2024

Trends and Challenges in Turbomachinery CFD – and the Differences to Marine Simulations

CAESES User Meeting 2024

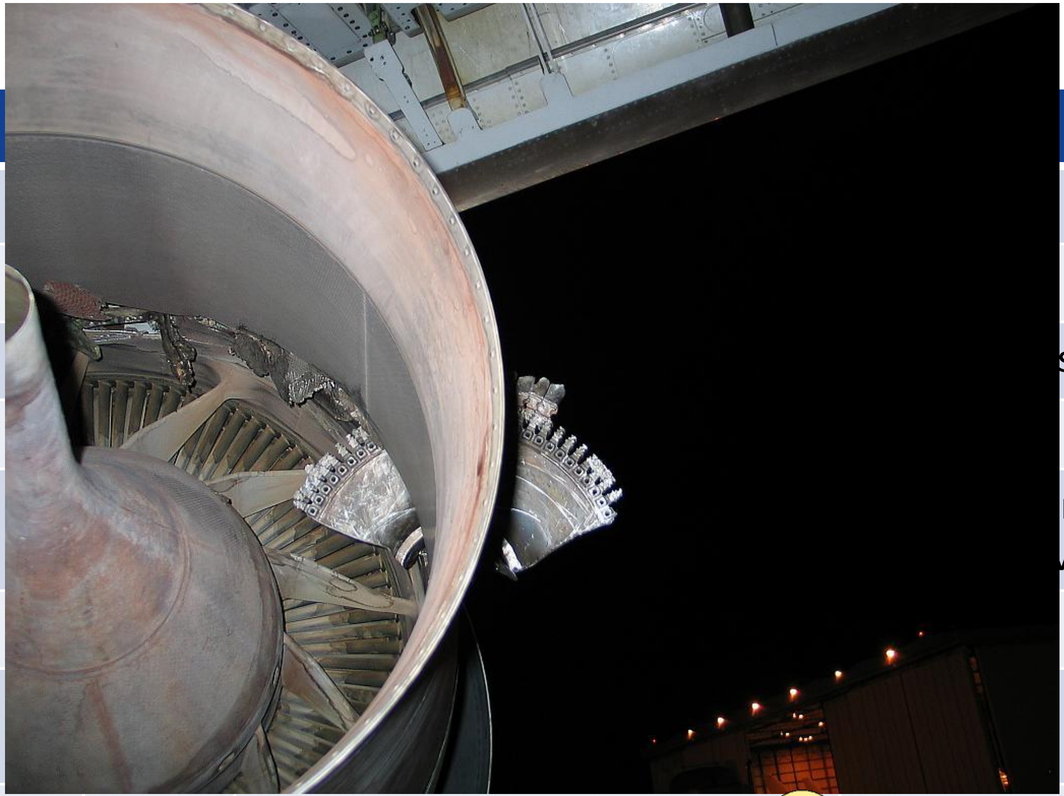
NUMECA INGENIEURBÜRO

A Day back in 2009….

Ummh, Thomas …
We don‘t call it a leading edge – it‘s a bow.

Let‘s have a workshop!

My first CAESES User Meeting:
- PANAMAX …. OK, makes sense.
- AFRAMAX ?????



			Turbo
Speed			
Size			
Fluid			s, Fluids
Re			
Multiphysics			mbustion, Radiation, vitation
Rotating Frames			
Time Domain			dy, Unsteady
Adaptive Grid Refinement		Yes – in good CFD Software.	No, and please don‘t ask why.
DoF		Up to 6	What?

We Don‘t Like DoF‘s!

*No Propellers, no wind turbines

Typical Behaviour of Industry (when I started):

		Marine	Turbo
Use of CFD		Not always	Always
Use of Optimisation		Often (applied to potential solvers)	Rarely (still)
(Model) Testing		Often (model scale)	After the design phase; Rarely scaled

Guideline to Today's CFD

*„Isolated Aerodynamics becomes less and less important!"**

- **Multi-Physics (= extended CFD):** Combustion, Spray, Radiation, Particle…..
- **Multi-Disciplinary (= CFD + Cxx):** Fluid-Structure Interaction (FSI), Conjugate Heat Transfer (CHT), Aeroacoustics (CAA), etc.
- **Multi-Component:** Single blade row → Stage → Compressor (Turbine) → Full Engine
- **High Fidelity / High Resolution:** Full CAD, 1 Billion + cells,
- **System Knowledge:** Optimisation, Uncertainty Quantification (UQ), Robust Design Optimisation
- **Less Modelling:** Unsteady Simulations, LES, DNS, HOM

*Li He, 2018

2

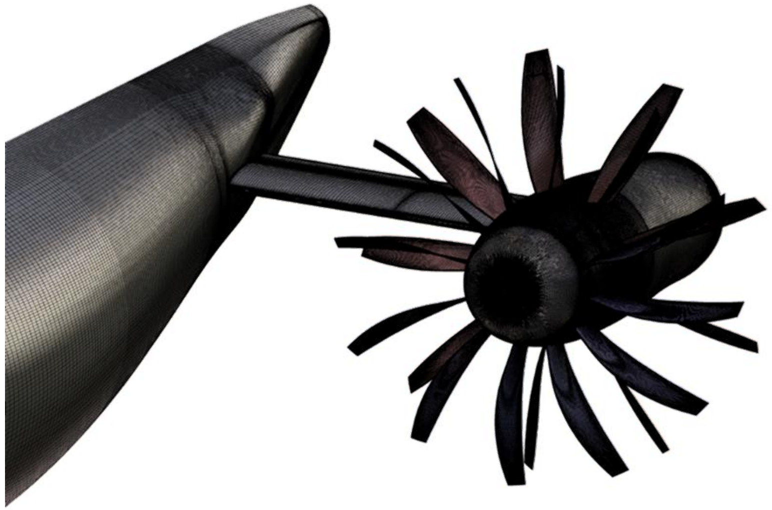
CFD: How far did we come?

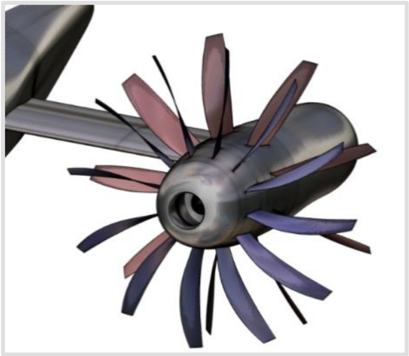
CFD: How far did we come?

CROR (Our Revenge for AFRAMAX)

Contra **R**otating **O**pen **R**otor:

- Huge SFC improvements
- Rotor-Rotor interaction
- Pressure fluctuations
- High acoustic loads
- Unsteady CFD simulation required



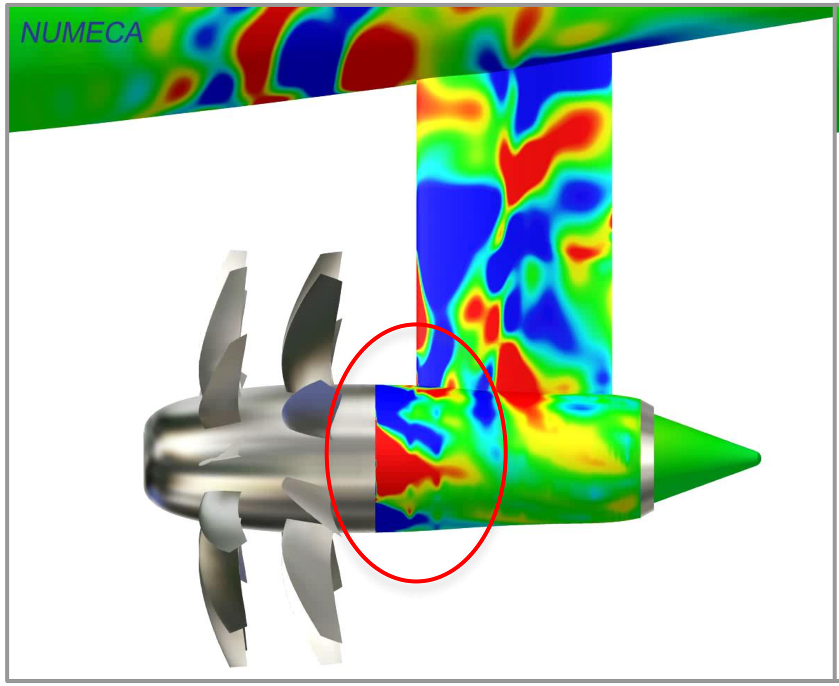


Nonlinear Harmonic Method (NLH) vs. classic unsteady

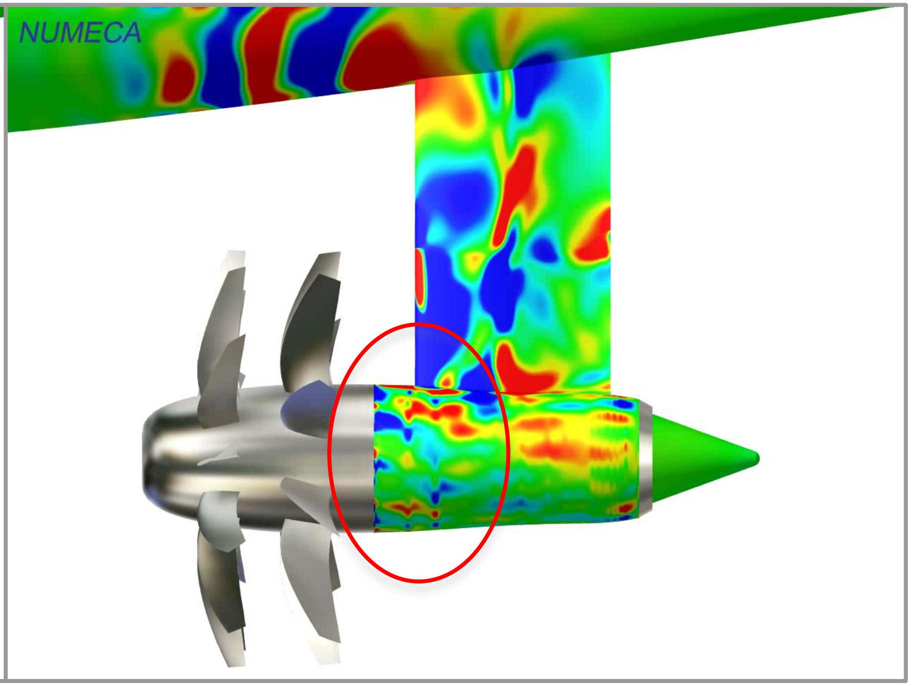
Quantity	NLH	Classic unsteady
Cells	~ 18 Mio.	~ 67 Mio.
Mesh Factor	1	3,7
Time steps	1000	360*20*2*1306
CPU time/ time step	780 s	269 s
CPU time	0.3 days	2,177 days
Factor	1	7,159

CFD: How far did we come?

CROR: Acoustic Waves



NLH Rank 1



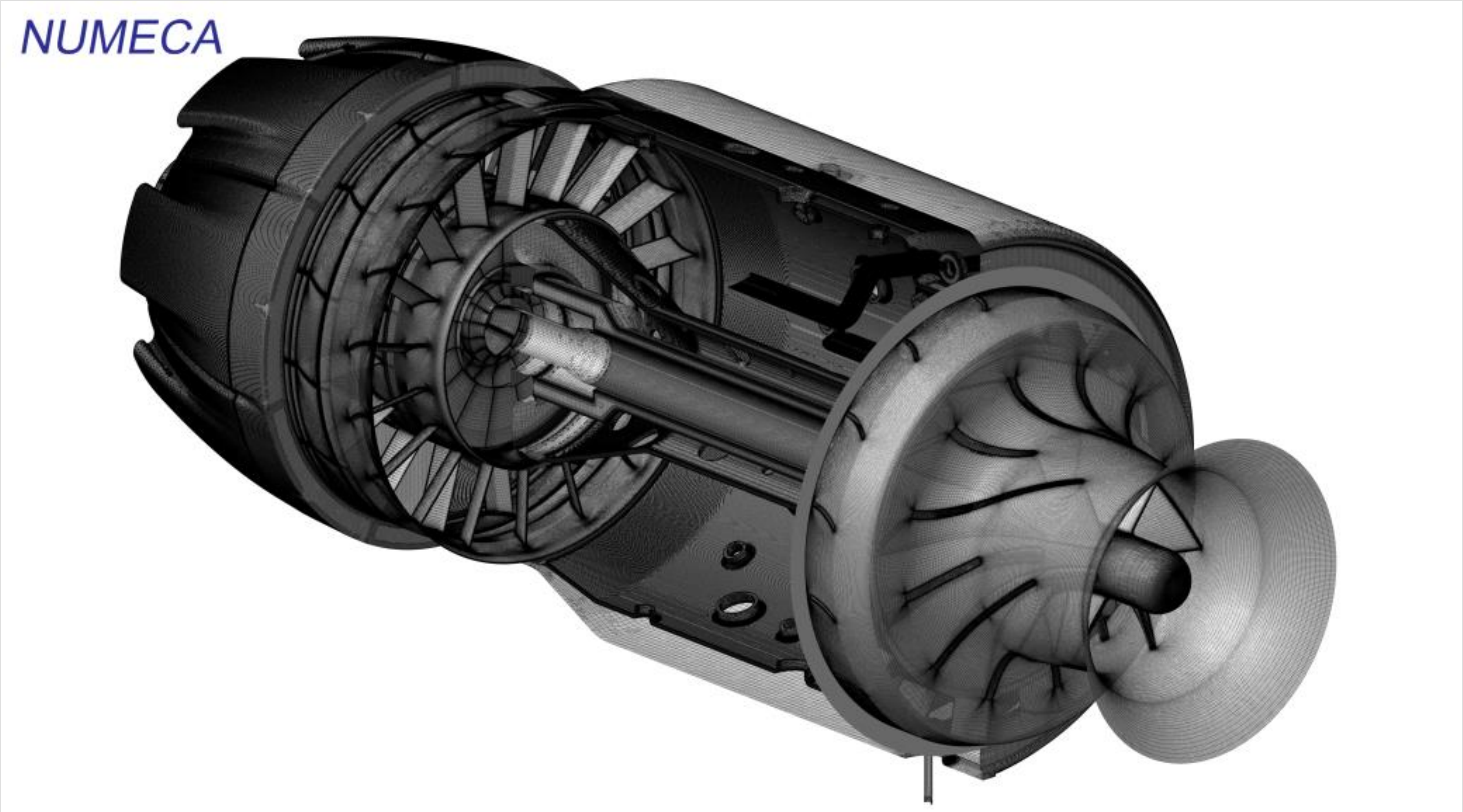
NLH Rank 2

$$\overline{p(t)} - p(t) \text{ using } \overline{p(t)} = \sum_{i=1}^{i=N} \frac{p(t)}{N}$$

Animation of static pressure difference on fuselage, pylon and nacelle

CFD: How far did we come?

Multi-Component Simulation: Full Engine

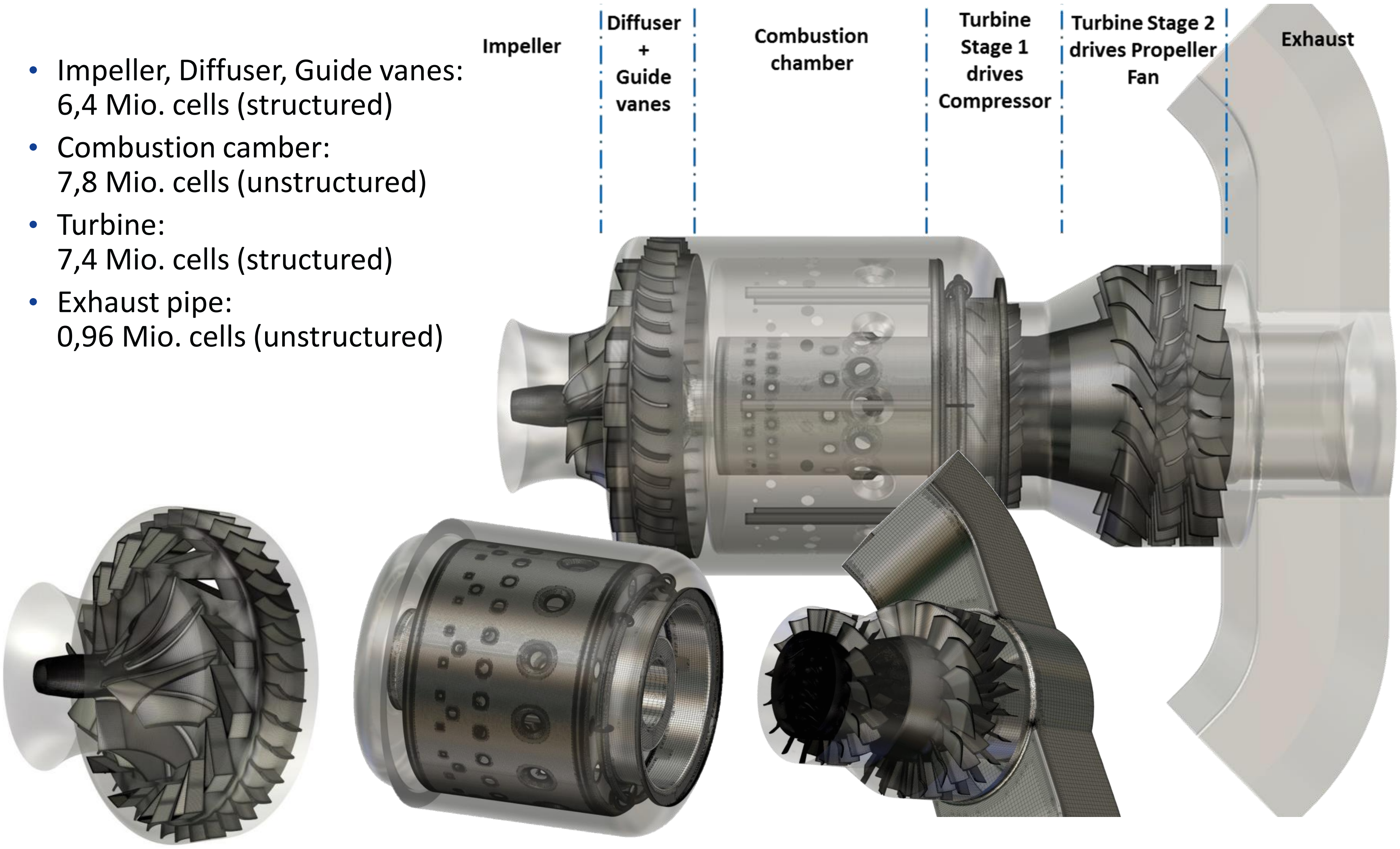


Full Micro Gas Turbine KJ-66

CFD: How far did we come?

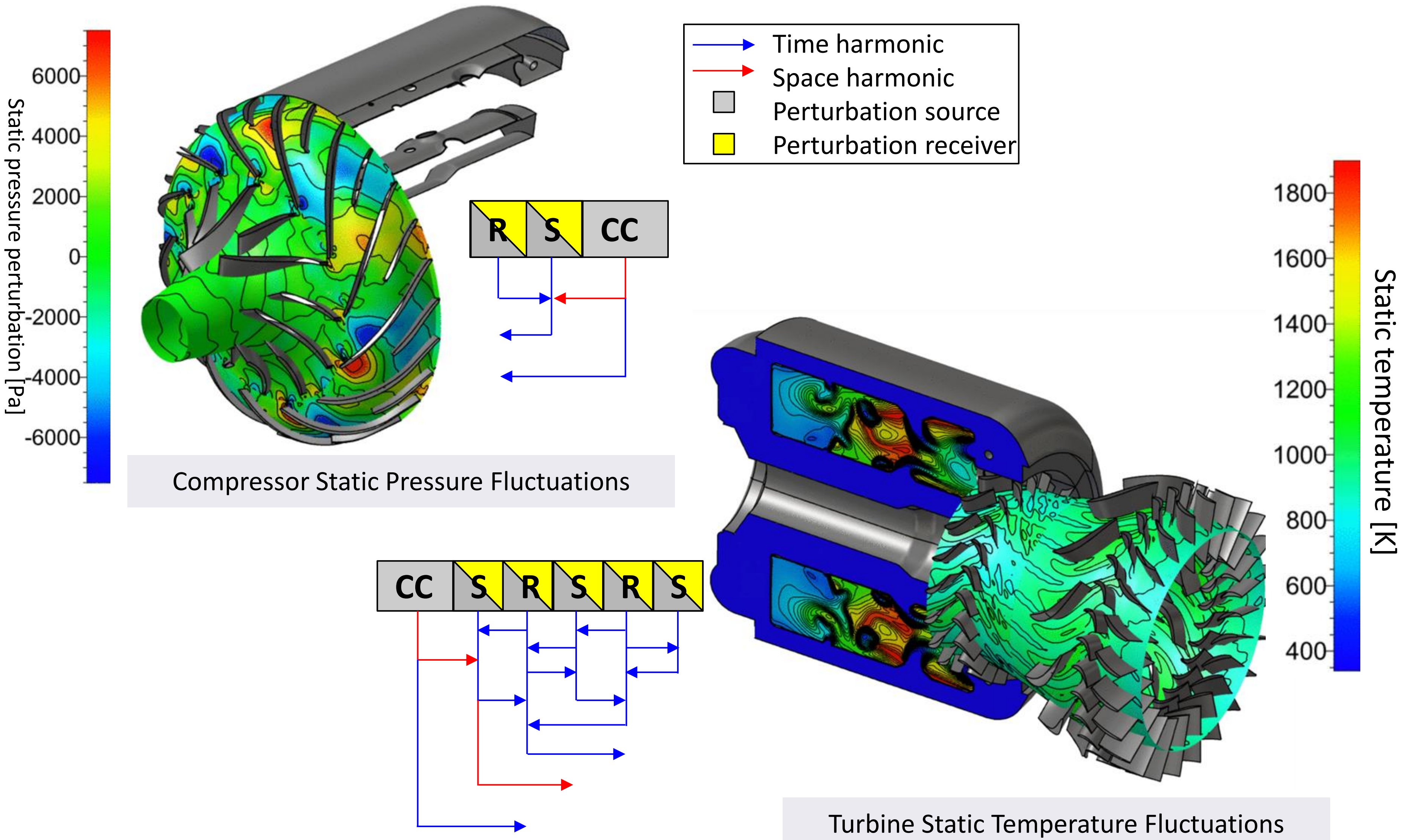
KJ-66 Micro Turbo Jet Engine

- Impeller, Diffuser, Guide vanes: 6,4 Mio. cells (structured)
- Combustion camber: 7,8 Mio. cells (unstructured)
- Turbine: 7,4 Mio. cells (structured)
- Exhaust pipe: 0,96 Mio. cells (unstructured)



CFD: How far did we come?

Reconstruction of Unsteady Flow Field

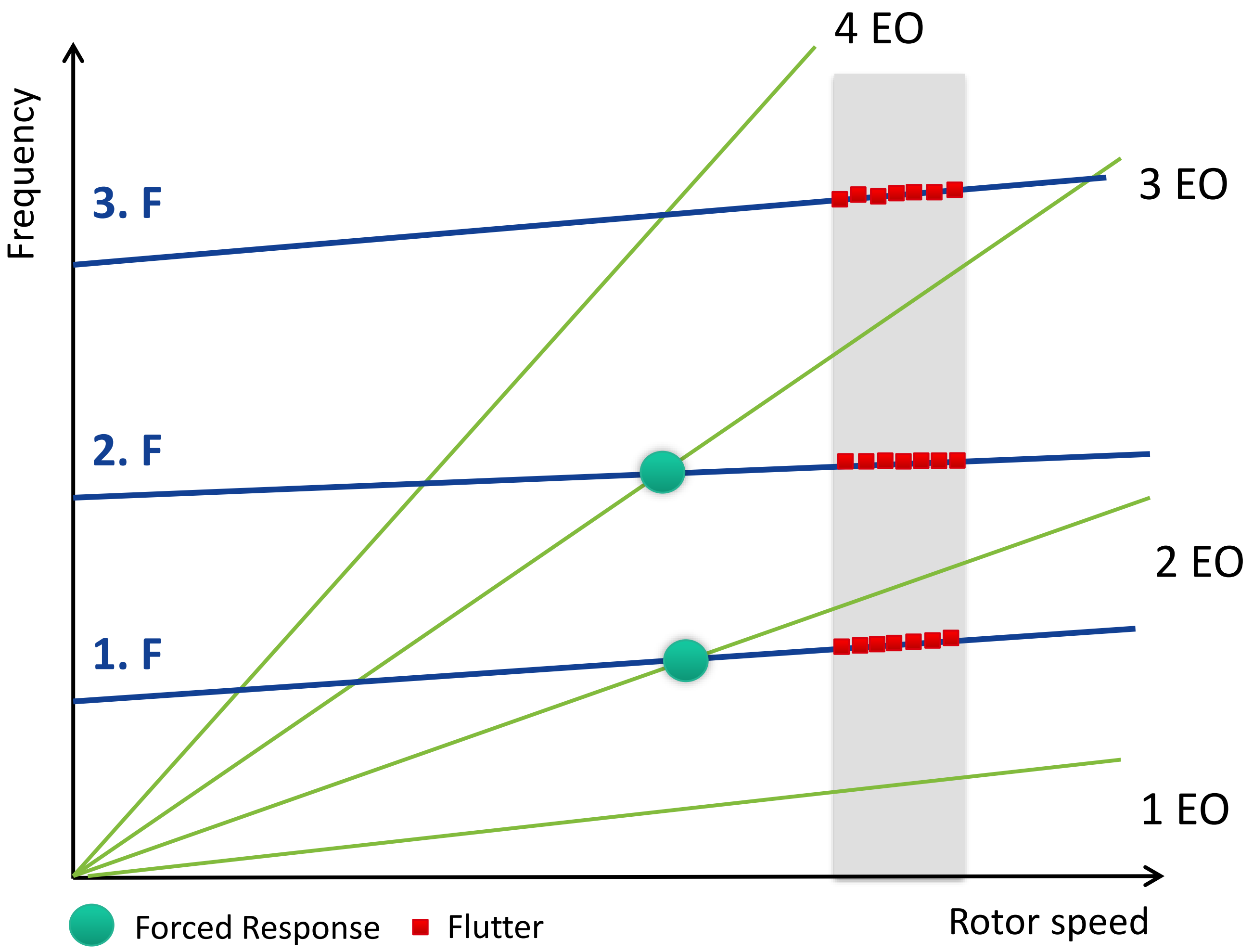


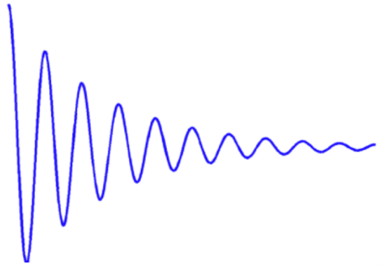
Compressor Static Pressure Fluctuations

Turbine Static Temperature Fluctuations

CFD: How far did we come?

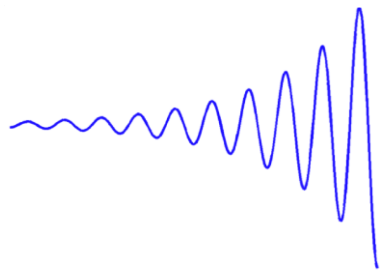
FSI: Campbell Diagram





Aero. Damping > 0

No Flutter



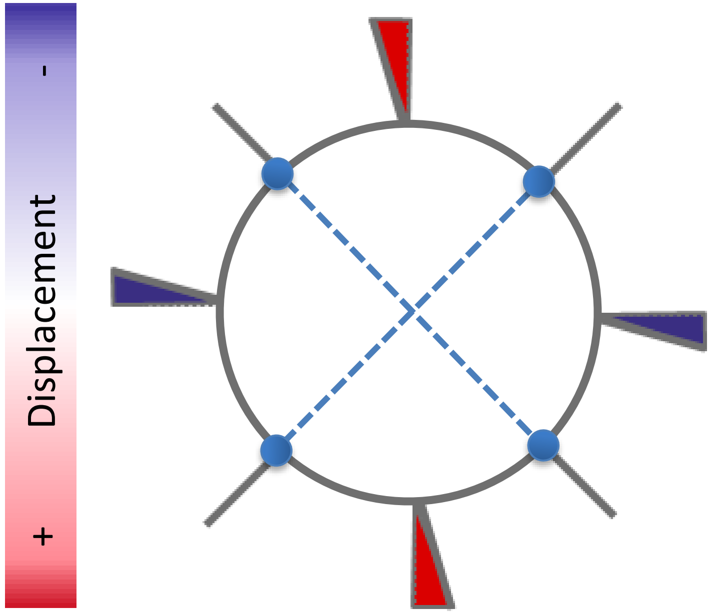
Aero. Damping < 0

Flutter

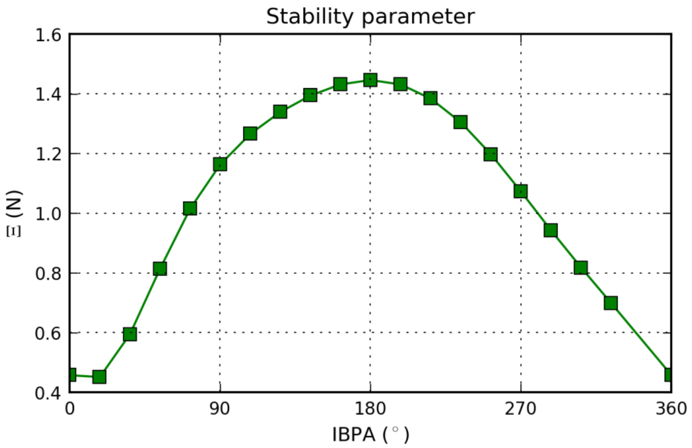
Dynamic FSI Phenomena: Forced response & flutter

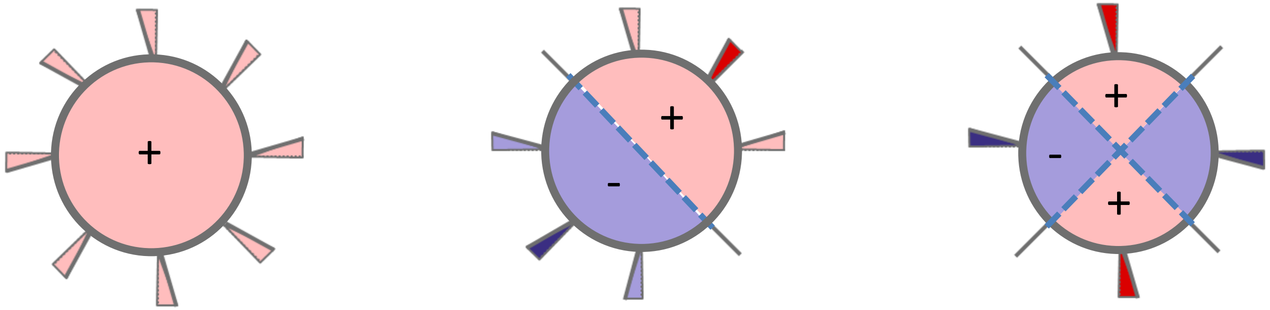
CFD: How far did we come?

Inter Blade Phase Angle



IBPA $\sigma = \left(\frac{360° \cdot ND}{N_{Blade}}\right)$





IBPA=0° ND=0 | IBPA=45° ND=1 | IBPA=90° ND=2

CFD: How far did we come?

Forced Response: Radial Turbine

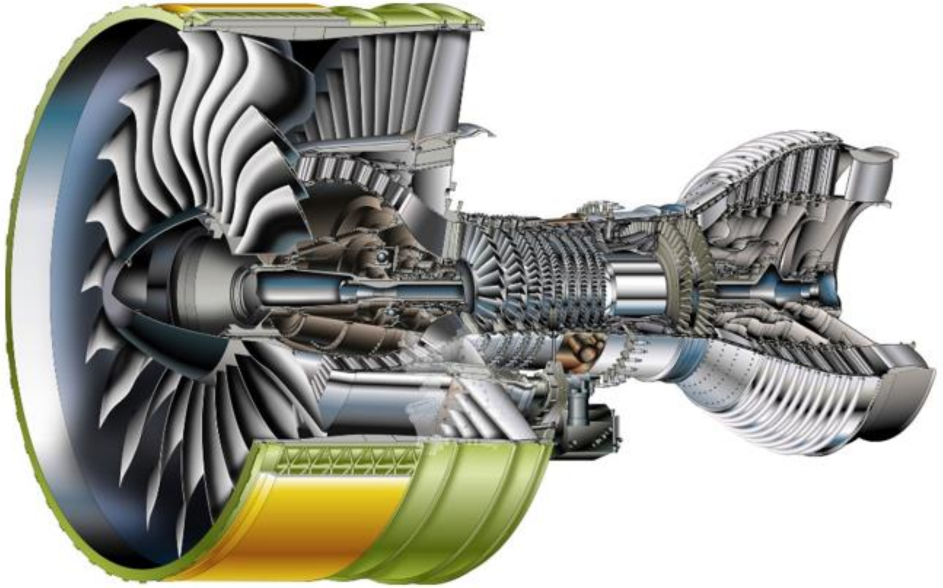
Aerodynamic forcing

Aerodynamic damping

Courtesy: ITSM Stuttgart

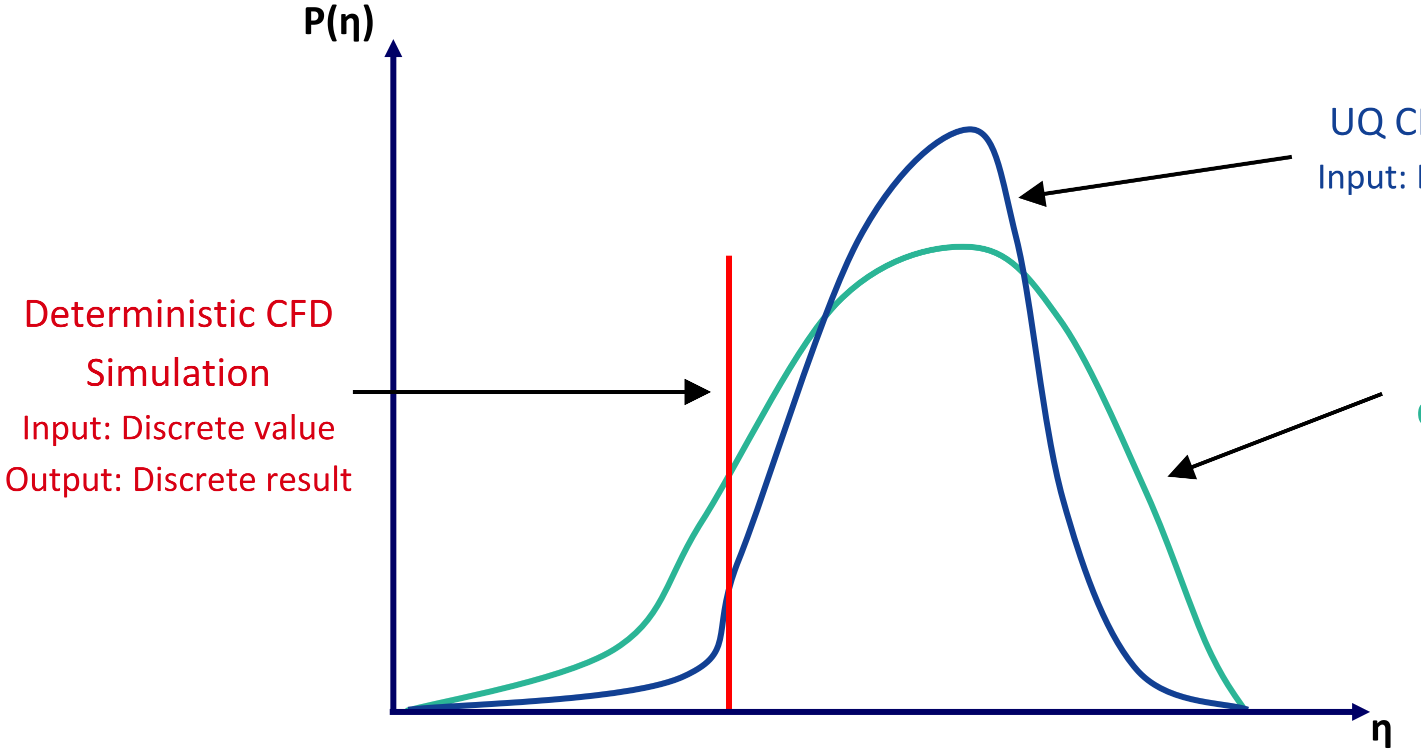
CFD simulations are run today with a unique set of input data. Real conditions are, however, subject to uncertainties:

- Uncertain operating conditions
  - Inflow conditions, pressures, (fuel) mass flow
- Manufacturing uncertainties
  - Milling, forging, assembly tolerances
- Geometrical shape variability
  - Life degradation such as erosion, foreign object damage, fouling , tip gap
- Examples are aero engines, aircraft wings, ship propellers or hulls



New type of simulations: Input & predicted quantities (loads, resistance, speed, efficiencies, manufacturing tolerances…..)

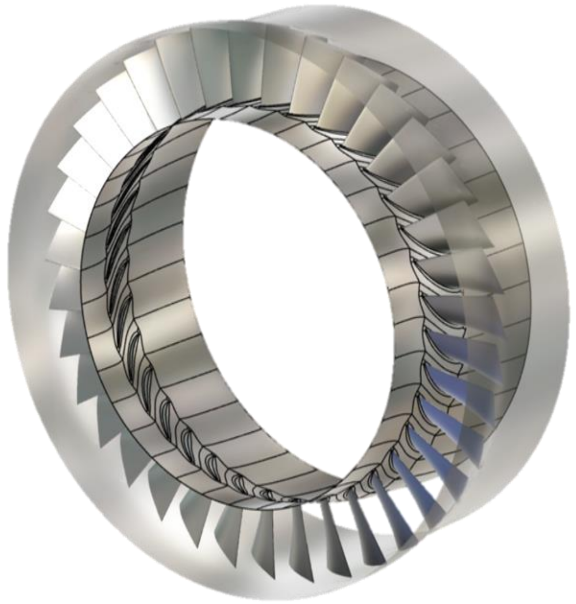
- No longer represented by a discrete value,
- But by a Probability Density Function (PDF)
- Provides a domain of confidence in relation to the considered uncertainties

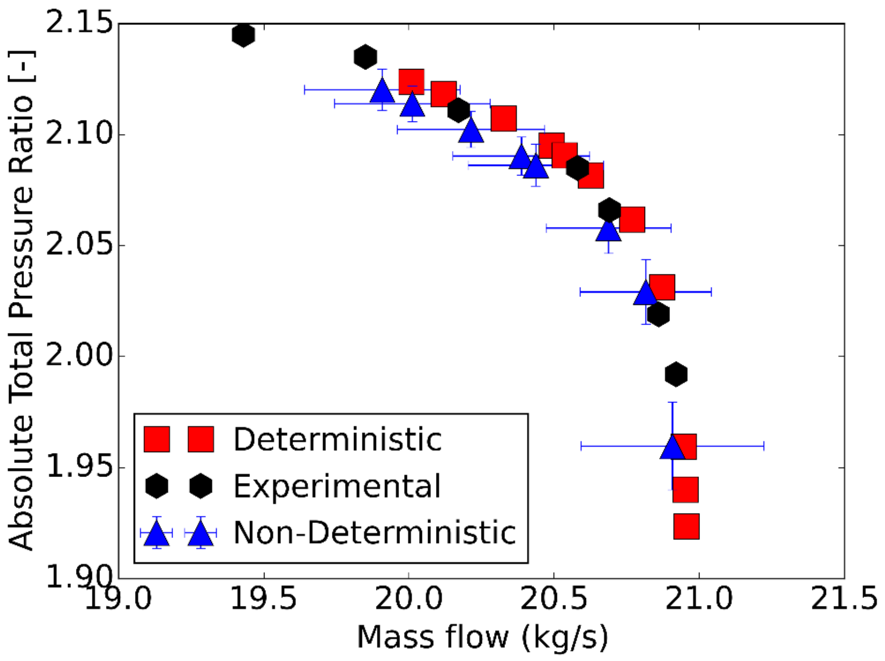


CFD: How far did we come?

UQ: Performance Curve

- NASA Rotor 37: 5 Uncertainties (Inflow, Outflow, Tip Gap)
- UQ provides a domain of confidence (here UQ bars: ±σ), which can be obtained with 11 simulations per operating point.
- Outcome: The most likely result of an UQ simulation is not identical with the result of a deterministic simulation using the most likely inputs!





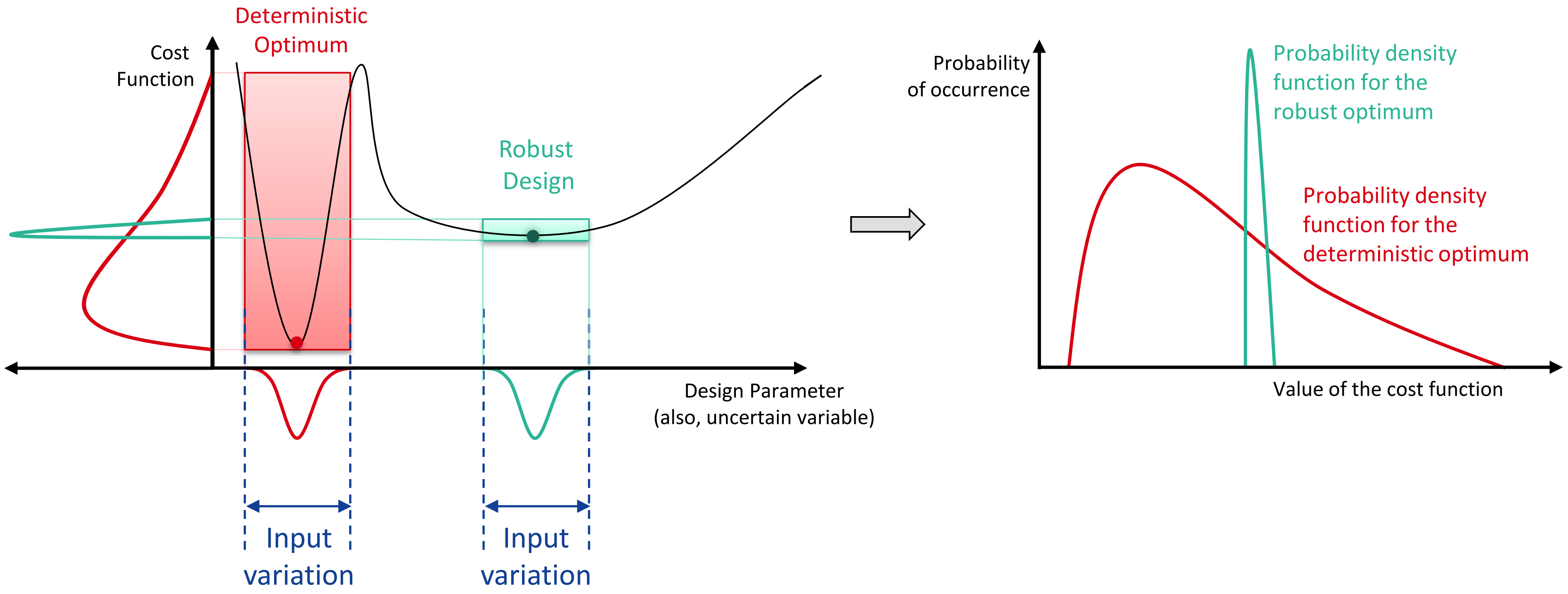
Total pressure ratio over mass flow

CFD: How far did we come?

Robust Design Optimisation

UQ + Opti. = RDO

- Minimise the variation of the system response
- By optimising for a decreased standard deviation: Min $\sigma(\eta)$
- Outcome: A **Design** which is **Robust** against a variation of input parameters



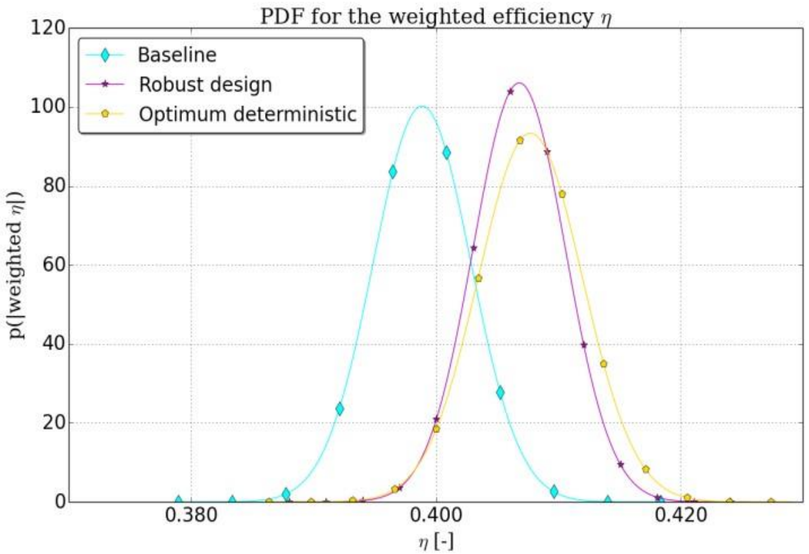
RDO Example: Ship Propeller

Operational variabilities:

- Operating loading
- Trim angle
- Inflow conditions

Geometrical shape variabilities:

- Erosion/damage / fouling
- Manufacturing tolerances

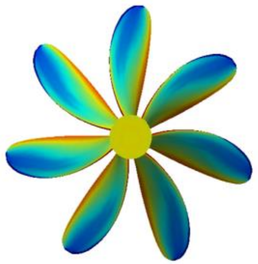


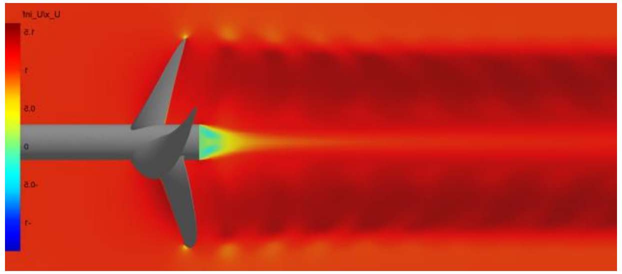
RDO:

- 18 design variables + 4 uncertainties
- Max $\bar{\eta}$ ↗ Min $\sigma(\eta)$ ↘

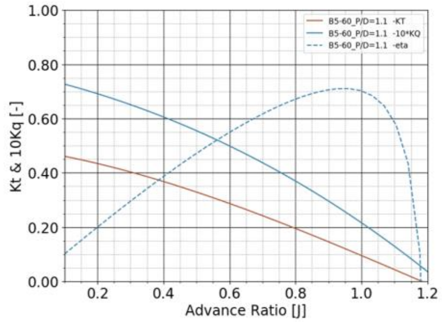
A more reliable and more efficient propeller!

- CFD simulations necessary for predicting and fine-tuning ship propulsion.





- Full curve (~ 20 operating points) needed.



No!

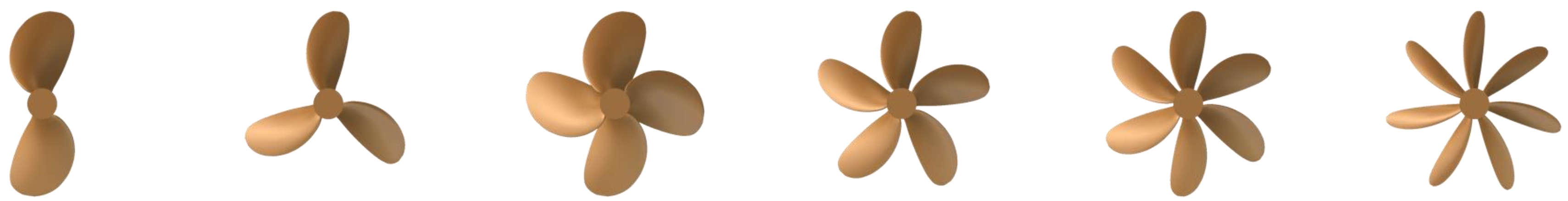
- Expensive. 100’s CPUh. ~~Exploration stage?~~

- Artificial Intelligence / Machine Learning offer instantaneous results – as exact as CFD.

Parametrized Geometry

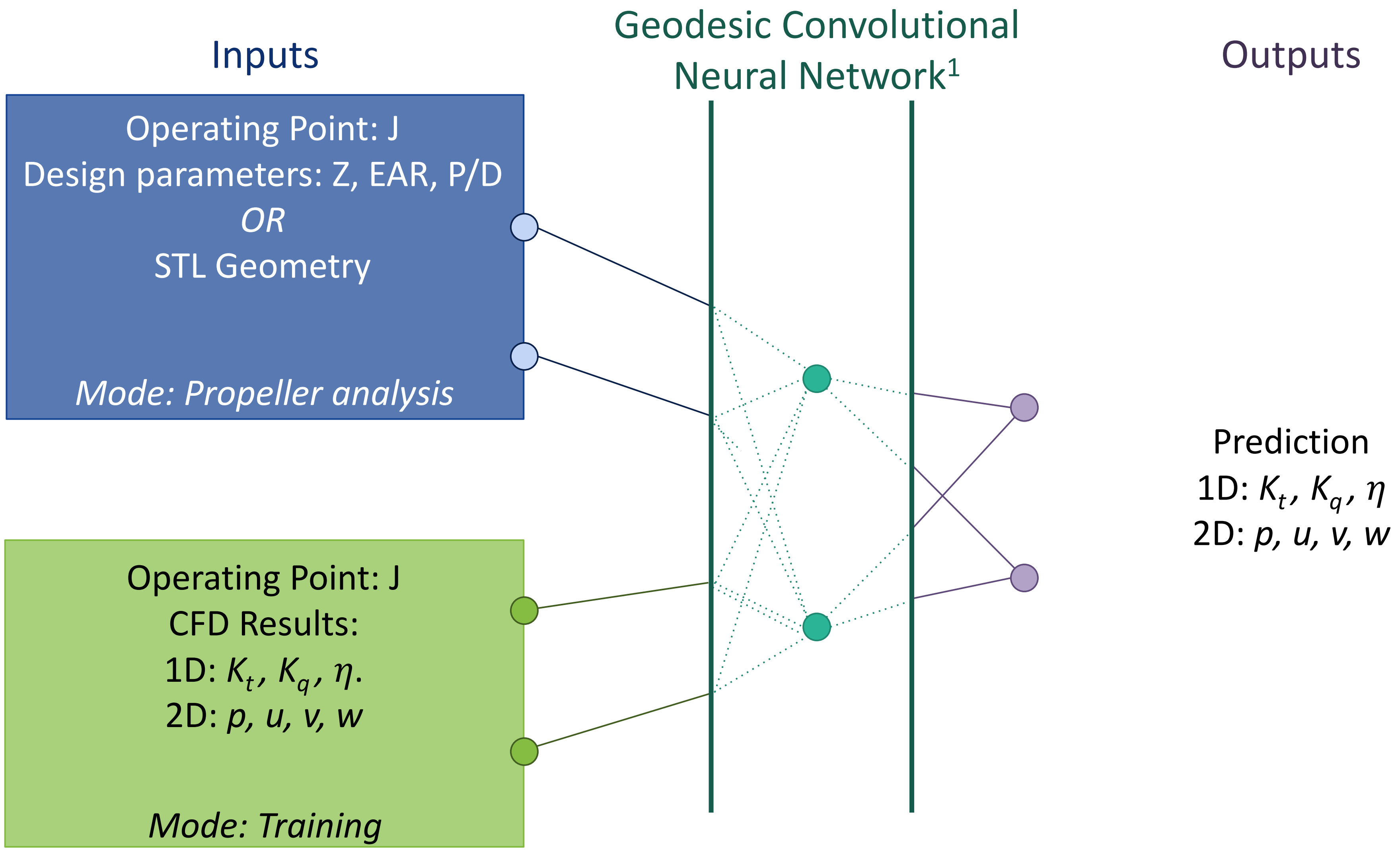
$$c(r) = \frac{K(r) \cdot \boxed{D} \cdot \boxed{(A_E/A_0)}}{\boxed{Z}} \qquad + \boxed{\frac{P}{D}}$$

Diameter | Number of blades | Expanded area ratio | Pitch-Diameter ratio



CFD: How far did we come?

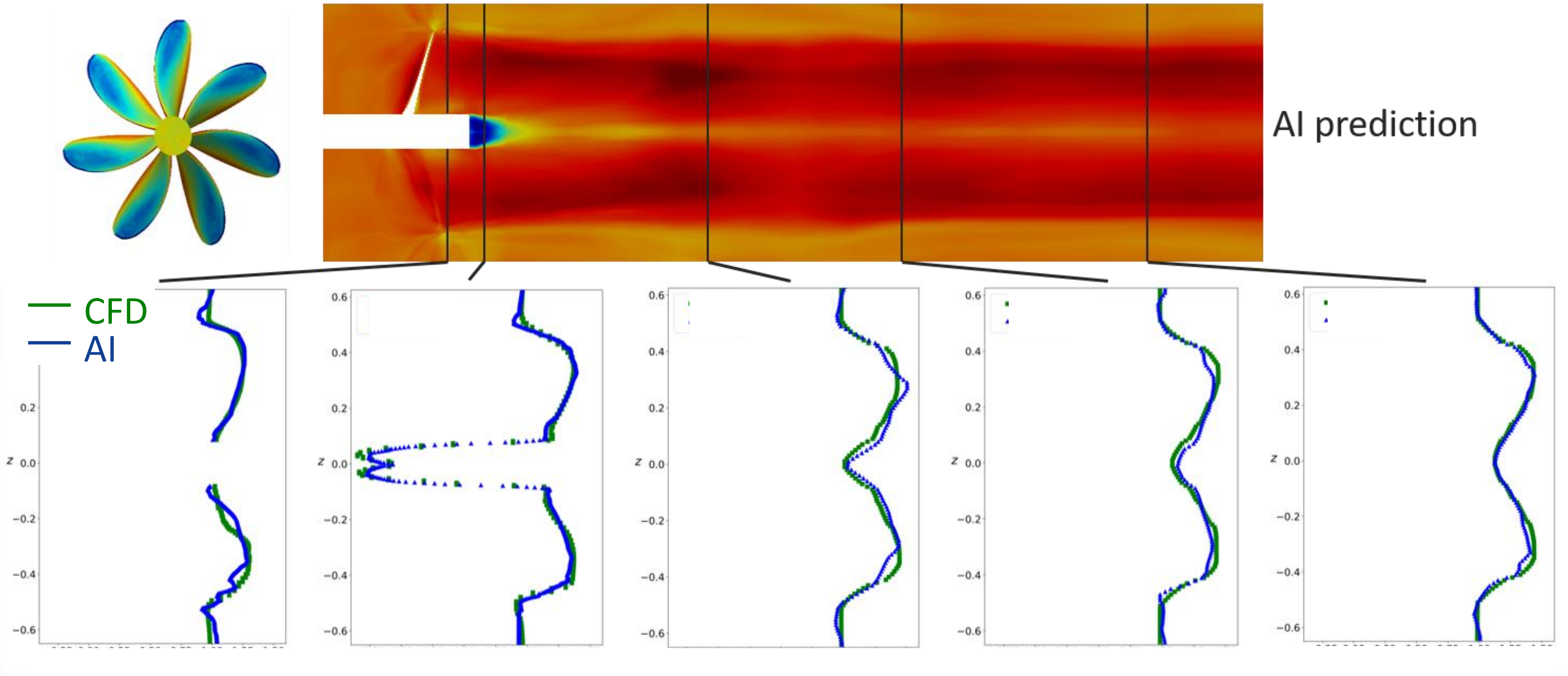
Workflow



[1] Baque, P., Remelli, E., Fleuret, F., & Fua, P. (2018, July). Geodesic convolutional shape optimization. In *International Conference on Machine Learning* (pp. 472-481). PMLR.

CFD: How far did we come?

Comparison of Axial Velocity in Wake - 7 Blades



- Good agreement between AI prediction and CFD.
- Small local differences in fluctuating regions.

CFD: How far did we come?

Good & Fast

	Averaged Error [%]
K_t	1.21
$10K_q$	1.48
η	1.5

- Averaged error over all samples below 1.5 %
- Same order of magnitude as modeling error in CFD

→ **Good Enough!**

	Time
CFD	~ 100 CPUh
AI	~ 20s

- Trained AI has negligible response time

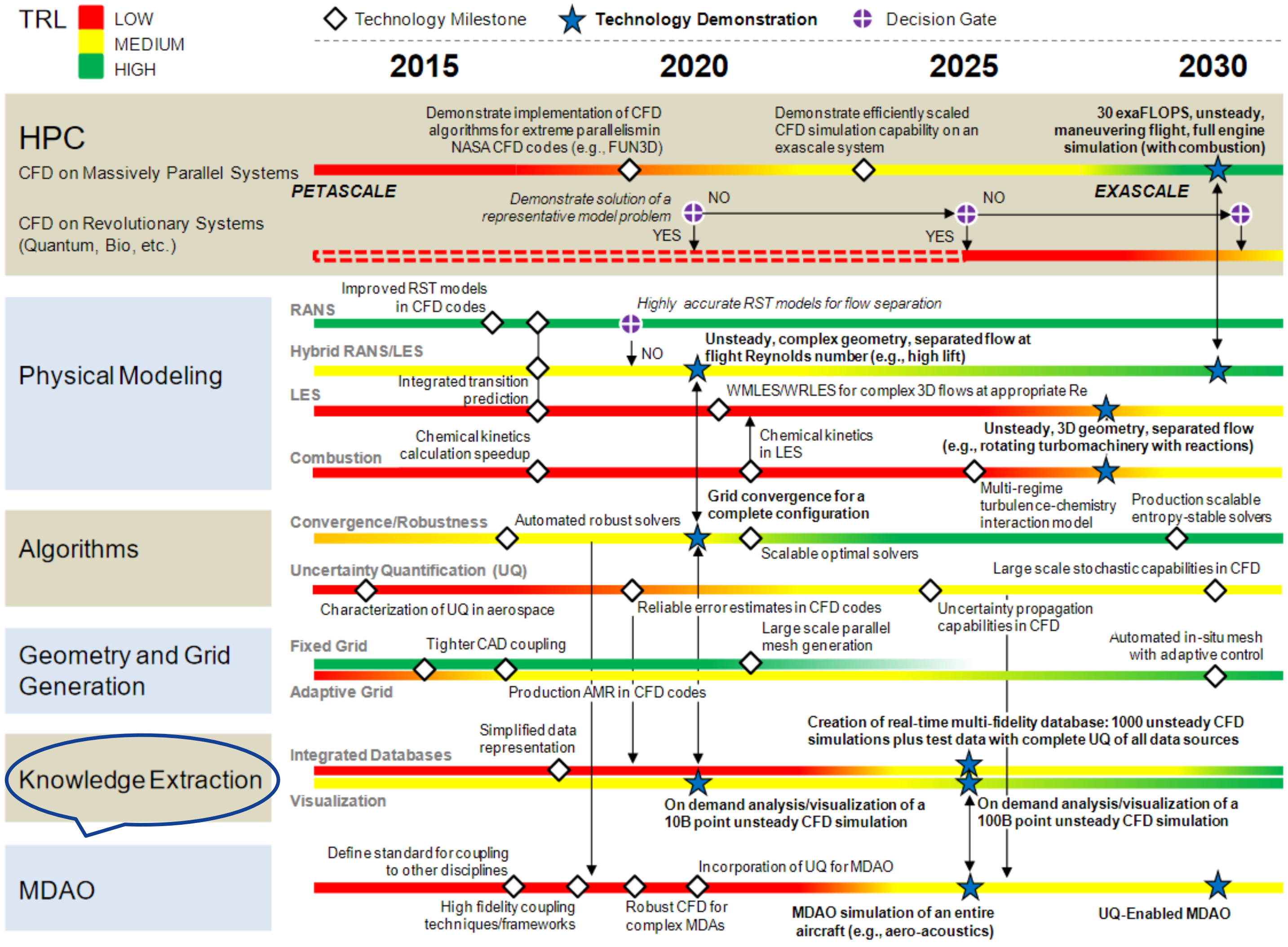
→ **Way Faster!**

3

Down the road: The near future

Down the road: The near future

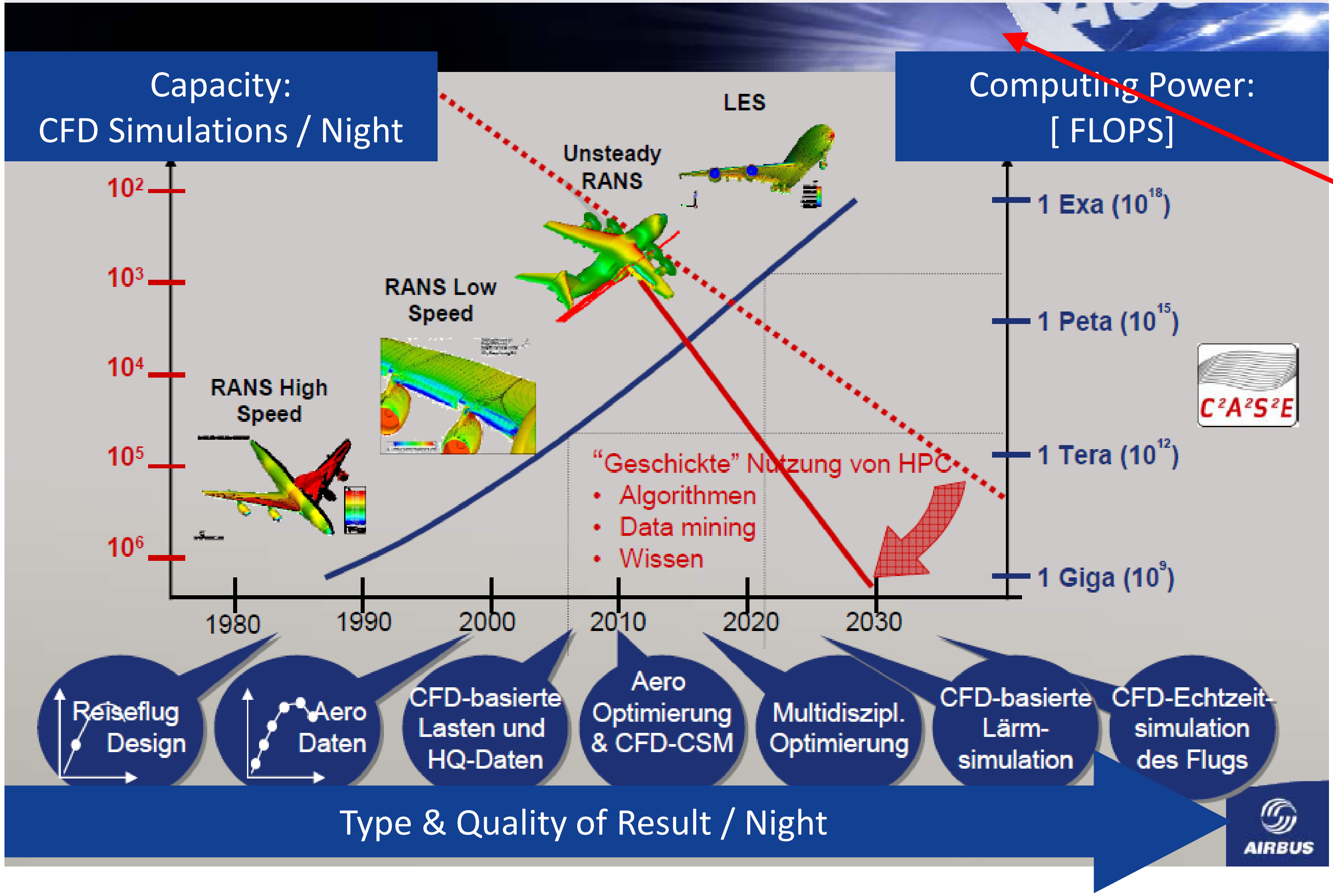
The Guideline: NASA Vision 2030



NASA Vision 2030 Roadmap

NASA/CR–2014-218178: CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences

Expectation in the Numerical Simulation



Japan Plans Zeta-Class Computer (2030)

AIRBUS Vision from 2008
Opening of the **C²A²S²E HPC Cluster**
13.05.2008 in Braunschweig

Down the road: The near future

Knowledge Extraction (Post-Processing): Paradigm Change

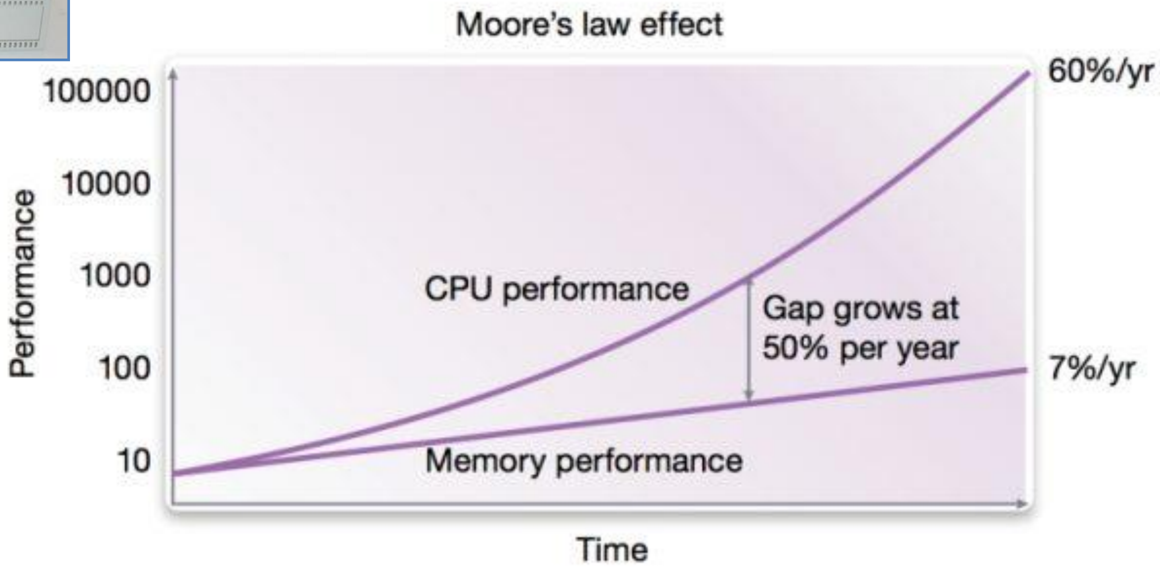
	1991	2020	Faktor
CPU [Mflops]	20	2,000,000	100,000
RAM [Mb]	64	512,000	8,000

Problem: Memory out-performed by CPU:

- Large calculations possible
- Bottleneck: I/O
- I/O today in the order (at least) of processing
- Post-Processing becomes a problem

Solutions:

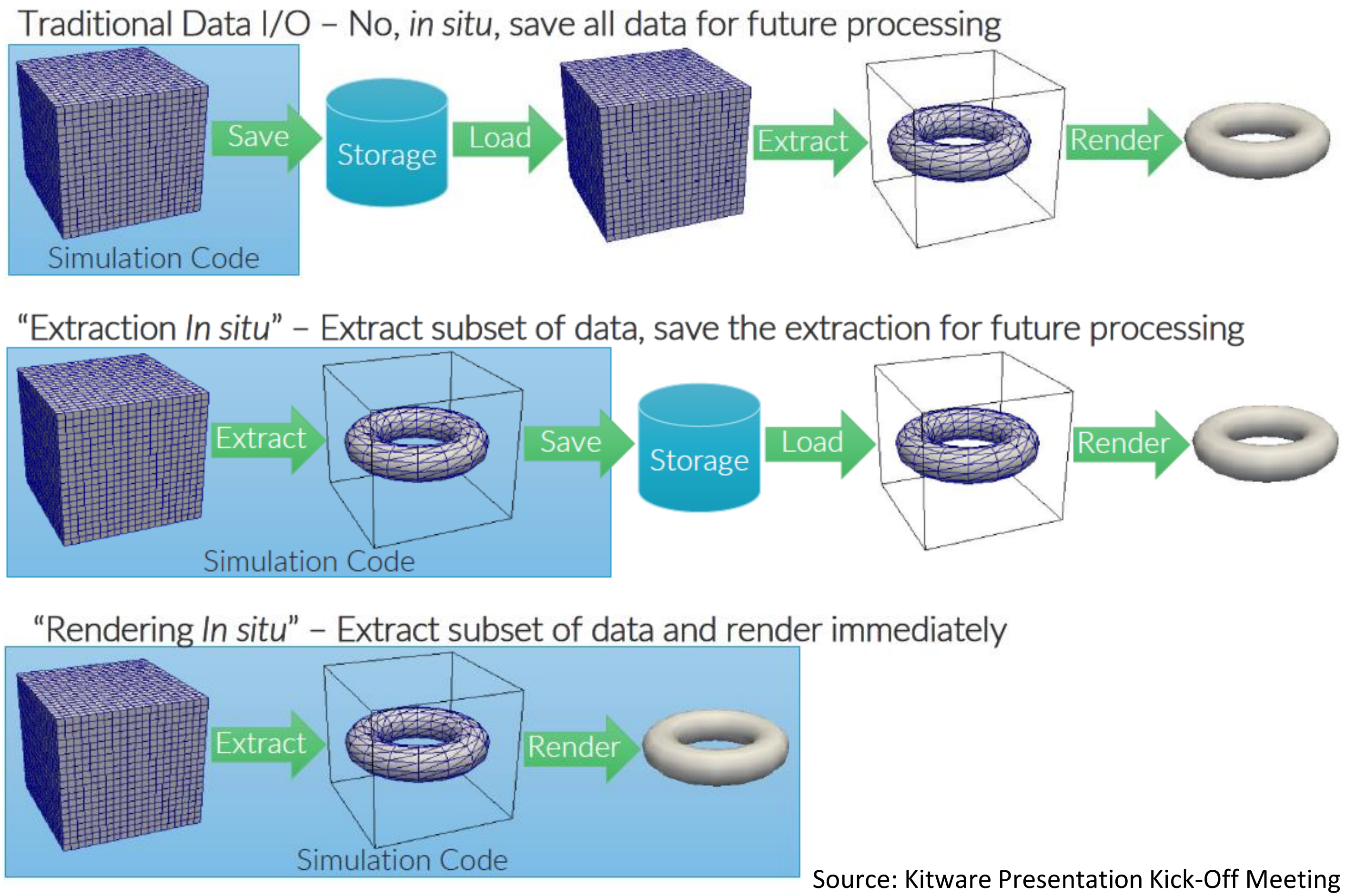
- Co-Processing ("in-situ" processing)
- Graphical Postprocessing (*.png)



https://www.extremetech.com/computing/233691-phase-change-memory-can-operate-thousands-of-times-faster-than-current-ram

>DEALING WITH I/O BOTTLENECK

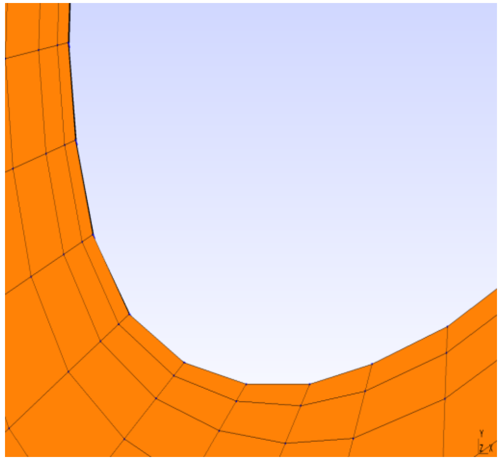
>>In-situ processing and rendering



Source: Kitware Presentation Kick-Off Meeting PRESTIGE 3.5.2018 Berlin

High Order Methods: Motivation

Probably the next generation CFD software for unsteady flows

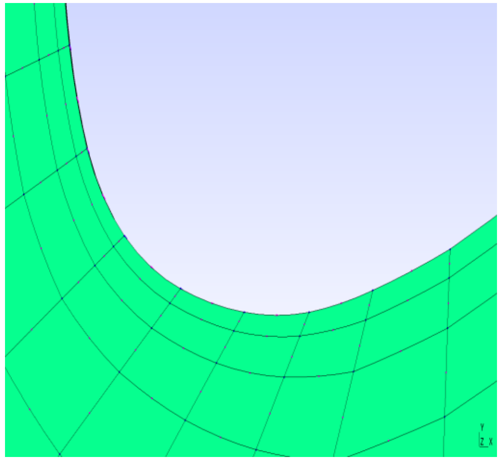


Current CFD codes are of second order (in the brochure):

- On smoothly varying cartesian grids
- On unstructured grids (?)

High order methods (HOM) on unstructured grids:

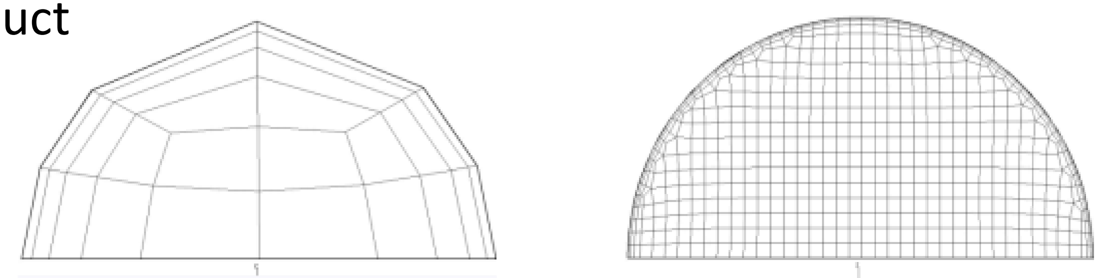
- Methods:
  - Discontinuous Galerkin methods (DG)
  - Flux Reconstruction methods (FR)
- Cell: Single values → Polynomials
- P-Adaptation: Accurate where necessary
- Provides highly accurate solutions on coarse grids
- Necessity for curved meshes at boundaries



Down the road: The near future

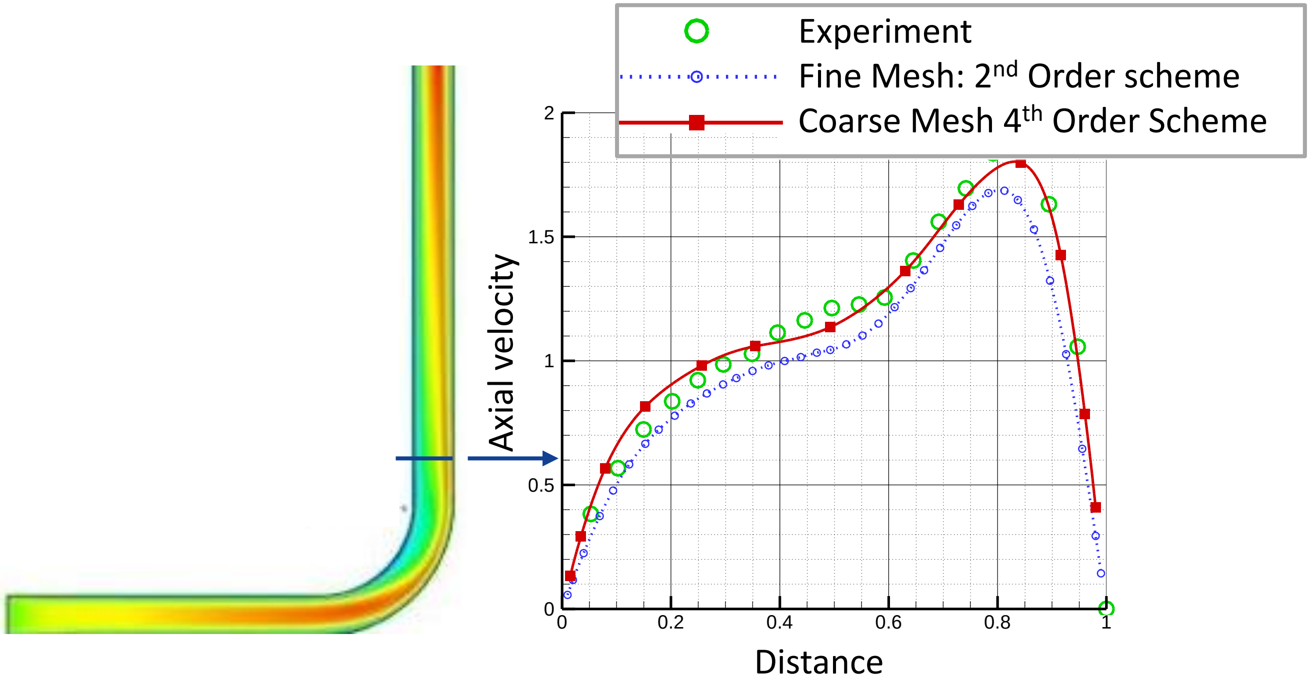
High Order Methods: Example

Laminar Flow Duct

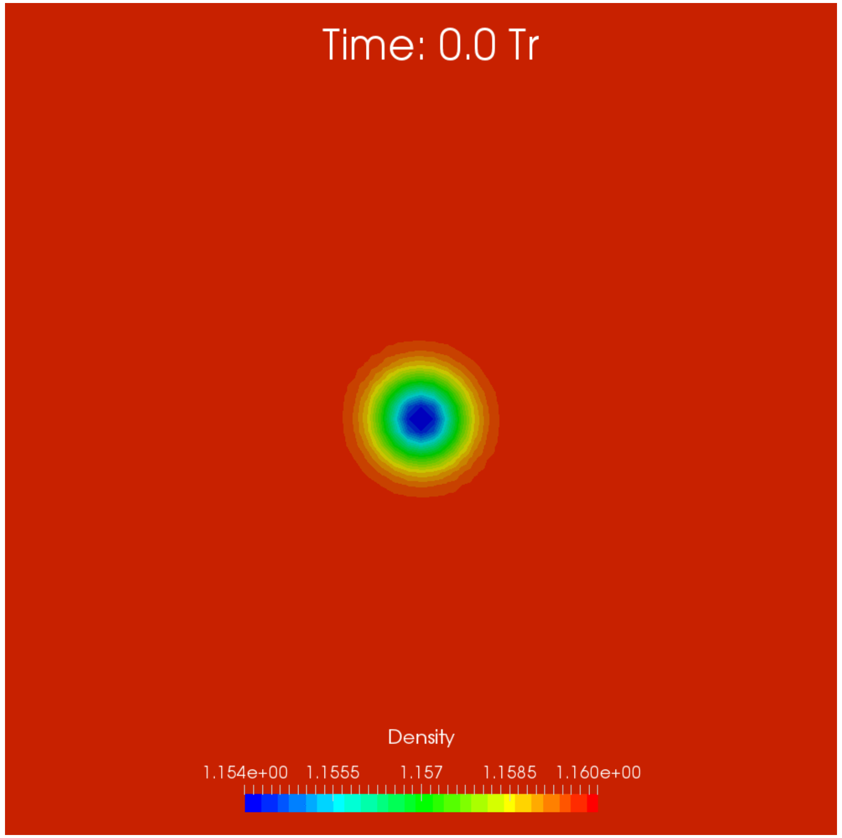


Cells: 2502

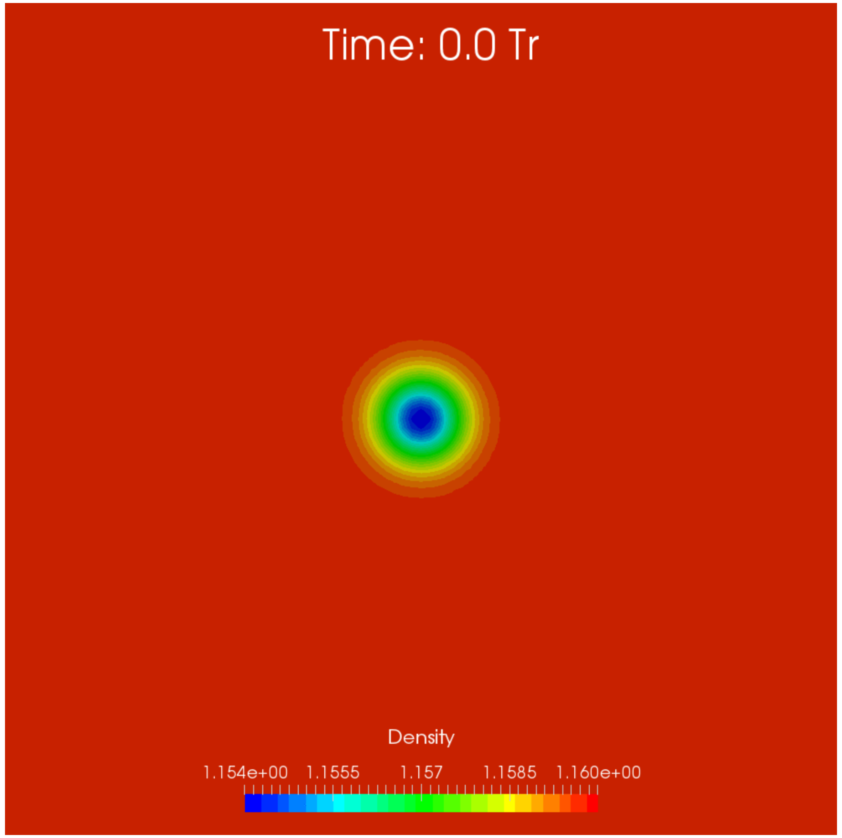
Cells: 139902



2nd Order Scheme
Mesh 64x64, P1 (=2nd order) 16384 DoFs



High Resolution 4th Order Scheme
Mesh 32x32, P3 (=4th order) 16384 DoFs



High Order Methods: Motivation

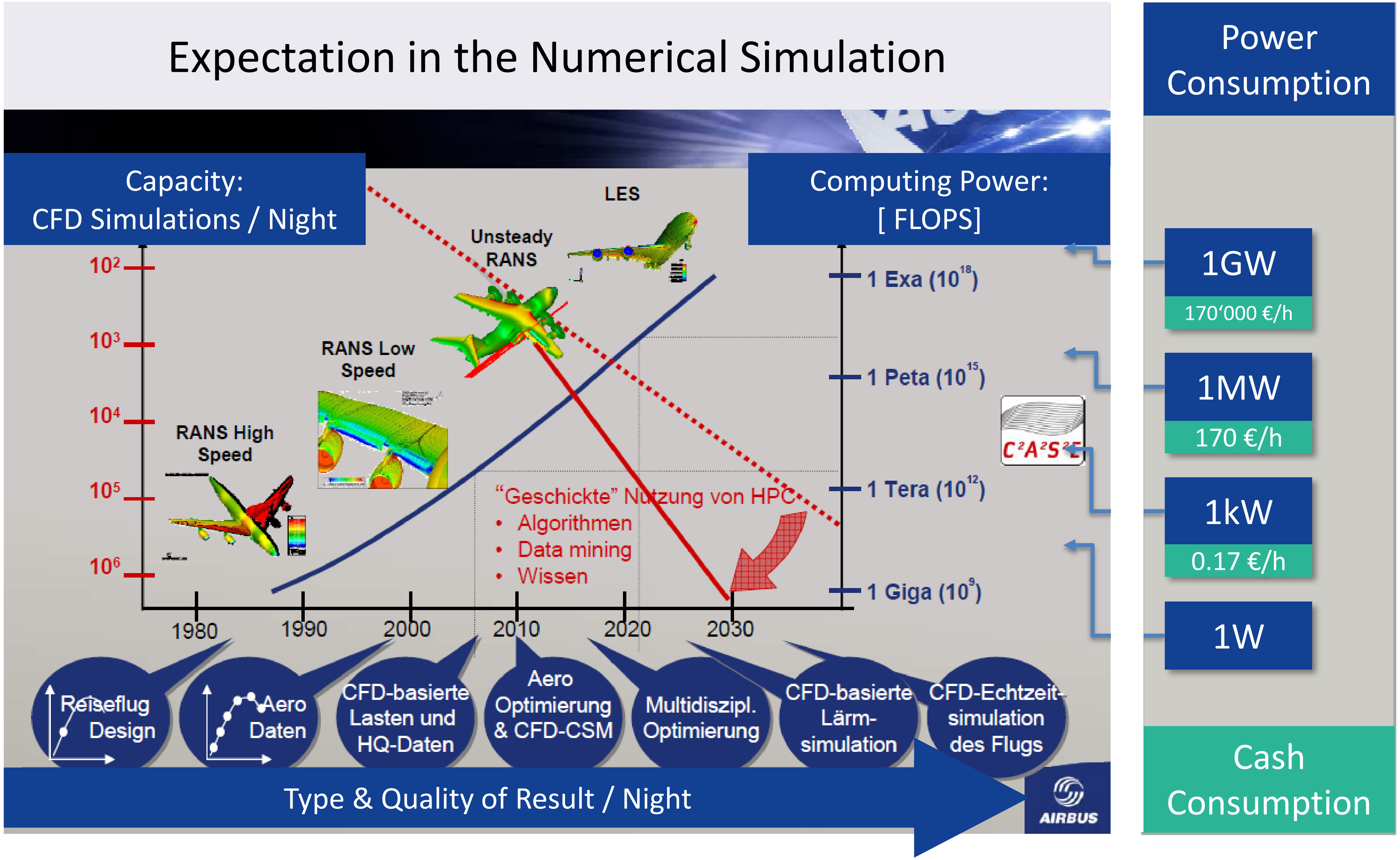
High Order Methods are computationally much more efficient than traditional methods (second order):

Order	DOF/cell	PPW	Mesh size (B)	Relative size	DOF (B)	Floats/Δt/ mesh cell	Relative floats	Relative cost
P1	8	75	421	1	16840	3.6×10^3	1	**1**
P2	27	15	3.3	0.0078	445	6.9×10^3	1.94	**1/66.2**
P3	64	8	0.51	0.0012	163	14.7×10^3	4.09	**1/203**

Bill Dawes, RR Aerothermal Conference 2016: Keynote 3

Down the road: The near future

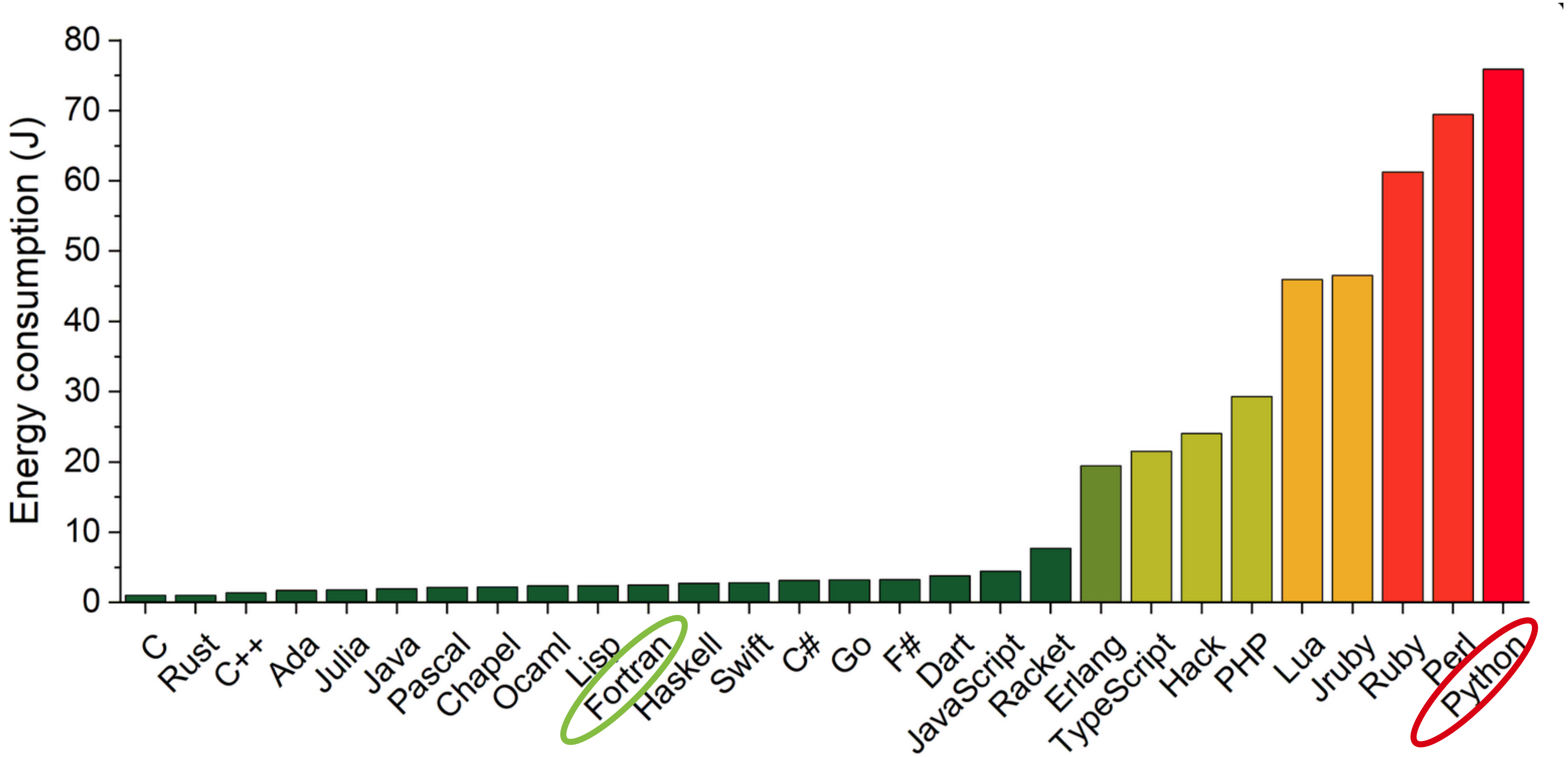
High Order Methods: Motivation



Bill Dawes, RR Aerothermal Conference 2016: Keynote 3

Down the road: The near future

Energy Efficient Programming



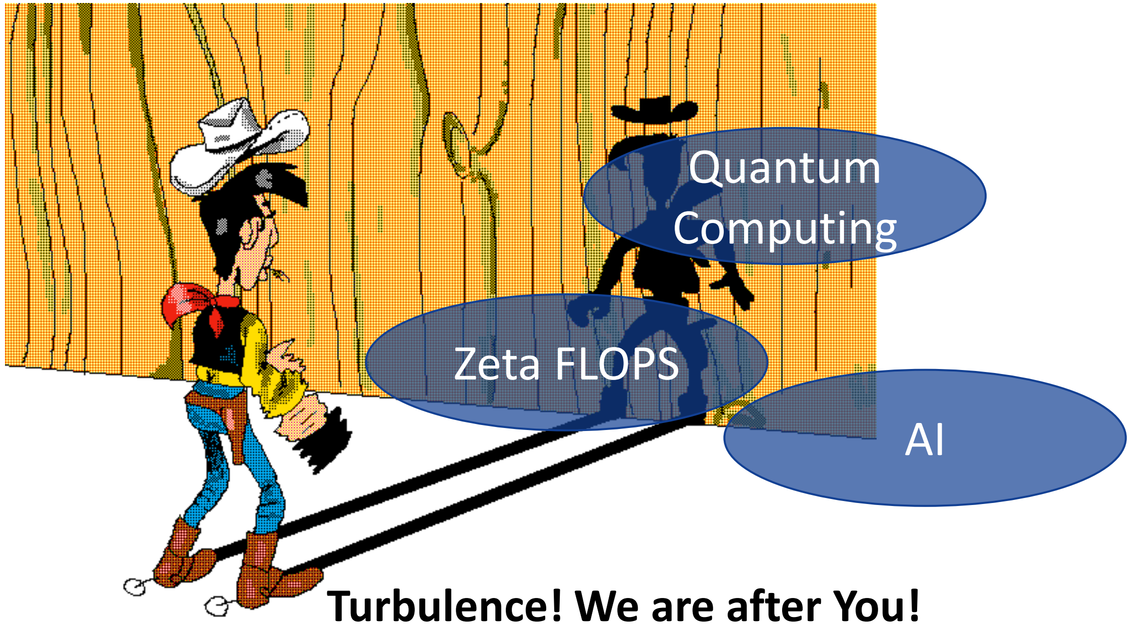
Glad to be old fashioned!

Blame on You!

Down the road: The near future

Turbulence: Still A Challenge

„Aristotle said a bunch of stuff that was wrong.
Galileo and Newton fixed things up.
Then Einstein broke everything again.
Now we basically got it all worked out, except for
Small stuff, big stuff, hot stuff, cold stuff,
fast stuff, heavy stuff, dark stuff,
The concept of time and ***Turbulence!****“**

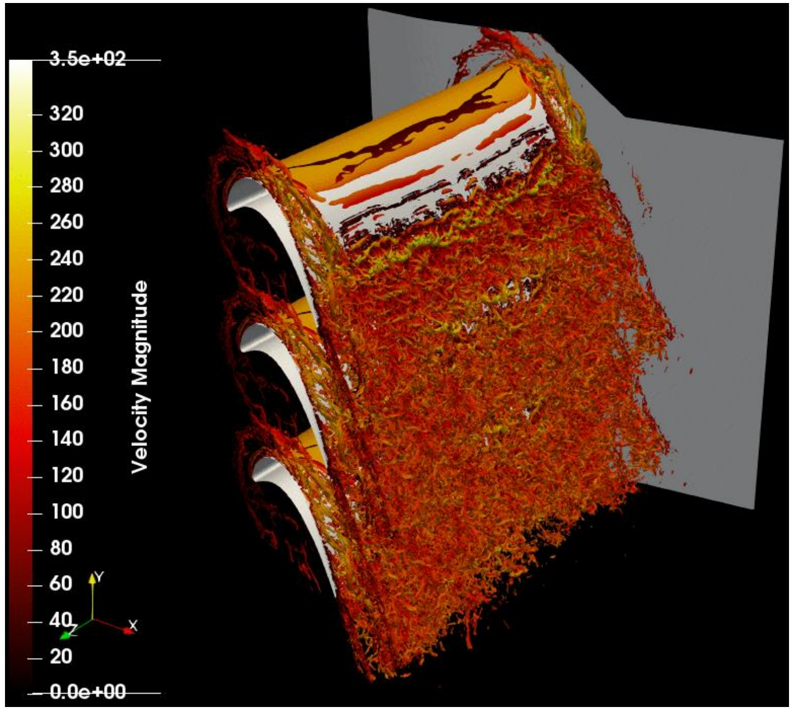


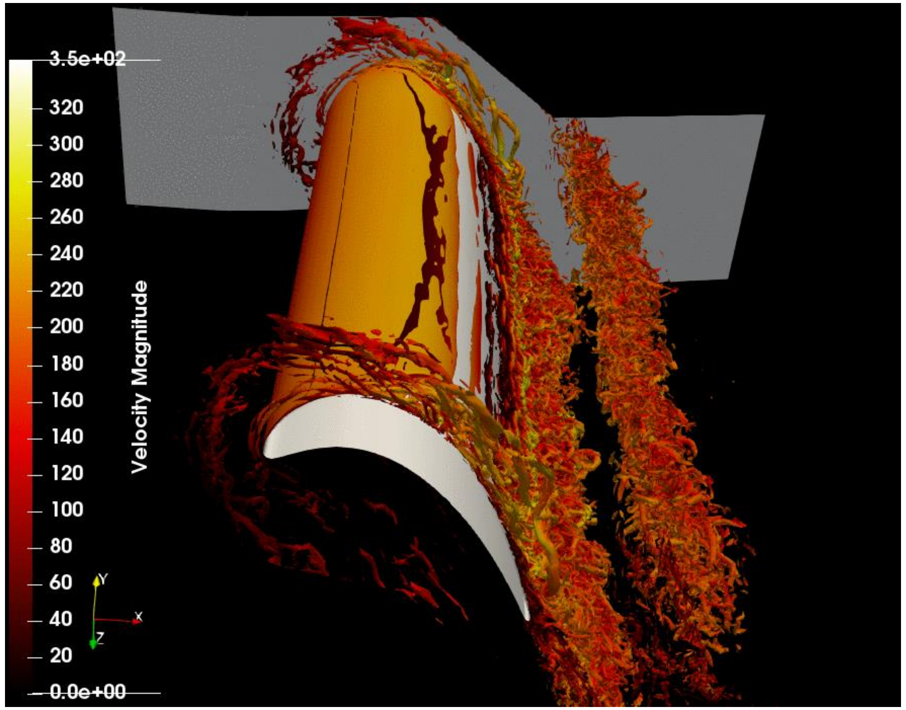
Turbulence! We are after You!

**Zach Weinersmith*

Down the road: The near future

LES Low Pressure Turbine





- T161 Cascade (MTU)
- Order 5

Down the road: The near future

LES Low Pressure Turbine

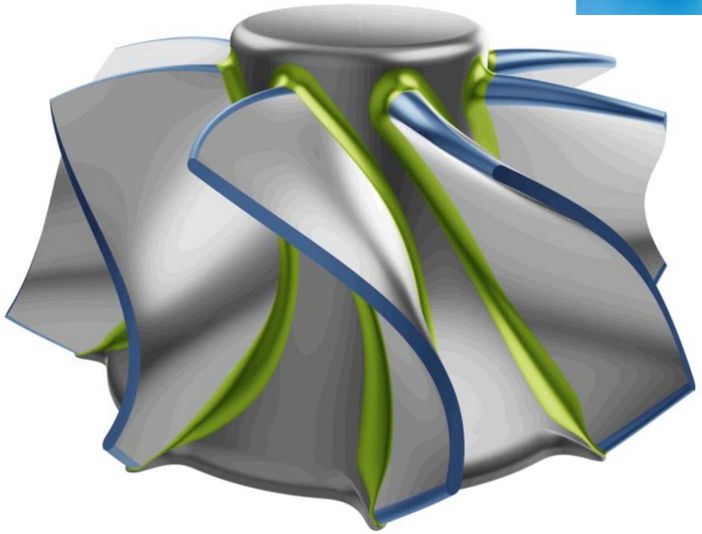
- From P. Vincent et al, Imperial College, 2016
- 119 Billion DoF
- Order 4
- 5,000 GPU in 35h

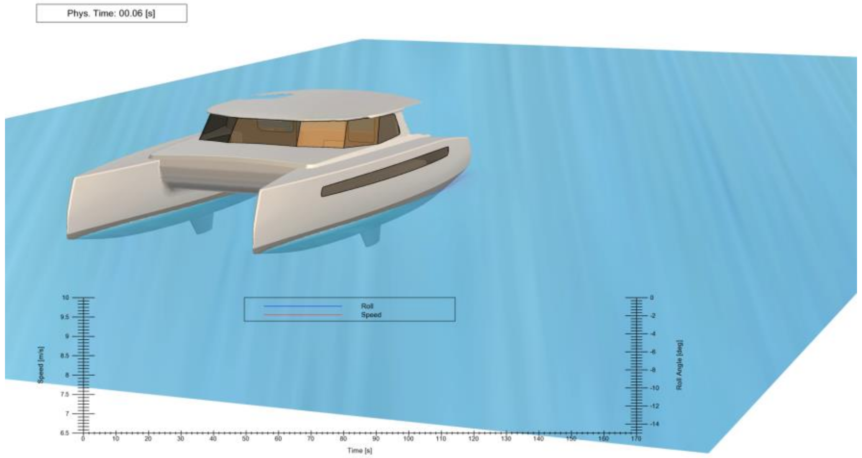
Exotic?

Colossus xAI:
100,000 NVIDIA H100

15 Years Later

A Great Collaboration





2024

Thank You!

NUMECA
INGENIEURBÜRO