Simulation of Hypersonic Flows in Real-life Configurations

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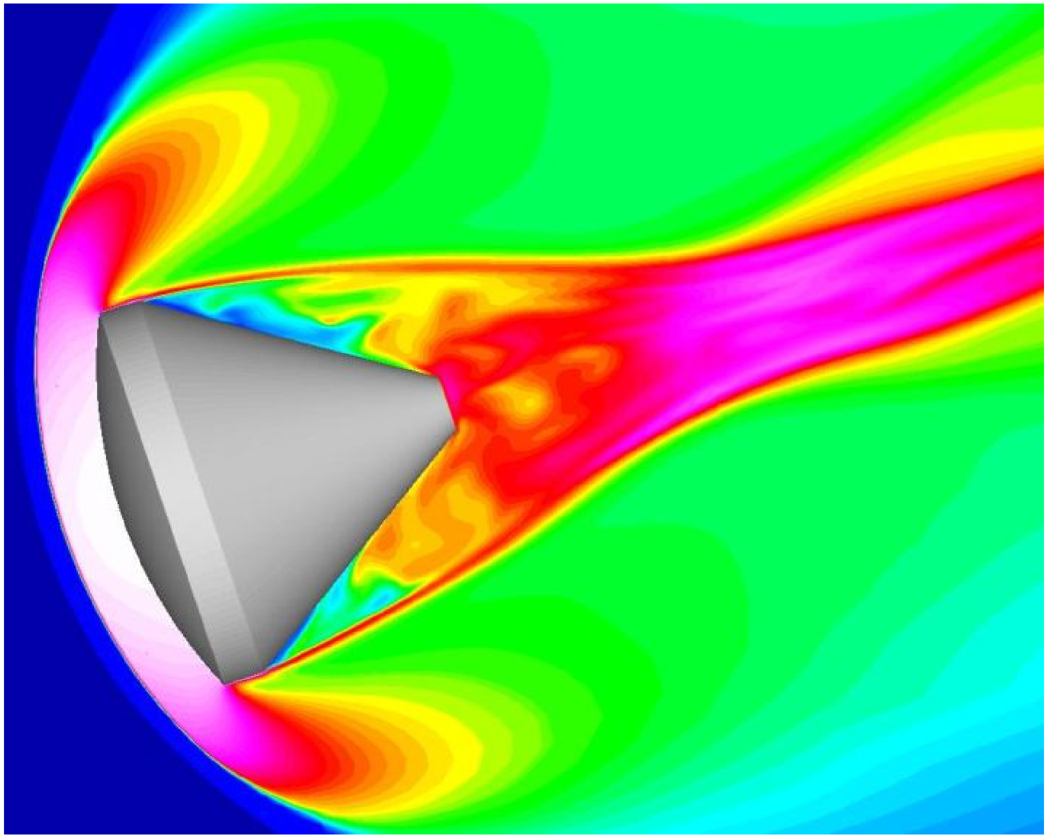
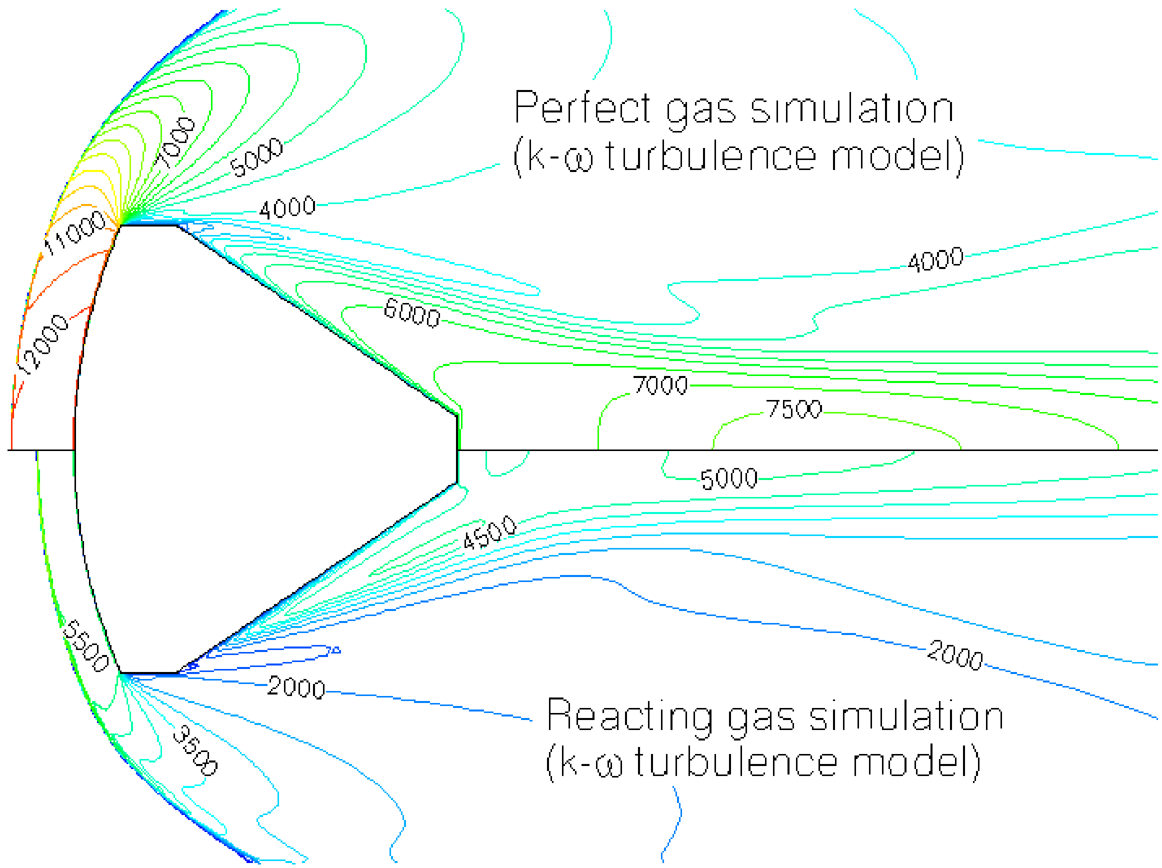
Hypersonic flows (Mach number > 5)

- Strong gas dynamic effects
- Shock waves
- Expansion fans
- High Temperature
- Large variation in density



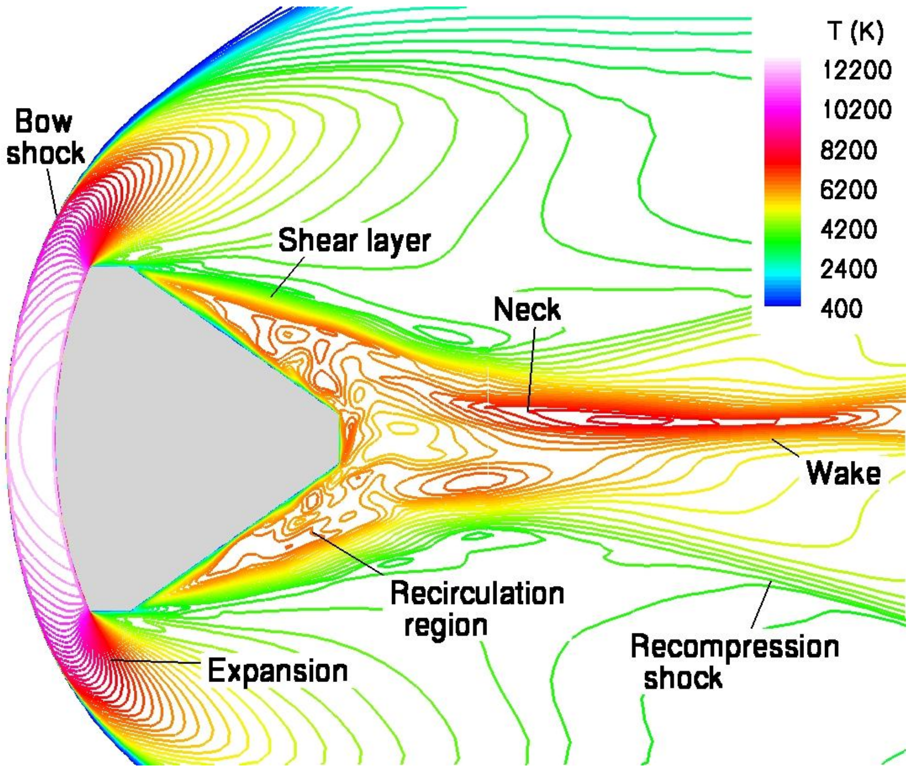
Non-equilibrium thermo-chemistry

- Dissociation of gas molecules
- Vibrational excitation
- Non-equilibrium effects



Turbulence effects in hypersonic flows

- Turbulent boundary layer
- Free shear layer
- Recirculation bubble

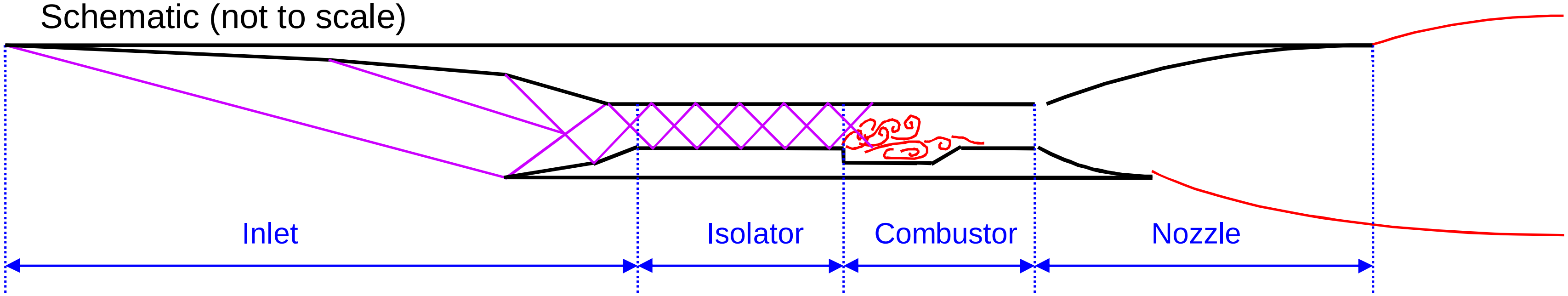


Hypersonic reacting turbulent flow simulation

- High Mach number
- High enthalpy
- High Reynolds number

X-43 flight at Mach 10 (2004)

Schematic (not to scale)



Governing equations

- Navier Stokes equations for mass, momentum and energy
- Species conservation equations for reacting flow simulation
- Conservation equation for vibrational energy

$$\frac{\partial U}{\partial t} + \frac{\partial F_I}{\partial x} + \frac{\partial G_I}{\partial y} + \frac{\partial F_V}{\partial x} + \frac{\partial G_V}{\partial y} = W$$

$$U = (\rho_1, \rho_2, ..., \rho_{ns}, \rho u, \rho v, E_v, E)^T$$

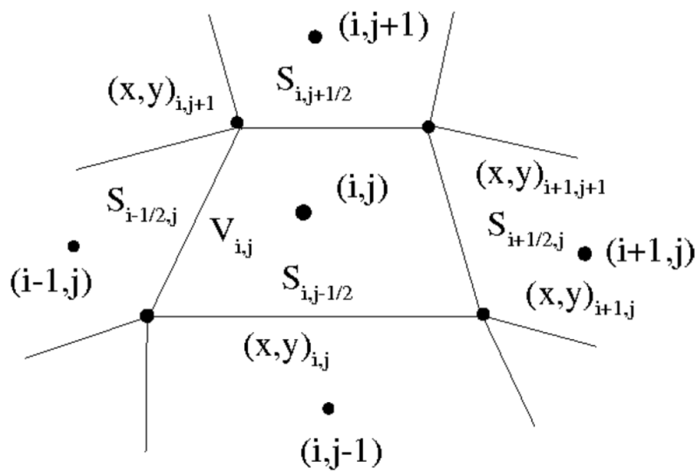
- Transport equations for turbulence quantities (k, epsilon, etc.)

Finite Volume CFD Code

- Discretized conservation equation for each grid cell

$$\frac{U^{n+1}_{i,j}-U^{n}_{i,j}}{\triangle t} = \frac{1}{V}\left[(\vec{F}.\hat{n})_{i+\frac{1}{2},j}S_{i+\frac{1}{2},j} - (\vec{F}.\hat{n})_{i-\frac{1}{2},j}S_{i-\frac{1}{2},j}\right] + \frac{1}{V}\left[+(\vec{F}.\hat{n})_{i,j+\frac{1}{2}}S_{i,j+\frac{1}{2},j} - (\vec{F}.\hat{n})_{i,j-\frac{1}{2}}S_{i,j-\frac{1}{2}}\right] + \bar{W}$$

- Fluxes = convective + diffusive
- Convective fluxes are nonlinear; pose numerical challenges.
- Structured grid.

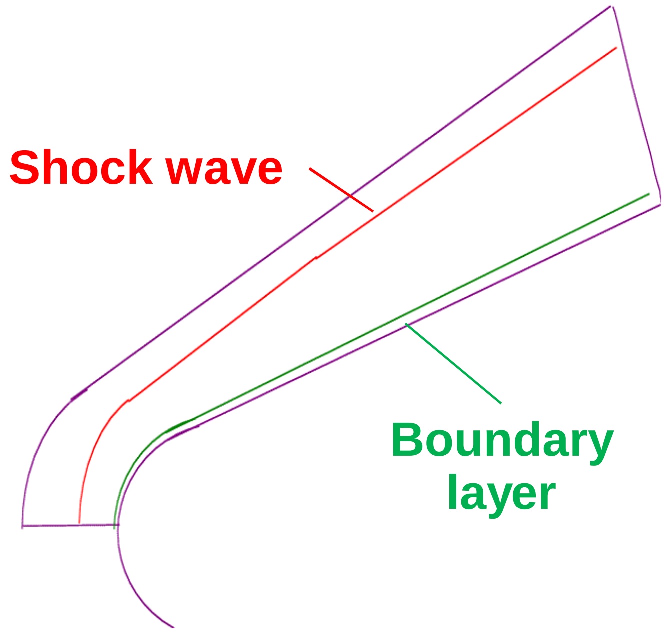


Implicit Time Integration

$$F_I'^{n+1} = F_I'^{n} + \left[\frac{\partial F_I'}{\partial U}\right]^n \left(U^{n+1} - U^n\right) \approx F_I'^{n} + A'^{n}\delta U^n$$

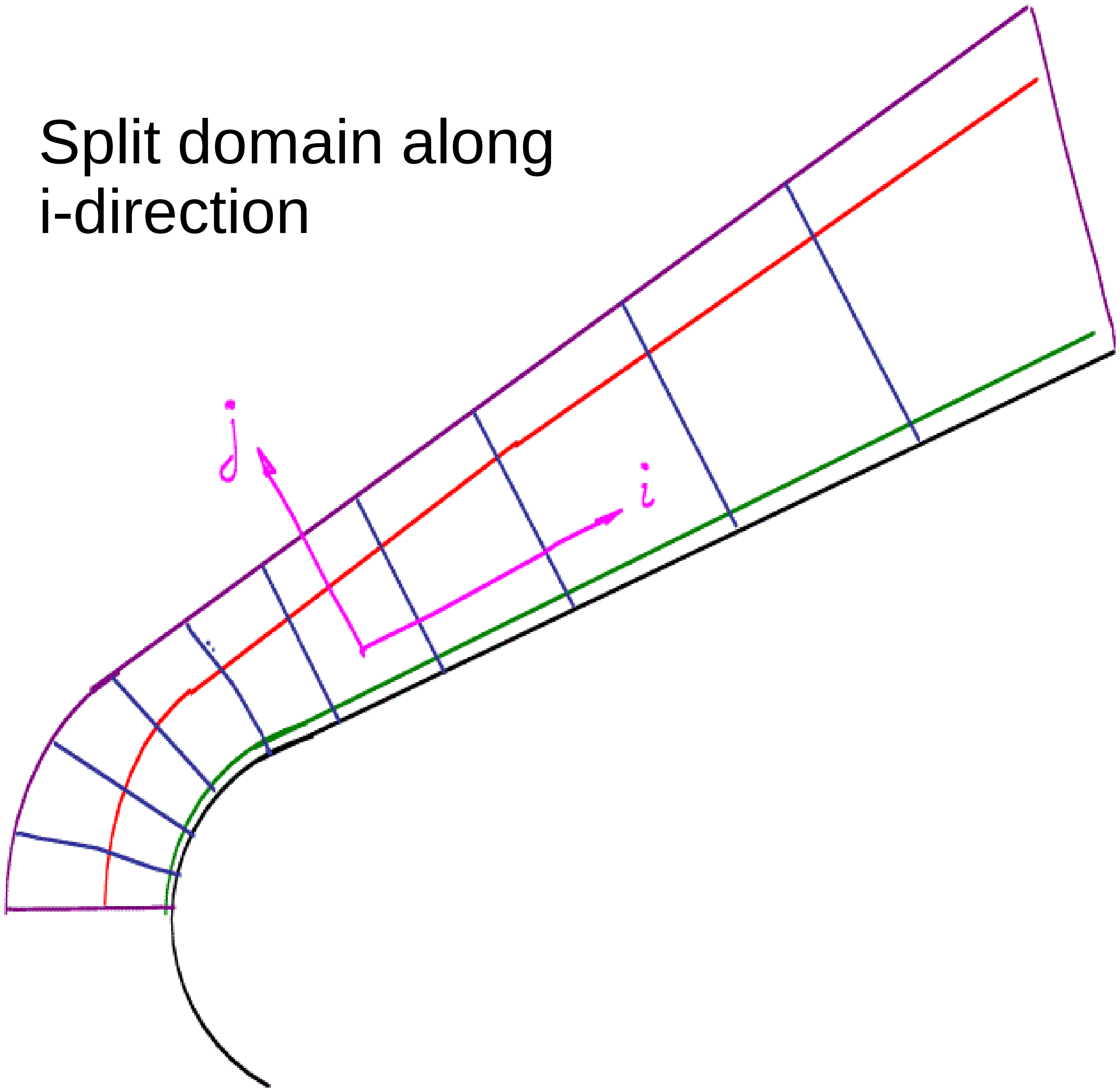
$$\hat{A}_{i,j}\delta U^n_{i,j} + \hat{B}_{i,j}\delta U^n_{i,j+1} + \hat{C}_{i,j}\delta U^n_{i,j-1} + \hat{D}_{i,j}\delta U^n_{i+1,j} + \hat{E}_{i,j}\delta U^n_{i-1,j} = \triangle U^n_{i,j}$$

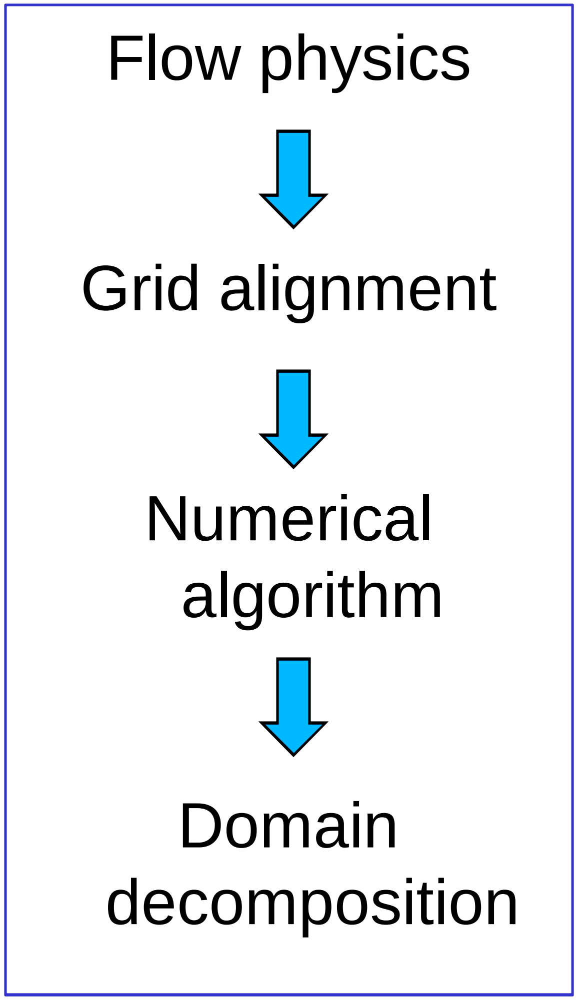
- Strong coupling in the j-direction => Invert matrices
- Forward and backward sweeps in the i-direction => flow convection



Data Parallel Implementation

Split domain along
i-direction





Dedicated HPC cluster for CFD

- Linux cluster running Rocks software suite
- Over 200 processor-cores
- Low-latency Myrinet switch
- PBS job scheduling/monitoring
- High-end compilers
- Precision cooling system

64-port Myrinet switch

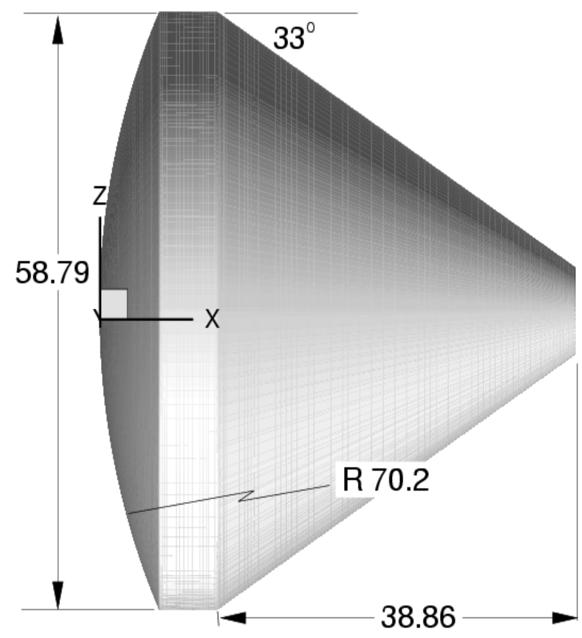
Simulation Methodology

- Configuration: geometry and free stream conditions
- Generate a computational mesh (Gridgen)
- Run the in-house parallel CFD code
- Obtain flowfield solution & residual history
- Post-processing software suite (in house)
- Flow visualization and analysis (Tecplot)

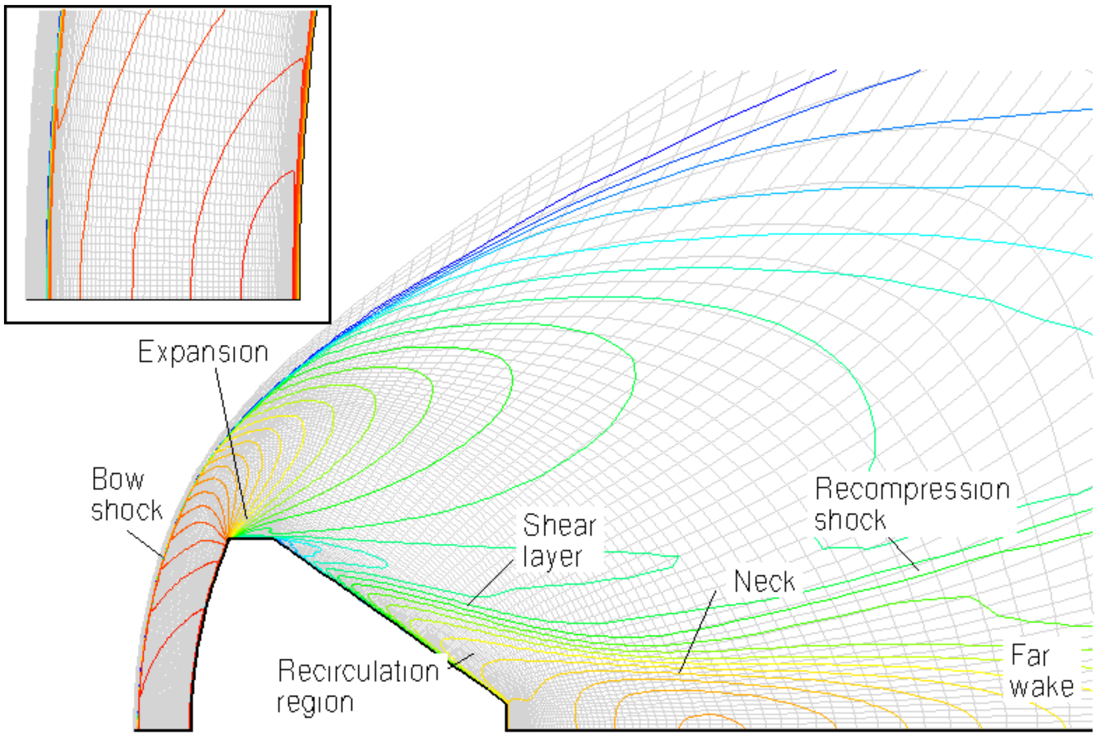
Re-entry Capsules for Planetary Missions

- Blunt nose to withstand extreme heat loads
- Afterbody houses payload and critical hardware

- Mach number: 5 - 25
- Velocity: 2000 - 8000 m/s
- Altitude: 35 km – 70 km
- Density: 10^{-2} - 10^{-4} kg/m^3
- Reynolds no.: 10^4 - 10^6

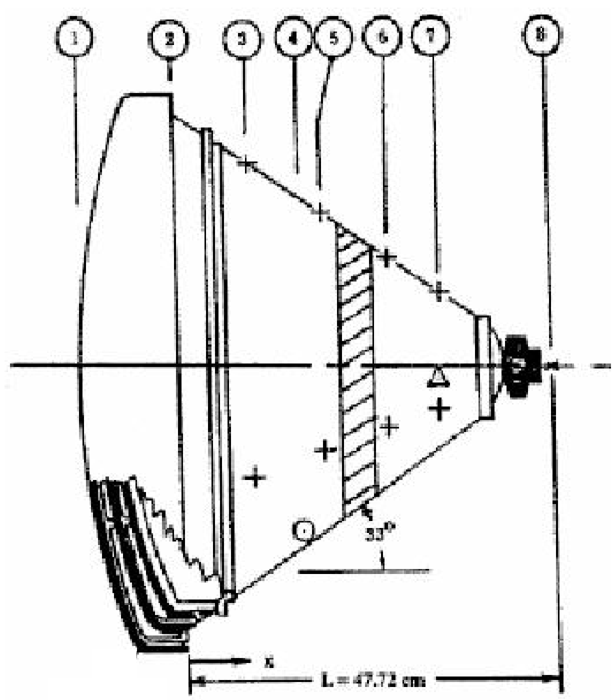


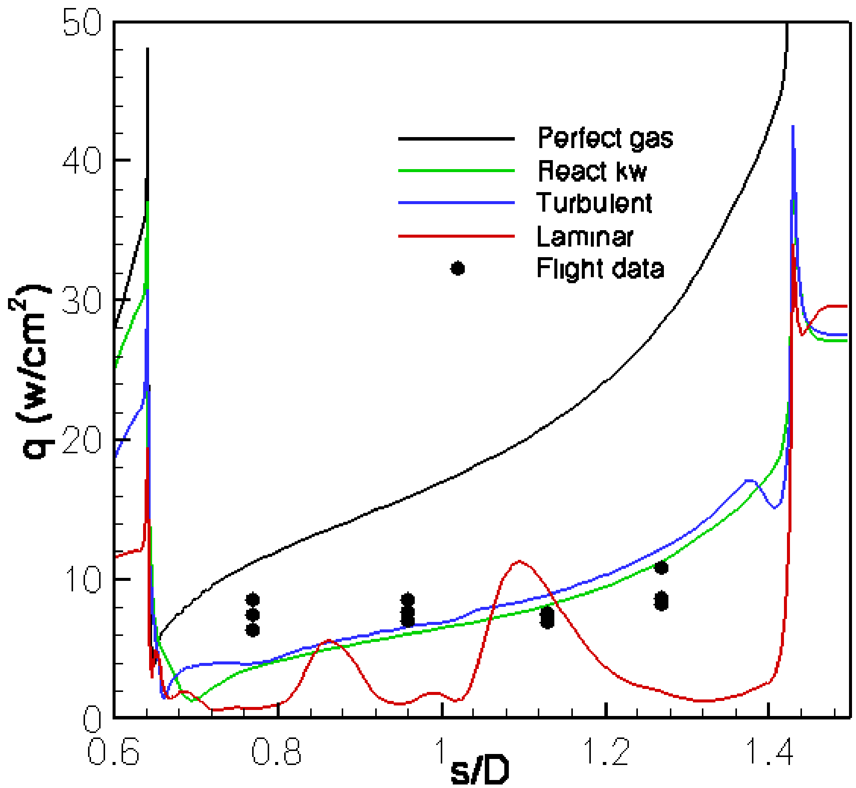
Computational grid tailored to flow features



- Axisymmetric simulation
- Grid: 200 x 200
- Steady state at 200 flow times
- 230 cpu-hours

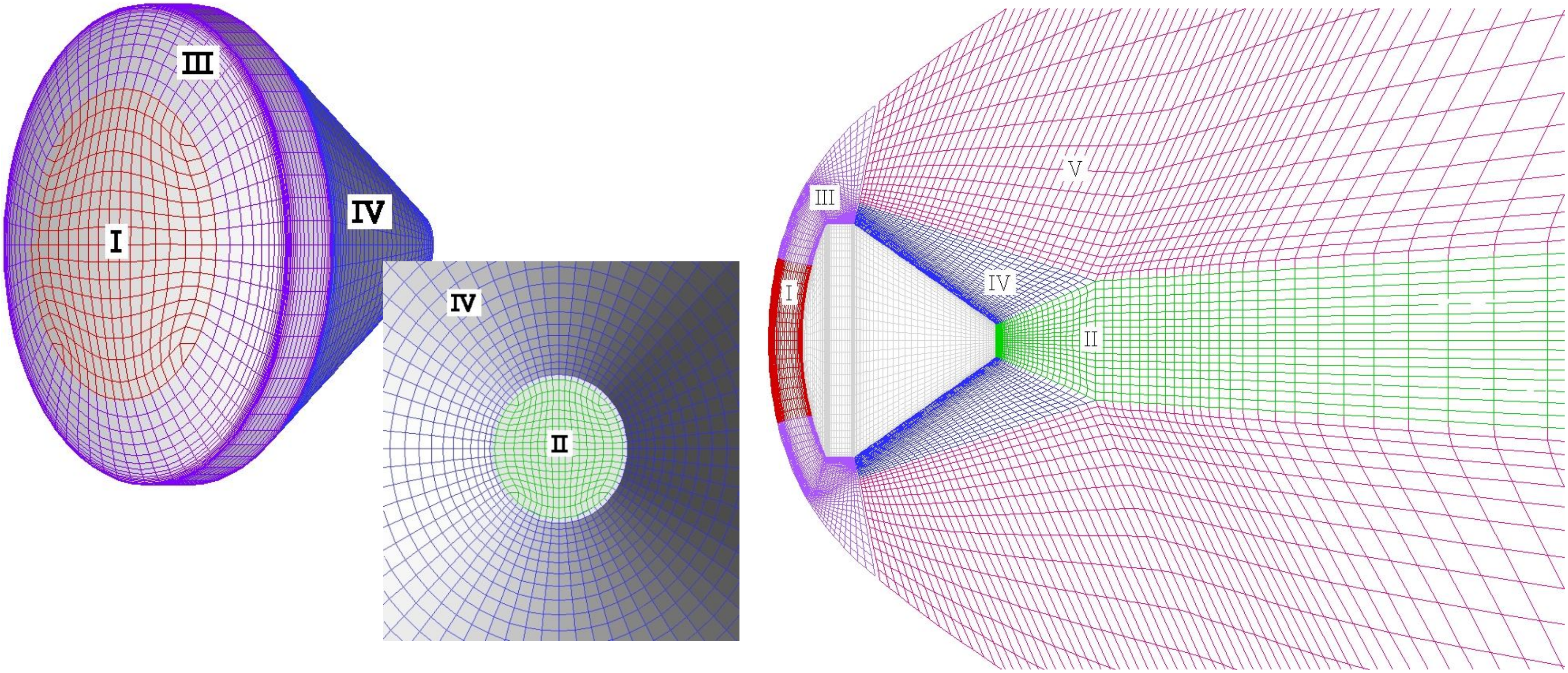
CFD Results comparable to Flight Data





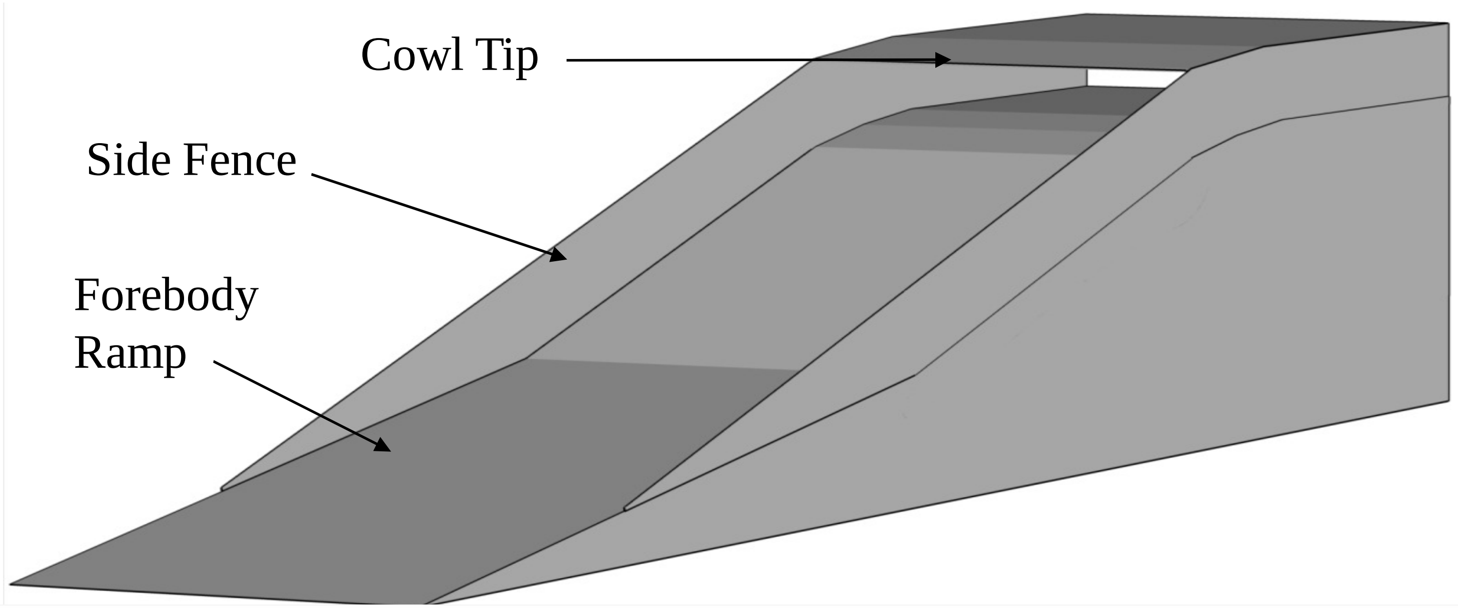
Fire II earth re-entry (1965) at M=16 and 35 km altitude

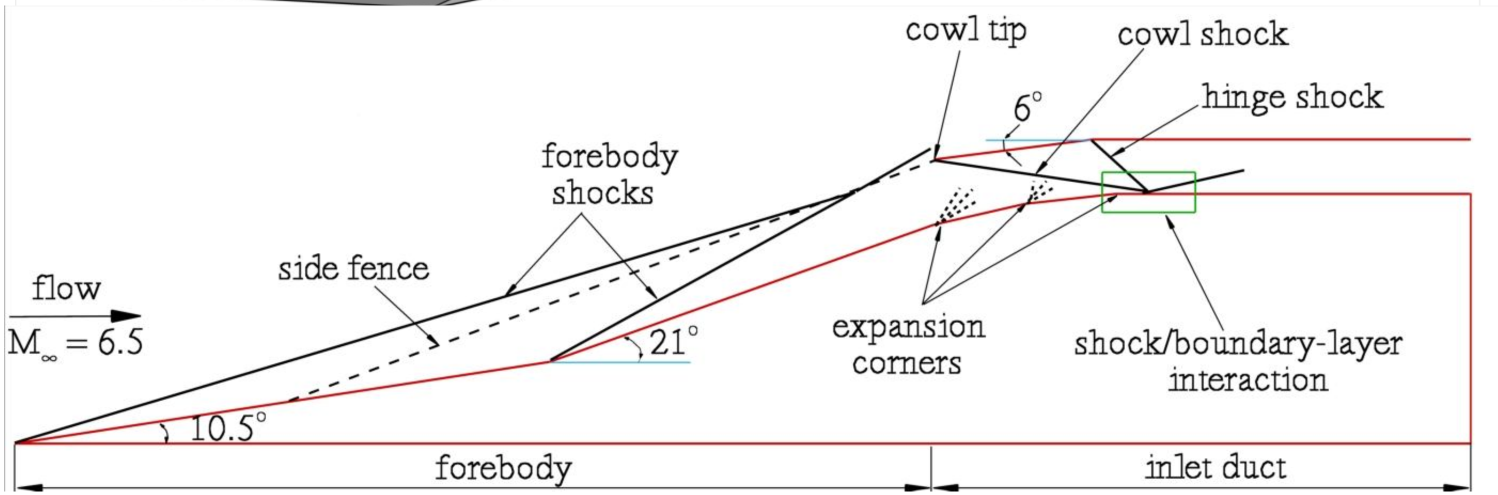
3D simulation with multi-block grid



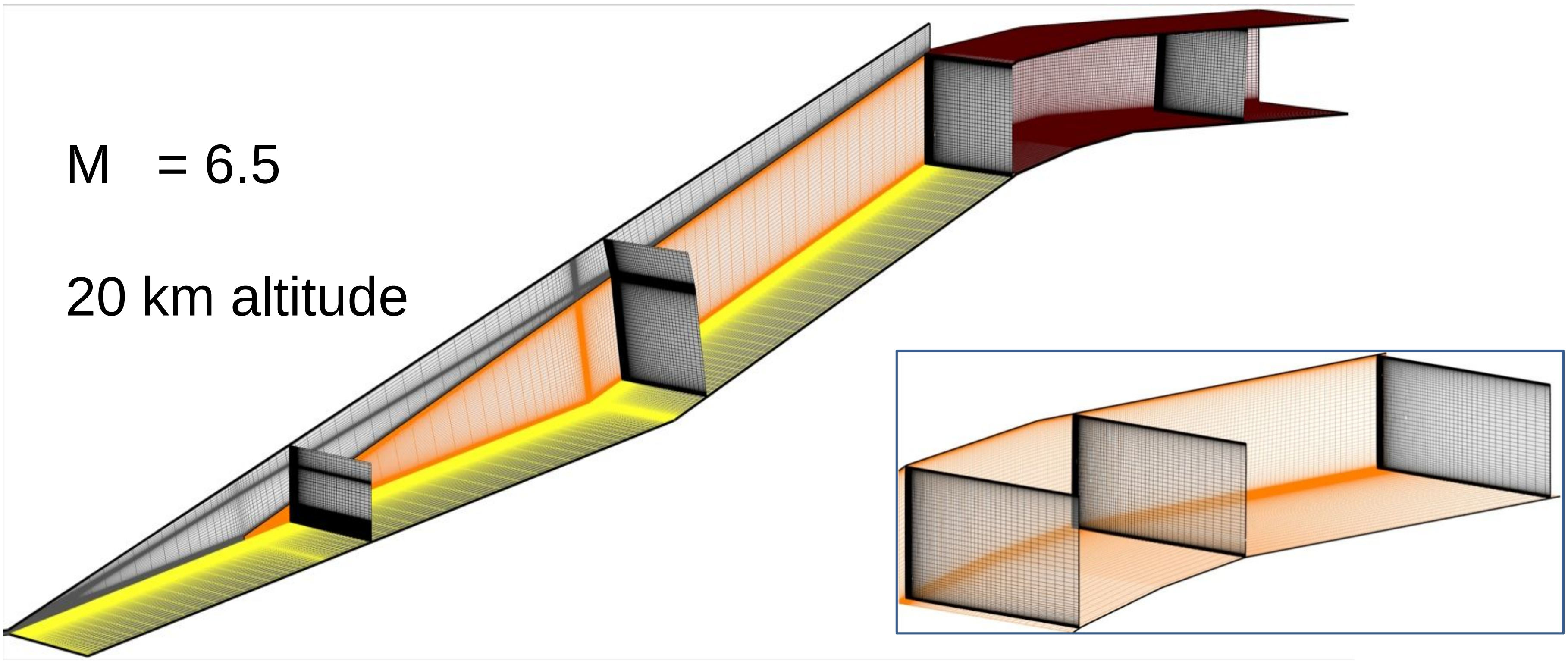
- Up to 9×10^6 grid points
- Load balancing across grid blocks
- 30,000 – 1,00,000 cpu-hours of computation

Hypersonic Intakes for Scramjet engines



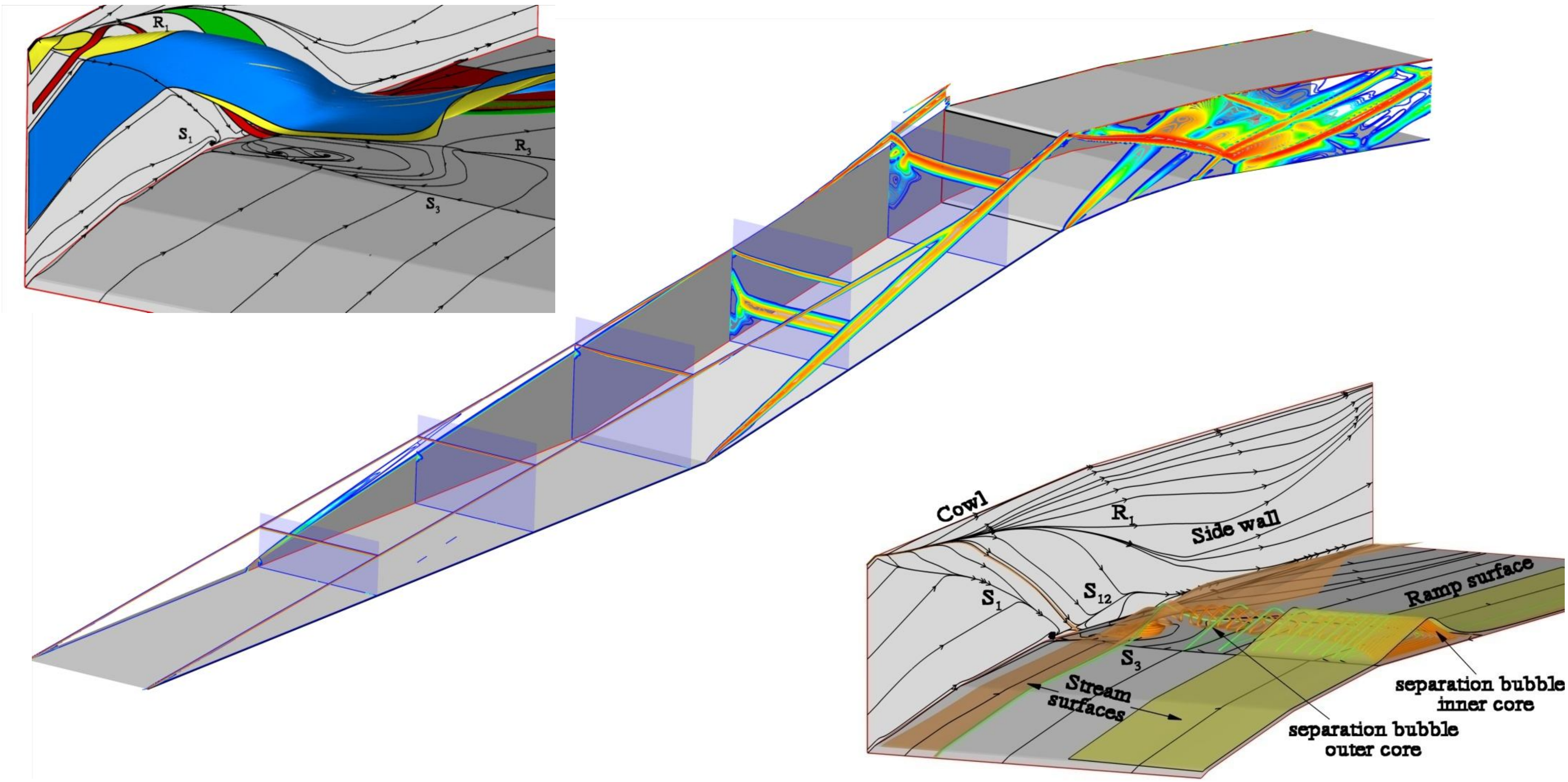


3D simulation of Scramjet Intake

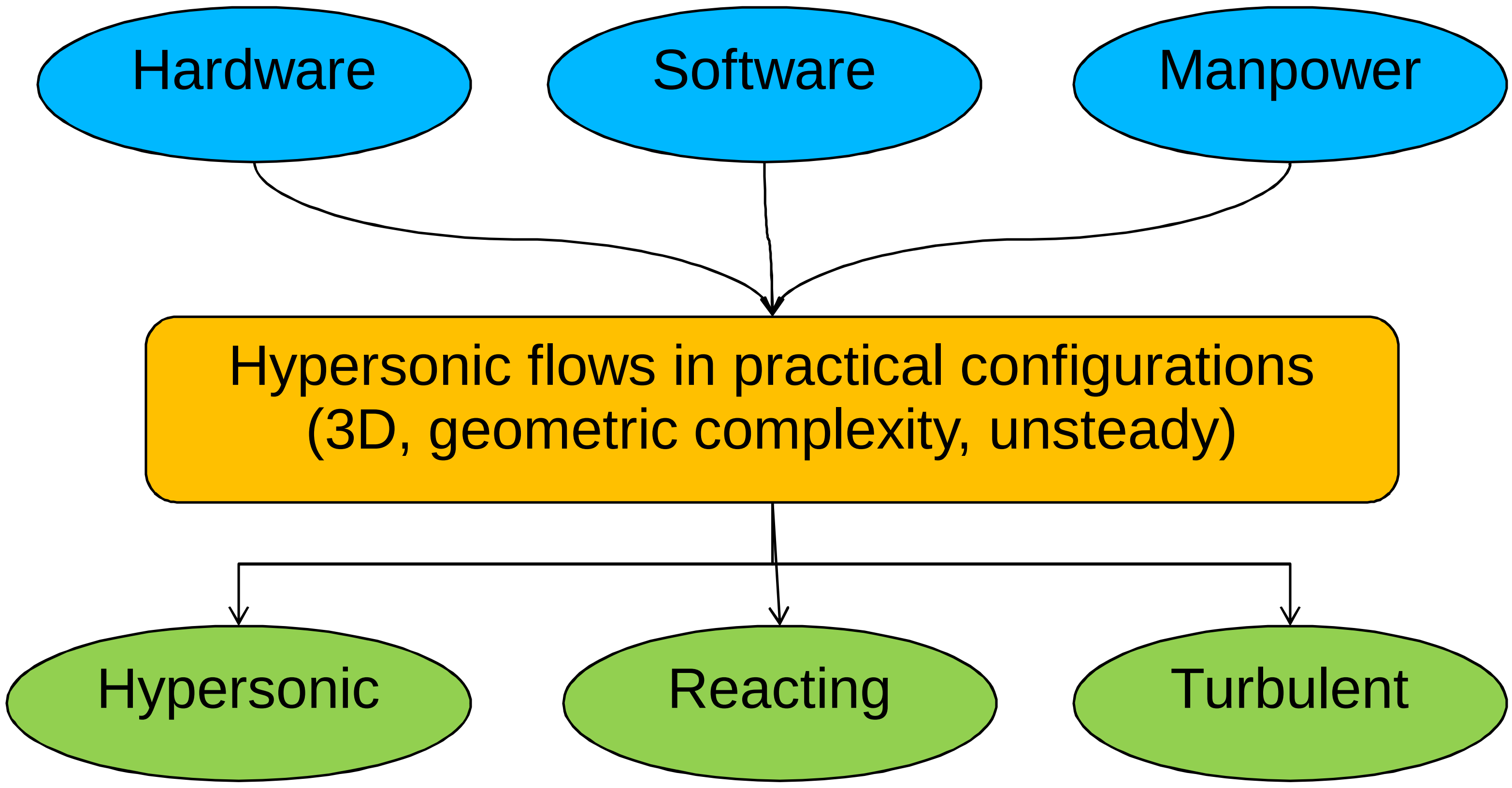


- Size: 395 x 150 x 200
- 30 hours on 40 processors

Complex pattern of shocks, expansion fans, vortices and recirculation region

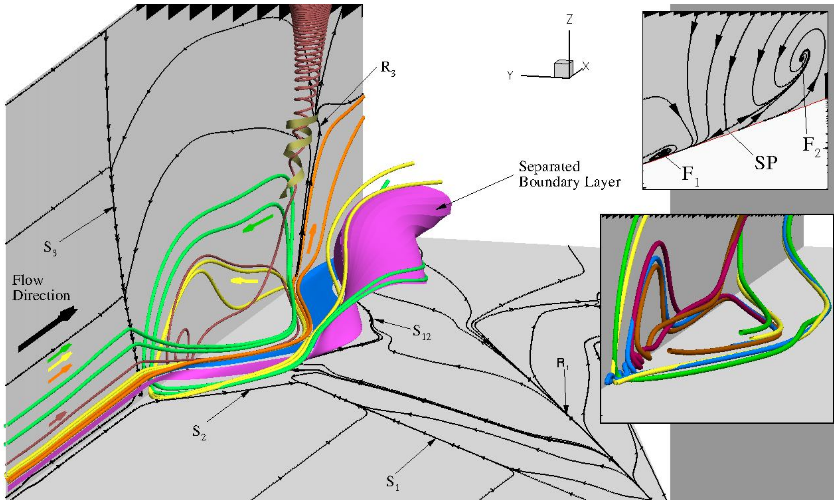


HPC for CFD of Real-life Problems

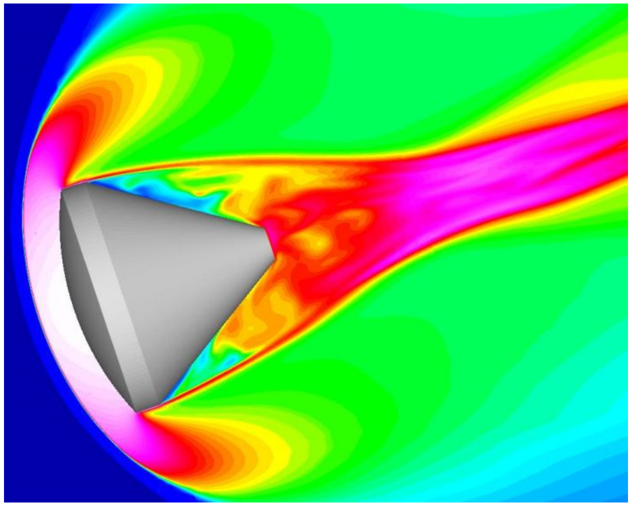


HPC as a Research Tool

Physical modeling along with Numerical Simulation



ISRO scramjet intake duct



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Thank you !