Forum on Tracking Detector Mechanics 2016
Bonn, 25 May 2016

Istituto Nazionale
di Fisica Nucleare
Sezione di Milano

LHCb UT Upgrade: studies and test for the detector cooling system design

Simone Coelli (I.N.F.N. MILANO)
For the LHCb UT Group

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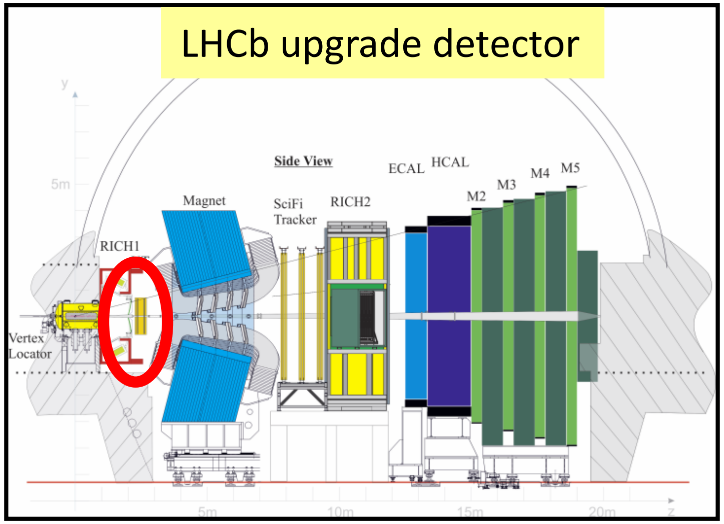
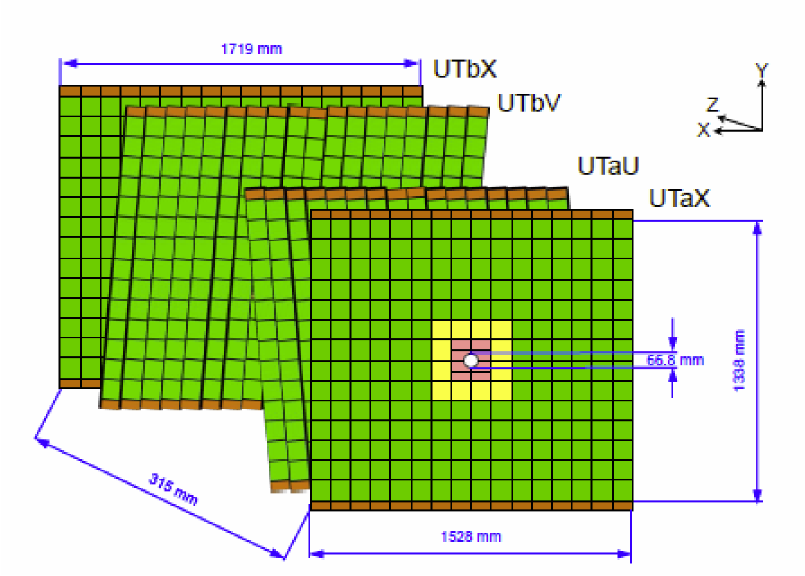
UPSTREAM TRACKER
FOR THE LHCb UPGRADE



UT detector

is the replacement for the present Trigger Tracker (TT)

- **Signals processed at the sensor level**
- **Low sensor temperature**



Geometry

- 4 planar detection layers
- width 1.5 m * heigth 1.3 m

THIS PRESENTATION WILL FOCUS ON THE DETECTOR THERMAL MANAGEMENT

THERMAL REQUIREMENTS

The detector cooling system has to:

- **Extract the thermal power dissipated by read-out chips**
- **Keep the sensor temperature < - 5 °C**

To prevent thermal runaway in presence of radiation damage

- **Keep the temperature difference over the silicon sensors < 5 °C**
- **Keep the ASICs max temperature < 40 °C**

Implementing:

- **CO_2 evaporative cooling system**
- **CO_2 evaporation temperature - 25 °C**
- **local support design and material properties**
- **automatically satisfied with the adopted design and cooling temperature**

Detector total power:

4192 ASICs ~ 0,8 W/each
+ cables + sensors + environment etc.
=> **~ 4 kW to be extracted** + 25 % safety

CO_2 Cooling plant:

- 2-Phase Accumulator Controlled Loop
- Common development with LHCb VELO detector

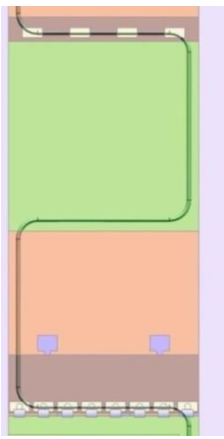
STAVE DESIGN

ASICs read-out chips:

main contribution to the thermal dissipated power

Design concept exploits:

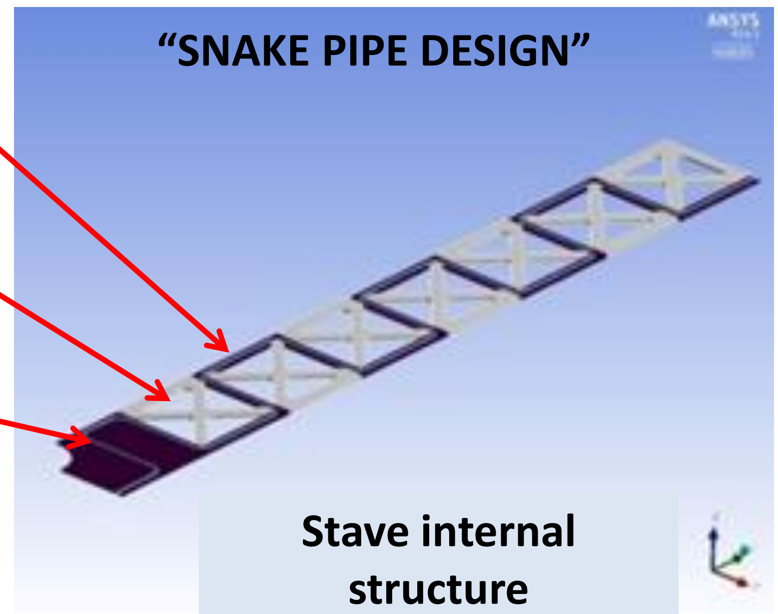
CO_2 evaporating inside a pipe passing underneath the ASICs



Highly conductive carbon foam (black)

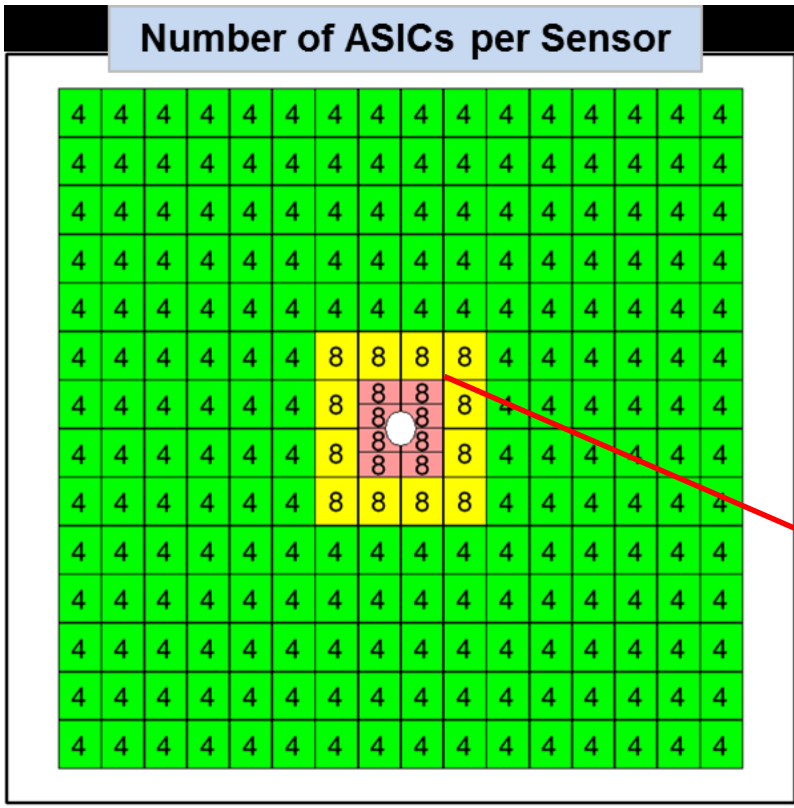
Structural light-weight Core foam (gray)

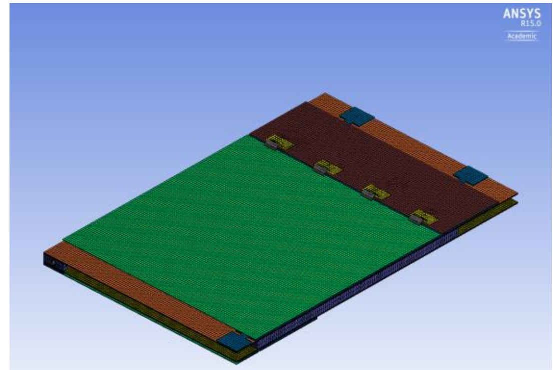
Snake pipe embedded into the carbon foam



COOLING PIPE:
Titanium C.P. 2
I.D. 2 mm
O.D. 2,275 mm

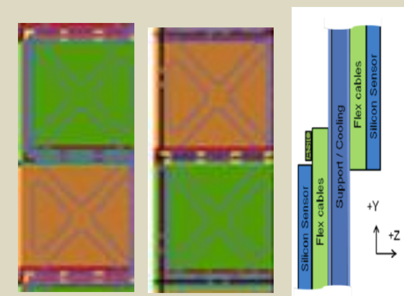
please refer to the Ray Mountain talk at this Forum "Mechanics and Construction of the LHCb Upstream Tracker Detector"

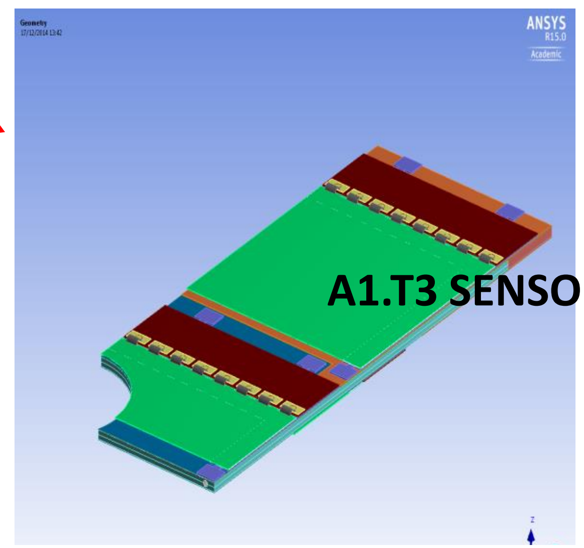




4 ASICs read-out

Sensor mounted on both sides of the stave



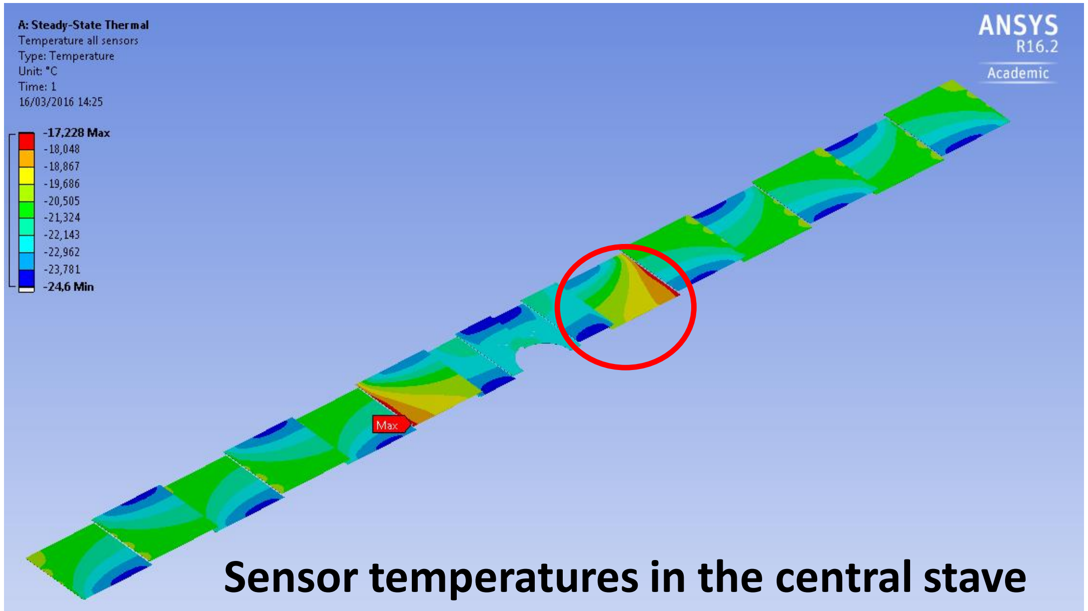


A1.T3 SENSOR

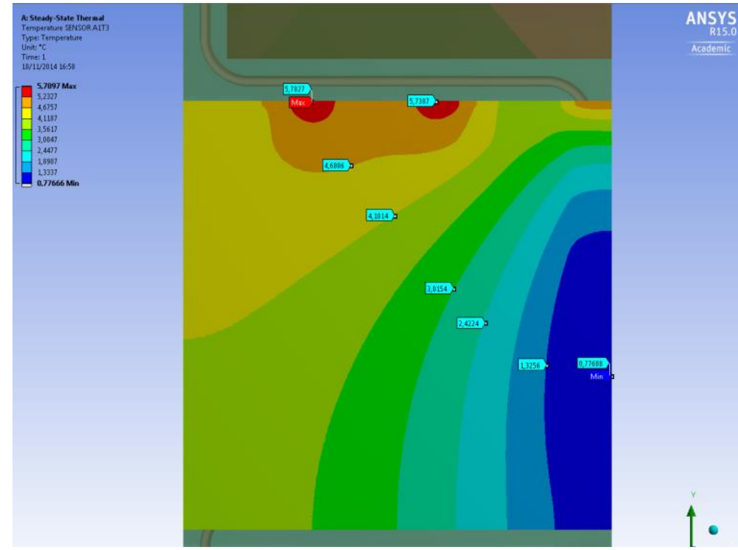
Attached over the power/data bus fcable (in brown)

8 ASICs read-out

CALCULATED THERMAL FIELD



Sensor temperatures in the central stave



A1.T3 Temperature gradient

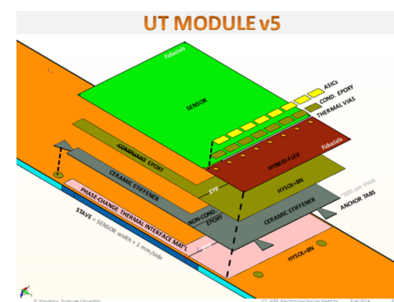
for the more critical sensor A1.T3:

Referring to the cooling pipe temperature

Min ΔT ~ 1 °C

Max ΔT ~ 6 °C

=> TEMPERATURE ESCURSION OVER THE SILICON SENSOR = ΔT ~ 5 °C



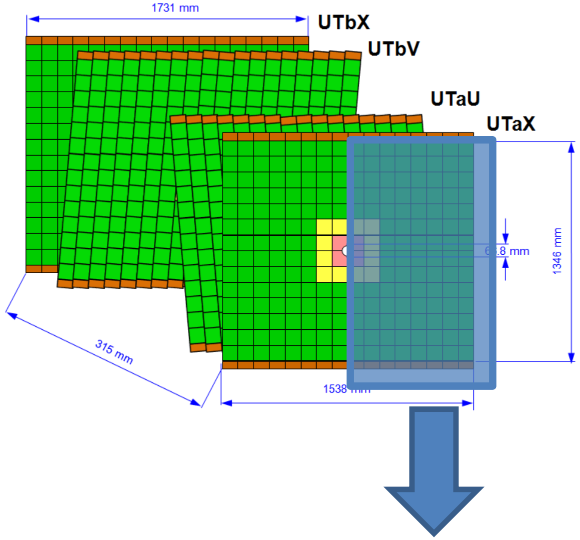
CURRENT LOCAL SUPPORT DESIGN SATISFIES THIS REQUIREMENT

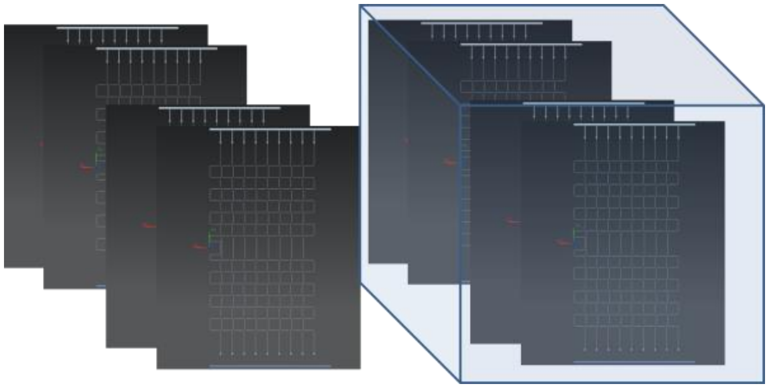
OPTIMIZATION WORK IN PROGRESS

DETECTOR COOLING

UT Detector can be split into two halves.

We can identify 4+4 “half-plane” units - having 8 or 9 parallel staves

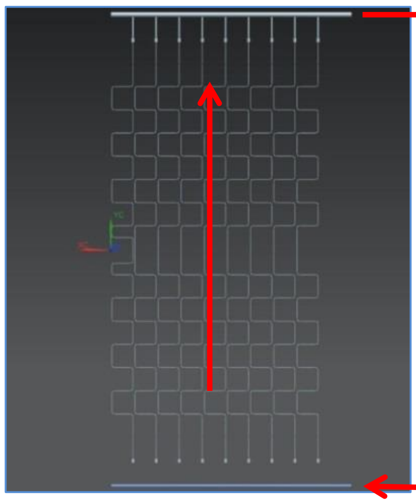




Top manifold

CO_2 upward flow

Bottom manifold



CO_2 exhaust

CO_2 supply

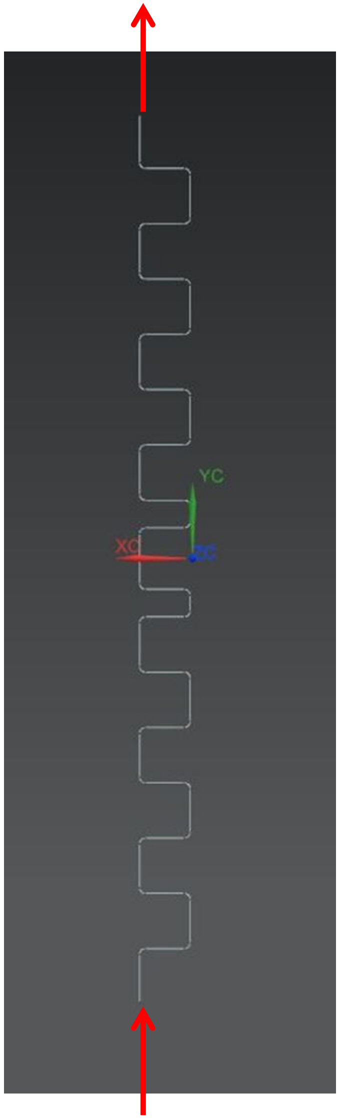
“half-plane” showing <u>only</u> the cooling system

STAVE ENERGY BALANCE

Inlet:
CO_2 liquid near to saturation

Outlet:
Vapour fraction X_{OUT}
30 % design point
50 % max

Γ CO_2



Γ CO_2

MASS FLOW-RATE CALCULATION:
Γ CO_2 = POWER / X_{OUT} *$DH_{LIQ-VAP}$

CENTRAL "C" STAVE
X OUT = 30 % =>
Γ = 75 W / 0,3*280 J/g = ~ 0.9 g/s

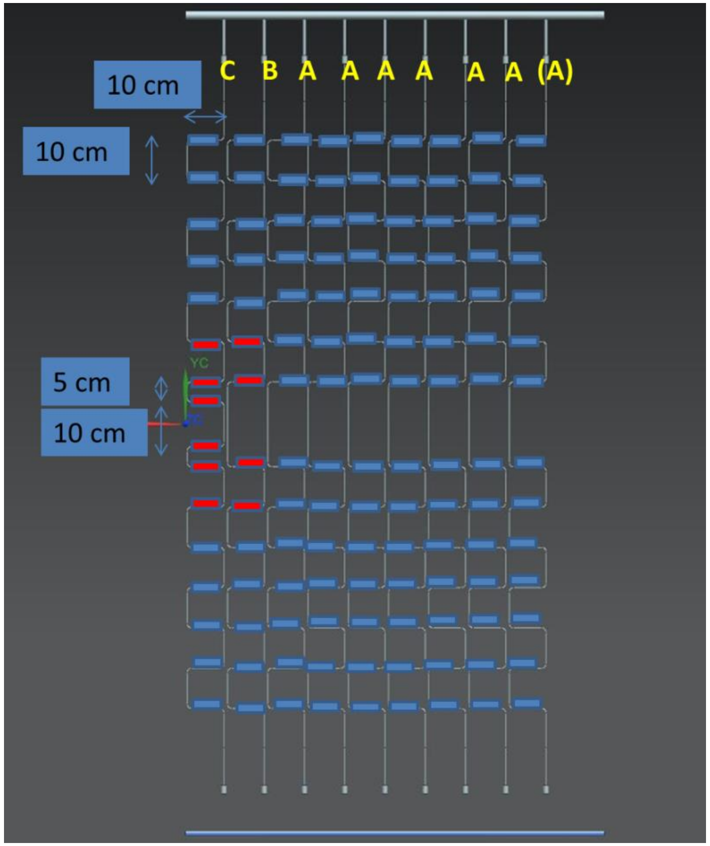
LATERAL "A" STAVE
X OUT = 30 % =>
Γ = 50 W / 0,3*280 J/g= ~ 0.6 g/s

$DH_{LIQ-VAP}$ = enthalpy difference liquid to vapour ~280 kJ/kg
At evaporation temperature of - 25 °C

POWER DISTRIBUTION

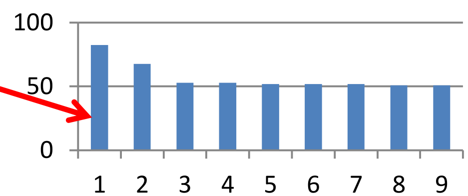
= 4 ASICs

= 8 ASICs



ASICs distribution on a “half-plane”

Central stave



Power (Watt)

Differencies beetwen the evaporators

pipe in the central stave:

- 6% longer
- 4 more 90° bends

thermal load:

- Lateral stave 50 W
- central stave 75 W (50% more)

CO_2 DISTRIBUTION LINES AND MANIFOLDING

STAVE INLET
CO_2 SUPPLY LINES

For stability in evaporating parallel channels
INLET connection lines MUST HAVE A PRESSURE DROP bigger than the evaporation channels pressure drop (e.g. > 5 times)

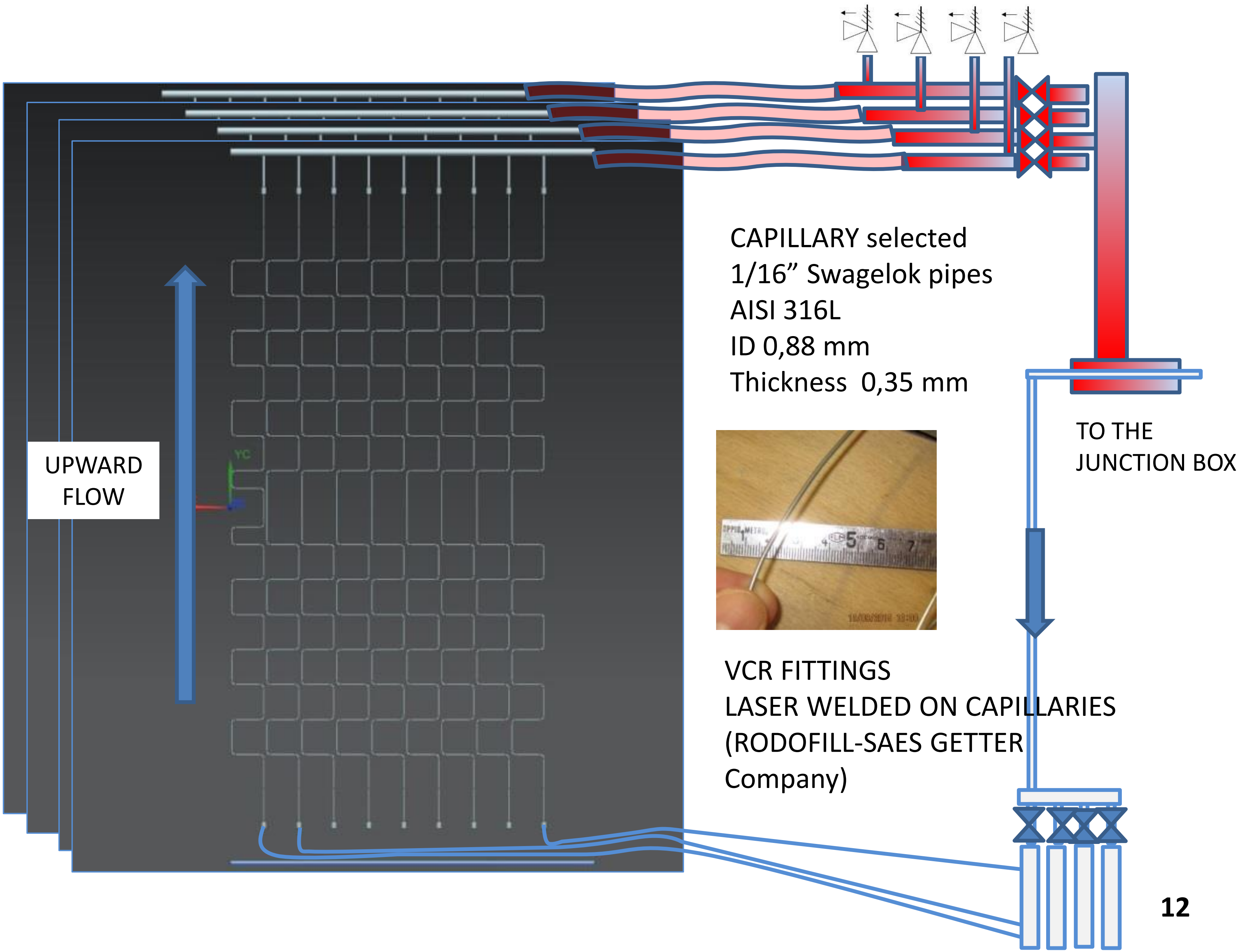
To be obtained using **passive elements.**
Two options investigated:

1. **calibrated orifices:** concentrated pressure drops,
inserted in the stave inlet line

2. **capillaries:** distributed pressure drops,
Coiled between stave and manifold, or running outside the detector box to external manifold

BOTH OPTIONS HAVE BEEN TESTED

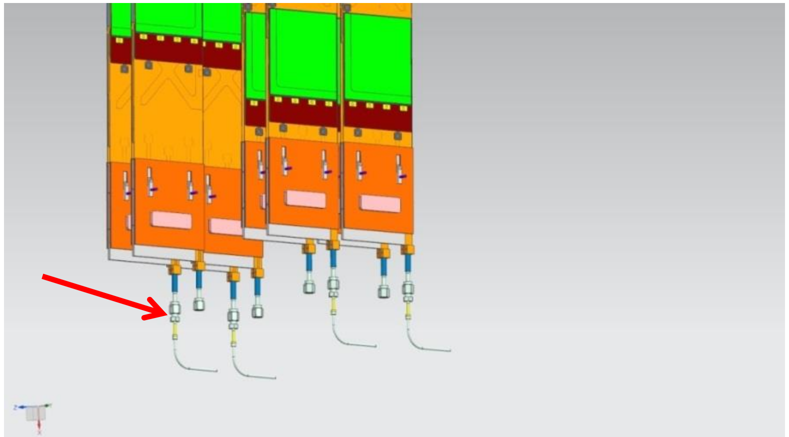
1. CO2 DISTRIBUTION USING CAPILLARIES



CAPILLARY selected
1/16” Swagelok pipes
AISI 316L
ID 0,88 mm
Thickness 0,35 mm

VCR FITTINGS
LASER WELDED ON CAPILLARIES
(RODOFILL-SAES GETTER
Company)

2. DISTRIBUTION IMPLEMENTING CALIBRATED ORIFICES



compact design:
flow restrictor incorporated in the inlet connection line

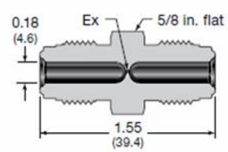
SWAGELOK flow restrictors

Flow Restrictors

This product can be used in liquid or gas delivery systems where repeatable flow reduction or limiting is required.

- One piece, compact design saves space
- Standard orifice sizes drilled through a 1/4 in. male VCR union
- No dead volume for clean operation
- Identification of orifice and heat code marked clearly on the body
- Electropolished, cleaned, and packaged in accordance with Swagelok *Ultrahigh-Purity Process Specification (SC-01)*, MS-06-61
- Working pressure 10 000 psig (689 bar)

Ordering Information and Dimensions



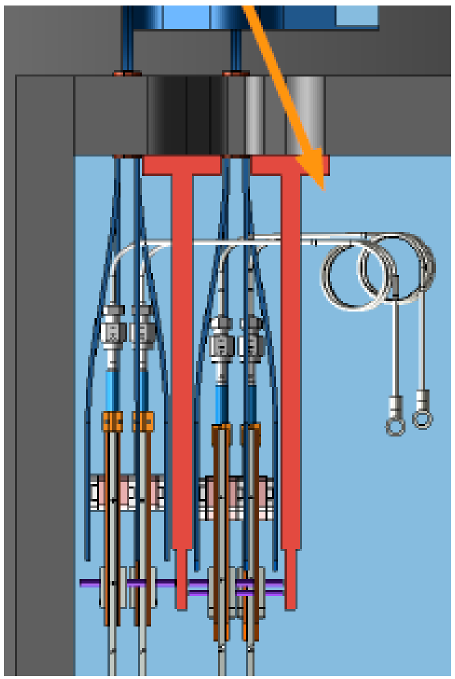
VCR components with fixed threads must remain stationary during normal installation. These fitting connections should be assembled only to glands with rotating female nuts.

Ex, in. (mm)	Ordering Number
0.010 (0.254)	6LV-4-VCR-6-DM-010P
0.012 (0.305)	6LV-4-VCR-6-DM-012P
0.015 (0.381)	6LV-4-VCR-6-DM-015P
0.017 (0.432)	6LV-4-VCR-6-DM-017P
0.020 (0.508)	6LV-4-VCR-6-DM-020P
0.023 (0.584)	6LV-4-VCR-6-DM-023P
0.025 (0.635)	6LV-4-VCR-6-DM-025P
0.026 (0.660)	6LV-4-VCR-6-DM-026P
0.027 (0.686)	6LV-4-VCR-6-DM-027P
0.030 (0.762)	6LV-4-VCR-6-DM-030P
0.035 (0.889)	6LV-4-VCR-6-DM-035P
0.040 (1.016)	6LV-4-VCR-6-DM-040P
0.045 (1.143)	6LV-4-VCR-6-DM-045P

Ex, in. (mm)	Ordering Number
0.050 (1.270)	6LV-4-VCR-6-DM-050P
0.055 (1.397)	6LV-4-VCR-6-DM-055P
0.060 (1.529)	6LV-4-VCR-6-DM-060P
0.065 (1.651)	6LV-4-VCR-6-DM-065P
0.070 (1.778)	6LV-4-VCR-6-DM-070P
0.075 (1.905)	6LV-4-VCR-6-DM-075P
0.080 (2.032)	6LV-4-VCR-6-DM-080P
0.085 (2.159)	6LV-4-VCR-6-DM-085P
0.090 (2.286)	6LV-4-VCR-6-DM-090P
0.093 (2.362)	6LV-4-VCR-6-DM-093P
0.095 (2.413)	6LV-4-VCR-6-DM-095P
0.100 (2.540)	6LV-4-VCR-6-DM-100P

STAVE OUTLET
CO_2 EXHAUST LINES

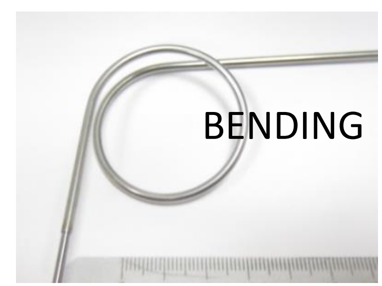
For stability in evaporating parallel channels
OUTLET connection lines MUST HAVE MINIMUM PRESSURE DROP



- AISI 316L PIPE
- **ID 2.0 mm = the same as Titanium cooling pipe NO RESTRICTION**
- OD 2.5 mm = minimum available thickness (P_{design} = 100 bar)

To increase the elasticity of the connections
=> COILING

VCR FITTINGS LASER WELDED ON PIPE (RODOFILL-SAES GETTER Company)

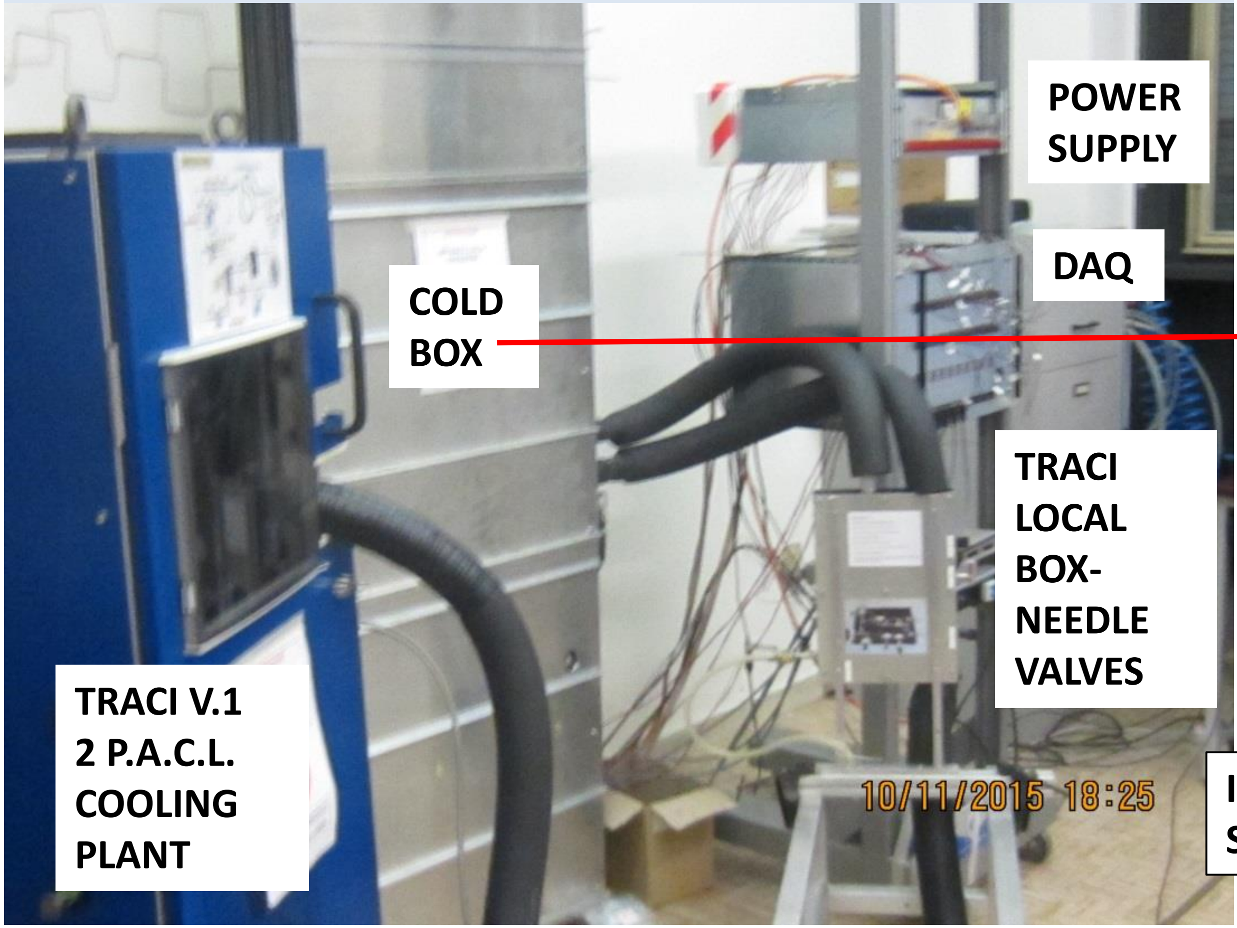


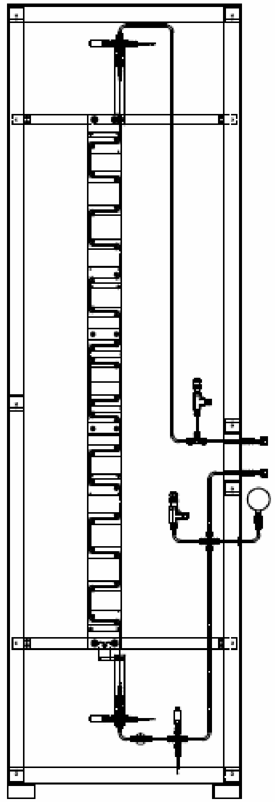
CO_2 COOLING TEST

CO_2 BOILING IN
- VERTICAL
- «SNAKE» PIPE
- 2 mm I.D.

THERMO-HYDRAULIC CHARACTERIZATION OF
- STAVE
- DETECTOR COMPONENTS PROPOSED FOR THE DESIGN

COOLING TEST SET-UP IN MILANO

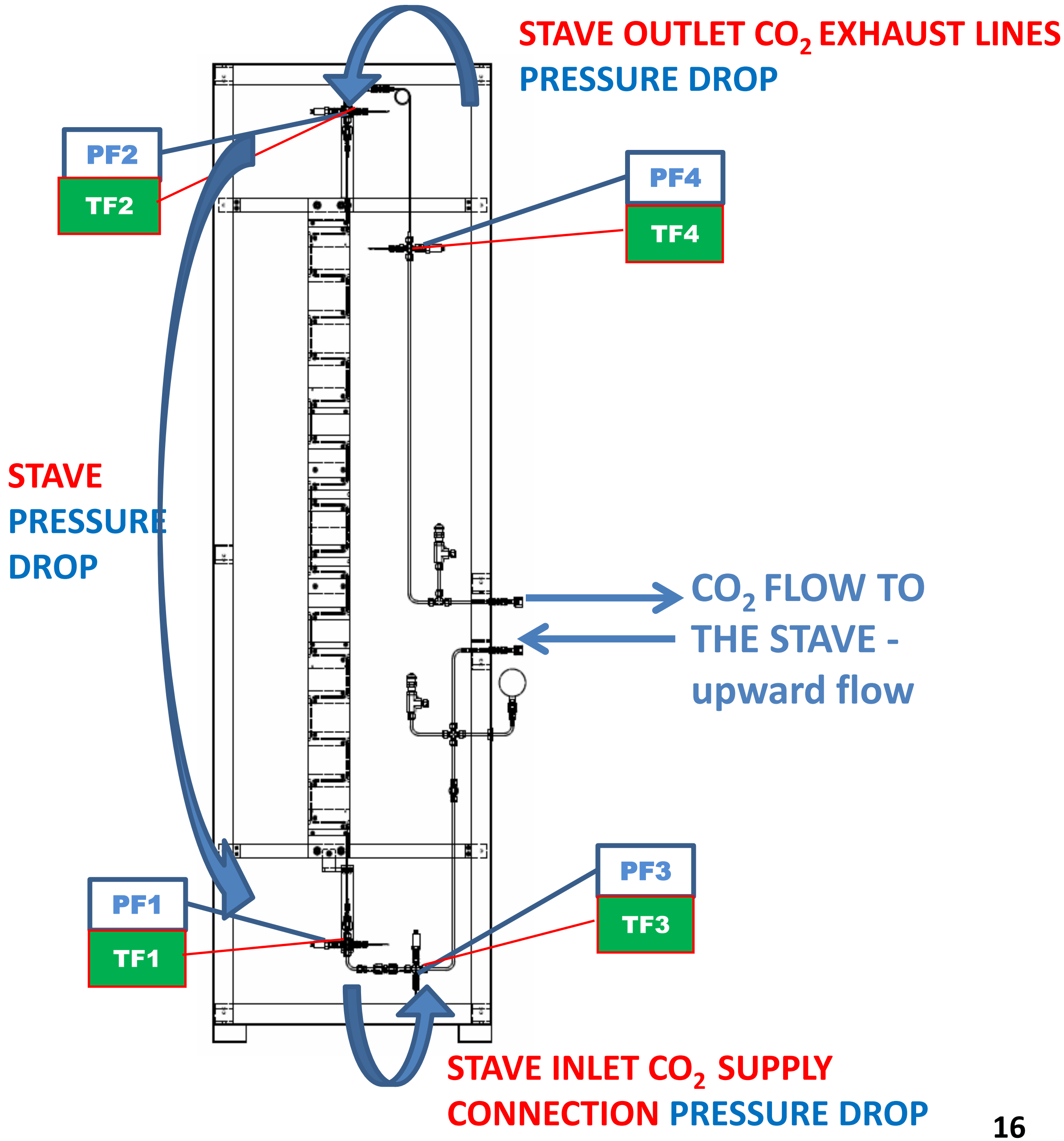




CO_2 MEASUREMENT POINTS

Fluid pressure trasmitters
Piezo-resistive Keller 21Y
Output 4-20 mA; 0-80 bar_A

Fluid temperature trasmitters
PT100-4wires Rodax
OD 4mm length 80 mm

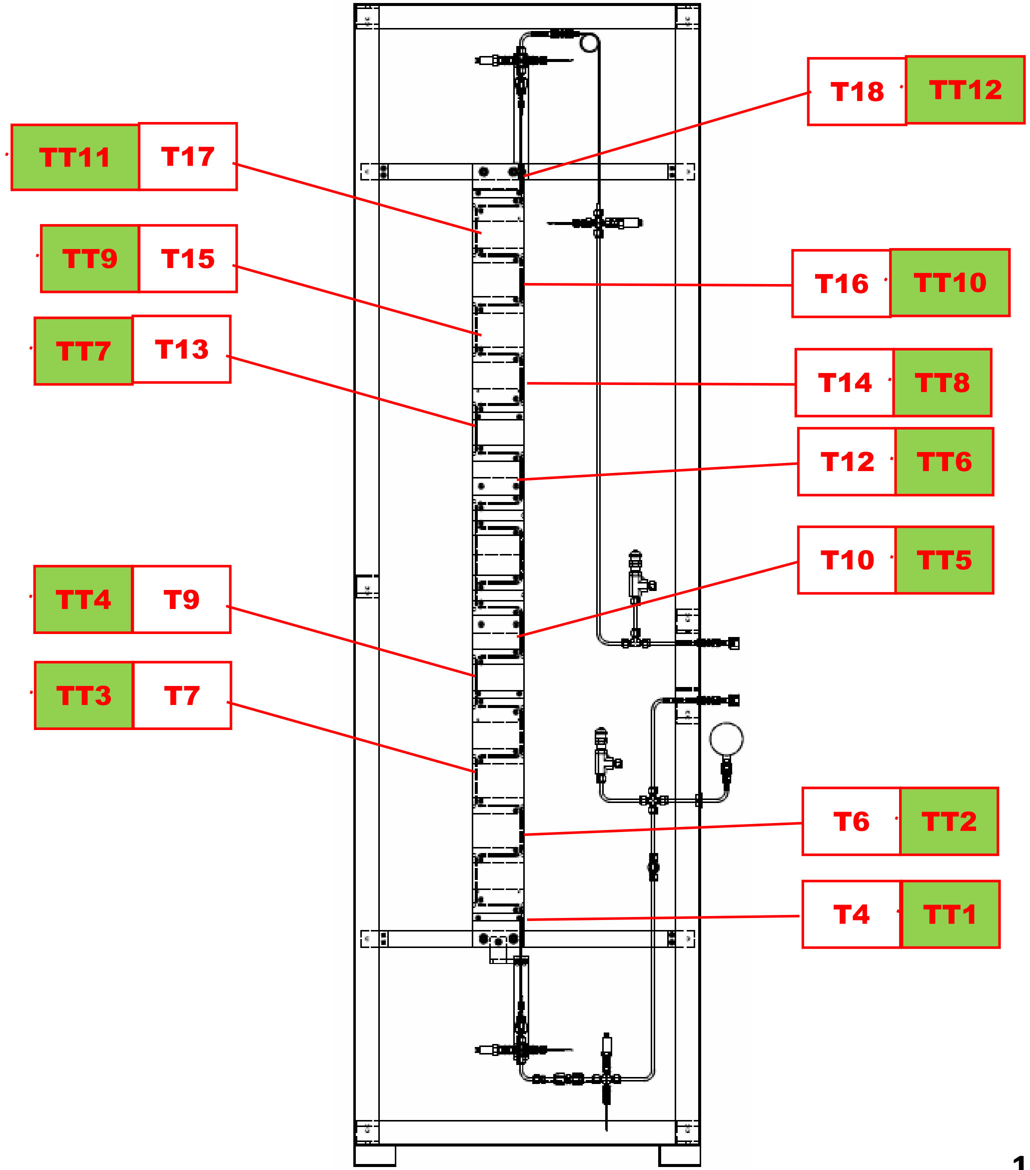


TEMPERATURE SENSORS
ALONG THE COOLING CIRCUIT

20 “T” type Thermo-couples along the cooling pipe circuit

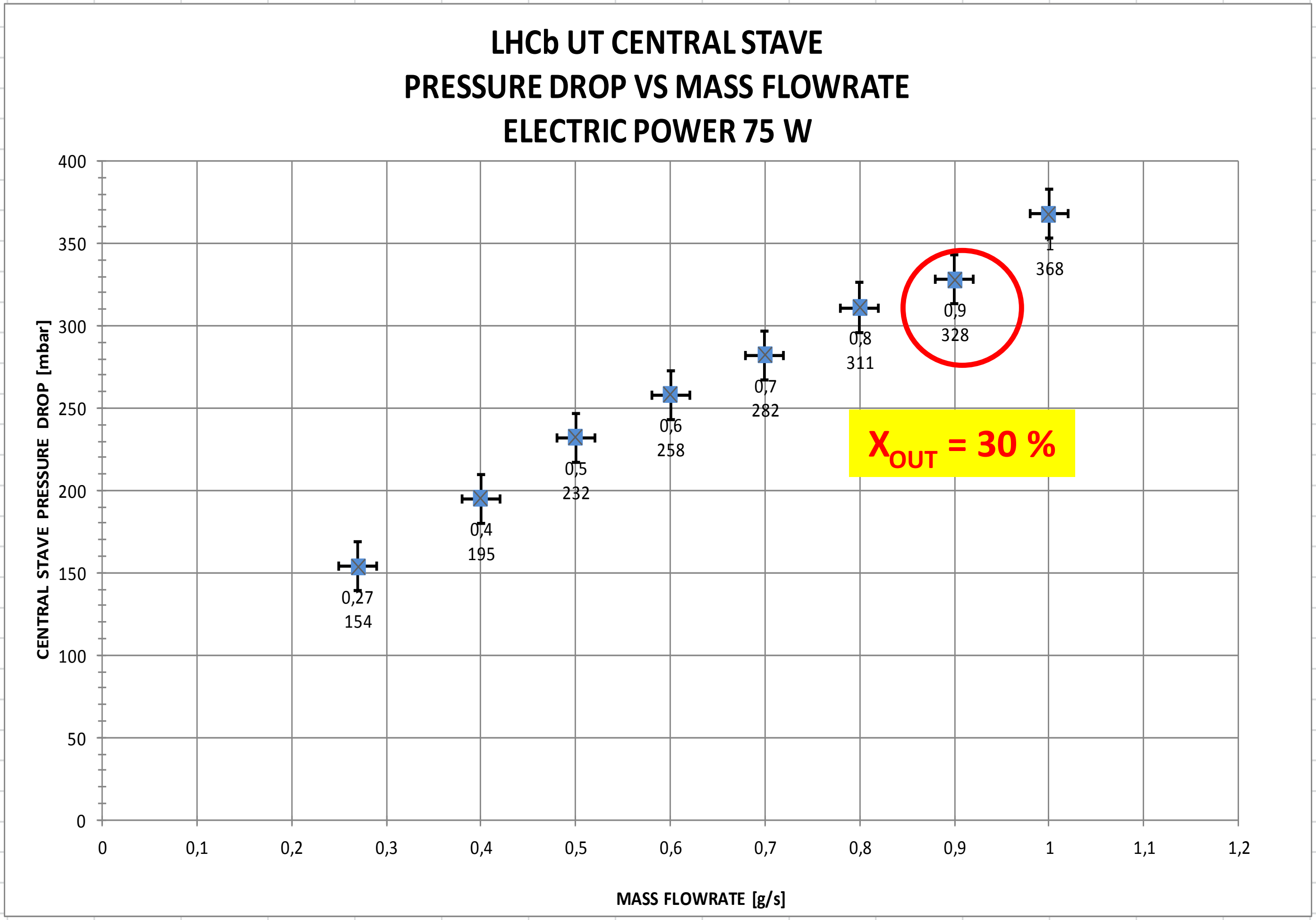
12 PT100-4wires

Glued on the external pipe wall using thermal paste K= 5 W/mK



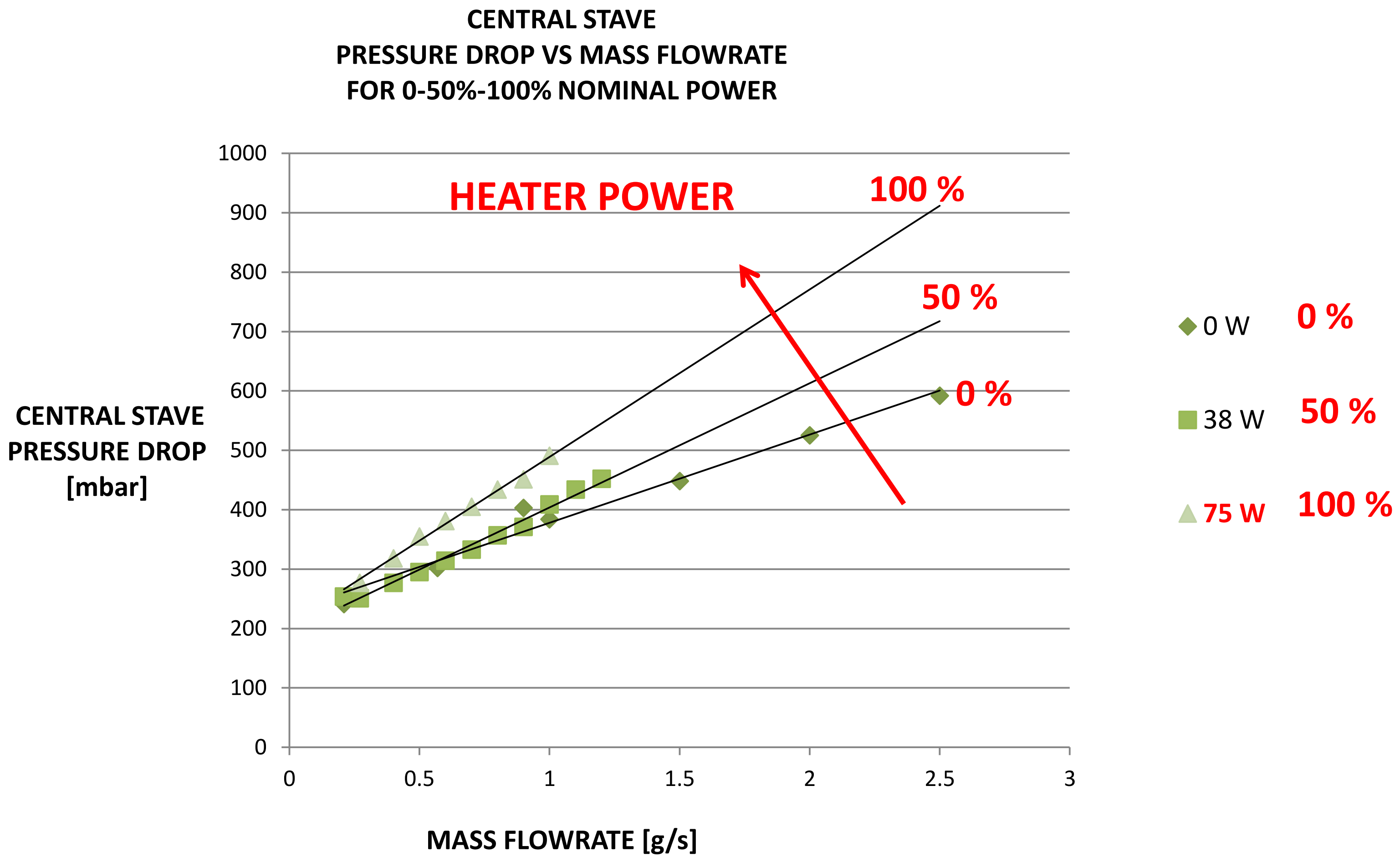
STAVE PRESSURE DROP VS MASS FLOW-RATE AT NOMINAL POWER

THERMO-HYDRAULIC CHARACTERIZATION OF THE CENTRAL STAVE



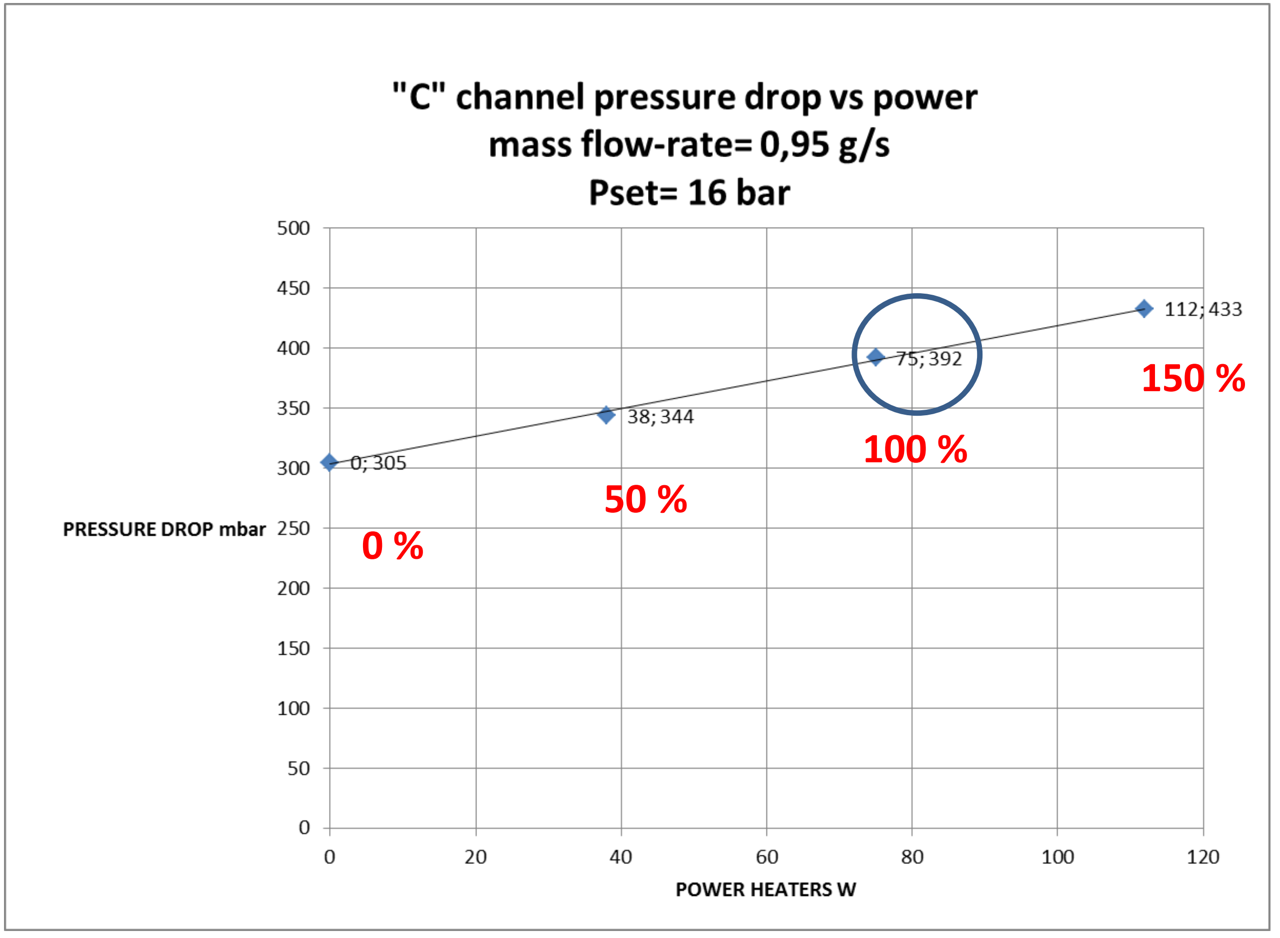
CENTRAL STAVE
FLOW-RATE FOR 30% Xout = 0.9 g/s
=> 0.33 bar STAVE PRESSURE DROP

STAVE PRESSURE DROP VS MASS FLOW-RATE AT SEVERAL POWER LOADS



WITHIN MEASUREMENT ERRORS
THE DATA CONFIRM THE EXPECTED BEHAVIOUR

STAVE PRESSURE DROP VS POWER
FOR A FIXED MASS FLOW-RATE

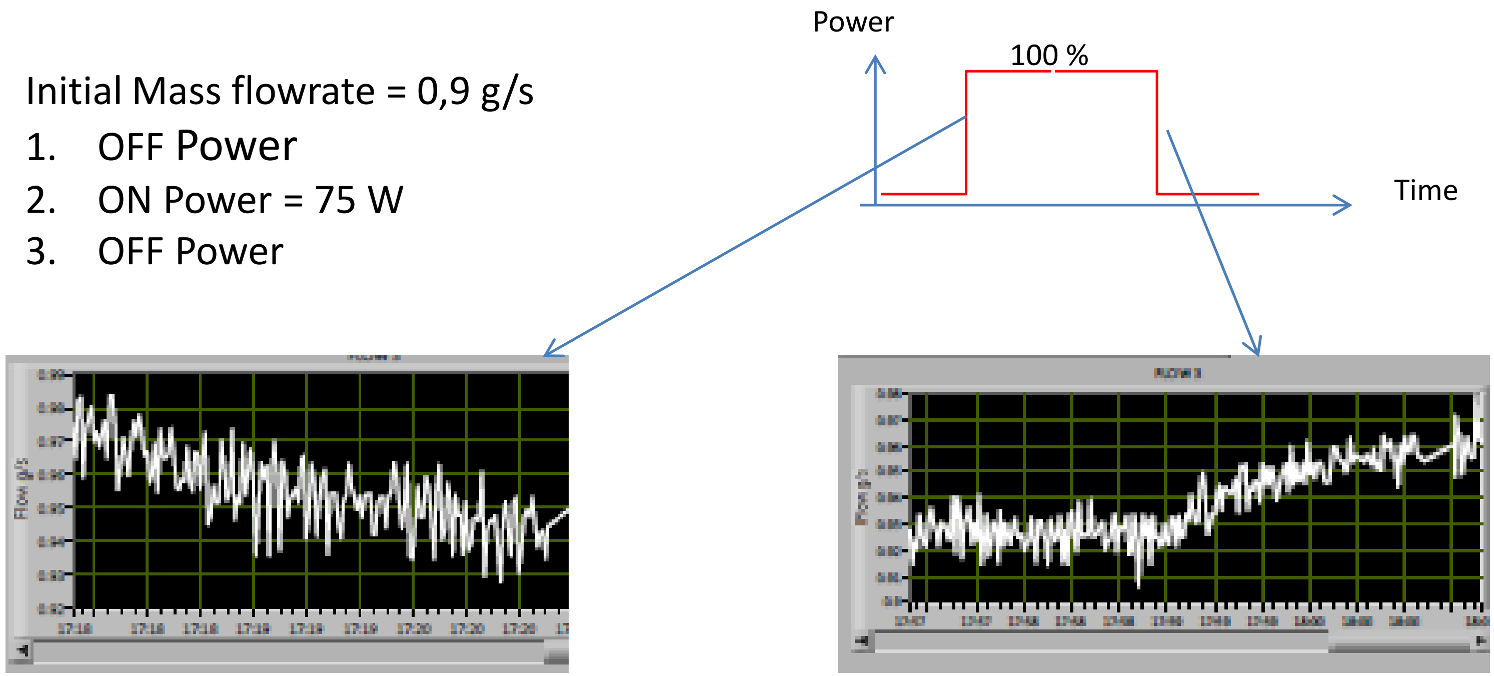


COOLING SYSTEM OPERATES INSIDE A STABLE OPERATIVE REGION AND CAN ACCEPT 50 % EXTRA LOAD

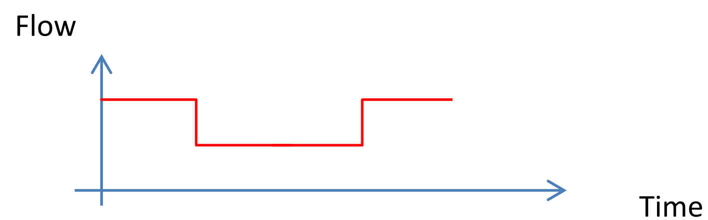
POWERING TRANSIENT
AT NOMINAL FLOW-RATE

Initial Mass flowrate = 0,9 g/s

1. OFF Power
2. ON Power = 75 W
3. OFF Power



when power is switched on the
Flow-rate decreases from ~0,9 to ~0,8 g/s



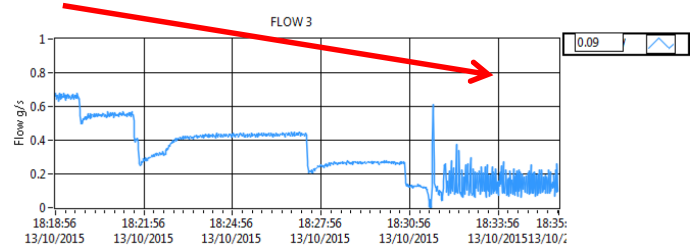
Stave pressure drop increase due to evaporation

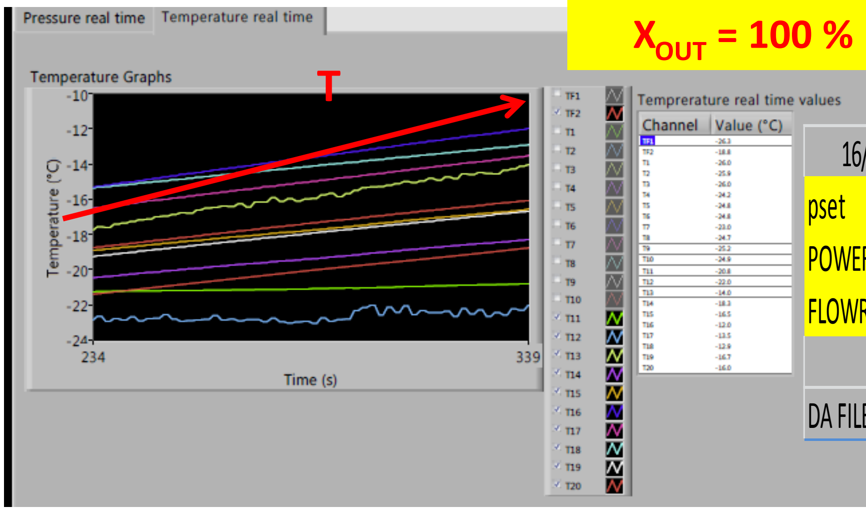
Vice-versa the flow come back to initial value when the power is switched off

DRY-OUT STUDY

TO VERIFY THE ENERGY BALANCE CALCULATION: GOING DOWN TO A SUFFICIENT LOW FLOW-RATE WE REACH THE NON DESIDERABLE DRY-OUT REGION

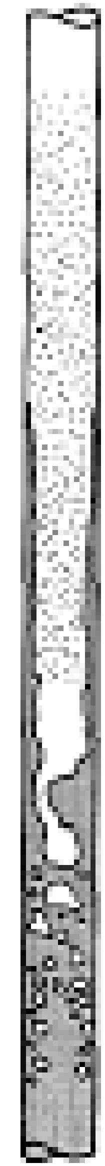
COOLING MASS FLOW-RATE





X_{OUT} = 100 %

16/09/2015	
pset	15 bar
POWER	75 W
FLOWRATE	0,27 g/s
DA FILE:	2015-09-16-Pset15bar-75W-F027GS-t.txt



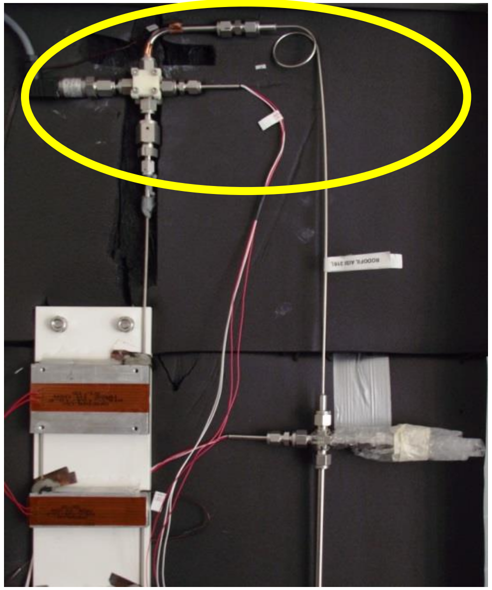
OSCILLATING TEMP. ARE OBSERVED AT A CERTAIN POINT IN THE STAVE (PIPE WETTED AND DRYED NEAR THE DRY-OUT REGION)

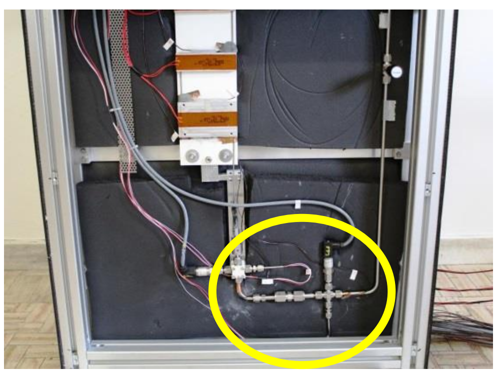
FROM THIS POINT CO_2 VAPOUR TEMPERATURE INCREASES IN TIME

EXPERIMENT IS THEN STOPPED BECAUSE THIS IS NOT A SUSTAINABLE OPERATIVE SITUATION IN THE LONG TERM

FLOW RESTRICTOR MEASUREMENT

OUTLET CONNECTION:
I.D. 2 mm PIPE COILED 1 LOOP





INLET CONNECTION:
SWAGELOK ORIFICE
0,01 INCH = 0,25 mm I.D.

DATE	2016-04-19
STAVE	“C”
FLOW DIRECTION	UPWARD
INSULATION	ARMAFLEX
STAVE INLET	RESTRICTOR 0,254 mm
STEADY-STATE	OK
TRACI P SET POINT	17 bar_A
SATURATION TEMP	-23°C
HEATER POWER	75 W “nominal”
MASS FLOW-RATE	0,84 g/s (*TRACI V.1 LIMIT*)
CALCULATED X out	32 %

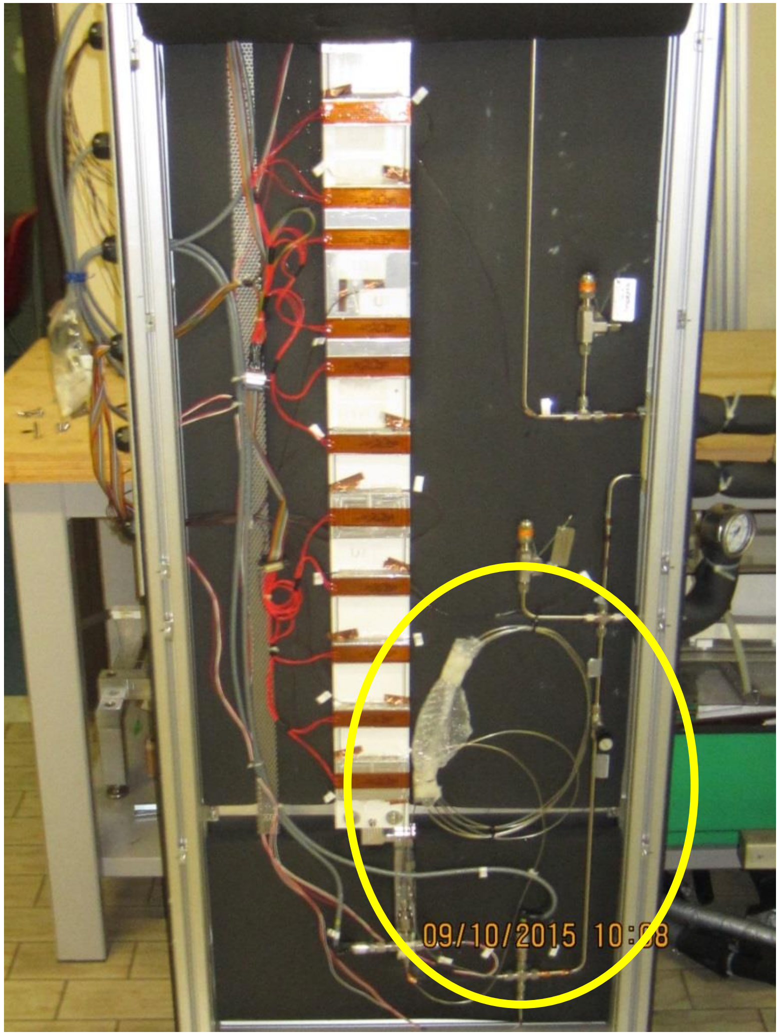
PRESSURE DROP	bar
INLET LINE WITH ORIFICE	2,875
EVAPORATOR (STAVE)	0,314
OUTLET LINE	0,034

RATIO 1:10

RATIO 1:10

THE MEASURED RATIO BETWEEN THE DP OF THE CIRCUIT COMPONENTS SHOULD GUARANTEE THE STABILITY IN THE EVAPORATING PARALLEL CHANNELS

CAPILLARY MEASUREMENT



DATE	2015-10-09
STAVE	"C"
FLOW DIRECTION	UPWARD
INSULATION	ARMAFLEX
STAVE INLET	CAPILLARY 1/16"
STEADY-STATE	OK
TRACI P SET POINT	16 bar_A
SATURATION TEMP	-28°C
HEATER POWER	75 W "nominal"

CAPILLARY LENGTH = 6 m
PRESSURE DROP AT 0,45 g/s ~ 3 bar

CAPILLARY LENGTH = 1 m
PRESSURE DROP AT 0,84 g/s ~ 1.6 bar

Darcy–Weisbach equation
works fine for the liquid phase into the capillary:

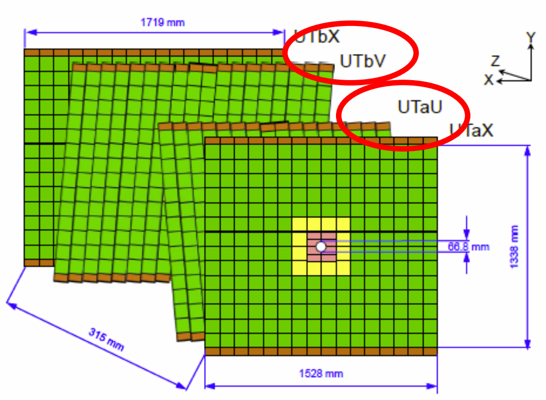
$$h_f = f \cdot \frac{L}{D} \cdot \frac{V^2}{2g}$$

INLET CONNECTION:
CAPILLARY SWAGELOK PIPE
1/16 INCH = 0.88 mm ID

CAPILLARY PRESSURE DROP IS PROPORTIONAL TO THE CAPILLARY LENGTH
3 bar CAN BE OBTAINED USING A 2 m LONG 1/16 INCH

INCLINED STAVE OPERATION

TO VERIFY THE OPERATION OF THE COOLING SYSTEM IN THE REAL GEOMETRY CONFIGURATION FOR THE UT PLANES UTbV AND UTaU



+ 5° C.W.

- 5° C.W.

TEMPERATURES AND PRESSURES ~ CONSTANT IN TIME AFTER THE STAVE MOVEMENT
THE SYSTEM COMES BACK TO THE SAME STEADY-STATE OPERATION

THE STAVE COOLING SYSTEM IS NOT AFFECTED BY THE - 5° TO + 5° DISPLACEMENT FROM THE VERTICAL POSITION

NEXT TEST PLANNED

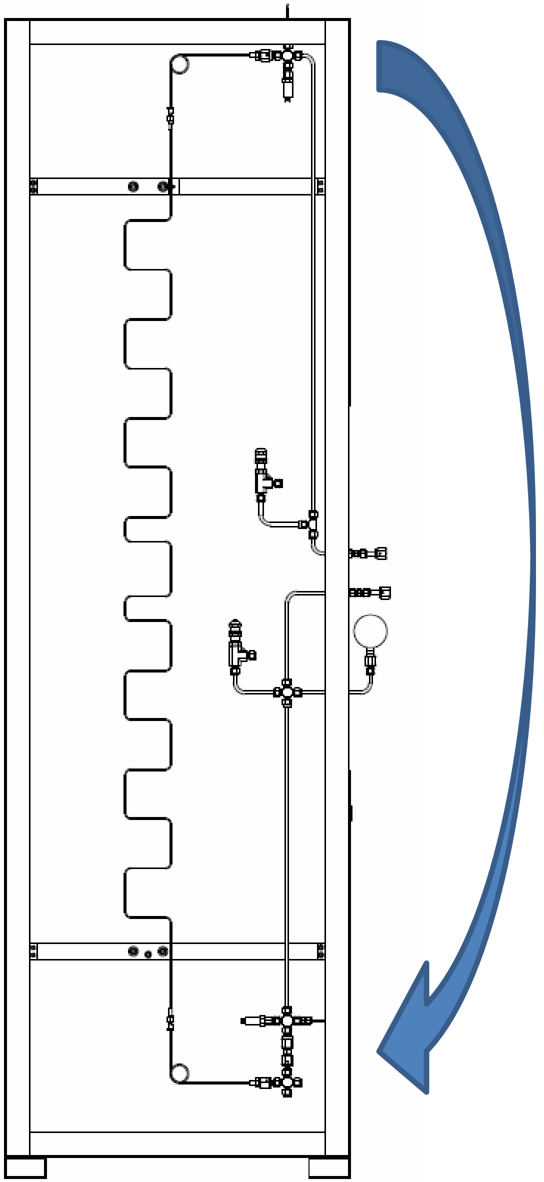
COMPARISON OF STAVE A/B/C

- ID 2 mm pipe with 1 coil mounted both at the inlet and the outlet
- calibrated orifice at the inlet
- Characterization of the stave circuit between the manifolds
- for the three different stave «flavours» A/B/C

TEST WITH DOWNWARD FLOW

BOX INSULATION

- Make the cooling test without Armaflex insulation
- controlled humidity cold box
- fluxed with dry air
- More similar to the detector box



CONCLUSIONS

From the thermal management point of view:

- **The design and test of all cooling related components of the UT detector is well advanced, in particular the manifold and distribution system**

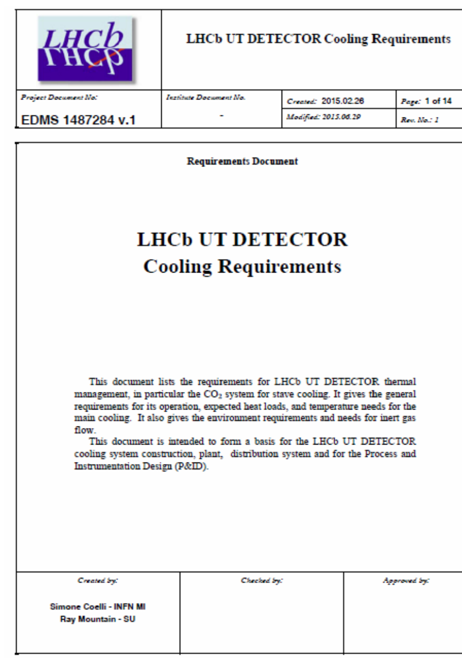
- **The correct operation of the CO_2 cooling system for a single stave with a snake pipe has been demonstrated by measurement and simulation**

We had these Engineering Design Reviews:

- **«Stave construction EDR», CERN, 19 June 2015**

- **«LHCb CO2 cooling EDR», CERN, 3 December 2015**

The **«LHCb UT Detector Cooling requirements»** document has been released.



LHCb	LHCb UT DETECTOR Cooling Requirements		
Project Document No: EDMS 1487284 v.1	Institute Document No. -	Created: 2015.02.26 / Modified: 2015.06.29	Page: 1 of 14 / Rev. No.: 1

Requirements Document

LHCb UT DETECTOR
Cooling Requirements

This document lists the requirements for LHCb UT DETECTOR thermal management, in particular the CO_2 system for stave cooling. It gives the general requirements for its operation, expected heat loads, and temperature needs for the main cooling. It also gives the environment requirements and needs for inert gas flow.

This document is intended to form a basis for the LHCb UT DETECTOR cooling system construction, plant, distribution system and for the Process and Instrumentation Design (P&ID).

Created by:	Checked by:	Approved by:
Simone Coelli - INFN MI Ray Mountain - SU		

IDEAS OR DREAMS

C.F.D.
COMPUTATIONAL FLUID-DYNAMIC STUDIES USING FLUENT
.. FOR TWO-PHASE EVAPORATING CO_2

FILM THE BUBBLES
LOOK INTO THE EXHAUST LINE WITH A VIDEO-CAMERA
..TO LOOK FOR VAPOUR FRACTION EXTIMATION

MICROPHONE FOR THE BUBBLES
USE THE PIEZO-RESISTIVE PRESSURE TRASMITTERS AS “BUBBLES-METERS”
..NEED A DIFFERENT ACQUISITION SYSTEM

R&D
STUDENTS FROM POLITECNICO DI MILANO FOR MORE GENERAL CO_2 STUDIES
..COULD BE IMPLEMENTED IN SIMULATION CODE LIKE COBRA

CONTRIBUTIONS

Colleagues from the INFN Milano Design & Mechanical Dpt.
Carlo Gesmundo (lines design..)
Andrea Capsoni (cooling system)
Mauro Monti (FEAs and design)
Ennio Viscione (system construction)

For the Power and DAQ system, Labview software:
Mauro Citterio
Alessandro Andreani
Fabrizio Sabatini
Andrea Merli

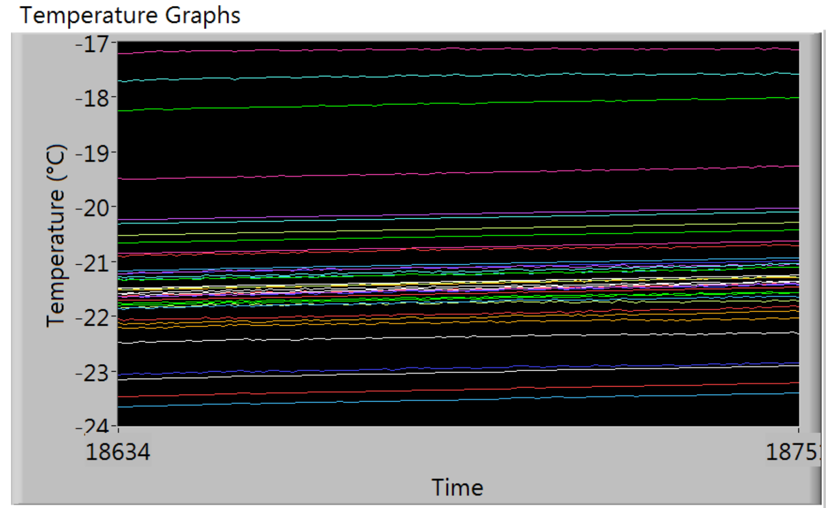
I'd like to aknowledge the CERN EP-DT cooling team
and colleagues from other institutes in the LHCb Collaboration.

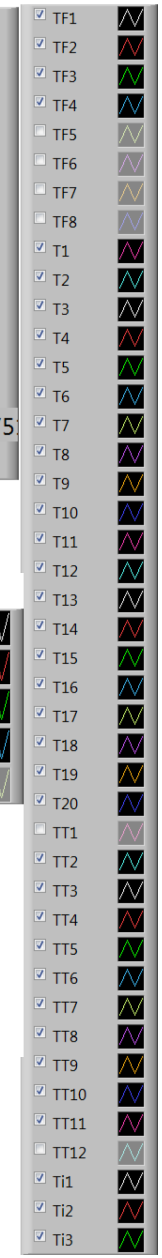
THANKS FOR THE ATTENTION.

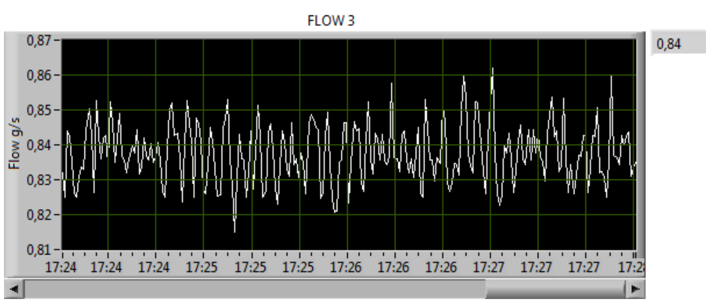
BACK-UP SLIDES =>

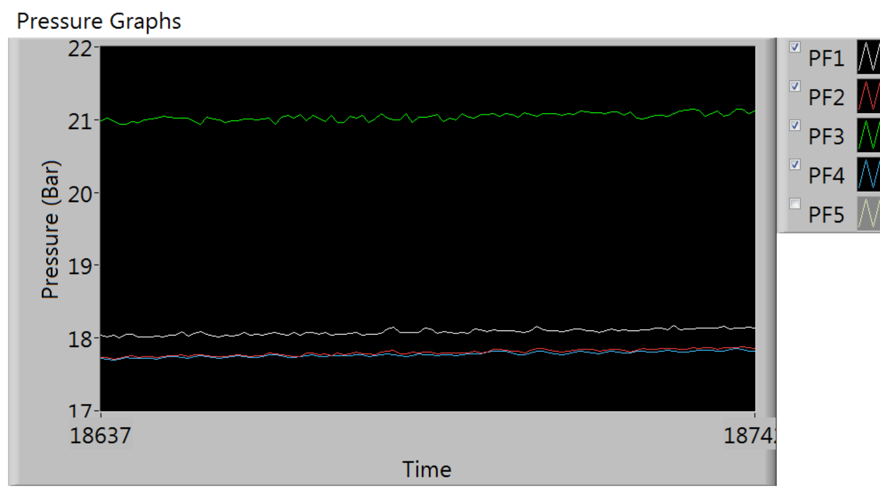
UT detector CO2 Cooling Test Results

DATE	**2016-04-19**
STAVE	**“C”**
FLOW DIRECTION	**UPWARD**
INSULATION	**ARMAFLEX**
STAVE INLET	**RESTRICTOR 0,254 mm**
STEADY-STATE	**OK**
TRACI P SET POINT	**17 bar_A**
SATURATION TEMP	**-23°C**
HEATER POWER	**75 W “nominal”**
MASS FLOW-RATE	**0,84 g/s (~ nominal)**









channel delta p	0,314		
orifice delta p		2,875	
outlet delta p			0,034

2019-04-19-P17BAR-75W-084GS-PT

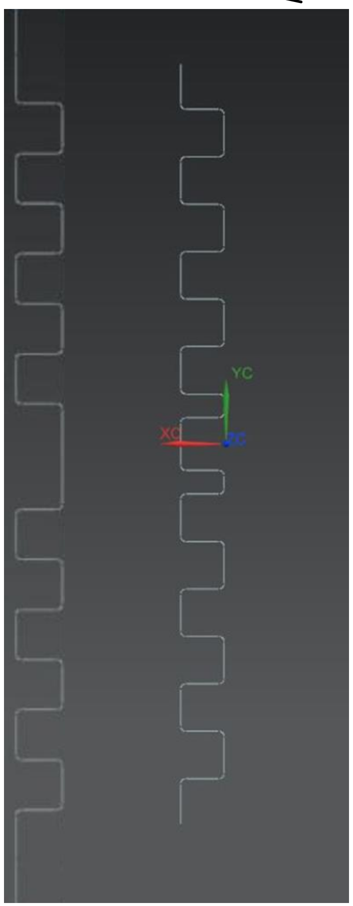
SNAKE COOLING PIPE DETAILS

There are 2 cooling pipe geometries:

Number: 60 staves

A,B type

Pipe Length 2,82 m
Heated length = 14 * ~85 mm = 1,19 m



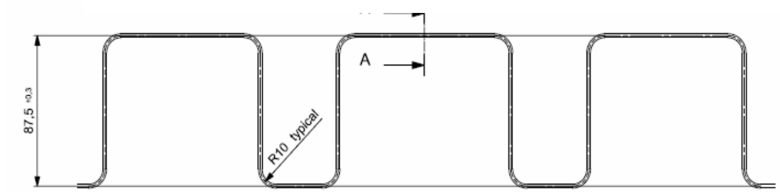
Number: 8 central staves

C type, it is required to have 2 more passages under 2 ASICs rows

Pipe Length 3 m
Heated length = 16 * ~85 mm = 1,36 m

Titanium C.P. 2 from HIGH-TECH U.K. Company
I.D. 2,025 mm
O.D. 2,275 mm

cooling snake pipe produced starting from a 3 .1 m long straight pipe annealed ¼ hard.
Bending radius R= 10 mm



REF. UNI EN 22768/1 CLASS m

3) TOTAL PIPE DEVELOPMENT LENGTH : 3000 mm

Optimal pipe material as for:

- high radiation length
- low thermal expansion coefficient
- Big strength
- Good thermal conductivity
- Thin pipe availability

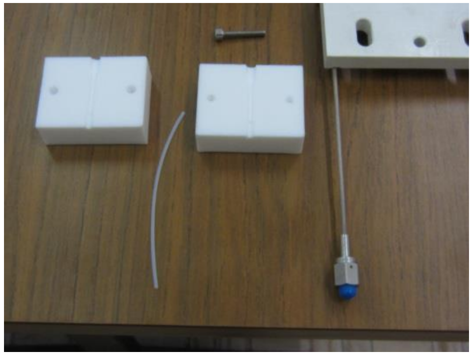
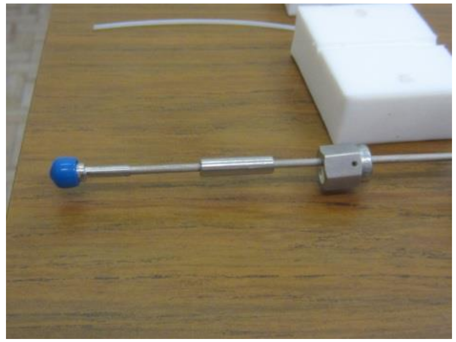
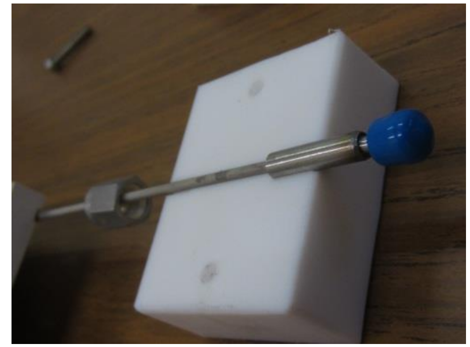
Bended pipes fit very well in the geometry mask after the bending

Titanium has a C.T.E. = 9.4 ppm/K
Stainless Steel C.T.E. = 17 ppm/K

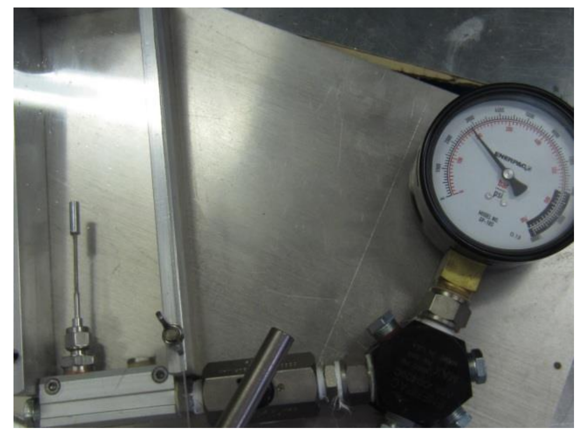
This determines its best performance from the contraction point of view
Ti Cooling pipe free contraction is ~ 0,8 mm

BENDING TITANIUM PIPES
Fit very well in the geometry mask

Titanium to swagelok 1/8 glued + stiffener


Dummy stave with attached reworked fittings on the Titanium snake pipe (dummy C central stave)



Glued joint ARALDITE 2011
Ti pipe –SS reworked dummy fitting
tested <u>without stiffener </u>up to 200 bar for several times

<u>OUTLET PIPING, design choice</u>:

2 mm ID

=no diameter restriction

2,5 mm OD

0,25 mm thickness= minimum commercial available

Weldable, Pdesign 100 bar ok factor ~ 5

S.S. AISI 304L annealed (and post-bending annealing foreseen in final system)

If ok

pipe procurement

We buy

30 m = 15 pipes 2 m long

min quantity

From “Castiglioni” company

If ok

welding prototyping

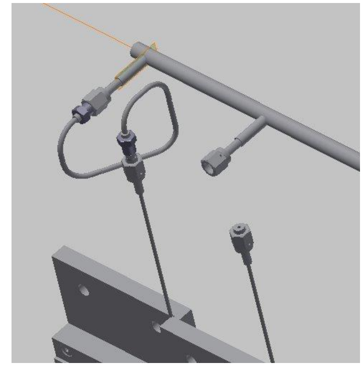
We’re asking offer to “Real –Vacuum” company

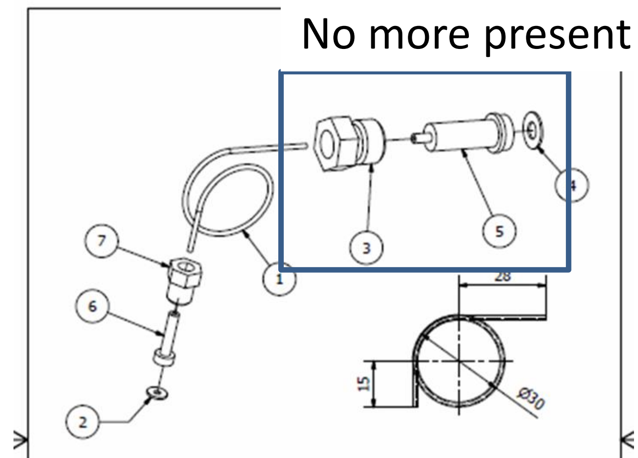
To produce prototyp

MICRO TIG welded

Swagelok 1/8 inch VCR fitting – pipe stave interface

Welded to the manifold (no disconnection on manifold side)





NOTE: item 1 - tubo AISI 304 - 2x2.5 mm
item 5/6 - componenti Swagelok modificati (foratura e sede tubo)

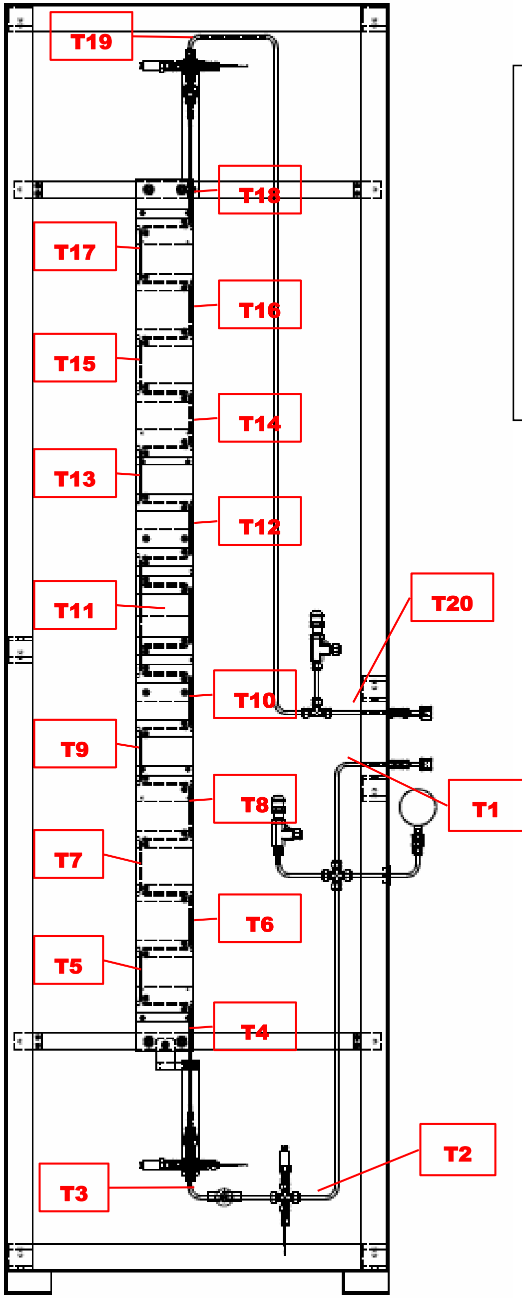
PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Part1_outlet_lunga	
2	1	SS_2_VCR_2_21751	
3	1	SS-4-VCR-4	
4	1	SS-4-VCR-2	
5	1	SS-4-VCR-3_BL-modif_pipe_1.58	
6	1	SS-1-VCR-3	
7	1	SS-2-VCR-4	

Designed by carlo | Checked by | Approved by | Date | Date 07/09/2015

Assieme tubazione uscita linea 1/16"

Stave.00.01.10idw | Edition | Sheet

TEST SET-UP



PIPE TEMPERATURE SENSORS INSTALLED

Tx = TEMPERATURE position x = 1 to 20

MODEL:

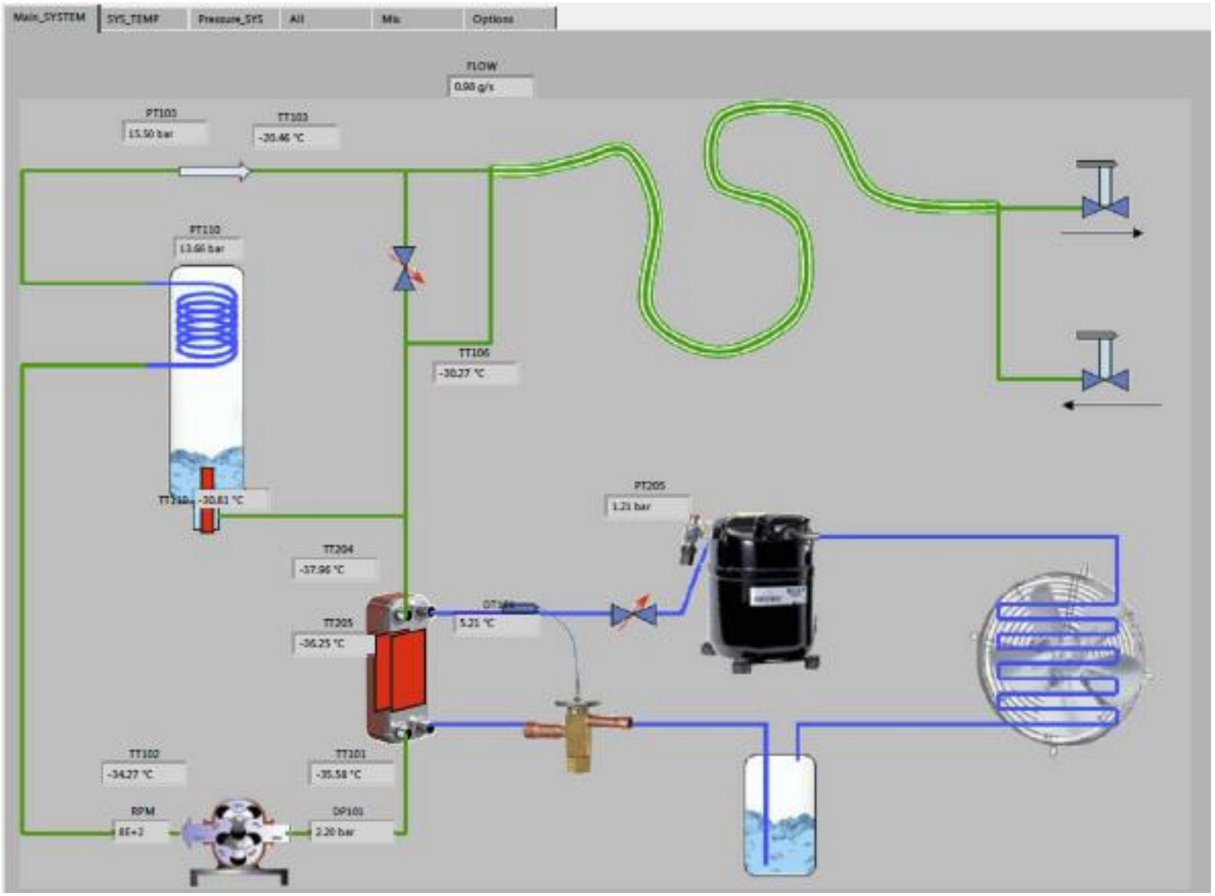
Thermocouple "T" type

2 wires

Type	Material		Color Code	Range (°C)	
Thermocouple Grade	Positive Wire	Negative Wire		Minimum	Maximum
J	Iron	Constantan	+	0	750
K	Chromel	Alumel	+	-200	1250
T	Copper	Constantan	+	-200	350
E	Chromel	Constantan	+	-200	900

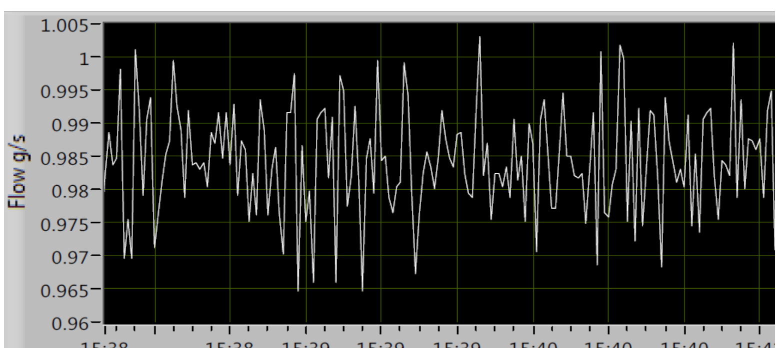
Experiment instrumentation

TEST SET-UP



Experiment instrumentation

TRACI V1
DAQ
Data acquisition



TRACI V1
Mass flowrate measurement

By Coriolis flowmeter

Pressures steady-state Nominal power and flux

one of the measurement points

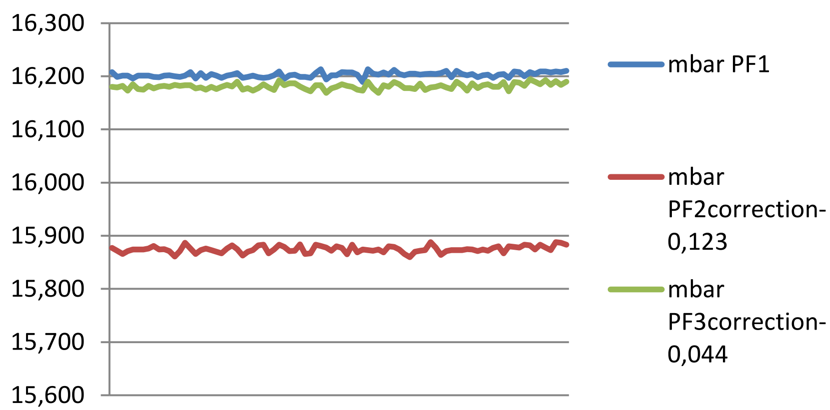
2015-09-16-Pset15bar-75W-F0,9GS-p.txt								
mbar	mbar	mbar	mbar					
PF1	PF2	PF3	PF4					
				mbar	mbar	mbar	mbar	mbar
PF1	PF2	PF3	PF4	**PF1**	**PF2correction-0,123**	**PF3correction-0,044**	DELTA PF1-PF2corr	DELTA PF1-PF3corr
16.208	15.877	16.180	1.380	16.208	15.877	16.180	331	28
16.199	15.872	16.179	1.379	16.199	15.872	16.179	327	20
16.201	15.866	16.182	1.375	16.201	15.866	16.182	335	19
16.201	15.871	16.173	1.385	16.201	15.871	16.173	330	28
16.196	15.874	16.185	1.385	16.196	15.874	16.185	322	11
16.201	15.874	16.176	1.381	16.201	15.874	16.176	327	25
16.201	15.874	16.175	1.383	16.201	15.874	16.175	327	26
16.201	15.876	16.182	1.386	16.201	15.876	16.182	325	19
16.199	15.881	16.177	1.380	16.199	15.881	16.177	318	22
16.198	15.874	16.181	1.379	16.198	15.874	16.181	324	17
16.201	15.875	16.182	1.387	16.201	15.875	16.182	326	19
16.202	15.871	16.180	1.387	16.202	15.871	16.180	331	22

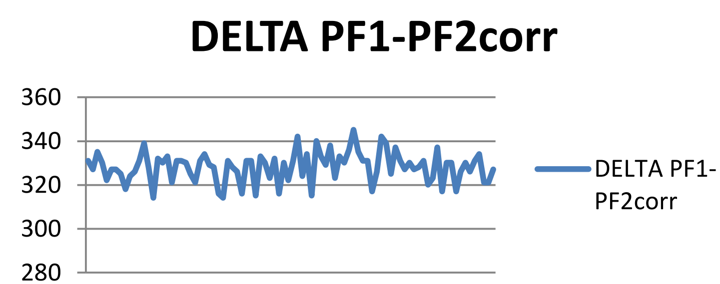
…. Only some data are posted here ….

16.208	15.887	16.184	1.382	16.208	15.887	16.184	321	
16.210	15.883	16.190	1.381	16.210	15.883	16.190	327	
							media	
							328	
							mbar	
							314	MIN
							345	MAX
							31	MAX-MIN

OLD

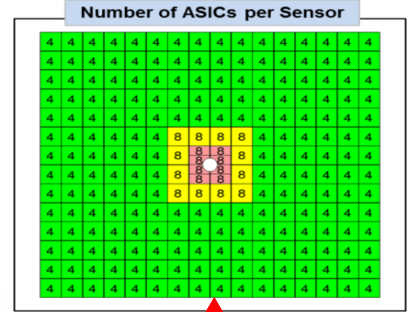
NEEDLE VALVE IN THE INLET LINE

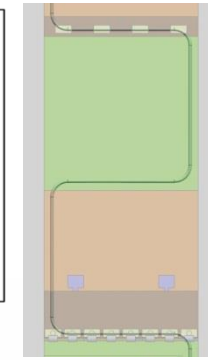


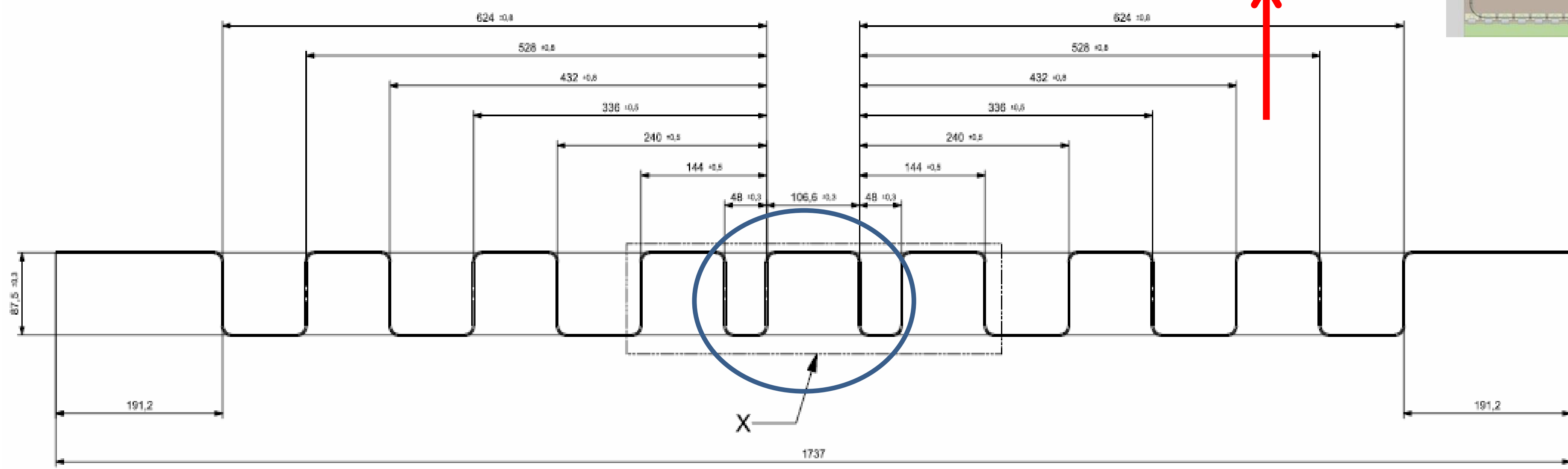


Stave SNAKE PIPE GEOMETRY

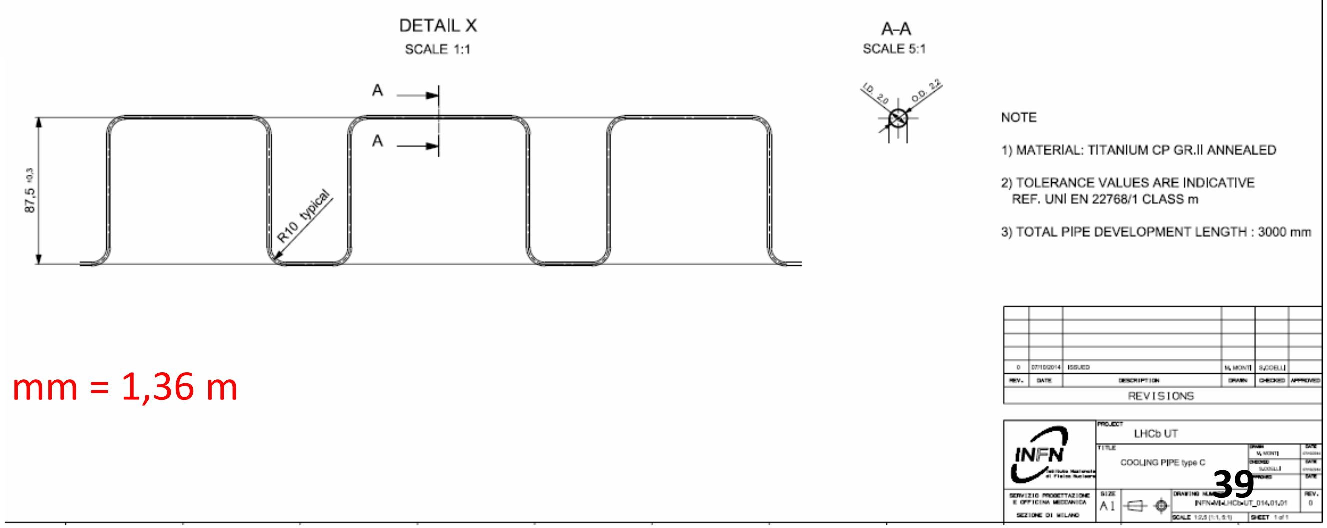
«C» central stave
8 on a total of 68 staves
under test





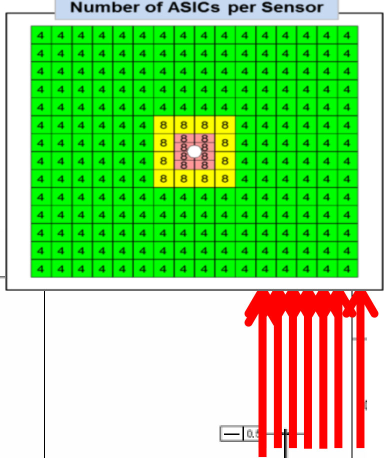


Titanium C.P. 2
I.D. 2,025 mm
O.D. 2,275 mm



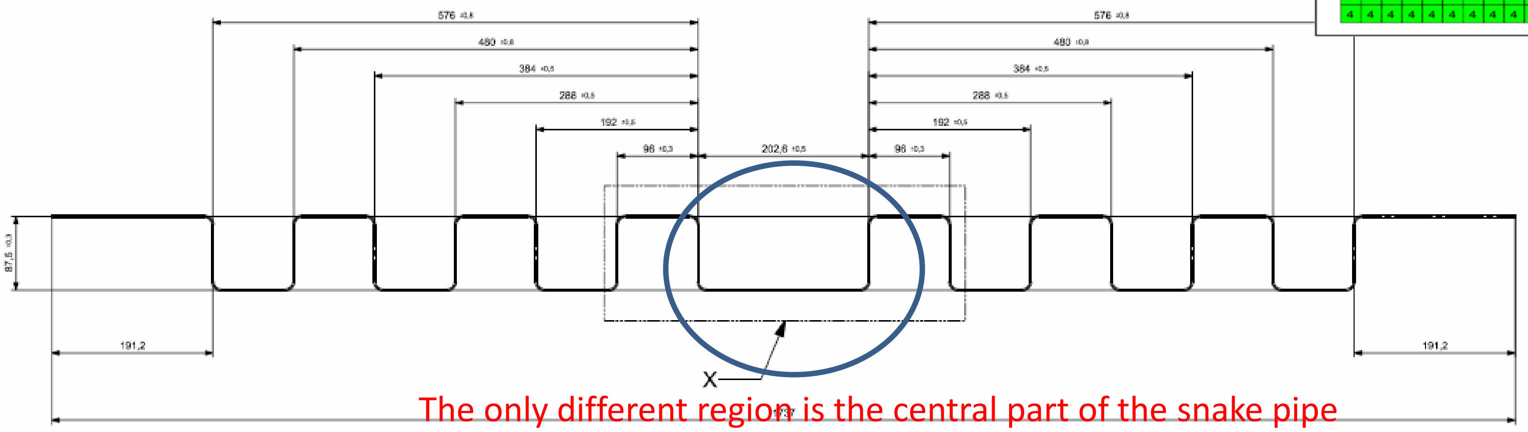
Pipe Length 3 m
Heated length = 16 * ~85 mm = 1,36 m

Stave SNAKE PIPE GEOMETRY

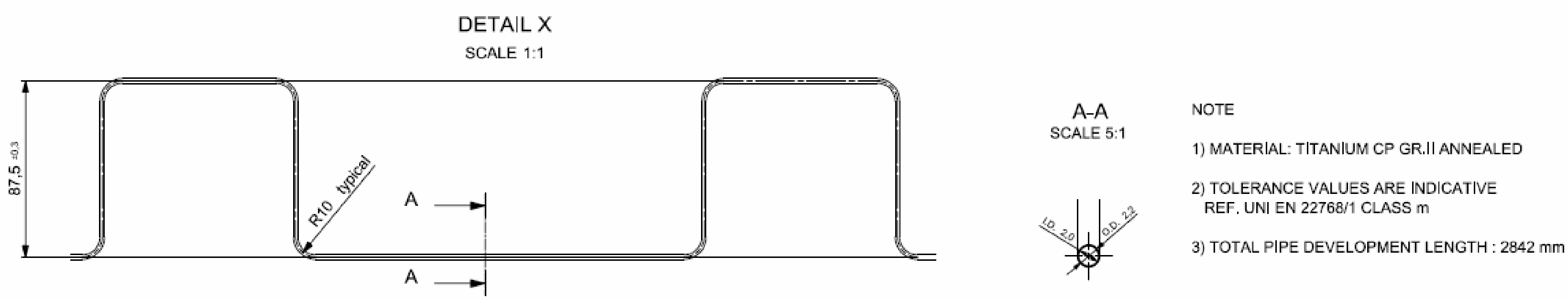


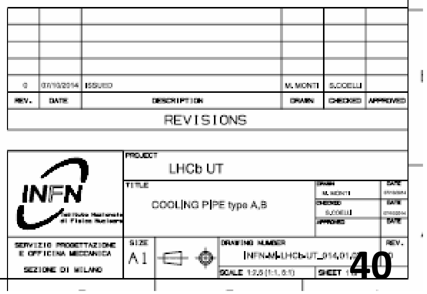
Identical for the «A» «B» staves

All the other detector stave apart the 8 central staves



The only different region is the central part of the snake pipe





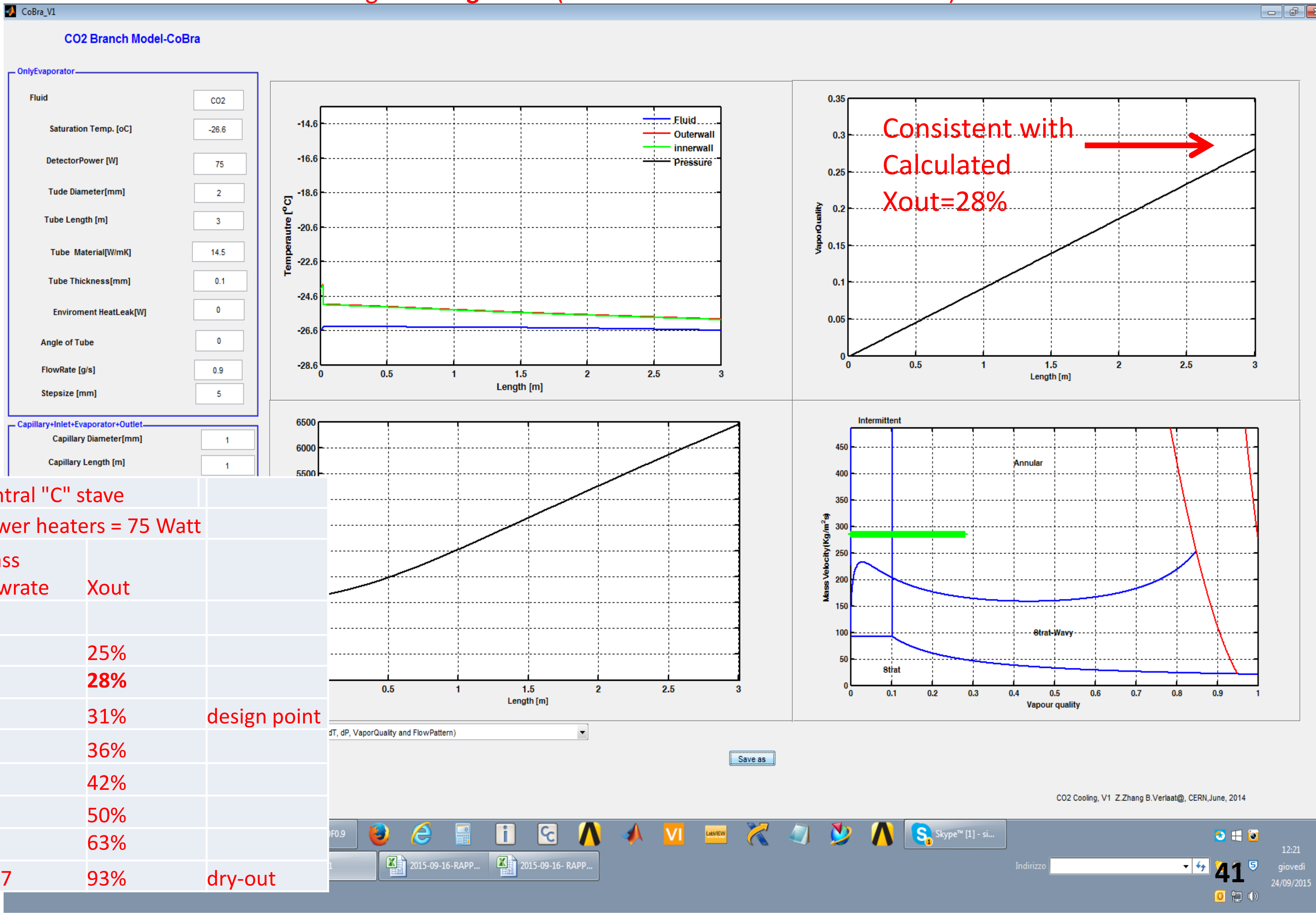
Pipe Length 2,82 m

Heated length = 14 * ~85 mm = 1,19 m

COBRA simulation for 100% power and nominal 0,9 g/s flux

horyzontal straight pipe correlation

Using **full length 3 m** (more correct for friction calculation)

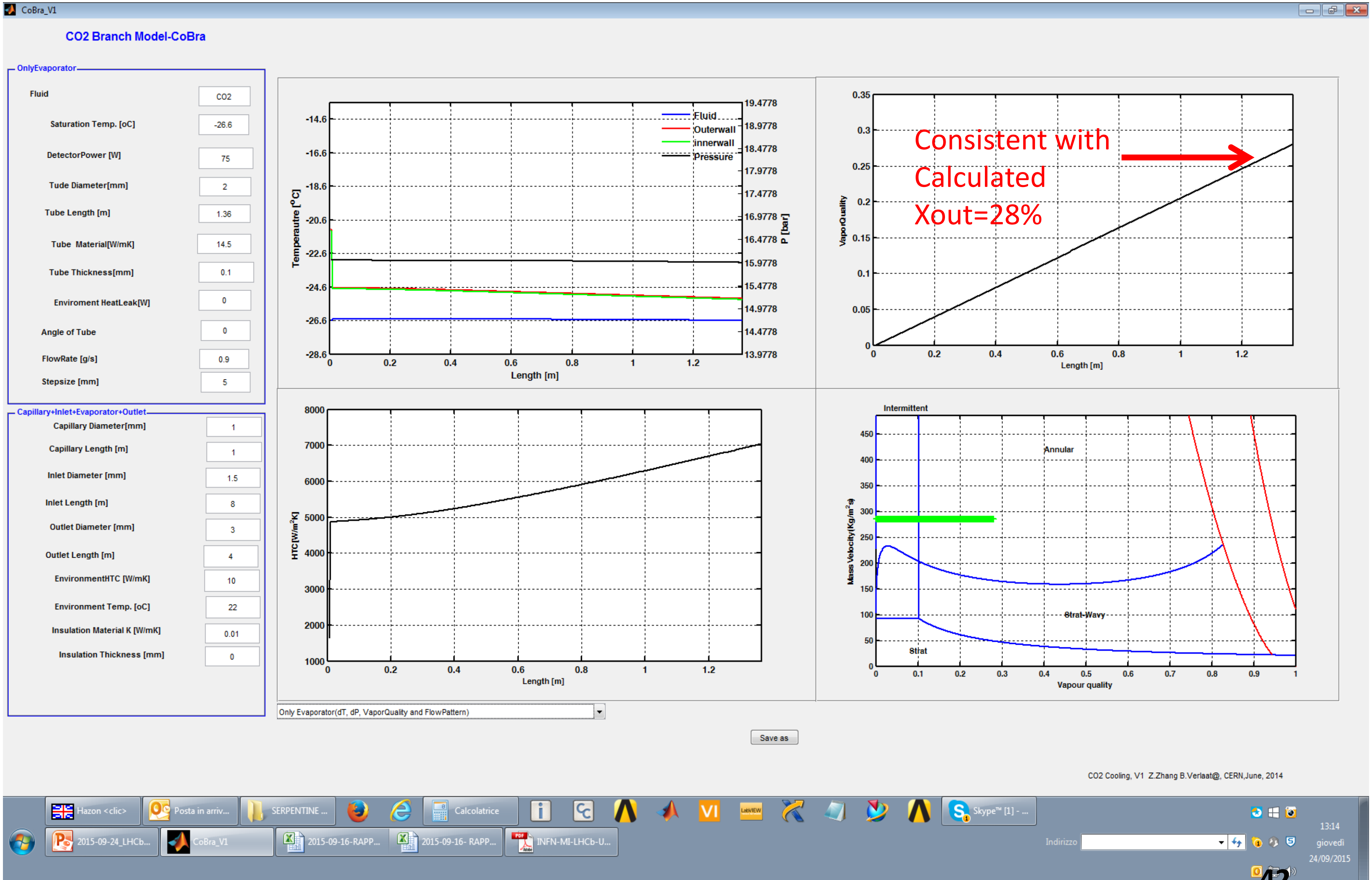


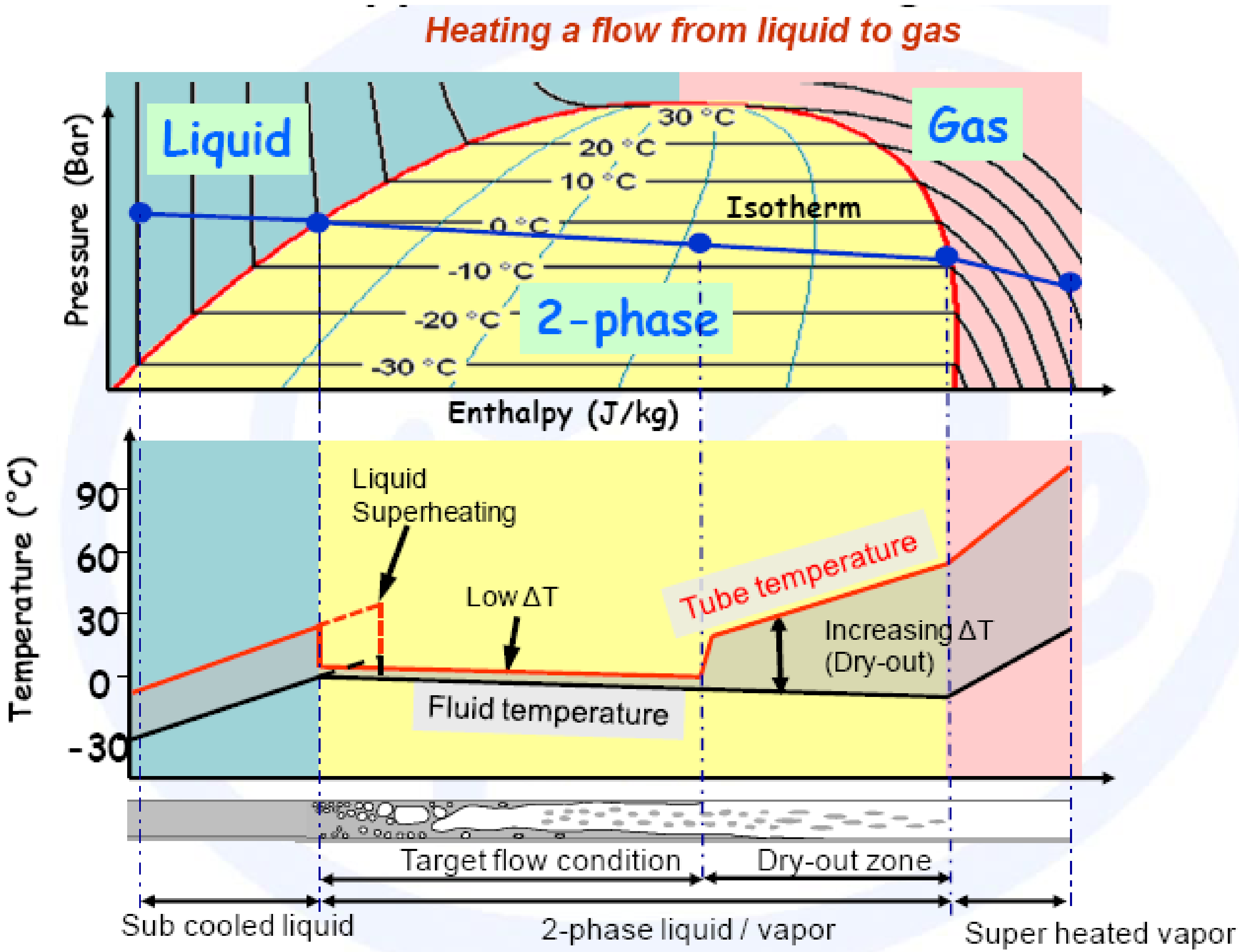
central "C" stave		
Power heaters = 75 Watt		
Mass flowrate	Xout	
g/s		
1	25%	
0,9	**28%**	
0,8	31%	design point
0,7	36%	
0,6	42%	
0,5	50%	
0,4	63%	
0,27	93%	dry-out

COBRA simulation for 100% power and nominal 0,9 g/s flux

horyzontal straight pipe correlation

Using **heated length 1,36 m**, more correct for heat exchange



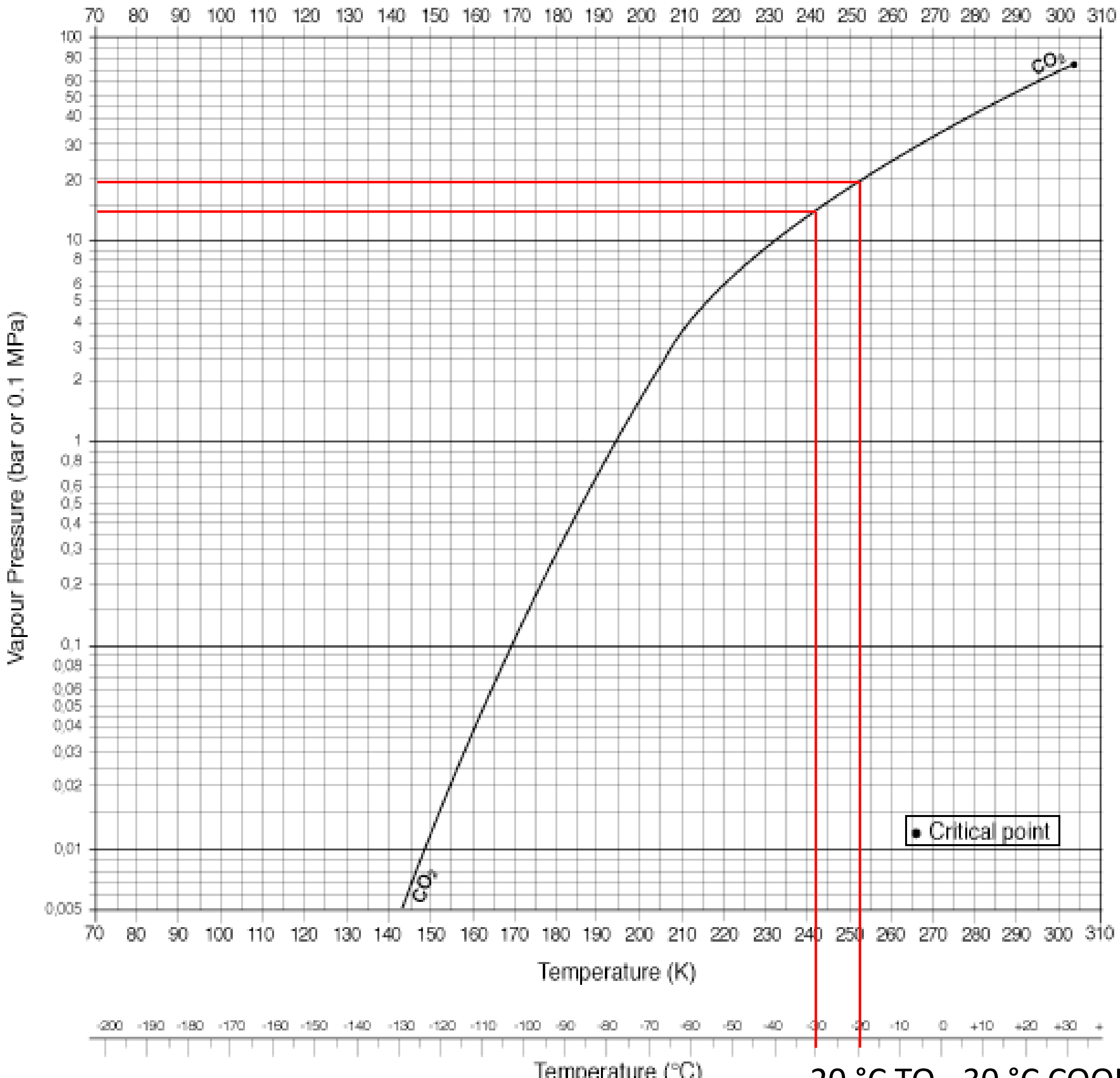


Heating a flow from liquid to gas
Liquid
Gas
2-phase
Isotherm
30 °C
20 °C
10 °C
0 °C
-10 °C
-20 °C
-30 °C
Pressure (Bar)
Enthalpy (J/kg)
Temperature (°C)
90
60
30
0
-30
Liquid Superheating
Low ΔT
Tube temperature
Increasing ΔT (Dry-out)
Fluid temperature
Target flow condition
Dry-out zone
Sub cooled liquid
2-phase liquid / vapor
Super heated vapor

PURE CO2 SATURATION CURVE

TEMPERATURE AND PRESSURE INSIDE THE EVAPORATION CHANNEL

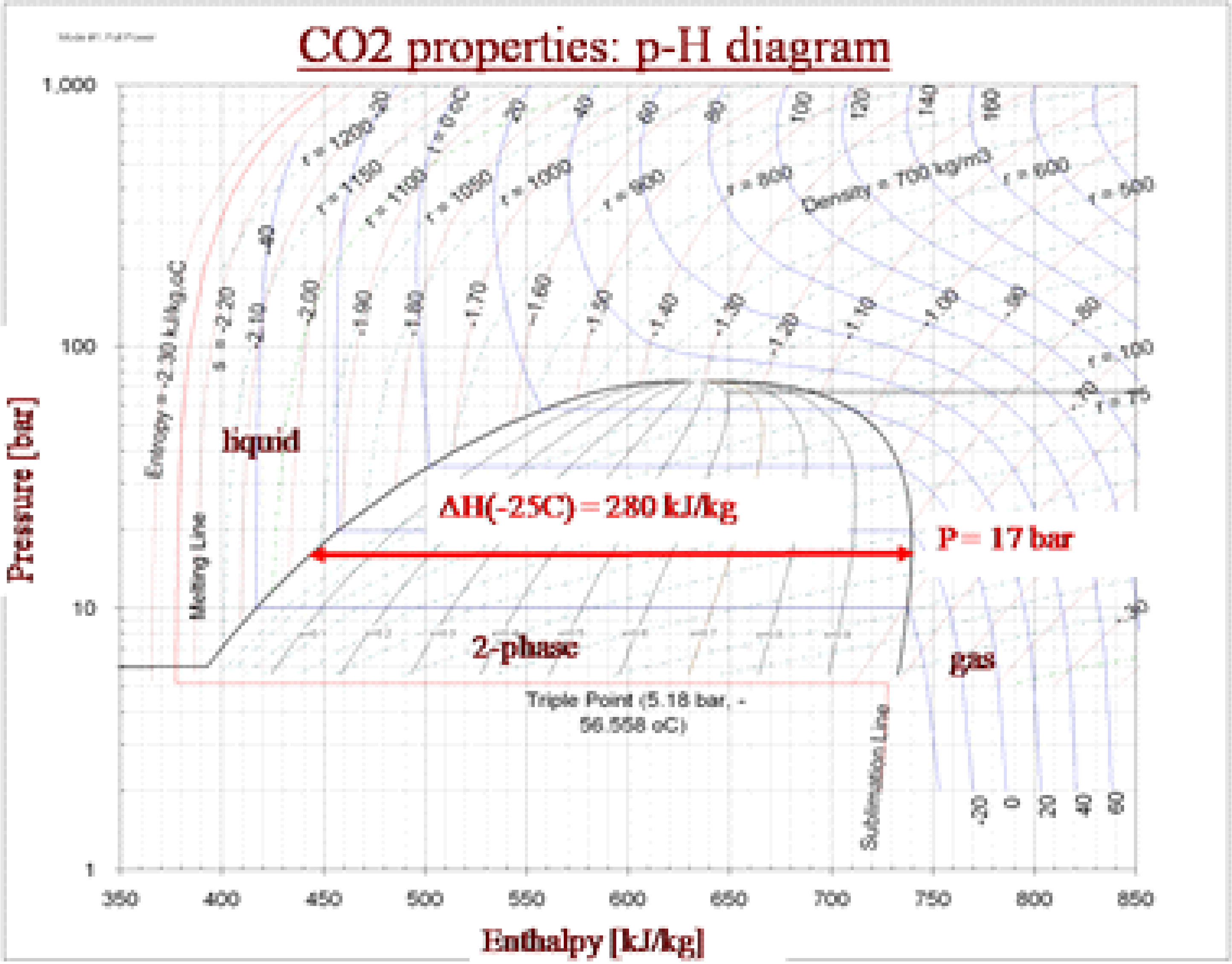
=> **15 TO 20 bar COOLING FLUID OPER. PRESSURE**



- 20 °C TO - 30 °C COOLING FLUID OPER. TEMP.

THE **LATENT HEAT OF VAPORIZATION FOR CO2** CAN BE KNOWN FROM THE CO2 PRESSURE-HENTALPY DIAGRAM

IN THE RANGE OF INTEREST
DELTA H liq.=> vap. = 280-300 kJ/kg



CO2 physical properties

Set point on TRACIv1:
Accumulator pressure P = 15 bar ABS / T saturation= - 28,5 °C

at 15 bar ABS
Hentalpy liquid (X=0)
Hentalpy vapour (X=100%)

1. General Properties | 2. Saturation Properties | 3. CO2 Turbine | 4. Flash Evaporator | 5. P-H Diagram | 6. P-H Diagram (large)

Input Data

Select function:	1. function (p, x)	
1. Pressure (absolute):	15	bar
2. Quality:	0	%

Calculate

Register and Create Account

	Property name	Property ID	Results (Liquid)	Results	Results (Vapor)	Units (SI)
	1. Thermodynamic Properties - Main					
1	Pressure (absolute)	p	15.0000000000	15.0000000000	15.0000000000	bar
2	Temperature	t	-28.5199041122	-28.5199041122	-28.5199041122	°C
3	Density	d	1069.3872426404	1069.3872426404	39.0557745757	kg/m³
4	Specific volume	v	0.0009351150	0.0009351150	0.0256044083	m³/kg
5	Specific enthalpy	h	-370.2278554471	-370.2278554471	-70.1517506628	kJ/kg

delta h L-V @15 bar ABS	**300**	**J/g**

calculated exhaust vapour fraction Xout
Xout = (h out-h in)/delta h L-V

(h out-h in)= Power/F
F= mass flowrate g/s
Power= elctrical heaters power W

=> Xout = (Power/F)/ delta h L-V

delta h L-V @15 bar ABS	300	J/g

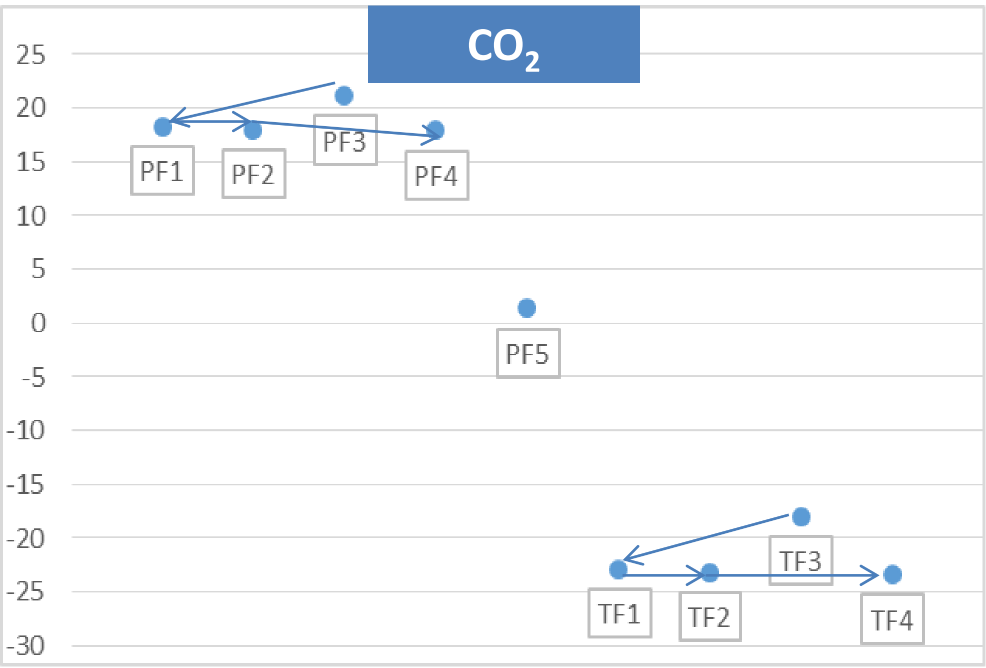
Xout = 75 / (300 * F) W/(J/g*g/s) =1

UT detector CO2 Cooling Test Results

DATE	2016-04-19
STAVE	"C"
FLOW DIRECTION	UPWARD
INSULATION	ARMAFLEX
STAVE INLET	RESTRICTOR 0,254 mm
STEADY-STATE	OK
TRACI P SET POINT	17 bar_A
SATURATION TEMP	-23°C
HEATER POWER	75 W "nominal"
MASS FLOW-RATE	0,84 g/s (*TRACI V.1 LIMIT)*
CALCULATED X out	32 %

	PRESSURE DROP	TEMPERATURE DROP
	bar	°C
INLET LINE WITH ORIFICE	2,875	4,9
EVAPORATOR CHANNEL	0,314	0,3
OUTLET LINE	0,034	0,2

PF1	PF2	PF3	PF4	PF5	TF1	TF2	TF3	TF4
18,166	17,852	21,041	17,818	1,247	-22,993	-23,308	-18,085	-23,49



2019-04-19-P17BAR-75W-084GS-PT

UT detector CO_2 Cooling Test Results

DATE	2016-04-19
STAVE	"C"
FLOW DIRECTION	UPWARD
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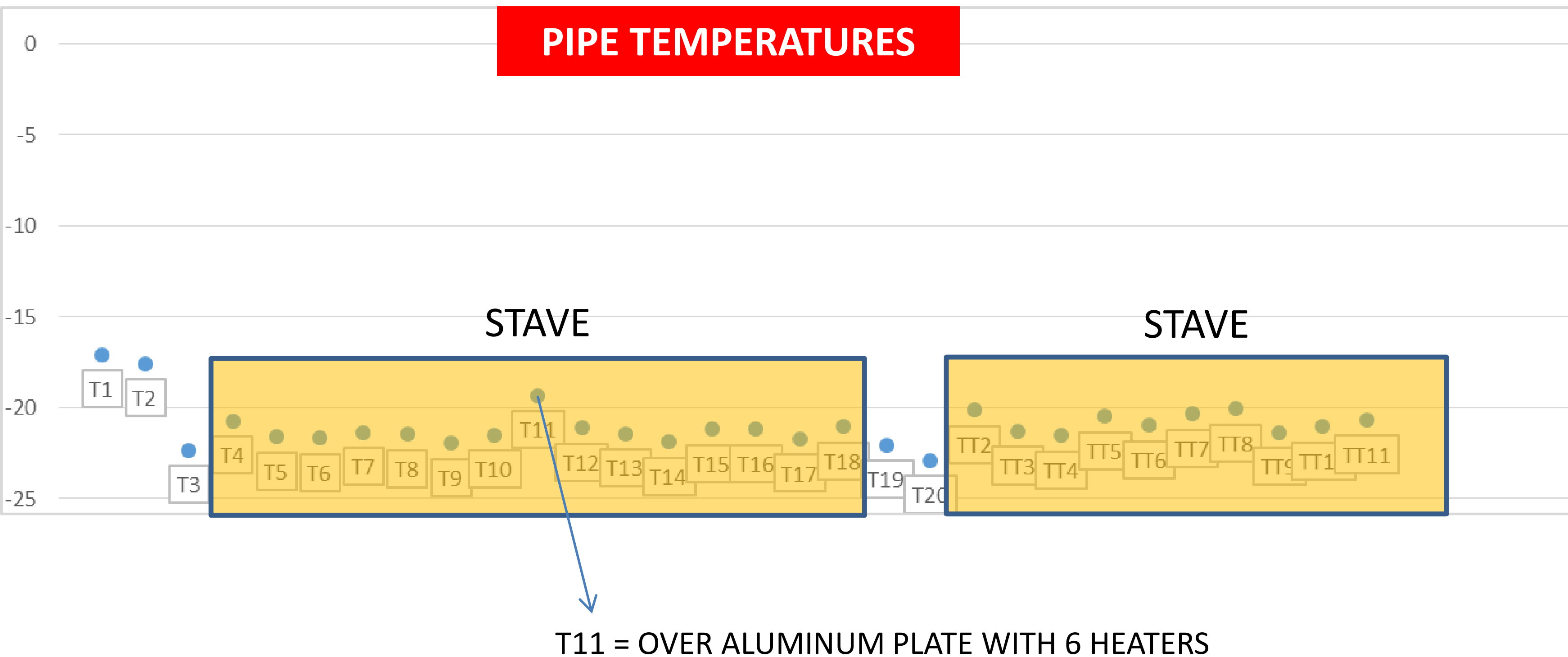
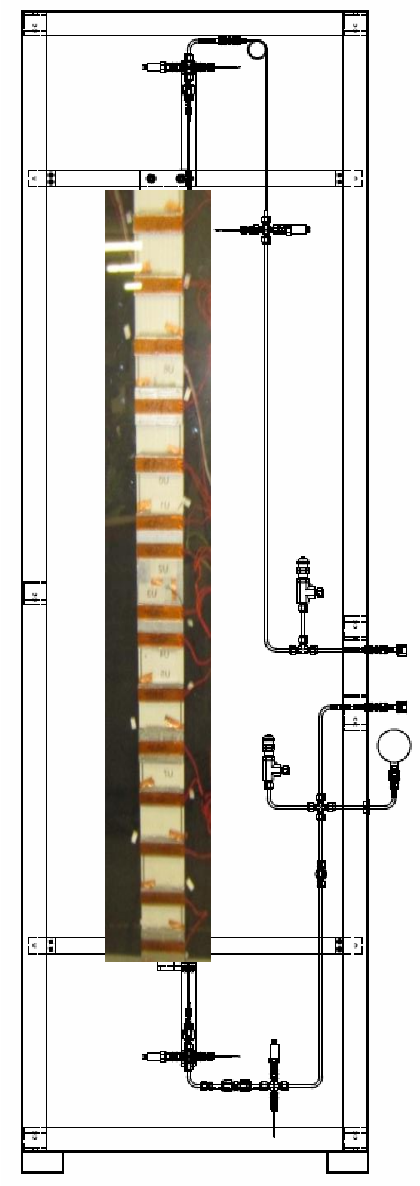
STEADY-STATE	OK
TRACI P SET POINT	17 bar_A
SATURATION TEMP	-23°C
HEATER POWER	75 W "nominal"
MASS FLOW-RATE	0,84 g/s (*TRACI V.1 LIMIT)*
CALCULATED X out	32 %

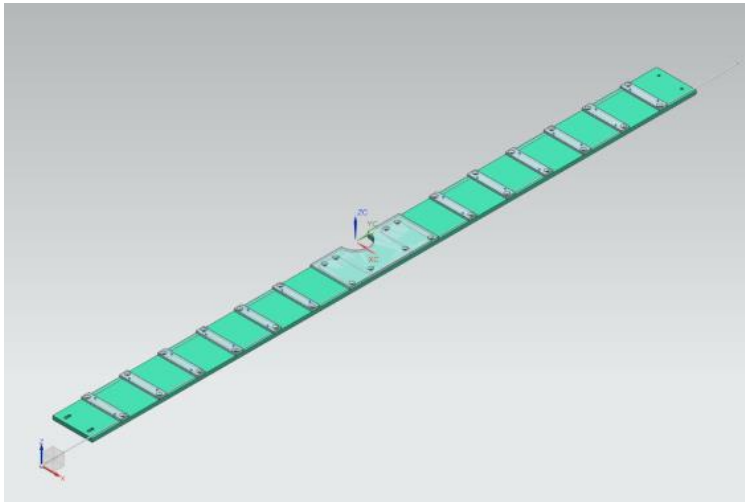


2019-04-19-P17BAR-75W-084GS-PT

DUMMY STAVE HEATING SYSTEM



«C» DUMMY STAVE WITH HEATERS



LHCb UT STAVE - MATERIAL PROPERTIES DATABASE

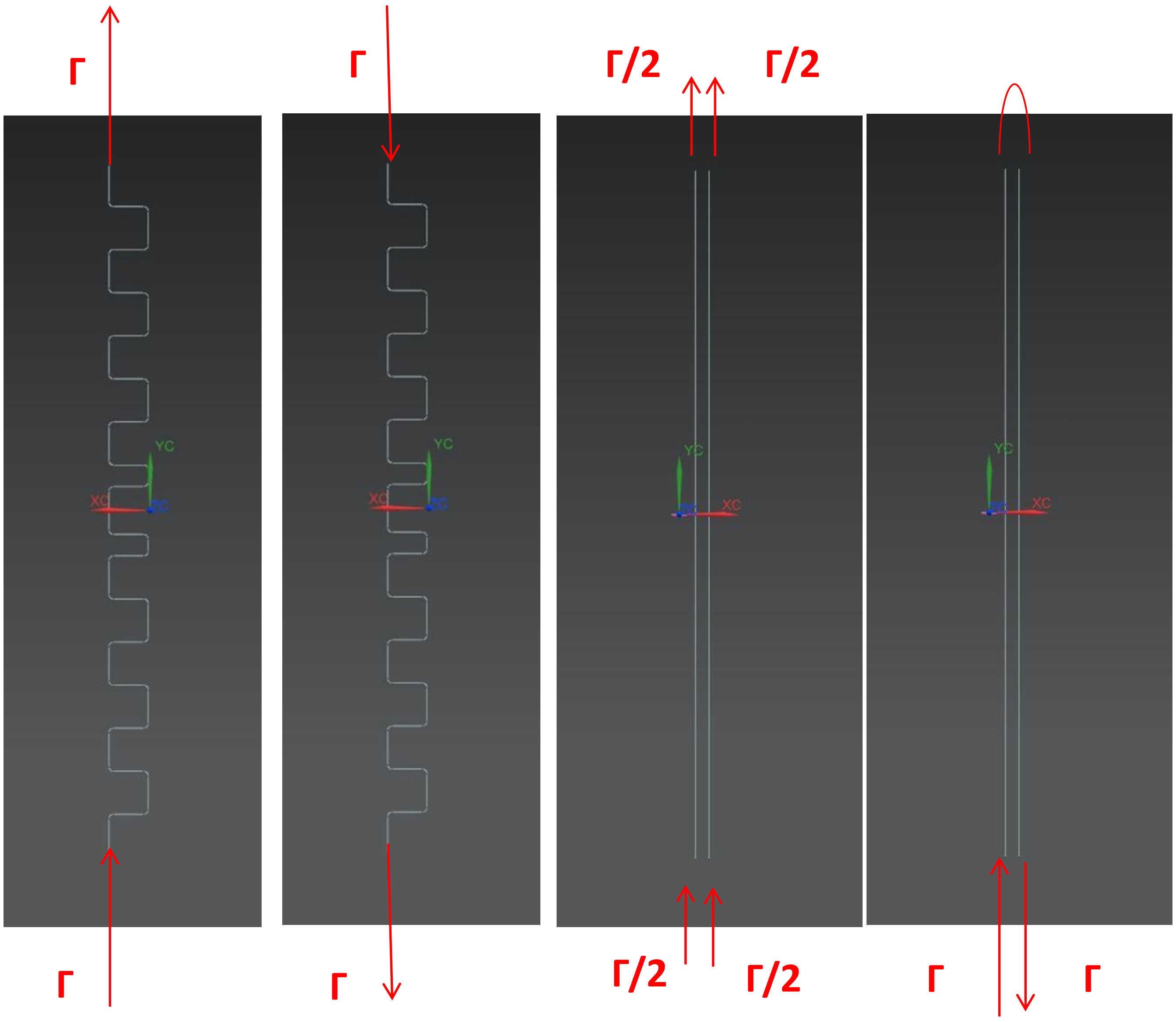
rev. 2 09/06/2014

Orthotropic Material / Type			Thickness [µm]	E_X [GPa]	E_Y [GPa]	E_Z [GPa]	G_{XY} [GPa]	G_{YZ} [GPa]	G_{XZ} [GPa]	PR_{XY}	PR_{YZ} PR_{XZ}	ρ [Kg/m³]	CTE_X [ppm/K]	CTE_Y CTE_Z [ppm/K]	K_x [W/m K]	K_y [W/m K]	K_z [W/m K]	Fiber Vol. Ratio
CFRP STAVE FACEPLATE HYBRID STIFFENER	Fiber K13C Resin Polycyanate RS3	Prepreg K13C/RS3	65	410	5,6	5,6	4,1	4,1	4,1	0,39	0,39	1731	-0,765	15				60%
	LAMINATE	Lay-up (0/90/0)	175	276	141		4,1			0,0156		1731	0,933	1,21	64	32	0.5	

Isotropic Material / Type		Thickness [µm]	E [GPa]	Poisson Ratio PR	ρ [Kg/m³]	CTE [ppm/K]	K [W/m K]
CARBON FOAM	ALLCOMP CARBON FOAM		0,7	0,25	200	3,5	35
ROHACELL	ROHACELL 51 IG		0,07	0,40	52,1	33 @20°C 24 @-100°C	0,029
COOLING PIPE I.D. 2,0 mm O.D. 2,2 mm	*BASELINE* TITANIUM CP grade 2	100	105	0,34	4510	8,6	16,4
	2nd *OPTION* STAINLESS STEEL AISI 316	100	193	0,30	8000	16,0	16,3
SIGNAL/POWER FLEX	KAPTON	230	2.5	0,34	1400	27	0,23
HYBRID FLEX	KAPTON	250	2.5	0,34	1400	27	0,23
SENSOR	SILICON	250	110	0,28	2400	2,5	124
ASIC		100					
GLUE	HYSOL 9396+35%BN	50	2,75	0.33 guess	1140	39,1 @ 20°C 27,1 @-40°C	1,4
	COMPLIANT EPOXY (SENSOR GLUE)	50	0,005	0,49	2360	200	1,34
	LOW CONDUCTIVE COMPLIANT EPOXY (SENSOR GLUE)	50	same	same	same	same	0,60
THERMAL VIAS	COPPER	250	110	0,34	8930	16,4	385
WIREBONDS	ALUMINUM		68	0,36	2700	24,0	210

Central stave energy balance

INLET = OUTLET MASS FLOWRATE in different cooling flow configurations



Q = 85 W

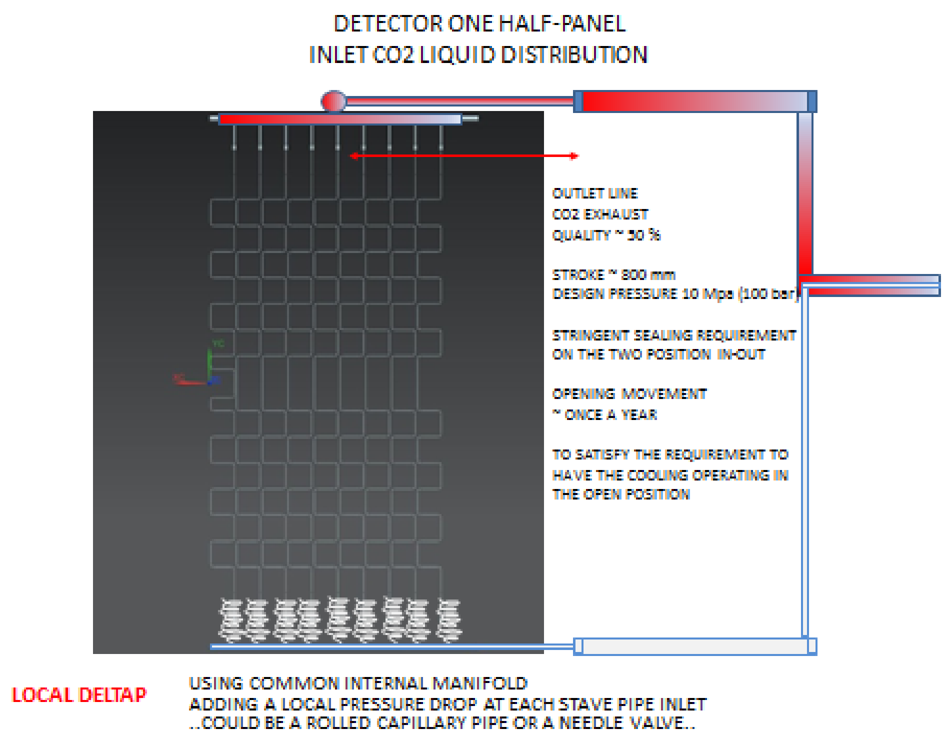
X = 30 %

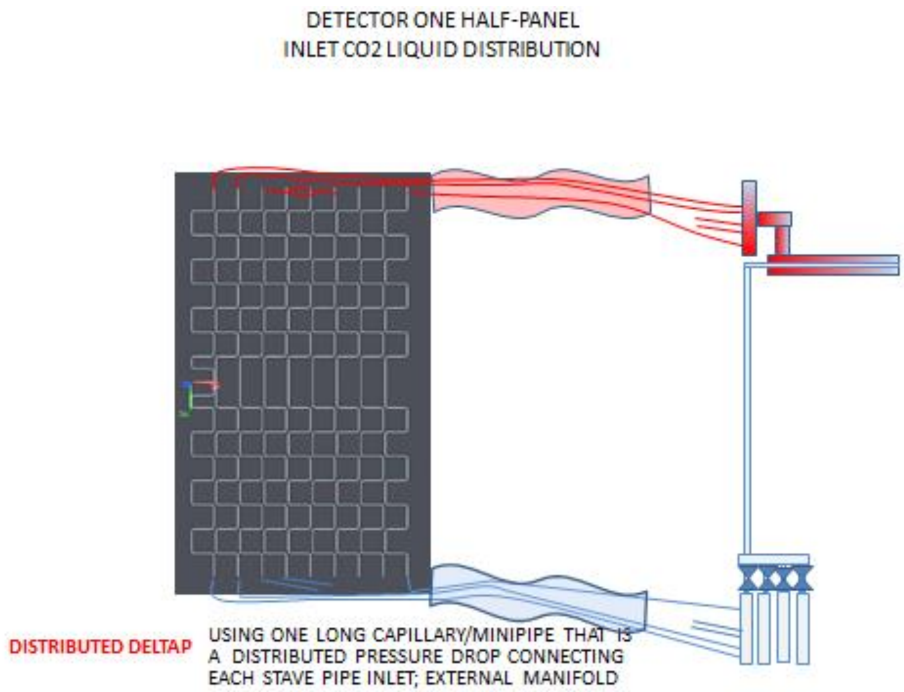
H lv =280 kJ/kg

Coolant Mass flow rate always

⇒ Γ = 1 g/s

Given the same boundary conditions

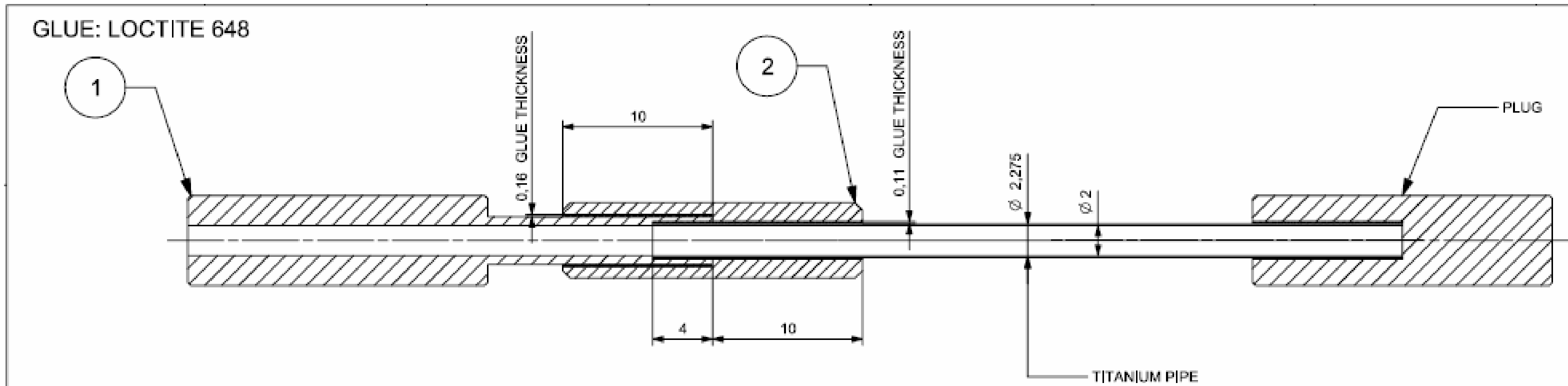




Design option:
2 - Manifolds both on the bottom (ADDING LOCAL PRESSURE DROPS) and on the top

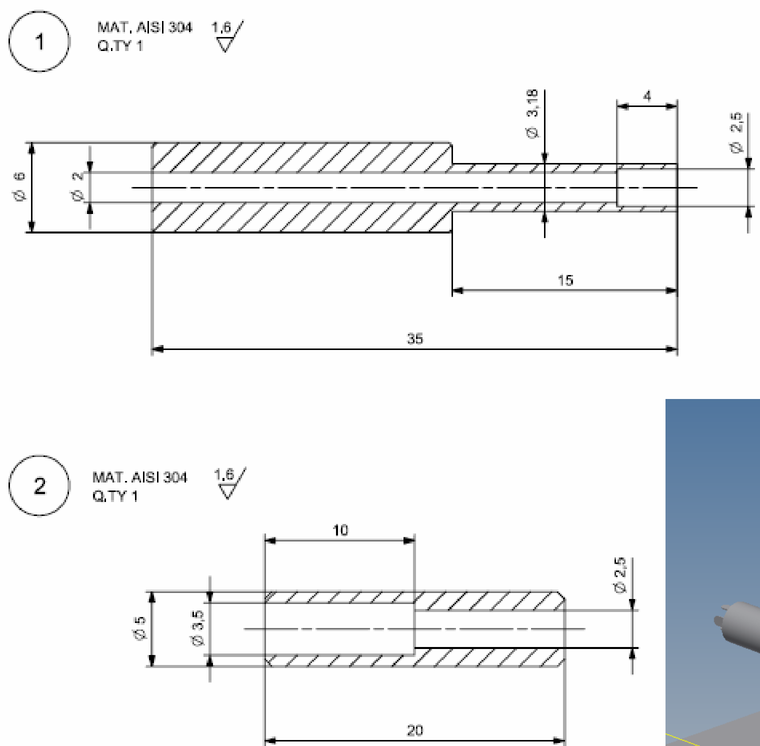
Design option:
3 - Capillaries both on the bottom and on the top

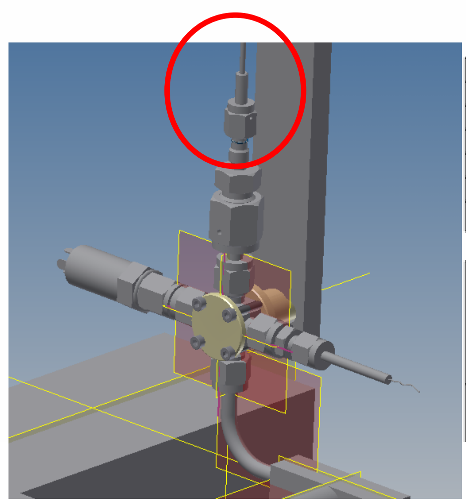
COOLING PIPE FITTINGS

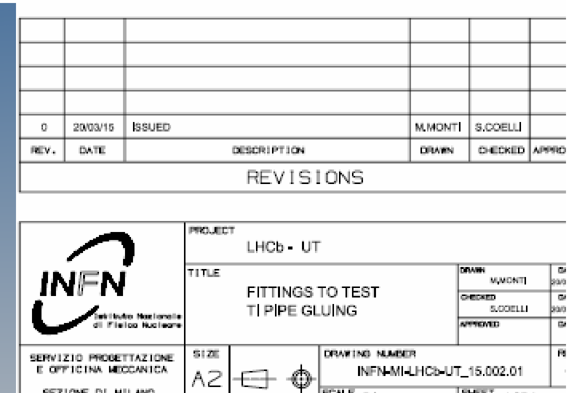


Glued connection between Titanium pipe and a «dummy swagelok VCR fitting»
Preliminary qualification

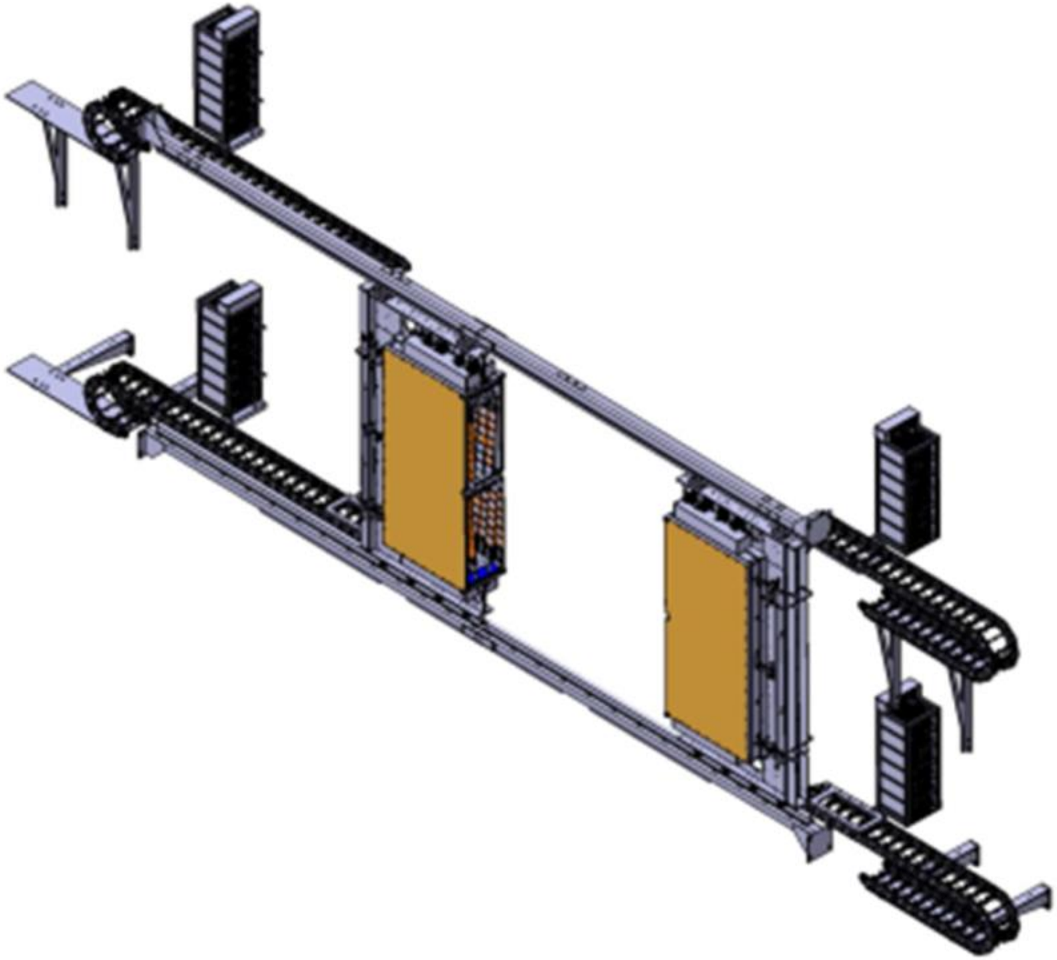
Then 2 VCR will be glued on the bended pipe sin the dummy staves



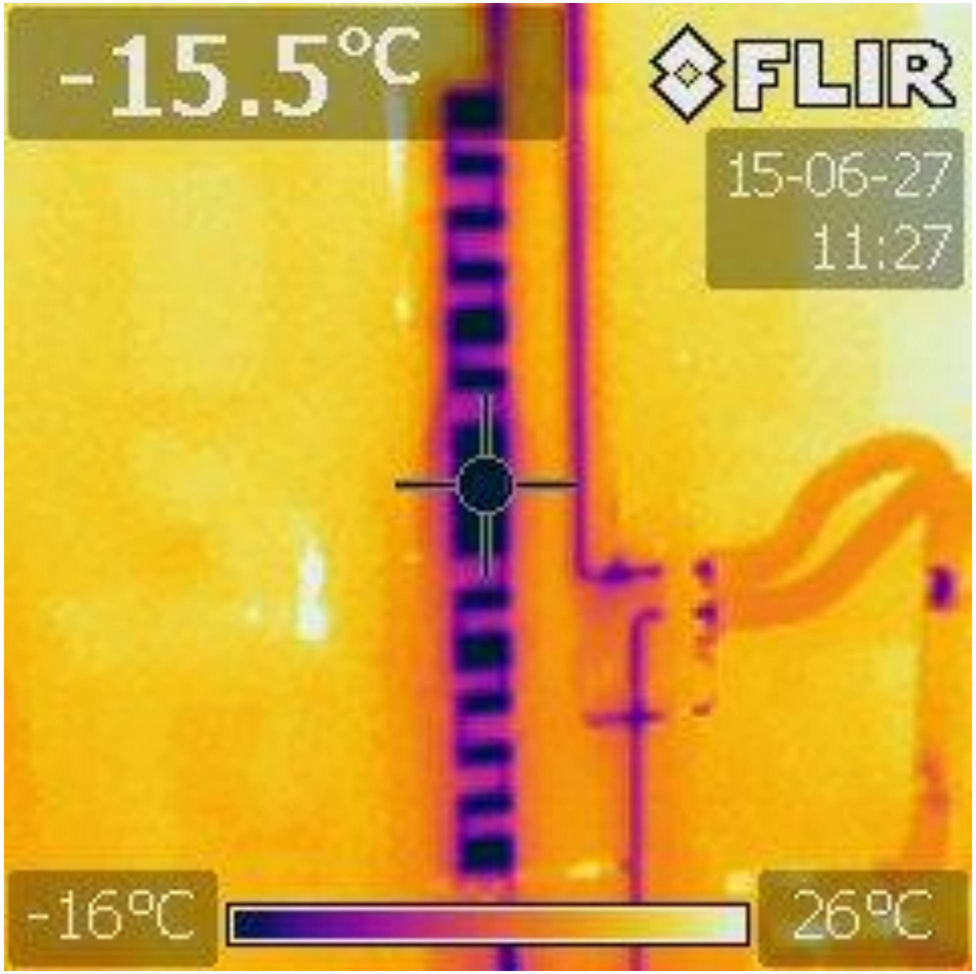




stiffener



INFRARED THERMO-CAMERA PICTURE
COLD-BOX OPEN

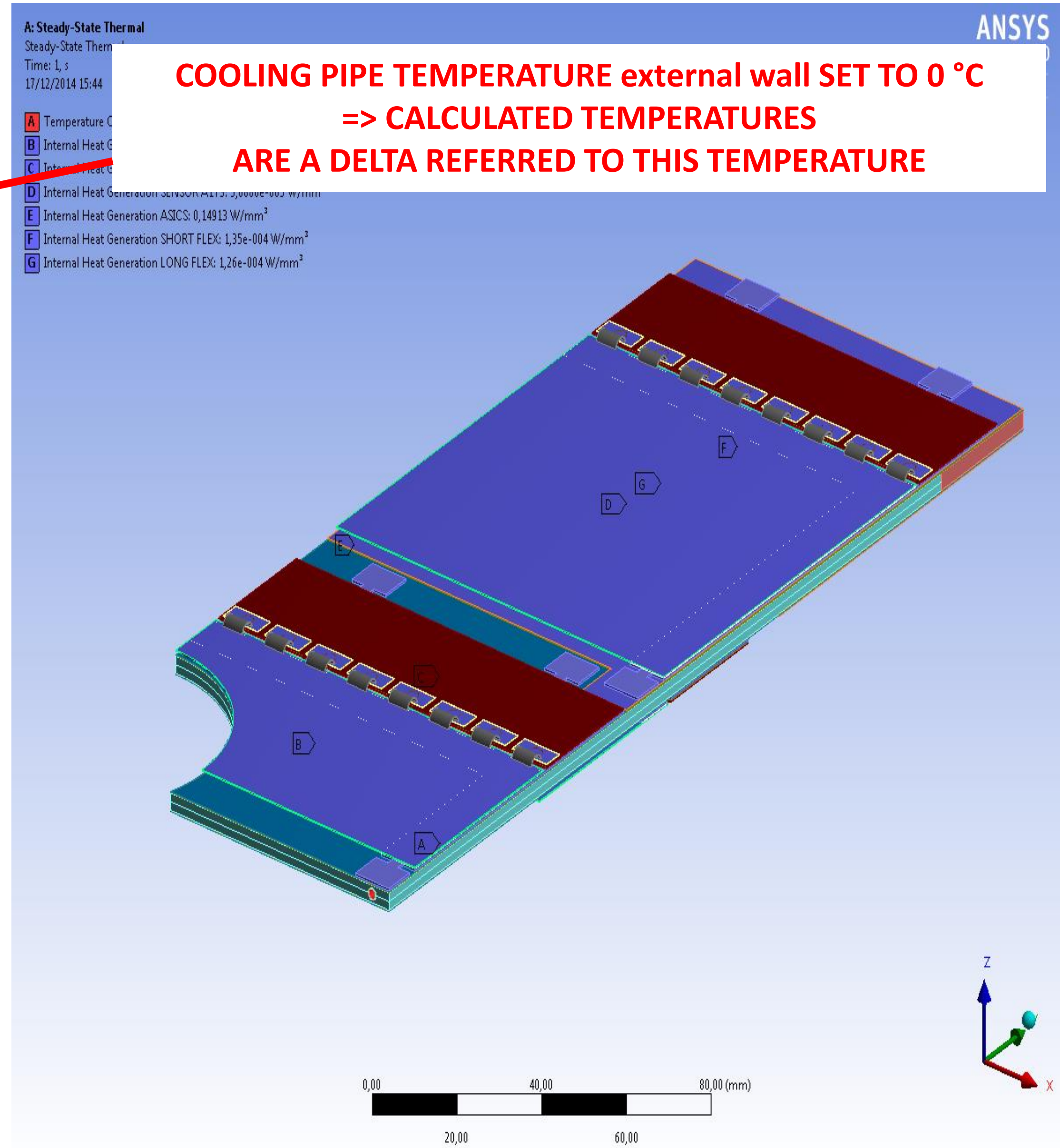


THERMAL FEA

THERMAL LOADS AND BOUNDARY CONDITIONS

A: Steady-State Thermal
Steady-State Thermal
Time: 1, s
17/12/2014 15:45

- **A** Temperature COOLING PIPE: 0, °C
- **B** Internal Heat Generation SENSOR A1T1: 2,6724e-004 W/mm³
- **C** Internal Heat Generation SENSOR A1T2: 1,4187e-004 W/mm³
- **D** Internal Heat Generation SENSOR A1T3: 5,6886e-005 W/mm³
- **E** Internal Heat Generation ASICS: 0,14913 W/mm³
- **F** Internal Heat Generation SHORT FLEX: 1,35e-004 W/mm³
- **G** Internal Heat Generation LONG FLEX: 1,26e-004 W/mm³



Read-out chip POWER:
+ 0.768 W / ASIC

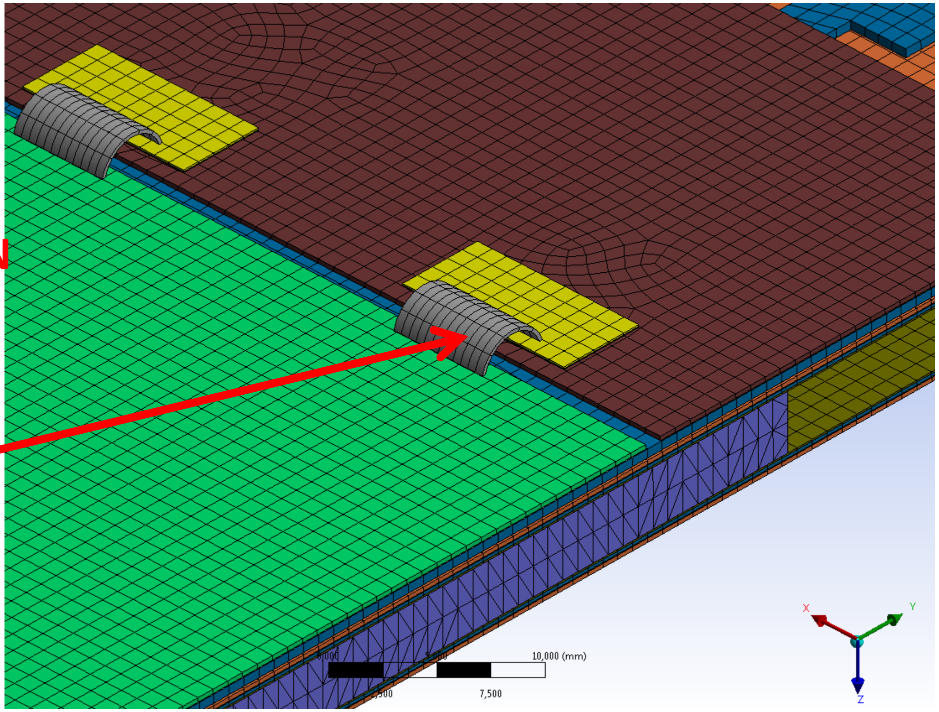
POWER dissipated in the FLEXBUS:
+ 10 % of transported power
(i.e. 8 * 0,768 = 6,14 W)

SENSOR SELF HEATING:
T1 = + 0.261 W
T2 = + 0.171 W
T3 = + 0.135 W

WIREBOND DETAIL

WIREBONDS HAVE A THERMAL INFLUENCE ON THE SENSOR HOT SPOT

thermal flux from ASIC to sensor



128 WIREBONDS
ALUMINUM
WIRE DIAMETER
25 µm

Hypothesis: 128 WIREBONDS PER ASIC - Diam. 25 µm

Total cross section area per ASIC: $A = 0.062832\ mm^2$

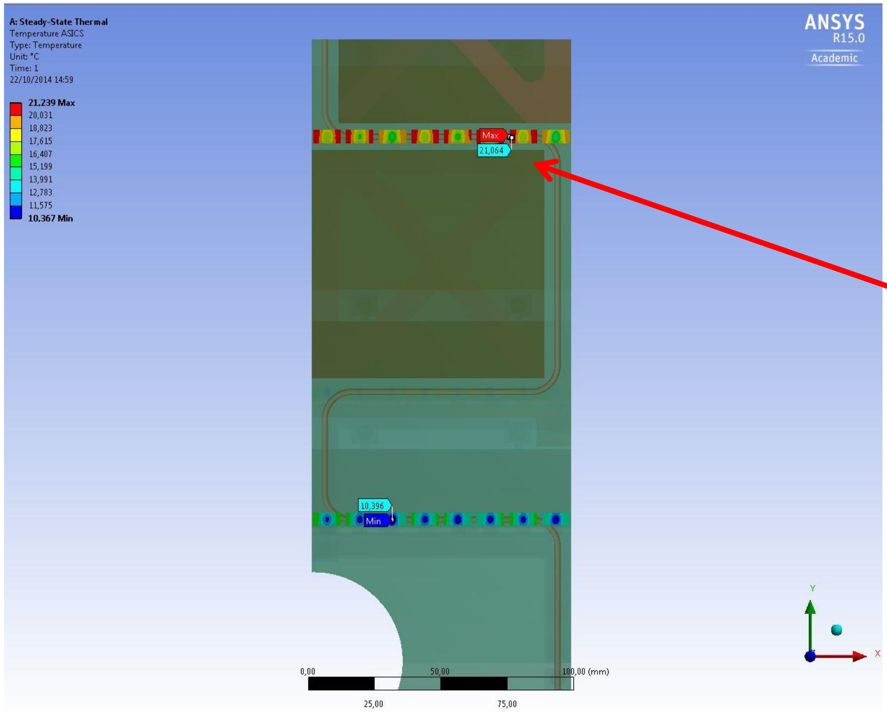
Total cross section area per ASIC of the FE model : $A_m = 1.130976\ mm^2$

Factor: $A_m/A = 18$

K Aluminum = 210 W/m K

Equivalent ribbon: $K_{eq} = 210/18 = 11.7$ W/m K

ASICs TEMPERATURE



Worst case
Max temperature
ASIC

ASIC temperature calculated ΔT = 21.2 °C over the cooling pipe temperature

Thermal Figure of Merit
TFoM = ΔT / P [°C·cm2/W]

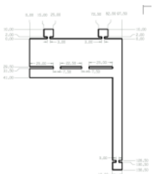
ΔT = max temperature difference between cooling tube and power dissipation source [°C]
P = thermal power flux [W/cm2]
meaningful only when P is not zero

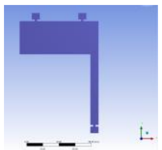
Valid only under the ASICs:

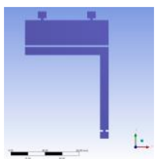
P under the ASICs = 1.25 W/cm^2
ΔT = 21.2 °C
⇒ **TFoM ≈ 17 [°C·cm2/W]**

Thermal F.E.A. - thermal performances for the actual design

RESULTS SUMMARY TABLE (for «C» central stave, sensors T1, T2, T3)







STIFFENER TYPE	STIFFENER MATERIAL	SENSOR A1.T1 MAX DELTA T [°C]	SENSOR A1.T2 MAX DELTA T [°C]	SENSOR A1.T3 MAX DELTA T [°C]	ASICs MAX DELTA T OVER THE PIPE [°C]
CERAMIC STIFFENER WITH SLITS	PBN - THICKNESS 500 µm	2.2	2.1	5.1	21
	AlN- THICKNESS 250 µm	2.2	2.0	5.0	17
CERAMIC STIFFENER WITHOUT SLITS	PBN - THICKNESS 500 µm	2.8	2.7	6.7	20
	AlN- THICKNESS 250 µm	2.5	2.4	5.9	17
CERAMIC STIFFENER SEPARATED INTO TWO PARTS	PBN - THICKNESS 500 µm	2.0	1.9	3.0	23
	AlN- THICKNESS 250 µm	1.8	1.8	2.2	19

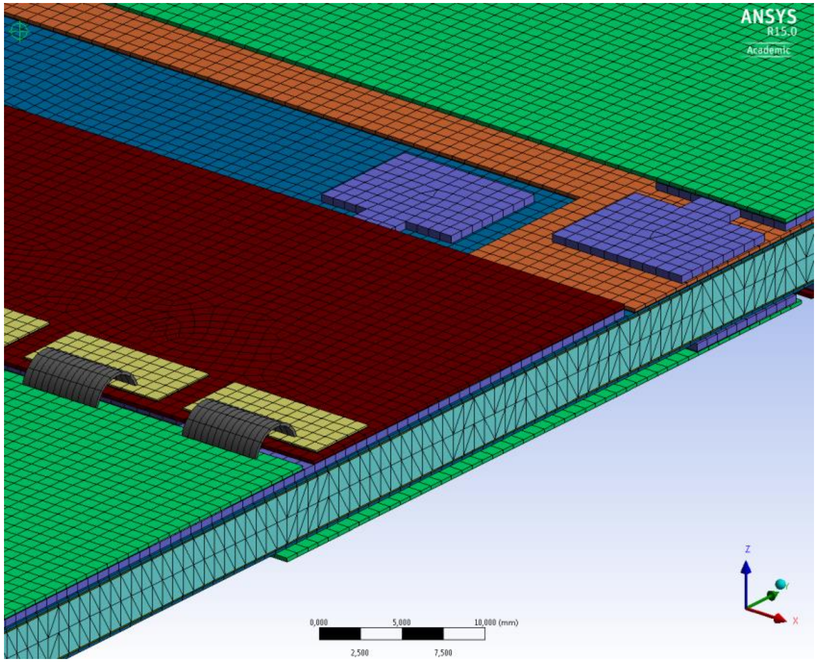
CONCLUSIONS:

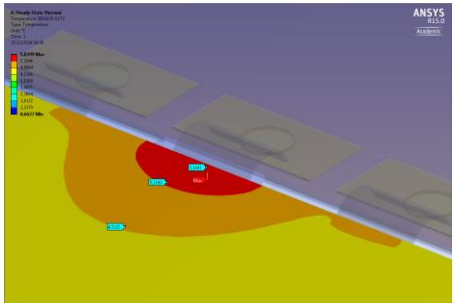
- **THE TEMPERATURE DIFFERENCE ACROSS THE SENSORS IS ALWAYS ACCEPTABLE FOR THE INNERMOST SENSORS T1 AND T2 (around 2 °C)**
- **THE TEMPERATURE DIFFERENCE ACROSS THE SENSOR T3 (in the central stave) ACCEPTABLE FOR BOTH THE CERAMIC MATERIALS IN THE DESIGN GEOMETRY WITH SLITS (around 5 °C)**

=> Both PBN and AlN solutions provide efficient heat transfer

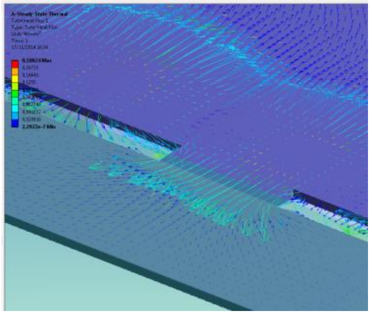
- **WITHOUT SLITS THE TEMPERATURE DIFFERENCE WORSEN. SENSOR T3 becomes critical in «C» stave**
- **AlN IS BETTER THAN PBN from the thermal point of view.**
- **ASICs TEMPERATURE ARE ALWAYS WITHIN SPECIFICATION. Operative temp. cooling pipe will be ~ -15 °C, ASICs ~ +5 °C, with a large margin against the limit of 40 °C.**

FEA DETAIL

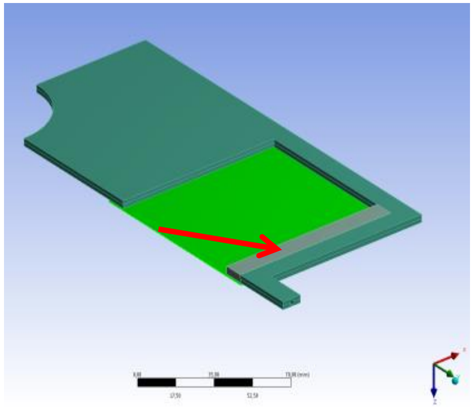




Local sensor thermal field



heat flux from ASICs trought the stiffener



Identification of the criticality => optimization of the design - extension of the carbon foam under the sensor

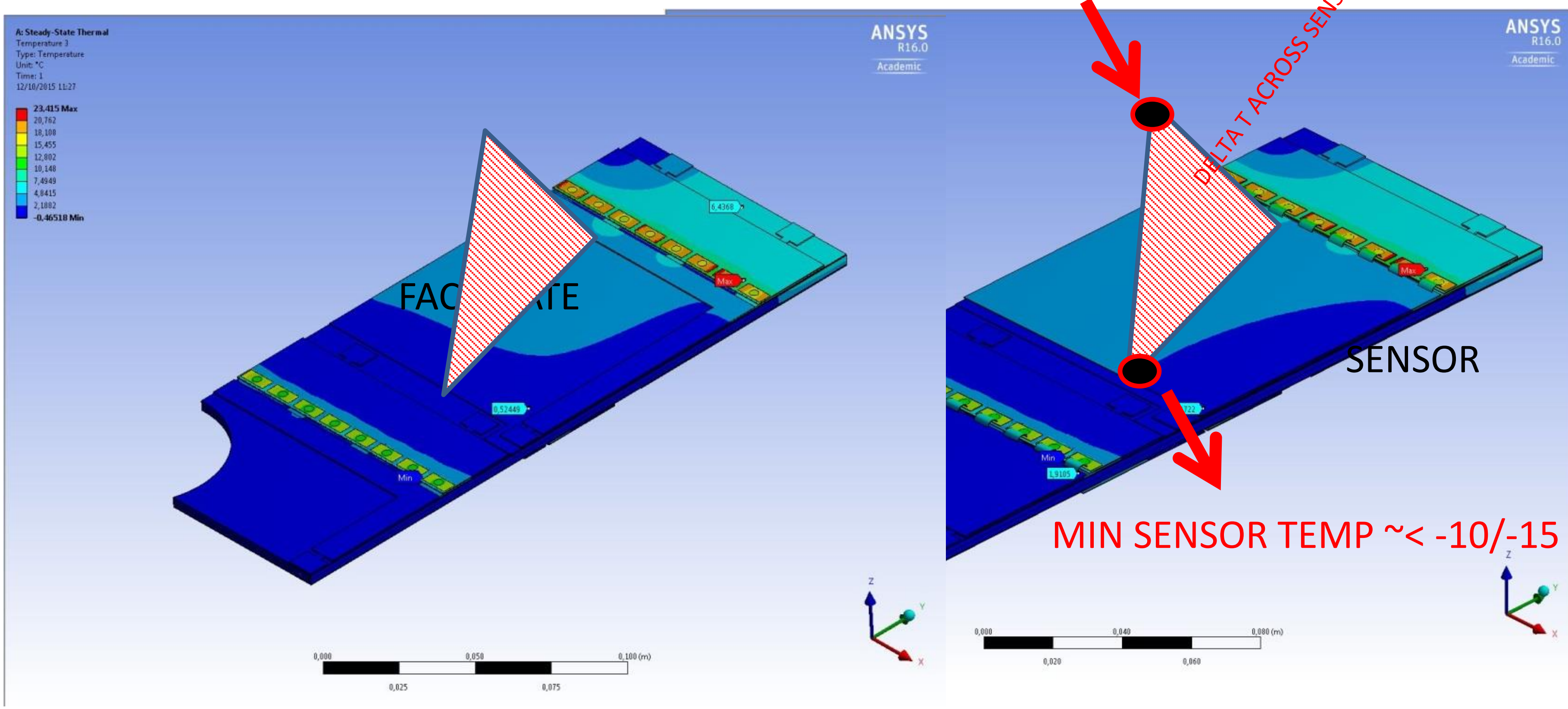
DETECTOR TEMERATURE FIELD
F.E.A. SIMULATION
COOLING PIPE TEMPERATURE SET TO 0 °C
=> TO SEE THE DETECTOR DISTRIBUTION OF TEMPERATURE

- SENSOR 8 ASICS (T3)

- VERSION V.5
- L-SHAPED SENSOR SUPPORT
- CERAMIC MATERIAL PBN /PYROLITIC BORON NITRIDE

REQUIREMENT MAX

SENSOR TEMP < -5 °C



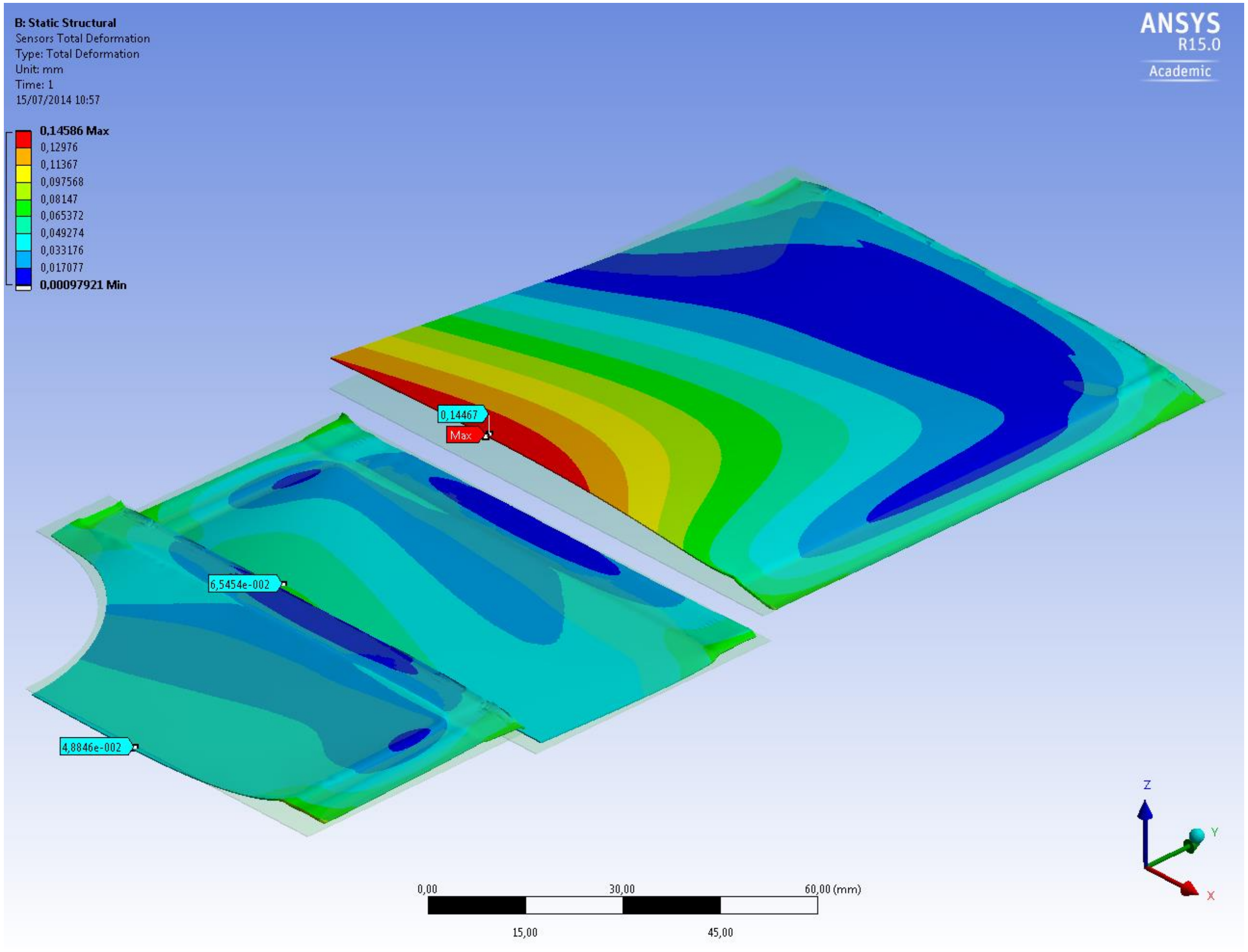
⇒ DETECTOR FACEPLATE AND STRUCTURE IS ALWAYS 1-6 °C OVER THE COOLING PIPE TEMPERATURE

⇒ SENSOR TEMPERATURE IS 1-7 °C OVER THE COOLING PIPE TEMPERATURE

TO RESPECT REQUIREMENT WITH MARGINS AND TAKING IN ACCOUNT CO_2 INTERNAL PIPE H.T.C. => COOLING PIPE -20 °C

THERMO-STRUCTURAL FEA

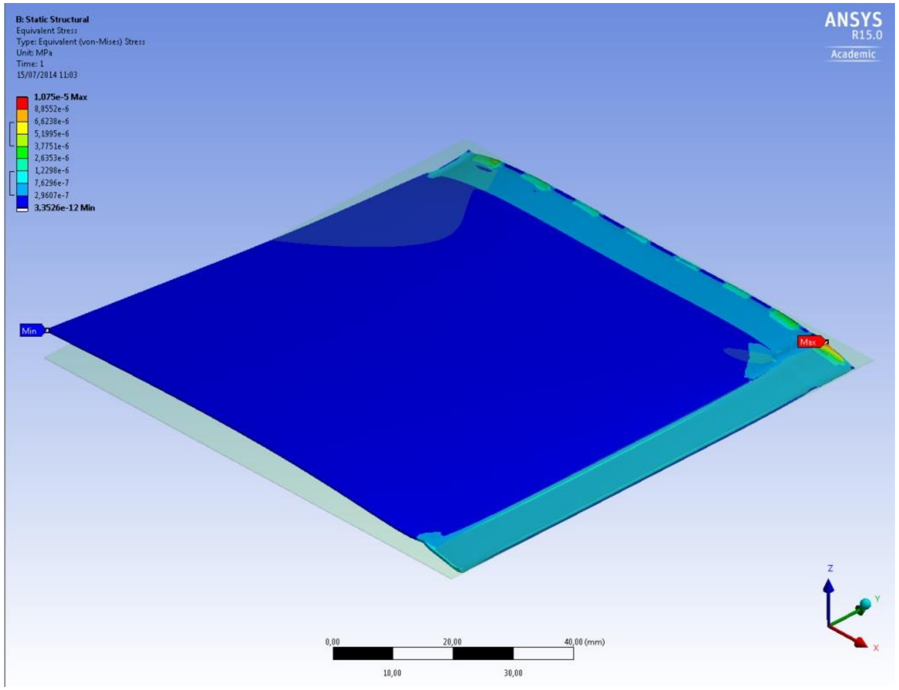
Thermo mechanical sensor thermal deformation



MAX DISPLACEMENT IN THE SENSOR A1.T3: 150 µm
almost all in the vertical direction Z axis, out of sensor plane

Thermo mechanical sensor thermal deformation

STRESS IN THE SILICON SENSOR

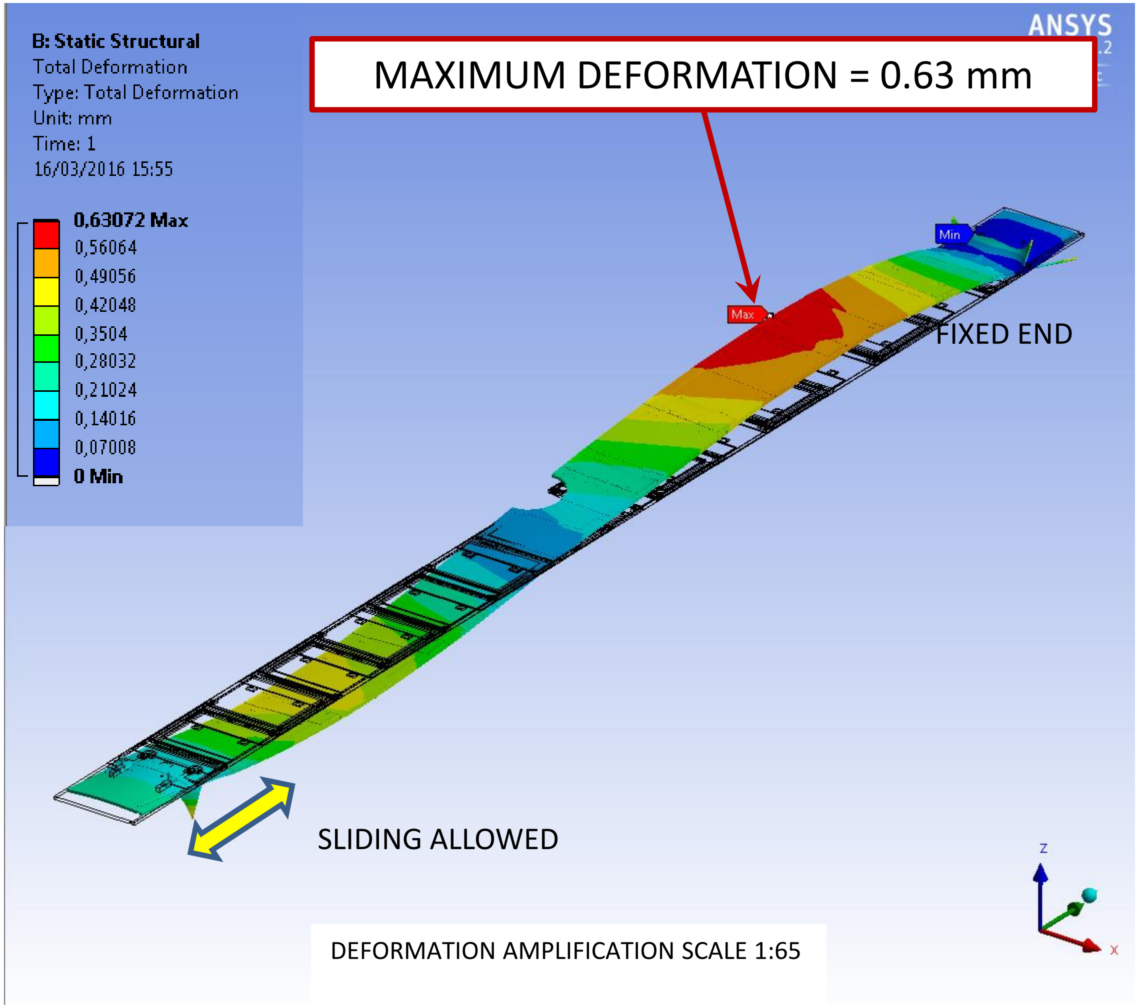


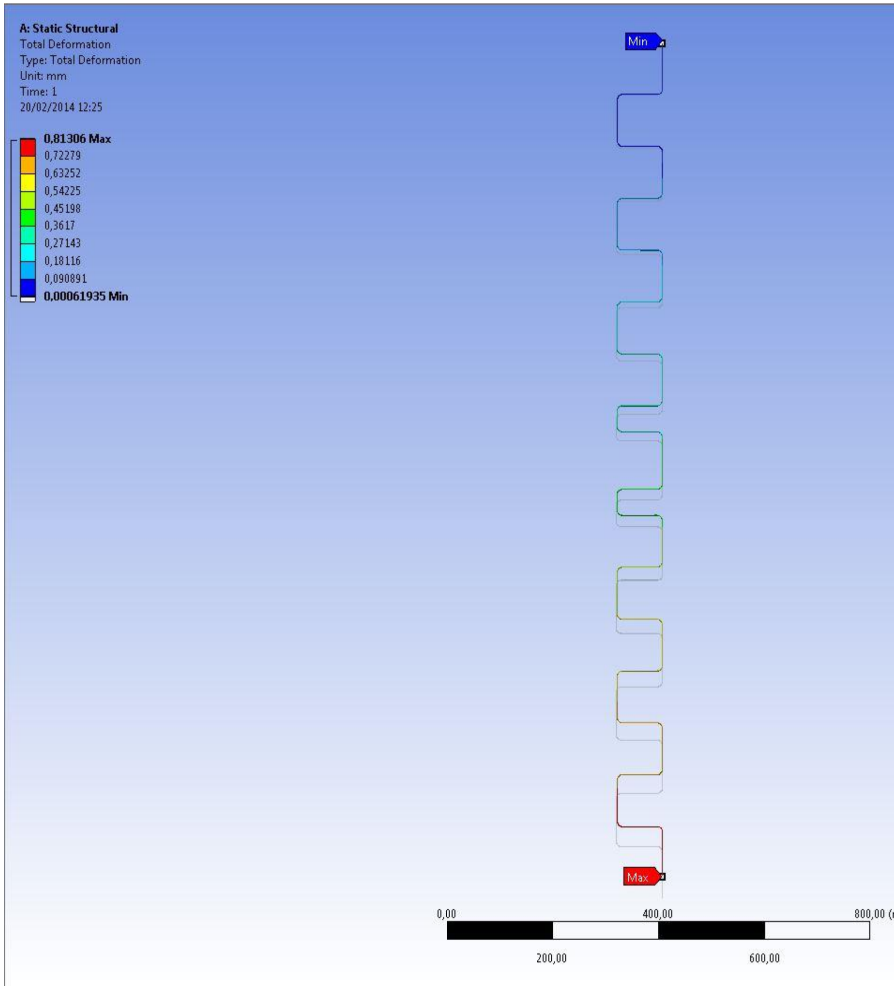
EQUIVALENT VON-MISES STRESS
CALCULATED IN THE SILICON SENSOR A1.T3:
1 e-5 MPa IS THE MAXIMUM VALUE, NEAR THE WIRE-BONDING
MEDIUM STRESS LEVEL AS LOW AS FRACTION OF A PASCAL

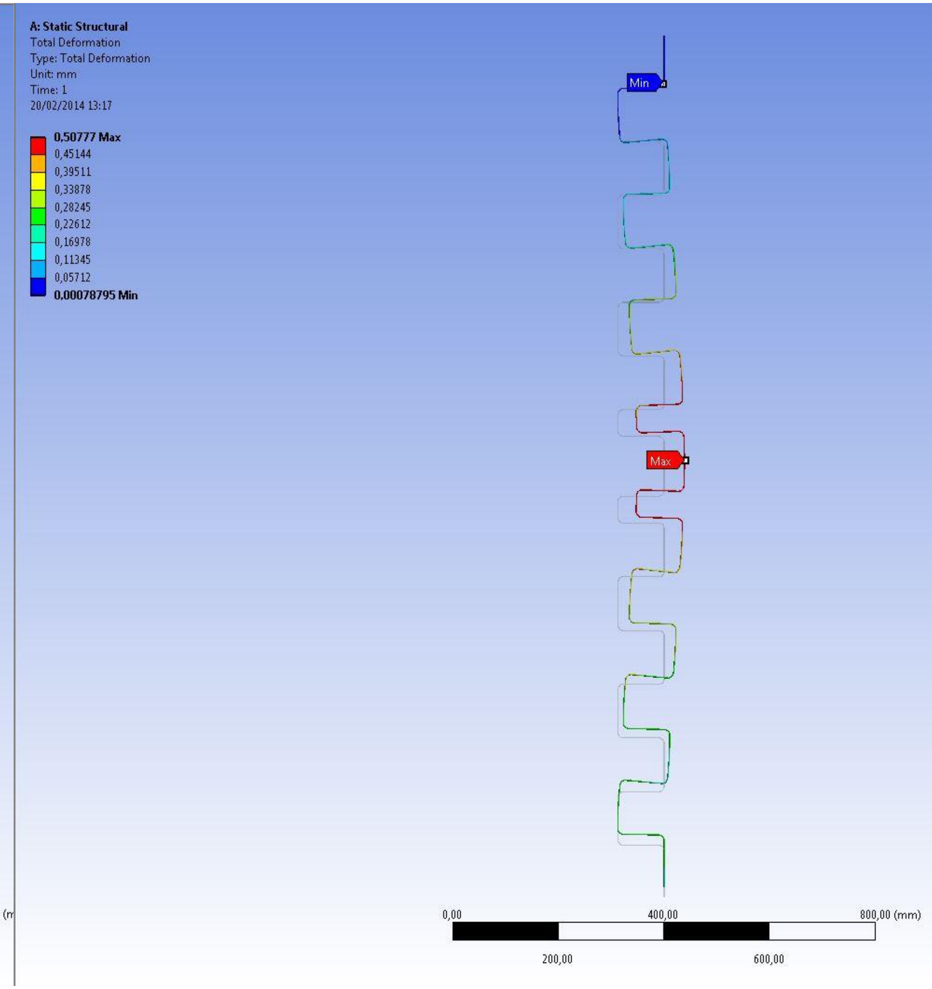
=> Conclusion:
Calculated deformations of the sensor, in vertical direction, are not representing a particular concern.

STAVE THERMO-MECHANICAL DEFORMATION

- PIPE TEMPERATURE SET TO - 25 °C
- THERMAL FIELD CALCULATED AT NOMINAL POWER
- THEN USED FOR THE STRUCTURAL FEA



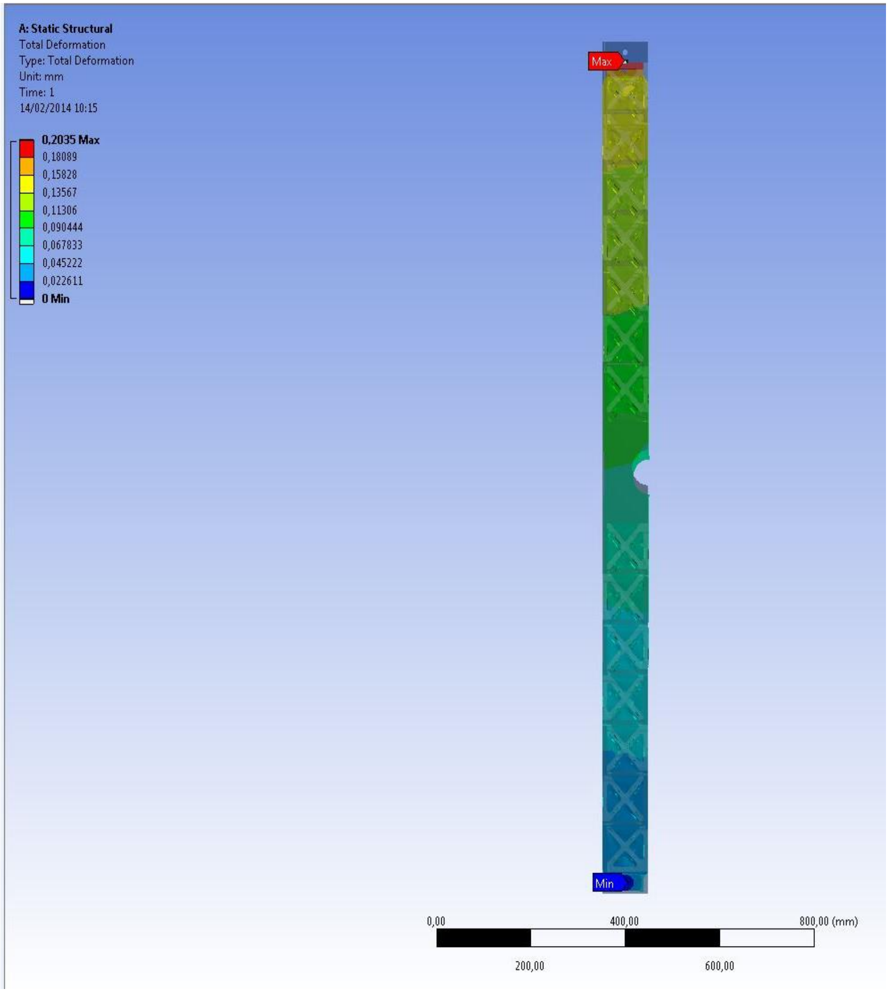




TITANIUM PIPE
DELTA T = - 60°C
MAX TOTAL DEFORMATION: 0.81 mm

TITANIUM PIPE
MDP = 10 MPa
MAX TOTAL DEFORMATION: 0.51 mm

Thermo mechanical F.E.A. - full length stave structural studies

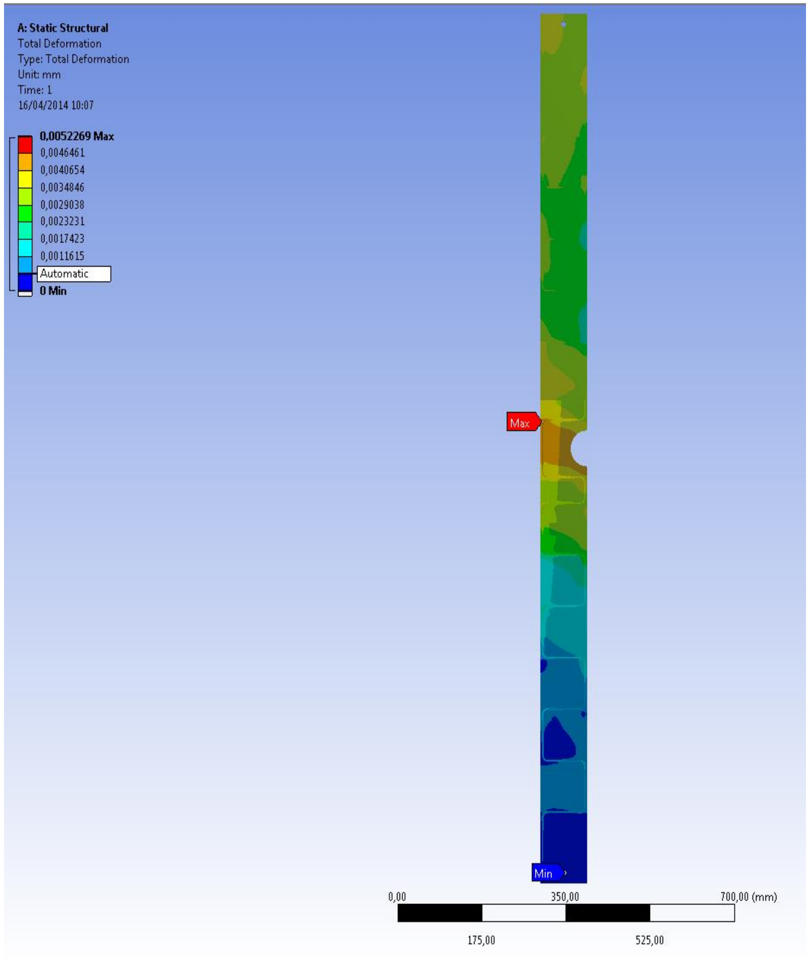


H.M. CFRP K13C-RS3

DELTA T = - 60°C

MAX TOTAL DEFORMATION: 0.20 mm

=> effect induced by the pipe contraction



H.M. CFRP K13C-RS3

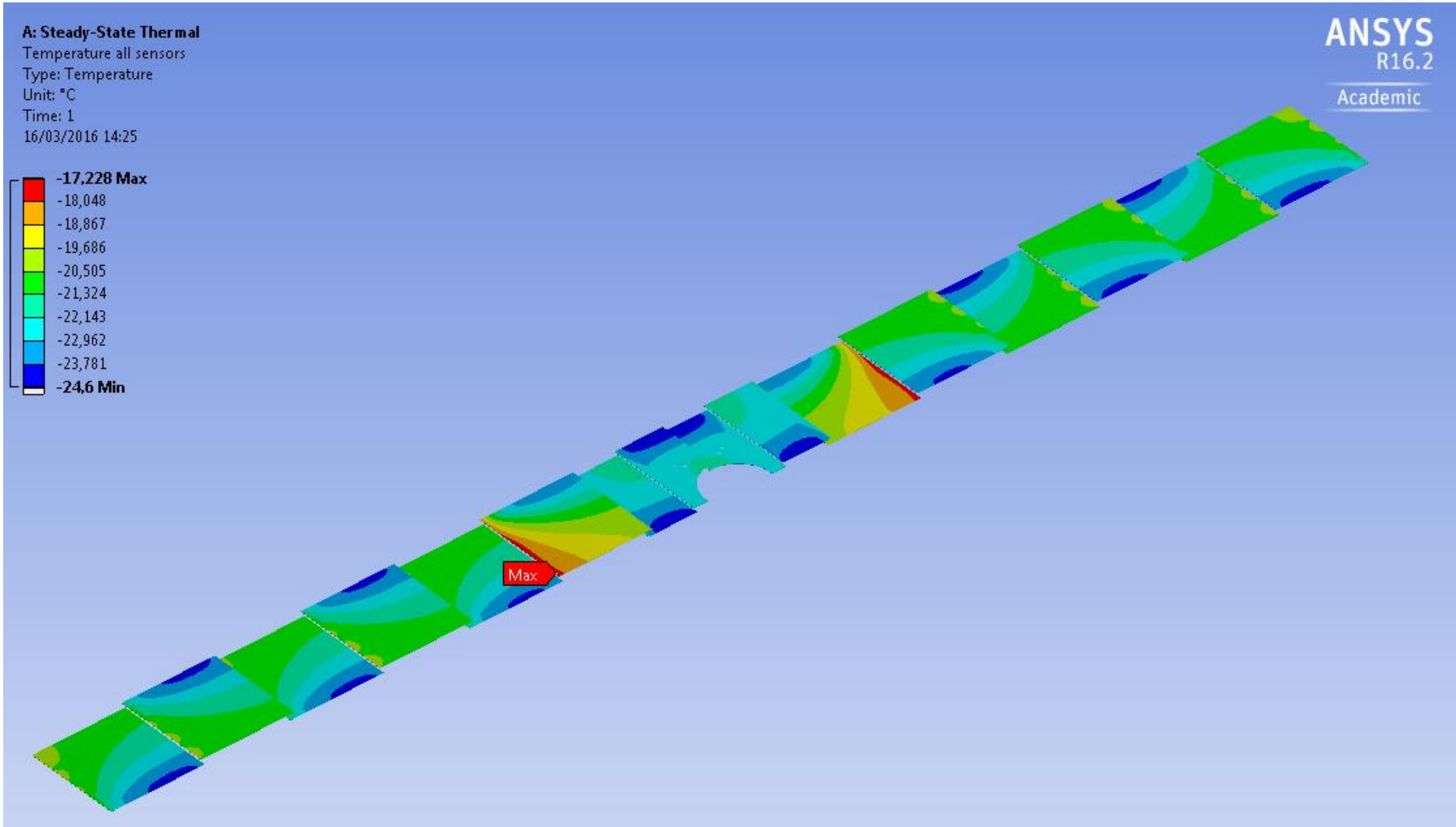
MDP = 10 MPa

MAX TOTAL DEFORMATION: 0.01 mm

=> Deformation induced by the pipe pressurization is almost negligible

FULL STAVE THERMO-MECHANICAL DEFORMATION

FULL STAVE UT STAVE type C THERMAL ANALYSIS RESULTS
SENSORS TEMPERATURE



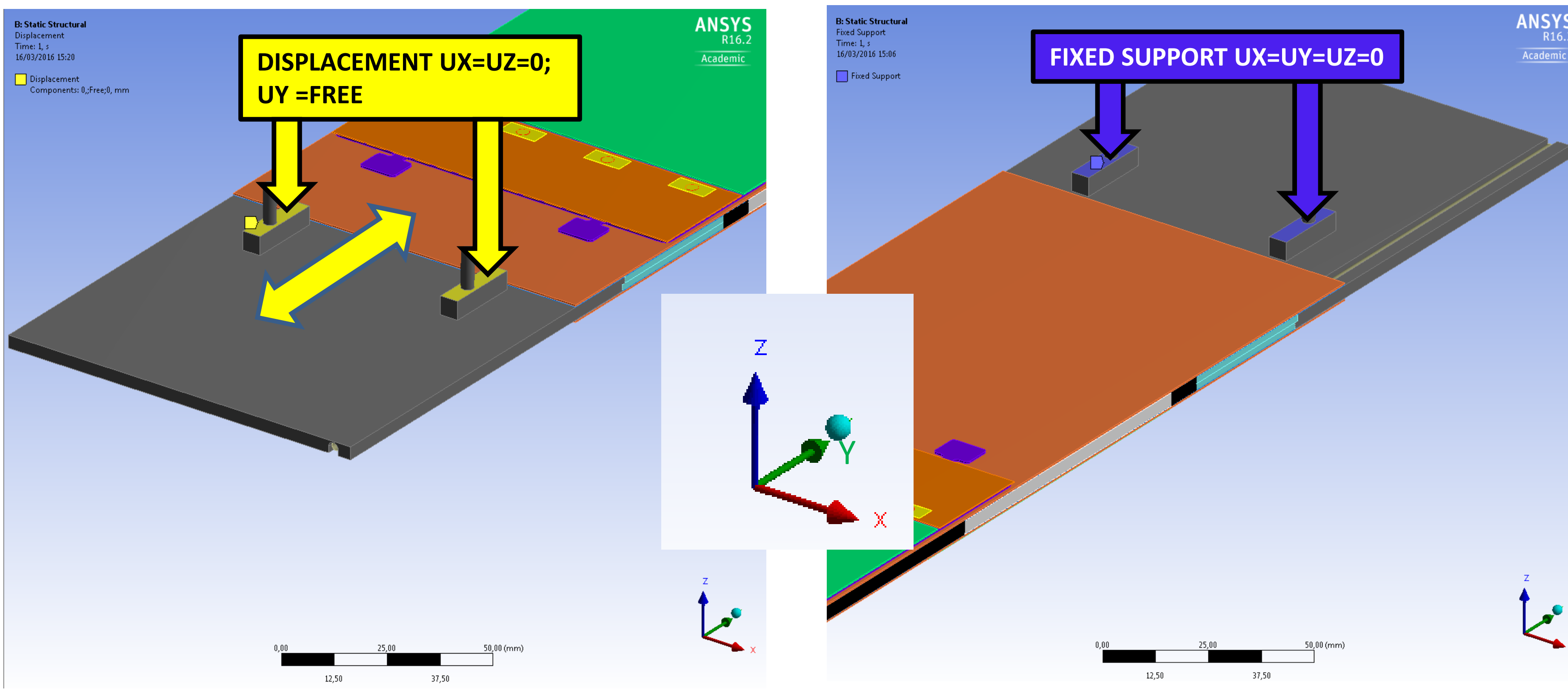
PIPE TEMPERATURE SET TO -25 °C

UT STAVE type C - THERMO-MECHANICAL ANALYSIS: BCs

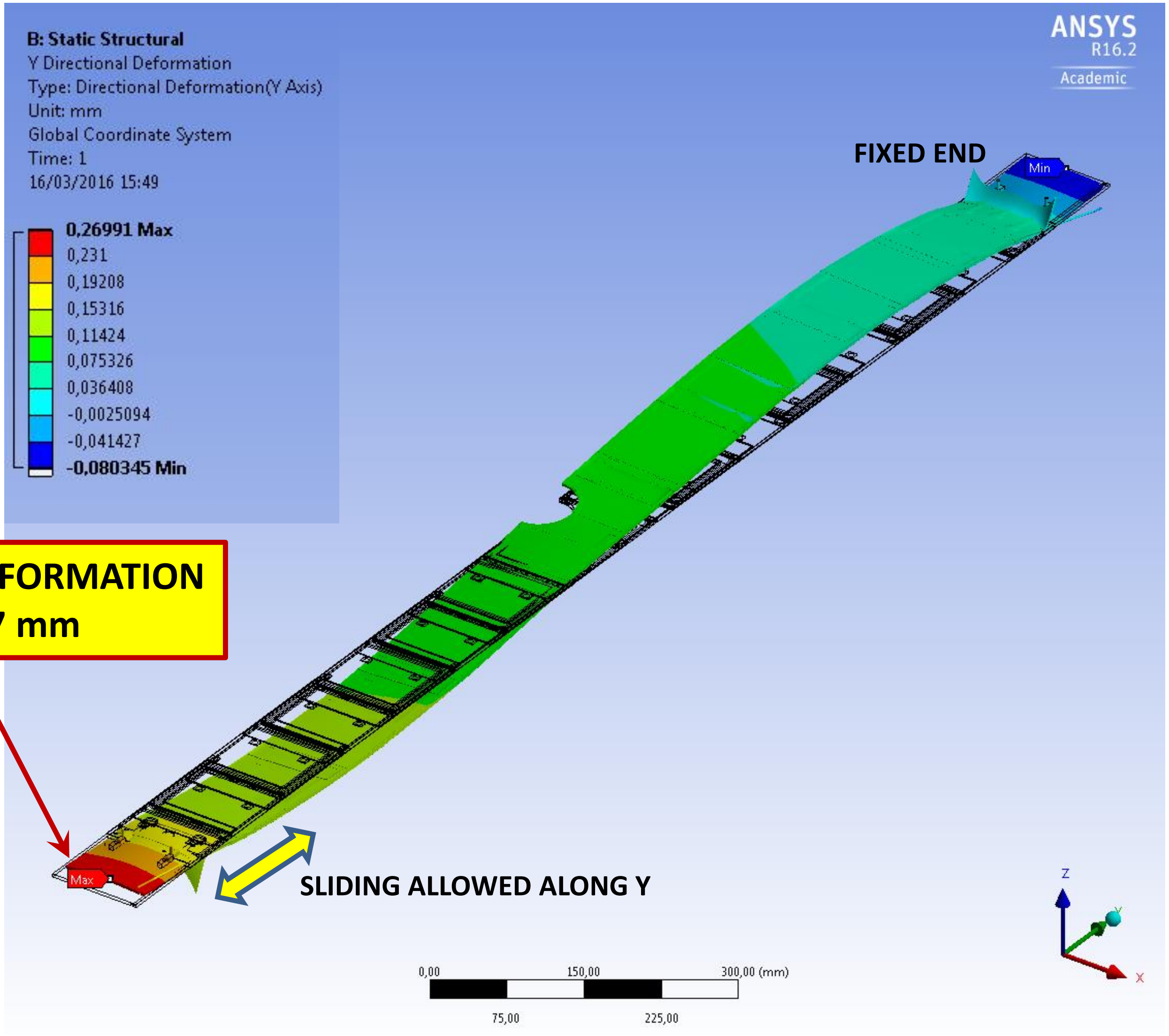
ONE END OF THE STAVE HAS BEEN CONSTRAINED AS FIXED SUPPORT.

THE OTHER END HAS BEEN CONSTAINED AS FIXED IN TRANSVERSAL (X) AND NORMAL TO MODULE (Z) DIRECTIONS AND FREE TO SLIDE IN THE LONGITUDINAL (Y) DIRECTION.

FOR BOTH ENDS EITHER THE TWO PLANAR FACES OF THE STAVE MOUNT IN ALUMINUM ALLOY HAVE BEEN CONSTRAINED.



UT STAVE type C - THERMO-MECHANICAL ANALYSIS
UY RESULTS



MAXIMUM Y DEFORMATION
UY = 0.27 mm

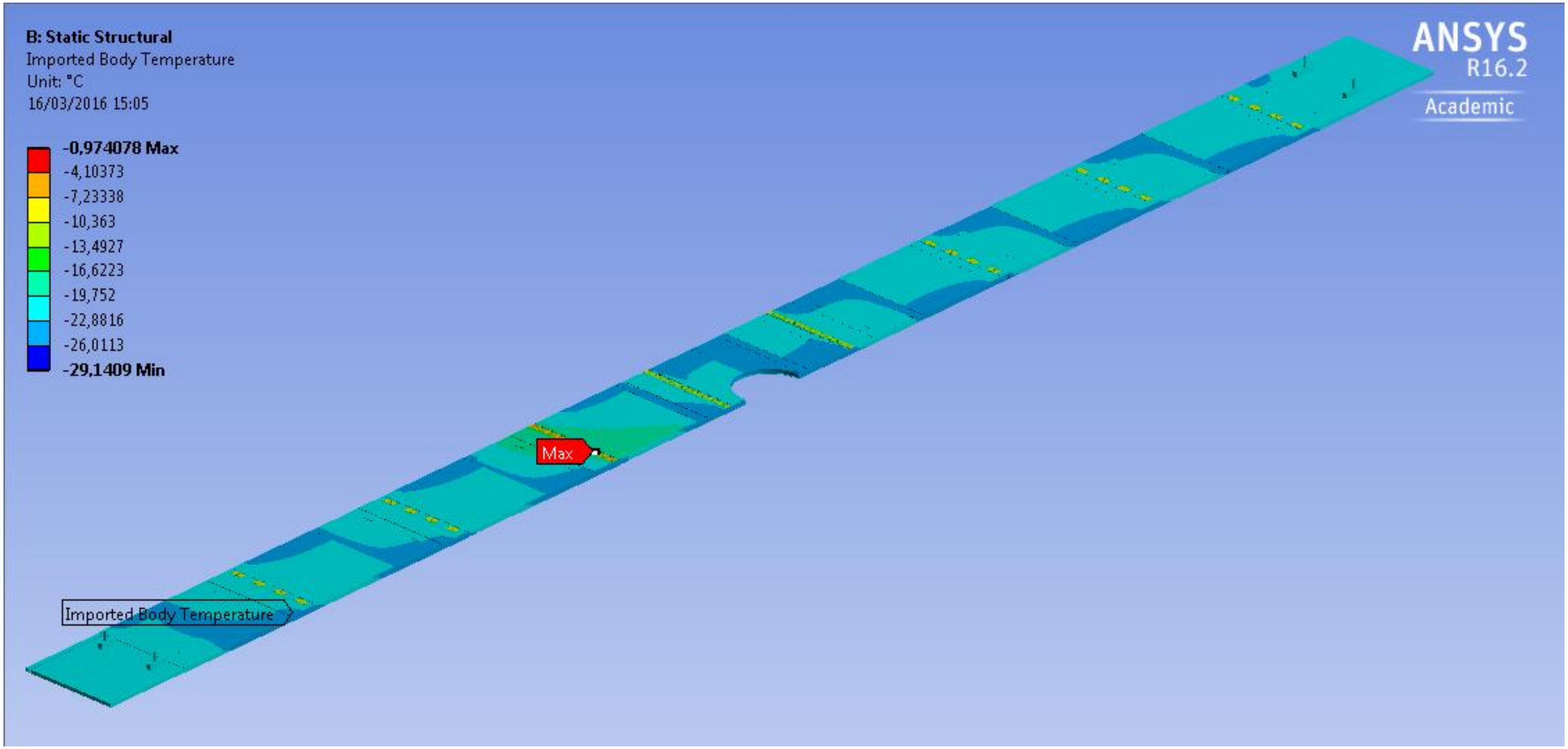
DEFORMATION AMPLIFICATION SCALE: 65

UT STAVE type C - THERMO-MECHANICAL ANALYSIS: FE MODEL and LOAD

THE THERMAL MODEL HAS BEEN SWITCHED IN THE MECHANICAL MODEL, CHANGING THE ELEMENTS TYPE BUT NOT THE NODES QUANTITY AND LOCATIONS.

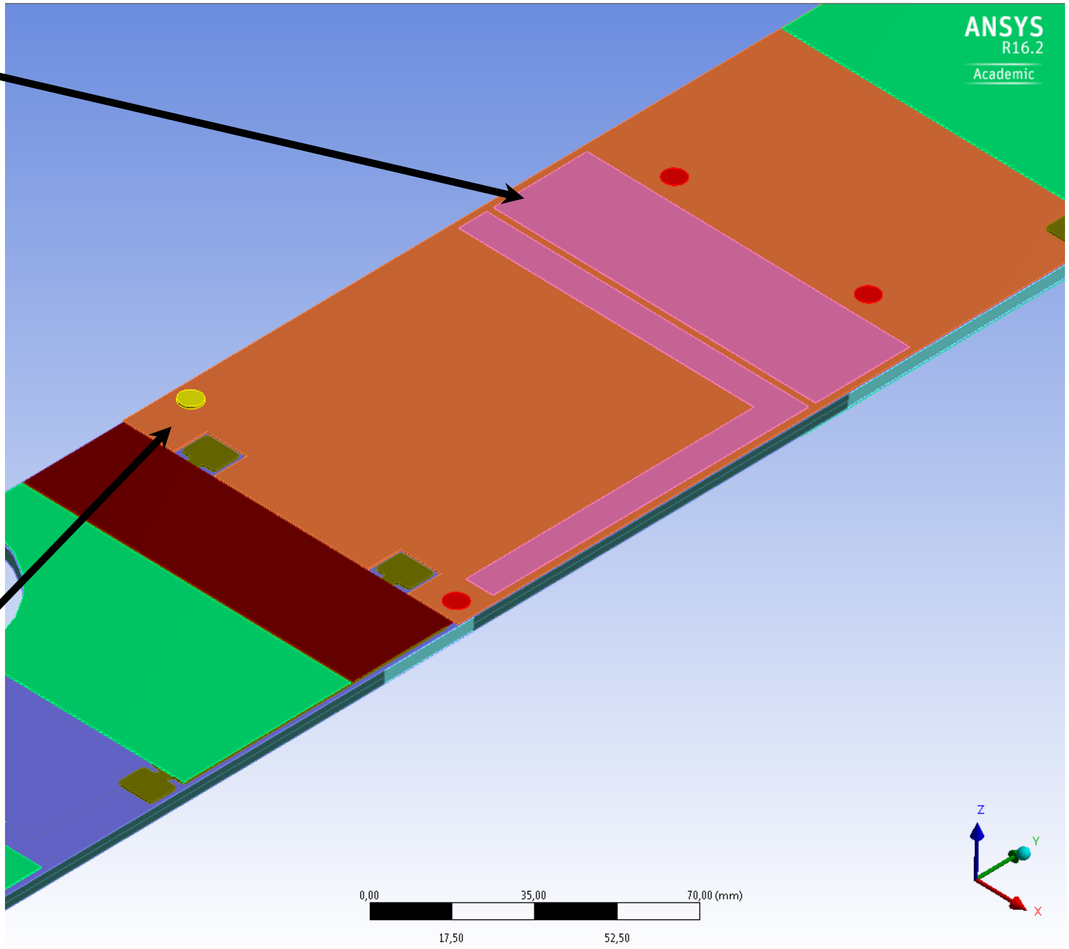
THE LOAD IS THE THERMAL FIELD OBTAINED BY THE THERMAL ANALYSIS AND IMPORTED IN THE MECHANICAL MODEL, NODE BY NODE.

THE COEFFICIENTS OF THERMAL EXPANSION OF THE MATERIALS HAVE BEEN ATTRIBUTED.



STAVE MODAL ANALYSIS

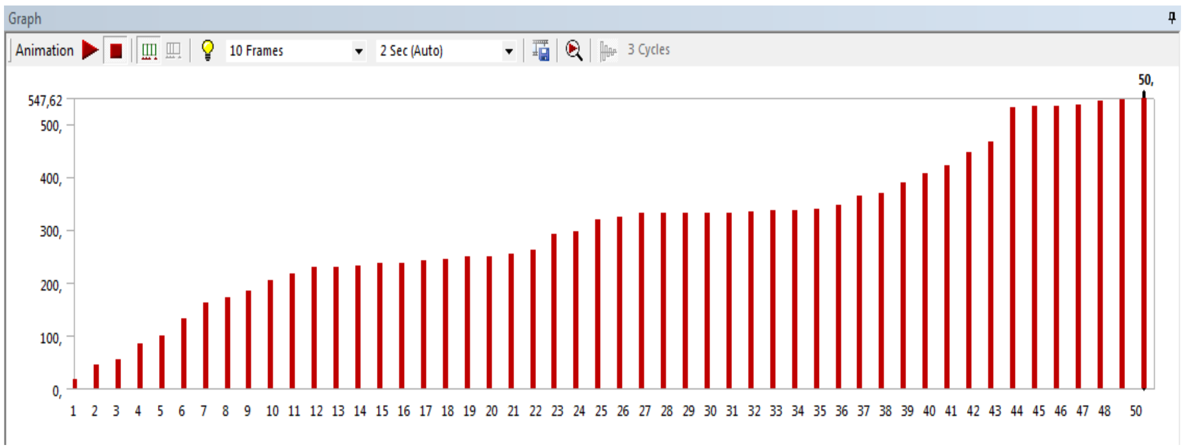
PHASE CHANGE
THERMAL INTERFACE
THERMFLOW T725
UNDERNEATH THE
STIFFENERS

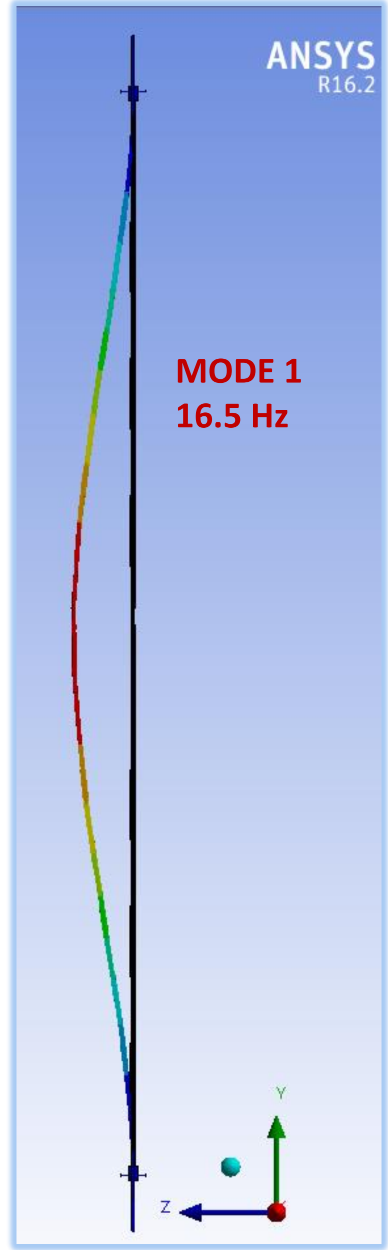


GLUE DOT NE0001
UNDERNEATH THE
FREE
SENSORS CORNER

STAVE MODAL ANALYSIS

STAVE MODAL FREQUENCY SPECTRUM





Tabular Data

	Mode	Frequency [Hz]
1	1,	16,479
2	2,	44,192
3	3,	55,53
4	4,	83,781
5	5,	100,46
6	6,	131,73
7	7,	162,75
8	8,	170,68
9	9,	185,27
10	10,	204,96
11	11,	217,52
12	12,	227,79
13	13,	229,55
14	14,	231,25
15	15,	236,97
16	16,	237,72
17	17,	242,15
18	18,	244,48
19	19,	249,16
20	20,	249,73
21	21,	253,14
22	22,	262,
23	23,	290,82
24	24,	296,76
25	25,	319,11
26	26,	324,17
27	27,	330,1
28	28,	330,16
29	29,	331,66
30	30,	331,79
31	31,	331,97
32	32,	333,6
33	33,	335,83
34	34,	336,72
35	35,	338,11
36	36,	344,83
37	37,	363,
38	38,	368,66
39	39,	387,23
40	40,	406,82
41	41,	419,48
42	42,	446,51
43	43,	464,81
44	44,	530,65
45	45,	531,62
46	46,	533,14
47	47,	534,13
48	48,	543,72
49	49,	545,07
50	50,	547,62

FEA MODAL RESULTS

	Mode	Frequency [Hz]
1	1,	16,479
2	2,	44,192
3	3,	55,529
4	4,	83,781
5	5,	100,46
6	6,	131,73