Design, construction and commissioning of a 15 kW CO_2 evaporative cooling system for particle physics detectors, lessons learnt and perspectives for further development

P. Tropea

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Content

- CO_2 evaporative cooling in HEP: why and how?
- The challenges for a “big system”
- The project strategy: full scale prototype @ TIF
- Design & construction of TIF plant
- Performances of the TIF system
- Lessons learnt & design changes to final system
- Possible scaling up strategy
- Conclusions

CO_2 cooling for particle physics detectors

Why?

High cooling efficiency & low material budget!

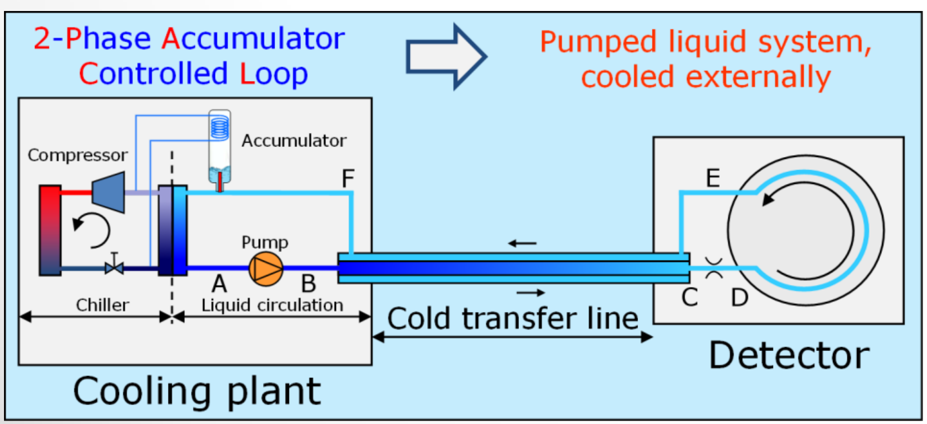
- large latent heat of evaporation (small thermal contacts)
- low liquid viscosity (small pressure drops=small pipes)
- high heat transfer coefficient & thermal stability
- operating temperature range (+20/-40^{0}C)

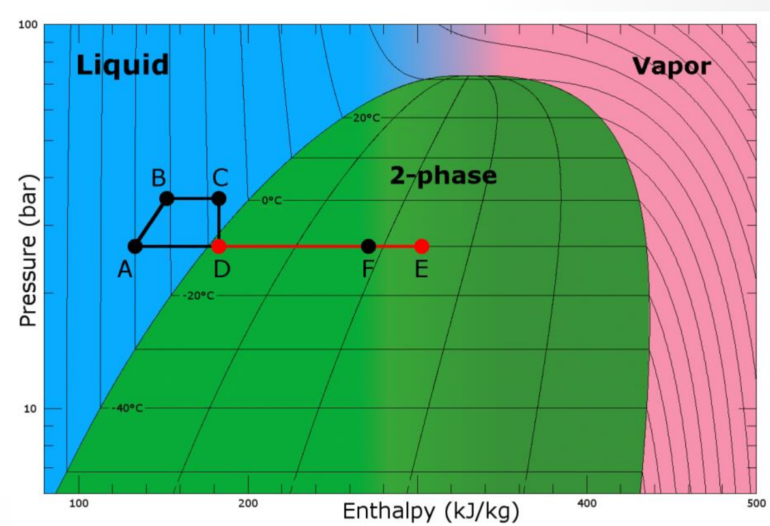
Environment & cost

- Radiation hard
- Not electrically conductive, not flammable
- Environmental impact & cost much lower than any fluorocarbon!

How?

The 2PACL operating principle, born in Nikhef for AMS Tracker and LHCb Velo





B. Verlaat, ECFA High luminosity LHC Experiments Workshop, 2013

CO_2 cooling in HEP applications

Numerous CO_2 cooling systems being designed & put in operation for HEP experiments @ CERN and other institutes

Ranges of evaporating T -40 to +15^{0}C

Ranges of cooling power 100 W to 15 kW

Experiment	Project name	Operating Temperature	Cooling power
ATLAS	SR1	-30 C	2kW
	IBL	- 40 C	2x3.3kW
CMS	TIF	-20 C	15kW
	Pixel phase 1	-20 C	2x15kW
General purpose ATLAS & CMS	CORA	-30 C	2kW
ATLAS & Belle	MARCO	-40 C	1kW
ATLAS & CMS & LHCb ILC-PPC	TRACI	-20/-30 C	100W

L. Zwalinski's talk in this session

This talk

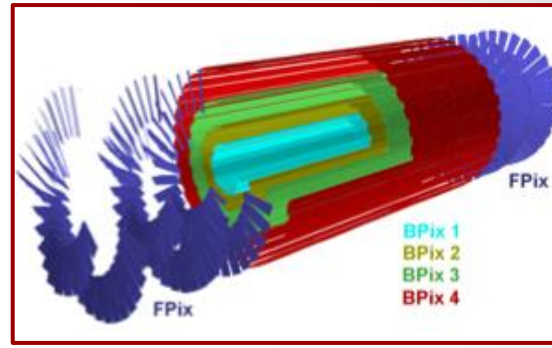
The CMS PIXEL Phase I upgrade

MOTIVATION

125 M silicon pixels (x2 wrt present)

- 4 Barrel layers
- 3 Forwards discs on each side

To be installed in 2016 – 2017 extended year end technical stop



On detector cooling requirements

Pipe wall max T = -15°C (-19C out)

- Sufficient margin wrt – 2°C on sensors, used for power calculations
- Sufficient margin on operation, i.e. away from CO_2 dryout

Independent T for FPIX and BPIX

Cooling power 15 kW

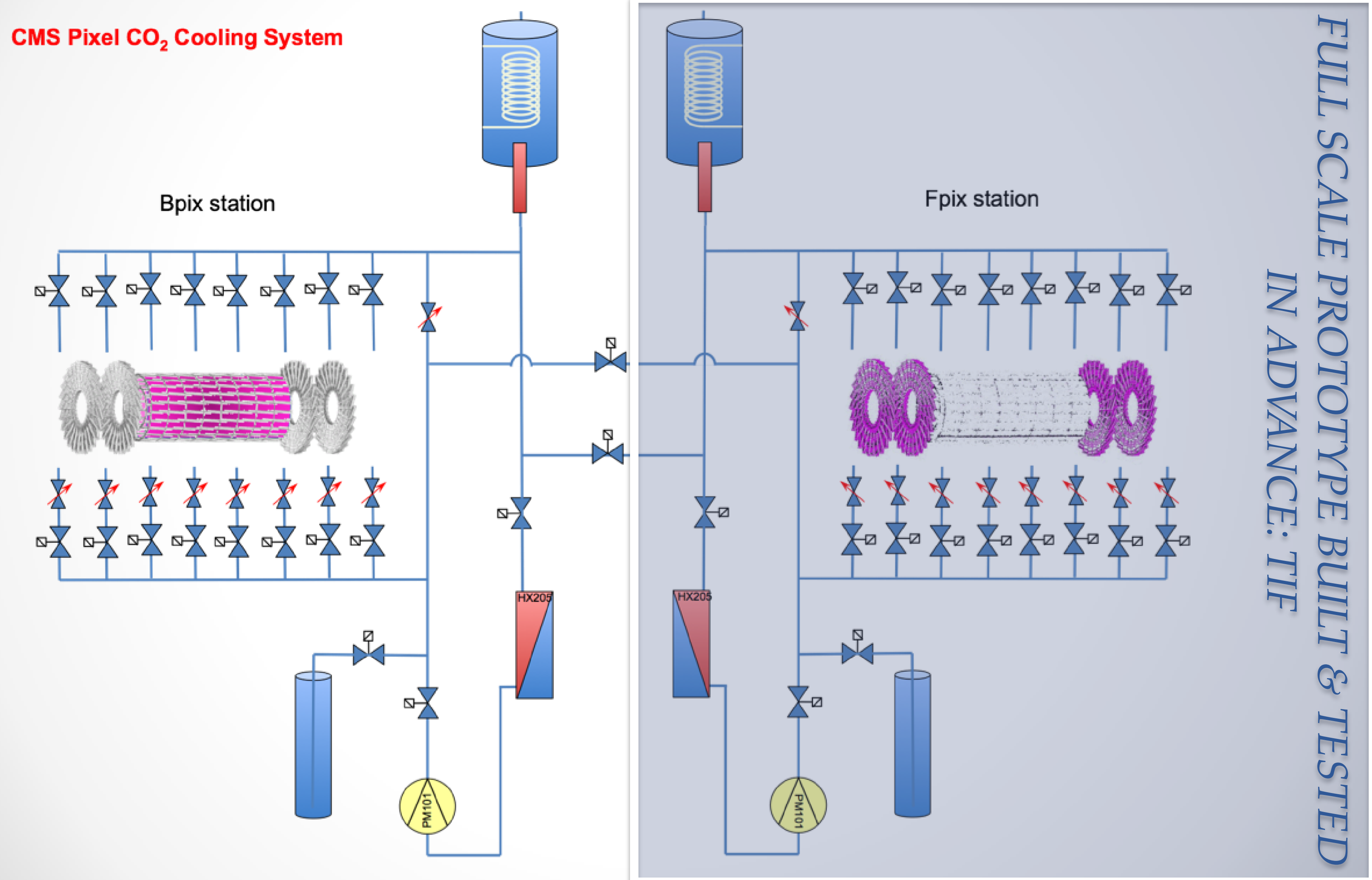
Barrel 6 kW + Forwards 3kW + Heat leaks along pipes 1÷2 kW + margin

CHALLENGES

- Most powerful system ever built with 2PACL operating principle
- -20°C evaporating T
- Full redundancy
- Fully proven system ready well ahead of the detector arrival

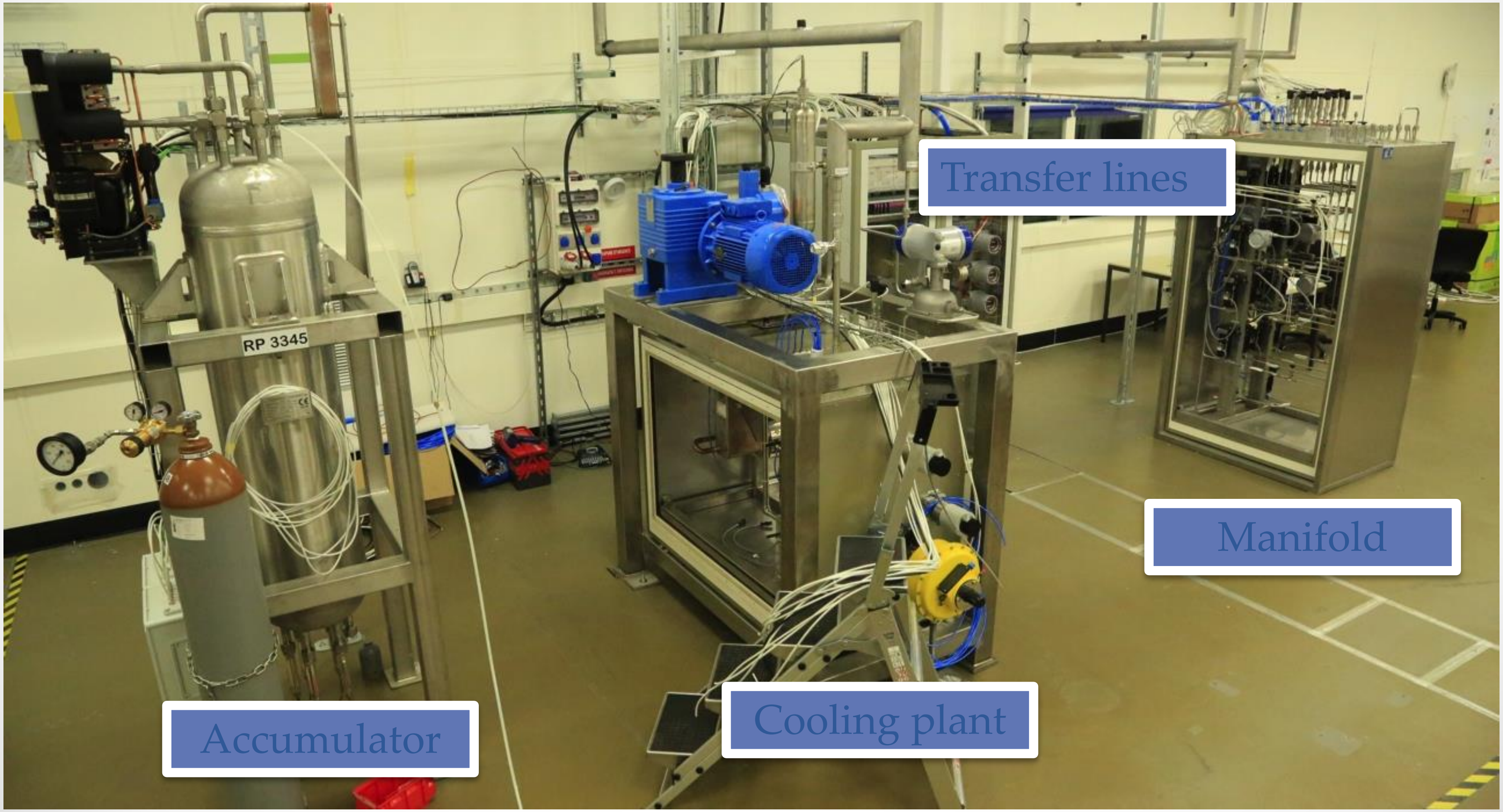
The project strategy

FULL BUILT-IN REDUNDANCY: 2 FULL POWER COOLING SYSTEMS (15 kW)



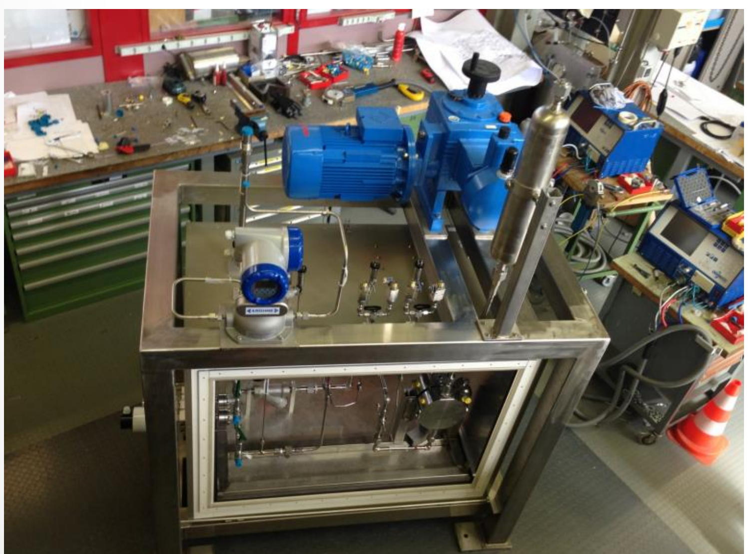
The TIF cooling plant

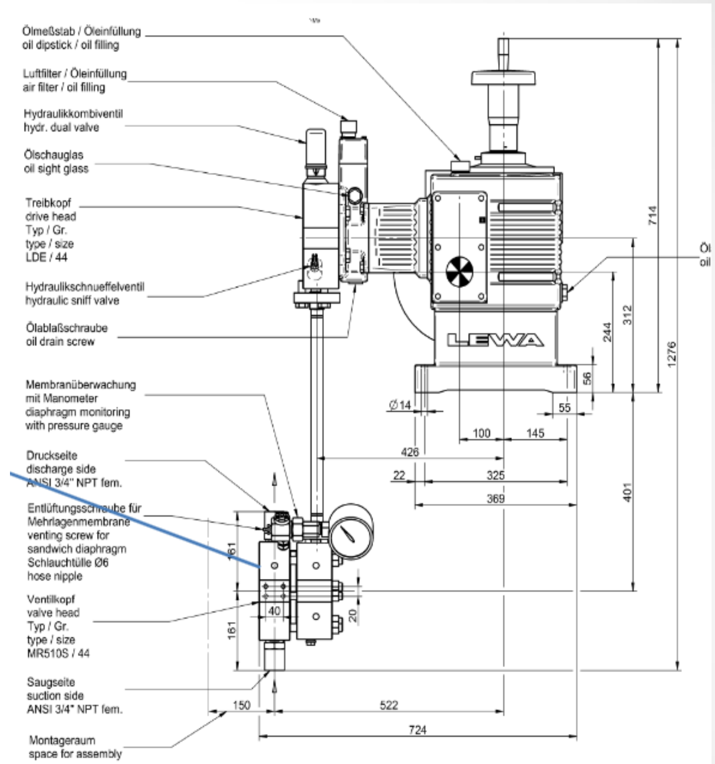
1 Plant, 1 Manifold, 1 Accumulator: modularity& accessibility (cold boxes)
Transfer lines between plant and accumulator: tri-axial vacuum insulated as in CMS environment



The construction

- Component specification:
  -40 ^{0}C &110 bar service pressure (proof testing @ 157 bar as per PED)
- Industrial standards: off the shelf components, proven tightness (welds or Swagelok VCR)
- Long term lifetime based on previous experience: LEWA membrane pump as on LHCb VELO cooling
- Strict QA on welds: 100% visual inspection, 10% X-rays

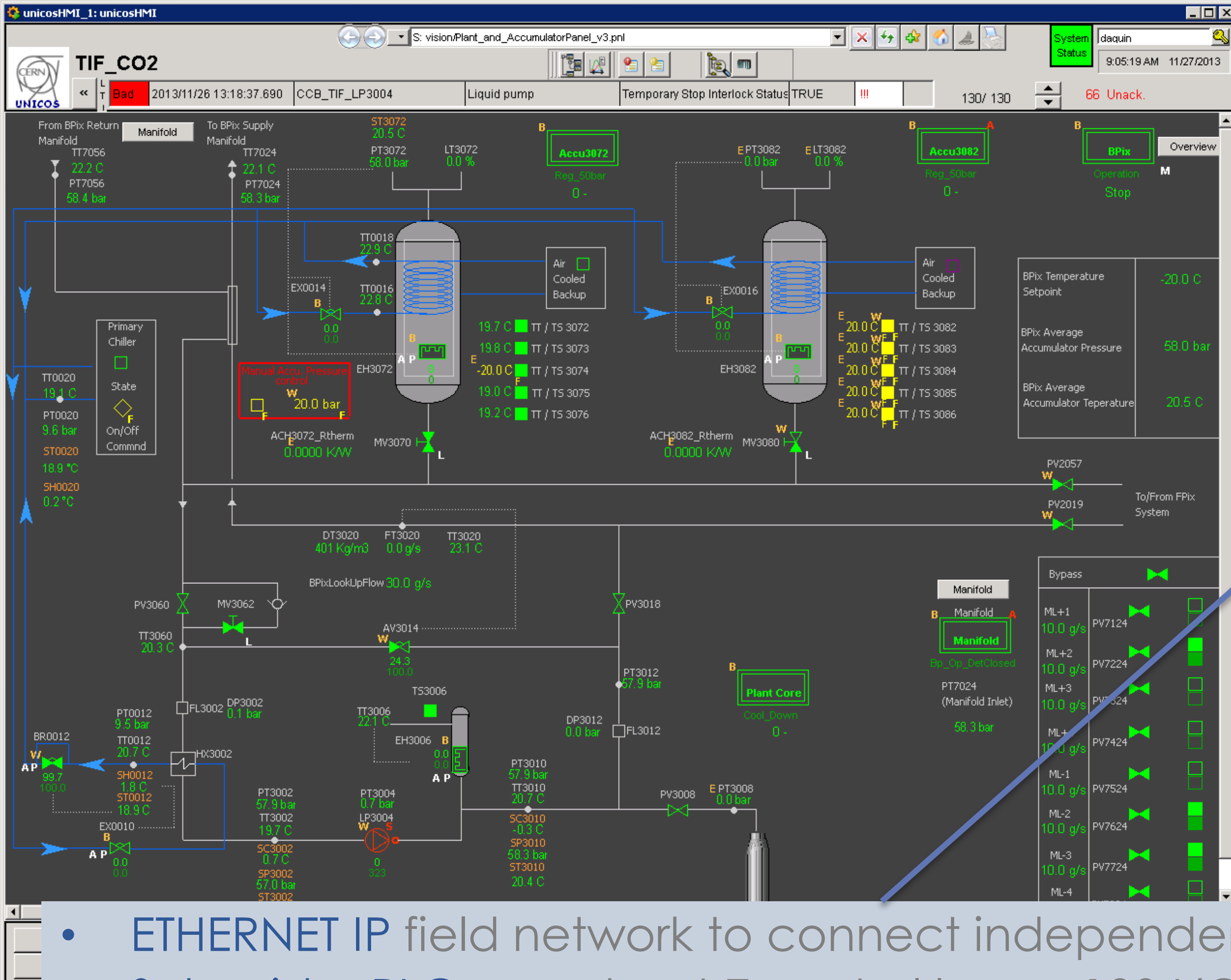




LEWA membrane pump

- 150 g/s liquid CO_2
- -40 to +15°C operating T
- Remote head
- Frequency driver (+Remote stroke adjustment)

The control system



Huge effort on standards common to all cooling & gas systems from the group, see also L. Zwalinski's talk in this session

- ETHERNET IP field network to connect independent system elements.
- Schneider PLC runs about 7 control loops, 180 I/Os
- User interface is based on a SCADA built on Siemens WinCC OA. The control software conforms to the UNICOS CPC6

Commissioning

Phase I

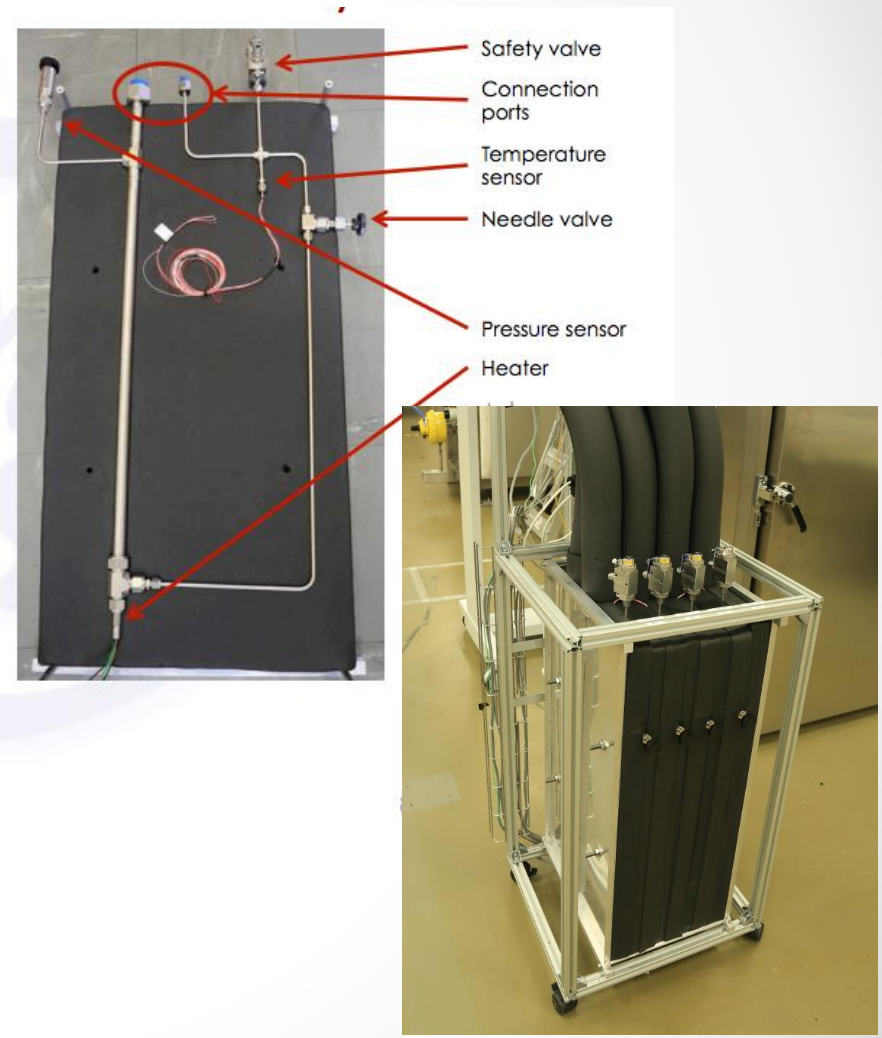
- Checkout
- Calibration of instrumentation
- Functional tests: component by component

Phase II: nominal performances

- Small dummy load (4x 2 kW)
- Stability of T varying flow or load nominal performances

Phase III: exploring the limits

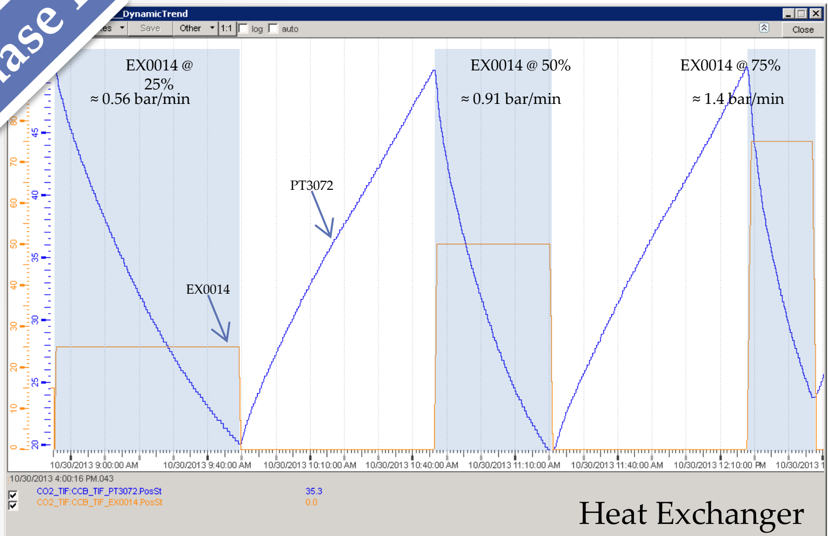
- "Big" dummy load (15 kW)
- Stability of T varying flow, load: maximum performances & exploring the limits!

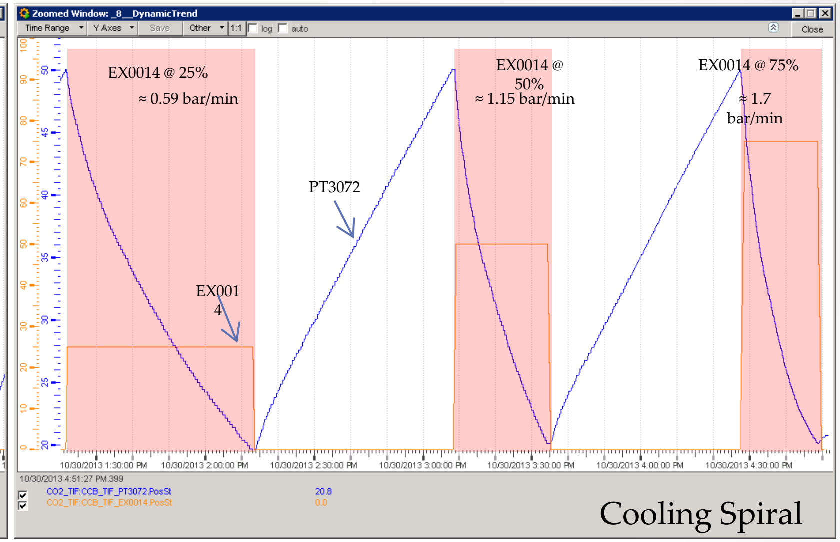


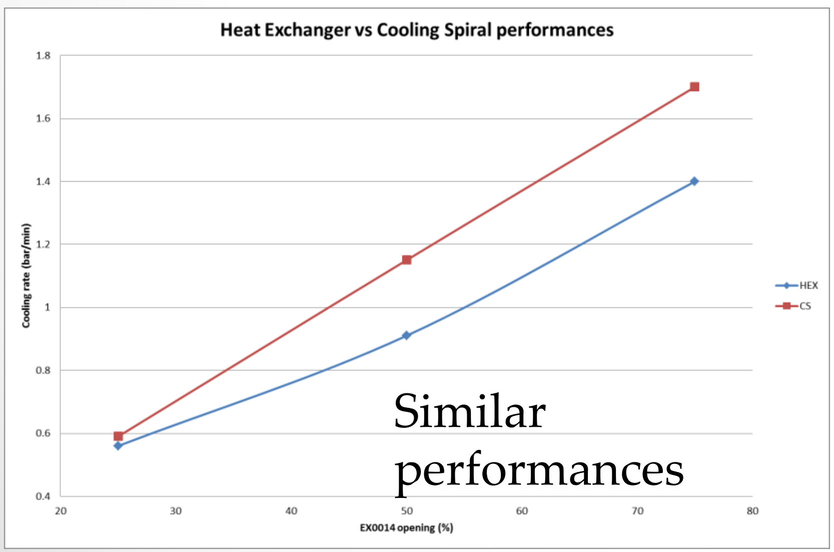
PH-DT
Detector Technologies

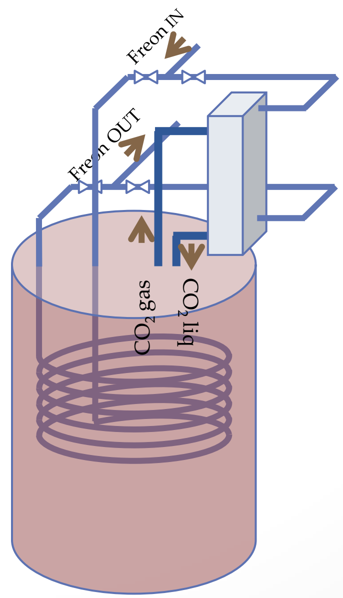
Accumulator performances

Phase I







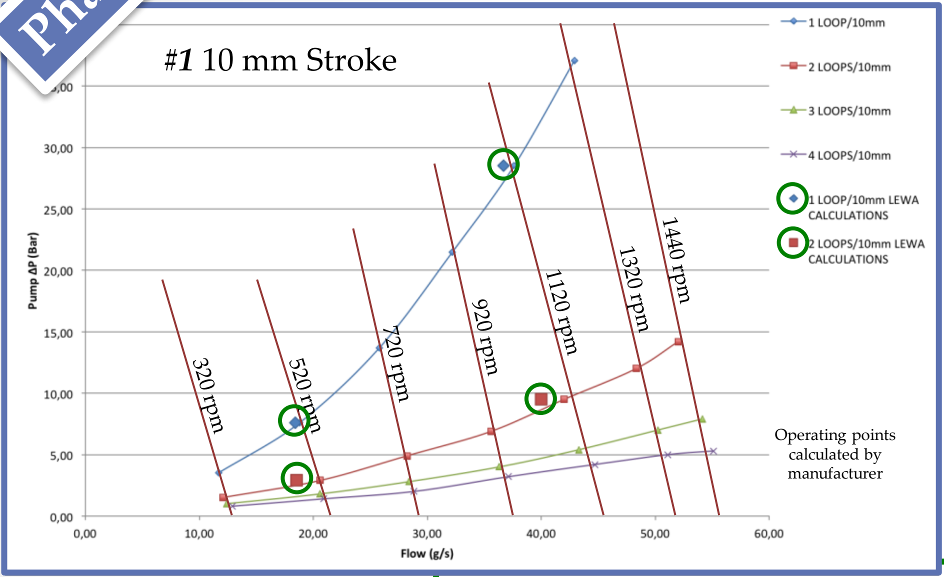


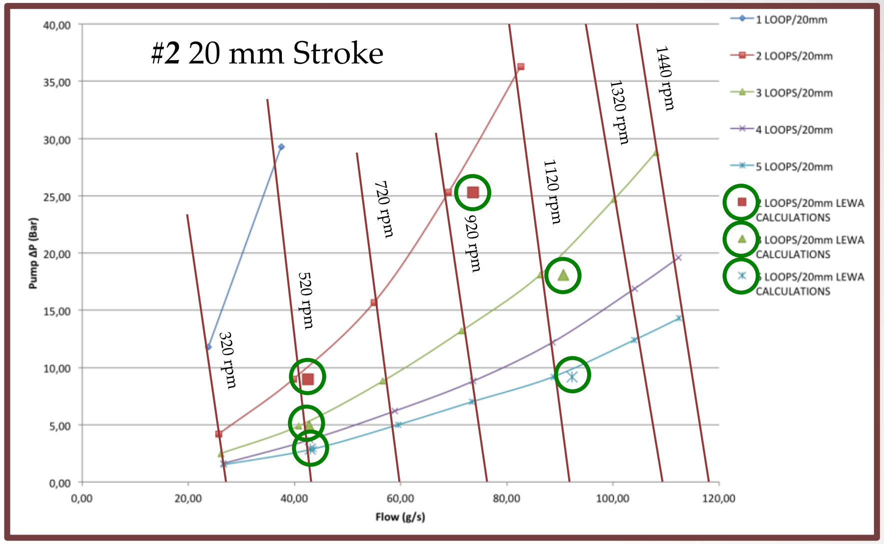
Cooling spiral: coiled pipe inside the accumulator
The CO2 vapour condenses around the pipe

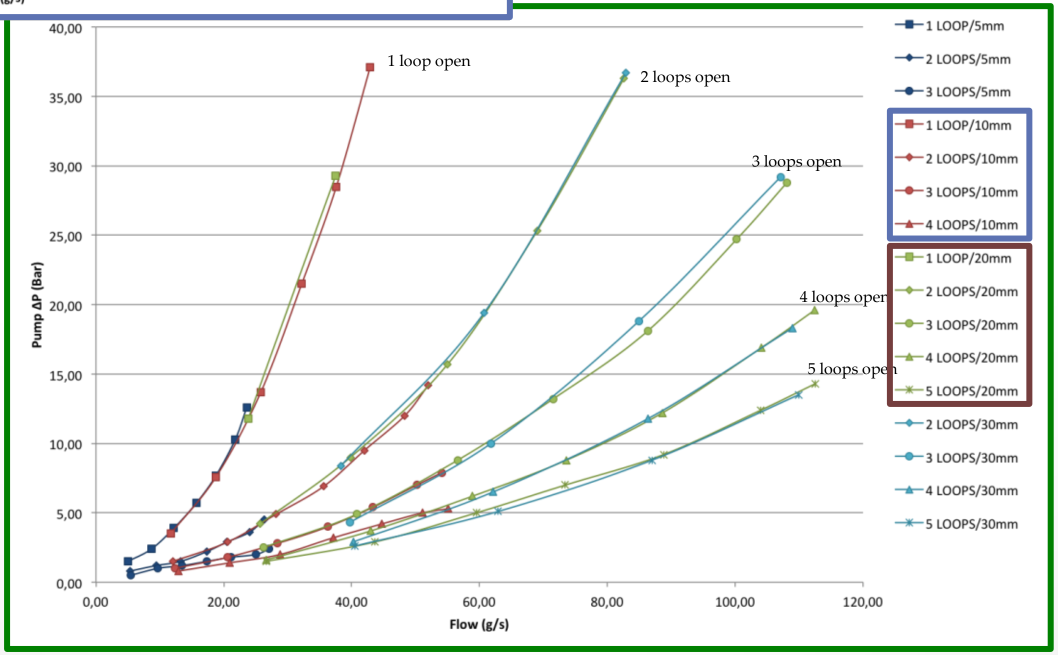
Heat exchanger: Plate heat exchanger installed on top of the accumulator
The CO2 vapour condenses inside the HEX

Phase I

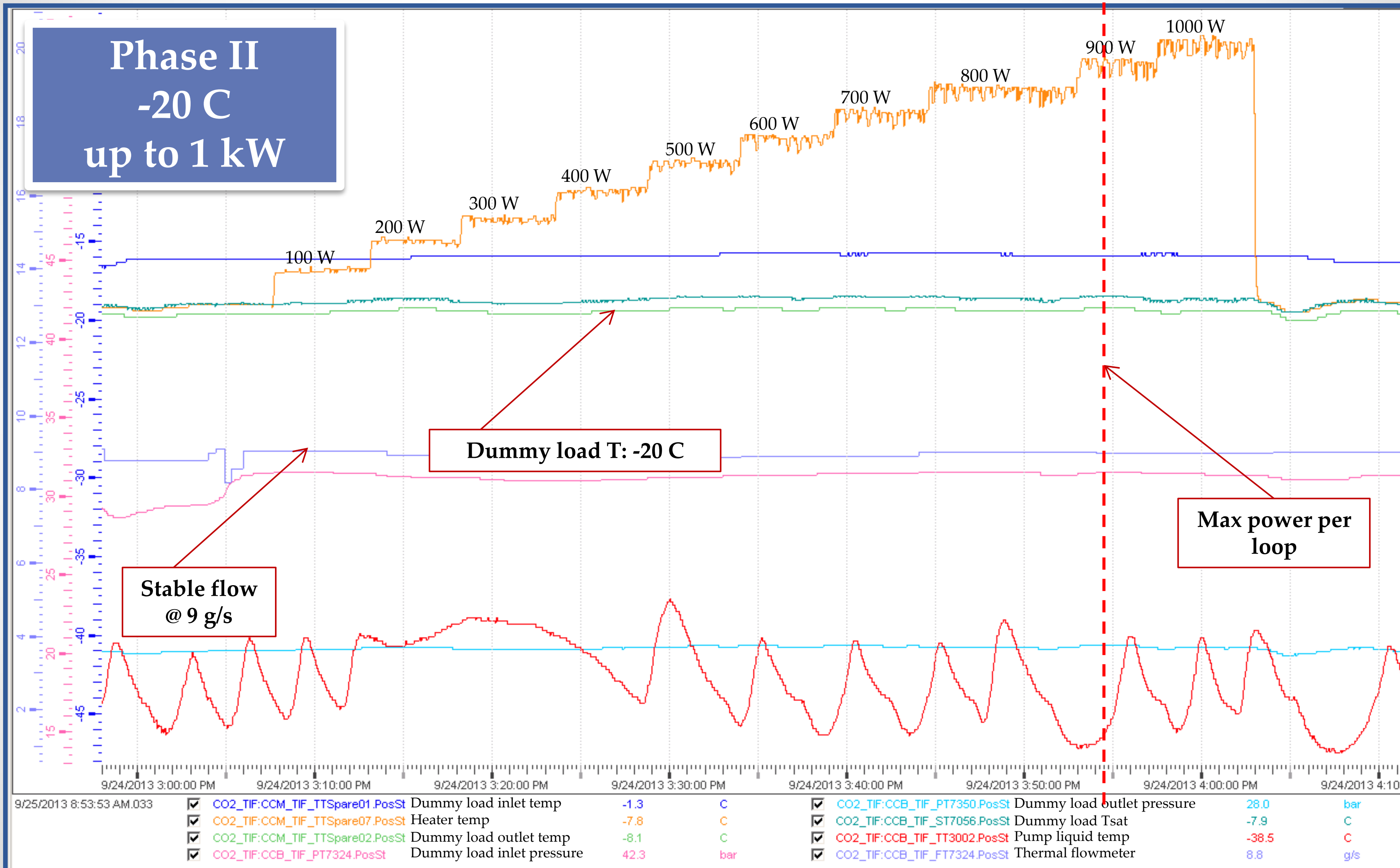
Membrane pump performances



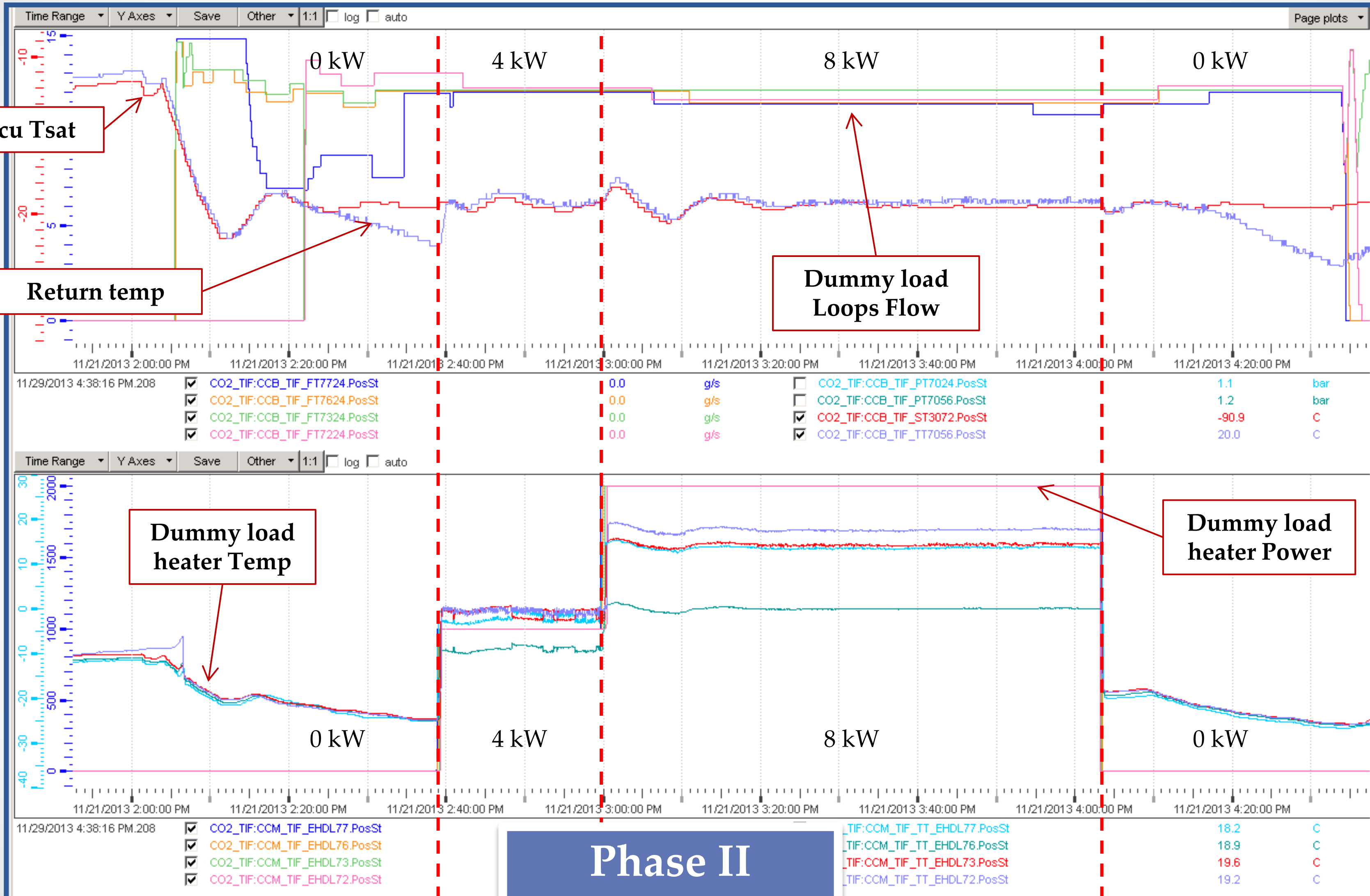




Nominal conditions: 1 cooling loop



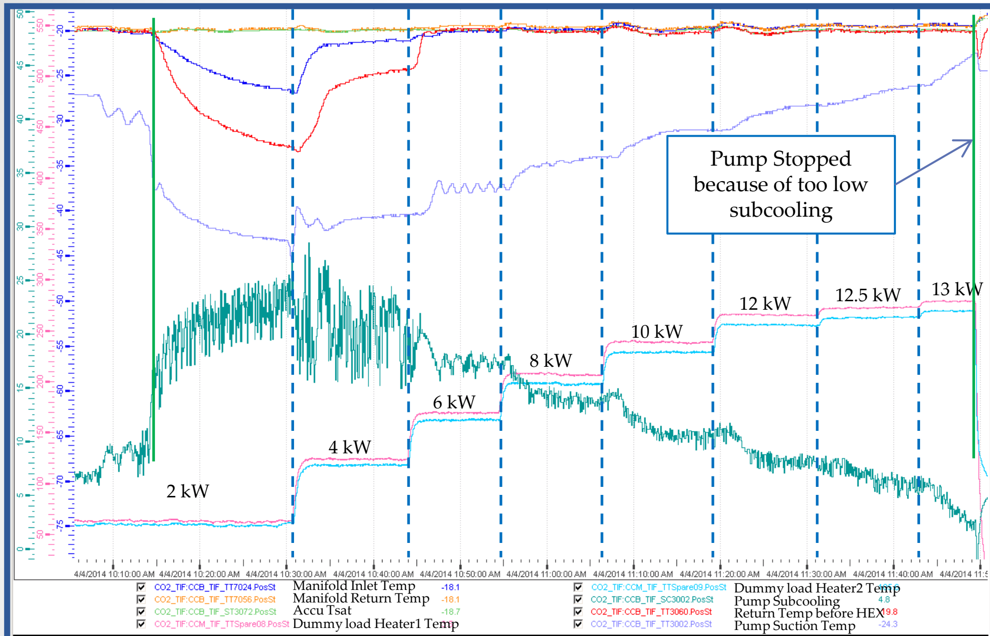
4 parallel loops operation



Phase II
-20 C
up to 8 kW

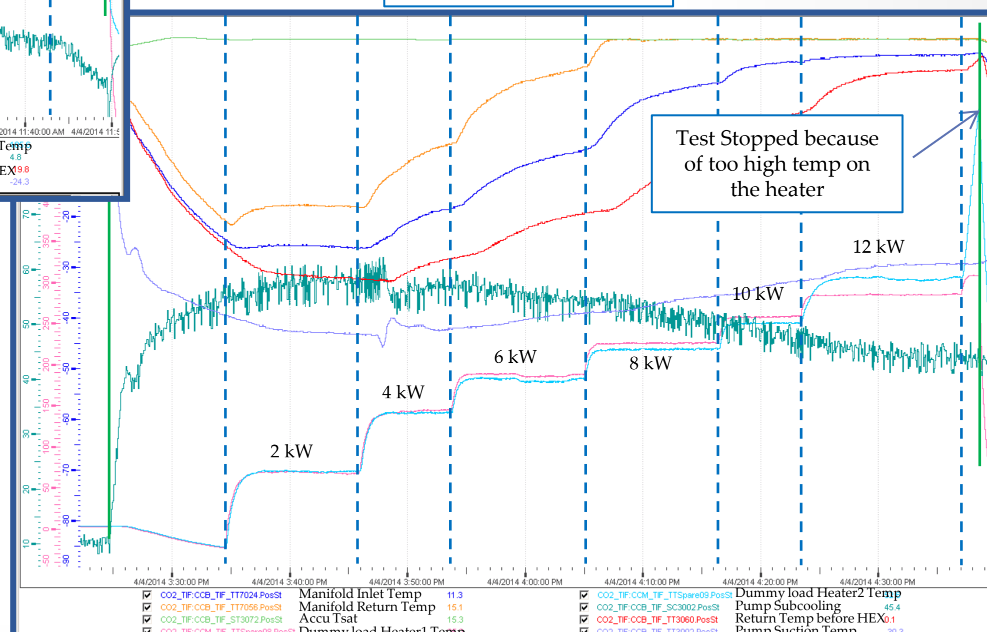
Towards full performance validation

-20 ^{0}C setpoint



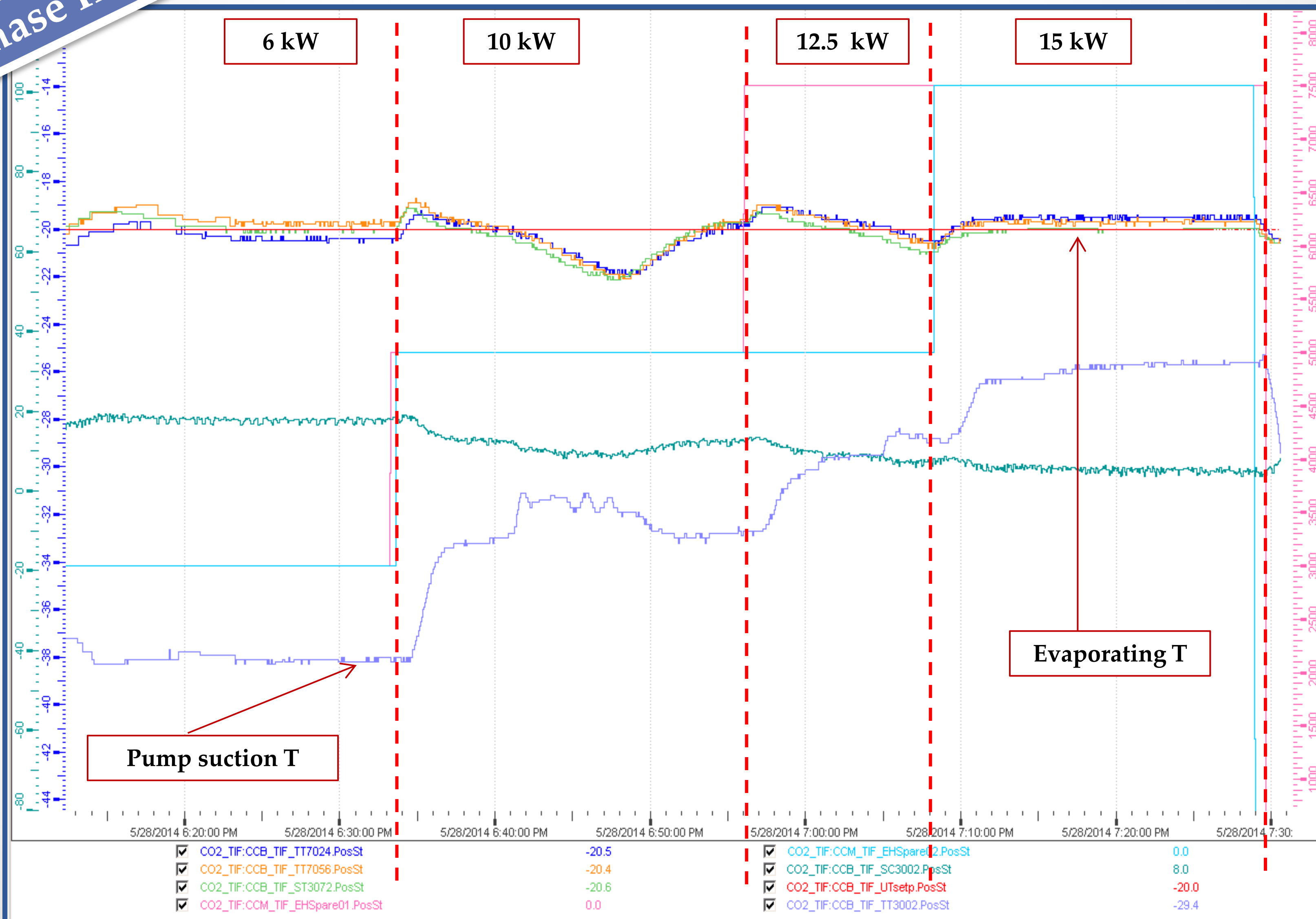
Phase III
15 kW dummy load, 120 g/s flow rate

+15 ^{0}C setpoint



Phase III

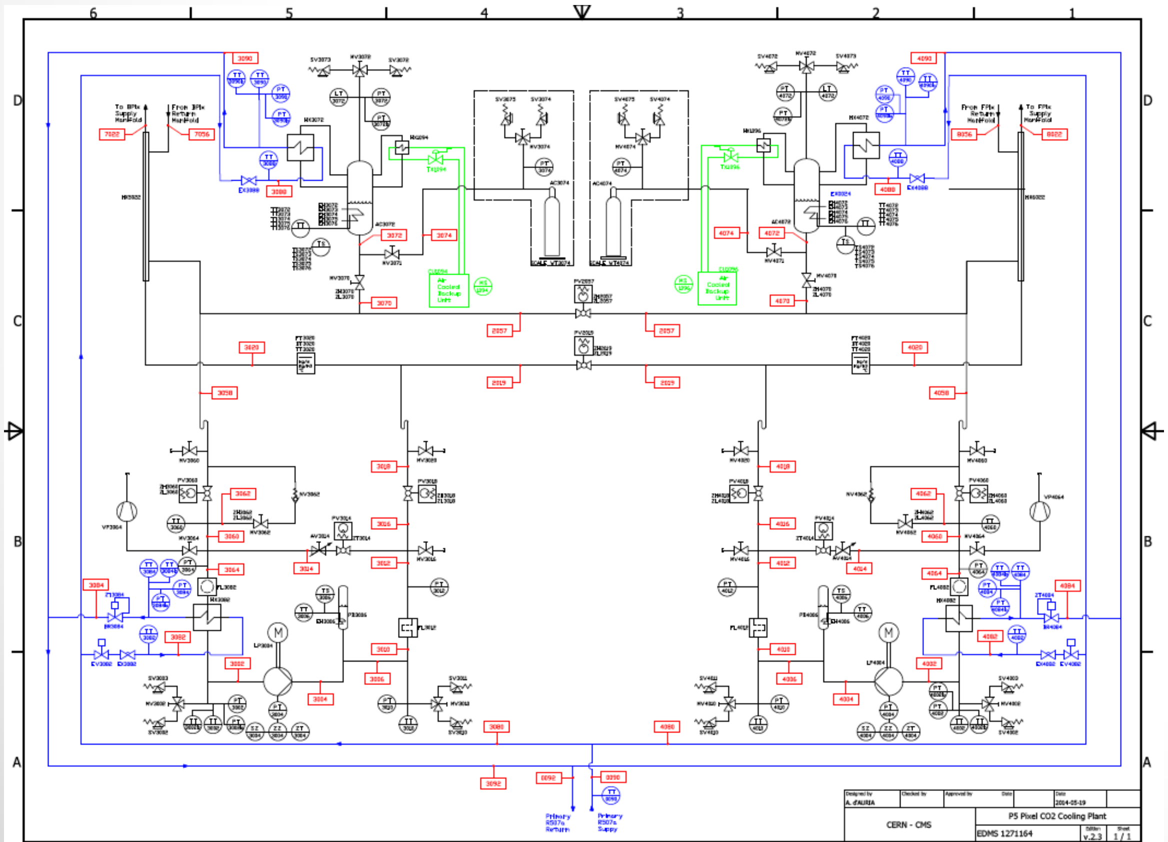
Increasing power: -20^0C, max flow

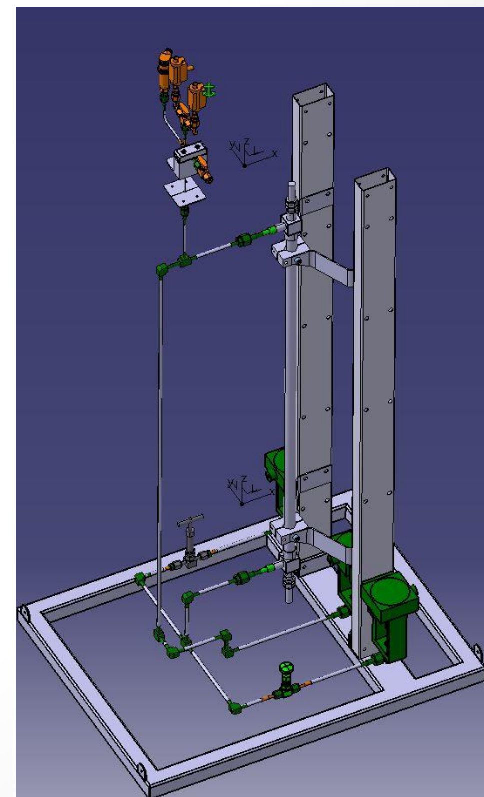


What's next? Tomorrow…

Lessons learnt for final system

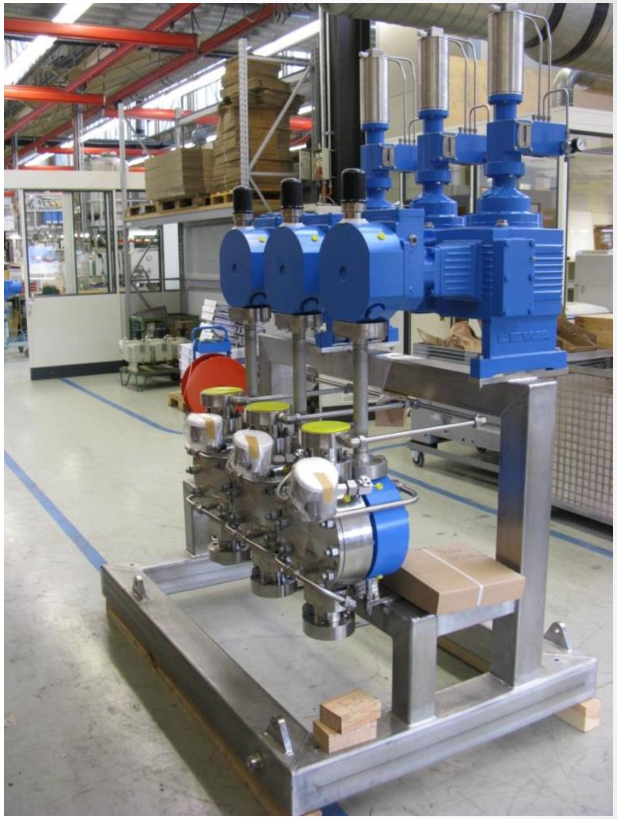
- Heat exchanger instead of spiral for accumulator: simplify design, accessible component
- Pump remote head: good choice! Add stroke adjustment for fine regulation instead of by-pass valve (which are a nightmare)
- QA on welds: save time in verification applying a very strict welding procedure, quality improvements!
- Think about testing without detector: 15 kW dummy load into manifold





What's next? The day after tomorrow

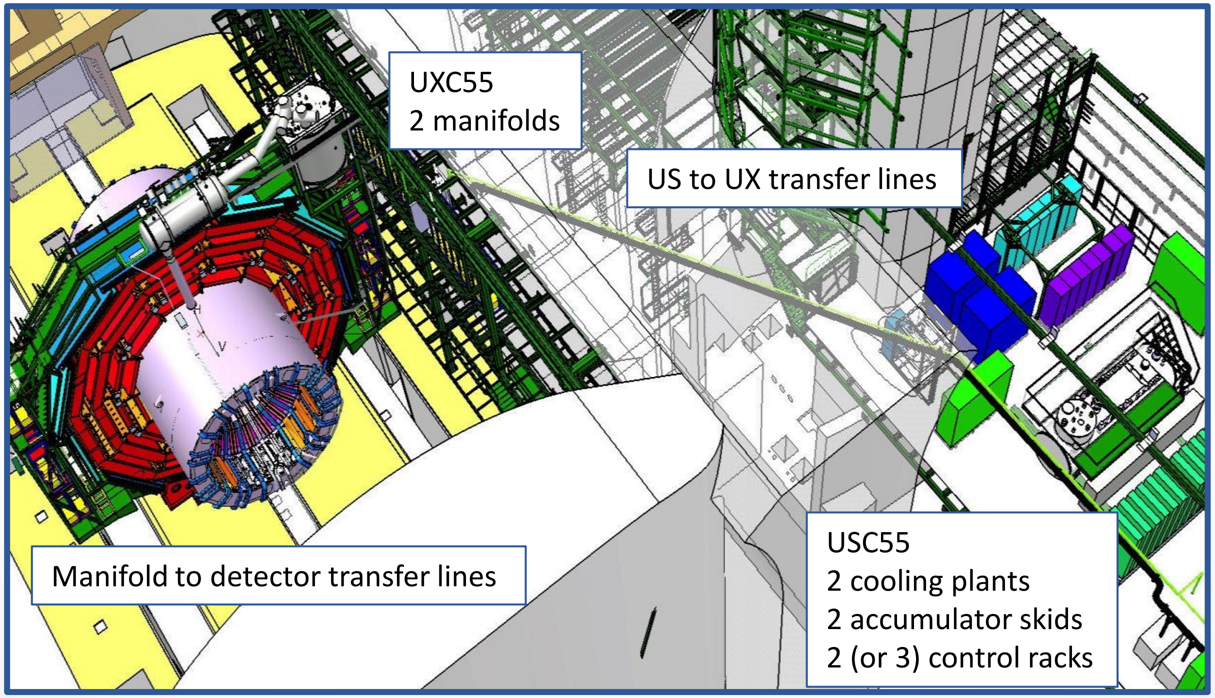
- Present 15 kW cooling plant designed around largest single head pump from LEWA, no other similar pumps available on the market
- These pumps are available in 2 and 3 head version
- This would result in 30 kW and 45 kW plants
- Experience with TIF system design in close collaboration between detector and cooling team to be continued!



Modularity of systems and collaboration between teams are the baseline for bigger systems!

Conclusions

- TIF cooling plant has proven to be a great test bench to develop a new and big system
- The testing will now continue concentrating on the detector mock-up systems newly installed
- Lessons learnt from this project can be used further!
- Looking forward to the installation in CMS of the final system at the end of LS1



Backup

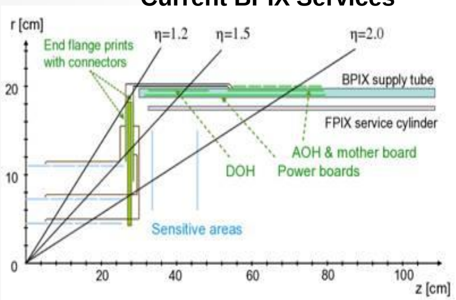
…

The CMS Pix phase I upgrade cooling

Today: liquid C_6F_{14}
- Low thermal capacity (≈1 $KJ.Kg^{-1}.K^{-1}$)
- High density (≈1,7 $kg.l^{-1}$)
- "Big" pipes (3.0 mm ID / 0.3 mm thick)

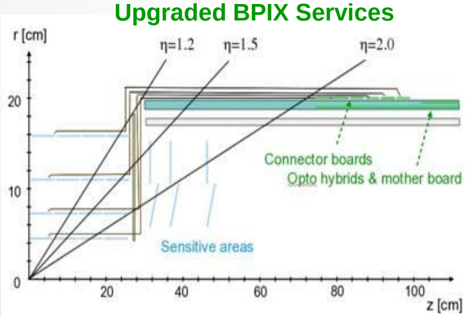
Tomorrow: evaporative CO_2
- Enhanced thermal capacity (≈2 KJ.Kg-1.K-1)
- Lower density (≈1.0 kg.l-1)
- Much smaller pipes (1.6 mm ID / 0.05 mm thick)

Current BPIX Services

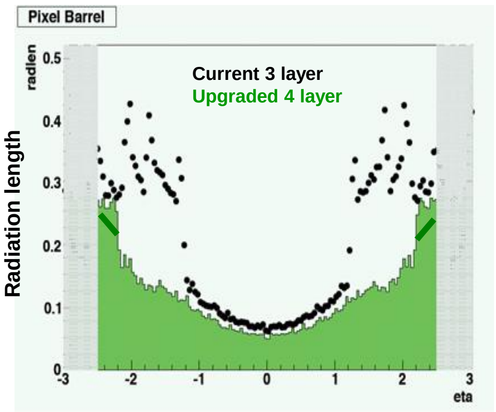


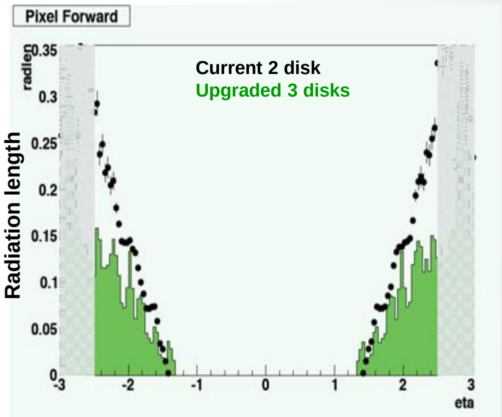
η<2.2 : weight = 16.9 Kg (3 layer)

Upgraded BPIX Services



η<2.2 : weight = 6.5 Kg (4 layer)

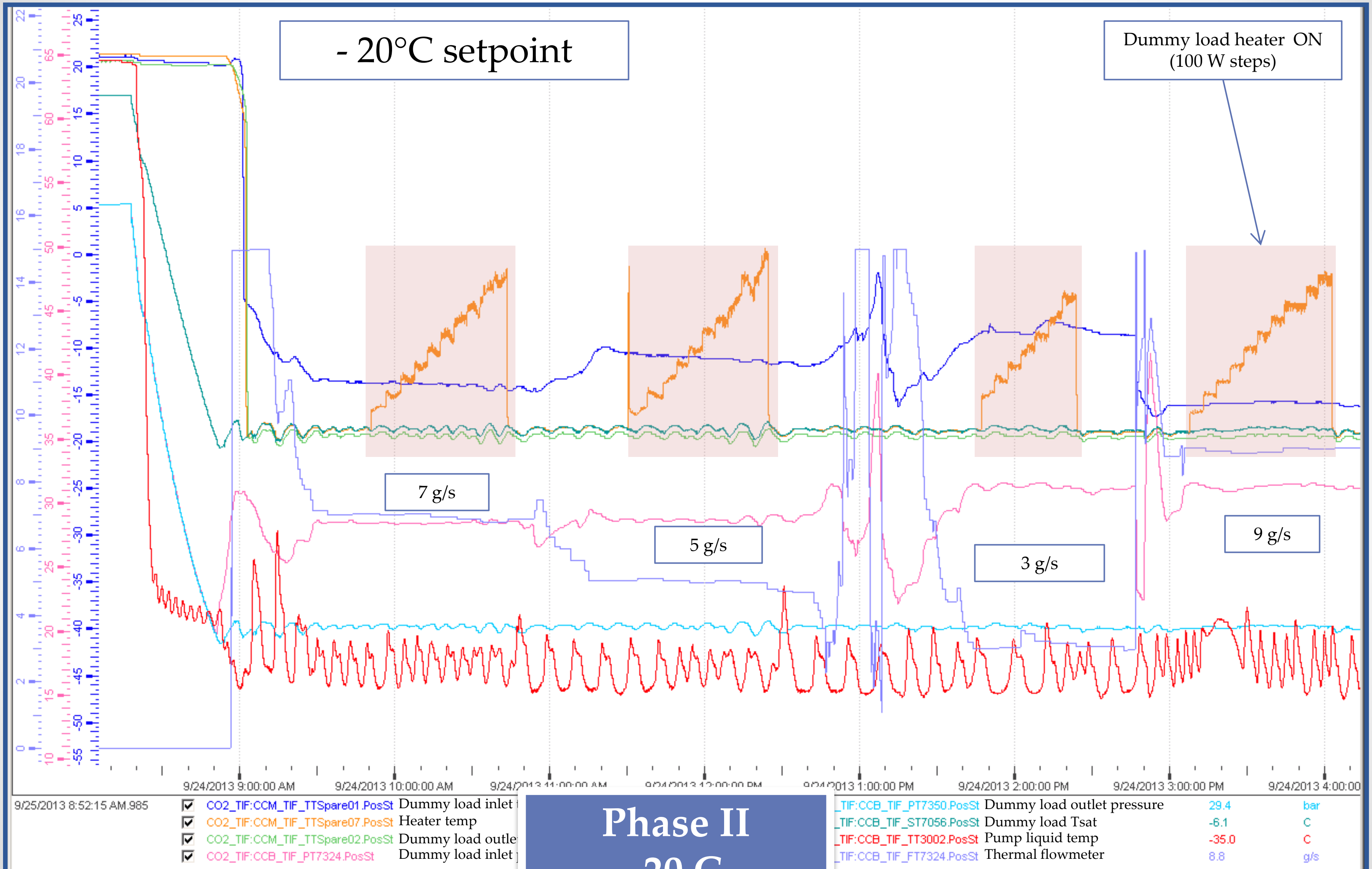




Barrel Pixel cooling details

Main Cooling Line	Main Mass Flow [g/s]	Detector Layer	Detector Cooling Loop	Mass Flow [g/s]	Irradiated Standby Power Operation (ISB) @ 15°C									Irradiated High Luminosity Power Operation (IHL) @ -20°C								
					Power [W]	Capillary ?P [bar]	Detector ?P [bar]	Return ?P [bar]	Detector ?T [°C]	Hotspot [°C]	Xout	Xdry	Xdiff	Power [W]	Capillary ?P [bar]	Detector ?P [bar]	Return ?P [bar]	Detector ?T [°C]	Hotspot [°C]	Xout	Xdry	Xdiff
+ZML1	2.91	Layer #1	L1D1PN	1.46	145.48	9.96	0.53	0.24	0.56	16.47	0.56	0.57	0.01	212.61	8.95	1.04	0.33	2.26	-16.11	0.51	0.65	0.14
			L1D2PF	1.46	145.48	9.96	0.53	0.24	0.56	16.47	0.56	0.57	0.01	212.61	8.95	1.04	0.33	2.26	-16.11	0.51	0.65	0.14
+ZML2	7.04	Layer #2	L2D2PN	3.52	224.13	7.50	2.46	0.59	2.14	18.15	0.35	0.36	0.01	278.49	6.68	2.62	0.84	4.93	-13.24	0.27	0.49	0.22
			L2D1PF	3.52	224.13	7.50	2.46	0.59	2.14	18.15	0.35	0.36	0.01	278.49	6.68	2.62	0.84	4.93	-13.24	0.27	0.49	0.22
+ZML3	8.40	Layer #3	L3D2PN	2.10	184.50	9.41	1.33	0.33	1.23	16.96	0.49	0.52	0.03	221.47	8.43	1.75	0.50	3.04	-15.74	0.37	0.62	0.25
			L3D3PF	2.10	184.50	9.41	1.33	0.33	1.23	16.96	0.49	0.52	0.03	221.47	8.43	1.75	0.50	3.04	-15.74	0.37	0.62	0.25
			L3D4PN	2.10	175.41	9.50	1.30	0.33	1.18	16.90	0.47	0.52	0.05	210.97	8.51	1.67	0.51	2.91	-15.89	0.35	0.63	0.28
			L3D1PF	2.10	175.41	9.50	1.30	0.33	1.18	16.90	0.47	0.52	0.05	210.97	8.51	1.67	0.51	2.91	-15.89	0.35	0.63	0.28
+ZML4	7.72	Layer #4	L4D1PN	1.93	177.54	9.43	1.79	0.31	1.63	17.27	0.51	0.55	0.04	204.35	8.49	2.15	0.47	3.85	-15.06	0.37	0.66	0.29
			L4D4PF	1.93	177.54	9.43	1.79	0.31	1.63	17.27	0.51	0.55	0.04	204.35	8.49	2.15	0.47	3.85	-15.06	0.37	0.66	0.29
			L4D3PN	1.93	169.41	10.08	1.40	0.30	1.30	17.00	0.49	0.54	0.05	195.23	9.06	1.68	0.45	3.17	-15.72	0.35	0.65	0.30
			L4D2PF	1.93	169.41	10.08	1.40	0.30	1.30	17.00	0.49	0.54	0.05	195.23	9.06	1.68	0.45	3.17	-15.72	0.35	0.65	0.30
-ZML1	5.35	Layer #1	L1D2MN	2.67	187.92	9.15	0.93	0.42	0.88	17.06	0.39	0.39	0	277.89	8.19	1.29	0.78	3.14	-14.64	0.36	0.49	0.13
			L1D1MF	2.67	187.92	9.15	0.93	0.42	0.88	17.06	0.39	0.39	0	277.89	8.19	1.29	0.78	3.14	-14.64	0.36	0.49	0.13
-ZML2	4.92	Layer #2	L2D1MN	2.46	199.50	8.57	1.78	0.44	1.63	17.48	0.45	0.47	0.02	247.95	7.70	2.19	0.66	4.14	-14.33	0.35	0.58	0.23
			L2D2MF	2.46	199.50	8.57	1.78	0.44	1.63	17.48	0.45	0.47	0.02	247.95	7.70	2.19	0.66	4.14	-14.33	0.35	0.58	0.23
-ZML3	8.41	Layer #3	L3D1MN	2.10	157.23	9.72	1.21	0.31	1.10	16.75	0.42	0.54	0.12	189.95	8.69	1.53	0.46	2.63	-16.30	0.31	0.65	0.34
			L3D4MF	2.10	157.23	9.72	1.21	0.31	1.10	16.75	0.42	0.54	0.12	189.95	8.69	1.53	0.46	2.63	-16.30	0.31	0.65	0.34
			L3D3MN	2.10	189.95	9.42	1.33	0.34	1.22	16.97	0.49	0.52	0.03	221.47	8.44	1.74	0.53	3.04	-15.70	0.37	0.62	0.25
			L3D2MF	2.10	189.95	9.42	1.33	0.34	1.22	16.97	0.49	0.52	0.03	221.47	8.44	1.74	0.53	3.04	-15.70	0.37	0.62	0.25
-ZML4	7.14	Layer #4	L4D2MN	1.78	169.41	9.77	1.33	0.29	1.25	16.94	0.53	0.56	0.03	195.23	8.82	1.65	0.44	3.12	-15.78	0.38	0.66	0.28
			L4D3MF	1.78	169.41	9.77	1.33	0.29	1.25	16.94	0.53	0.56	0.03	195.23	8.82	1.65	0.44	3.12	-15.78	0.38	0.66	0.28
			L4D4MN	1.78	161.29	9.84	1.29	0.28	1.21	16.88	0.51	0.57	0.06	186.12	8.89	1.58	0.42	2.97	-15.97	0.36	0.67	0.31
			L4D1MF	1.78	161.29	9.84	1.29	0.28	1.21	16.88	0.51	0.57	0.06	186.12	8.89	1.58	0.42	2.97	-15.97	0.36	0.67	0.31
			TOTAL	51.88	4283.54									5283.47								

Single loop performances



Phase II
-20 C
up to 1 kW

T set point change at full power!

Phase III