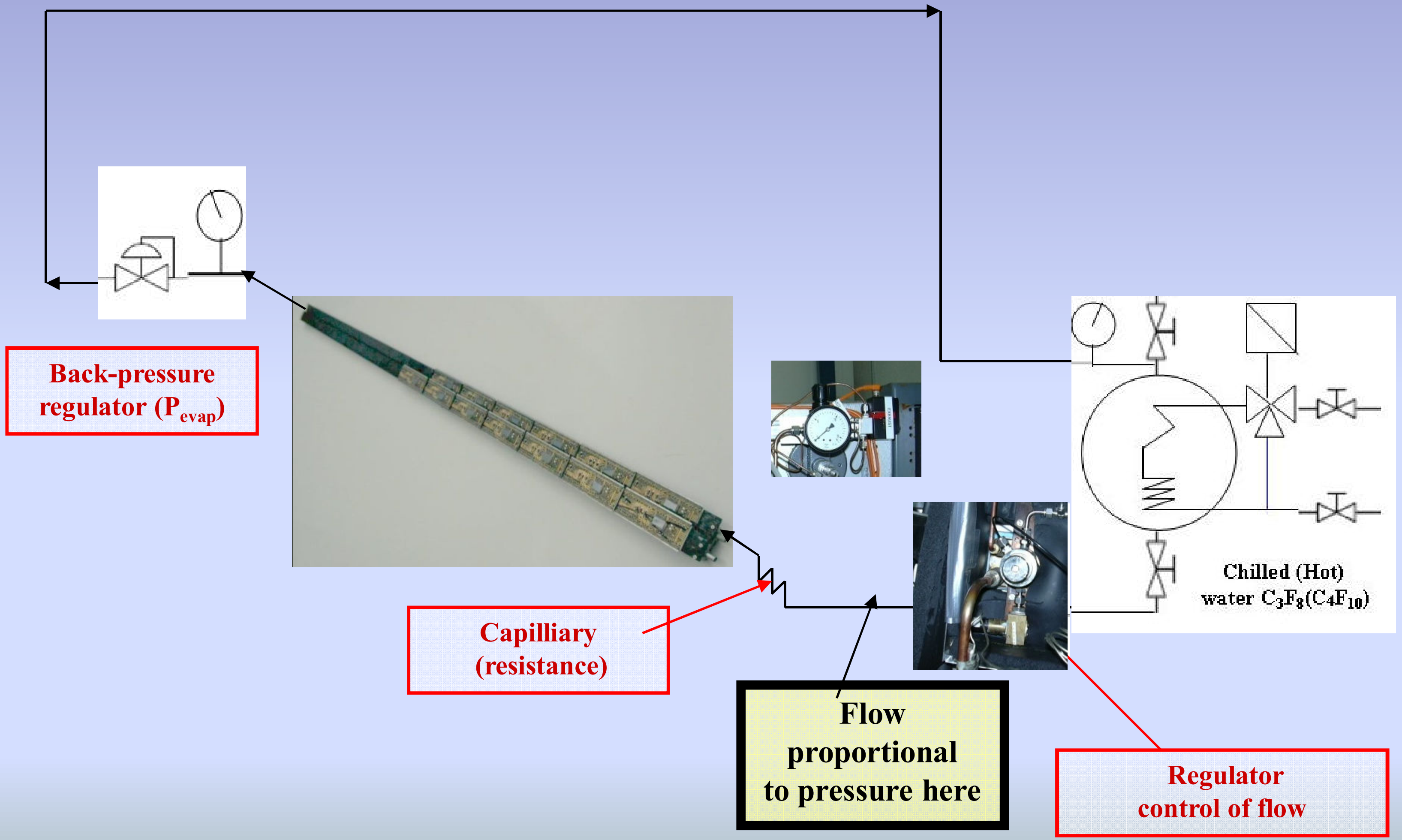
Dispositif de réglage
de la température
moyenne de fluide
dans la structure à refroidir



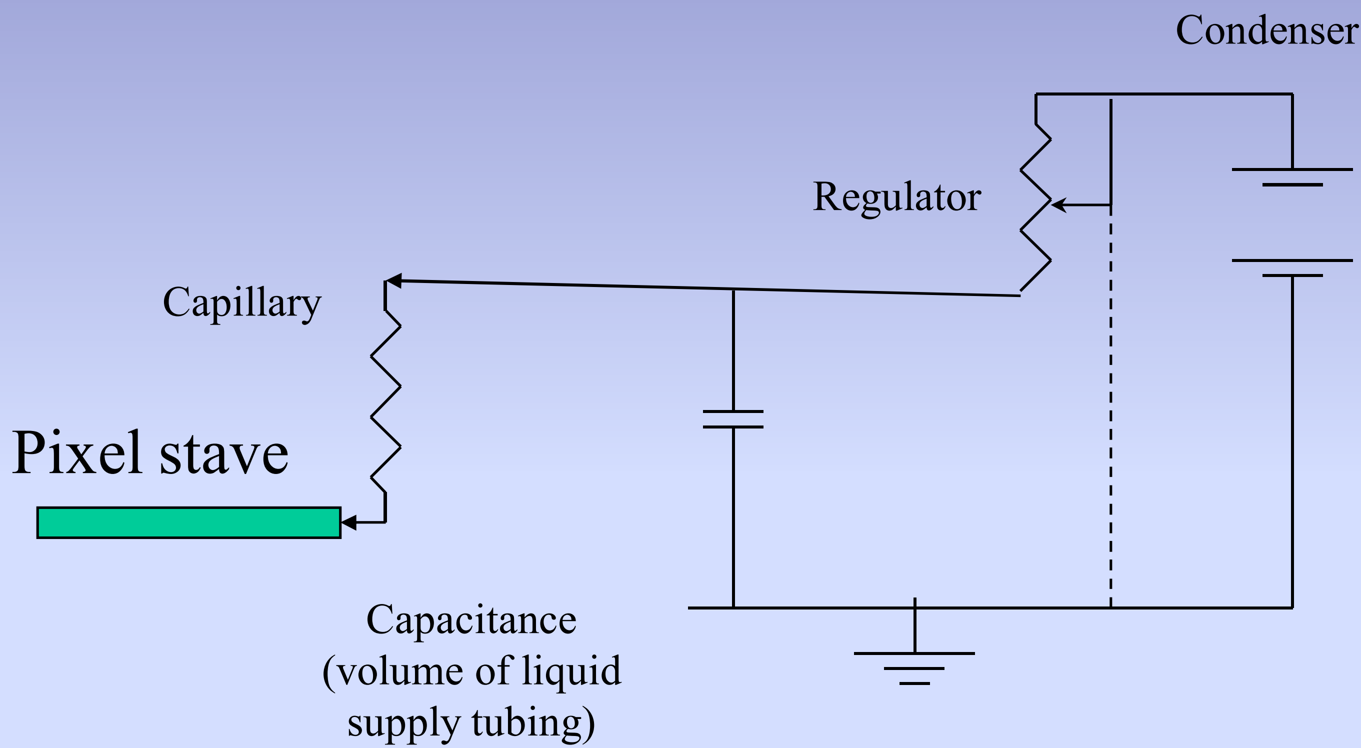
Déverseur/
Back-pressure
regulator pour
chaque circuit
(P_{evap} individuelle)

Reunion ATLAS –mécanique IBL,
LAPP, Annecy, le 10 juin 2009

Flow variation (flow regulator) for variable thermal load on a pixel stave

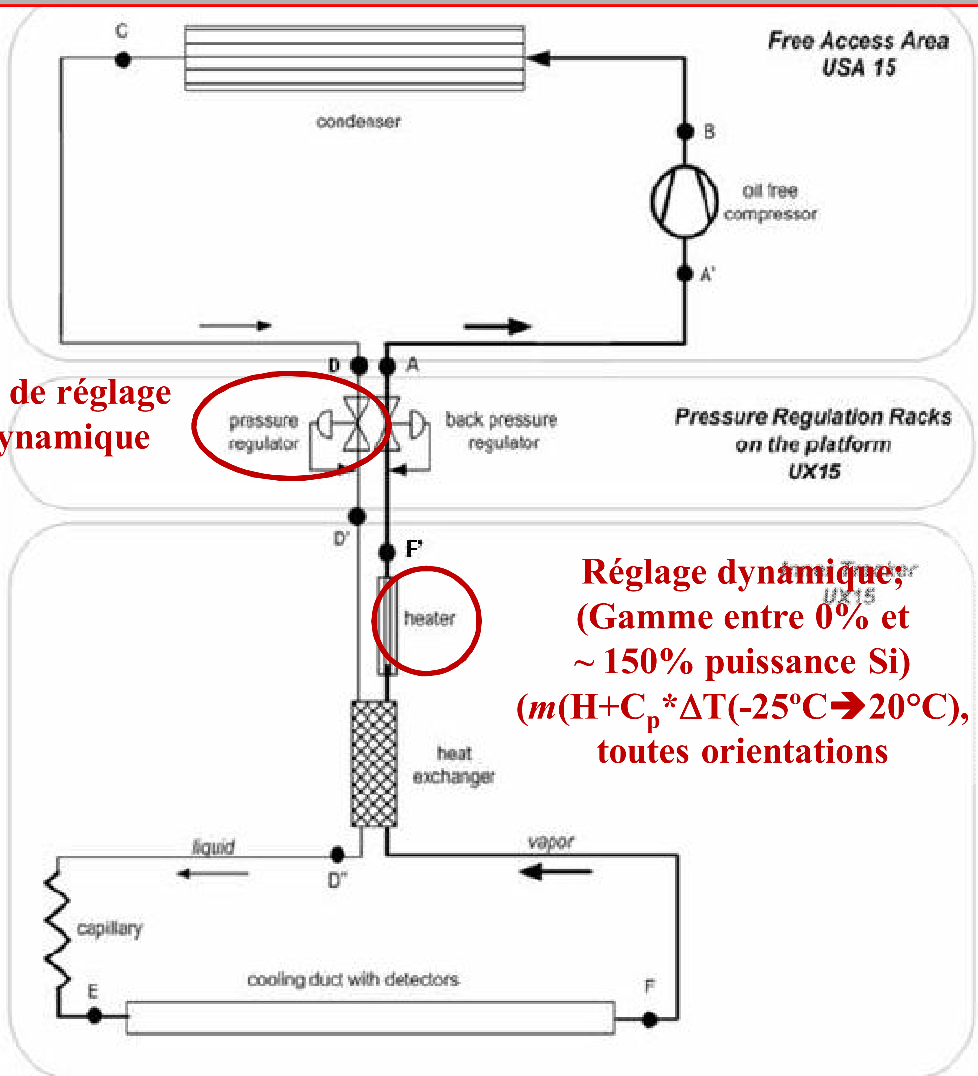


Equivalent electric circuit



Discharge of capacitance through capillary

Ce qui a été implementé par ATLAS (2)



Pas de réglage dynamique

Réglage dynamique;
(Gamme entre 0% et ~150% puissance Si)
(m(H+C_p*ΔT(-25ºC➔20°C),
toutes orientations

Figure 3. Schematic diagram of the evaporative system.

Development of Fluorocarbon Evaporative Cooling Recirculators and Controls for the ATLAS Pixel and Semiconductor Tracking Detectors.

Bayer, C.[1], Berry, S.[2], Bonneau, P.[2], Bosteels, M.[2], Burckhart, H.[2], Cragg, D.[3], English, R.[3], Hallewell, G.[3,4+], Hallgren, B.[2], Kersten, S.[1], Kind, P.[1], Langedrag, K.[5], Lindsay, S.[6], Merkel, M.[2], Stapnes, S.[5], Thadome, J.[1], Vacek, V.[2,7]

[1] Physics Department, Wuppertal University, Germany; [2] CERN, 1211 Geneva 23, Switzerland;
[3]Rutherford Appleton Laboratory, Chilton, Didcot, OX11OQX, UK;
[4] Centre de Physique des Particules de Marseille, Campus des Sciences de Luminy, 13288 Marseille, France;

Proc 6th Workshop on Electronics for LHC Experiments, Crackow, Poland, September 2000
CERN 2000-101 CERN/LHCC/2000-041, 25 Oct 2000

pressure in each circuit is individually tuned via feedback according ... it load variation, using analog air pressure-p... rs. A hard-wired thermal interlock system ... lly cuts power to individual silicon m... temperature exceed ... values.

All eleme... been implemented ... pressure and flow ... channels of standard ... Board") DAQ and DA... administered through ... Prototype 16 channel ...

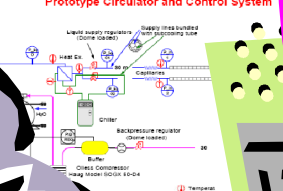
Highly satisfactor... steady state, parti... seen with propor... power. Future de...

(pressure) of ~ -25 °C (~1.7 bar_{abs}).

II. Apparatus and Principles

...ototype circulator Figure 1 is centred around ... oil-less piston compressor[2] operating at ... on pressure of ~ 1 bar_{abs} and an output pressure ...

Prototype Circulator and Control System



...pe Evaporative R...

...ed via PID varia... ...om zero to 100%[3]

...Corp. Specialty Chemicals Division, ... MN5511... USA

Mfr: Yaska... ...u, Tokyo, 105-6891 Japan

IV. Experimental Results from the Present Study

1) Studies of Heater Interlock Hysteresis

To reduce the influence of noise, the comparator circuits of the I-Box are equipped with hysteresis. The hard-wired switching temperatures of two comparators are defined with a fixed resistor network. In the pixel detector, the interlock signal ("POWER DISABLE") is set at 0.15 ºC and reset ("POWER RE-ENABLE") at – 0.79 ºC.

To simulate the behaviour of the final power supplies in the present tests, relays were put between the power supplies and the dummy modules Figure 5. The I-Box channels controlled these relays. Starting from stable

temperature distribution on powered silicon modules under steady state, partial-load, interlock-trip, start-up and shutdown conditions using two methods of proportional fluid control.

2.1) I-Box Bit Counting.

In the first, the number of powered modules was counted via I-Box bits asserted, and the flow varied according to a protocol:

P ... + m*(#powered modules) (1)

...by the WAGO DAC output acting ... to the dome loaded ... of proportionality m ... red to drive sufficient ... the capillary to evacuate t... CT module (~ 10 Watts max). ... analysing hea... were ... wnstream of the ... un-evaporated C3... of circuit power ... ndicated that ... variations in ... d to:

(2)

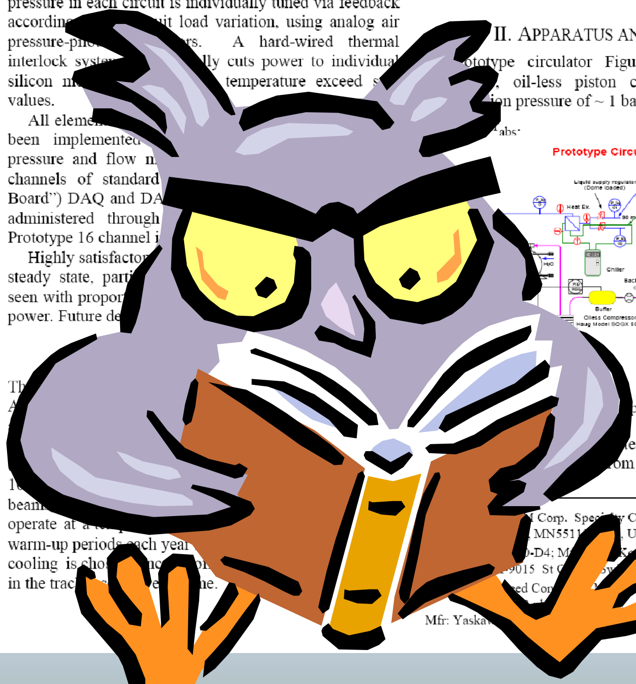
... m is the pressure/power conversion constant (mbar W^{-1}). This protocol requires (i) DCS access to the monitored voltages and currents on several supply rails per module and (ii) that the power supplies continue to supply this information.

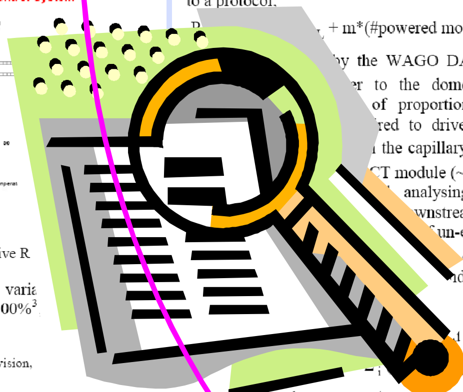
2.2) Direct PID control of Fluid Flow.

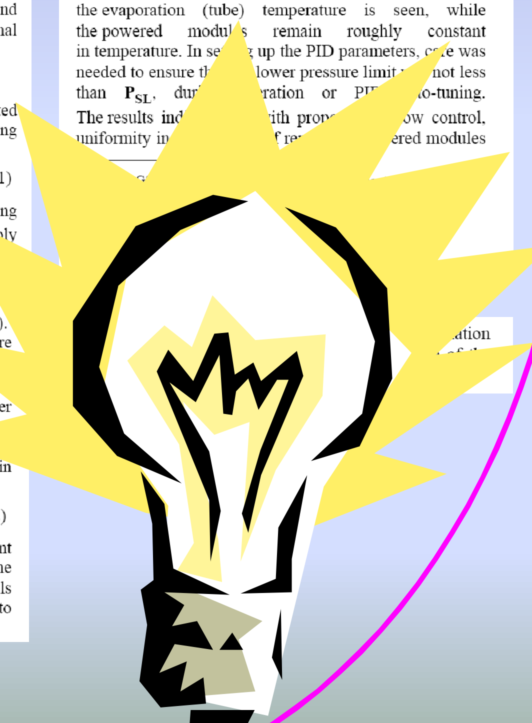
Direct PID control of circuit flow on the basis of sensed exhaust temperature has proved an effective means of control. In a first study, a commercial PID controller[10] directly piloted the E2P driver. In a second study, a PID algorithm was implemented directly in a microcontroller chip[11] of the same family as that used[12] for system programming and monitor functions in the recently-developed "Embedded-LMB": [7], currently under test. In a third study, PID control was implemented using BridgeVIEW PID extension toolkit, using WAGO DAC modules to pilot the E2P drivers.

In each case, it was possible to maintain the temperature at a point ~50 cm downstream of the evaporation zone a significant margin (>10 °C) above the

in temperature of the un-powered modules toward the evaporation (tube) temperature is seen, while the powered modul... remain roughly constant in temperature. In se...g up the PID parameters, c...e was needed to ensure th... lower pressure limit ... not less than P_{SL}, dur...ration or PI... o-tuning. The results ind... ith prop... ow control, uniformity in... ered modules







Condensation risk if vapour exhaust tube temperatures are below the local dew point(s)

How to avoid this?

Deliver sufficient fluid to evacuate the heat from the Si modules (variable; function of n° of modules powered per stave, I_{leak} etc…)
but not too much (to avoid evaporation in ~ 25m tubing)!

One intelligent technique;

Feedback from temp. Sensors on exhaust tubing to flow regulators;

Done by Proportionnel, Intégrale & Dérivative *firmware* bloc;

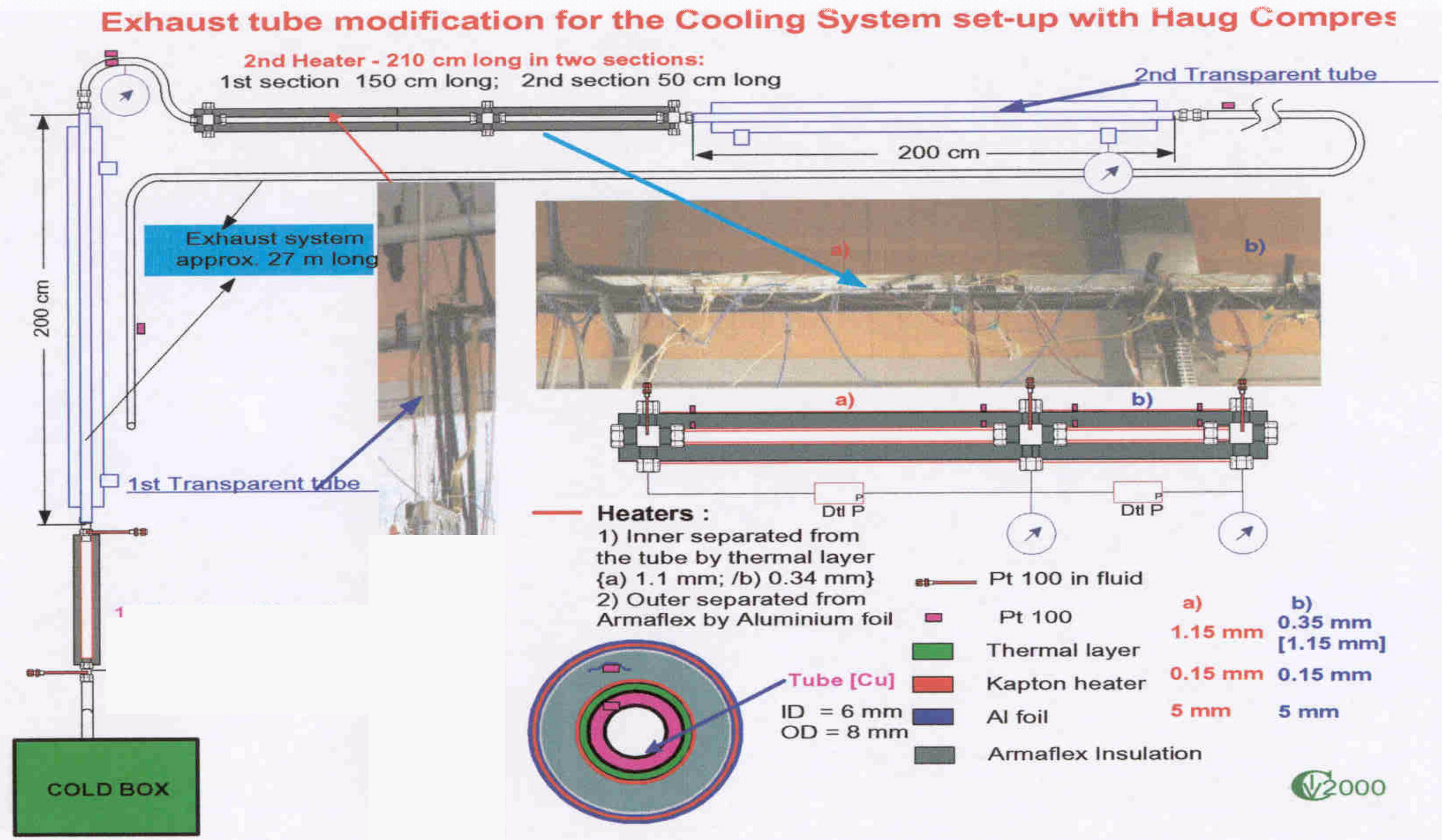
$$p(t) = K_c[e(t) + (1/\tau_I) \int_0^t e(t^*)dt^* + \tau_D(de/dt)]$$

Object: maintain temperature downstream of evaporator a few °C above T_{evap} defined by the backpressure regulator downstream of 25m exhaust tubing:

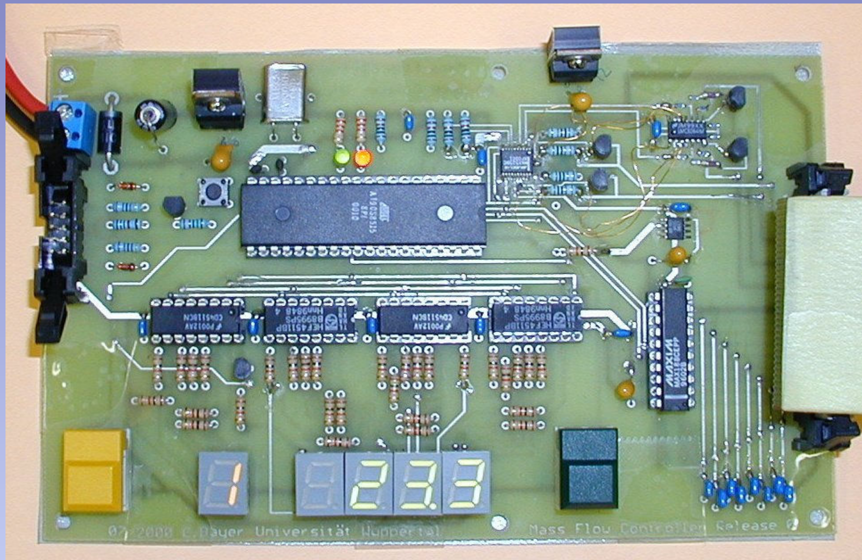
Thermistor or PT100 to E-LMB analog input
+ DAC output (0-10VDC) to flow regulator (coolant mas flow)

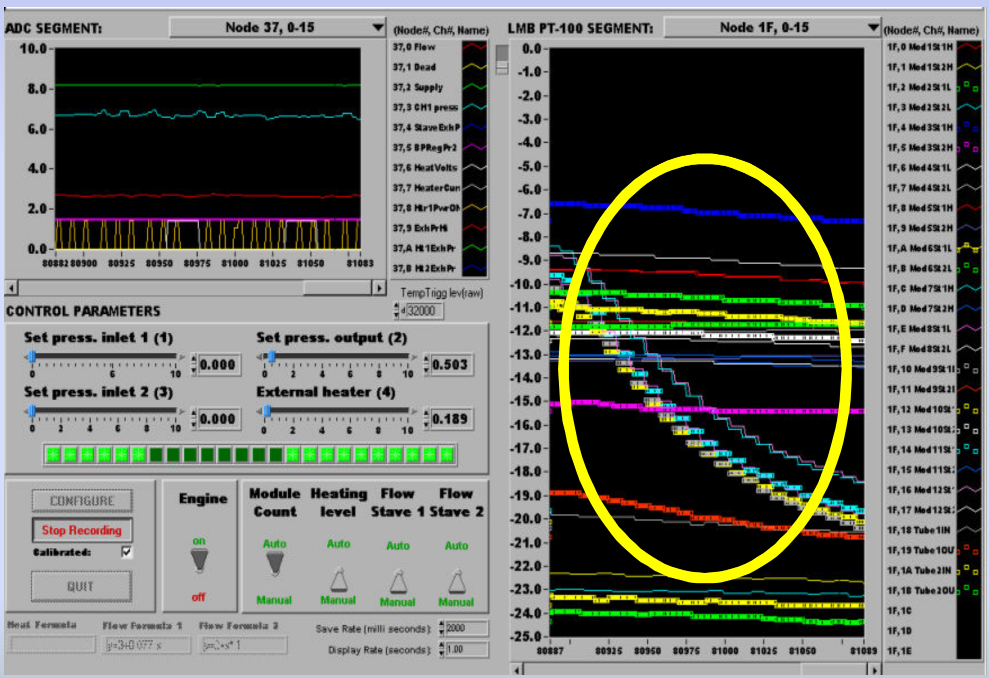
PID could have been easily added to E-LMB (sufficient memory in µcontroller)

Evaporative Cooling System Exhaust Tube Studies
verification of operation of proportional flow



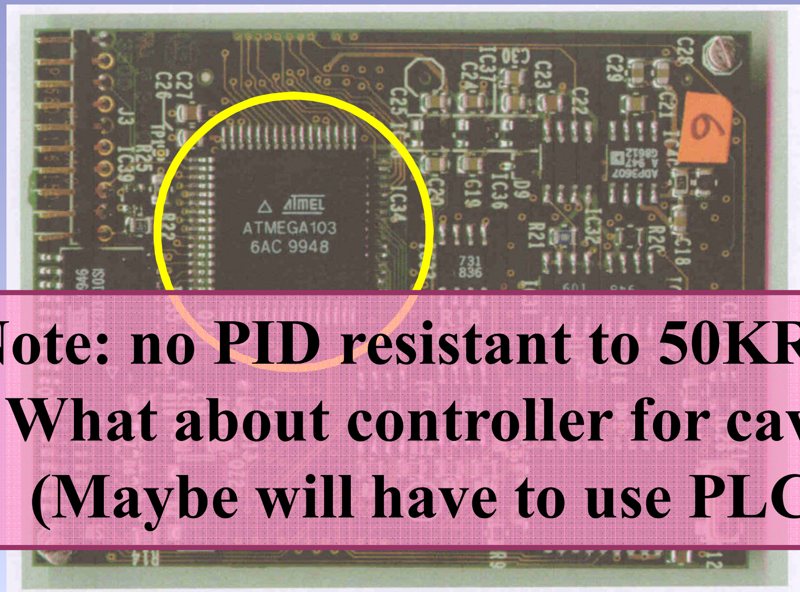
PID Algorithm burned into ATMEL microcontroller GNU ➔ microcode






```
#include <io.h>
#include <interrupt.h>
#include <math.h>
#include <sig-avr.h>
#include <timer.h>
#include <wdt.h>
#include <eeprom.h>
#include "mfc.h"
uint8_t volatile dispch, map, input, ziff, flash, fon;
int16_t volatile temp, disp[DISPLAYS], par[PARAMS], aktpar,
aktsig
n;
int16_t last_error, acc_error, lastout;
static int16_t dummy_attribute_((section (".eeprom"))) = 0;
static int16_t savepar[PARAMS] _attribute_((section
(".eeprom"))
) = {
PAR1, PAR2, PAR3, PAR4, PAR5, PAR6, PAR7
};
void delay( uint8_t anz ) {
uint8_t i;
uint16_t j, k;
for ( i = 0; i < anz; i++ )
                    for ( j = 0;  j < 32768; j++ ) k += j;
}
int16_t round (float t ) {
t *= 10;
 if ( fabs( t ) == t ) return (int16_t) ( t - 0.5 ) ;
 else return return (int16_t) ( t + 0.5 ) ;
}
void display( int16_t n) {
 uint8_t tmp;
if  ( n < 0) {
n = -n ;
sbi( PORTC, CMINUS ) ;
}
else cbi ( PORTC, CMINUS) ;
if ( input && aktsign && (  ziff ! =4 || fon ) )
sbi( PORTC, CMINUS ) ;
if  ( n > 999 ) n = 999;
tmp = ( n / 100 ) ;
if ( ziff  == 1 ) FLASH ( SEG1, tmp ) ;
else {
                    if ( tmp == 0 && ! ziff )
                                        SEG ( SEG1,
SEGBLANK ) ;
                    else
                                        SEG ( SEG 1, tmp )
}
```

ATLAS DCS E-Local Monitor Board



Front side of Embedded Local Monitor Board ELMB Size 50x66 mm October 2000 version

Note: no PID resistant to 50KRad existed in commecial market
What about controller for cavern rates at L~10^{34} operation?
(Maybe will have to use PLCPID or E-LMBs in USA15…)

- Node CAN bus (➔32 on a bus)
- Resistant to 50KRad (10 yr/cavern ATLAS @10^{33})
- 64 analog inputs (PT100 etc.)
- 32 bits DI/O
- 2Mo program space in μ-controller

Carte mere

ELMB PID-controller (framework)

ELMB-based multiple PID-controller with CANopen interface

software user manual, version 0.1 (draft)

20 May 2002

Henk Boterenbrood
boterenbrood@nikhef.nl

NIKHEF

ELMB-DAC
16-channel 12-bit DAC-module
for the ELMB

user manual, version 0.0

18 Feb 2002

Jaap Kuijt, Piet de Groen, Paul Timmer,
Daniel Tascon Lopez, Sander Schouten, Henk Boterenbrood

NIKHEF
Amsterdam, NL

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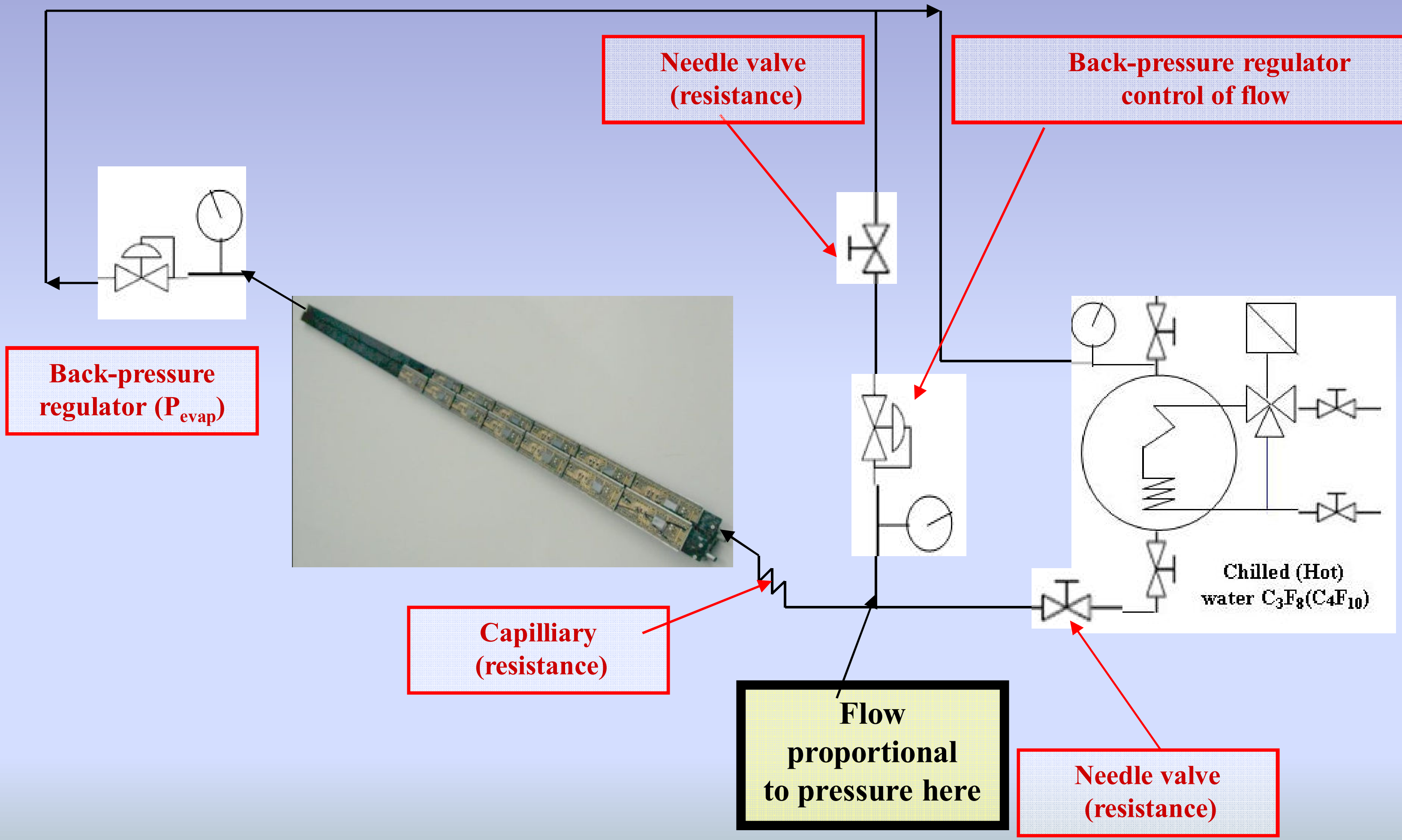
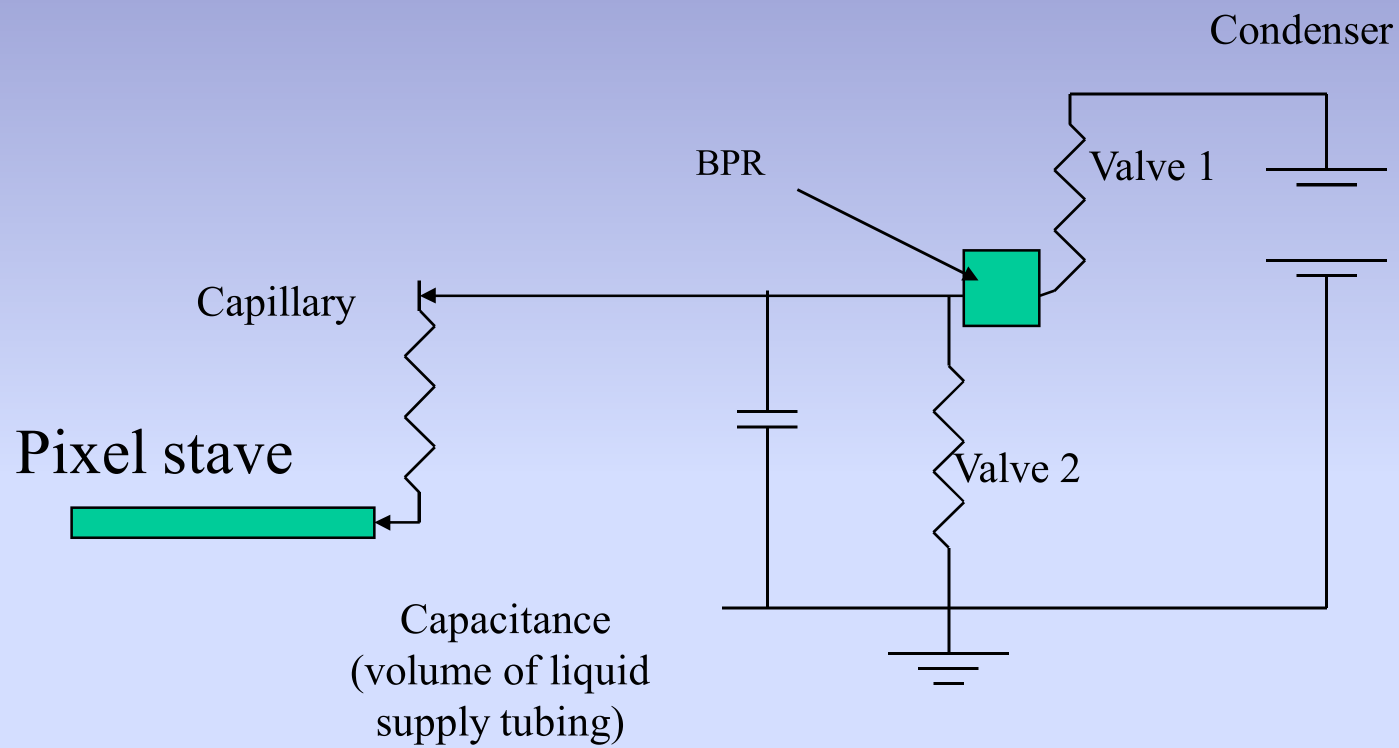
Rapid response pressure regulation (by backpressure regulator only) for variable thermal load on a pixel stave

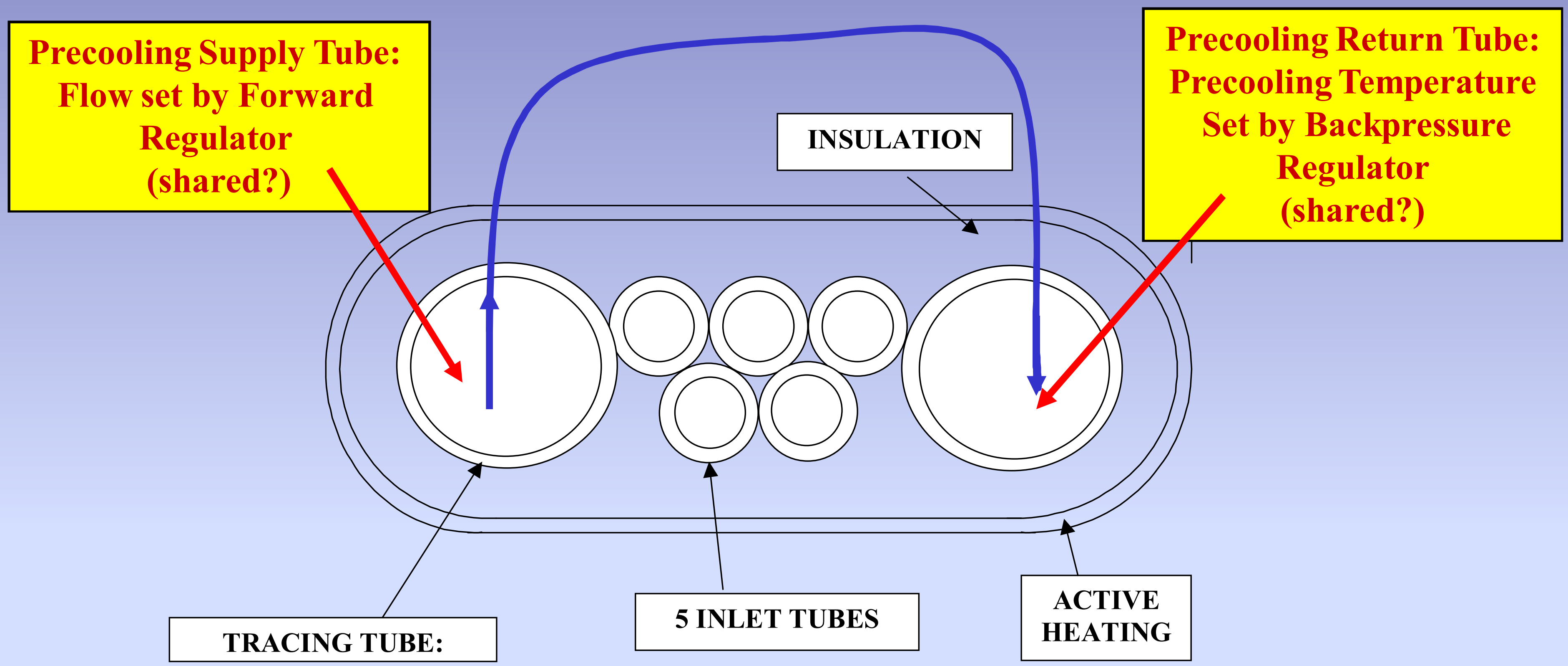


Equivalent electric circuit



Rapid discharge of capacitance via parallel path
(BPR+ valve 2)

“Cold-Nosing” The Liquid Supply Tubes

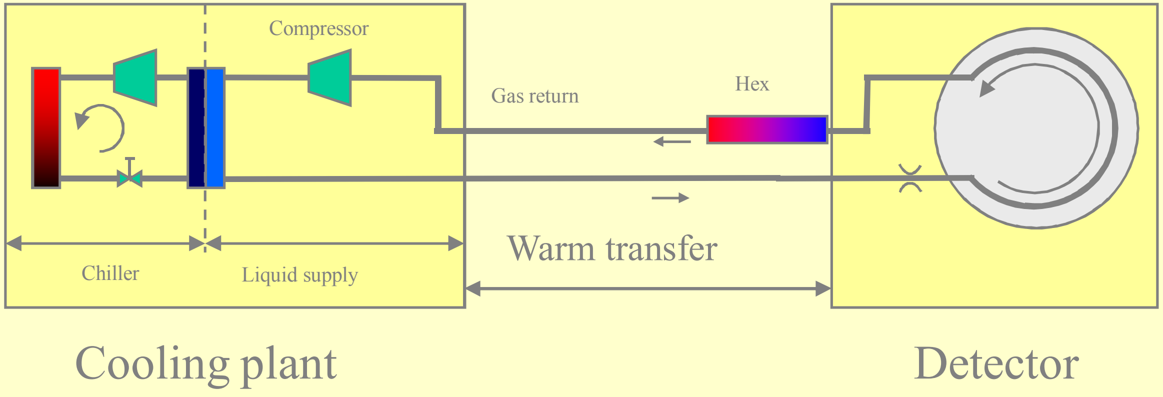


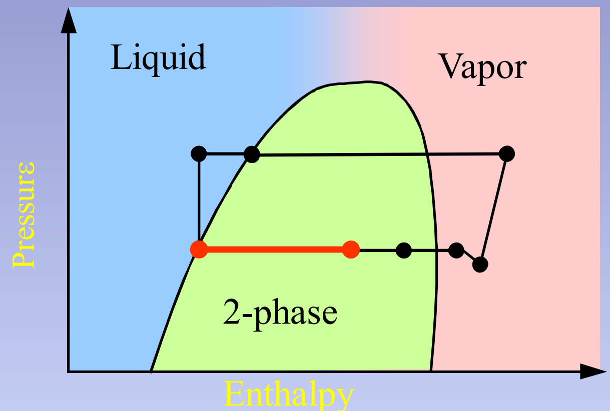
Capillary Connection between Input and Output Pre-Cooling Tubes in Type 1 Service Area

CO_2 Closed cycle systems

As in CO_2 refrigeration industry :

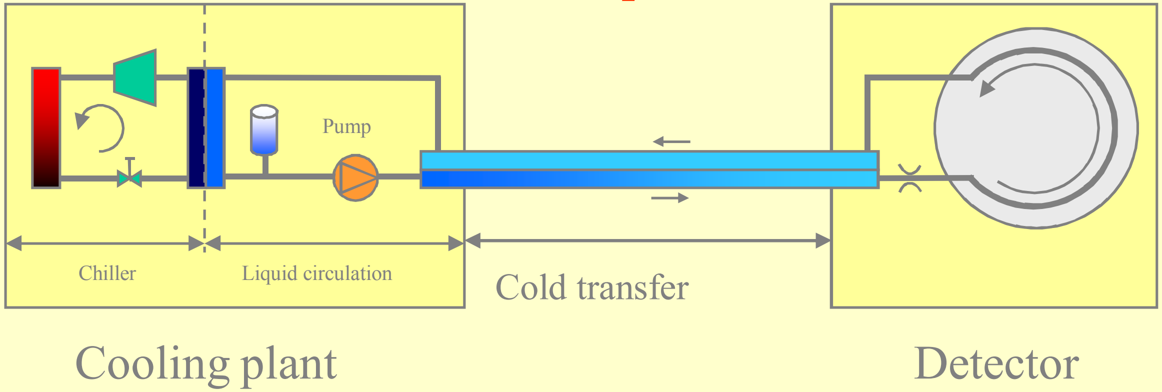
Subritical vapor-compression cycle

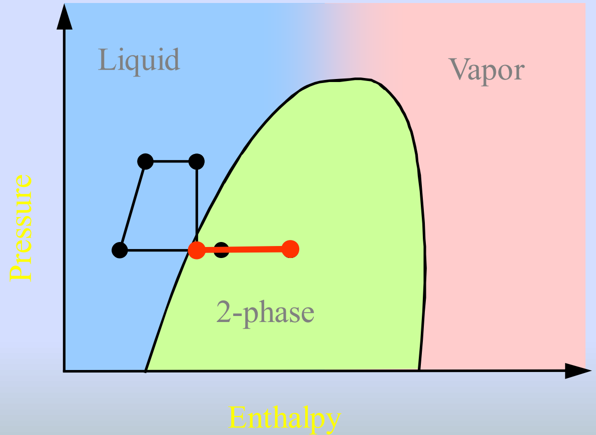


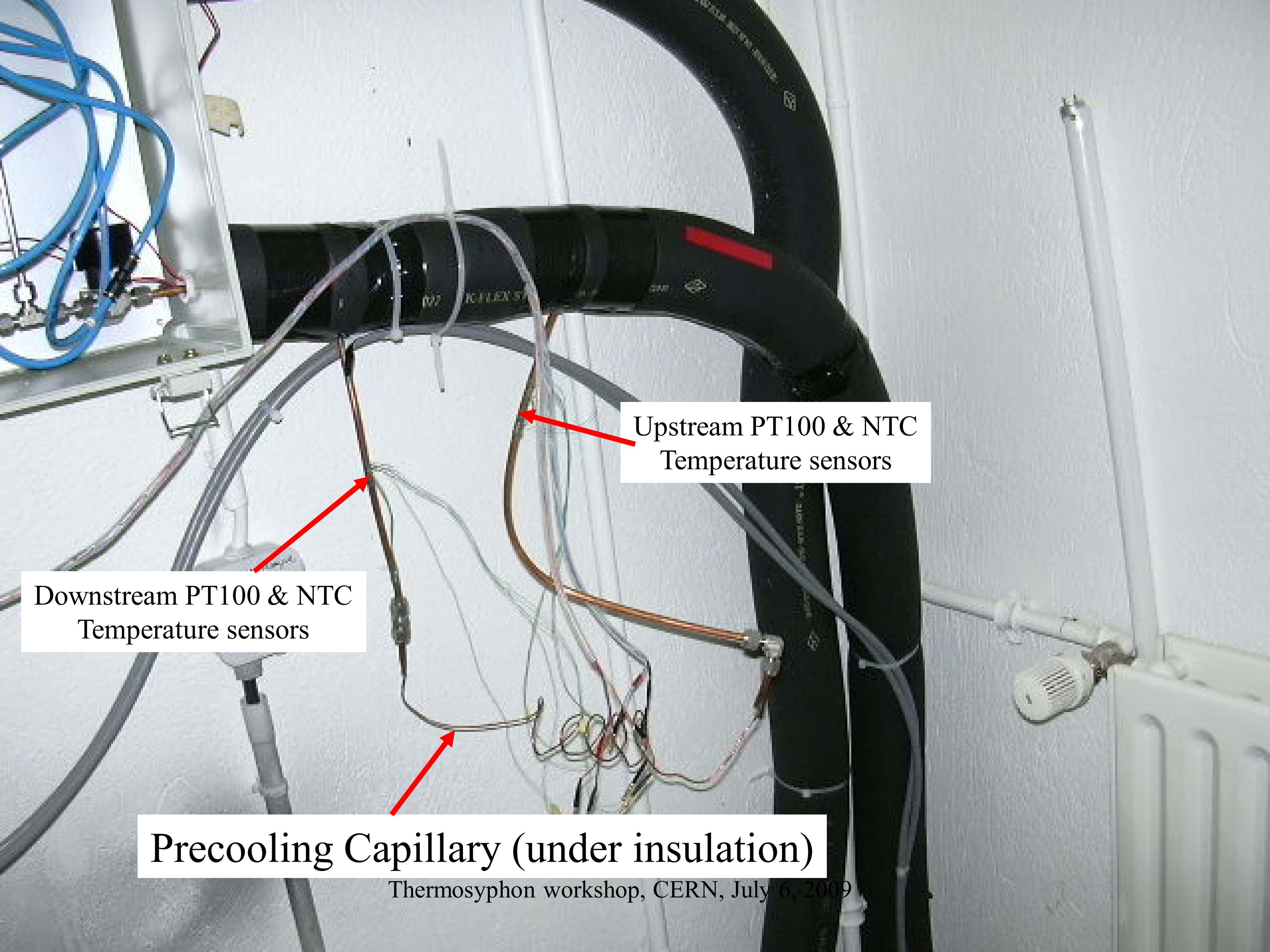


LHCb-VELO: **2PACL pumped liquid system**

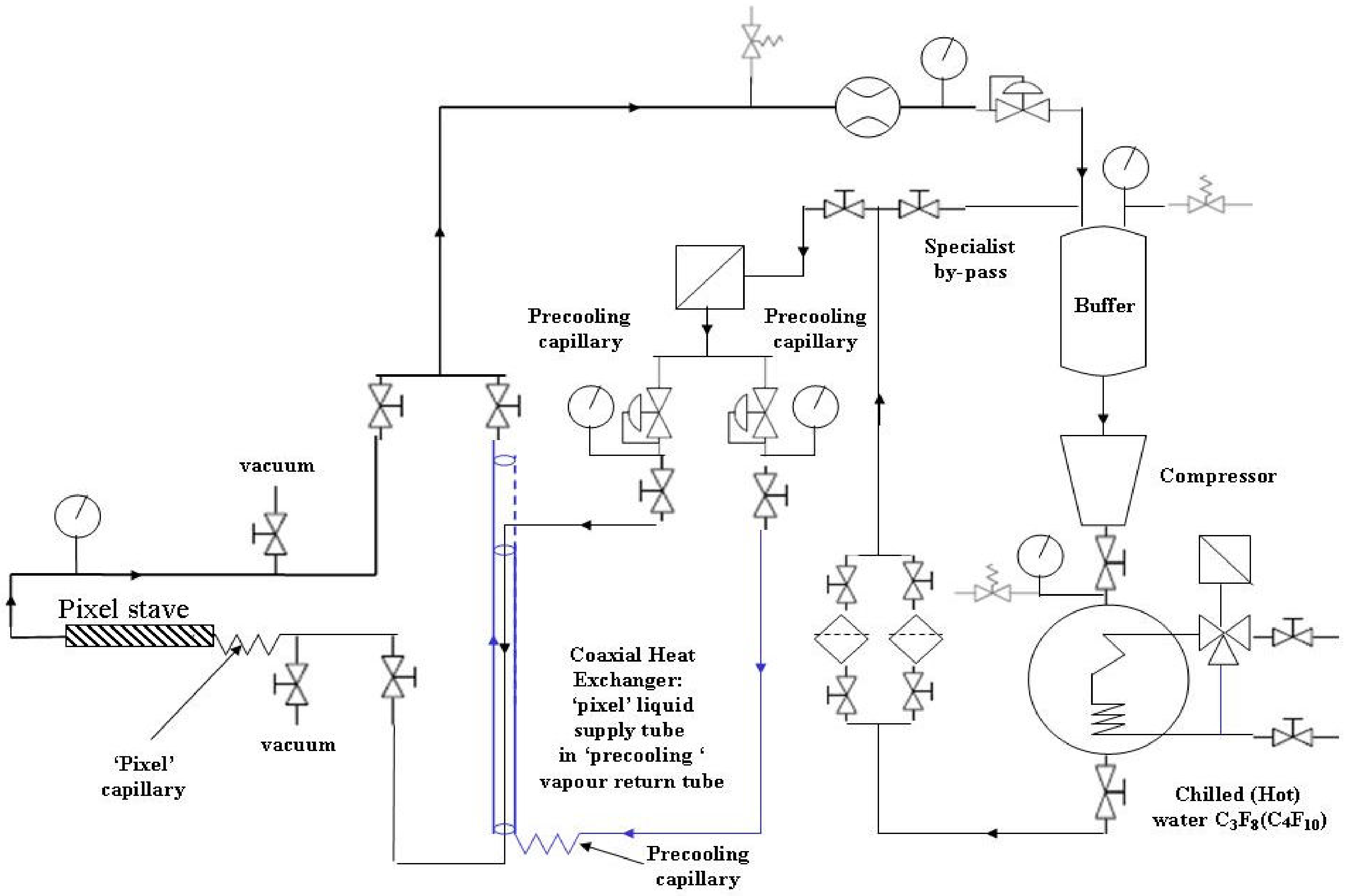
Fluid: CO_2



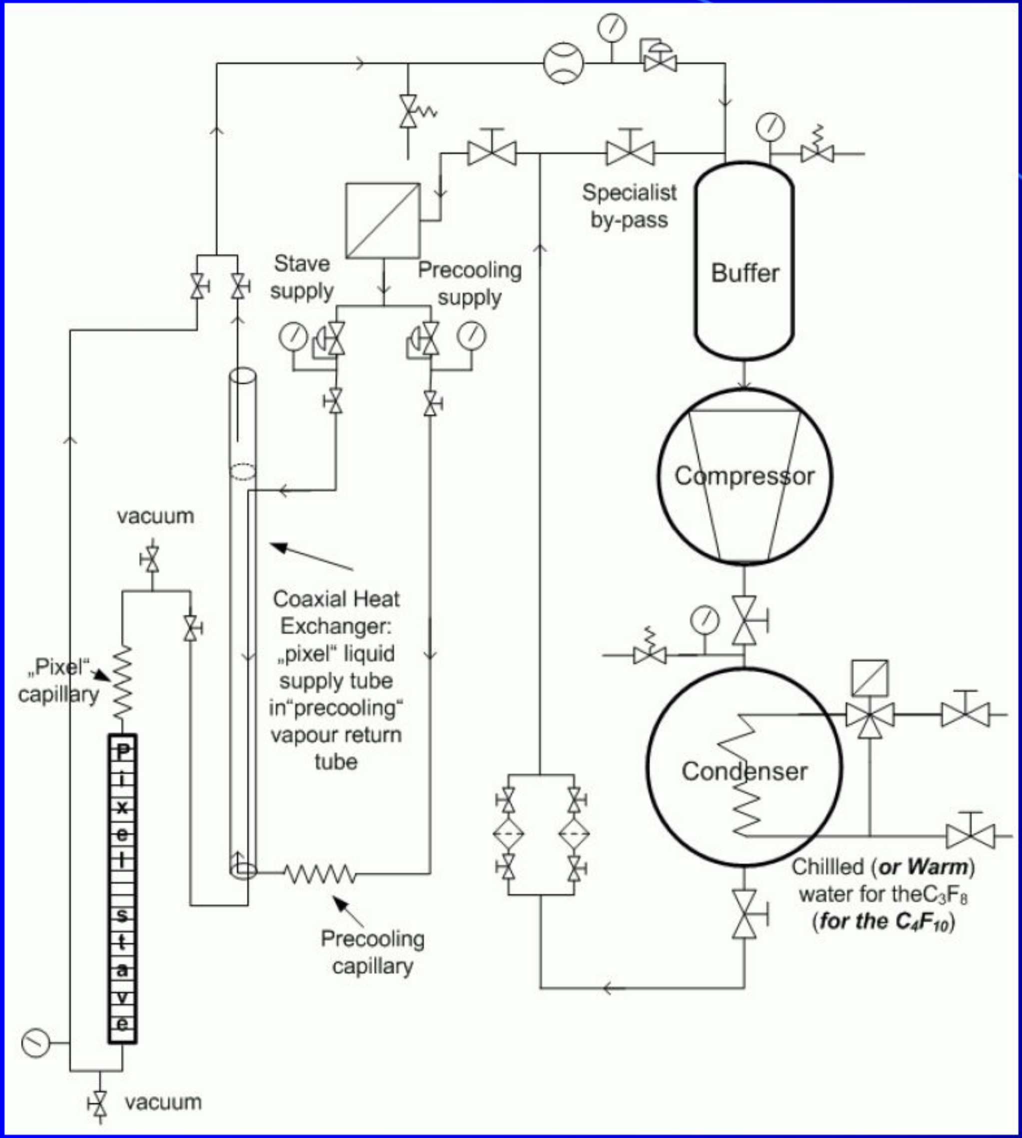



Upstream PT100 & NTC Temperature sensors
Downstream PT100 & NTC Temperature sensors
Precooling Capillary (under insulation)

Système au CPPM pour qualification des échelles ("staves") ATLAS Pixels



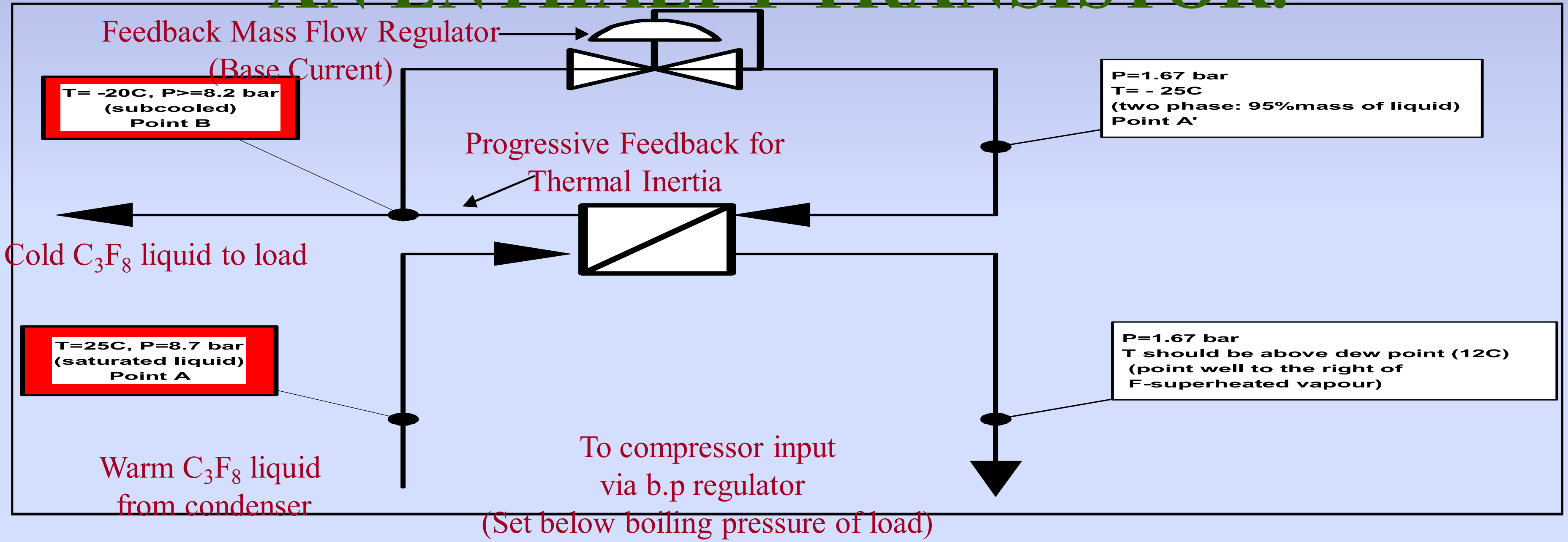
Support studies - circulator for “dual-fuel”, operation



- Theoretical prediction of the fluid replacement had to be proven and verified experimentally
- Experimental setup at CPP Marseille has been used for the verification

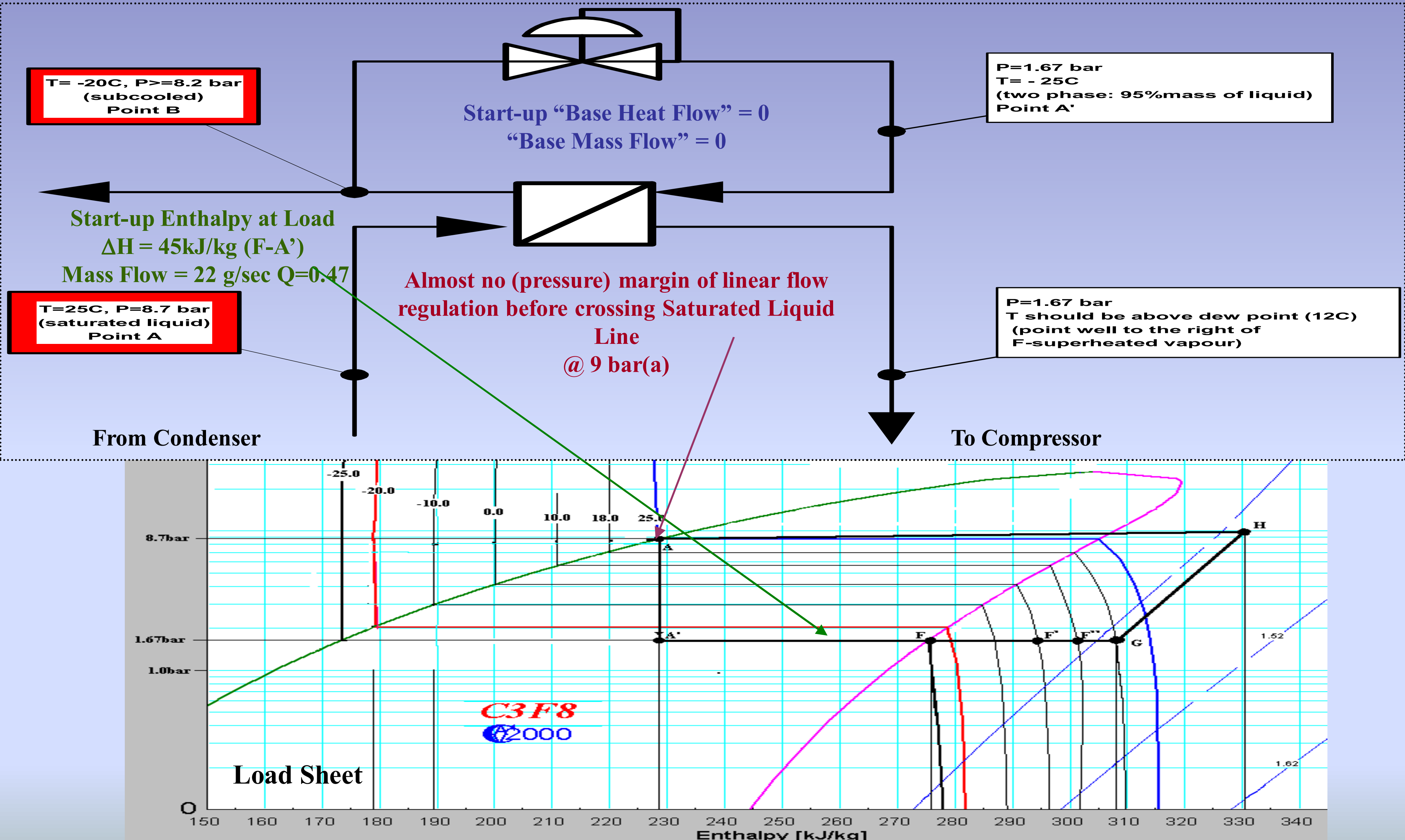
Evaporative Cooling Demonstrator: Concept for Sub-cooling of C_3F_8 liquid with Counter-Evaporating C_3F_8 liquid in Heat Exchanger.

AN ENTHALPY TRANSISTOR.



HOW DOES IT WORK? (1)

STARTUP (The case for 1 kW load cooling)



HOW DOES IT WORK? (2)

RUNNING (The case for 1 kW load cooling)