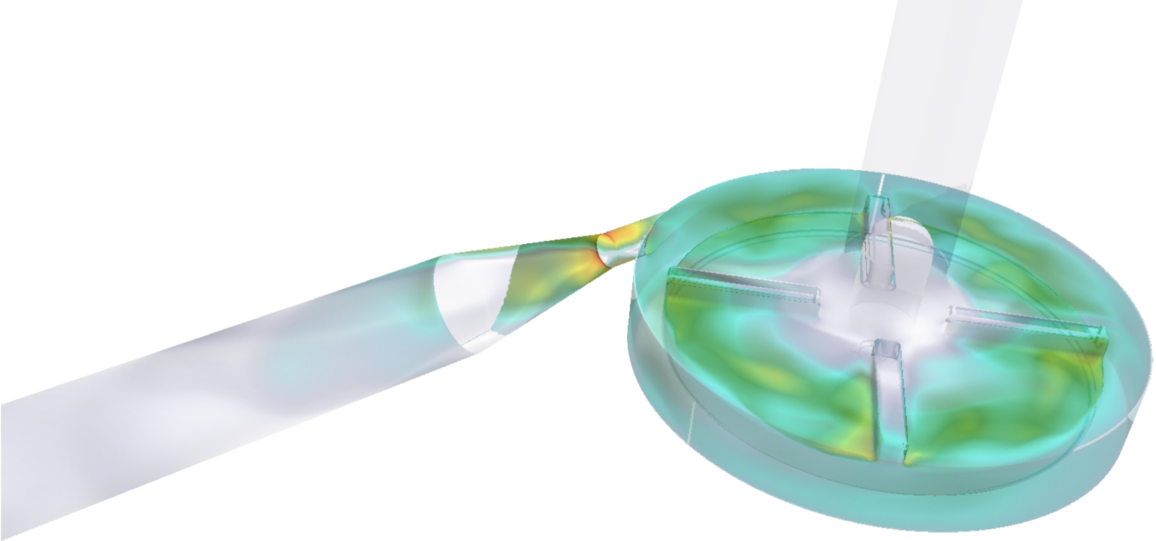

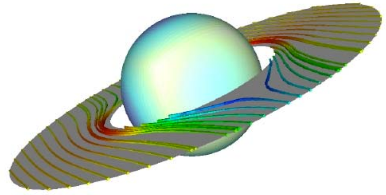

FH AACHEN
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Numerical Analysis of Blood Flow in a Ventricular Assist Device Using High Performance Computing

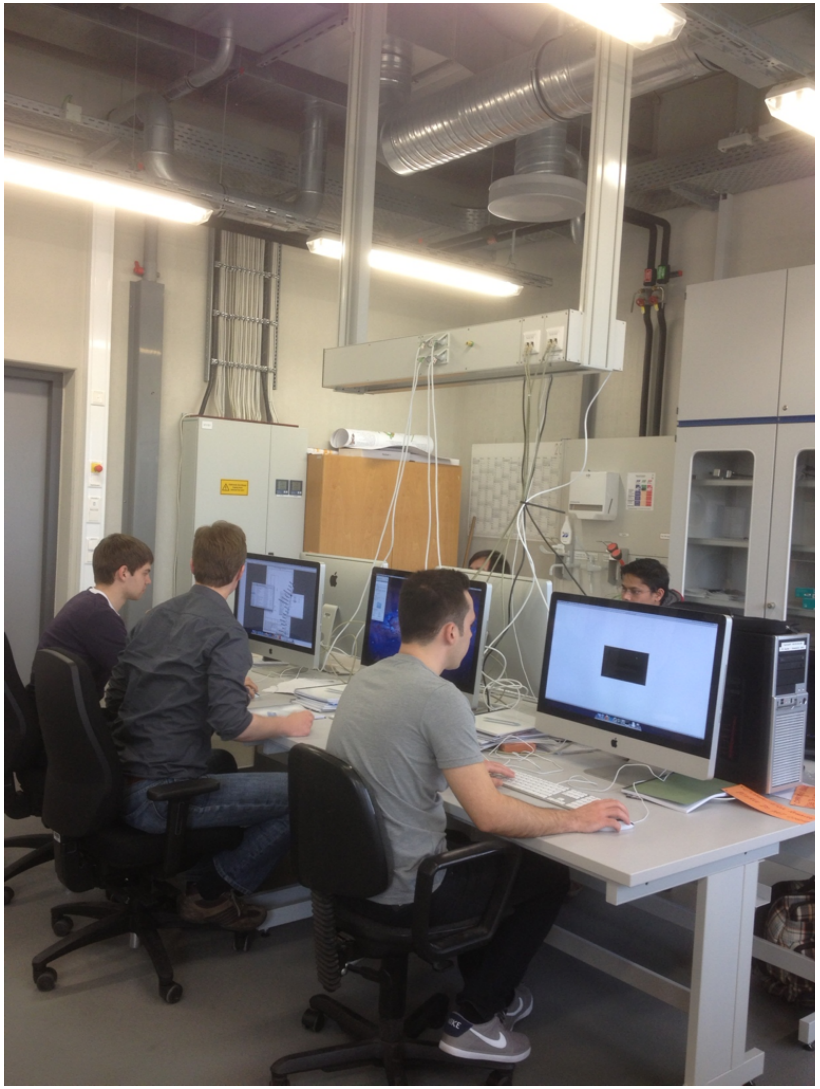
Prof. Dr.-Ing. Mehdi Behbahani

Faculty of Medical Engineering and Technomathematics
FH Aachen, Campus Jülich, Institute of Bioengineering,
Biomaterials Laboratory

Talk given at Club U, Paris, Chatou

April 2, 2015

Workgroup and Hardware



<u>typically used is Apple`s 27" iMac</u>:

<u>Processor</u>:

Quad-Core Intel Core i7 (Turbo Boost up to 3,9 GHz).

<u>cores</u>: 4 - 8

<u>RAM</u>: 8 - 20 GB 1600 MHzDDR3

<u>GPU</u>: NVIDIA GeForce GTX 675MX

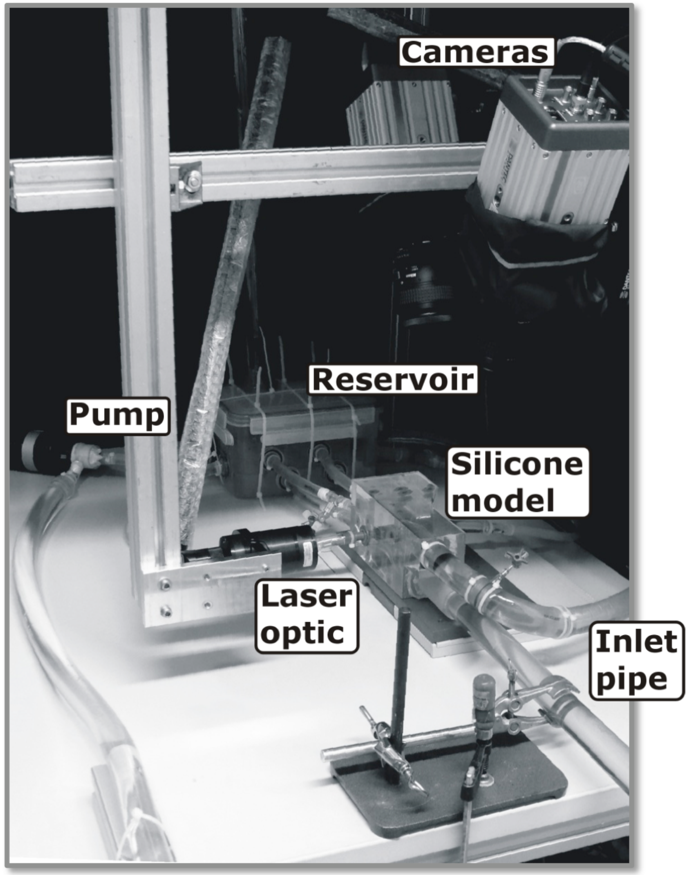
Fluid Dynamics Group at FH Aachen

existing since 2012 - focusing on blood flow applications

CFD work

Aortic / stenosed vessel flow
Abdomial aortic aneurysms
Organ conservation
Fluid structure interaction

Experimental work



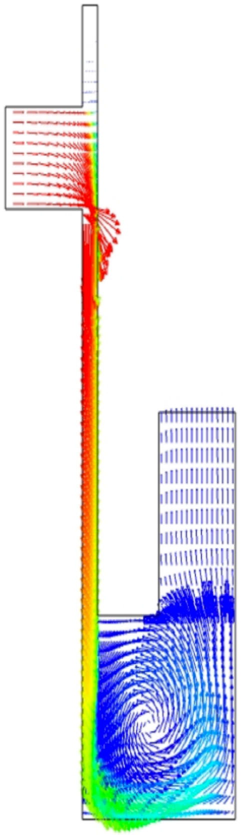
PIV
Flow experiments
(Couette flow, Taylor vortices, Non-Newtonian effects, ...)

Fluid Dynamics Group at FH Aachen

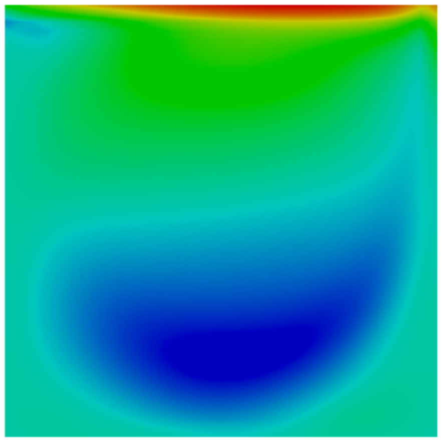
using code Saturne since 2012 with high satisfaction

For teaching purposes we use existing EDF tutorials:

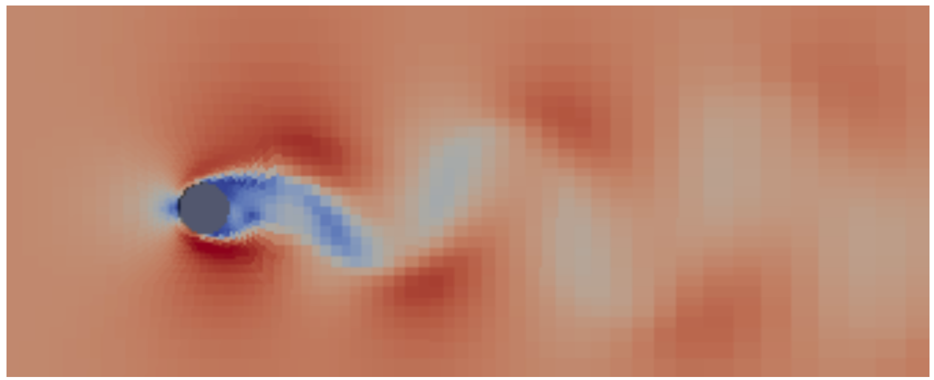
Simple junction



Shear driven cavity flow



Fluid structure interaction

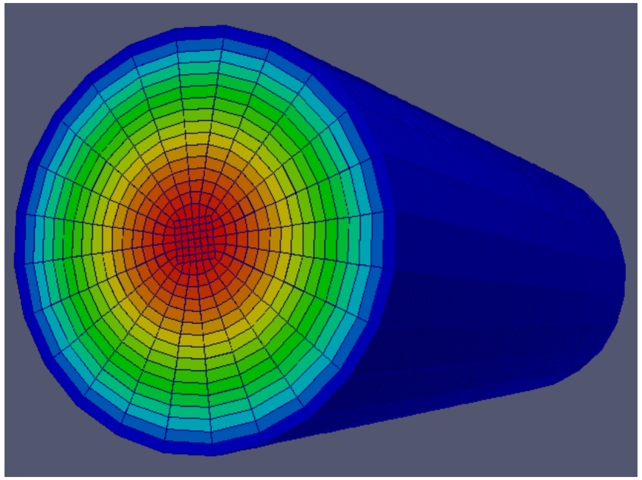


Fluid Dynamics Group at FH Aachen

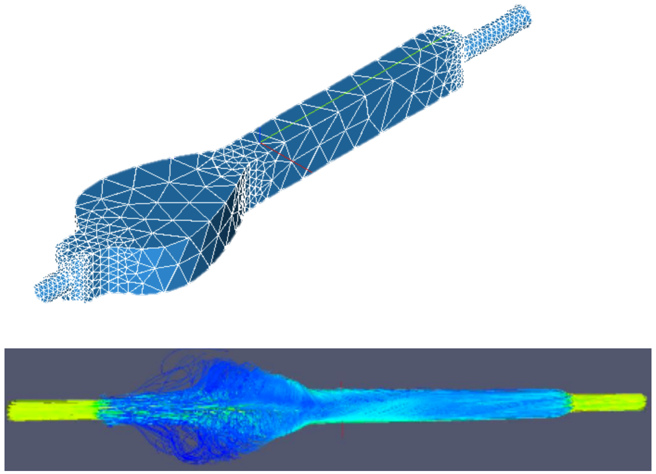
using code Saturne since 2012 with high satisfaction

For teaching purposes we also use self-written tutorials:

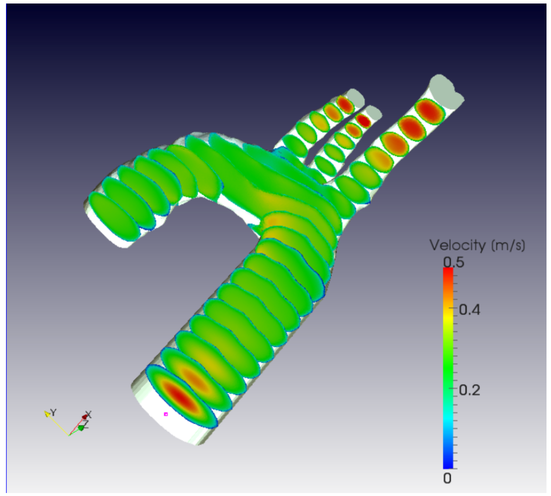
Butterfly mesh for blood vessel flow



Tube of a dialysis device



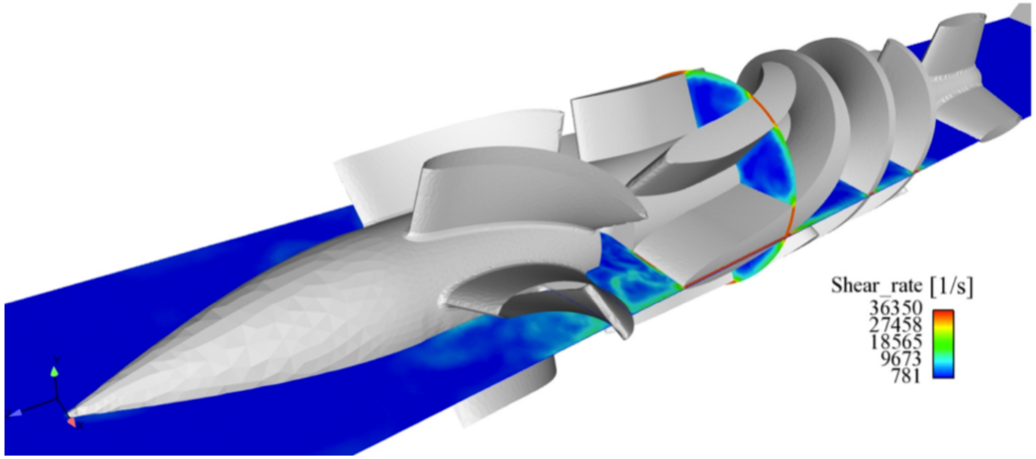
Pulsatile flow through a human patient aorta

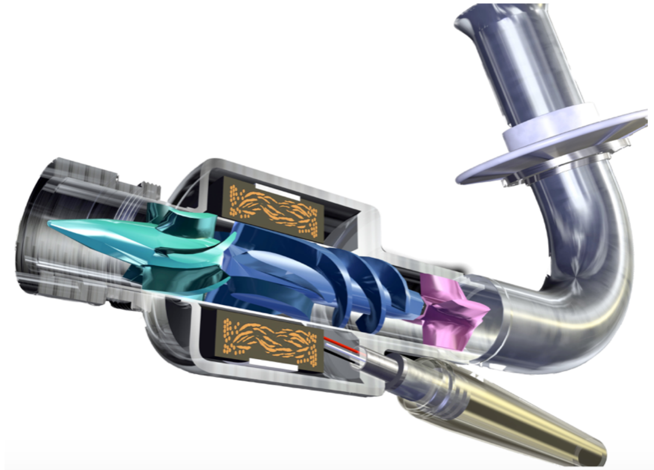


Fluid Dynamics Group at FH Aachen

Code Saturne for use in rotating geometries

By end of 2013 we wished to start to use Code Saturne for research purposes, especially for rotating geometries



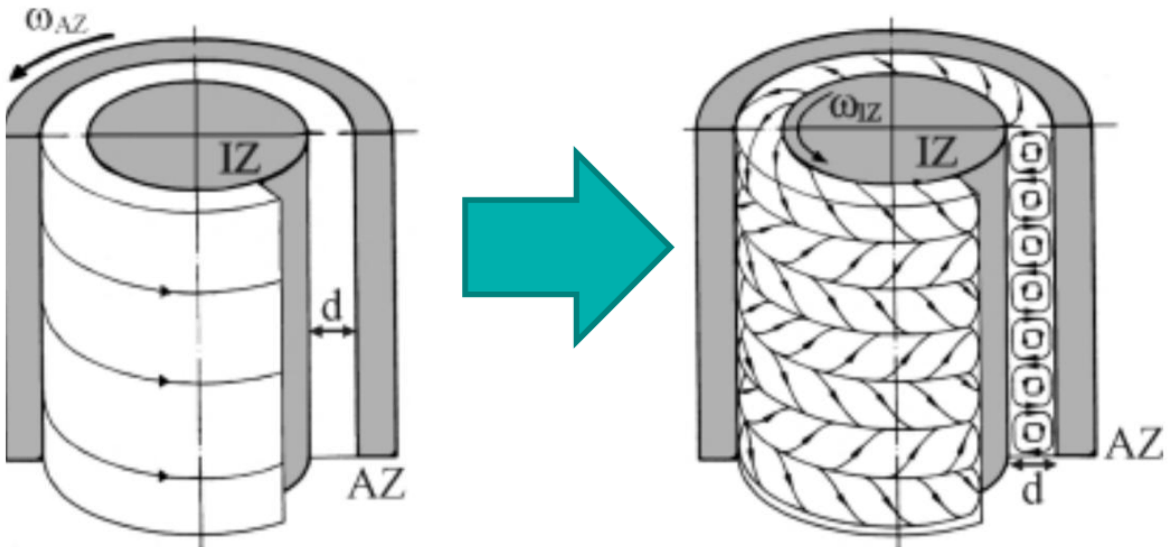


No tutorial for such applications found - so we decided to try a first test case

Experimental Couette system

We also built an experimental device for a simple system of two coaxially rotating concentric cylinders (Couette system)

$$Ta_{crit} = 40.7 \pm 0.9$$



The Taylor number: $$Ta = \frac{R_i \omega_i \rho}{R_o \mu} \left(d^3 \frac{R_i + R_o}{2} \right)^{\frac{1}{2}}$$

Fluid Dynamics Group at FH Aachen

Method for computing rotating geometries

Pre-processor: SALOME 6.6.0

Geometry

Mesh

Solver: Code Saturne 3.0.1

Navier-Stokes equations

Physical properties, Boundary conditions

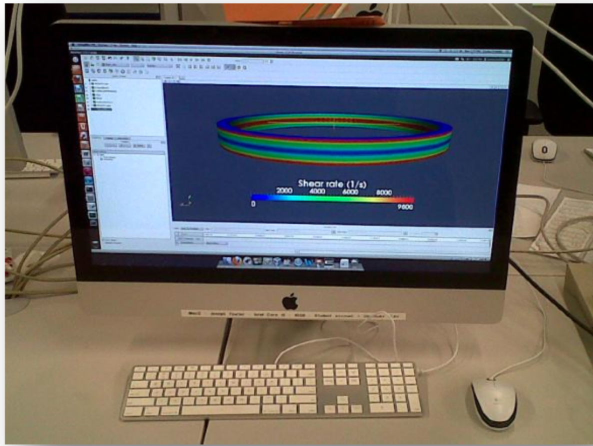
Numerical parameters

Post-processor: ParaView 3.14.1

Velocity visualization

Streamline visualization

Shear rate visualization

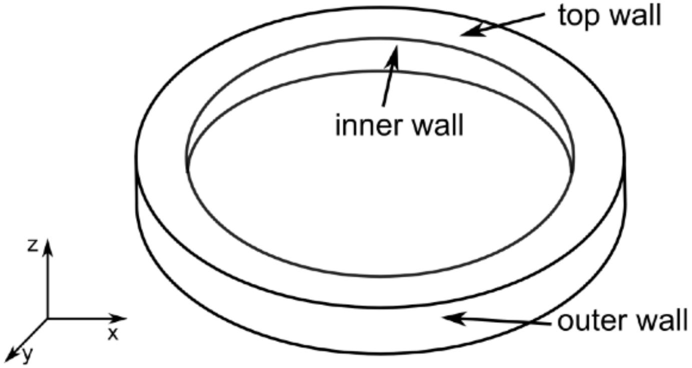


Fluid Dynamics Group at FH Aachen

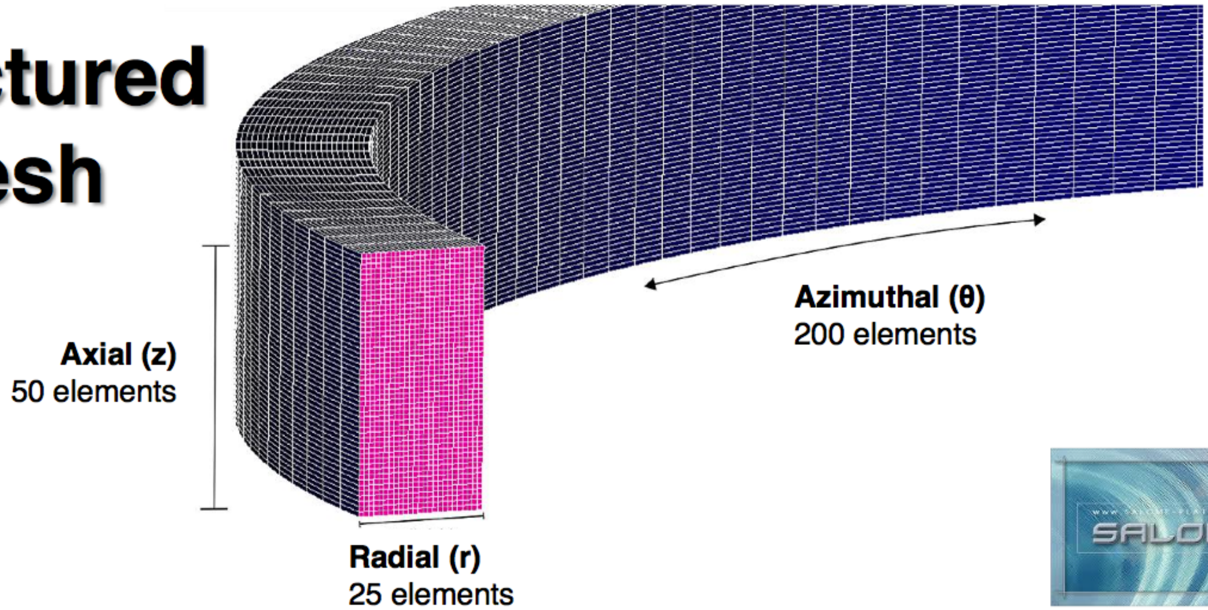
Method for computing rotating geometries

Geometry

Geometric parameters	
Inner cylinder radius (R_i)	5.0 cm
Outer cylinder radius (R_o)	5.5 cm
Gap length (d)	0.5 cm
Domain height (L)	1.0 cm

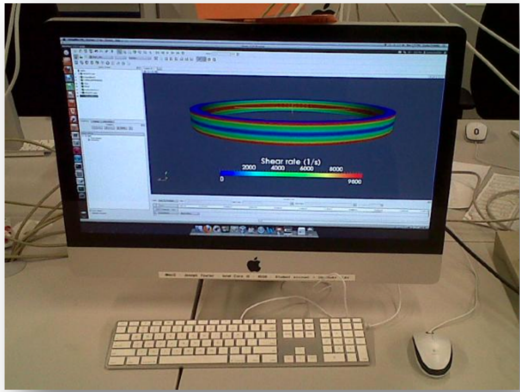


Structured Mesh



Fluid Dynamics Group at FH Aachen

Method for computing rotating geometries



Fluid properties – 55 % Glycerol-Water solution

Fluid density:	1140 kg/m^3
Dynamic viscosity:	8.0 x 10^{-3} Pa.s

Boundary conditions (cs_boundary_conditions.f90)

Top/bottom walls:	Symmetry
Inner/Outer walls:	Smooth wall, no-slip boundary condition, fixed or rotating.

Numerical parameters

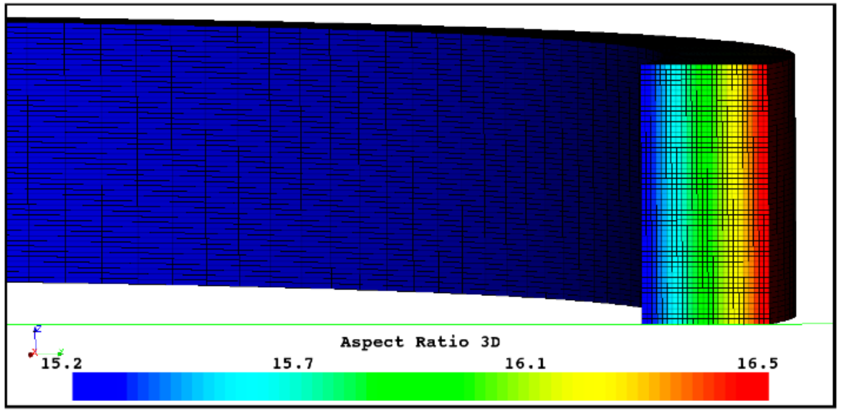
Time-step:	0.1 – 0.01 seconds
Iterations :	1000- 10000 iterations

Fluid Dynamics Group at FH Aachen

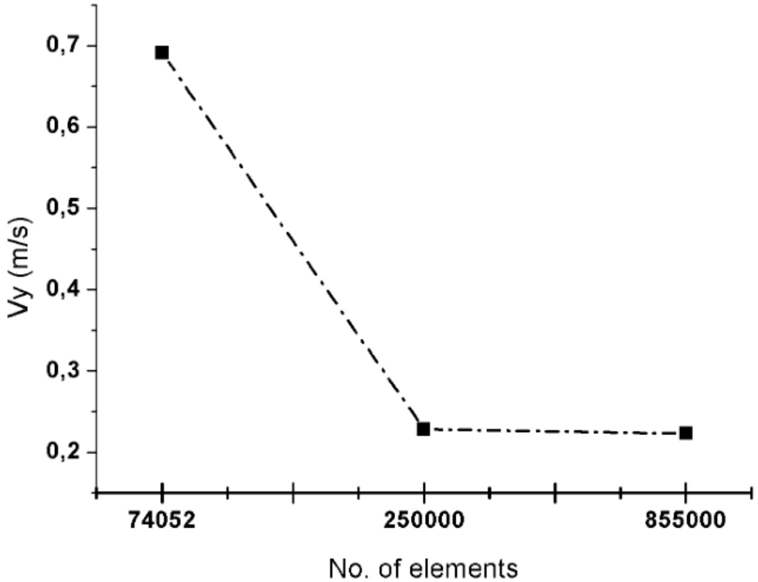
Method for computing rotating geometries

Mesh quality assesment

Aspect Ratio
Skewness
Volume Ratio



Mesh sensitivity analysis

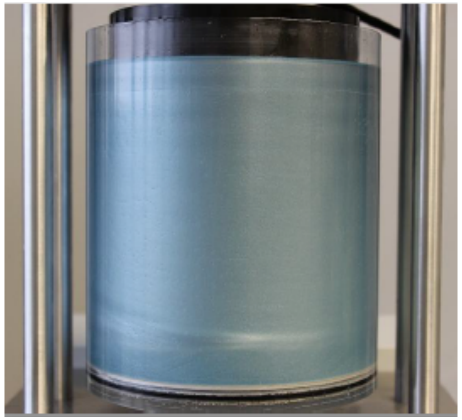


Mesh sensitivity analysis for AZI and TVF computations. Three meshes are computed. The solution for Mesh 2 (250,000 elements) is grid independent. The line is an indication of convergence, but does not represent linearity between two points.

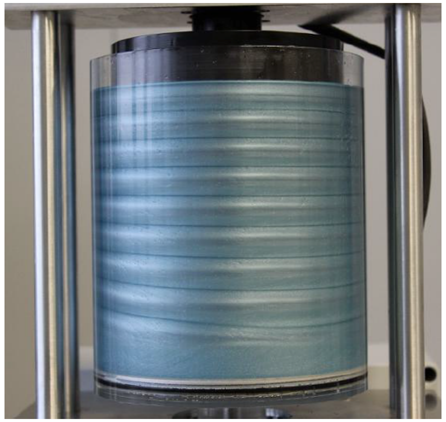
Fluid Dynamics Group at FH Aachen

Code Saturne for use in rotating geometries

Good agreement between numerical and experimental data for a Couette system with rotating inner cylinder

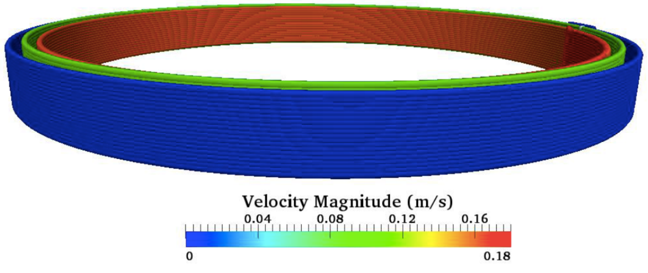


30 rpm, Ta=33, Rein=112

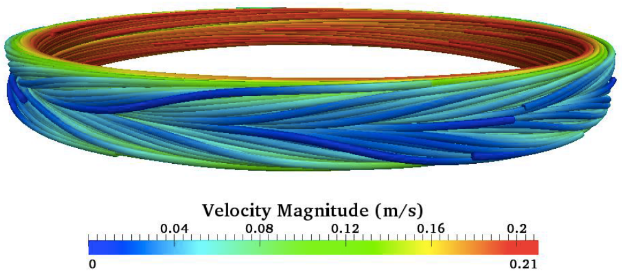


42 rpm, Ta=47, Rein=157

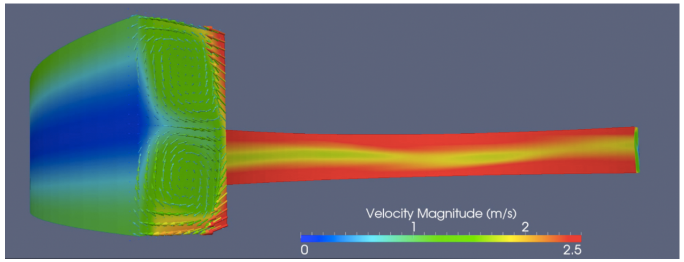
163rpm, Ta=180, Re_{in}=609



Velocity magnitude



Velocity magnitude

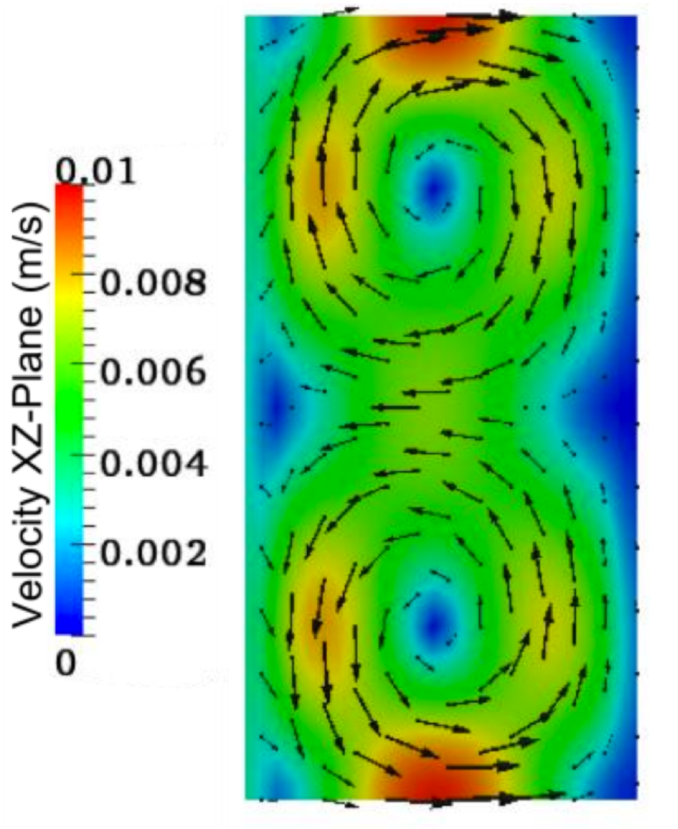


Velocity magnitude for a given point in time.

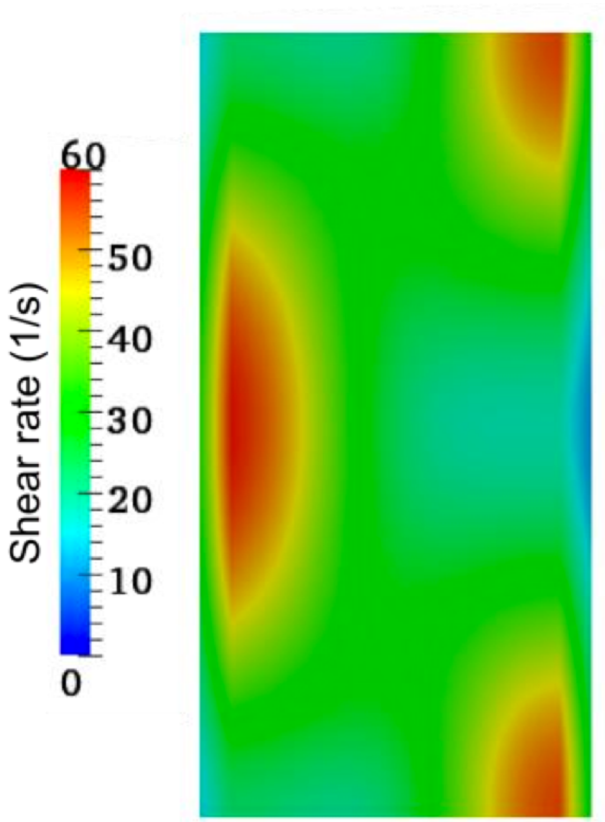
Issue with derived quantities such as shear rate

Shear rate computations did not show right results in ParaView

Correct velocity values



Wrong shear rate values



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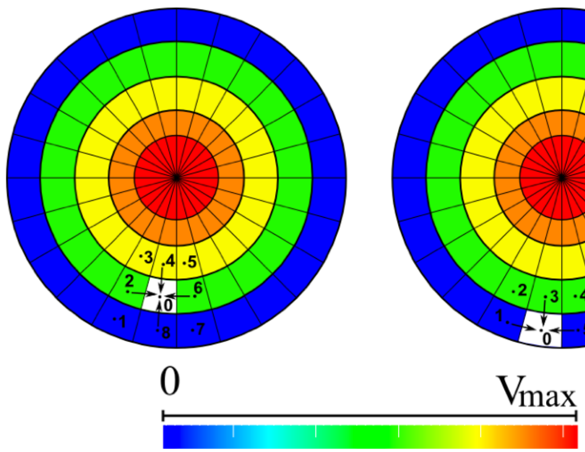
Calculation of the shear rate in Paraview

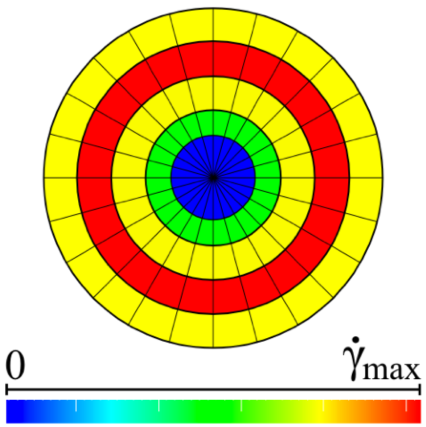
Shear rate visualization in Paraview



Velocity profile

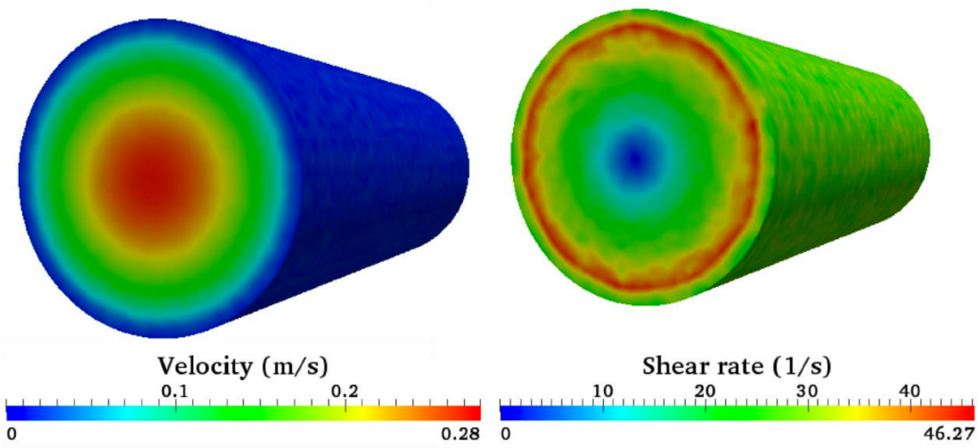
To calculate the shear rate at cell element [0], the difference in velocity is computed from the neighbour cells. Since the cells at the wall have fewer neighbours, the gradient cannot be calculated accurately.

c.



Shear rate

a. b.

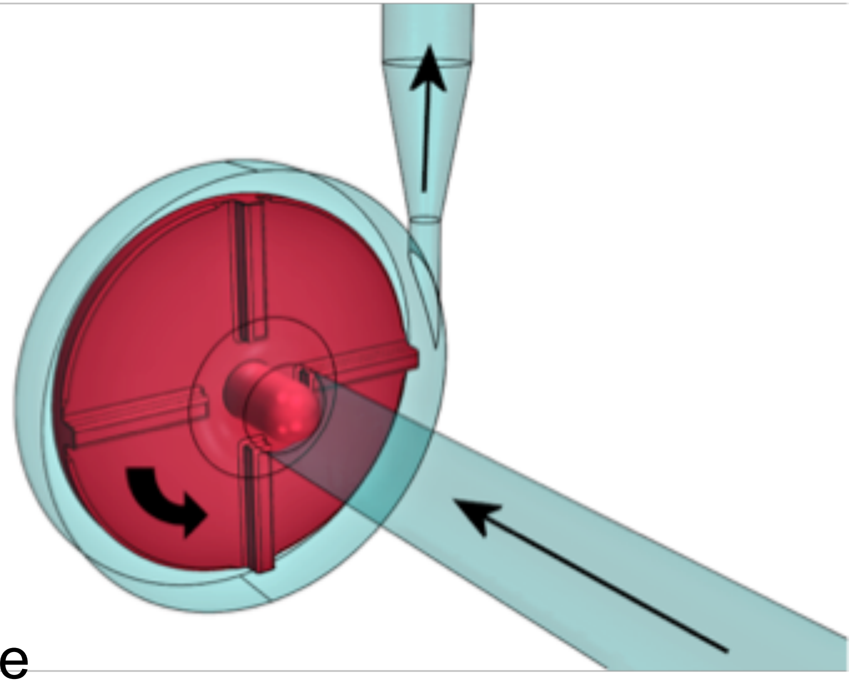


FDA benchmark

American Food and Drug Administration benchmark

- Study goal

- worldwide benchmark
- numerical blood flow analysis of the shown centrifugal pump
- prediction of shear stresses
- optional: computation of hemolysis
- **answer the question: how good an estimate can CFD give today**



- Validation

- three laboratories were asked to produce experimental PIV data for comparison

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FDA benchmark

American Food and Drug Administration benchmark

FDA asked for the simulation of 6 highly turbulent flow conditions:

Case	volume flow rate [L/min]	pump speed [RPM]	REYNOLDS number
1	2.5	2500	293,073
2	2.5	3500	209,338
3	4.5	3500	293,073
4	6.0	2500	209,338
5	6.0	3500	293,073
6	7.0	3500	293,073

[1] Standard setup parameters of the blood pump benchmark as defined by the FDA.

$$Re = \rho v 2\pi d^2/\eta \qquad d = 0.052m \;\; \eta = 0.0035Pa \quad \rho = 1035.0kg/m^3$$

Turbulence models used: RANS models
e.g. k-ε, k-ω and a Reynolds Stress Model (RSM)

It was believed that an RSM represents an appropriate choice with respect to modeling high-Reynolds number flow cases. Especially, the **Rij-SSG (Speziale, Sarkar, Gatzki) model.**

Using code Saturne with BlueGene/Q super computer at Juelich research facility

- 28 racks (7 rows à 4 racks) - 458.752 nodes (**458,752 cores**)
  Rack: 2 midplanes à 16 nodeboards (16,384 cores)
  Nodeboard: 32 compute nodes
  Node: 16 cores
- Main memory: 448 TB
- Overall peak performance: **5.9 Petaflops**
- Linpack: > 4.141 Petaflops
- power consumption: 1.7 MW (4000 households)

BlueGene/Q JUQUEEN

FDA blood pump study

Cooperation partners

Dr. Paolo Corsetto

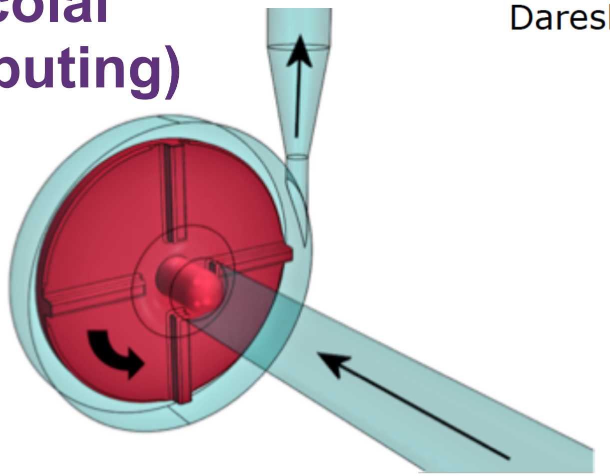
JÜLICH
FORSCHUNGSZENTRUM

Dr. Mike Nicolai

(high performance computing)

Science & Technology Facilities Council
Daresbury Laboratory, UK

Dr. Charles Moulinec (turbo-machinery)



Dr. Mehdi Behbahani

FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

Sebastian Rible

eDF
Électricité de France

Yvan Fournier (code Saturne developer)

(CFD users, biomedical engineering)

FDA blood pump study

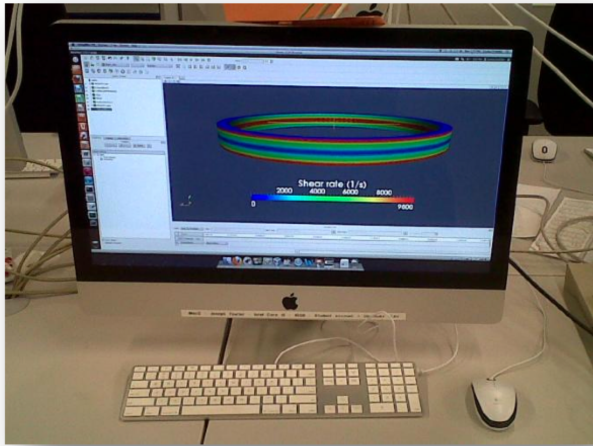
Computational resources

- In February 2014 **proposal written for 21 million** hours of computing time on JUQUEEN

- In May 2014 only **4 million hours** of computing time **were granted**

FDA blood pump study

Method for computing rotating geometries



Pre-processor: SALOME 6.6.0

- Geometry
- Mesh

Solver: Code Saturne 3.2.2 3.2.3

- Navier-Stokes equations
- Physical properties, Boundary conditions
- Numerical parameters

Post-processor: ParaView 3.14.1

- Velocity visualization
- Streamline visualization
- Shear rate visualization

FDA blood pump study

Pump geometry and computational domain

- Inlet:

Curvature: R=90 mm
Diameter: 12 mm
Length: 200 mm

- Housing:

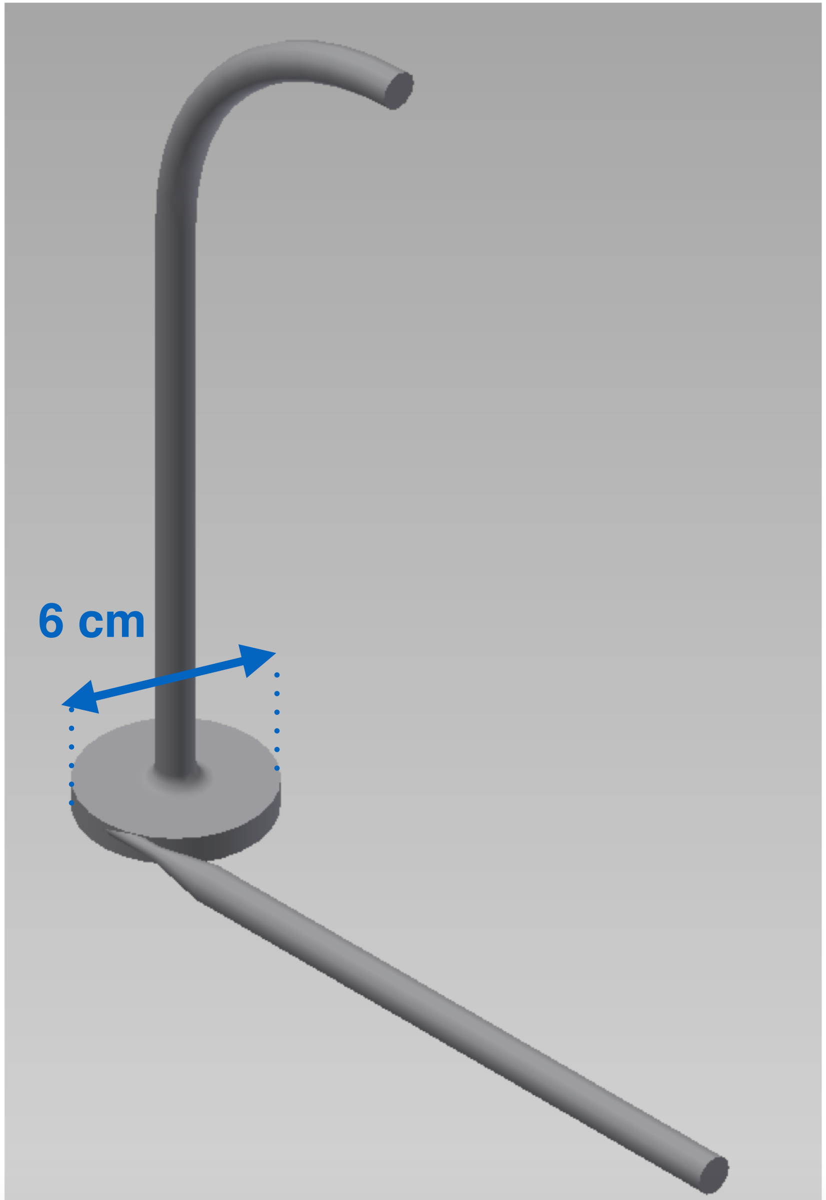
Diameter: 60 mm
Height: 9 mm

- Diffusor:

Diameter: 4,39 - 12 mm (angle 20°)
Length: 21,54 mm

- Outlet:

Diameter: 12 mm
Length: 200 mm



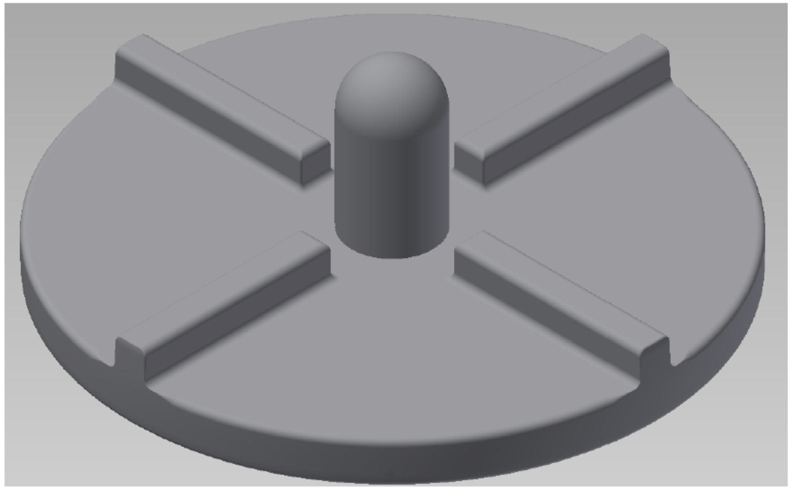
FDA blood pump study

Pump geometry and computational domain

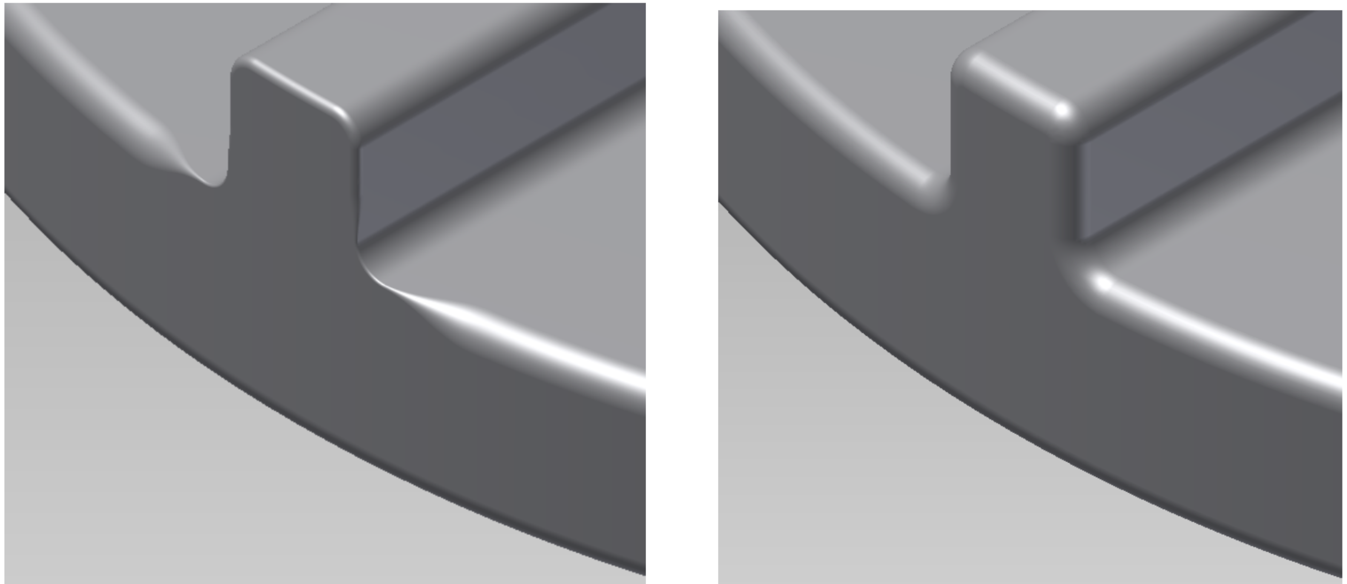
- Diameter 52 mm

- Rotor blades
Height 3 mm
Width 3 mm
Length 18.5 mm

- Shaft
Diameter 3.5 mm
Height 10 mm



Rotor

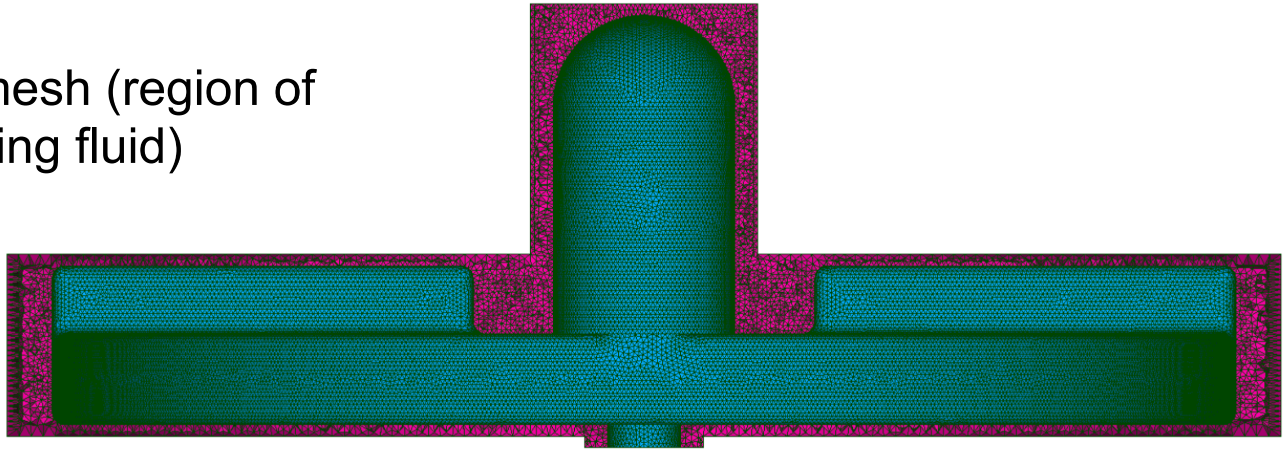


Blade region (Salome could not produce variable roundings)

FDA blood pump study

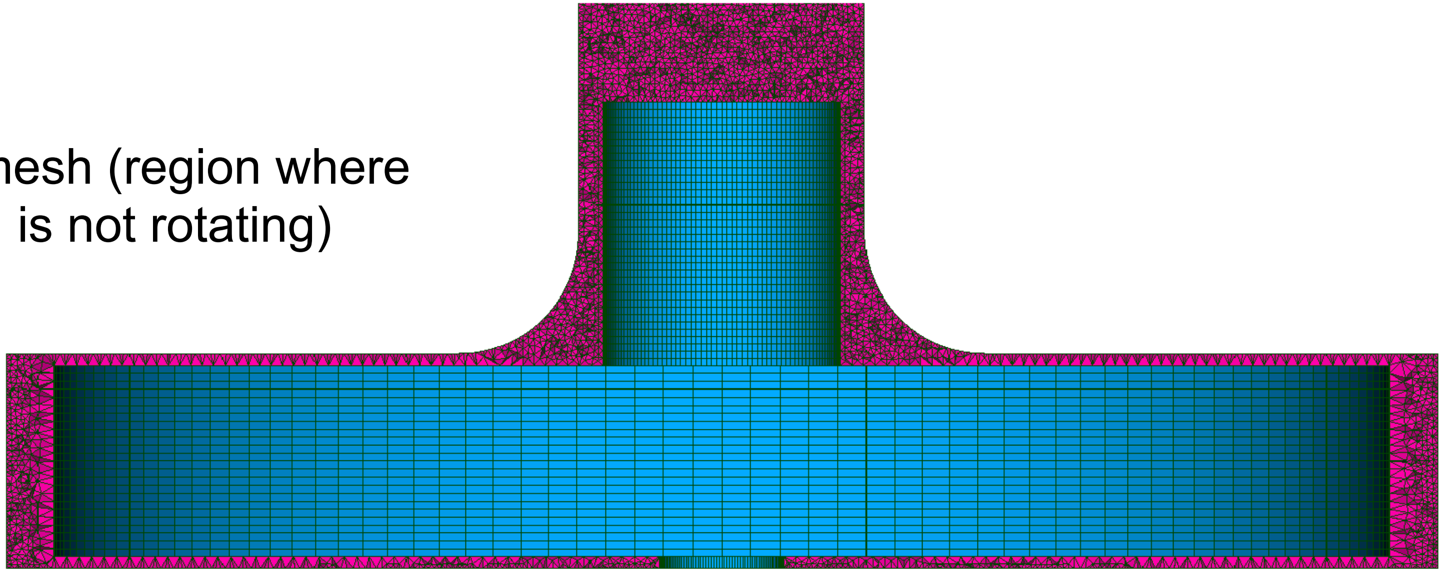
First steps - hybrid meshes preparation

Dynamic mesh (region of rotating fluid)



dynamic mesh of 5 million tetrahedral volume elements

Static mesh (region where fluid is not rotating)

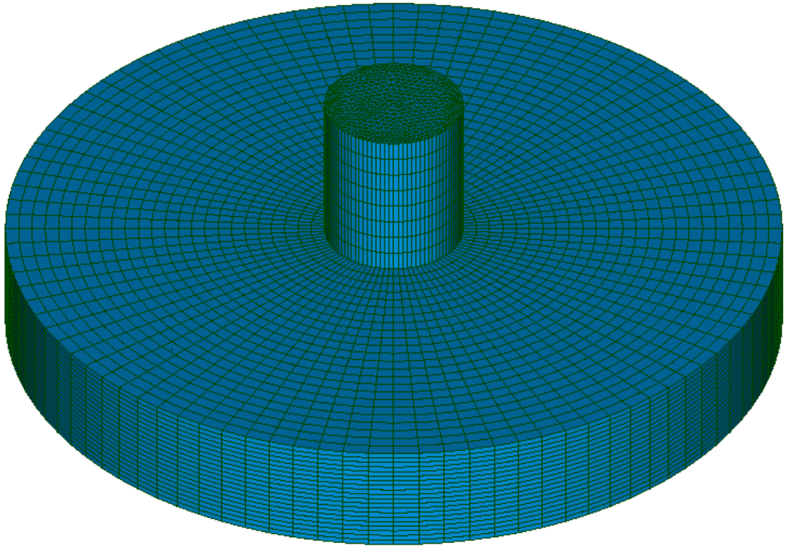


static mesh of 9 million tetrahedral volume elements

FDA blood pump study

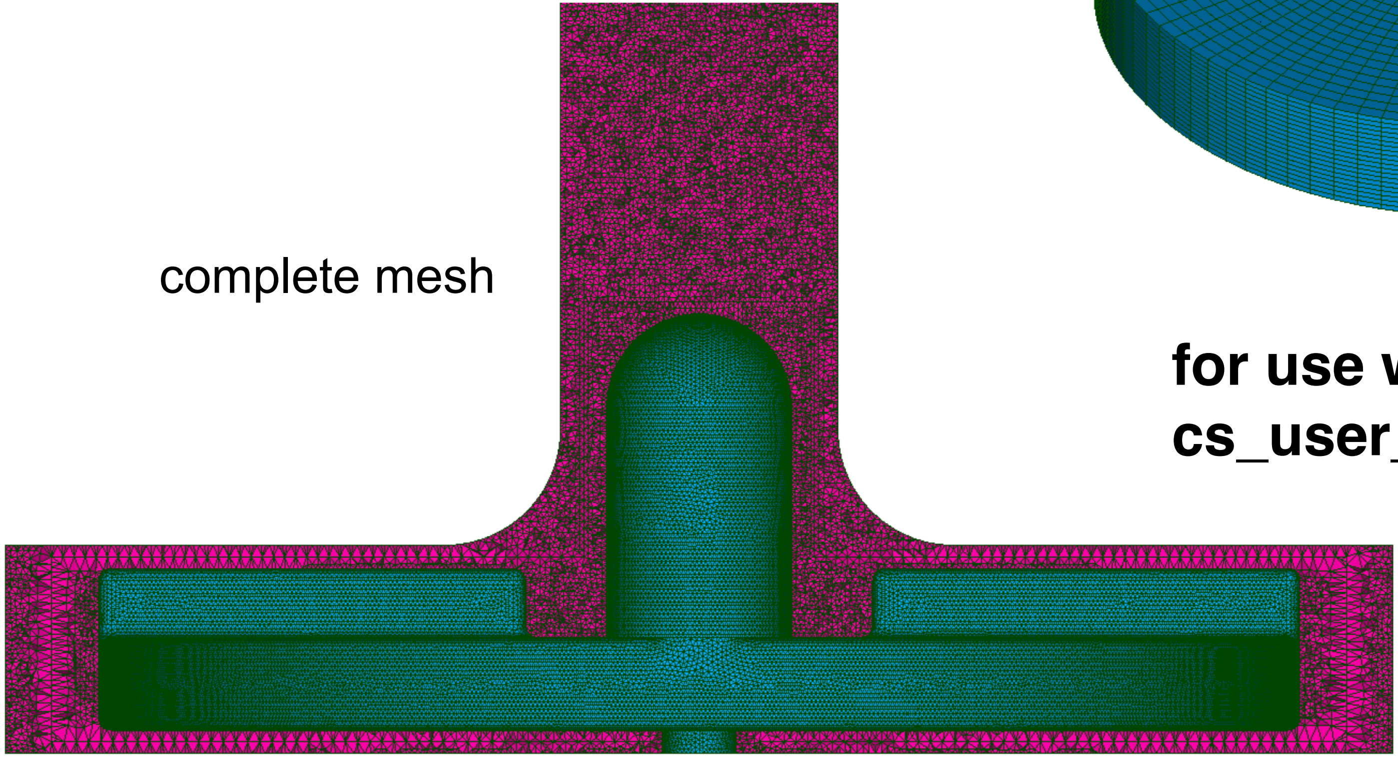
First steps - hybrid meshes preparation

Interface between the two meshes (static and dynamic)



tetrahedral elements combined with pyramidal elements at the interface

complete mesh



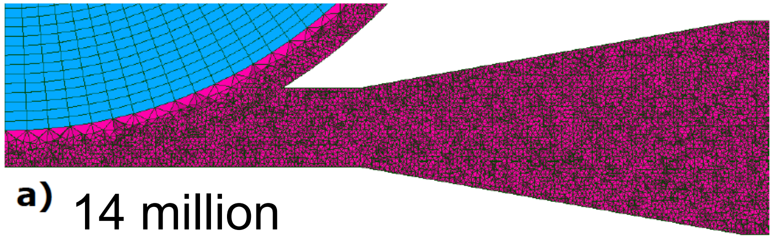
for use with subroutine cs_user_turbomachinery.c

computational mesh of 14 million tetrahedral volume elements

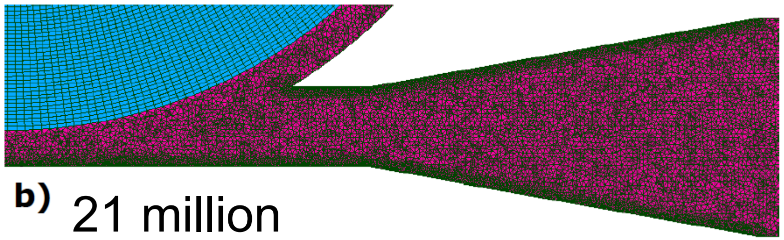
FDA blood pump study

Mesh refinement

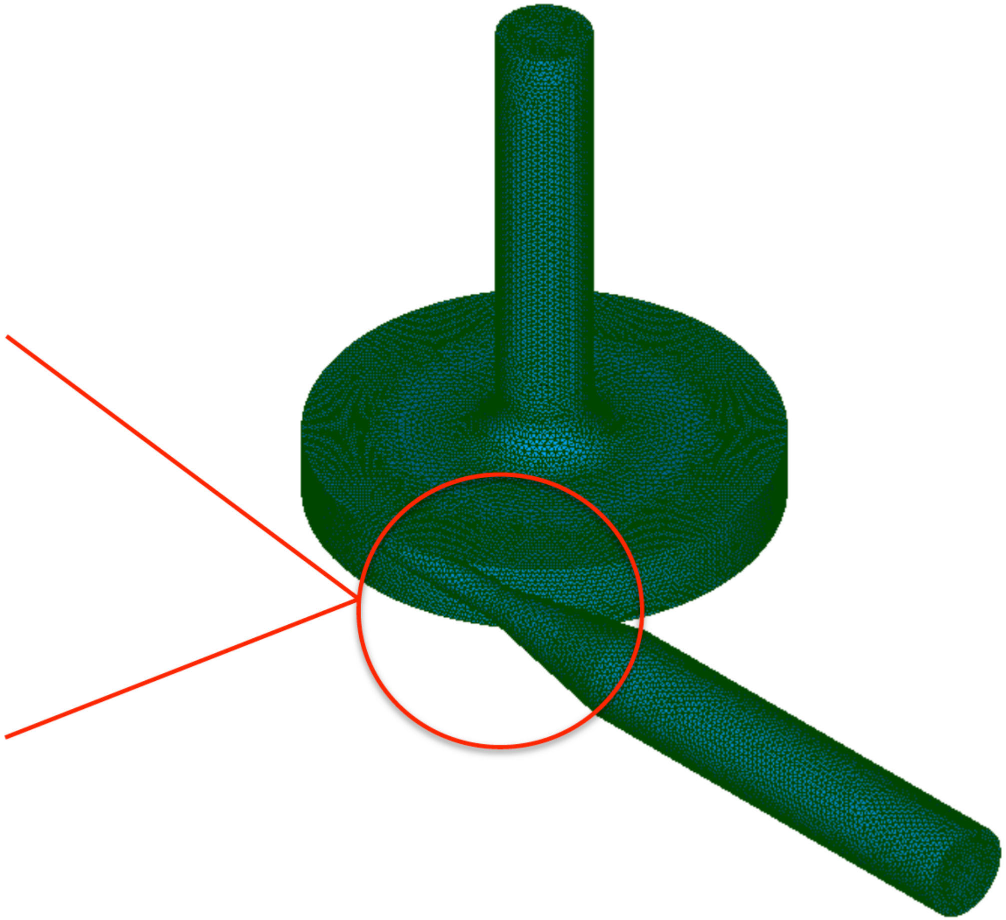
- Local refinement of neck and diffusor



a) 14 million

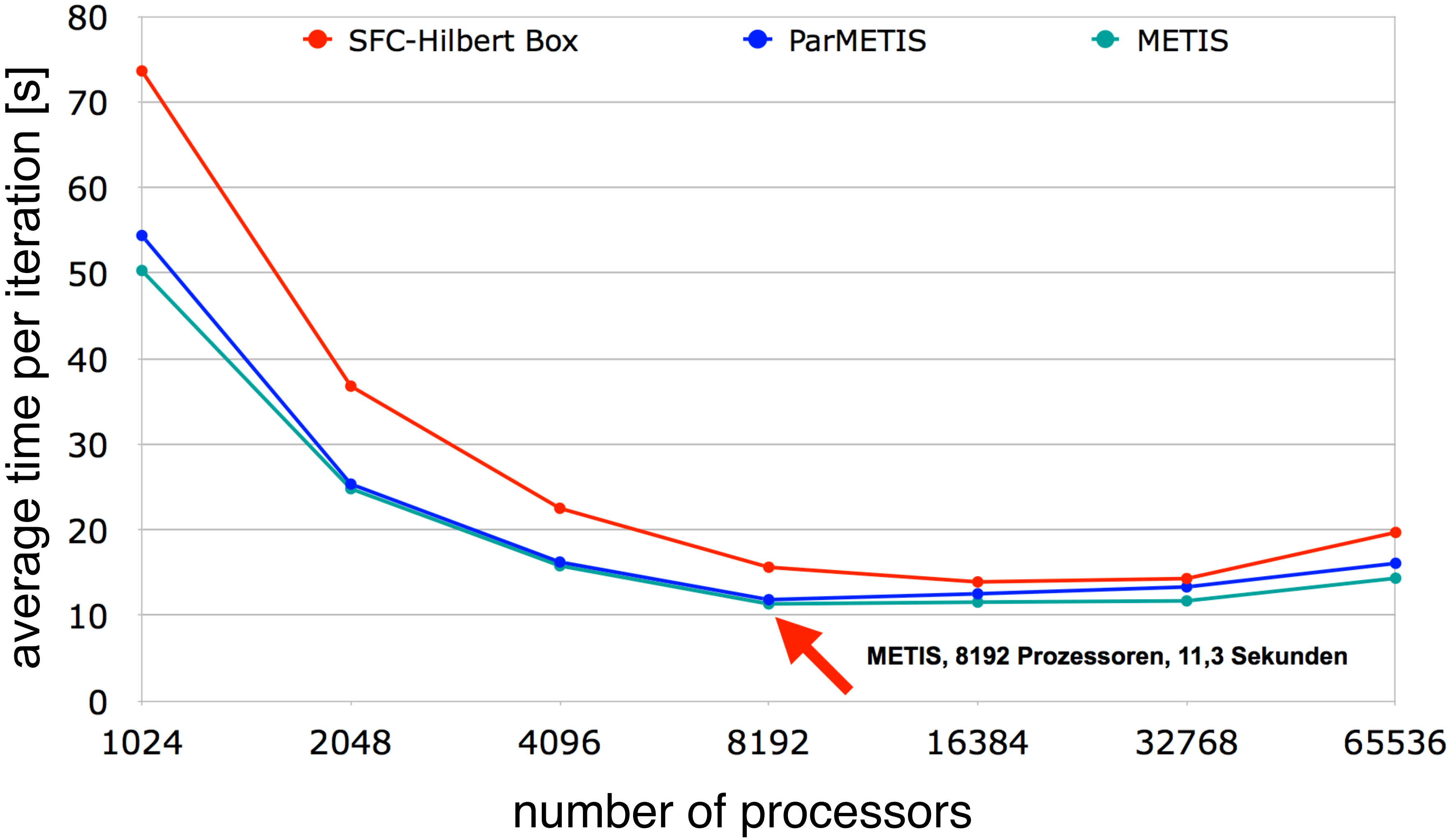


b) 21 million



FDA blood pump study

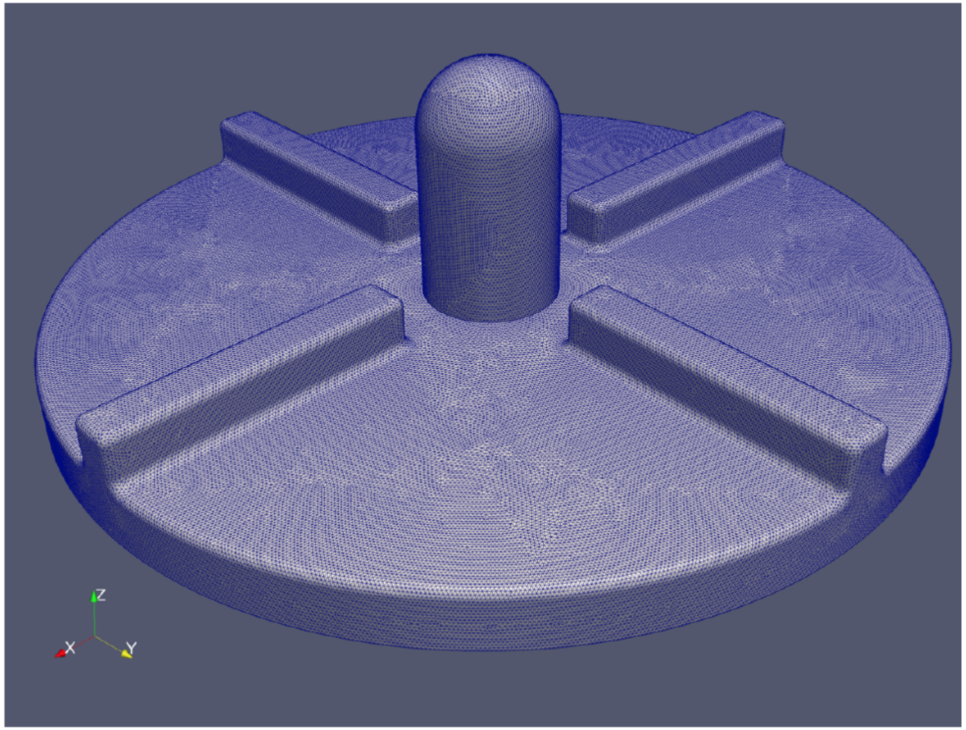
Scaling on the BlueGene\Q for a 21 million element mesh

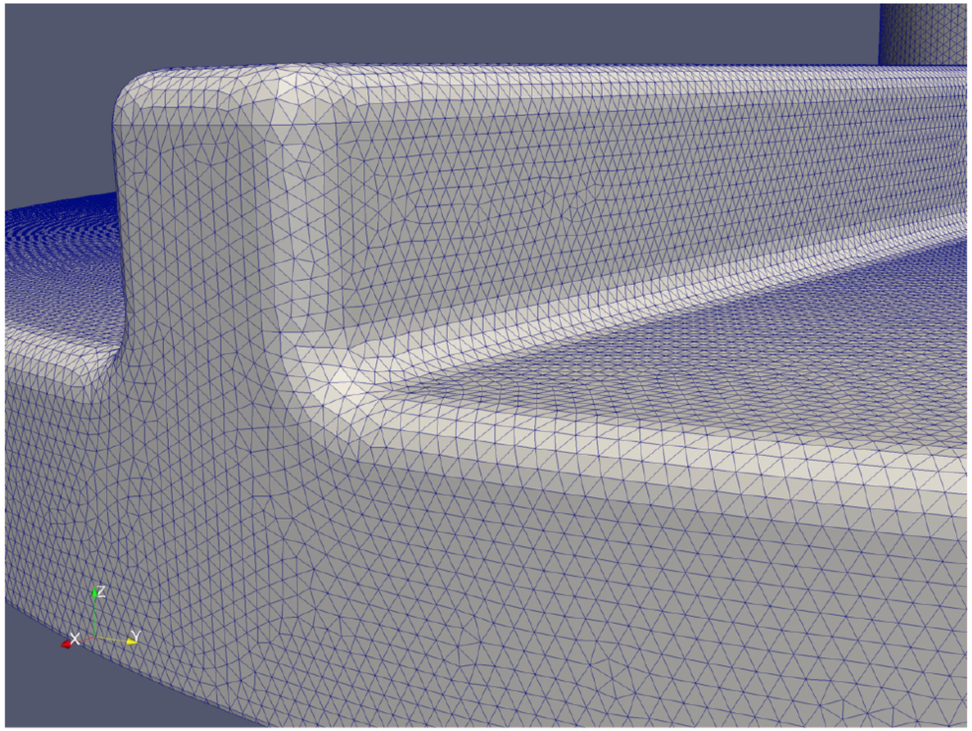


Scaling study for a 21 million mesh shows that best results are achieved using partitioner Metis and 8192 processors

FDA blood pump study

Final mesh of 76 million elements





For the final computations a more refined mesh of 76 million elements also with prolonged in- and outflow cannula was used

smallest cell volume in m^3: $5.05*10^{-15}$

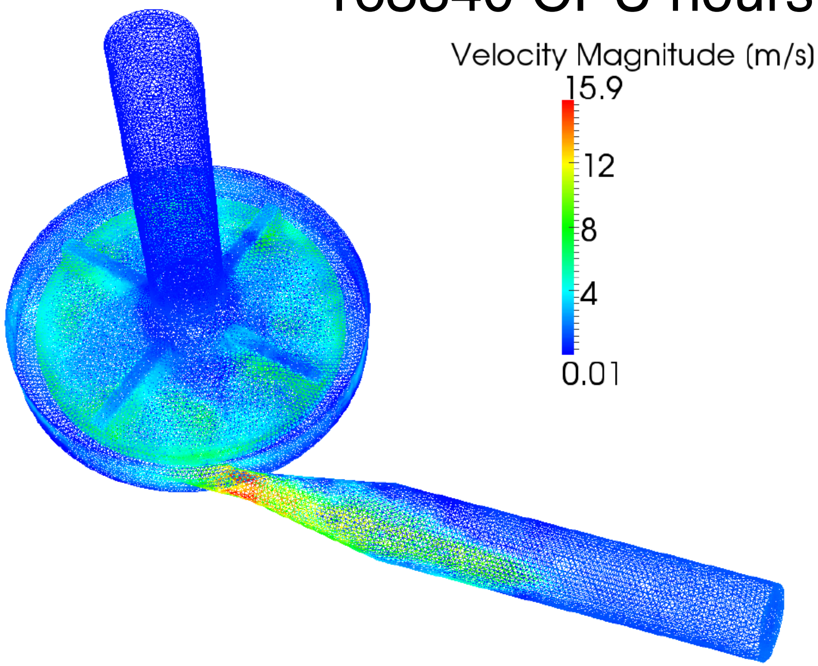
largest cell volume in m^3: $9.14*10^{-12}$

FDA blood pump study

Computational effort for the 76 million elements

first 5 revolutions were computed using:

- 3500 time steps
- 1 time step = $2.45 \cdot 10^{-5}$ s
- typically 8192 processors
- total time = 69222s = 19hours
- Dynamic memory used 221 GB
- Size on disk 109 GB
- 163840 CPU hours per job

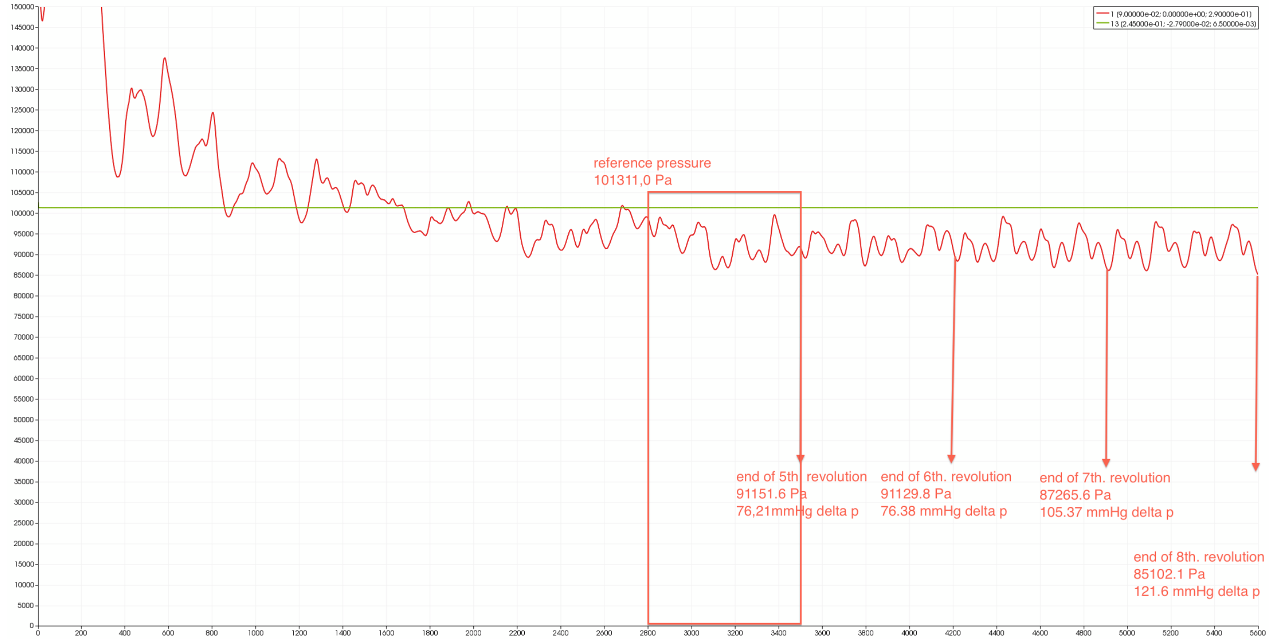


FDA blood pump study

Computational effort for the 76 million elements

after result inspection it became clear that a minimum of 10 revolutions was required, if not 20

- restart function in Code Saturne did not work
- seems to be fixed in new Code Saturne versions now



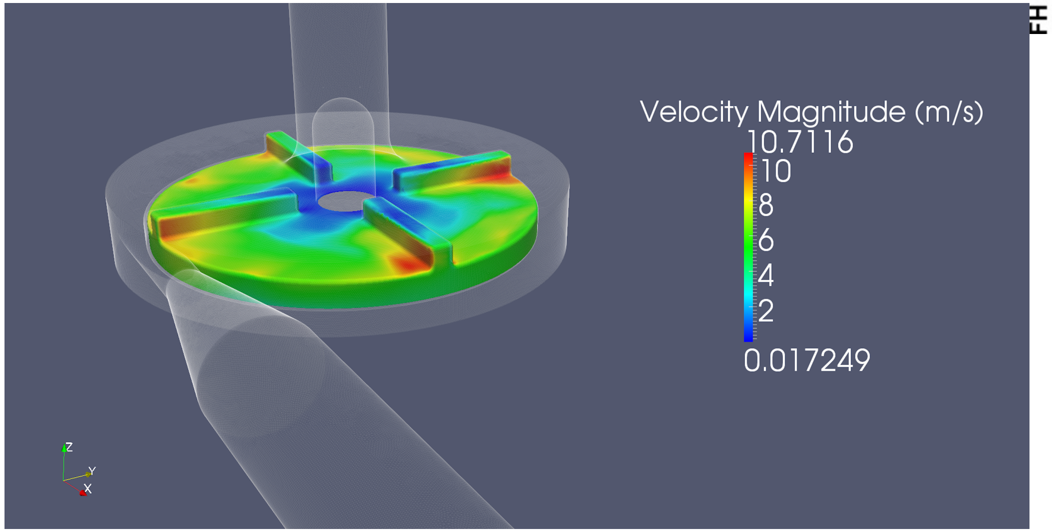
as a result we repeated all computations from scratch for 10 revolutions this time using 32768 processors

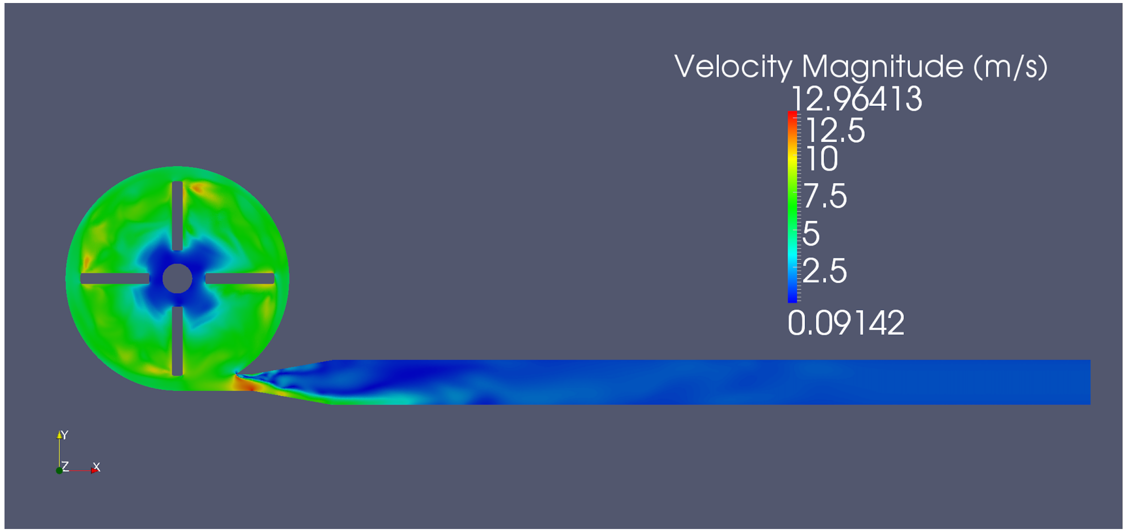
FDA blood pump study

Results for the 76 million elements

Observed flow phenomena:

- Maximum velocity in the diffusor neck region
- Highest velocity in the rotor region behind blades

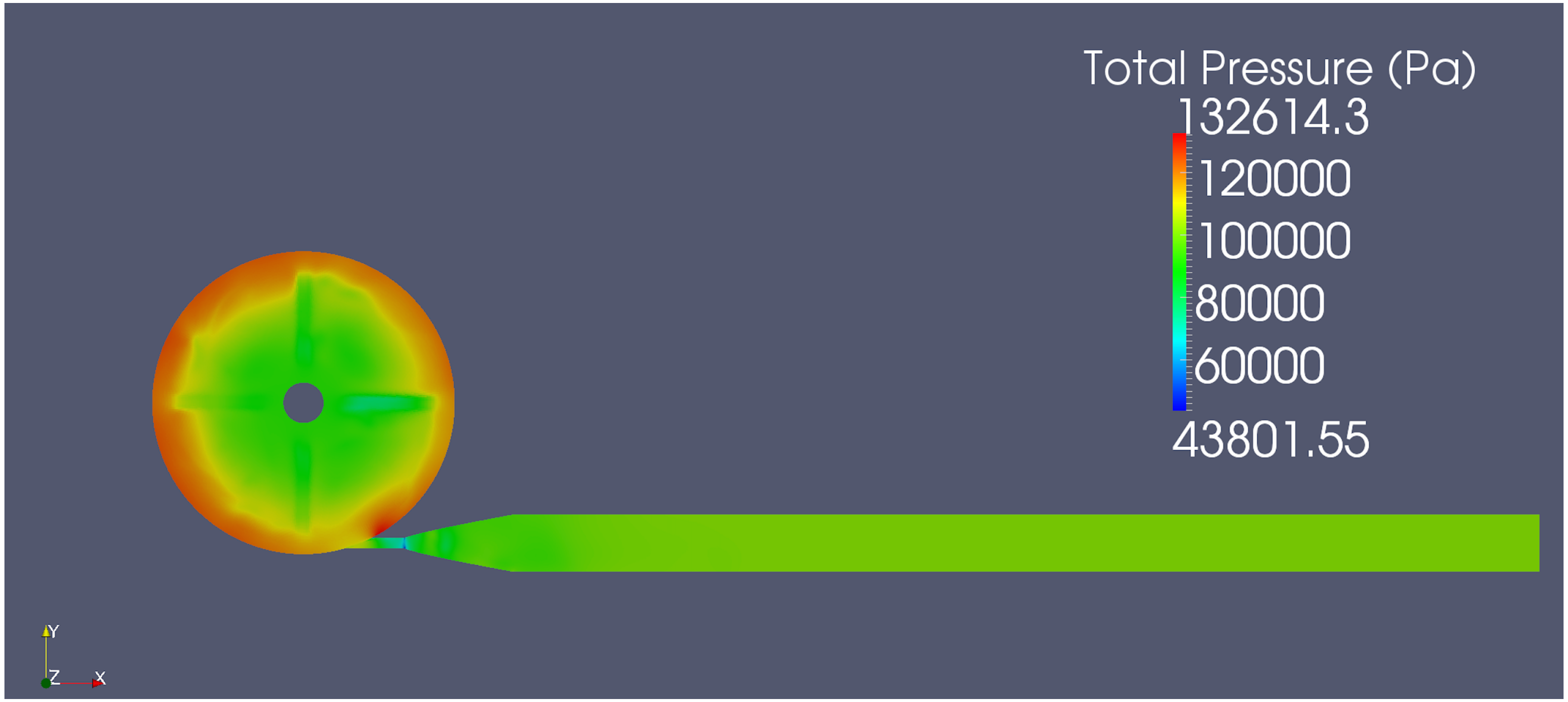




FDA blood pump study

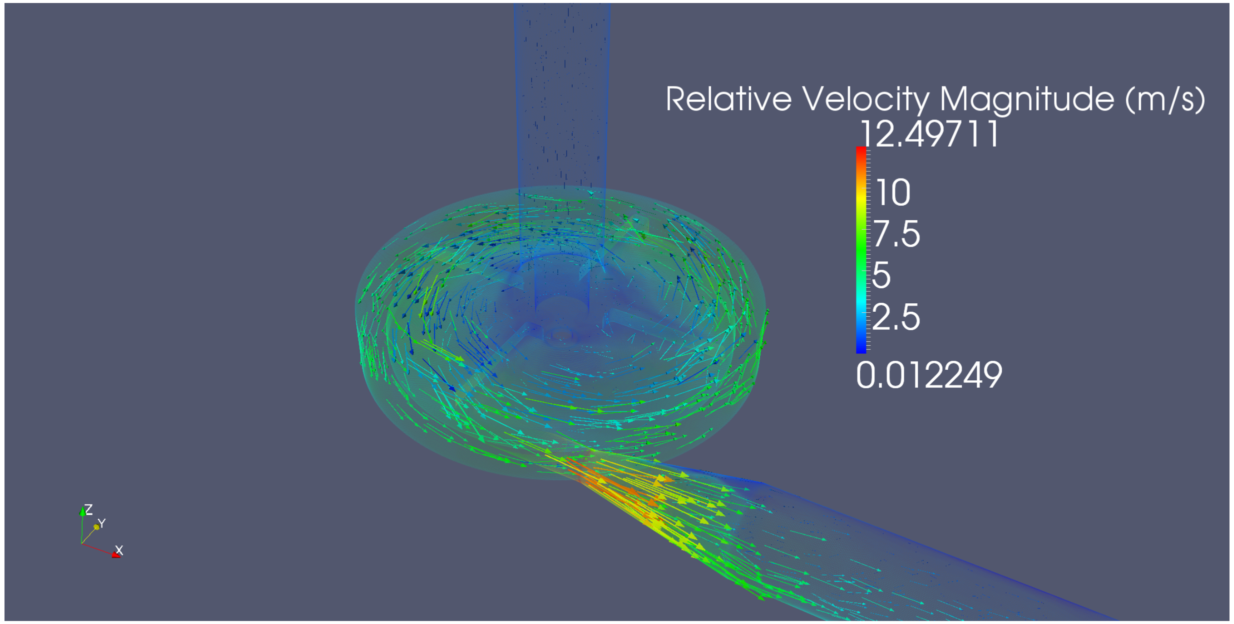
Results for the 76 million elements

- pressure across blades (difference at inner and outer diameter) is similar to values computed with Bernoulli equation
- pressure head seems to fit well with literature for centrifugal blood pumps
- physiological pressure heads are received



FDA blood pump study
Visualization methods

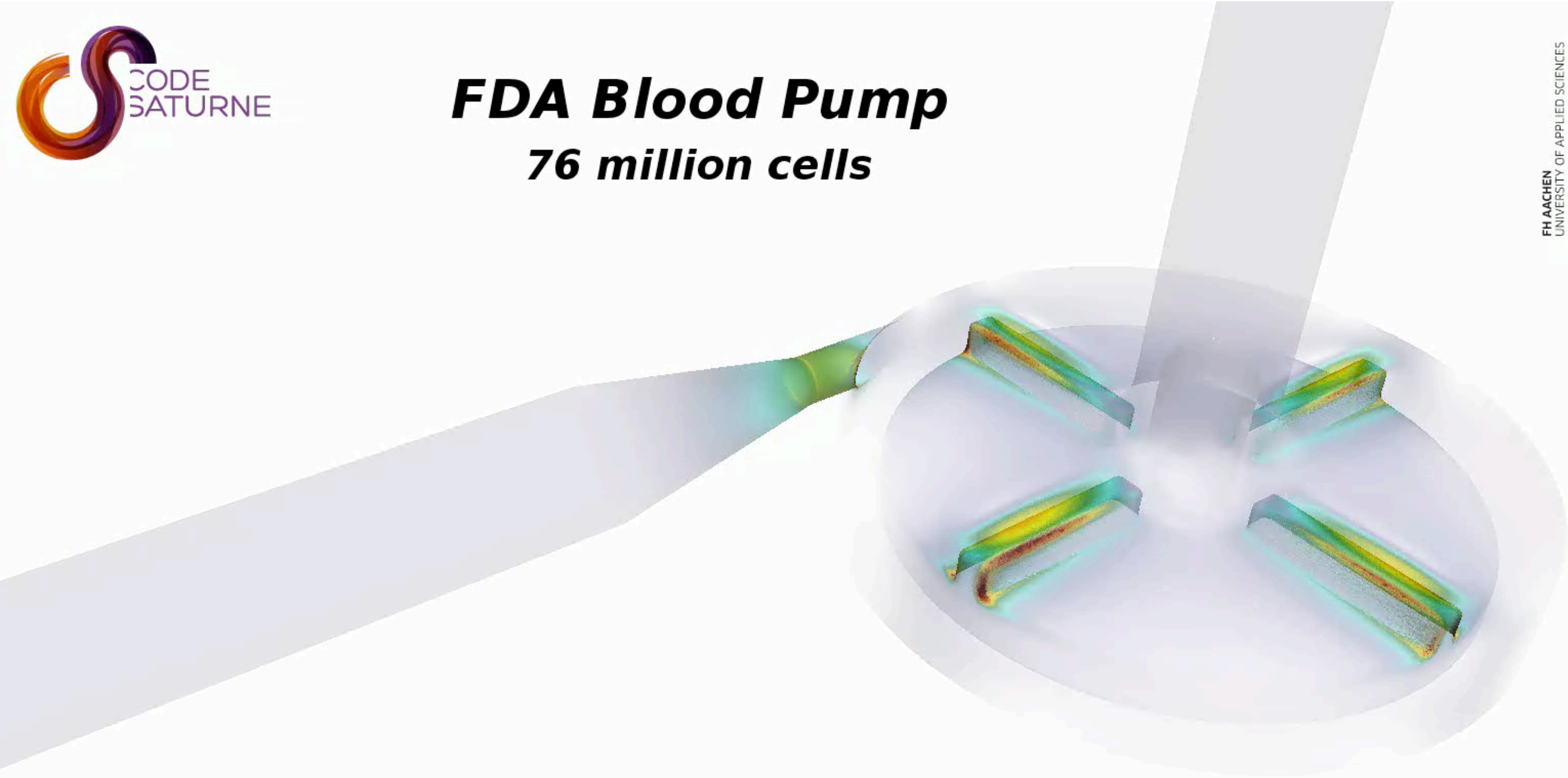
If only few time steps were loaded, then the simulation data could still be visualized on local iMacs with 20 GB RAM



For visualization of many time steps or pathlines JUVIS, a special visualization cluster in Research Facility Jülich had to be used. One fat node with 100 GB RAM was also available there.

FDA Blood Pump

76 million cells



CODE SATURNE

FH AACHEN UNIVERSITY OF APPLIED SCIENCES

Science & Technology Facilities Council Daresbury Laboratory

JÜLICH FORSCHUNGSZENTRUM

FDA blood pump study

Summary of Experiences with Code Saturne

Advantages

Well suited for High Performance Computing

Good scalability

Several turbulence models implemented

Good support

Can be improved:

Combination with Code Salome necessary, but **Code Salome cannot produce all geometrical details**

Shear rate visualization with **ParavView** does not yield adequate results in the wall regions

Restart function was not functioning at the time

Outlook / Future Objectives with Code Saturne

Next steps

Computations with a 200 million element mesh to perform RANS and LES computations

Use parallel visualization clusters

Immersive visualization

hemolysis computation

Outlook / Future Objectives with Code Saturne

New proposal for 11 million hours of computational time was submitted

Milestone	Activity	2015				2016	
M1	grid generation for three meshes		■	■			
M2	LES simulations on three meshes			■	■	■	
M3	grid convergence study				■	■	
M4	comparison to the RANS results					■	
M5	hemolysis analysis					■	
M6	post-processing the results				■	■	■
	publication						■
M7	scalability analysis		■	■	■	■	■

Table 2. Work schedule for the analysis of blood flows in a FDA blood pump. Each segment in the table corresponds to a period of three months starting from May 2015 and ending in April 2016.

Thank you very much for your attention!