9th IIR Gustav Lorentzen Conference 2010
natural refrigerants real alternatives

12–14 April 2010 • Sydney, Australia

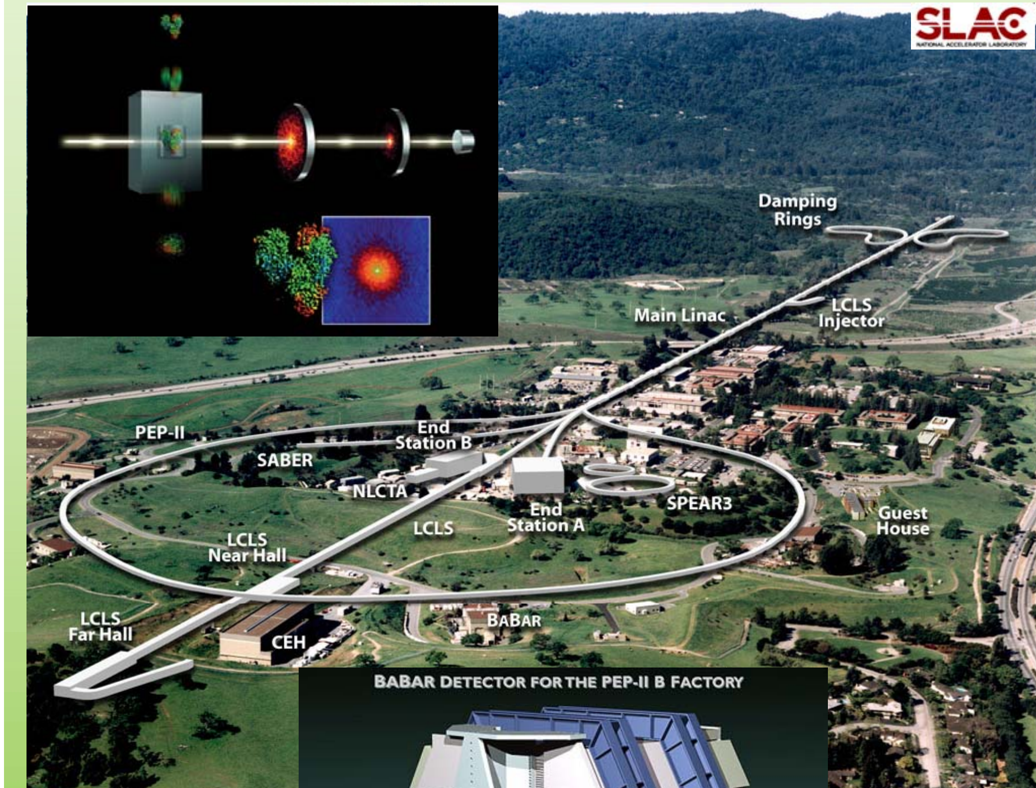
Evaporative Cooling With Carbon Dioxide for The Detectors Upgrade At The Large Hadron Collider

Presenter: M. Oriunno, SLAC National Accelerator Laboratory- USA

achieving recognition

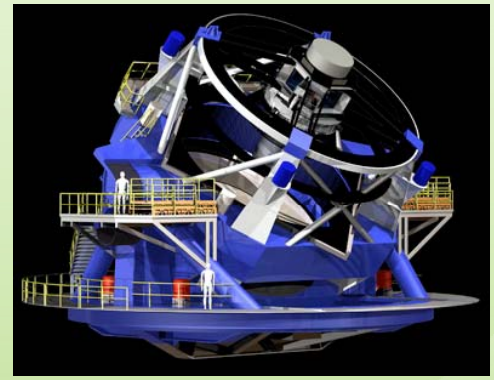
SLAC National Accelerator Laboratory, Menlo Park, CA,
Operated by Stanford University for the U.S. Dept. of Energy

LCLS (free electron laser)

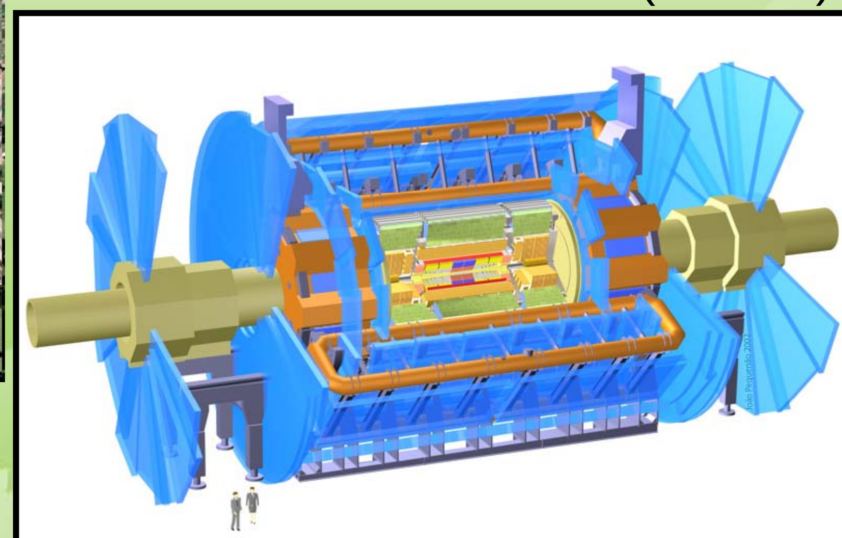


BABAR

FERMI (aka GLAST)



LSST (in Chile)



ATLAS Experiment at LHC

LHC : A Truly Large Scale Project

Operated by
20 countries

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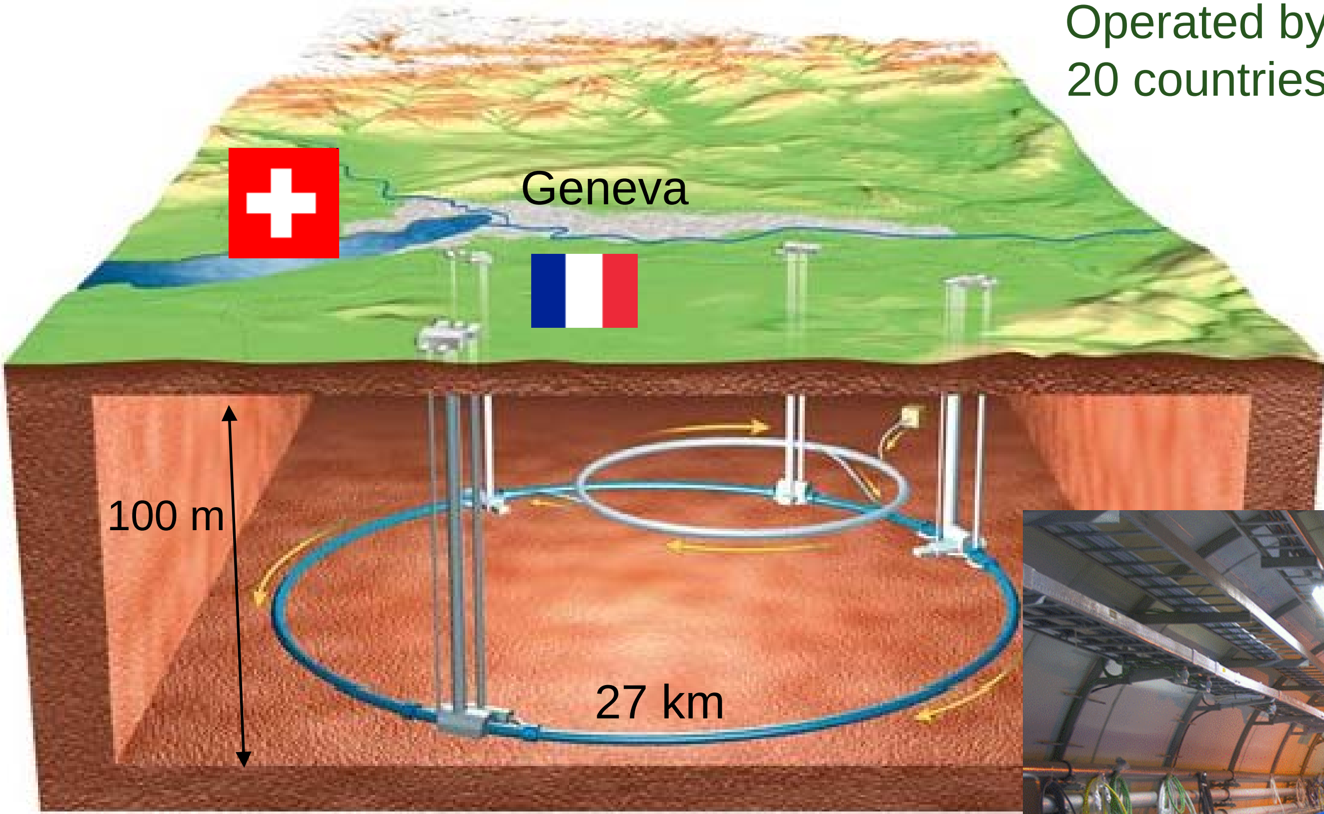


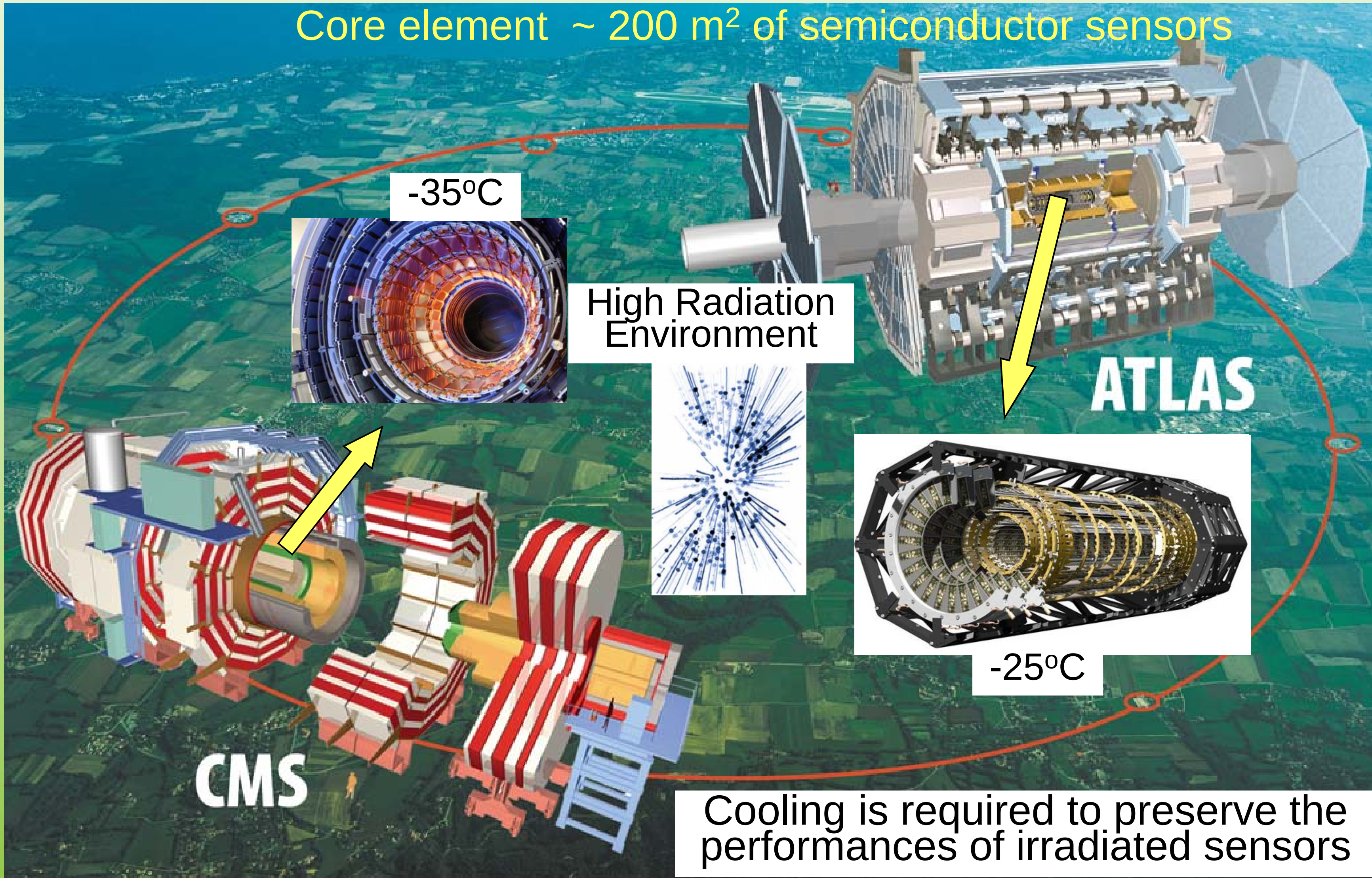
World's largest fridge,
Super fluid He, 1.9 K

First collisions at 7 TeV on March 30 !

Set World Record from Fermilab-Tevatron

R&D started for a staged upgrade of
accelerator and experiments in ~2016

The Detectors :



The Challenge

"Provide reliable performances at low temperature with low material"

1. Low Temperature = Low electrical noise $I_{leak}(\Phi,T) = \Phi \times T^2 \times e^{(-k/T)}$
   Protection vs. Thermal Runaway $P_{si}(\Phi,T) = V_{bias} \times I_{leak}$

2. Low Material (small tube) = Improved physics resolution, low multiple scattering

3. Low Pressure Drop = Temperature uniformity & more pressure head to reach the compressor

4. High Heat Transfer Coefficient = Increased protection vs. Thermal Runaway

Evaporative Carbon Dioxide as refrigerant

CO_2 is cheap, natural, not flammable, non toxic and radiation hard

+ High Static Pressure (10 bars) at Low Temperatures of interest (~-40^{o}C)

+ High volumetric refrigeration capability, i.e. high mass flux

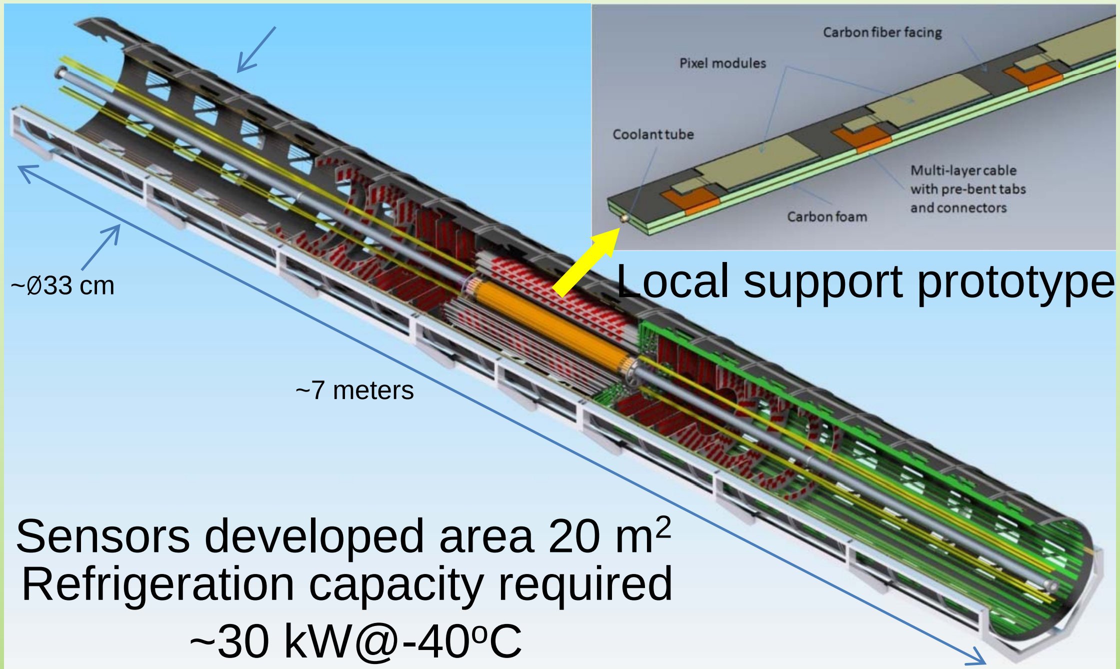
+ Steeper Vapor Pressure curve, i.e. Low $\Delta T/\Delta P$

= Small tubes with low pressure drops

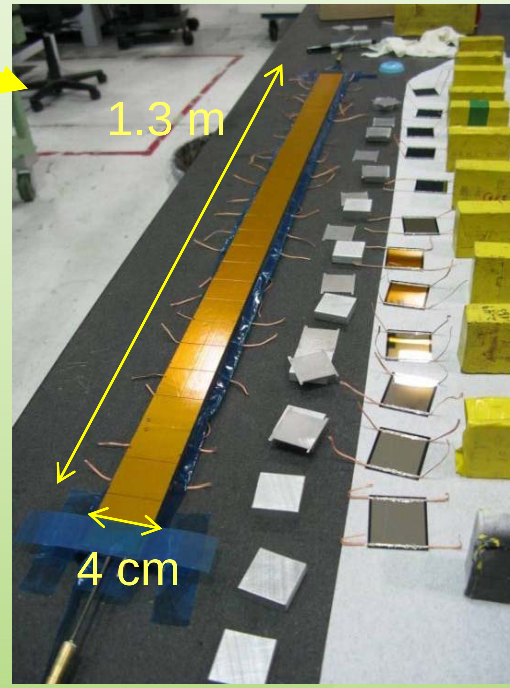
High Pressure & Low Surface Tension induce dominating Nucleate Boiling with high heat transfer rate.

Also…..CO_2 is GREEN !

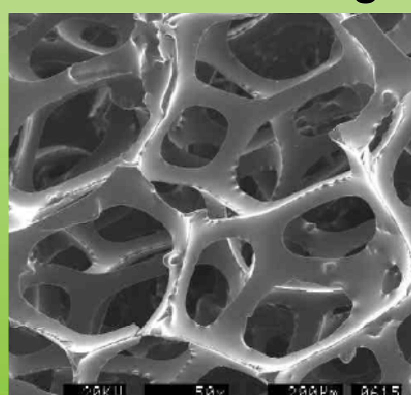
The Pixel Detector Upgrade of ATLAS

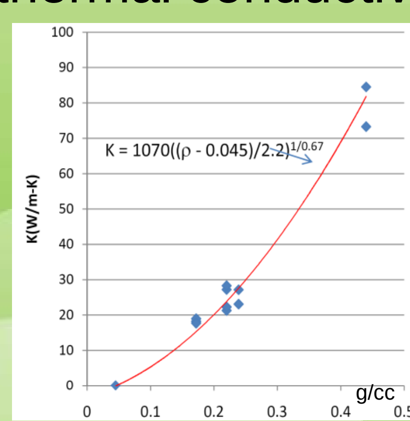


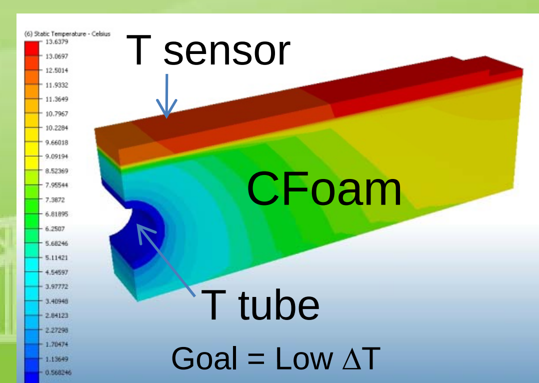
Sensors developed area 20 m^2
Refrigeration capacity required
~30 kW@-40ºC



Carbon Foam with low mass high thermal conductivity :

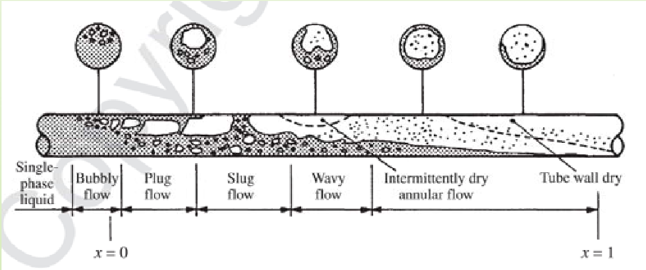


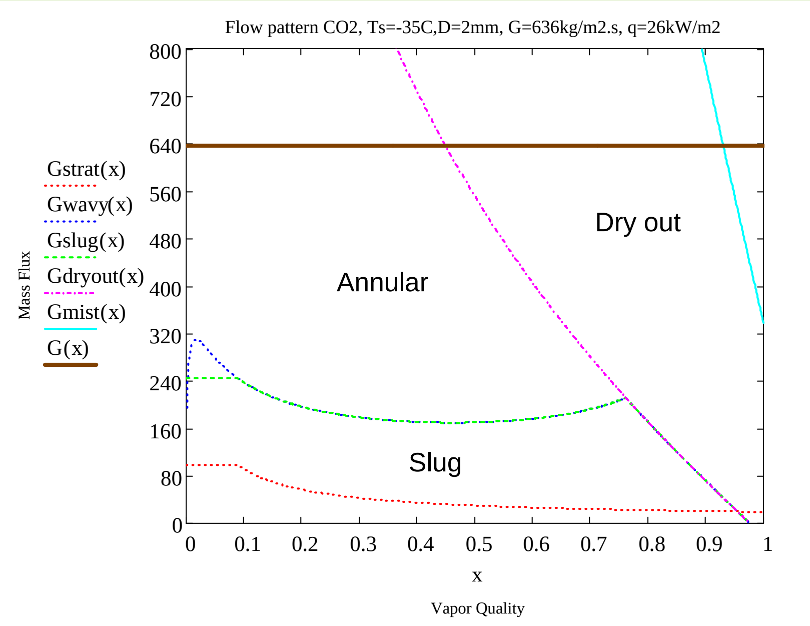


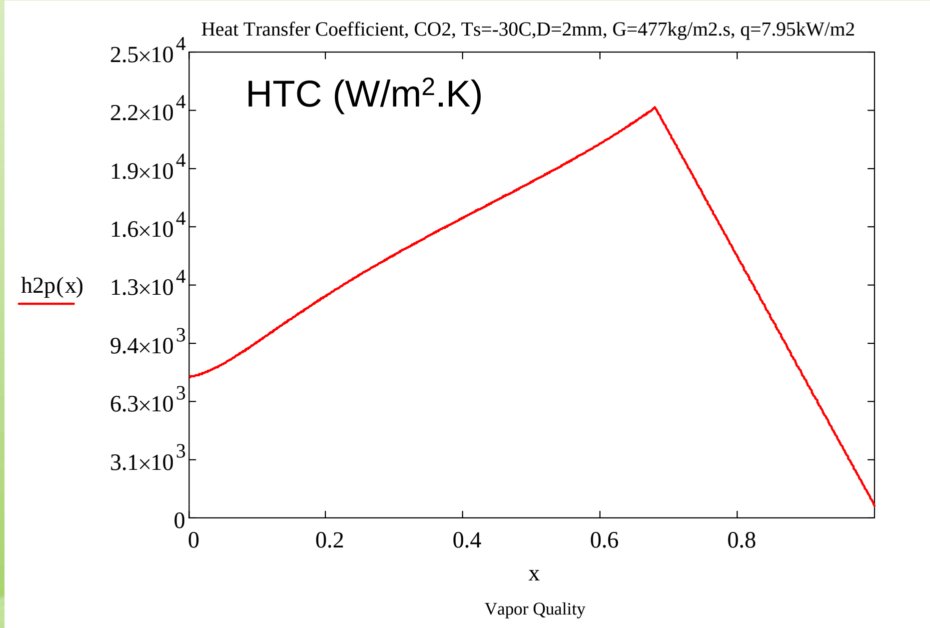


Sizing the Cooling Channel

Requirements : Heat Load 220 W
Evaporation temperature -35^{o}C
Channel length 1.3 m
Tube ID 2mm

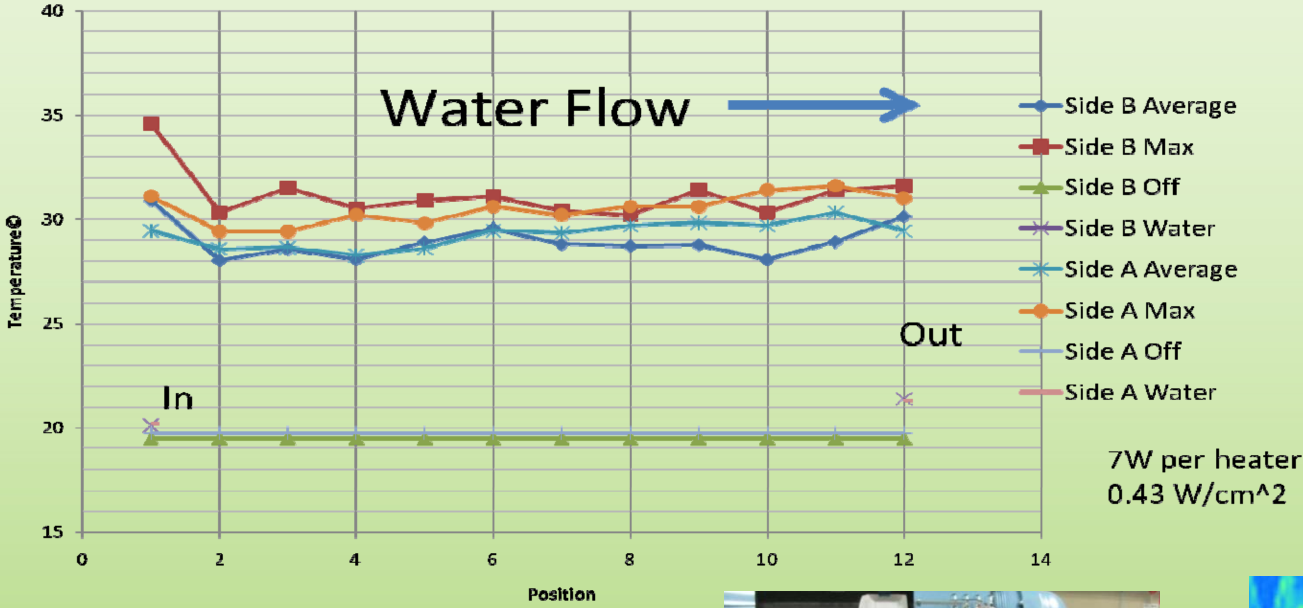




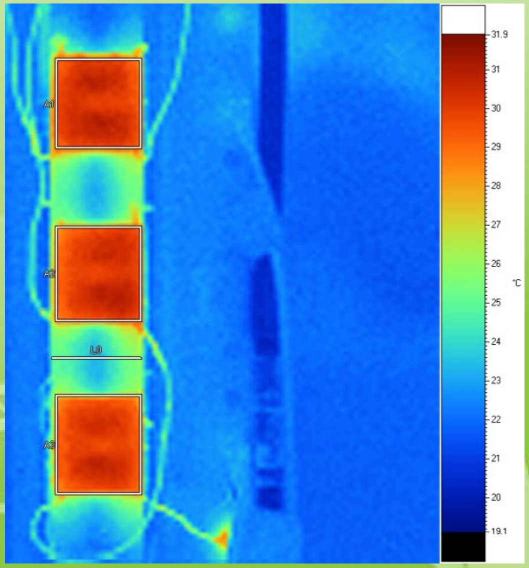


Thome's Pattern Flow Map (L. Cheng et al. 2006)

Test with Water at 20ºC

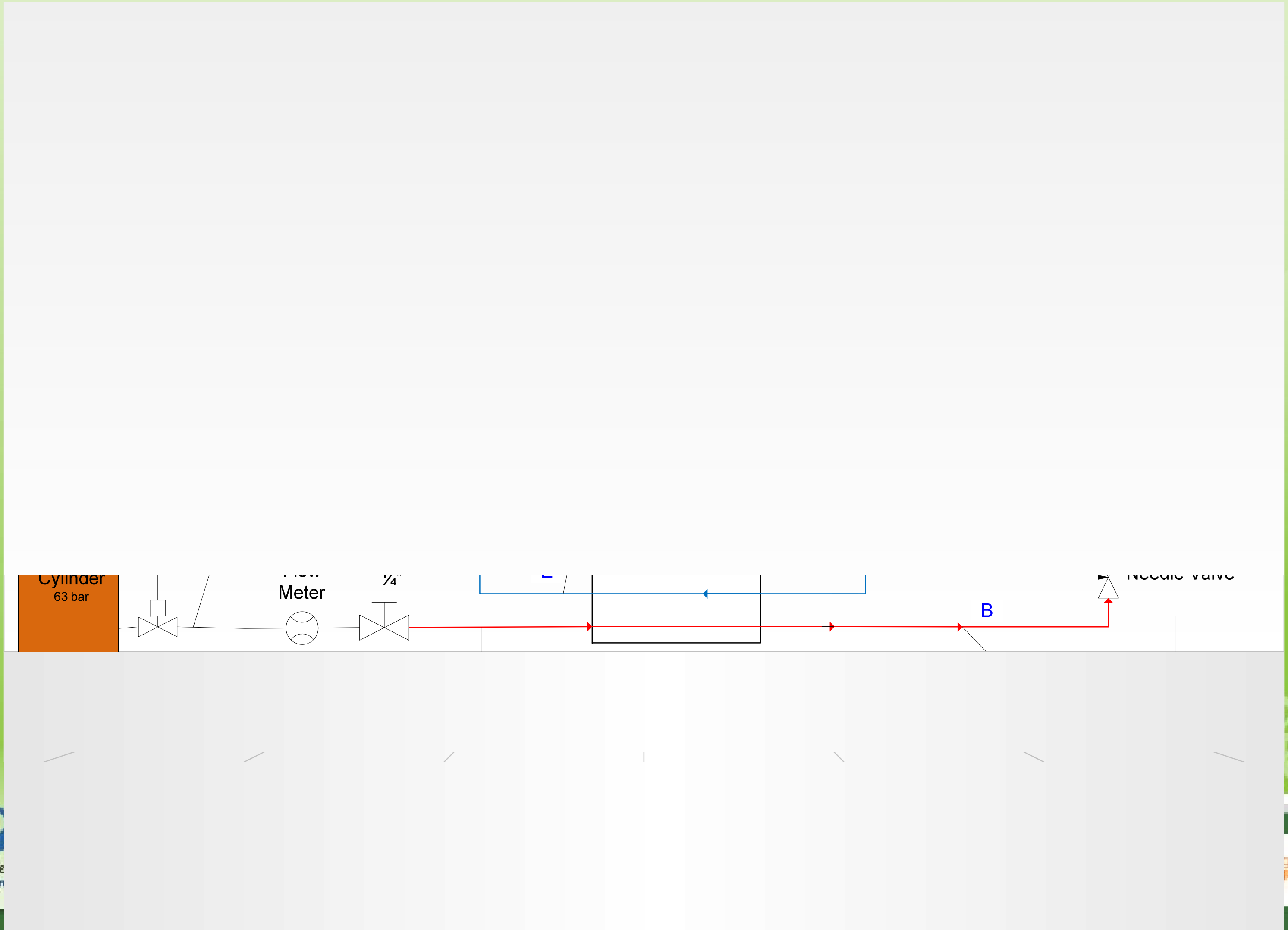


H_2O at 1 l/min
Single side heat

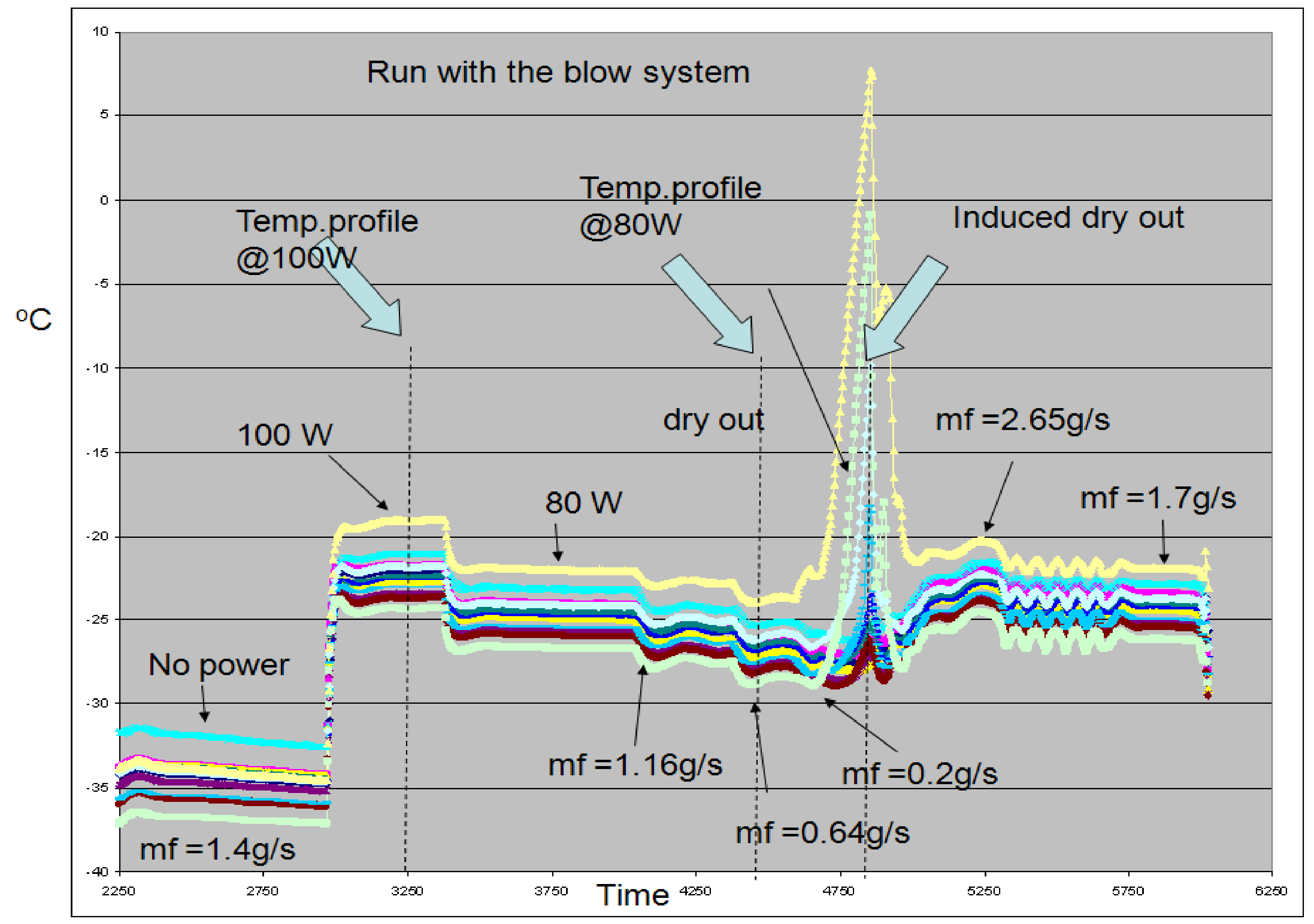


Blow System

1. Open system with CO_2 vented in the atmosphere
2. Flexible, Cheap, Max.500 W at-40ºC

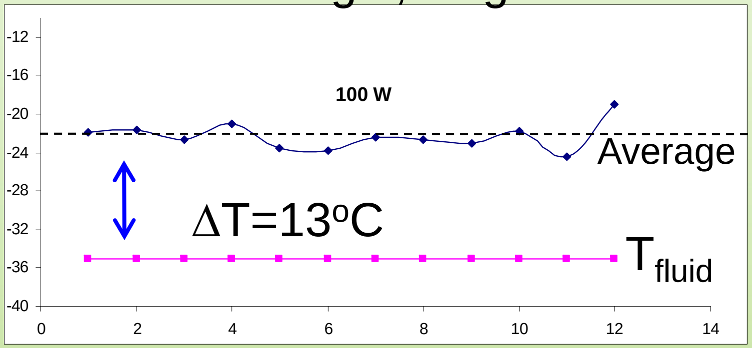


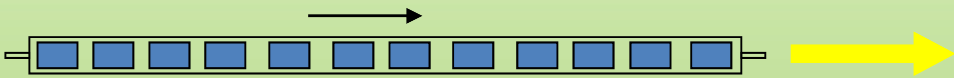
Typical run with the CO2 blow System

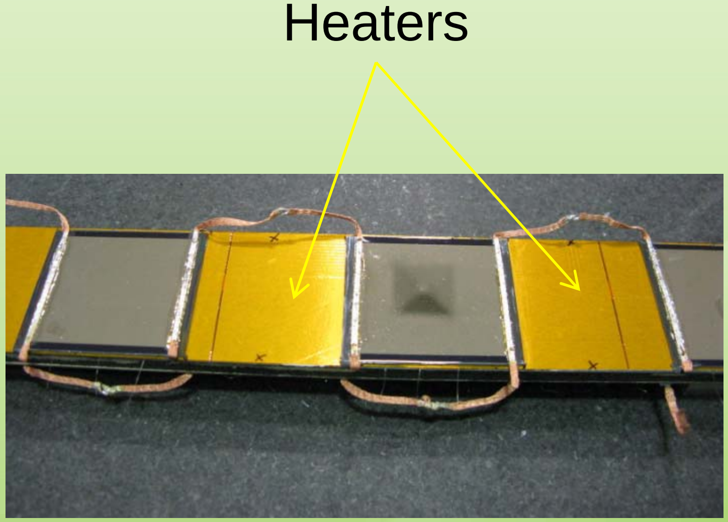


Evaporative CO2 at -35ºC

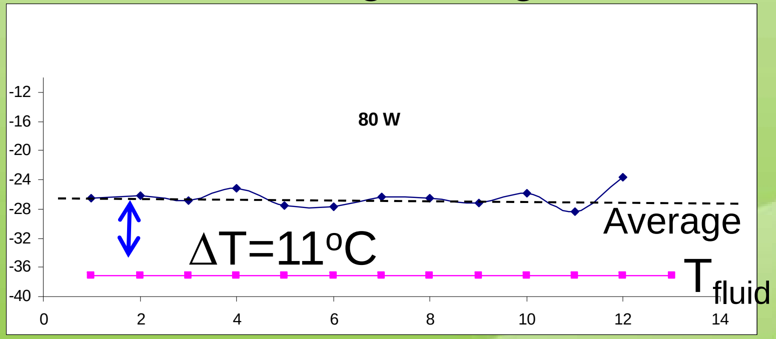
Mass flow 1.4 g/s, single face







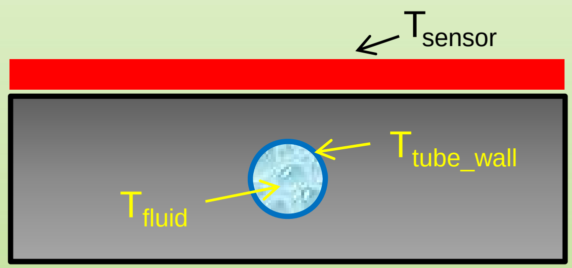
Mass flow 1.16 g/s, single face



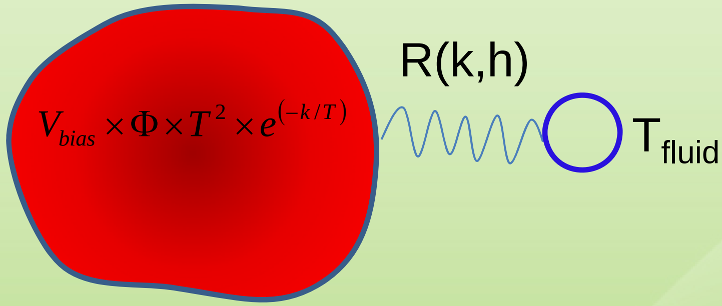
Thermal Impedance and Thermal runaway

Thermal impedance R = $(T_{sensor}-T_{tube\_wall})$/Heat,

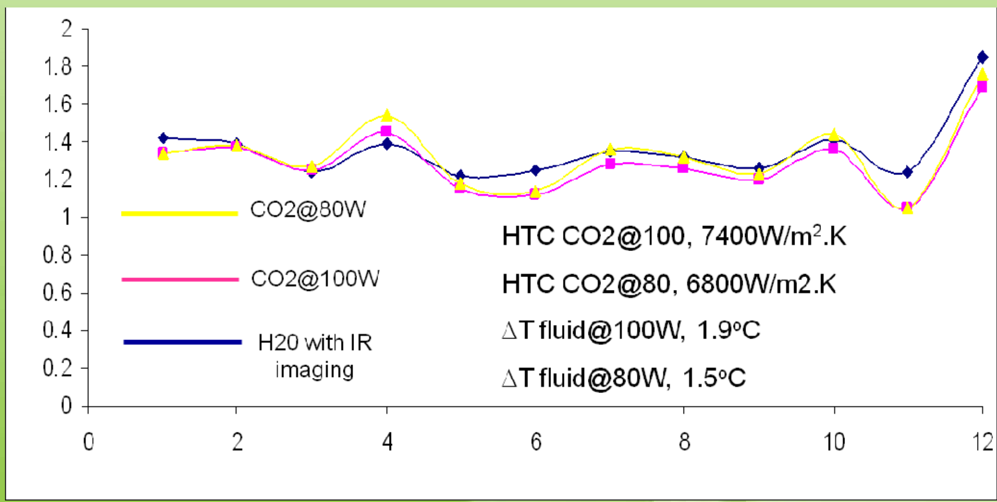
where $(T_{sensor}-T_{tube\_wall}) = (T_{sensor}-T_{fluid})$ -Q/(hA)

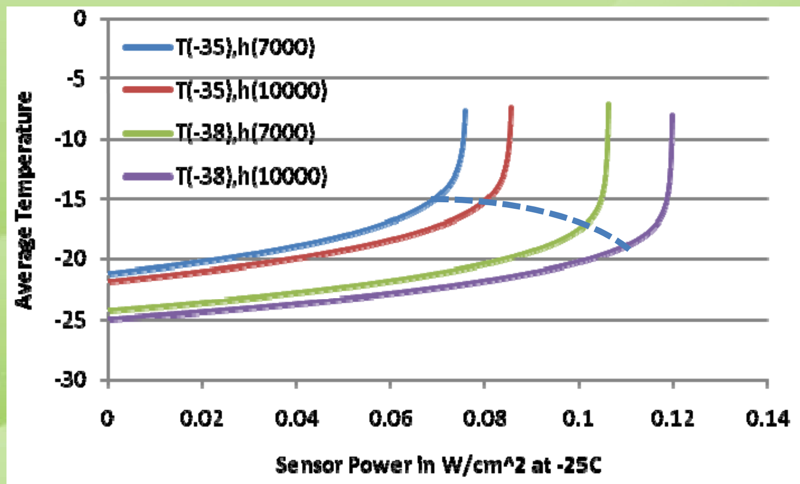


Thermal Impedance



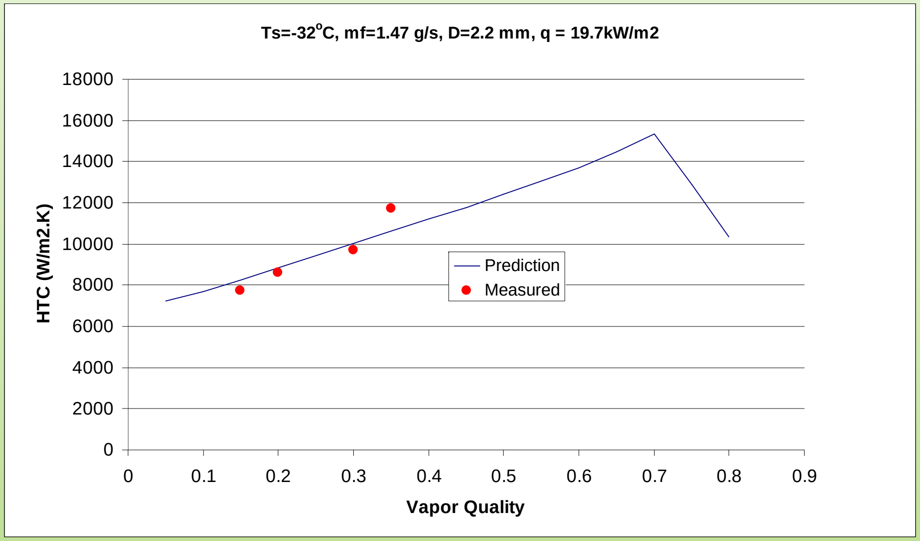
Thermal Runaway

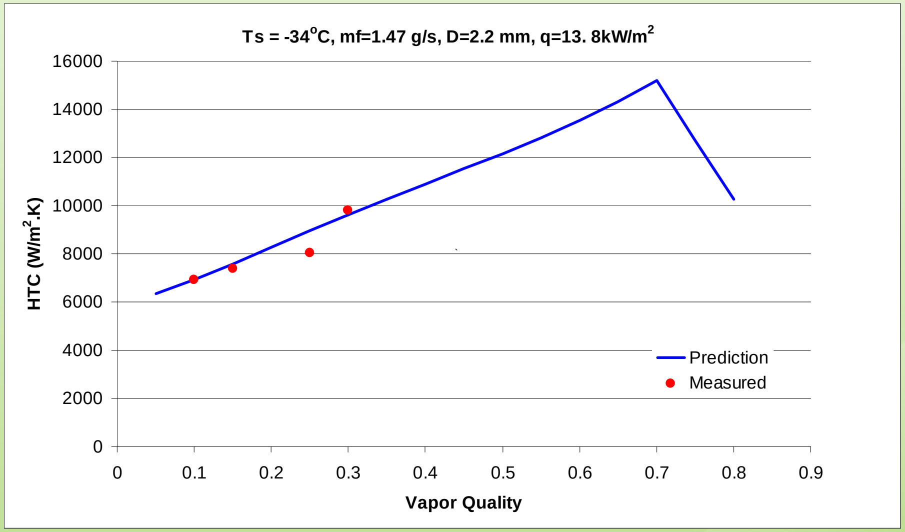


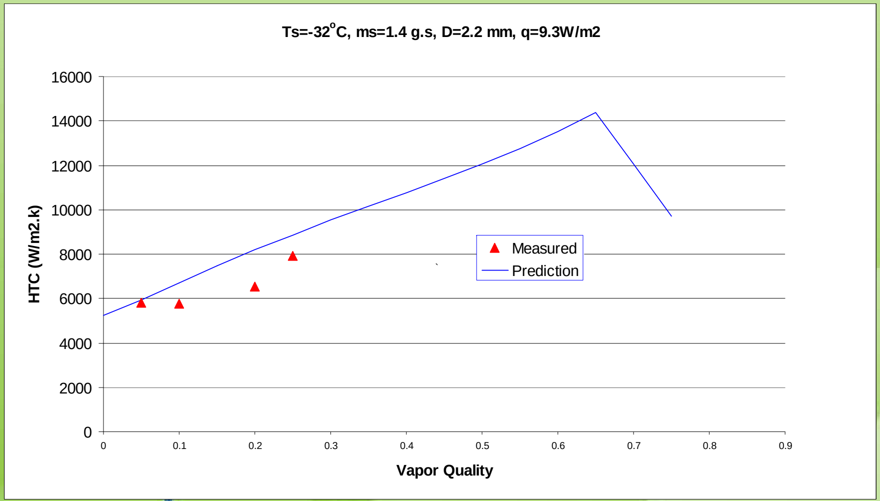


Bare tubes 2.2 ID (SSteel)

CO_2 at -35°C, Heating by direct current







Mass flux = 400 g/s.m^2,

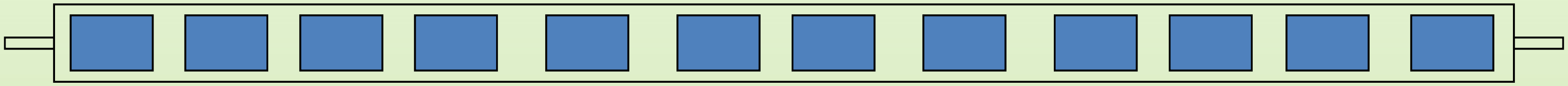
Heat fluxes applied:

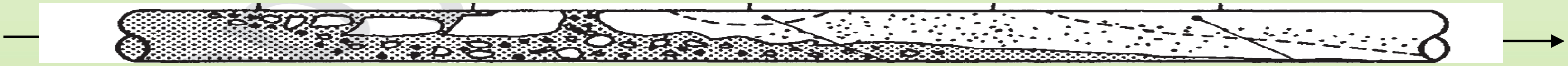
9.3kW/m^2(75W),

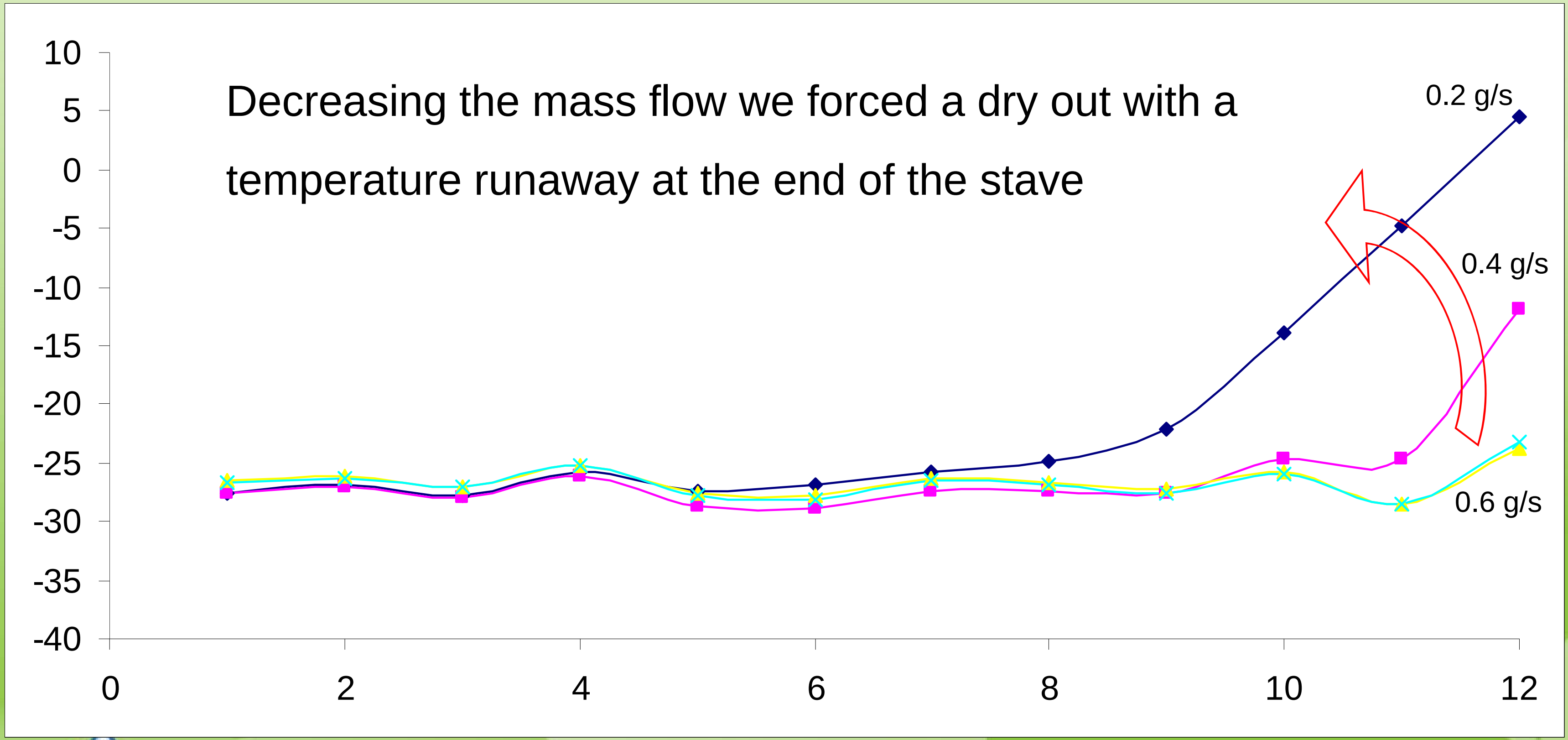
13.8kW/m^2(100W),

19.7kW/m^2(150W)

Dry-out

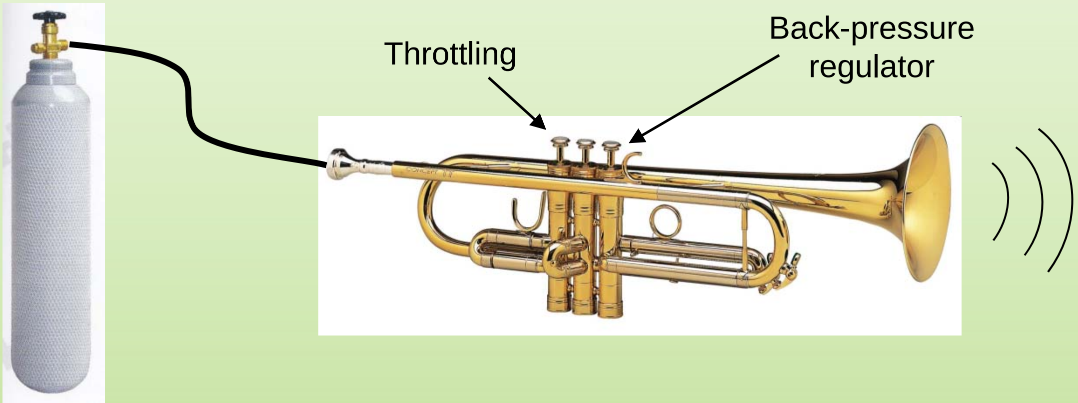


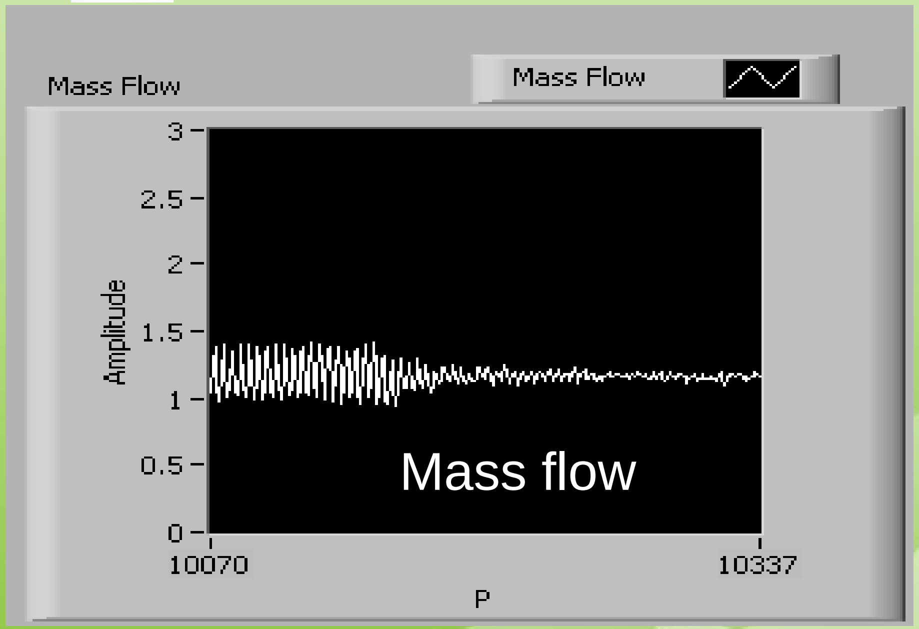


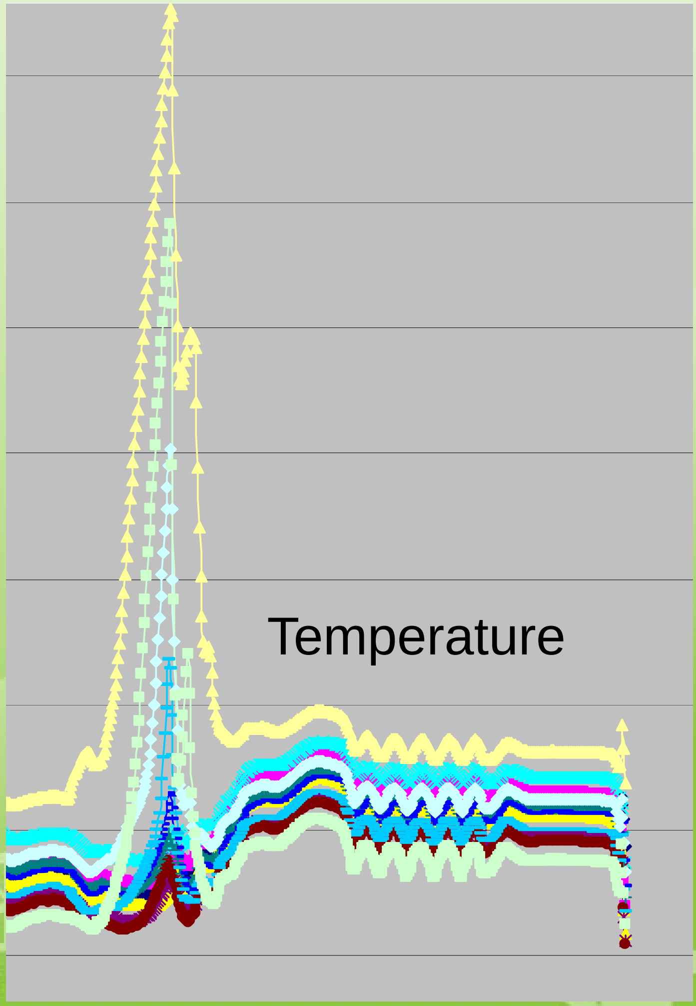


Decreasing the mass flow we forced a dry out with a temperature runaway at the end of the stave
0.2 g/s
0.4 g/s
0.6 g/s
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
0
2
4
6
8
10
12

Blow system limitations : Pressure Waves



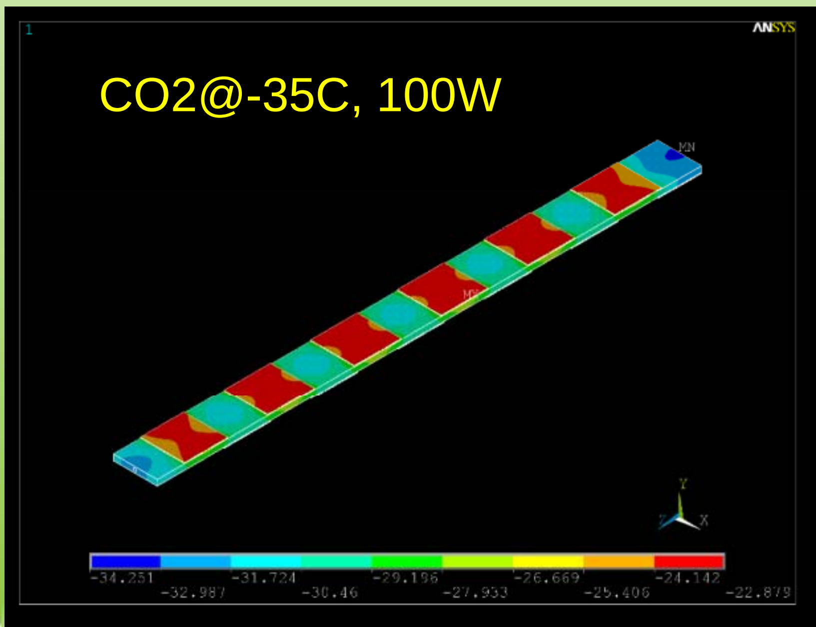


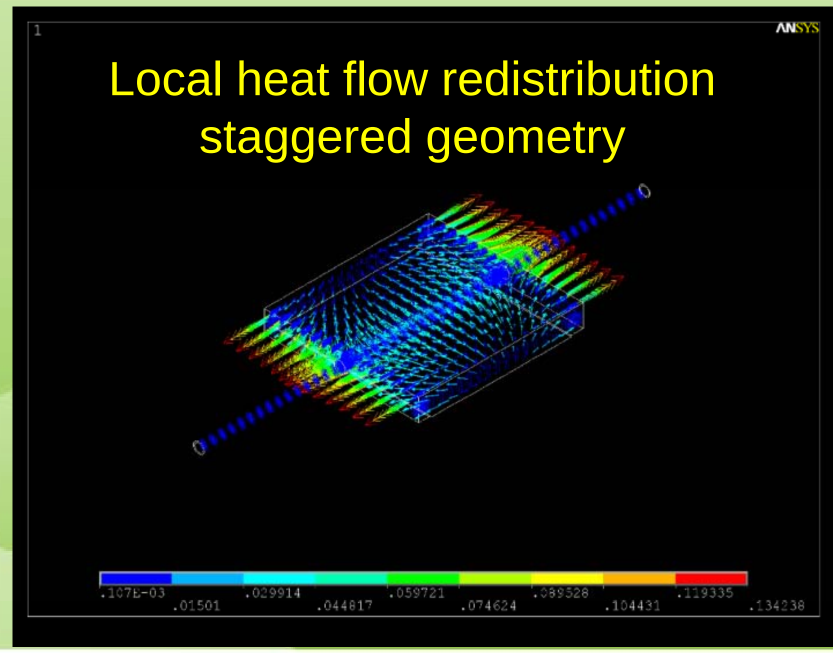


Finite Element Model

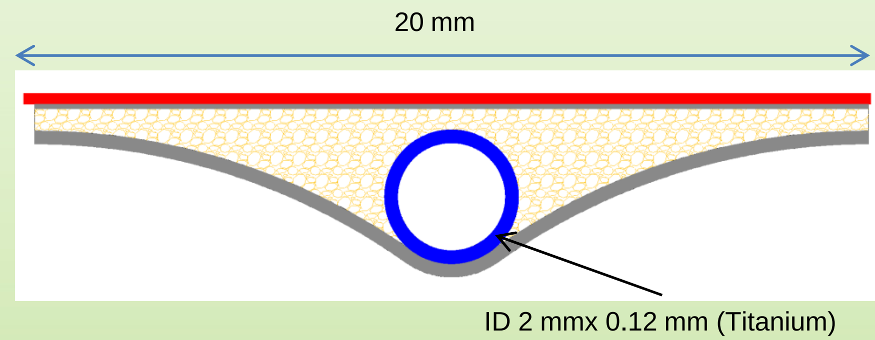
Good correlation between experiments and FEA simulation

Load Case	Heat flux kW/m²	T fluid ºC	HTC W/m2.K	Ts FEA ºC	TS experiment ºC
Water@84W	16.8	20	16347	29.2	28.94
CO2@100W	17.6	-35	7800	-22.87	-22.32
CO2@80W	21.8	-37	6400	-26.9	-26.47



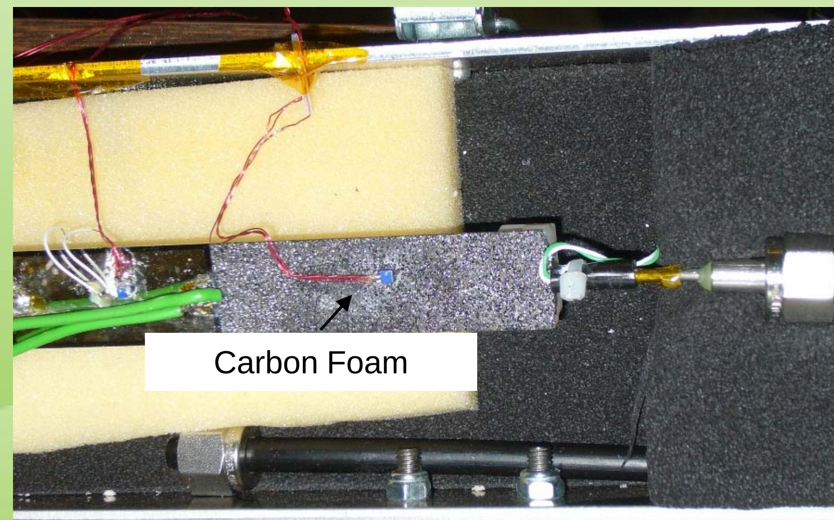


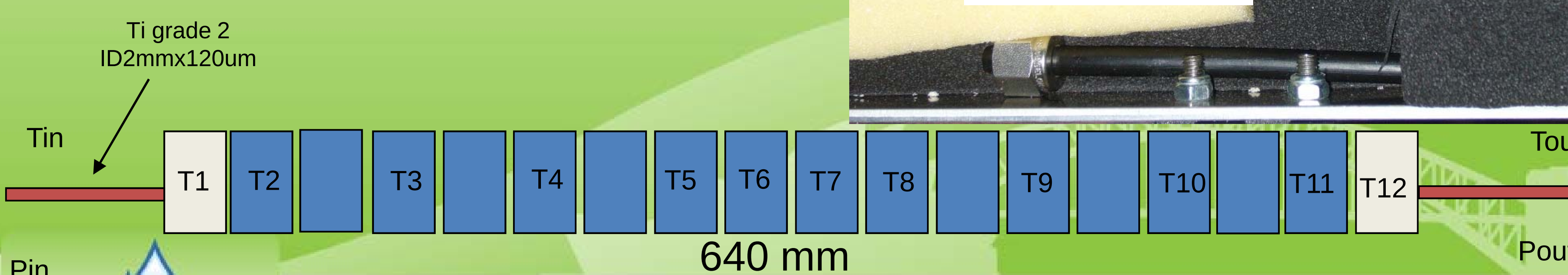
Insertable B-layer-Prototype



- 16 Platinum heaters 2 x 4 cm^2
- Fittings glued with epoxy on Titanium
- 12 Pt100 sensors,
- Two temperature sensors at the inlet and the outlet,
- Two pressure gauges at the inlet and the outlet

- - Warm Test with liquid Water/Glycol
- - Cold Test with evaporative CO_2
- - Thermal FEA Simulations



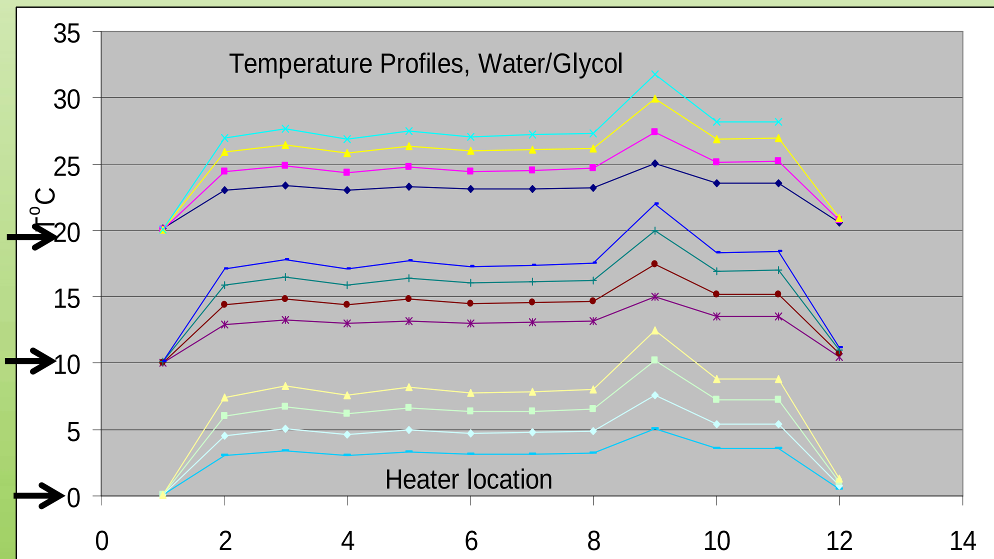


Warm test with Water/Glycol mixture 90/10

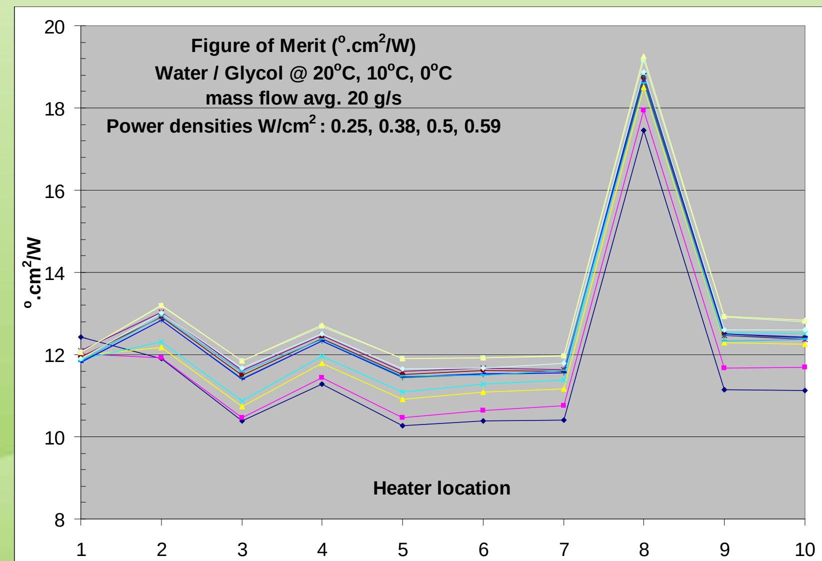
Chiller set points : 20°c, 10°C, 0°C

Power densities : 0.25, 0.38, 0.5, 0.63 W/cm^2

Flow rate 20 g/s, Pressure drop ~2 bars



Temperature profiles



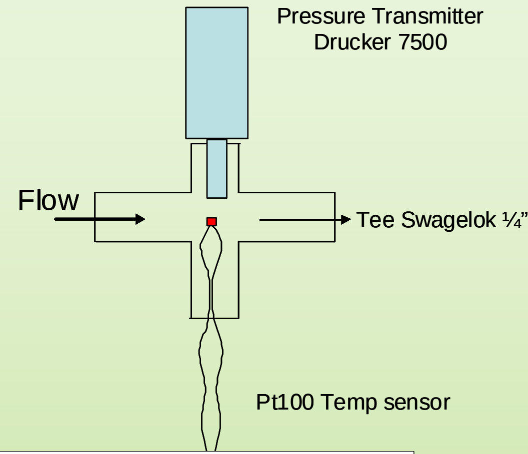
Figures of merit T_{sensor}-$T_{tube\text{-}wall}$

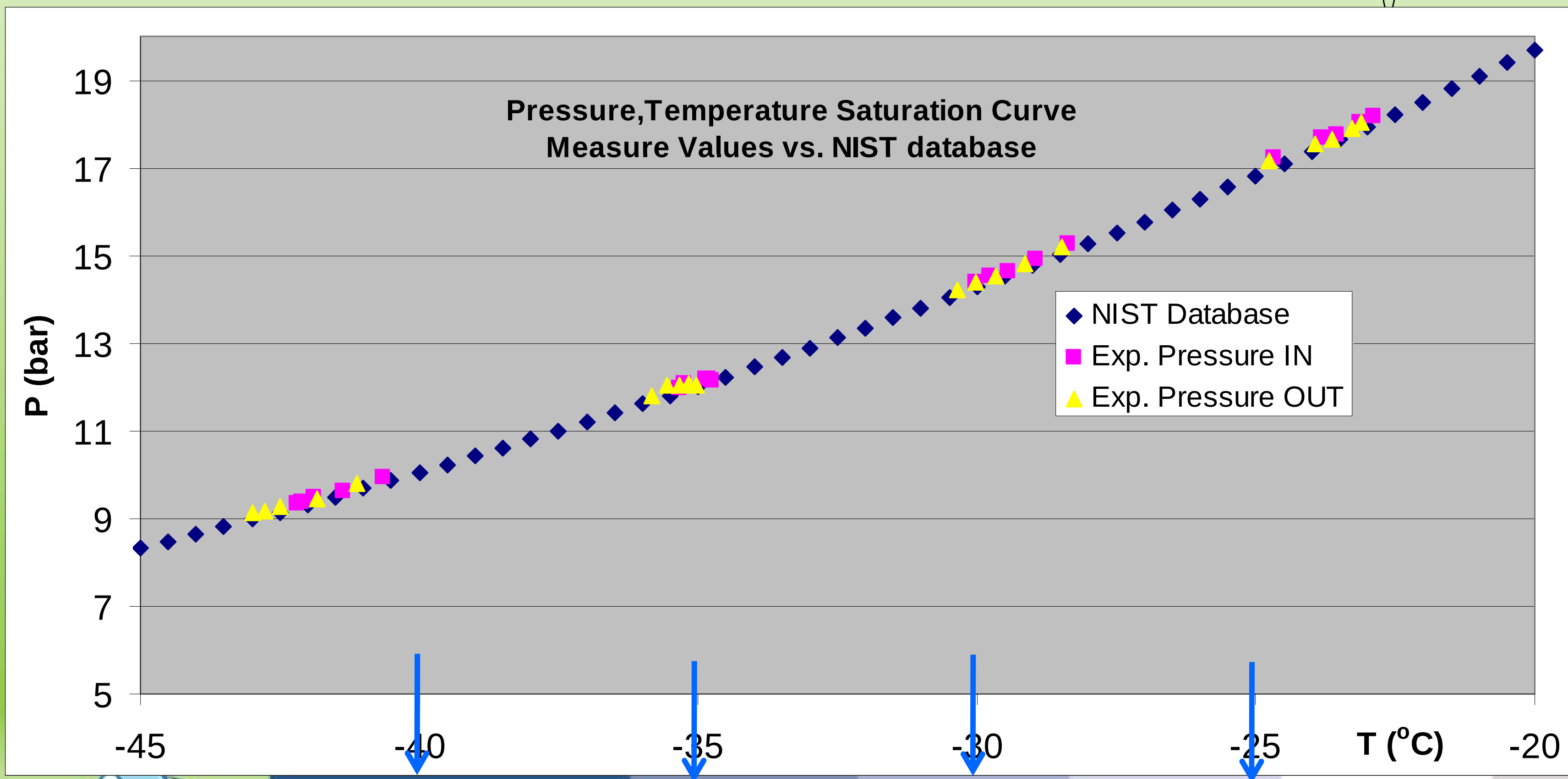
Pressure-temperature curve

Blow System set points : -25ºC, -30ºC, -35ºC, -40ºC

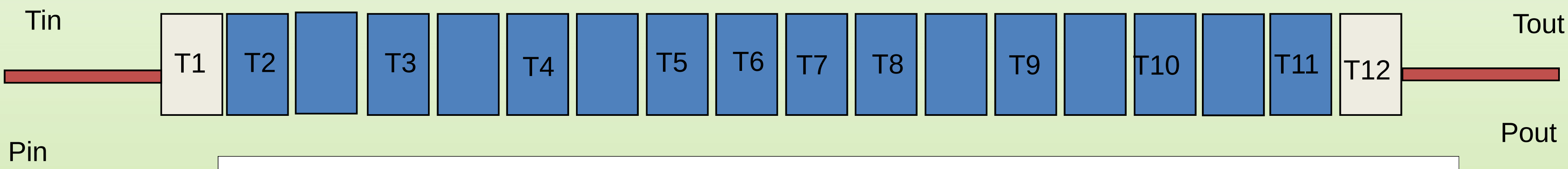
Power densities : 0.25, 0.38, 0.5, 0.63 W/cm2

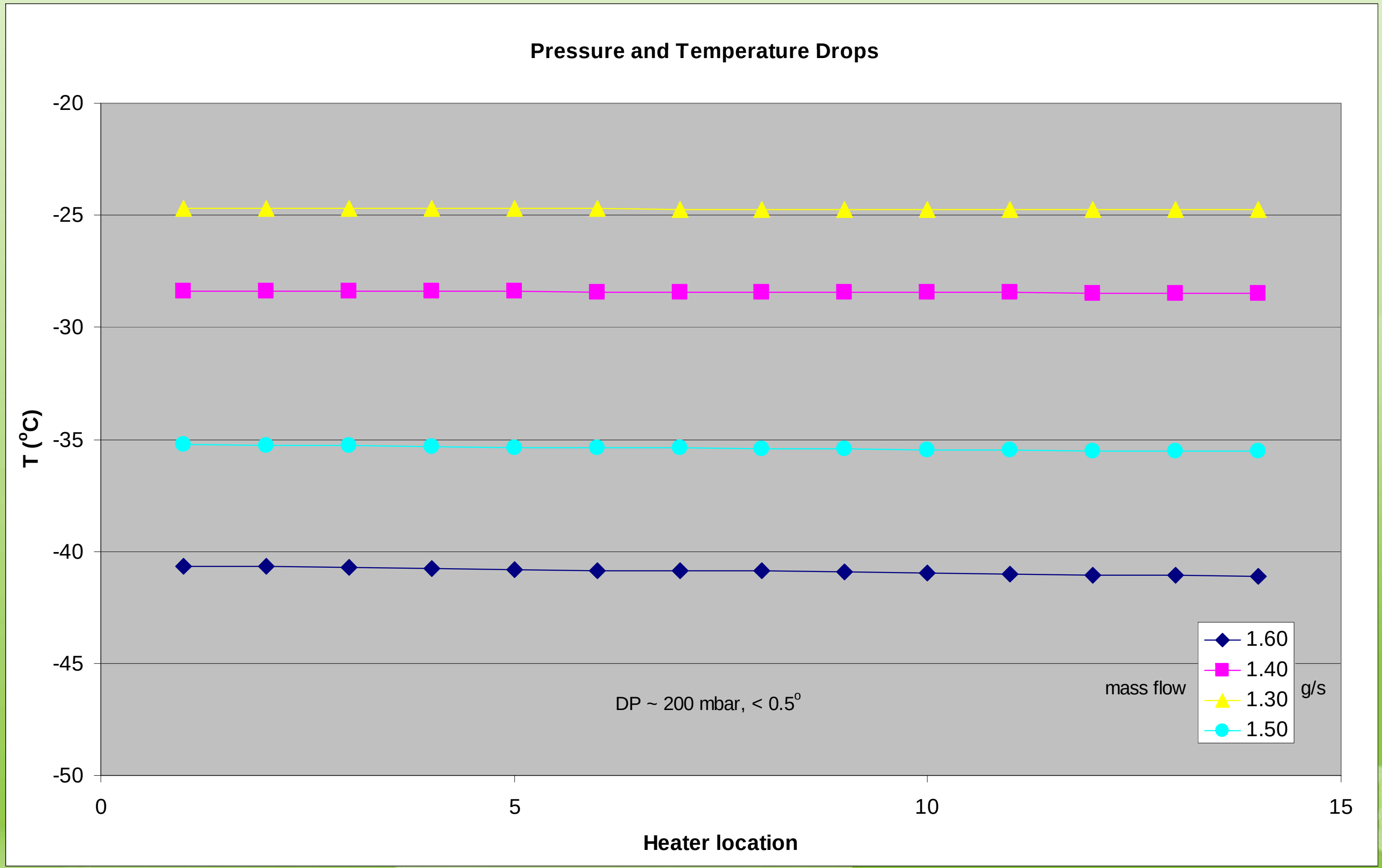
Flow rate ~1.5 g/s,



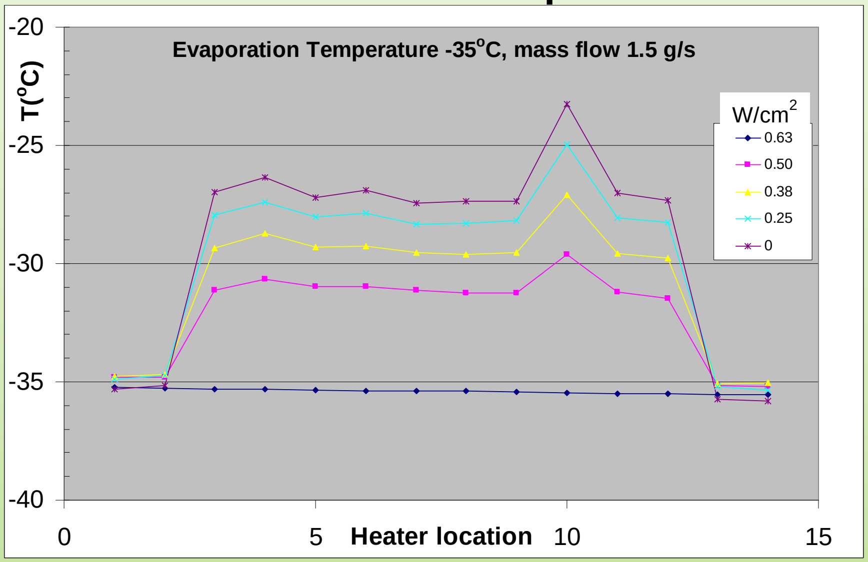


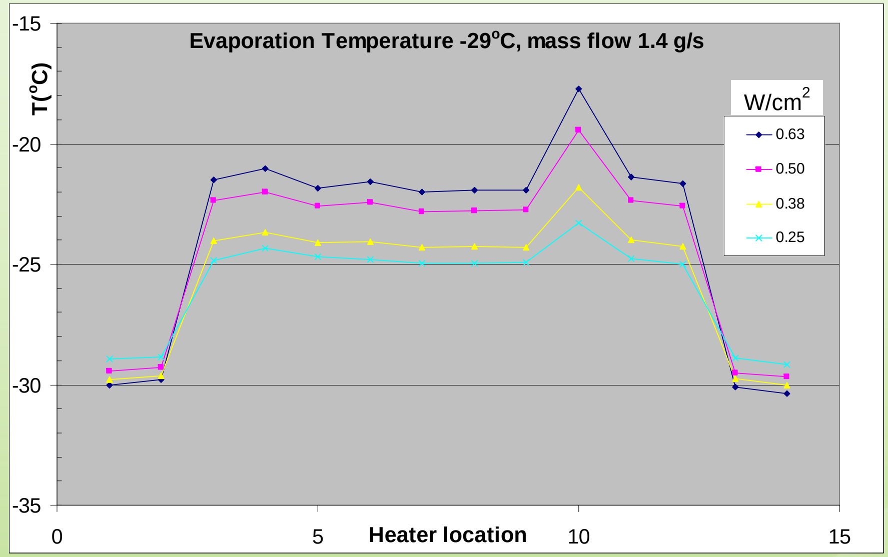
Evaporative CO2,Temp. drop without power

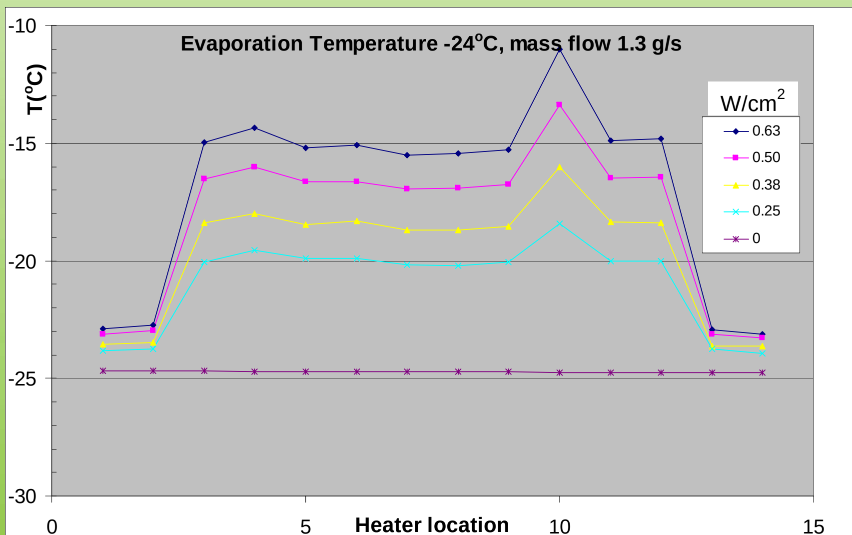


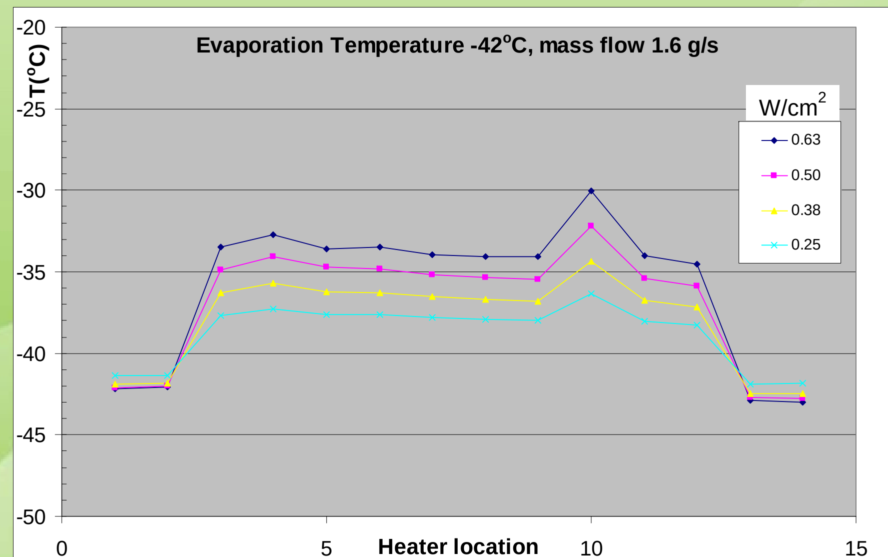


CO2, Temp. Profiles for different Power densities





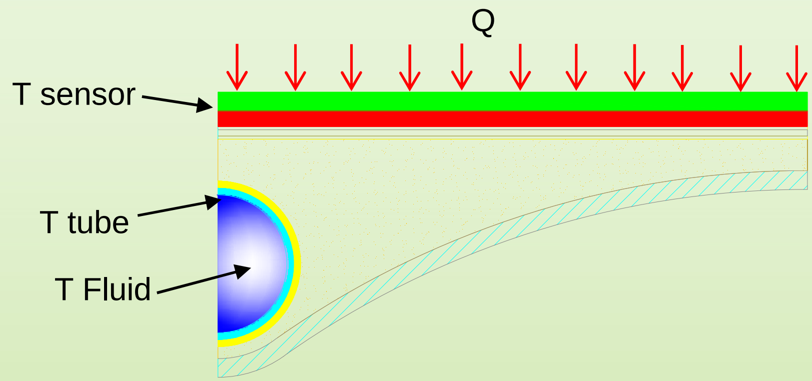


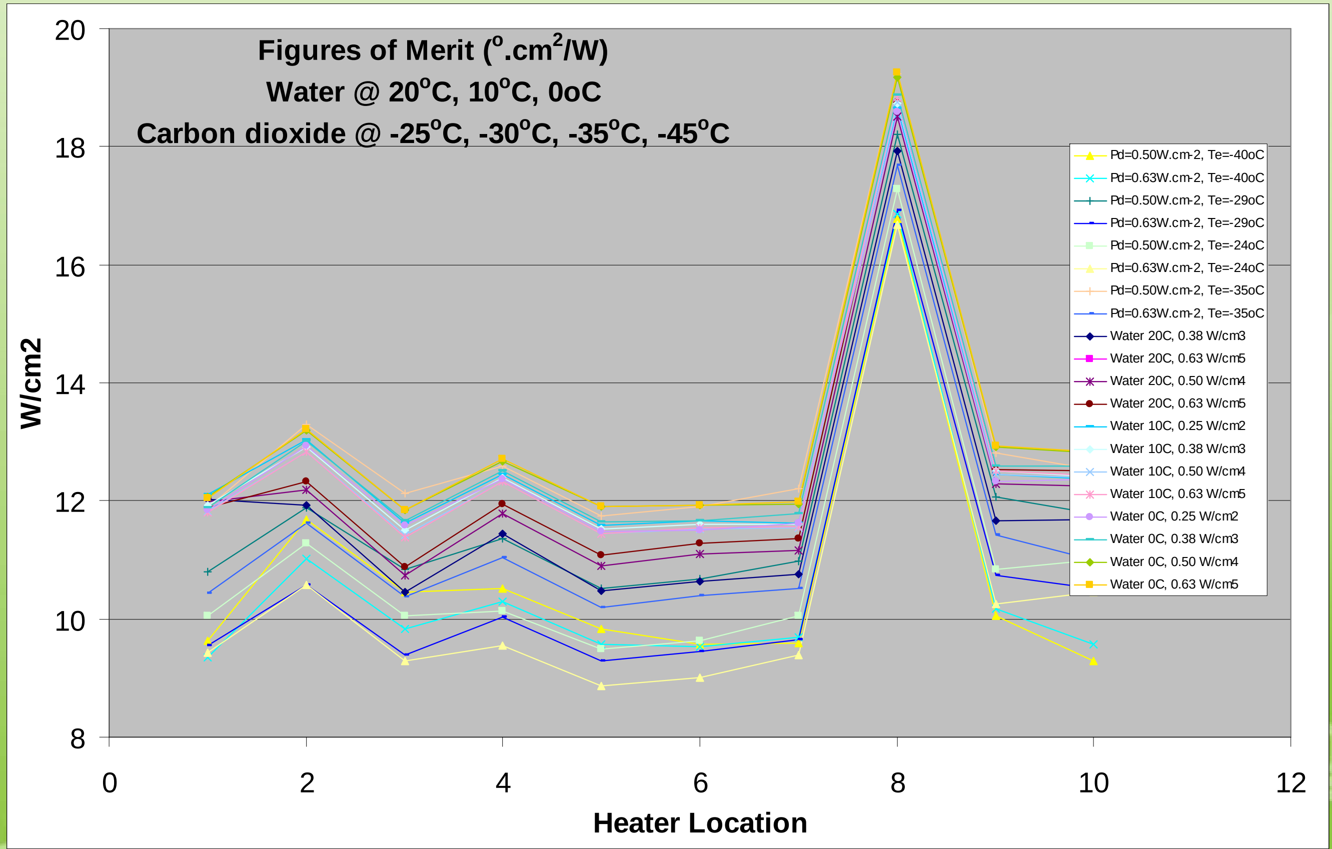


Thermal Impedance

$$FoM = \frac{Tsensor - Ttube}{PowerDensity}$$

$$Ttube = Tfluid + \frac{Q}{h \cdot \pi \cdot D \cdot L}$$

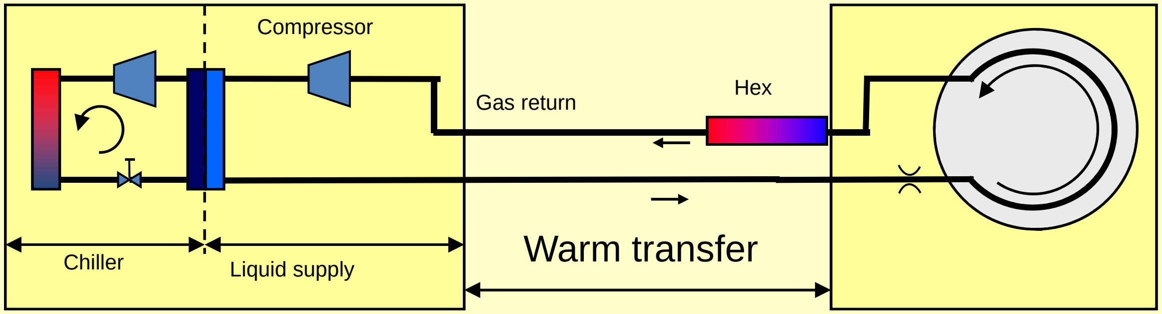




CO2 Closed loop systems

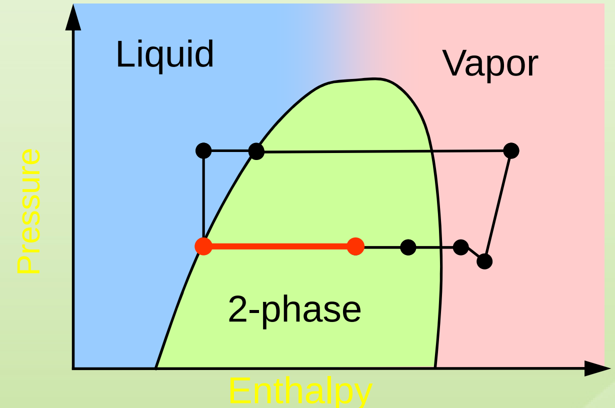
As in CO2 refrigeration industry :

Subritical vapor-compression cycle



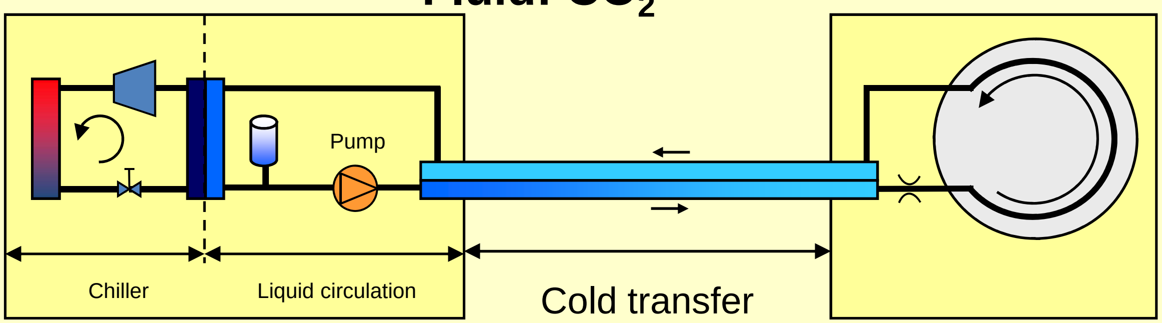
Cooling plant

Detector



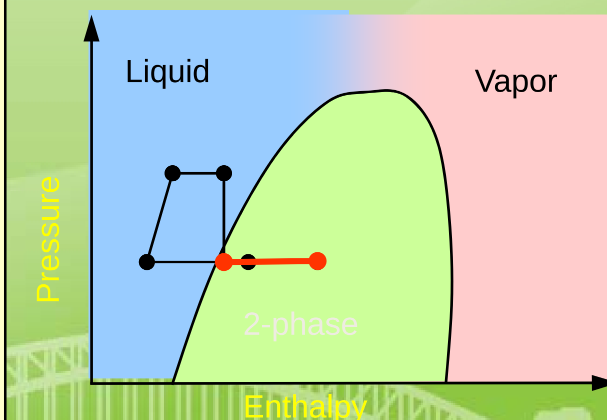
LHCb-VELO: **2PACL pumped liquid system**

Fluid: CO_2



Cooling plant

Detector



Recirculation plant at SLAC (in construction)

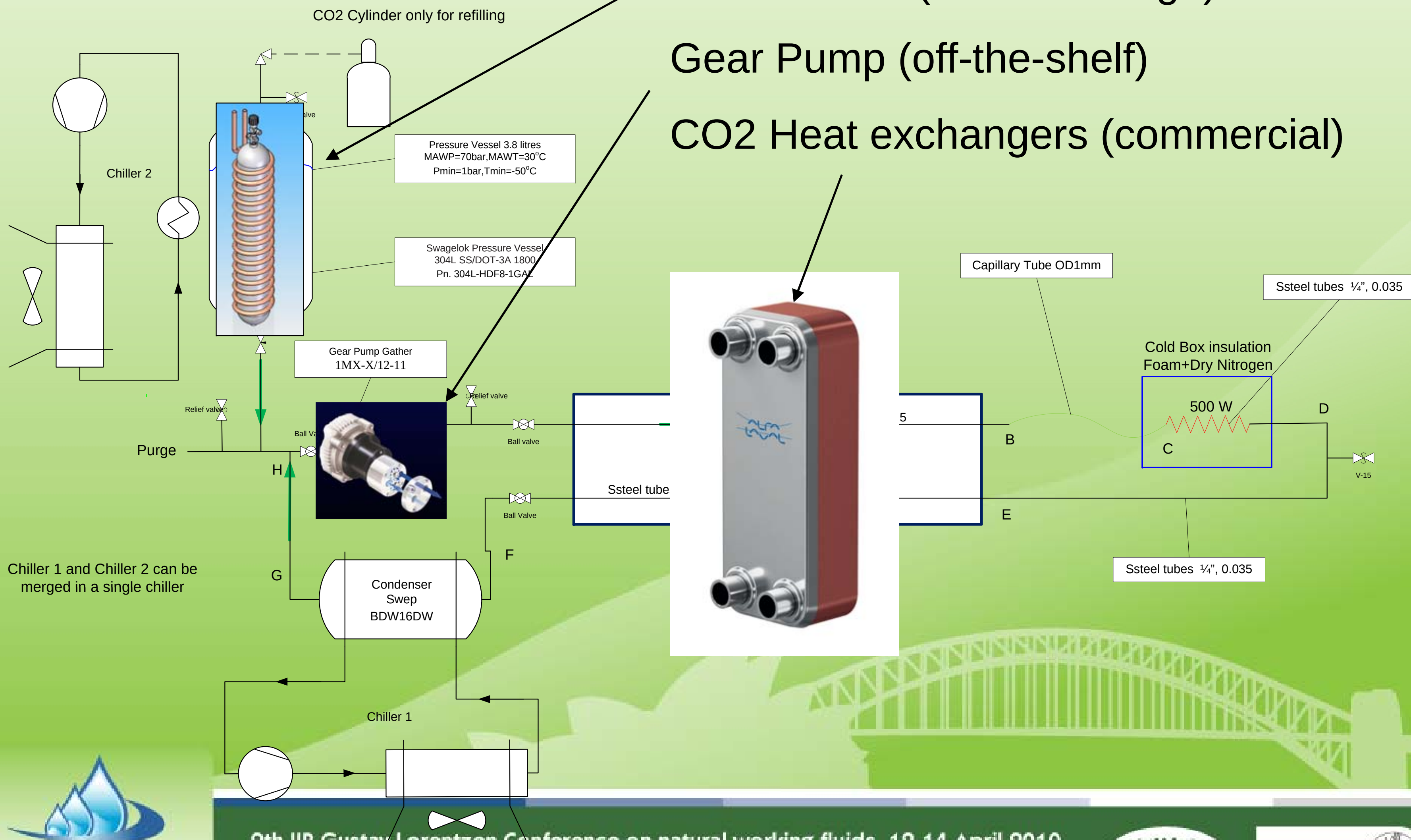
Max Cooling Power
~ 2 kW at -40^{o}C

Critical items :

Accumulator (custom design)

Gear Pump (off-the-shelf)

CO2 Heat exchangers (commercial)



Summary

Evaporative CO_2 addresses many critical issues related to the refrigeration of Particle Detectors in highly irradiated environments, as for the LHC upgrade.

A Blow System is a flexible, cheap and effective way to characterize evaporative CO_2 for small structure

The preliminary results on full scale prototypes show that with evaporative CO_2 it is possible to improve the reliability of the detector operations, with lower temperatures and with lower detector mass.

Recirculation plants with larger refrigeration capacity (~2 kW) and smooth operations are required to continue the R&D phase. Their design and construction is in progress.