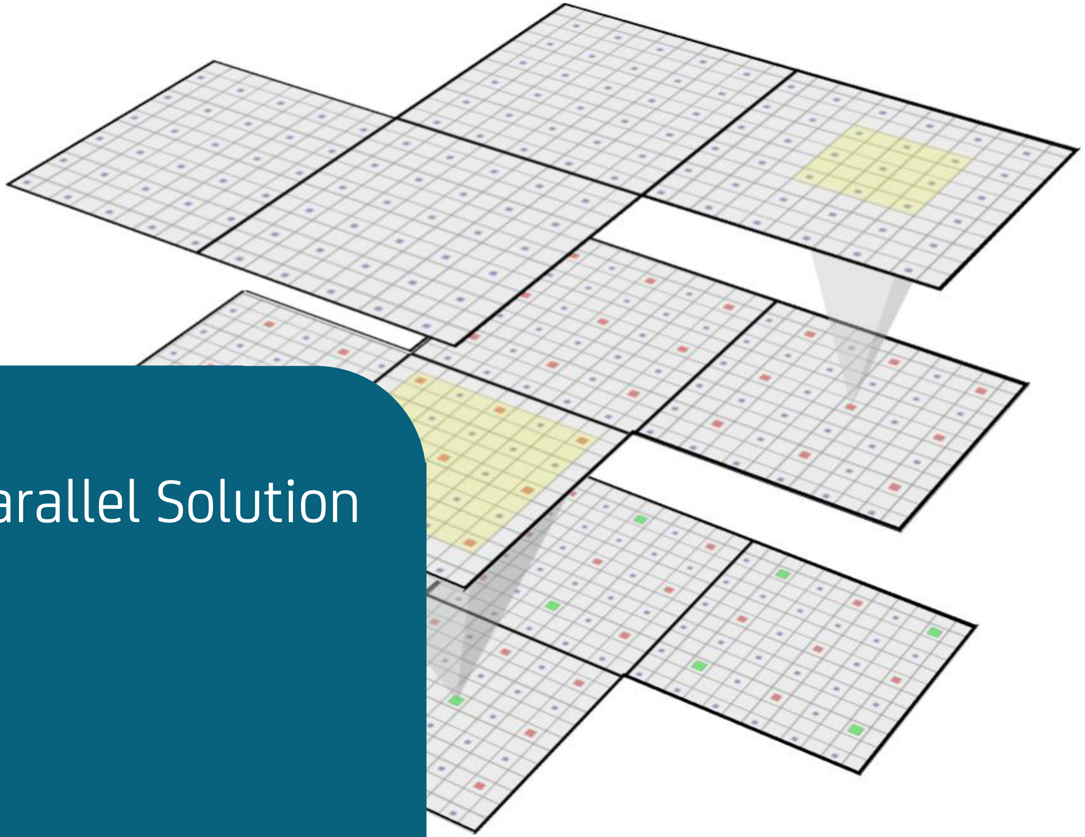


Numerical Insights into the Parallel Solution of the FDS Pressure Equation

Scalability and Accuracy

Dr. Susanne Kilian

hhpberlin - Ingenieure für Brandschutz

10245 Berlin - Germany

hhpberlin

Content

1 Characteristics of the FDS pressure equation

2 Different parallel FDS pressure solvers

3 Numerical accuracy and scalability tests

4 Conclusions

5 Outlook

Characteristics of the FDS pressure equation

Mathematical properties

1

Characteristics of the FDS pressure equation

Elliptic partial differential equation of Poisson type

$$\nabla^2 \mathcal{H} = -\frac{\partial(\nabla \cdot \mathbf{u})}{\partial t} - \nabla \cdot \mathbf{F}$$

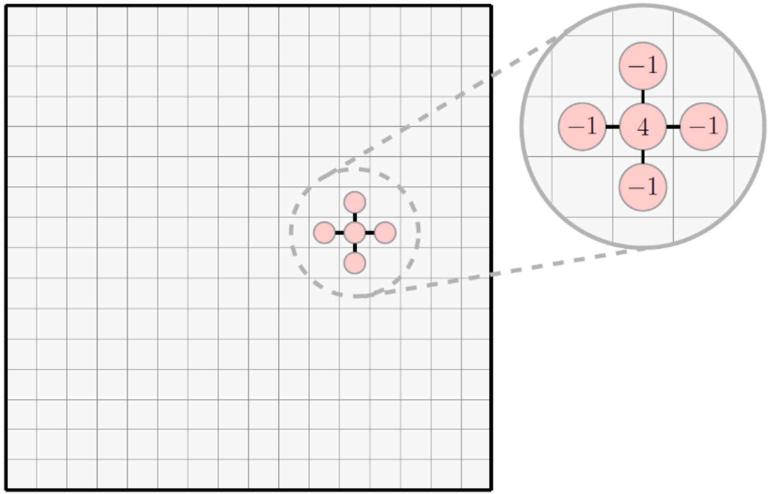
Source terms from previous time step (momentum flux terms)

- Important component in complete solution process
- Solved at least twice in every time step
- Strongly linked with the computation of the other required quantities

Pressure solution strongly influences the quality of the whole simulation

Finite Difference Discretization

Single-Mesh Case



1 linear system of equations:

$$Ax = b$$

Discretization stencil (cell-centered):

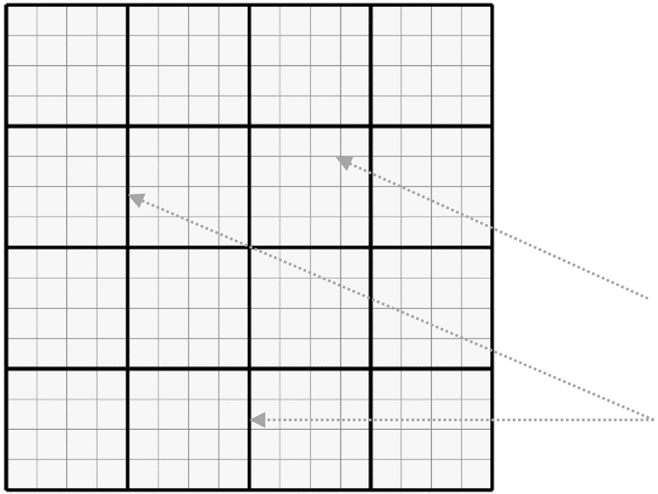
Specifies the physical relationships between grid cells

Finite Difference Discretization

1

Characteristics of the FDS pressure equation

Multi-Mesh Case



M linear systems of equations:

$$A_i x_i = b_i$$

Multiple meshes, assigned to different processors of a parallel computer

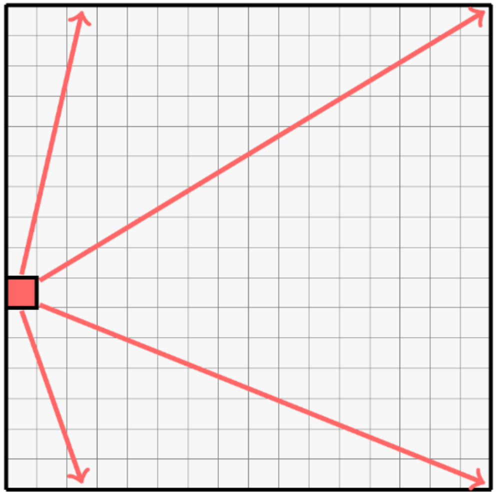
New artificial interior boundaries: Data exchange for coupling needed

Properties in the Single-Mesh case

1

Characteristics of the FDS pressure equation

High velocity for the propagation of information



Local information spreads immediately across whole domain

Local data have impact to entire solution

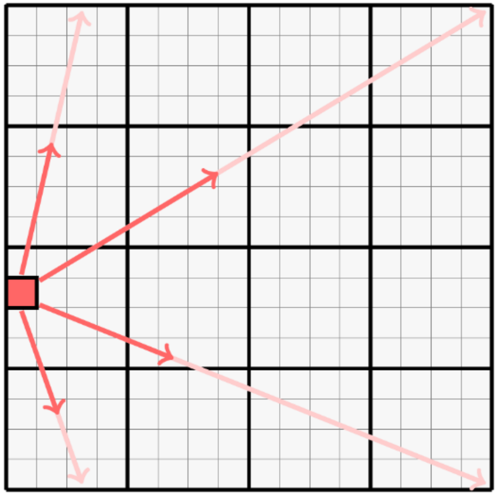
Very strong global coupling

Properties in the Multi-Mesh case

1

Characteristics of the FDS pressure equation

Requirements to the Multi-Mesh pressure solver



Fast spread of data must be reproduced best possible

Fragmentation of physical connectivity must be avoided

Approximation quality of Single-Mesh solver should be preserved

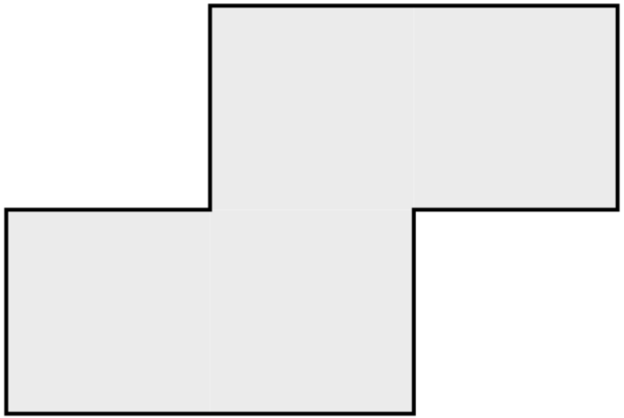
Different parallel FDS pressure solvers

Presentation of two different approaches

2

Different parallel FDS pressure solvers

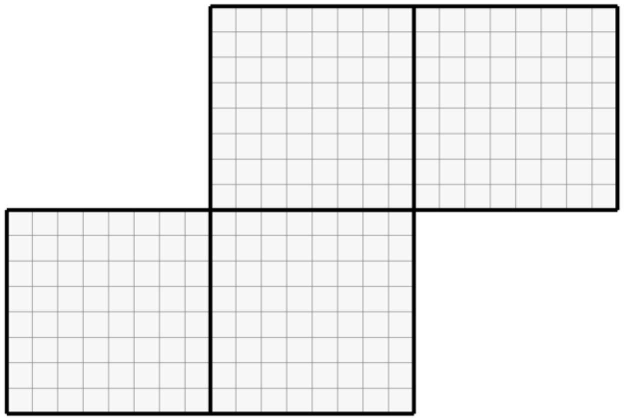
- Explanation of both strategies for pipe-shaped geometry in 2D



Allows for a simple graphical visualization of the underlying concepts

Presentation of two different approaches

- Explanation of both strategies for pipe-shaped geometry in 2D



Subdivision in 4 submeshes

Current official approach: Multi-Mesh FFT

Fast Fourier Transformation:

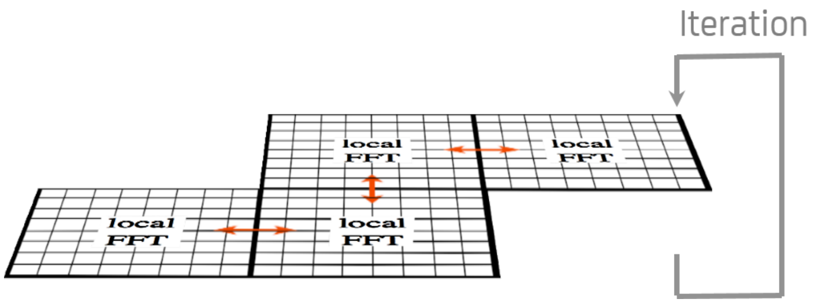
- Locally working method
- Embedded in an iterative averaging process along internal boundaries (and solid obstructions)
- Doesn‘t solve the same system of equations as a corresponding Single-Mesh solver would do (if available)

Current official approach: Multi-Mesh FFT

2

Different parallel FDS pressure solvers

- Local FFT-methods plus averaging process



Local FFT-methods on subgrids:

Data exchange only between direct neighbors (computationally cheap)

Surrounding iteration:

Responsible for the consistency along internal boundaries

- High local efficiency, but only slow global data flow

Current official approach: Multi-Mesh FFT

2

Different parallel FDS pressure solvers

Stopping criterion:

Difference of velocity components at internal mesh boundaries < tol !!

&PRES VELOCITY_TOLERANCE=0.01, MAX_PRESSURE_ITERATIONS=100

Default: (characteristic mesh size)/10

Default: 10

Optimal choice of the tolerance for a given case: tol = ?

- tolerance too coarse: insufficient accuracy
- tolerance too fine: computational time too high

Alternative approach: ScaRC

Scalable **R**ecursive **C**lustering:

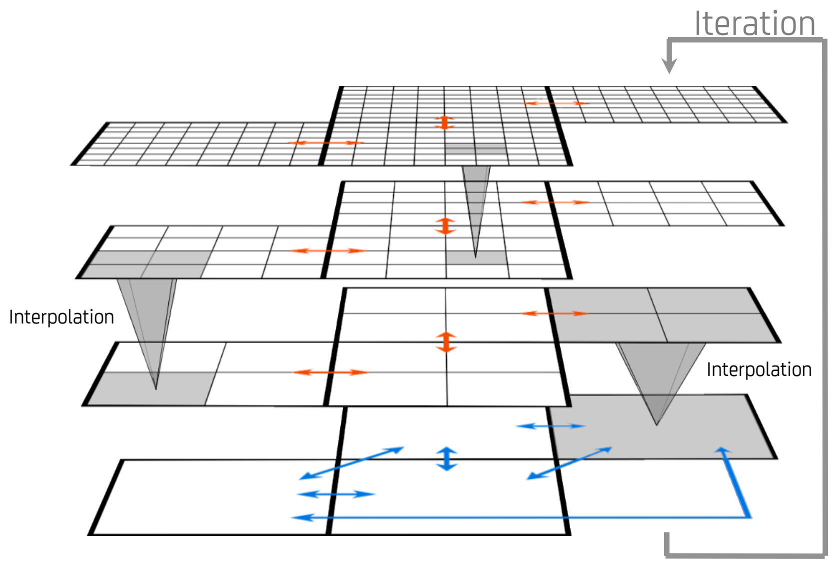
- Globally working method
- Combines domain decomposition techniques with multigrid methods
- Solves the same system of equations as a corresponding Single-Mesh solver would do (if available)

Alternative approach: ScaRC

2

Different parallel FDS pressure solvers

Geometric multigrid variant:



Sequence of grid levels with different resolutions:

Data exchange only between direct neighbors
(computationally cheap)

Averaging process on coarse grid:

Data exchange between all meshes
(computationally expensive)

Each level covers a different range of the global information (strong coupling)

Alternative approach: ScaRC

2

Different parallel FDS pressure solvers

Geometric Multigrid (GMG):

- Uses only the geometric information included in the problem/grid
- Works efficiently for problem classes with certain regularity properties

Algebraic Multigrid (AMG):

- Uses only algebraic information included in the system of equations
- Works efficiently for more general and irregular problem classes

Common requirements: Interpolation between levels / Suitable stopping criterion

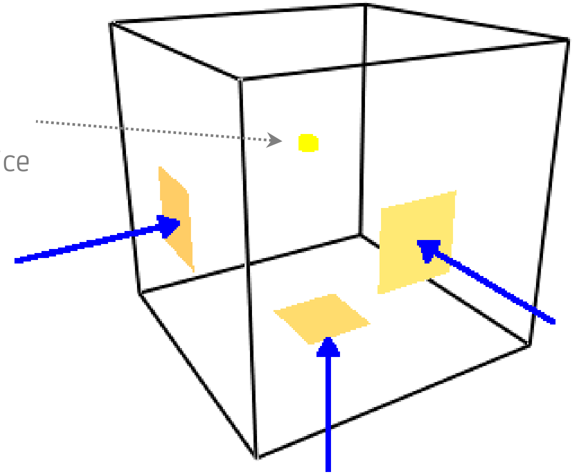
Numerical accuracy and scalability tests

Scarc3D: Frequently changing global behavior

3

Numerical accuracy and scalability tests

ScaRC verification case for a cube-shaped domain in 3D



Evaluation point for pressure device

Grid resolution 128^3

Different inflows from three sides

Global situations changes in small time intervalls of 0.05 s

Great challenge for different solvers

Can Multi-Mesh FFT and ScaRC reproduce the global data flow?

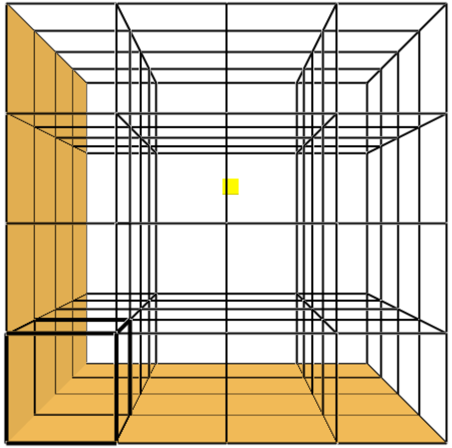
Scarc3D: Frequently changing global behavior

3

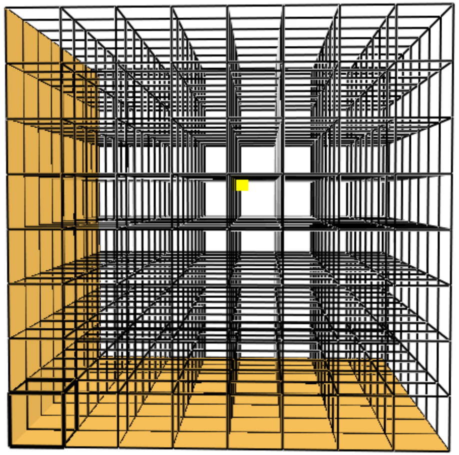
Numerical accuracy and scalability tests

- High level of fragmentation by subdivision

64 Meshes (4x4x4)



512 Meshes (8x8x8)

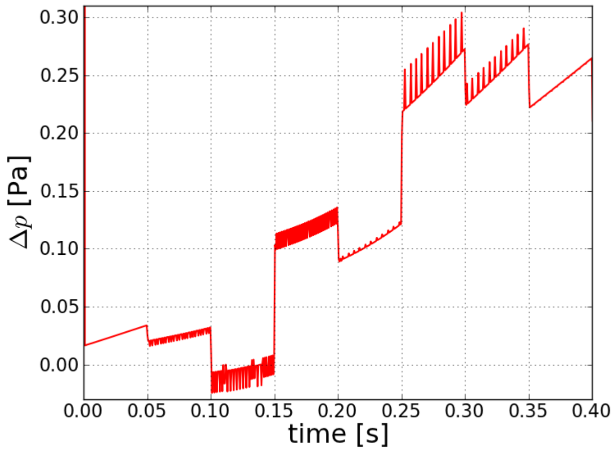


- Compare pressure devices: “Multi-Mesh FFT & ScaRC versus Single-Mesh FFT”

Scarc3D: Frequently changing global behavior

- Stepwise/oszillating evolution of pressure device

Pressure-Device, 1 mesh



- Pressure device of corresponding Single-Mesh FFT case is taken as reference

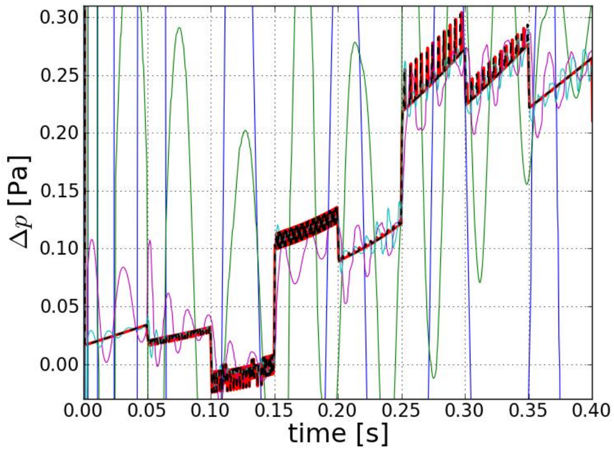
Scarc3D: Frequently changing global behavior

3

Numerical accuracy and scalability tests

Stepwise/oszillating evolution of pressure device

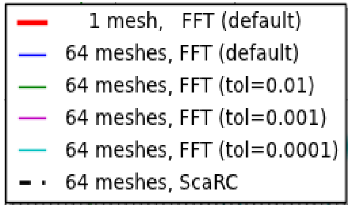
Pressure-Device, 64 meshes



Comparison of:

- Single-Mesh FFT
- Multi-Mesh FFT with

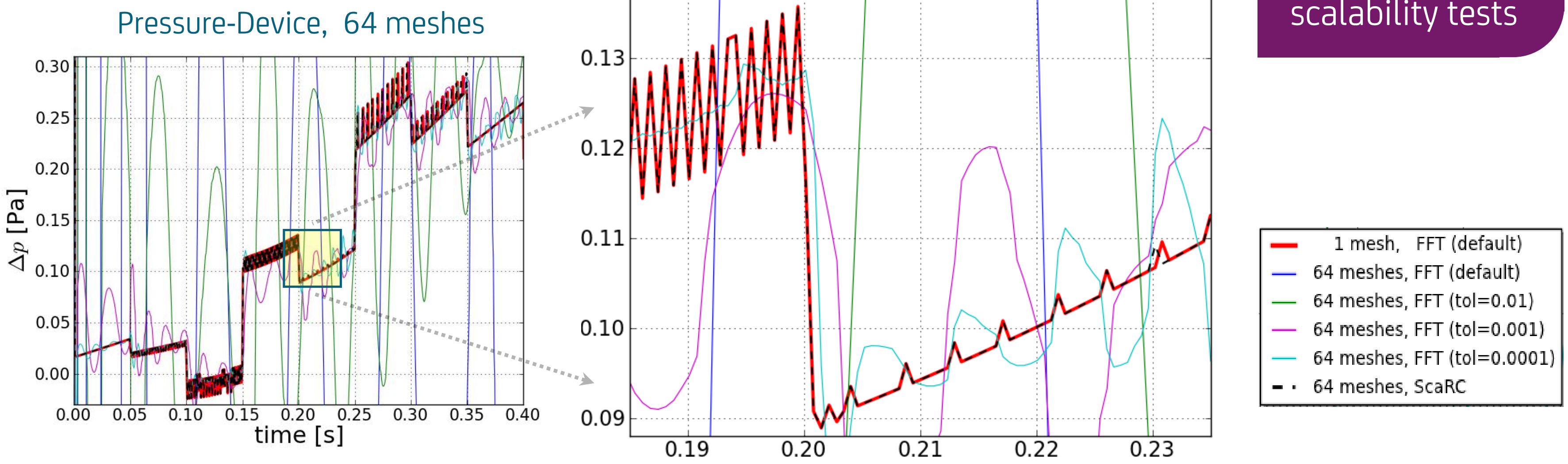
  tol = default, 10^{-2}, 10^{-3}, 10^{-4}
- ScaRC



Acceptable consistency only for Multi-Mesh FFT(10^{-4}), full consistency for ScaRC

Scarc3D: Frequently changing global behavior

- Stepwise/oszillating evolution of pressure device



- Acceptable consistency only for Multi-Mesh FFT(10^{-4}), full consistency for ScaRC

3

Numerical accuracy and scalability tests

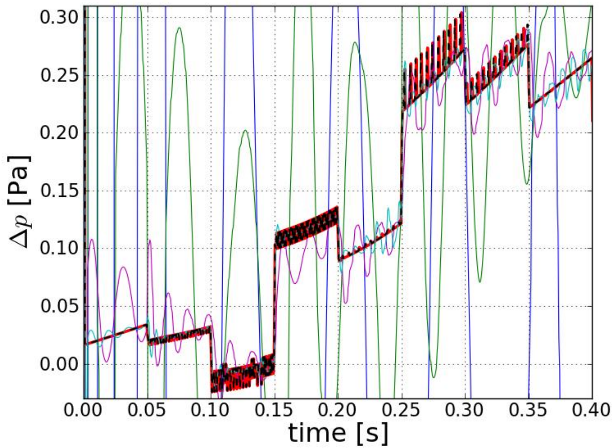
Scarc3D: Frequently changing global behavior

3

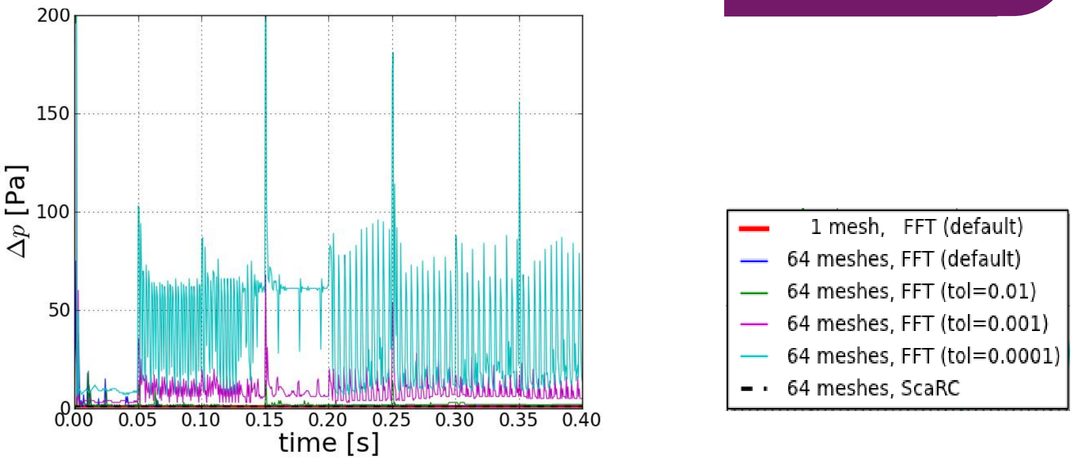
Numerical accuracy and scalability tests

Multi-Mesh FFT: Drastic increase of iteration numbers

Pressure-Device, 64 meshes



Number of iterations, Multi-Mesh FFT



Big rise of computational overhead to achieve a sufficient accuracy

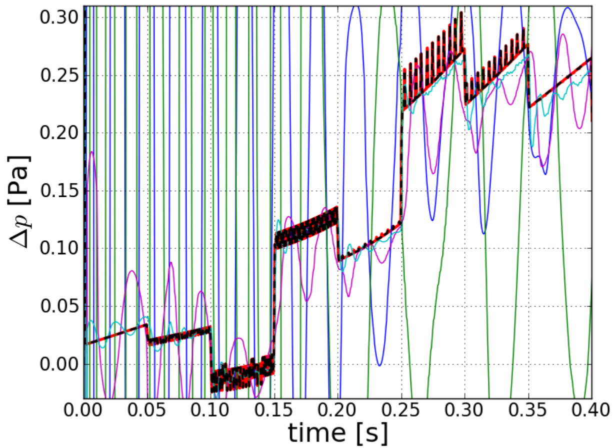
Scarc3D: Frequently changing global behavior

3

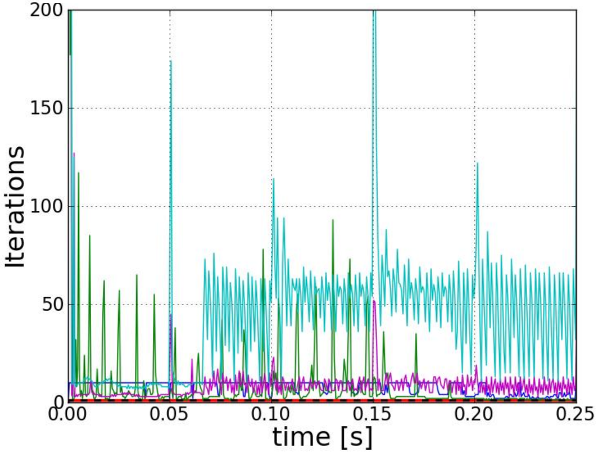
Numerical accuracy and scalability tests

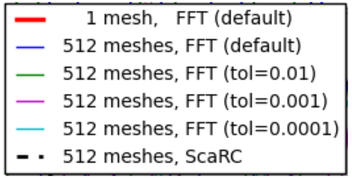
- Similar comparisons for the 512-mesh case

Pressure-Device, 512 meshes



Number of iterations, Multi-Mesh FFT



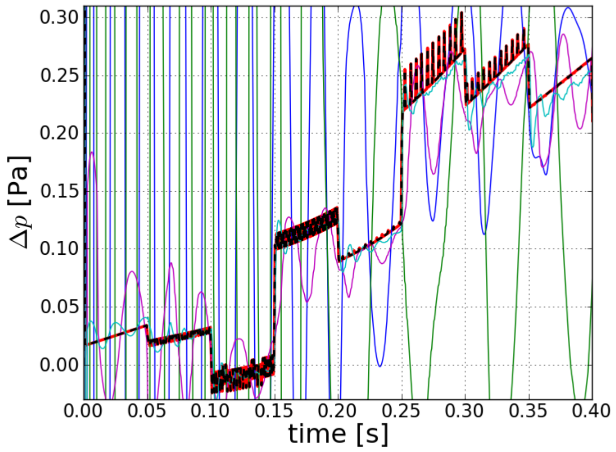


- The more meshes, the bigger the differences

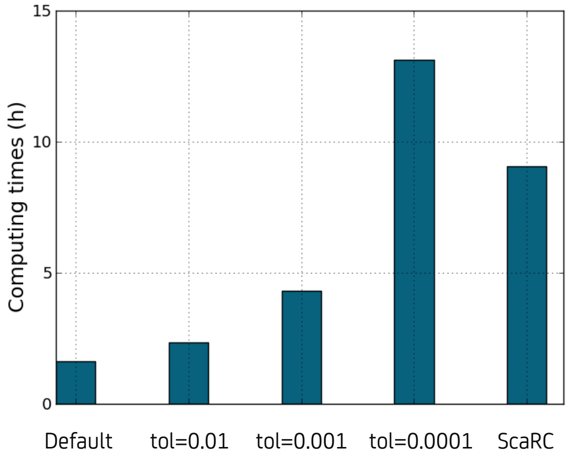
Scarc3D: Frequently changing global behavior

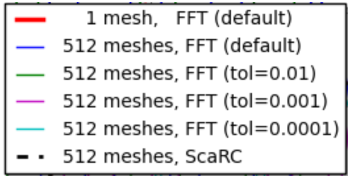
- Very different computing times

Pressure-Device, 512 meshes



Computing times, 512 meshes





- Fair comparison only for Multi-Mesh FFT(10^{-4}) and ScaRC

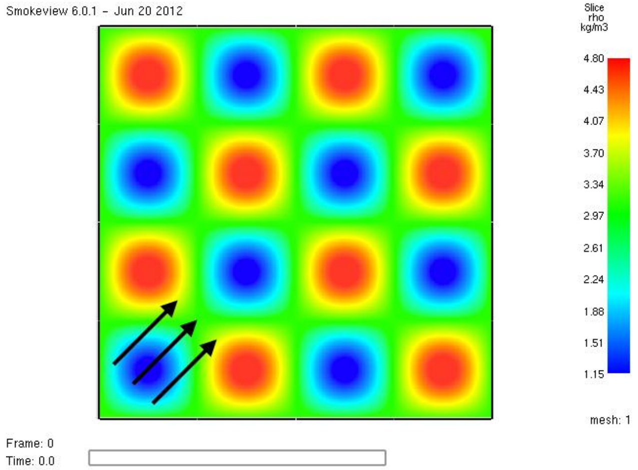
3

Numerical accuracy and scalability tests

Shunn3: Multi-Mesh convergence study

- From Verification Guide: „Variable Density Manufactured Solution“

1 Mesh



Constant velocity field: U = W = 0.5

CFL = 0.5

N = { 32, 64, 128, 256, 512}

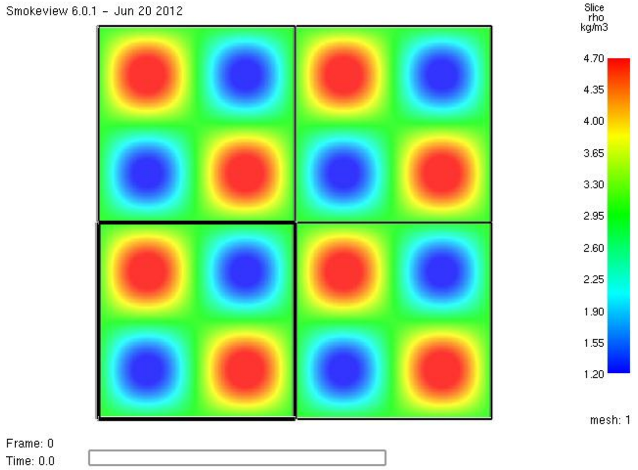
Analytical solutions for different quantities are known

- 2. order convergence of FDS time-stepping algorithm for Single-Mesh case

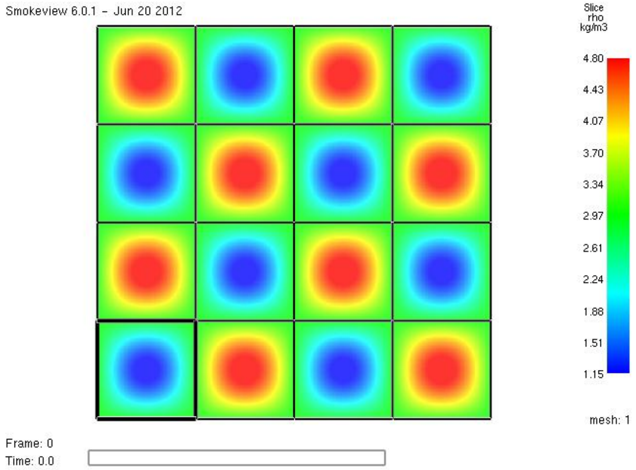
Shunn3: Multi-Mesh convergence study

- Analyze convergence behavior for different subdivisions with ScaRC

4 Meshes



16 Meshes

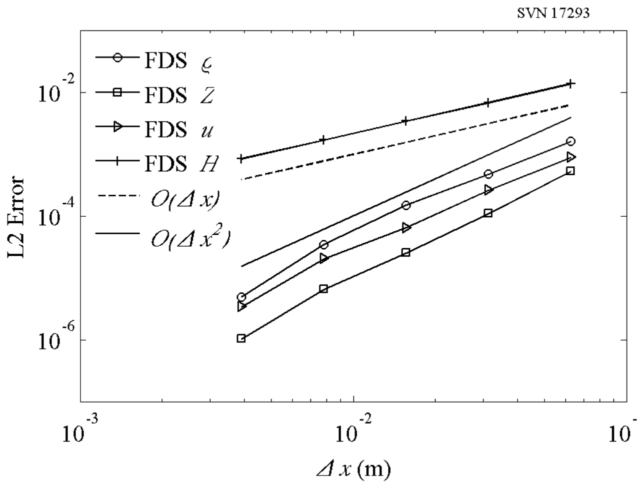


- Can ScaRC perserve the 2. order convergence of the Single-Mesh case?

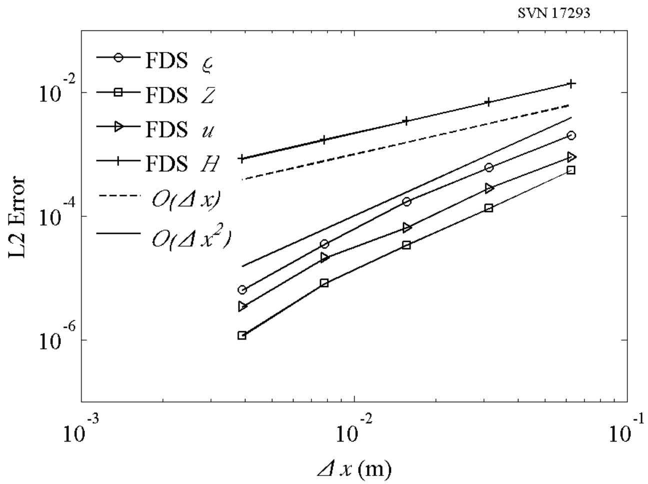
Shunn3: Multi-Mesh convergence study

- L2-errors for mixture fraction, density, velocity and pressure

4 Meshes



16 Meshes



- ScaRC is able to keep the 2. order convergence for both subdivisions

3

Numerical accuracy and scalability tests

Conclusions

Conclusions for Multi-Mesh FFT

Advantages:

- Local FFT-solvers on the single submeshes are extremely fast and robust (high local efficiency)

Disadvantages:

- Slow/delayed computation of global effects (scalability questionable)
- Optimal stopping tolerance only hardly to predict (parameter choice difficult)
- Possibly many pressure iterations necessary (slow convergence)
- Usually differences to corresponding Single-Mesh case (no full consistency)

Conclusions for ScaRC

Advantages:

- Better accordance to Single-Mesh case (good consistency)
- Higher approximation accuracy than Multi-Mesh FFT(good accuracy)
- Better reproduction of global dependencies even for high number of submeshes (good scalability)

Disadvantages:

- Method parameters must be chosen carefully (parameter choice difficult)
- Computing times mostly higher than for Multi-Mesh FFT (higher computational costs)

Outlook

Outlook

5

Outlook

Further optimizations:

- Improving the algebraic multigrid variant (AMG)
- Including concepts to use meshwise different grid resolutions
- Improving the run-time behavior

Outlook

Further optimizations:

- Improving the algebraic multigrid variant (AMG)
- Including concepts to use meshwise different grid resolutions
- Improving the run-time behavior

Further verification tests:

Analyzing separated physical phenomena, possibly with analytical solution

Outlook

Further optimizations:

- Improving the algebraic multigrid variant (AMG)
- Including concepts to use meshwise different grid resolutions
- Improving the run-time behavior

Further verification tests:

Analyzing separated physical phenomena, possibly with analytical solution

Further application tests:

Checking the applicability of ScaRC on realistic, complex geometries

Thank you very much for your attention!

Questions ?

hhpberlin
Ingenieure für Brandschutz GmbH

Hauptsitz
Rotherstraße 19 · 10245 Berlin

Amtsgericht
Berlin-Charlottenburg
Register-Nr.: HRB 78 927
Ust-ID Nr.: DE217656065

Geschäftsführung:
Dipl.-Ing. Karsten Foth
Dipl.-Inf. BW [VWA] Stefan Truthän

Beirat:
Dipl.-Ing. Margot Ehrlicher
Prof. Dr.-Ing. Dietmar Hosser
Dr.-Ing. Karl-Heinz Schubert