Online workshop:
The Path to Future HPC Technologies in Wind Energy Modelling & Simulation

HPC developments in Alya for Wind Energy Applications

September 15, 2020

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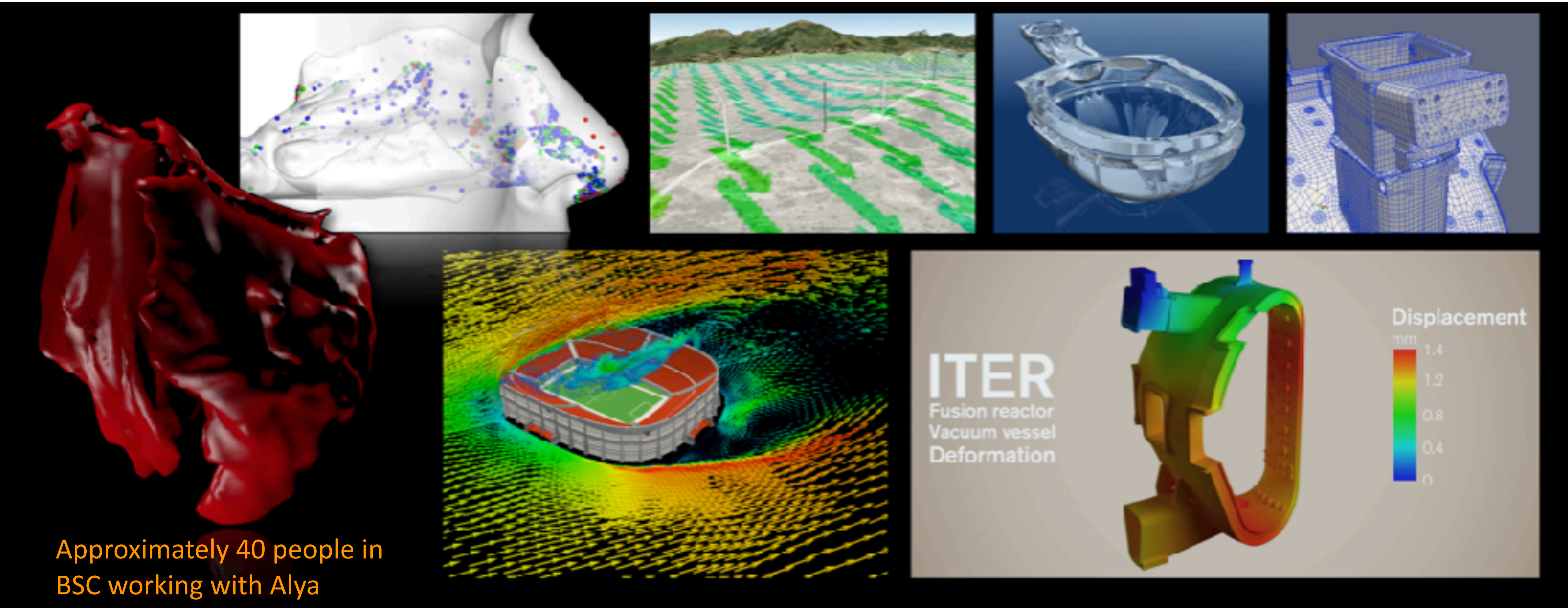
Computer Applications in Science and Engineering Department

European Commission | Horizon 2020
European Union funding
for Research & Innovation

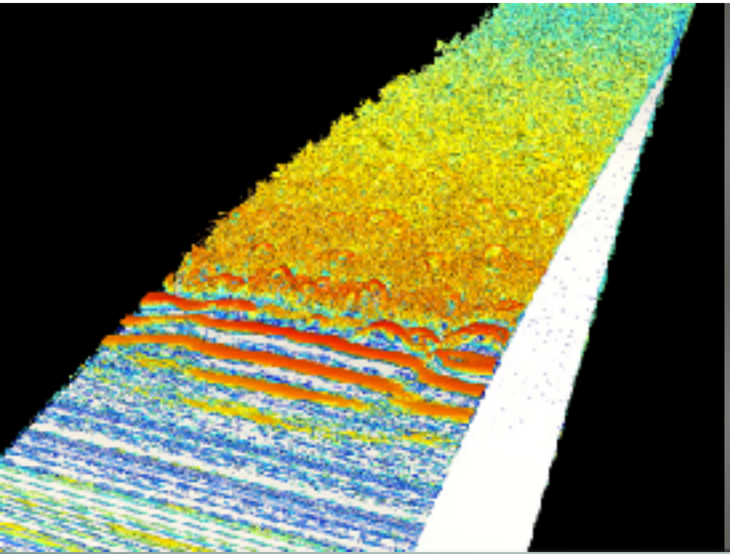
Alya: HPC finite element multiphysics code @BSC

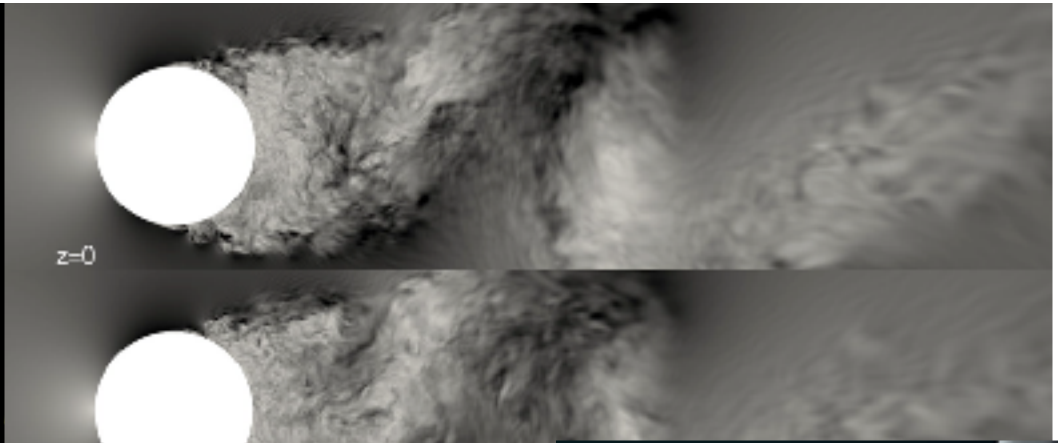


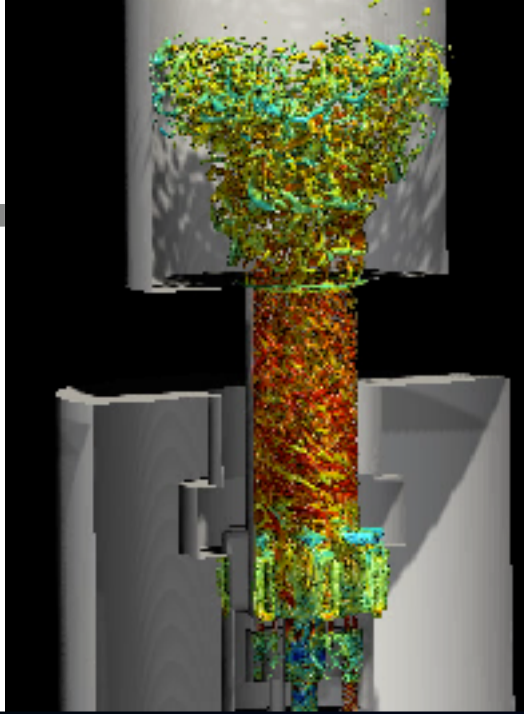
Approximately 40 people in BSC working with Alya

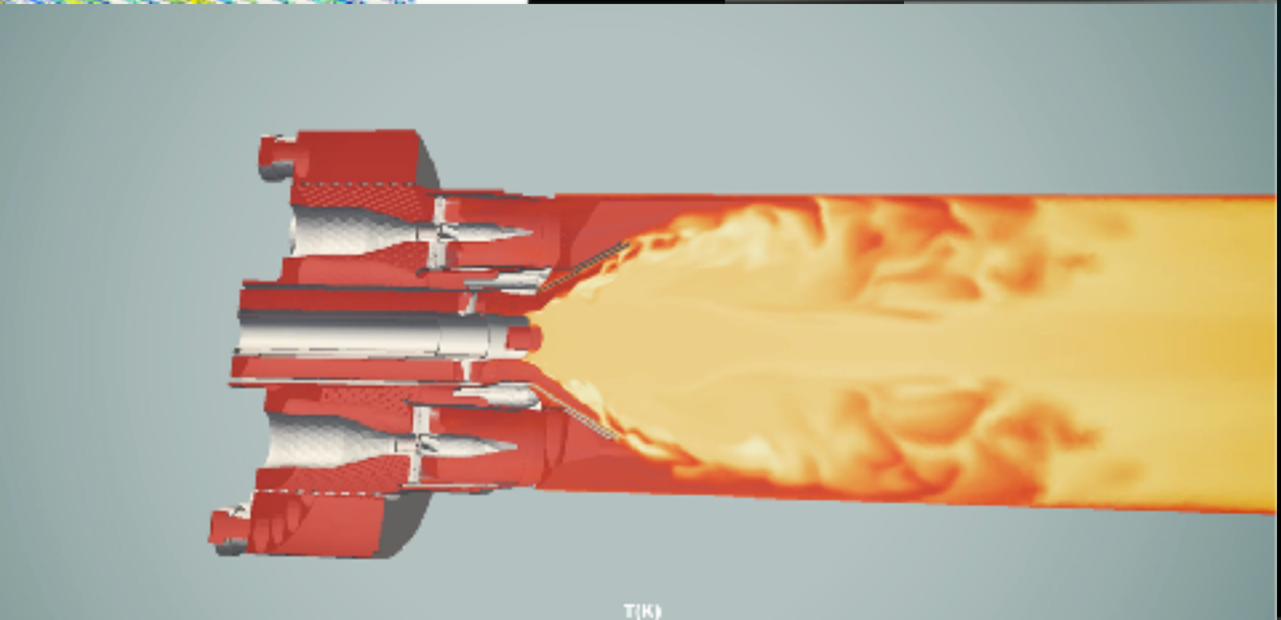
https://www.bsc.es/research-development/research-areas/engineering-simulations/alya-high-performance-computational

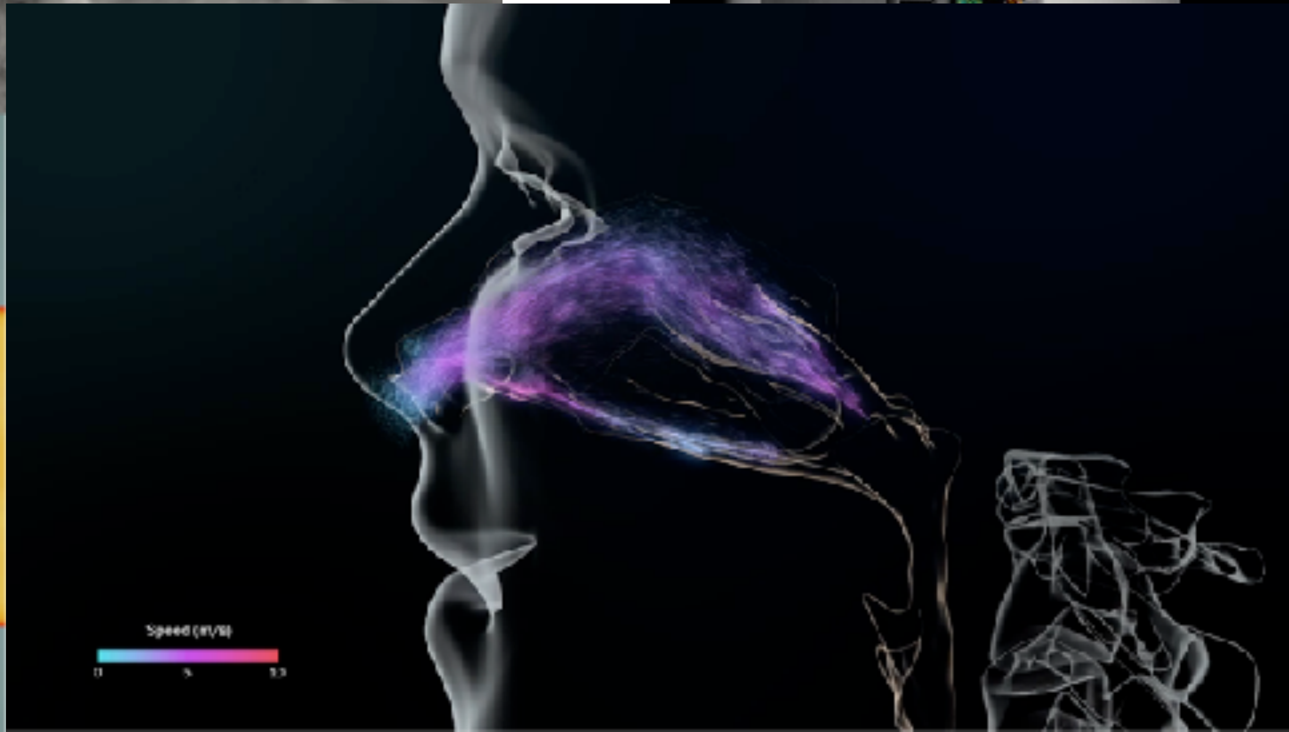
Alya: HPC finite element multiphysics code @BSC











Alya: HPC finite element multiphysics code @BSC

Our LES has recently undergone huge transformation.

FROM: VMS with implicit treatment of momentum equation.

TO: Galerkin with explicit (RK3/4) treatment.

EMA - Energy, momentum and angular momentum conserving convective term.

Stabilisation for the p-v interaction coming from Laplacian approximation in Fractional Step Method.

Physical based SGS modelling (Vreman). ILSA in development with Prof. Hugo Piomelli.

SIMPLE and no user defined numerical parameters. ☺

EMA scheme: S. Charnyi, T. Heister, M. A. Olshankii, and L. G. Rebholz. On conservation laws of Navier-Stokes Galerkin discretizations. J. Comput. Phys., 337:289–308, 2017

Alya: HPC finite element multiphysics code @BSC

High Order: Quadratic and some cubic FE
Approximation of the Consistent Mass Matrix (Guermond) instead of Lumped Mass Matrix.

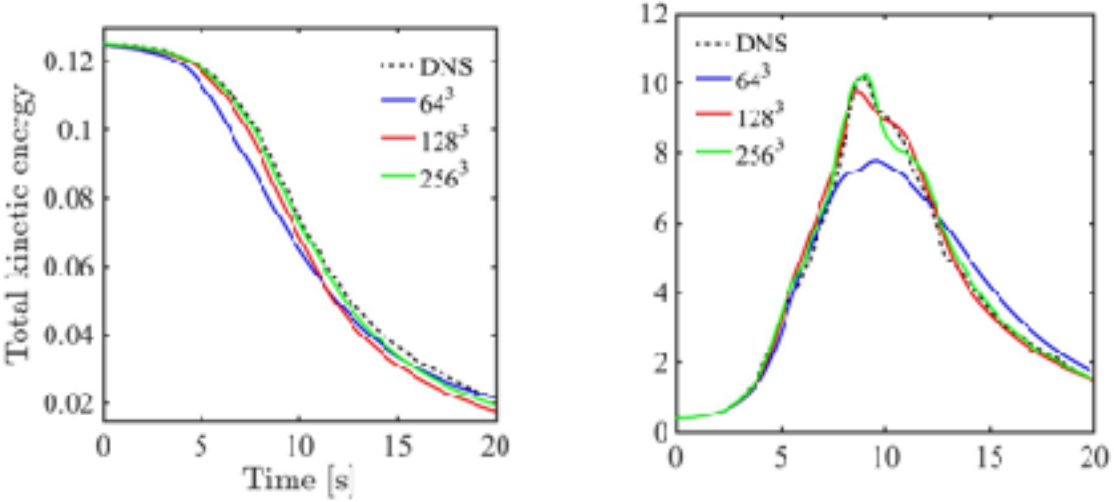
Temperature equation:
Enstrophy viscosity method (Guermond)

Solids module: (here for wind turbine blade deformation)
Continuum Shell elements for anisotropic laminates.
Key challenge: mesh generation. We use ANSA for both Solids and Fluids.
Mumps direct solver or iterative solvers.

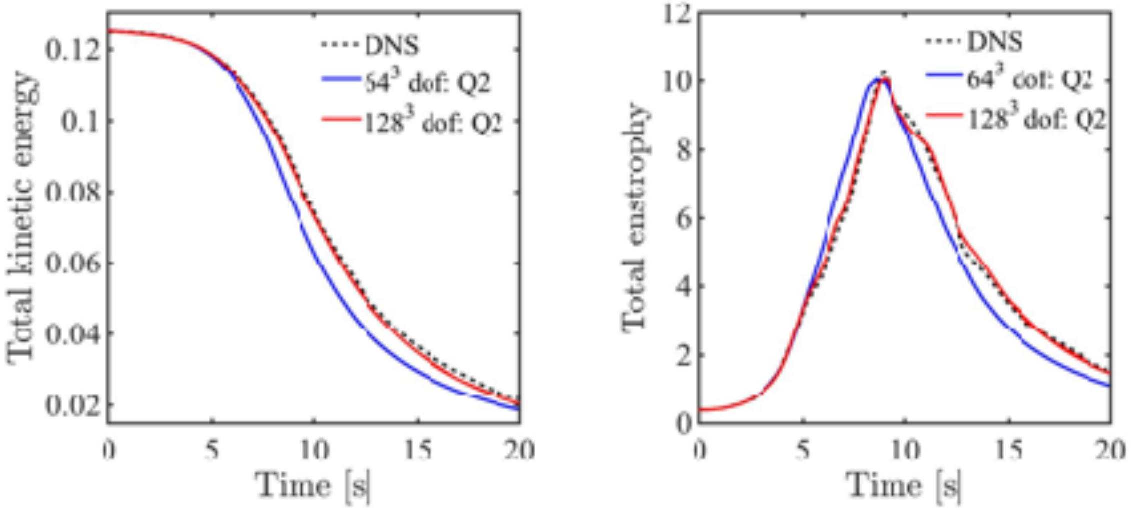
Alya: HPC finite element multiphysics code @BSC

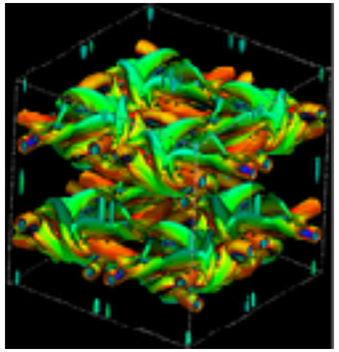
Test case: Taylor-Green vortex
Re = 1600 *

EMA approximation: Q1

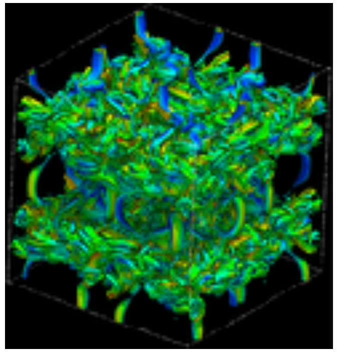


EMA approximation: Q2

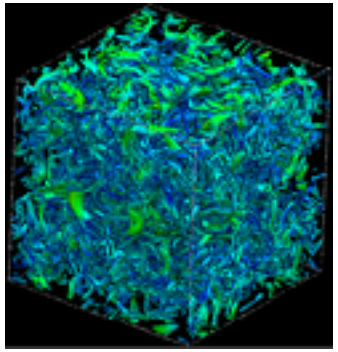




t = 5



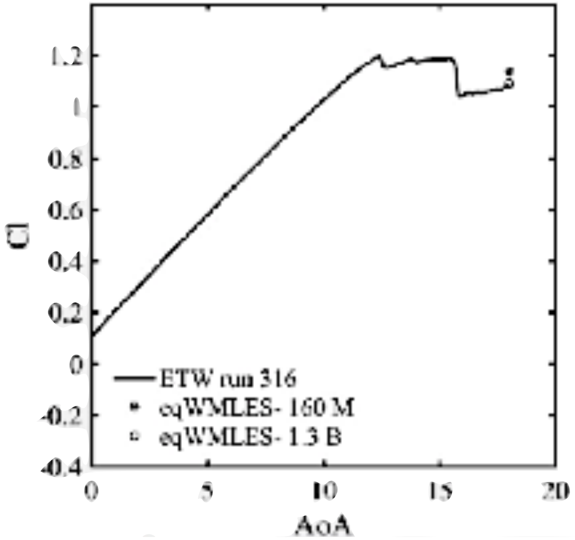
t = 10

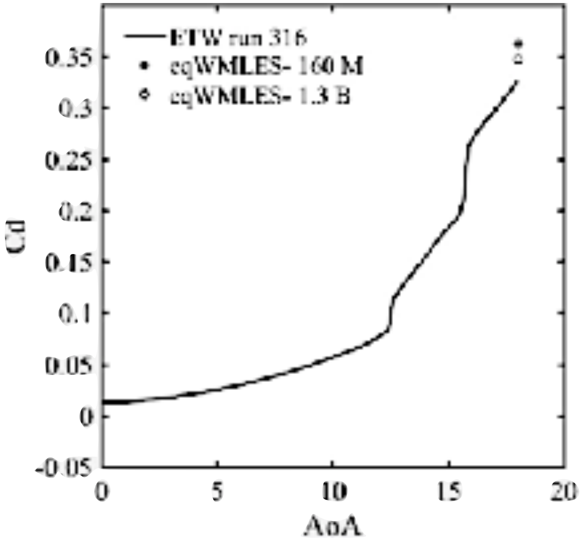


t = 20

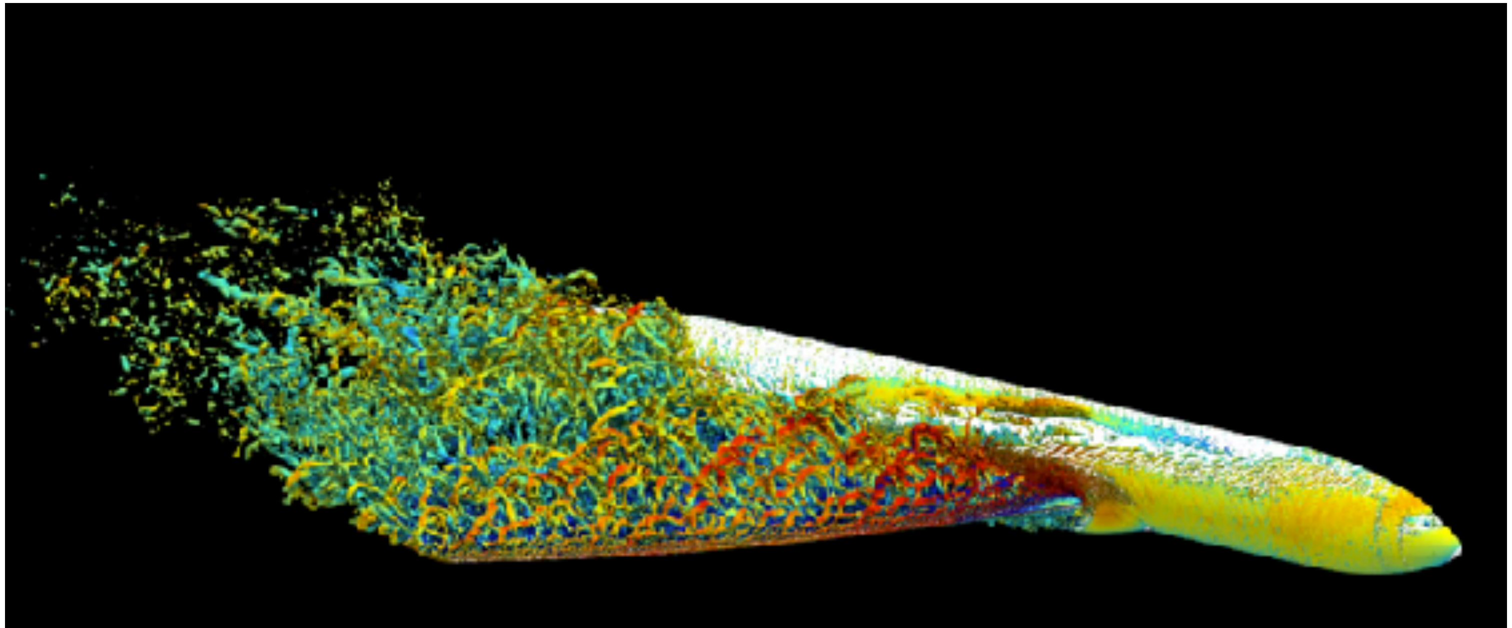
A low-dissipation finite element scheme for scale resolving simulations of turbulent flows, Lehmkuhl et al. Journal of Computational Physics

Alya: HPC finite element multiphysics code @BSC





WMLES for stall regime (static Vreman SGS model)
Re = 11M   Ma = 0.2
Experiments coming from DLR
Mesh from O(150M) to O(1.5B)
Obtained results are one of the first large scale demonstration of WMLES technology *



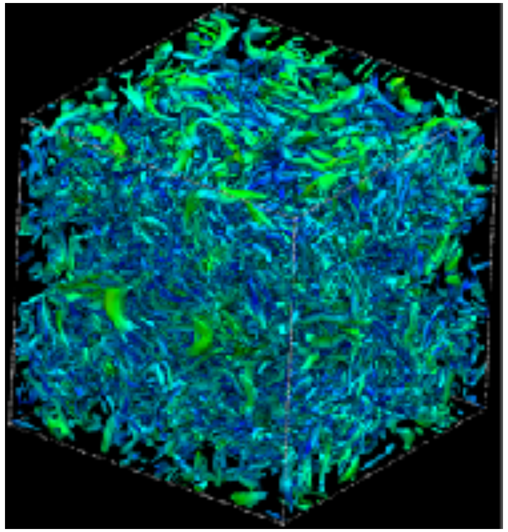
Result from Oriol Lehmkuhl (BSC)
@ Stanford CTR Summer programm

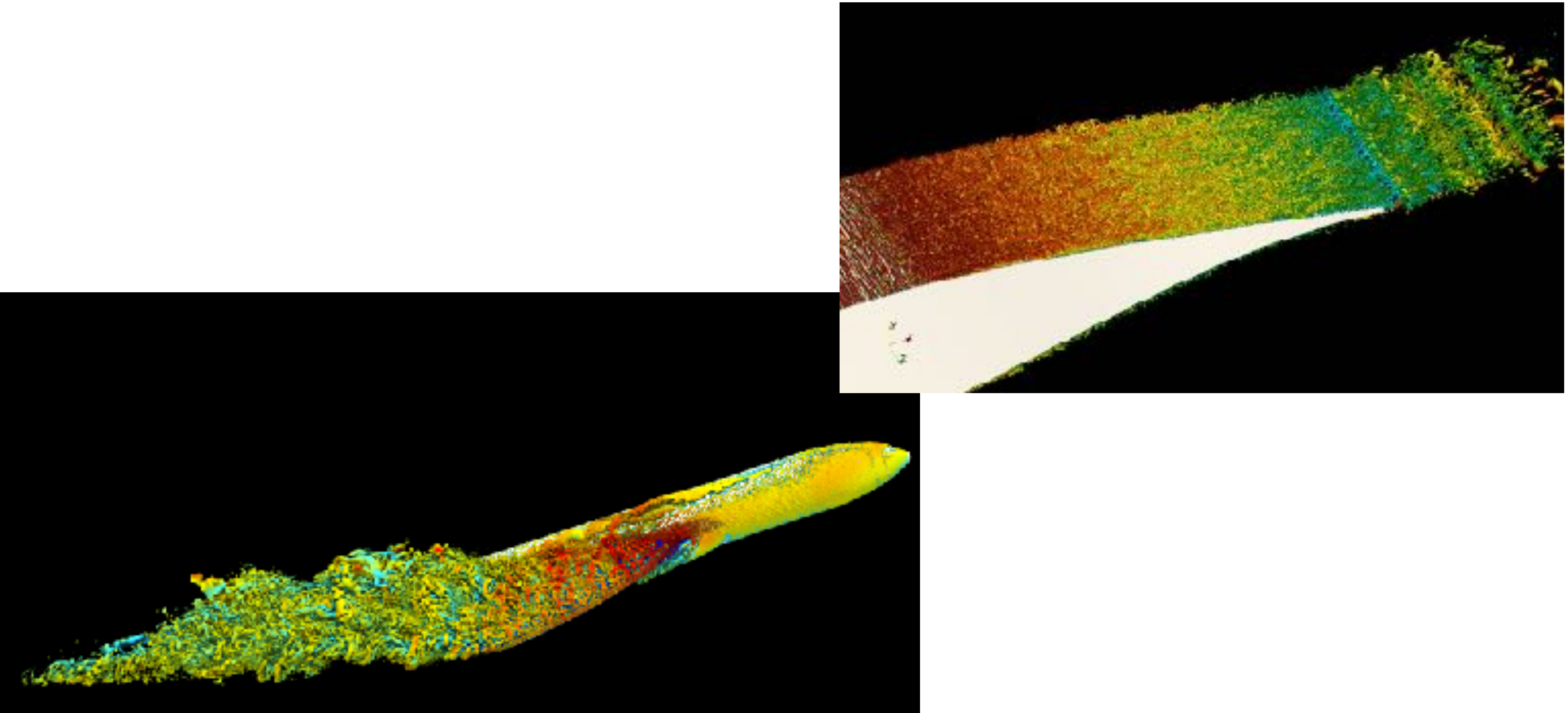
* Sanjeeb T Bose and George Ilhwan Park. Wall-modeled large-eddy simulation for complex turbulent flows. Annual Review of Fluid Mechanics , 50(1), 2018.

Alya: HPC finite element multiphysics code @BSC

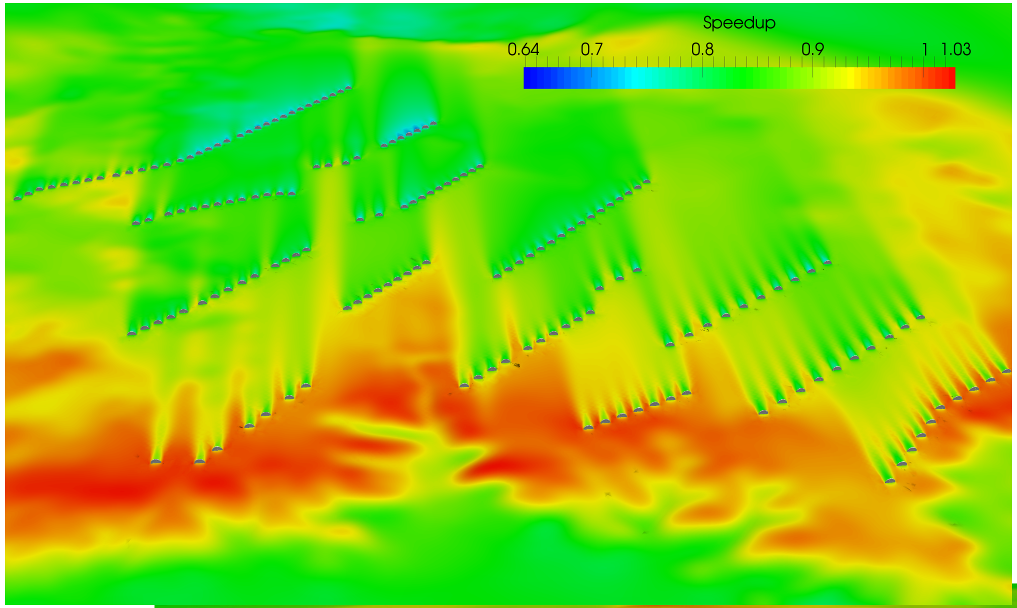
Exactly the same formulation for problems of different complexity

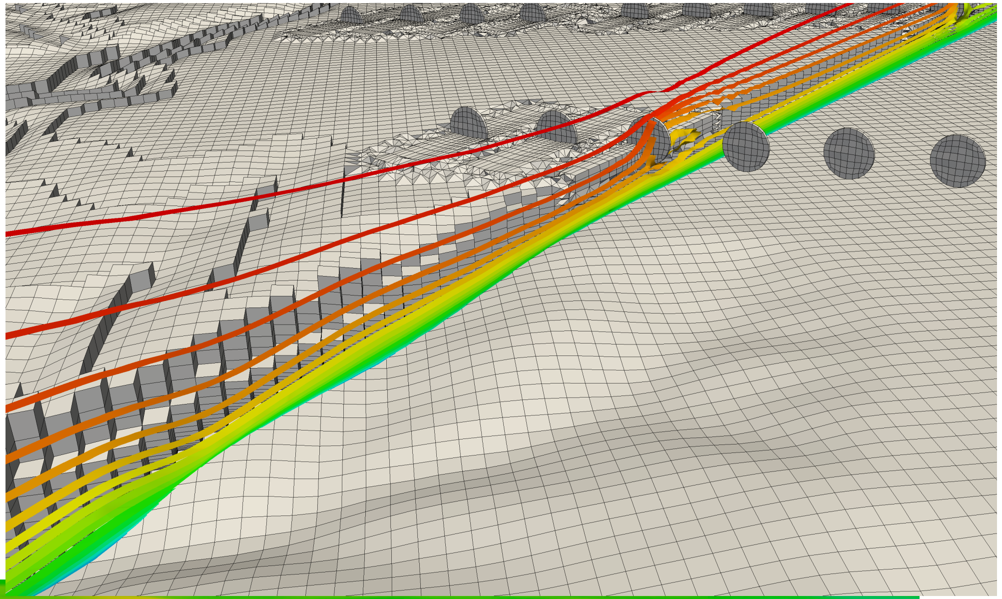
No playing with parameters

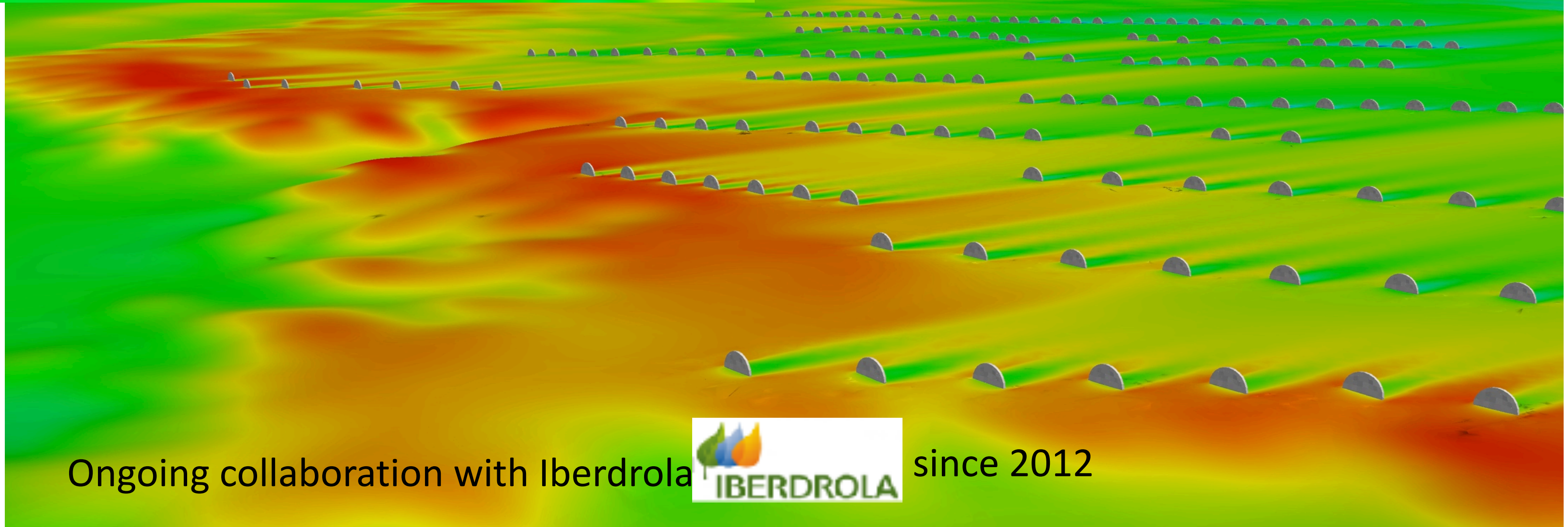




Wind Farm Modelling - Industrial applications



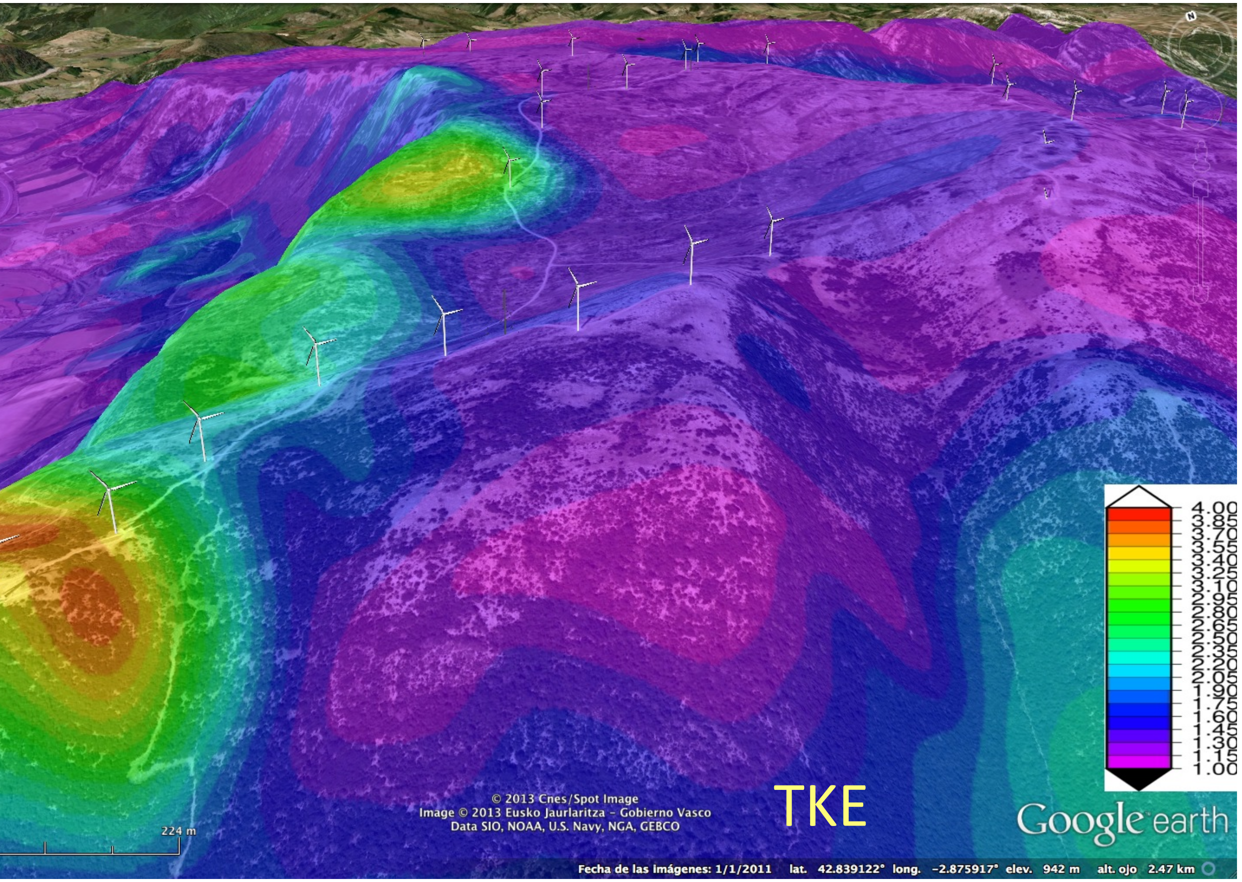


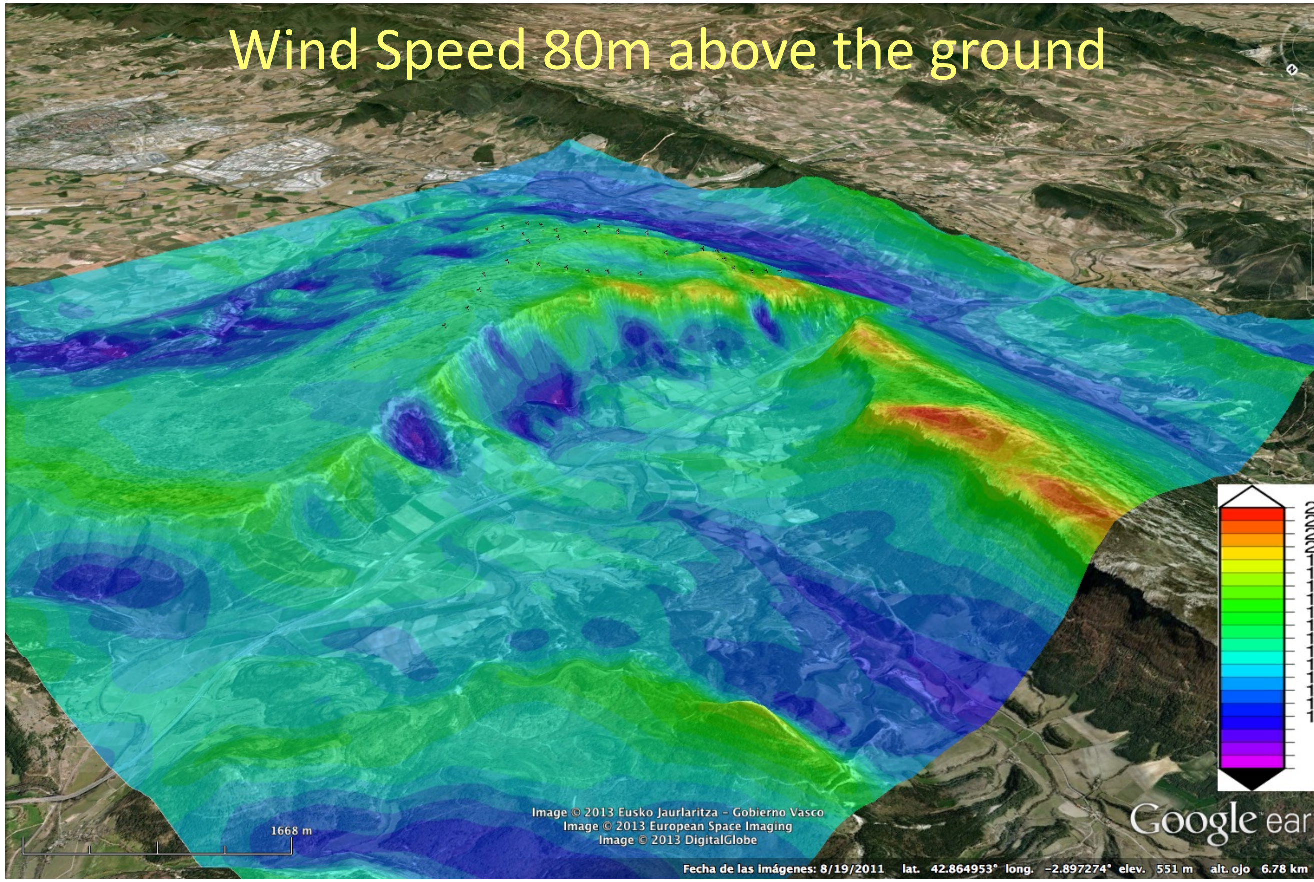


Ongoing collaboration with Iberdrola IBERDROLA since 2012

Wind Farm Modelling - Industrial applications

Currently RANS - LES in EoCoE II - target 10^{11} unknowns

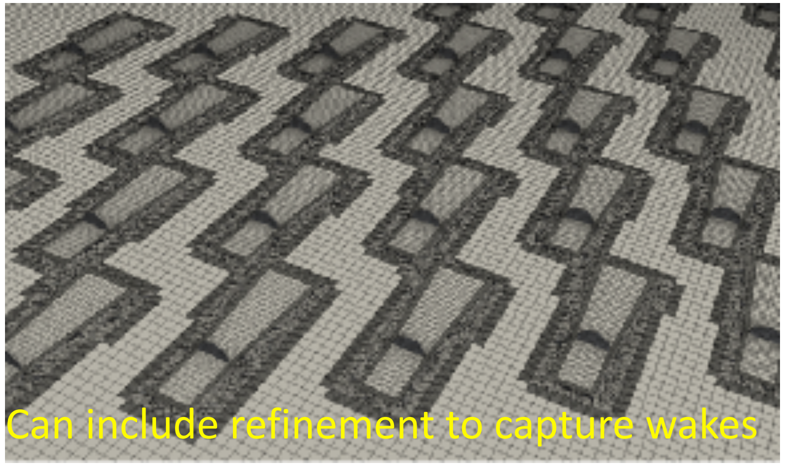




Ongoing collaboration with IBERDROLA since 2012

Wind Farm Modelling - Alya Workflow

WindMesh inputs:
Topography and roughness files (grd, map, etc) +
wind farm location + ..

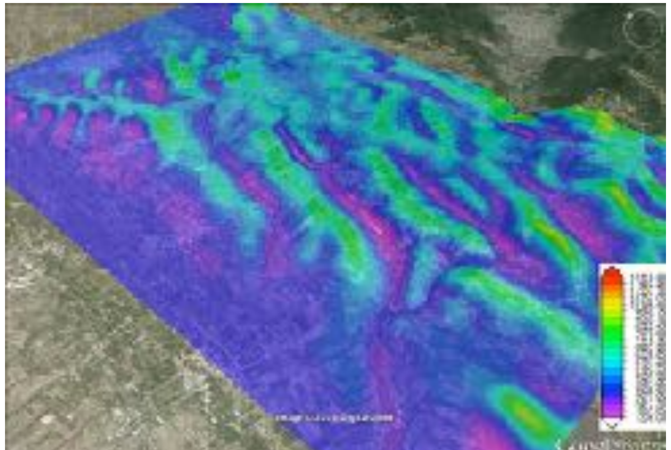


Can include refinement to capture wakes

AlyaFix. Boundary conditions with minimal user input:
Latitude + Geostrophic wind + ..

Run ALYA in supercomputer

PostFarm. Obtain WRG file with Weibull parameters A & k + Visualisation of results in Google Earth or Paraview



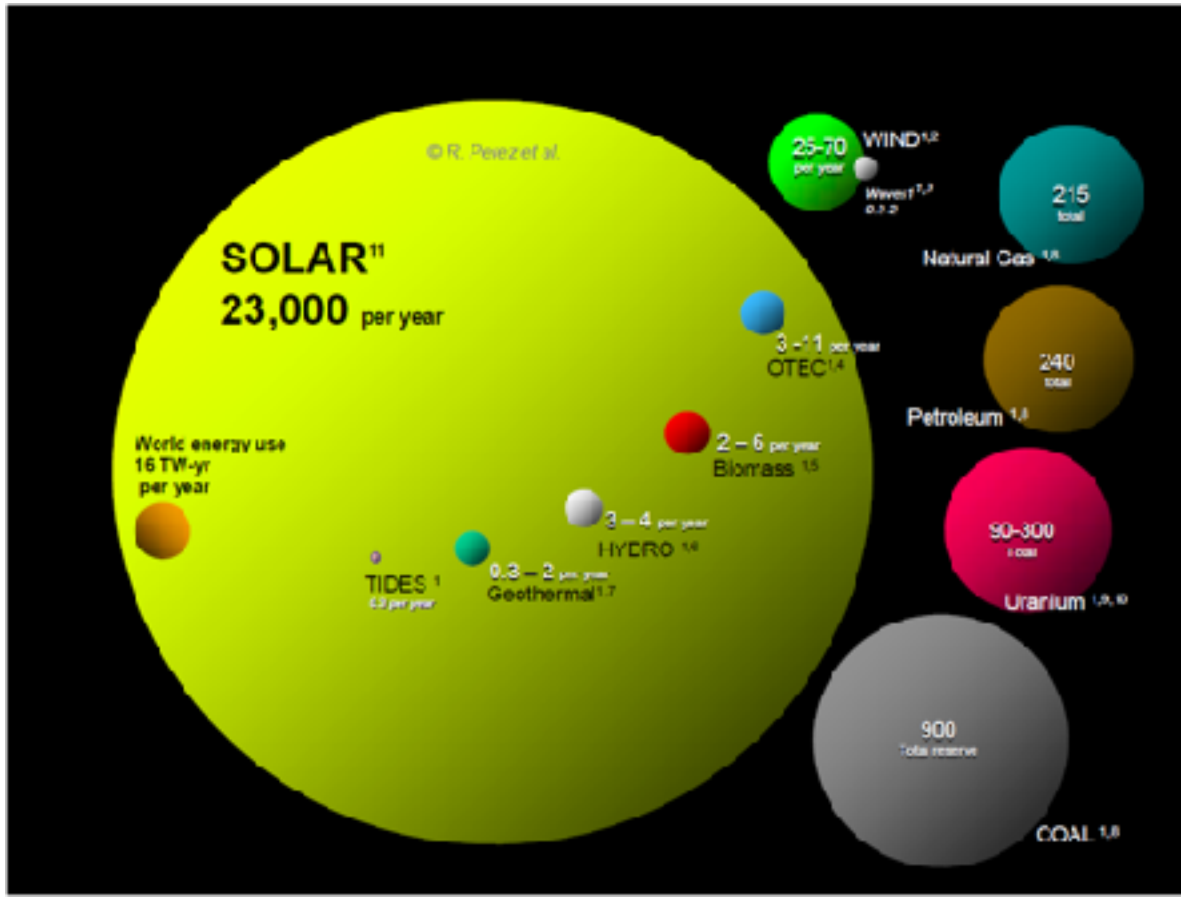
Developed for

IBERDROLA

Used by them as an alternative to comercial tools

EoCoE : Toward Exascale for Energy

Renewables can power the world in principle



EoCoE is at the crossroad of the numerical and energy revolution

Main objective : **Using the prodigious potential offered by the ever-growing computing infrastructure to foster and accelerate the European transition to a reliable and low carbon energy supply.**

Exascale — revolution in both hardware and software

- 4 key exascales technical challenges.
- 5 renewable energy scientific challenges.

EoCoE : Scientific Challenges

Objective 1 :

Enable transformational Energy Science breakthroughs in 5 key low-carbon sectors: Wind, Meteorology, Materials, Water and Fusion, by re-designing and promoting flagship exascale application codes from these user communities

EoCoE : Project consortium

7 countries, 18 partners
13 research institutes
4 universities
1 SME

www.eocoe.eu

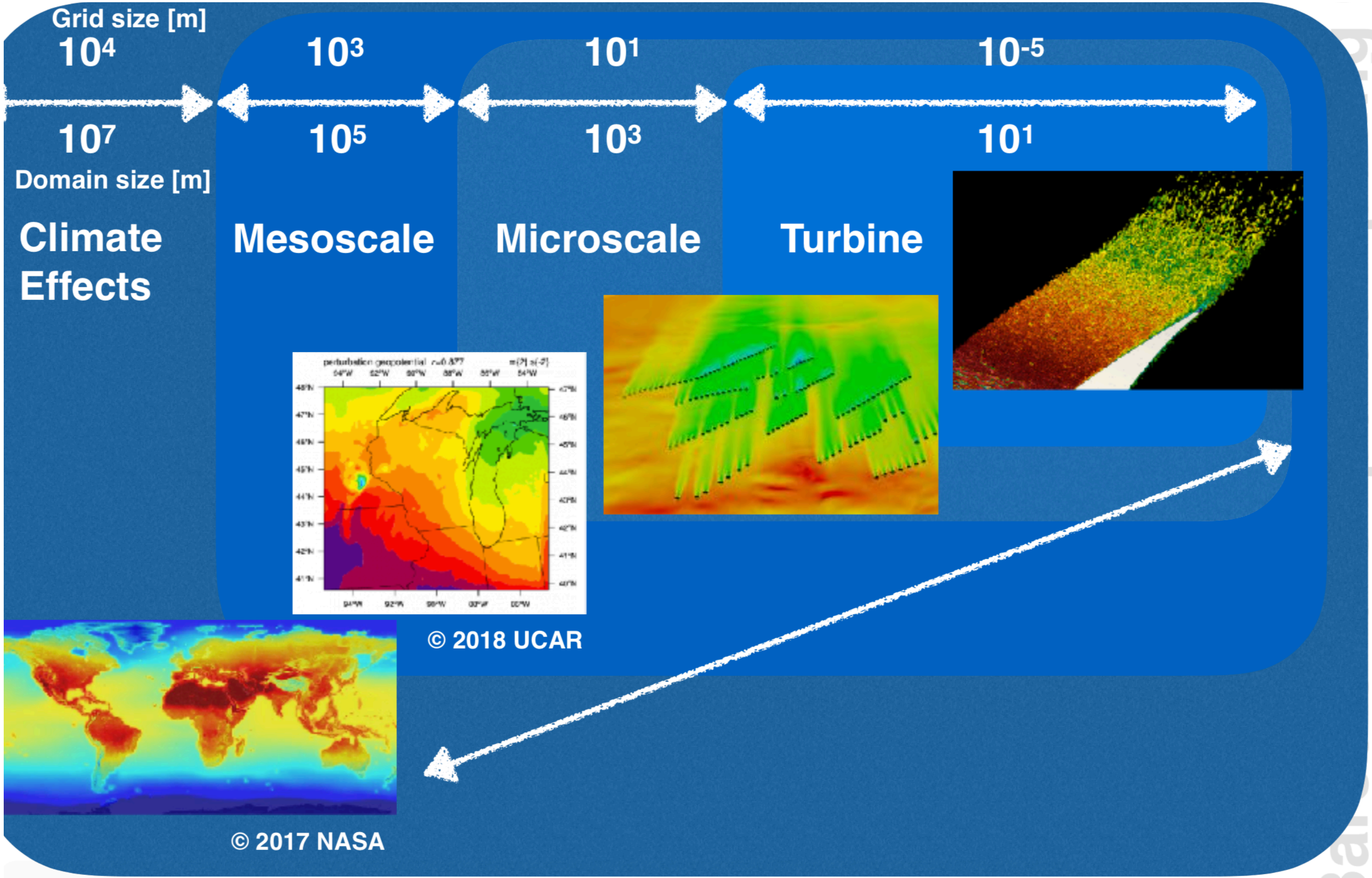
EoCoE : Wind for Energy - BSC-CASE

Wind for Energy

- Scientific Payload
  - Large eddy simulation of flow over complex terrain.
  - Realistic Large eddy simulation of Full Rotor cases.
  - Advance understanding of the flow physics governing whole wind plant.
- Exascale Ambition
  - Flagship code: **Alya** - Open for Wind community - Alternative to SOWFA & NALU
  - Permit simulations with $10^{10} – 10^{11}$ grid points on unstructured grids.
  - Alternative code: https://www.walberla.net Lattice Boltzmann. Ulrich Rude - FAU and CERFACS
- Impact
  - ➢ Optimisation of turbine placements to maximise power
  - ➢ increase power output and reduce wind turbine maintenance;
  - ➢ Increase European competitiveness by reducing the cost of wind energy.

EoCoE : Wind for Energy - BSC-CASE

Motivation



Grid size [m]

10^4 | 10^3 | 10^1 | 10^{-5}

10^7 | 10^5 | 10^3 | 10^1

Domain size [m]

Climate Effects

Mesoscale

Microscale

Turbine

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Wind Farm Large Eddy Simulation - Key ingredients

- Complex terrain — unstructured grids
- Coriolis Forces
- Temperature Coupling (gravity forces & Fractional Step)
- Canopy
- Actuator discs
- Wall modelled LES
- Turbulent inflow & coupling to the mesoscale

Large Eddy Simulation - The bolund Benchmark

http://www.bolund.vindenergi.dtu.dk

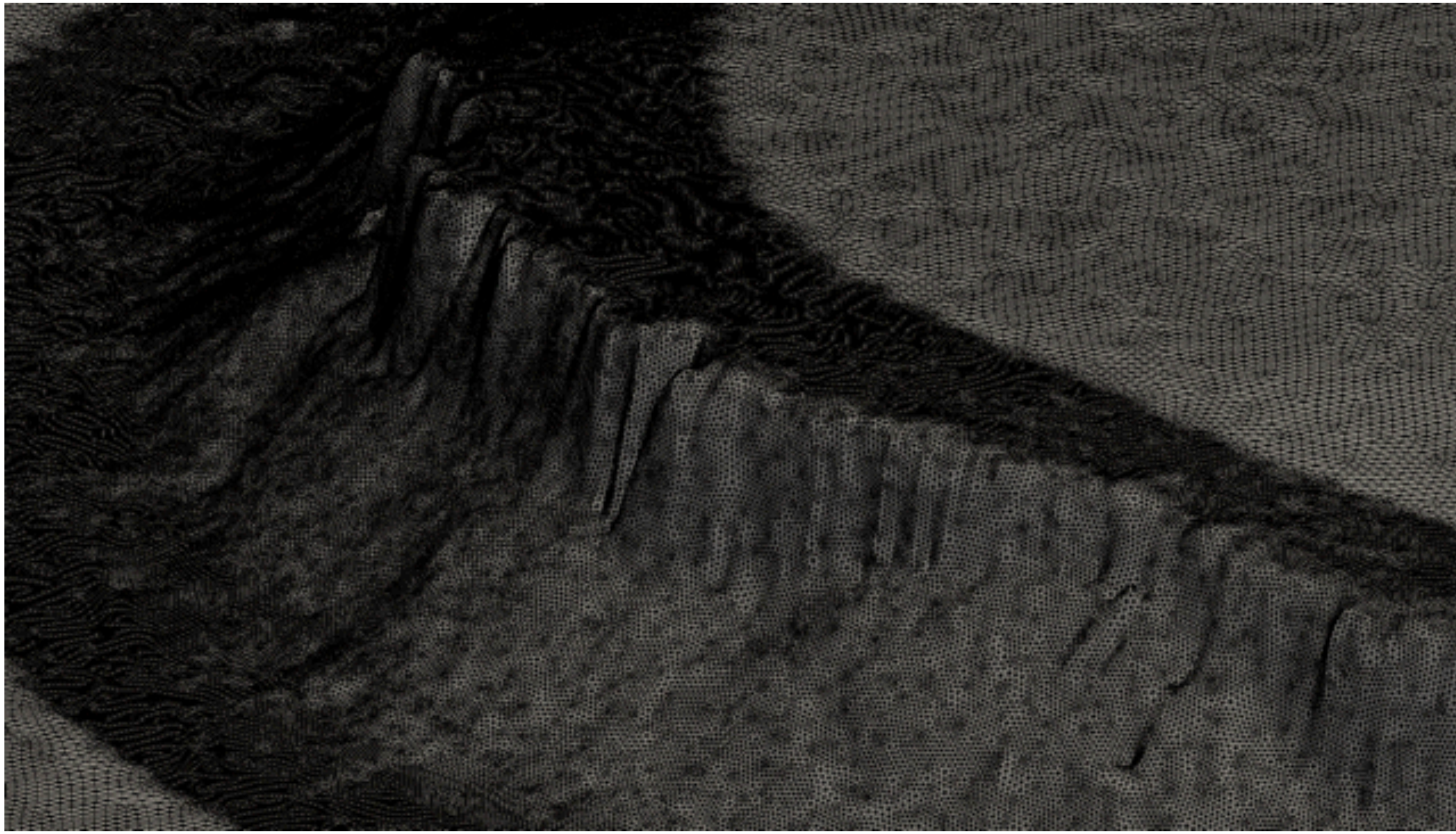
Experimental Campaign performed in 2007 and 2008.

It has been the basis for a unique blind comparison of flow models.

- Geometrical shape that induces complex 3D flow.
- Low height (h = 12m) ensures that measurements are performed in the surface layer and that the flow can be modelled to be neutrally stratified . No need to take into account Coriolis.
- ‘Free wind’ inflow for westerly winds . Coming from Sea.

Large Eddy Simulation - The bolund Benchmark

Wind direction from WEST (270º)



5.7 M nodes
26 M elements

CFL = 0.85

Typical run:
960 cores
48 h
312kstep
0.5 sec /time step

Large Eddy Simulation - The bolund Benchmark

Two options for inflow boundary conditions have been tested

1. Synthetic Inflow: A. Kempf et al.
2. Precursor run — Periodic flow over flat terrain.

No significant difference between both options.

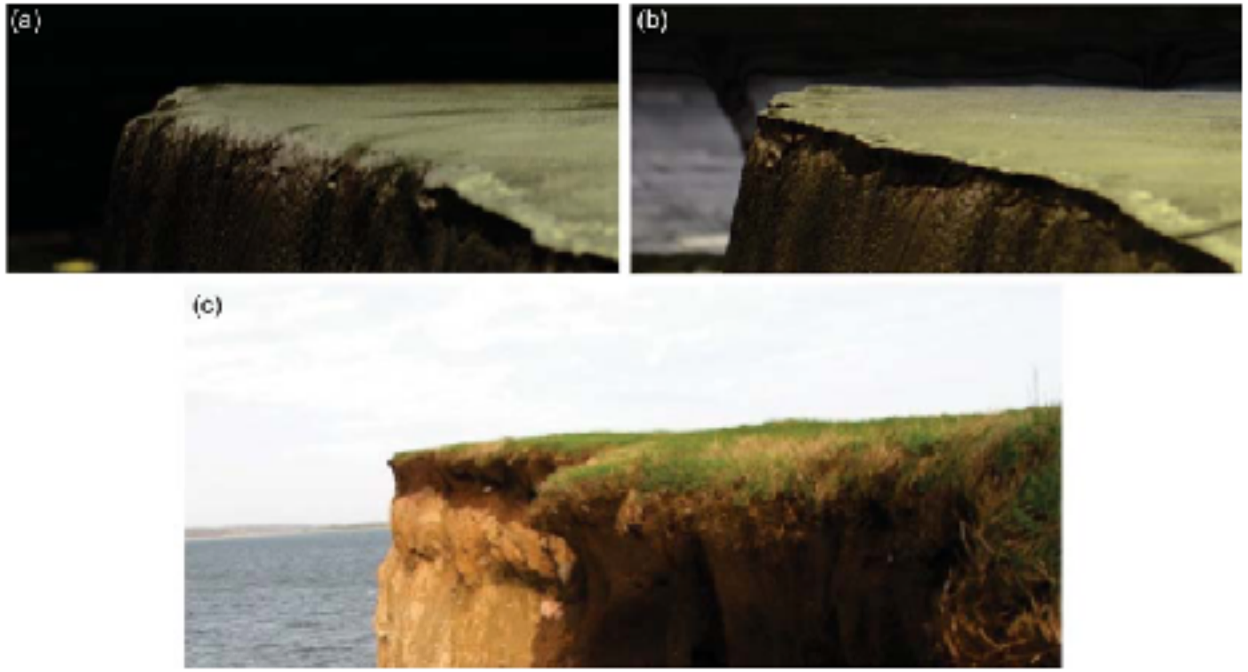
A. Kempf, M. Klein, and J. Janicka. Efficient generation of initial and inflow-conditions for transient turbulent flows in arbitrary geometries. Flow Turbul. Combust., 74:67–84, 2005

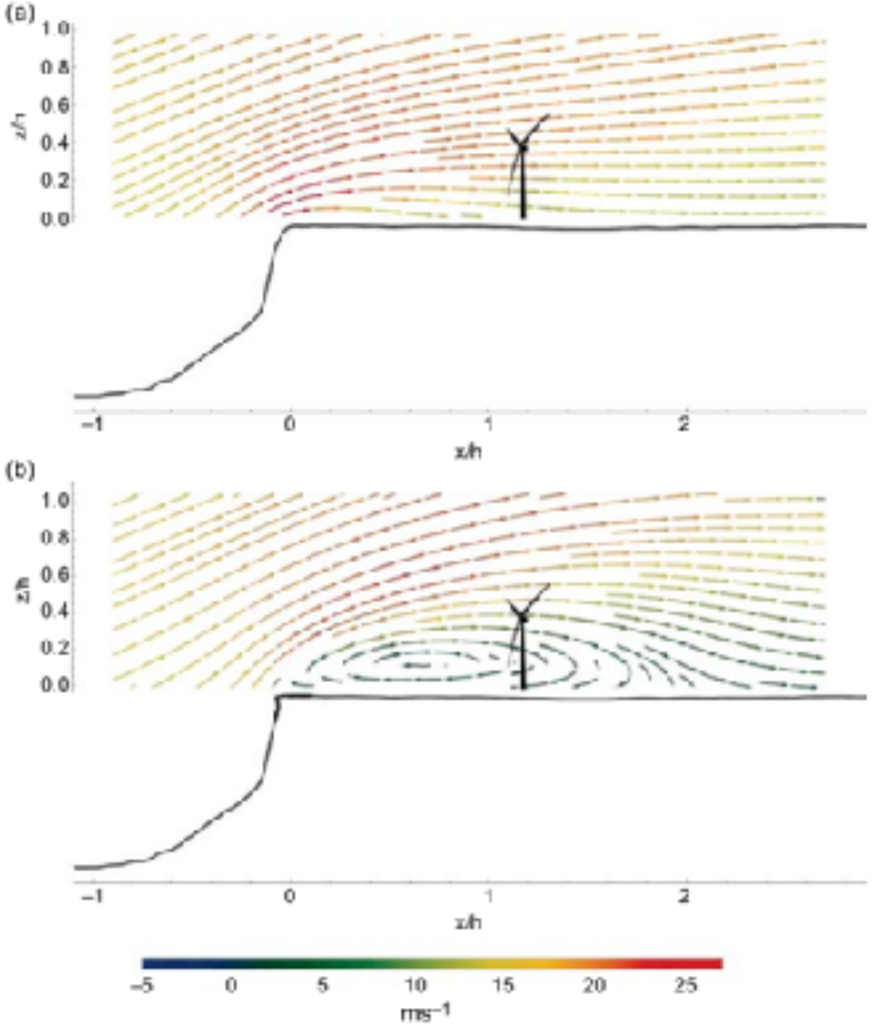
Large Eddy Simulation - The bolund Benchmark

Comparison with results available in the literature

Model Type	mean error	References
RANS - 2eq	11.4	Bechmann et al. 2011 (best RANS)
RANS - 2eq	15.1	Bechmann et al. 2011 (mean RANS)
LES	14.1	Bechmann et al. 2011 (best LES)
LES	17.3	Bechmann et al. 2011 (mean LES)
RANS - 2eq	10.3	Prospathopoulos et al. (2012)
LES	10.9	Vuorinen et al. (2015)
LES	8.8	Chaudhari et al. (2017)
LES	11	Conan, Chaudhari et al. (2016)
LES	12.4	Alya

Large Eddy Simulation - The bolund Benchmark





The triangulation of the laser-scan data and the subsequent interpolation to the grid were estimated to remove 0.25 to 0.35 m of the edge, roughly corresponding to the added clay in the experiment.

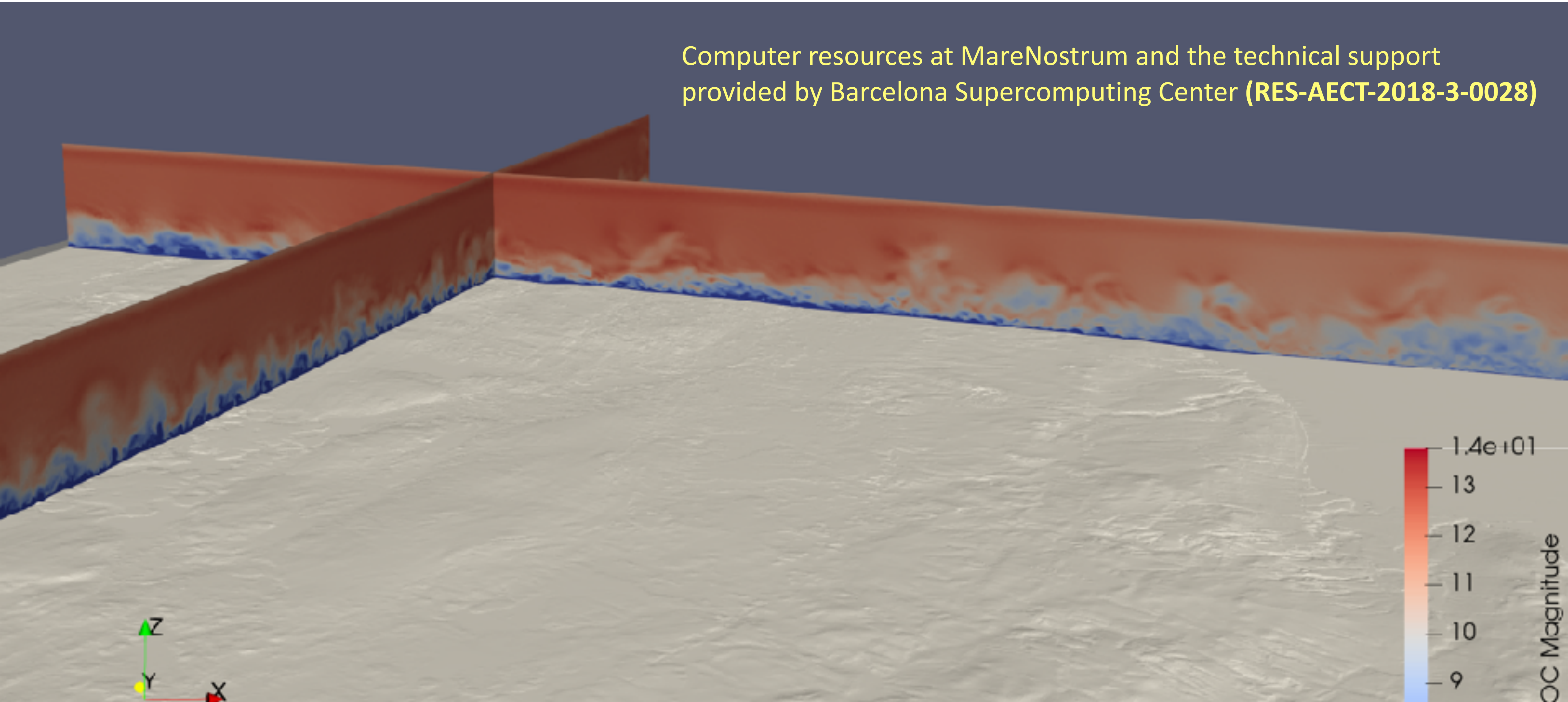
For wind turbines in complex terrain, the devil is in the detail,
Julia Lange et al. 2017 Environ. Res. Lett. 12 094020

Large Eddy Simulation - The bolund Benchmark

Observations:

- The wind community is stepping to more realistic/ complex examples.
- Hornamossen, Alaiz, Perdigao.
- Canopy
- Coriolis
- Thermal coupling
- Need coupling to mesoscale.
- Validation/Conclusions in more simple cases such a Bolund are debatable.

Wind Farm Modelling - Large Eddy Simulation



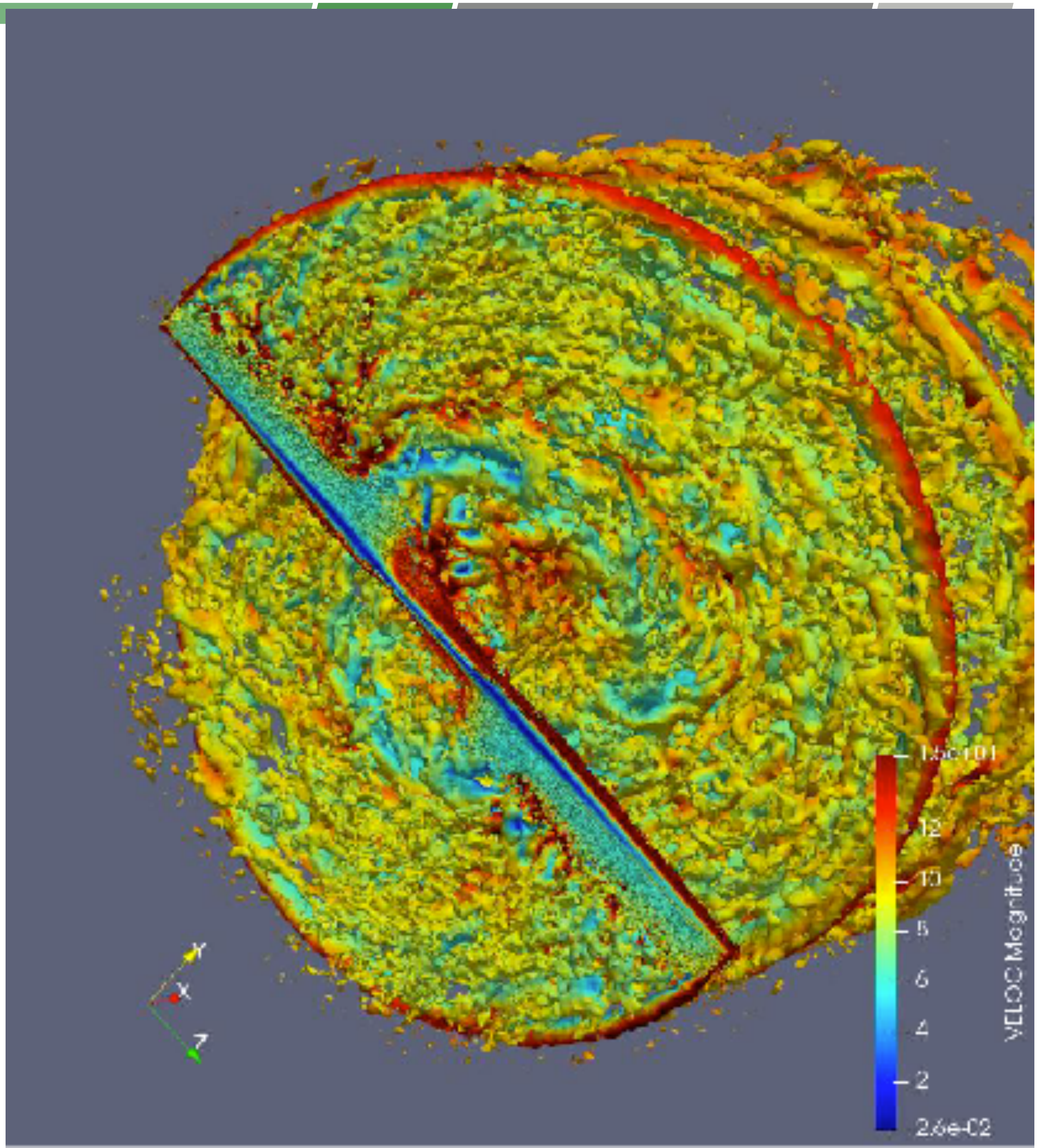
Computer resources at MareNostrum and the technical support provided by Barcelona Supercomputing Center **(RES-AECT-2018-3-0028)**

Full Rotor Model

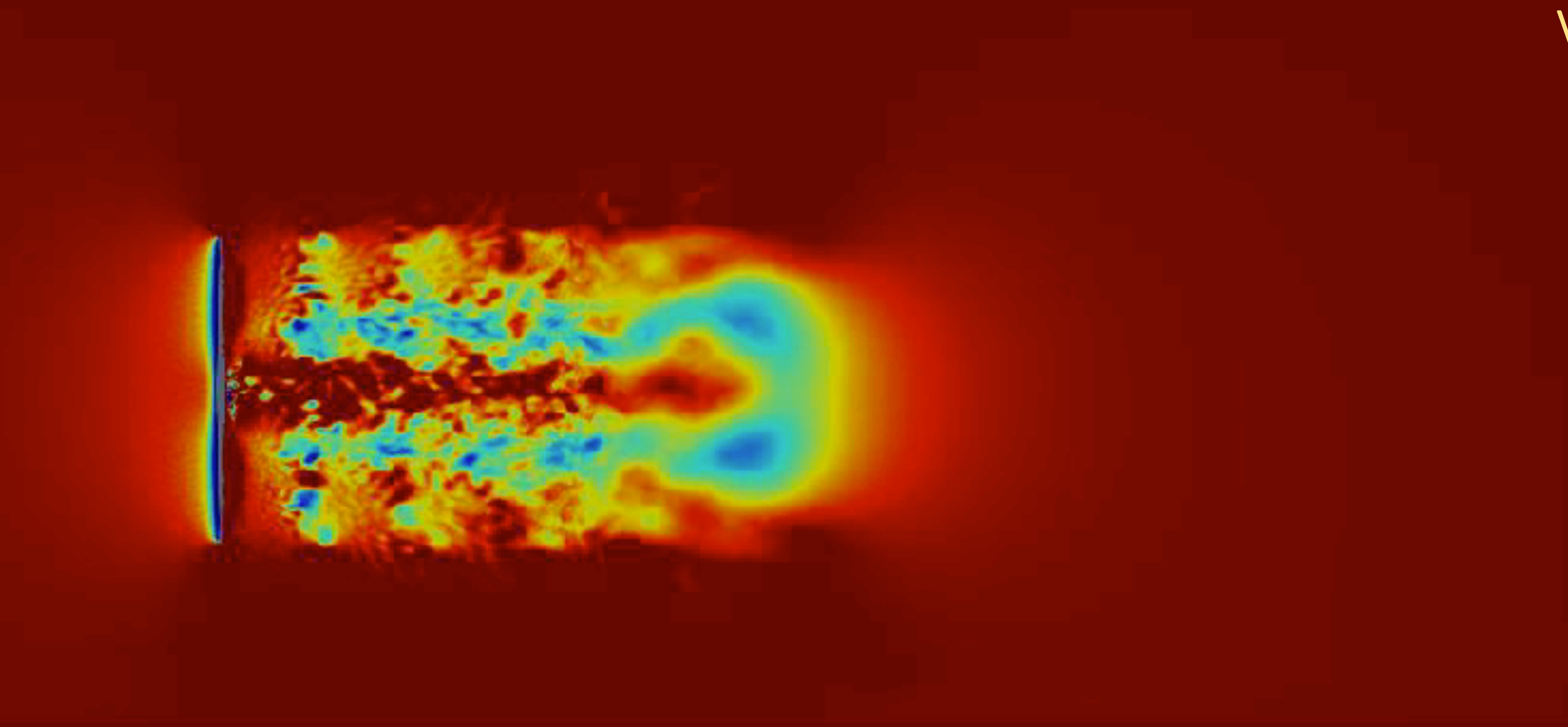
Geometry-resolved large-eddy simulation of the NREL VI wind turbine

- Full rotor model where the actual geometry of the wind turbine blades and tower is modelled exactly
- A sliding mesh approach to incorporate the rotation of the blades.
- The model will be compared against the full rotor model available in the code FLOWer. (U Stuttgart)

support letter from Vestas®



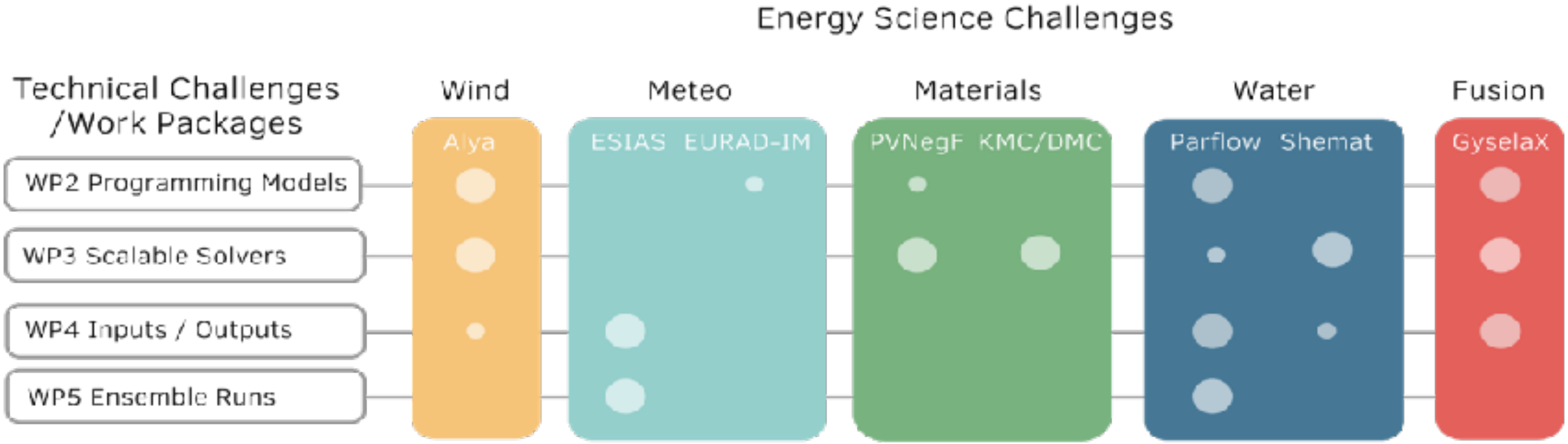
Full Rotor Model



49Melem
10Mnodes
Vreman model

Exascale approach

The project structure is adapted and specifically designed to address the exascale challenge



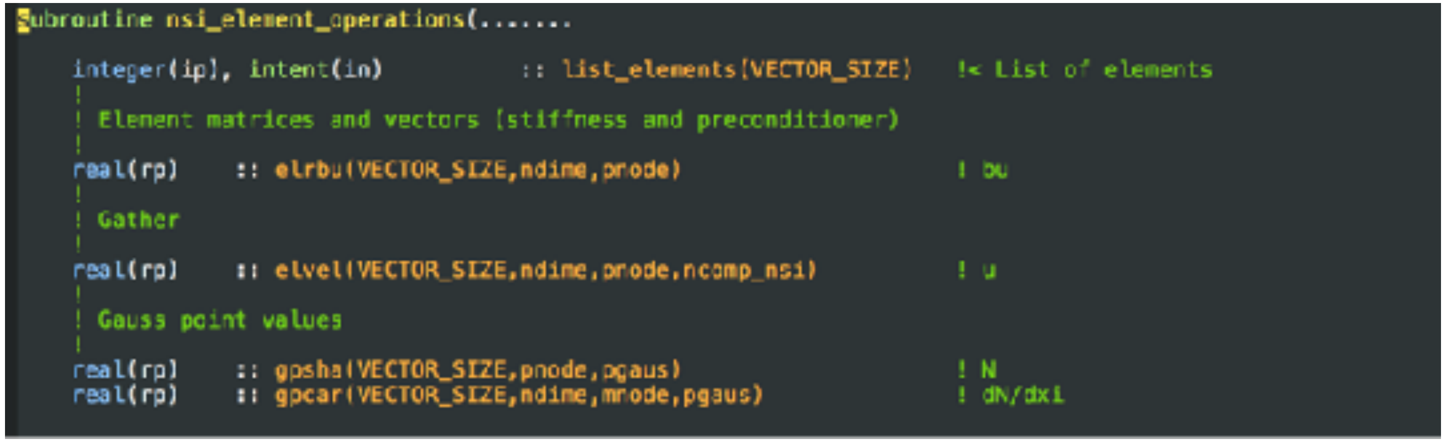
EU requirements: 20 % Scientific Challenge - 80% HPC Challenge

Programming Models

- Porting to GPUs
- Co-execution on heterogeneous clusters (CPU + accelerators)
- Fast and scalable mesh partitioning based on Space Filling Curve
- Dynamic load Balancing.
- Dynamic coupling between rotating meshes and a fixed mesh.
- Node level optimisation in collaboration with George Hager and PoP.
- Scaling up to $10^{10} – 10^{11}$ grid points on unstructured grids.

Programming Models - Porting to GPUs

Started at EuroHack17 @CSCS - 4-8 september 2017 - Lugano

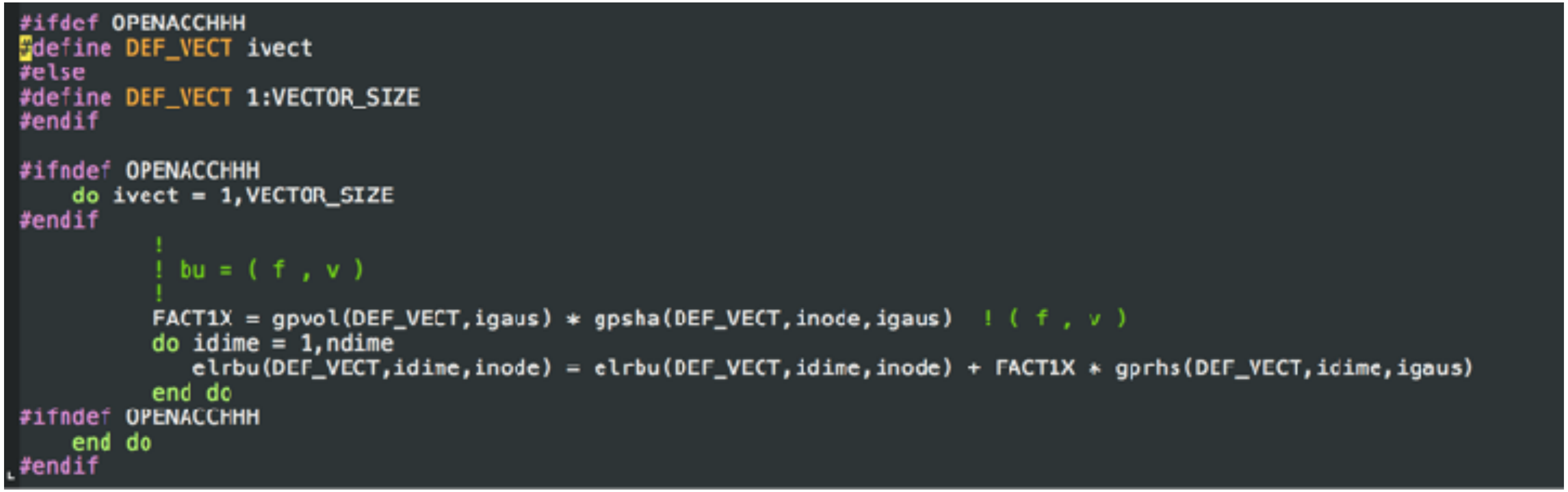


```
subroutine nsi_element_operations(.......

   integer(ip), intent(in)          :: list_elements(VECTOR_SIZE)   !< List of elements
   !
   ! Element matrices and vectors (stiffness and preconditioner)
   !
   real(rp)    :: elrbu(VECTOR_SIZE,ndime,pnode)                   ! bu
   !
   ! Gather
   !
   real(rp)    :: elvel(VECTOR_SIZE,ndime,pnode,ncomp_nsi)         ! u
   !
   ! Gauss point values
   !
   real(rp)    :: gpsha(VECTOR_SIZE,pnode,pgaus)                   ! N
   real(rp)    :: gpcar(VECTOR_SIZE,ndime,mnode,pgaus)             ! dN/dxi
```

Group of elements at a time VECTOR_SIZE

Same code CPU/GPU



```
#ifdef OPENACCHHH
#define DEF_VECT ivect
#else
#define DEF_VECT 1:VECTOR_SIZE
#endif

#ifndef OPENACCHHH
    do ivect = 1,VECTOR_SIZE
#endif
          !
          ! bu = ( f , v )
          !
          FACT1X = gpvol(DEF_VECT,igaus) * gpsha(DEF_VECT,inode,igaus)  ! ( f , v )
          do idime = 1,ndime
             elrbu(DEF_VECT,idime,inode) = elrbu(DEF_VECT,idime,inode) + FACT1X * gprhs(DEF_VECT,idime,igaus)
          end do
#ifndef OPENACCHHH
    end do
#endif
```

Programming Models - Porting to GPUs

Performance baseline

#CPU cores	VECTOR SIZE 8
12	6.21
24	2.99

- Workloads: **SMALL (2M elements)**
- Systems: **CSCS**(Piz Daint)
- Compilers: **INTEL**
- Paradigms: **MPI**
- svn version: **7331**

2GPU compared to 24cpu CORES

VECTOR_SIZE	EXECUTION TIME ON 2 GPUs
16k	2.6
32K	2.01
64K	1.88
128K	1.64(2x to pizdaint cpu)
256K	1.65

Currently working on porting to CUDA

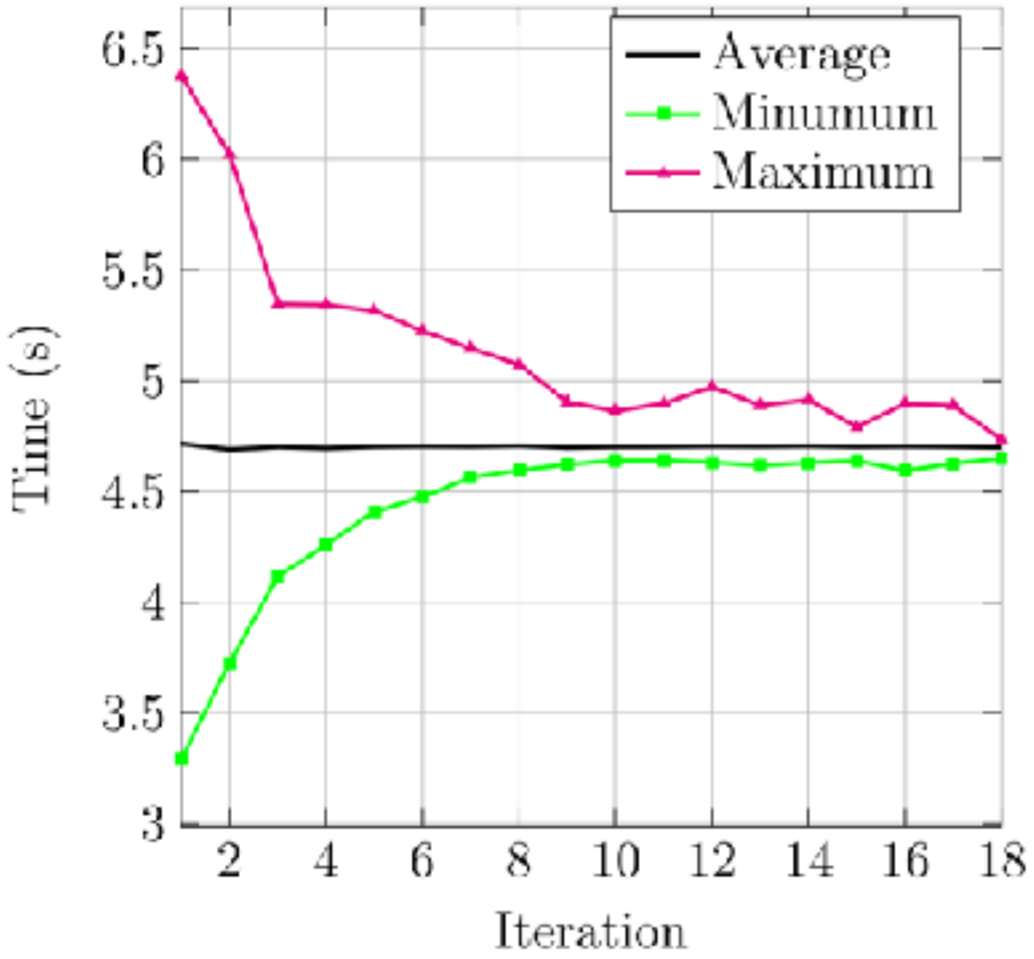
Faster, but:

- More difficult to code
- Implies two different codes CPU & GPU

Co-execution on heterogeneous clusters (CPU + GPU)

- GPUs can not work alone.
- Typically CPU has little or no work.
- Co-execution makes full use of the machine.
- GPU Alya and CPU Alya working at the same time.
- GPU receives more load.
- Key: Dynamic load balancing to give each hardware a load according to its capabilities.

Dynamic Load Balancing



Convergence of the balancing process on a 176M element mesh.

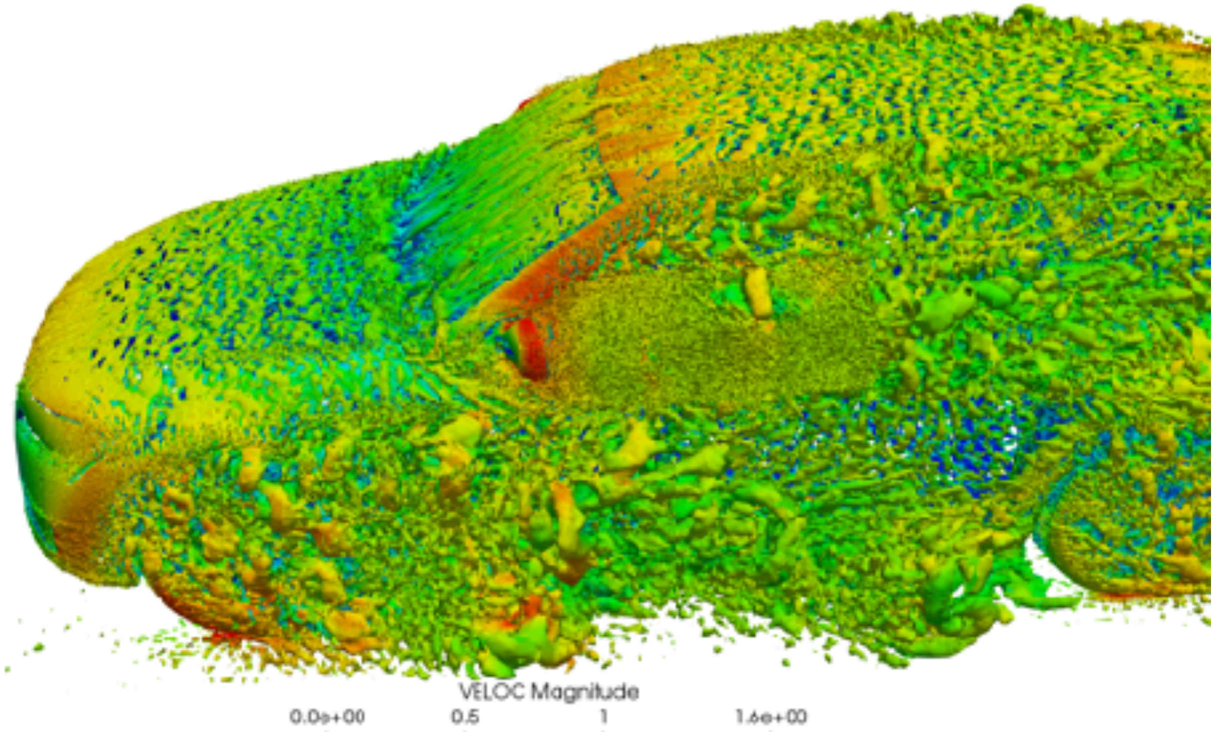
Parallel Partitioning based on Space Filling Curves (SFC) is used.

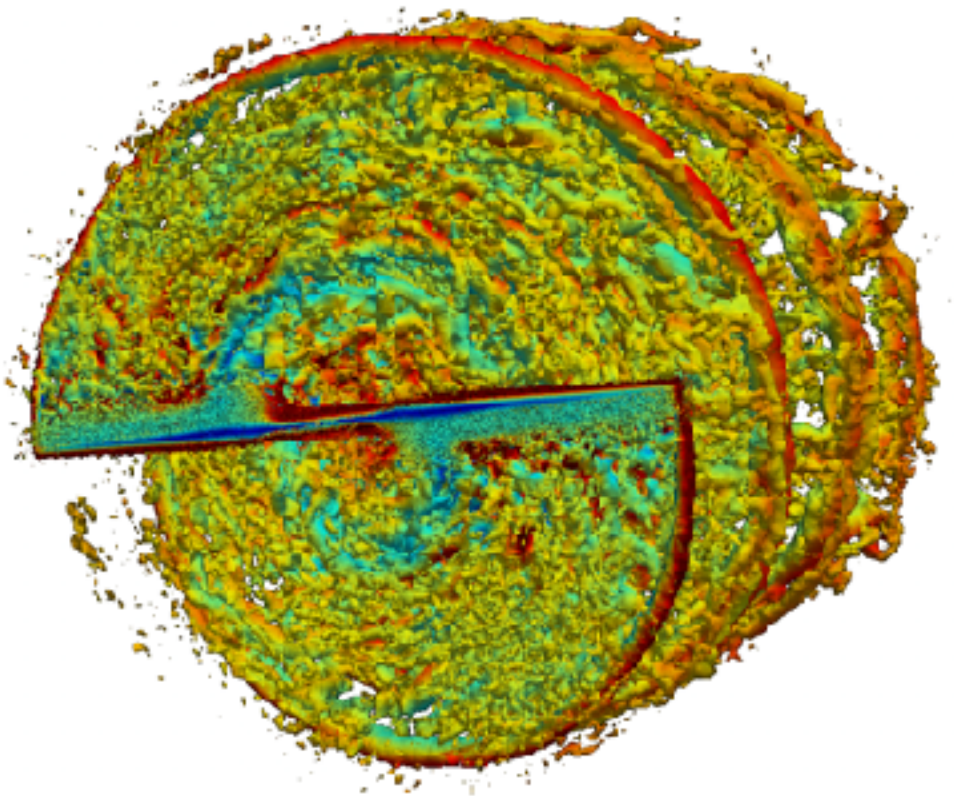
Heterogeneous CPU/GPU co-execution of CFD simulations on the POWER9 architecture, R. Borrell et al., Future Generation Computer Systems, 2020

Dynamic coupling between rotating and fixed mesh.

Mathematical and Parallel implementation challenges

$$\begin{pmatrix} \mathbf{A}_{11} & \mathbf{A}_{1\Gamma_1} & 0 & 0 \\ 0 & \mathbf{I} & 0 & -\mathbf{T}^D \\ 0 & 0 & \mathbf{A}_{22} & \mathbf{A}_{2\Gamma_2} \\ \mathbf{T}^N\mathbf{A}_{\Gamma_2 1} & \mathbf{T}^N\mathbf{A}_{\Gamma_1\Gamma_1} & \mathbf{A}_{\Gamma_2 2} & \mathbf{A}_{\Gamma_2\Gamma_2} \end{pmatrix} \begin{pmatrix} \mathbf{u}_1 \\ \mathbf{u}_{\Gamma_1} \\ \mathbf{u}_2 \\ \mathbf{u}_{\Gamma_2} \end{pmatrix} = \begin{pmatrix} \mathrm{b}_1 \\ \mathbf{0} \\ \mathrm{b}_2 \\ \mathrm{b}_{\Gamma_2} + \mathbf{T}^N \mathrm{b}_{\Gamma_1} \end{pmatrix}$$





G. Houzeaux et al. Domain decomposition methods for domain composition pur- pose: Chimera, overset, gluing and sliding mesh methods. Arch. Comp. Meth. Eng., 2017

Node level optimisation

Collaboration with:

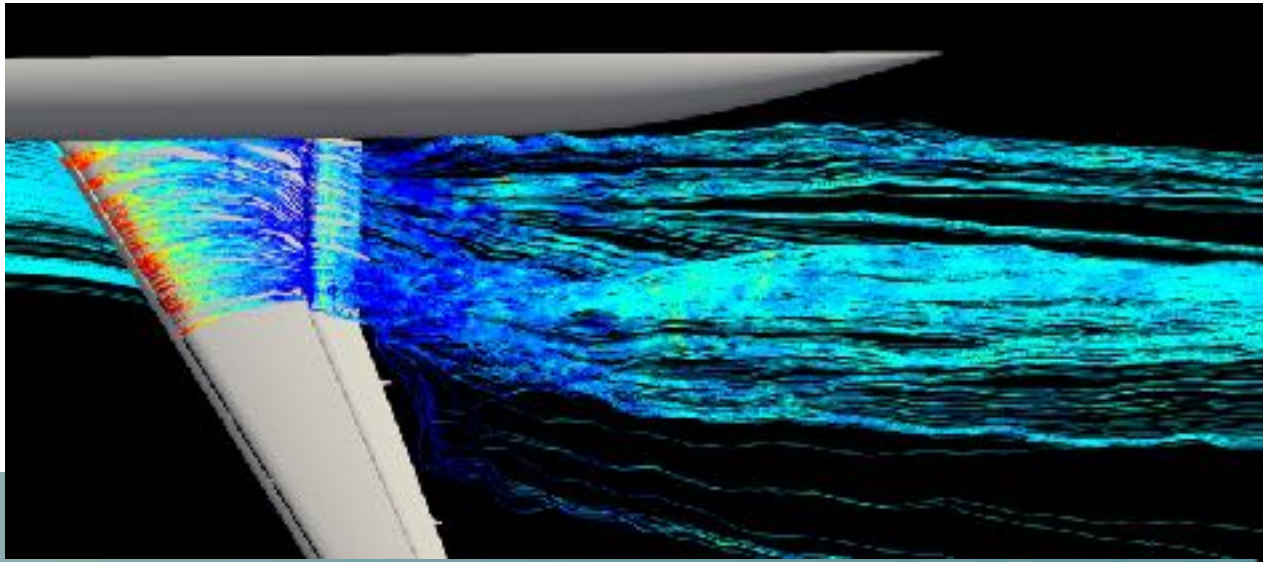
- George Hager et al. from FAU — LIKWID
- PoP COE — Paraver

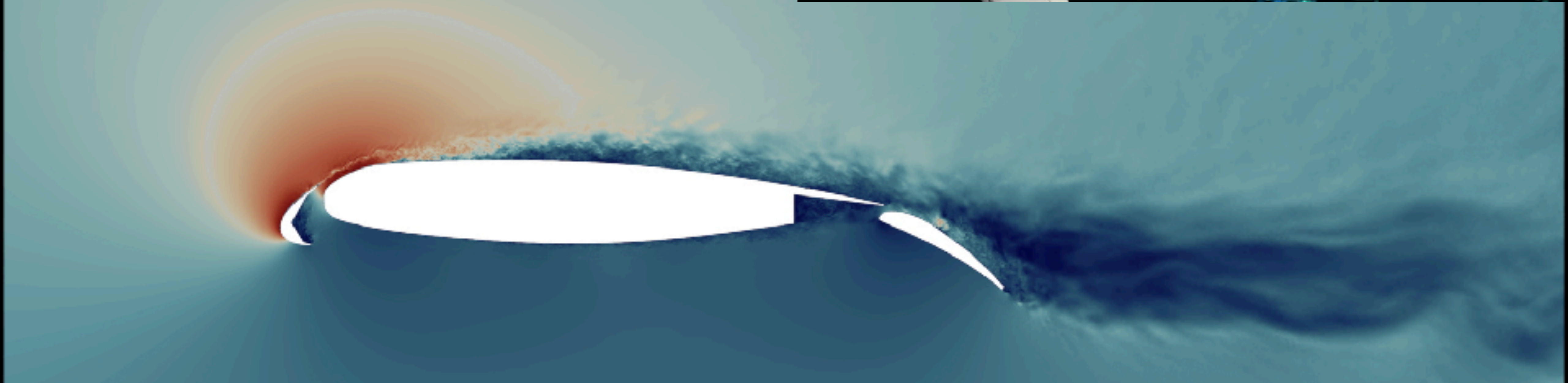
Alya has 2 main tasks matrix creation and linear solver.

- For the solver we have decided to explore external solvers instead of improving Alya' solver.
- For the calculation of the matrix, in EoCoE I, using mainly Intel Inspector, we reduced the time by 30%.

Scaling up to 10^{10} – 10^{11} grid points on unstructured grids

- NASA Common Research Model
- $2x10^9$ elements Large Eddy Simulation.
- Taking advantage of the annual maintenance of Marenostrum IV.
- Run for 24 hours on 2000 nodes (96k cores - 96k mpi processes).





Solvers

Iterative Solvers:

- AGMG 5-10 times than Alya’s solver for some problems.
- PsBlas/MLD2P4 - Advantage CPU/GPU version - Better Scalability
- Maphys: Preliminary testing

Direct Solvers:

- Pastix: Interfaced with Alya
- Mumps: Started tests and optimisation for Solids problems (WT blades)

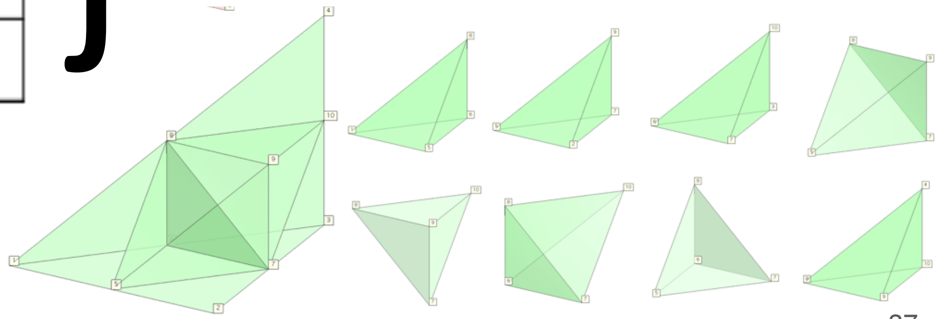
Solvers - Weak Scalability - Bolund Case

Cores	Total Million Unknowns	AGMG	PSBLAS
48	5.6	8	3
96	5.6	8	3
192	5.6	8	3
384	44.8	14	5
768	44.8	14	5
1536	44.8	13	5
3072	358.4	6	4
6144	358.4	6	4
12288	358.4	6	4

No mesh multiplication

1 mesh multiplication

2 mesh multiplication



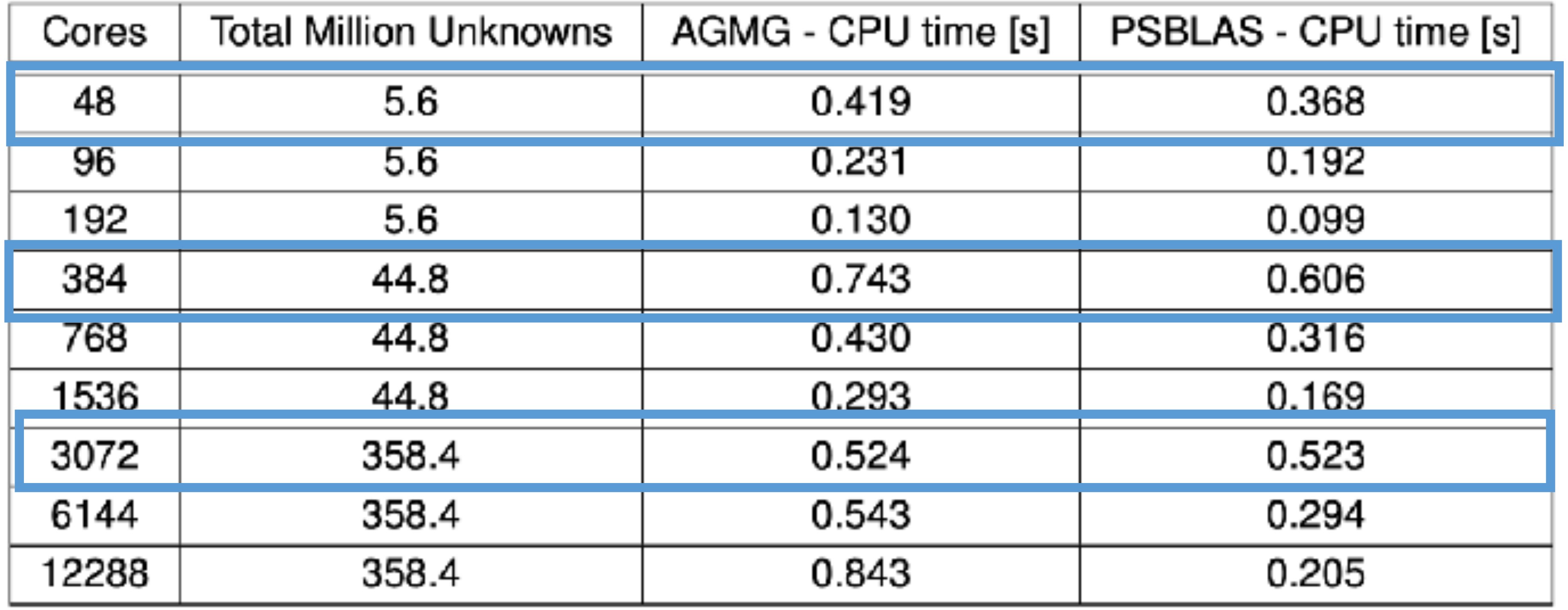
Number of iterations per time step

Fair case? — Strange behaviour 1 MM

Solvers - Weak Scalability - Bolund Case

- Algorithmic scalability (number of iterations) is very good for both solvers.
- With AGMG the number of iterations falls between no Mesh Multiplication and 2 levels of Mesh Multiplication.
- With 1 divisor both solvers show poorer results. Fairness of usage of MM on complex geometry.
- Note that a fixed CFL is used - thus time step is not the same when the mesh is refined.
- One could think of other ways to do weak scalability on complex geometry. But they would be less useful for real cases. Example periodic.

Solvers - Weak Scalability - Bolund Case



Cores	Total Million Unknowns	AGMG - CPU time [s]	PSBLAS - CPU time [s]
48	5.6	0.419	0.368
96	5.6	0.231	0.192
192	5.6	0.130	0.099
384	44.8	0.743	0.606
768	44.8	0.430	0.316
1536	44.8	0.293	0.169
3072	358.4	0.524	0.523
6144	358.4	0.543	0.294
12288	358.4	0.843	0.205

No mesh multiplication

1 mesh multiplication

2 mesh multiplication

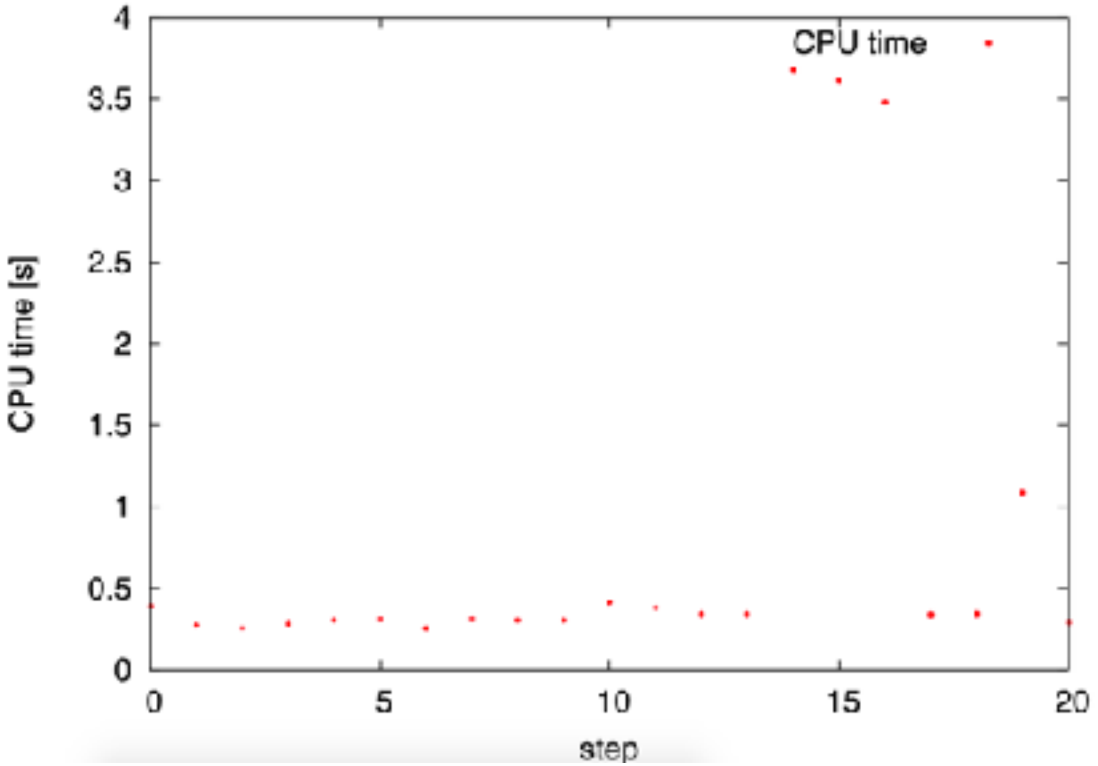
Cpu time per time step

Solvers - Weak Scalability - Bolund Case

- Both AGMG & PSBlas show good acceptable weak scaling for 100k unknowns/core (48-384-3072)
- Computational scaling degrades significantly for AGMG with 50k and 25k unknowns per core.
- PSBlas, much better for low number of unknowns per core.

Solvers - Weak Scalability - Bolund Case

- Runs in Marenostrum IV
- We have used minimum CPU times from 20 time steps. Marenostrum exhibits significant ‘noise’ as the number of cores increases.



Benefits

Simulating the entire wind plant including Full rotor on an exascale platform will:

- drive innovation and improvements in the wind turbine, and wind plant design
- provide new knowledge at fidelity that is unattainable in field measurement campaigns.
- complement and bridge the fidelity gaps in field experiments.

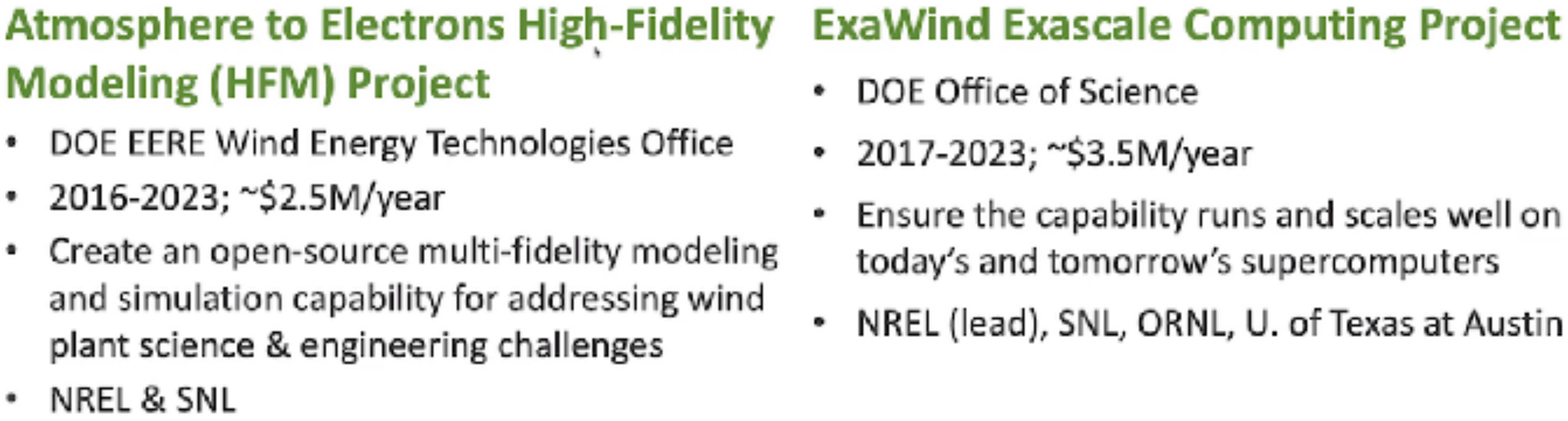
Benefits

Increase efficiency of wind farms by:

- making wind energy cheaper and thus more competitive, (Wind energy is 5cts/ kWh, which is cheaper than fossil sources which cost an average of 5.4 cts/ kWh and could be lowered to 2 cts/kWh);
- understand noise production and help decrease it (3dB reduction without loss of energy production)

Challenges

- Validation - Cases are getting too complex. Simple cases must be recovered
- Alya - Open for Wind community - Alternative to NALU (SOWFA replacement)
- US - Michael Sprague - NALU code - much higher resources



Atmosphere to Electrons High-Fidelity Modeling (HFM) Project

- DOE EERE Wind Energy Technologies Office
- 2016-2023; ~$2.5M/year
- Create an open-source multi-fidelity modeling and simulation capability for addressing wind plant science & engineering challenges
- NREL & SNL

ExaWind Exascale Computing Project

- DOE Office of Science
- 2017-2023; ~$3.5M/year
- Ensure the capability runs and scales well on today's and tomorrow's supercomputers
- NREL (lead), SNL, ORNL, U. of Texas at Austin

Wind Energy

LES Modelling of wind flow at Bolund hill

Large Eddy Simulation of wind flow over Bolund hill, one of the benchmark cases for complex terrain. [illegible] shows the [illegible] of the overall computational domain, where we visualise the turbulent flow structures through [illegible] (Q [illegible]).

Horizon 2020
European Union funding
for Research & Innovation

Grant Agreement Number: 824158

Thanks!!!

European Commission

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