CFD of the upper plenum and its hot legs – How to deal with unsteadiness

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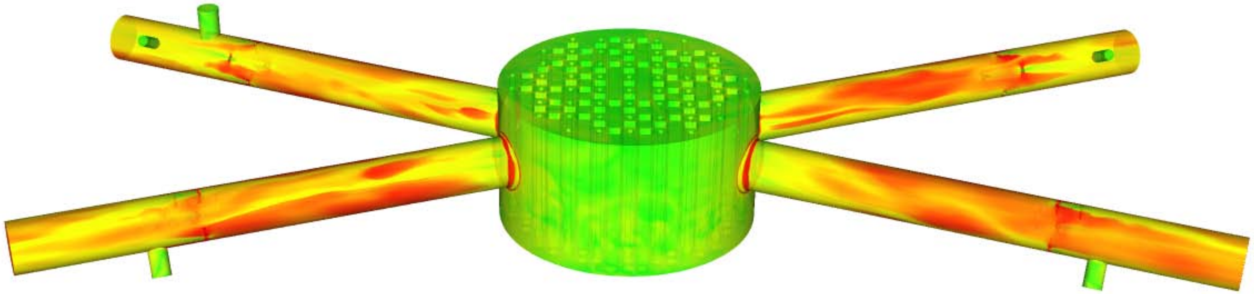
1 Year long Internship R&D / SEPTEN



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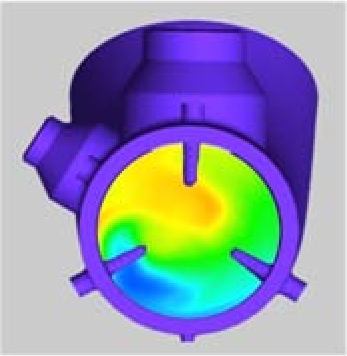
Industrial Context

Temperature Heterogeneity
in a hot leg section



- Uncertainty of the Temperature Measurement :
  - Heterogeneity generates uncertainty in the measurement

- Temperature measurements are useful for several task in the plant operation:
  - Protection systems based on core Inlet/Outlet Temperature differences
  - Control rod guide tubes insertion/extraction
  - Primary Flow measurement by enthalpy balance

- Primary Volume Flow Q_p :

$$Q_P \propto \frac{(W_{th} - W_p)}{H_{HL} - H_{CL}}$$

W_{th} Power extracted by the Steam generators
W_p Power furnished by the pumps
H_{HL} Hot Leg Enthalpy
H_{CL} Cold Leg Enthalpy

Overview of the CFD study

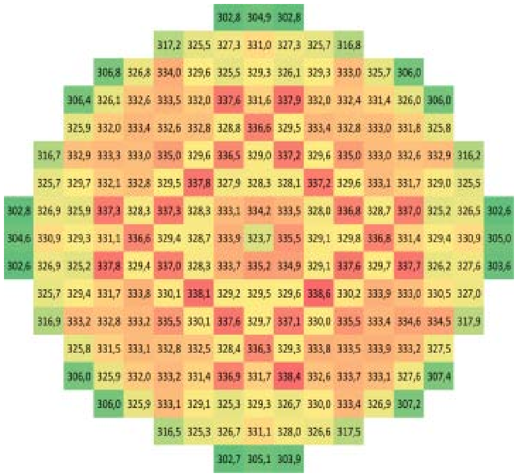
<u>Temperature heterogeneities</u>:

- Appear in the reactor core due to the power distribution
- Transported through reactor by secondary structures
- Still present at the end of the hot leg

<u>Objectives of the study</u>:

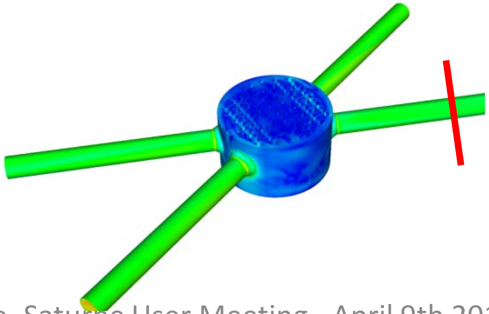
- Get a better understanding of the physical phenomena leading to heterogeneities
- Reduce the uncertainty on the temperature measurement in the hot leg
- Validate CFD results by comparing with experimental results

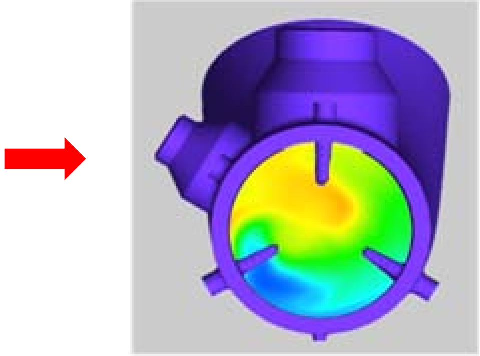
Temperature map at the core outlet



Experimental set

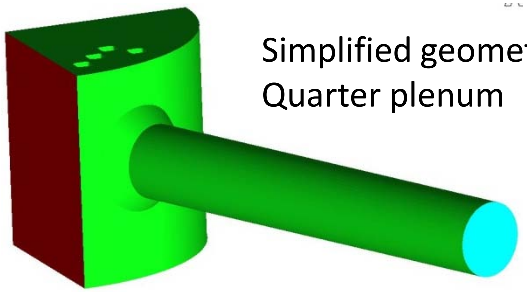
CFD Mesh



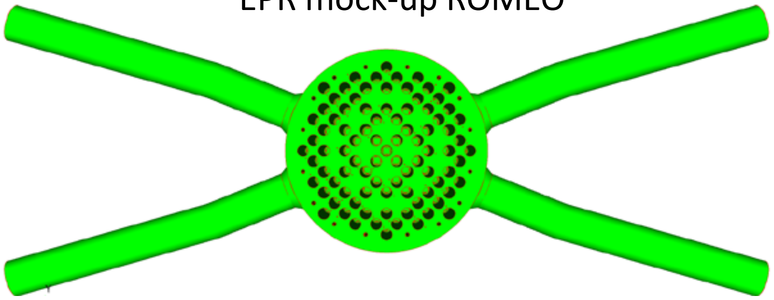


Overview - Different cases of the study

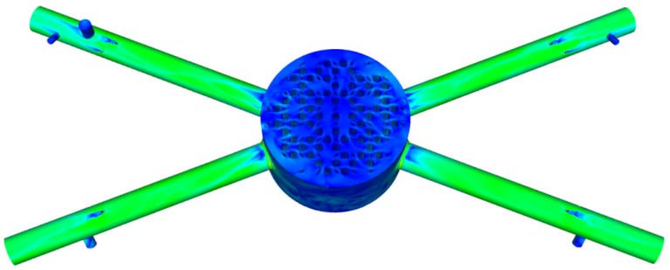
- <u>Elementary case</u>
  - Try different configurations
  - Scalabily tests (mock-up scale to full-scale)



- <u>Mock-up scale studies</u>
  - Reynolds 10^6 in the hot legs
  - Comparison with experimental data
  - Validation of the CFD code



- <u>Reactor scale studies</u>
  - Reynolds 10^8 in the hot legs
  - Reactor measurements available
  - Full scale validation

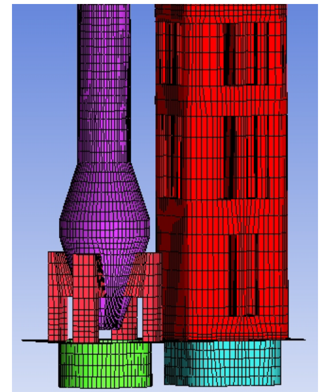


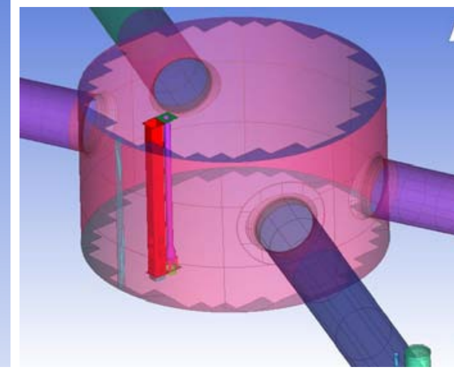
Overview - Computational cost

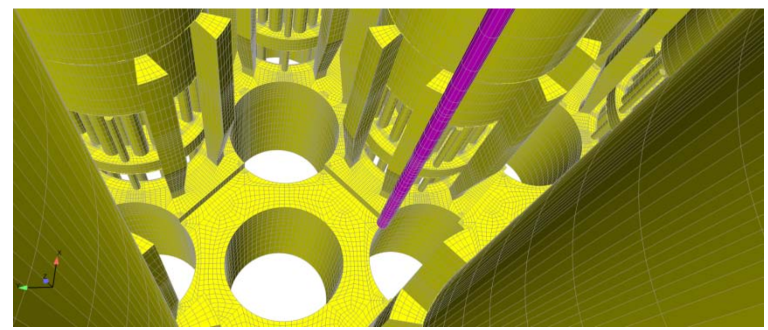
- Mock-up scale calculations :
  - **Y+ up to 1500** in the hot leg for a **35M** cells mesh!
  - 2 months calculations

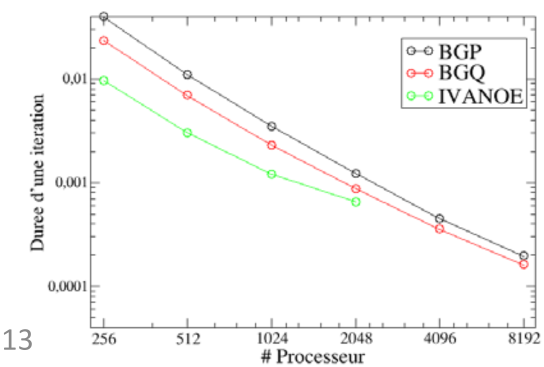
- Reactor Scale calculations :
  - First results on a 30M cells mesh yields values of **y+ up to 10 000**
  - Necessity to refine the mesh to reach optimal values of y^+
  - Refined mesh may exceed 200M cells

- Hardware
  - Blue Gene Q 65000 Processors Cluster
  - Calculations done on 8000 Processors

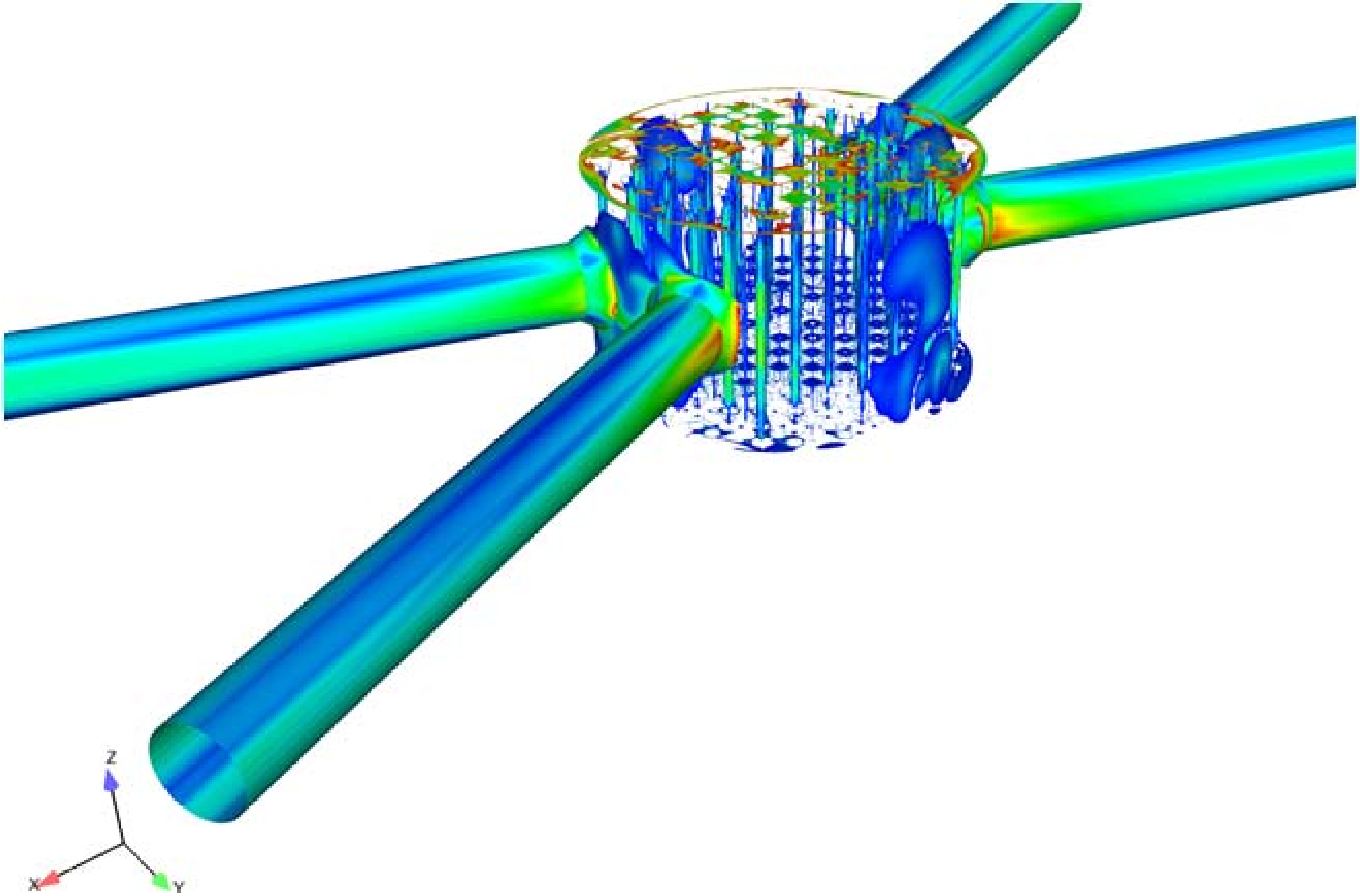






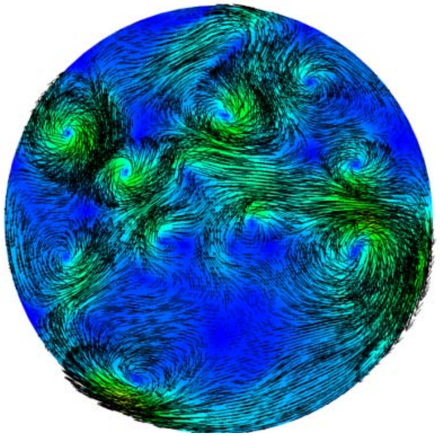


CFD Results



Results – Secondary Structures

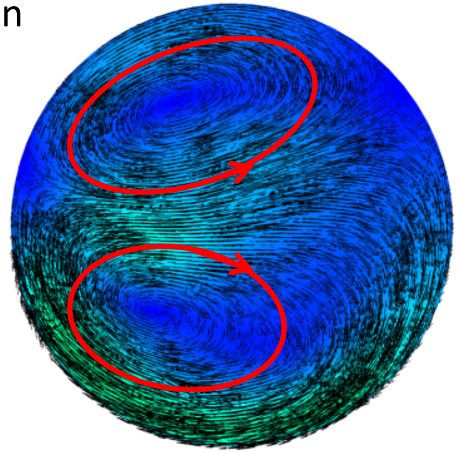
Instantaneous Tangential velocity in a hot leg section



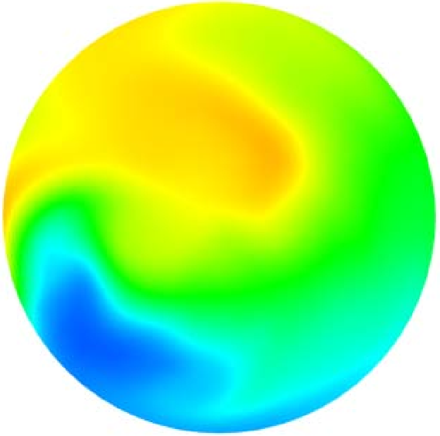
- We could show using CFD that secondary structures can prevent the good mixing of the flow

- We could also show the influence of the control rod guide tubes on the secondary structures

Average Tangential velocity in a hot leg section



Average Temperature in a hot leg section

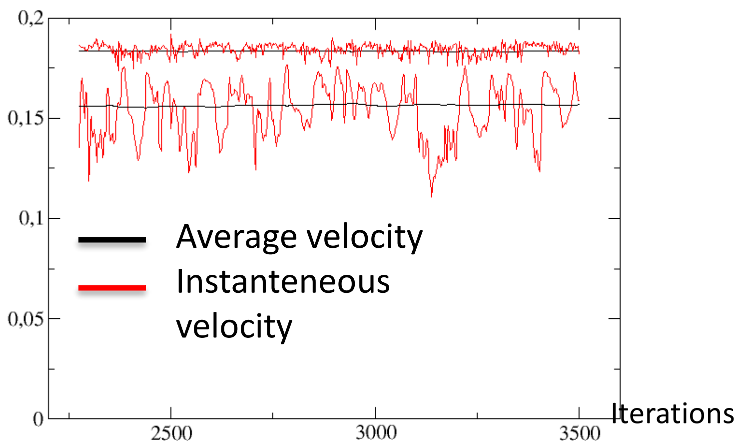


Results - Temperature Heterogeneity in the Hot Leg

- <u>Unsteady Results</u>

Numerically and experimentally, we observe an unsteady behavior

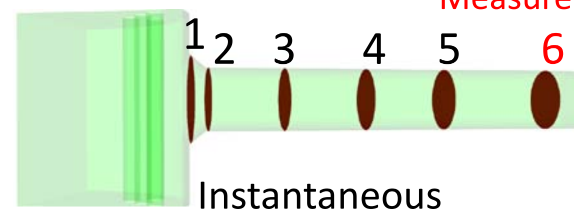
Velocity at 2 different points in the hot leg



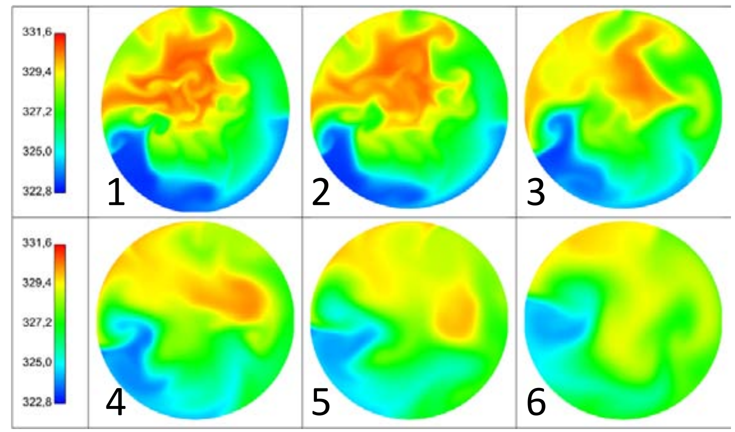
- <u>Temperature Heterogeneity</u>

We thus consider the **time average** to characterize the heterogeneity

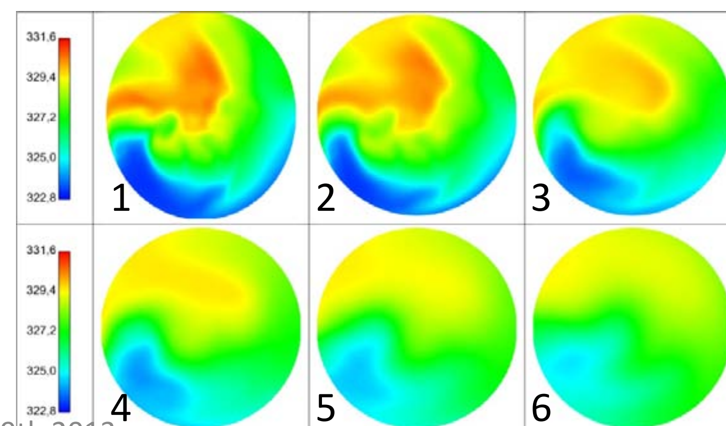
Measurements



Instantaneous



Evolution of the **Temperature** map along the hot leg



Time Average

Results - Time step dependence

- A Time step dependence is observed

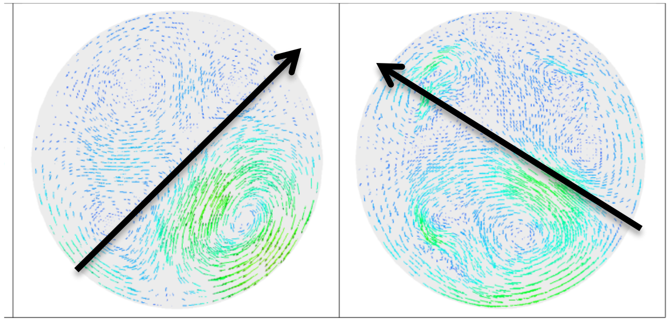
- Criteria frequently used in *Code_Saturne* to choose the time step value:

➡ Maximum CFL ≈ 1

$$CFL = v(\vec{x},t)\frac{\Delta t}{\Delta(\vec{x})}$$

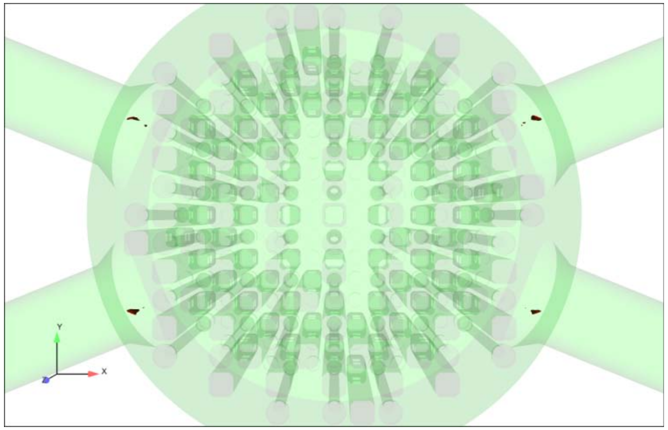
- Investigation of the representativeness of the criteria to choose the time step

Dt = 5e-4 CFL_{max}= 19 **Dt = 5e-5** CFL_{max}= 2.1



Tangential velocity in a hot leg section

Location of the maximum of the CFL



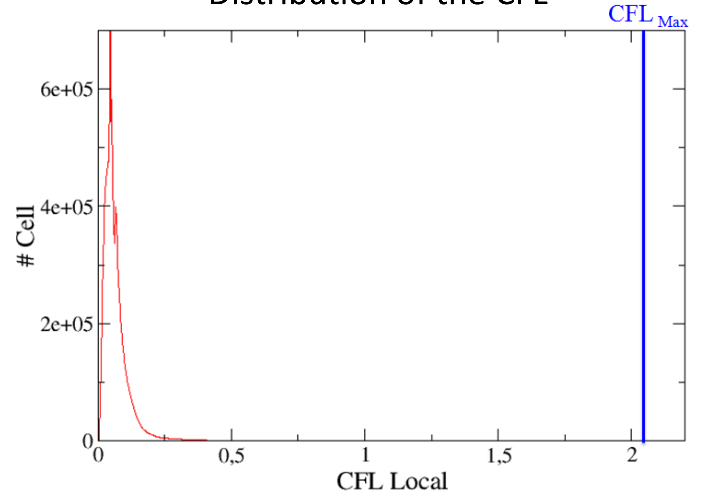
Which CFL criteria have to be used?

- Distribution of the CFL over the mesh:
  - Maximum CFL : 2.1
  - Space Averaged CFL : 0.066
  - Ratio Max/Average : 32

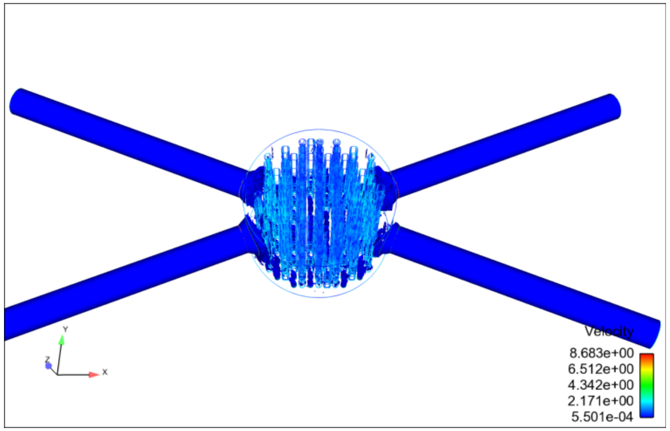
- Disadvantage of the Mean CFL:
  - Takes into account cells with lower influence on the physics

- Possible criteria investigated:
  - Average CFL over a Given part of the mesh
  - Discriminate cells of lower importance using a Criteria (example slower velocities)

Distribution of the CFL



Discrimination of lower velocity cells



Steady-State – Upper plenum case

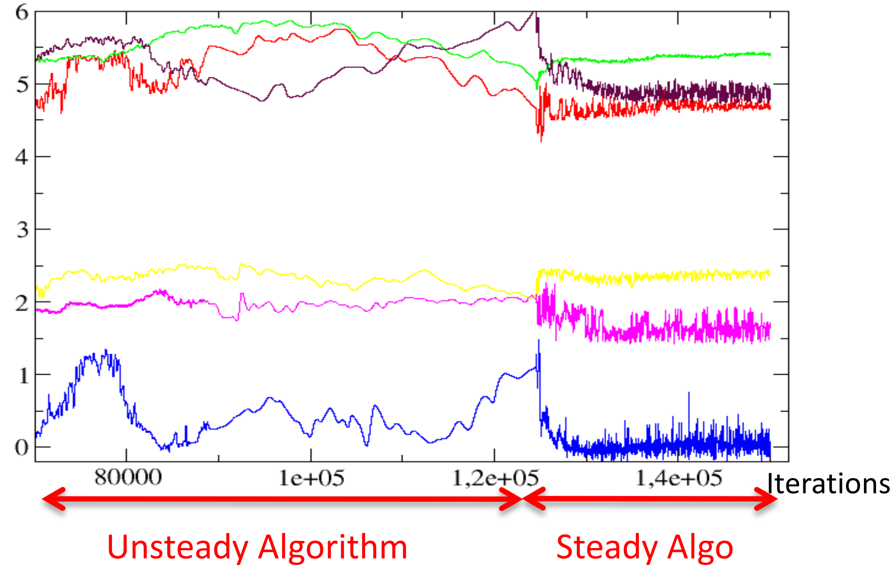
• One objective of the Steady-State calculation is to reduce calculation time.

Time gain: from several months to
a few weeks

• Usage of the *Code_Saturne* Steady-State Algorithm:
(space and time dependent time step)
The results **couldn't** be made steady

• Considering the very high number of cells involved in full scale calculations, it seems necessary to have a different Algorithm

Velocity at different points in the mesh



Steady-State – New Algorithm

- **Basic Idea of the Algorithm:**

Force current solution towards a target solution by adding a term in Navier-Stokes

Navier-Stokes: $$\frac{df}{dt} = A(f) \Longrightarrow \frac{df}{dt} = A(f) + \mathbf{X}(\mathbf{f} - \mathbf{f}_{\mathbf{Target}})$$

- **Target solution f_{target} :**

The target solution is the filtered current solution

Differential form of the Filtered Solution : $$f_{\mathbf{target}} = \int_0^t T(\tau - t; \Delta) f(\tau) d\tau$$

Exponential filter T : $$T(\tau - t; \Delta) = \frac{1}{\Delta} \exp\left(\frac{\tau - t}{\Delta}\right)$$

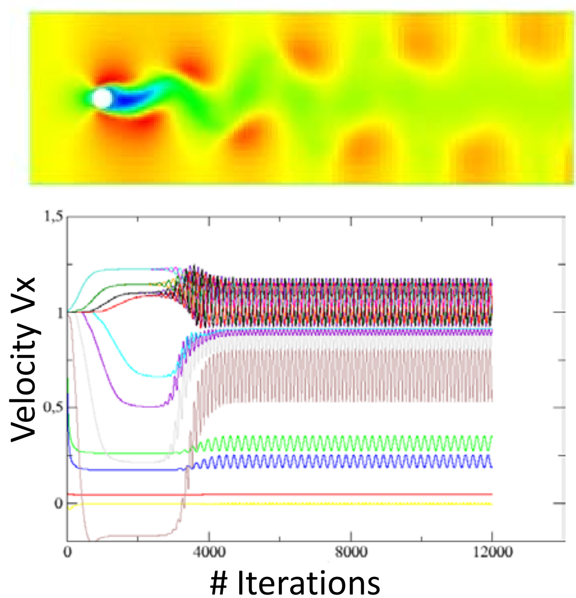
Differential form of the Filtered solution filter : $$\dot{f}_{\mathbf{target}} = \frac{1}{\Delta}(f - f_{\mathbf{target}})$$

Steady-State – Cylinder in a flow

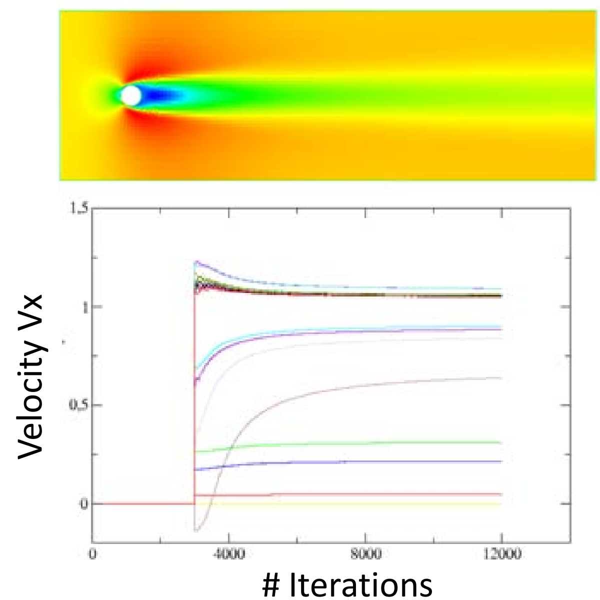
- Test of a different algorithm on the elementary case “Cylinder in a laminar flow”

Reynolds Re= 100	Inlet : Uniform velocity
Free Outlet	No slipping conditions on cylinder wall

Velocity Vx – **Unsteady Calculation**



Velocity Vx - **Time Averaged**



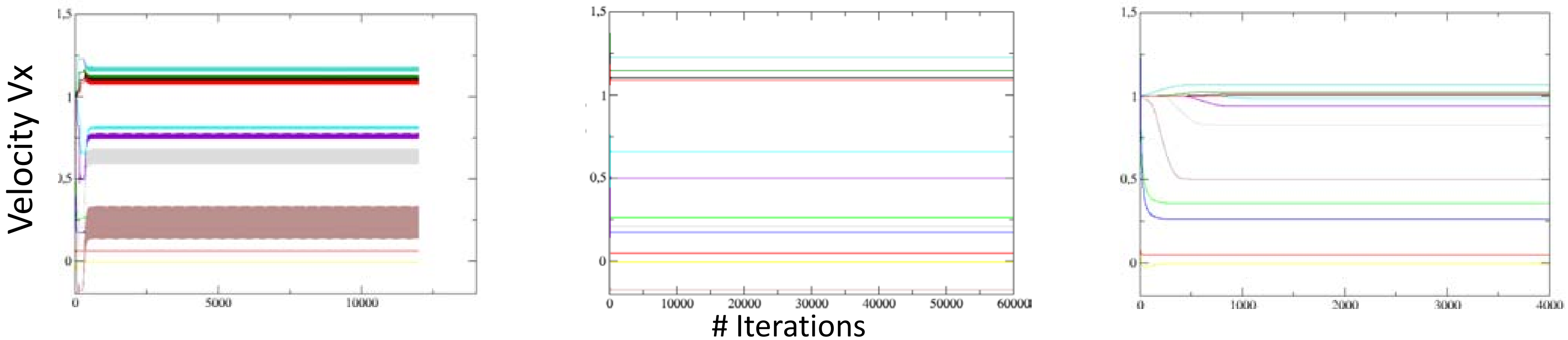
Steady-State – Results

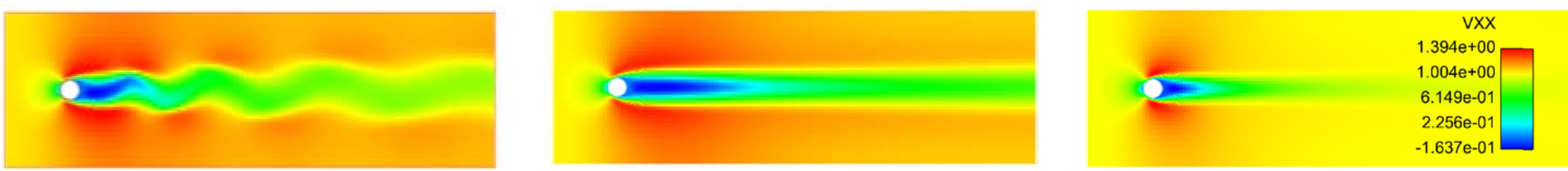
- **<u>Steady Results:</u>**

Saturne basic Steady-State Algo
(IDTVAR = 2) (COUMAX = 1)

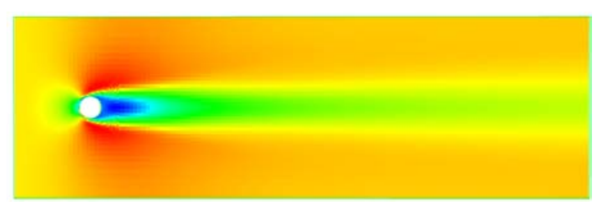
Saturne Steady-State
(IDTVAR = -1)

New Algorithm





Time Averaged Unsteady Result :

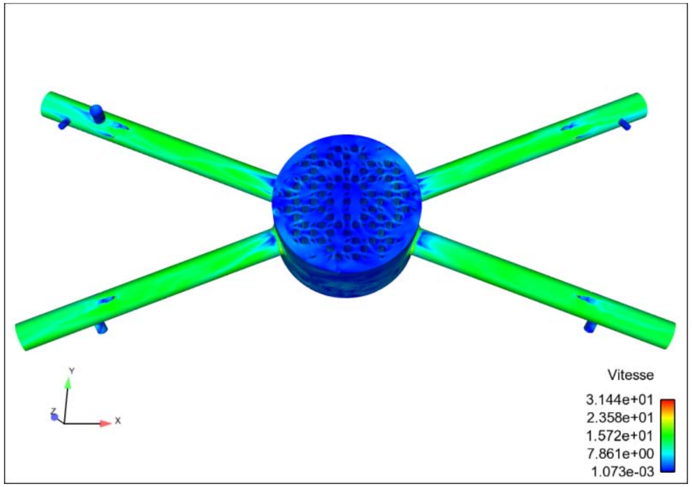


Perspectives of the study

- Reactor Scale validation on the go
  - Involves Fine Meshes !

- Very long computation time expected

- Steady Calculation could avoid months of calculation time



Thank you for your attention !

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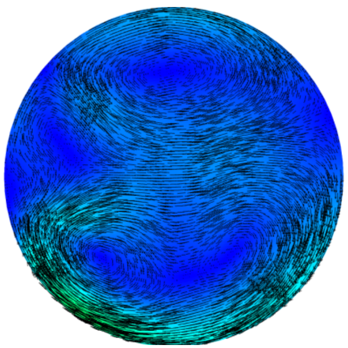
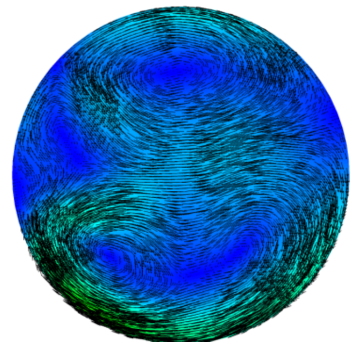
Results - Turbulence Models dependence
(Test on elementary case)

- **K-ϵ - **(Isotropic modelisation of Reynolds Stresses and Turbulent thermal flux)

Instantaneous Tangential Velocity

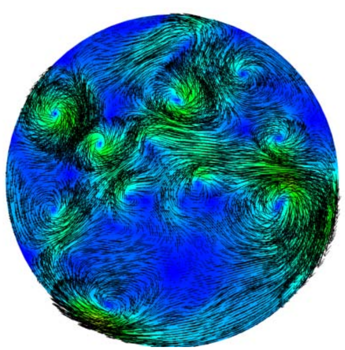


Time Averaged Tangential Velocity



- **Rij - **(Anisotropic modelisation of Reynolds Stresses, Isotropic modelisation of Turbulent thermal flux(SGDH))

Instantaneous Tangential Velocity



Time Averaged Tangential Velocity