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Industrialization of high-resolution numerical analysis of complex flow phenomena in hydraulic systems

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Visualization Research Center
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Industrialization of high-resolution numerical analysis of complex flow phenomena in hydraulic systems

- Adaptation of high-order CFD method for simulations of real gases and cavitating flows
- High performance and scalability on modern supercomputers
- Development of postprocessing and visualization tools
- Application on industrially relevant cases
- OpenSource publication of code

Duration: 01.09.2013-31.12.2016

Method

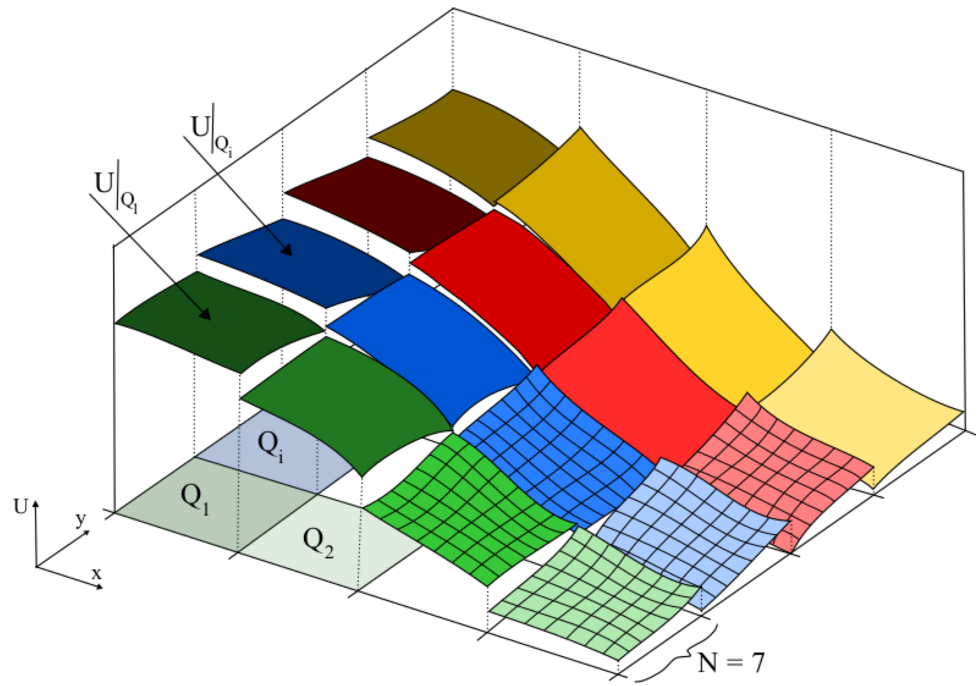
- Compressible Navier-Stokes-Equations

$$\frac{\partial U}{\partial t} + \vec{\nabla} \cdot \vec{F}^a(U) - \vec{\nabla} \cdot \vec{F}^d\left(U, \vec{\nabla} U\right) = 0,\ U = (\rho, \rho\, \vec{v}, \rho e)^T$$

- $\vec{F}^a$ and $\vec{F}^d$: advective and diffusive fluxes
- For application to real gases and cavitating flows: equation of state to compute temperature, pressure and sound velocity

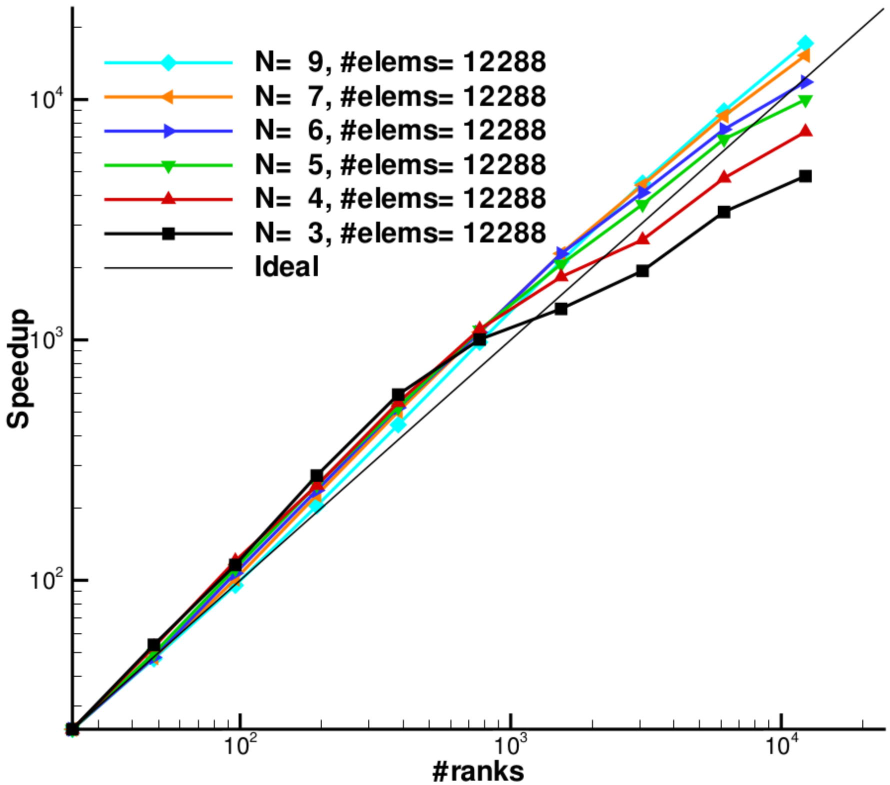
Method

- CFD-Solver based on Discontinuous Galerkin Method
- Polynomial approximation of solution within each cell
- Discontinuous across cell boundaries
- Riemann solver to resolve discontinuity at element interface



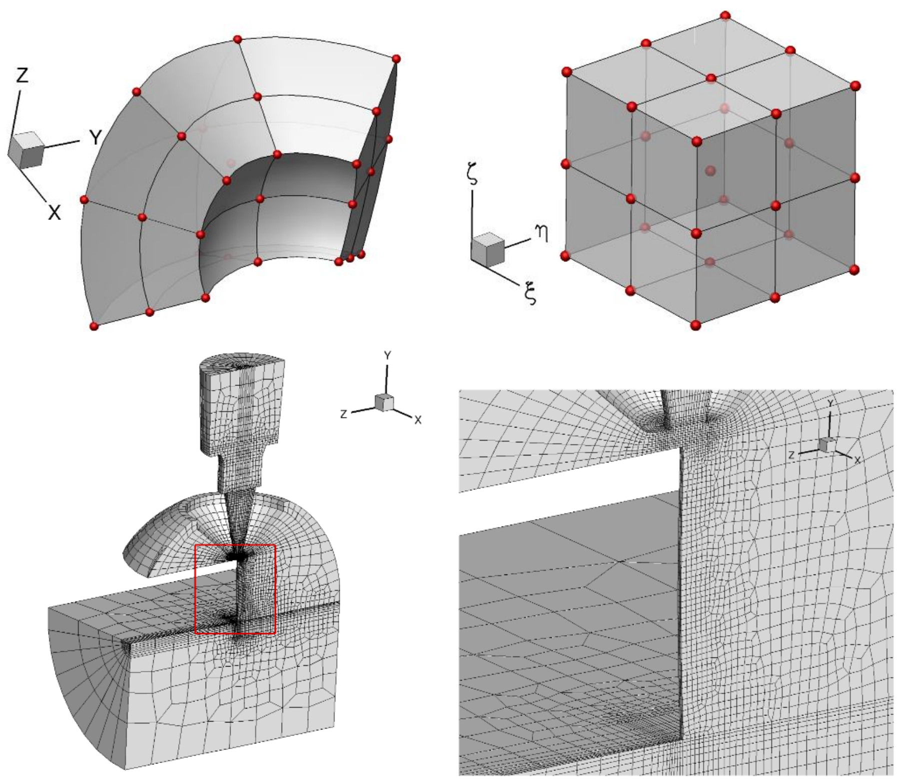
Discontinuous Galerkin CFD-Solver

- CFD-Solver based on Discontinuous Galerkin Method.
- Polynomial approximation of solution within each cell
- Discontinuous across cell boundaries
- Riemann solver to resolve discontinuity at element interface
- Very high parallel scaling due to mostly element local operators



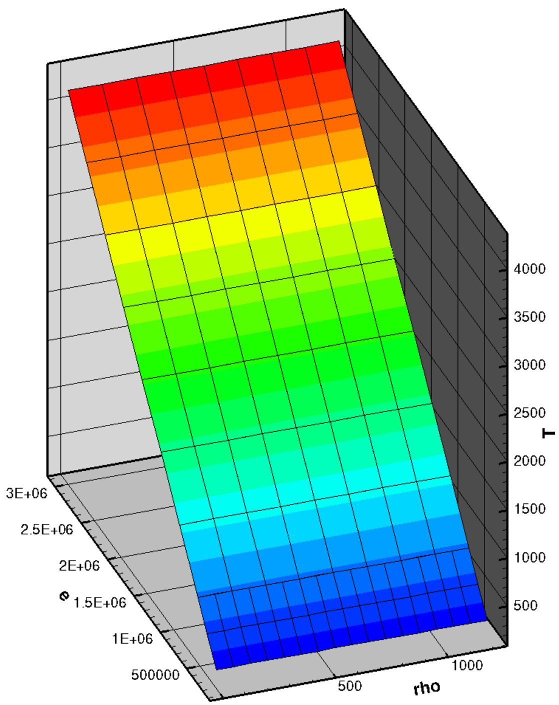
Method

- Unstructured grid with higher-order hexahedrons
- $(N+1)^3$ interpolation points per cell
- Transformation to reference element $[-1,1]^3$ for calculations

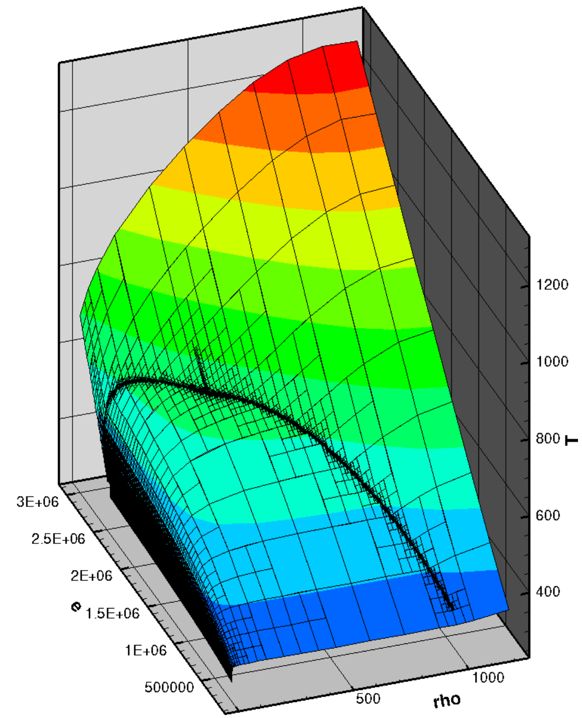


Real fluids: Equations of State

- Ideal gas law: $p = \rho R T$ and $e = c_v T$
- Real fluids: Complex Equations of State (EOS)
- Use data provided by Coolprop library



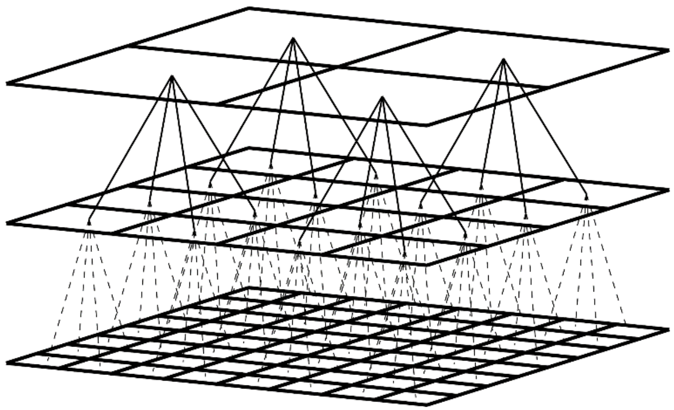
Ideal Gas



Real Fluid

Real fluids: Equations of State

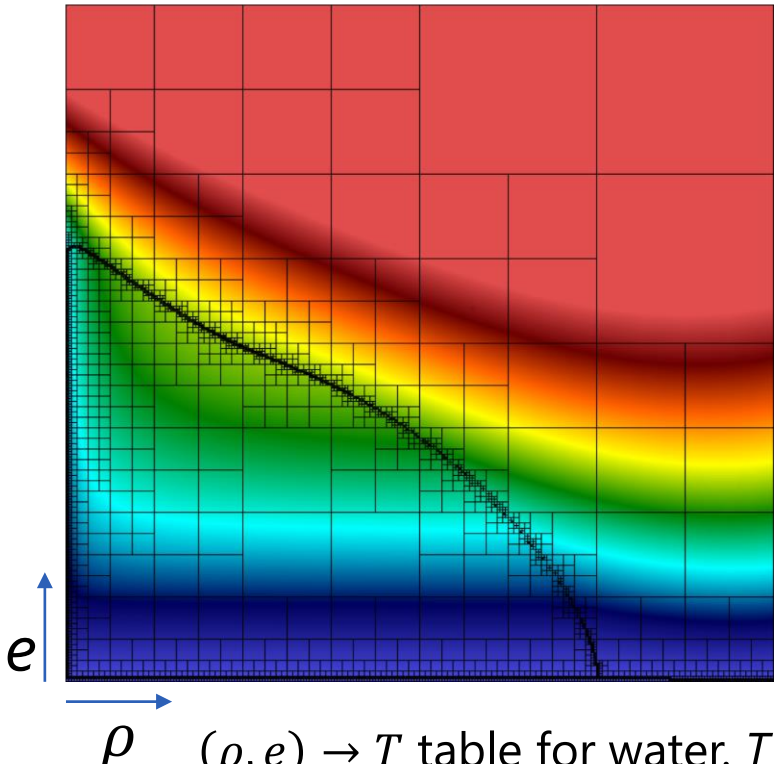
- Evaluation of EOS with Coolprop prohibitively slow for simulation
- Efficient MPI-parallelized pre-evaluation of EOS to a table
- Quadtree based refinement structure



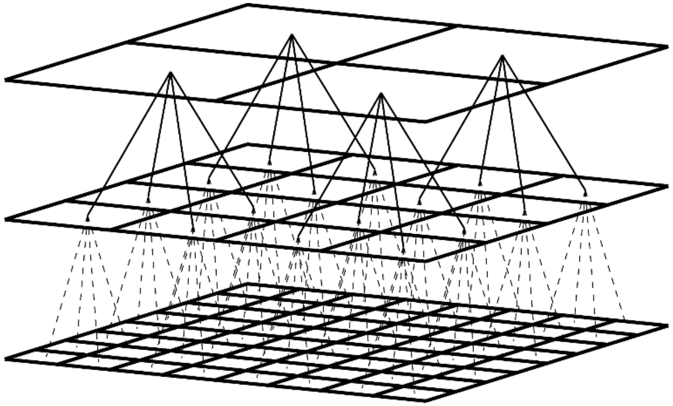
Quadtree structure for table refinement

Real fluids: Equations of State

- Evaluation of tabulated EOSs faster by about a factor 1000 compared to Coolprop



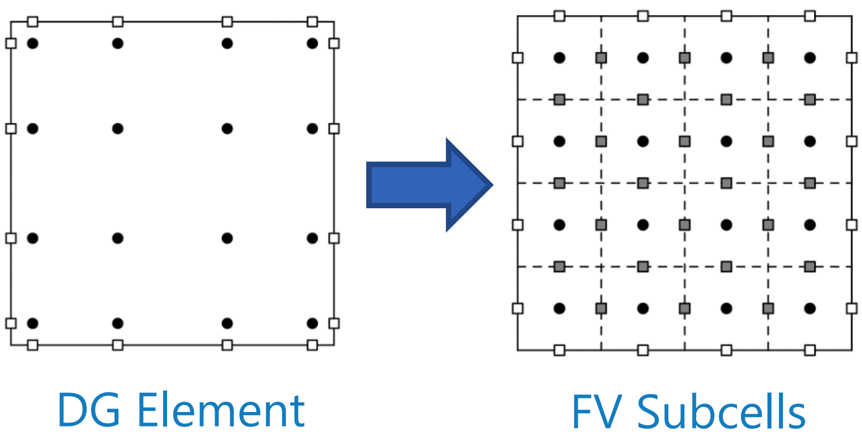
$(\rho, e) \rightarrow T$ table for water. T color coded.



Quadtree structure for table refinement

DG Method and Shock Capturing

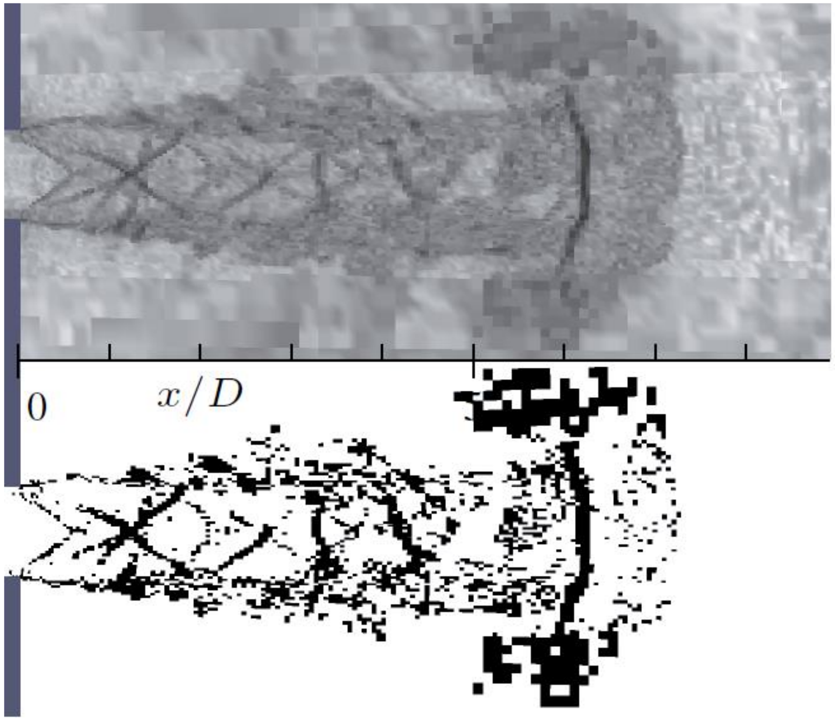
- Polynomial DG solution can become unstable
  - Shock waves
  - Phase transitions
  - Underresolved simulations
- Detection of instabilities with various sensors
- Program switches to Finite-Volume Scheme in these regions
  - One FV cell per DG interpolation point



Shock Capturing and Load Balancing

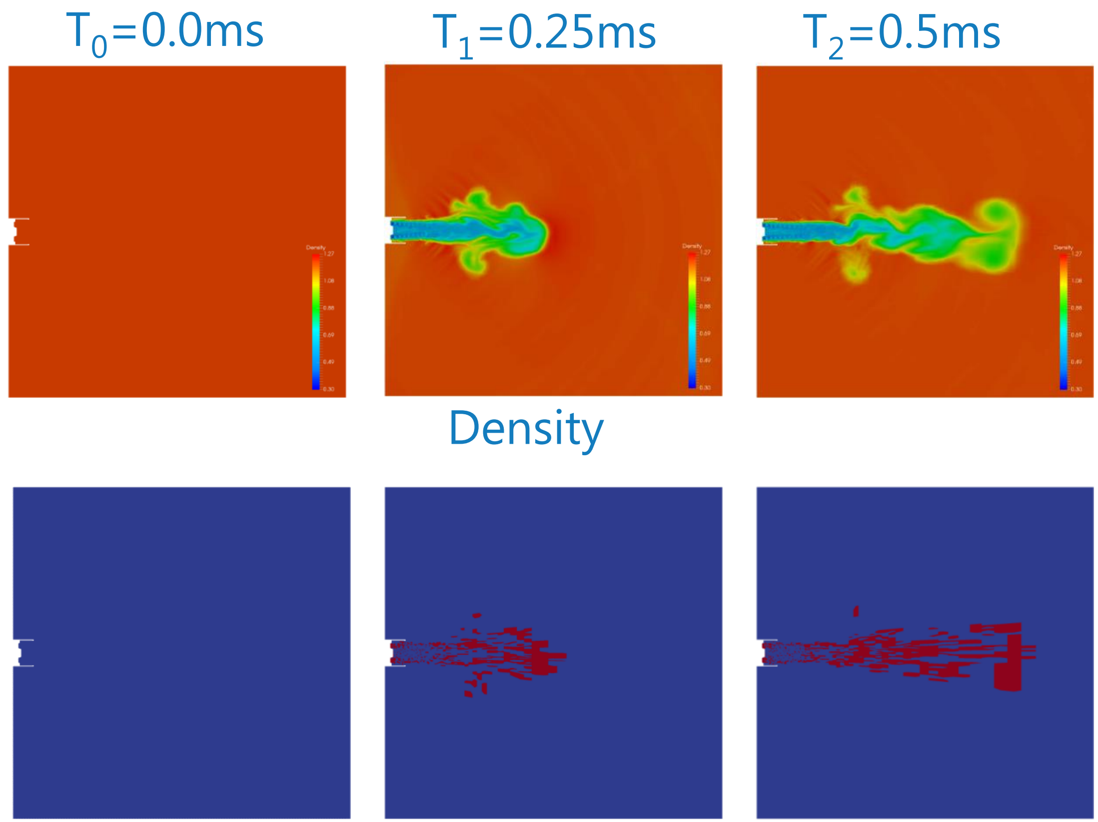
Computational cost of DG cells and FV cells differs by about 50%

Load imbalances



Jet Simulation. Top: Persson sensor value, bottom: FV cells.

Dynamic Load Change

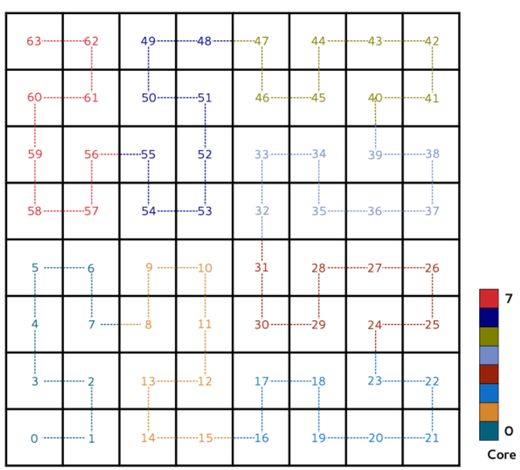


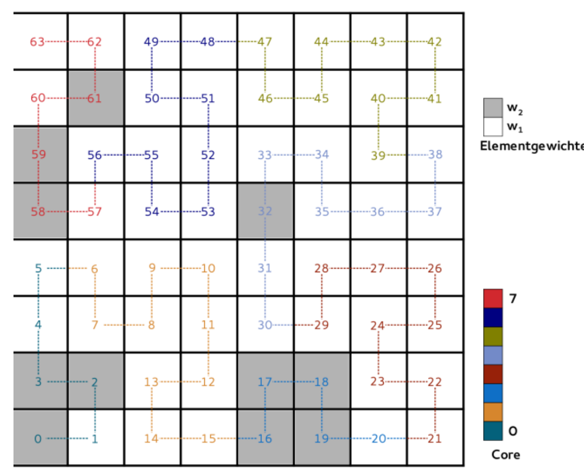
Simulation domain (blue) with FV-Subcells (red)

- DG-FV distribution strongly time-dependent
- Load balancing must be dynamic

Dynamic Load Balancing Strategy

- Elements are evenly distributed among processors along Hilbert-Curve
  - Effectively 1D
- Assign different weights to DG and FV cells and distribute weights evenly
- Cores with many FV cells get fewer cells altogether

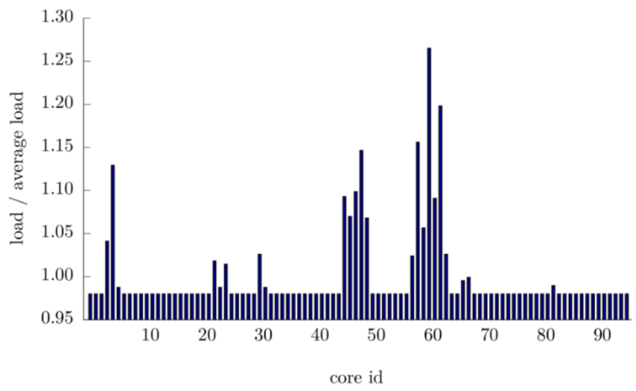


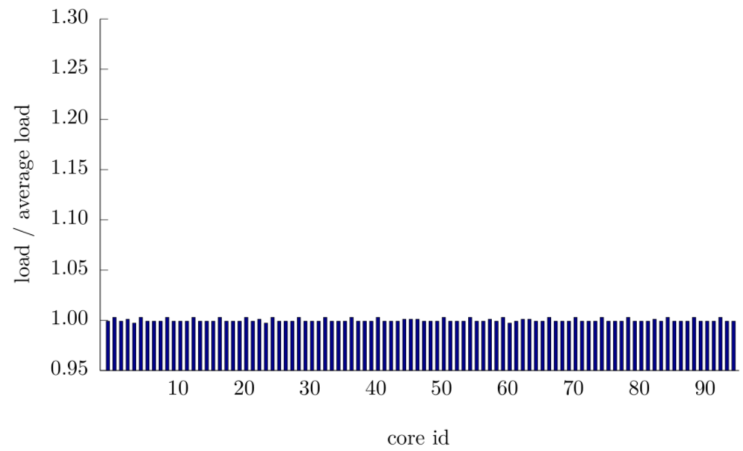


Load-Dependent Domain Decomposition

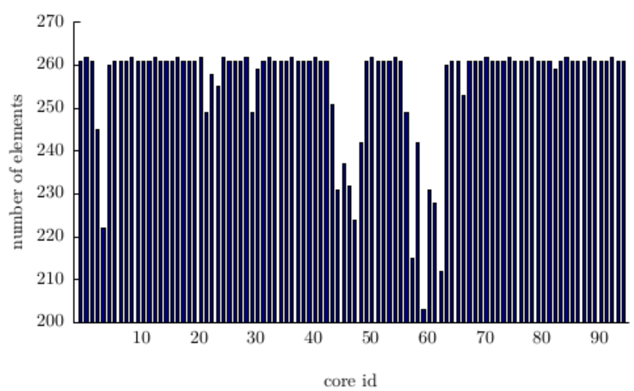
- Reassignment of elements:
  - Shared memory model on node level
  - Each node permanently allocates memory for additional elements
  - All-to-all communication between nodes only of current DG-FV distribution
  - Each core can independently compute new element distribution
  - One-to-one inter-node communication to reassign elements
- Performance gain ~10%

Load-Dependent Domain Decomposition



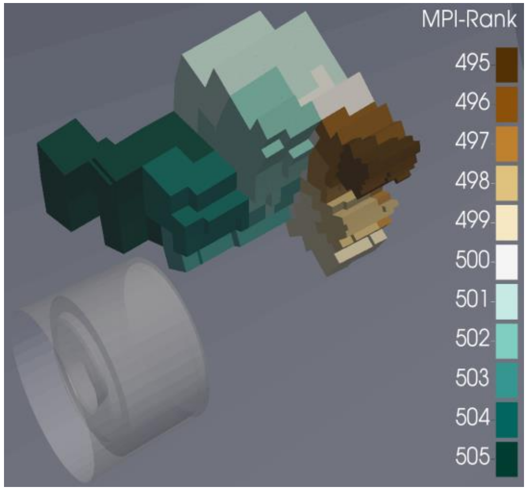


Load distributions on 96 cores before and after load balancing

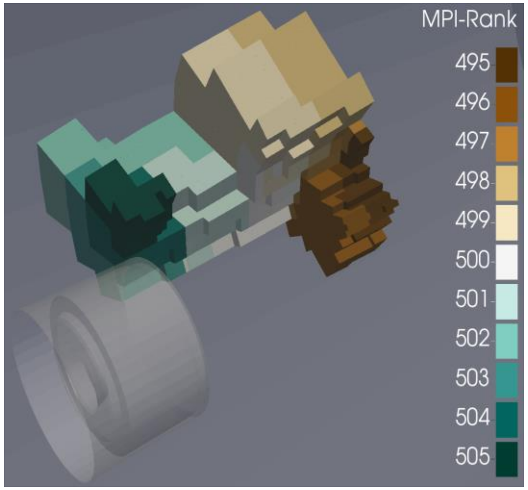


Element distribution on 96 cores after load balancing

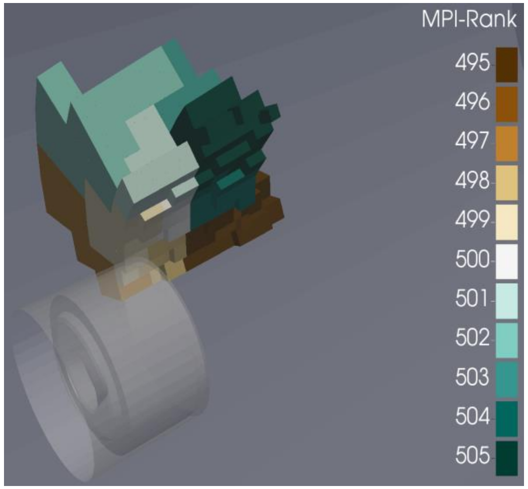
Dynamic Load balancing: Time-dependent element distribution



T_0=0.0ms



T_1=0.25ms



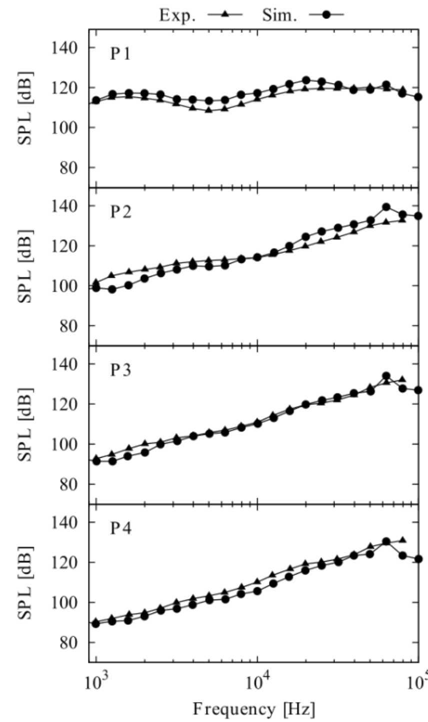
T_2=0.5ms

- Currently load balancing applied repeatedly after a fixed number of timesteps
- Method exploits Hilbert-Curve structure and the relatively small difference in computational cost of DG and FV cells

Use Case: Engine Gas Injection

Natural gas injector

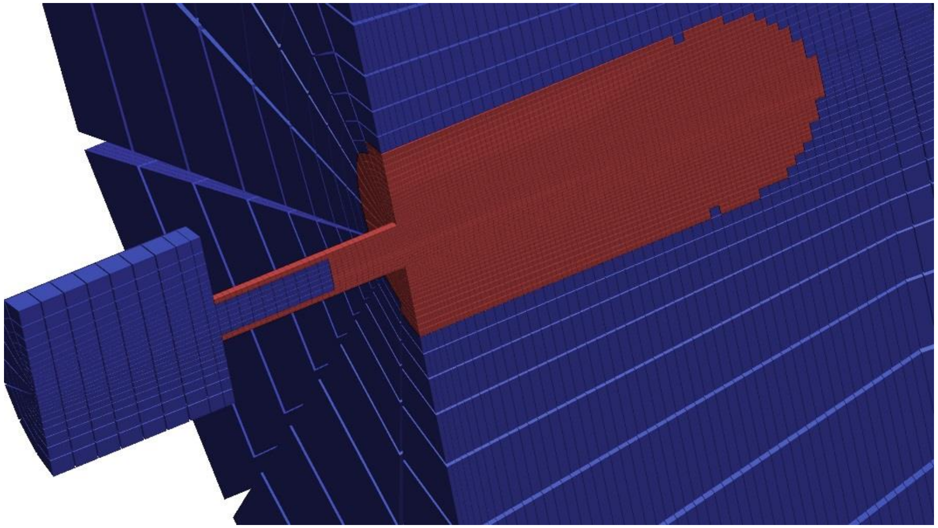
- Previously: Acoustic Simulation



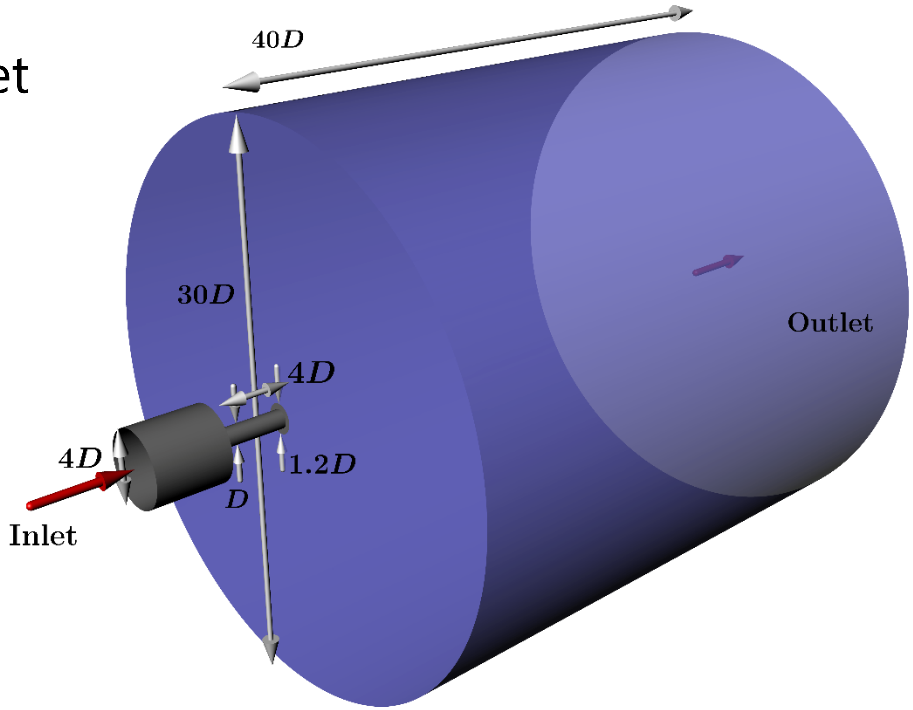
Measured and simulated sound pressure levels

Real Gas Jet Simulation

- Real gas throttle flow with Methane
- Inlet pressure: 500 bar, varying outlet pressure
- Micro throttle with a diameter of D = 0.5 mm



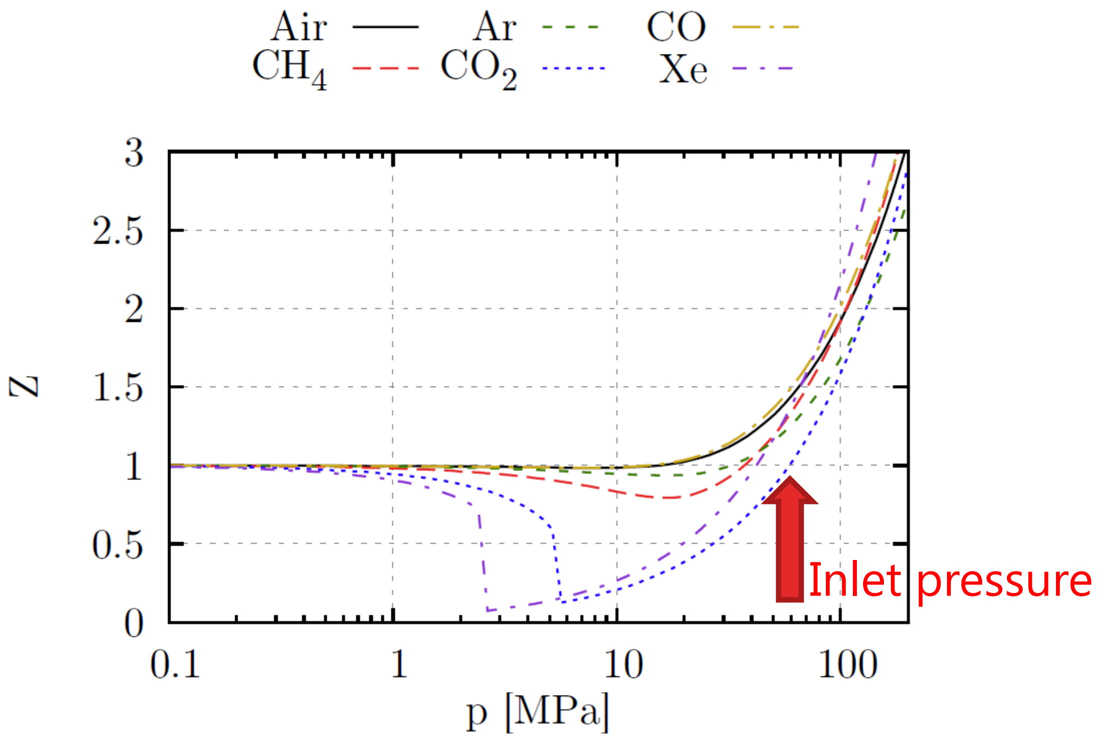
Simulation mesh, high-resolution region in red.



Overview of simulation domain.

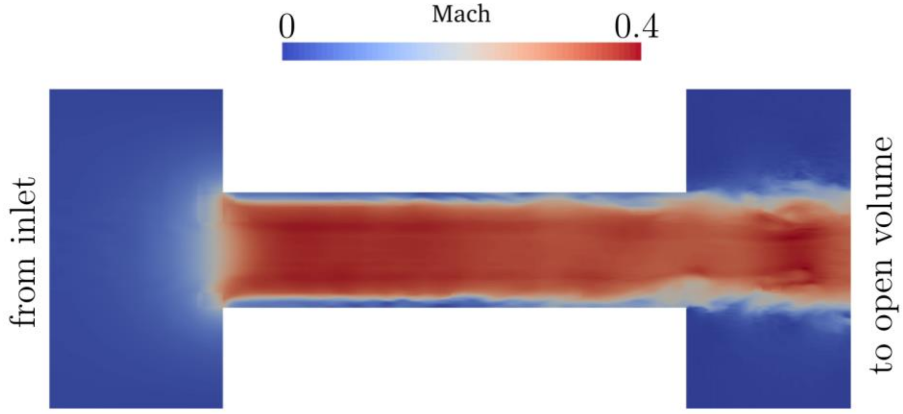
Real Gas Jet Simulation

- Real gas properties of gaseous fluids need to be considered at high pressures

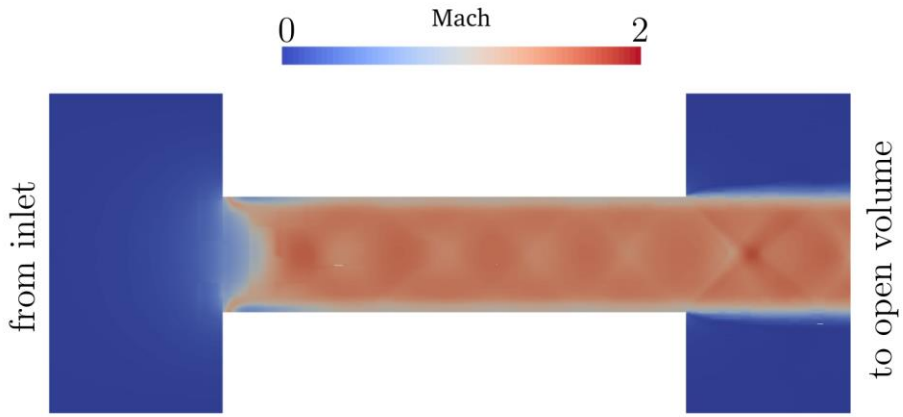


Compressibility factor $Z = p/(\rho RT)$ as a function of pressure for different gases.

Real Gas Jet Simulation



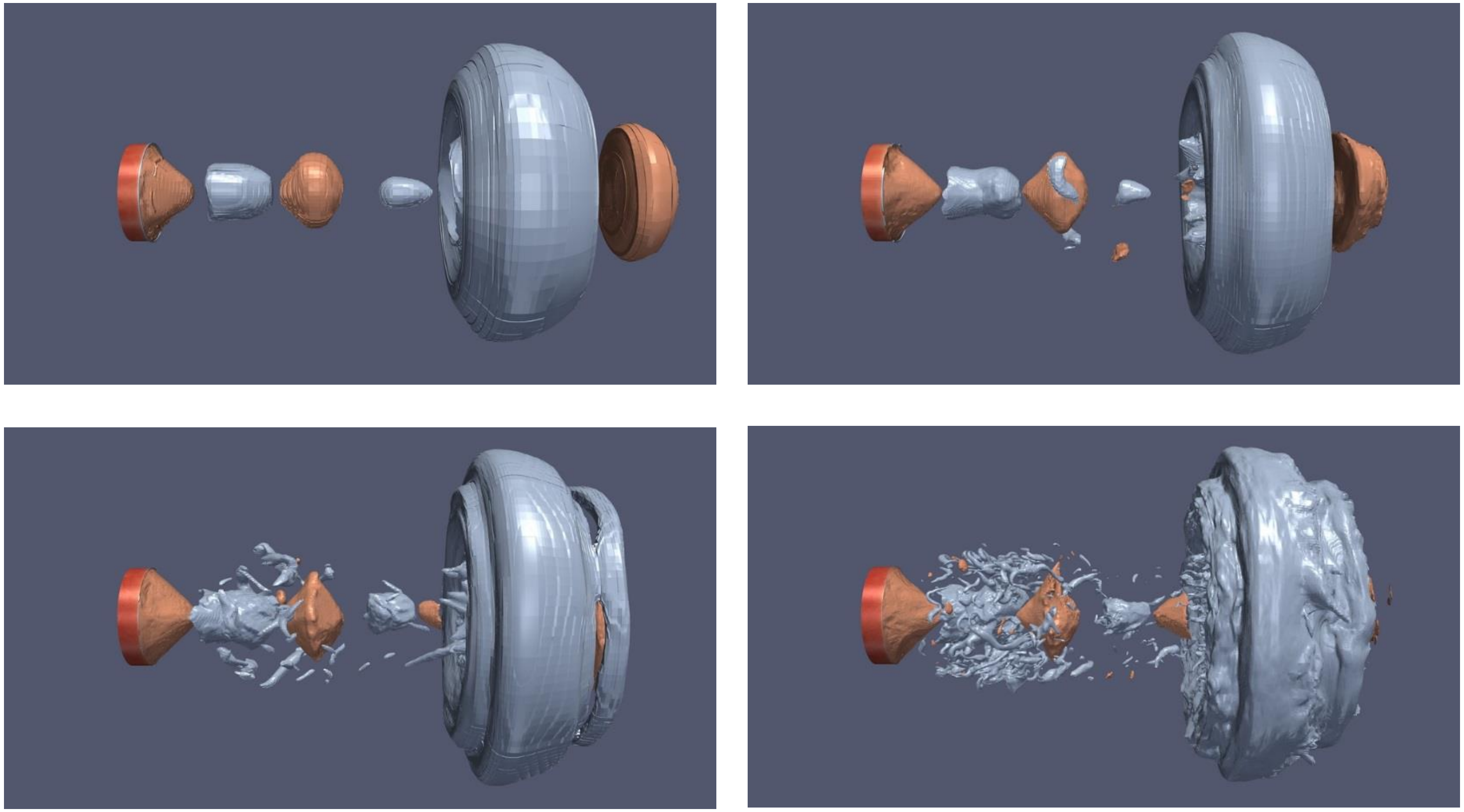
(a) $\mathcal{R}_p = 1.25$



(b) $\mathcal{R}_p = 5.00$

- Flow through throttle subsonic or supersonic, depending on pressure ratio $R_\mathrm{p} = p_\mathrm{in}/p_\mathrm{out}$

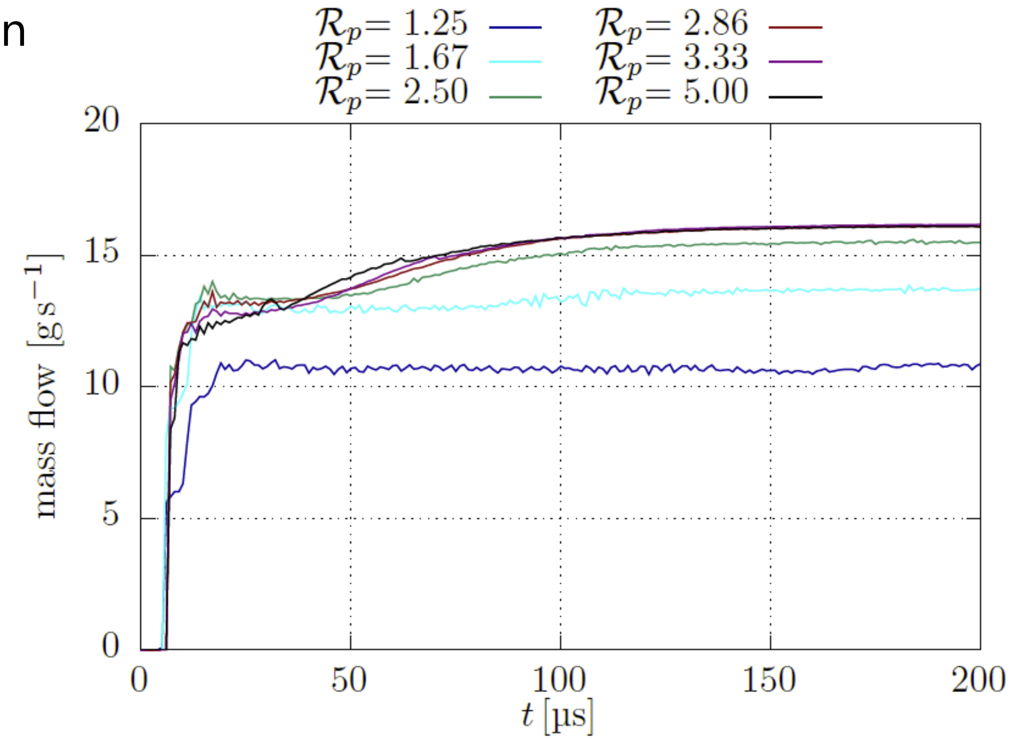
Influence of Grid Resolution



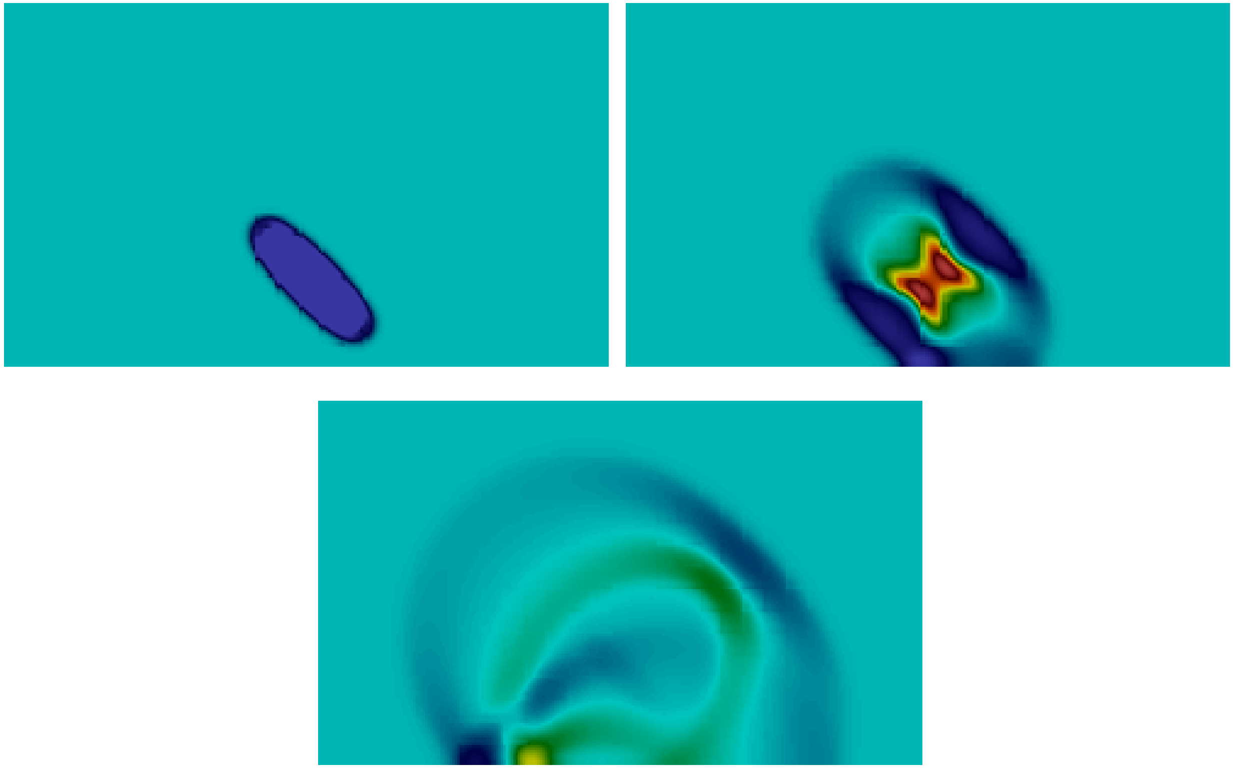
- Mixed DG-FV approach can accurately predict major structure of shock locations for all grid resolutions

Real Gas Jet Simulation: Mass Flow Analysis

- Accurate prediction of mass flow is essential to design of gas injectors
- Dynamic behavior of mass flow at beginning of simulation
  - Interesting because gas injection occurs at high frequencies
- For $R_{\mathrm{p}} > 2.5$ maximum value virtually independent of R_{p}



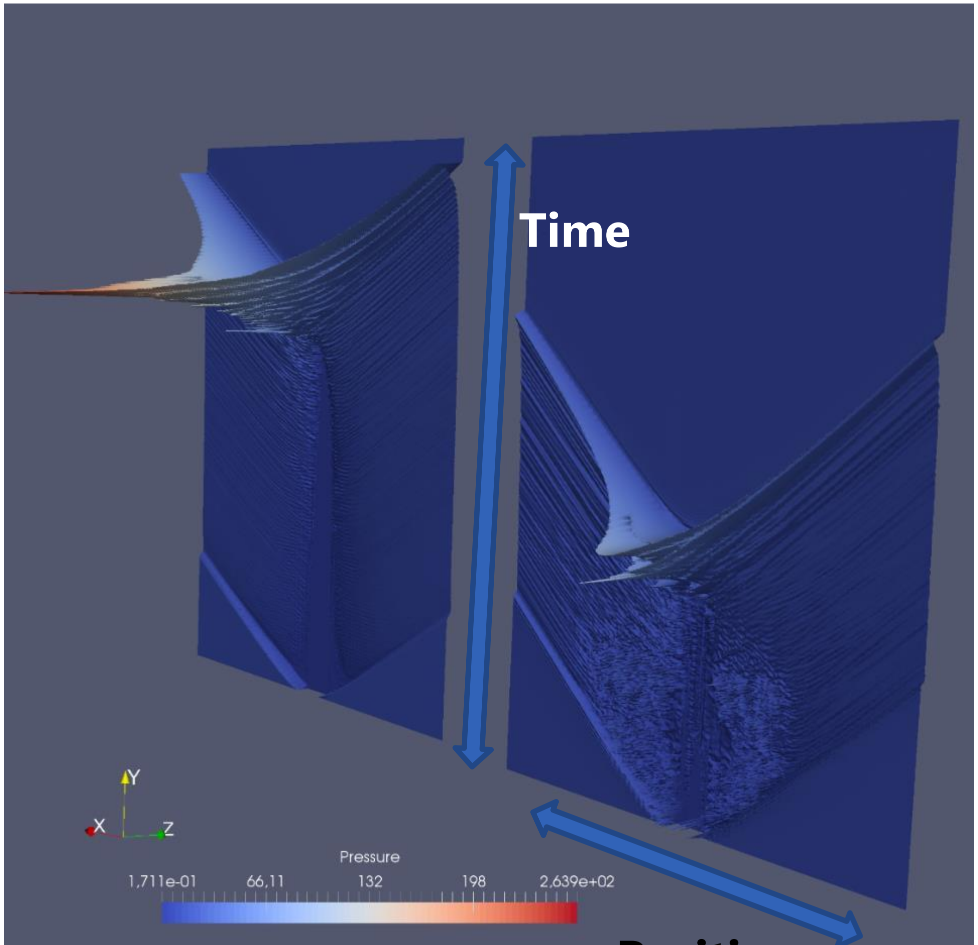
Investigation of Single Bubble Collapse



Ellipsoidal gas bubble collapsing close to a surface

- Test case for behavior of solver in cavitating flows
- Investigation of pressure waves hitting nearby surfaces

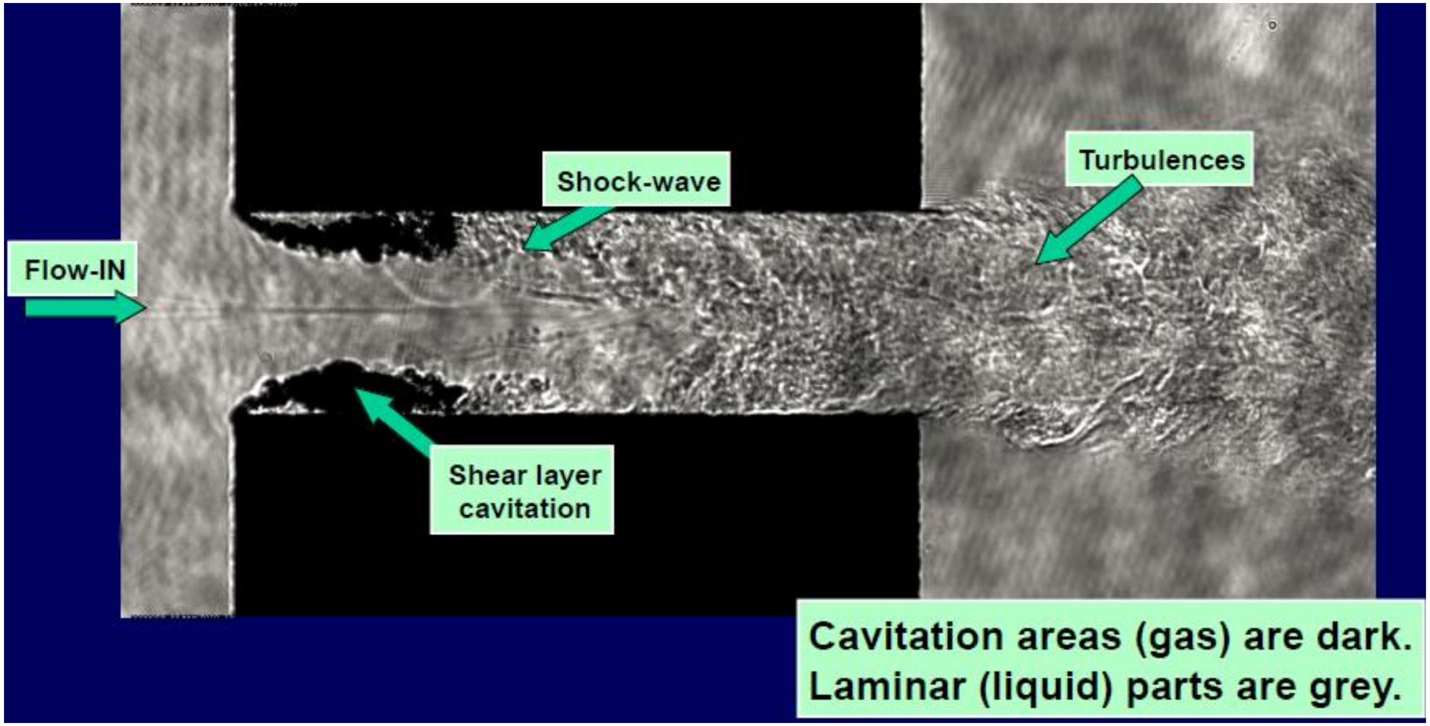
Investigation of Single Bubble Collapse



Position on Surface

- Spatio-temporal depiction of pressure $p(x,t)$ along line.
- Full time resolution, no timesteps omitted
- Efficient comparison of different simulations
  - Mesh resolution
  - Initial conditions
- Steep gradients at bubble boundary are challenging for tabular EOS

Use Case: Cavitation

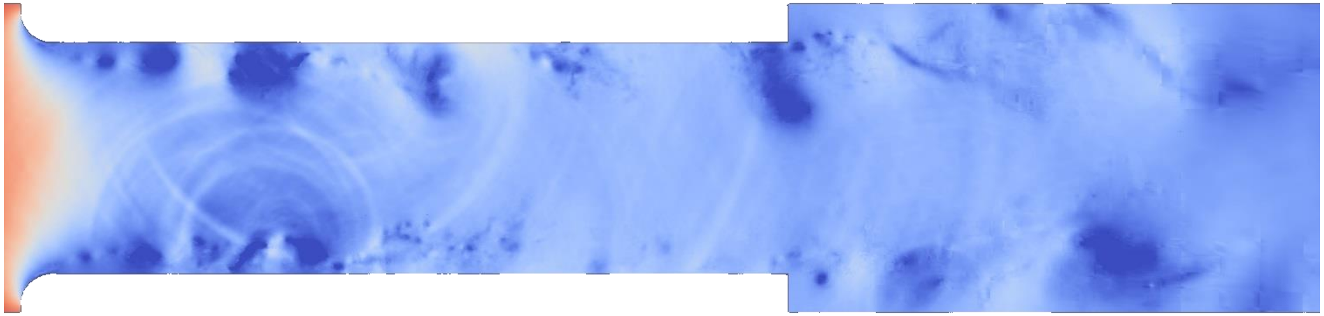


- Evaporation of liquid because pressure drops below vapor pressure
- High pressure peaks if vapor areas collapse
- Industrially relevant due to large damage potential in technical devices

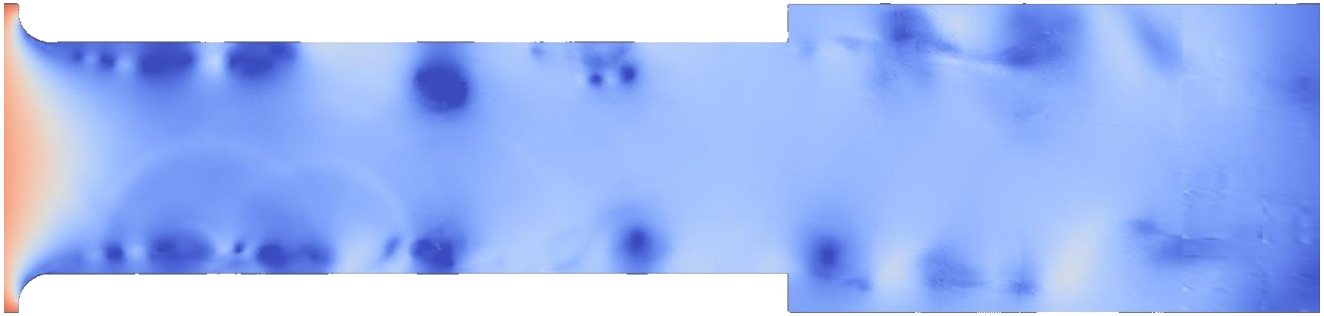
Cavitation

- Micro channel flow with water
  - Strong shocks due to caviation

DG (5th Order)
+
FV (2nd Order)

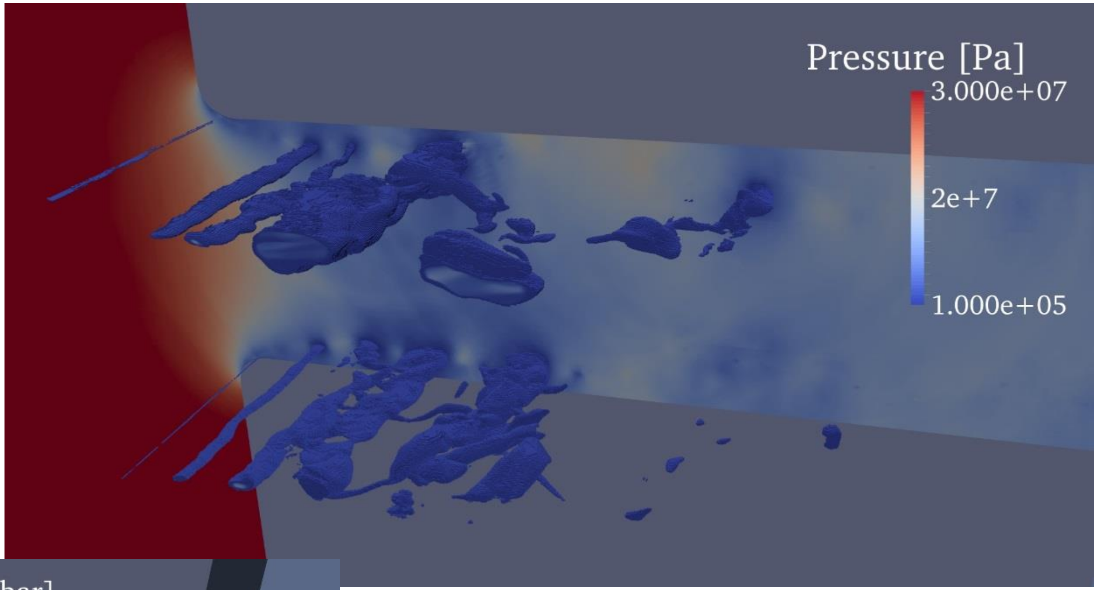


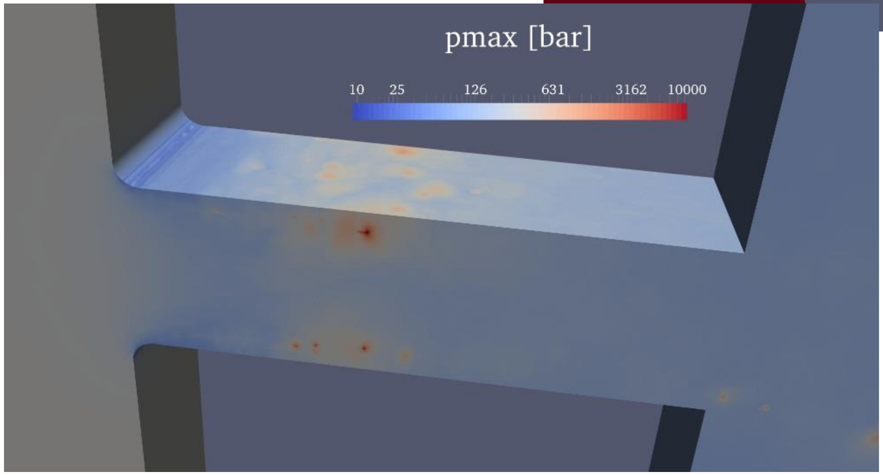
Only
FV (2nd Order)



- Mixed DG-FV approach can resolve much finer scales than FV alone

Cavitation


Pressure [Pa]
3.000e+07
2e+7
1.000e+05


pmax [bar]
10 25 126 631 3162 10000

Conclusion

- Large portfolio of different fluid dynamic simulations
- Efficient usage of highly accurate real gas approximations
- Analysis of the difference between ideal and real gas approximation
  - Mass flow very dynamic for real gas
- Simulation of cavitation show promising results for high order multi-phase flow

Thank you.

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