DE LA RECHERCHE À L'INDUSTRIE

HIGH PERFORMANCE LARGE EDDY SIMULATION OF TURBULENT FLOWS AROUND PWR MIXING GRIDS

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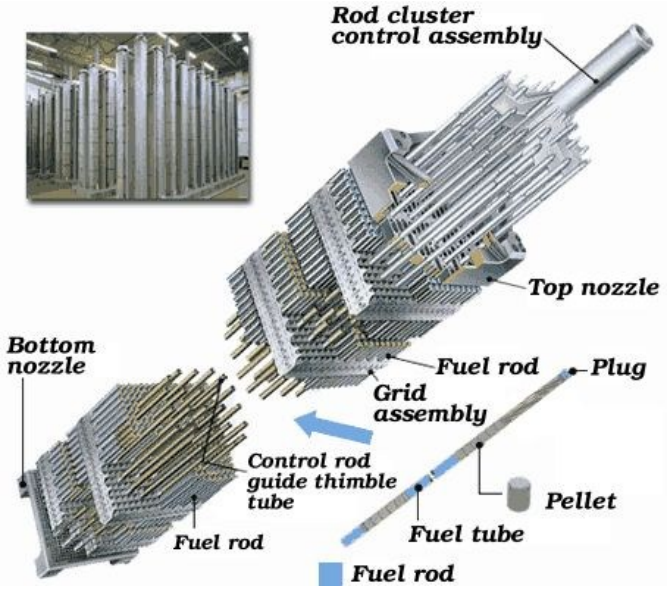
INTRODUCTION

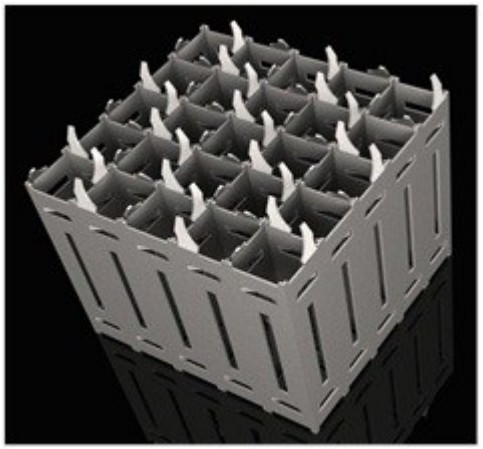
PWR Mixing grids

- Mixing grids are designed by nuclear power plant vendors to create a specific coolant mixing behavior in the fuel assembly.
- The mixing grid acts as momentum source which increases the turbulence level and guides the transvers flow pattern as a function of the specific vane design.



Case studies

- Flow in fuel assemblies of PWRs with mixing grids (AGATE experiment)
- Estimation of pressure and viscous forces onto two PWR mixing grids



Modeling approach

- Non-isotropic high turbulent flow behavior → LES
- Very large CFD simulations → HPC compulsory

- Use of 3D CFD parallel Trio_U code

OUTLINE

Trio_U CFD code

- Short presentation.
- Parallel performances.

Single PWR mixing grid calculation (AGATE exp.)

- Modeling and calculation route
- Results

Two mixing grids calculation

- Modeling and calculation route
- First results

Conclusion

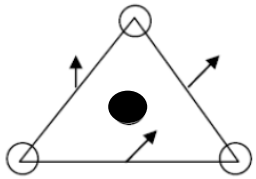
TRIO_U: 3D PARALLEL CFD CODE

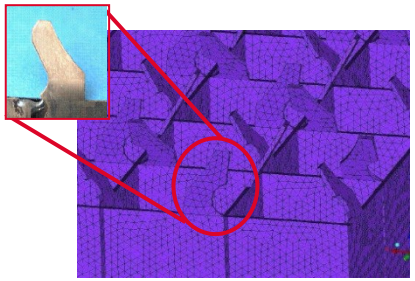
Trio_U CFD code

- CFD code for unsteady, low Mach number, turbulent flows.
- Designed for industrial CFD calculations on structured (parallelepipeds) and non-structured (tetrahedrons) grids of several hundreds of millions of control volumes
- The platform independent code, developed at CEA, is based on an object oriented, intrinsically parallel approach and is coded in C++.
- Flexible code structure
  - allows the user to choose a suitable discretization method
  - combine various appropriate physical models, including different treatments of turbulence.
  - several convection and time marching schemes as well as a wide range of boundary conditions are available.
  - run successfully on massively parallel computers (up to 10.000 cores).

Numerical schemes for LES

General	Mesh Discretization	Tetrahedral mesh P0+P1 for: P P1NC for: U
Time scheme	Runge-Kutta	3rd order explicit
Spatial Discretisation	Convection Diffusion Pressure solver Wall law	2nd order centred 2nd order centred PETSc GCP with SSOR preconditioning Reichhardt
Turbulence	LES	WALE



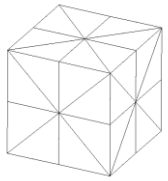


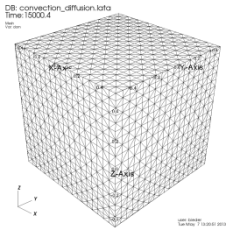
TRIO_U: 3D PARALLEL CFD CODE

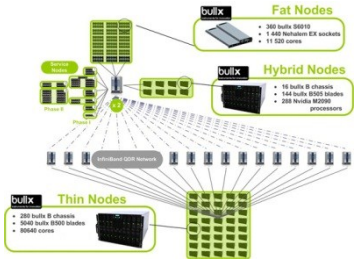
Parallel performances

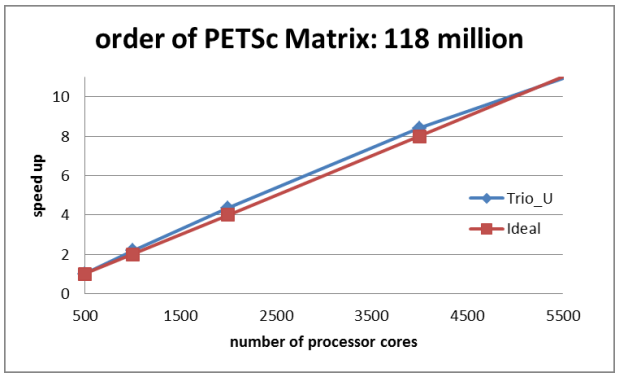
- For targeted simulations → several millions of unknowns → HPC required.
- Need to evaluate parallel performances of the code up to 10k cores
- The solution method for LES calculations of Trio_U is based on the pressure projection method → between 60% and 80% CPU time spent in linear solver
- Strong scaling analysis on 100M cells benchmark.

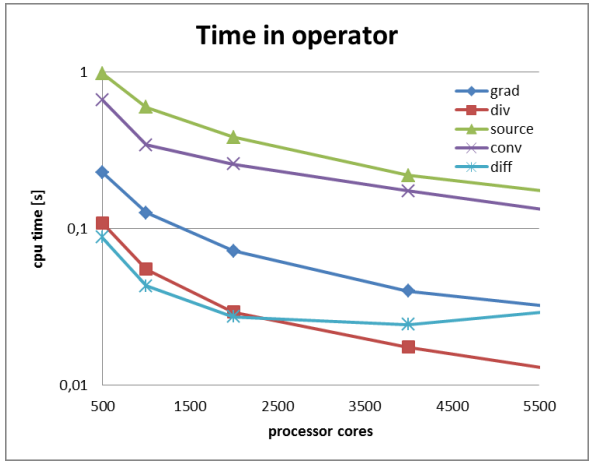
Processor cores	Iterations to convergence	CPU time in s	tetras/core
500	5733	181,4	213260
1000	5735	82,9	100663
2000	6019	43,6	50331
4000	5877	22,1	25165
6000	6018	16,2	16777
8000	6042	13,2	12583
10000	5979	11,9	10066









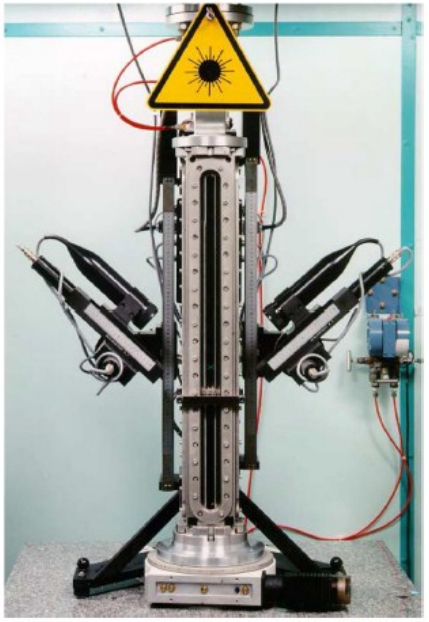


AGATE CALCULATION

AGATE experiments

- The AGATE facility was in operation from 1992-2001.
- More than 30 different mixing grids have been characterized.
- The test section consists of a 5x5 rod bundle and a mixing grid, which is placed within a metallic channel of a quadratic cross section.
- LDA measurements are placed on one channel side.
- A range of Re between 10.000 and 100.000 has been analyzed.

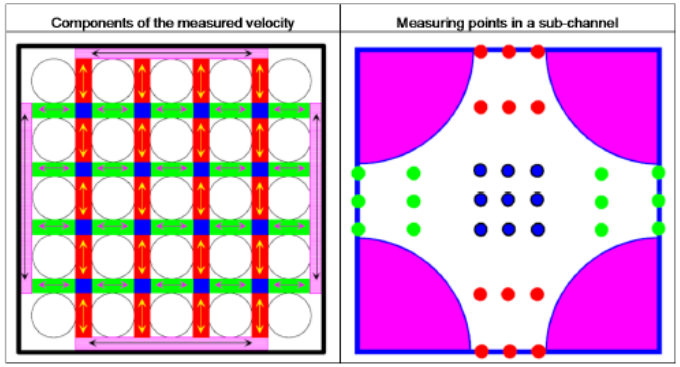
- High quality local data of the velocity components and of the turbulence level were measured. The uncertainty on the cross flow velocity is below 1%.



2D instantaneous velocities v_x and v_z

2D instantaneous velocities v_y and v_z

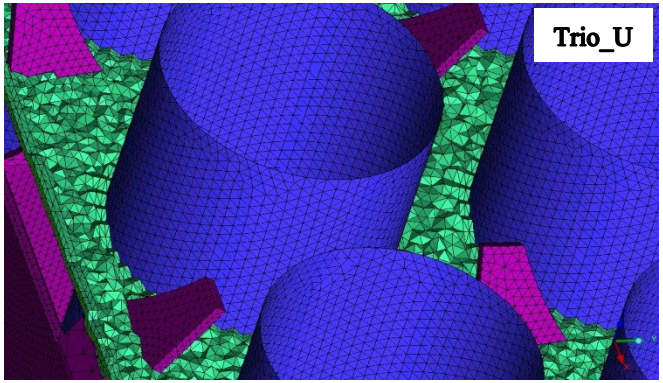
3D instantaneous velocities v_x, v_y and v_z

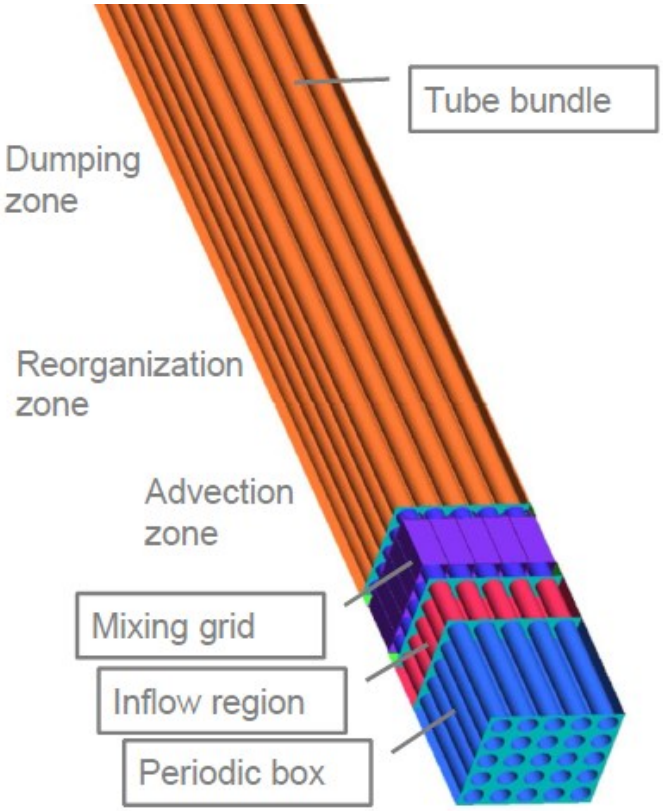


AGATE CALCULATION

CAD model and meshing

- CAD modeling with SALOME
- Full tetra mesh generation of the mixing grid with ICEM
- Two prismatic layers near walls (cut into tetra)
- 300 million velocity calculation points
- 20 days of CPU on 4600 cores of CURIE



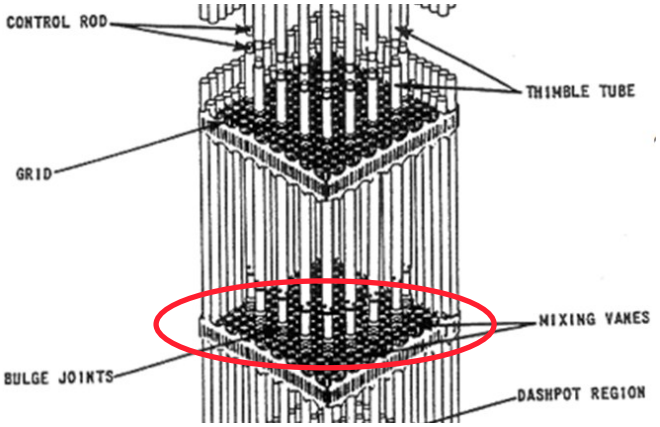


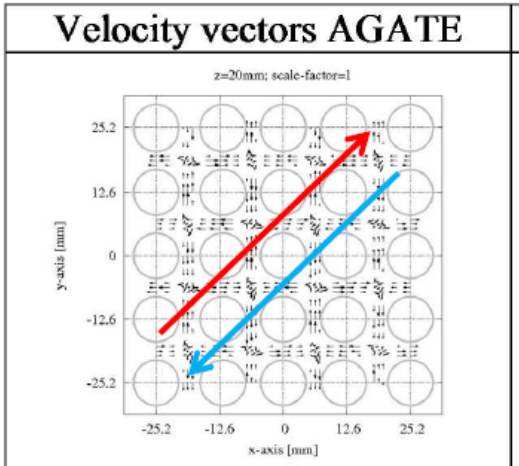
AGATE CALCULATION

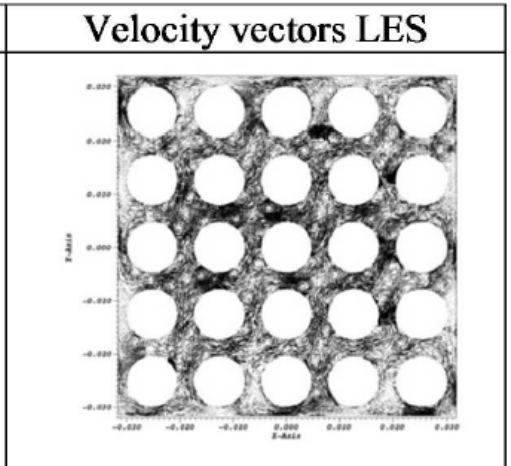
Results: Near grid cross flow

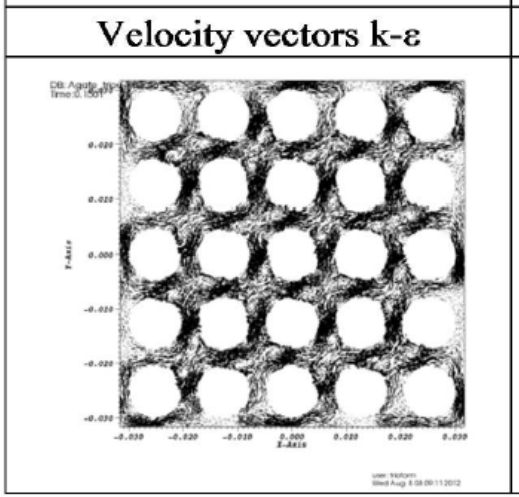
- The measurements show a main cross flow at the 45° diagonal.
- LES and RANS modeling show the formation of the 45° flow direction.
- The LES approach shows much more tiny swirls than the RANS approach.

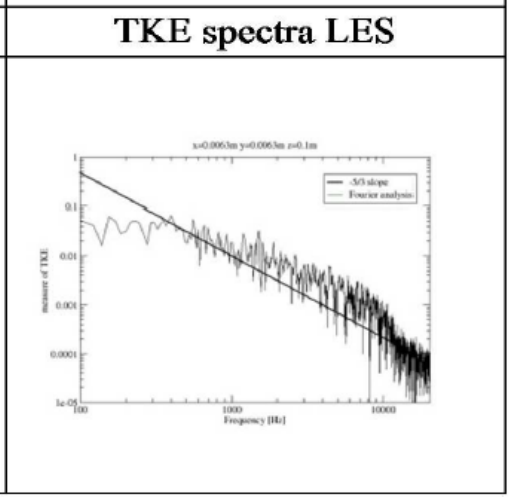
- The TKE energy spectra follows the -5/3 slope for about ½ decade of frequencies with an accumulation of energy at high frequencies (this point is still under investigation)







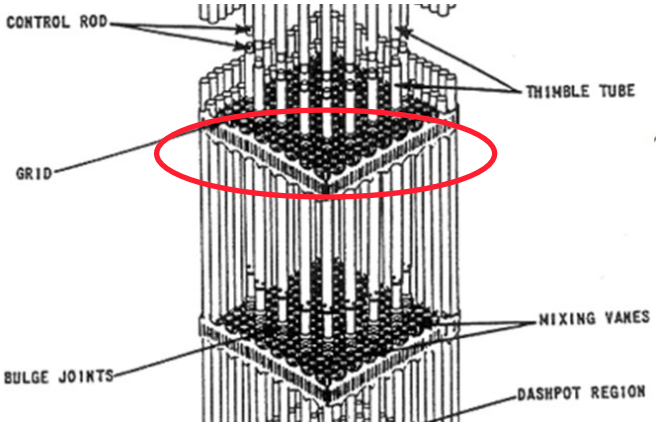


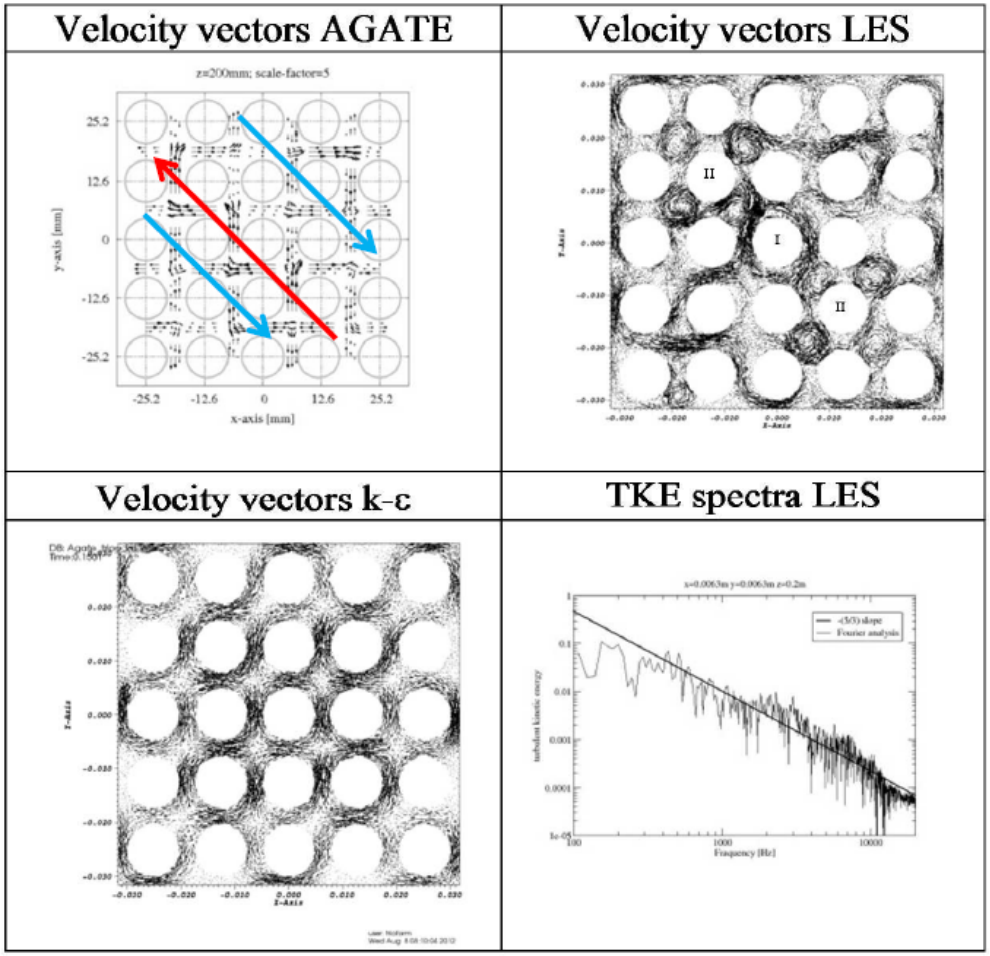


AGATE CALCULATION

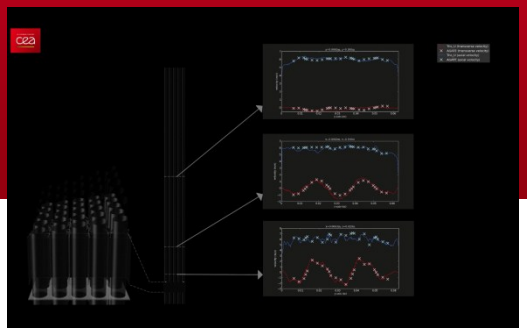
Results: Far grid cross flow

- The measurements show a reorganization of the main cross flow (developing the 135° diagonal).
- The LES approach shows a reorganization of the cross flow (formation of dominant swirls in sub channels).
- RANS modeling keeps the 45° diagonal flow direction.
- The TKE energy spectra follows the -5/3 slope for almost 1 decade of frequencies with an reduction of the former accumulated energy at high frequencies.

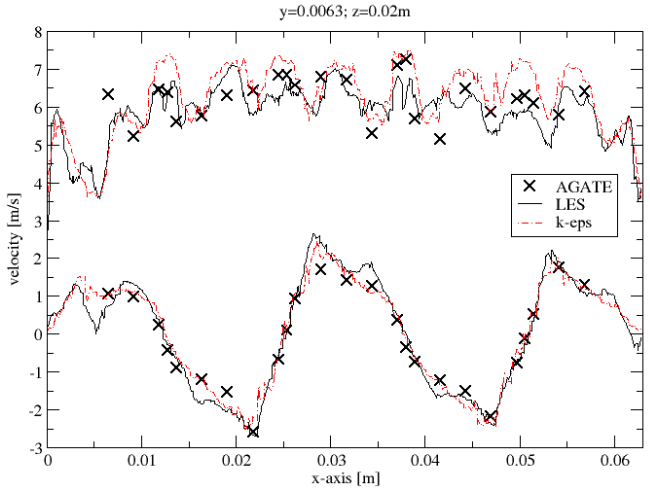


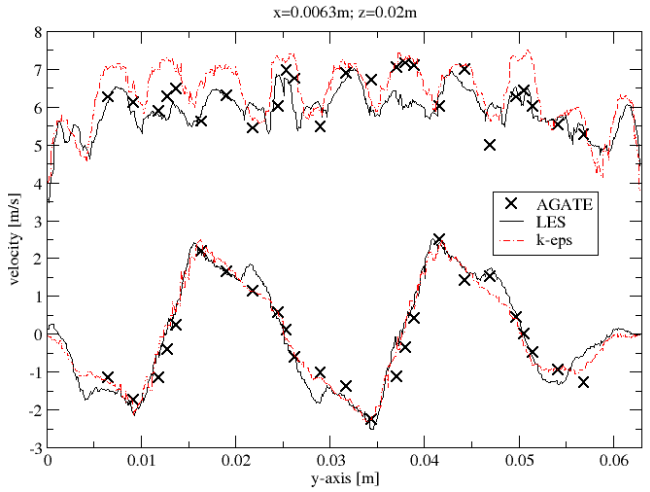


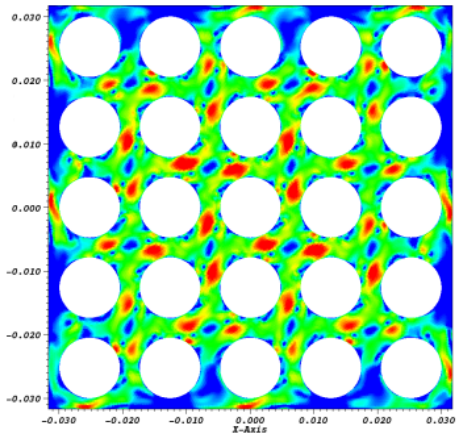
AGATE CALCULATION



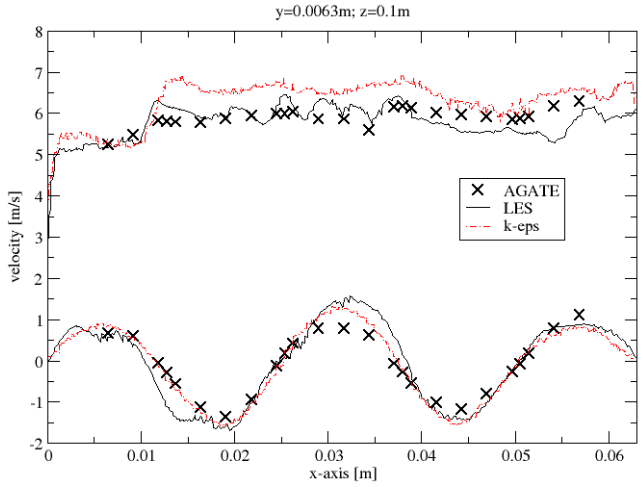
Results: K-eps vs LES

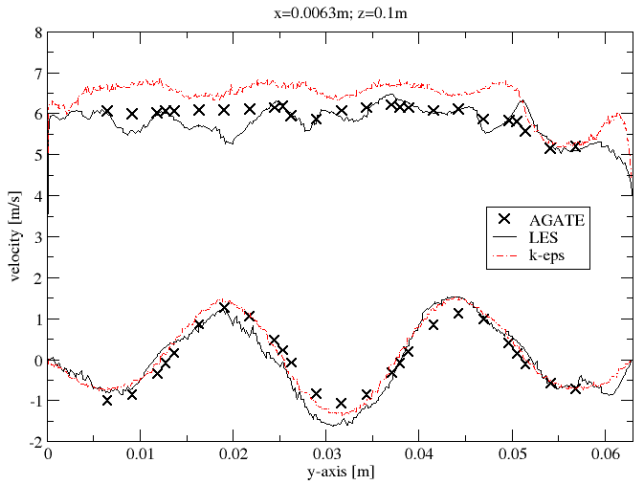


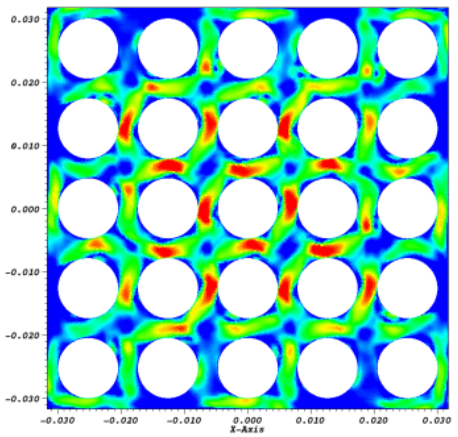




$z=1.7d_h$





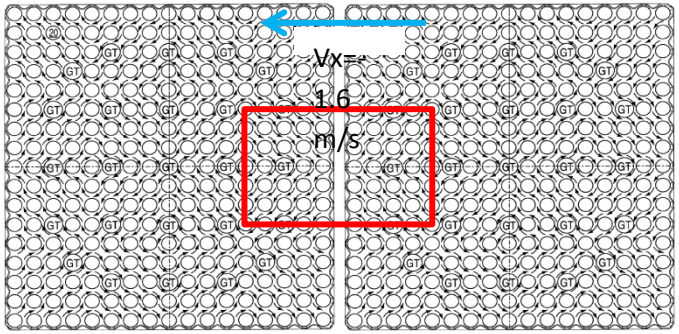


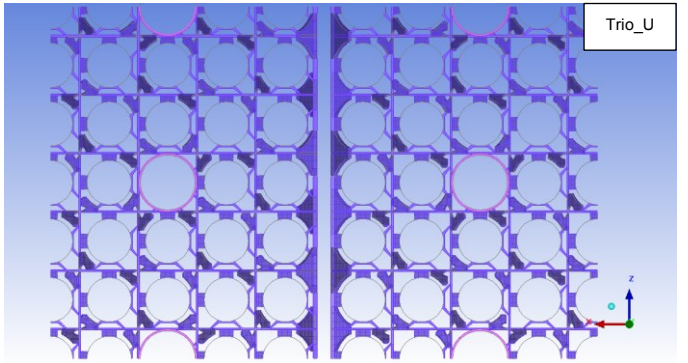
$z=3.4d_h$

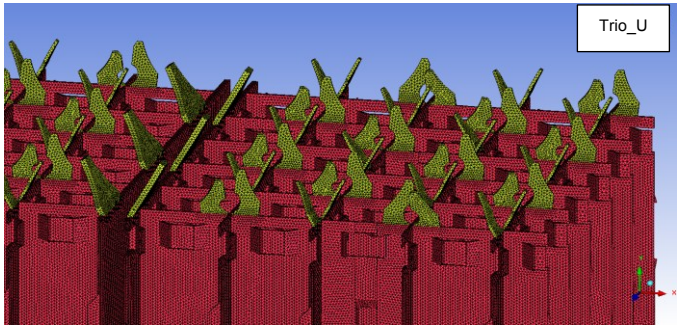
TWO MIXING GRIDS CALCULATION

Calculation route

- Determine pressure and viscous forces onto two PWR mixing grids in case of transverse flows.
- Similar approaches as for the AGATE study have been used to model and mesh the geometry
- More than 1 billion of velocity control volume (550M of tetra):
  - 400 M VCV for recirculation box
  - 700 M for the computational domain
- 10K cores on the CURIE machine



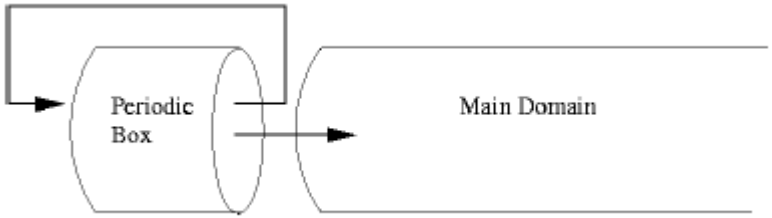




TWO MIXING GRIDS CALCULATION

Recirculation box

- Recirculation periodic box is used in order to initialize the right boundary conditions for the input turbulent flow



- In the context of massively parallel execution, one have to take care on the calculation core usage for recirculation box and for the main domain:
  - **Sequential coupling**: efficient when the resolution time for the recirculation box is small compared to the resolution time for the main domain.

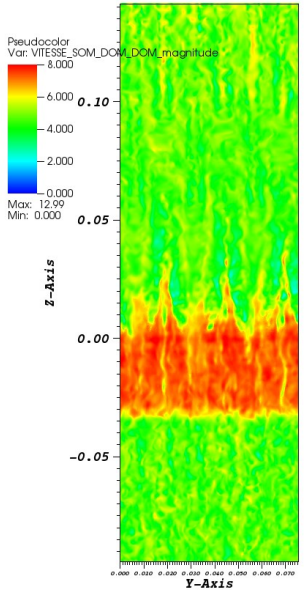
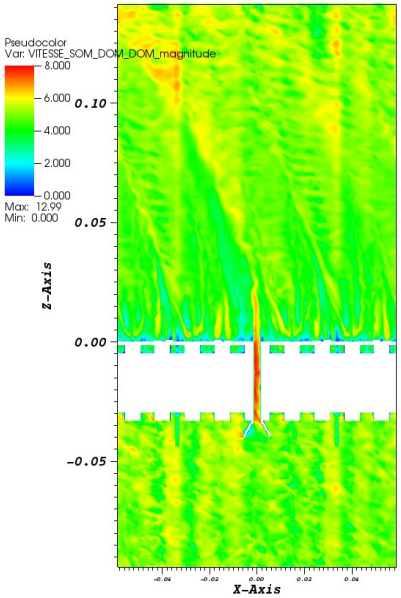
  - **Parallel coupling**: using a parallel coupling approach within the Trio_U framework, resolution for the recirculation box and main domain are achieved in parallel

Save 30% of CPU time

TWO MIXING GRIDS CALCULATION

First results

- The computation is still ongoing
- The calculation was running for 20 days on 10,000 CPU cores up to reach convergence of the mean values

Cut plane normal to the x-axis along the water gap	Cut plane normal to the z-axis between the rods
	

Norm of the instantaneous velocity in two cut planes

CONCLUSION

- Large LES simulation of PWR mixing grids have been achieved thanks to Trio_U code and the use of HPC
  - 300 M VCV and 4.6k cores
  - 1.1 B VCV and 10k cores
- For the single PWR mixing grid, LES results shown very good agreement with AGATE experimental results and improve k-eps ones especially in the case of long distance simulation (just before the next mixing grid)
- For the two mixing grid case:
  - Calculation is still ongoing
  - Specific calculation procedure have been set-up in order to improve the calculation time (parallel coupling procedure)
  - In spite of the use of 10k cores, calculation domain is only a small part of the whole geometry:
    - Need for more CPU
    - Need for efficient turbulence model coupling (RANS+LES)
- The setup of such very large calculation is a tricky problem, especially when the # of cores used is greater than 10% of the whole production machine …

Thank you !

Questions ?

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