Computational modeling of space re-entry aerothermodynamics and magnetized plasmas with COOLFluiD

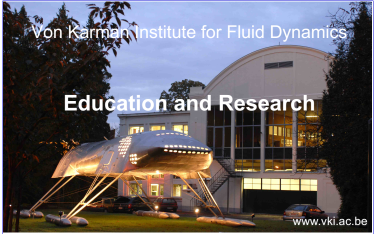
Andrea Lani
Research expert @CmPA (andrea.lani@kuleuven.be)
Research expert (guest) @VKI (lani@vki.ac.be)

Seminar 16th August 2019 @NASA ARC

Presentation Outline

Background

Von Karman Institute



Mission as conceived today: Excellence Center in Fluid Dynamics

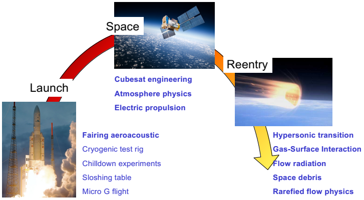
(Aerospace, turbomachinery, propulsion, environmental, industrial, …)

- Academic programs
  - Postgraduate Research Masters (1 academic year = 9 months) recognized (accredited) as Master after Master (60 ECTS)
  - PhD program (1 to 4 years)
  - Short Training Program (2-3 months) for undergraduates
  - Lifelong learning: Lecture Series (1 week duration short courses)
- Research & Development
  - Fundamental research in Fluid Dynamics (e.g. turbulence, transition …)
  - Applied research (Industry, ESA, EU, IWT, …)
- Stimulate International cooperation

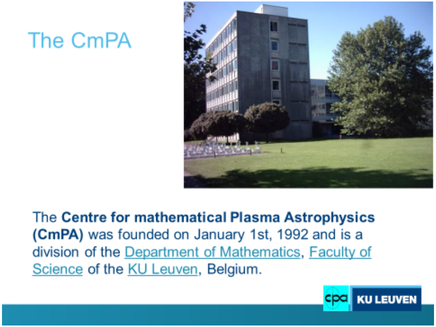
History and status of VKI

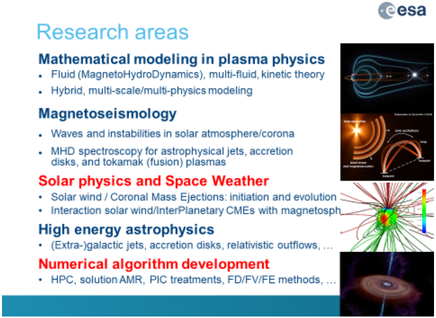
- Founded 60 years ago
  - In 1956, by Prof. Th. von Karman
  - International training center for advanced education in aeronautics
  - On the grounds of former Belgian government Aeronautics Center in Sint-Genesius-Rode
- Status
  - Non-profit, (INPA) International Scientific Association, presently supported by 12 countries, all member of NATO
  - Belgian funding from FOD Science Policy (BELSPO)

Aeronautics Research Activities



Center for mathematical Plasma Astrophysics (CmPA)





Leuven Computational Modeling Center

https://set.kuleuven.be/LCMC

Mission: numerical modeling of multi-scale systems and their mapping onto modern HPC systems

New structure and stakeholders since December 2018

- Me (**director**), Ward Melis and Jorge Amaya (**co-directors**)
- CmPA (Prof. Poedts, **president**), CS (Prof. Roose, Prof. Samaey), Bioscience/eng. (Prof. Ramon), Mech. Eng. (Prof. Meyers, Prof. Steelant)

Numerical methods and modelling tools (POC: Andrea Lani)

- AMR, high-order CFD methods, particle algorithms (e.g. for graphics, radiation, MD)
- UQ, control & optimization problems, reduced order models

HPC and data analysis (POC: Jorge Amaya)

- Hardware, software, programming for heterogeneous systems
- Big Data science: methods/analysis for voluminous datasets, parallel I/O, visualization

Multi-scale, multi-physics and control systems (POC: Ward Melis)

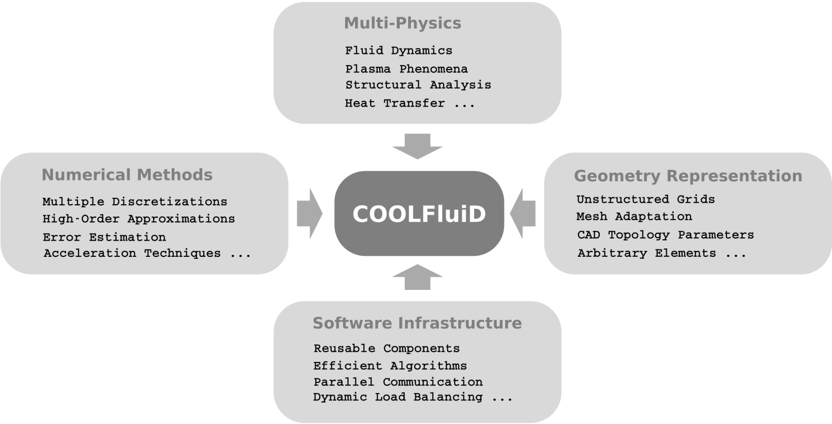
- Dynamical networks (social networks, smart grids, ...)
- Materials, chemistry, fluids, plasma, kinetic problems (e.g. turbulence, reacting flows)
- Multi-scale modeling and simulation tools

LCMC L(a)unch event (7/11/2019): https://wis.kuleuven.be/events/lcmc-2019/home

COOLFluiD overview

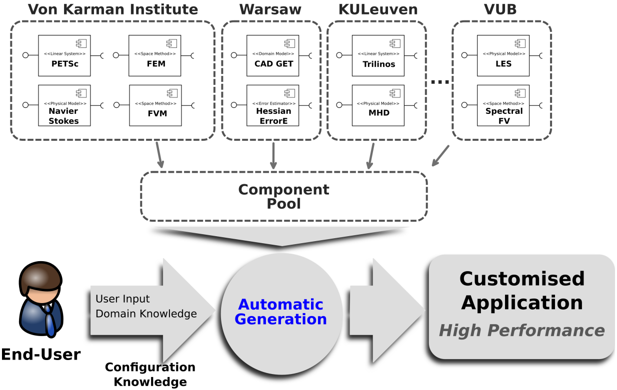
COOLFluiD platform (T. Quintino & A. Lani, 2002)

Developing & consolidating **multi-disciplinary** modeling expertise . . .



Collaborative Component-based Simulation Environment

. . . requires a flexible software platform and fruitful collaborations!



Open source: https://github.com/andrealani/COOLFluiD/wiki

Some statistics

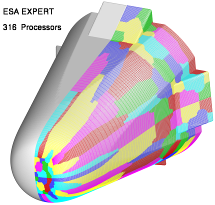
COOLFluiD team and quick facts

- **16** defended & **3** ongoing PhD thesis
- **100+ contributors** since 2002 from various institutions
- 1,000,000+ lines of codes, 100+ modules
- C++ / MPI / CUDA, interfaces to a few FORTRAN libraries
- **80+ scientific publications** (journal & conference articles)
- 20+ funded projects so far (ESA, EU FP7, US AFOSR, national)
- Subversion repository and website on **Github**
- **Open source** under LGPL v3 license since 10/2014

Wiki: https://github.com/andrealani/COOLFluiD/wiki

Twitter: https://twitter.com/coolfluid

Infrastructure for massively parallel HPC



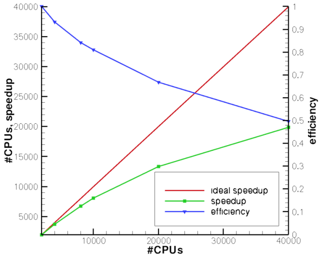
Parallel I/O: reading/writing tested up to 60,000 cores (PRACE)

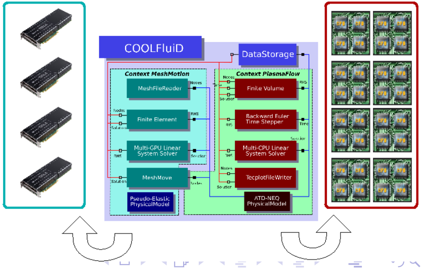
Parallel mesh extrusion to 10^9 cells

Concurrent simulation infrastructure

Scalability on NASA Pleiades (Top13)

Heterogeneous HPC on **CPU/GPU**





Algorithmic & multi-physics modeling features

Unstructured all-speed flow & plasma CFD solvers

- Finite Volume, high-order Flux Reconstruction, FEM
- In-flight/laboratory re-entry aerothermodynamics
- Single-fluid ideal MHD
- Multi-fluid/Maxwell, reactive & radiative plasma

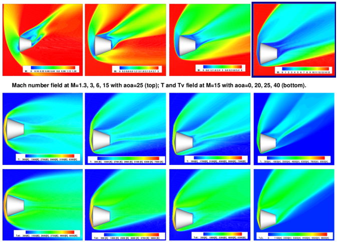
Massively parallel radiation transport algorithms

- Monte Carlo methods
- Finite Volume/Discrete Ordinate methods
- API's to multiple spectroscopic databases
- Spectra reduction algorithms for LTE & non-LTE

Mesh adaptation algorithms

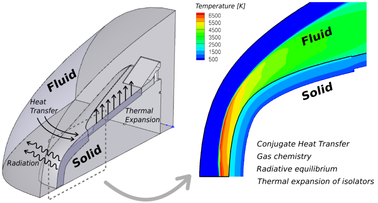
- Pseudo-elastic mesh deformation methods
- New generation shock-fitting/remeshing techniques

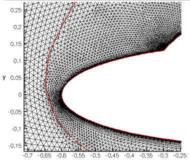
https://github.com/andrealani/ShockFitting

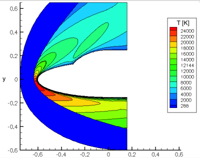


⇑ $M_\infty = 1.3 \div 15$ re-entry flow over ESA vehicle

⇓ ESA EXPERT: aerothermoelastic study







Shock-fitting around double ellipse at $M_\infty = 25$

Implicit Time Stepping

Newton Linearization

$$\tilde{\mathbf{R}}(\mathbf{P}) = \frac{\partial \mathbf{U}}{\partial \mathbf{P}}\frac{\partial \mathbf{P}}{\partial t} + \mathbf{R}(\mathbf{P}) = 0 \quad \Longrightarrow \quad \tilde{\mathbf{R}}(\mathbf{P}) = \tilde{\mathbf{R}}\left(\mathbf{P}^k\right) + \frac{\partial \tilde{\mathbf{R}}}{\partial \mathbf{P}}\left(\mathbf{P}^k\right) = 0 \quad \Longrightarrow \quad \left[\frac{\partial \tilde{\mathbf{R}}}{\partial \mathbf{P}}\left(\mathbf{P}^k\right)\right] \Delta \mathbf{P}^k = -\tilde{\mathbf{R}}\left(\mathbf{P}^k\right)$$

Implicit time integration schemes

$$
\begin{aligned}
\tilde{\mathbf{R}}(\mathbf{P}) &= \frac{\mathbf{U}(\mathbf{P}) - \mathbf{U}(\mathbf{P}^n)}{\Delta t}\Omega + \mathbf{R}(\mathbf{P}) && \text{Backward Euler (steady)} \\
\tilde{\mathbf{R}}(\mathbf{P}) &= \frac{\mathbf{U}(\mathbf{P}) - \mathbf{U}(\mathbf{P}^n)}{\Delta t}\Omega + \frac{1}{2}[\mathbf{R}(\mathbf{P}) + \mathbf{R}(\mathbf{P}^n)] && \text{Crank-Nicholson (unsteady)} \\
\tilde{\mathbf{R}}(\mathbf{P}) &= \frac{3\mathbf{U}(\mathbf{P}) - 4\mathbf{U}(\mathbf{P}^n) + \mathbf{U}(\mathbf{P}^{n-1})}{2\Delta t}\Omega + \mathbf{R}(\mathbf{P}) && \text{3-Point Backward (unsteady)}
\end{aligned}
$$

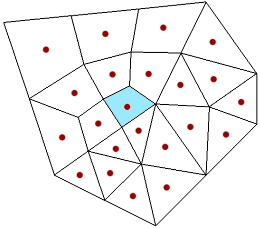
Linear system solvers (e.g. from PETSc, PARALUTION, Trilinos)

- GMRES solver
- Matrix storing and Matrix free
- Parallel preconditioners: ASM, ILU, B-Jacobi, AMG, etc.

Finite Volume Method ($\mathcal{FV}$), cell-centered

$$\frac{d}{dt}\int_{\Omega_i} \mathbf{U}\, d\Omega_i + \oint_{\partial\Omega_i} \mathbf{F}^c \cdot \mathbf{n}\;\, d\partial\Omega_i = \oint_{\partial\Omega_i} \mathbf{F}^d \cdot \mathbf{n}\, d\partial\Omega_i + \int_{\Omega_i} \mathbf{S}\, d\Omega_i$$

$$\frac{\partial \mathbf{U}}{\partial \mathbf{P}}(\mathbf{P}_i)\frac{d\mathbf{P}_i}{dt}\Omega_i + \mathbf{R}^{FV}(\mathbf{P}_i) = 0$$



Cell-centered discretization

$$\mathbf{R}^{FV}(\mathbf{P}_i) = \sum_{f=1}^{N_f} \mathbf{F}_f^c\, \Sigma_f - \sum_{f=1}^{N_f} \mathbf{F}_f^d\, \Sigma_f - \mathbf{S}_i\, \Omega_i$$

Linear Reconstruction + Flux Limiter Φ

$$\tilde{\mathbf{P}}(\mathbf{x}_q) = \mathbf{P}_i + \Phi_i\, \nabla\mathbf{P}_i \cdot (\mathbf{x}_q - \mathbf{x}_i)$$

Upwind schemes for interface convective flux

$$\mathbf{F}_f^c = \begin{cases} \frac{1}{2}\left[\mathbf{F}_R^c + \mathbf{F}_L^c - \mid \bar{\mathbf{A}} \mid (\mathbf{U}_R - \mathbf{U}_L)\right] & \text{Roe} \\ \mathbf{F}^+ + \mathbf{F}^- = \mathbf{A}^+\mathbf{U}_L + \mathbf{A}^-\mathbf{U}_R & \text{S-W} \\ \dot{m}_{1/2}\, \Psi_{L/R} + \mathbf{p}_{1/2} & \text{AUSM} \end{cases}$$

Central discretization for interface diffusive flux

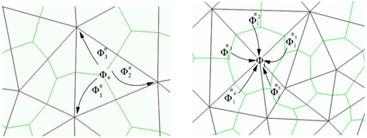
$$\mathbf{F}_f^d = \mathbf{F}^d\, (\mathbf{P}_f, \nabla\mathbf{P}_f, \mathbf{n}_f)$$

$$\nabla\mathbf{P}_f = \frac{1}{\Omega^v}\oint_{\Sigma^v} \mathbf{P}\; \mathbf{n}\; d\Sigma^v = \frac{1}{\Omega^v}\sum_{s=1}^{N'_l} \bar{\mathbf{P}}_l \mathbf{n}_l \Sigma_l^v \quad \text{(Green-Gauss)}$$

$$\nabla\mathbf{P}_f = \frac{\mathbf{P}^R - \mathbf{P}^L}{d_{LR}}(\vec{e}\cdot\vec{n})\vec{n} + \frac{1}{2}(\mathbf{I} - \vec{n}\otimes\vec{n})\left((\nabla\mathbf{P})^L + (\nabla\mathbf{P})^R\right)$$

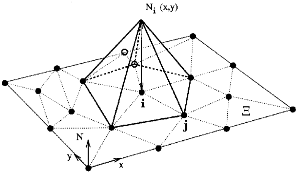
Residual Distribution Method ($\mathcal{RD}$), vertex-centered

$$\frac{\partial \mathbf{U}}{\partial \mathbf{P}}(\mathbf{P}_l)\frac{d\mathbf{P}_l}{dt}V_l + \mathbf{R}^{RD}(\mathbf{P}_l) = 0$$



FEM linear interpolation

$$\mathbf{P}^h(\mathbf{x}, t) = \sum_{j=1}^{d} \mathbf{P}_j(t) N_j(\mathbf{x}), \quad N_j(\mathbf{x}_k) = \delta_{jk}$$



Vertex-centered discretization

$$\mathbf{R}^{RD}(\mathbf{P}_l) = \Phi_l^c - \Phi_l^d - \Phi_l^s$$

Discretization of convective term

$$\Phi_l^c = \sum_{\Omega \in \Xi_l} \mathbf{B}_l^{\Omega}\left(\mathbf{K}_l^{\pm}\right)\Phi^{c,\Omega}, \quad \mathbf{K}_l^{\pm} = \frac{1}{N_d}\bar{\mathbf{R}}_l\,\bar{\mathbf{\Lambda}}_l^{\pm}\,\bar{\mathbf{L}}_l$$

Galerkin discretization of diffusive term

$$\Phi_l^d = -\sum_{\Omega \in \Xi_l} \frac{1}{\Omega d}\int_{\Omega} \mathbf{F}^d(\mathbf{P}, \nabla \mathbf{P}) \cdot \mathbf{n}_l \, d\Omega$$

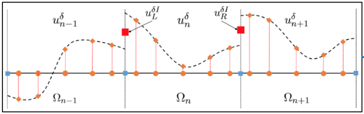
Petrov-Galerkin discretization of source term

$$\Phi_l^s = \sum_{\Omega \in \Xi_l} \int_{\Omega} \mathbf{w}_l^{\Omega}\,\mathbf{S}\, d\Omega \overset{\text{1-point}}{\Longrightarrow} \sum_{\Omega \in \Xi_l} \mathbf{B}_l^{\Omega}\,\mathbf{S}_c\,\Omega$$

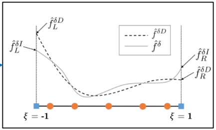
High-Order Flux Reconstruction ($\mathcal{FR}$) (**PhD R. Vandenhoeck**)

High-order Finite Element-type method (~DG, SD, SV)

- H. T. Huynh, 2007
- High-order reconstruction using correction polynomials: VCJH



Reconstruction



$$\frac{d\hat{u}^{\delta}_i}{dt} = -\frac{\partial \hat{f}^{\delta}}{\partial \xi}$$

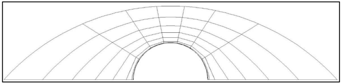
Conservative equation

FR

$$\hat{f}^{\delta} = \hat{f}^{\delta D} + \hat{f}^{\delta C} = \hat{f}^{\delta D} + (\hat{f}^{\delta I}_L - \hat{f}^{\delta D}_L)h_L + (\hat{f}^{\delta I}_R - \hat{f}^{\delta D}_R)h_R$$

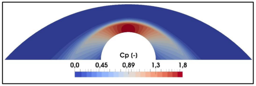
Discontinuous flux (P) · Correction flux (P+1) · Interface flux · Correction polynomial (P+1)

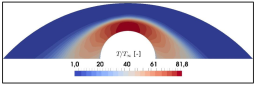
Gnoffo's cylinder case ($M_{\infty} = 17.6$): FR vs. reference FV solution (**AIAA-2019-1153**)

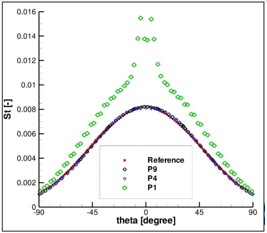


P9 Coarser mesh

- 77 element Q2 mesh
  - 7 elements along cylinder
  - 11 elements normal



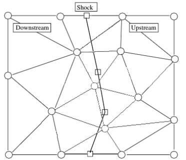


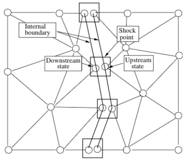


Shock-Fitting (S-F) solver (**R. Pepe**, **V. De Amicis**, **V. Giangaspero**)

Collaborators: **Prof. Paciorri** (University of Rome), **Prof. Bonfiglioli** (UniBas)

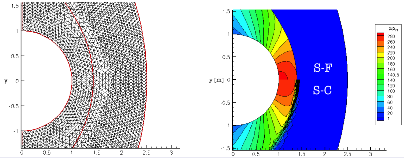
S-F code is open source: https://github.com/andrealani/ShockFitting



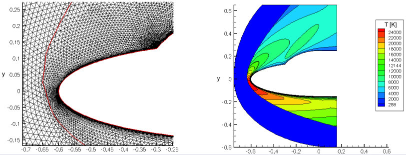


S-F algorithm

1. Extract shock-profile from shock-capturing solution
   - ▶ automatically via shock-sensor + LS fitting
2. Solve the S-F system (R-H + subsonic inlet condition) for downstream conditions
3. Advance shock-mesh points with $\mathbf{X}_i^{t+\Delta t} = \mathbf{X}_i^t + \mathbf{w}_i^t \Delta t$
4. Reconstruct upstream and downstream mesh (constrained Delanauy triangulation)
5. Interpolate solution on new mesh and run CFD solver for one or more iterations
6. Restart from (2) till when shock stops moving



S-F vs. Shock-Capturing at $M_\infty = 15$ ($\mathcal{RD}$ N)



S-F on double ellipse at $M_\infty = 25$ ($\mathcal{RD}$ B_x)

A. Lani, V. De Amicis, Shock Fitting, **Springer book**

Mesh deformation solver (F. Huhn, P. Santos, F. Benameur)

Minimize integral: $I_{ij} = L_{ij} W_{ij} (\mathbf{X_j} - \mathbf{X_i})^2$

- I_{ij} represents potential energy of a spring with stiffness $W_{i,j}$ and zero equilibrium length
- Find equilibrium nodal positions of the spring system if $\frac{\partial \mathbf{I}}{\partial \mathbf{X}} = 0$ and $\frac{\partial^2 \mathbf{I}}{\partial \mathbf{X}^2} > 0$:

$$\frac{\partial I_{ij}}{\partial \mathbf{X}_i} = 2 L_{ij} W_{ij} (\mathbf{X}_i - \mathbf{X}_j) = 0$$

- Collect contributions over all nodes:

$$\sum_{j=1}^{n} L_{ij} W_{ij} (\mathbf{X}_i - \mathbf{X}_j) = 0, \quad \text{with} \quad W_{ij} = |U_j - U_i|$$

- Solve the nonlinear system:

$$\mathbf{A}\,\mathbf{X} = 0, \quad \text{where} \quad A_{ij} = \begin{cases} -L_{ij} W_{ij} & i \neq j \\ \sum_{j=1}^{n} L_{ij} W_{ij} & i = j \end{cases}$$

- BCs: $\mathbf{P_i} = \mathbf{P_i^0}$ or $\frac{\partial (\mathbf{P_i} \cdot \mathbf{n})}{\partial n} = 0$.

$\Uparrow$ AMR on $M_\infty = 2$ flow on a wedge channel
$\Downarrow$ AMR on 2D MHD rotor case

Benameur & Lani, **AIAA-2019-1997**

Monte Carlo radiation algorithm (**A. Sanna**, **P. Santos**, **B. Tershanski**)

Radiative Transfer Equation (RTE)

$$\frac{\partial I_\nu(\mathbf{r},\nu,\mathbf{\Omega})}{\partial \mathbf{r}} = e_\nu(\mathbf{r},\nu,\mathbf{\Omega}) - \alpha_\nu(\mathbf{r},\nu,\mathbf{\Omega}) I_\nu(\mathbf{r},\nu,\mathbf{\Omega})$$

1. Assign the total emitted radiative energy in each cell to N_e of virtual photons.
2. Send each photon to a random direction: $\mathbf{d} = \mathbf{d_r}/|\mathbf{d_r}|, \quad \mathbf{d_r} = -\mathbf{1} + 2 \cdot \mathbf{R}$
3. A **ray tracing algorithm** traces the photon path through the computational domain:
   - Our algorithm is based only on vector operations for 2D/axi/3D unstructured grids.
4. Beer's law defines absorption criteria in the gas: $\int_0^S \alpha_\lambda ds \geq -\ln(1 - R_s)$
5. At the wall, photons can be absorbed or reflected depending on local emissivity ϵ.
6. **Domain decomposition** strategies take care to allow photons to cross partition boundaries.
7. Assemble radiative heat flux divergence in cell i for each randomly selected frequency ν_k:

$$Q_{rad} = \nabla \cdot q_{rad\,i} = \sum_{k=1}^{N_\nu} \left(\frac{P_i(\nu_k)}{V_i} - \sum_{j \neq i} \frac{P_j(\nu_k)}{V_j} R_{ij}(\nu_k) \right)$$

- R_{ij} determines which portion of P emitted by photons from cell j is absorbed by cell i.

A. Lani, P. Duarte Santos, A. Sanna, **AIAA-2013-2893**

P. Duarte Santos and A. Lani, **Comp. Phys. Comm.**, 2016

Aerothermodynamics modeling

Governing equations for TCNEQ

Advection-diffusion-reaction PDE's

$$\frac{\partial \mathbf{U}}{\partial \mathbf{P}} \frac{\partial \mathbf{P}}{\partial t} + \nabla \cdot \mathbf{F}^c = \nabla \cdot \mathbf{F}^d + \mathbf{S}$$

Conservative and natural variables for Multi-T model

$$\mathbf{U} = [\rho_s \ \ \rho\mathbf{u} \ \ \rho E \ \ \rho_m e_{v,m} \ \ \rho e_e]^T \qquad \mathbf{P} = [\rho_s \ \ \mathbf{u} \ \ T \ \ T_{v,m} \ \ T_e]^T$$

Fluxes and Source Terms for Multi-T model (ionized mixture)

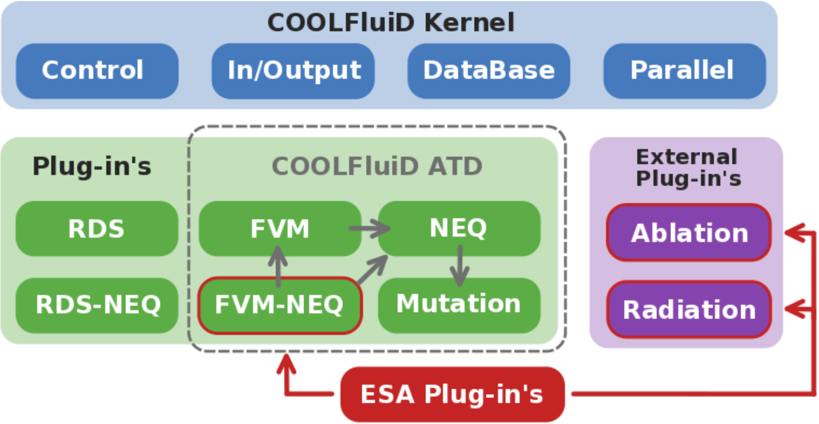
$$\mathbf{F^c} = \begin{pmatrix} \rho_s \mathbf{u} \\ \rho \mathbf{u}\mathbf{u} + p\hat{I} \\ \rho \mathbf{u} H \\ \rho_m \mathbf{u} e_{v,m} \\ \rho \mathbf{u} e_e \end{pmatrix}, \quad \mathbf{F^d} = \begin{pmatrix} -\rho_s \mathbf{u_s} \\ \bar{\bar{\tau}} \\ (\bar{\bar{\tau}} \cdot \mathbf{u})^T - \sum_s \rho_s \mathbf{u_s} h_s - \mathbf{q} \\ -\rho_m \mathbf{u}_m h_{v,m} - \mathbf{q}_{v,m} \\ -\sum_s \rho_s \mathbf{u_s} h_{e,s} - \mathbf{q_e} \end{pmatrix}, \quad \mathbf{S} = \begin{pmatrix} \dot{\omega}_s \\ 0 \\ -Q_{rad} \\ \Omega_m^{v,t} + \Omega_m^{v,e} + \Omega_m^{cv} + \Omega_m^{v,v} \\ -p_e \nabla \mathbf{u} + \Omega^{e,t} + \Omega^I - \sum_m \Omega_m^{v,e} - Q_{rad} \end{pmatrix}$$

MUTATION by T. Magin (VKI) & M. Panesi (UIUC), **PLATO** by A. Munafo' (UIUC)

Computation of transport, thermodynamics, chemistry, energy transfer, radiative properties

COOLFluiD Aerothermodynamics

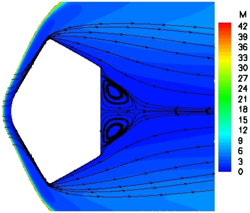
Models, algorithms, aerothermochemical properties are plugins



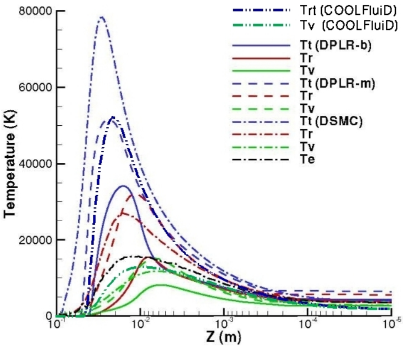
Stardust Sample Return Capsule

- **Air-11**, 2T (T, T_{ve}), $M_\infty = 42$ (Fastest re-entry!)

Stardust capsule after landing



Mach number, FV AUSM+

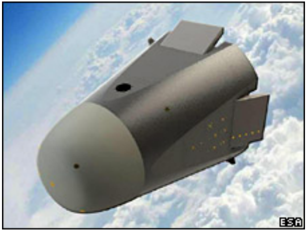


Stagnation temperatures profiles COOLFluiD vs. NASA DPLR

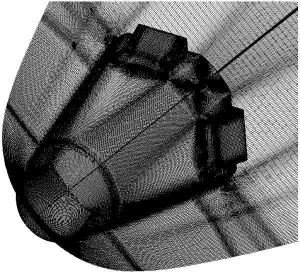
G. Degrez, A. Lani, M. Panesi et al., **J. Phys. D: App. Phys.**, 2009.

ESA EXPERT (EXPErimental Re-entry Test-bed) vehicle

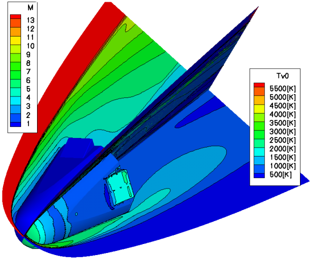
- **Air-5**, 2T (T, T_v), $M_\infty = 13.5$, $\alpha = 0^o$



EXPERT re-entry vehicle: to be launched soon



Computational mesh (3,840,453 hexa)



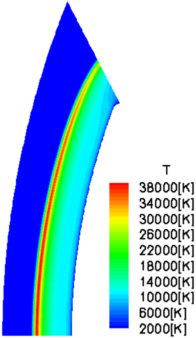
Mach number and T_v FV AUSM+

M. Panesi, A. Lani et al., **AIAA-2007-4317**, 2007.

FIRE II experiment: Collisional Radiative (CR) models

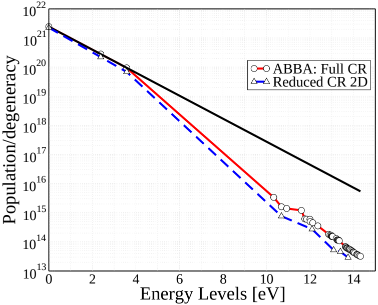
- **Air-11**, 2T (T, T_{ve}), $V_\infty = 11360$ [m/s], $\alpha_{esc} = 0$, t=1634 [s]

FIRE II launch



Roto-translational T
FV AUSM+

ABBA CR-116 (1D) vs CR-18 (2D)



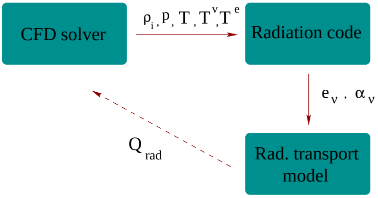
Electronic energy populations for N at 1.0 cm from the shock front

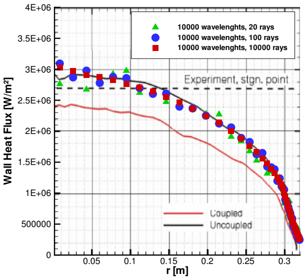
M. Panesi, A. Lani and O. Chazot, **AIAA-2009-3920**.

M. Panesi and A. Lani, **Phys. of Fluids**, 2013.

FIRE II experiment: flow-radiation coupling

- **Air-11**, 2T (T, T_v), $U_\infty = 10480$ [km/s], $T_\infty = 276$ [K], t=1643 [s]





Flow-radiation coupling infrastructure

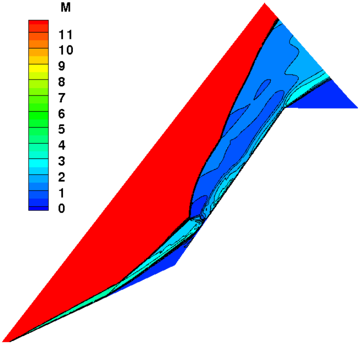
Radiative heat flux (FV + Monte Carlo)

A. Lani, A. Sanna, N. Villedieu, M. Panesi, **WRHTG Barcelona**, 2012.

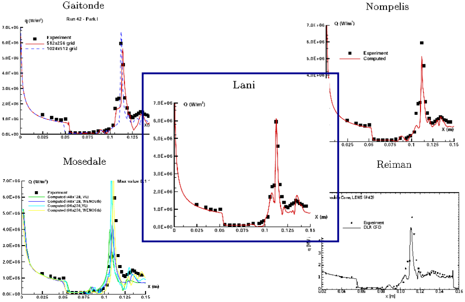
A. Lani, P. Duarte Santos, A. Sanna, **AIAA-2013-2893**, 2013.

NATO STO experiments: double cone flows (AVT 136)

- **Nitrogen-2**, 2T (T, $T^v_{N_2}$), $M_\infty = 11.5$



Mach number field



Surface heat flux measurements: COOLFluiD (CRD-Bx) vs. FV solvers

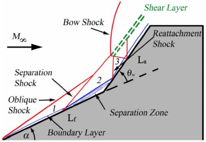
A. Lani and H. Deconinck, **AIAA-2009-460**, 2009.

A. Lani, M. Panesi and H. Deconinck, **J. Comm. Comput. Phys.**, 2013.

D. Knight, J. Longo, D. Drikakis, D. Gaitonde, A. Lani et al., **J. Progr. Aerospace Sciences**, 2012.

NATO STO experiments: double wedge flows (AVT 205)

- **Air**, perfect gas, $M_\infty = 7.11$, unsteady



Wedge configuration

Movie: temperature field

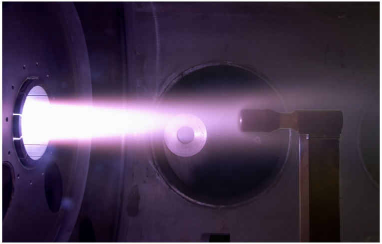
Movie: wall heat flux (CFD vs. experiments at t=0.327 *ms*)

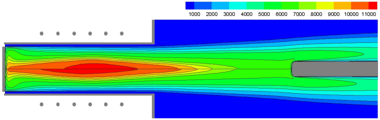
D. Knight, O. Chazot, ..., A. Lani et al., **J. Progr. Aerospace Sciences**, 2017

Inductively Coupled Plasma: testing in VKI Plasmatron

- **Air-11**, LTE, $\dot{m} = 8$ [g/s], $p = 10000$ [Pa], $P = 90$ [kW]

Incompressible subsonic testing

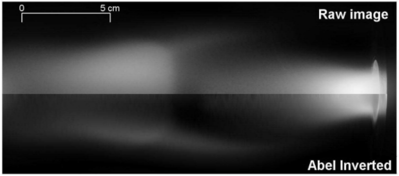


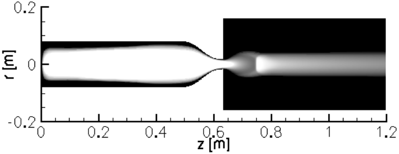


Temperature field (Sartori)

ICP-LTE solver, Rhie-Chow scheme

Incompressible to supersonic testing



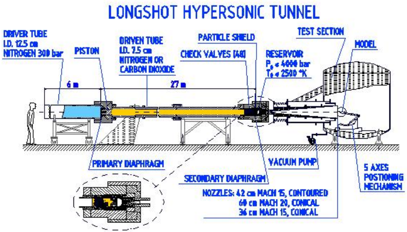


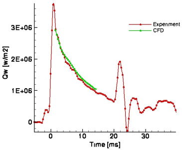
Temperature field (V. Van der Haegen)

ICP-LTE solver, modified AUSM+up scheme

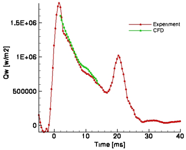
Expanding hypersonic flows: VKI Longshot facility

- **Nitrogen**, $P_0 = 3256.22$ [Pa], $T_0 = 2652.1$ [K]





High Reynolds number.



Low Reynolds number.

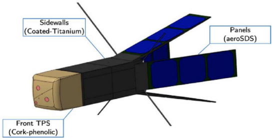
Stagnation heat flux: experiments vs. CFD

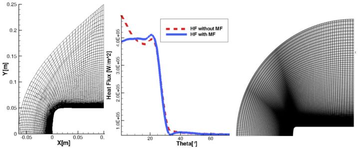
Movie: expansion in nozzle up to M=14
Pressure, 3-point Backward Euler, FV Roe
(courtesy of **K. Bensassi**)

K. Bensassi, A. Lani et al., **AIAA-2011-3886**, **AIAA-2010-4857**, **AIAA-2012-3265**, **AIAA-2013-2694**.

QARMAN Cubesat for Aerothermodynamics research

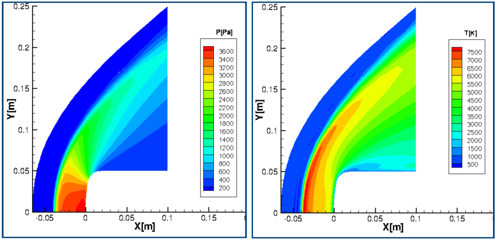
- **Air-5**, 2T (T, T_v), $M_\infty = 8.46$, steady (**PhD F. Ben Ameur**)





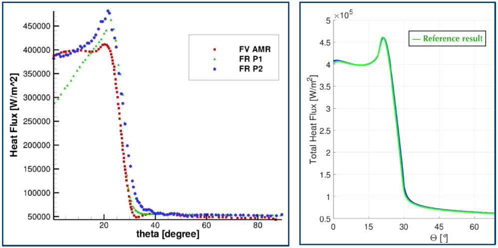
Effect of AMR (r-adaptation) on heat flux

First high-order FR results with thermo-chemical NEQ (**AIAA 2019-1391**) $\Longrightarrow$



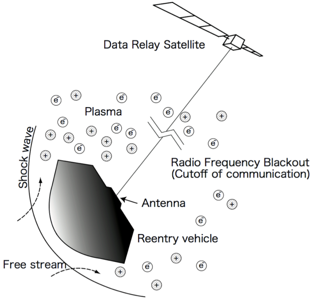
⇑ Pressure, temperature field for P2-Q2 FR

⇓ Surface heat fluxes in FV AMR and FR (P1, P2) vs reference



Radio blackout during re-entry (PhD V. Giangaspero)

Hypersonic speed→High temperature→Gas ionizations→Plasma Layer→RF Blackout



Re-entry plasma
Ionized charged particles

↓

Ionization level
Electron number density

↓

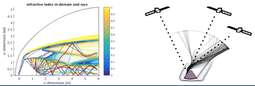
Plasma Frequency f_p
Natural frequency of plasma

↓

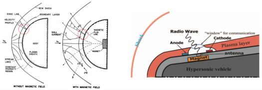
Blackout Condition
$f_p > f_{radio}$

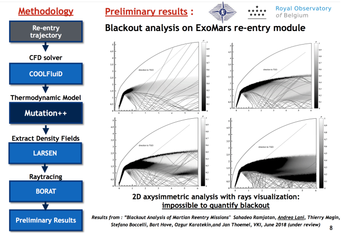
3

Improve prediction of radio blackout by use of raytracing



Investigate electromagnetic mitigation based on plasma flow control





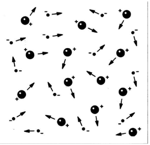
Magnetized plasma modeling

CmPA core research: Space Weather modeling

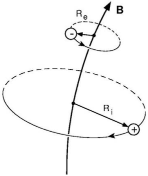
Space weather events: from Sun to Earth, from CME to aurora borealis (courtesy from NASA)

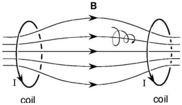
Magnetized plasmas modeling: from kinetic to single-fluid

Plasma is a mixture of **charged particles** (ions and electrons) and **neutrals** that is affected by **external magnetic fields**



plasma





Magnetized plasma models

KINETIC THEORY	MULTI-FLUID THEORY	ONE-FLUID THEORY
✓ Molecular scale resolution	✓ Collisional and chemical effects	✗ No microphysics effects
✗ Computationally too costly for full scale representation	✓ Full-Scale phenomena representation	✓ Full-Scale phenomena representation

Multi-fluid magnetized plasma (PhD A. Alvarez Laguna)

Each **species** α (ions, electrons, neutrals) has **its speed & temperature**

Fluid dynamics

$$\frac{\partial \mathbf{U}}{\partial \mathbf{P}}\frac{\partial \mathbf{P}}{\partial t} + \nabla\cdot\mathbf{F}^c = \nabla\cdot\mathbf{F}^d + \mathbf{S}$$

$$\mathbf{U} = [\rho_\alpha \quad \rho_\alpha\mathbf{u}_\alpha \quad \rho_\alpha E_\alpha]^T, \quad \mathbf{P} = [\rho_\alpha \quad \mathbf{u}_\alpha \quad T_\alpha]^T$$

$$\mathbf{F^c} = \begin{pmatrix} \rho_\alpha\mathbf{u}_\alpha \\ \rho_\alpha\mathbf{u}_\alpha\mathbf{u}_\alpha + p_\alpha\hat{I} \\ \rho_\alpha\mathbf{u}_\alpha H_\alpha \end{pmatrix}, \quad \mathbf{F^d} = \begin{pmatrix} 0 \\ \bar{\bar{\tau}}_\alpha \\ (\bar{\bar{\tau}}_\alpha\cdot\mathbf{u}_\alpha)^T - \mathbf{q}_\alpha \end{pmatrix}$$

$$\mathbf{S} = \begin{pmatrix} \dot{m}_\alpha \\ Q_\alpha\vec{E} + \vec{j}_\alpha\times\vec{B} + \sum_{\beta\neq\alpha}\vec{R}_\alpha^{\alpha\beta} \\ \vec{j}_\alpha\cdot\vec{E} + \sum_{\beta\neq\alpha}\vec{R}_\alpha^{\alpha\beta}\cdot\mathbf{u}_\alpha + \sum_{\beta\neq\alpha}H_\alpha^{\alpha\beta} + \dot{Q}_\alpha \end{pmatrix}$$

Collisional terms

Maxwell-Fluid coupling terms

Chemical reactions terms (e.g. ionization, recombination, charge exchange)

Maxwell + HDC

$$\frac{\partial\vec{B}}{\partial t} + \nabla\times\vec{E} + \gamma\nabla\psi = 0$$

$$\frac{\partial\vec{E}}{\partial t} - c^2\nabla\times\vec{B} + \chi\, c^2\nabla\phi = -\frac{\vec{j}}{\epsilon_0}$$

$$\frac{\partial\psi}{\partial t} + \gamma c^2\nabla\cdot\vec{B} = 0$$

$$\frac{\partial\phi}{\partial t} + \chi\nabla\cdot\vec{E} = \chi\frac{\rho_c}{\epsilon_0}$$

- Two scalar fields ϕ and ψ
- Artificial waves at χc and γc clean divergence errors

A. A. Laguna et al, **J. Comput. Phys.**, 2016.

Solar wind/Earth magnetosphere interaction (unsteady)

06/04/00 magnetic storm, input based on the ACE satellite data

Movies: proton density, *B* lines and physics-based mesh r-adaptation

Time-accurate parallel implicit FVM-MHD solver (also GPU-enabled)

Integrated into the ESA **Virtual Space Weather Modeling Center**

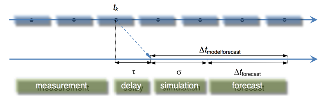
A. Lani, M. S. Yalim and S. Poedts, **Comp. Phys. Comm.**, 2014.

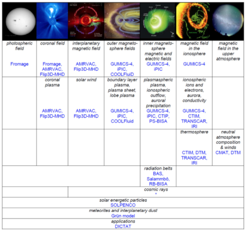
ESA Virtual Space Weather Modeling Center (VSWMC)

Collaborators: **SAS**, **KUL**, **DH Consultancy**, **BIRA**, **ROB**, **British Antartic Survey**

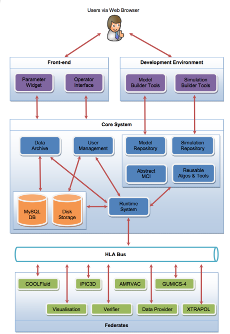
Ambitious long term goals (EU equivalent of US SWMF, NASA CCMC)

- integrate and couple together all European assets for real-time Sun-to-Earth SW forecasts
- mitigate impacts of SW events possibly affecting space operations, power systems, health...





European Space Weather models overview

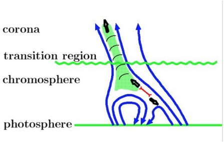


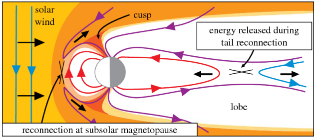
Current components of the VSWMC system

I am involved as **co-designer of the core software infrastructure** & **SW model developer**

Two-fluid simulations of Magnetic Reconnection (MR)

Ubiquitous process transforming magnetic energy into thermal & kinetic energy





$\Uparrow$ Schematics of **MR in chromosphere**

$\Downarrow$ Current sheet + B lines (plasma-neutral model)

A. A. Laguna et al., **ApJ**, 2018

$\Uparrow$ Schematics of **MR in magnetotail** (GEM)

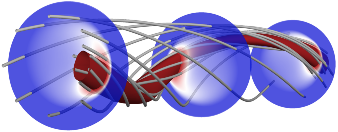
$\Downarrow$ e^- momentum (ion-electron model, **GPU-enabled**)

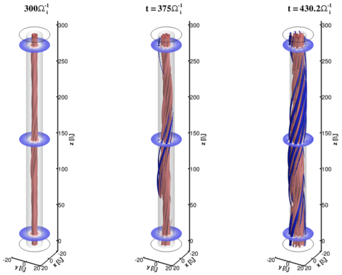
I. Alonso et al., **Comp. Phys. Comm.**, 2019

Fusion: characterization of instabilities in screw pinch

by **A. A. Laguna**, **N. Ozak**, **Prof. G. Lapenta**

Screw pinch simulation in Tokamak: plasma column compressed by helical magnetic field





Electric current (red) showing kink instability

Development status & perspectives

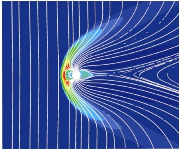
COOLFluiD highlights

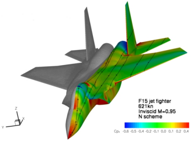
- Arguably the most advanced open source software platform for ATD and plasma modeling
- Parallel solvers taking profit of massive heterogeneus HPC on multi-CPUs/GPUs
- Thermochemical nonequilibrium models for characterizing ATD flows
- Pioneering multi-fluid/Maxwell models for characterizing space physics
- Advanced tools for radiation transport characterization
- Plasma/radiation solvers to study very fast re-entry of natural/artificial objects

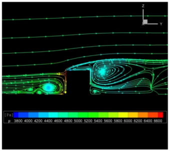
Ongoing and target research

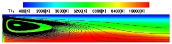
- Data-driven global coronal models starting from magnetogram data (AFOSR Postdoc)
- Multi-fluid modeling of wave propagation from photosphere to corona (FWO Postdoc)
- Coupling of ATD and plasma solvers to radiation transport algorithms
- UQ of magnetic reconnection in magnetospheric conditions (FWO PhD)
- Development of high-order solvers for ATD and hypersonic transition (FWO PhD)
- Radio blackout analysis and mitigation via magnetic windows (FWO PhD)
- Exploiting heterogeneus HPC (CPU/GPU) towards exascale simulations
- Development of r- and p-adaptive FR algorithms

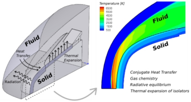
Thank you all for the attention!

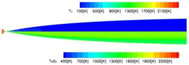


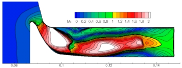












https://github.com/andrealani/COOLFluiD/wiki