Acceleration of Turbomachinery steady CFD Simulations on GPU

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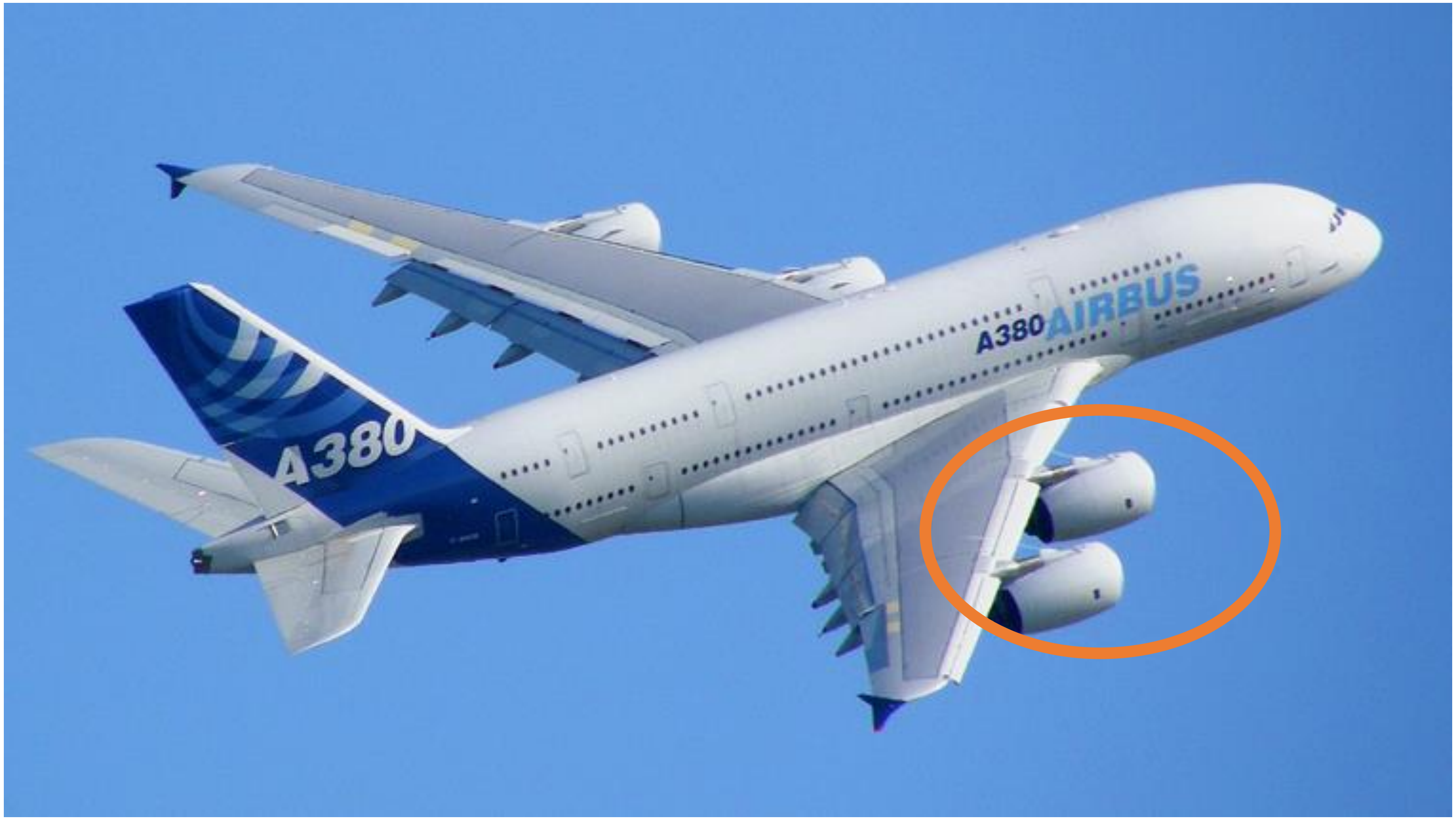
VON KARMAN INSTITUTE FOR FLUID DYNAMICS

TU Delft Delft University of Technology

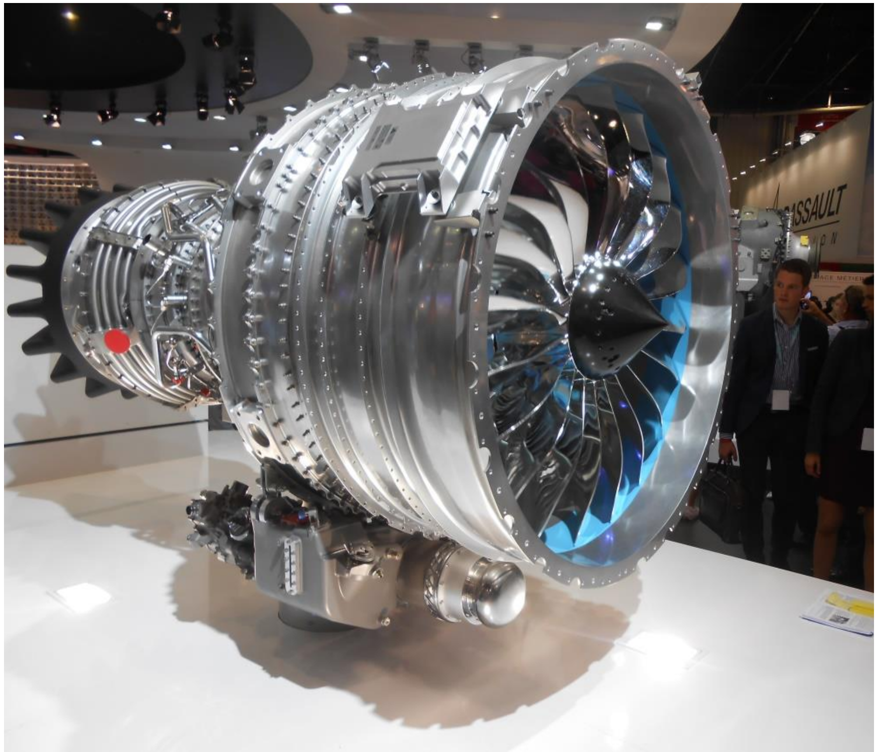
Unconventional HPC,
EuroPar 2016 WS
Grenoble, 23.08.2016

Topic of Interest:
Reduce Fuel Consumption and CO_2 Emission

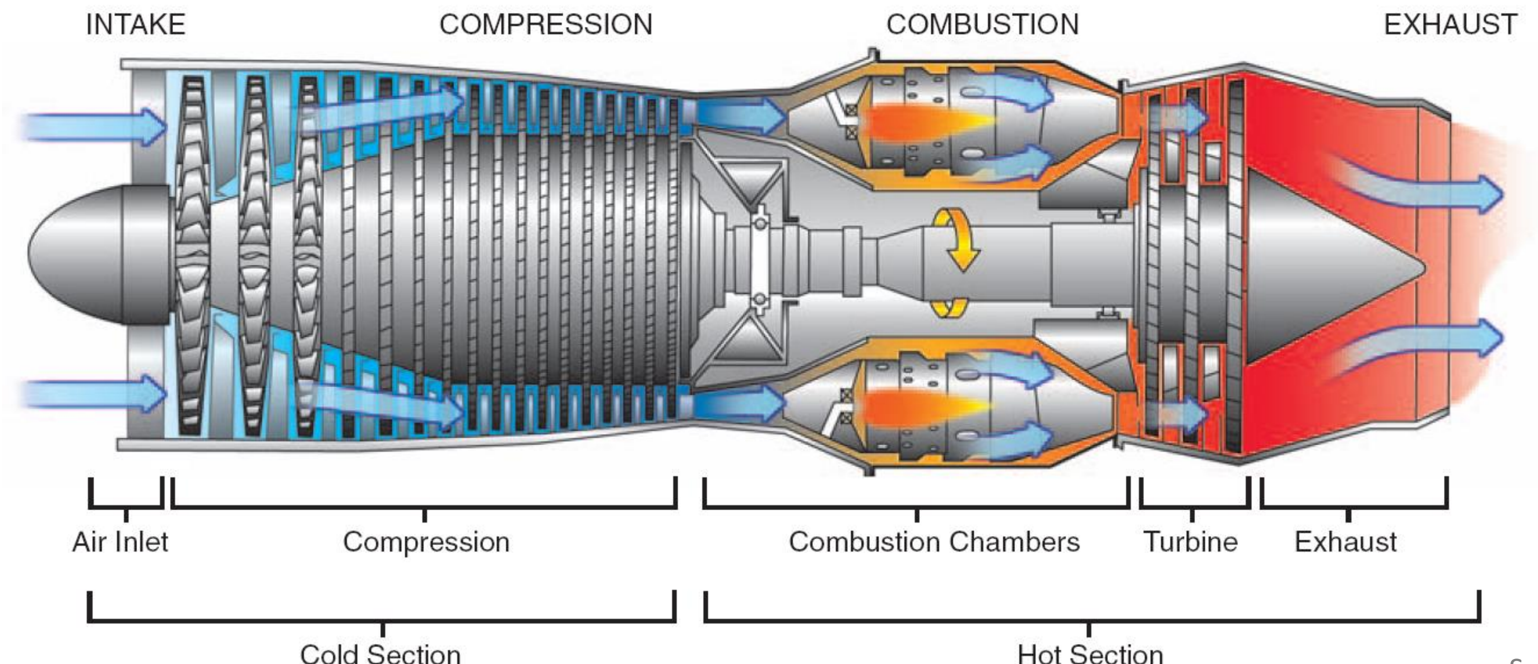


Wikipedia.org

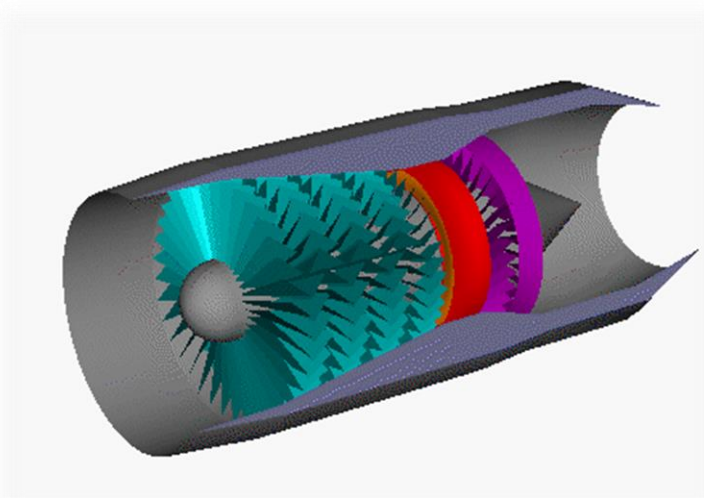
Turbomachinery is about Performance and Efficiency



Axial Jet Engine



Source:
Wikipedia.org



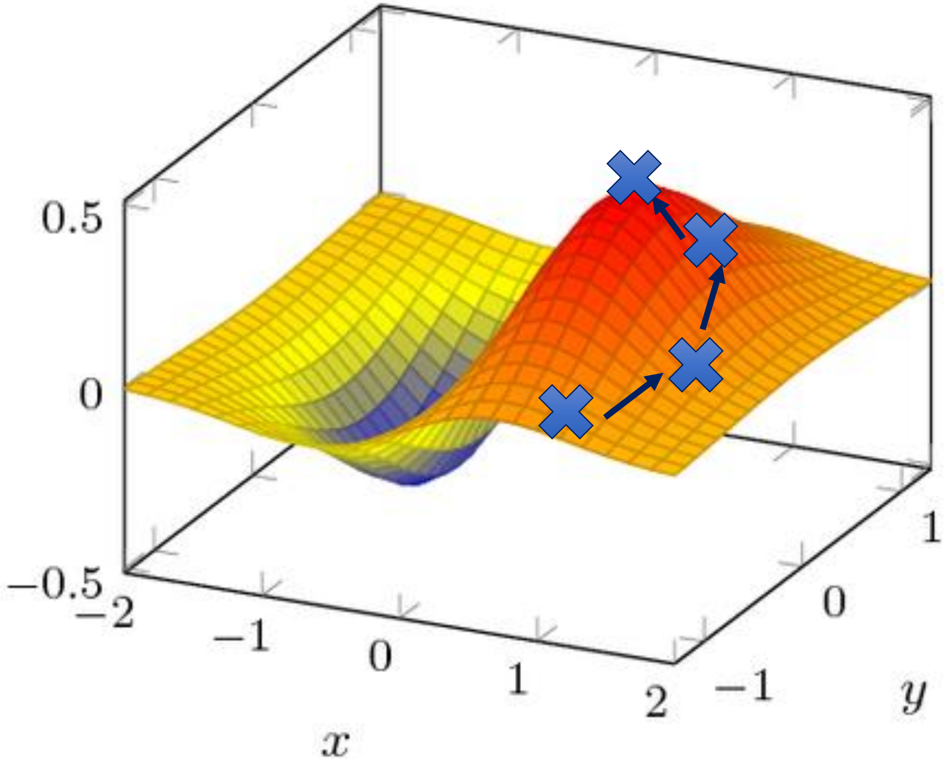
Content

- Multidisciplinary Optimization
- CFD simulations on GPU
  - Literature review
  - Implicit RANS Implementation
  - Benchmark
- Optimization Case

Optimization algorithm

Derivative-based optimization	Derivative free methods: e.g. Population based
• fast convergence but .. • derivative evaluation could be complicated and problem specific (adjoint, automatic differentiation)	• Simplicity • Black box approach of the evaluation but .. • Large number of evaluations

$$\min f(\boldsymbol{x})$$
$$\textit{subject to}$$
$$g(\boldsymbol{x}) \leq 0$$



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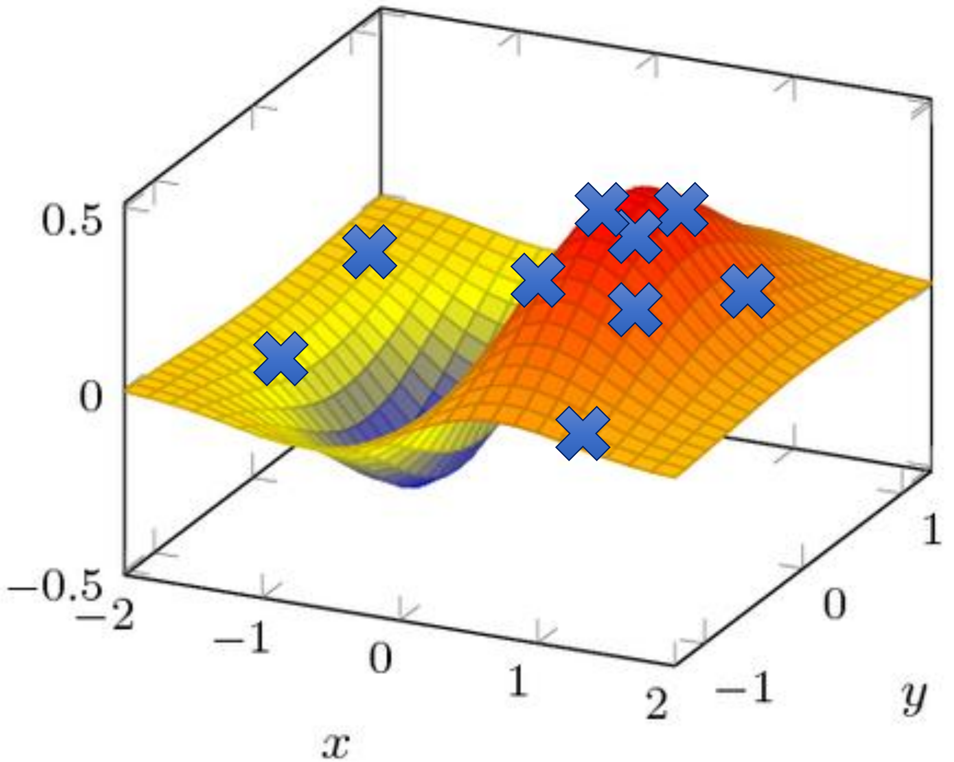
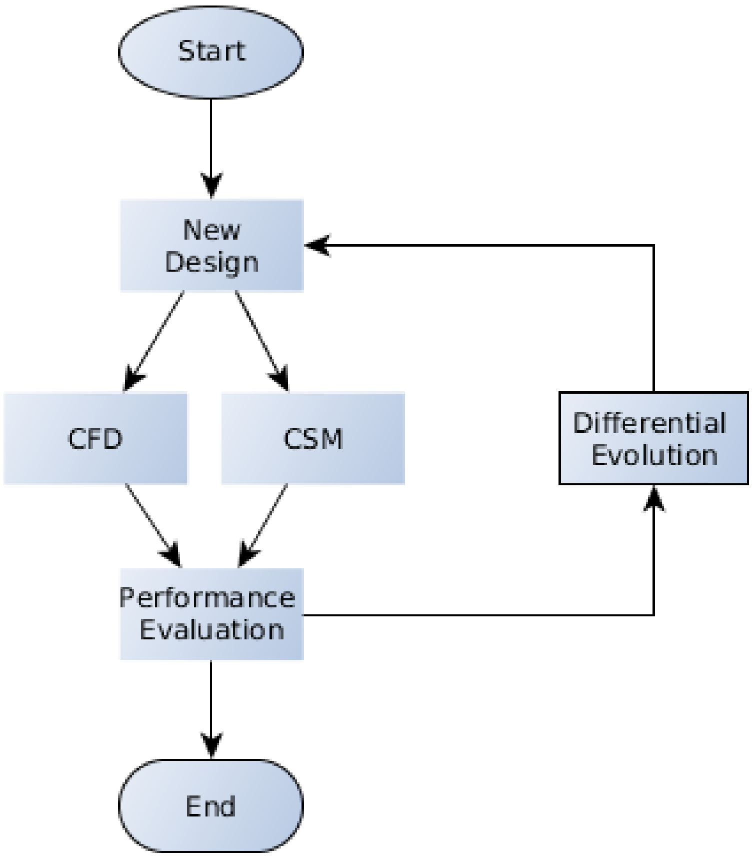


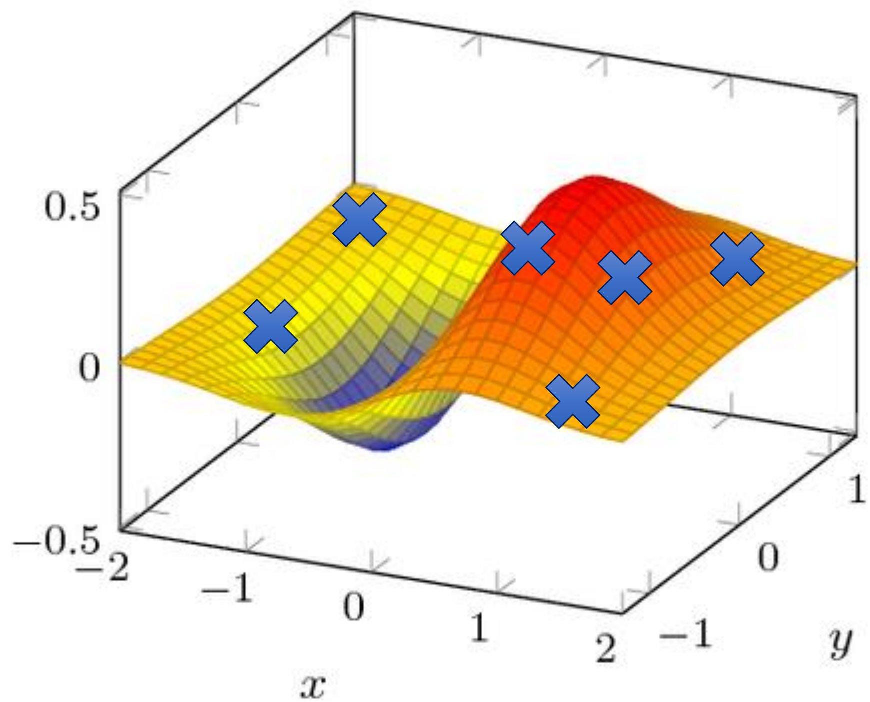
CFD: Core of the Optimization

CFD much slower than CSM

Need for acceleration -> GPU

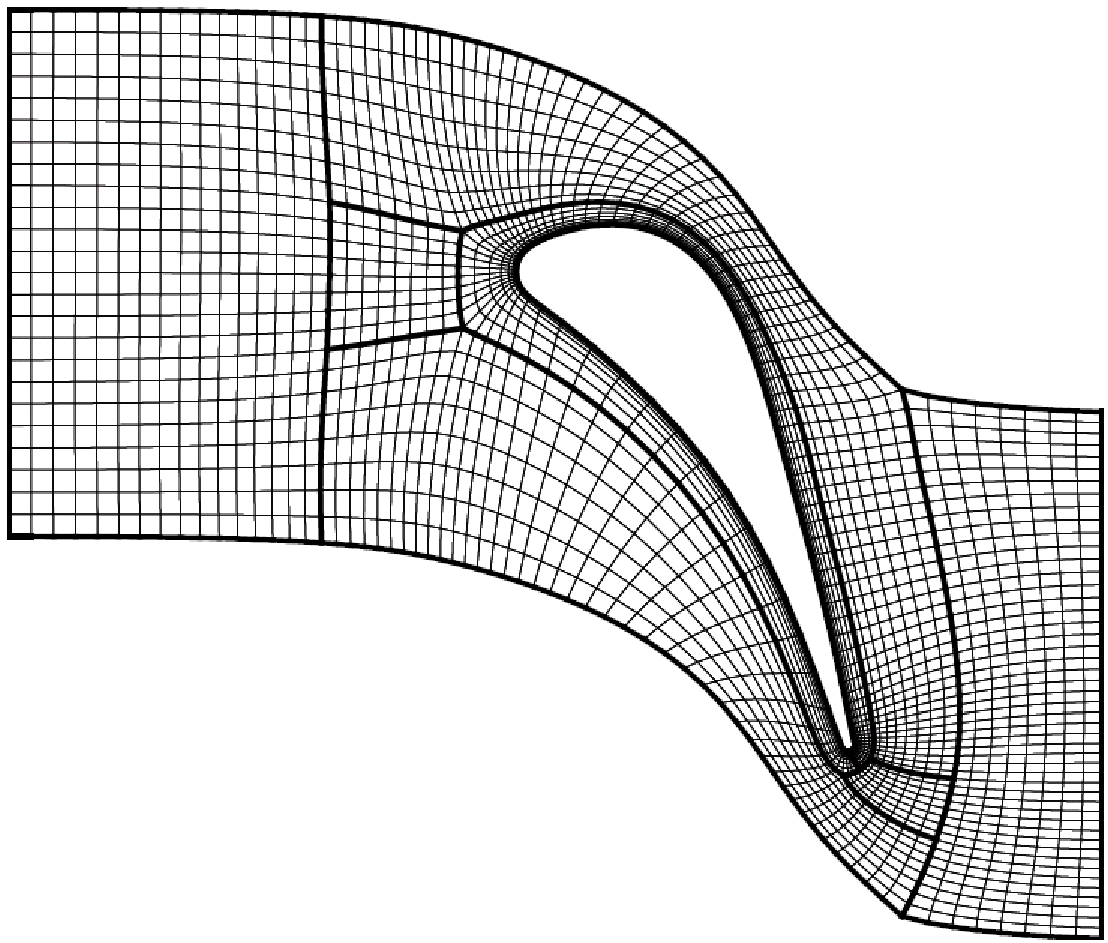


CADO: the VKI in-house optimizer



Steady CFD Simulations

- Simulation with a unique solution for given boundary Conditions.
- A start solution is advanced iteratively in time until convergence



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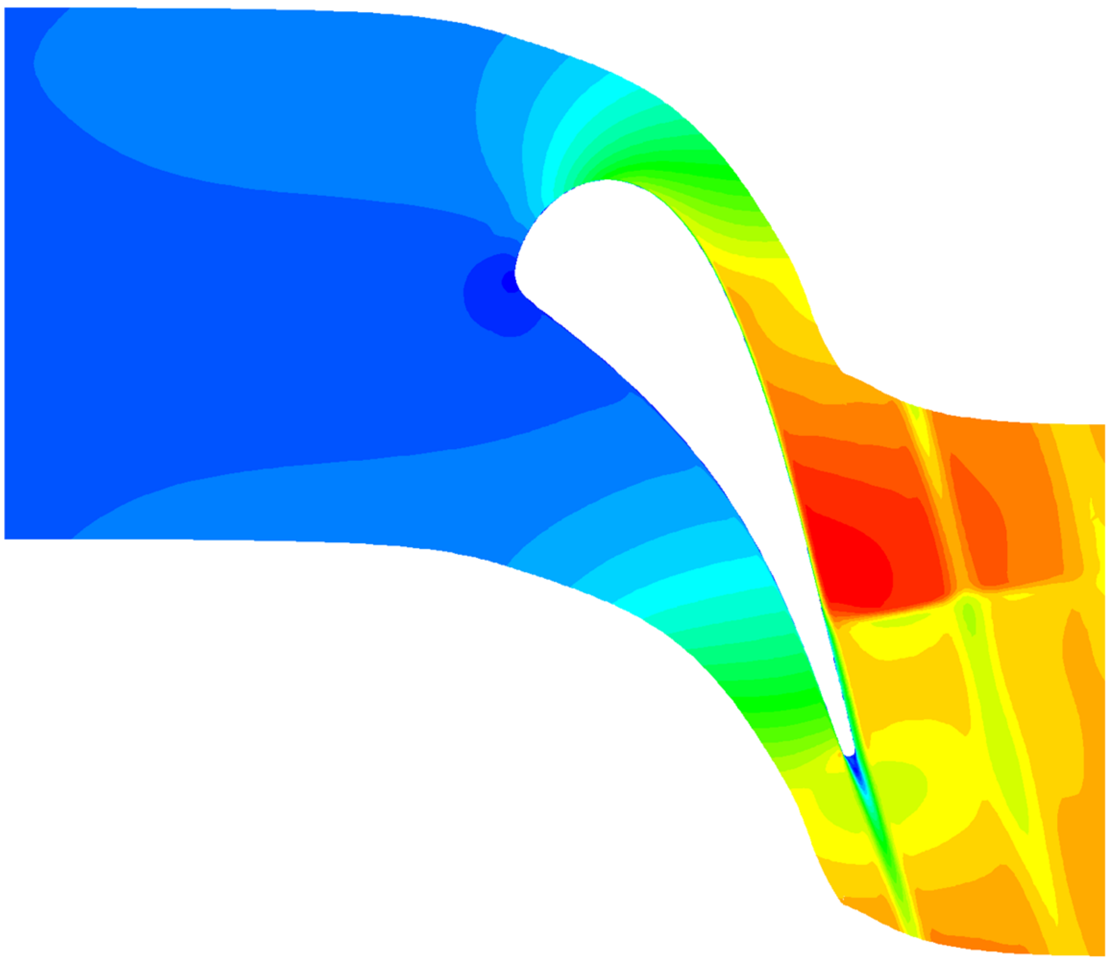


Numerical Scheme:

$$\frac{\partial}{\partial t}\int_{\Omega} \boldsymbol{W}\, d\Omega + \oint_{\partial\Omega} (\boldsymbol{F_c} - \boldsymbol{F_v})\, dS = \int_{\Omega} \boldsymbol{Q}\, d\Omega \qquad \boldsymbol{W} = \{\rho, \rho V_x, \rho V_y, \rho V_z, \rho E\}$$

$$\frac{(\Omega\bar{M})_I}{\Delta t_I}\Delta\vec{W}_I^n = -\beta\vec{R}_I^{(n+1)} - (1-\beta)\vec{R}_I^n$$

Explicit Time Stepping (β=0):

$$\Delta\boldsymbol{W}^n = -\frac{\Delta t}{\Omega}\boldsymbol{R}^n$$

Implicit Time Stepping (β=1):

$$\vec{R}_I^{n+1} \approx \vec{R}_I^n + \left(\frac{\delta\vec{R}}{\delta\vec{W}}\right)_I \Delta\vec{W}^n$$

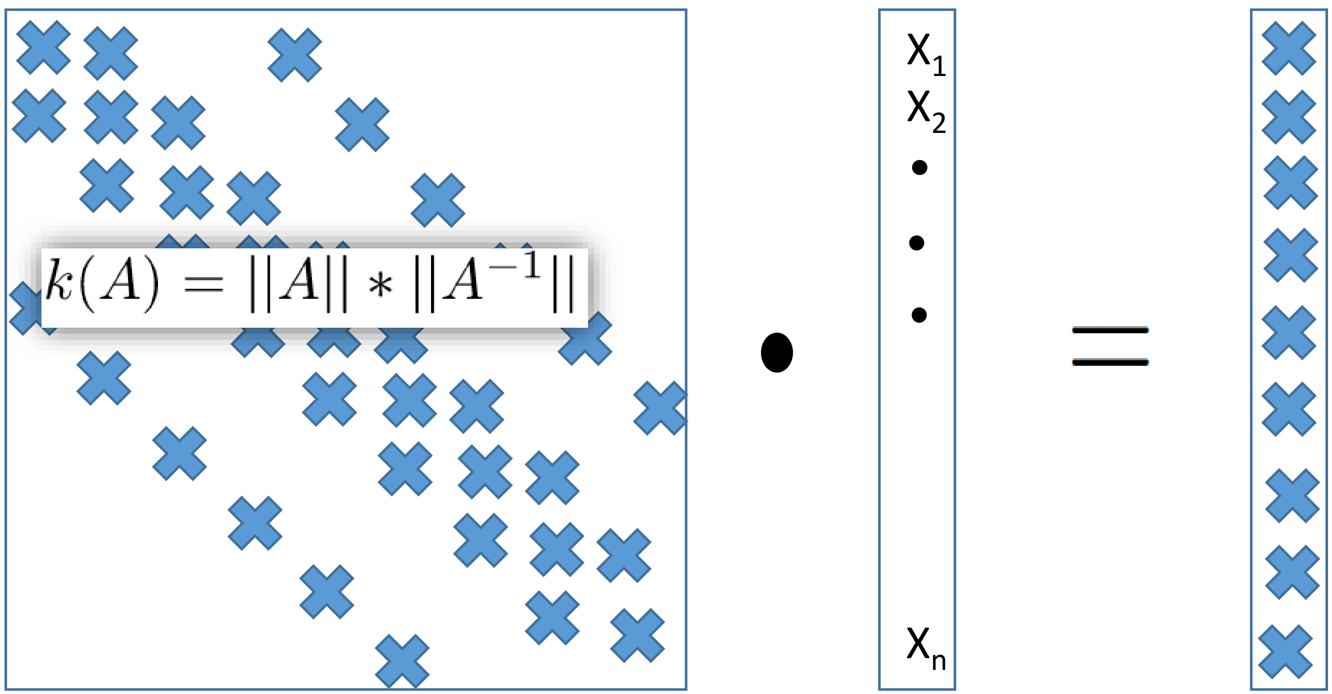
$$\left[\frac{(\Omega I)}{\Delta t} + \left(\frac{\delta\boldsymbol{R}}{\delta\boldsymbol{W}}\right)\right]\Delta\boldsymbol{W}^n = -\boldsymbol{R}^n$$

Aissa, M.H., Verstraete, T., Vuik, C. "Aerodynamic Optimization of Supersonic Compressor Cascade using Differential Evolution on GPU". 13th Int. Conf. of Numerical Analysis and Applied Mathematics (ICNAAM 2015)

Implicit Time Stepping is more Stable but …

$$\left[\frac{(\Omega I)}{\Delta t} + \left(\frac{\delta \boldsymbol{R}}{\delta \boldsymbol{W}}\right)\right] \Delta \boldsymbol{W}^n = -\boldsymbol{R}^n$$

$$A\,x = b$$



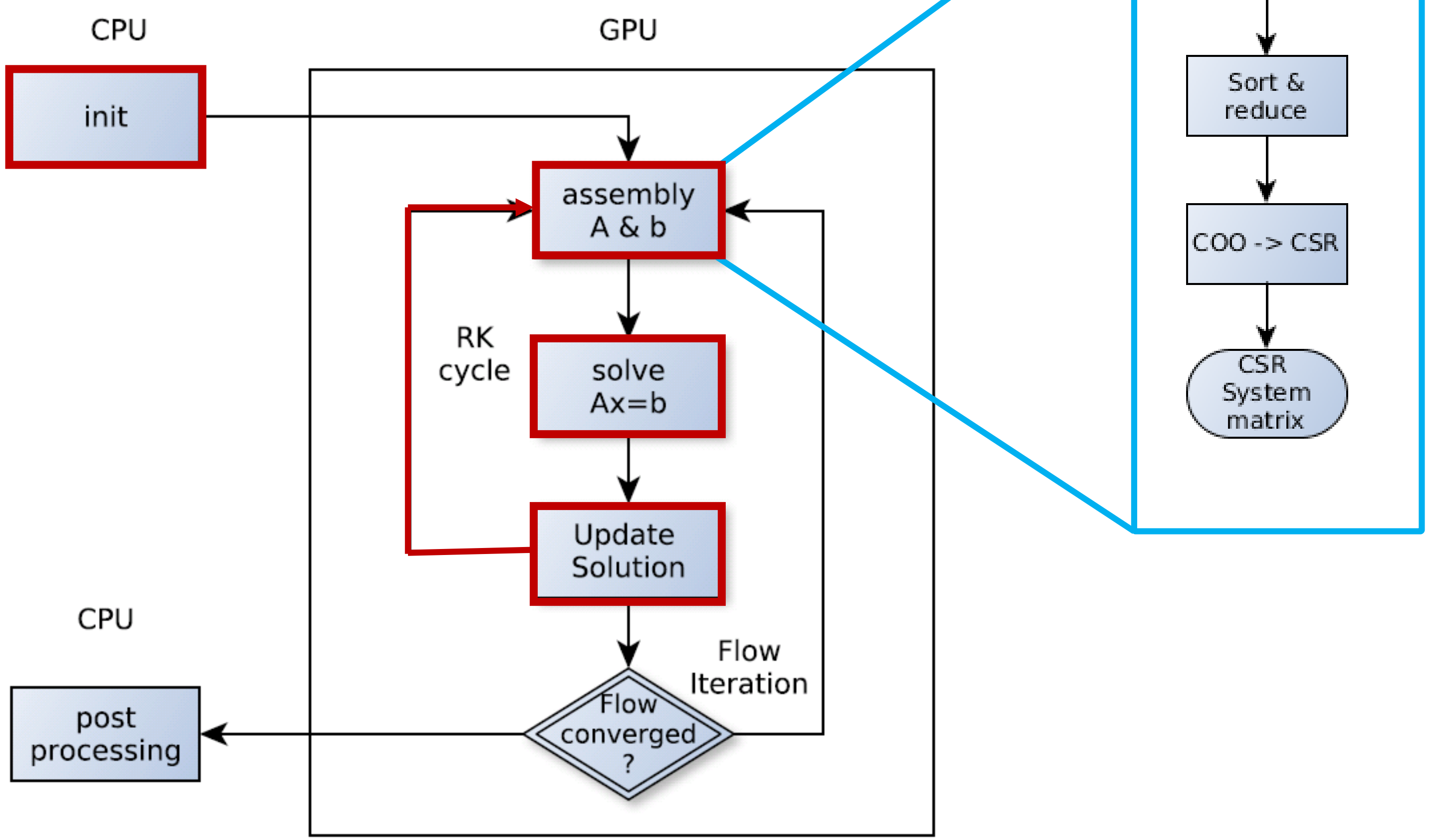
$$M^{-1}Ax = M^{-1}b$$

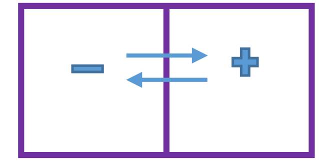
Literature Review

- What to Port
  - only linear solver when it is dominant
  - both assembly and solve is optimal (no communication)
- Linear solver
  - Library : code maturity but restrictive
    (petsc-dev, Paralution, AmgX, ViennaCL …)
  - Own code: flexibility
- Storage format
  - Standard (CSR,DIA …)
  - New (hybrid)

CFD Solver (Standard)

$$\left[\frac{(\Omega I)}{\Delta t} + \left(\frac{\delta \boldsymbol{R}}{\delta \boldsymbol{W}}\right)\right] \Delta \boldsymbol{W}^n = -\boldsymbol{R}^n$$





Thrust

CUSP

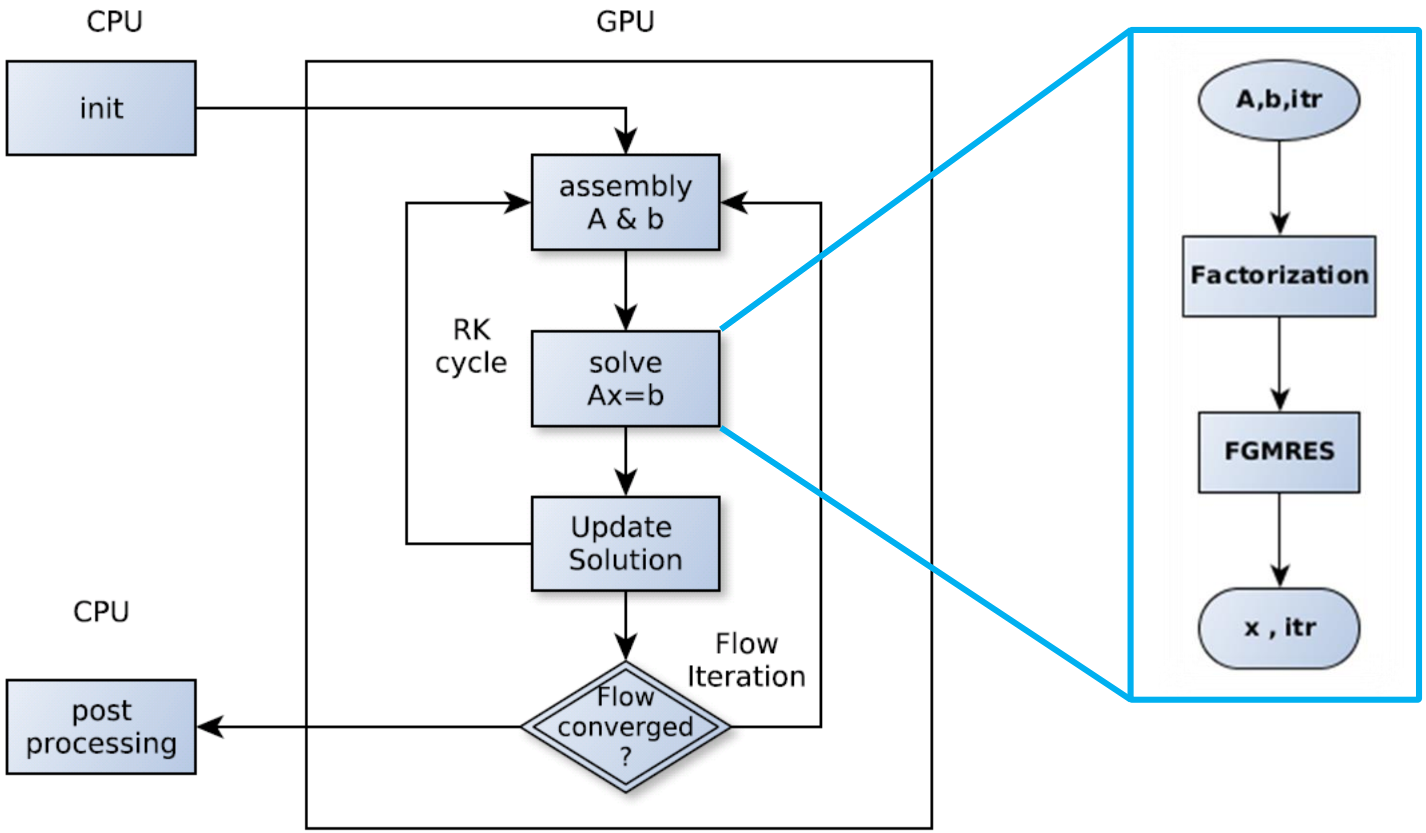
PARALUTION

$$\begin{aligned}
\boldsymbol{W}^{(0)} &= \boldsymbol{W}^n \\
A^{(0)}[\boldsymbol{W}^{(1)} - \boldsymbol{W}^{(0)}] &= -\alpha_1 \boldsymbol{R}(\boldsymbol{W}^{(0)}) \\
A^{(0)}[\boldsymbol{W}^{(2)} - \boldsymbol{W}^{(0)}] &= -\alpha_2 \boldsymbol{R}(\boldsymbol{W}^{(1)}) \\
&\vdots \\
A^{(0)}[\boldsymbol{W}^{(m)} - \boldsymbol{W}^{(0)}] &= -\alpha_m \boldsymbol{R}(\boldsymbol{W}^{(m-1)}) \\
\boldsymbol{W}^{n+1} &= \boldsymbol{W}^{(0)} + [\boldsymbol{W}^{(m)} - \boldsymbol{W}^{(0)}]
\end{aligned}$$

Implicit Runge-Kutta scheme

Xu et Al. JCP 2015

CFD Solver (Standard)



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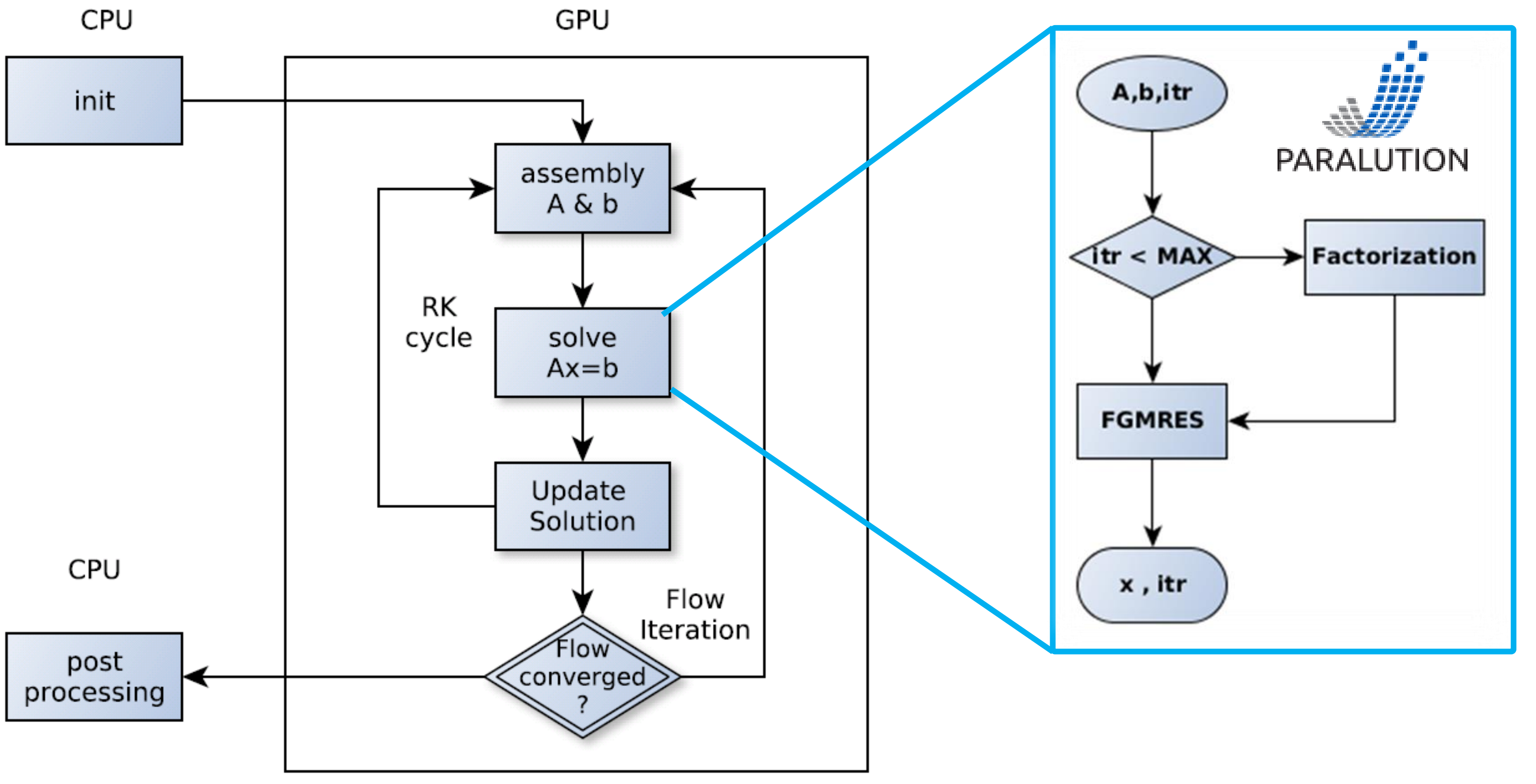
\end{aligned}
$$

CFD Solver (*On-demand* Factorization)



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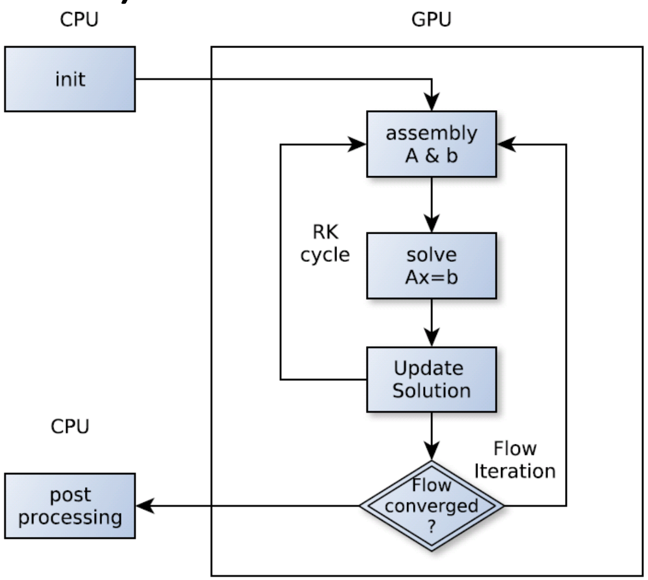
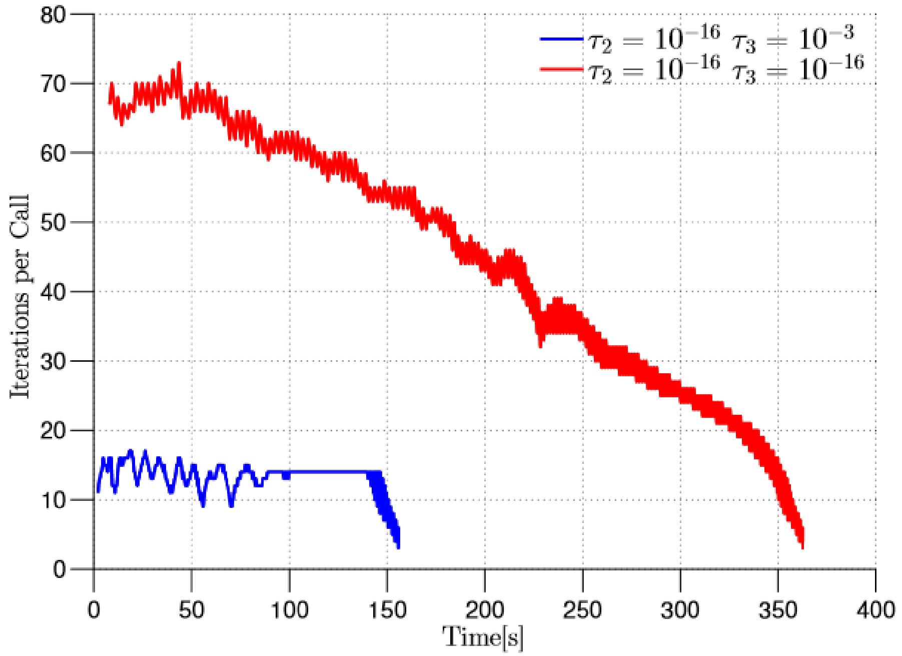


$$r = Ax - b$$

Stop condition relative, absolute or a combination

$$\frac{||r_k||}{||b||} < \tau_3 \qquad ||r_k|| < \tau_2$$



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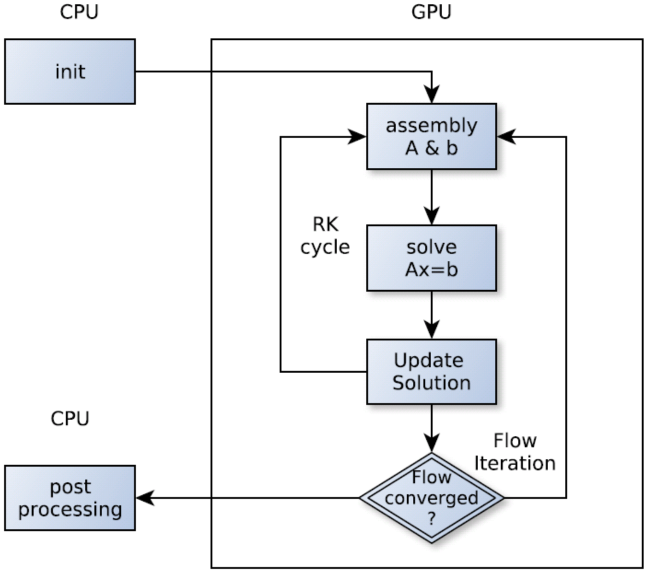
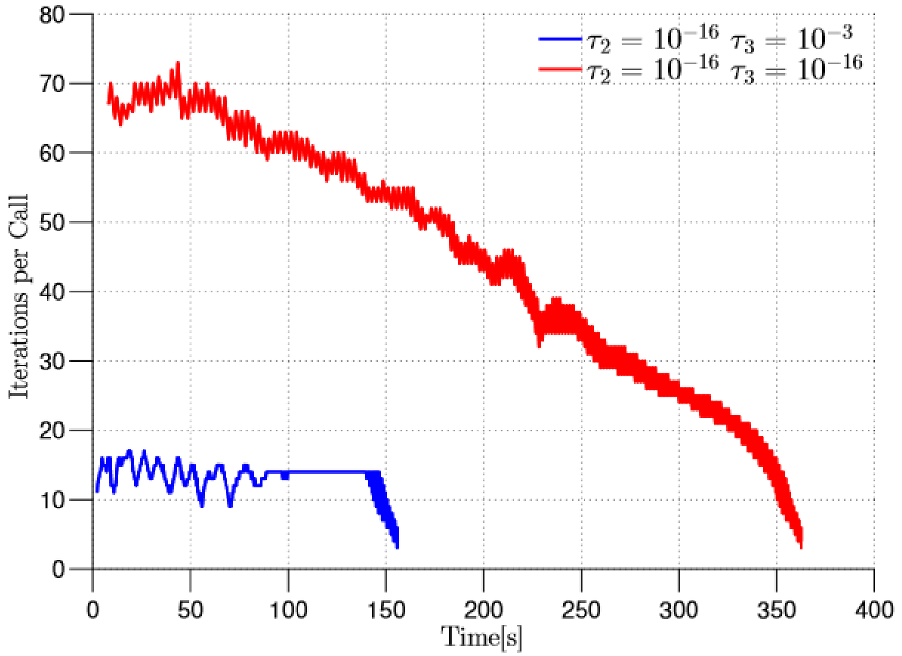
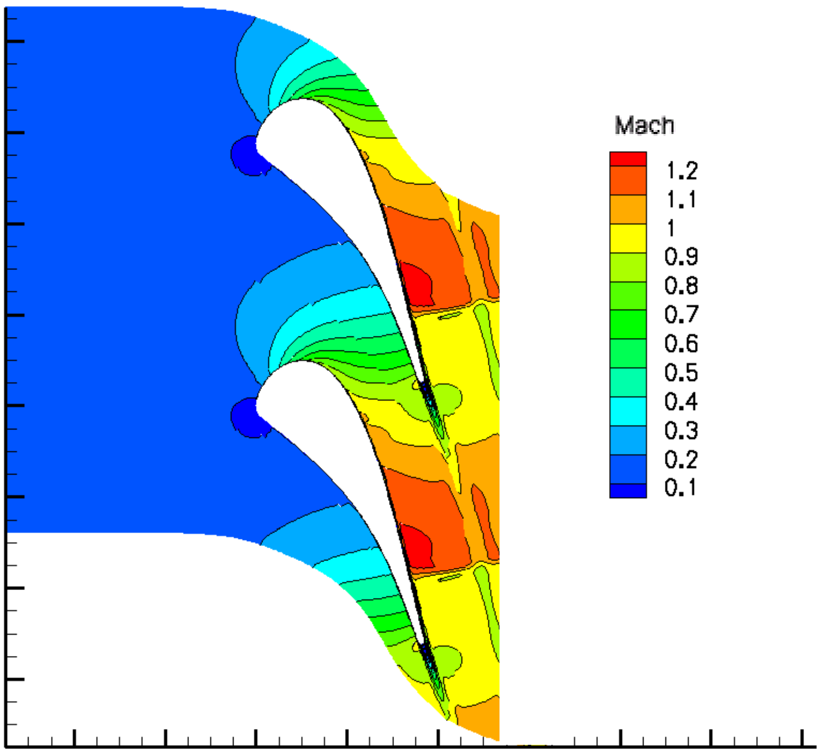
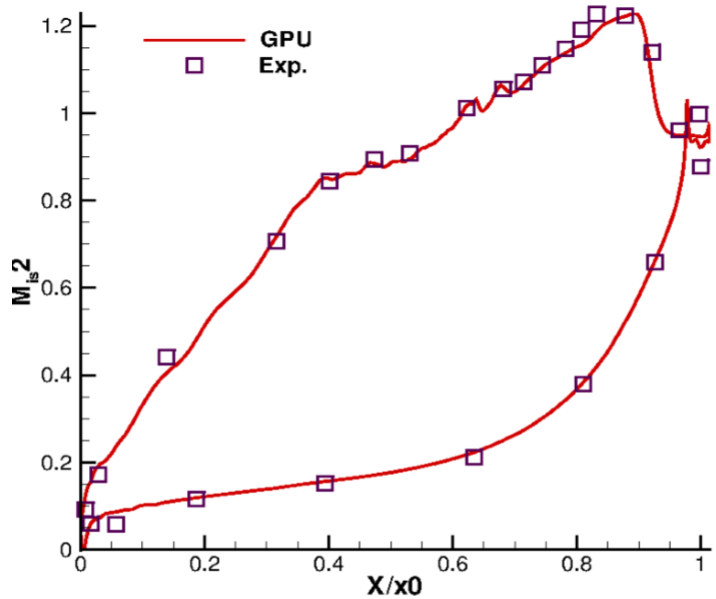




$$MAX\_ITR = \alpha * \frac{1}{m}\sum_{1}^{m} N_{ITR_i}$$

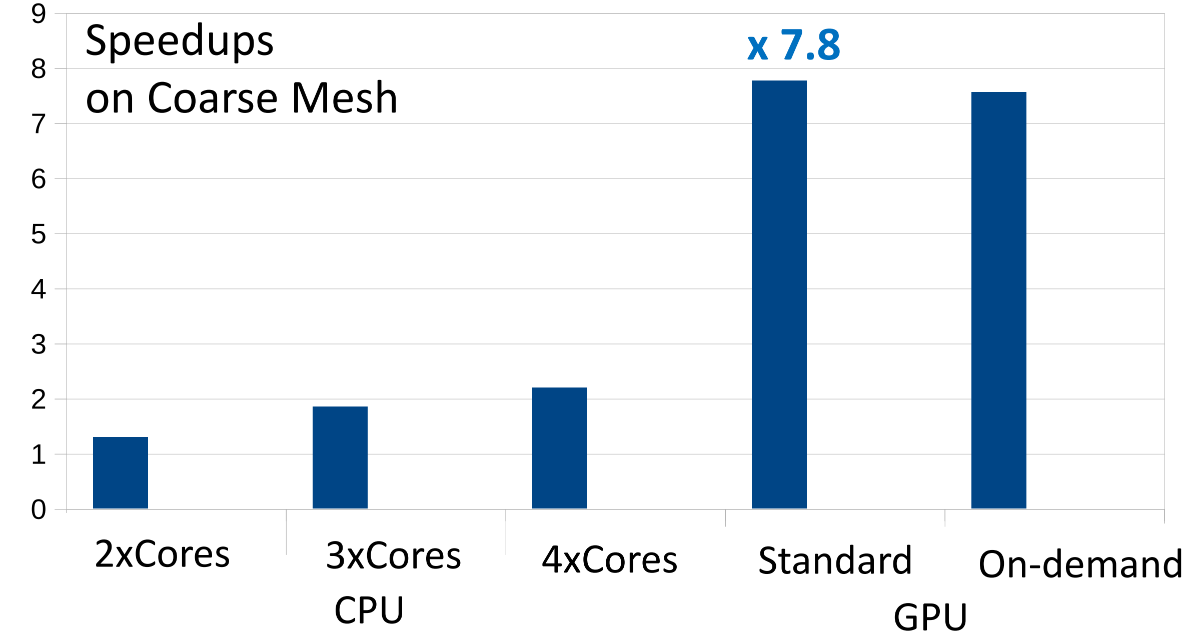
Benchmark: Flow around LS89
2-Stages Runge-Kutta

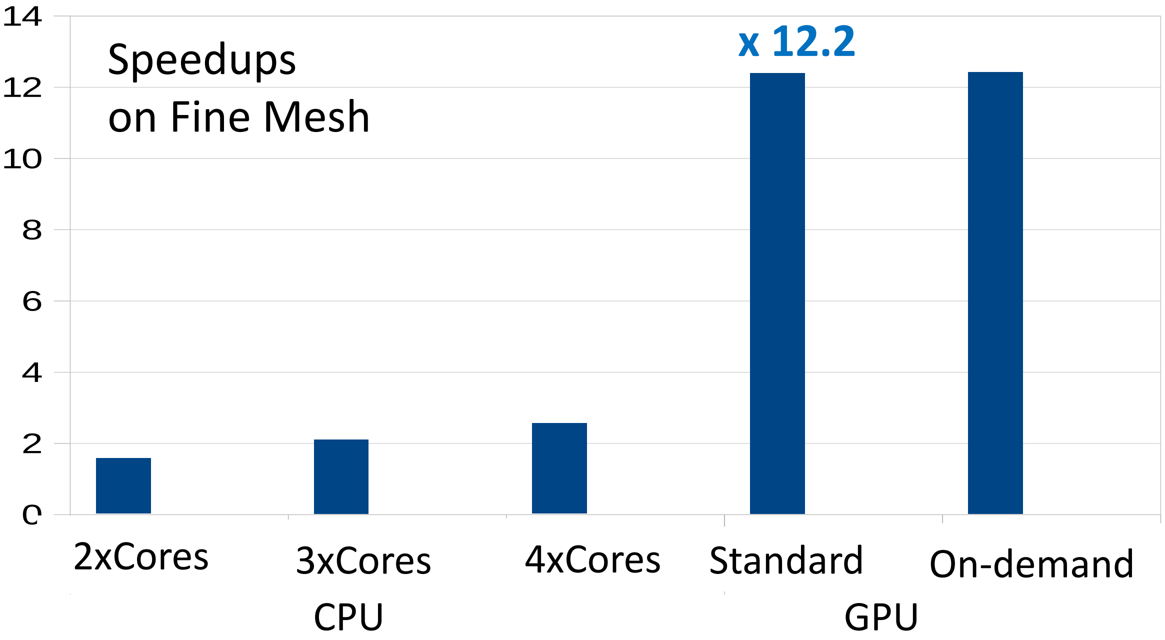


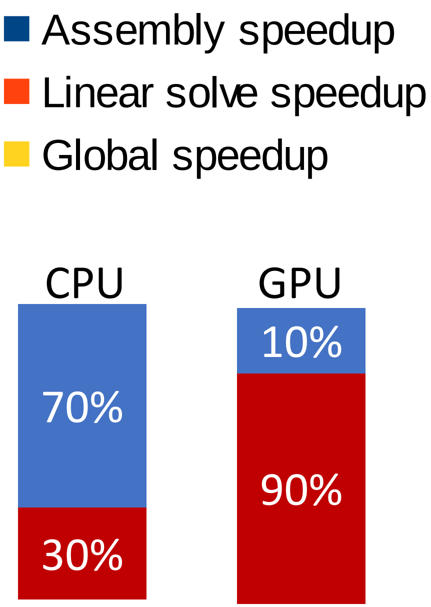


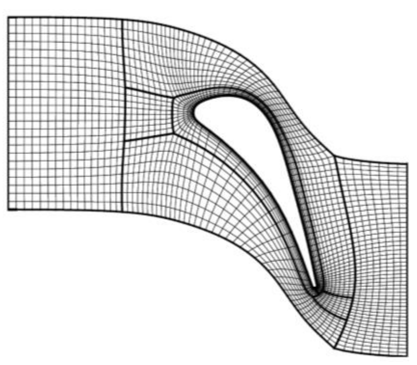
Mesh	N_{Cells}	N_{Rows}	nnz	nnz/row
Coarse	40k	200k	5.7M	[20 .. 30]
Fine	300k	1500k	52.6M	[20 .. 35]

Assembly Acceleration

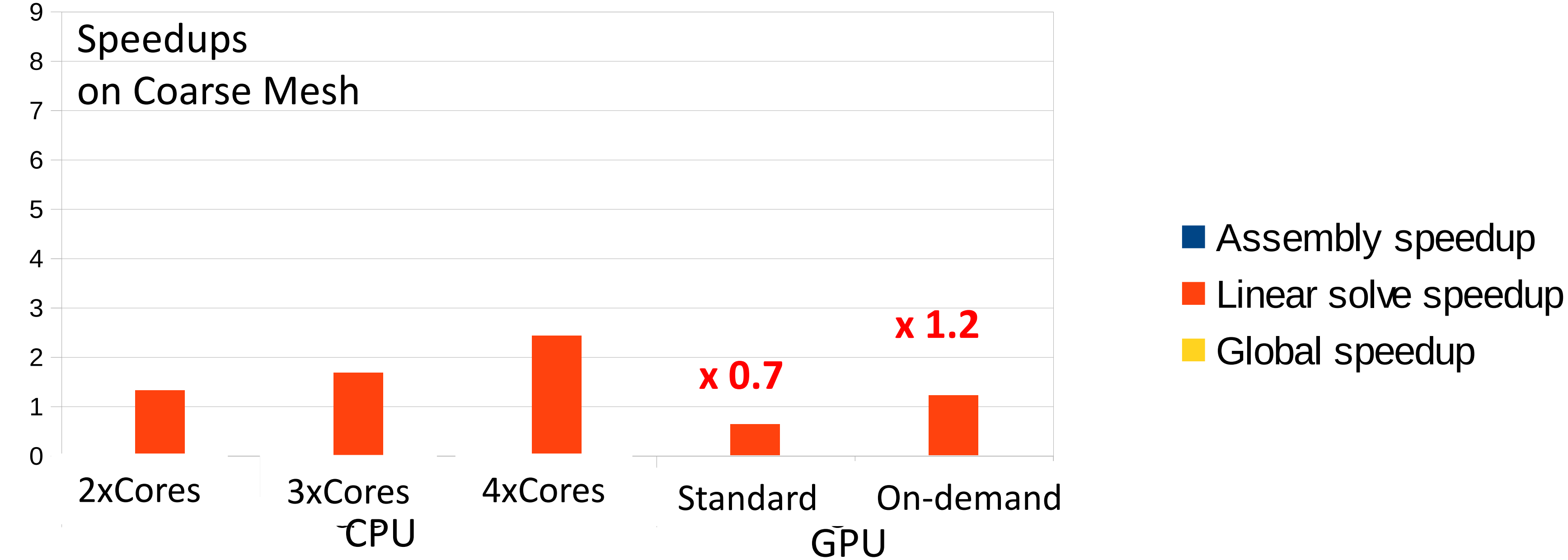


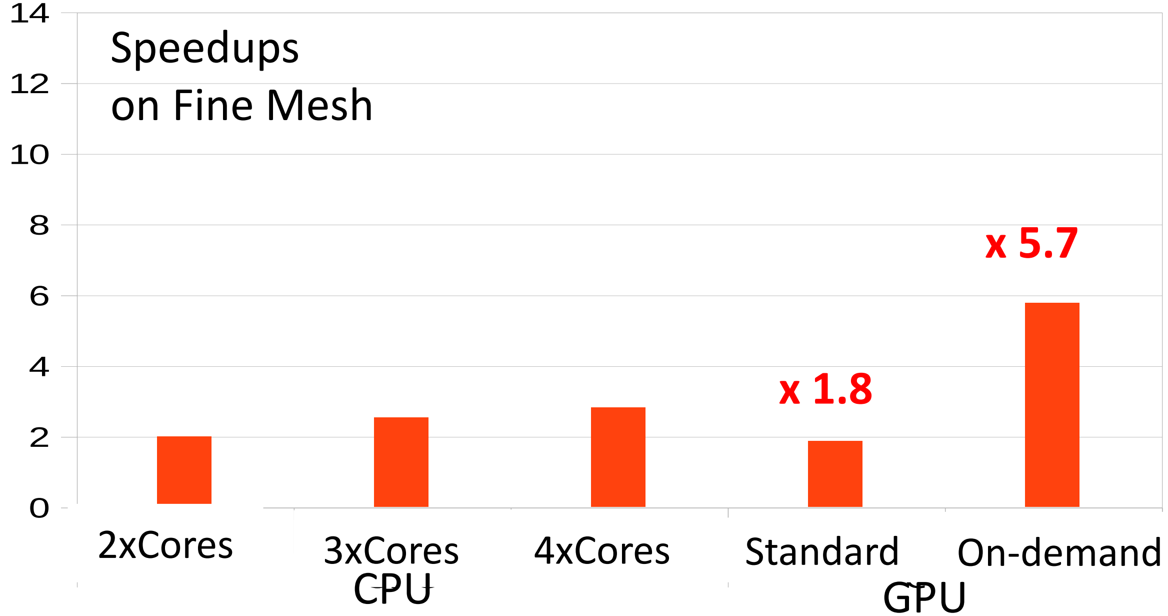


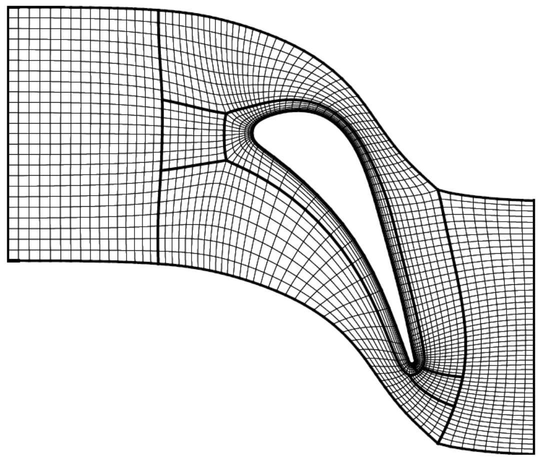




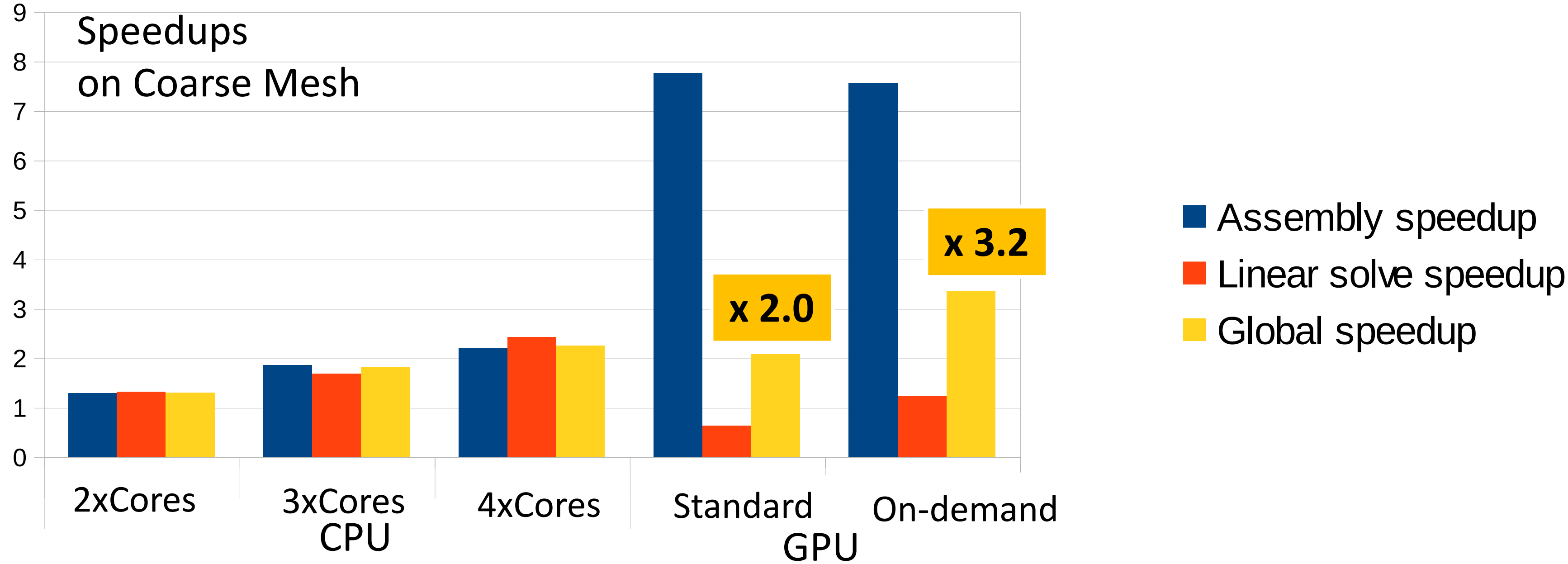
Linear Solver Acceleration

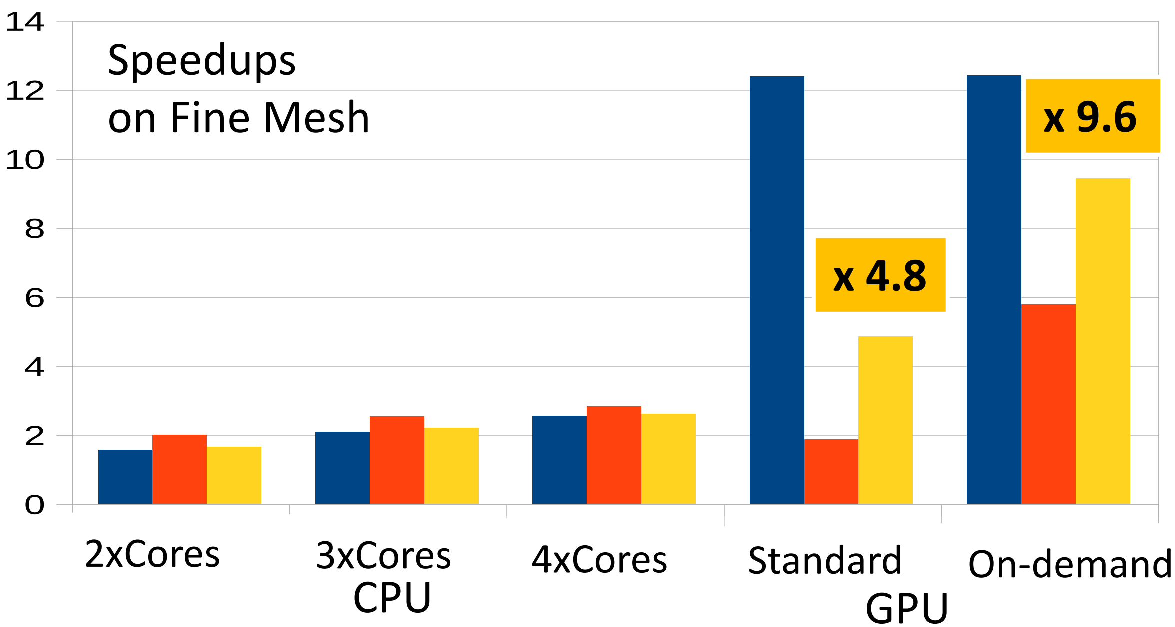






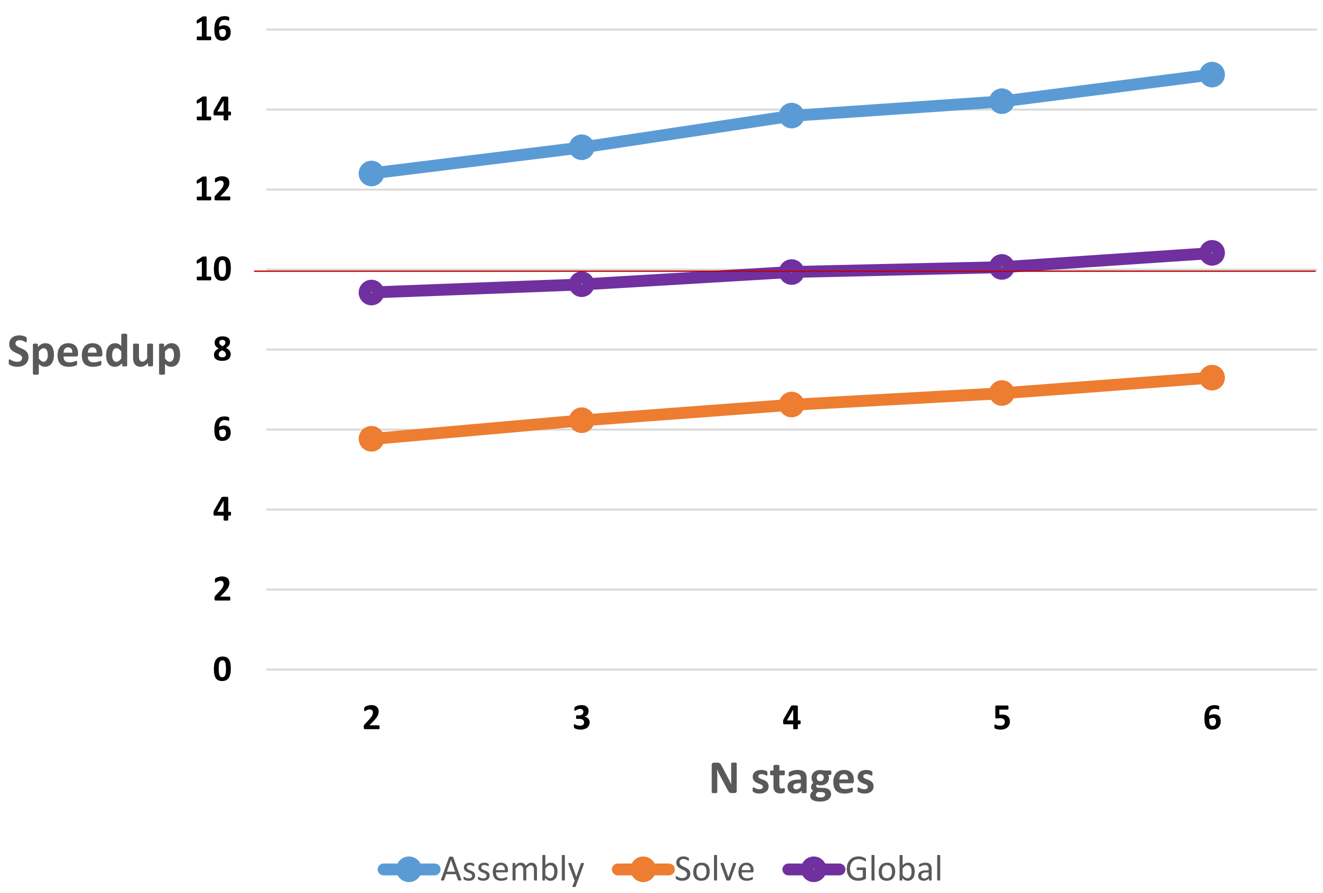
Global Acceleration





Suggestion for better Performance assessment are very welcome!

Increase of the Speedup for higher Numbers of Runge-Kutta Stages on Fine Mesh



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- Optimization Case

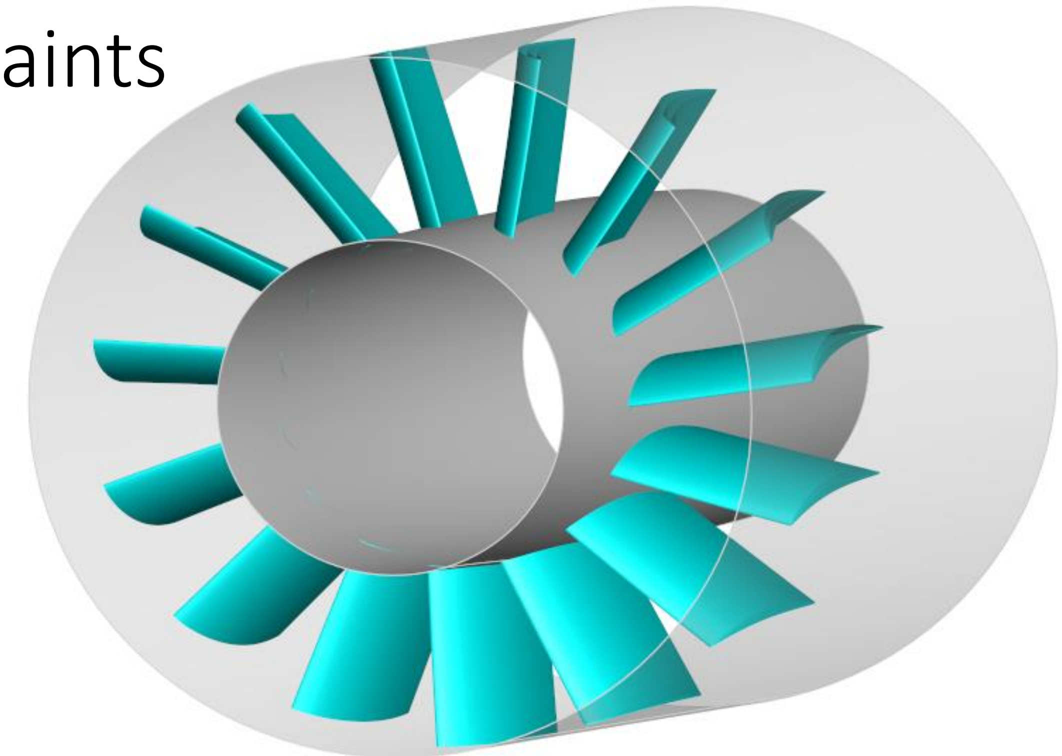
Test Case 3: TU Berlin TurboLab Stator Optimization requirements

Objectives:

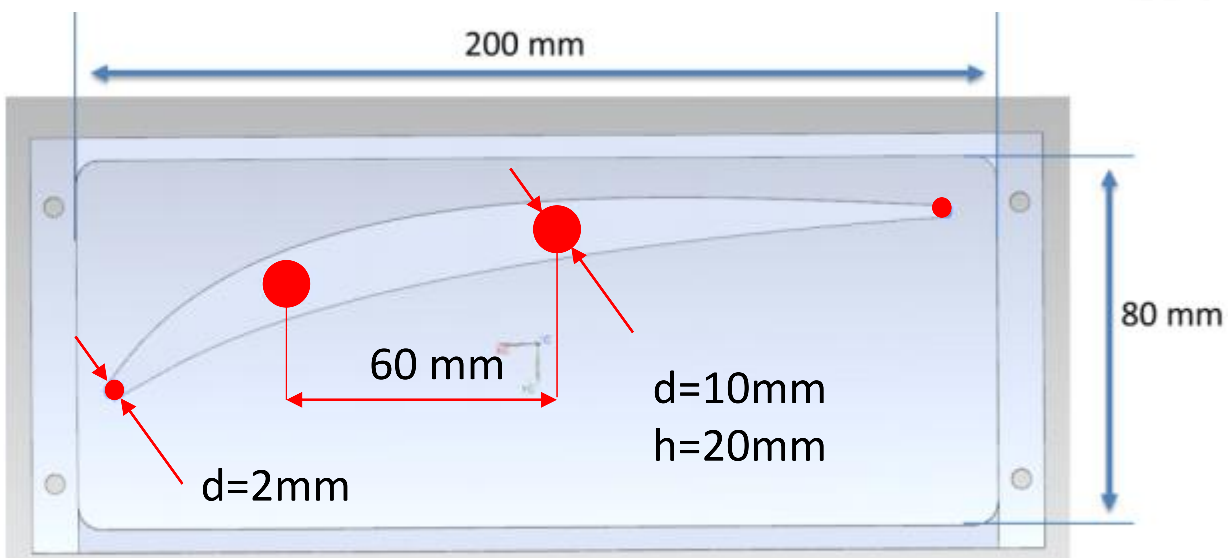
- Decrease outfow axial deviation
- Decrease total pressure loss

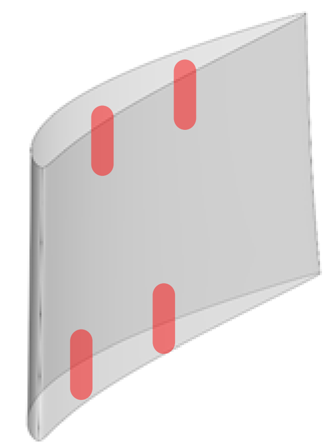
Considering 3 operating points

TurboLab
Manufacturing Constraints

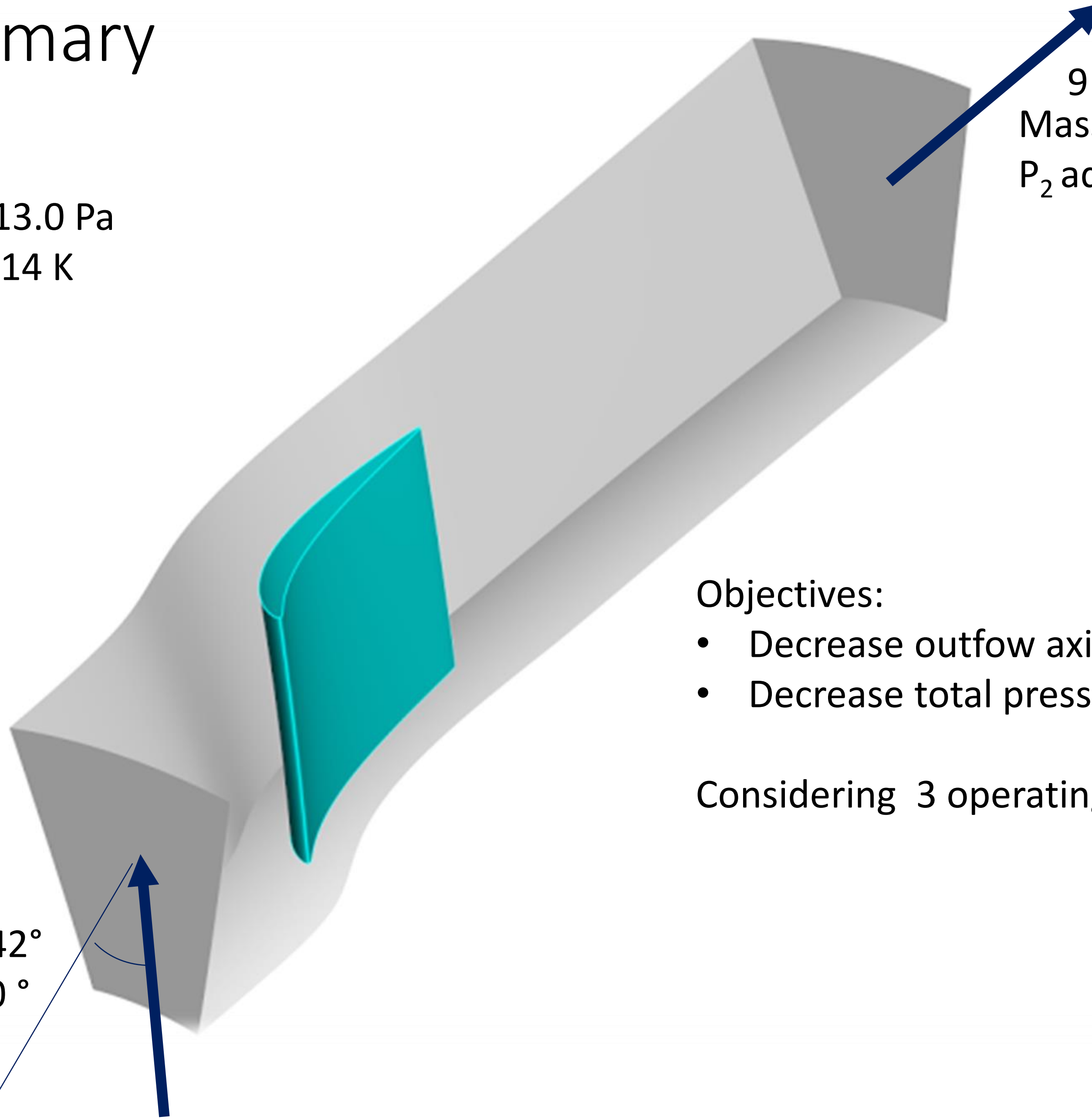


- $N_{blades} = 15$
- Chord length fixed
- Casing fixture





TurboLab: Boundary conditions and summary



9 kg/s +/- 0.1
Massflow imposed
P_2 adapted

Inlet P_0: 102713.0 Pa
Inlet T_0: 294.314 K

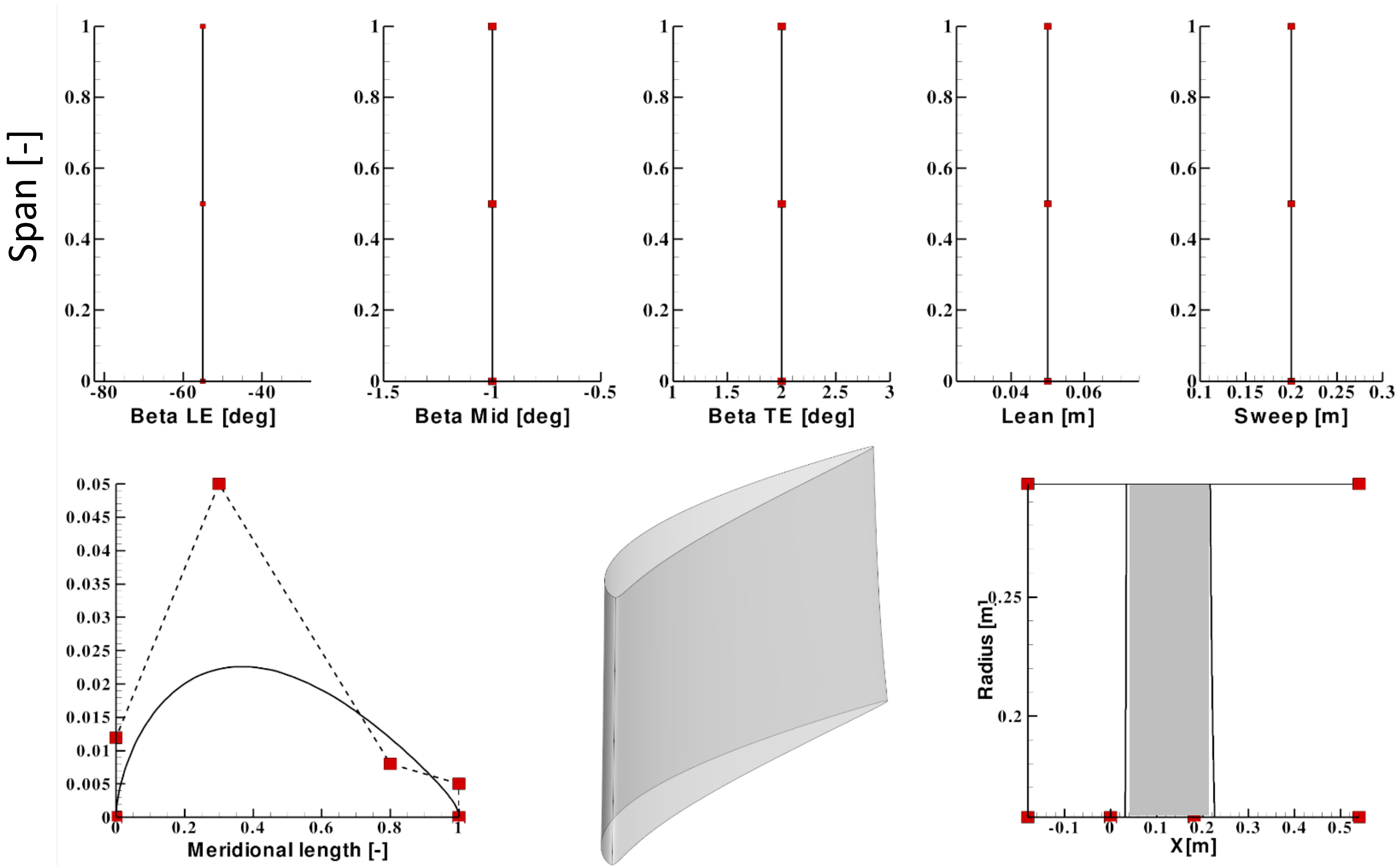
Objectives:

- Decrease outfow axial deviation
- Decrease total pressure loss

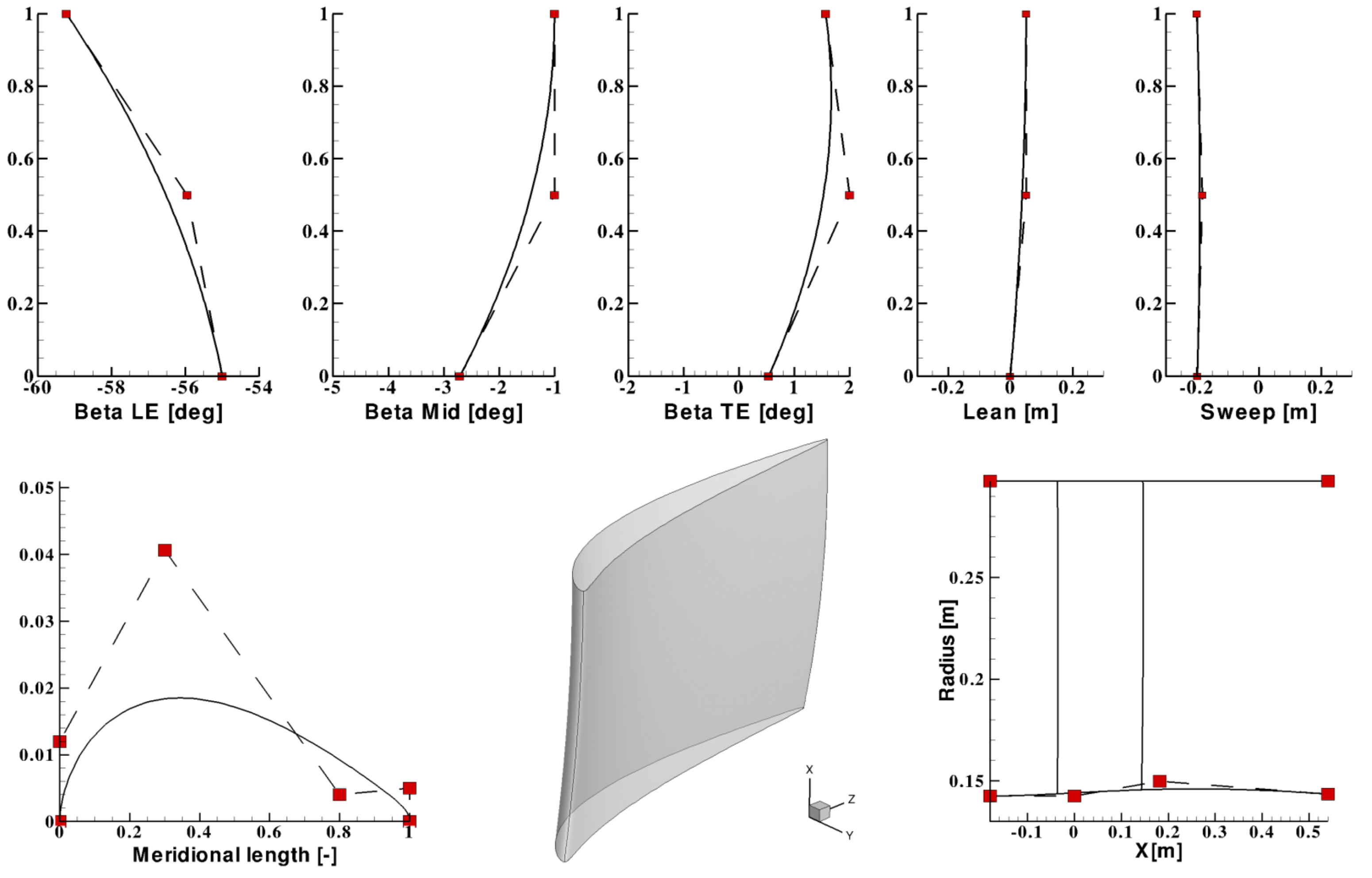
Considering 3 operating points

Inlet whirl angle: 42°
Inlet pitch angle: 0 °

Parametrization
21 Design variables

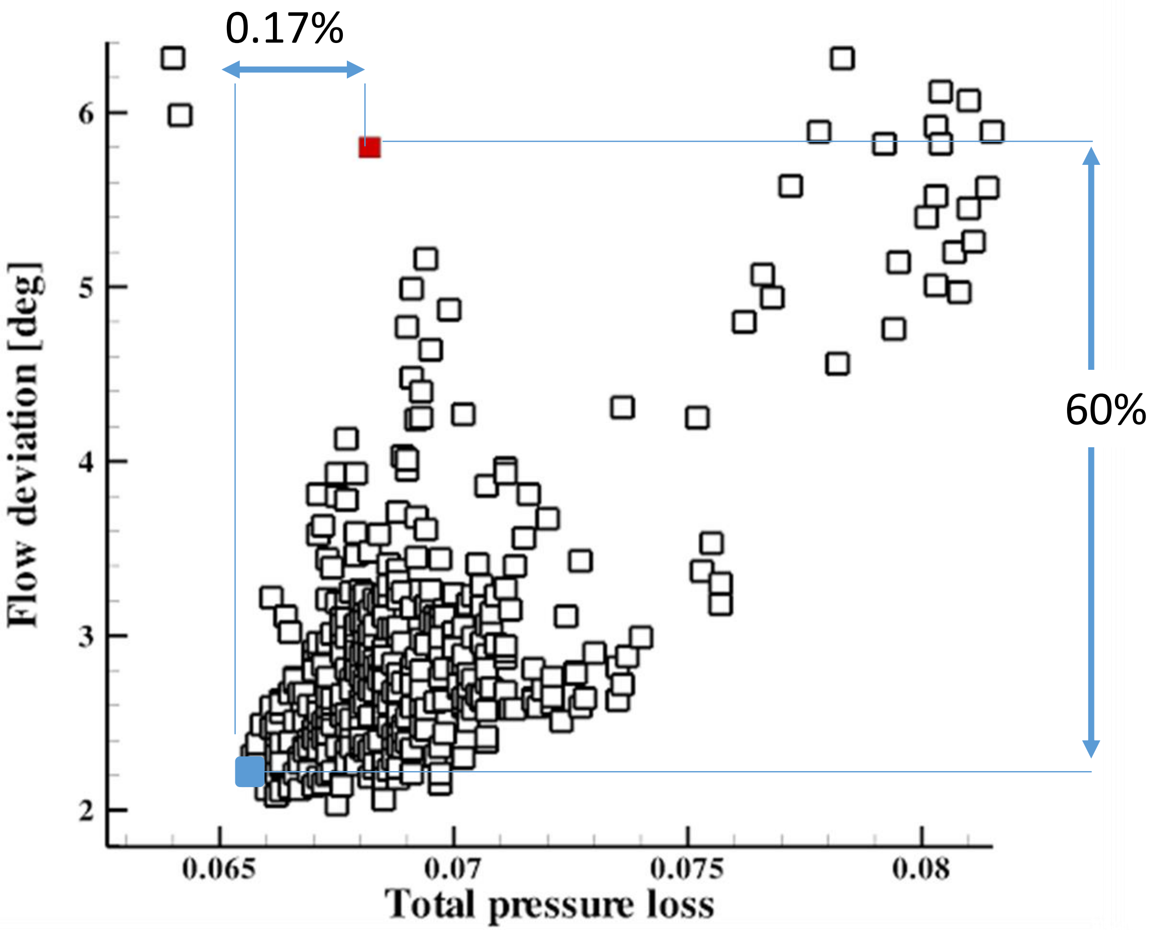


Turbolab Parameterization



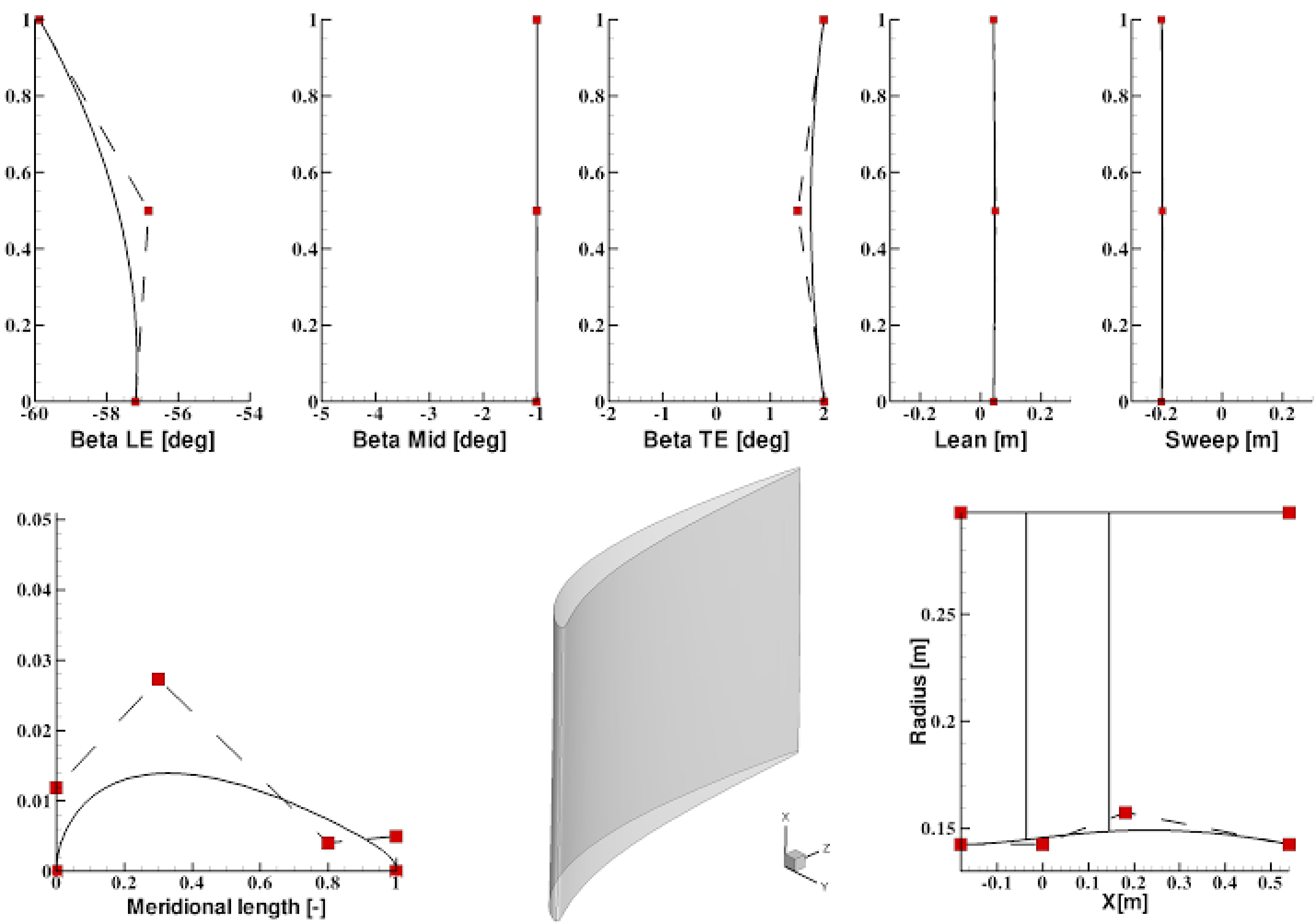
Optimization Results

$$\int_{hub}^{casing} \alpha_{whirl}^2$$

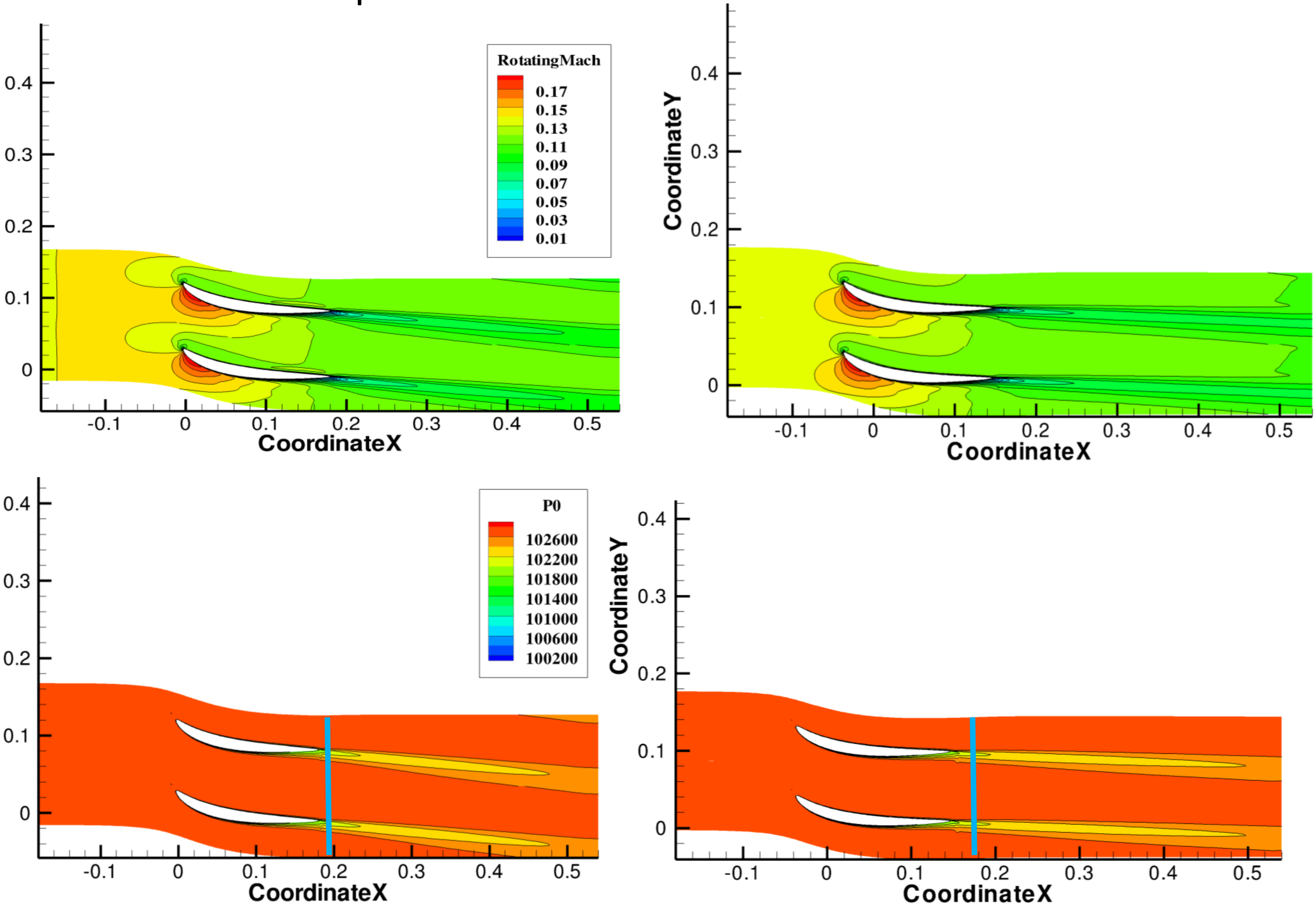


$$Loss_{P_0} = \frac{p_{01} - p_{02}}{p_{01} - p_1}$$

Optimized Blade



Baseline Vs Optimized



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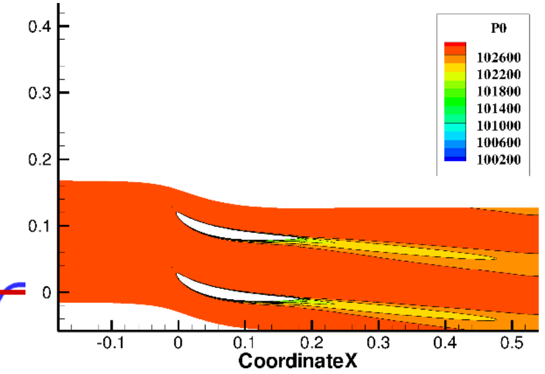
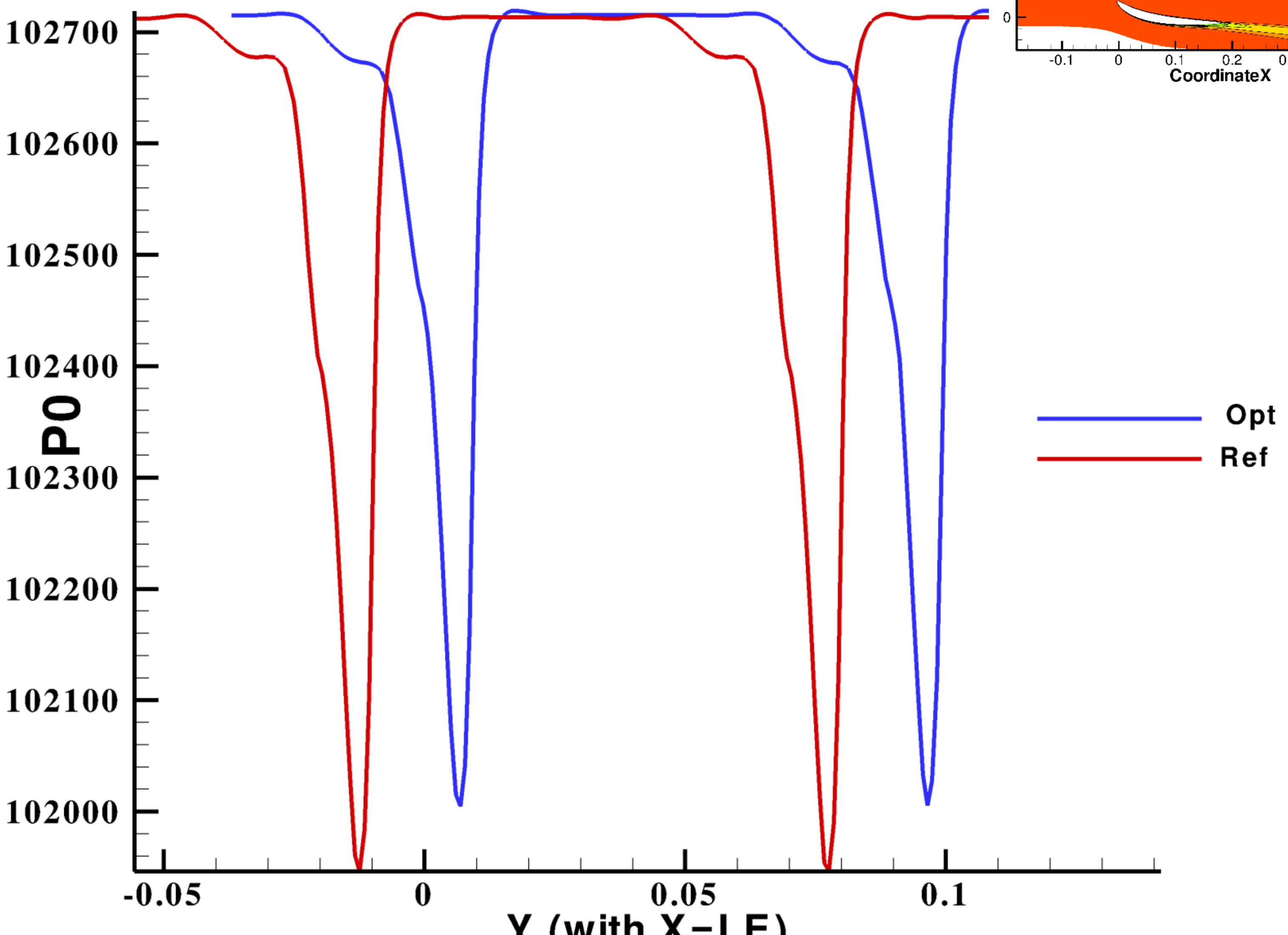
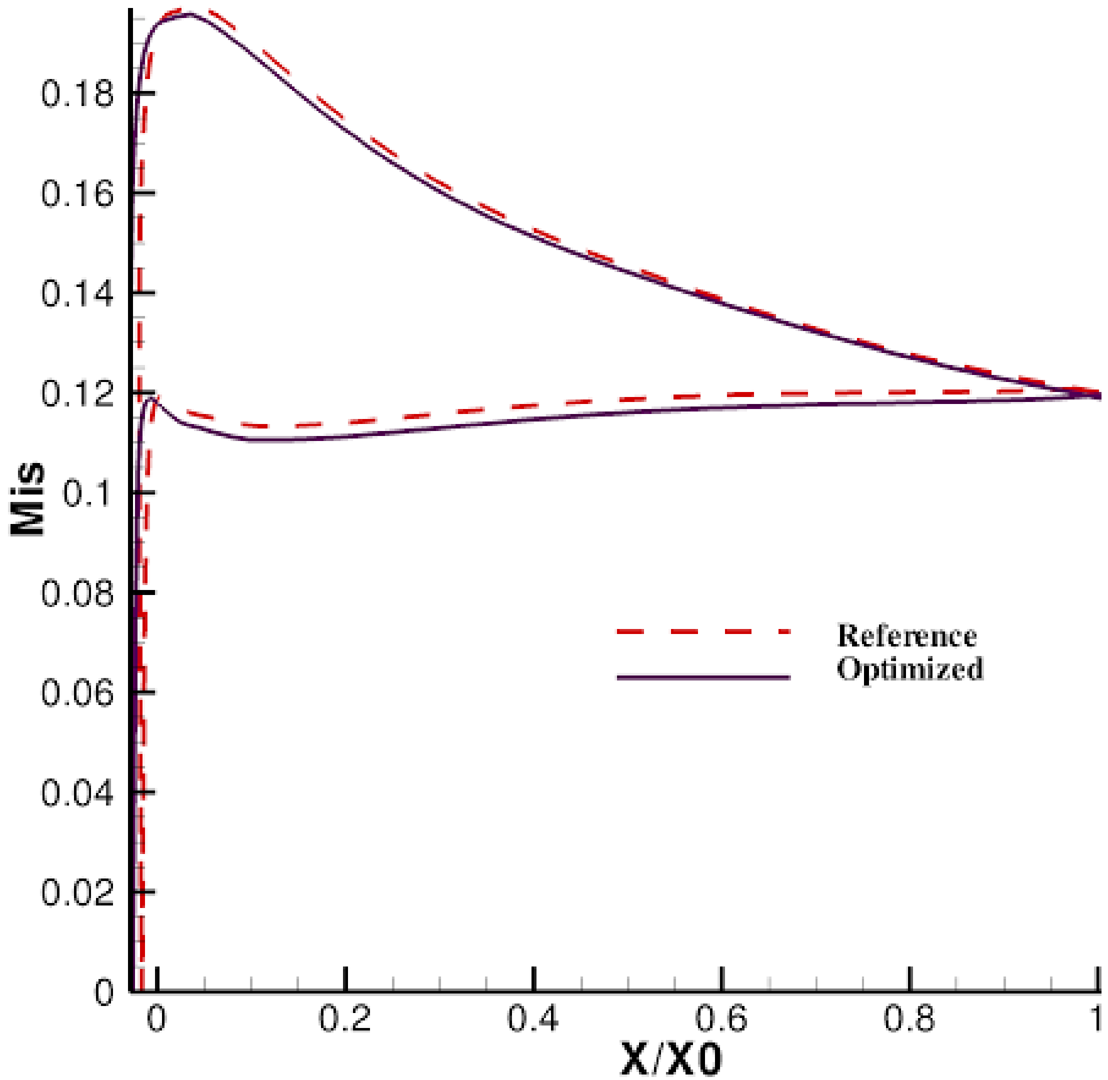
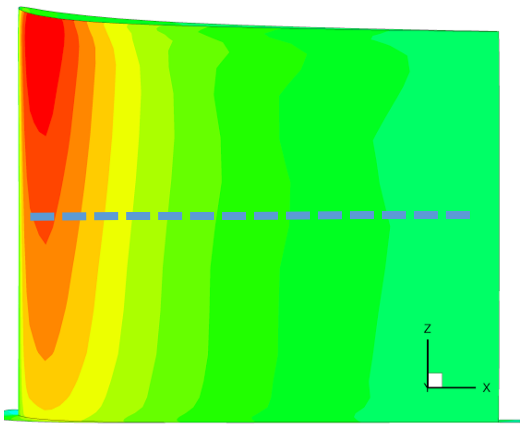




Isentropic Mach Number at mid-span



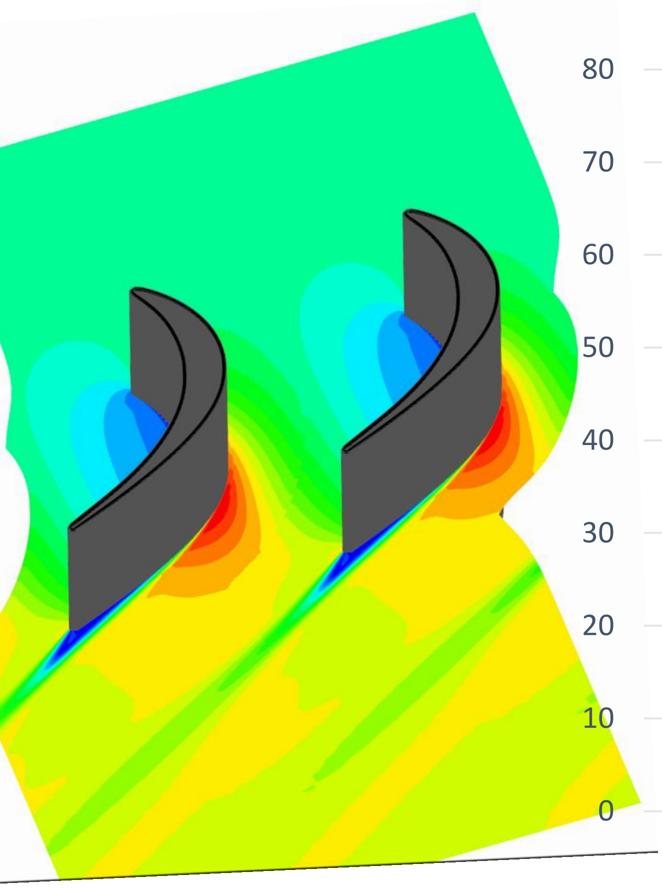


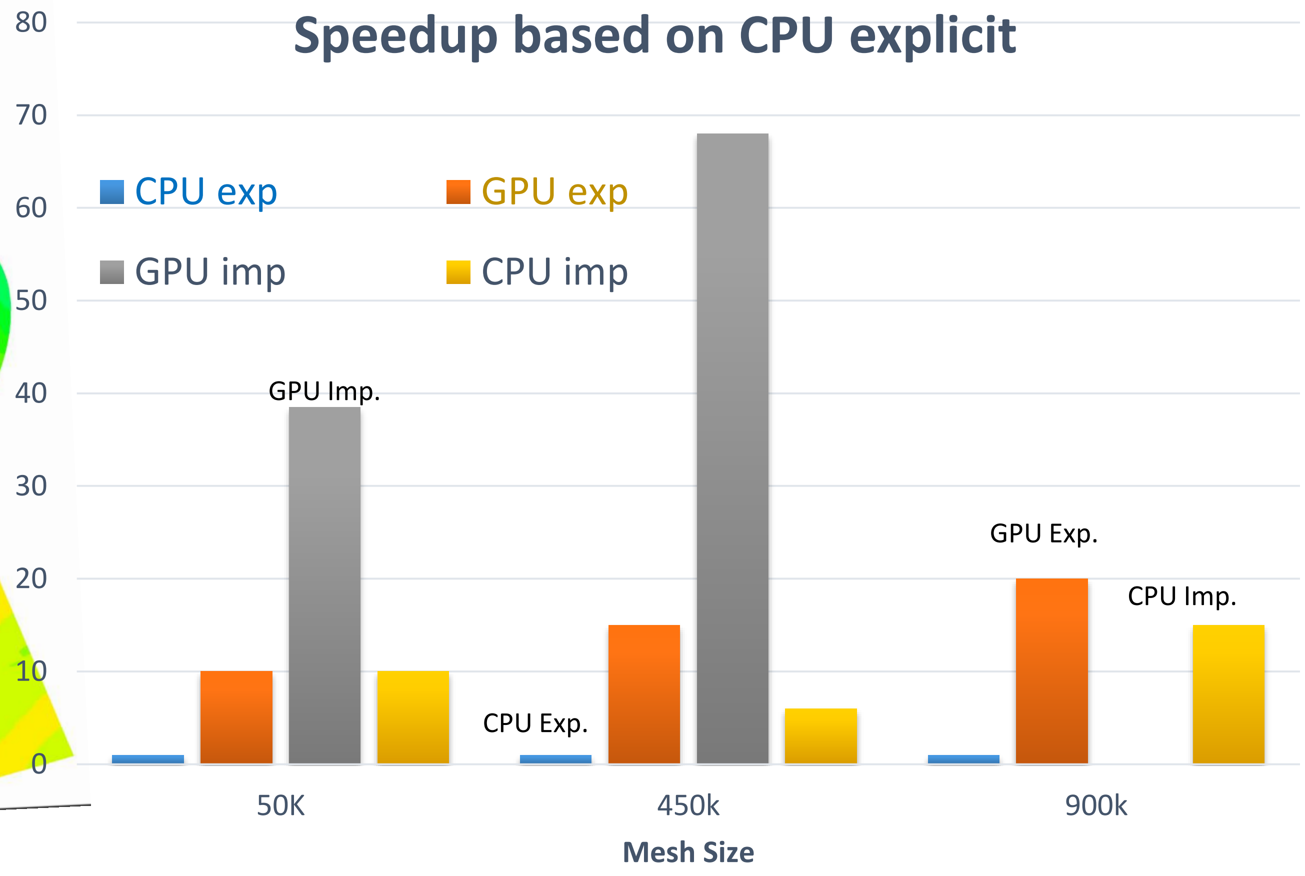
Conclusion

- Optimization
- GPU Solver with implicit time stepping
- *On-demand* (incomplete) Factorization
- 10x speedup
- Aerodynamic shape optimization

Future Work

Benchmark Case: Transonic Turbine Stator T106c





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TU Delft Delft University of Technology

Thanks for your attention

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PARALUTION
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MARIE CURIE ACTIONS