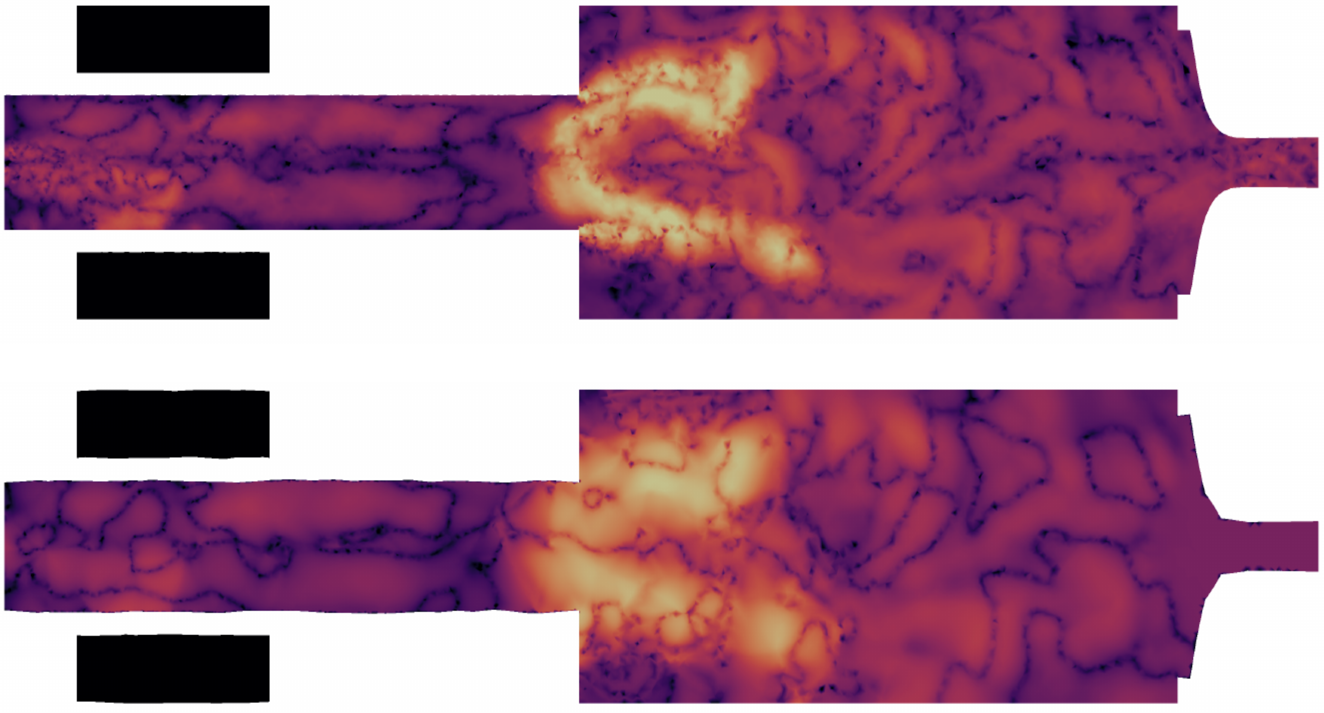
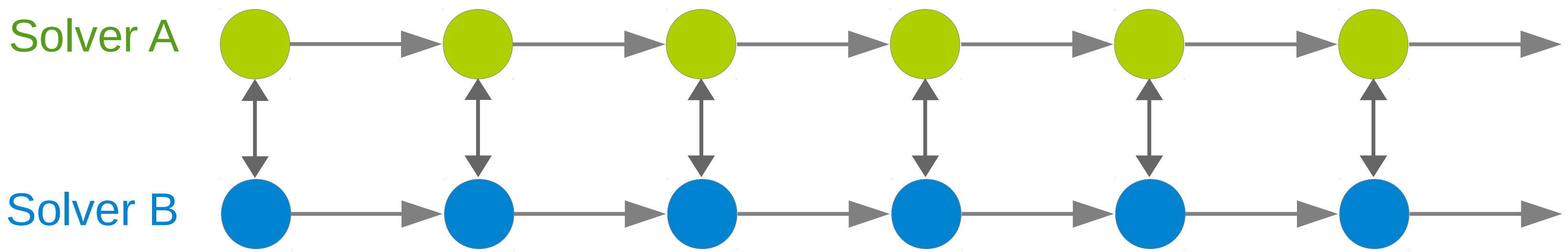
Multiphysics Simulations with Nektar++ using a Co-Simulation Approach

Kilian Lackhove 2017-06-14



Co-Simulation

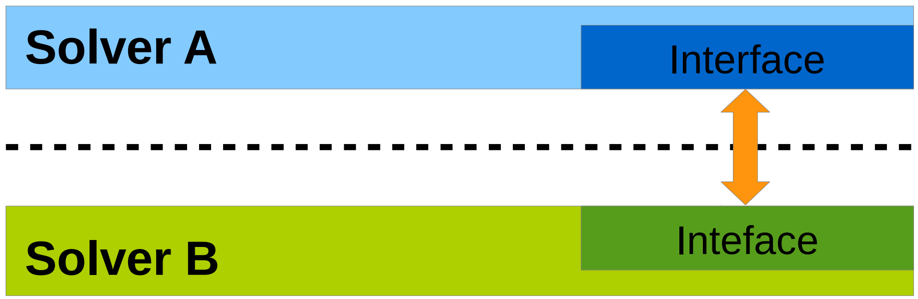
Wikipedia: “In co-simulation the different subsystems which form a coupled problem are modeled and simulated in a distributed manner.”



Applications

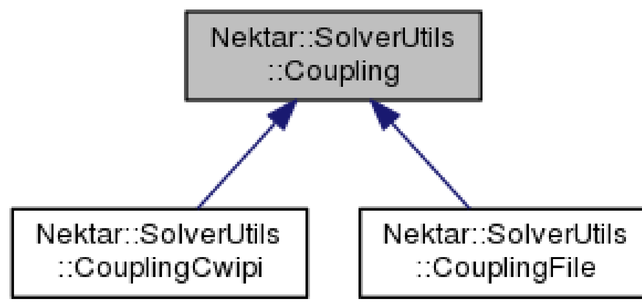
- Multi-physics: e.g. aeroacoustics, heat-transfer, fluid-structure-interaction etc.
- Split-domain: e.g. incompressible ↔ compressible, steady ↔ rotating, non-reacting ↔ reacting, different Δt, etc.
- Multi-Code: Combine features of different tools

Nektar++ Coupling Interface



Implementation

- Factory-pattern
  - → extensible (e.g. CHIMPS, MpCCI, etc.)
  - → currently file-based and CWIPI-based
- Works with all UnsteadySystem based equation systems
- Not (yet?) in master



File-based Coupling

TECHNISCHE UNIVERSITÄT DARMSTADT

Demo Implementation!

- Most features already available through CheckpointFilter + Functions
- Useful for testing

```
<FUNCTION NAME="CouplIn">
 <F VAR="Vx,Vy" FILE="Vxy.csv"/>
</FUNCTION>
```

Receive:

- Arbitrary fields read from Nektar++ functions (analytic expressions, pts, csv or fld files)
- Inverse distance interpolation

Send:

- Fields stored to pts files at quadrature points

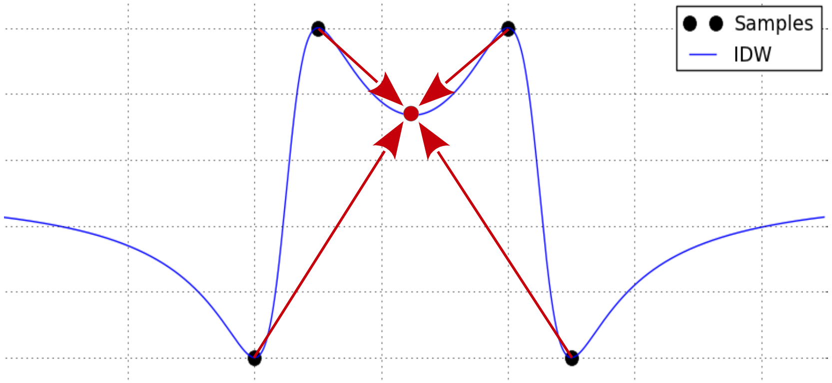
File-based Coupling: Interpolation

```
<FUNCTION NAME="CouplIn">
 <F VAR="Vx,Vy" FILE="Vxy.csv"/>
</FUNCTION>
```

- 1D: Quadratic Interpolation
- 2D, 3D: **Modified Shepard** inverse distance method (subclass of radial basis functions, RBF):

$$w_i(\mathbf{x}) = \frac{1}{d(\mathbf{x}, \mathbf{x}_i)^p}$$

→ Fast & low memory footprint
→ Can cause wiggles and peaks
→ Probably not ideal for Spectral hp Element Method
→ Different basis function?



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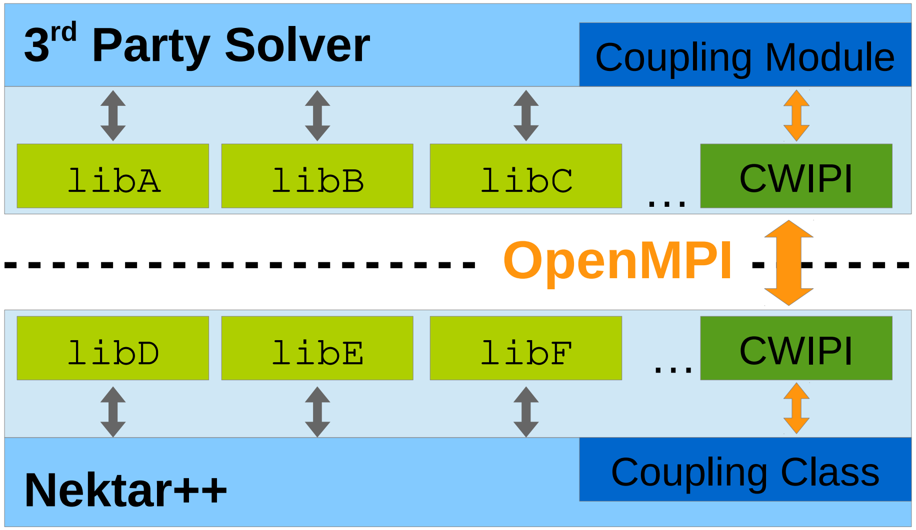
CWIPI/MPI-based Coupling

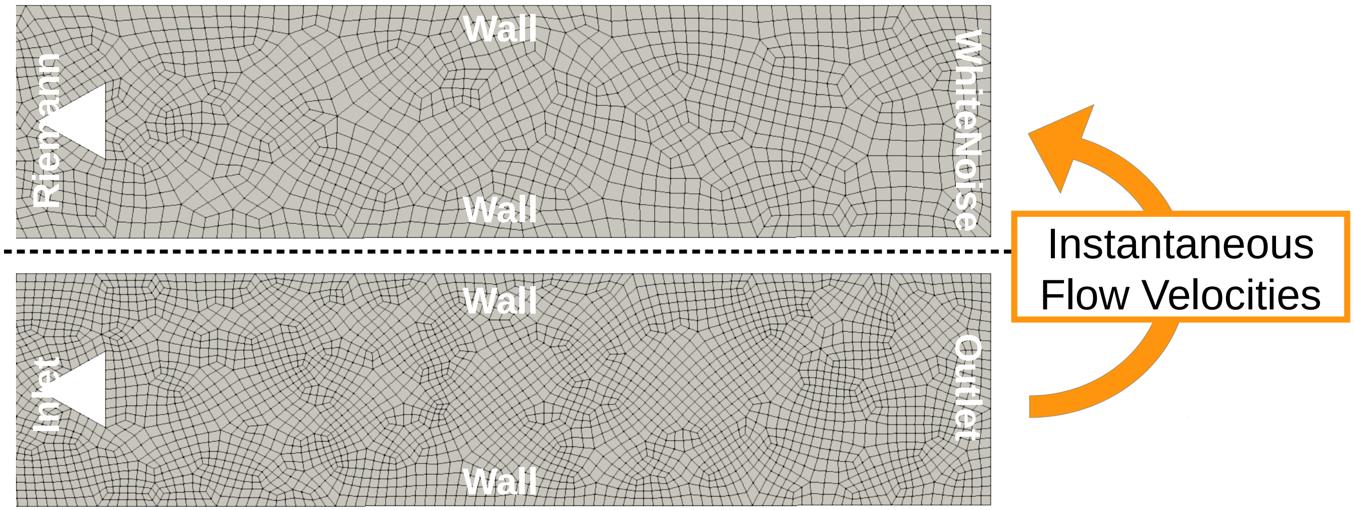
- **CWIPI**: Open source C++ coupling library, developed by ONERA
  → Plain MPI interface, Decentralized, linear interpolation
- Designed for bi-directional, real-time data exchange
- Spatial and temporal interpolation & spatial filtering



Example: Nektar++ → Nektar++

- Δh = 15 mm
- P = 3
- Δt = 1E-6 s

Nektar++
APESolver



- Δh = 10 mm
- P = 3
- Δt = 1E-5 s

Nektar++
IncNavierStokesSolver

Usage

~/BluffBody/CFD/CFD.xml

```
<NEKTAR>
  ...
<COUPLING NAME="cpl1" TYPE="Cwipi">
  <I PROPERTY="RemoteName"     VALUE="CAA"/>
  <I PROPERTY="SendVariables"  VALUE="u,v"/>
  <I PROPERTY="SendSteps"      VALUE="1"/>
</COUPLING>

<CONDITIONS>
  <SOLVERINFO>
    <I PROPERTY="EQType"
              VALUE="UnsteadyNavierStokes"/>
...
```

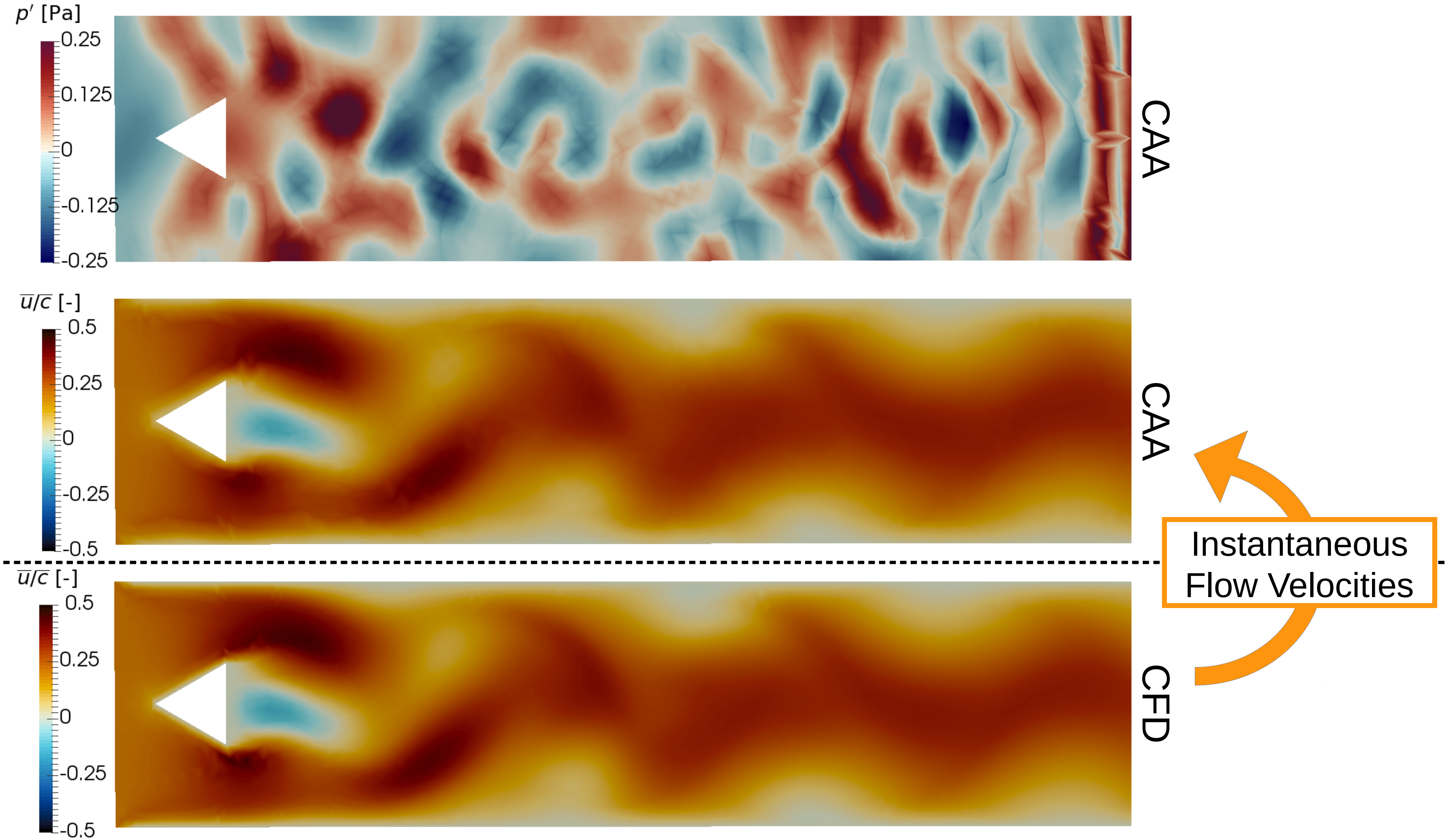
~/BluffBody/CAA/CAA.xml

```
<NEKTAR>
...
<COUPLING NAME="cpl1" TYPE="Cwipi">
  <I PROPERTY="RemoteName"    VALUE="CFD"/>
  <I PROPERTY="ReceiveVariables"
                              VALUE="u0,v0"/>
  <I PROPERTY="ReceiveSteps" VALUE="10"/>
</COUPLING>

<CONDITIONS>
  <SOLVERINFO>
    <I PROPERTY="EQType"     VALUE="APE"/>
...
```

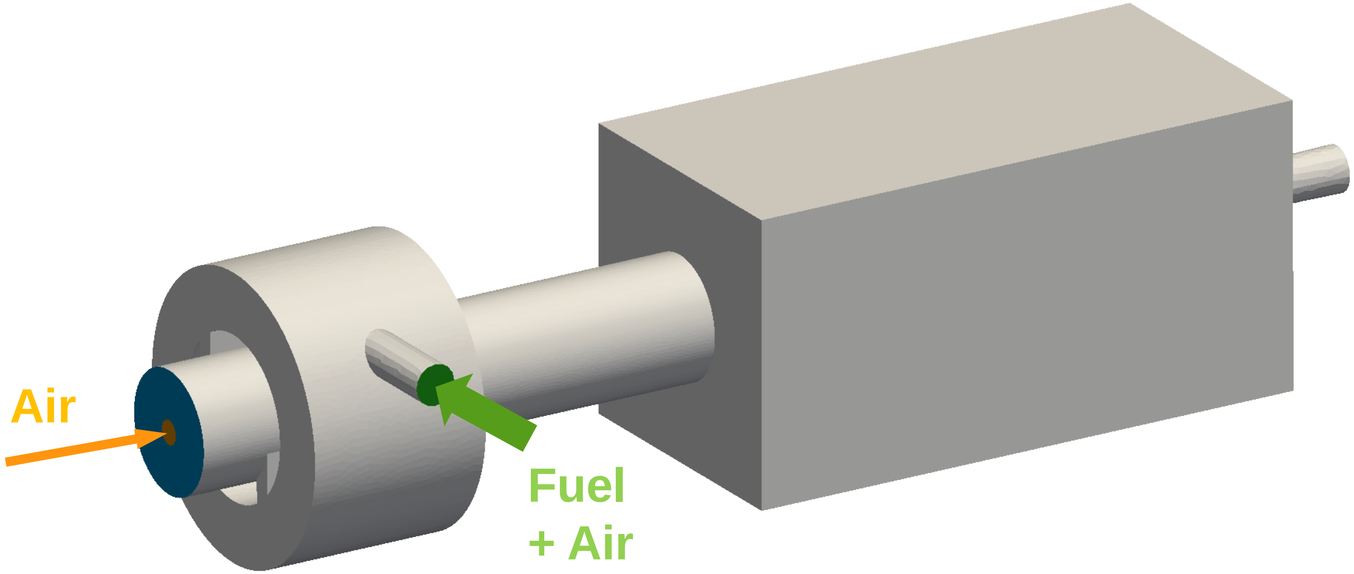
```
$ mpirun -wd CAA -n 8 APESolver --cwipi CAA CAA.xml \
            : -wd CFD -n 8 IncNavierStokesSolver --cwipi CFD CFD.xml
```

Example: Nektar++ → Nektar++

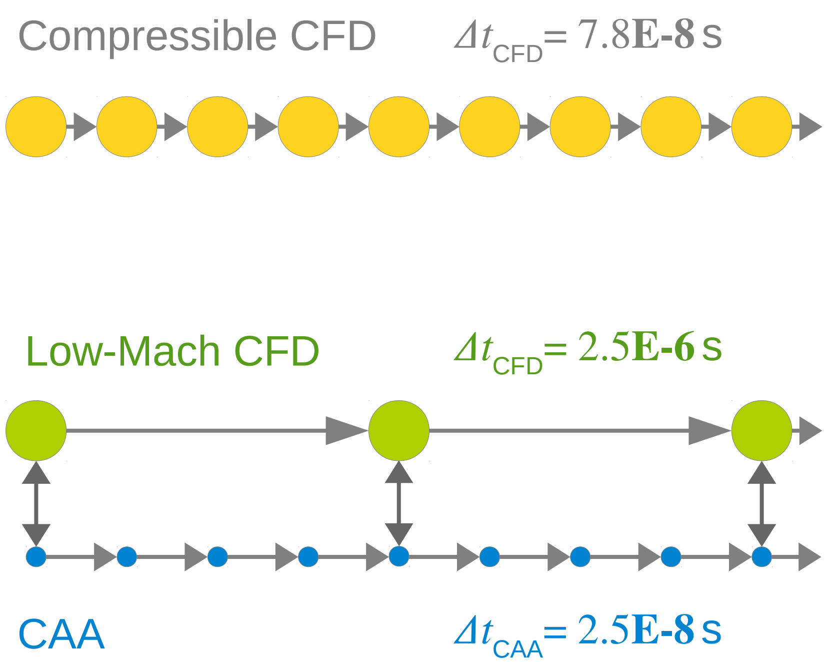


Example: PRECISE-UNS ↔ Nektar++ APESolver

- **CESAM-HP (EM2C, CNRS Paris)**
  - Combustion Noise testrig
  - Enclosed premixed flame
  - Propane (OP-16-2-0 & OP-13-5-0)



Combustion Noise: Multiphysics Approach



- Compressible CFD
  → High spatial resolution
  → Small time steps
  expensive
- Acoustic time scales are up to 30 times smaller
- Multiphysics Approach: Large Δt_{CFD}, small Δt_{CAA}

Advantages

- Reduced computational effort
- Different CAA and CFD meshes & domains
- Best numerical schemes for each problem

Coupling: Governing Equations

CFD

Incompressible Navier-Stokes

$$\frac{D\varrho}{Dt} = 0$$

$$\frac{D\varrho\mathbf{u}}{Dt} = -\nabla p + \nabla \cdot \tau - \nabla p^{\mathrm{a}}$$

p^{a}

p, ρ, $\boldsymbol{u}$, S

Acoustic Perturbation Equations 1/4

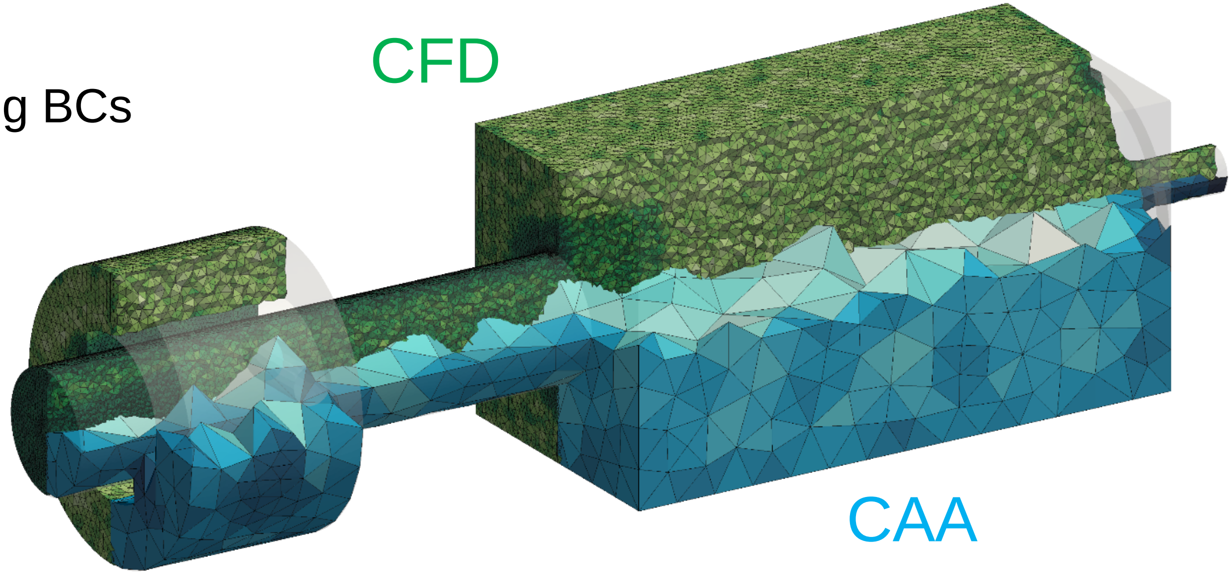
$$\frac{\partial p^{\mathrm{a}}}{\partial t} + c^2 \nabla \cdot \left(\varrho \mathbf{u}^{\mathrm{a}} + \mathbf{u} \frac{p^{\mathrm{a}}}{c^2} \right) = c^2 \frac{\partial \varrho}{\partial t}$$

$$\frac{\partial \mathbf{u}^{\mathrm{a}}}{\partial t} + \nabla \left(\mathbf{u} \cdot \mathbf{u}^{\mathrm{a}} \right) + \nabla \left(\frac{p^{\mathrm{a}}}{\varrho} \right) = 0$$

CAA

Example: PRECISE-UNS ↔ Nektar++ APESolver

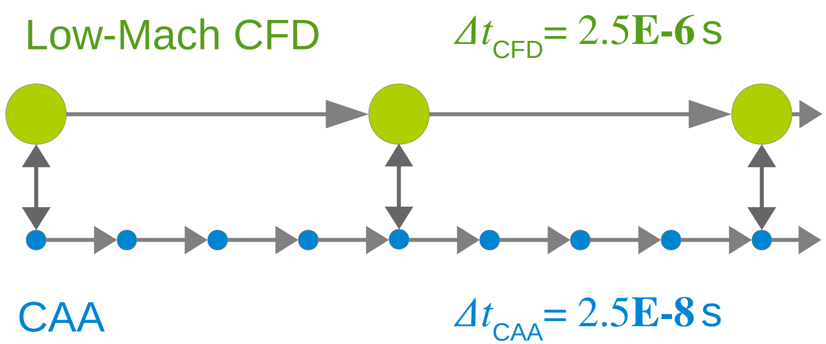
- **CESAM-HP (EM2C, CNRS Paris)**
  - Enclosed premixed flame
  - Propane (OP-16-2-0 & OP-13-5-0)
- CAA (Nektar++ APESolver)
  - 6870 Elements
  - 4th Order Expansion
  - APE-RF Equations
  - Solid Wall & Non-reflecting BCs
- CFD (PRECISE-UNS)
  - 1.4 Mio CVs
  - LES: Germano
  - FGM & ATF
  - **FVM & Implicit Euler**



Coupling: Scales

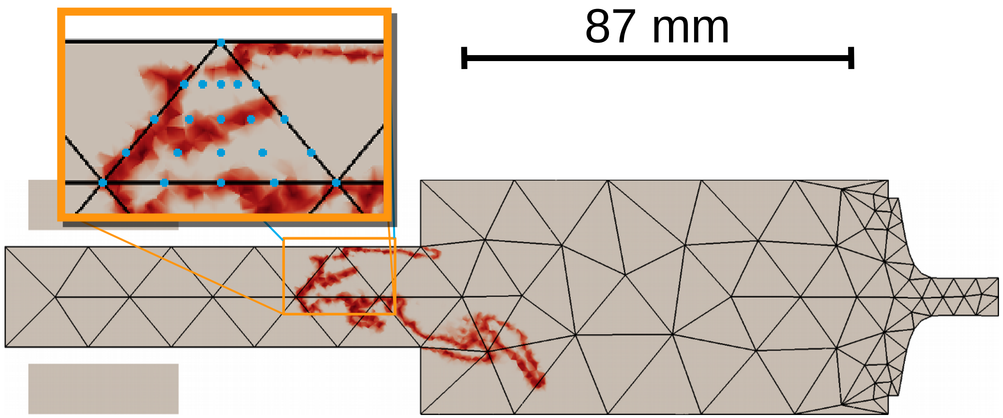
Time Scales

- CFD: $\Delta t_{CFD} = 2.5\mathbf{E\text{-}6}$ s
- CAA: $\Delta t_{CAA} = 2.5\mathbf{E\text{-}8}$ s



Length Scales

- Flame: δx = **1 mm**
- CAA (f_{max} = 5 kHz, c=341 m/s, P=5): Δx = **87 mm**

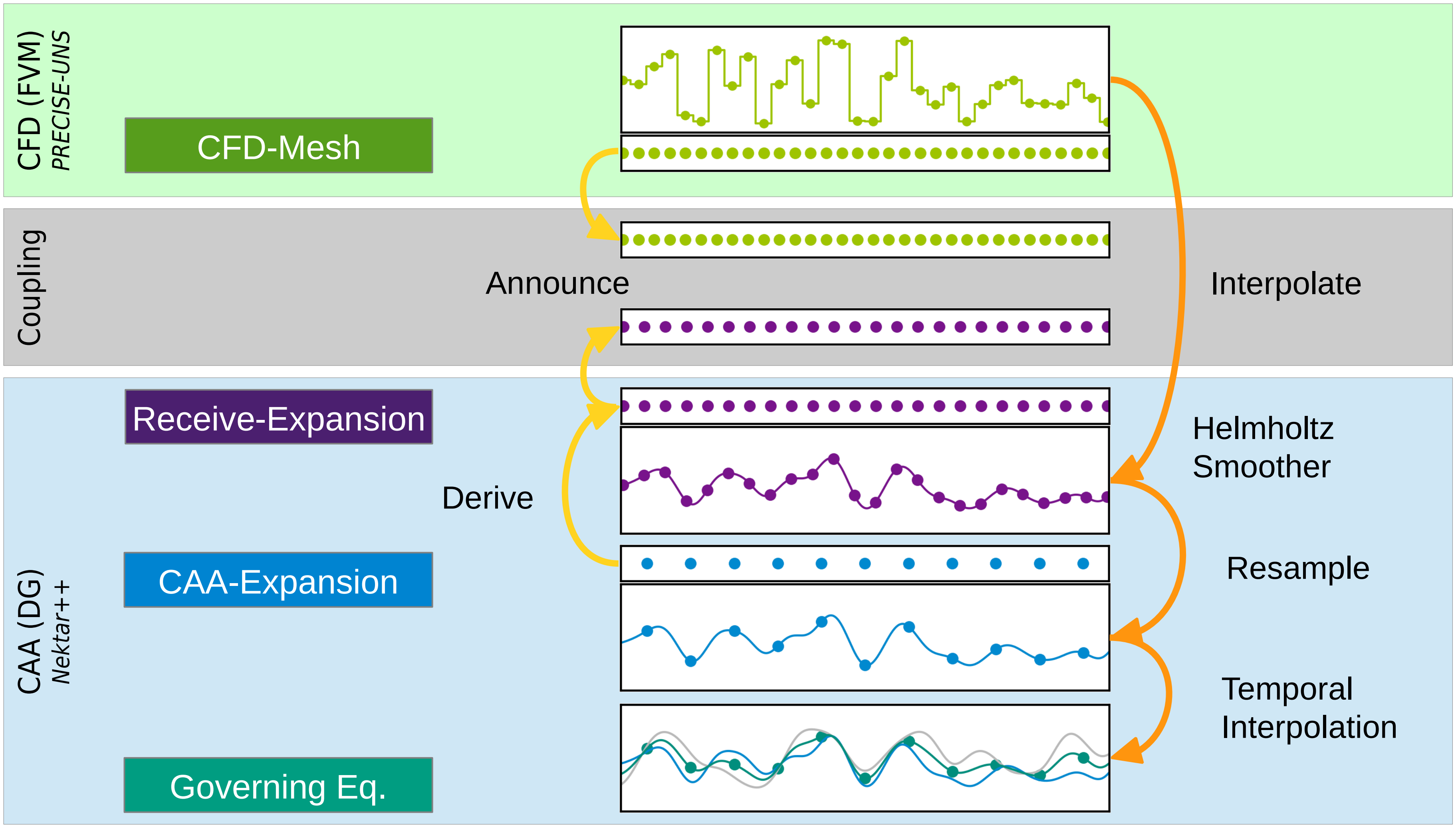


Refined CAA Mesh (4^{th} *order Expansions*) vs. 10x Thickened Flame

➡ Linear Interpolation

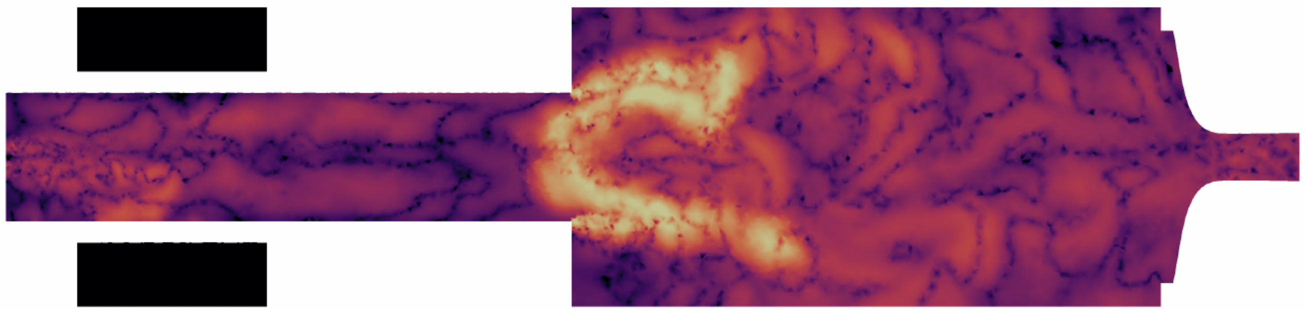
➡ Interpolation & Filtering

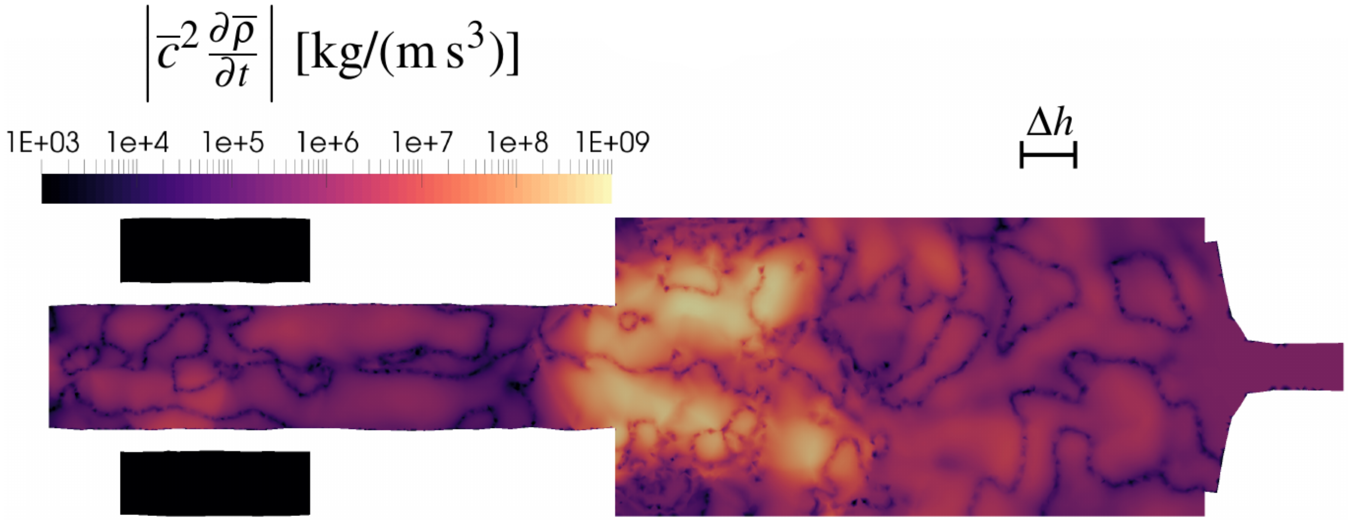
Coupling: Interpolation & Filtering



CESAM-HP Testrig: Source Terms

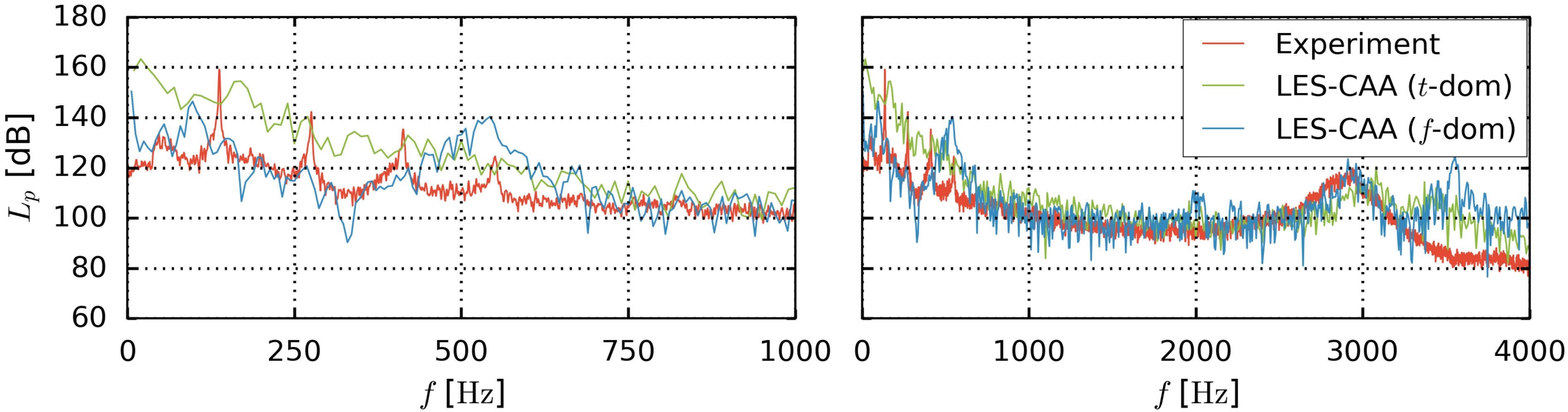
CFD





CAA

Results



- Experiments by **EM2C, CNRS Paris** [1]
- Reference data from Frequency domain simulations, cooperation of **TU Munich** (CAA), **TU Darmstadt** (CFD) and **Rolls Royce Deutschland** [2]
- **Time-domain data** obtained with presented approach [3] (bi-directional)

[1] Mazur, M., Tao, W., Scouflaire, P., Richecoeur, F., & Ducruix, S. (2015)
[2] Ullrich, W., Lackhove, K., Fischer, A., Hirsch, C., Sattelmayer, T., Sadiki, A., & Staufer, M. (2016)
[3] Lackhove, K., Sadiki, A., & Janicka, J. (2017)

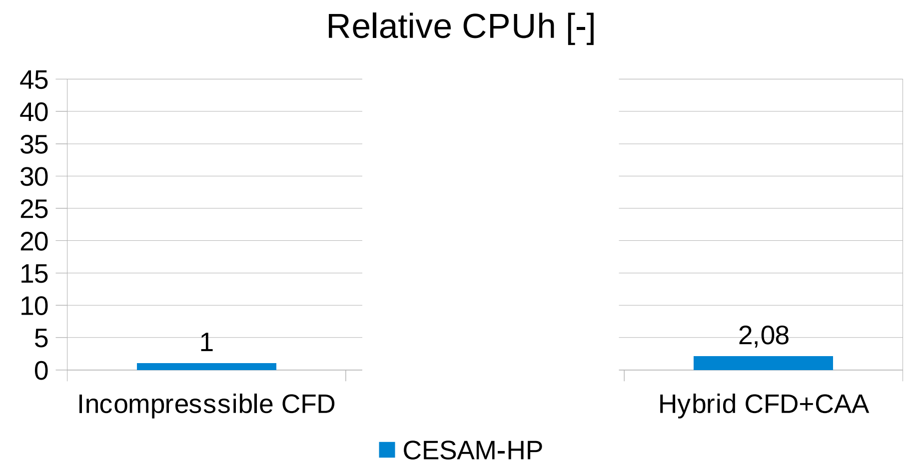
Computational Cost

CESAM-HP:

Theroretical Computational Cost:

- CFD: 112 Cores → 9 s/step
- CAA: 112 Cores → 0.09 s/step

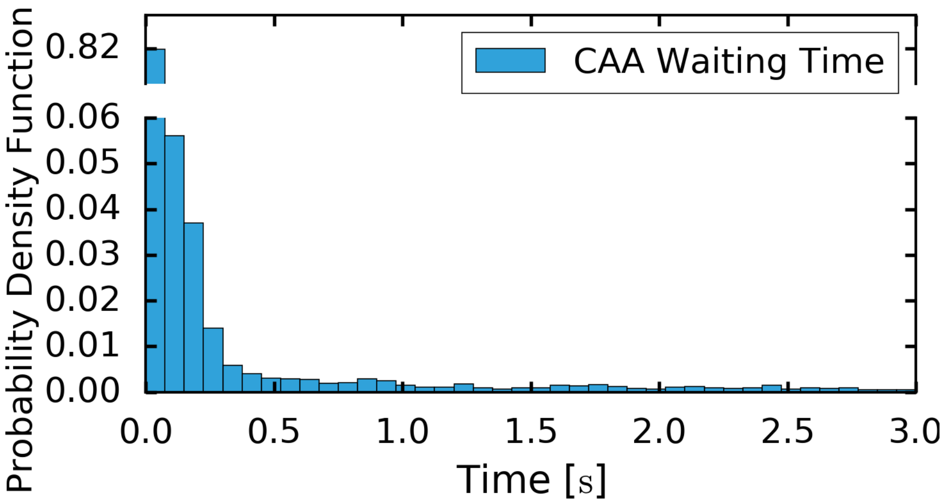
→ 224 Cores or **twice the cost**!



Huge data exchanged every CFD step → Efficiency crucial

- Passed data minimized
- MPI-based transfers
- Asynchronous Calls
- Helmholtz Smoother + MUMPS

→ Less than 4% overhead!



Summary

- **2 coupling interfaces**: File Based (testing) & CWIPI (MPI-based, real-time)
- Example 1: **IncNavierStokes & APE**
- Example 2: **Nektar++ APE & PRECISE-UNS**
  - Multiphysics CFD & CAA for **combustion noise** simulations
  - Temporal interpolation & spatial **interpolation & filtering scheme** based on intermedia receive-expansion
  - Promising results
  - Less than 4% computational overhead
  - **20 times faster than compressible CFD**