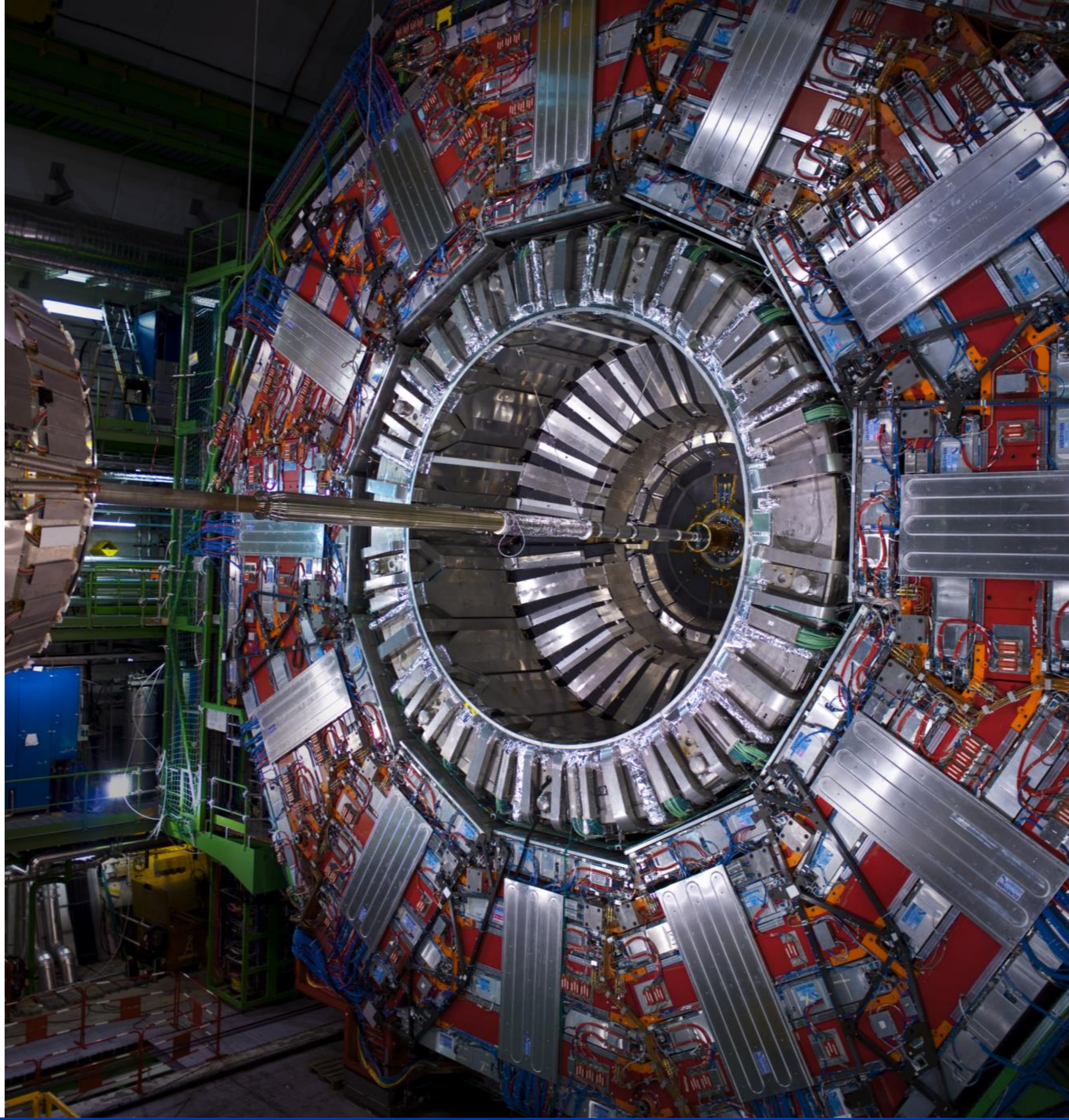
Flow distribution capillary tube testing for the CMS silicon detector upgrades

Forum on Tracking Detector Mechanics 2024
Purdue University, Indianapolis, Indiana U.S.

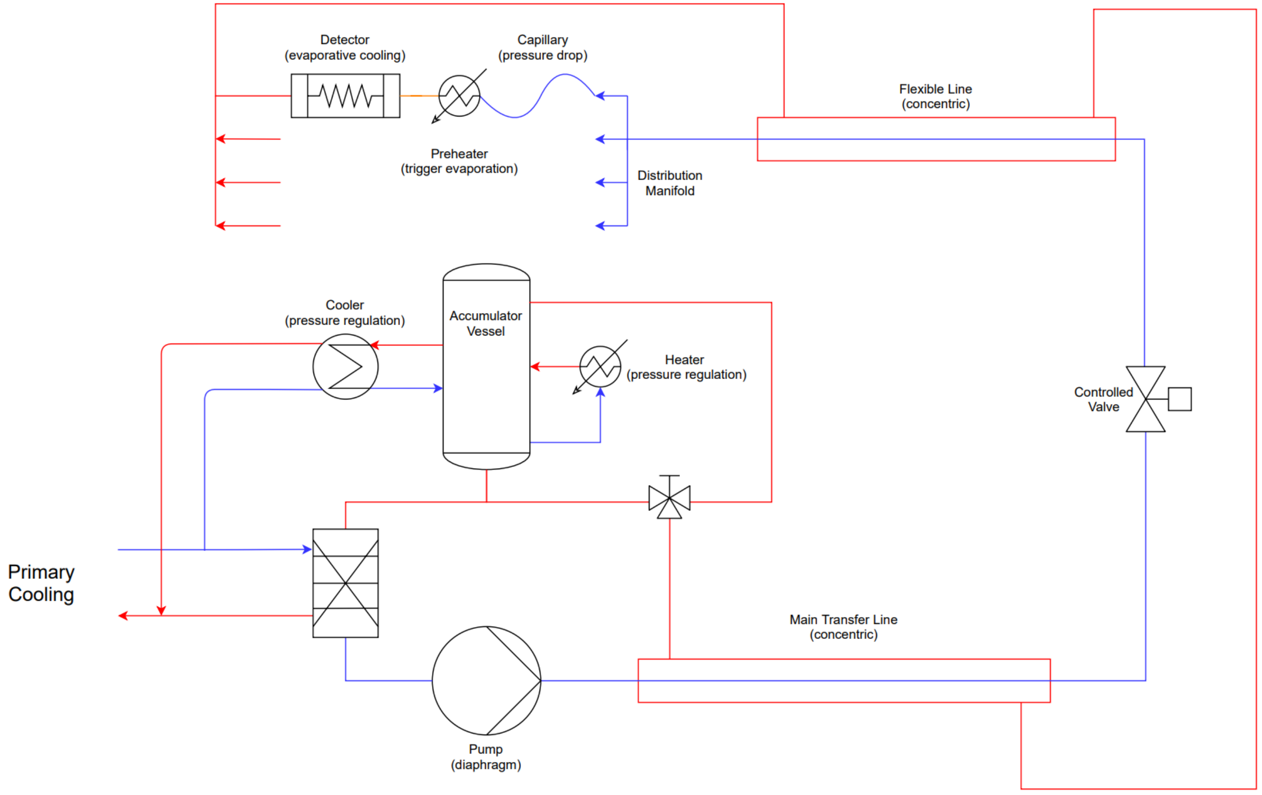
Derek Jan Langedijk
CERN, CMS Cooling Integration
May 29th, 2024

Content

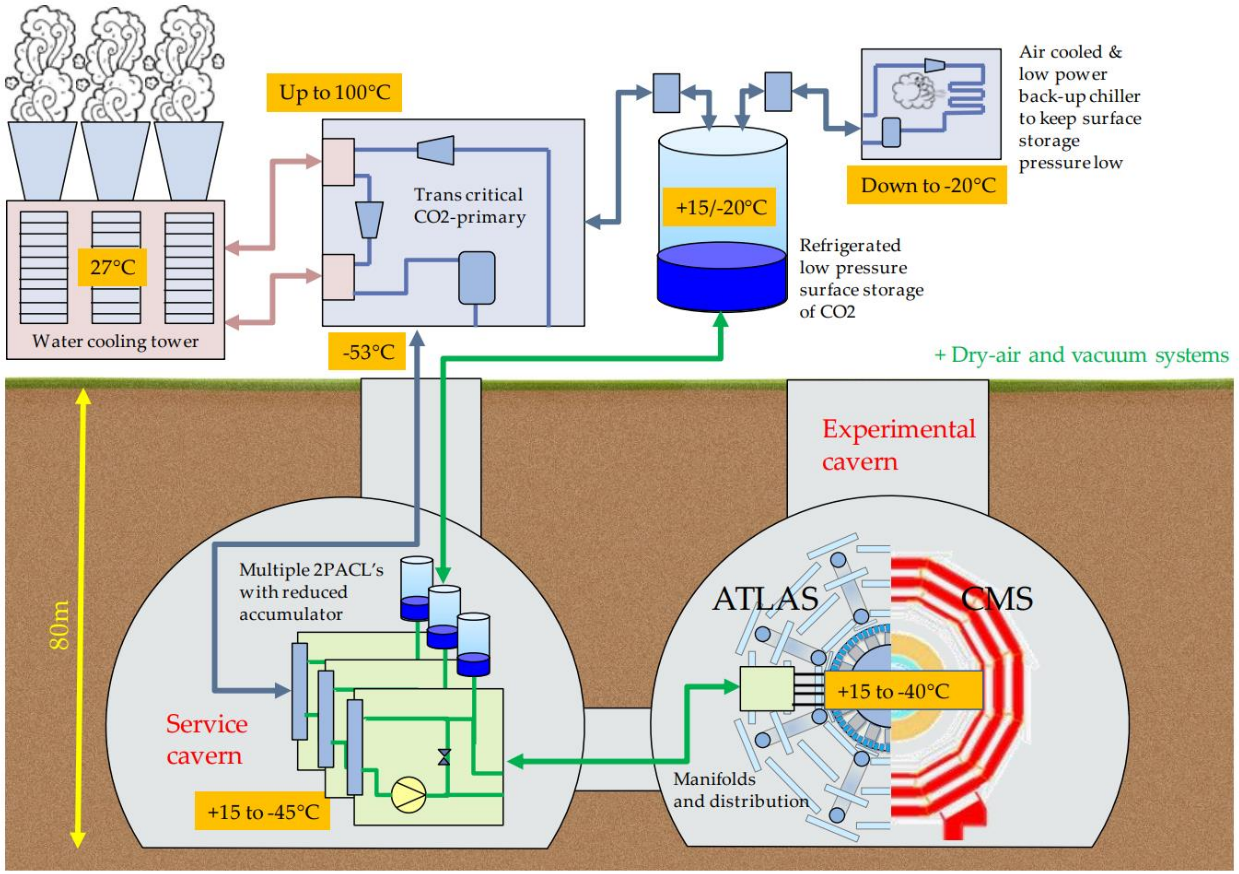


The 2PACL Principle – Components and Layout

Surface and Underground layout with schematic system overview



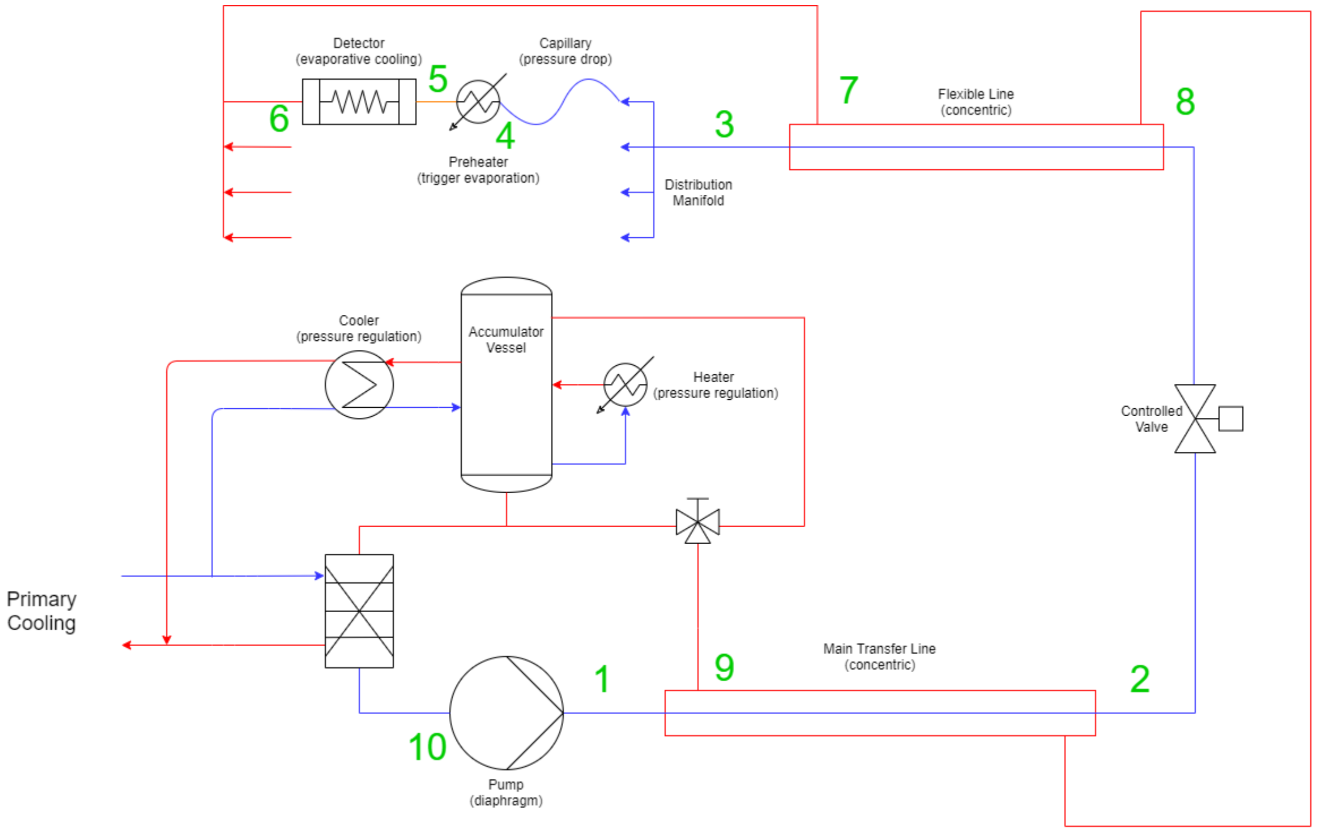
Schematic overview of 2PACL system

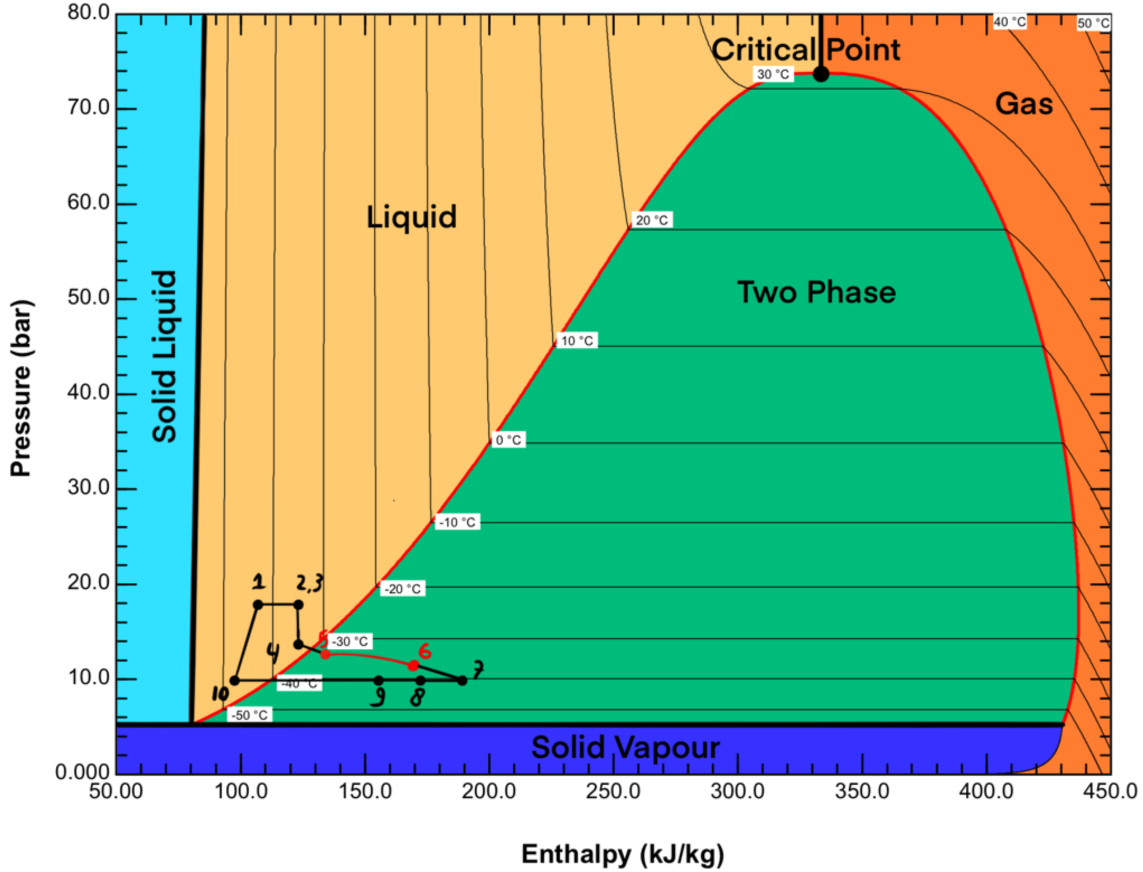


Surface and underground layout

The 2PACL Principle – Thermodynamic Cycle

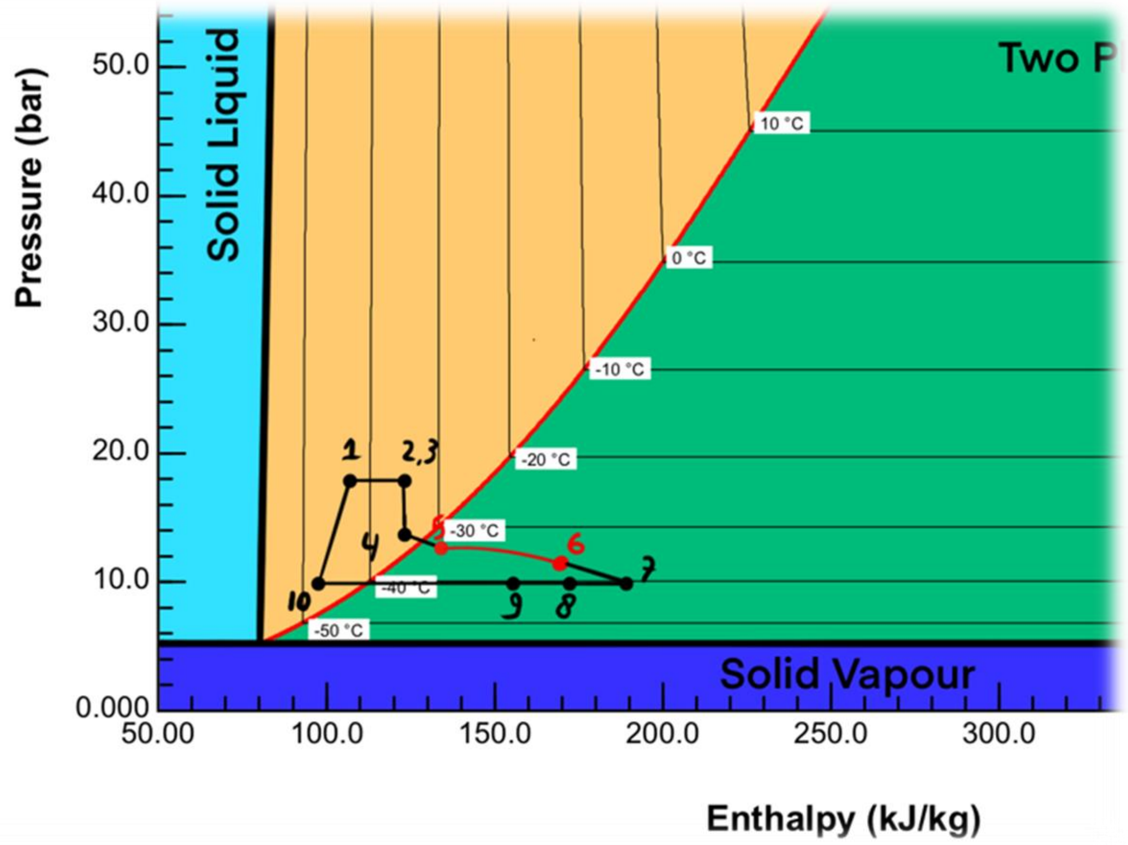
Components visualized in PH-Diagram

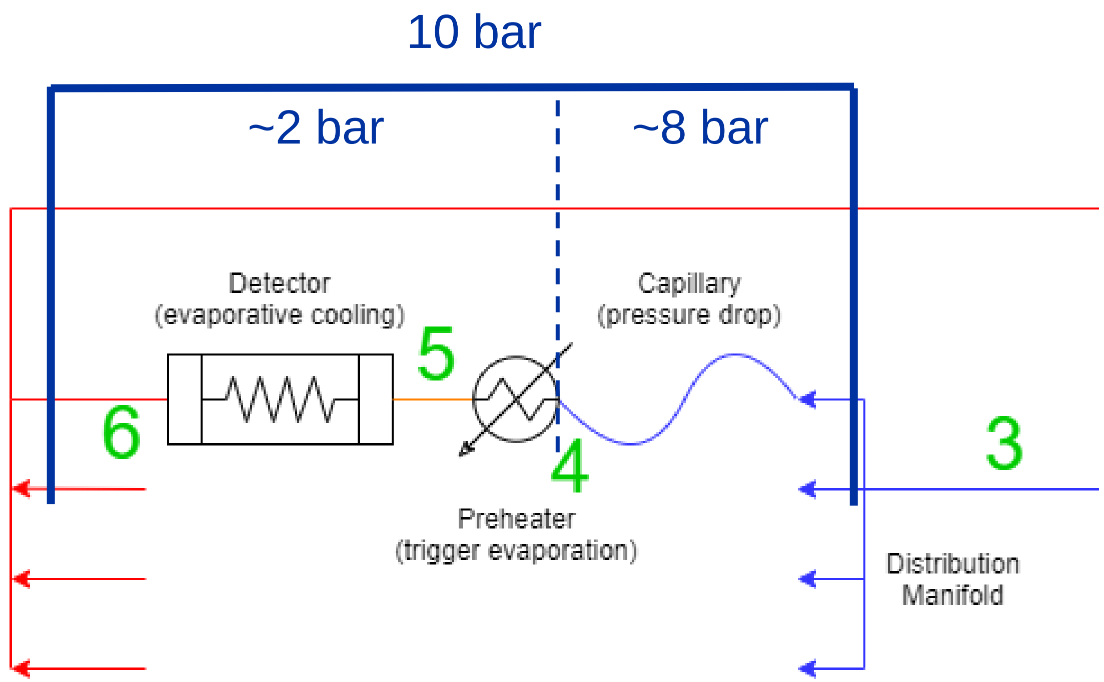




Capillaries in CO2 Cooling – Why?

1. Trigger Boiling
2. Passive Flow Distribution
3. Detector Loop Failure





Theoretical Prediction – Principle

Prediction based on the Darcy-Weisbach equations modelled in MatLab

Δp using Darcy-Weisbach:

$$\Delta p = f_D * \frac{\rho}{2} * \frac{{W_v}^2}{D_h} * L$$

f_D during laminar flow:

$$f_D = \frac{64}{Re}$$

f_D during turbulent flow:

$$\frac{1}{\sqrt{f_D}} = -2 * log_{10}\left(\frac{e}{3.71 * D_h} + \frac{2.51}{Re * \sqrt{f_D}}\right)$$

Differential Pressure	(Δp)	[Pa]
Length of Tube	(L)	[m]
Darcy friction factor	(f_D)	[-]
Density of the Fluid	(ρ)	[kg/m^3]
Fluid Velocity	(W_v)	[m/s]
Hydraulic Diameter of the Tube	(D_h)	[m]
Inner Surface Roughness	(e)	[mm]
Reynolds Number	(Re)	[-]

Reynolds number:

$$Re = \rho * W_v * \frac{D_h}{\mu}$$

Theoretical Prediction – Example from Detector List

Prediction based on the Darcy-Weisbach equations modelled in MatLab

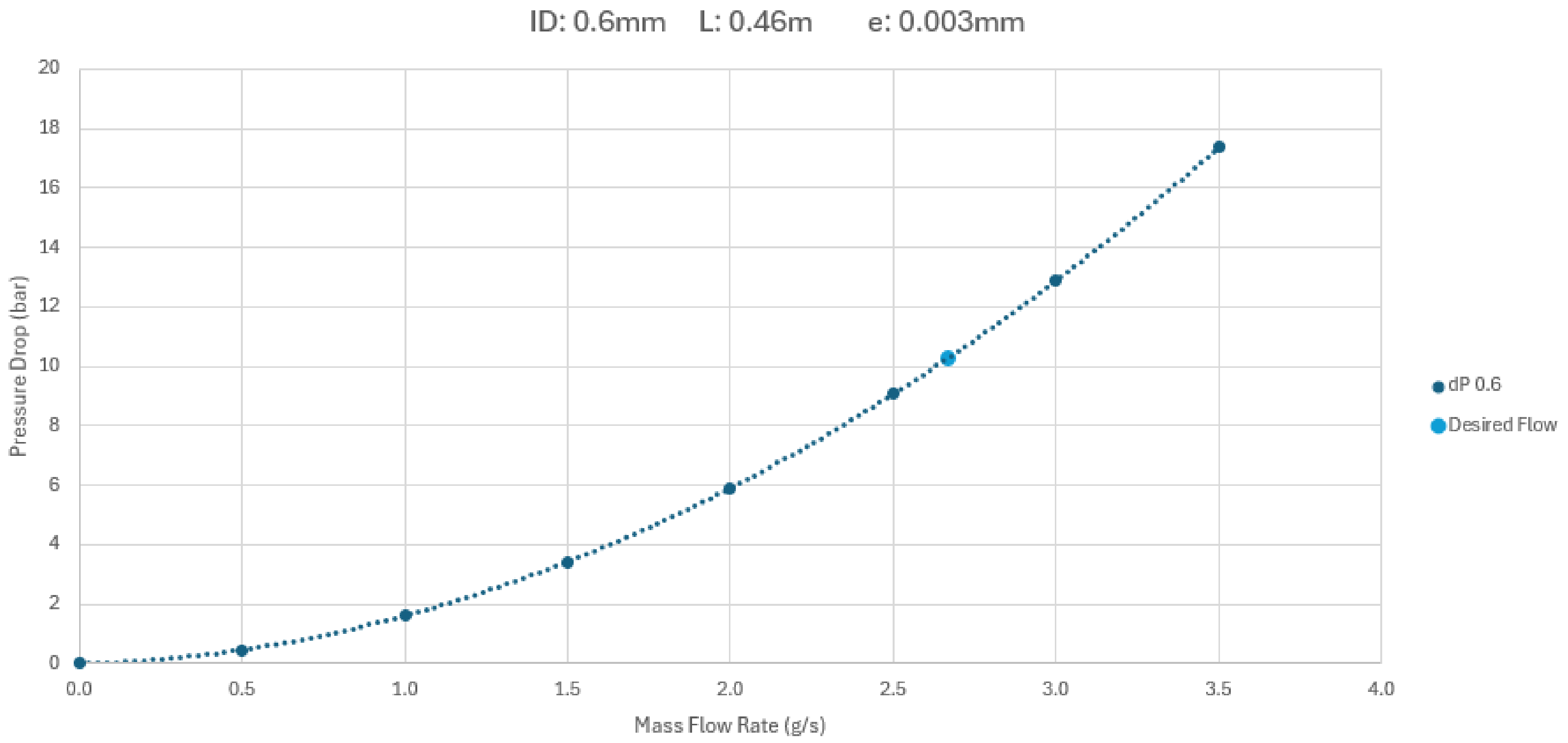
Detector System | Sub-System | Capillary Properties | Desired Δp Capillary | Quantity

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	System		Component	ID (mm)	OD (mm)	Min length (m)	Max length (m)	Min Mass flow (g/s)	Max Mass flow (g/s)	Max dP (bar) (EOL)	Min dP (bar) (EOL)	Roughness (micron)	Quantity	Predicted Length (m)	Fraction of total (quantity)	Fraction of total (Length per Size)	Budgetcode	Responsible
2	MTD	BTL		0.6	1.2	0.46	0.46	2.67	2.67	7.9	7.3	1	144	66.24	7.84%	6.32%	T641901	Adi Bornheim
3		ETL	Evap 1	0.7	[illegible]	1.40	1.40	2.39	2.39	9.17	9.17	1	17	33.80	8.33%	5.20%	T273310	Natalia Koss
4			Evap 2 to 9	0.9	1.4	1.3	2.30	3.54	4.69	9.41	8.68	1	136	352.80		100.00%		
5	HGCAL	Electromagnetic		0.8	1.2	[illegible]	1.38	3.23	4.43	9.46	8.09	1	336	463.68	44.42%	85.79%	38354	Karol Rapacz
6		Hadronic		0.7	1.2	1.13	2.00	1.84	2.52	9.24	8.38	1	216	432.00		66.51%		
7				0.6	1.2	0.94	1.46	1.45	1.84	9.3	8.31	1	264	385.44		36.80%		
8	IT	TBPX	Layer 1	0.5	1.2	1	1	1.47	1.8				8	8.00	39.41%	11.59%	38352	Francesco Bianchi Duccio Abbaneo
9			Layer 2	0.5	1.2	1	1	1.22	1.72				14	14.00		20.29%		
10			Layer 3	0.5	1.2	1	1	[illegible]	1.94				16	16.00		23.19%		
11			Layer 4	0.5	1.2	1	1	1.04	1.92				18	18.00		26.09%		
12		TFPX		0.7	1.2	1	1	2.22	2.22				64	64.00		9.85%		
13		TEPX	TEPX 1	0.7	1.2	1	1	1.11	[illegible]				32	32.00		4.93%		
14			TEPX 2	0.7	1.2	1	1	1.11	1.11				32	32.00		4.93%		
15		FBCM		0.5	1.2	1	1						4	4.00		5.80%		
16	OT	TBPS flat	Layer 1	0.5	1.2	1.00	1.00	1.25	1.25			1	9	9.00		13.04%	38352	Chi Meng Lei Douglas Ryan Berry
17			Layer 2	0.7	1.2	1.70	1.70	1.84	1.84			1	13	22.10		3.40%		
18			Layer 3	0.8	1.2	2.00	2.00	2.45	2.45			1	18	36.00		6.66%		
19		TBPS tilted	Layer 1	0.6	1.2	1.25	1.25	1.63	1.63			1	24	30.00		2.86%	38352	Fernando Perea Albela
20			Layer 2	0.7	1.2	1.40	1.40	2.2	2.2			[illegible]	24	33.60		5.17%		
21			Layer 3	0.8	1.2	1.70	1.70	2.94	2.94			1	24	40.80		7.55%		
22		TB2S	All layers	0.6	1.2	1.90	1.90	1.33	1.39			1	[illegible]	349.60		33.38%	T630250	Antti Onnela
23		TEDD	TEDD 1	0.6	1.2	0.90	0.90	2	2			1	96	86.40		8.25%	T630260	Christof Delaere
24			TEDD 2	0.6	1.2	0.90	0.90	1.61	1.61			1	144	129.60		12.37%		
25									Total				1837	[illegible]	100%	500%		
26																		
27	Capillaries Procurement			Inner Diameter	Outer Diameter									Predicted length	[illegible]pares	To be ordered (Spools of ~300m)		
28	Batch#1			0.5	1.2									69.00	83	300		
29				0.6	1.2									1047	[illegible]	1500		
30				0.7	1.2									650	779	900		
31				0.8	1.2									540	649	900		
32				0.9	1.4									353	423			

Theoretical Prediction – Example from Detector List

System		Component	ID (mm)	Max length (m)	Max Mass flow (g/s)	Max dP (bar) (EOL)	Predicted Length (m)
	BTL		0.6	0.46	2.67	7.9	66.24

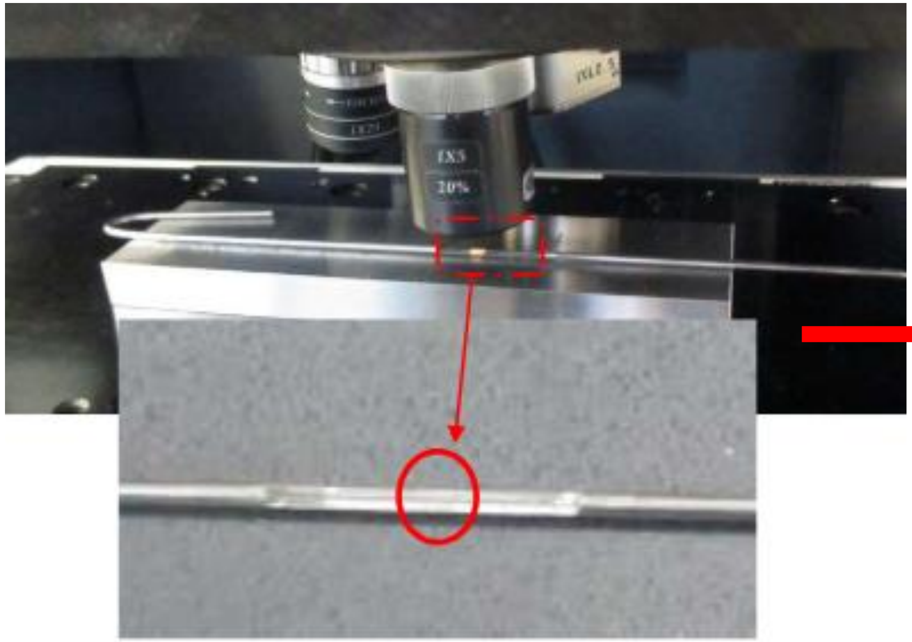
Result Theoretical Prediction:

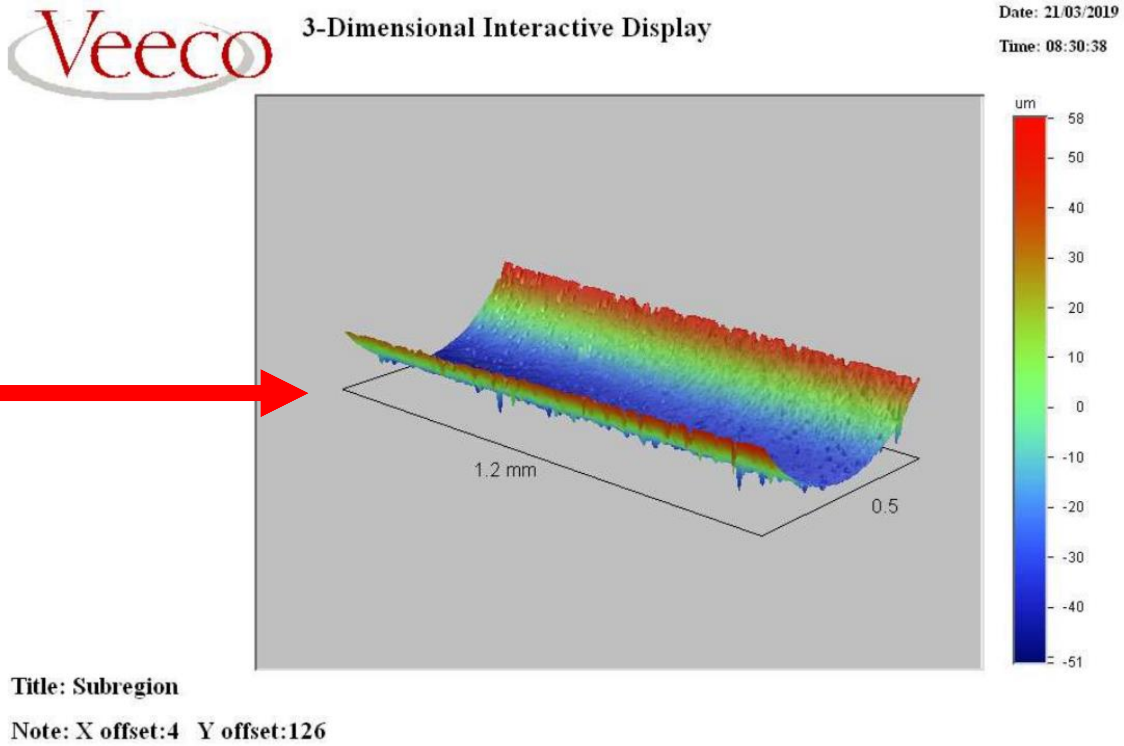


Super easy!
Right…?

Theoretical Prediction – Why is it still so difficult?

Capillaries are not perfect…



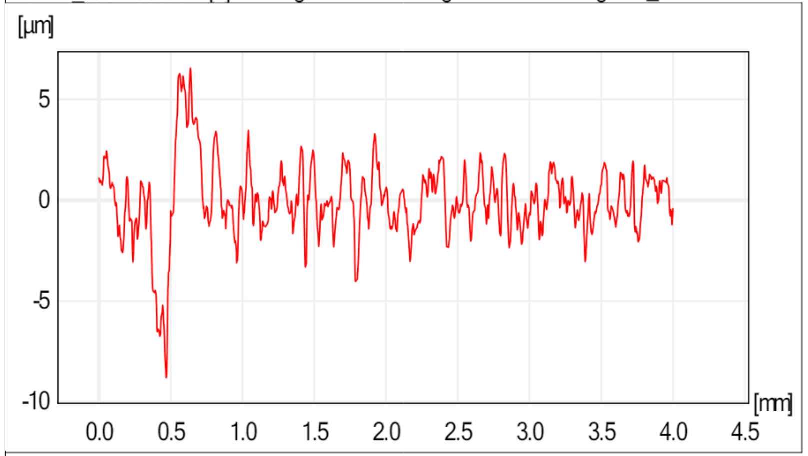


Theoretical Prediction – Why is it still so difficult?

Same Manufacturer!

Rapport de contrôle
EDMS.3057136 J3091252
Capillary 1.2x0.25

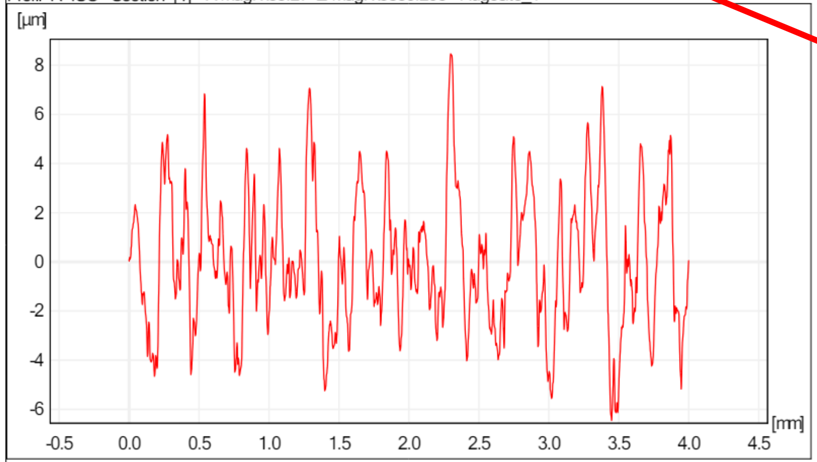
Profil=R_ISO - Section=[1] X Mag: x27.846 Z Mag: x3468.843 <Rugosité_1>



Contenu	Mesuré
Rugosité 2D<Rugosité_1>	
Profil=R_ISO - Section=[1]	
Ra	1.323um
Rq	1.683um
Rsk	-0.092
Rp	3.556um
Rv	4.376um
Rz	7.932um
Rt	15.445um
RSm4	0.1432mm
Rpk	2.573um
Rvk	3.280um

Rapport de contrôle
EDMS.3057136 J3091252
Capillary 1.2x0.35

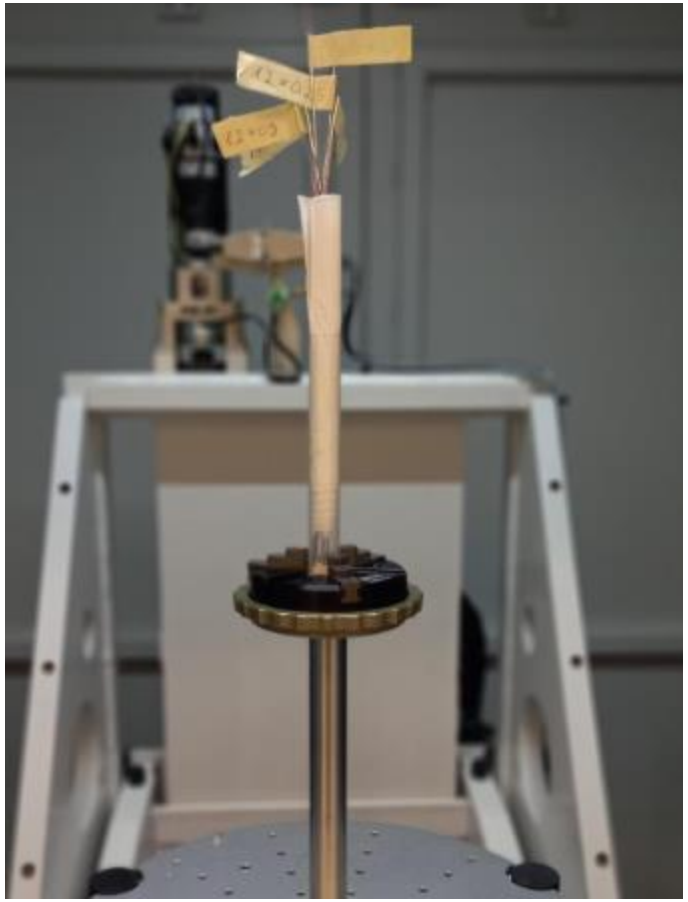
Profil=R_ISO - Section=[1] X Mag: x33.27 Z Mag: x5839.293 <Rugosité_1>



Contenu	Mesuré
Rugosité 2D<Rugosité_1>	
Profil=R_ISO - Section=[1]	
Ra	2.214um
Rq	2.760um
Rsk	0.385
Rp	6.953um
Rv	5.143um
Rz	12.097um
Rt	14.972um
RSm	0.1793mm
Rpk	2.952um
Rvk	1.908um

Theoretical Prediction – Why is it still so difficult?

CT Scan on capillaries… BIGGER Inner Diameters



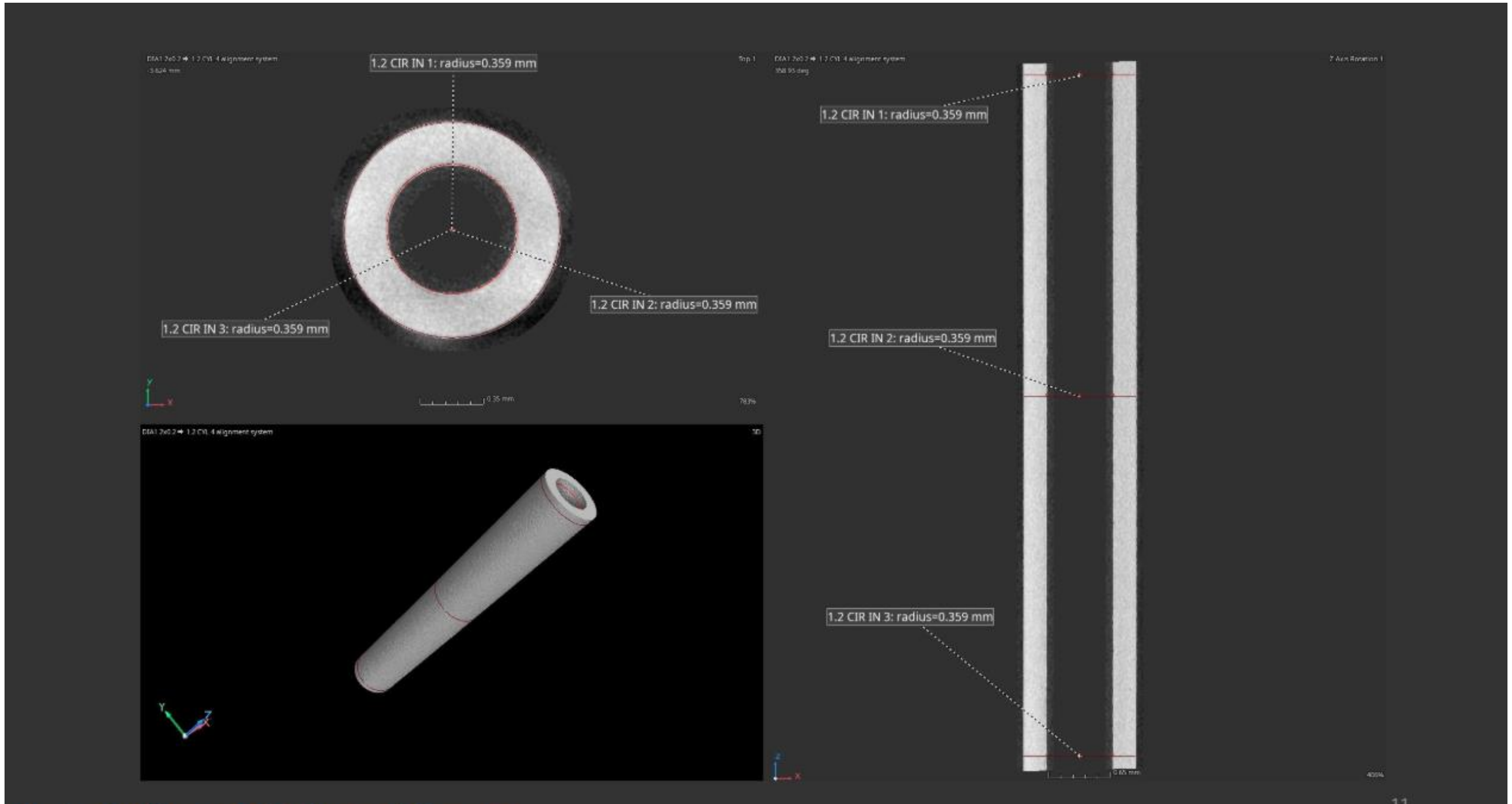


Fig. 3 – Capillary 1.2x0.25 internal diameter

Theoretical Prediction – Why is it still so difficult?

Overview of Results – Tolerance between +0.01mm and +0.03 mm

Results

Below are the results of the internal and external diameters/radiuses.

1.2x0.2 — **0.8mm**

Exterior	Diameter	1.194		
Exterior	Diameter	1.194		
Exterior	Diameter	1.194		
Interior	Diameter	0.824	W. th.	0.185
Interior	Diameter	0.824	W. th.	0.185
Interior	Diameter	0.824	W. th.	0.185

1.2x0.25 — **0.7mm**

Exterior	Diameter	1.194		
Exterior	Diameter	1.194		
Exterior	Diameter	1.194		
Interior	Diameter	0.718	W. th.	0.238
Interior	Diameter	0.718	W. th.	0.238
Interior	Diameter	0.718	W. th.	0.238

1.2x0.3 — **0.6mm**

Exterior	Diameter	1.188		
Exterior	Diameter	1.188		
Exterior	Diameter	1.188		
Interior	Diameter	0.624	W. th.	0.282
Interior	Diameter	0.624	W. th.	0.282
Interior	Diameter	0.624	W. th.	0.282

1.2x0.35 — **0.5mm**

Exterior	Diameter	1.184		
Exterior	Diameter	1.184		
Exterior	Diameter	1.184		
Interior	Diameter	0.536	W. th.	0.324
Interior	Diameter	0.534	W. th.	0.325
Interior	Diameter	0.532	W. th.	0.326

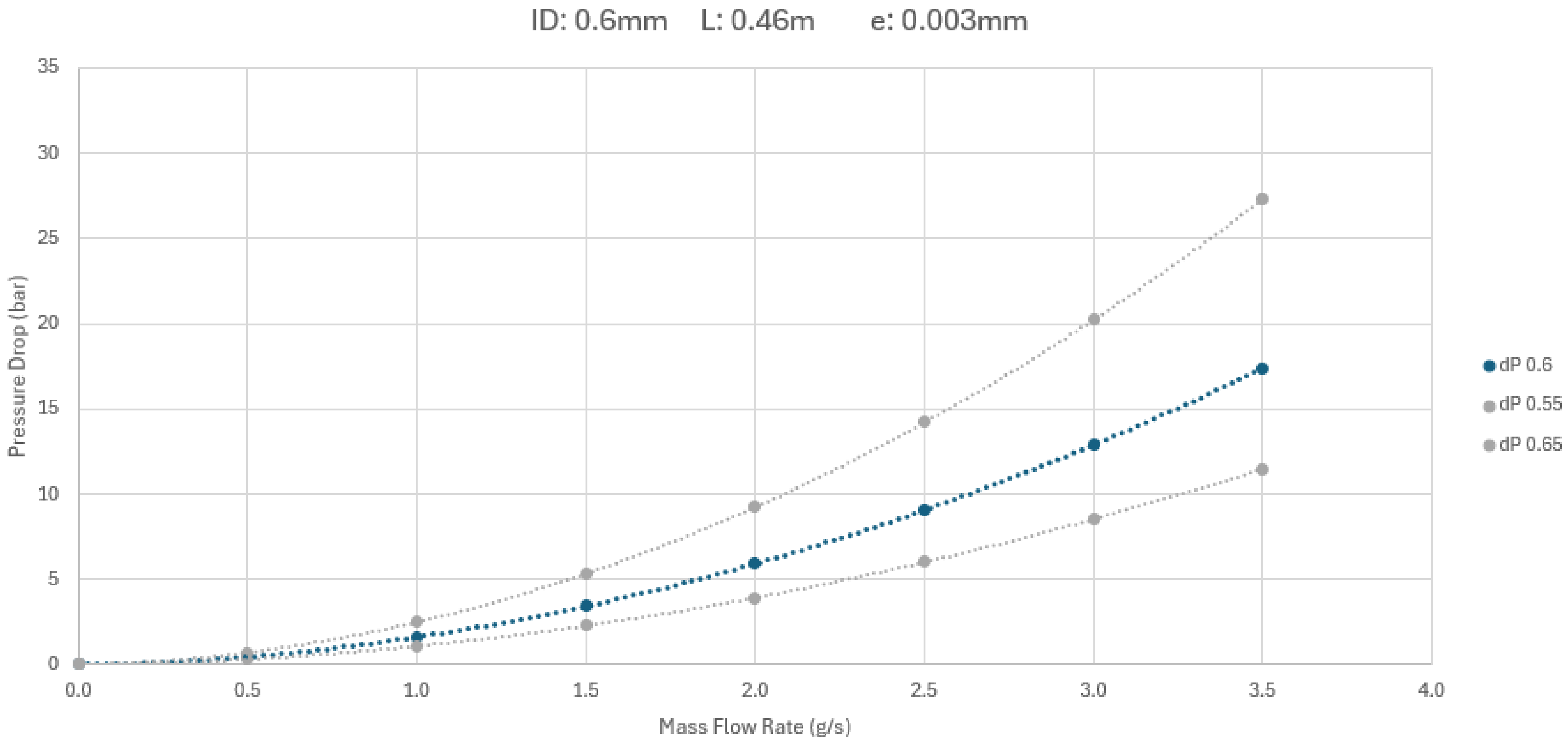
1.4x0.25 — **0.9mm**

Exterior	Diameter	1.386		
Exterior	Diameter	1.386		
Exterior	Diameter	1.386		
Interior	Diameter	0.916	W. th.	0.235
Interior	Diameter	0.916	W. th.	0.235
Interior	Diameter	0.916	W. th.	0.235

Theoretical Prediction – Why is it still difficult?

How strong is a 0.05mm ID tolerance influencing the pressure drop?

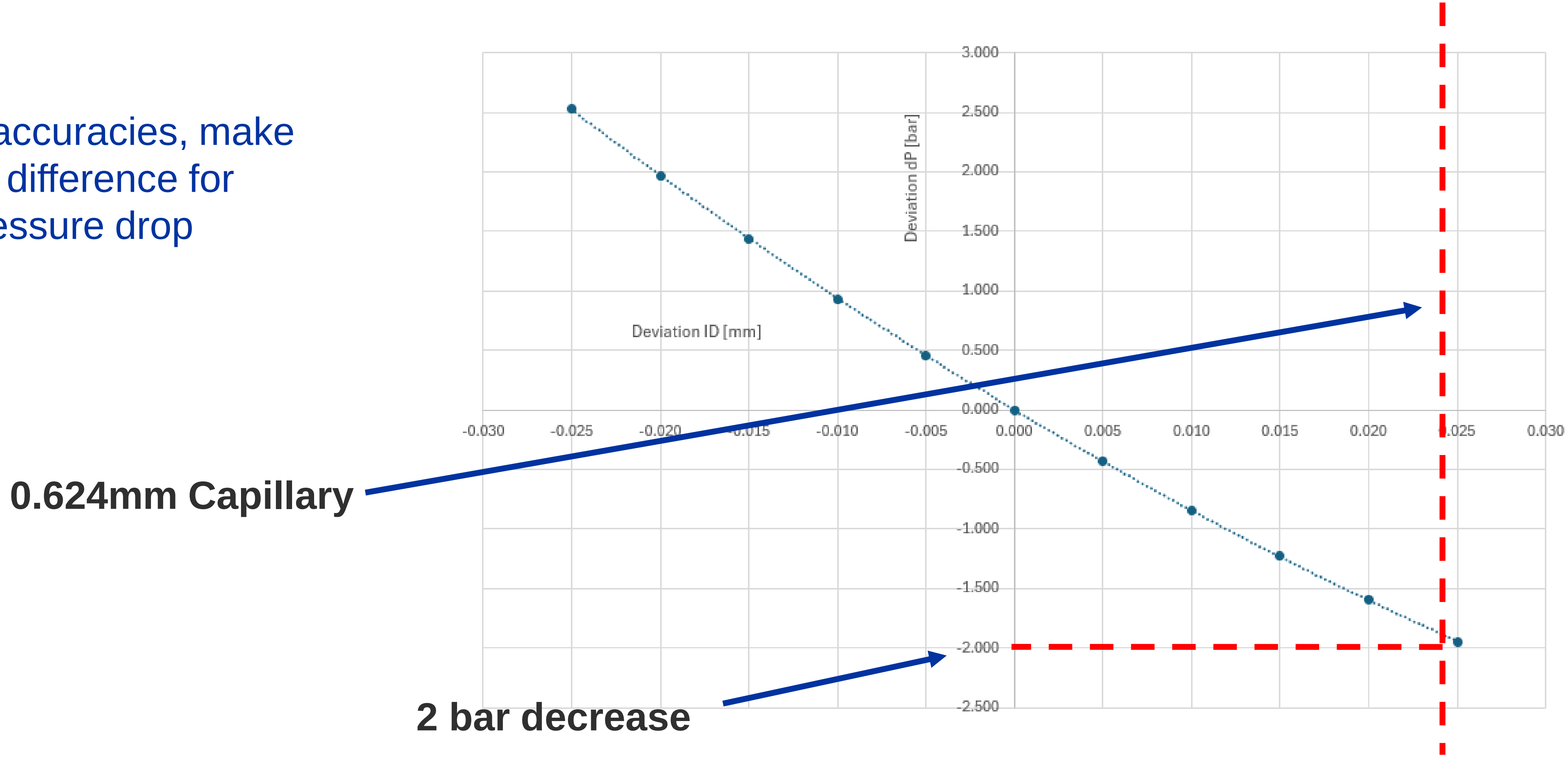
Strong… →



Theoretical Prediction – Why is it still difficult?

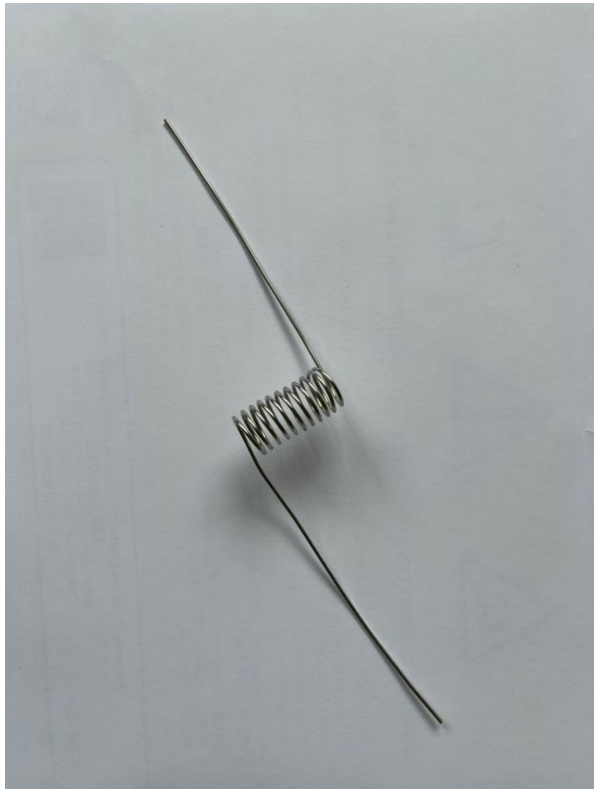
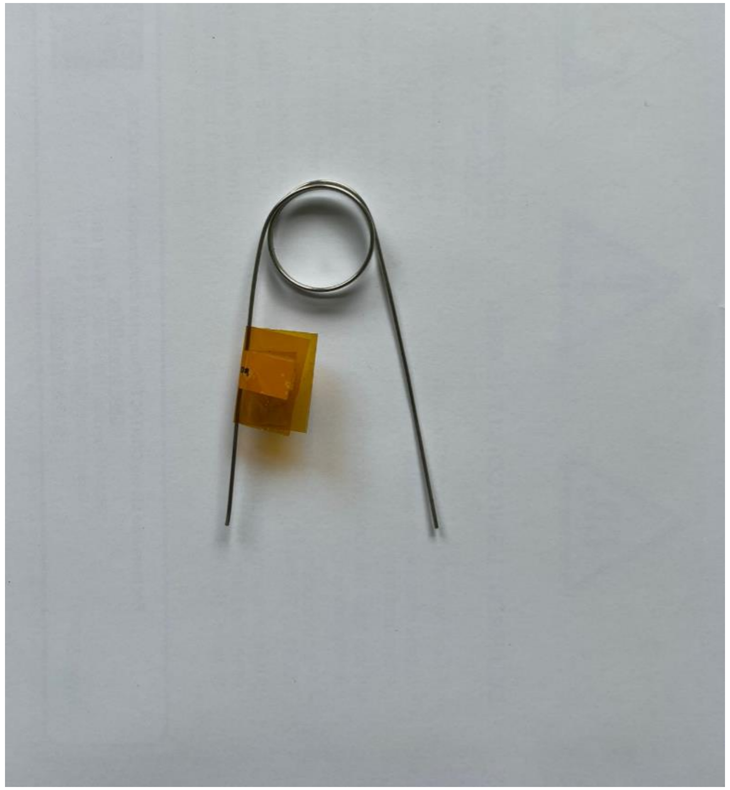
How strong is a 0.05mm ID tolerance influencing the pressure drop?

Small inaccuracies, make a big difference for pressure drop



Theoretical Prediction – Why is it still difficult?

Coiling increases pressure drop.
Also, coiling is subjective… see below:

Research is ongoing to better understand the effects of coiling on pressure drop!

Theoretical Prediction – Testing each capillary!

Conclusion: Testing is a necessity; theory does not give sufficient accuracy.

Capillaries are not consistent:

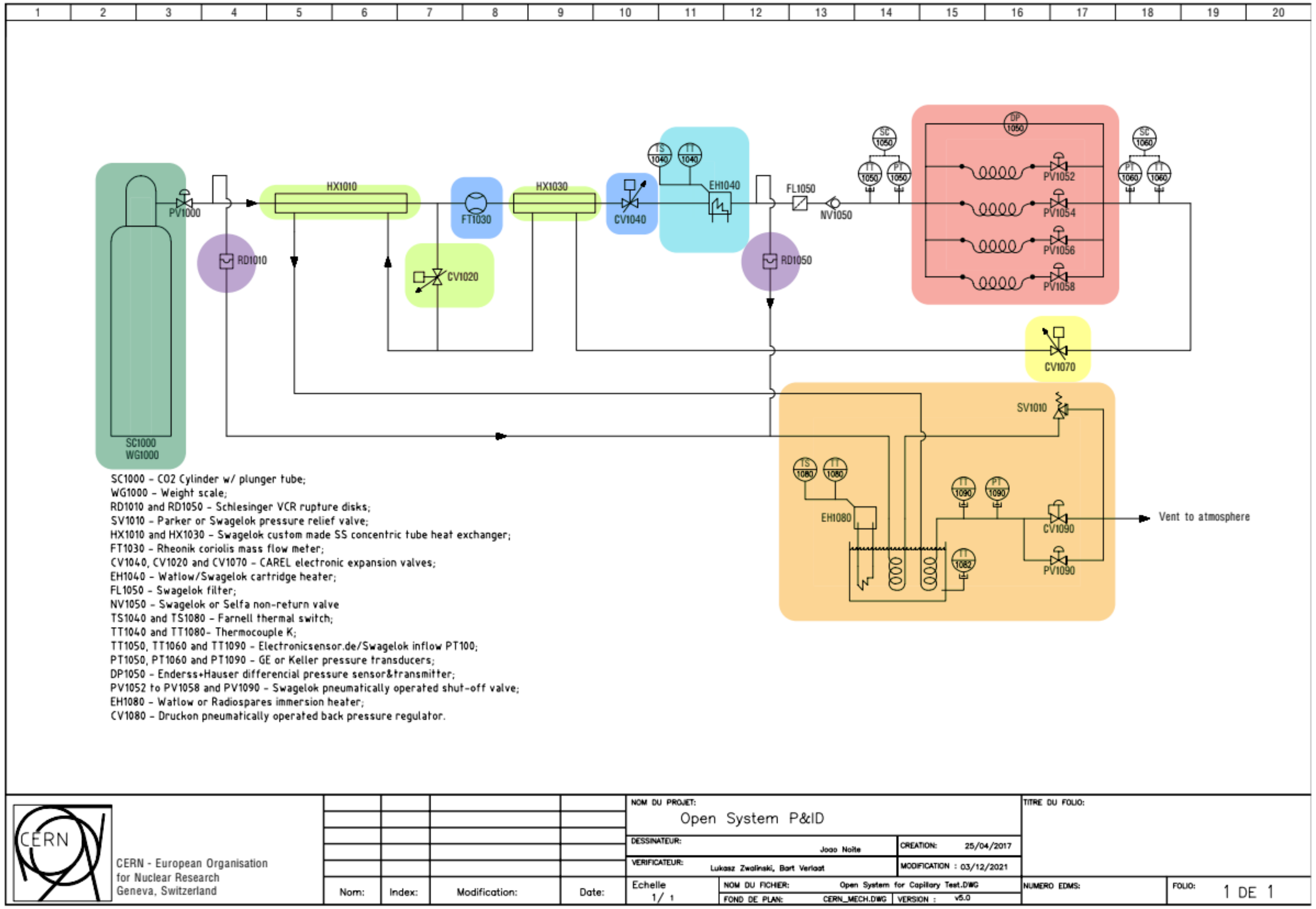
1. Uncertainties with roughness
2. Uncertainties with inner diameter
3. Uncertainties with coiling

Solution: *Build a test factory that can test all capillaries!*

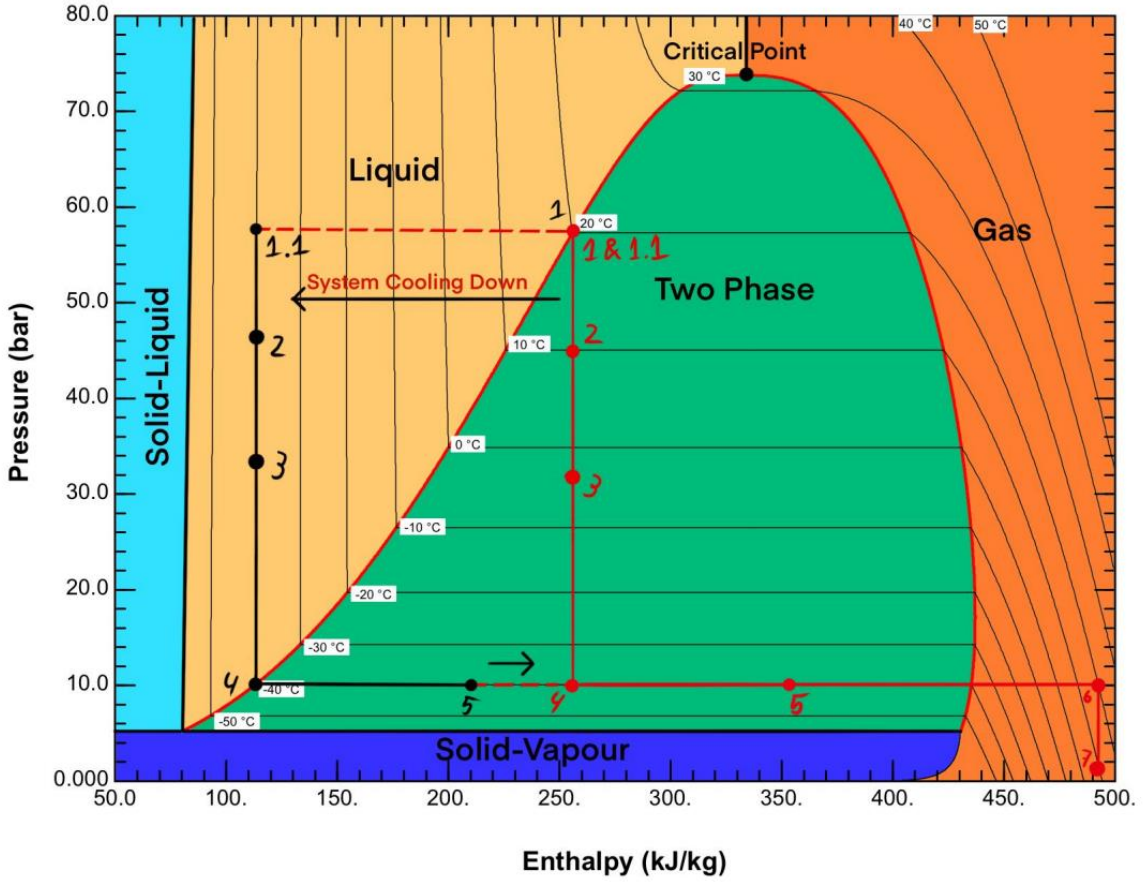
Capillary Open System – Principle

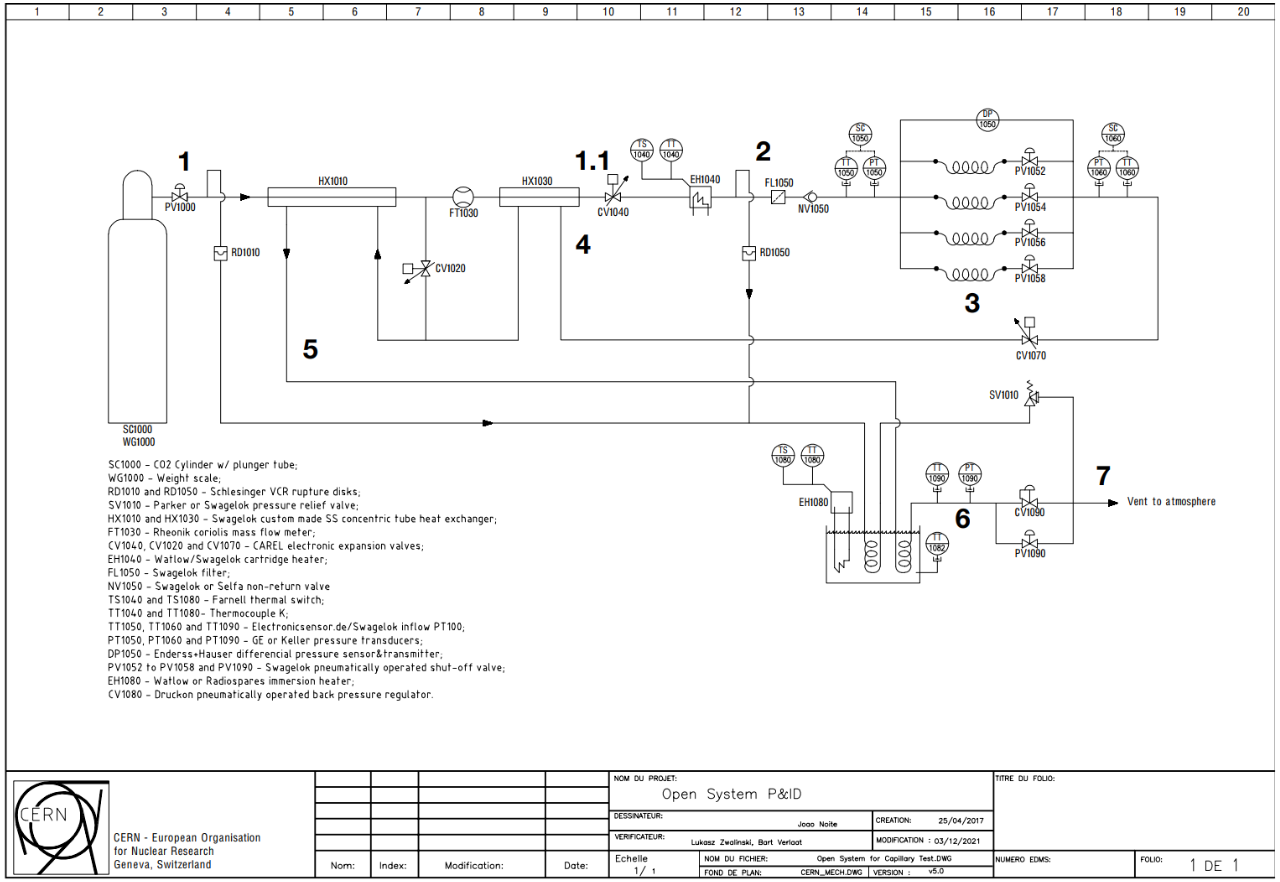
*“2 Identical Setups for **ATLAS** and **CMS**”*

- **Capillaries**
  - Δp sensor
  - Shut-off valves
- **Flow measurement and regulation**
- **Bottle supply**
- **Exhaust system (Single phase, gas)**
- **Safety Burst Discs**
- **Supply Subcooling**
  - Heat exchangers
  - Bypass Valve
- **Subcooling regulator**
- **Warm Nose Heater (ATLAS Only)**



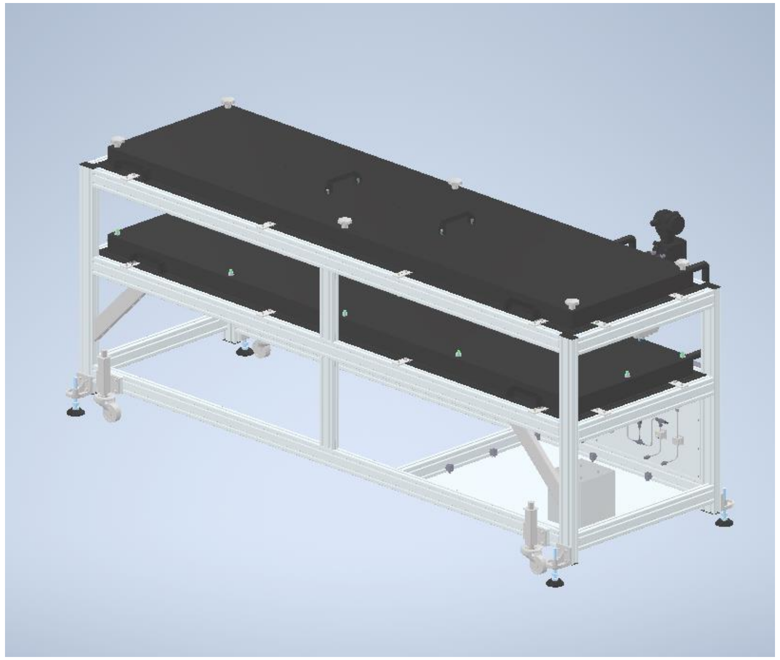
Capillary Open System – Principle





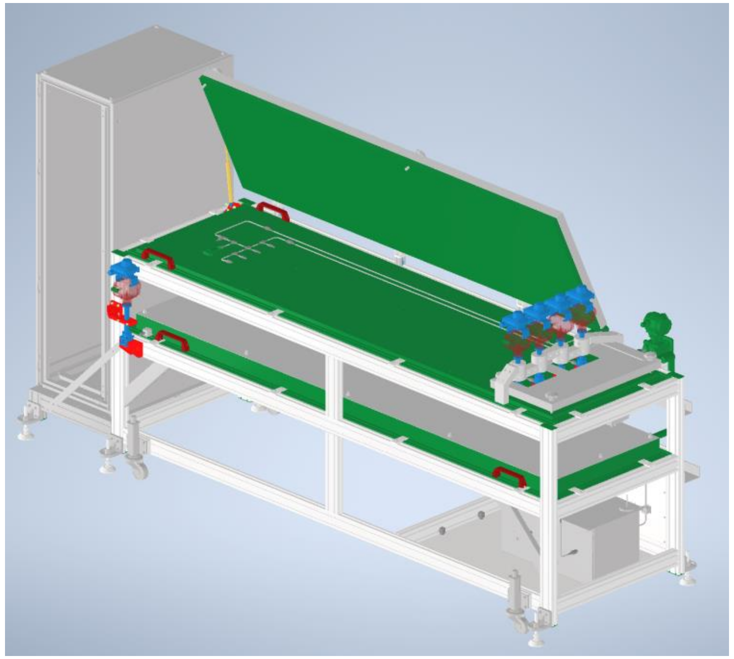
P&ID COS – Joao Noite, ATLAS Collaboration

Capillary Open System – Mechanical Design



Original Design

Liam Cooper
Science & Technology Facilities Council, United Kingdom

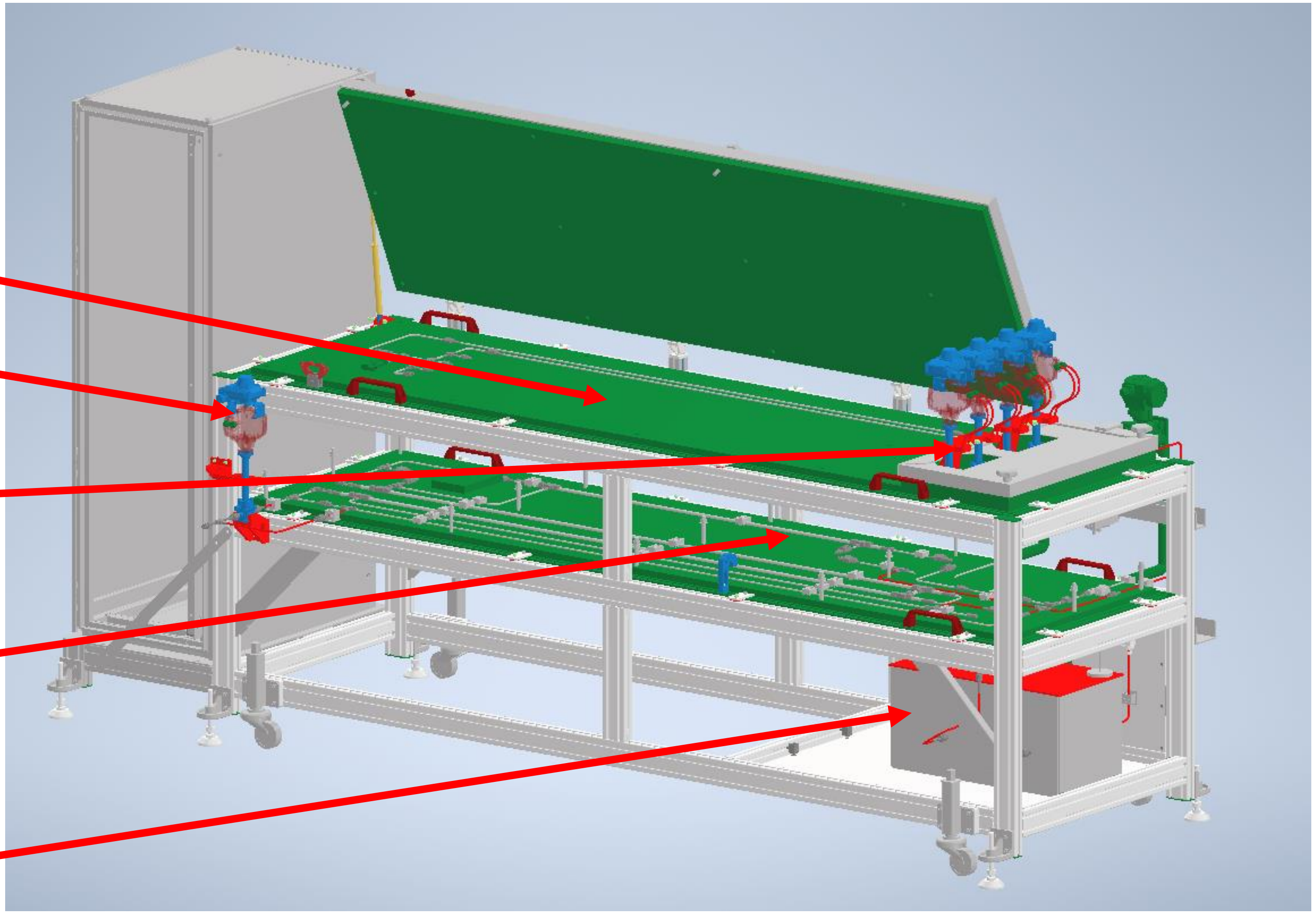


Final Design

Martin Machac & Derek Jan Langedijk
CERN

Capillary Open System – Mechanical Design

- Capillaries
- Bottle connection
- Capillary shut off valves
- Heat exchangers
- Exhaust system (water tank)



Capillary Open System – Constructed @ CERN

February 2023

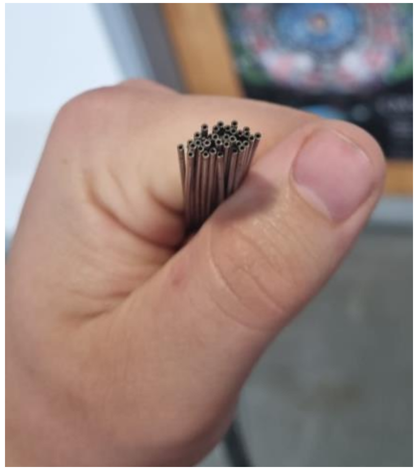
Commissioning with ATLAS Setup
October 2023

Making a Capillary – Electronic Discharge Machining

Spools with different ID's
Over 2km (1.25mi) total

Cut from Spool
using pliers

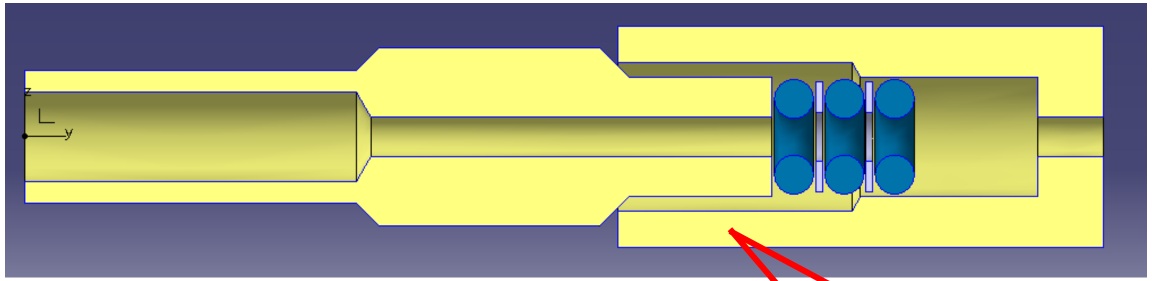
Flattened ends…
because of pliers
(right side)



Remove ends with
EDM Wire Cutting

Result

Measurement – Example in Practise



Design by Fernando Albela Perea

Connector used in the Capillary Open System does not affect the capillary in any way:

No deformation
No welding/brazing

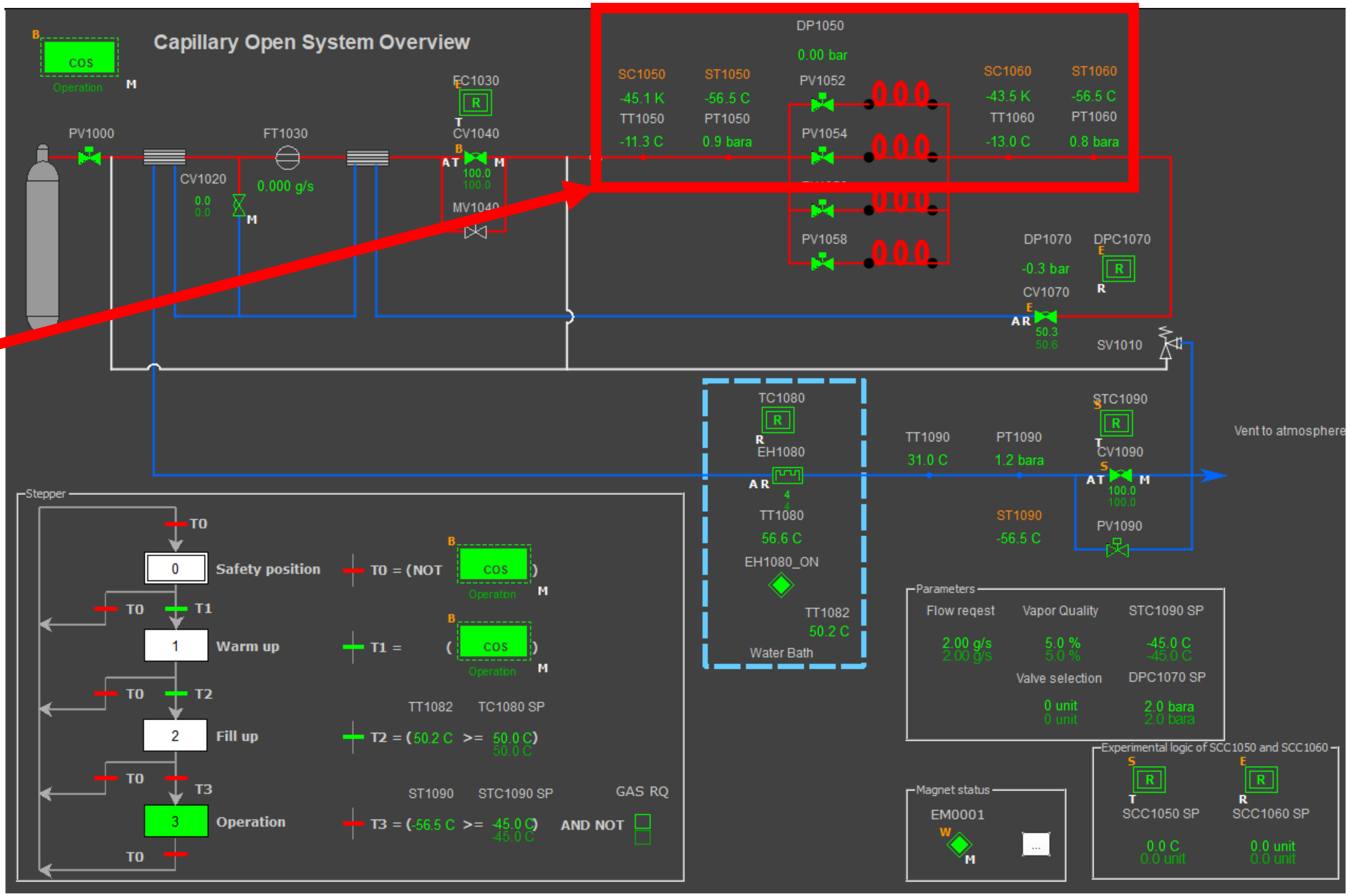
4 Installed capillaries

Measurement – SCADA Data Acquisition

Operation and Data Acquisition through SCADA

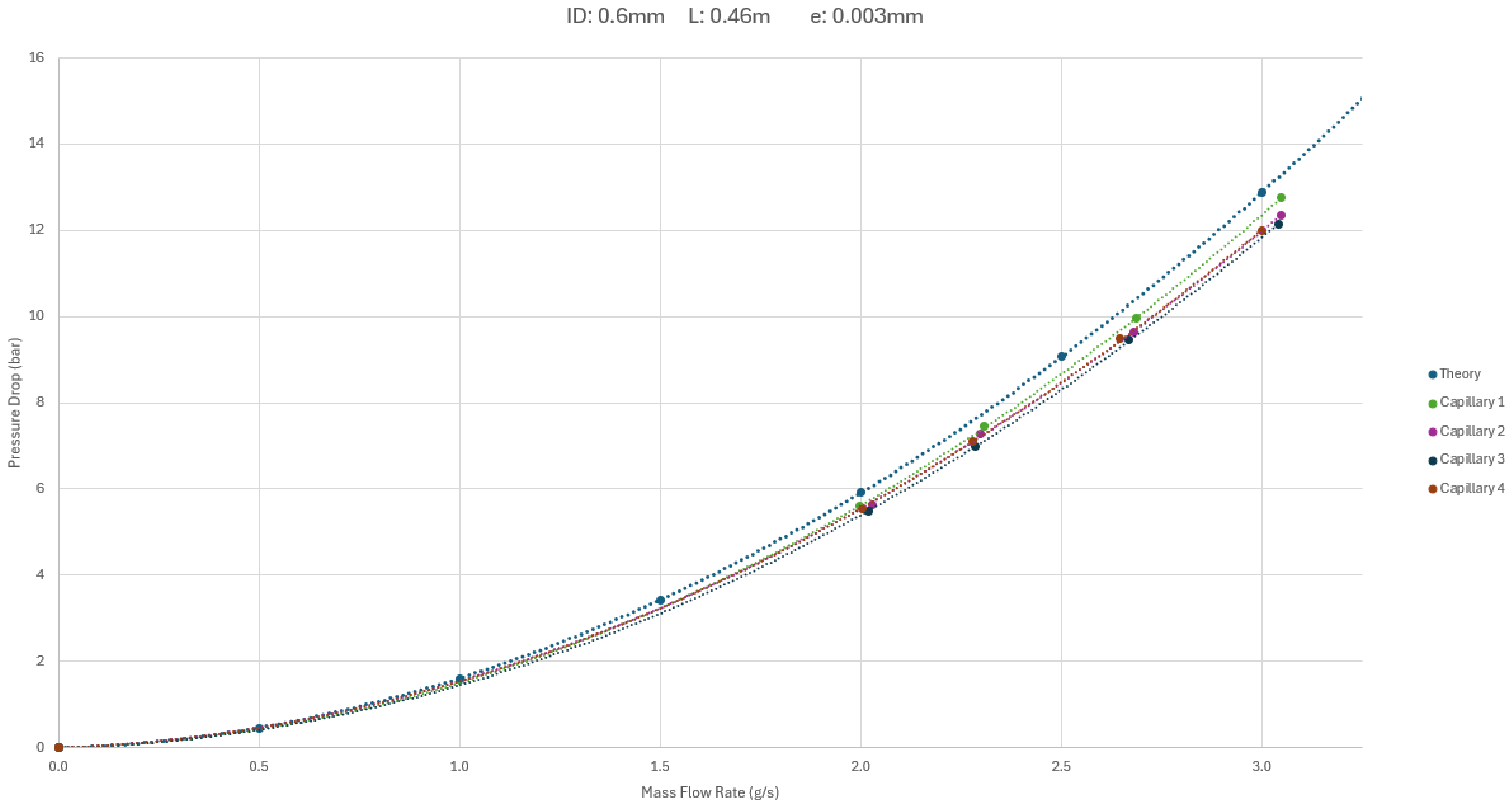
Important: Always ensure stable conditions on inlet and outlet of the capillary.

After which, data is recorded for 5 minutes and averaged.



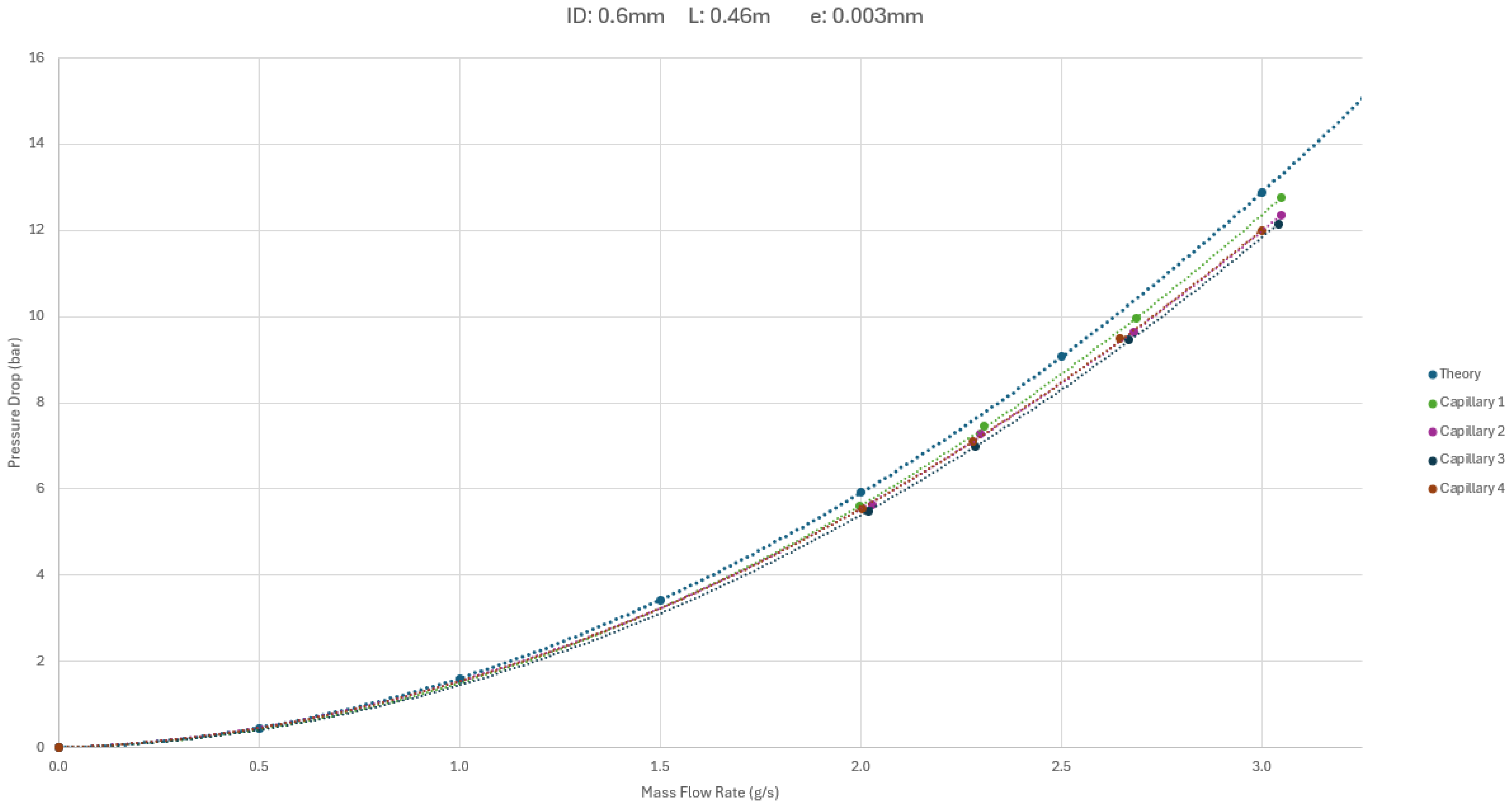
Measurement – Example in Practise

First measurements compared to theory from earlier:



Measurement – Example in Practise

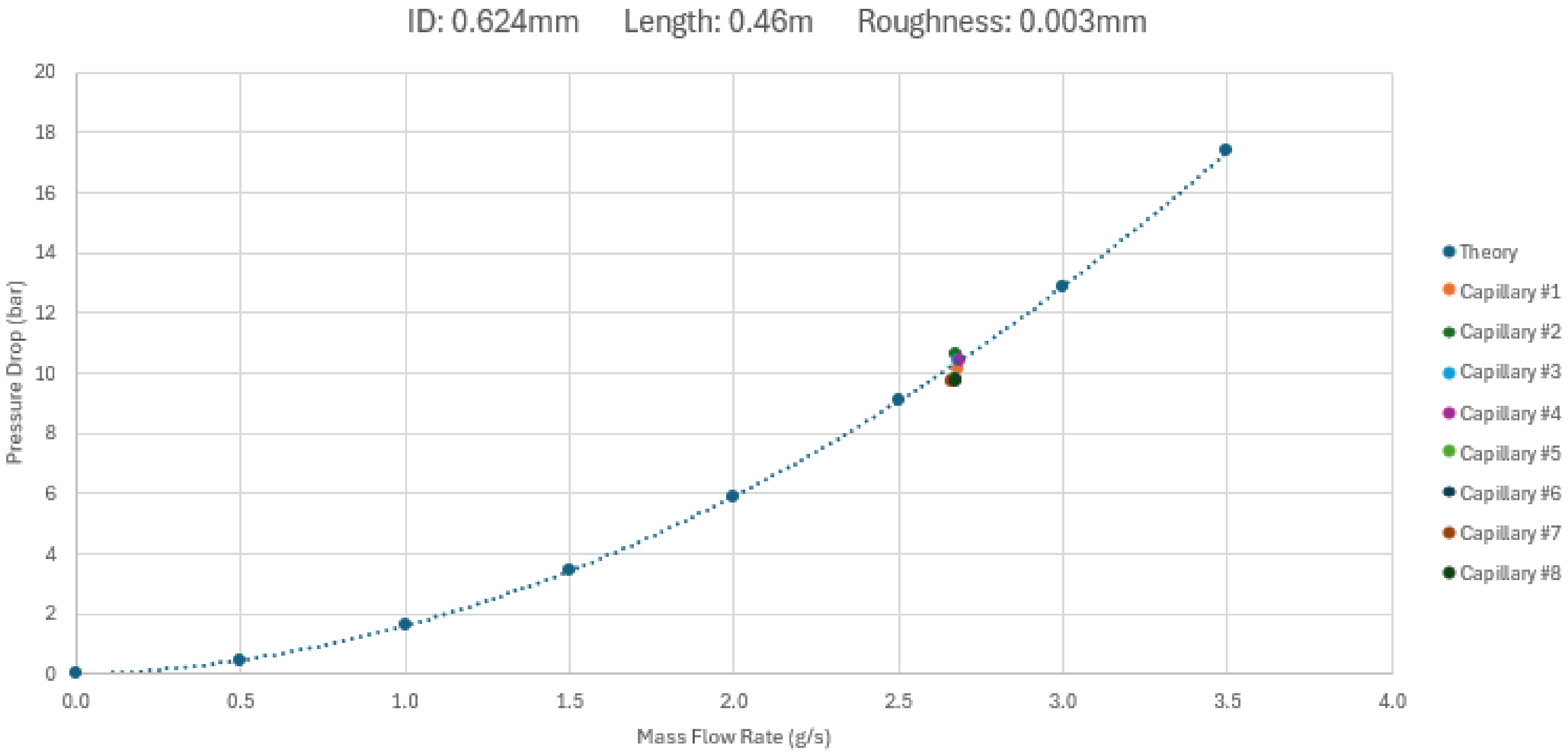
First measurements compared to theory from earlier:



Measurement – Consistency in larger batches

A batch of 8 capillaries, what consistency are we measuring?

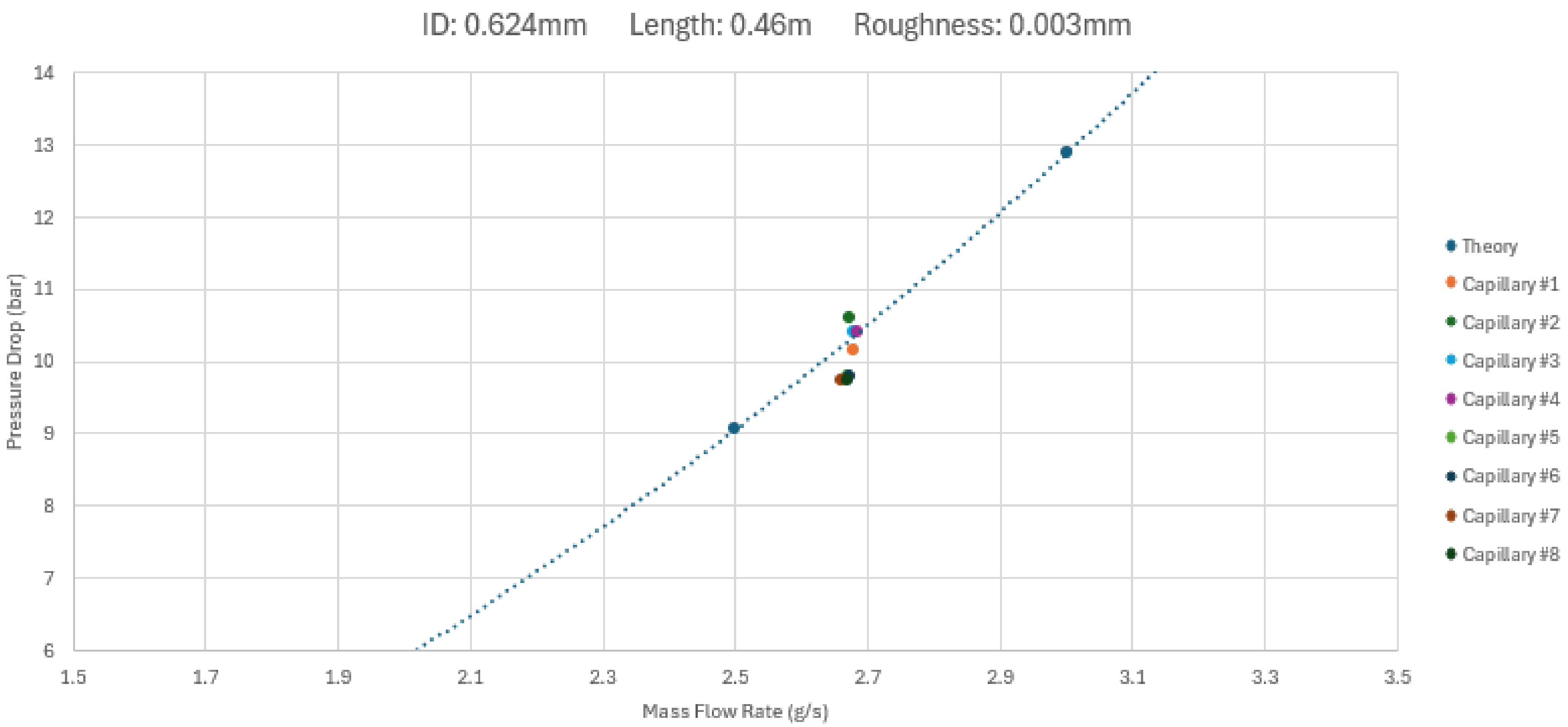
Calculation based on measurements at Micro-lab.



Measurement – Example in Practise

Performance of the Theoretical prediction when compared to measured data

Result: +-5%
Still acceptable for flow distribution inside the detector



Capillary Tested – Now what?

Capillary is done, and ready for installation in the detector system:

- Vacuum Brazing of end connections
- Installation and routing into the detector

Future:
We are currently waiting for the detector teams to give us the final pressure drops of the evaporators, after this we can size the capillaries accordingly…

The End

Thank you for your attention

Thank you to all the contributors of the project:

Derek Jan LANGEDIJK[a], Joao NOITE[a], Liam COOPER[b], Leonid HLUSHENKO[a], Szymon MLECZKO[a], Karol GORNY[a], Martin MACHAC[a], Szymon GALUSZKA[a], Aleksandra ONUFRENA[a], Michal ZIMNY[a], Loic DAVOINE[a], Lukasz ZWALINSKI[a], Jerome DAGUIN[a], Bart VERLAAT[a]

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