CFD Simulations for CAST

2. Density estimation

- Do we need CFD ? -

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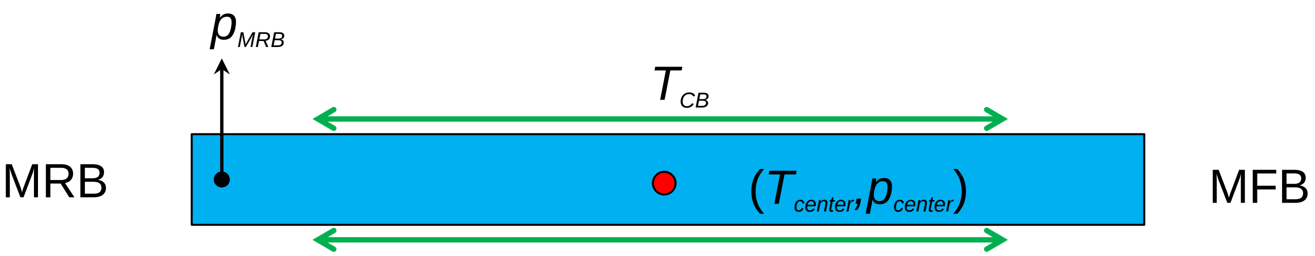
Why do we need CFD?

INFORMATION NEEDED

A. Gas density at cold bore center (tilting angle dependent).

B. Gas density distribution all along the axis of the cold bore (coherence length).

EXPERIMENTAL MEASUREMENTS AVAILABLE



☐ Experimental measurements available: 1) temperature of the superfluid cooling helium (T_{CB})

2) pressure at the MRB side (p_{MRB})

☐ $T_{center} = T_{CB}$

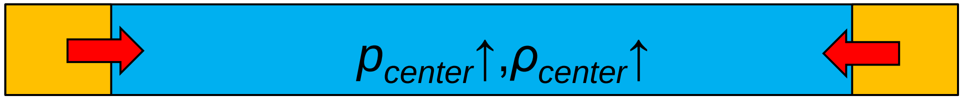
☐ $p_{center} \sim p_{MRB}$

Why do we need CFD?

A. IDEAL CASE

- Uniform temperature, density and pressure all along the cold bore: density can be calculated since the total volume and the injected mass are known.

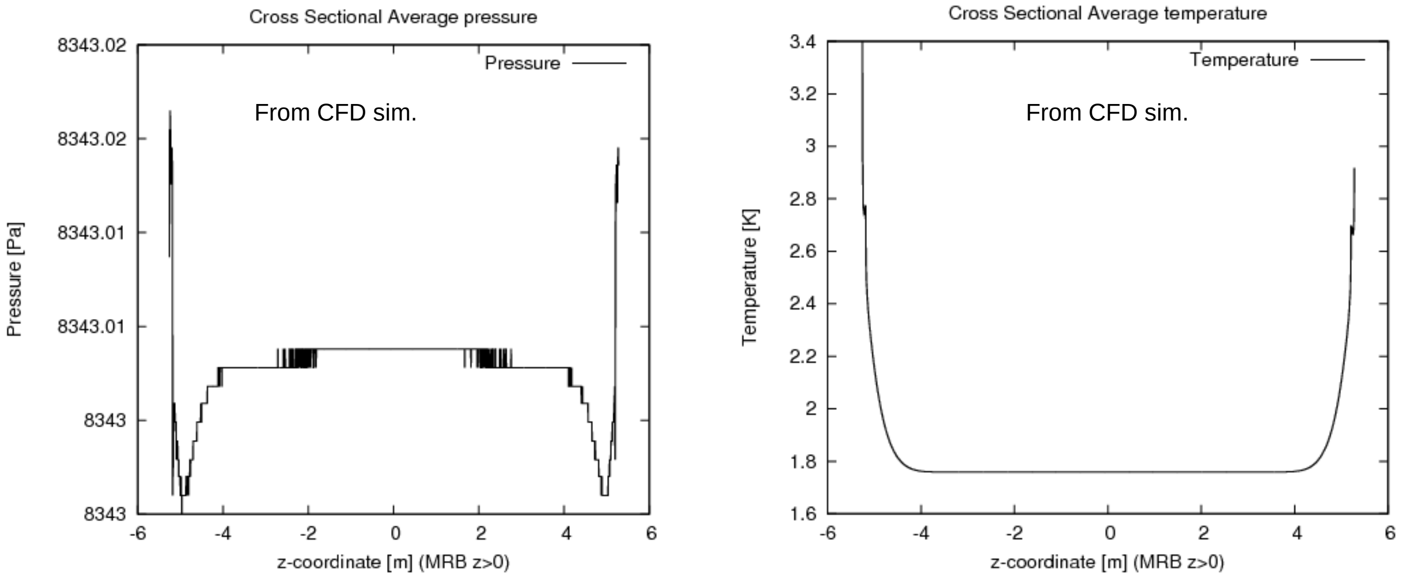
B. REAL CASE - HORIZONTAL



- As compared to the ideal case, the fluid at the sides is hotter and less dense → the gas is "compressed" to the center of the bore, both p and ρ increases (CONVECTION EFFECT)
- Since the magnet is horizontal and the gas velocities are small (< ~1 m/s), the pressure can be considered uniform: $p_{center} = p_{MRB}$.
- $(p_{center}, T_{center}) \rightarrow \rho_{center}$: the density at center can be computed through an Equation of State.
- Some uncertainty is given by the EoS (e.g. -1% density maximum deviation Peng-Robinson/NIST, +1.4% Van-der-Waals/NIST*).

***EDMS 1184174** v.**1**

Example horizontal 83 mbar



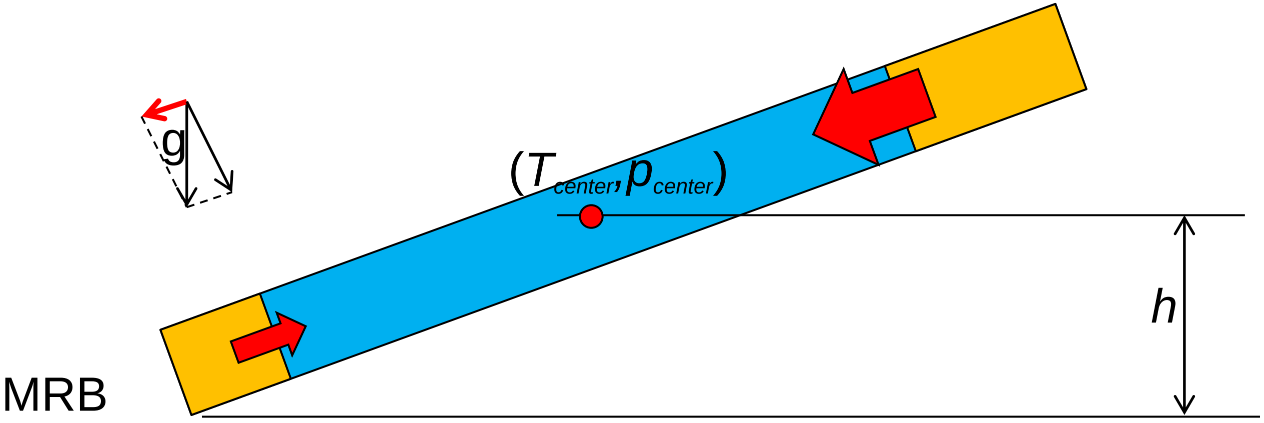
Error source	Value	Density error
p_{MRB} measurement accuracy	±4 Pa (±0.05 % of reading*)	$\pm 10^{-3}$ kg m^{-3}
Pressure non-uniformity (from CFD)	~ 0.02 Pa	5 10^{-6} kg m^{-3}
T_{CB} measurement resolution**	$\pm 10^{-3}$ K	$\pm 10^{-3}$ kg m^{-3}
$T_{center} - T_{CB}$ (from CFD)	$< 10^{-6}$ K	negligible
Equation of State (P-R vs NIST)		~10^{-2} kg m^{-3}

* MKS baratron 690A

** Resolution as seen from experimental measurements, actual accuracy is expected to be worse

Why do we need CFD?

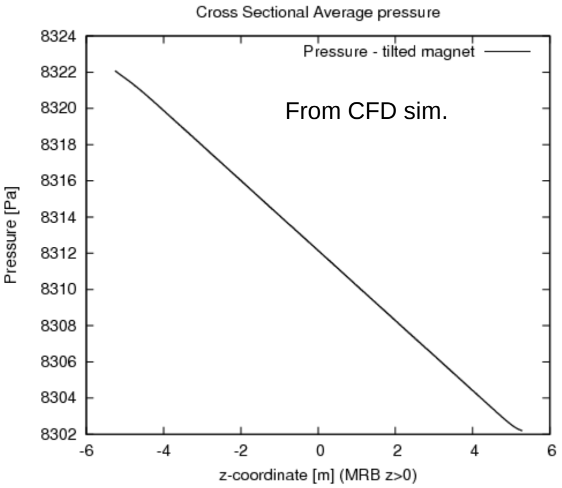
C. REAL CASE - TILTED

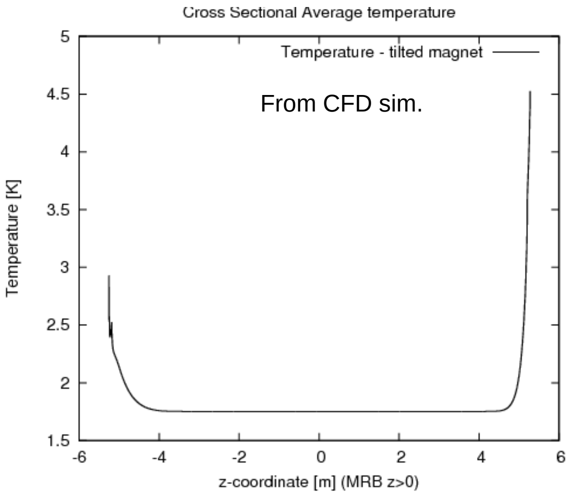


$$p_{center} - p_{MRB} = \int_{y=0}^{y=h} \rho\, g\, dy \sim \rho(p_{MRB}, T_{CB})gh$$

- The two hot regions at the ends are now affected by gravity; it cannot be known *a priori* if this implies an increase or a decrease of pressure as compared to the horizontal case (CONVECTION EFFECT).
- The HYDROSTATIC EFFECT (i.e. the weight of the gas) could be important: pressure and density decreases moving from bottom to top.
- p_{center} can be estimated as $\rho(p_{MRB}, T_{CB})gh$

Example tilted 83 mbar

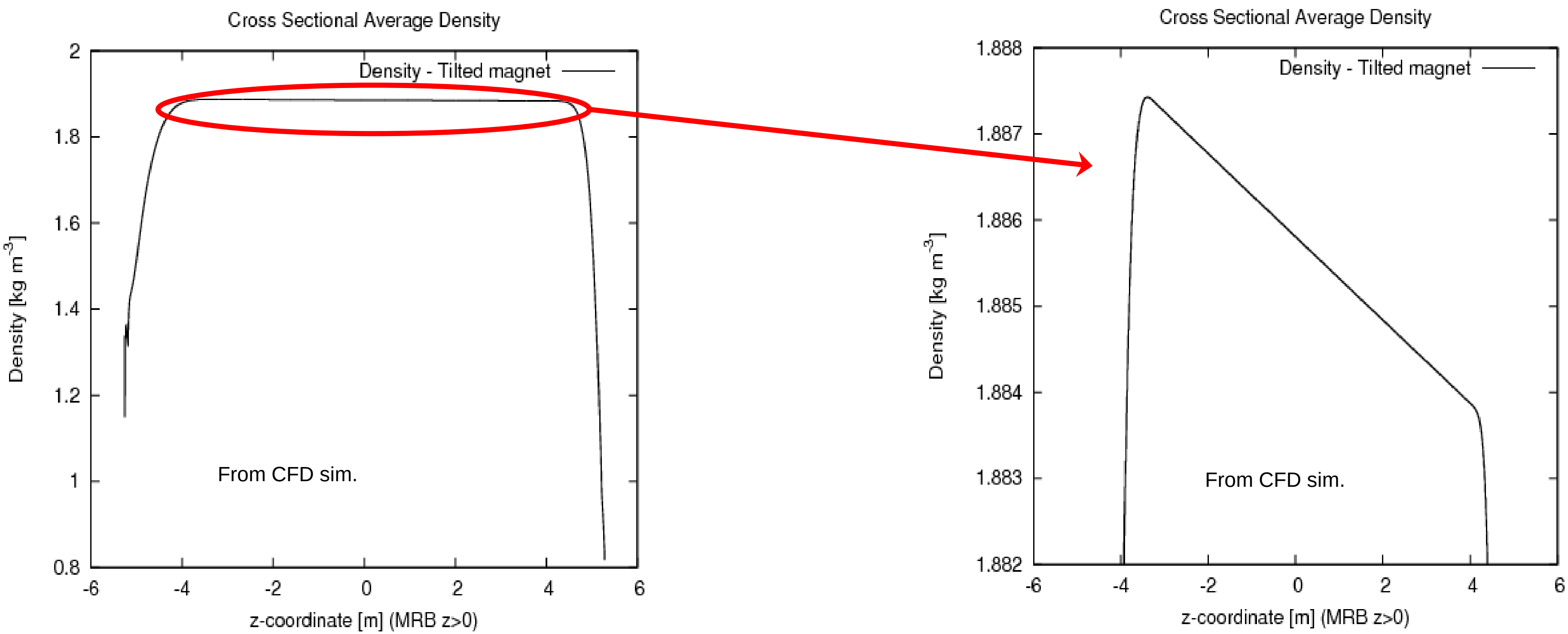




Error source	Value	Density error
p_{MRB} measurement accuracy	±4 Pa (±0.05 % of reading*)	$\pm 10^{-3}$ kg m^{-3}
Error estimation hydrostatic (from CFD) $p_{center} - \rho(p_{MRB},T_{CB})gh$	~ 0.2 Pa	$5\ 10^{-5}$ kg m^{-3}
T_{CB} measurement resolution**	$\pm\ 10^{-3}$ K	$\pm\ 10^{-3}$ kg m^{-3}
$T_{center} - T_{CB}$ (from CFD)	$< 10^{-6}$ K	negligible
Equation of State (P-R vs NIST)		$\sim 10^{-2}$ kg m^{-3}

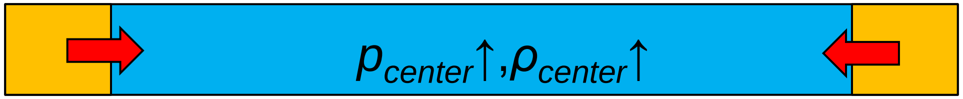
- ☐ If neglecting the hydrostatic effect ($p_{center}=p_{MR}$) the density error would be ~ $2\ 10^{-3}$ kg m^{-3}

Example tilted 83 mbar



- Because of the hydrostatic effect, the density is not constant anymore in the center of the magnet.
- In the example above (i.e. *p* = 83 mbar, 6° tilting), the density profile spans around 3 times the “coherence length criterion” (i.e. 10^{-3} kg m^{-3}).
- This phenomenon is directly proportional to the density of the gas → it`s important at high pressures ($\rho \sim 2.5$ kg m^{-3} @ 100 mbar, $\rho \sim 0.3$ kg m^{-3} @ 14 mbar).

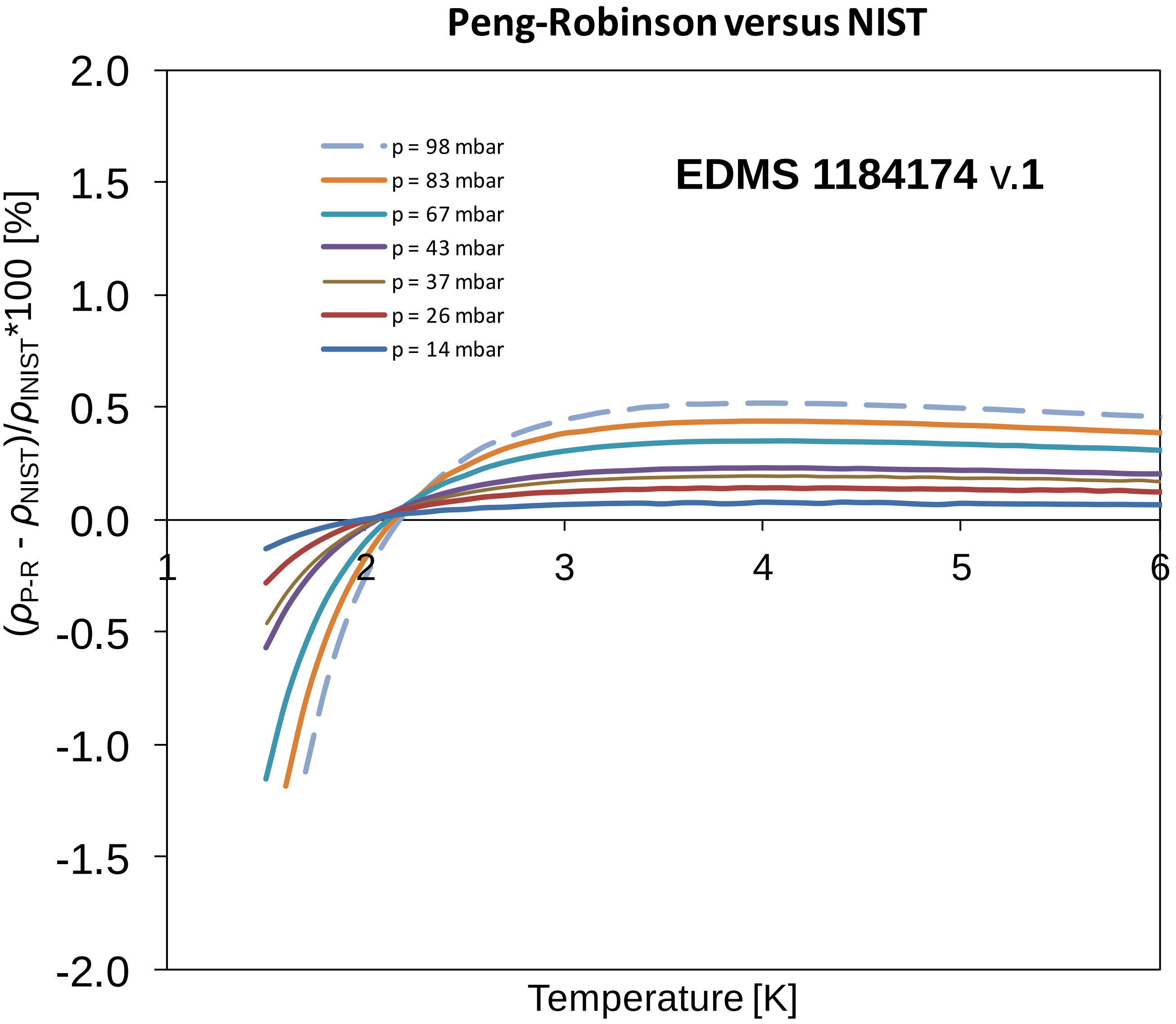
CONCLUSIONS



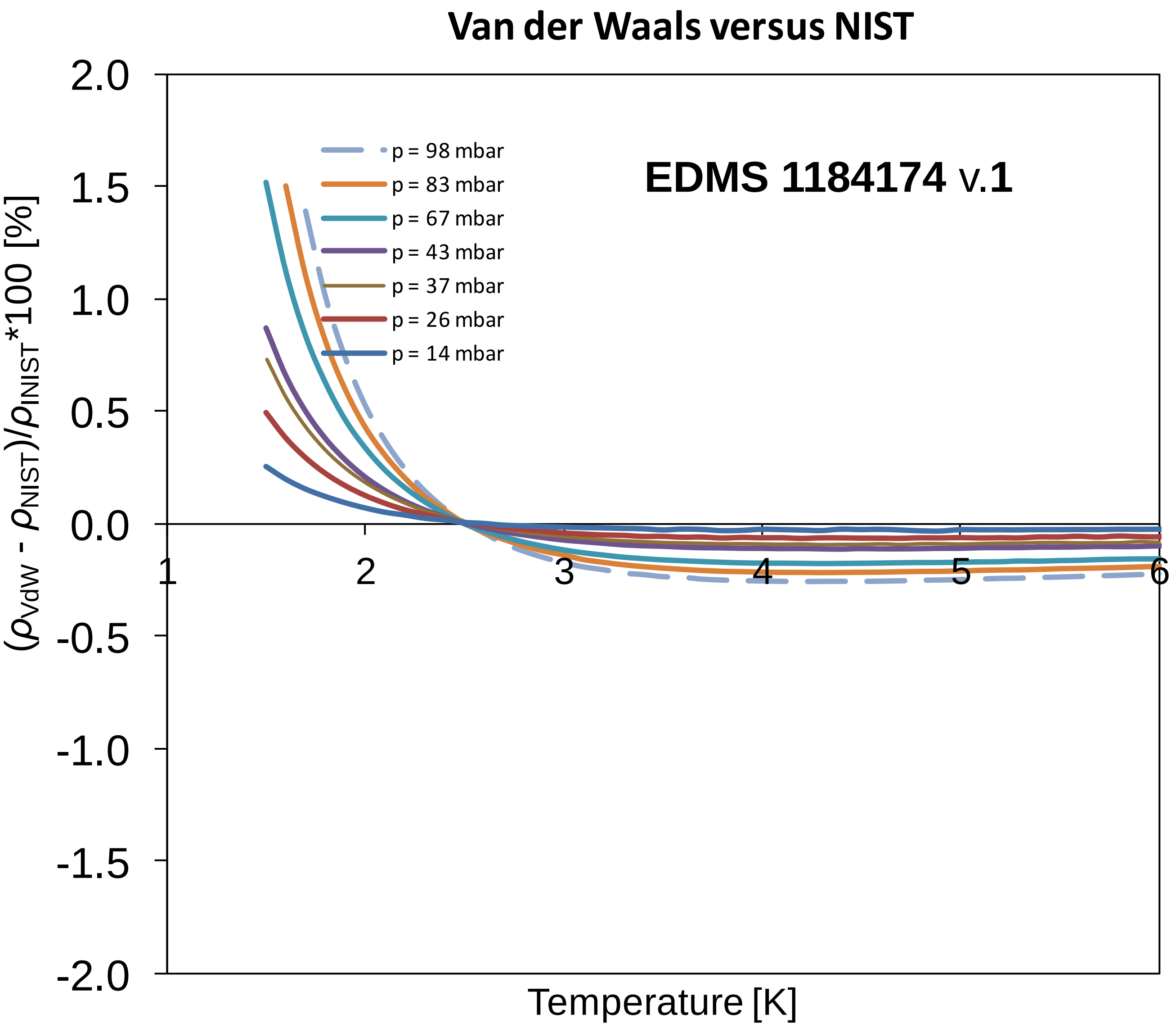
- The gas density at the center of the bore can be obtained from the experimental values of (p_{MRB},T_{CB}) without any need of CFD simulations.
- The major sources of error are the Equation of State and the experimental measurements.
- The HYDROSTATIC EFFECT can be estimated with enough accuracy without CFD.
- CFD is needed only to reproduce the CONVECTION EFFECT and obtain the actual density distribution along the axis (coherence length).
- Because of the CONVECTION EFFECT, the pressure is changing when tilting in a non-trivial way (i.e. increasing with "cold windows" and decreasing with "hot windows"): being able to predict this would be a proof of CFD simulations reliability.

Back up slides

Peng Robinson versus NIST comparison



Van der Waals versus NIST comparison

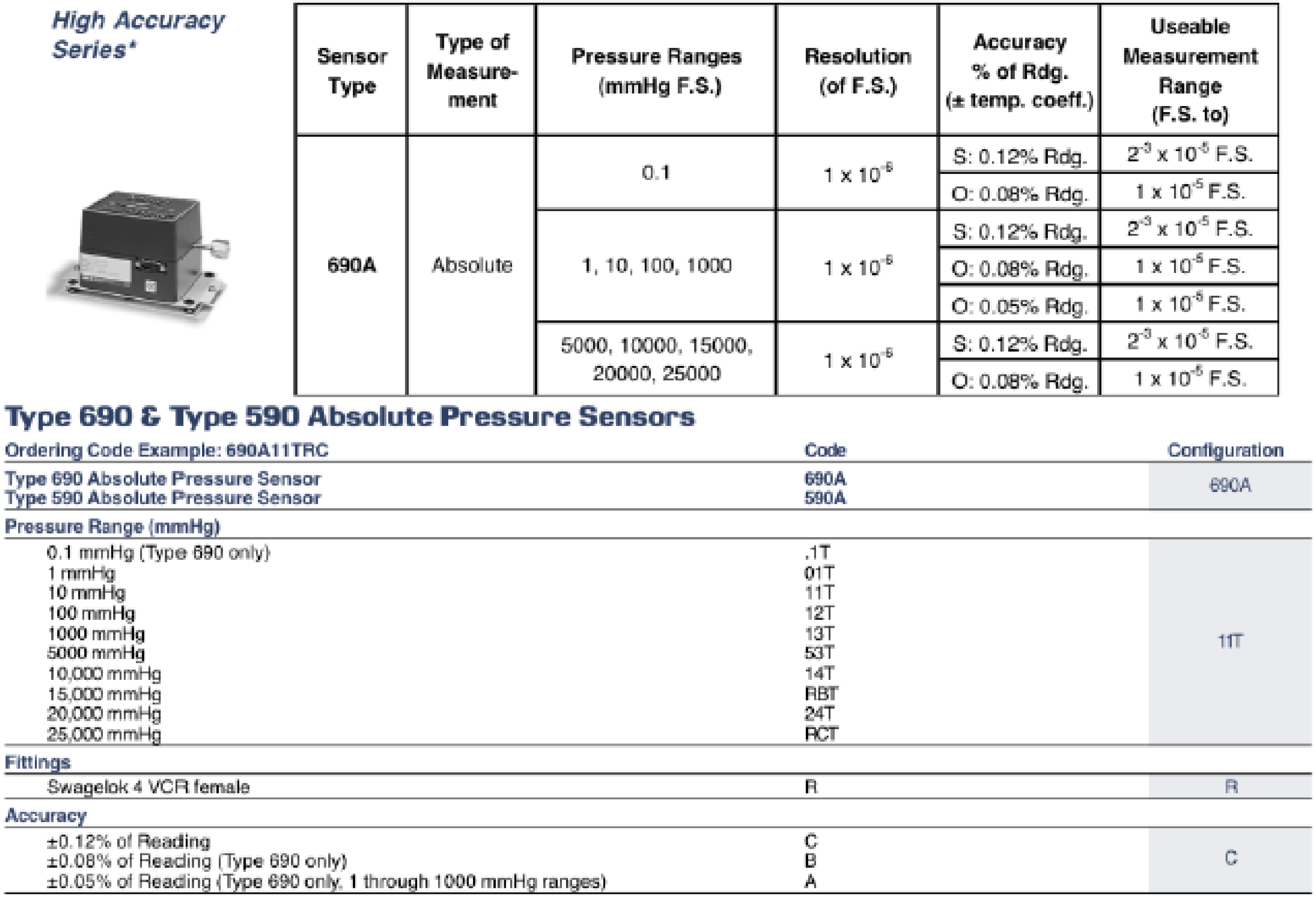


EoS comparison

Temperature [K]	Pressure [Pa]	P-R/Ideal-Gas [%]	P-R/NIST [%]	P-R/NIST [kg m^{-3}]	VdW/NIST [%]	VdW/NIST [kg m^{-3}]
1.83	9800	10.6	-0.6	-1.4E-02	0.9	2.0E-02
1.75		11.7	-0.9	-2.1E-02	1.2	2.7E-02
1.83	3700	3.6	-0.11	-8.7E-04	0.30	2.3E-03
1.75		3.9	-0.17	-1.4E-03	0.37	3.0E-03
1.83	1400	1.3	-0.03	-7.8E-05	0.11	3.1E-04
1.75		1.4	-0.04	-1.3E-04	0.14	4.0E-04

- ☐ Typical T_{CB} during “warm windows” test: 1.83 K
- ☐ Typical T_{CB} during “cold windows” test: 1.75 K

Pressure sensor



*High Accuracy Series**

Sensor Type	Type of Measure-ment	Pressure Ranges (mmHg F.S.)	Resolution (of F.S.)	Accuracy % of Rdg. (± temp. coeff.)	Useable Measurement Range (F.S. to)
690A	Absolute	0.1	1×10^{-6}	S: 0.12% Rdg.	$2^{-3} \times 10^{-5}$ F.S.
				O: 0.08% Rdg.	1×10^{-5} F.S.
		1, 10, 100, 1000	1×10^{-6}	S: 0.12% Rdg.	$2^{-3} \times 10^{-5}$ F.S.
				O: 0.08% Rdg.	1×10^{-5} F.S.
				O: 0.05% Rdg.	1×10^{-5} F.S.
		5000, 10000, 15000, 20000, 25000	1×10^{-6}	S: 0.12% Rdg.	$2^{-3} \times 10^{-5}$ F.S.
				O: 0.08% Rdg.	1×10^{-5} F.S.

Type 690 & Type 590 Absolute Pressure Sensors

Ordering Code Example: 690A11TRC	Code	Configuration
Type 690 Absolute Pressure Sensor	690A	690A
Type 590 Absolute Pressure Sensor	590A	
Pressure Range (mmHg)		
0.1 mmHg (Type 690 only)	.1T	11T
1 mmHg	01T	
10 mmHg	11T	
100 mmHg	12T	
1000 mmHg	13T	
5000 mmHg	53T	
10,000 mmHg	14T	
15,000 mmHg	RBT	
20,000 mmHg	24T	
25,000 mmHg	RCT	
Fittings		
Swagelok 4 VCR female	R	R
Accuracy		
±0.12% of Reading	C	C
±0.08% of Reading (Type 690 only)	B	
±0.05% of Reading (Type 690 only, 1 through 1000 mmHg ranges)	A	

Figure 91: *Sensor MKS 690A characteristics.*