CFD Simulations for CAST

83 mbar cold windows He^3
37 mbar warm windows He^3

- Enrico Da Riva -
CERN (EN/CV/PJ)

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Problem & solution strategy 1/2

Information needed:

- Gas density at the center of CB: can be computed from the experimental values of gas pressure and temperature of the magnet (see previous collaboration meeting).
- Coherence length: CFD simulations are needed.

Experimental measurements available:

- Pressure change when tilting:
  1. Magnet temperature change.
  2. Hydrostatic.
  3. Convection effect.
- Windows temperature.
  1. Temperature when horizontal at MFB and MRB.
  2. Temperature change when tilting.
- Total mass in the system.

Problem & solution strategy 2/2

CFD simulations strategy:

A) Horizontal magnet:

- Gas pressure and magnet temperature are used as boundary conditions.
- Windows temperature and total mass are results of the simulation and are compared against experimental data.

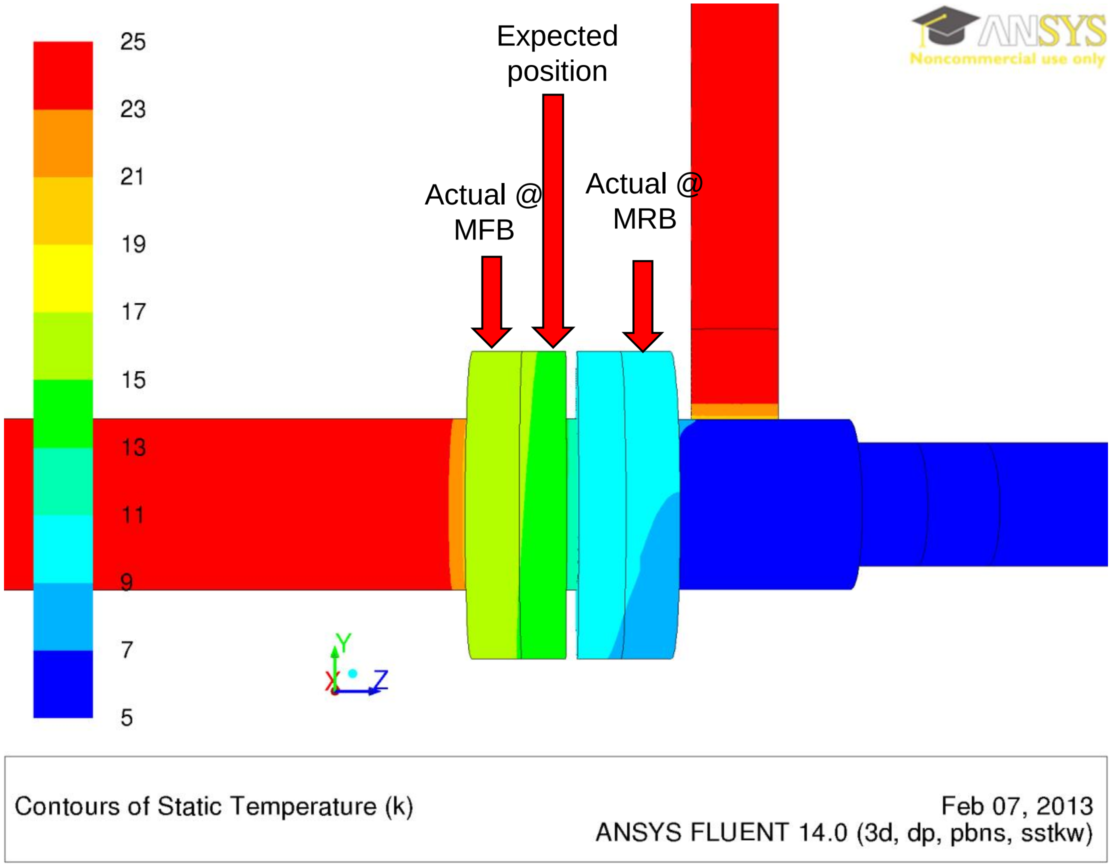
B) Tilted magnet:

- The total He^3 mass obtained in the horizontal case is now kept constant.
- The magnet temperature is not updated (the pressure change due to the magnet temperature changes depends only on the equation of state, no need for CFD).
- Windows temperature change because of tilting is compared against experimental data.
- The pressure change due to "convection effect" is compared against the value reduced from experimental data.

Experimental cases considered till now:

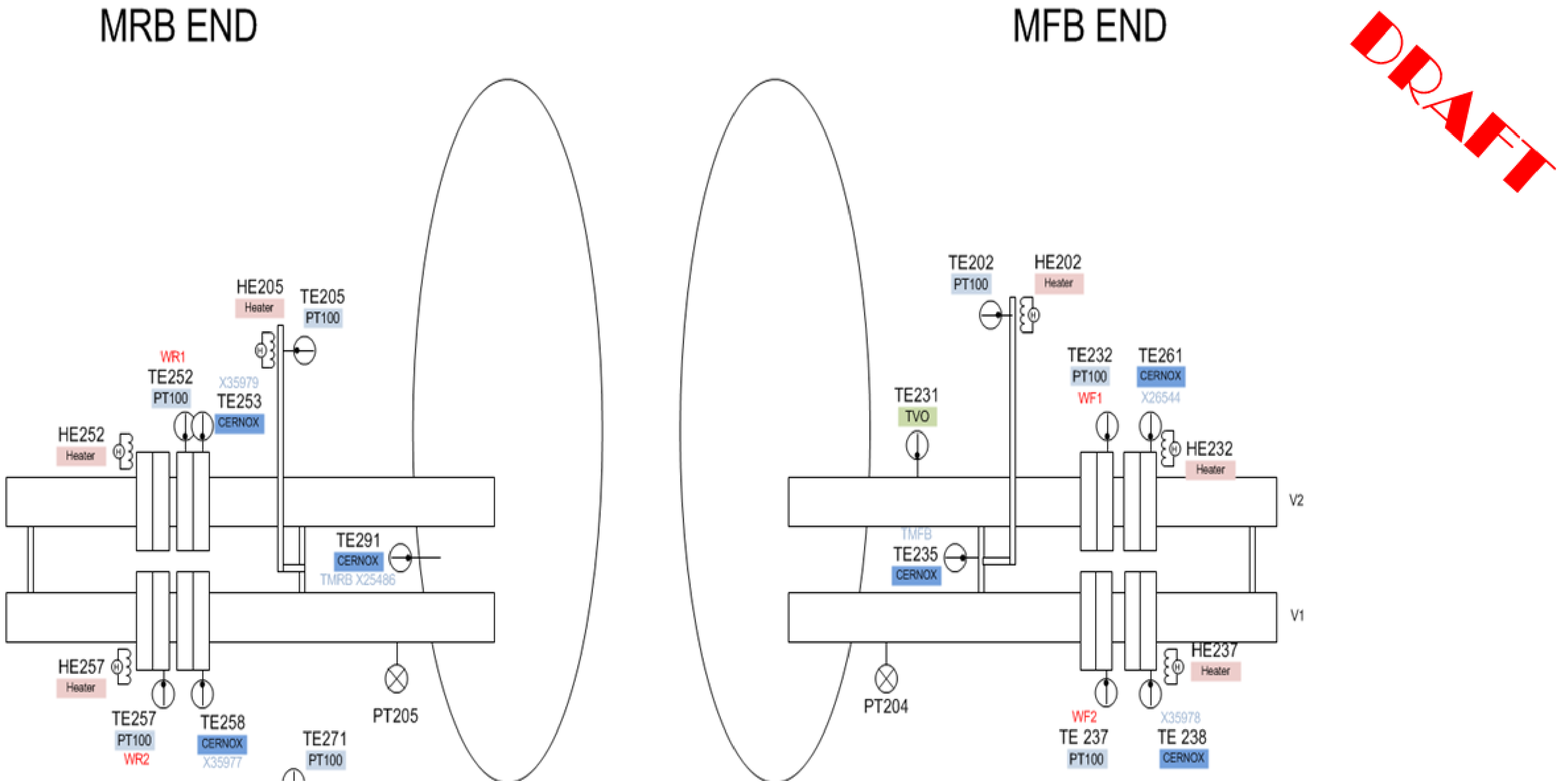
- 83 mbar, cold windows
- 37 mbar, warm windows

Swapped windows temperature sensors



- Accurate windows temperature information is essential to correctly set up CFD simulations.
- Experimental windows temperature measurements are always lower at MRB.
- Swapped sensors position was supposed as possible explanation of the inconsistent CFD results and was confirmed by the inspection recently done.

Swapped windows temperature sensors



Cold Windows 83 mbar

- Experimental data and comparison against CFD -

EDMS 1184174 v.1

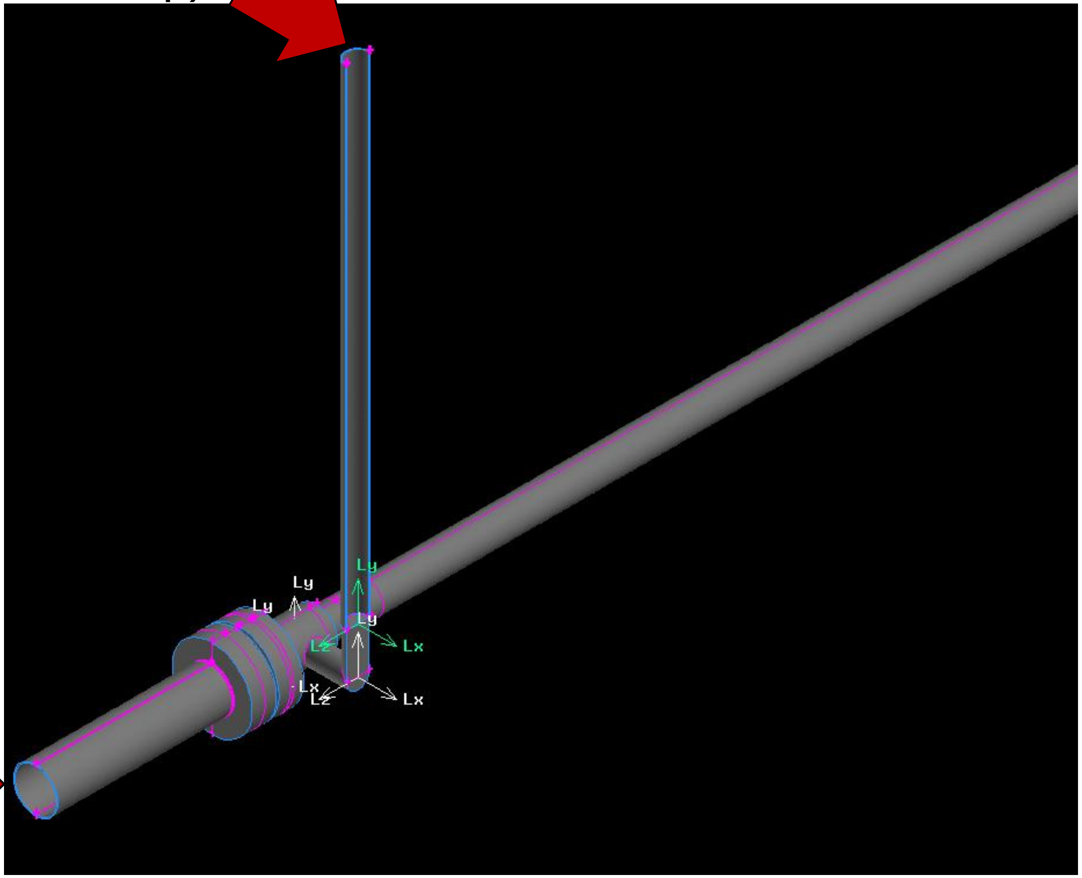
Case #	N_T [mol]	T_{Mag} [K]	T_{W-MFB1} [K]	T_{W-MFB2} [K]	T_{W-MRB1} [K]	θ [degree]	P_{CB} [mbar]
A	18.887	1.758	19.0	16.6	11.2	0	83.39
B1 B2		1.778 1.738	19.0	16.6	11.2	0	84.39 82.25
C1 C2		1.758	19.0	16.6	11.2	-6* +6*	
D		1.765	20.2	17.8	10.5	-6	84.30
E		1.766	20.2	18.0	10.5	-4	84.20
F		1.761	19.9	17.3	10.7	-2	83.72
G		1.759	19.1	16.5	11.0	0	83.43
I		1.750	18.9	16.2	11.8	2	83.04
J		1.749	18.9	16.0	12.8	4	83.11
K		1.752	18.8	16.0	14.1	6	83.42

Tracking of real tilting process (cases D–K)

* positive tilting means MRB above MFB

CFD model update (cold windows)

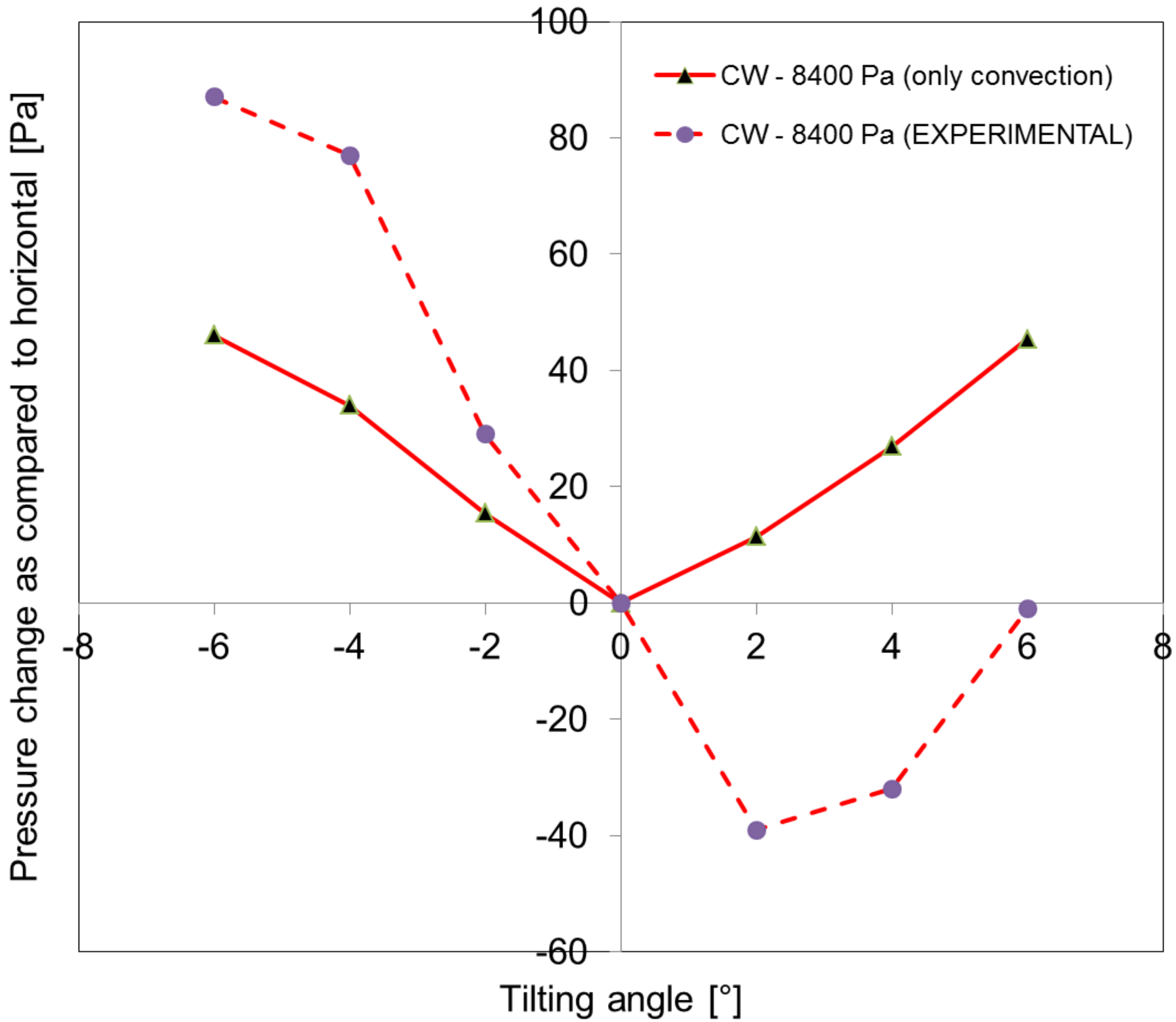
Temperature b.c.
(thermal clamp)



Temperature b.c.
(thermal clamp)

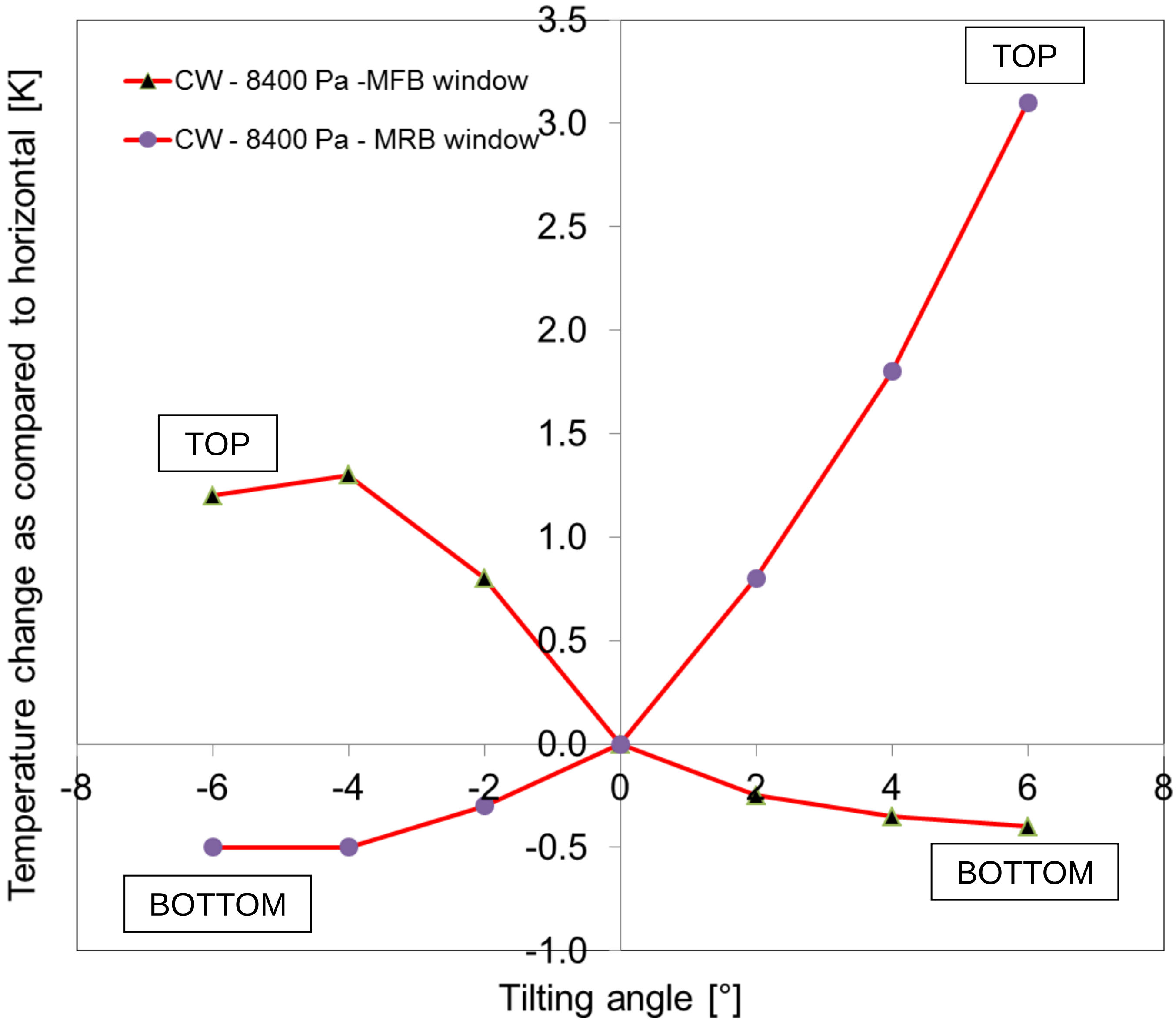
- Gas “dead volumes” added.
- Model geometry extended to the thermal clamps.
- Temperature of thermal clamps used as boundary conditions.

Pressure (experimental and "convection effect")



- Removing the components due to the "hydrostatic effect" and the "magnet temperature change" the pressure change during tilting due to the "convection effect" only display a nice V shape.

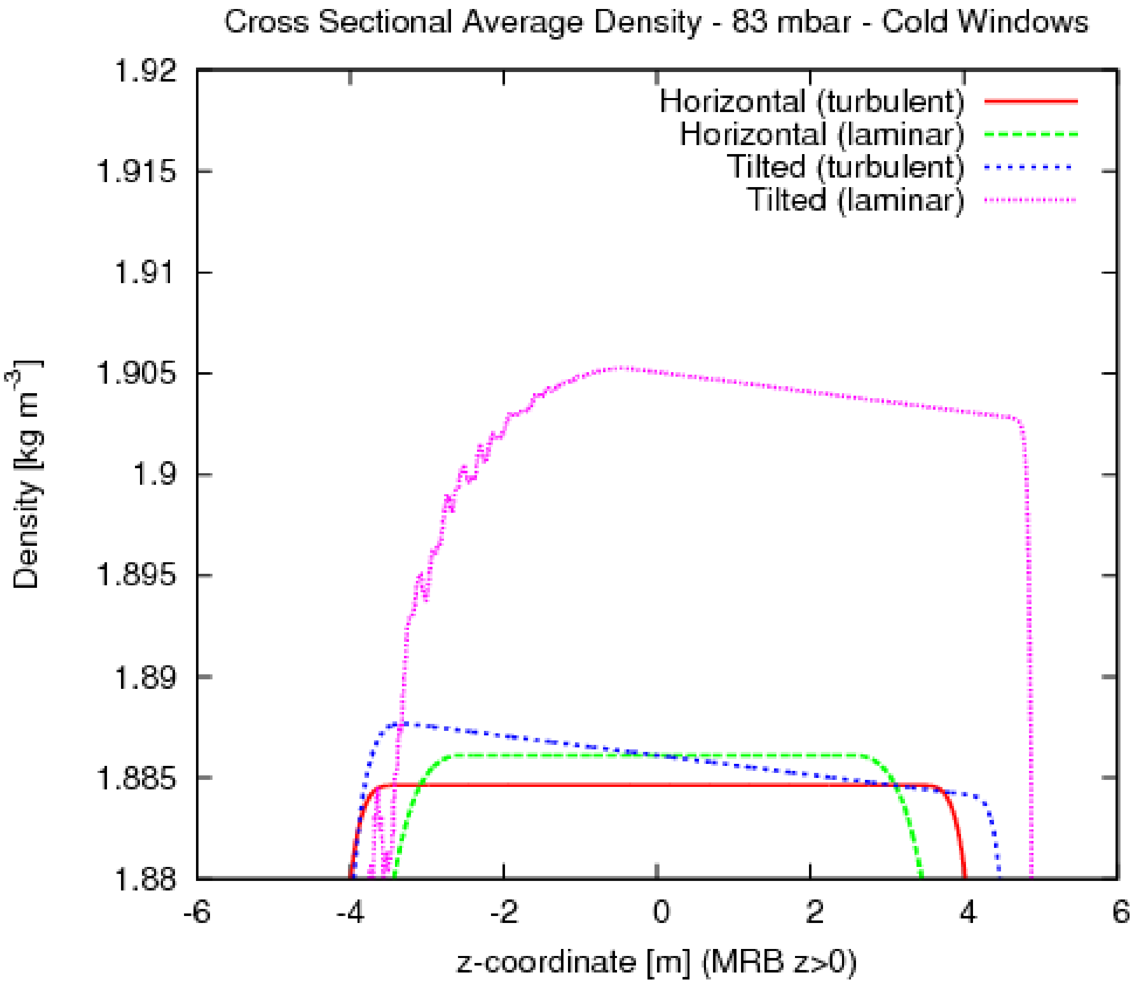
Experimental windows temperature change when tilting



Cold Windows 83 mbar
- CFD vs experimental-

Case	P change "convection effect"	T_{MFB} horizontal	T_{MFB} change tilt (top/bottom)	T_{MRB} horizontal	T_{MRB} change tilt (top/bottom)	Mass comparison
EXPERIMENTAL	+45 Pa	17.8 K	+1.2 K / -0.4 K	11.0 K	+3.0 K / -0.5 K	
TURBULENT ($k\omega$-SST)	+ 6 Pa	14.9 K	+1.0 K / -0.3 K	9.4 K	+1.7 K / -0.5 K	-0.2%
LAMINAR	+80 Pa	14.6 K	+1.4 K / -0.2 K	8.9 K	+2.4 K / -0.3 K	+2.6%

Coherence length CW 83 mbar



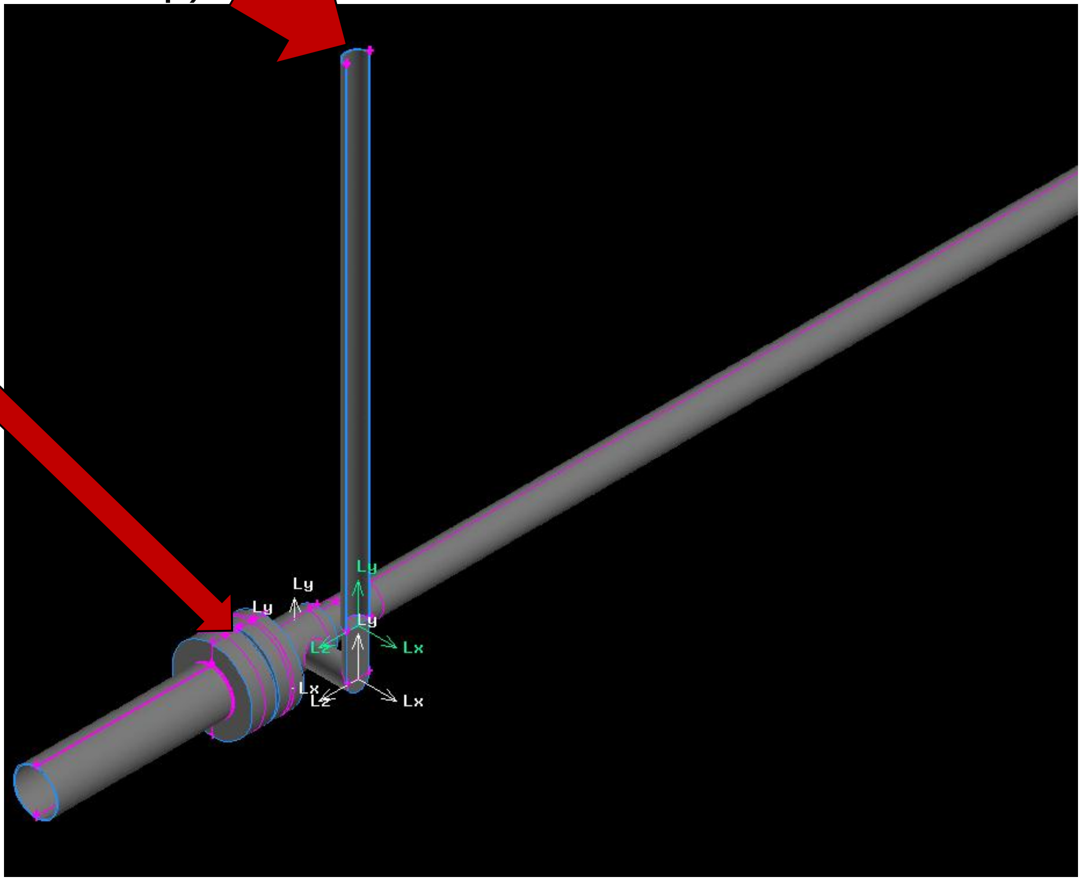
- Coherence length computed under the assumption of laminar flow is noticeably lower.
- Some converge problems for the tilted laminar results still needs to be solved.
- The plot above doesn`t take into account the actual magnet temperature change: it should be used to estimated the coherence length only, while the density in the center of the CB should be obtained from the experimental measurement of magnet temperature and gas pressure

Warm Windows 37 mbar

CFD model (warm windows)

Temperature b.c.
(thermal clamp)

Temperature b.c.
(70K)



Boundary conditions (37 mbar)

Case : 37 mbar, warm windows

The data corresponds to the morning tracking of 13/11/2008 (step number 410).

Number of moles : 7.367541

Before the magnet movement (stable conditions):

P_cb= 37.10 mbar

Tmag= 1.798 mbar

Tw_MFB1= 61.8 K

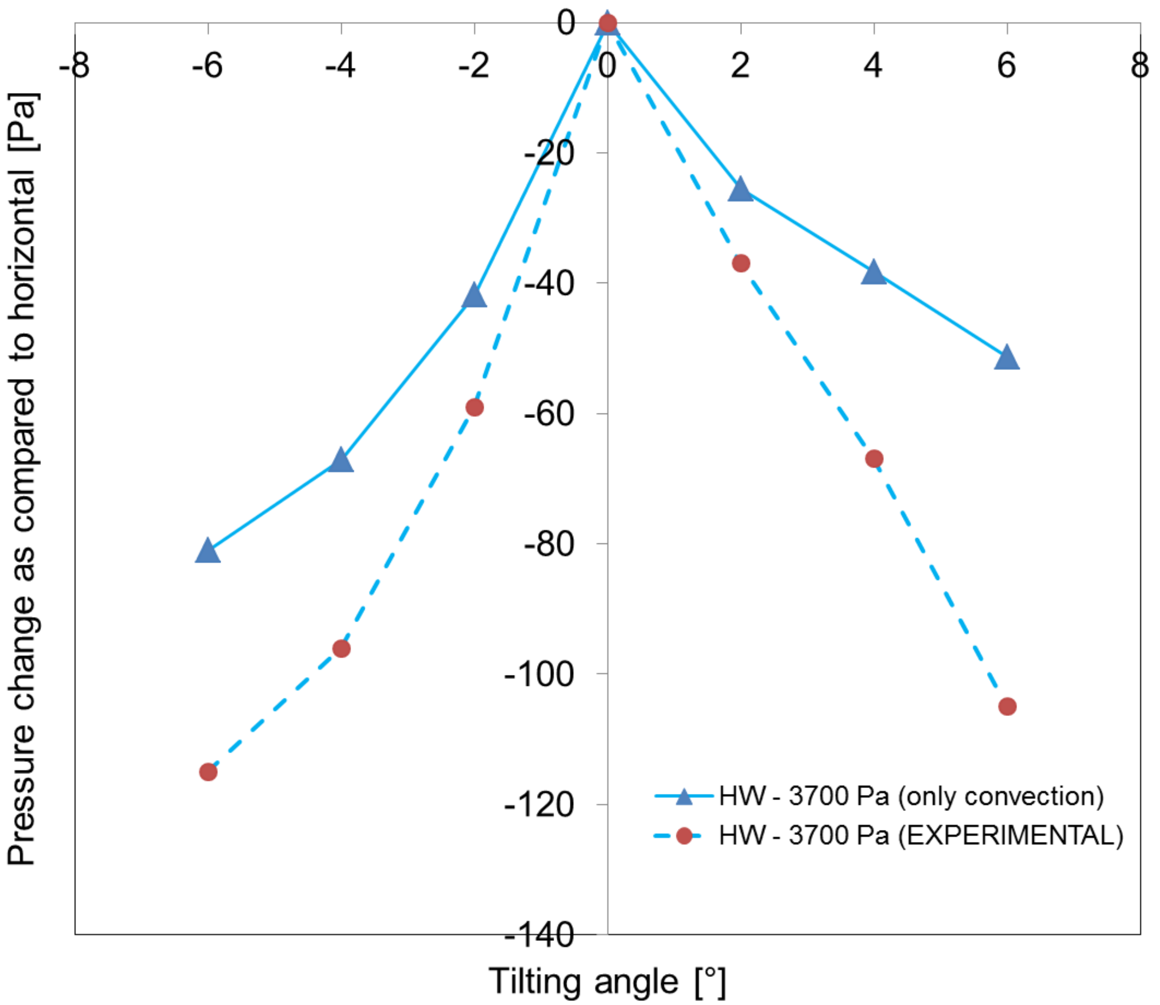
Tw_MFB2= 64.3 K

Tw_MRB1= 60.6 K

Tw_MRB2= 64.8 K

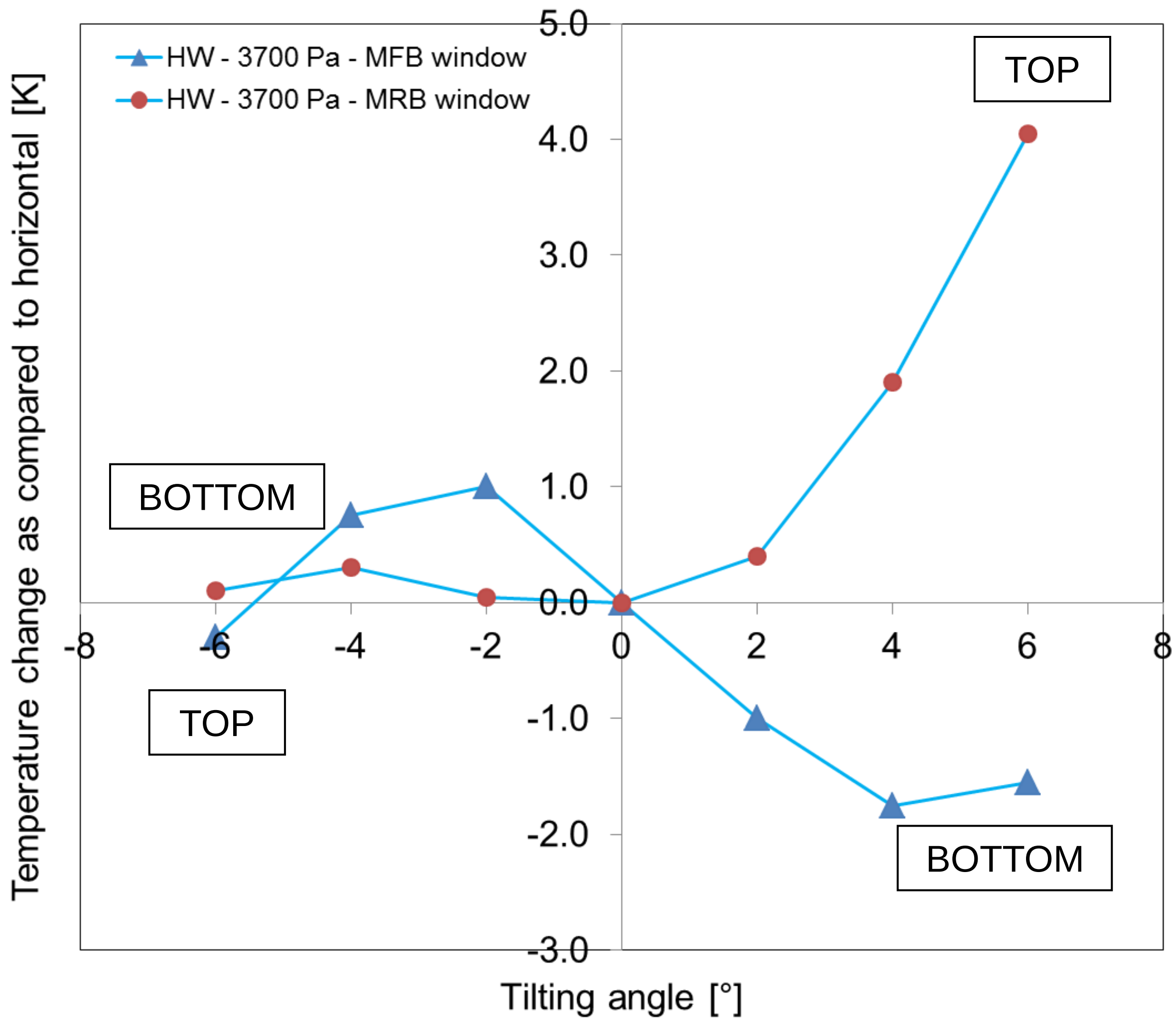
angle	Time	Tmag [K]	Pcb [mbar]	Tw_MFB1 [K]	Tw_MFB2 [K]	Tw_MRB1 [K]	Tw_MRB2 [K]
-6°	7:01:32	1.7869	36.19	68.4	70.9	60.3	64.5
-4°	7:14:03	1.7899	36.38	69.4	72.0	60.2	65.0
-2°	7:26:44	1.7960	36.75	69.6	72.3	60.1	64.6
0°	7:39:36	1.8046	37.34	68.6	71.3	60.0	64.6
2°	7:52:42	1.7999	36.97	67.5	70.4	60.7	64.7
4°	8:06:05	1.7925	36.67	66.8	69.6	62.6	65.8
6°	8:19:49	1.7815	36.29	67.8	69.0	64.9	67.8

Pressure (experimental and "convection effect")



- The test run at 37 mbar does not display the same "nice behavior" as the 83 mbar one.

Experimental windows temperature change when tilting

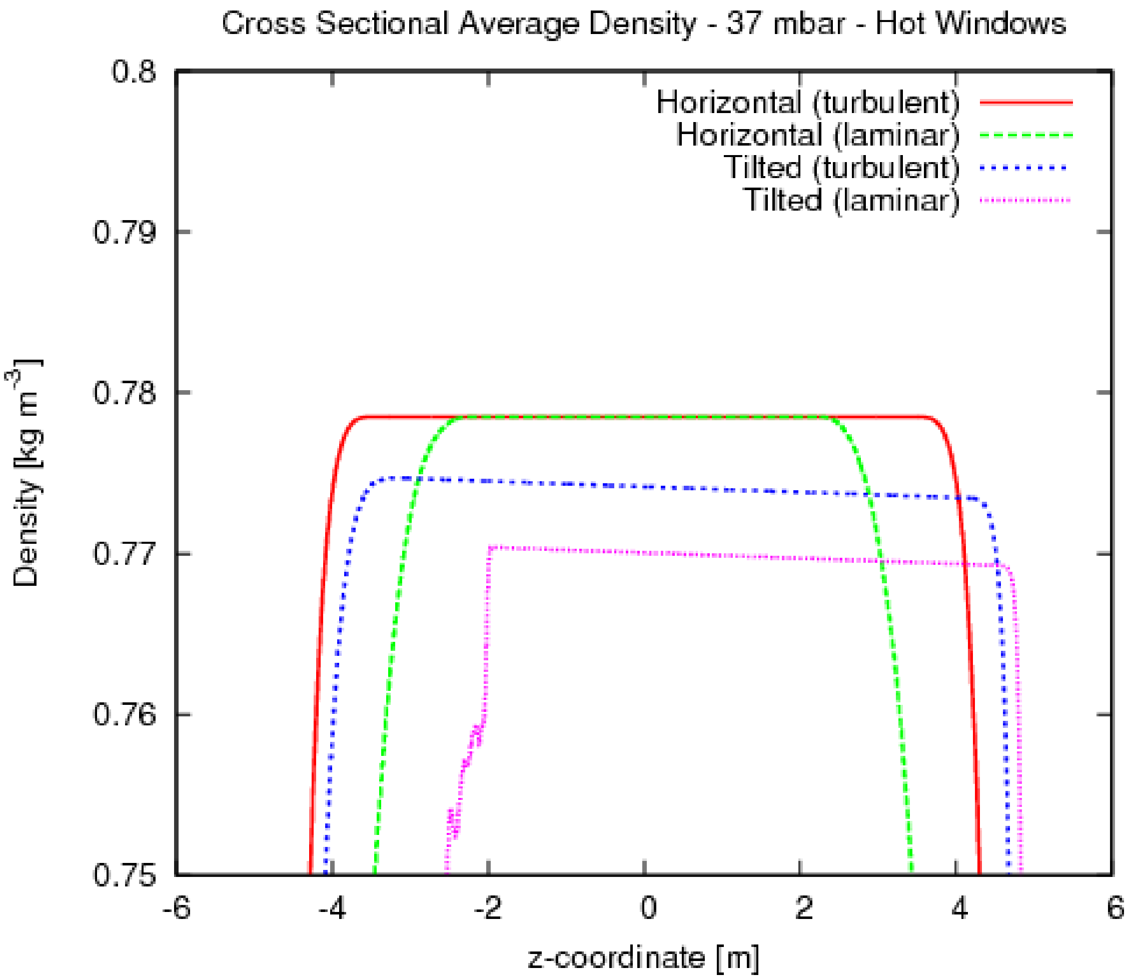


- Reference horizontal case in the plot is the 0° tilting during tracking.

Warm Windows 37 mbar
- CFD vs experimental-

Case	P change Pure tilting	T_{MFB} horizontal	T_{MFB} change tilt (top/bottom)	T_{MRB} horizontal	T_{MRB} change tilt (top/bottom)	Mass comparison
EXPERIMENTAL	-50 Pa (+6°) -80 Pa (-6°)	70.0 K	-0.3 K / -1.5 K	62.3 K	+4.1 K / +0.1 K	
TURBULENT (*kω*-SST)	-20 Pa	70 K (b.c.)	-- (70 K fixed as b.c.)	60.1 K	+2.1 K / -1.0 K	+0.7%
LAMINAR	- 40 Pa	70 K (b.c.)	-- (70 K fixed as b.c.)	56.2 K	+5.1 K / -0.1 K	-1.6%

Coherence length –warm windows - 37 mbar



- Coherence length computed under the assumption of laminar flow is noticeably lower.
- Some converge problems for the tilted laminar results still needs to be solved.
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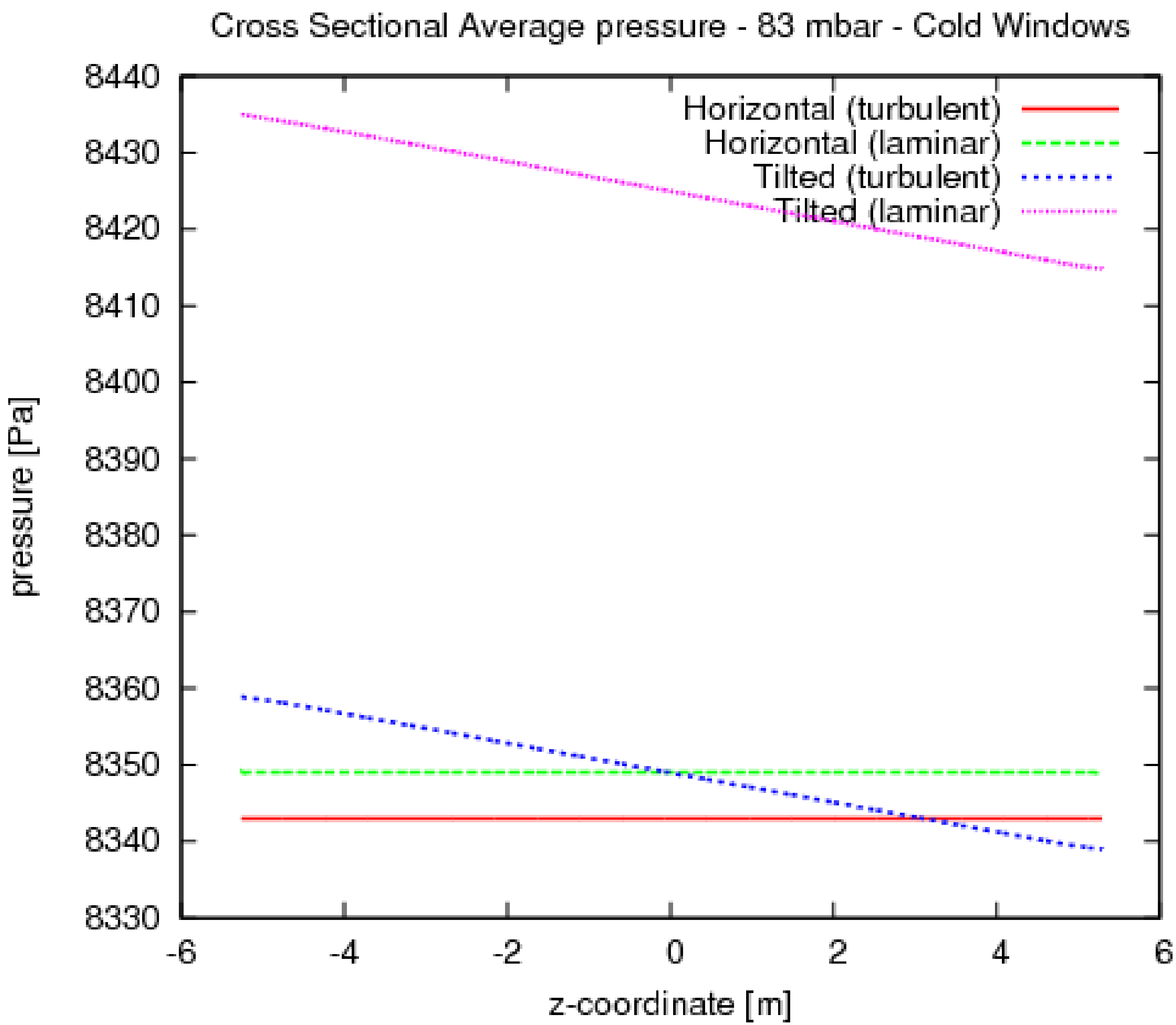
CONCLUSIONS

- CFD simulations could qualitatively reproduce the experimental pressure change when tilting: the pressure change due to the “convection effect” only is proved to be positive at “83 mbar – cold windows” and negative at “37 mbar – warm windows”.
- The turbulence model used may fail to accurately predict the He3 flow.
- Both the turbulent and the laminar solutions should be computed and the shortest computed coherence length is suggested to be used as the worst case for CAST data reduction.
- CFD model setup has been difficult because of inconsistencies in the windows temperature experimental measurements: swapped sensors position was supposed as possible explanation of results and was finally confirmed by the inspection recently done.

Back up slides


Cross Sectional Average pressure - 83 mbar - Cold Windows
Horizontal (turbulent)
Horizontal (laminar)
Tilted (turbulent)
Tilted (laminar)
pressure [Pa]
8440
8430
8420
8410
8400
8390
8380
8370
8360
8350
8340
8330
-6
-4
-2
0
2
4
6
z-coordinate [m]

Natural Convection laminar/turbulent transition

ρ - density
ν - kinematic viscosity
κ - thermal diffusivity
β - isobaric volume expansion coefficient $\quad \beta = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$
λ - thermal conductivity
L - characteristic length
ΔT - temperature difference
g - acceleration of gravity.

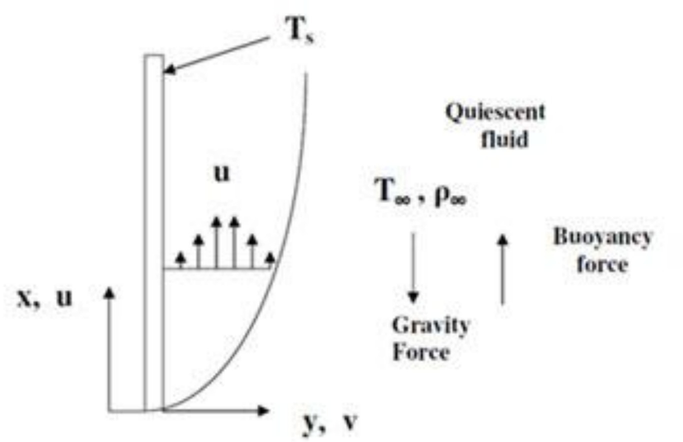
$\mathrm{Pr} = c_p\, \mu / \lambda$

Rayleigh nondimensional number:

$$\mathrm{Ra} = \frac{\beta g \Delta T L^3}{\nu \kappa}$$

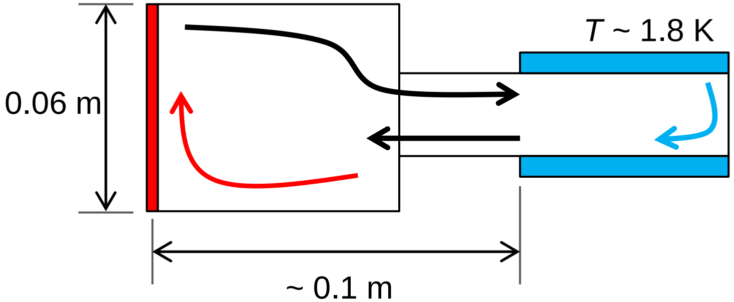
Examples of laminar-turbulent transitions:

- Vertical heated surface, external flow*: transition at $10^8 < \mathrm{Ra} < 10^9$



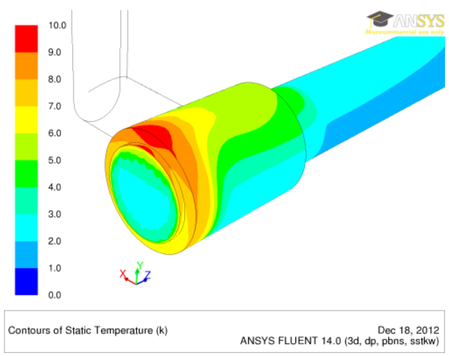
Source: * VDI Heat Atlas, Springer, 2nd edition;

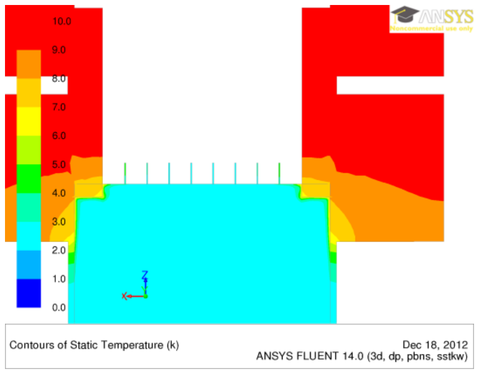
Rayleigh number for CAST?

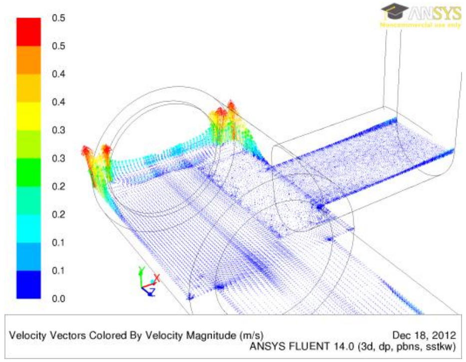


$$Ra = \frac{\beta g \Delta T L^3}{\nu \kappa}$$

$Pr = c_p \mu / \lambda$ $Gr = Ra/Pr$







- Geometry more complex than “classical examples”
- Properties don`t vary linearly, cannot compute them at an average temperature
- ß depends a lot on temperature (0.68 K^{-1} at 1.8 K, 0.35 K^{-1} at 3 K, 0.1 K^{-1} at 10 K)
- 1.8 K < ΔT <10 K for CW
- 0.06 m < L < 0.1 m
- Properties computed @ 1.8K, ΔT=10 K, L=0.1 m → **Ra ~ 2 10^{11}**, Ra/Pr ~ 9 10^{11}
- Properties computed @ 3K, ΔT=1 K, L=0.06 m → **Ra ~ 4 10^{8}**, Ra/Pr ~ 6 10^{8}