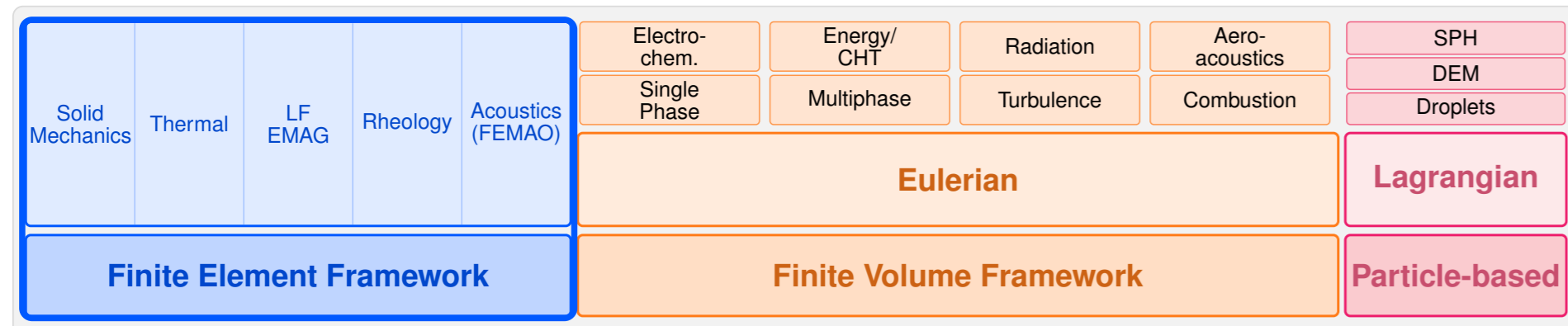


Simcenter STAR-CCM+

Simcenter STAR-CCM+ is a comprehensive multiphysics engineering simulation platform that combines Finite Element (FE), Finite Volume (FV), and Lagrangian particle methods on a shared high-performance computing infrastructure. A unified environment covers geometry import, meshing, physics setup, and post-processing for structural, thermal, electromagnetic, acoustic, and fluid problems — eliminating the need for multiple specialised tools.

STAR-CCM+ Simulation Platform Architecture



Core Functionality

CAD • Meshing • Visualization • Post-Processing • Design Exploration • Job Management

Framework

HPC • Memory Management • Client-Server Architecture • File I/O • OS Abstraction

Simcenter Components & Tools

HEEDS • Teamcenter Simulation • Model-Based Systems Engineering • AI/ML

Finite Element Framework

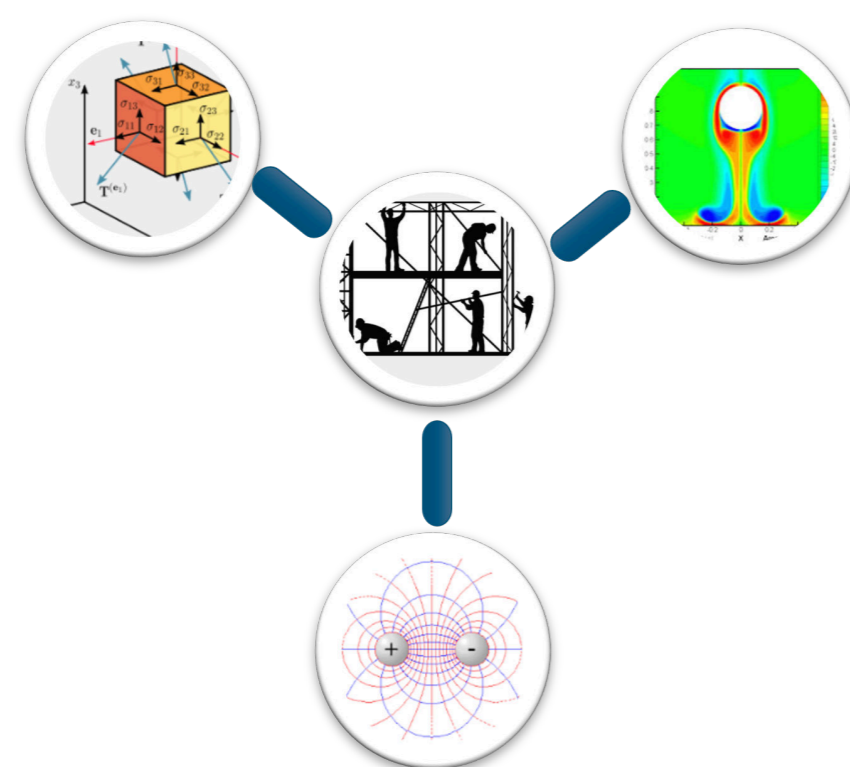
A common Finite Element Framework underpins all FE physics, providing a shared discretizer, assembler, and solver infrastructure. Five physics modules are built on this core:

- **FE Solid Stress (FESS)** — static, transient, and modal structural analysis with shells, contact, and plasticity
- **FE Solid Energy (FESE)** — heat conduction, coupled thermoelasticity, thermal shells
- **FE Electromagnetics (EMAG)** — low-frequency A* and T-Ω solvers; harmonic balance; high-order (HO) H(curl) elements
- **FE Acoustics (FEMAO)** — high-order Helmholtz solver for Heating, Ventilation and Air Conditioning (HVAC), fan noise, and vibro-acoustics
- **FE Viscous Flow (FEVF)** — computational rheology for extrusion and film casting

Cross-physics coupling enables Fluid-Structure Interaction (FSI) via one-way and two-way surface coupling for 3D solid and shell structures, Conjugate Heat Transfer (CHT) linking FV fluid thermal fields to FE solid energy, and EMAG-to-structural force mapping for e-motor Noise, Vibration and Harshness (NVH) prediction.

Finite Element Framework Evolution (2012–2026)

- 2012 FE Solid Mechanics prototype (monolithic)
- 2013 FE Rheology (standalone)
- 2014 FE Magnetic Vector Potential (A*)
- 2015 **Common FE Framework**: Solid Mech. refactored
- 2016 FE Thermal Energy (Solid Energy)
- 2017 LF EMAG refactored into shared framework
- 2019 Harmonic Balance EMAG; FSI & CHT coupling
- 2021 HO EMAG A* prototype (Nédélec, $p \geq 1$)
- 2022 HO A* production; T-Ω initiated
- 2023 FE Acoustics / FEMAO project launched
- 2024 Thermal Shells in FE Solid Energy
- 2025 Structural Shells in FE Solid Stress
- 2025 FEMAO MVP; Iterative-Direct reuse
- 2026 Shell FSI & plasticity; GPU (cuDSS)



Weak Form & Functional Spaces

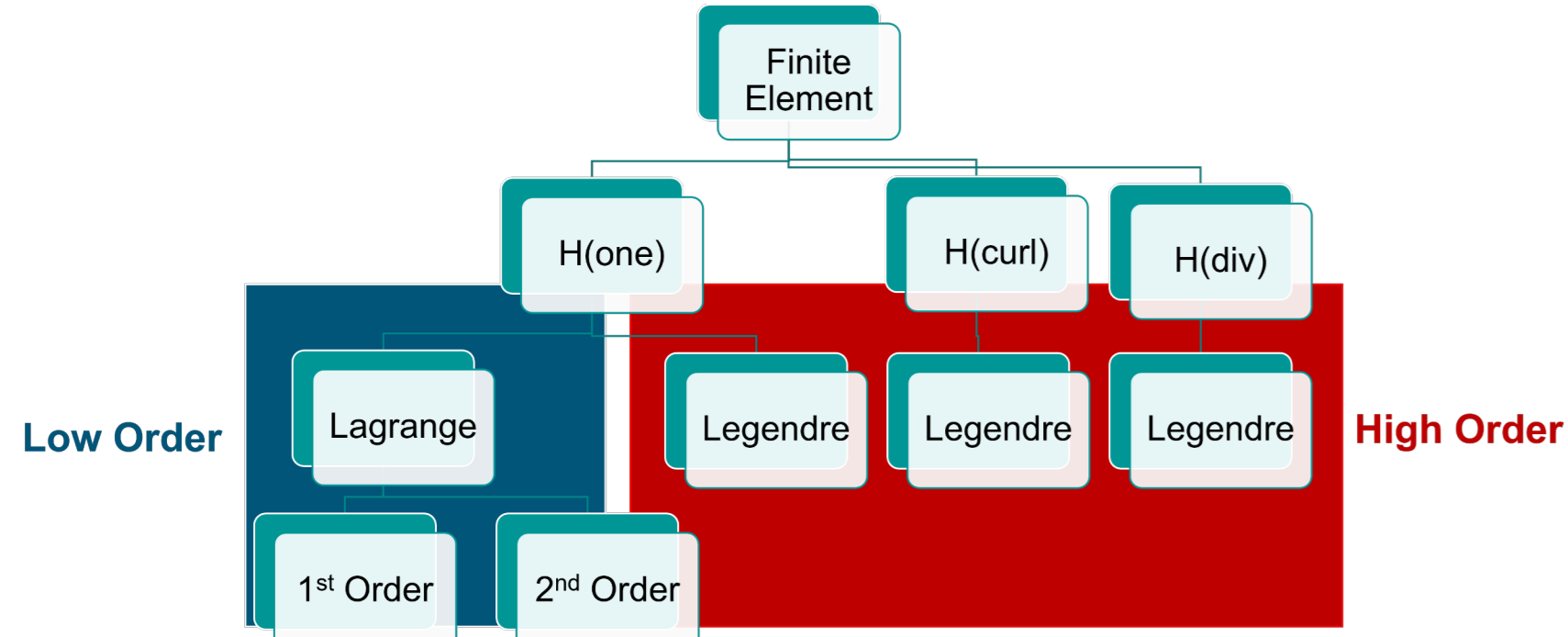
All FE physics share a common variational structure. Find $u \in V$ such that:

$$a(u, v) = l(v) \quad \forall v \in V$$

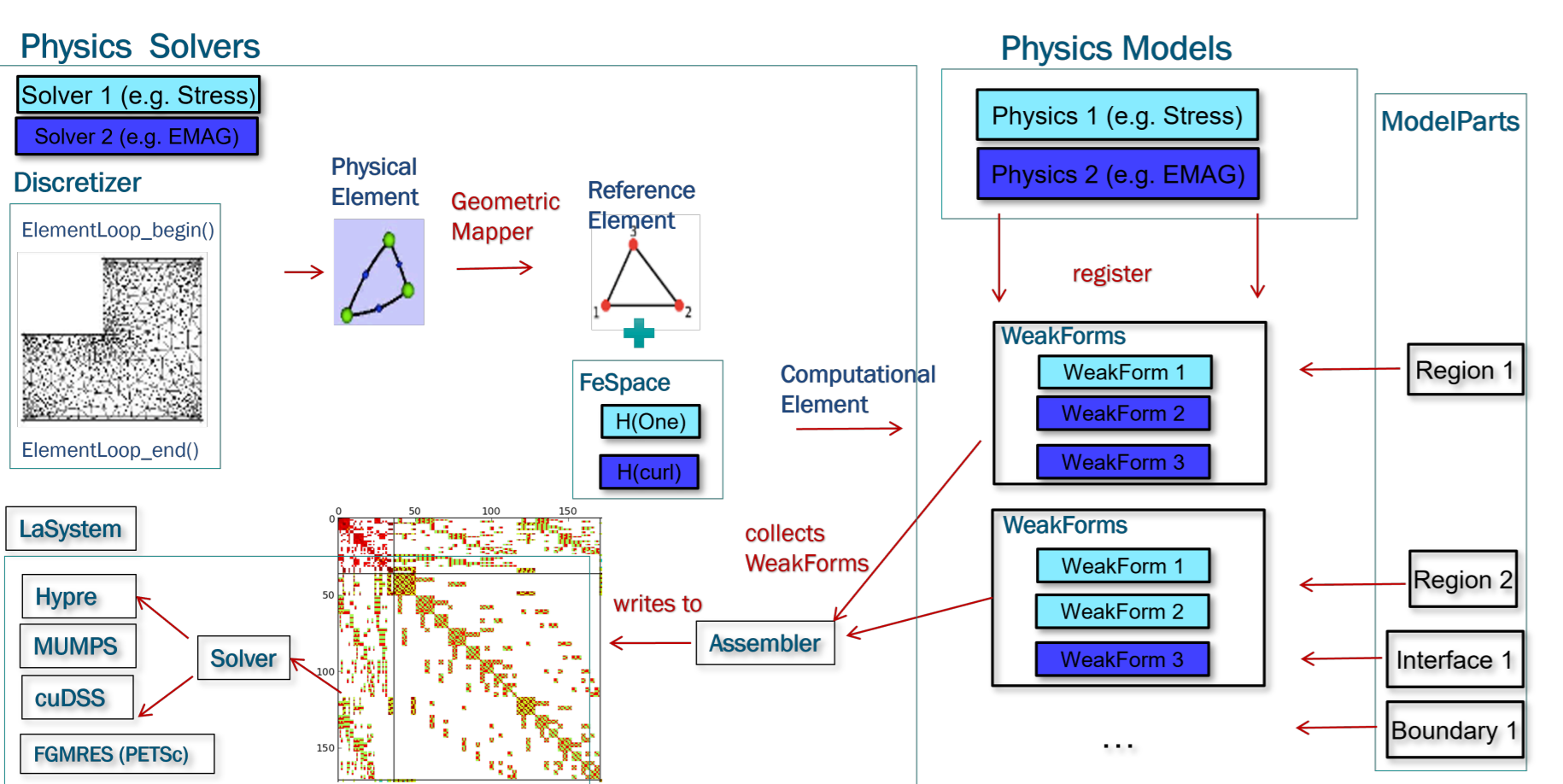
Physics models register bilinear and linear forms yielding element matrices via the BDB assembly pattern:

$$k_e = \int_{\Omega_e} \mathbf{B}^T \mathbf{D} \mathbf{B} d\Omega$$

Depending on the physical variable, shape functions from different Sobolev spaces are employed — H^1 (scalar continuous; temperature, displacement, acoustic pressure), $H(\text{curl})$ (tangentially continuous; magnetic vector potential, electric field), and $H(\text{div})$ (normally continuous; magnetic flux density). High-order hierarchical Legendre bases ($p \geq 1$) extend all spaces; interior degrees of freedom may be eliminated by static condensation.



Discretization Workflow



Linear Solvers & Dense Linear Algebra

- **Direct**: MUMPS (distributed-memory parallel sparse)
- **Iterative-Direct**: PETSc FGMRES preconditioned by MUMPS — single-precision preconditioner, reuse across steps, matrix symmetrization, Block Low-Rank approximation ($N > 1M$ DoFs)
- **Iterative**: Hypr AMG-preconditioned CG/GMRES (EMAG: T-Ω CG+AMG, A* CG+AMS; FE Solid Energy)
- **GPU**: NVIDIA cuDSS as direct solver and Iterative-Direct preconditioner (planned soon); fallback to MUMPS on insufficient GPU memory

Dense linear algebra currently relies on **Blaze**; a transition to **Eigen** is planned.



STAR-CCM+ Multiphysics Simulation – FE-Centric View

	Flow		Energy		Solid Stress		EMAG		Viscous
	FV	FE	FV	FE	FV	FE	FV	FE	
Flow	FV	Segregated / Coupled Flow	FSI (1-way/ 2-way)	Plasma / Forces	Plasma / Forces				
Energy	FV		CHT	Thermoelasticity	Ohmic Heating	Ohmic Heating	(CHT)		
Solid Stress	FE		Thermoelasticity		Lorentz Forces	Lorentz Force / Maxwell Stress Tensor (Magnetostriction)	1-way FSI		
EMAG	FV								
Viscous	FE								

Legend:
 - FV Coupling
 - FE Coupling
 - FV-FE Coupling
 - Planned Feature

FE Solid Energy & Solid Stress

Mathematical problem.

- Solid Stress (elastodynamics): $\nabla \cdot \sigma + f = \rho \ddot{u}$
- Solid Energy (heat conduction): $\rho c_p T = \nabla \cdot (k \nabla T) + Q$

Weak form with H^1 basis functions and BDB stiffness assembly:

$$\int_{\Omega} \varepsilon(\mathbf{v}) : \mathbf{C} : \varepsilon(\mathbf{u}) d\Omega = \int_{\Omega} \mathbf{v} \cdot \mathbf{f} d\Omega + \int_{\Gamma_N} \mathbf{v} \cdot \mathbf{t} dS$$

Key capabilities:

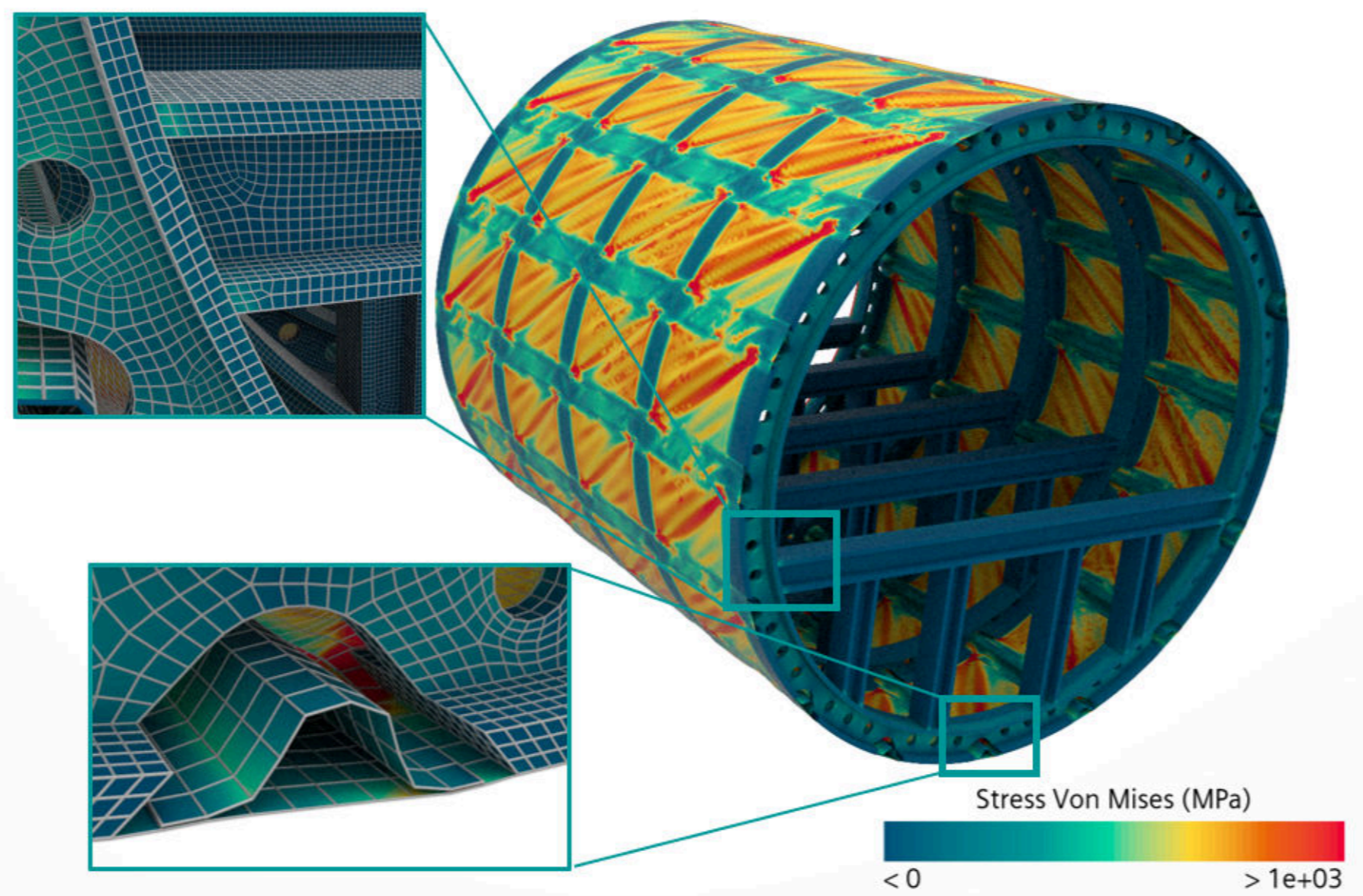
- Steady, implicit unsteady (transient), normal mode (eigenvalue/modal) analysis
- Geometrically nonlinear — large deformation with logarithmic strain measure; adaptive time stepping
- Materials: linear elastic (iso/ortho/transversely iso), hyperelastic (Neo-Hookean, Mooney-Rivlin, Ogden, Holzapfel), J2 plasticity, Anand viscoplastic creep
- Shell elements (Quad4/Tri3) with EAS + ANS locking prevention; through-thickness plasticity (5-pt Simpson)
- Contact: rigid contact (Penalty + Uzawa), solid/solid sliding contact, and non-conforming bonded interfaces for multi-body assembly
- Tet, Hex, Wedge, Pyra + shells ($\mu=1,2$)

What's special:

- Single physics continuum — no separate thermal/structural models
- Machine-precision accuracy on analytical benchmarks

Application — Fuselage structural analysis:

A Boeing fuselage-like structure combines **shell elements** (Quad4/Tri3) for thin-walled skin panels with **3D continuum elements** (Hex8/Wedge6) for stiffeners and frames, coupled through a non-conforming bonded interface. Nonlinear torsion load case with large displacements and logarithmic strain measure; $\sim 5.7M$ elements ($\sim 2.2M$ Tet4, $\sim 3.5M$ Wedge6), $\sim 8.7M$ DoFs. The model validates shell–solid coupling at HPC scale and demonstrates that mixed-element assemblies with many parts are handled efficiently in a single STAR-CCM+ simulation.



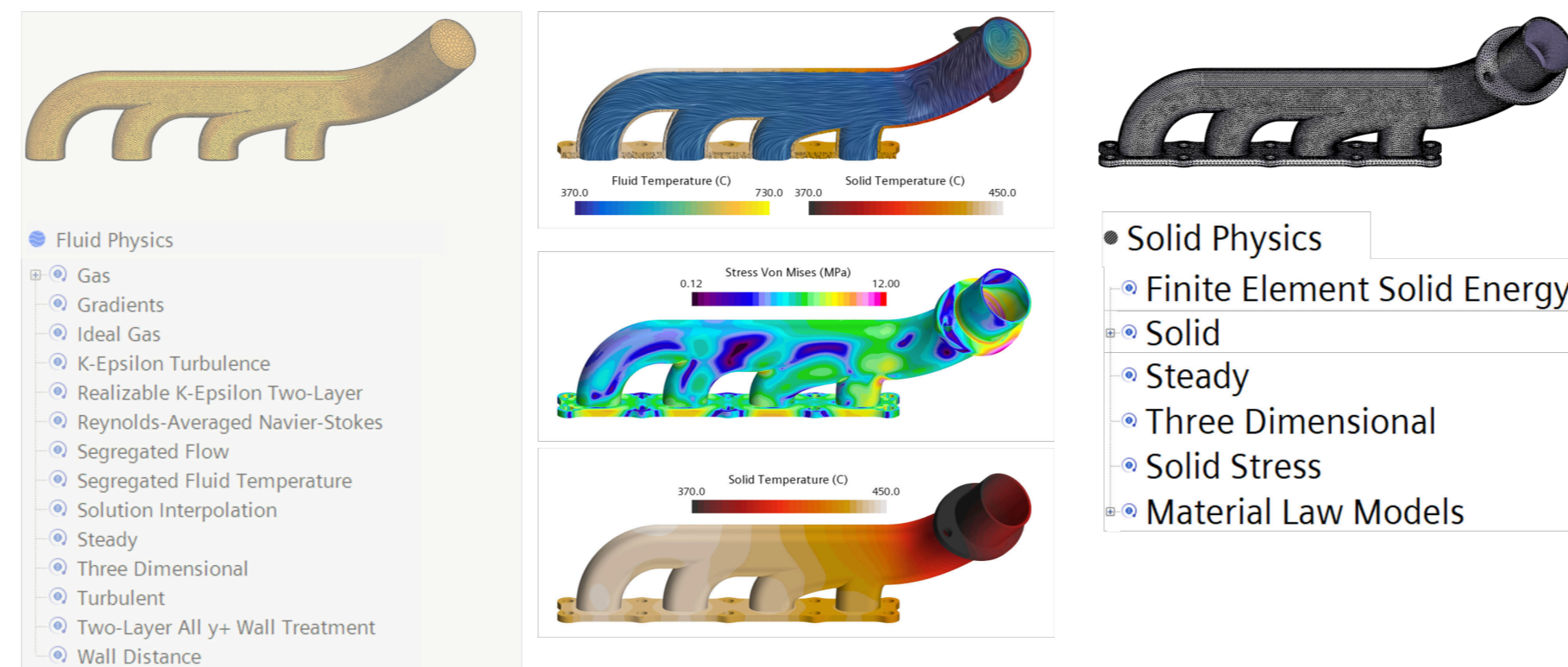
Conjugate Heat Transfer & Fluid-Structure Interaction

Conjugate Heat Transfer (CHT). Coupled FV fluid energy and FE solid energy across shared interfaces:

- Automatic heat flux / temperature matching at fluid–solid boundaries
- Supports FV \leftrightarrow FE and FE \leftrightarrow FE thermal coupling
- Consistent with thermoelastic stress analysis in the same continuum

Application — Exhaust manifold (CHT + thermal stress):

FV polyhedral cells (exhaust gas) and FE tet elements (solid manifold) share a non-conformal Mapped Contact Interface. Sequential physics activation: the converged temperature field directly drives thermoelastic stress ($\sigma = \mathbf{C} : (\varepsilon - \alpha \Delta T)$) on the same FE mesh — no external coupling tool or data conversion.



Fluid-Structure Interaction (FSI).

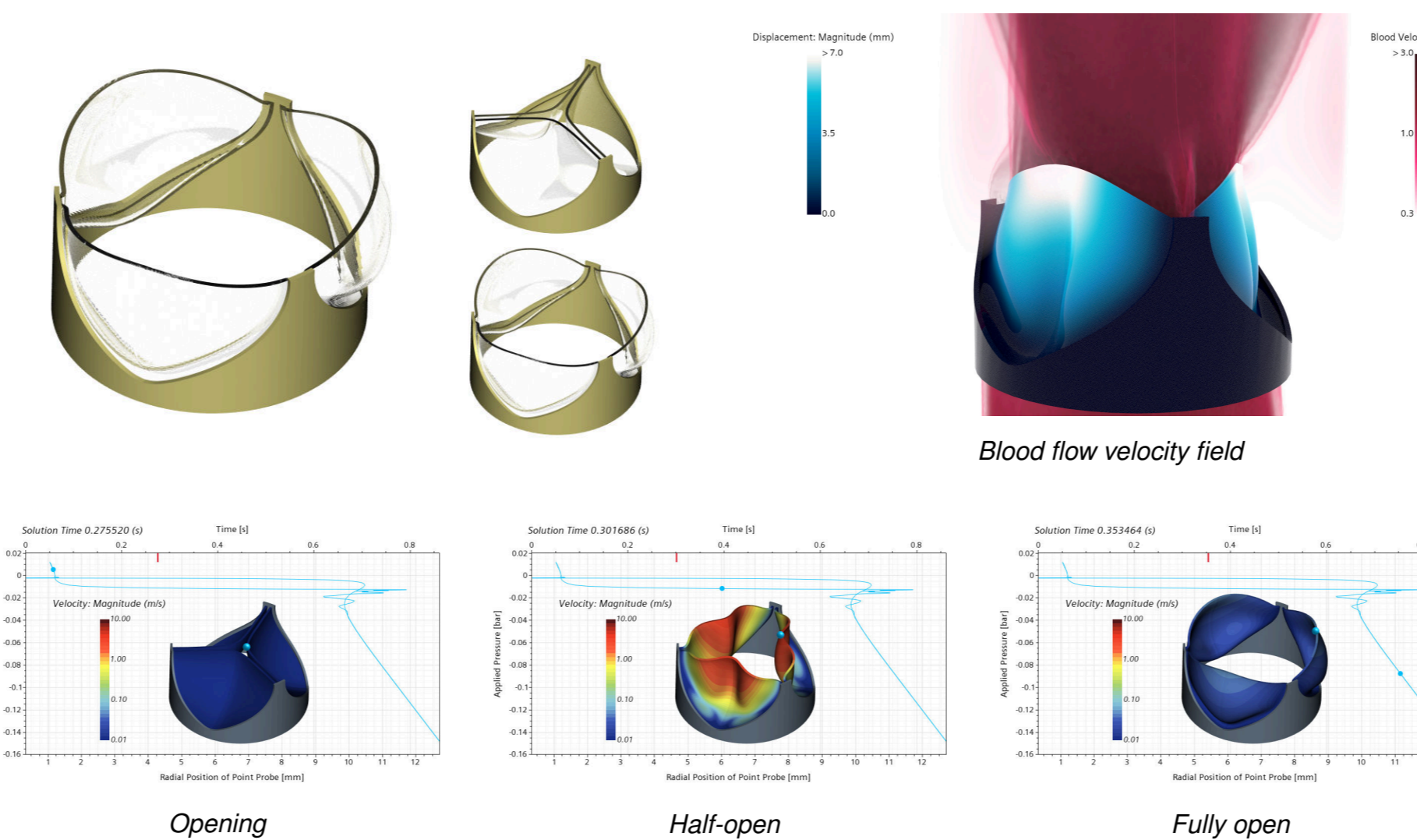
- **One-way**: aerodynamic pressure and thermal loads mapped from FV CFD onto the FE mesh across non-conformal interfaces; supports both 3D solid and shell elements
- **Two-way**: FE solid \leftrightarrow FV fluid with morphing + overset + re-meshing; production-ready for 3D solid elements

Application — Trileaflet heart valve (two-way FSI):

A 30° sector of a trileaflet polymer prosthetic heart valve is modelled with directed hex mesh (3 Hex8 elements through the 0.4 mm leaflet thickness) and isotropic hyperelastic material ($E = 3.2 \text{ MPa}$, $\nu = 0.49$). Periodic physiological pressure loading (period = 0.861 s) drives large leaflet deformations; frictionless rigid contact models leaflet-to-leaflet closure. Two-way FSI couples FV Navier-Stokes blood flow to the FESS hyperelastic solid with a fluid–solid mass ratio ≈ 1 , making this one of the most challenging FSI benchmarks.

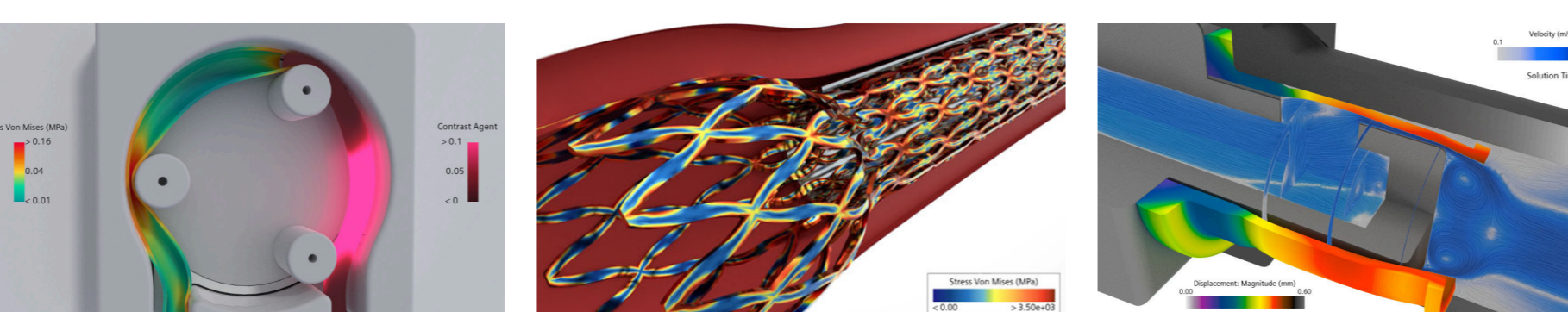
Key challenges:

- **Snap-through instability**: near-zero stiffness during opening/closing — adaptive time stepping keeps the simulation stable without user tuning
- **Strong coupling**: blood density \approx leaflet density; fluid domain handled by morphing + overset + re-meshing
- **FSI Dynamic Stabilisation**: 2nd-order BDF integration on the solid side significantly improves coupling convergence



Further FESS / FESE applications:

- Peristaltic blood pump (two-way FSI, solid/solid mortar contact)
- Stent deployment (hyperelastic + rigid contact, crimp & deploy)
- Rubber seal / noodle (nearly incompressible hyperelastic, large deformation contact)
- Solder creep in ball grid array (BGA) electronic packaging (Anand viscoplastic, thermal cycling)
- ... and many more



FE Electromagnetics — A* & T-Ω Formulations

Mathematical problem. Maxwell's equations in the magnetoquasistatic limit:

$$\nabla \times \mathbf{H} = \mathbf{J}, \quad \nabla \cdot \mathbf{B} = 0$$

A* formulation (Magnetic Vector Potential):

- Unknown: A such that $\mathbf{B} = \nabla \times \mathbf{A}$
- $H(\text{curl})$ edge elements throughout the domain
- Available in 3D, 2D, and axisymmetric configurations

T-Ω formulation (next generation):

- Current vector potential \mathbf{T} in conductors ($H(\text{curl})$ edge elements)
- Scalar magnetic potential Ω in insulators (H^1 nodal elements)
- Uses $\sim 7 \times$ fewer DoFs than A* for comparable accuracy

Key capabilities:

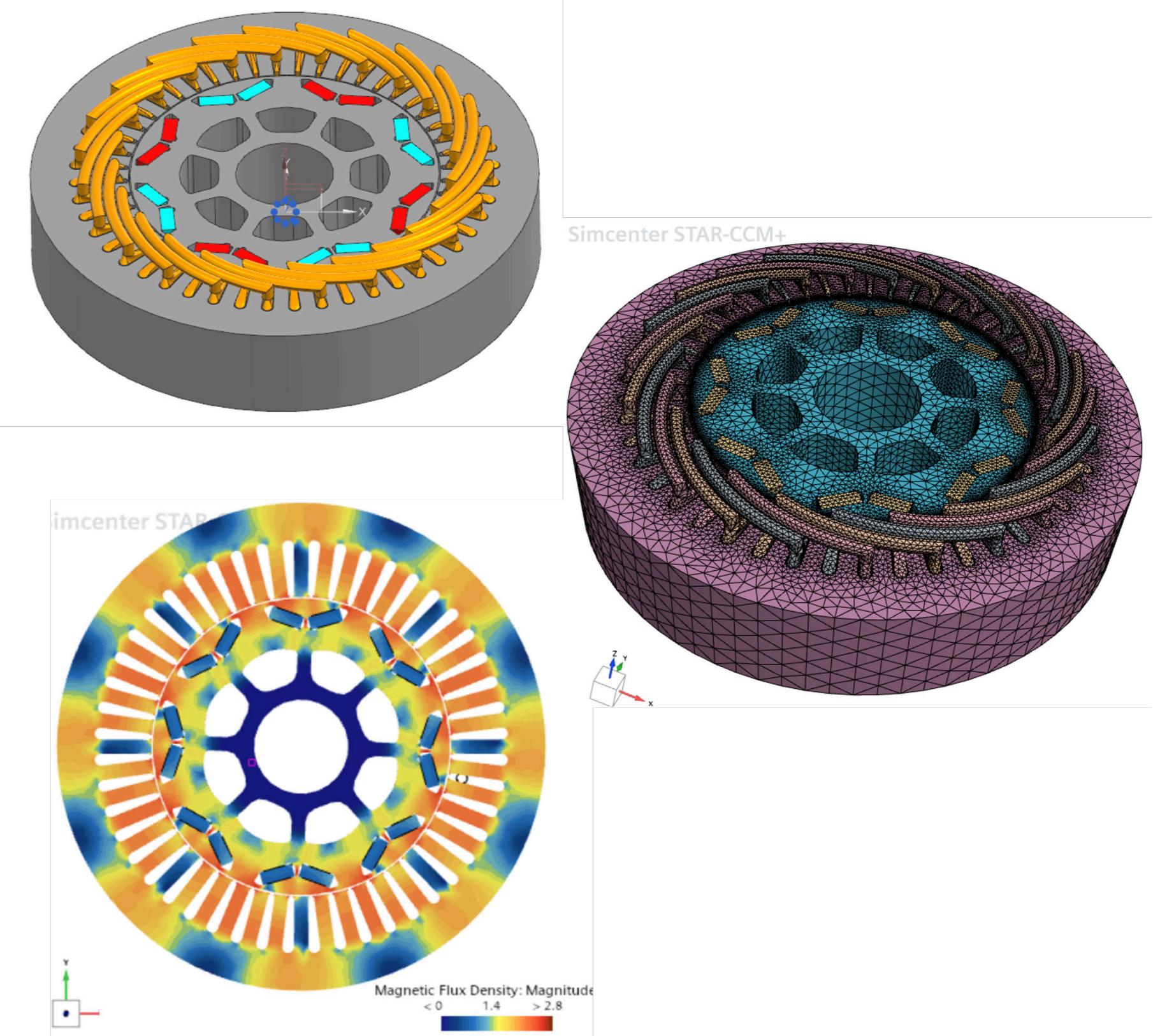
- Steady and unsteady (magnetoquasistatic/magnetodynamic)
- Permanent magnets, excitation coils (open/closed, stranded/strip)
- Nonlinear permeability, periodic BCs, velocity-driven motion
- High-order $H(\text{curl})$ elements with per-region polynomial order ($p=0, \dots, 3$); prism/wedge support
- Air Gap Remeshing (AGR) for rotating machinery
- Iron loss, Ohmic loss, and torque (Maxwell stress tensor)
- EMAG \rightarrow structural force mapping for NVH prediction
- EMAG-Thermal staggered coupling via SimOps automation

What's special:

- Excellent HPC scalability for both A* and T-Ω
- Validated against experiment and industry-reference tools (JMAG, Simcenter MAGNET)

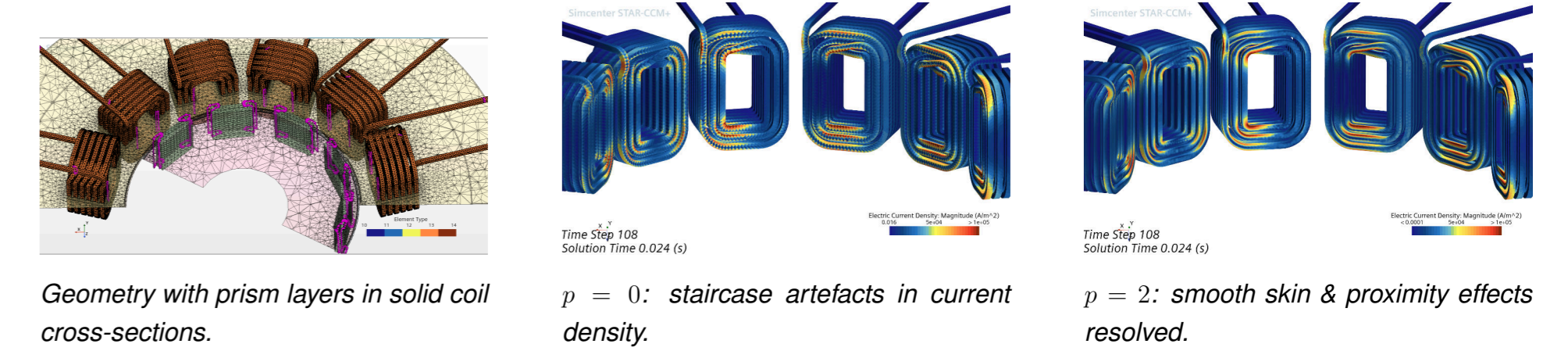
Application — Interior permanent magnet motor (T-Ω vs JMAG benchmark):

Transient magnetodynamic analysis of an automotive interior permanent magnet (IPM) motor (stranded coils, nonlinear B-H iron). Comparable meshes generated in JMAG (A- ϕ + iterative, sliding non-conformal air gap) and STAR-CCM+ (T-Ω + iterative, EMAG Template with Air Gap Remeshing); coarse mesh $\sim 3.8M$ cells, fine mesh $\sim 12M$ cells. Torque matches experiment within $\sim 5\%$ and JMAG within $\sim 5\%$.



Application — E-machine with solid coils: skin & proximity effects via HO prism elements:

A synchronous e-machine with solid (unsuppressed) coil windings demonstrates high-order $H(\text{curl})$ shape functions for prism and wedge elements. Prism layers on the inside of the wire cross-sections carry $H(\text{curl})$ basis functions of order $p = 0, 1, \text{ or } 2$; the rest of the machine stays at $p = 0$. Raising the order in the *Wires* region resolves the skin and proximity effects that $p = 0$ misses, delivering smooth current density distributions on the same coarse mesh without h -refinement.



FE Acoustics — Adaptive Order (FEMAO)

Mathematical problem. Frequency-domain Helmholtz equation with high-order p -FEM:

$$\nabla^2 p + k^2 p = 0, \quad k = \omega / c$$

Weak form with frequency-dependent materials, PML, and absorbing boundary conditions. Adaptive polynomial order per element selected via a-priori error indicators.

Key capabilities:

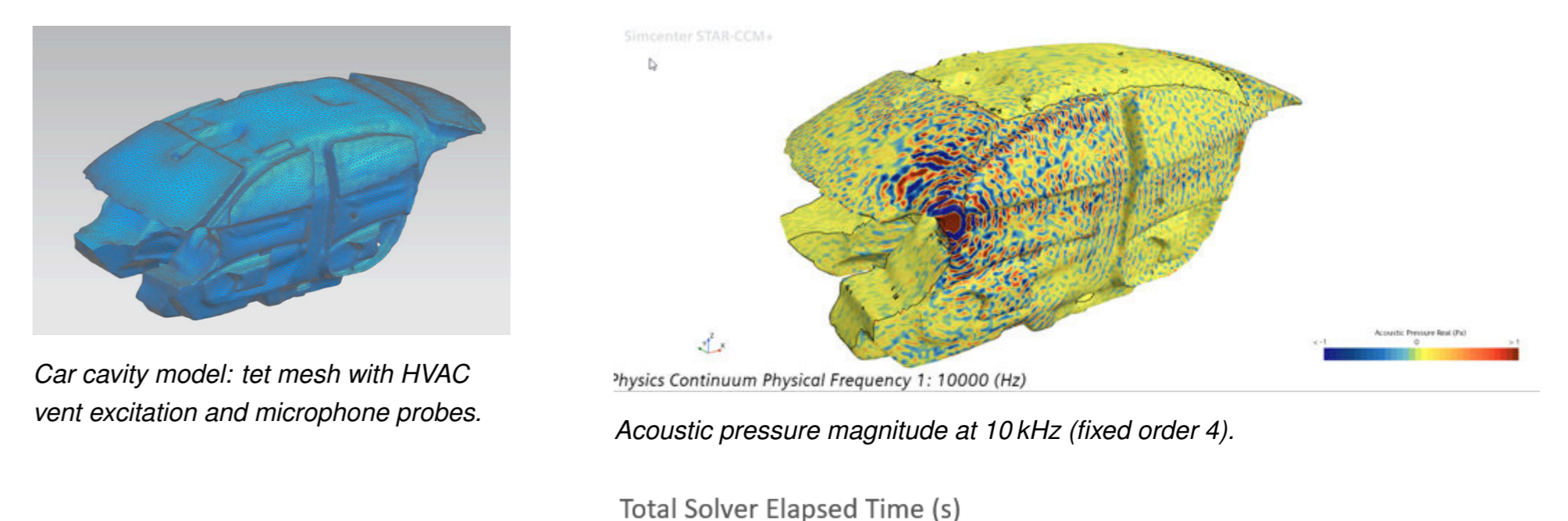
- Broadband frequency analysis (20 Hz–20 kHz) on a single mesh
- A-priori error indicators adjust polynomial order per frequency step
- Isotropic (element-centric) and anisotropic (edge-centric) order strategies
- User-defined accuracy targets: Coarse / Standard / Fine
- Frequency-dependent materials and contribution analysis

What's special:

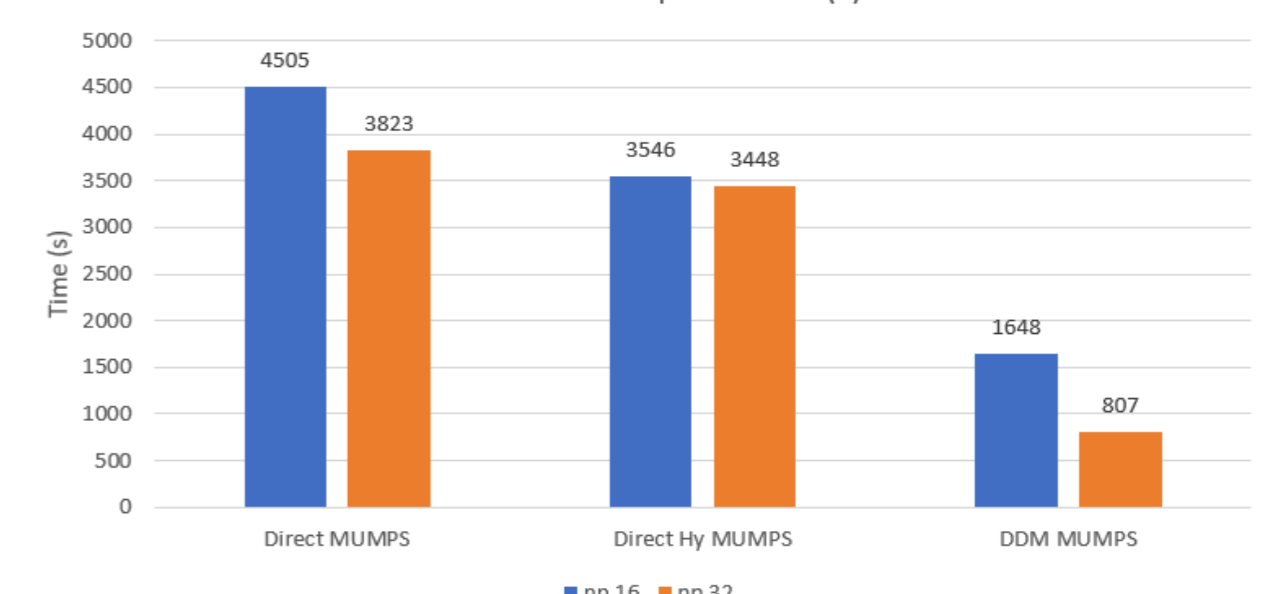
- Under extensive development — significant new functionality coming in upcoming releases
- Anisotropic orders for high-aspect-ratio elements and flow-dependent dispersion

Application — HVAC car cabin acoustics:

Acoustic pressure in a full car cavity is solved in the frequency domain using a tetrahedral mesh with a unit-pressure excitation (1 Pa) at the HVAC vent. Impedance boundary conditions are applied at seats, roof, and firewall. Microphone probes at the driver and co-driver ear positions validate solver consistency across three methods — Direct MUMPS, Hybrid MUMPS, and Domain Decomposition (DDM with MUMPS) — at fixed polynomial order 4 and 10 kHz. All methods yield identical acoustic pressure; DDM scales efficiently with core count.



Total Solver Elapsed Time (s)



Solver performance at 10 kHz, fixed order 4 (Leuven HPC). DDM MUMPS scales better with core count; DDM with $np=32$ is 2 \times faster than $np=16$. DDM memory \approx Hybrid MUMPS.

Further Applications

For more multiphysics FE application examples in Simcenter STAR-CCM+, visit the Simcenter Blog:

<https://blogs.sw.siemens.com/simcenter/>