Istituto Nazionale
di Fisica Nucleare
Sezione di Milano

Forum on Tracking Detector Mechanics
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Calibrated orifices for CO_2 cooled detectors

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INFN MILANO

Working for LHCb UT and ATLAS ITk Endcap Collaborations

SUMMARY

- **ISSUES USING EVAPORATIVE COOLING**

- **COOLING SYSTEM DESIGN**

  IMPLEMENTING ORIFICES AS FLOW RESTRICTORS

- **ORIFICES CHARACTERIZATION**

  EXPERIMENTAL MEASUREMENTS WITH CO_2

- **PROS AND CONS**

INTRODUCTION

Focus on **Silicon particle trackers**

Detector **dissipate power:**

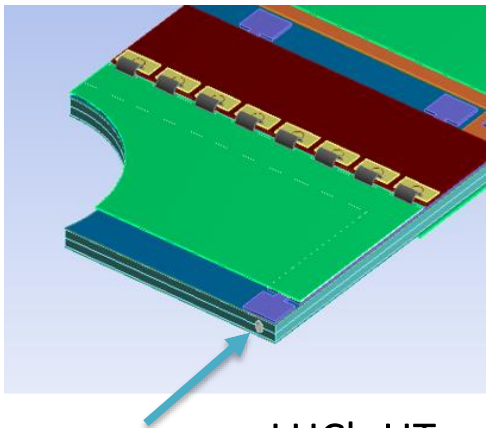
- main contribution: **Front-End electronics**
- The **Sensors dissipation increase** toward the end of life, in high-radiation environment, near interaction point

To survive ‘thermal run-away’:

- **thermal power** has to be extracted
- **sensor temperature** has to be maintained low, i.e. under -5 °C

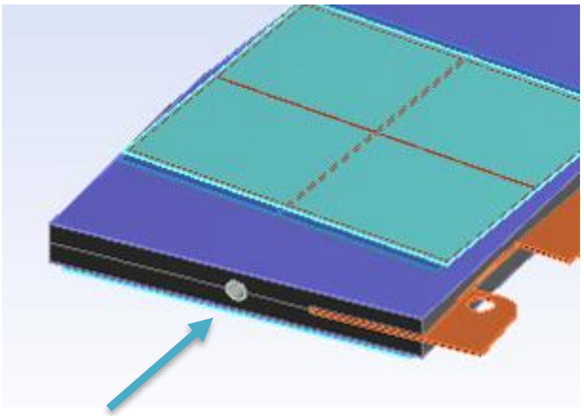
DETECTOR COOLING USING BOILING FLUIDS

Several trackers have a **cooling channel integrated** into the local support for the sensors



LHCb UT stave

CO_2 BOILING IN THE CHANNEL AT TEMPERATURES IN THE RANGE -20 °C …-40 °C



ATLAS ITk ENDCAP Half-ring

BENEFITS:

Good heat transfer efficiency

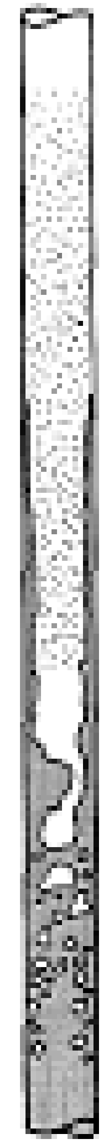
=> smaller flow-rate needed => smaller diameter => Less material => higher radiation length

Nearly uniform temperature

Saturation temperature drops slowly along the cooling channel in relation to the fluid pressure drop

DRAWBACKS USING BOILING FLUIDS

High pressure system
Max Design Pressure > 80 bar
(i.e. rupture disk installed dictates 130 bar)



Risk of thermal-hydraulic instabilities
When the detector has parallel evaporator channels
the circuit design is very important to ensure a margin against uneven flow distribution

Risk of dry-out
If the cooling flow-rate decreases in an evaporating channel
=> detector damage

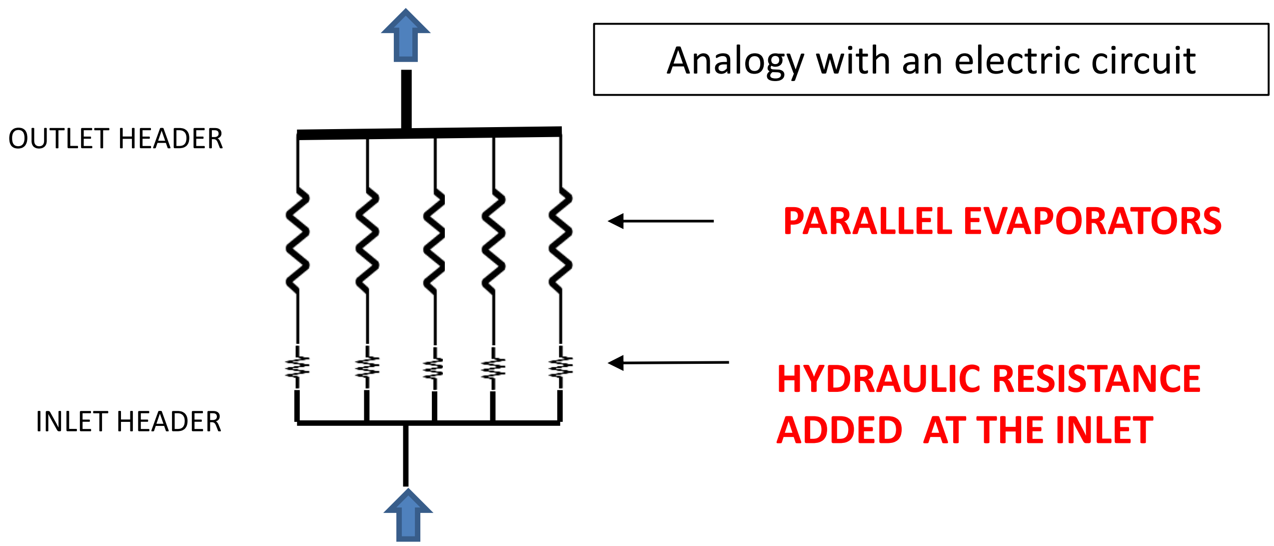
PARALLEL BOILING CHANNELS

For parallel evaporators connected to common headers:

❑ **Hydraulic resistance at the inlet improves stability:**

System less sensible to the pressure drop variations of the two-phase region

⇒ The cooling distribution has to implement INLET HYDRAULIC RESISTANCE that should **induce a pressure drop 5 … 10 times bigger than the EVAPORATORS pressure drop** in nominal operation



Both need to be:

1. **calculated**
2. **measured**

❑ **Hydraulic resistance at the evaporator outlet is detrimental**

=> avoid exhaust flow cross-section restrictions

boiling cooling system with parallel channels

↓

Add inlet hydraulic resistance

↓

Technical choice between:

- **Distribuited pressure drop => capillary pipes**
- **Local pressure drop => flow restrictors**

↓

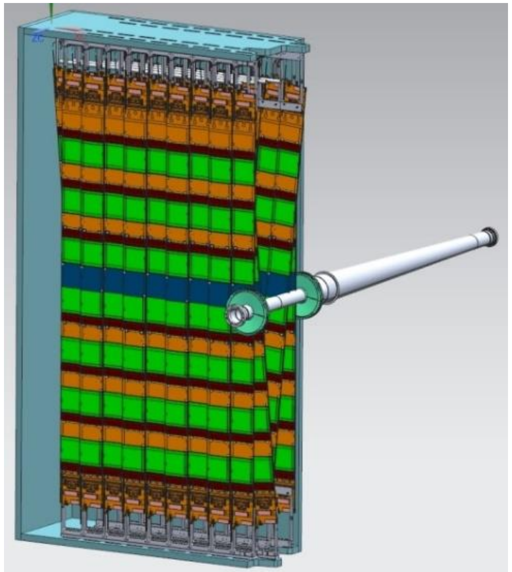
Evaporator characterization => to set the required inlet geometry

↓

Experimental set-up
to test and validate the design

COOLING SYSTEM DESIGN IMPLEMENTING ORIFICES AS FLOW RESTRICTORS

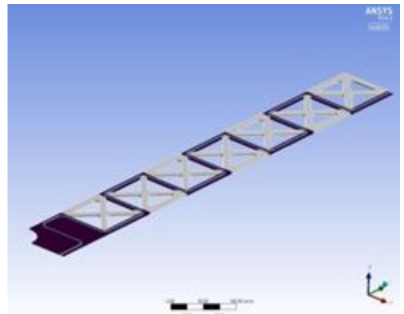
LHCb UT TRACKER



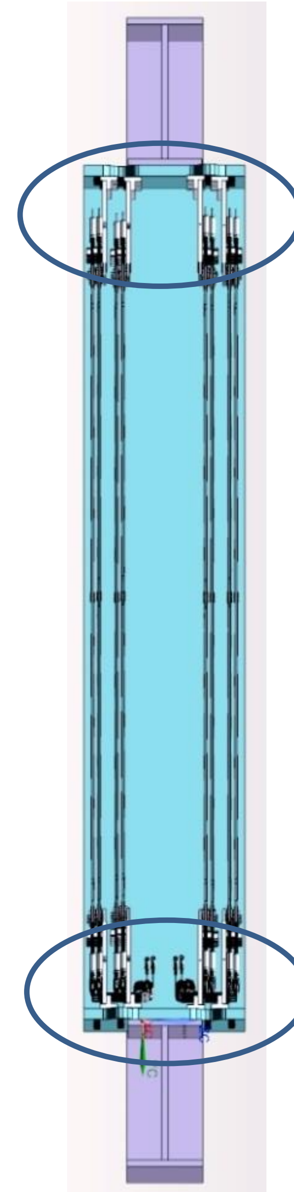
One half of the UT Box

Total cooling power ~ 4 kW

CO_2 evaporating in 68 parallel 'serpentines'



2 mm inner diameter
Titanium cooling pipe



EVAPORATORS Thermal-hydraulic characterization

Analytical calculations difficult when no correlations are available for peculiar design typologies

=> **Experimental investigation:**

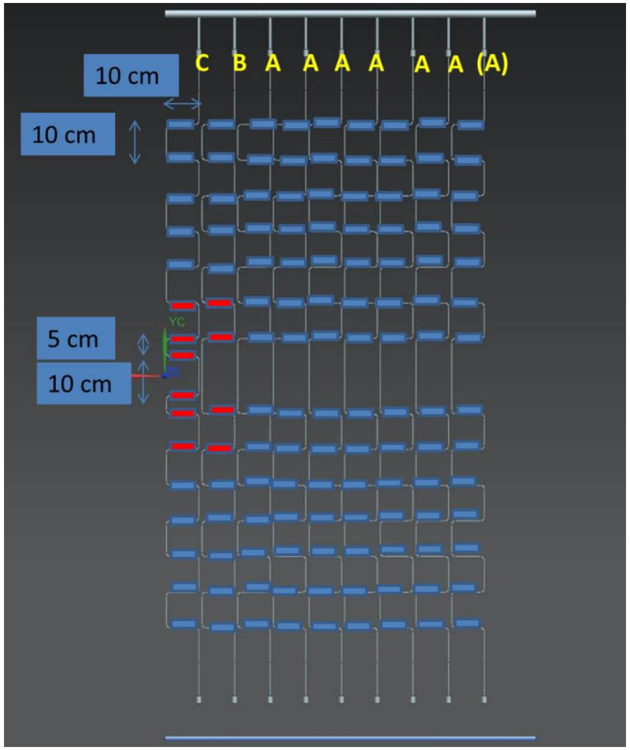
- **measurements on 1:1 prototypes**
- **Full power with dummy heaters**
- **TRACI 2-Phase Controlled Pressure cooling unit**

UT DETECTOR PARALLEL EVAPORATORS

UT is made of 8 similar units

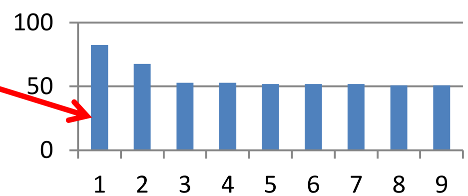
= 4 ASICs

= 8 ASICs



Read-out ASICs distribution

Central stave



Power (Watt)

Differencies beetwen parallel evaporators:

pipe in the central stave:

- Longer
- More bends

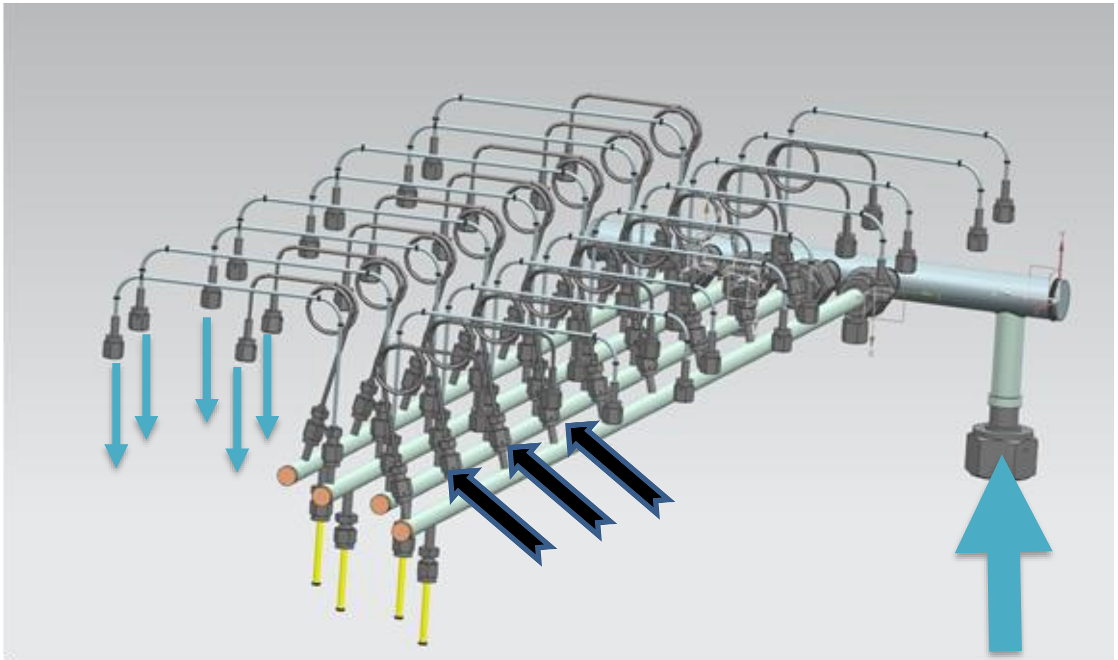
thermal load:

- Central sta 50% more power than lateral staves

Cental stave
measured pressure drop
at working point is around 350 mbar

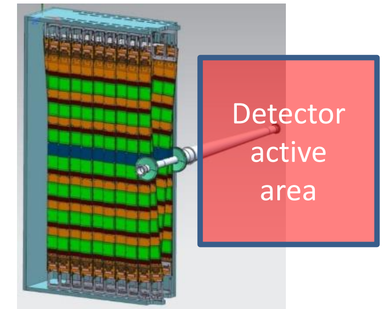
⇒ **design pressure drop for the inlet restrictors = 3 bar**

UT CO_2 DISTRIBUTION SYSTEM

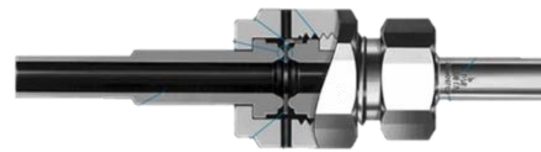


Manifolding and connection piping

LHCb UT manifold are outside the detector active area



=> Possible to use Swagelok Stainless Steel components



VCR connections are used in the assembly

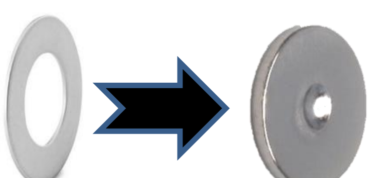
CALIBRATED ORIFICES are used as inlet flow restrictor

Advantages:

- **space saving** in a crowded area
- **no need for 68 capillaries** and additional joints

WARNING: install the flow restrictors on the correct side (the inlet)!

VCR gasket



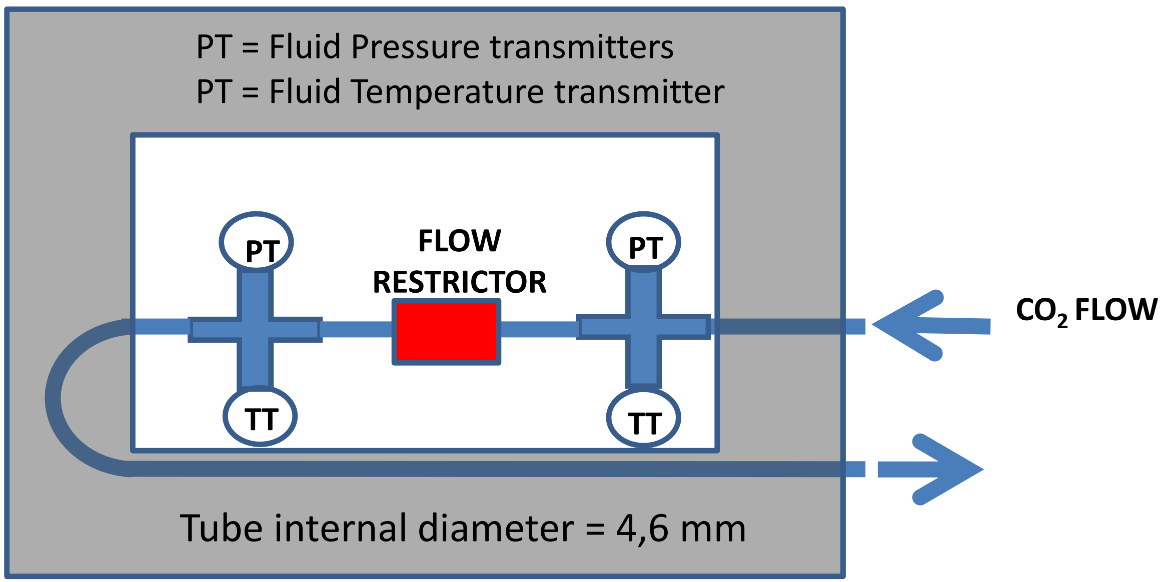
Laser orifices on VCR blind gaskets

ORIFICES CHARACTERIZATION EXPERIMENTAL MEASUREMENTS WITH CO_2

CHARACTERIZATION OF FLOW RESTRICTORS WITH CO_2

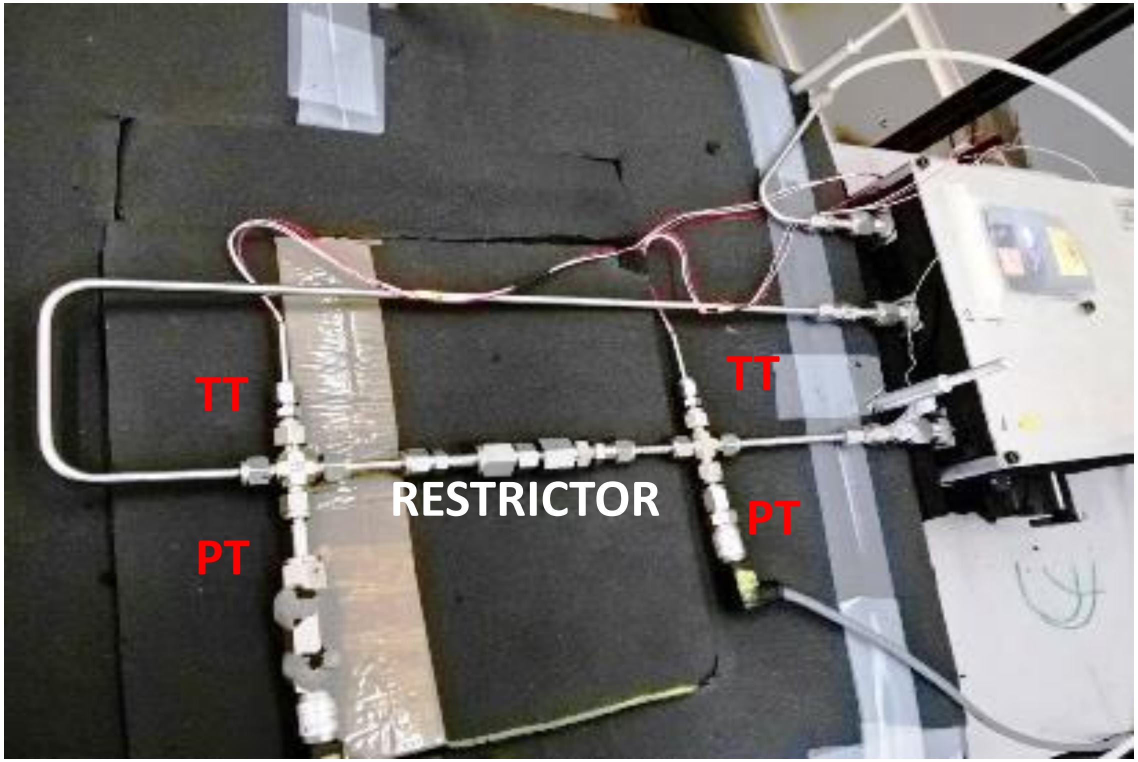
Experimental measurement of the hydraulic resistance to be mounted at the inlet

Investigations are in progress in Milano:
capillary and orifices
pressure drop and temperature drop



The actual work is dedicated to both the LHCb UT tracker and the ATLAS ITk Pixel Encap, but the measurements and outcomes can be **useful for any CO2 cooled system**

TEST CIRCUIT FOR THE CO2 TEST



TEST LOOP

- COLD-BOX WITH ARMAFLEX INSULATION
- CO_2 COOLING SUPPLY FROM TRACI COOLING UNIT WITH CO_2 MASS FLOW-RATE MEASUREMENT
- CO_2 PRESSURE AND TEMPERATURE TRANSMITTERS BEFORE/AFTER THE COMPONENT UNDER INVESTIGATION

Flow restrictors tested:

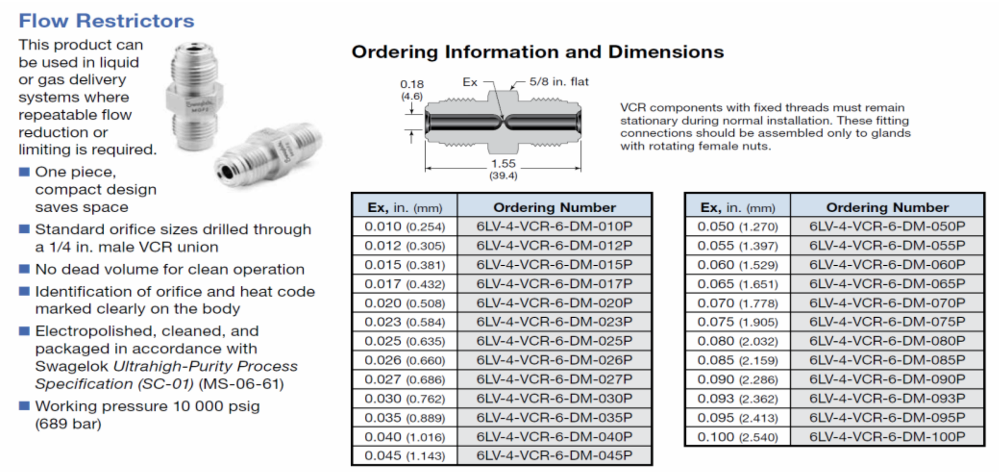
- **200 micron (0.008'') Laser orifice in VCR gasket**
- 250 micron (0.010'') Swagelok flow restrictor
- 305 micron (0.012'') Swagelok flow restrictor
- 380 micron (0.015'') Swagelok flow restrictor.

FLOW RESTRICTORS FOR THE CO_2 COOLING TEST

SWAGELOK ¼ INCH FLOW RESTRICTOR

FROM CATALOGUE:

6LV-4-VCR-6-DM-010P, 6LV-4-VCR-6-DM-012P, 6LV-4-VCR-6-DM-015P, 6LV-4-VCR-6-DM-017P



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

0.18 (4.6) Ex 5/8 in. flat 1.55 (39.4)

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

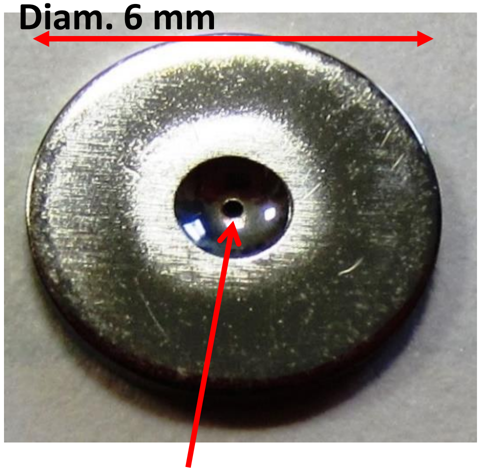
Ex, in. (mm)	Ordering Number
0.050 (1.270)	6LV-4-VCR-6-DM-050P
0.055 (1.397)	6LV-4-VCR-6-DM-055P
0.060 (1.529)	6LV-4-VCR-6-DM-060P
0.065 (1.651)	6LV-4-VCR-6-DM-065P
0.070 (1.778)	6LV-4-VCR-6-DM-070P
0.075 (1.905)	6LV-4-VCR-6-DM-075P
0.080 (2.032)	6LV-4-VCR-6-DM-080P
0.085 (2.159)	6LV-4-VCR-6-DM-085P
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

LASER HOLE IN VCR GASKET

CUSTOM ORIFICES:
200, 225, 250, 275 µm
OTHER GEOMETRICAL CHARACTERISTICS USABLE FOR THE PRESSURE DROP CALCULATION IS LENGTH l =0,2 mm

1/8 INCH VCR GASKET

Diam. 6 mm



Hole: 0,250 mm (= 250 µm)

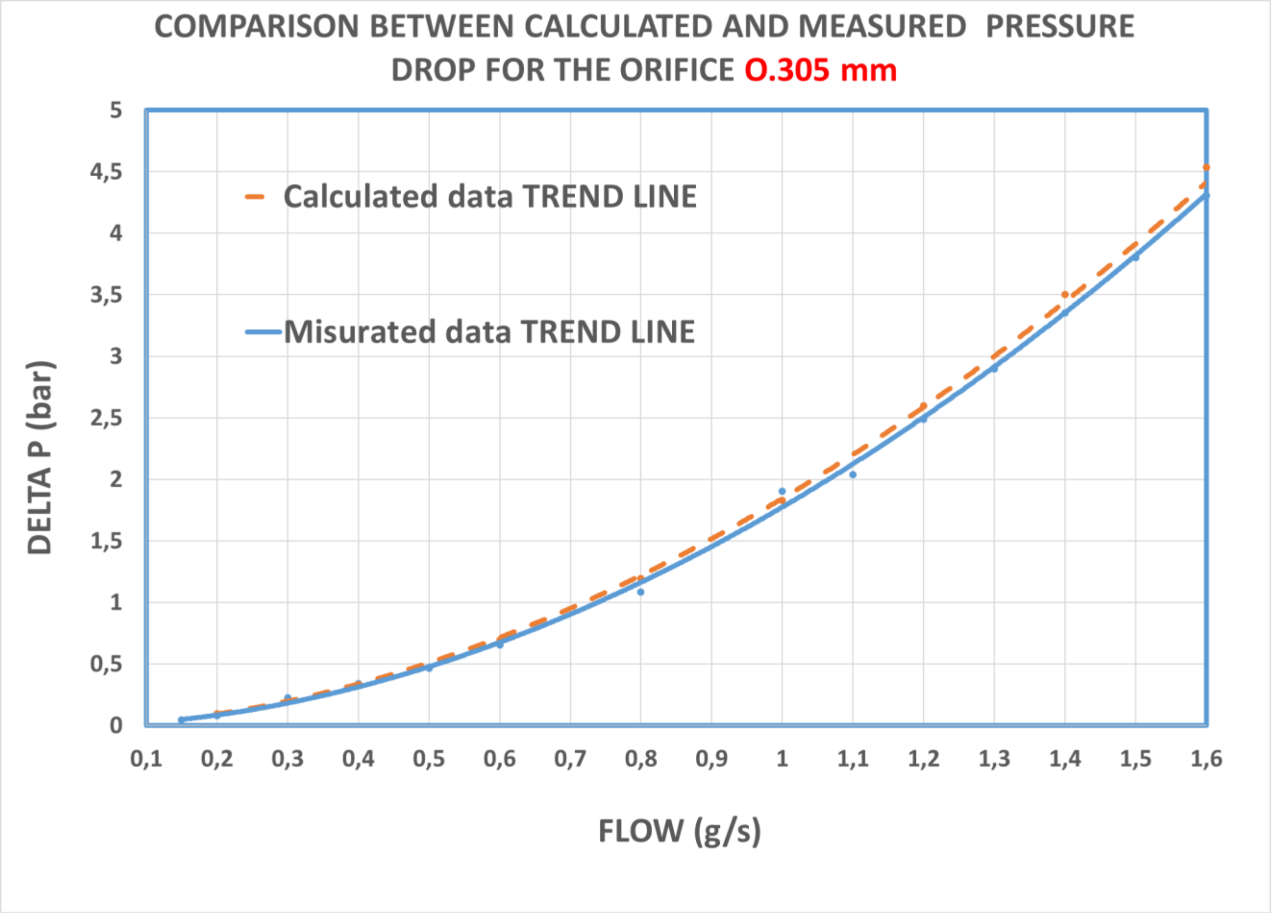
SPREADSHEET FOR ORIFICE PRESSURE DROP CALCULATION

Prediction formulas found in the “IDELCHIK HANDBOOK OF HYDRAULIC RESISTANCE” for the **‘THICK-EDGED ORIFICE’** model. We are outside range of validity in many cases.

pressure drop spread sheet				IN	OUT	
					SI Units of measurement	
d,orifice diameter	**305**	micron	0,305	mm	0,000305	m
D	diameter of the channel section before the narrow section of the stretch of the orifice		**4,6**	mm	0,0046	m
F_0	Area of the narrowest section of the stretch of the orifice			A=(π*ϕ^2)/4	7,30246E-08	m^2
F_1	Area of the channel section before the narrow section of the stretch of the orifice			A=(π*ϕ^2)/4	1,66106E-05	m^2
F_0/F_1					0,004	
F_1/F_0					227,465735	
l	lenght of the stretch, depth of the orifice		**1,5**	mm	0,0015	m
l/Dh	(Dh=d)				4,9180	
ρ	fluid density				**1050**	Kg/m^3
q_m	mass flow rate		**1**	g/s	0,001	Kg/s
w_1	mean stream velocity in the section before the narrowest section of the orifice				0,0573	m/s
l^-8					3,90184E+22	
ϕ(l')					0,785	
τ					0,393	
υ	CO_2 cinematic viscosity				**0,00000014**	m^2/s
R_e	Reynolds number				1883,888	
λ	friction coefficient of referred lenght of conduit (in laminar flow)				0,034	
ζ	resistance coefficient of stretch				105953,1229	
Δp	pressure drop			Δp=(ζ*ρ*w1^2)/2	182862	Pa
					1,83	**bar**

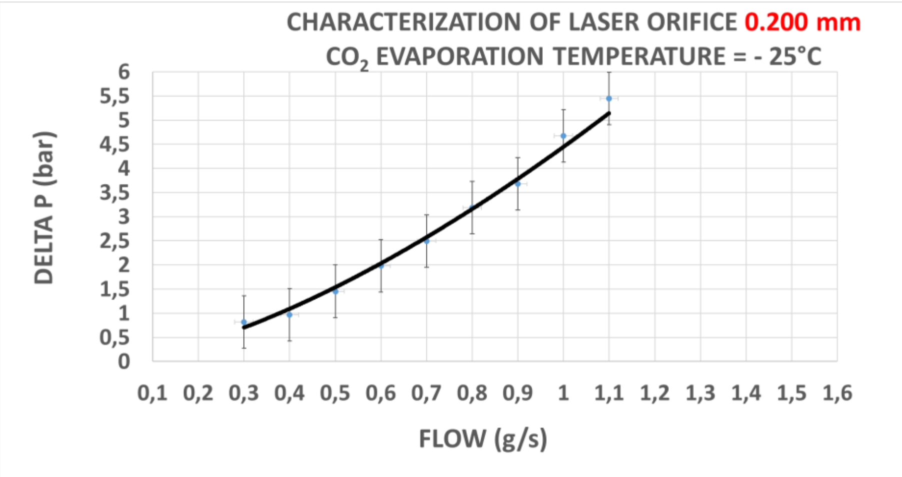
Geometrical parameters **CO_2 physical properties** **Flow parameter**

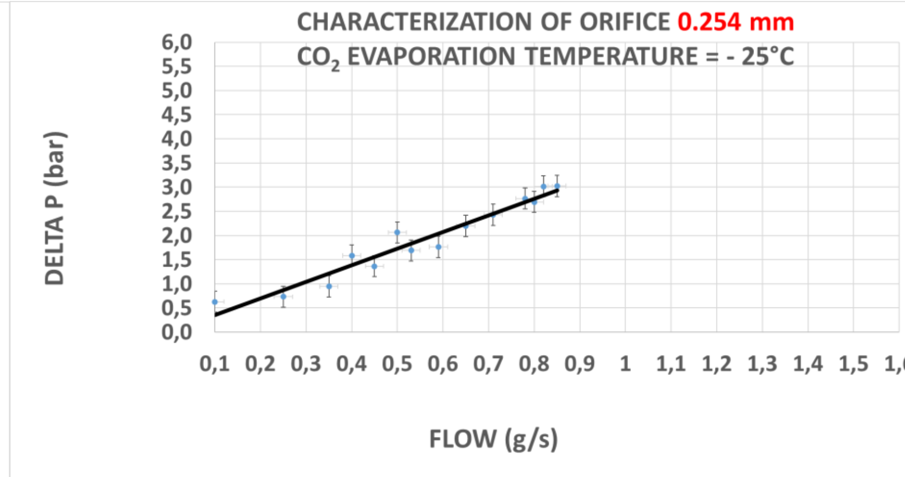
ORIFICE PRESSURE DROP CALCULATION-MEASUREMENT

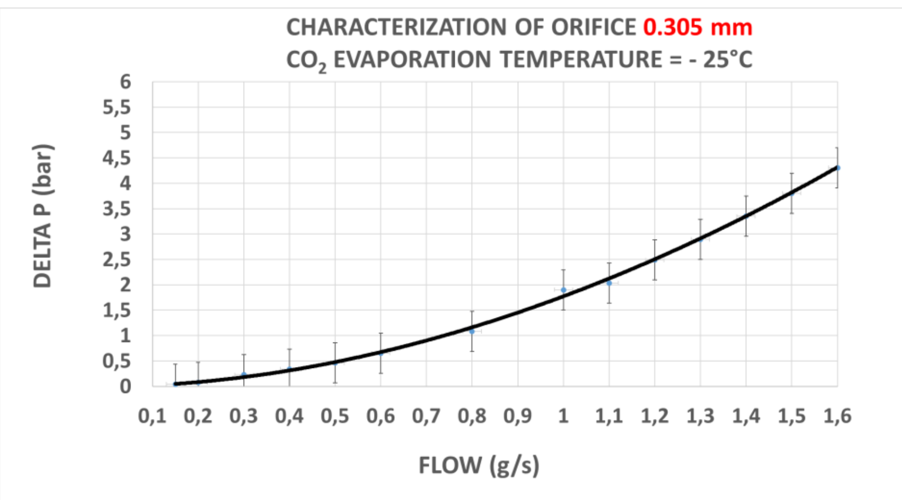


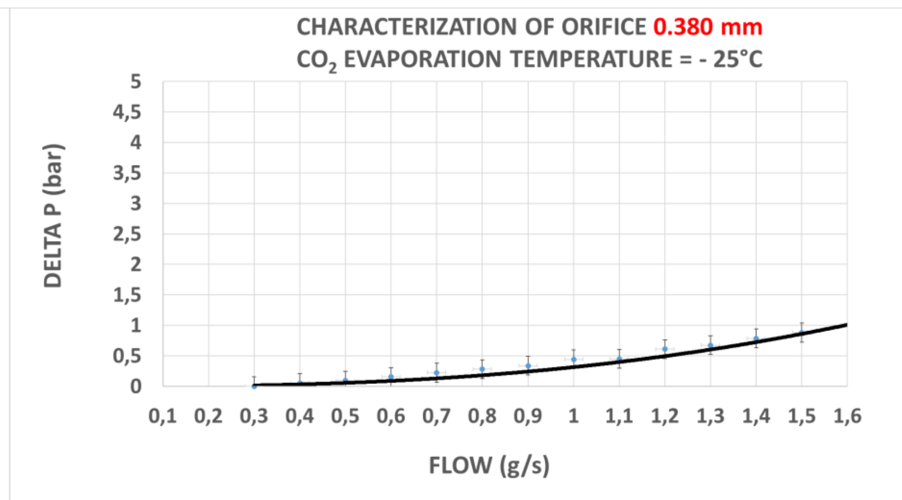
The expected parabolic behavior for a liquid pressure drop is observed here
Work in progress for the other geometries

MEASURED PRESSURE DROP VERSUS MASS FLOW-RATE AT SATURATION TEMPERATURE -25°C









PROS AND CONS

HYDRAULIC RESISTANCE ADDED AT THE INLET

CAPILLARY PIPE

- **Usually adopted solution**
- Require two connections at both sides
- Additional risk of leakage
- Can be long
- Can need to be coiled to reduce the necessary space

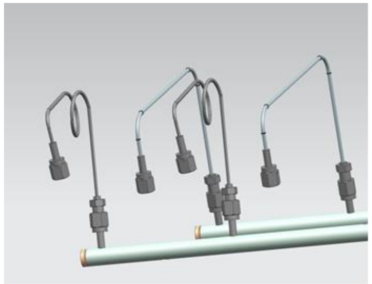
FLOW RESTRICTOR

- Less used in present tracker detectors
- A gasket (VCR) can become a restrictor
- **Small diameter orifice => risk of clogging**
- **IT IS MANDATORY**
  - **To use proper filtering elements**
  - **To use a pure fluid (no moisture)**
  - **Take care of the cleanness of the plant lines**
  - **Vacuum the lines before filling**

WORK IN PROGRESS

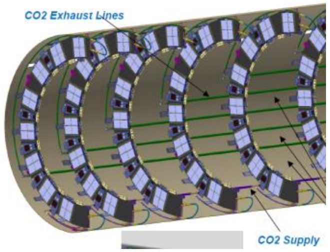
LHCb UT

- Manifold and connection pipe **prototype is under construction**
- Prototypes will be used at CERN for integration and cooling test



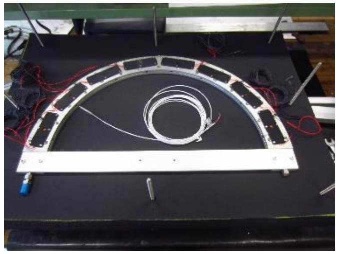
ATLAS ITk Pixel Encap

- Distribution system in this detector is **inside the active area**
- Titanium CO_2 piping
- We're going to make **thermal-hydraulic characterization** of Half-Ring prototypes on the CO_2 Baby-demonstrator



Under study:

- the **use of flow restrictors** alternative to capillary pipes
- the feasibility to **embed an orifice into the electrical breaker**



General

- On BD cooling plant we'll try to **extend the measurements on flow restrictors at larger flows**
- Define a spreadsheet for pressure drop predictions

Acknowledgements

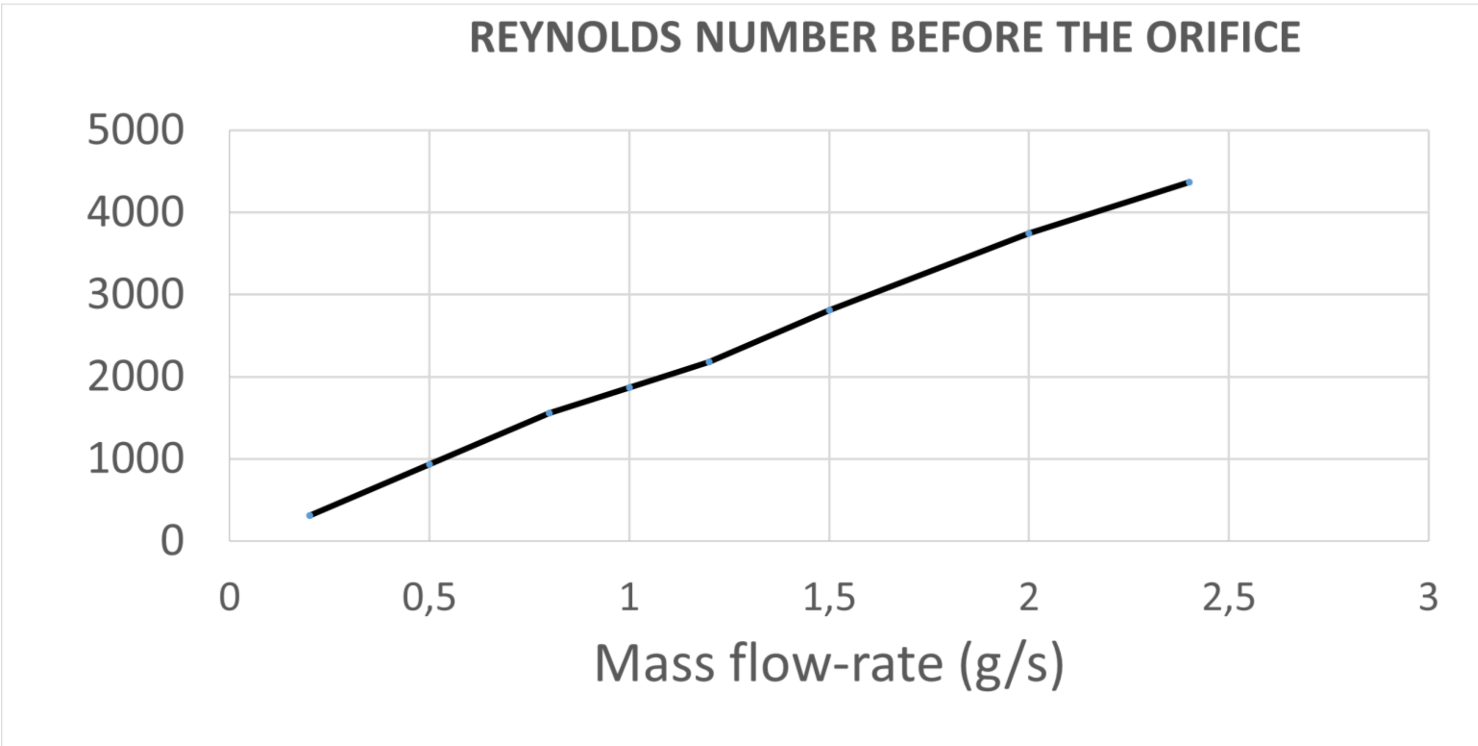
Special thanks to the CERN cooling team
always supporting our work

Thanks for the Attention

E-mail: coelli@mi.infn.it

Back-up slides =>

ESTIMATION OF THE FLOW REYNOLDS NUMBER



CO_2 PHYSICAL PROPERTIES:

Saturation Properties for Carbon Dioxide CO_2
In the range of interest: -20 °C …-40 °C

CO_2 physical properties <u>used in the pressure drop calculation</u>:

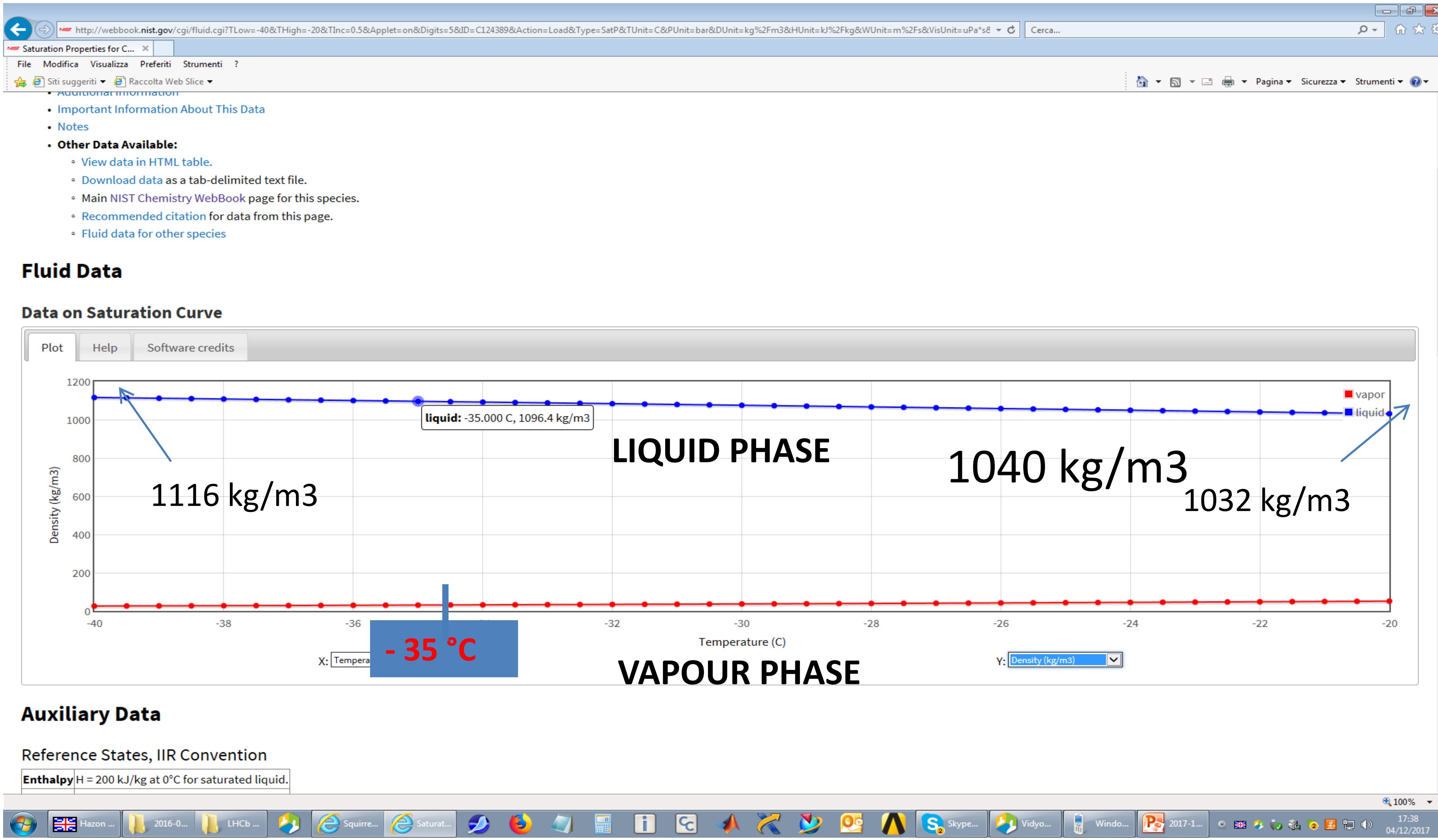
- **Density**
- **Dynamic viscosity**

(note: Kinematic viscosity is the ratio of dynamic viscosity to density)

Next slides show some plots captured from the web site of National Institute of Standards and Technology (NIST)

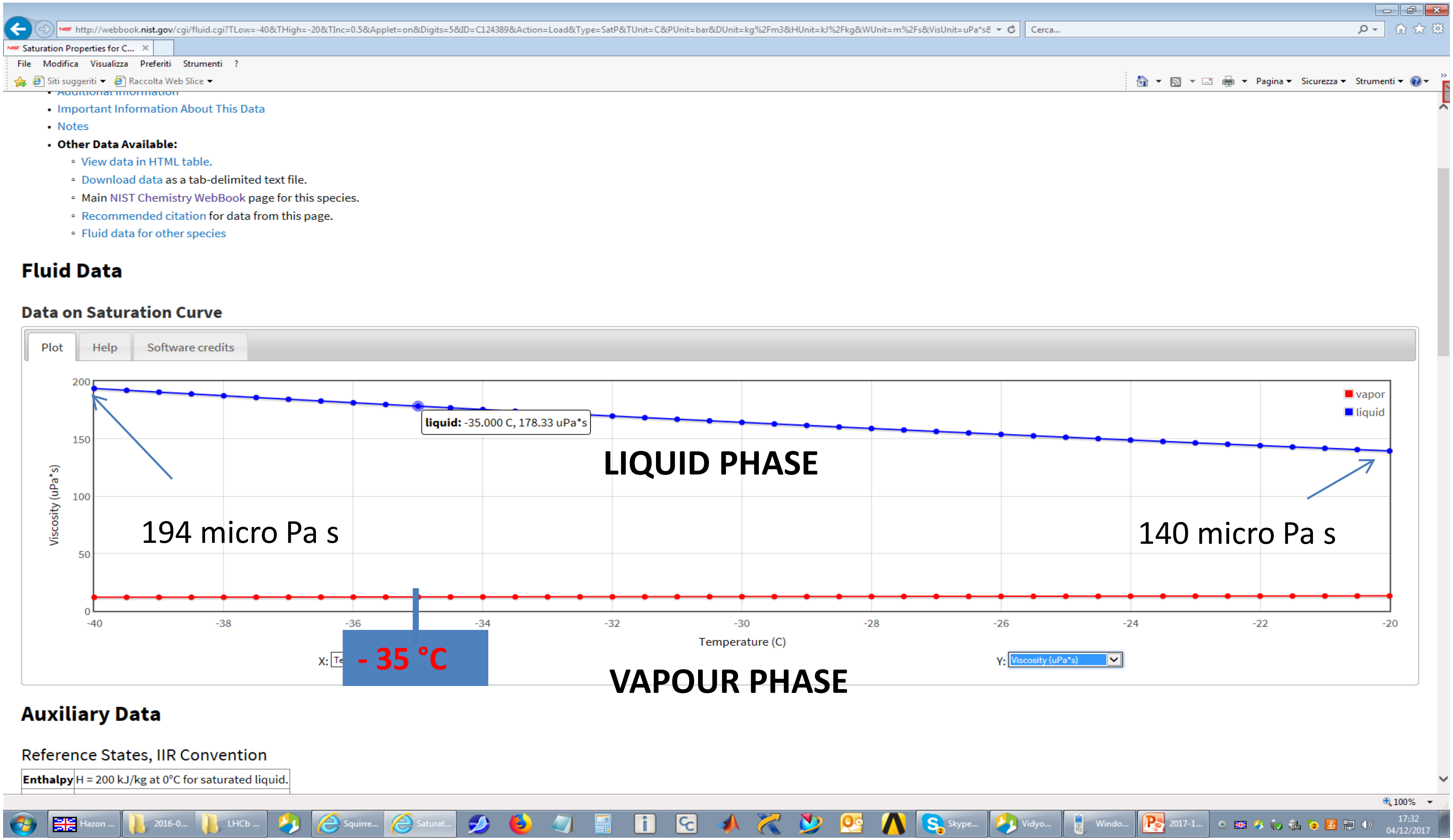
CO2 temperature = -25 °C
CO2 Density at -25°C = 1040 Kg/m3
CO2 Viscosity at -25 °C = 150 micro Pa s

CO_2 DENSITY



Important Information About This Data
Notes
Other Data Available:
View data in HTML table.
Download data as a tab-delimited text file.
Main NIST Chemistry WebBook page for this species.
Recommended citation for data from this page.
Fluid data for other species
Fluid Data
Data on Saturation Curve
Plot
Help
Software credits
liquid: -35.000 C, 1096.4 kg/m3
LIQUID PHASE
1116 kg/m3
1040 kg/m3
1032 kg/m3
vapor
liquid
Density (kg/m3)
Temperature (C)
- 35 °C
VAPOUR PHASE
Auxiliary Data
Reference States, IIR Convention
Enthalpy H = 200 kJ/kg at 0°C for saturated liquid.

CO_2 Dynamic Viscosity:



Kinematic viscosity is the ratio of *dynamic viscosity to density*

CO_2 Enthalpy liquid to vapour:

THIS FIGURE IS USED TO CALCULATE THE NEEDED COOLING MASS FLOW-RATE

- **FOR A GIVER DIISIPATED POWER**
- **AND FOR A GIVEN CO_2 EXHAUST (DETECTOR OUTLET) VAPOUR FRACTION, i.e. X_{OUT}= 30 %**

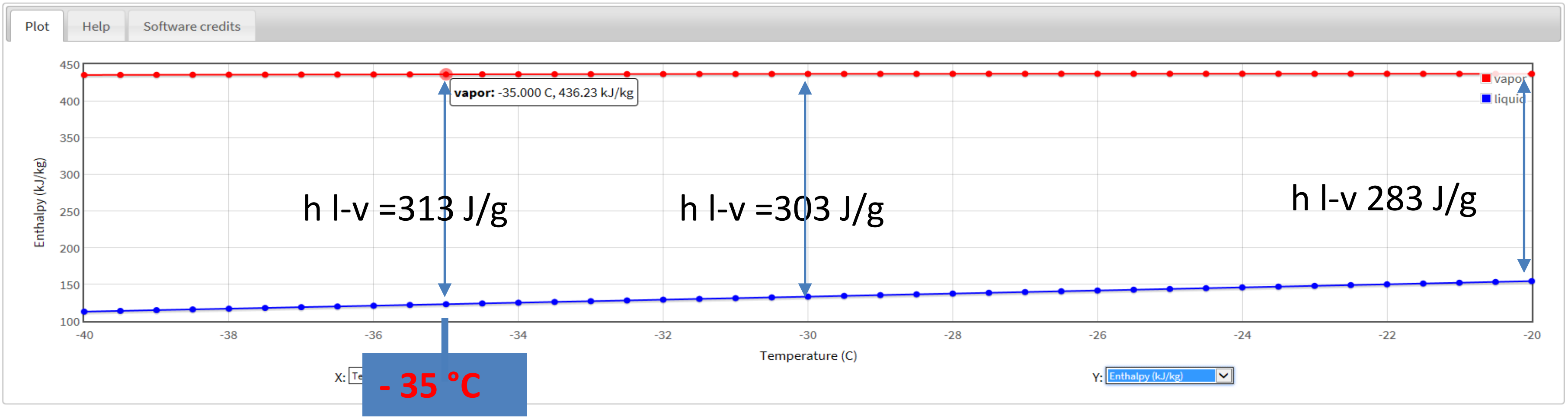
- Notes
- **Other Data Available:**
  - View data in HTML table.
  - Download data as a tab-delimited text file.
  - Main NIST Chemistry WebBook page for this
  - Recommended citation for data from this pa
  - Fluid data for other species

- **Dissipated power Q (W)**
- **Outlet vapour fraction X out (%)**
- **Latent heat of vaporization H vap - h liq = H l-v (J/g)**

=> calculated FLOW (g/s) = Q (W) / (0,30 * H l-v (J/g))

Fluid Data

Data on Saturation Curve



Auxiliary Data

Reference States, IIR Convention

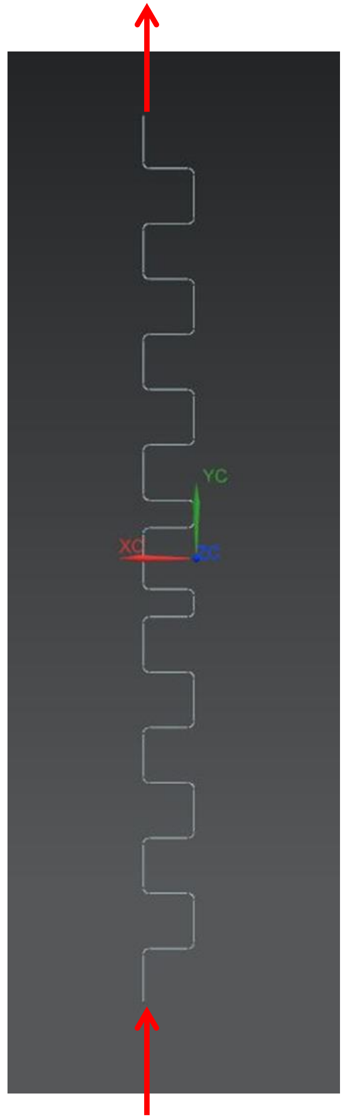
Enthalpy	H = 200 kJ/kg at 0°C for saturated liquid.

STAVE ENERGY BALANCE

Inlet:
CO_2 liquid near to saturation

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

$\Gamma\ CO_2$



$\Gamma\ CO_2$

MASS FLOW-RATE CALCULATION:
$\Gamma\ CO_2 = POWER / X_{OUT} * \Delta H_{LIQ\text{-}VAP}$

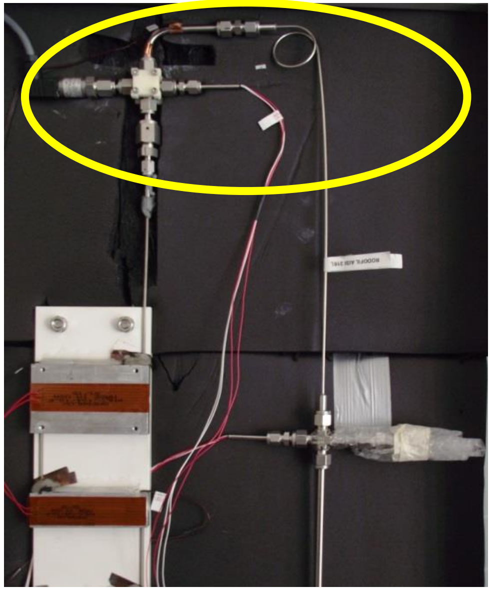
CENTRAL "C" STAVE
X OUT = 30 % =>
Γ = 75 W / 0,3*280 J/g = ~ 0.9 g/s

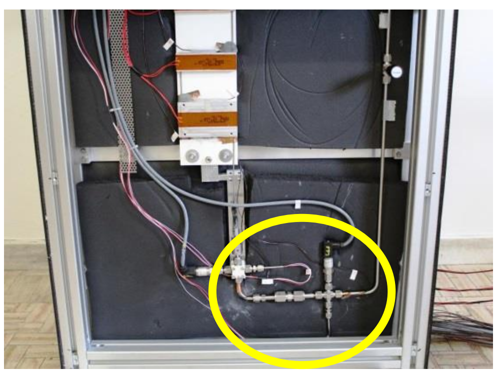
LATERAL "A" STAVE
X OUT = 30 % =>
Γ = 50 W / 0,3*280 J/g= ~ 0.6 g/s

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

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 ΔP OF THE CIRCUIT COMPONENTS SHOULD GUARANTEE THE STABILITY IN THE EVAPORATING PARALLEL CHANNELS