Experience in Design and Implementation of CO_2 Cooling Control Systems

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PH/DT/PO - Cooling

Presentation overview

- Introduction
- CO_2 cooling systems control principle
- Control system standardization approach
- CO_2 cooling test stands at CERN
  - ✓ 2kW CORA – ATLAS and CMS (PH-DT-PO)
  - ✓ 100W TRACI – ATLAS & LHCb (PH-DT-PO)
  - ✓ 2kW CO_2 SR1 – ATLAS (EN-CV-DC & PH-DT-PO)
- What's next?

Introduction

Why CO_2?

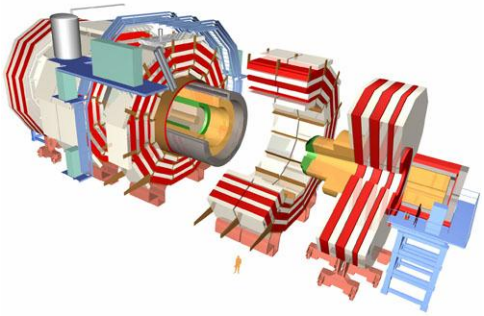
- Allows very small tubing (material budget)
- High heat transfer coefficient
- High thermal stability due to the high pressure

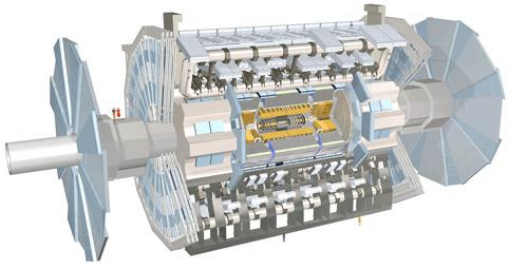
Where currently successfully used?

- AMS-TTCS (Tracker Thermal Control System)
  Q = 150 W
  T = +15 ºC to -20 ºC
- LHCb-VTCS (Velo Thermal Control System)
  Q = 1500 W (2 parallel systems of 750 W)
  T = +8 ºC to -30 ºC

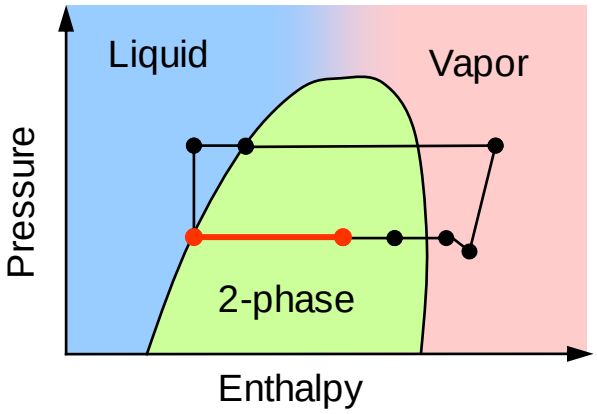
CO_2 cooling systems under development

- ATLAS IBL
- CMS - tracker upgrade
- KEKb-Bell 2



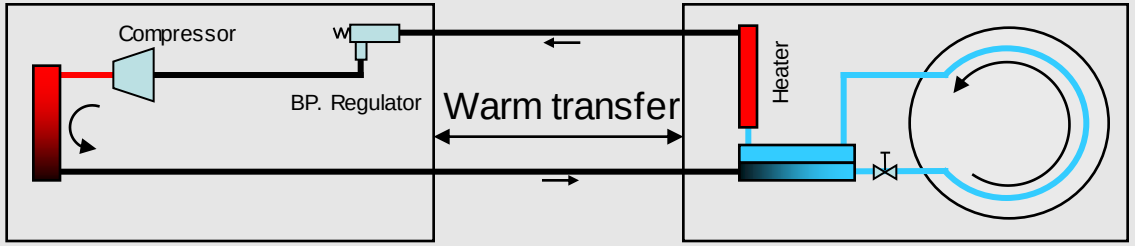


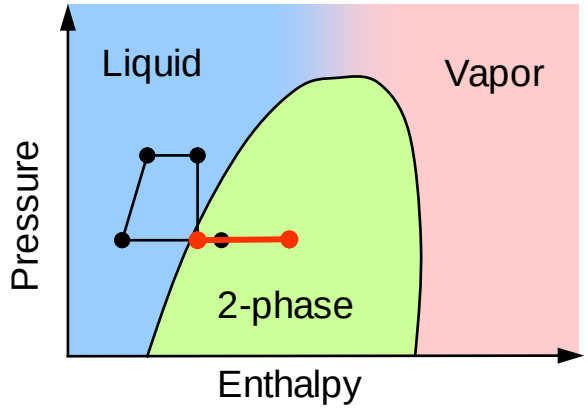
Principle



Refrigeration method: (Atlas)

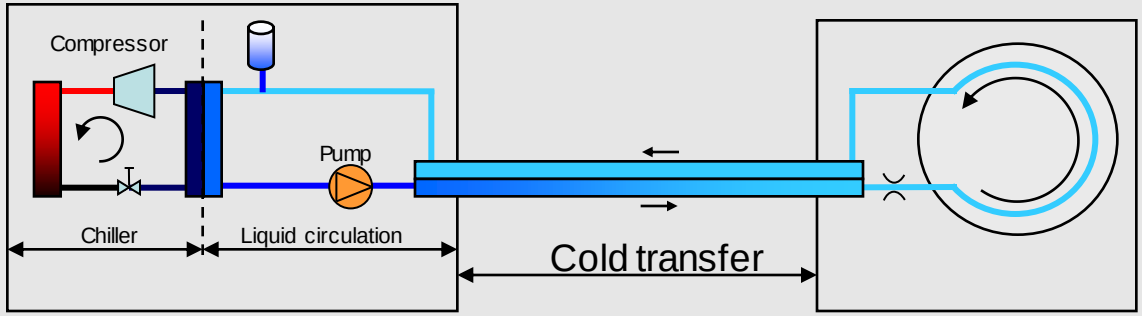
Vapor compression system





2-Phase Accumulator Controlled Loop method: (LHCb)

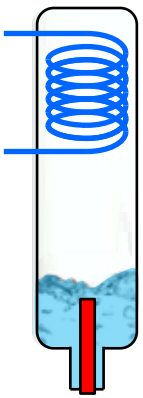
Pumped liquid system, cooled externally



Introduction to control CO_2 cooling system

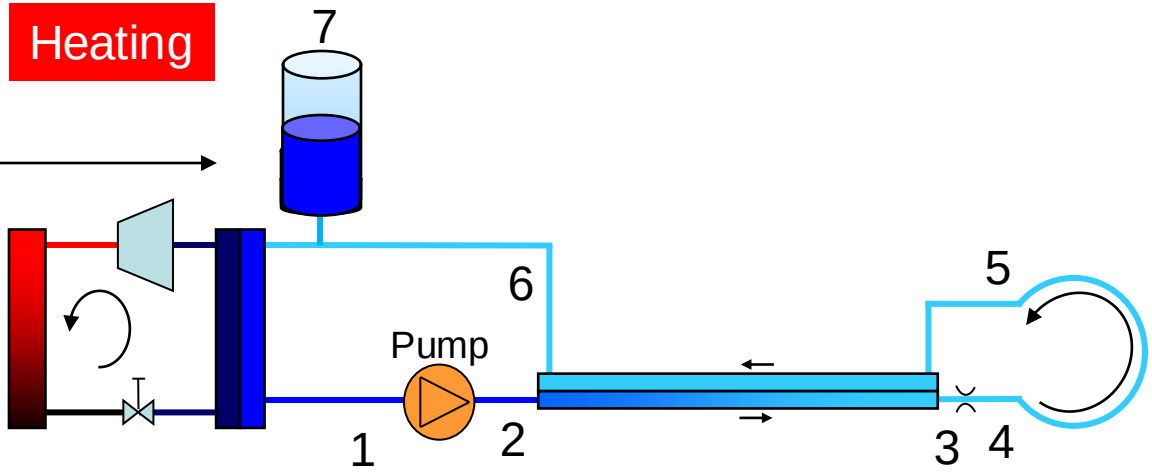
Accumulator

Cooling regulated by pulse modulated control valve



Heating – regulated by pulse modulated heater

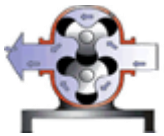
Heating



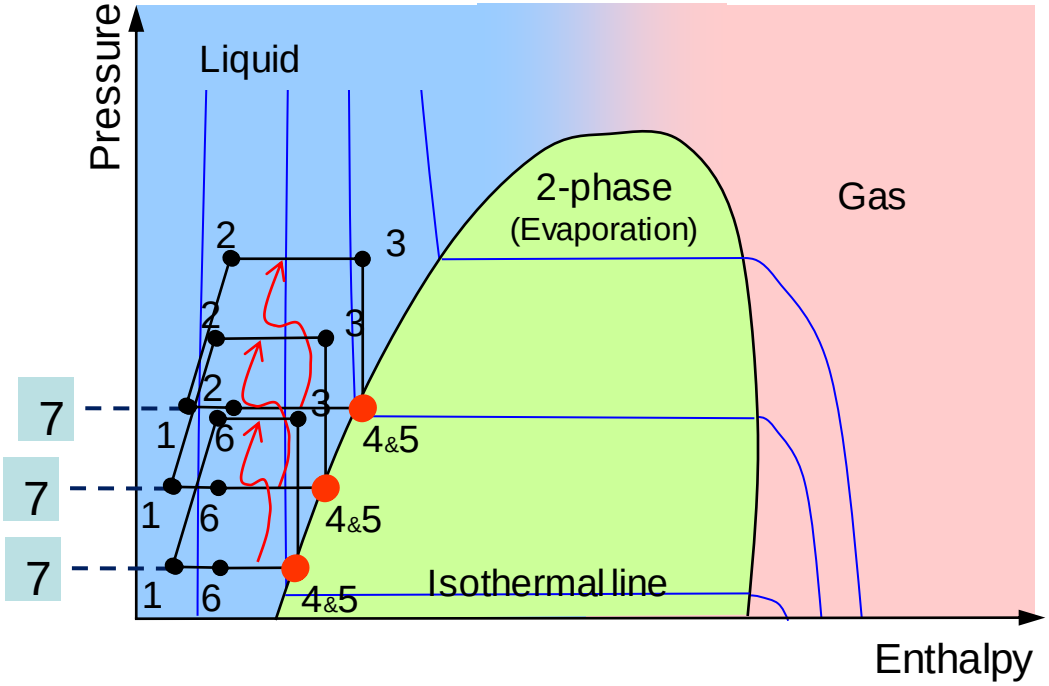
Chiller

Heaters

Pump



Control valves



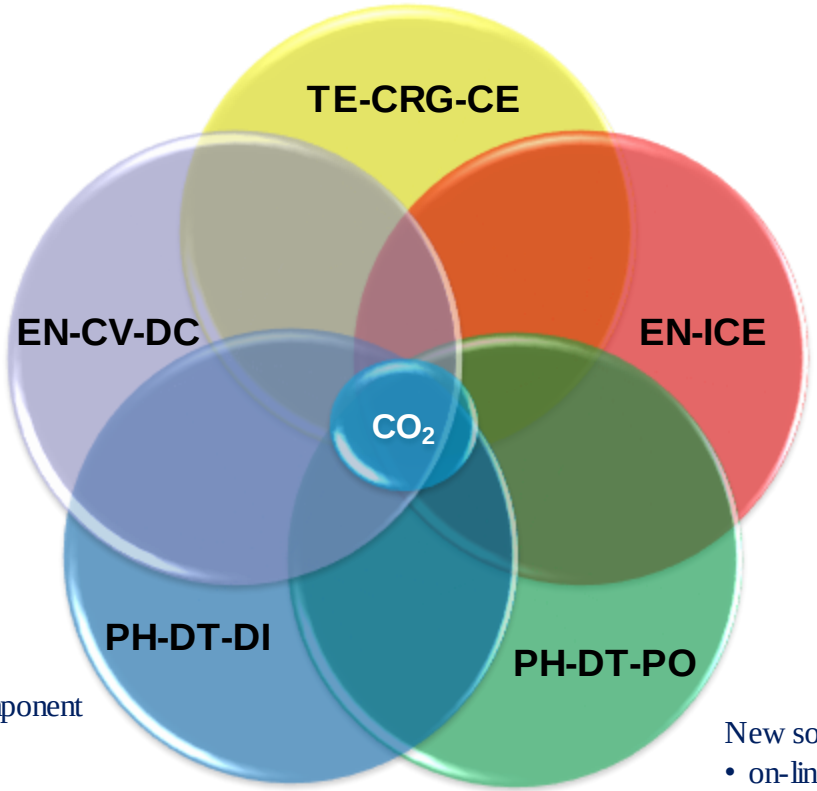
Control system standardization approach

- Why do we need standardization?
  - To design and fully test complete base model of future detector cooling systems (mechanical/electrical/control)
  - Provide a control system in accordance with CERN standards
  - Provide a system easy to integrate with **D**etector **C**ontrol **S**ystem

- How do we apply it?
  - Common and easy to manipulate human machine interface for PLC based systems with long term data archiving, trending tools, alarms history and diagnostic tools. PVSS as supervision and data acquisition system well known and widely used at CERN in LHC and in Detector Control Systems (ATLAS)
  - Industrial control/electrical components: Siemens/Schneider/Phoenix/PR electronics
  - **UN**ified **I**ndustrial **CO**ntrol **S**ystem framework – object orientated framework for PLC and PVSS programming

Standardization approach

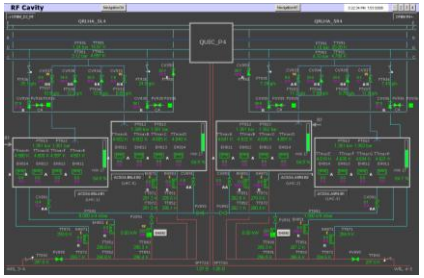
Industrial electrical components
Control hardware equipment
Electrical diagnostic tools
Siemens PLC standard



Schneider PLC standard

Recipes component

UNICOS framework
IEC61512-1 standard
PVSS



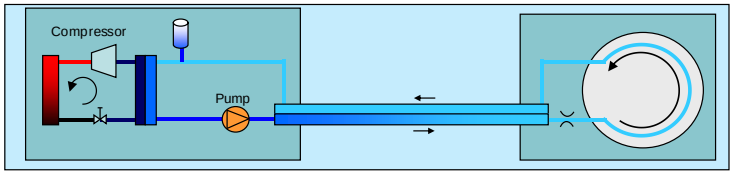
New software components:
- on-line pressure enthalpy diagram
- one button PVSS system start/stop

Alarm diagnostic

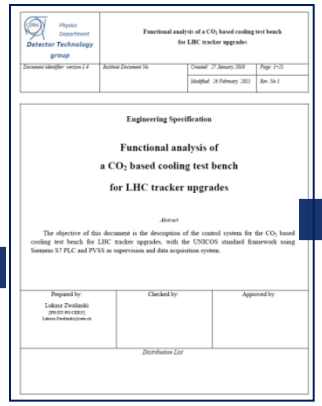
Control system design and implementation

Work flow for control system design and implementation

Process concept

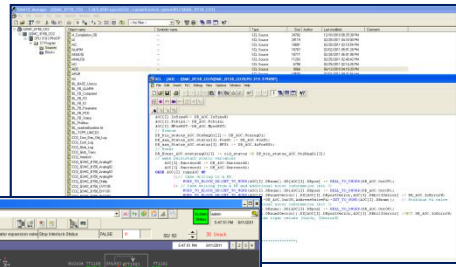


Functional analysis

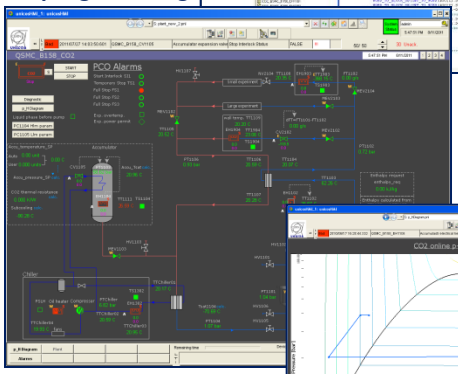


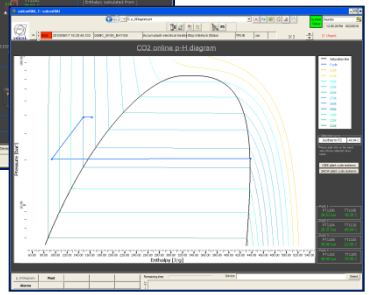
UNICOS

PLC programming

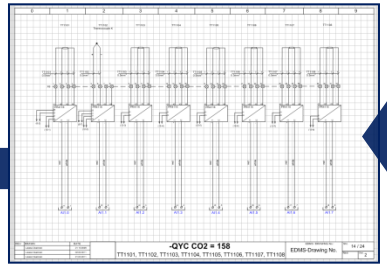


SCADA programming

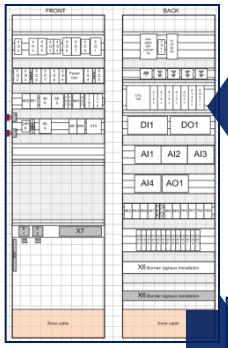


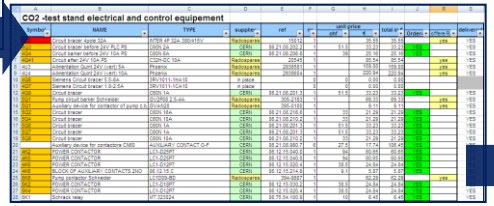


Electrical design



Electrical assembly



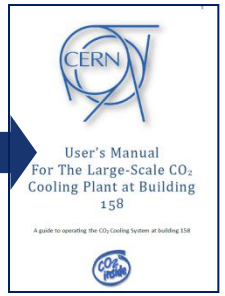


Component selection and ordering

Assembly

Commissioning

User manual

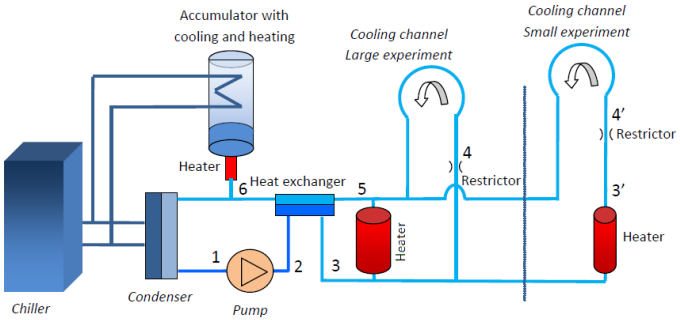


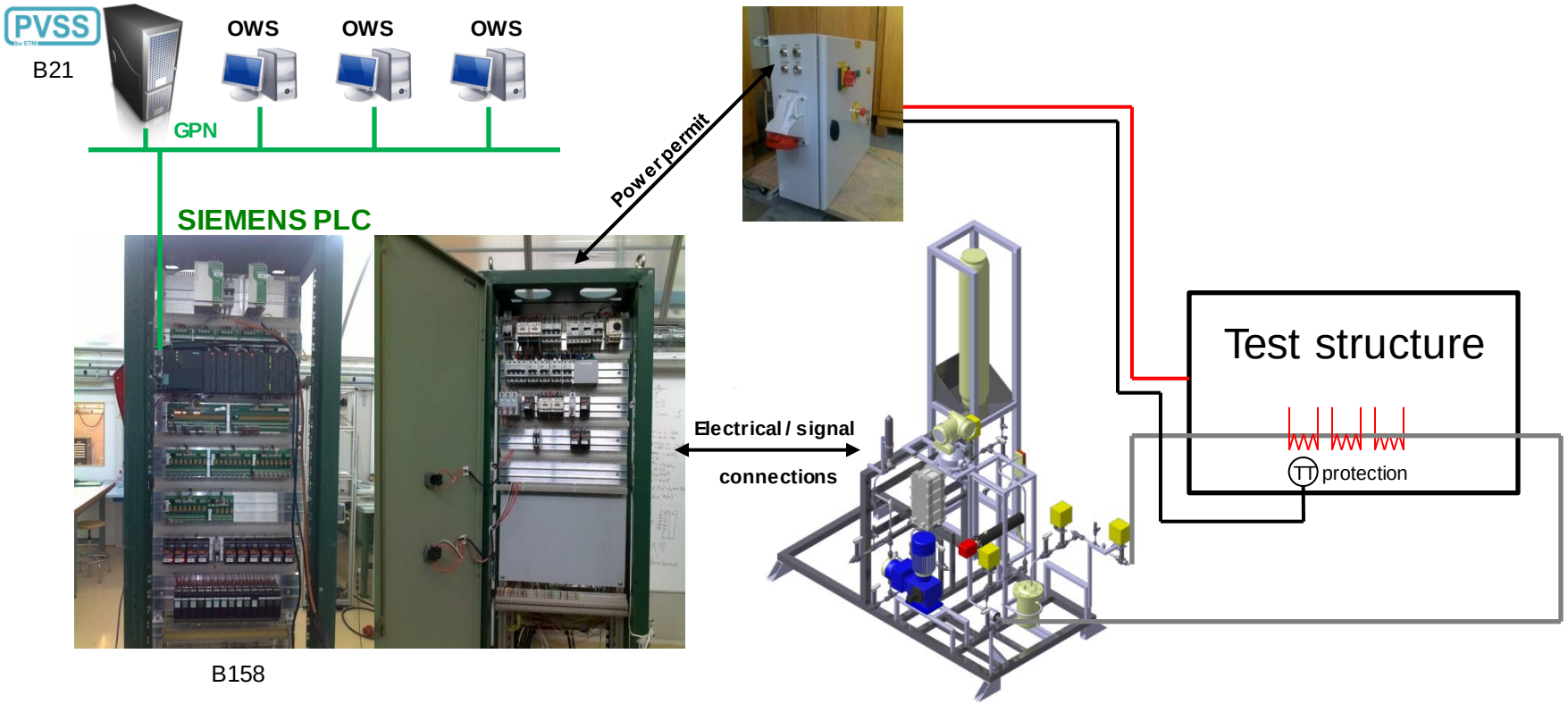
Project organization

CORA 2kW – control system architecture

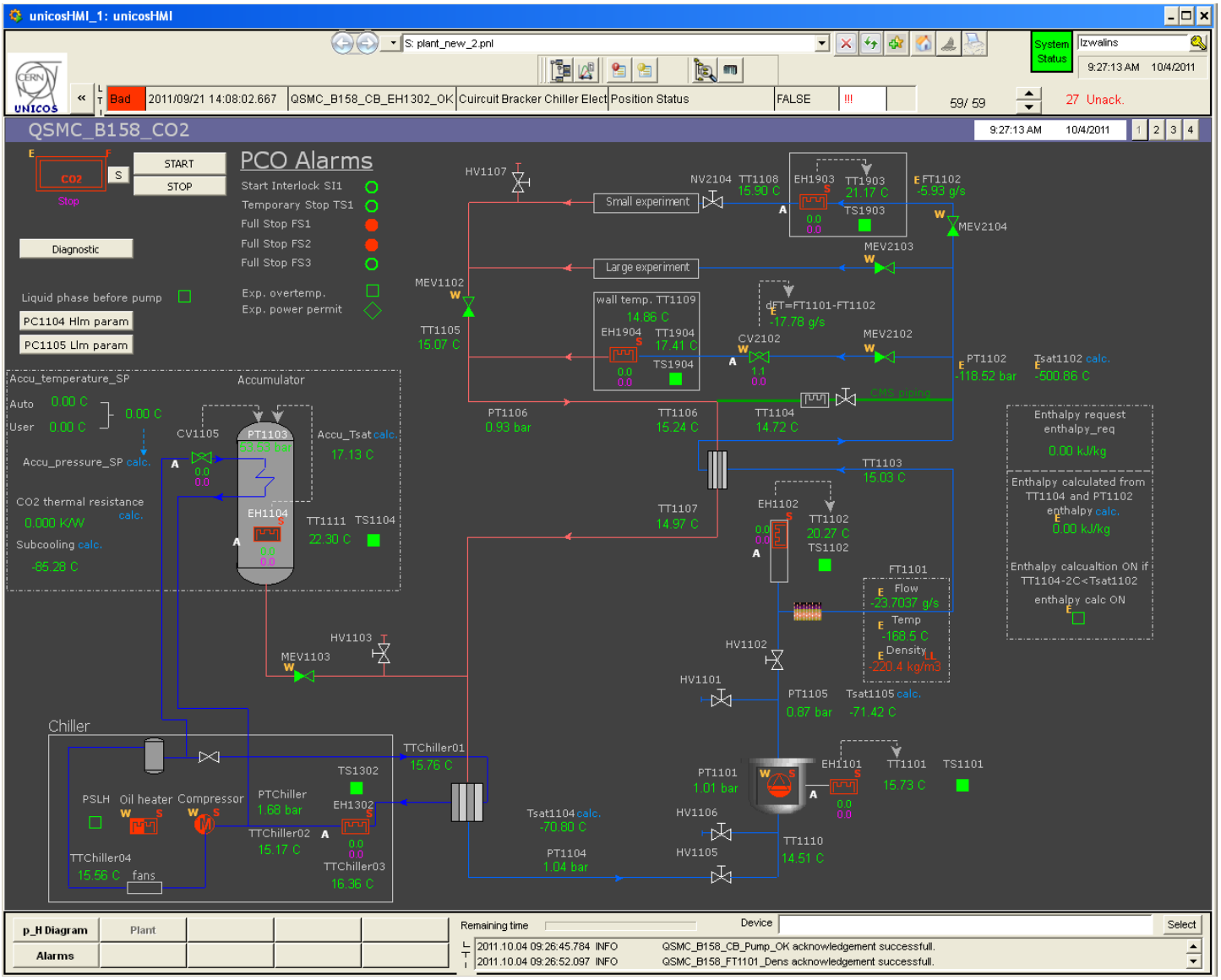
CO_2 Research Apparatus - **CORA**

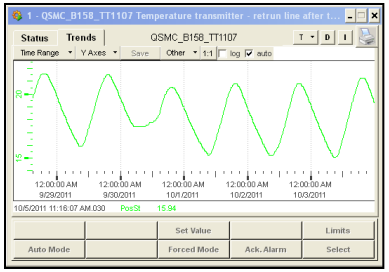
- Siemens S7 319 PLC (building 158)
- PVSS 3.8 data server on Windows PC (building 21)
- UNICOS framework (32AI, 4AO, 32DI, 32DO, 7 closed control loops)
- Experiment power redistribution box with temperature protection

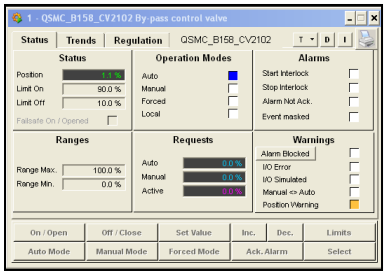


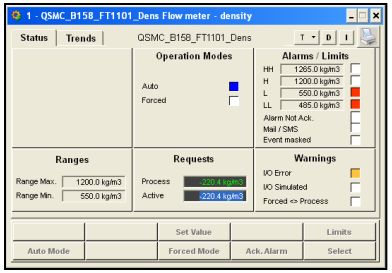


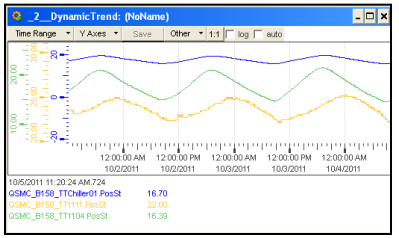
CORA 2kW – control system





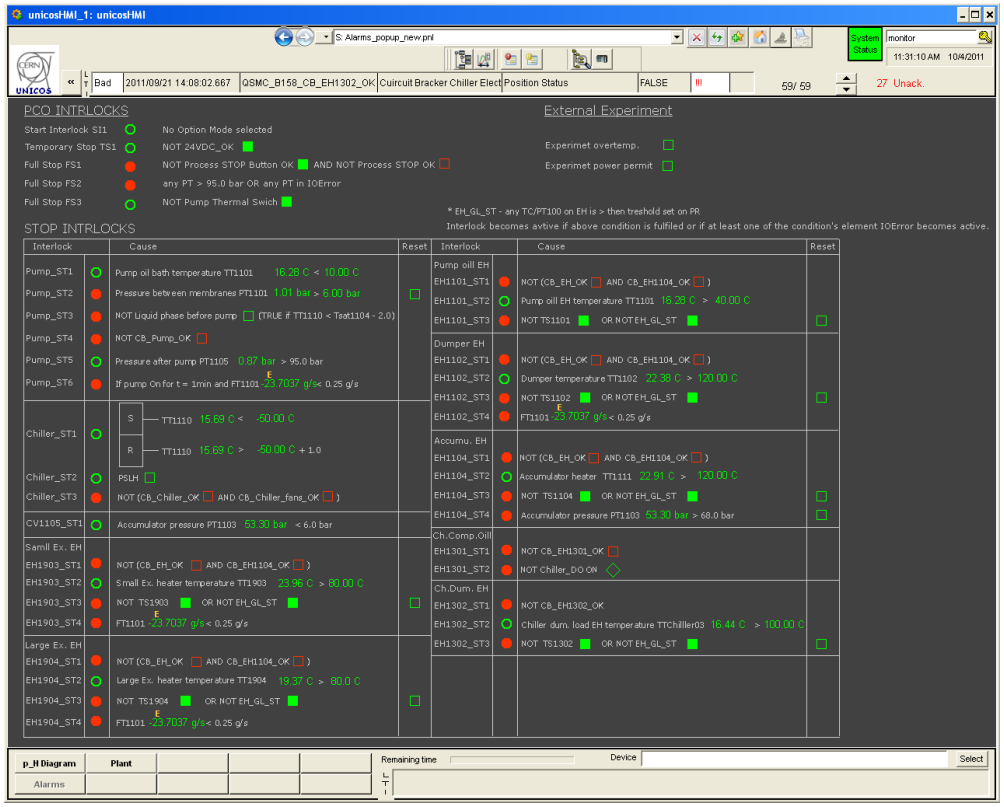




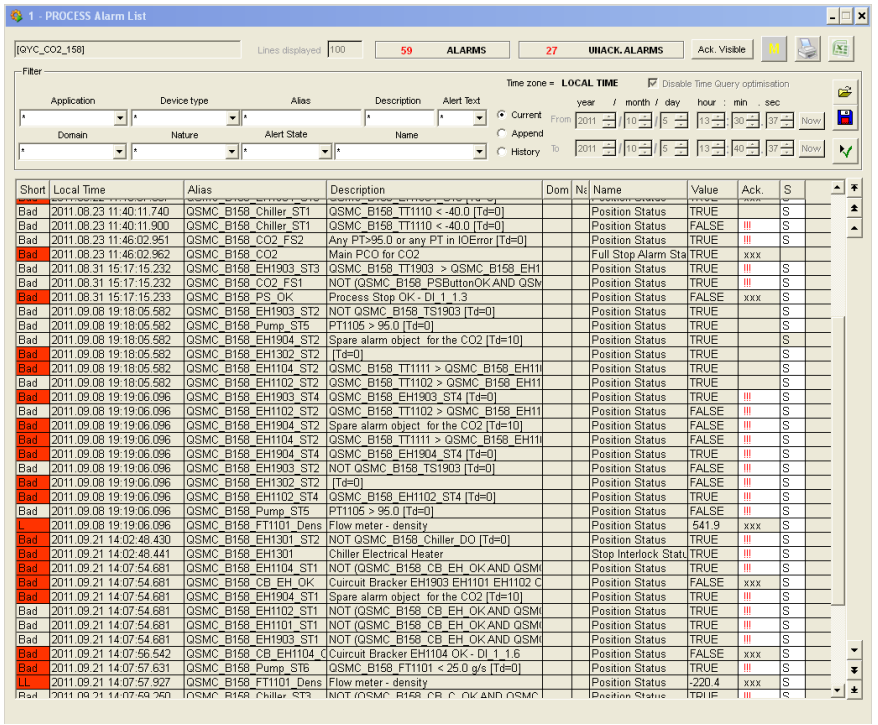


CORA 2kW – control system

Alarm diagnostic



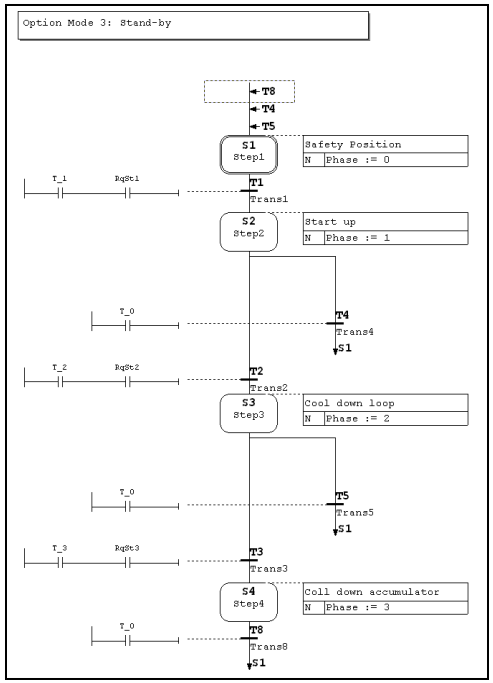
Alarm list



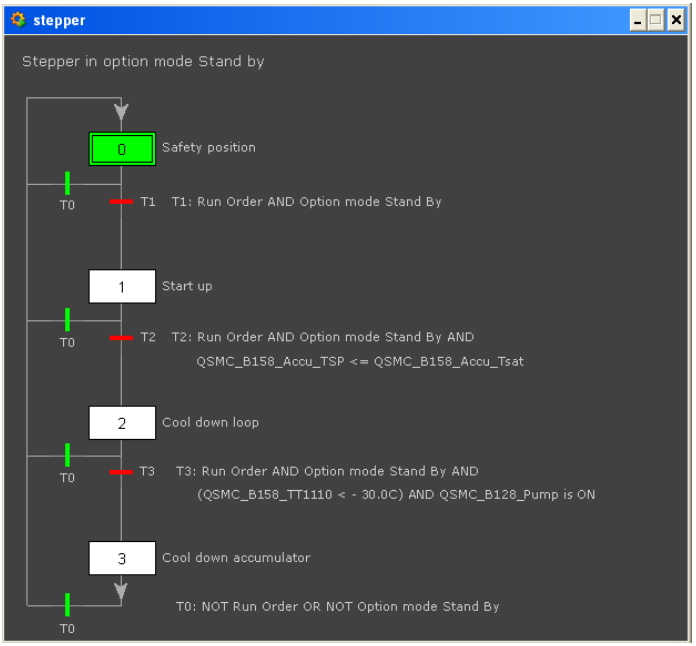
+ email & SMS alarm notification

CORA 2kW – control system

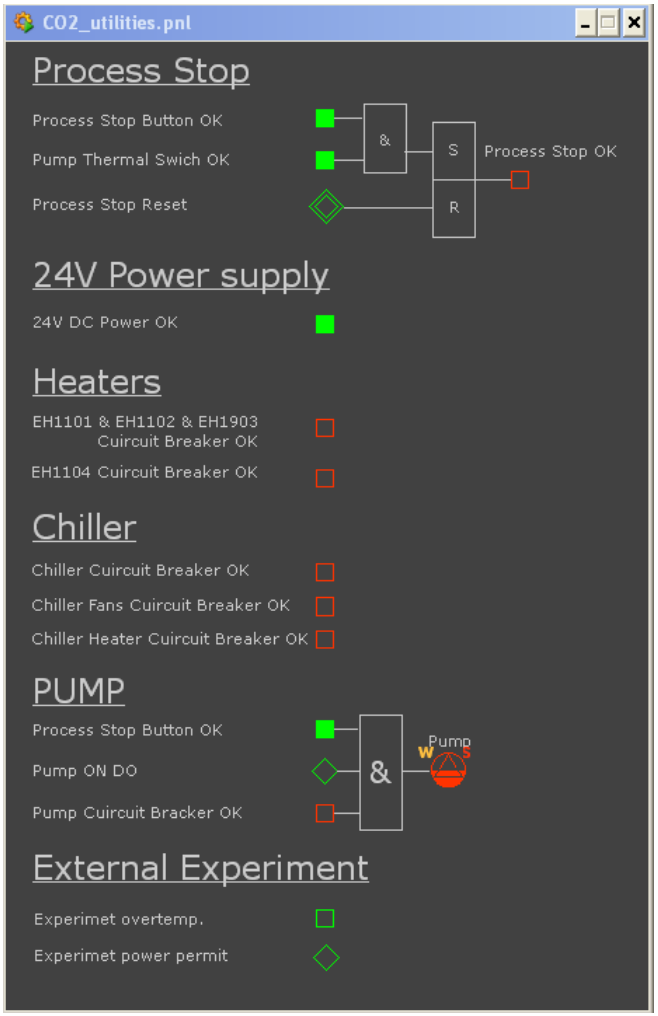
PLC graph



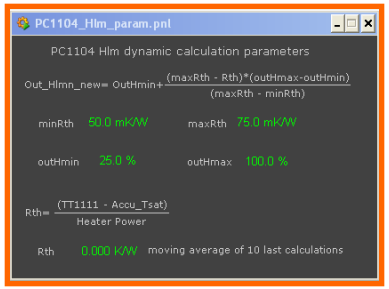
System stepper



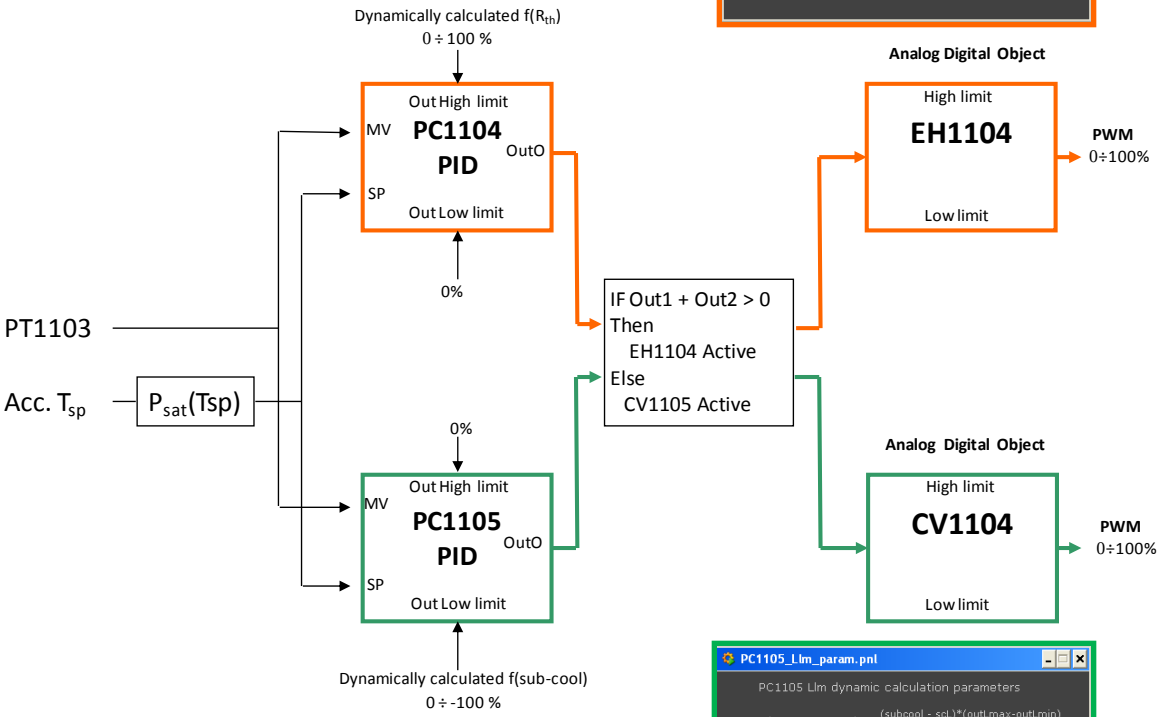
Electrical diagnostic



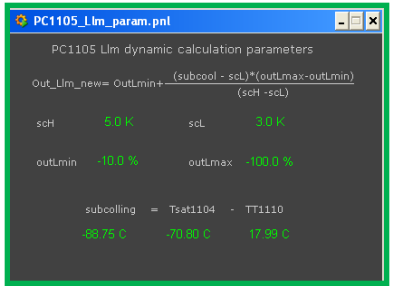
CORA 2kW – accumulator control

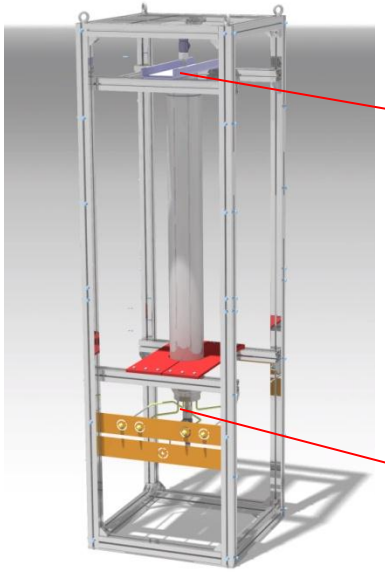


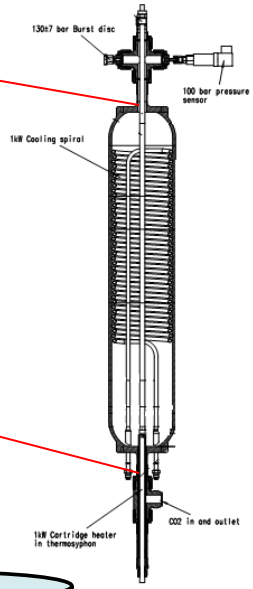
To avoid of overheating
(dry out prevention)

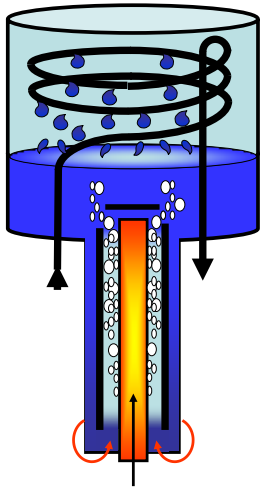


To keep sub cooling
condition









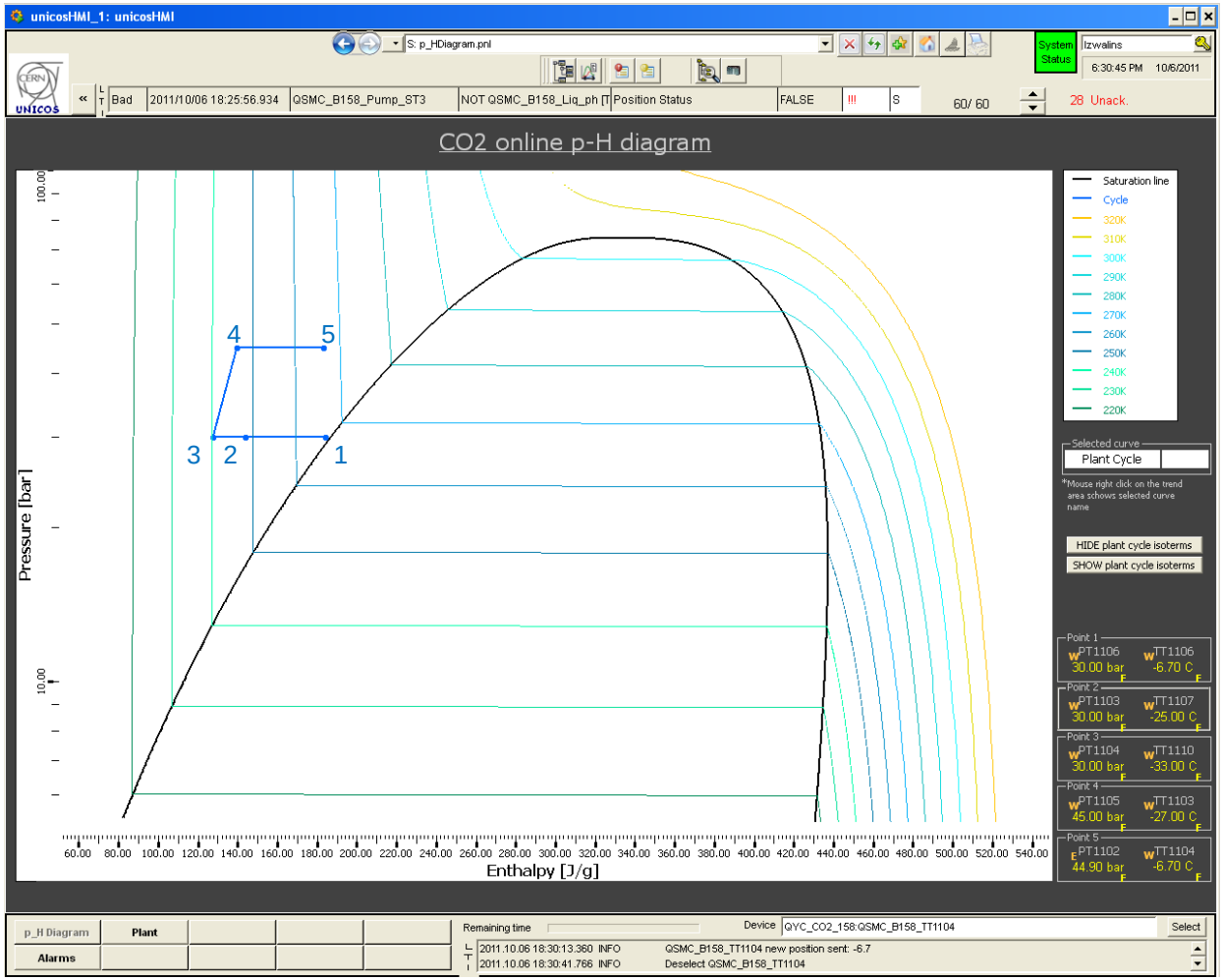
CORA 2kW – pressure, enthalpy online diagram

PVSS control extension:

- Real time calculation
- Connection to external data base REFPROP 8
- 11 constantly plotted isotherms
- Possibility of displaying isotherms in measured points
- Proposed as future JCOP component

Point 1 - Outlet of experiment lines
Point 2 - Outlet of return line of internal heat exchanger
Point 3 - Pump inlet
Point 4 - Pump outlet
Point 5 - Outlet of supply line of internal heat exchanger

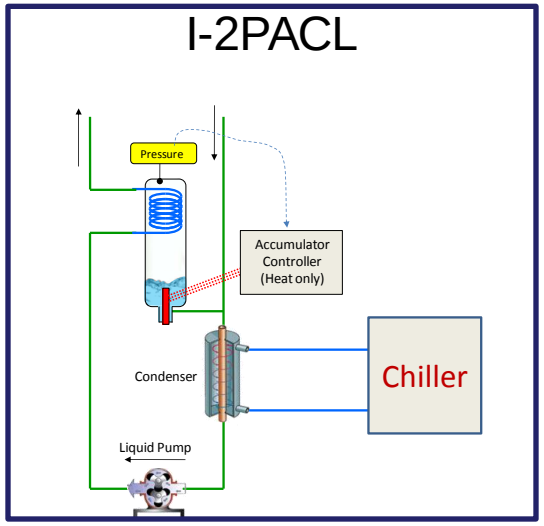
This control extension currently is available on Windows machine only!

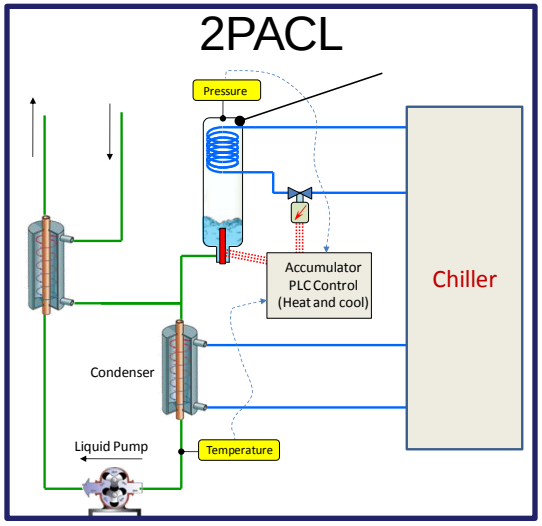


100W TRACI - concept

Transportable Refrigeration Apparatus for CO_2 Investigation

Simplified concept of 2 Phase Accumulator Controlled Loop





To simplify the concept the internal heat exchanger function and the accumulator cooling function are integrated by cooling the accumulator with the pump outlet flow. The concept is called **I**ntegrated **2PACL** (I-2PACL).

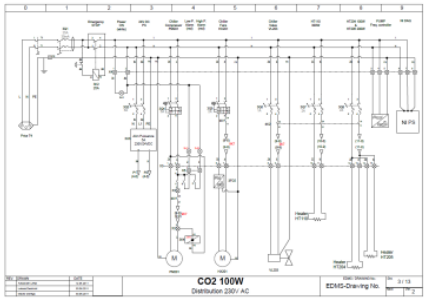
The simplified concept was patented on Friday September 9th, 2011.

I/O	Number
TT (PT100)	4
TT (TC type K)	3
ΔT	1
PT	3
ΔP	1
EH	3
Compressor	1
VL	1
Pump	1

100W TRACI – control system

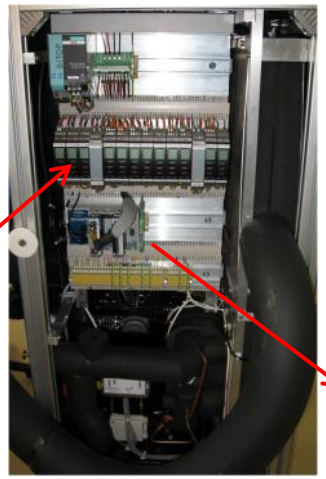
Requirements:

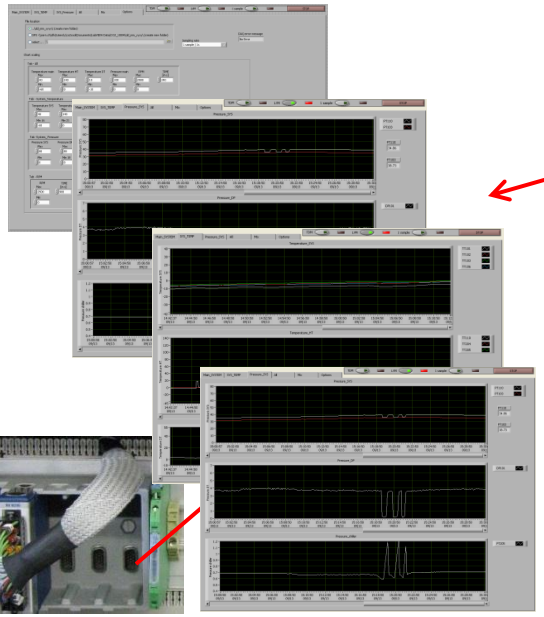
- Simplified control concept = **NO PLC!**

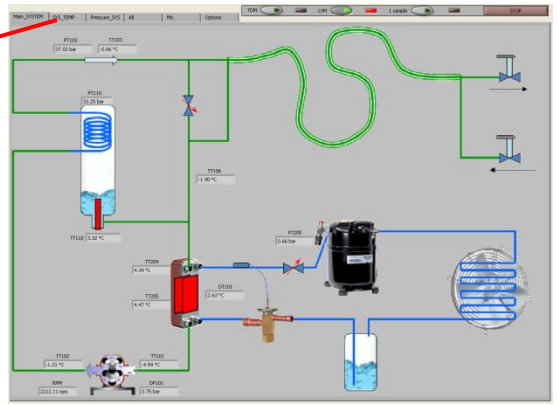


Solution:

- On-shelf industrial control/electrical components
- All logic realized by relays, universal transmitters and 1 PID controller
- Integrated National Instruments DAQ
- LabVIEW user interface, open to add experimental part
- No need to have PC/PVSS to run the plant



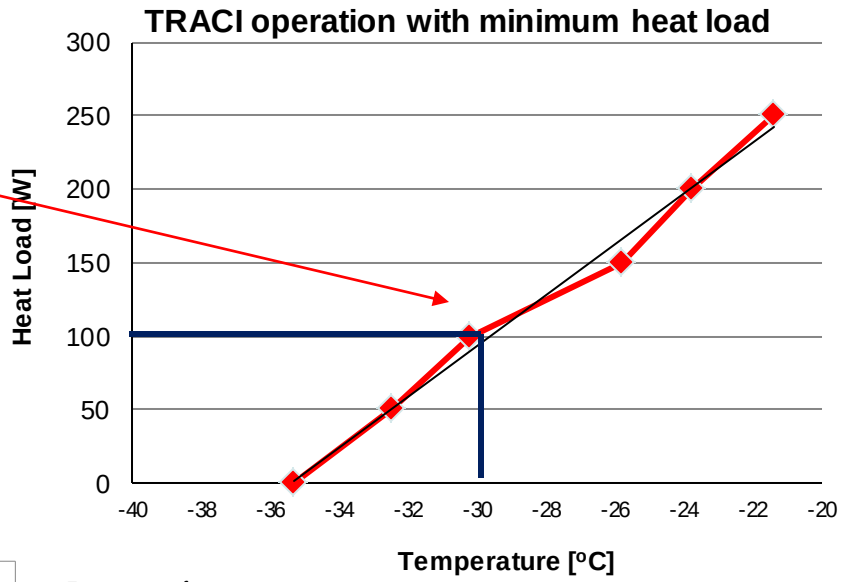


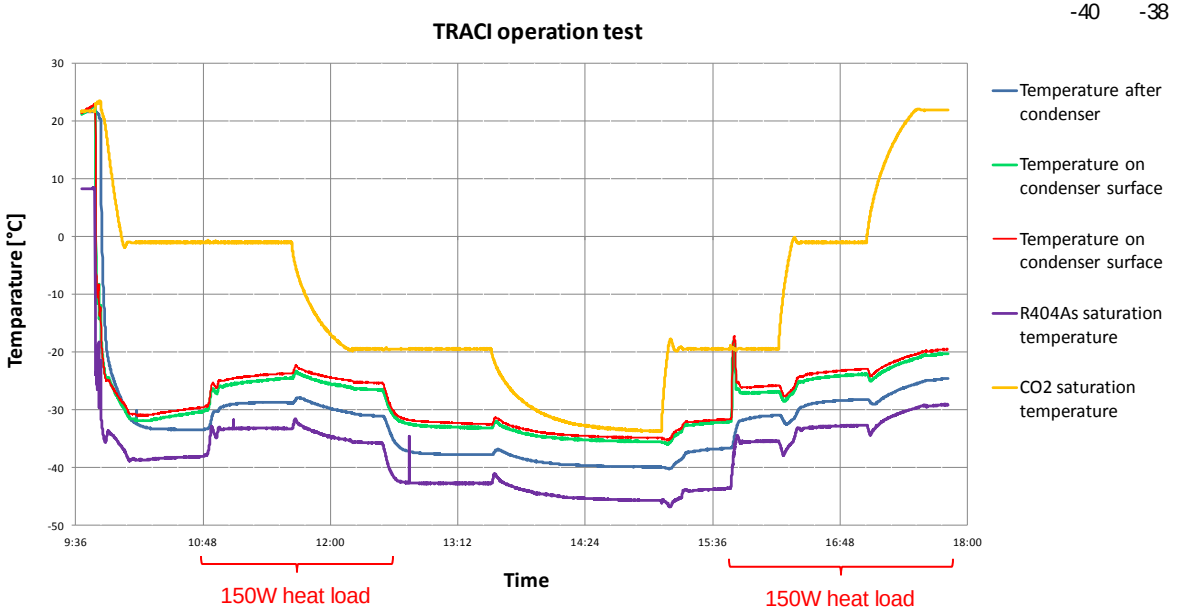


100W TRACI – first results and future improvements

Goal: 100W @ -40°C to +20°C

- -40°C not met
  - More heatleak than expected
- 1.5x larger chiller possible in same mechanical envelope





Future control improvements:

- Reduce electronics to micro-controller
- Skip some functionalities in control
- Replace pump to be fixed speed (no frequency control)
- More powerful chiller

CO_2 SR1 concept – collaboration with EN-CV-DC

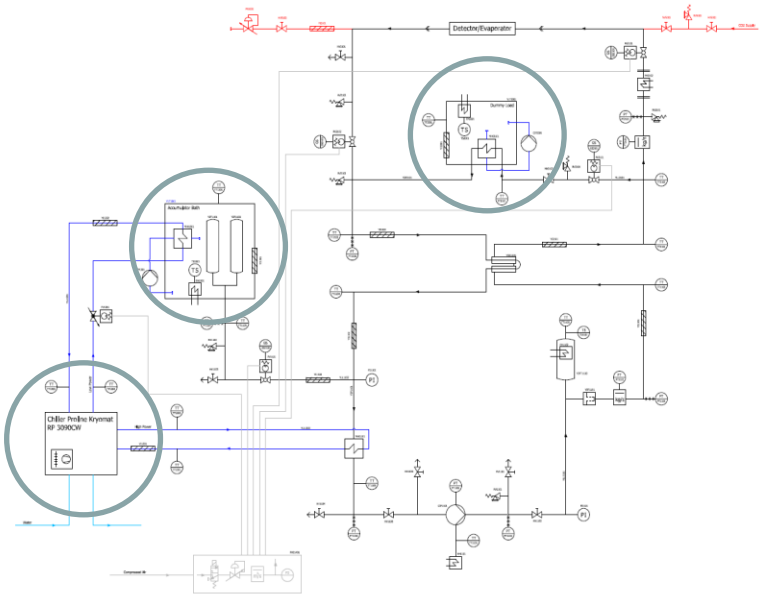
Differences to CORA

accumulator design

dummy load design

primary chiller

PLC brand



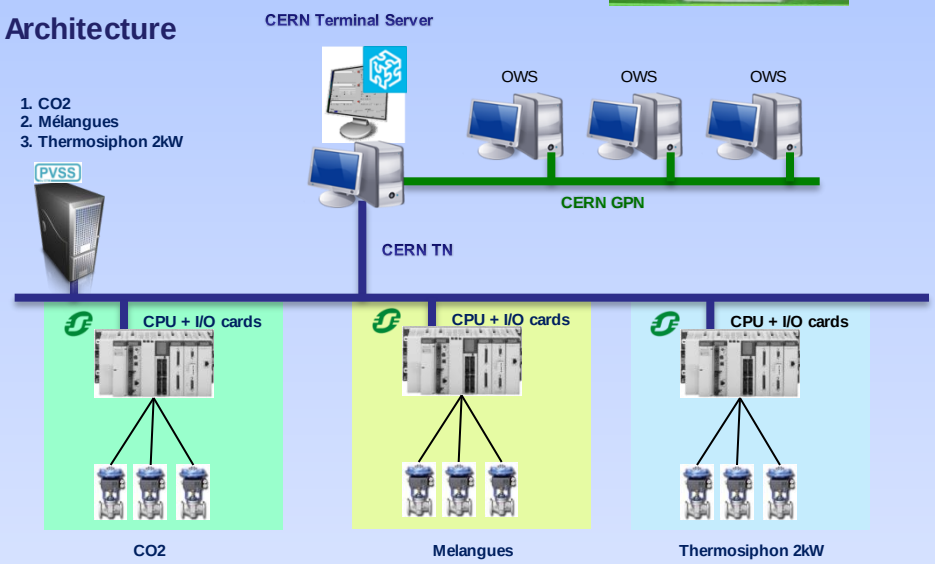
CO_2 SR1 - control system

Modifications

Schneider PLC (EN-CV-DC hw. standard)

PROFIBUS flow meters

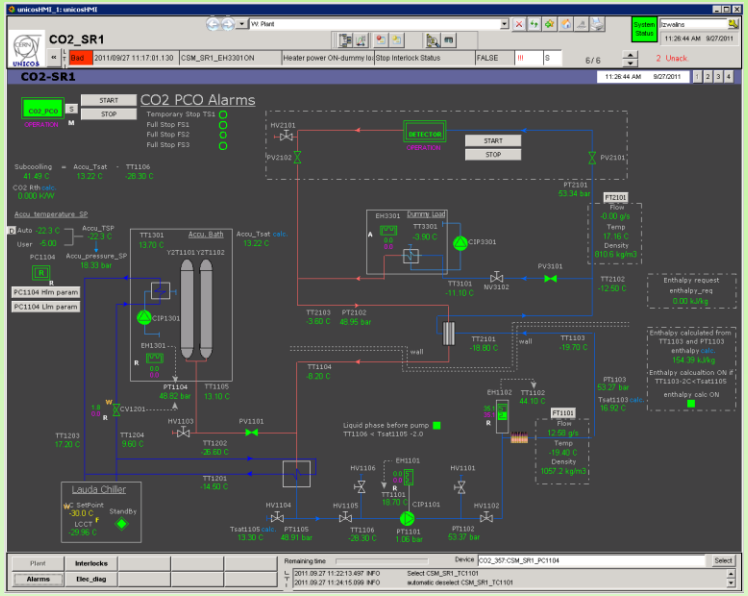
Architecture



- One central PVSS data server in BE-CO for all “test” applications
- Access to all applications form one terminal server
- PVSS accesses control with personal NICE login and password
- All applications in Technical Network

based on CORA experience

Main user SCADA panel



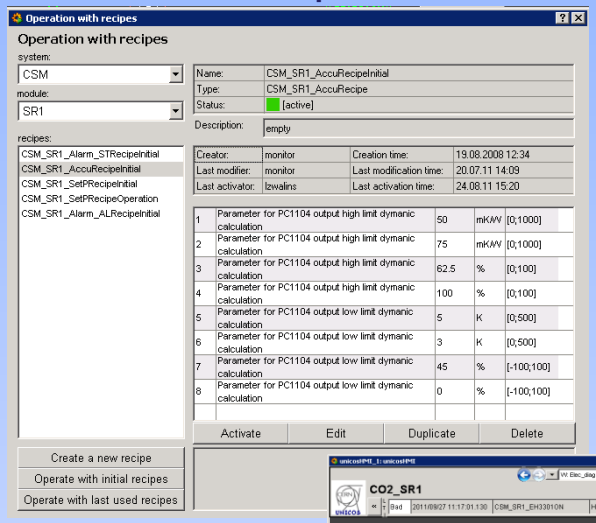
UNICOS based PLC software

UNICOS based PVSS implementation

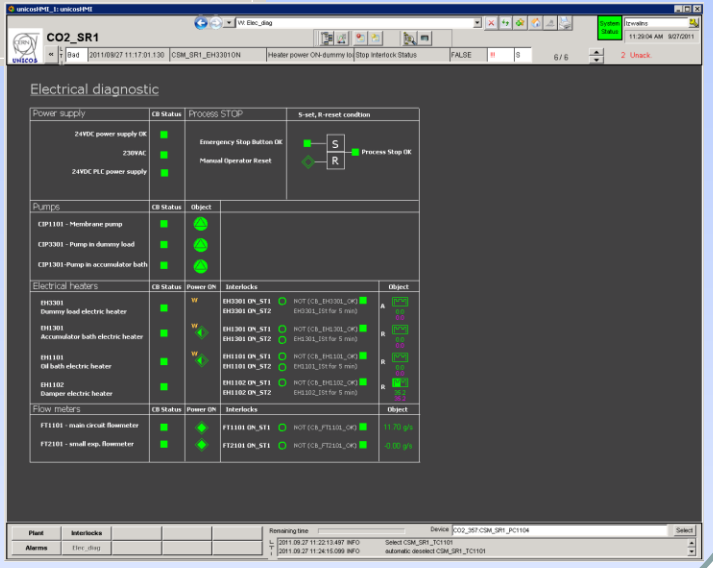
CO_2 SR1 PVSS interface

Modifications

Recipes

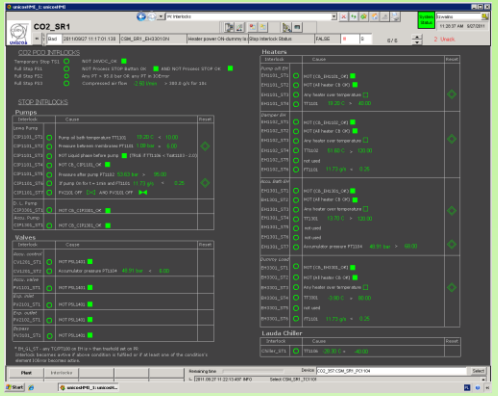


Electrical diagnostic



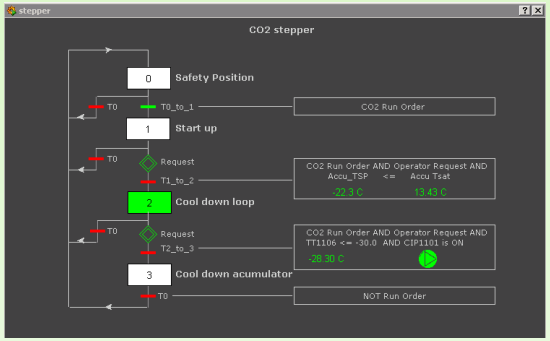
based on CORA experience

Interlocks diagnostic



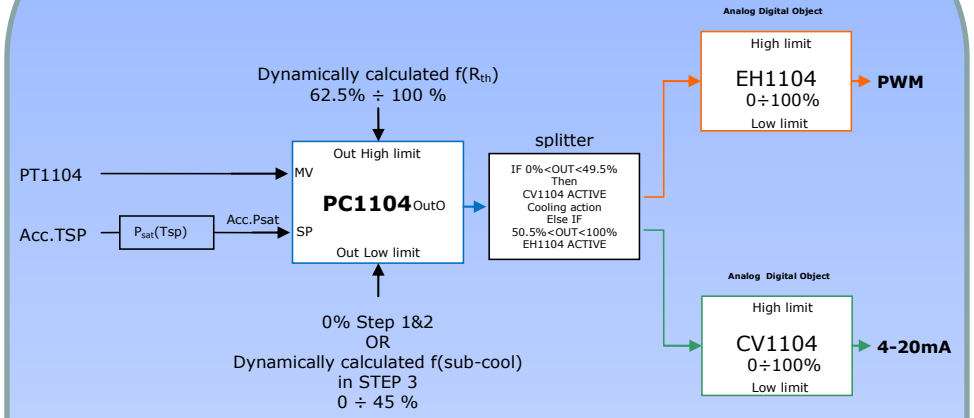
Accumulator limiters

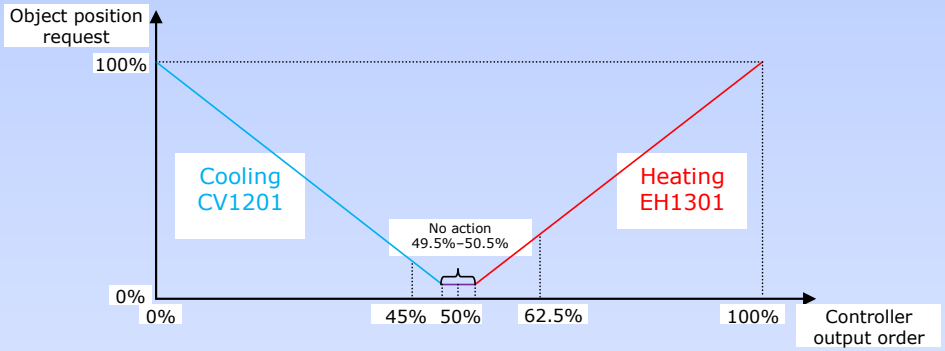
Stepper



Functional analysis and control

Modifications



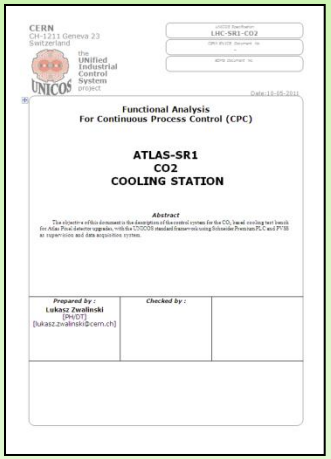


based on CORA experience

Functional analysis:

- process
- actuator operation logic
- system states and transitions
- alarms
- computed parameters
- recipes parameters

https://espace.cern.ch/CO2-SR1/Shared%20Documents/Control/CO2_SR1_Functional_Analysis.doc



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UNICOS

Functional Analysis
For Continuous Process Control (CPC)

ATLAS-SR1
CO2
COOLING STATION

Abstract

Prepared by : Lukasz Zwalinski [PH/DT] [lukasz.zwalinski@cern.ch]

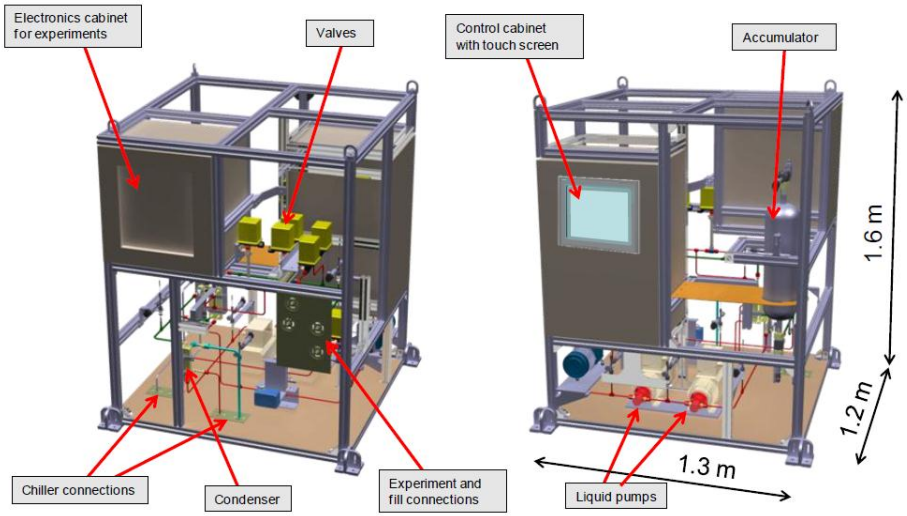
Checked by :

Equipement	Operation			
	STOP	RUN		
	Safety position(0)	Start-up(1)	Cool down loop(2)	Cool down accumulator(3)
PV1101 Accu out	CLOSE	IF Accu_Tsat>= Accu_TSP Then OPEN Else CLOSE	OPEN	OPEN
PV3101 By-pass	CLOSE	OFF	IF CIP1101.OnSt Then OPEN Else CLOSE	IF CIP1101.OnSt Then OPEN Else CLOSE
CV1201 Accu	CLOSE	OFF	OFF	Reg on PT1104 AuPosR:=PC1104 [Accu_Psat=f(User Accu temp SP)] PC1104 OUT HighLim-calculation OUT LowLim-calculation
EH3301 By-pass	OFF	OFF	Manual operation	Manual operation
EH1301 Accu	OFF	Reg on PT1104 AuPosR:=PC1104 SP=Accu_Psat [TSP:=ATSP; IF TSP>27 Then TSP:=27C END_IF;] PC1104 OUT HighLim-calculation OUT LowLim-fixed to 0	Reg on PT1104 AuPosR:=PC1104 SP=Accu_Psat [TSP:=ATSP; IF TSP>27 Then TSP:=27C END_IF;] PC1104 OUT HighLim-calculation OUT LowLim-fixed to 0	Reg on PT1104 AuPosR:=PC1104 SP=Accu_Psat [Accu_Psat=f(User Accu temp SP)] PC1104 OUT HighLim-calculation OUT LowLim-calculation
EH1101 Pump oil bath	OFF	Reg on TT1101 Def SP=18C	Reg on TT1101 Def SP=18C	Reg on TT1101 Def SP=18C
EH1102 Damper	OFF	Reg on TT1102 Def SP=50C	Reg on TT1102 Def SP=50C	Reg on TT1102 Def SP=50C
CIP1101 Lewa pump	OFF	OFF	IF TT1106 < Accu_Tsat (TTsat calculated from PT1104) - 2°C for 30s THEN ON	IF TT1106 < Accu_Tsat (TTsat calculated from PT1104) - 2°C for 30s THEN ON
CIP3301 By-pass	OFF	IF EH3301.PosSt <> 0 THEN ON	IF EH3301.PosSt <> 0 THEN ON	IF EH3301.PosSt <> 0 THEN ON
CIP1301 Accu pump	OFF	ON	ON	ON
EH3301ON EH power ON	OFF	ON	ON	ON
EH1301ON EH power ON	OFF	ON	ON	ON
EH1101ON EH power ON	OFF	ON	ON	ON
EH1102ON EH power ON	OFF	ON	ON	ON
FT1101ON EH power ON	ON	ON	ON	ON
FT2101ON EH power ON	ON	ON	ON	ON
LCStandBy	OFF	OFF	Chiller = ON SP = -40.0C	Chiller = ON SP = -40.0C

What's next?

MARCO: Multipurpose Apparatus for Research on CO_2

- 2PACL concept
- Temperature range from -40C to room temperature
- Capacity 1kW
- Base for future **ATLAS IBL** and **KEKb-Bell 2** detectors



Control system approach:

- Control system to be easily integrated in DCS
- Siemens PLC
- UNICOS framework
- Integrated control panel (to be introduced, currently not supported solution)
- Use recipe component
- Select tested in previous CO2 cooling units electrical and control components

Status:

- PLC components delivered
- Electrical study in progress (electrical schematics)

Conclusions

Existing test CO_2 cooling stations at CERN:

- ✓ CORA operational
- ✓ TRACI 1a(LHCb) and TRACI 1b(ATLAS) operational
- ✓ CO_2 SR1 under commissioning
- ✓ MARCO under construction

CO_2 cooling systems in HEP experiments:

- ✓ AMS
- ✓ LHCb

CORA 2kW – experiment inlet enthalpy control

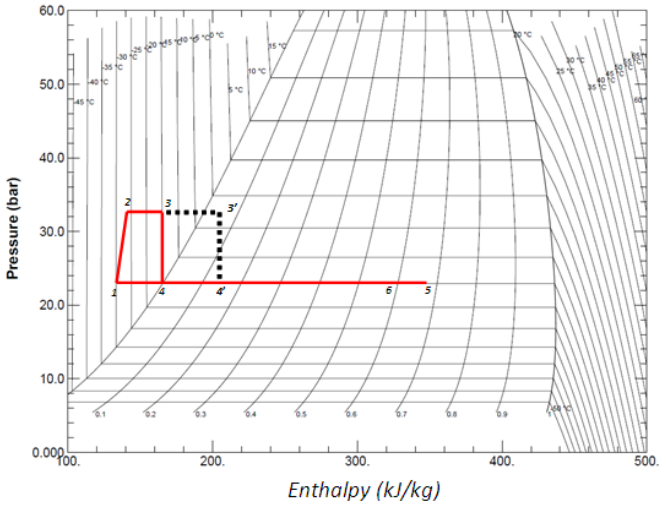
$$\varnothing_m = Q_{experimet} / (h_5 - h_4)$$

$$Q_{heater} = (h_{requested} - h_3) * \varnothing_m$$

It is not possible directly control the enthalpy in a PID loop.

The enthalpy can be derived from measured pressure and temperature only when the state point is present in the liquid phase which means that measured temperature should be at least 2^0C lower than calculated T_{sat}.

PLC is calculating enthalpy from measured temperature TT1104 and pressure PT1102 and it's ON only if TT1104 -2^0C $\leq T_{sat}$(PT1102) is true.




```
Pressure:    ARRAY[1..67] OF REAL:=
79,78,77,76,75,74,73,72,71,70,69,68,67,66,65,64,63,62,61,60,59,58,57,56,55,54,53,52,51,50,49,48,47,46,45,44,43,42,41,40,39,38,37,36,35,34,33,32,31,30,29,28,27,26,25,
24,23,22,21,20,19,18,17,16,15,14,13,12,11,10,9,8;

A_parameter: ARRAY[1..67] OF REAL:=
0.000330087,0.000351146,0.000377535,0.000301473,0.000293458,0.000194552,0.000190681,0.000177297,0.00017412,0.000171229,0.000161049,
0.000158539,0.000156122,0.000147898,0.000134719,0.000132666,0.000123677,0.000123474,0.000121931,0.000117032,
0.000115618,0.000111319,0.000107269,0.000105915,0.00010228,0.000099666,0.0000960497,0.0000905969,0.0000861368,0.0000853435,
0.0000816698,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;

B_parameter: ARRAY[1..67] OF REAL:=
-0.2516,-0.26826,-0.25713,-0.22869,-0.22224,-0.14256,-0.1395,-0.12923,-0.12672,-0.12443,-0.11663,-0.11466,-0.11273,-0.10642,-0.10473,-0.09935,
-0.09785,-0.09135,-0.09183,-0.08765,-0.08643,-0.0827,-0.08159,-0.07853,-0.07525,-0.0745,-0.07164,-0.06945,-0.06675,-0.06286,-0.06262,-0.05929,
-0.05866,-0.05592,0.00493,0.00477,0.00472,0.00457,0.00453,0.00437,0.00434,0.00418,0.00405,0.00398,0.0039,0.00379,0.00365,0.0036,0.00352,0.00341,
0.00331,0.00321,0.00311,0.00302,0.00293,0.00282,0.00276,0.00263,0.00253,0.00242,0.00234,0.00222,0.00206,0.002,0.00183,0.00179,0.00142;

C_parameter: ARRAY[1..67] OF REAL:=
65.84498,70.16474,67.2146,59.77127,58.05257,36.72947,35.93366,33.32263,32.66822,32.07125,30.09135,29.57678,29.07389,27.47502,27.03431,25.67267,
25.27728,24.09589,23.74758,22.69711,22.37093,21.44142,21.15094,20.23052,19.55854,19.28868,18.59443,18.08704,17.41601,16.45795,16.3927,15.54741,
15.40709,14.72817,-0.33638,-0.24074,-0.23273,-0.16019,-0.13478,-0.0618,-0.04517,0.03583,0.09803,0.1384,0.17074,0.22456,0.29452,0.32008,0.35621,
0.41158,0.45813,0.50495,0.55639,0.59938,0.64335,0.69313,0.72243,0.78339,0.83165,0.88079,0.91853,0.97422,1.04928,1.07534,1.15247,1.1692,1.23587;

D_parameter: ARRAY[1..67] OF REAL:=
-5745.44168,-6118.12308,-5859.01671,-5211.77878,-5060.06916,-3165.13783,-3096.68149,-2876.60239,-2820.30402,-2768.9269,-2602.32708,-2558.05979,
-2514.80901,-2380.57887,-2342.70115,-2228.55209,-2194.61308,-2095.74116,-2065.87909,-1976.10067,-1950.85587,-1872.6577,-1847.03299,-1779.51544,
-1715.31429,-1692.39677,-1634.71041,-1593.43918,-1537.0966,-1458.62012,-1432.70047,-1364.91095,-1371.3875,-1315.68867,-76.44853,-85.44907,
-89.32862,-98.13718,-101.23891,-110.3094,-112.58081,-122.33742,-130.01053,-133.97038,-139.14426,-145.46587,-153.96815,-157.07925,-161.56368,
-168.15629,-173.82709,-179.39933,-185.59778,-190.7022,-195.99206,-201.86222,-205.41386,-212.53876,-218.24277,-223.96622,-228.42276,-235.07432,
-243.47346,-246.51266,-255.3031,-257.23596,-275.8601;
```

Measured pressure => look for p_up & p_down in table and associated A,B,C,D up& down constants

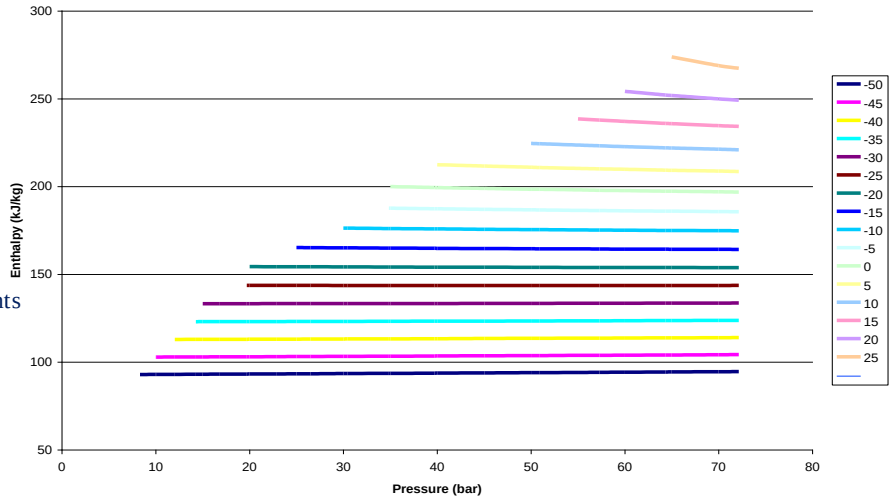
h_up := A_up*(input_TT**3) + B_up*(input_TT**2) + C_up*input_TT + D_up;

h_down := A_down*(input_TT**3) + B_down*(input_TT**2) + C_down*input_TT + D_down;

//Enthalpy search, interpolation

Output:= ((h_up-h_down)*(input_PT-input_PT_down)/(input_PT_up-input_PT_down))+h_down;

PT to H conversion



CO_2 allows small tubing

Why?

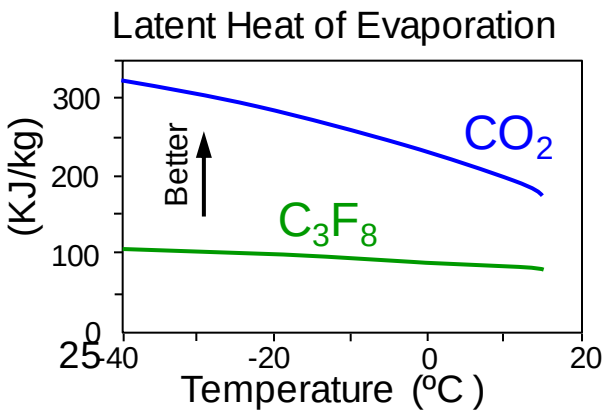
Large latent heat & Low viscosity & High pressure

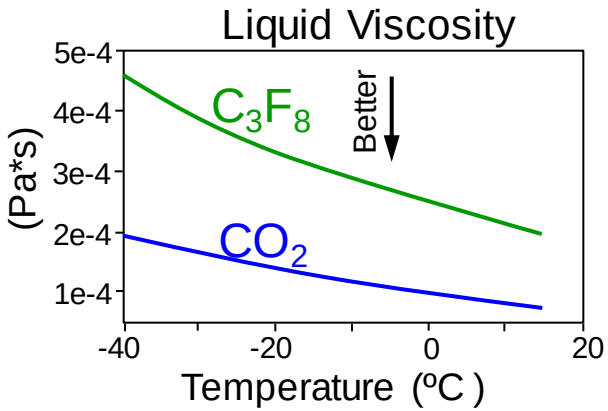
Allow low flow → Low pressure drop

Low pressure drop → Lower pressure drop

Allow high pressure drop

Lower pressure drop → Allow very small tubing





But with very high heat transfer capability!