CFD Simulations for CAST He-4
CFD-2015-02_CAST-4He

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CAST Collaboration Meeting, Geneva

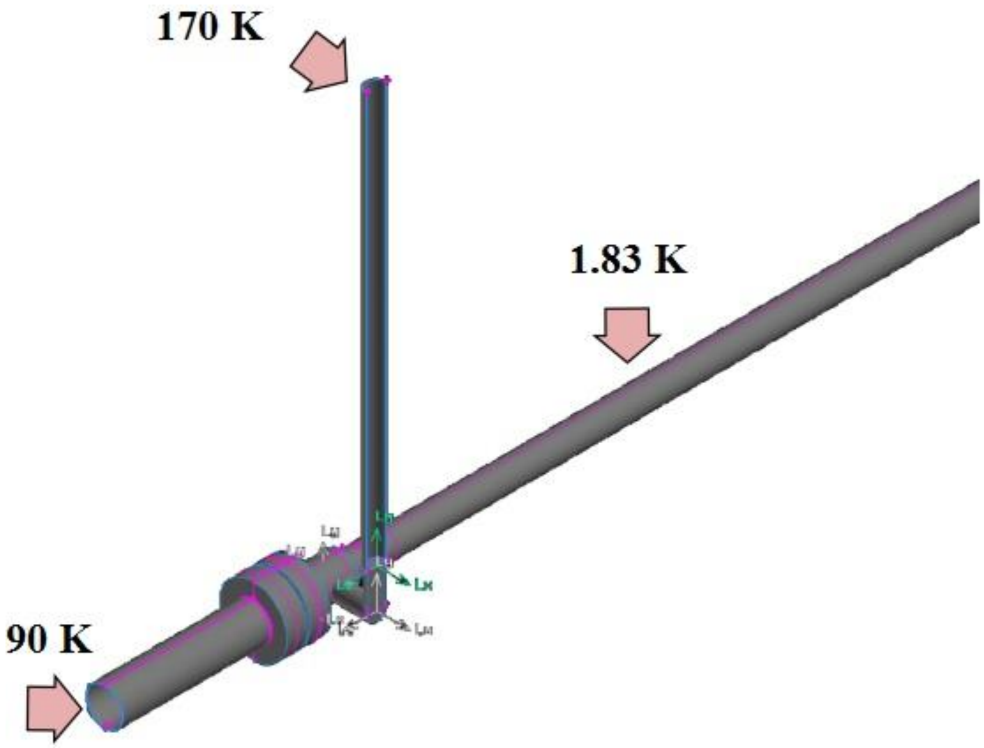
History of the CFD studies

CFD-2010-06_CAST (report - EDMS 1179773)

He-3 system with StarCD, only horizontal

CFD-2012-01_CAST-Tilted (project request - EDMS 1184174)

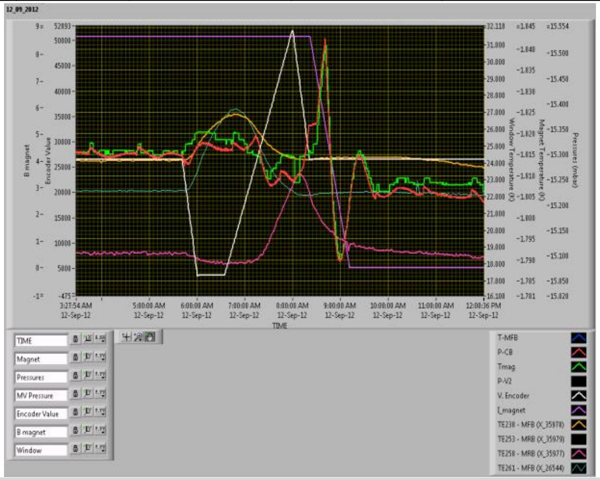
He-3 system with ANSYS Fluent, tilted, change in boundary conditions, final one chosen from 2012-11-08.pdf



Goal of the new CFD study

- Simulations for the He-4 system with ANSYS Fluent
- Settings as the last tilted simulations, laminar for horizontal and “half-laminar” for tilted
- For pressure around 15 mbar, 2.99 moles gas in the system
- Tilting angle from -8˚ to 8˚, with a step of 2˚

	Date	Shift	Window status	N moles	Step Number	Pressure [mbar]			
	12/09/2012	Morning	cold	2.99E+00	151	15.1			
	V encoder	Angle [degrees]	Time	Tmag [K]	Tmag_new [K]	Pcb [mbar]	Tw_MFB1 [K]-TE261	Tw_MFB2 [K]-TE238	Tw_MRB2 [K]-258
before shift	26464	0	AV(04:30-05:30)	1.816	1.8357	15.302	22.345	24.1415	18.644
during shift	6510.56	-6	06:39:38	1.818	1.8377	15.309	27.002	26.872	18.027
	13161.71	-4	06:51:32	1.82	1.8397	15.316	27.119	26.842	18.07
	19812.85	-2	07:03:20	1.817	1.8367	15.313	26.573	26.584	18.206
	26464	0	07:15:01	1.815	1.8347	15.335	25.525	26.034	18.268
	33115.15	2	07:26:38	1.811	1.8306	15.257	24.181	25.291	18.917
	39766.29	4	07:38:11	1.812	1.8316	15.243	23.276	24.768	20.232
	46417.44	6	07:49:42	1.815	1.8347	15.264	22.628	24.438	21.609

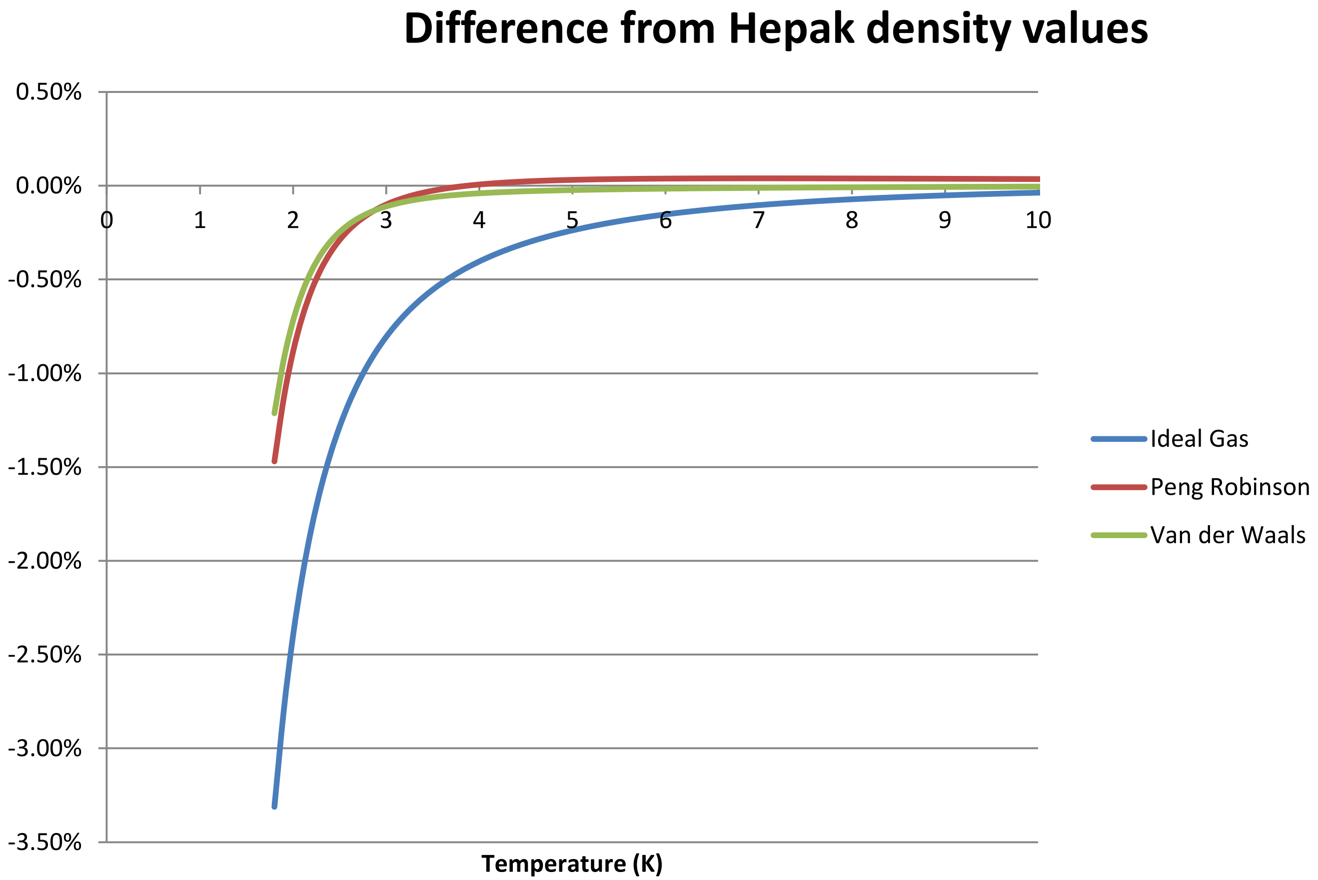


Main changes in the new study

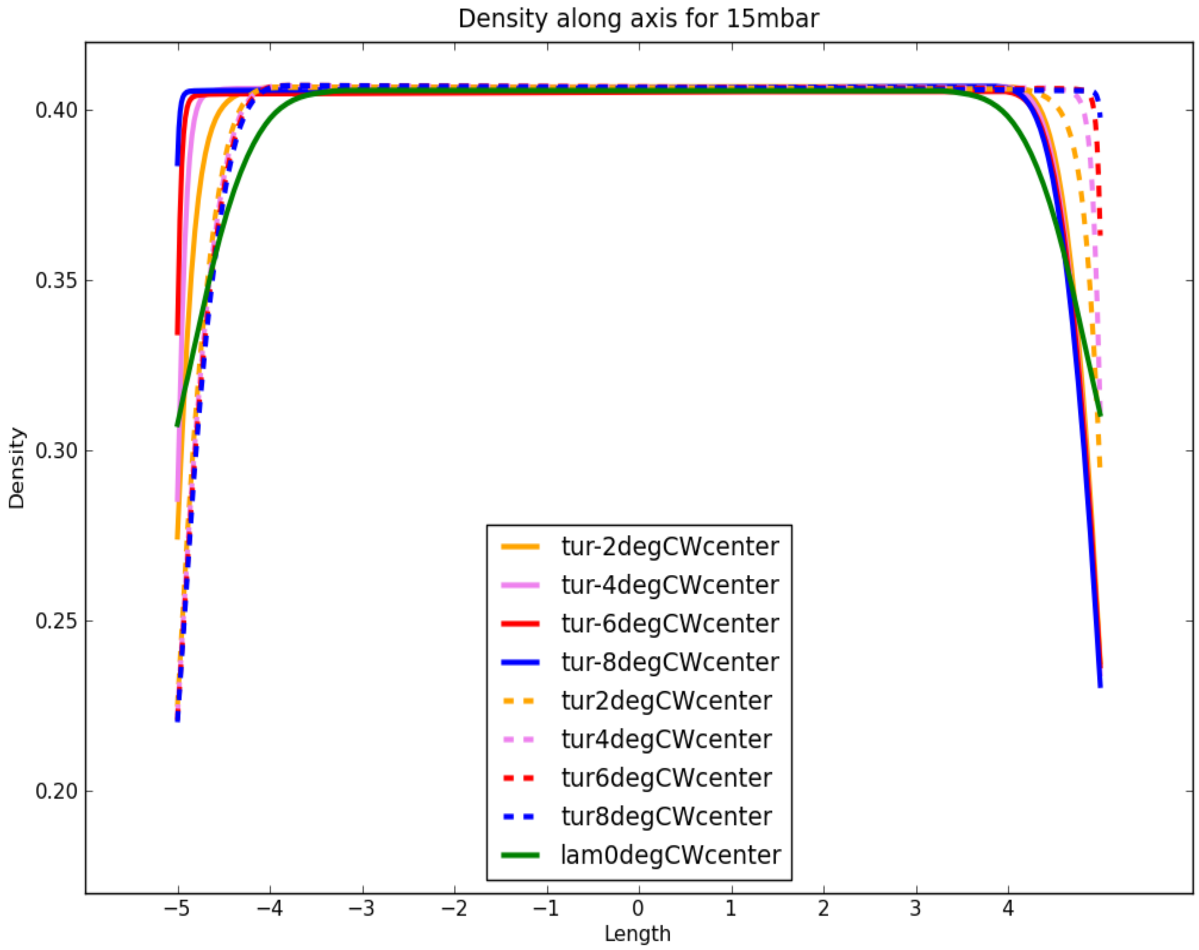
The final version of the tilted project was kept.

Changes only in the new fluid, He-4 vapour specification:

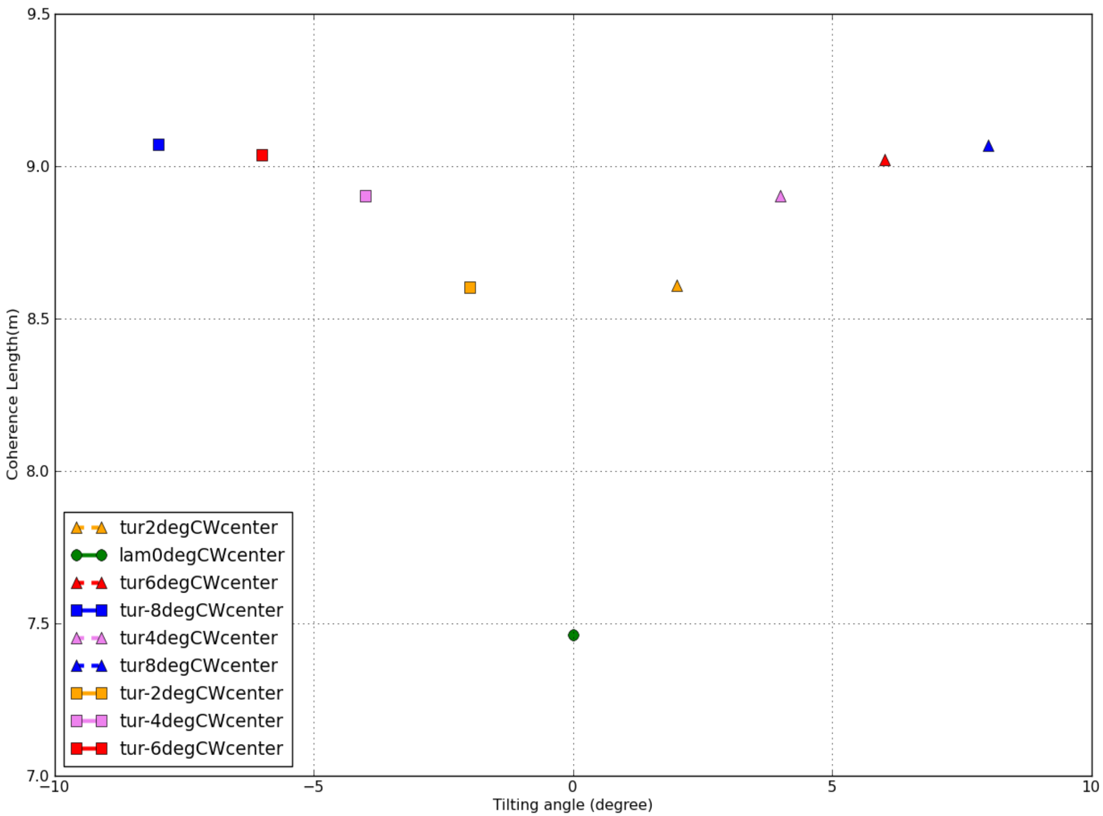
- Based on Hepak values
- Peng Robinson equation of state
- Fitted viscosity, conductivity and heat coefficient



Density variations along axis

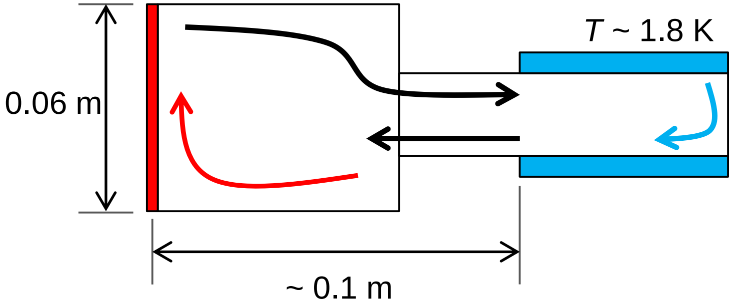


Coherence length versus tilting angle



Thank you for your attention!

Backup and old slides



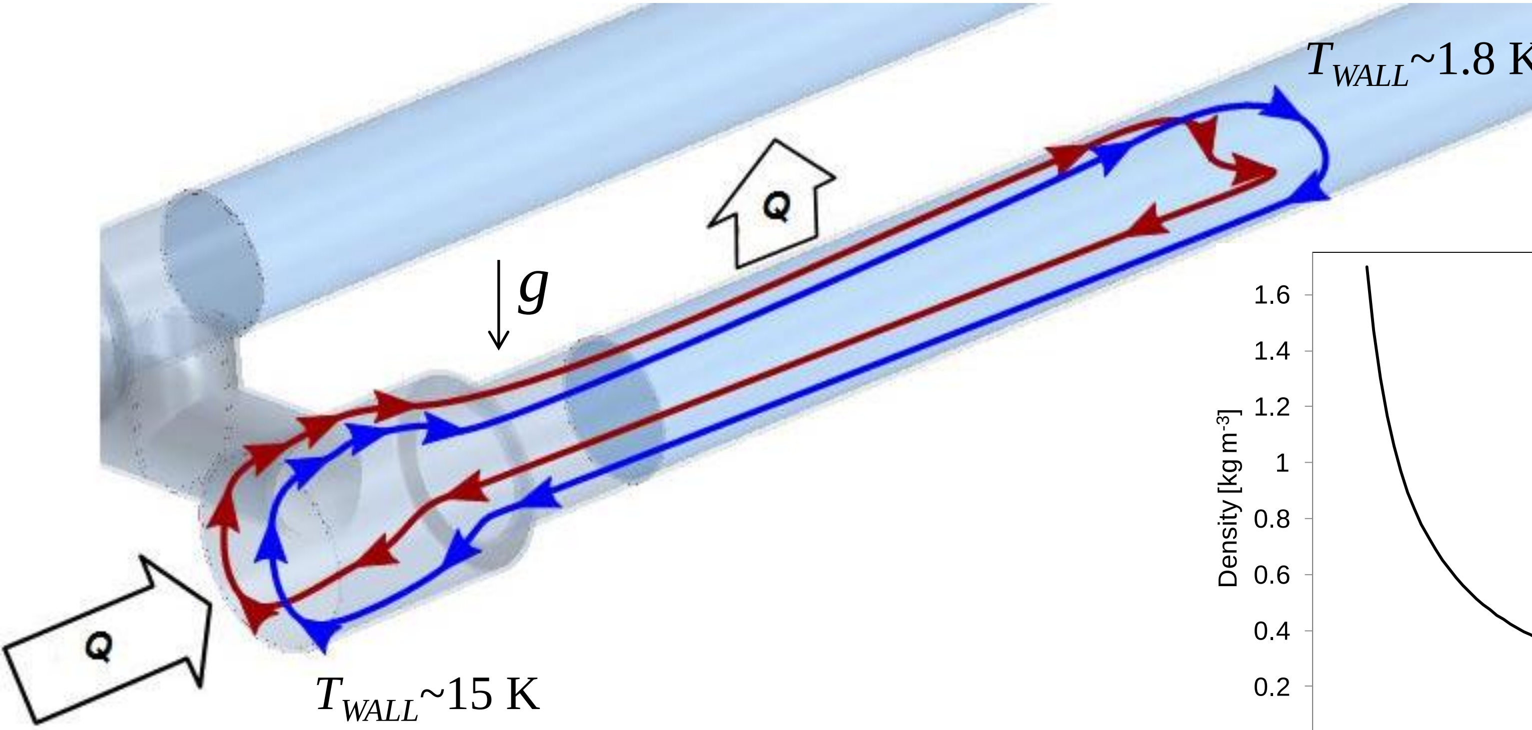
Simulation

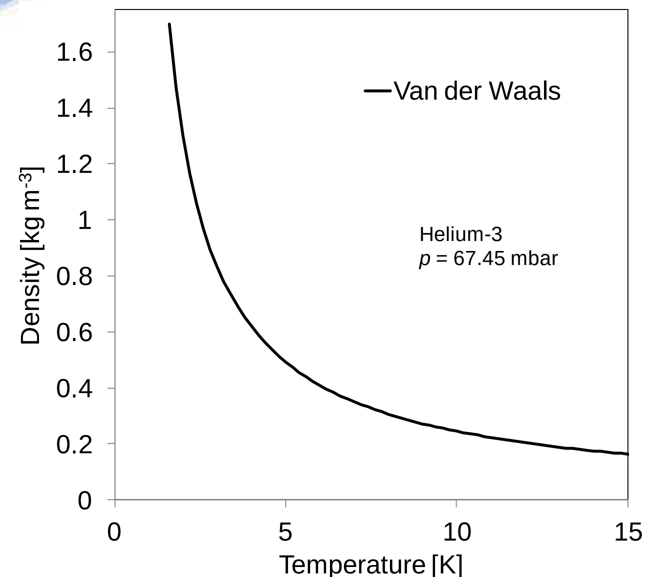
Tilting angle	Coherence length	Pressure prescribed	T-mfb	T-mrb
[degree]	[m]	[mBar]	[K]	[K]
0	7.46	15.19	22.116	16.28
-2	8.60	15.24	22.119	19.92
-4	8.90	15.26	24.042	19.334
-6	9.04	15.19	25.594	18.634
-8	9.07	15.21	28.835	18.516
2	8.61	15.18	23.751	17.933
4	8.90	15.19	23.263	20.337
6	9.02	15.22	22.883	22.92
8	9.07	15.21	22.578	26.084

Experiment

Tilting angle	Pcb	Tw_MFB1 - TE261	Tw_MFB 2-TE238	Tw_MRB 2-258
[degrees]	[mbar]	[K]	[K]	[K]
0	15.302	22.34	24.14	18.64
-2	15.31	26.57	26.58	18.21
-4	15.32	27.12	26.84	18.07
-6	15.31	27.00	26.87	18.03
2	15.26	24.18	25.29	18.92
4	15.24	23.28	24.77	20.23
6	15.26	22.63	24.44	21.61

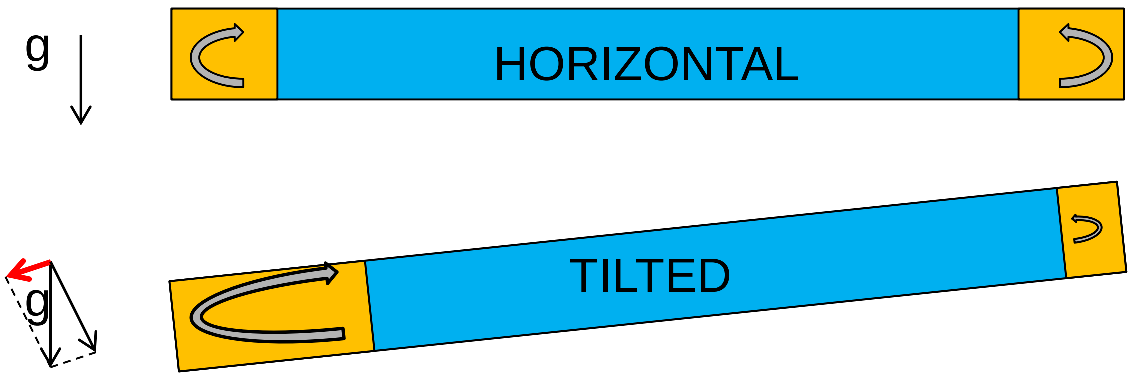
What`s happening? 1/2





- ❑ Because of heat conduction from the outer environment through the solid parts, the temperature of the window wall is higher than the cryostat set point.
- ❑ Natural convection occurs at the window and helium-3 is heated up: hot & light helium enters the cold bore, is cooled down, falls to the bottom of the cold bore and comes back.
- ❑ The heat entering the fluid at the window is given back to the cryostat at the cold bore.
- ❑ The phenomenon is due to the huge dependence of density on temperature.

What`s happening? 2/2



- When tilting, gravity enhance the natural convection at the bottom and tries to suppress natural convection at the top.
- Experimentally, the temperature of the bottom window decreases (i.e. more convective cooling given by He^3 flow) and the temperature of the top window increases (i.e. less cooling).
- The distribution of He^3 density inside the magnet changes when tilting → the pressure in the system can change (even if the He^3 total mass is the same).

CONCLUSIONS

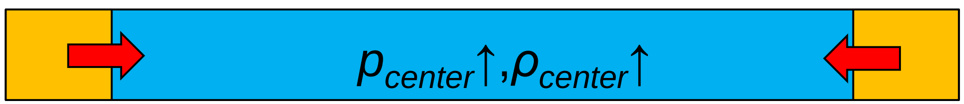
- Being able to predict the pressure change when tilting due to the "<u>CONVECTION EFFECT</u> only" would be a proof of CFD simulations reliability.
- The old (i.e. before May 2012) CFD model could not predict this phenomenon.
- The CFD model have been updated adding the flanges and the vacuum pipe up to the thermal shields.
- Accurate windows temperature measurements during test runs without gas are essential to "tune" the updated CFD model, but several temperature measurements inconsistencies have been found.
- The experimental window temperature measurements during tracking are not used anymore as boundary conditions; they are now a result of the simulation.
- The predictions of the updated model are now qualitatively closer to the experimental values, but the pressure increase when tilting is underpredicted.
- Adding to the CFD model geometry the connection pipes between the CBs is expected to enhance the predicted pressure change when tilting.

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

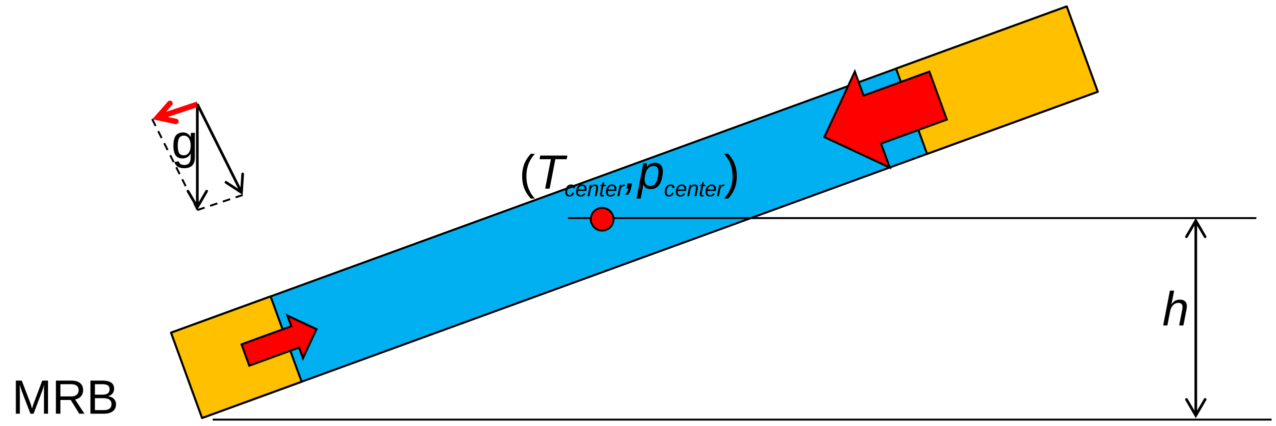


- ❑ As compared to the ideal case, the fluid at the sides is hotter and less dense → the gas is "compressed" to the center of the bore, both p and ρ increases (CONVECTION EFFECT)
- ❑ Since the magnet is horizontal and the gas velocities are small (< ~1 m/s), the pressure can be considered uniform: $p_{center} = p_{MRB}$.
- ❑ $(p_{center}, T_{center}) \rightarrow \rho_{center}$: 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

Why do we need CFD?

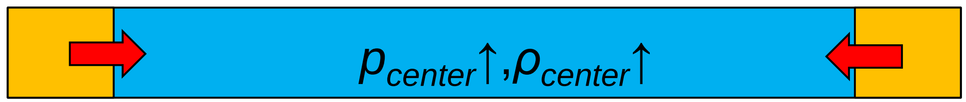
C. REAL CASE - TILTED



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

- 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 $\rho(p_{MRB}, T_{CB})gh$

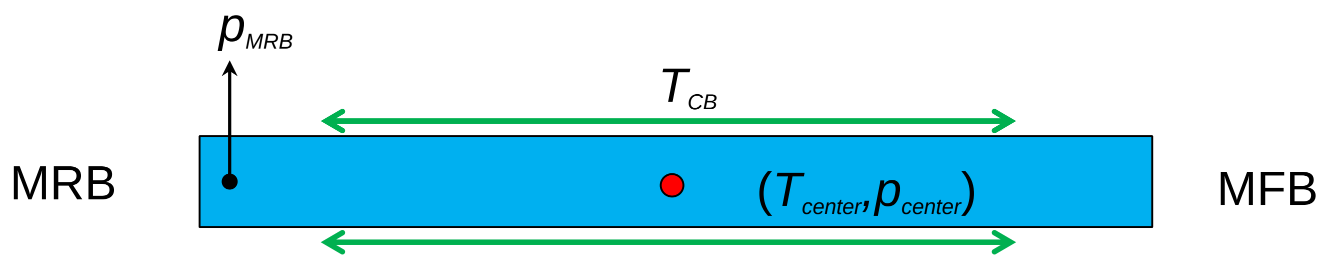
CONCLUSIONS



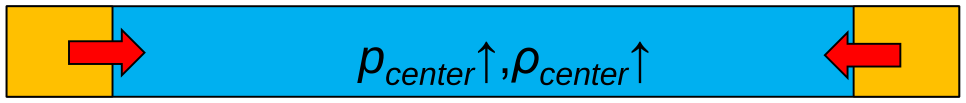
- The gas density at the center of the bore can be obtained from the experimental values of (p_{MRB},T_{CB}) without any need of CFD simulations.
- The major sources of error are the Equation of State and the experimental measurements.
- The HYDROSTATIC EFFECT can be estimated with enough accuracy without 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.

Pressure change due to density distribution change

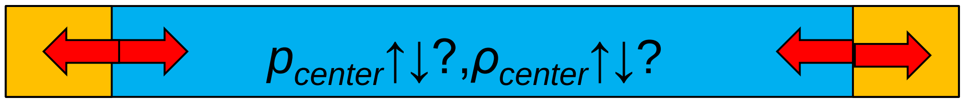
- Ideally, the magnet should be isothermal and the density uniform,



- Since the two ends are hotter, two regions with higher temperature and lower density are present at the extremities of the magnet.



- When tilting, these two regions can either expand or contract because of several reasons.
- Any change of the mass distribution gives rise to same change in the system pressure.



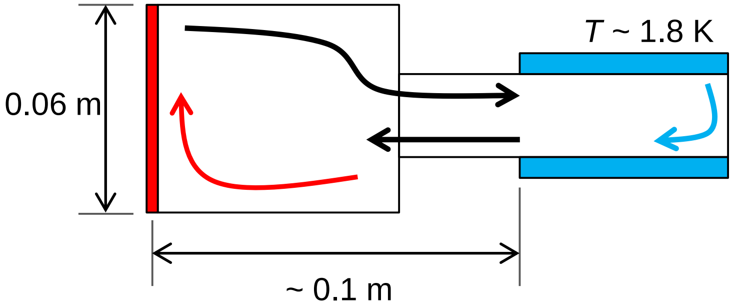
Why do we need to predict the pressure change when tilting?

- The density at the center of the magnet can be computed from p_{MRB} and T_{CB} without any need of CFD;
- p_{MRB} is an experimental value, it cannot be “validated” by a CFD simulations;
- Being able to predict the pressure change by means of CFD is important to:

  a) be more confident about the CFD results of coherence length;

  b) exclude the need to look for alternative hypothesis (e.g. non uniform temperature of the cryostat).

Natural Convection, laminar/turbulent transition



The flow going towards the center of the magnet can be heavily affected by the tilting angle.

Rayleigh non-dimensional number:

DEPENDS ON PRESSURE

HEAVILY DEPENDS ON WARM/COLD WINDOWS

$$\mathrm{Ra} = \rho\, c_P \left(\frac{\partial \rho}{\partial T}\right)_P \frac{g\, \Delta T\, L^3}{\mu\, \lambda}$$

HEAVILY DEPENDS ON TILTING

ρ - density
ν - kinematic viscosity
κ - thermal diffusivity
β - isobaric volume expansion coefficient
λ - thermal conductivity
L - characteristic length
ΔT - temperature difference
g - acceleration of gravity.

- **When tilting: bottom window increases turbulence, top window decreases it;**
  laminar→turbulent transition may occur at bottom;
  turbulent→laminar transition may occur at top;
- **The flow is more likely to be turbulent for Warm Windows as compared to Cold Windows and for high pressure as compared to low pressure.**

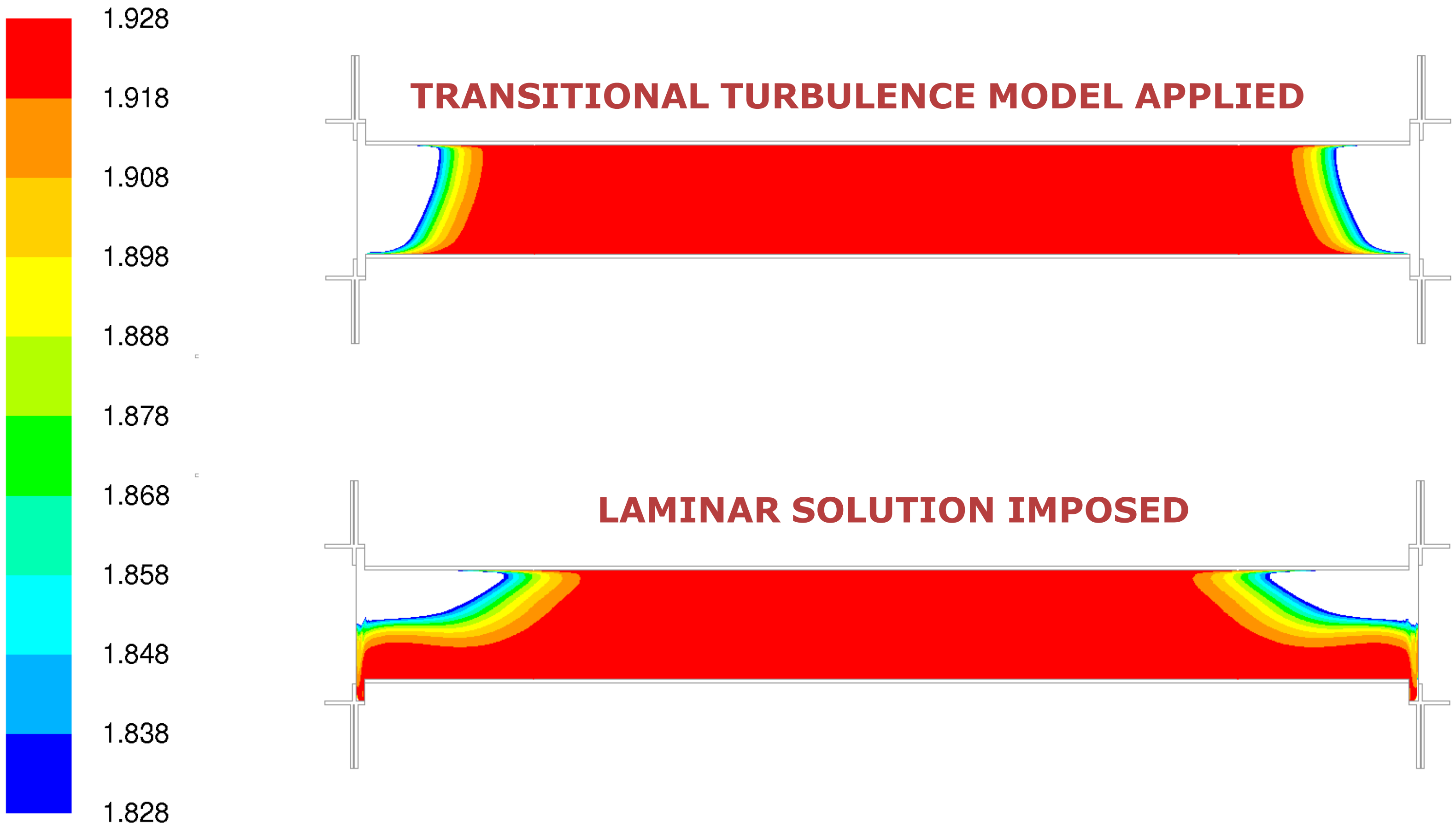
Numerical modeling of turbulence

- The turbulence model used (low-Re form of *k-ω* SST) is a *transitional* model: it is supposed to be able to predict the laminar/turbulent transition.
- Turbulence transitional models are known to usually predict an earlier laminar-to-turbulent transition.
- The CAST case is even more demanding than usual for a turbulence model (internal flow, heavy dependence of properties on temperature, uncommon fluid and temperature, complex geometry, etc…)

- The possibility that turbulence is over-predicted in some cases must be taken into account.
- Laminar flow can be forced in a part or all the computational domain for the sake of comparison.
- Reaching convergence when imposing the laminar flow may be impossible when the "natural solution" is fully turbulent (e.g. at the bottom window when tilted).
- The "correct" solution most likely will lay between the "laminar" and the "turbulent" CFD results.

Example of difference between laminar and turbulent solutions

(83mbar, CW, horizontal, scaled picture)



Contours of Density (kg/m3)

- A laminar/turbulent transition can give rise to relevant changes in the mass distribution.
- This can explain relevant pressure changes.

Tuning w/o gas

b.c. vacuum	b.c. connection	T_{cernox}	T average "pipe" surface	T average "connection" surface
70 K	170 K	41.8 K	31.0 K	43.1 K
70	70	39.5	28.7	35.3
70	adiabatic	38.7	27.7	32
80	170	45.3	33.3	45.3
90	170	48.6	35.4	47.4
90	200	49.2	36.0	49.5
120	170	58.4	41.3	53.6

- Experimental: 45 K < T_{cernox} < 55 K
- Small influence of connection b.c. on T_{cernox}
- Temperature sensor "somewhere in the connection" gives ~50K w/o gas