Mechanical energy transfer in liquid metal MHD flows in DCLL breeding blanket singularities

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Spanish Fusion HPC Workshop

Outline

- Introduction
  - Personal presentation
  - Motivation for the PhD thesis
- Component of study
- Incompressible MHD phenomena
- The mechanical energy balance: problem, solution, and validation of the method
- Application to MHD expansion
- Final Remarks

Personal Presentation

- Industrial engineer ETSEIB by UPC
- 10 years working as nuclear power plant operations instructor
- 6 years working part-time on my PhD on nuclear engineering
- 5 years as assistant professor at UPC

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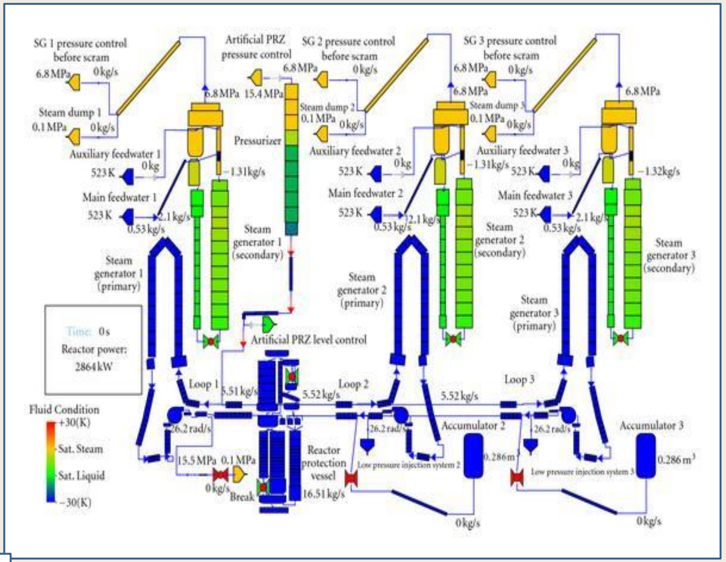
Motivation of the PhD thesis

Heat and Mass transfer correlations for liquid metal flows under nuclear fusion conditions

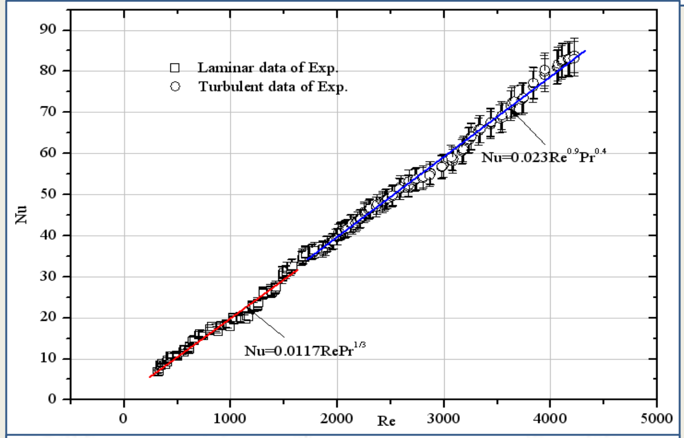
Supervisors:

Lluís Batet
Elisabet Mas de les Valls

A **system code** is a useful tool to analyze the dynamics of a power plant for design purposes



RELAP5 3D



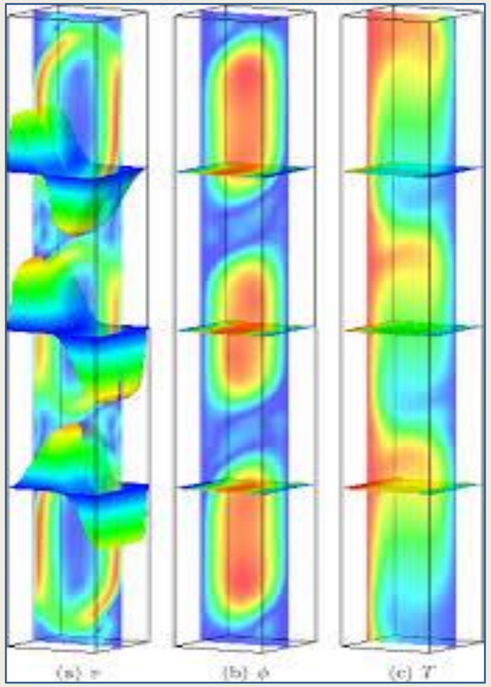
Dittus–Boelter correlation

$$Nu = 0.023Re^{0.8}Pr^{1/3}$$

The transport phenomena is modeled using **correlated data** from experiments

Motivation of the PhD thesis

A well validated **component code (CFD)** can provide “numerical experimental” data that can be **correlated** and used in a system code



OpenFOAM

3D case
Component Code

post-processing

f_D

Nusselt

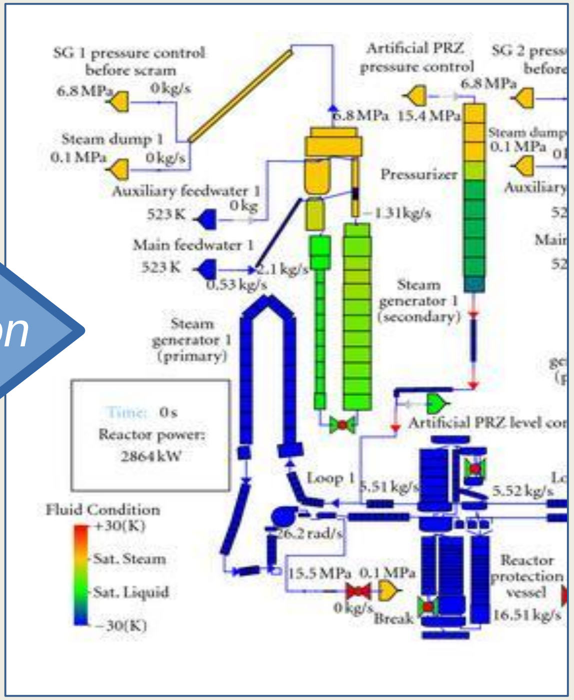
Sherwood

transfer coefficients

the *bridge* coefficients

1D case
System Code

future implementation

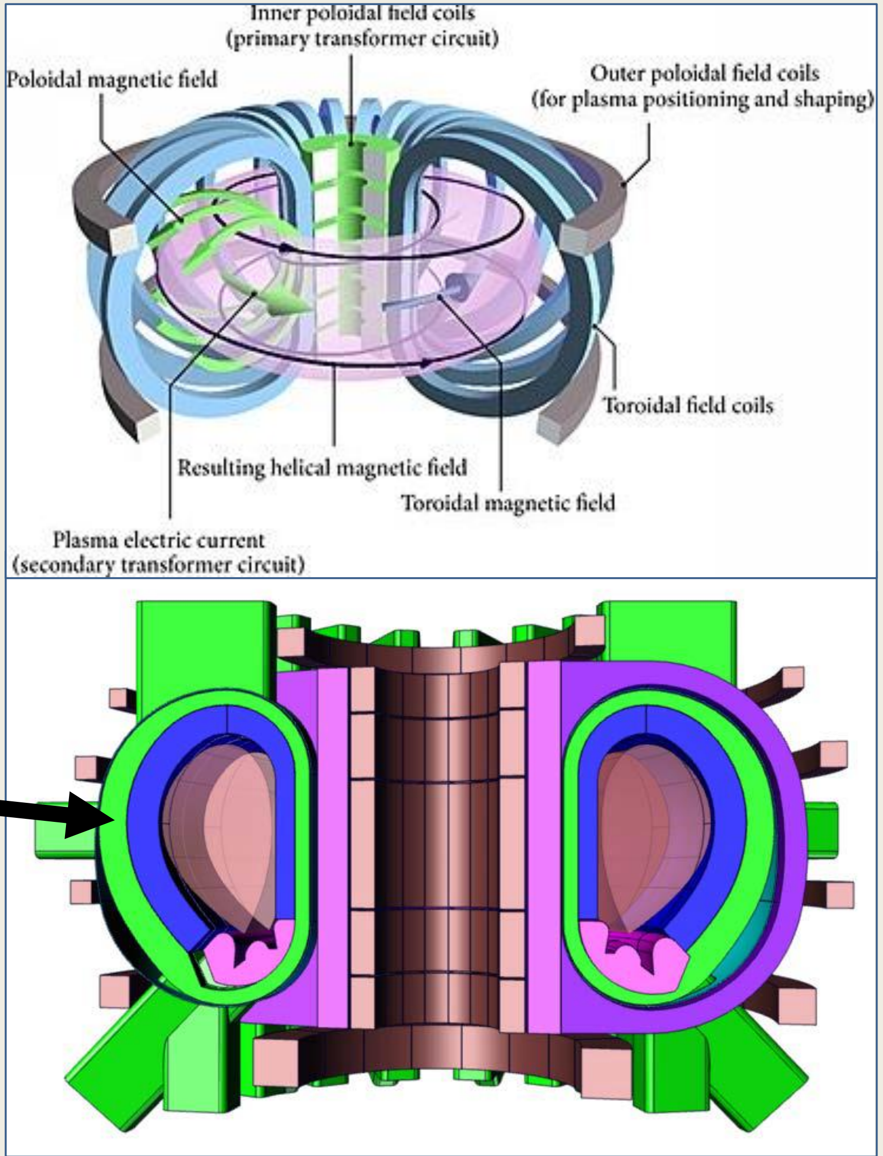


RELAP5 3D

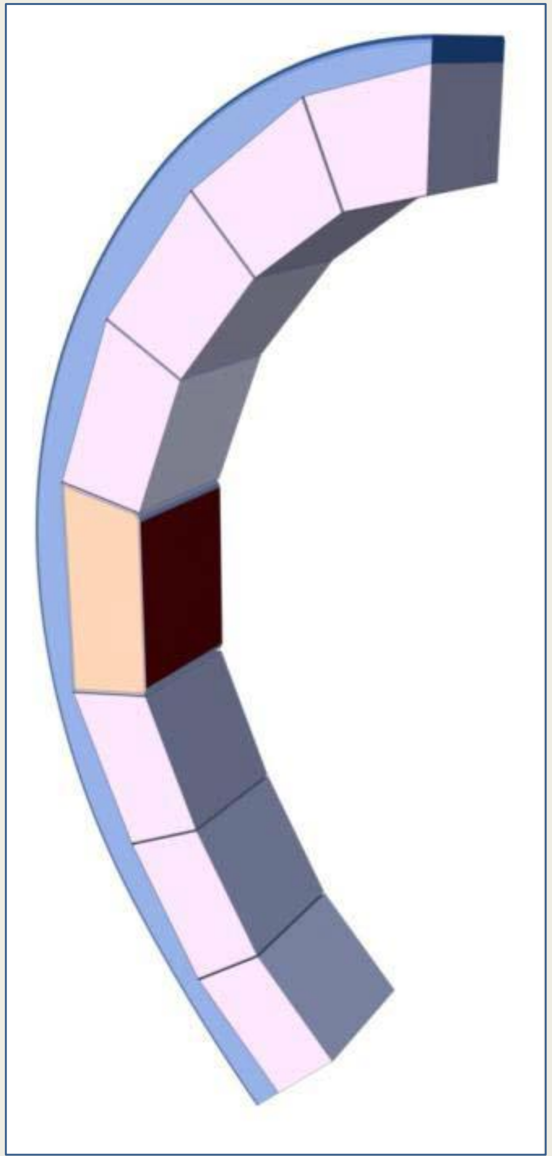
Component of study

the tokamak

the breeding blanket

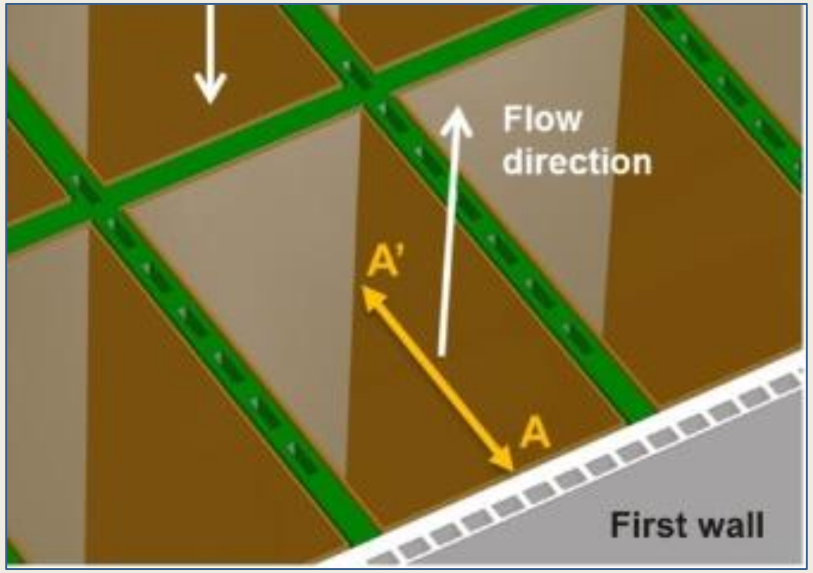


Component of study

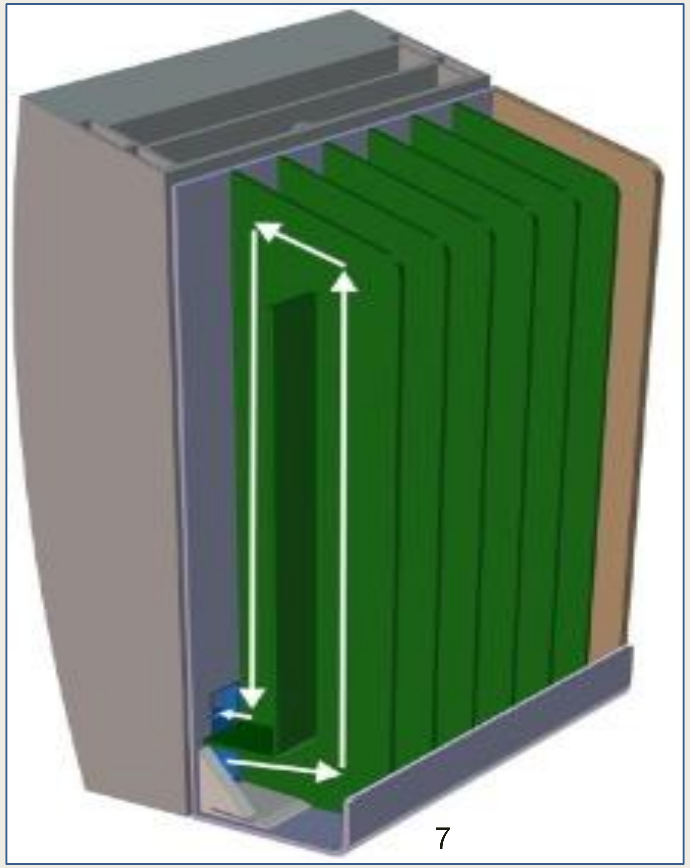


- Dual Coolant Lead-Lithium (DCLL) concept
  1. Helium for structural cooling
  2. Lead-lithium (PbLi) for heat extraction

- High velocity PbLi flow under magnetic field → incompressible MHD



Manifold for flow distribution



Incompressible MHD phenomena

1. Continuity equation
2. Momentum equation
3. Electric potential equation
4. Ohm's law (electric current equation)

$$\nabla \cdot v = 0 \quad (1)$$

$$\frac{\partial v}{\partial t} + (v \cdot \nabla) v = -\frac{\nabla p}{\rho} + \nu \nabla^2 v + \frac{j \times B}{\rho} \quad (2)$$

$$\nabla^2 \phi = \nabla \cdot (v \times B) \quad (3)$$

$$j = \sigma_m(-\nabla \phi + v \times B) \quad (4)$$

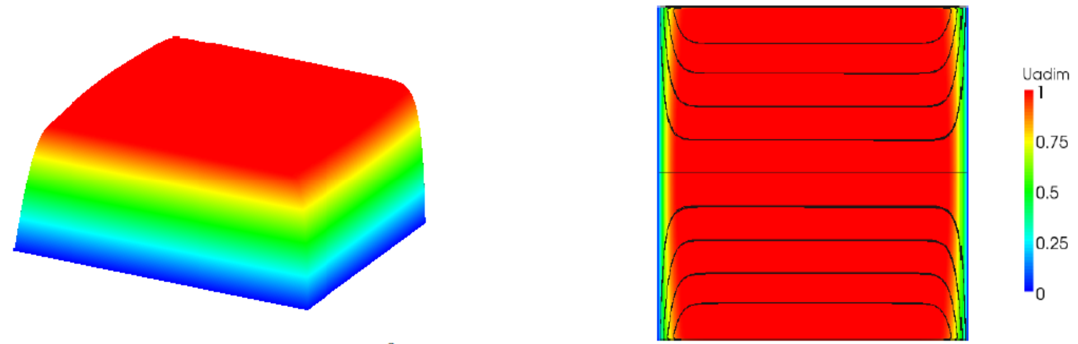


Figure 3.3: $Ha = 300$, $N = 9 \cdot 10^3$, $C_{w,side} = C_{w,Ha} = 0$, velocity profile on the left and electric current stream lines on velocity on the right.

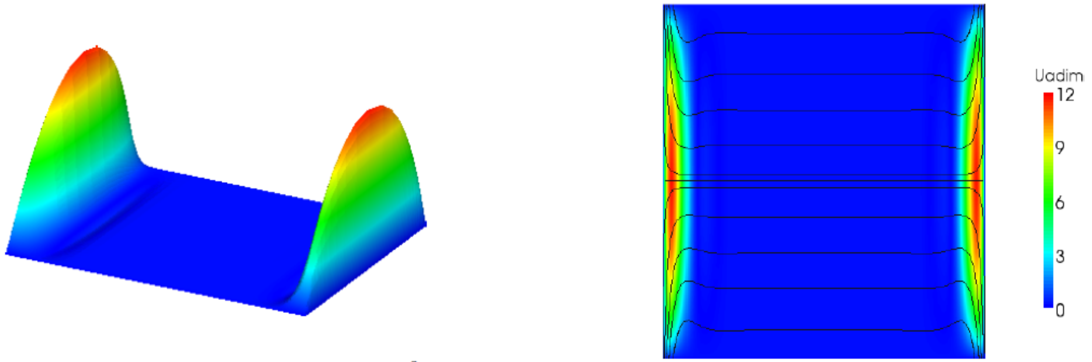
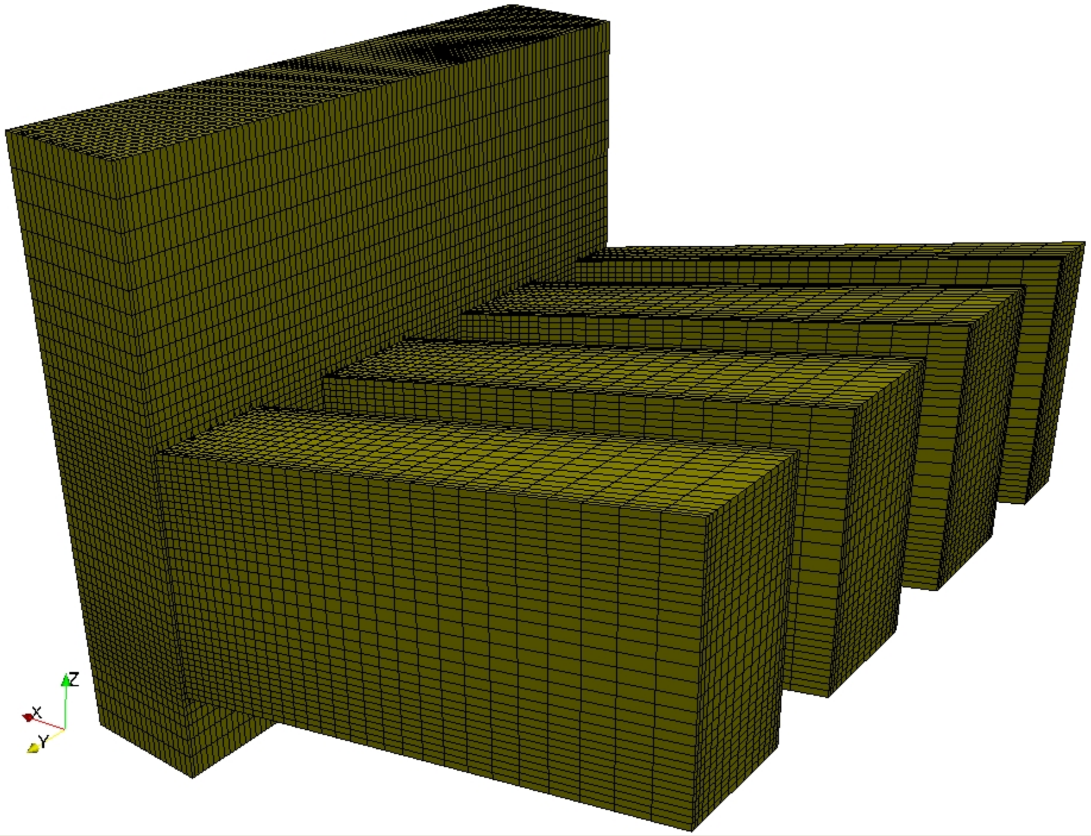
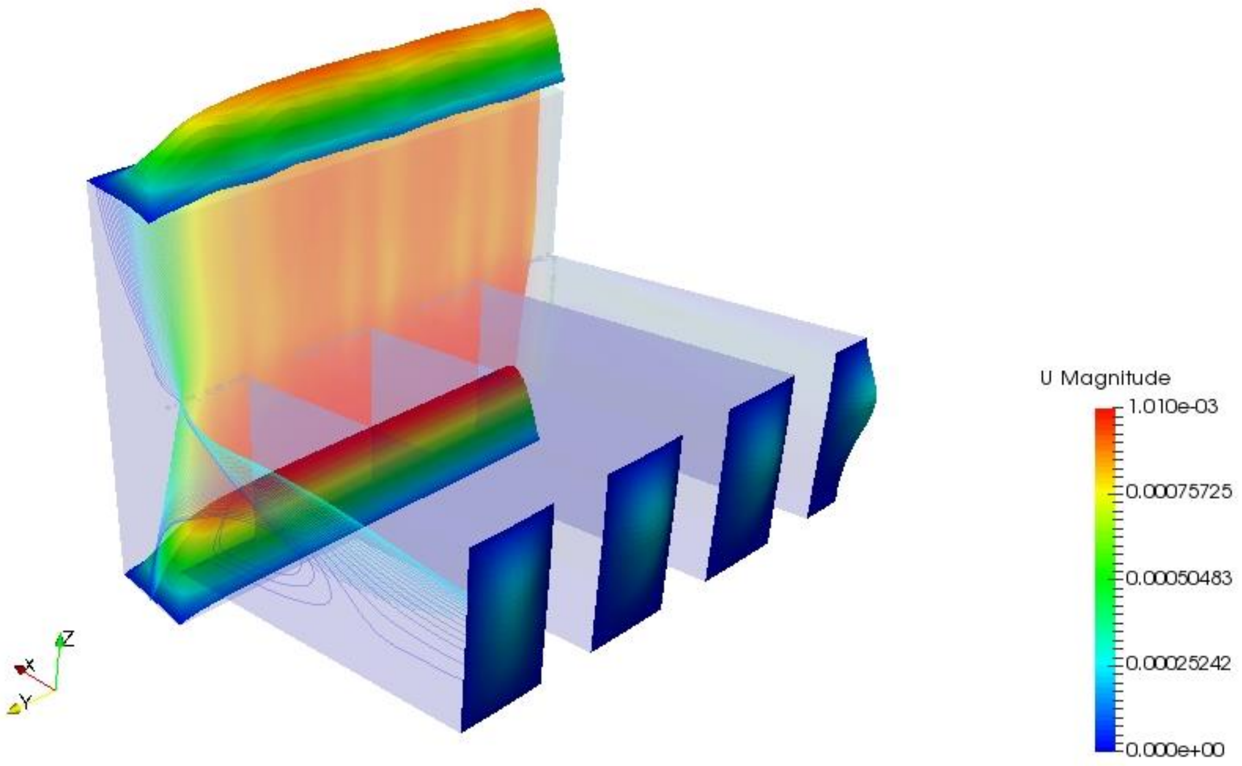


Figure 3.4: $Ha = 300$, $N = 9 \cdot 10^3$, $C_{w,side} = 0$, $C_{w,Ha} = \infty$, velocity profile on the left and electric current stream lines on velocity on the right. Side boundary layer velocity jets can be observed.

DCLL cold manifold

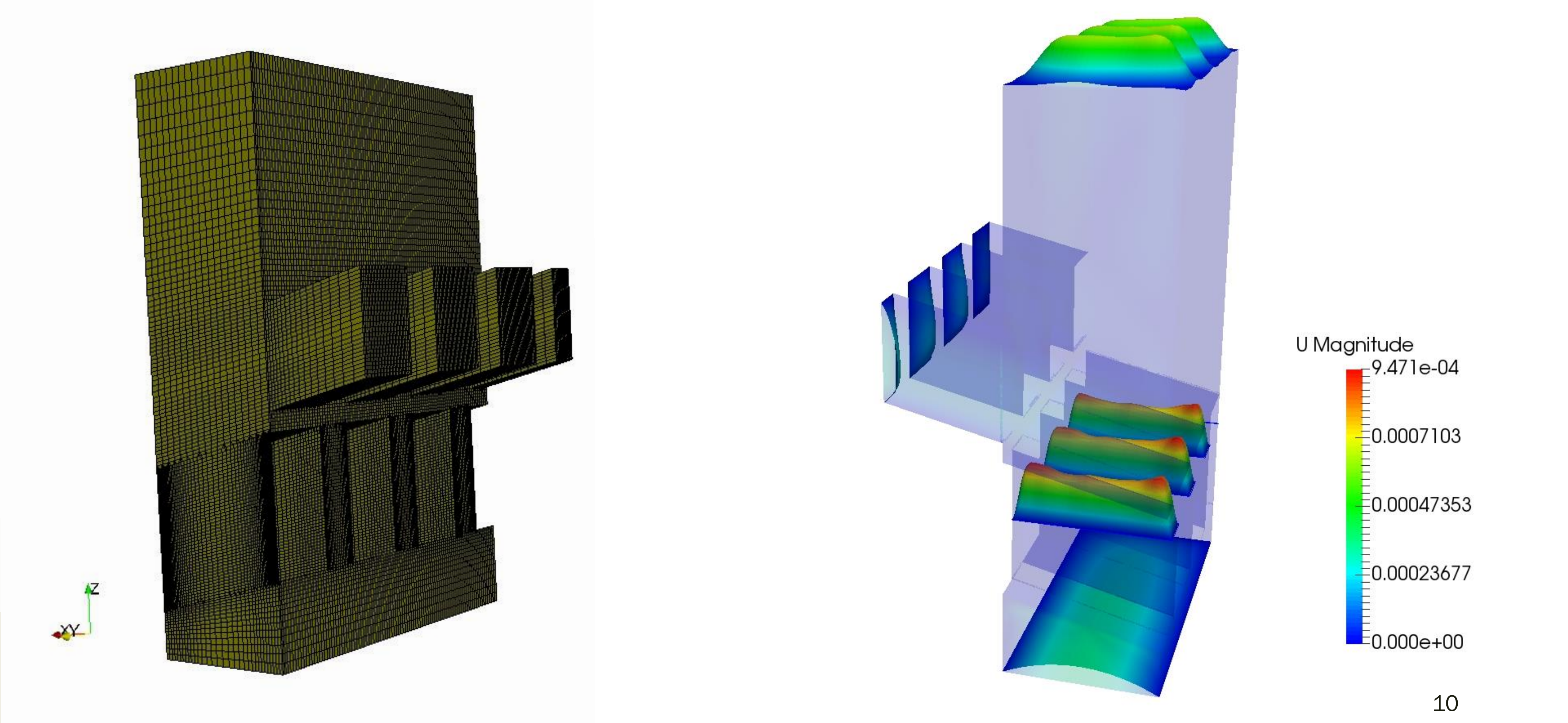
- The cold manifold distributes the flow through the blanket channels



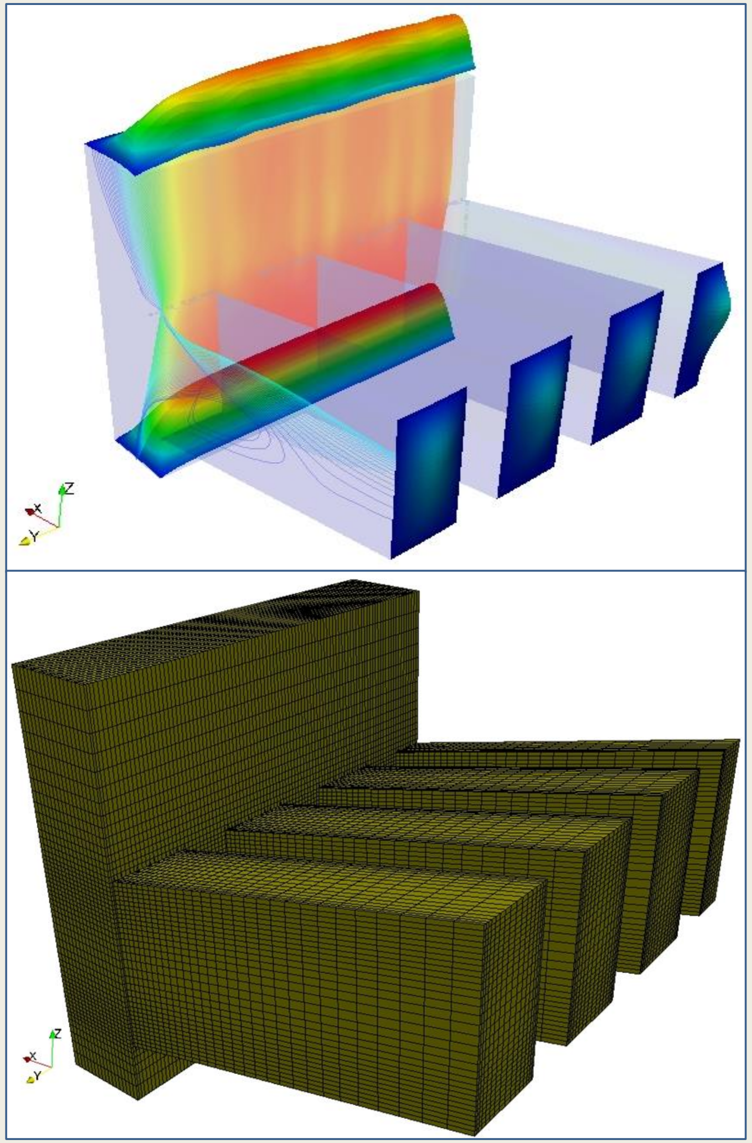


DCLL hot manifold

- The hot manifold receives flow coming from the blanket module



The problem

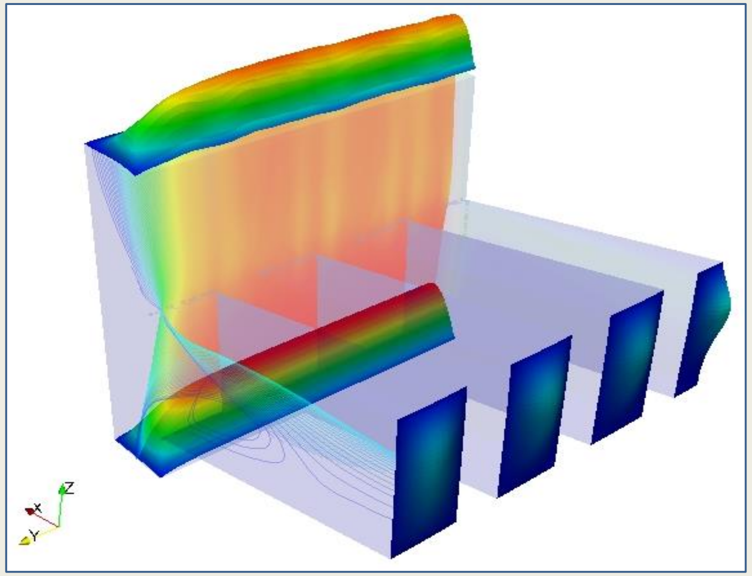


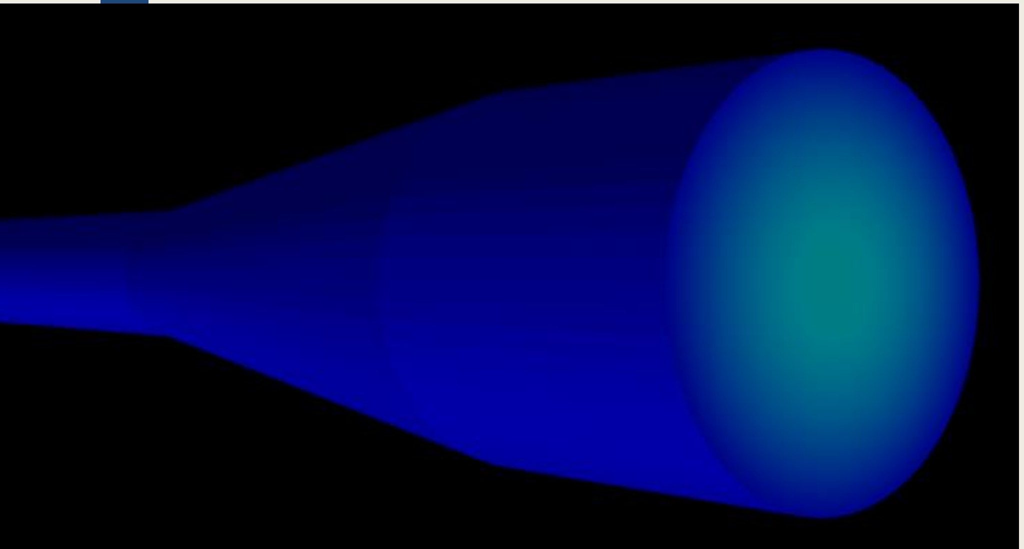
- The Bernoulli equation was applied to find the head losses in the manifold:
  - the flow is steady
  - the flow is frictionless
  - there is no shaft work involved
  - the flow is incompressible
  - there is no heat transfer involved
  - *the flow goes along a streamline*

$$(\rho g z_1 + p_1 + \frac{\rho \cdot v_1^2}{2}) - (\rho g z_2 + p_2 + \frac{\rho \cdot v_2^2}{2}) = \sum_{i=0}^{N} h_{Li}$$

- The cold manifold case postprocessing suggested a **head gain** (instead of head loss) in the domain, just like if the geometry increased mechanical energy, **something clearly wrong.**

The problem





- The cold manifold showed an outlet area larger than the inlet area. Just like in an expansion. Following continuity:

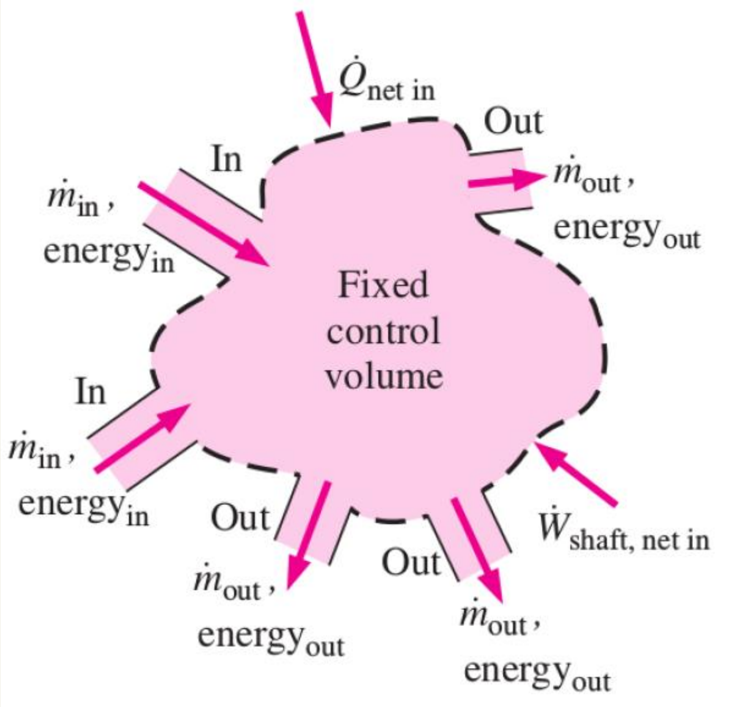
$$v_1 \cdot A_1 = v_2 \cdot A_2$$

$$(\rho g z_1 + p_1 + \frac{\rho \cdot v_1^2}{2}) - (\rho g z_2 + p_2 + \frac{\rho \cdot v_2^2}{2}) = \sum_{i=0}^{N} h_{Li}$$

- The pressure increase is expected; however the head gain must be resolved.

- The assumption of the streamline was carefully reviewed.

The solution



- The energy conservation principle applied to a control volume with several inlets and outlets allowed to convert 3D case results to 1D case result.
- The singularity head loss can be obtained from the calculated domain head loss.

$$h_{L\_domain} = h_{L\_upstream\_pipe} + h_{L\_singularity} + h_{L\_downstream\_pipe}$$

$$\dot{Q}_{netadded} + \dot{W}_{shaftnetadded} = \sum_{o}^{outlets} \dot{V}_o \cdot \left(p_o + \frac{\rho \cdot v_o^2}{2} + \rho g z_o\right) - \sum_{i}^{inlets} \dot{V}_i \cdot \left(p_i + \frac{\rho \cdot v_i^2}{2} + \rho g z_i\right)$$

$$Power\ losses = \dot{V} \cdot h_{L\_domain} = \sum_{i}^{inlets} \dot{V}_i \cdot \left(p_i + \frac{\rho \cdot v_i^2}{2}\right) - \sum_{o}^{outlets} \dot{V}_o \cdot \left(p_o + \frac{\rho \cdot v_o^2}{2}\right)$$

The validation

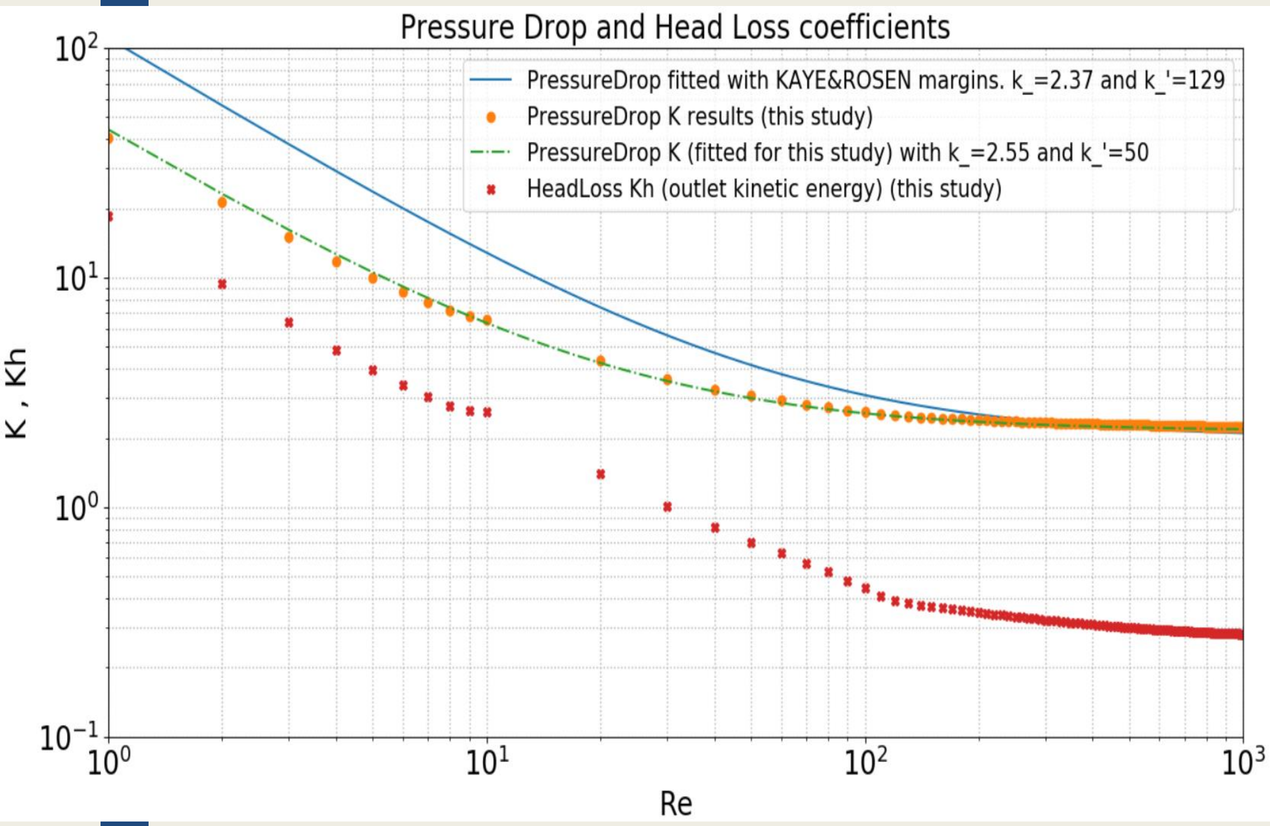
- A postprocess was designed to account for the singularity head loss and validated in **hydrodynamic** well-known cases.
- Selected cases were **sudden contraction** and **sudden expansion**.
- The head loss was normalized by the outlet flow kinetic energy associated with mean velocity (1D).
- A comparison between the dimensionless pressure drop coefficient and the head loss coefficient was carried out.

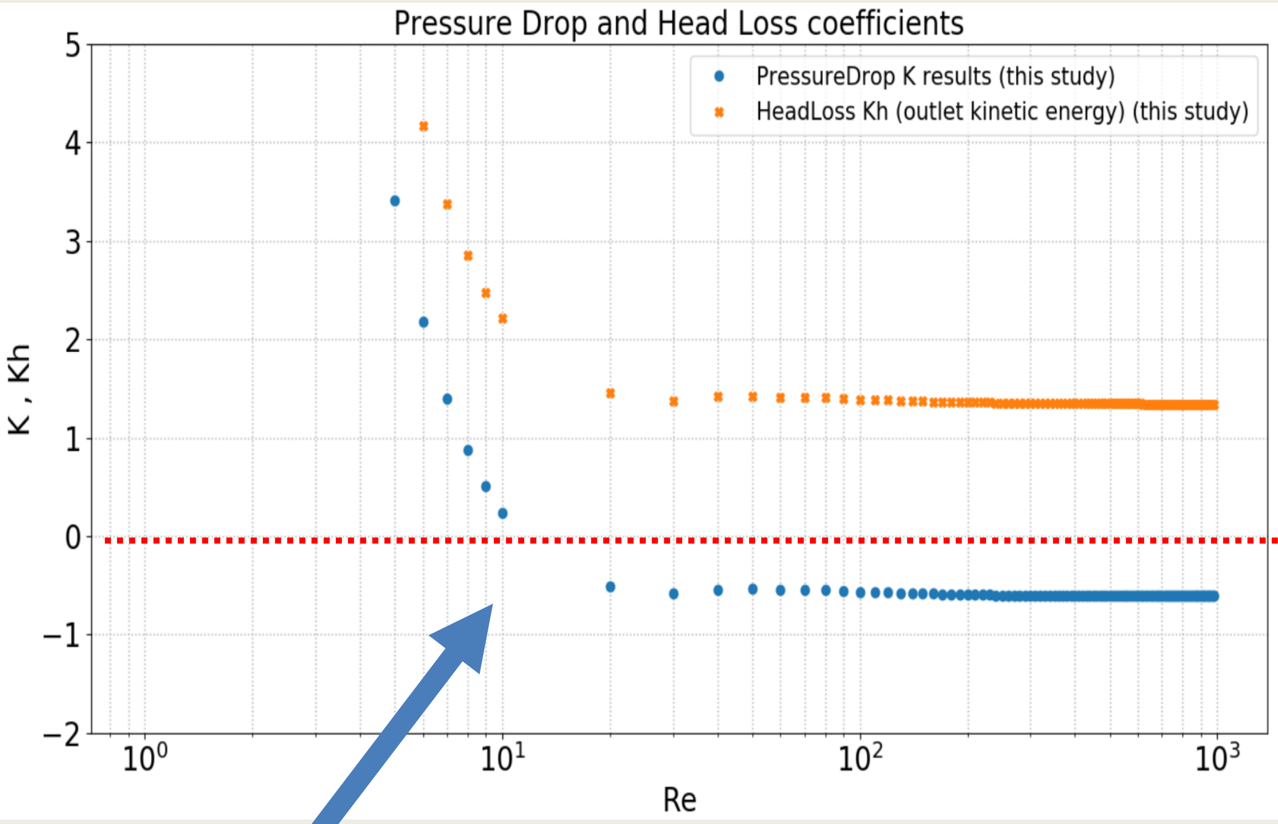
$$K = \frac{\Delta p}{\rho\, v^2/2}$$

$$K_h = \frac{h_{L\_singularity}}{\rho\, v^2/2}$$

The validation

Sudden contraction vs. Sudden expansion





Mind the negative coefficient

Application to MHD

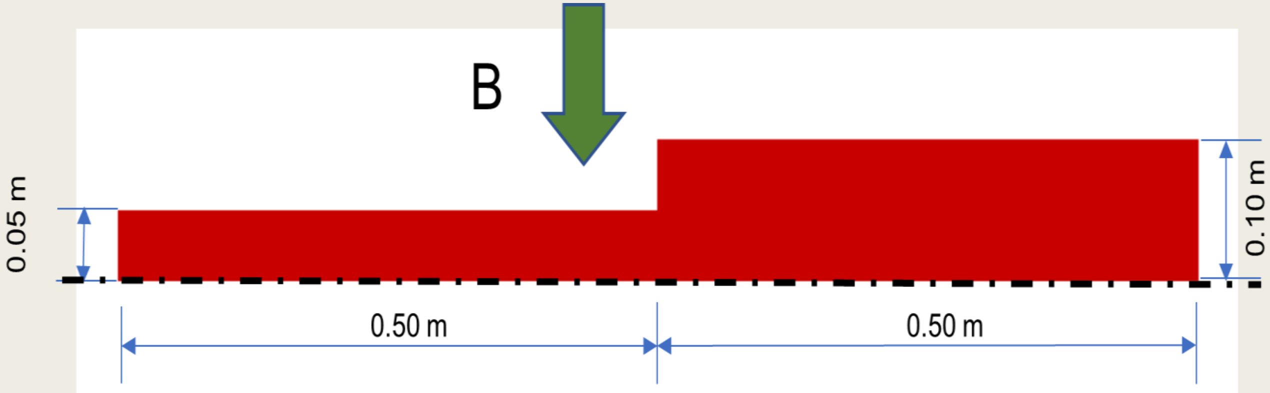
- The studied expansion MHD case is defined by its dimensionless parameters:
- Re=100 C_w=0,01

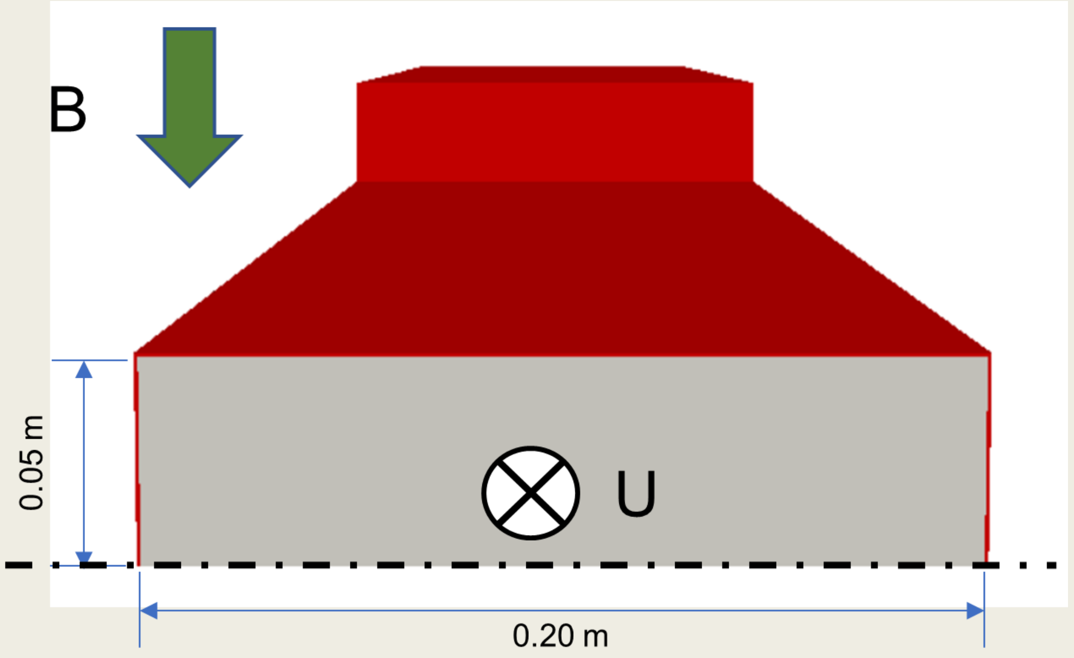
$$Re = \frac{\rho \cdot v \cdot L_s}{\mu} \qquad Ha = BL_s\sqrt{\frac{\sigma}{\rho v}}$$

- Five cases of different Hartmann number:

$$N = \frac{Ha^2}{Re} \qquad C_w = \frac{\sigma_w \cdot \tau_w}{\sigma \cdot L_s}$$

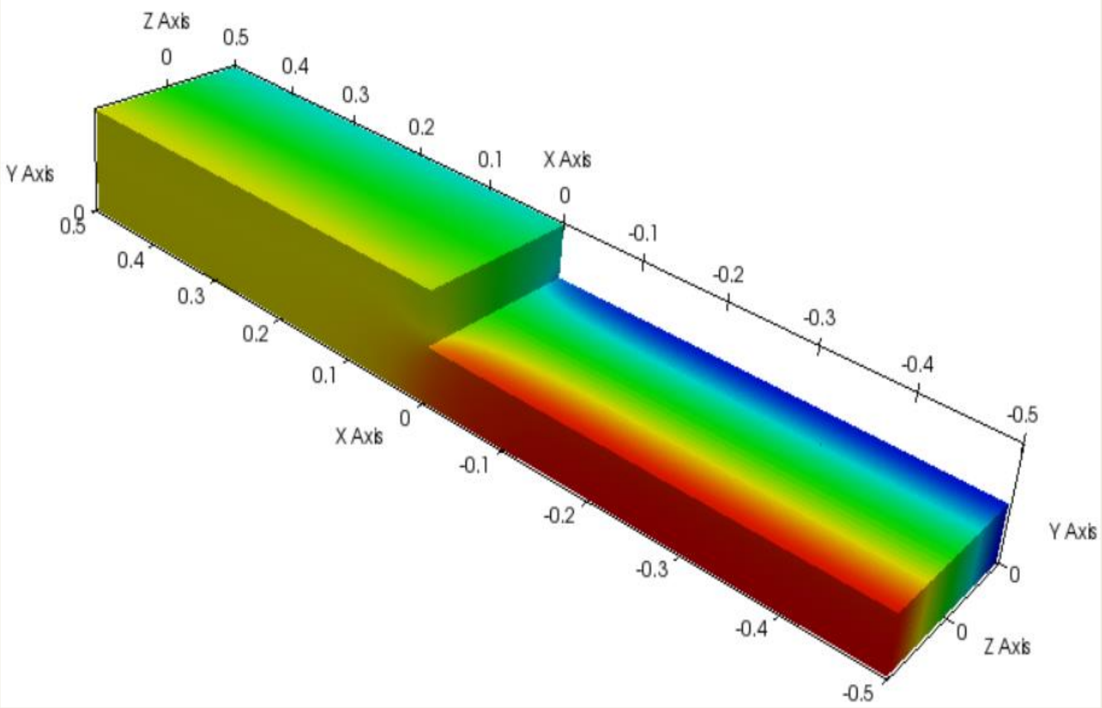
Ha=50, 100, 150, 200, 250





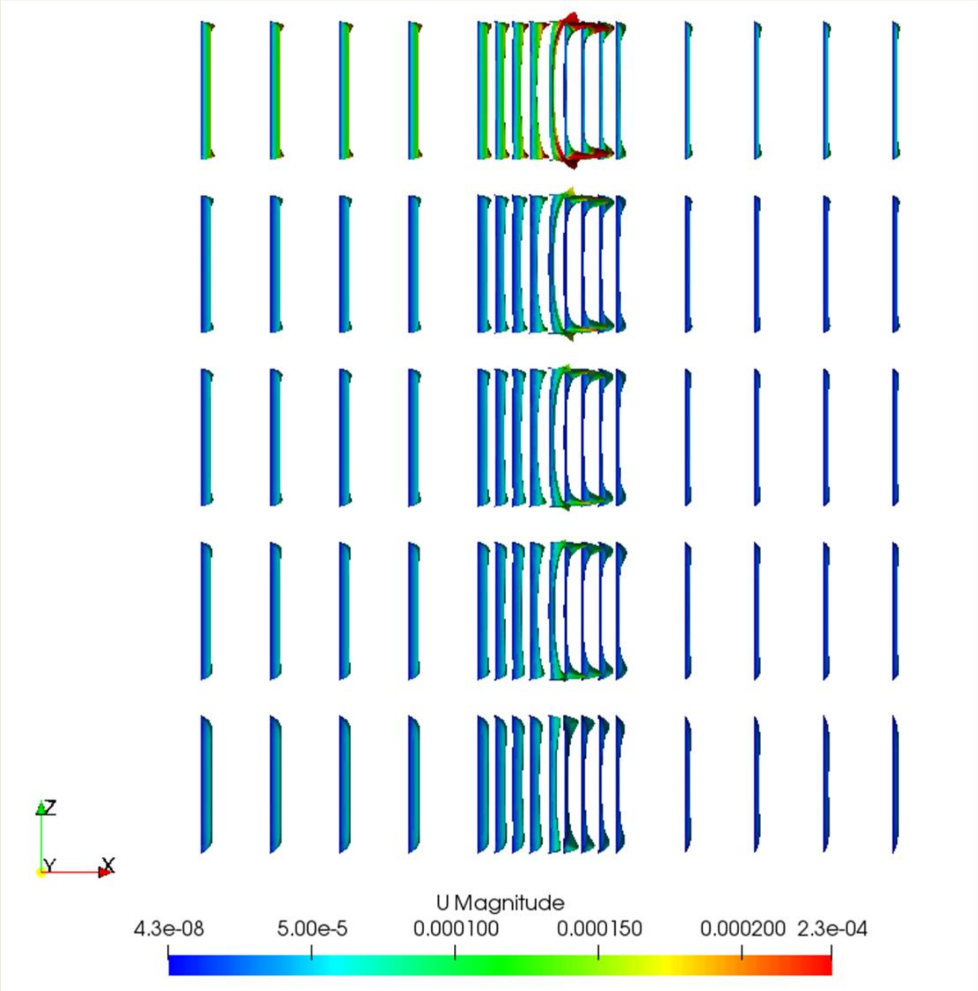
Application to MHD

- The electric potential distribution in the domain can be seen in the figure.
- The axial electric potential differences generate axial electric currents that contribute to increase mechanical energy losses.



Electric potential distribution for a MHD expansion

Application to MHD



Ha = 250

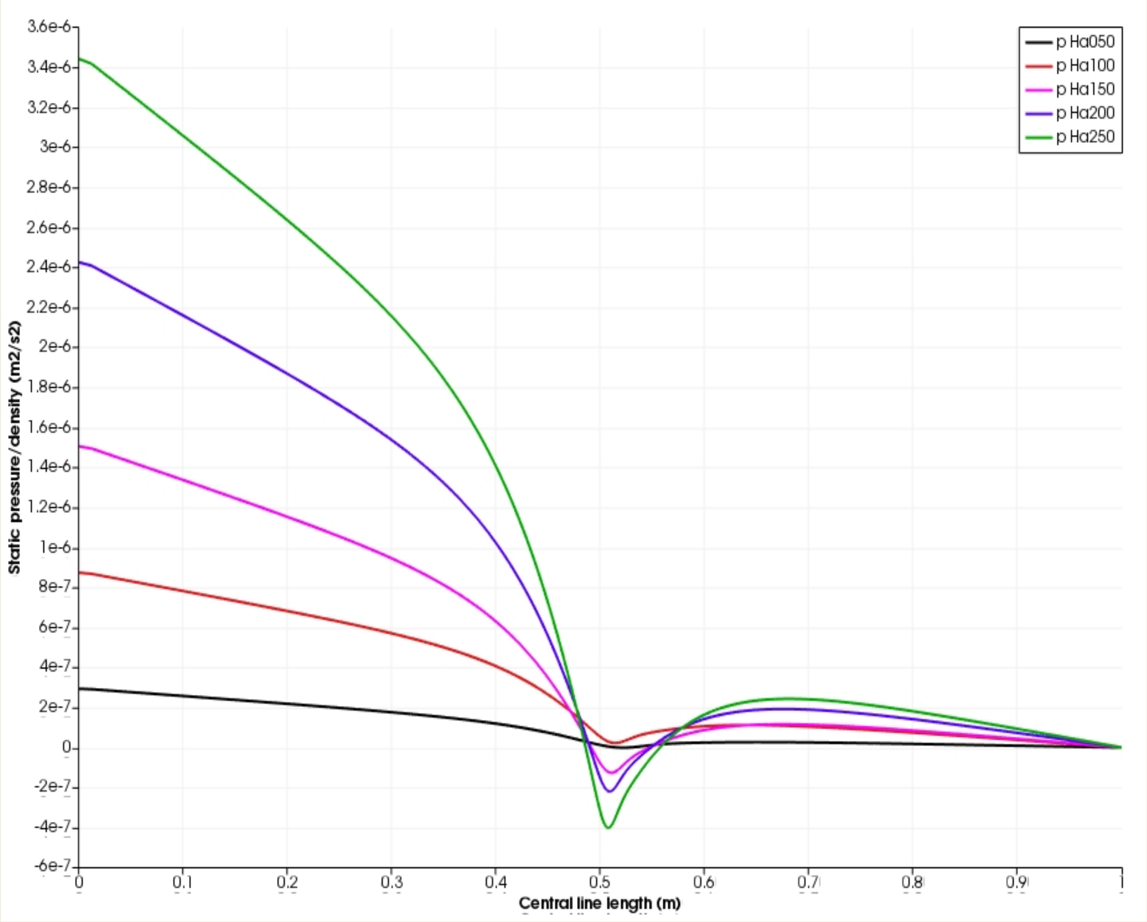
Ha = 200

Ha = 150

Ha = 100

Ha = 050

Velocity profiles for different Ha numbers



Centerline axial pressure distribution for different Ha numbers

Application to MHD

- Fusion community has used the following expression to account for 3D MHD associated pressure drop:

$$\Delta p_{3D} = \xi \frac{\rho v^2}{2}$$

With $\xi = kN$, where k is found experimentally and is suggested to be between $0.25 < k < 2$.

- The proposed head loss calculation method yields the associated coefficient:

$$h_{L\_3D} = \xi_{hL\_3D} \frac{\rho v^2}{2}$$

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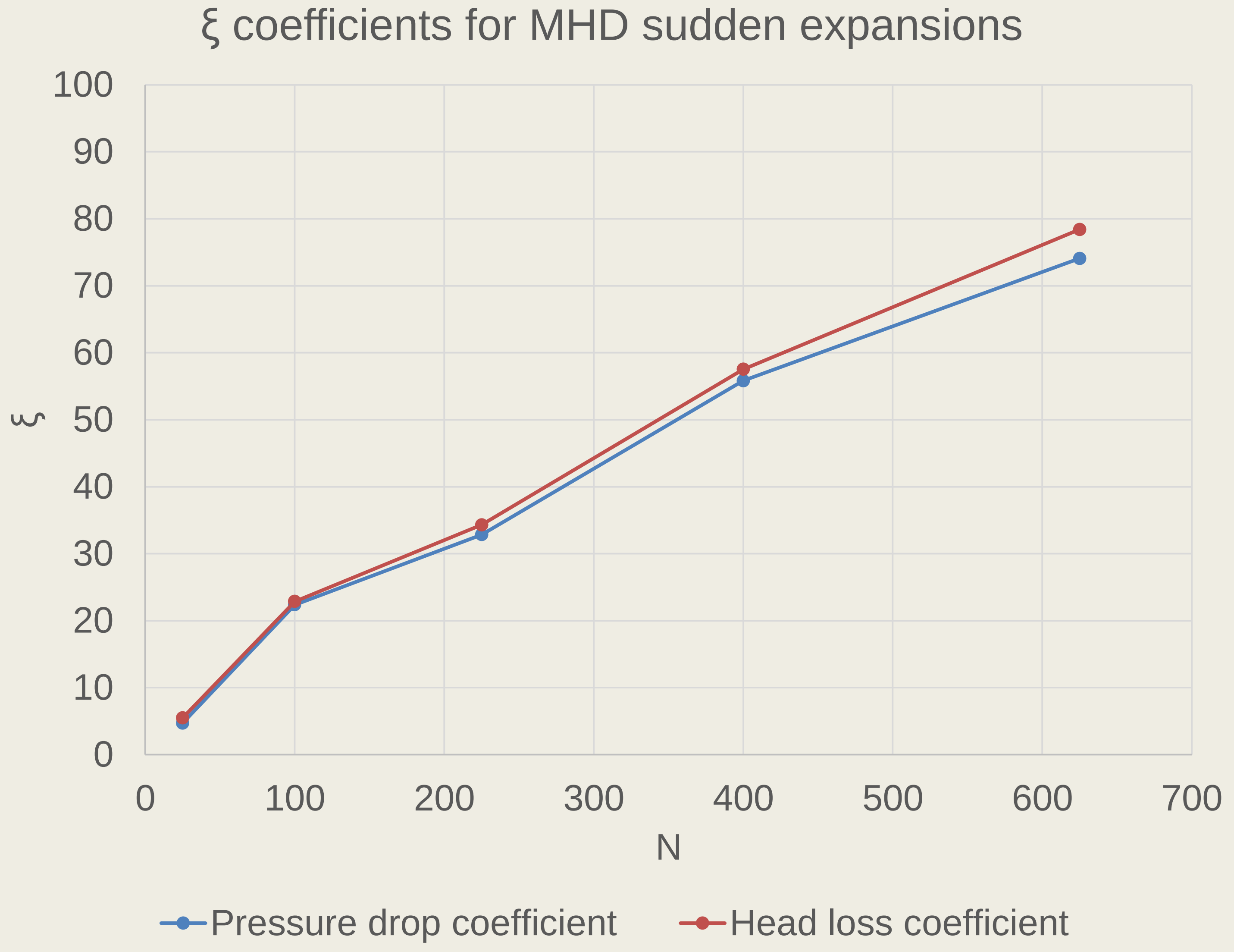
Application to MHD

Case Ha	N	ξ (Δp_{3D})	k (Δp_{3D})	ξ (h_{L_3D})	k (h_{L_3D})
50	25	4,69	0,1877	5,48	0,2193
100	100	22,37	0,2237	22,87	0,2287
150	225	32,82	0,1459	34,29	0,1524
200	400	55,82	0,1396	57,51	0,1438
250	625	74,07	0,1185	78,39	0,1254



Final Remarks

- A mechanical energy losses calculation method was developed to retrieve the bridge parameters from a CFD result necessary to design a hydraulic system.
- The multi-material incompressible MHD code developed at UPC was used to solve the expansion case.
- Currently a parametric study of the head losses coefficient in MHD expansions and contractions is under investigation using Marconi HPC at CINECA (with EUROfusion support). This computation power will allow to largely increase the Hartmann number.

THANK YOU

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