C I R A

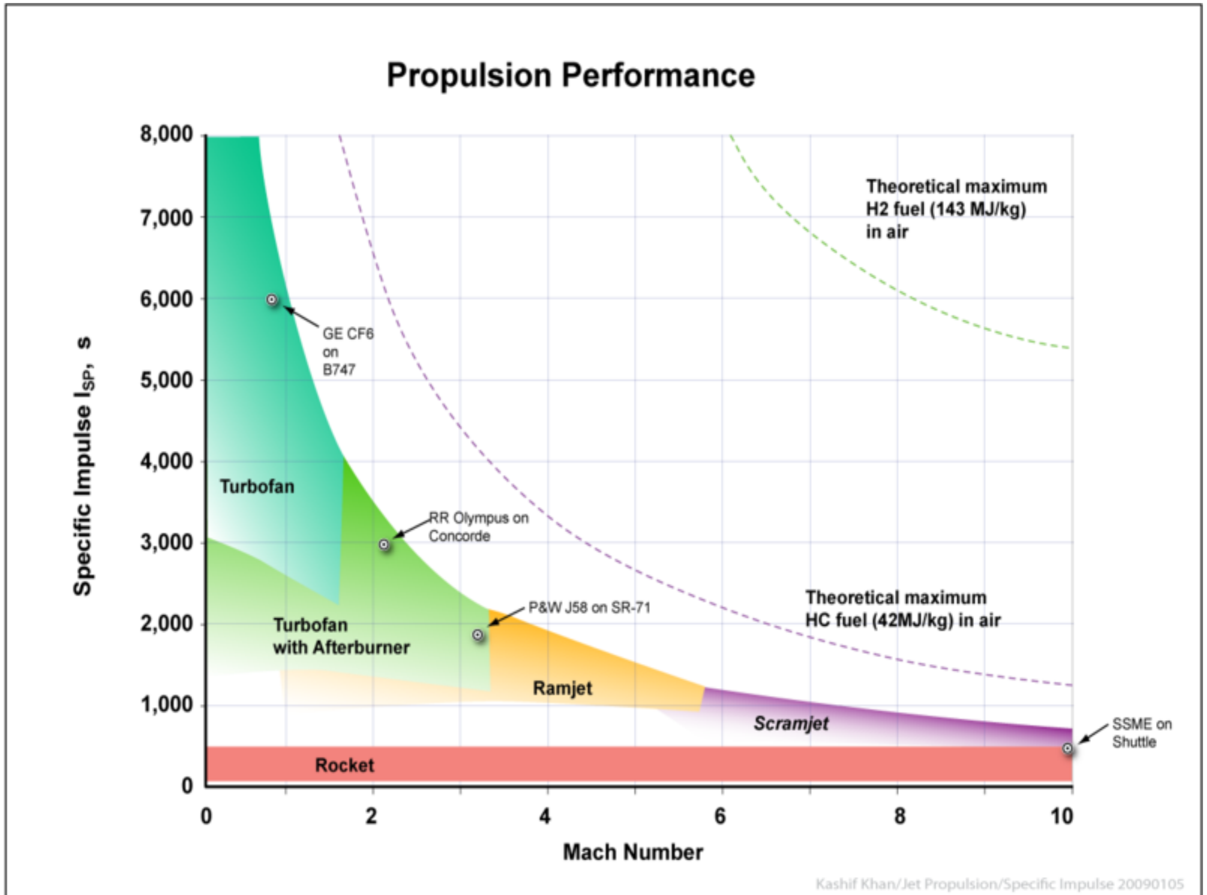
Italian Aerospace Research Centre

PROPULSION DIVISION

PROPULSION SYSTEMS FOR HYPERSONIC VEHICLES

SALVATORE BORRELLI

High-Speed Airbreathing Propulsion: Motivations

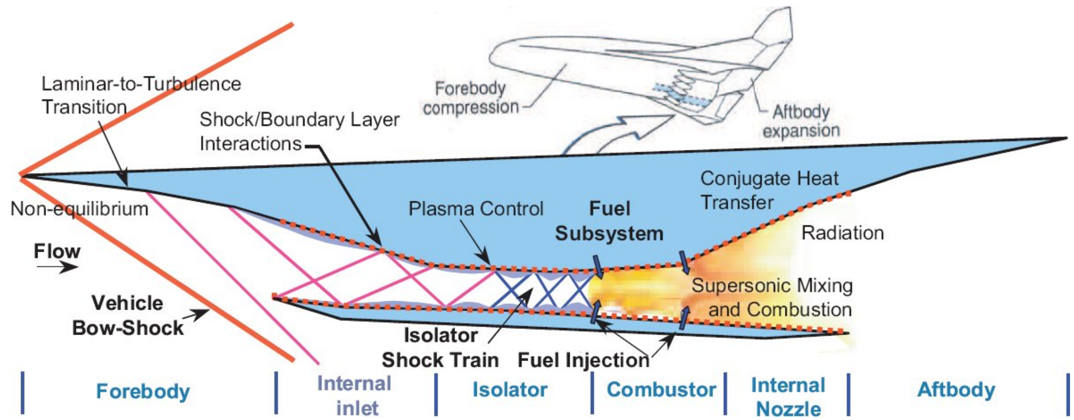


$$I_s = \frac{F}{g_0 \dot{m}_f}$$ (Specific Impulse)

- Mission requirements define the most suitable propulsion system
- Airbreathing engines use atmospheric oxygen for combustion thus allowing for weight and volume reduction and specific impulse increase w.r.t. rockets
- The operative envelope is reduced w.r.t. rockets since the engine functioning strongly depends on Mach number
- For hypersonic flight (M>5) the most efficient airbreathing engine is the scramjet

High-Speed Airbreathing Propulsion: Advantages and Drawbacks

- ✓ Aircraft engines: it reduces the time for long flights
- ✓ Weapon systems: it increases the range and reduces time-to-target
- ✓ Launchers: it reduces the fraction of the weight of the propulsion system



Scramjet Engine

Mandatory Hypotheses

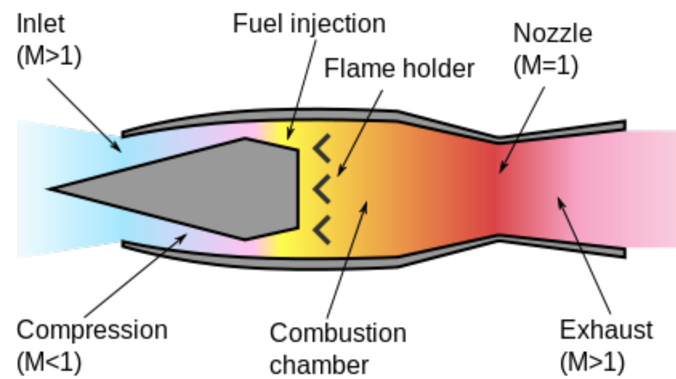
- ✓ Airframe-engine integration
- ✓ Optimized combustor and injection strategy/layout

Advantages

- ✓ Mechanical simplicity
- ✓ High propulsive efficiency
- ✓ Wide Mach number range: $2 < M < 6÷8$

Drawbacks

- ✓ High thermal loads for combustor and nozzle
- ✓ Needs to adjust intake and/or nozzle geometry to the different flight conditions



Ramjet Engine

Main Interests

- ✓ Create an Italian competency into an innovative research field with great opportunities for both civilian and military applications
- ✓ Participate to European future experimental flight campaigns to forward advanced technologies requests at the Italian manufacturing industry

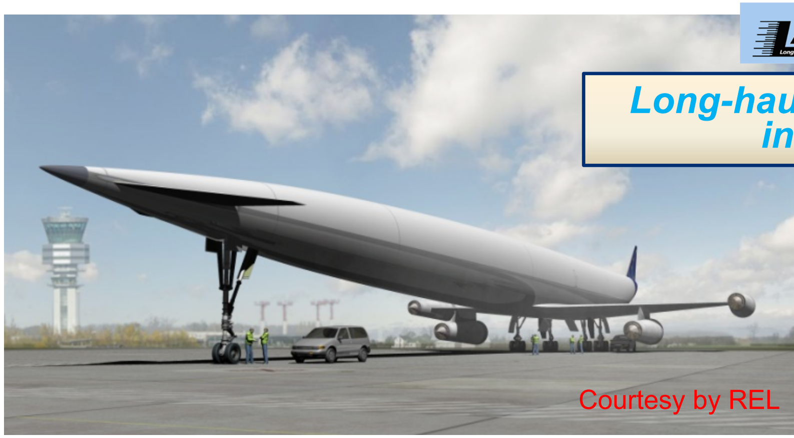
Activities

- Design of airbreathing propulsive system components (intake, combustor, nozzle)
- Aero-propulsive database of hypersonic propelled vehicles
- Flight experiment of a scramjet engine mounted on a hypersonic vehicle
- Scramjet propulsive system of a hypersonic tactical missile
- MHD bypass for a scramjet engine
- Ramjet Testing facility

Hypersonic Vehicles with Ram/Scramjet Propulsion

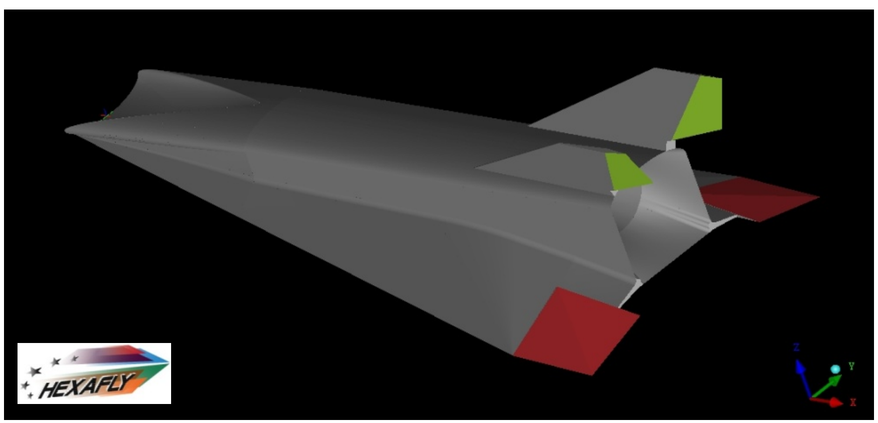
LAPCAT II

Long-haul routes (EU-AUS) in 2÷4 hours

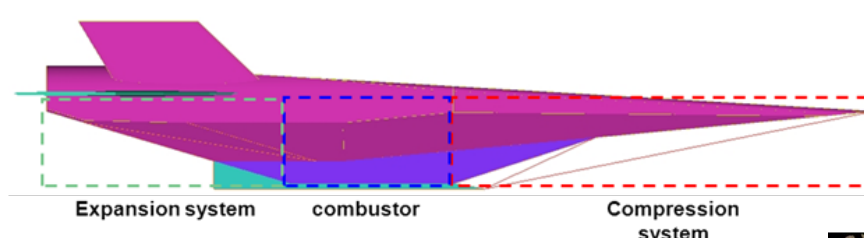


LAPCAT A2 vehicle for passenger transportation (300 PAX, cruise at Mach 5, 25.4 km altitude)

LAPCAT MR2.4 vehicle for passenger transportation (300 PAX, cruise at Mach 8, 32÷33 km altitude)



HEXAFLY scramjet propulsion flight experiment (3m vehicle, cruise at Mach 7.4, 28÷33 km altitude)

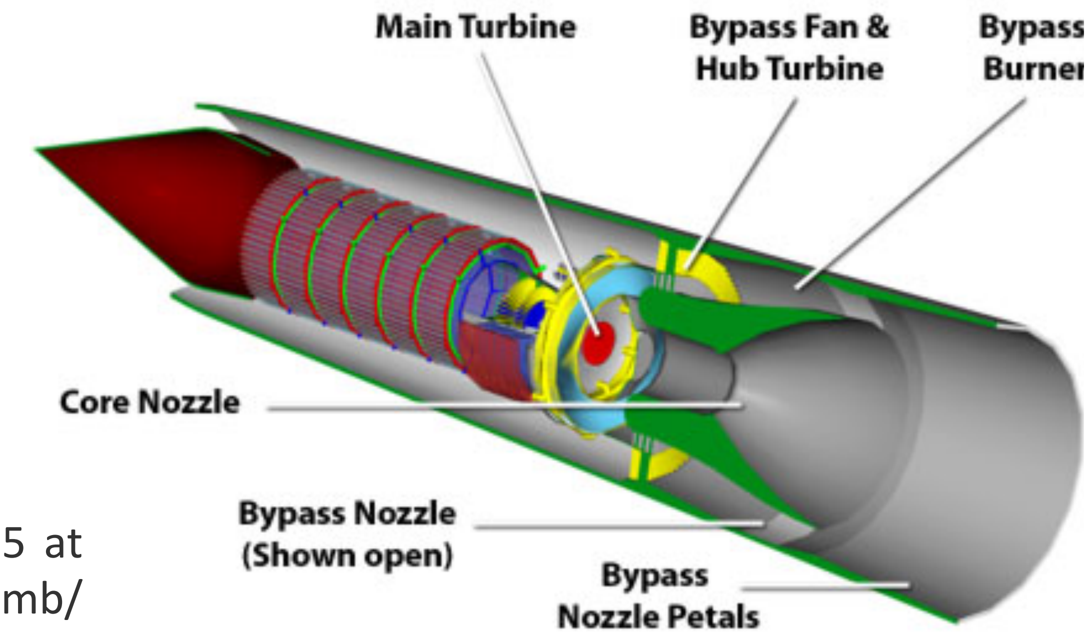


HYTAM feasibility study of scramjet propelled hypersonic tactical missile (4.5m vehicle, cruise at Mach 7.5, 30 km altitude, time-to-target=460s for 1000 km)

Ramjet Propulsion: design of Mach 5 ramjet engine components

- CFD support to the detailed design of main components (intake, combustor, nozzle) of the LAPCAT A2 Mach 5 cruiser pre-cooled turbofan/ramjet engine
- CFD support to wind tunnel test campaigns

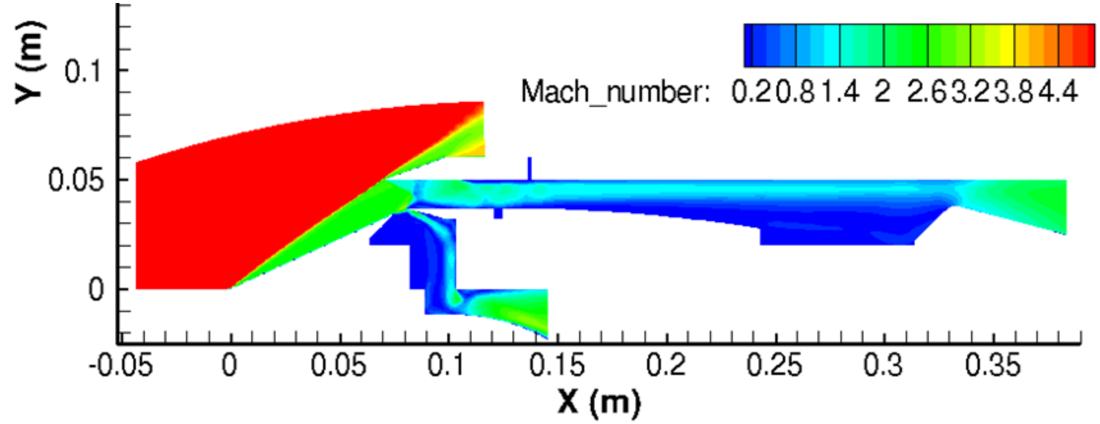
- Cruise condition: Mach Number 5 at an altitude of 25.4 km (end of climb/ acceleration cruise condition)

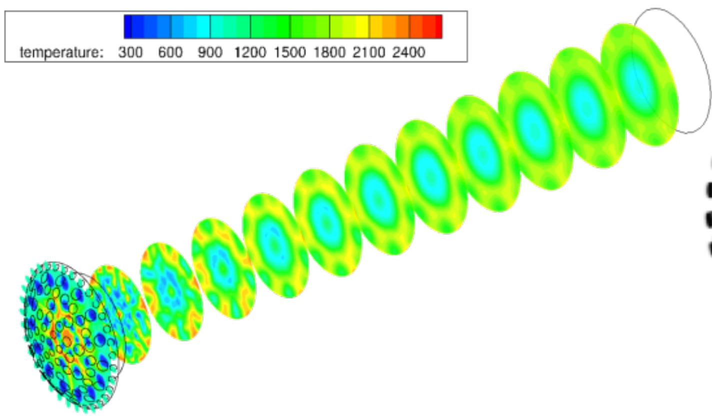


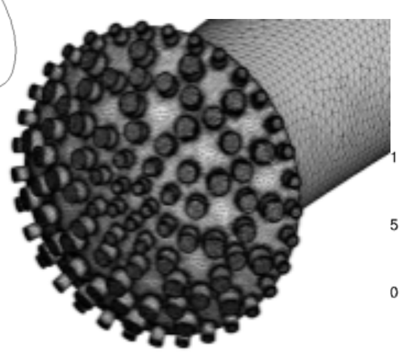
Courtesy by REL

Ramjet Propulsion: design of Mach 5 ramjet engine components

- Intake: pressure recovery factor, shock at throat, flow uniformity and unsteadiness in the diffuser, boundary layer effects, massflow bleed
- support to design and analysis of performance of GDL model







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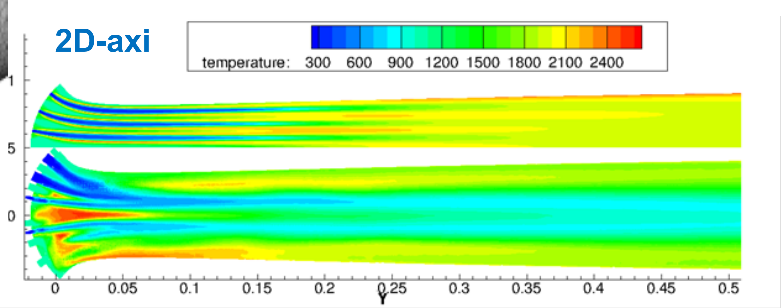


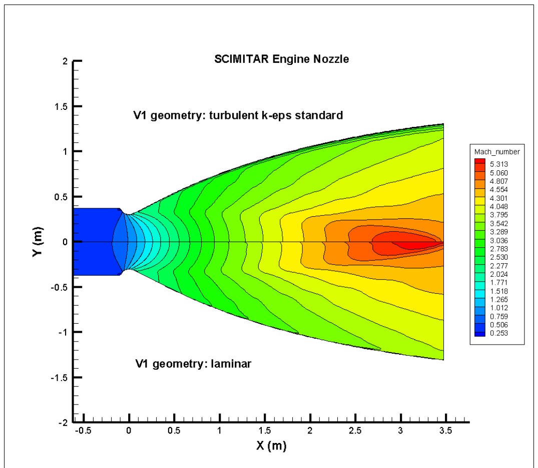
3D

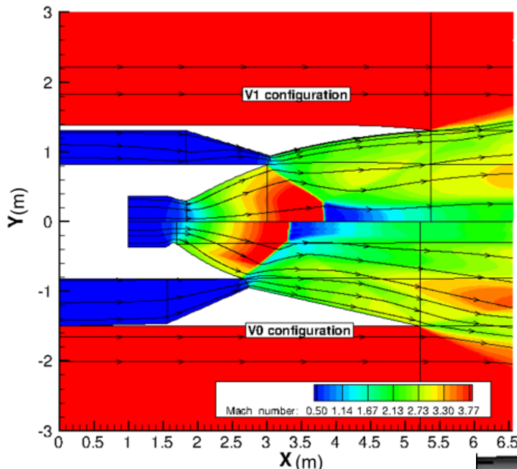
- Combustor: injection, mixing, combustion, EINO, H_2O, unburned H_2

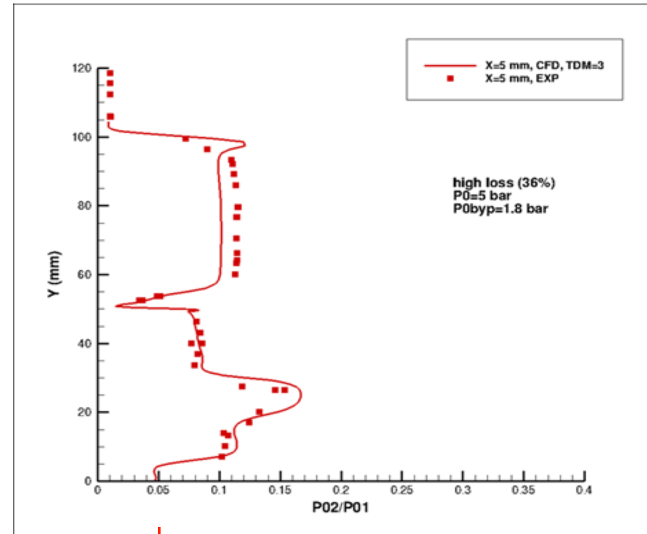
Ramjet Propulsion: design of Mach 5 ramjet engine components

LAPCAT II Long-term Advanced Propulsion Concepts And Technologies II

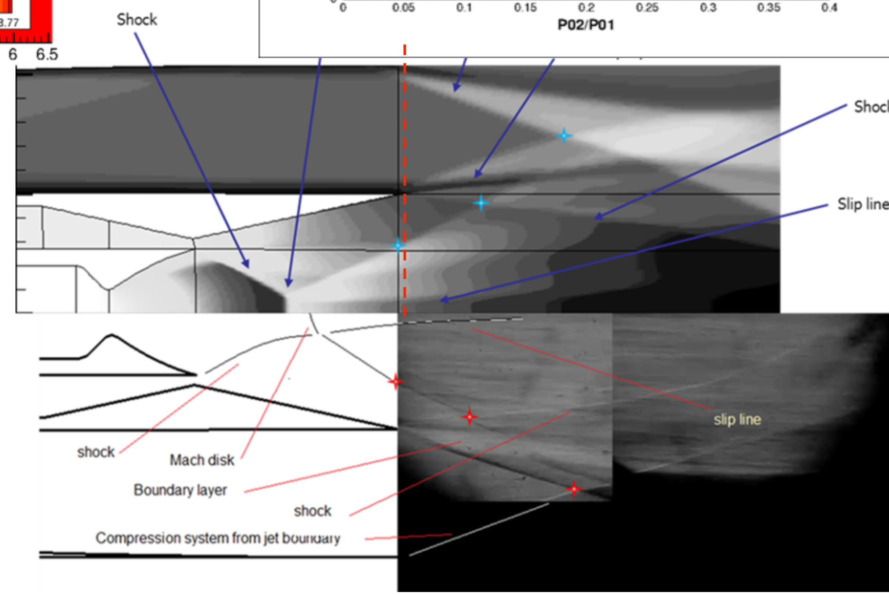
- Nozzle: flow uniformity, thrust, EINO, H_2O, unburned H_2







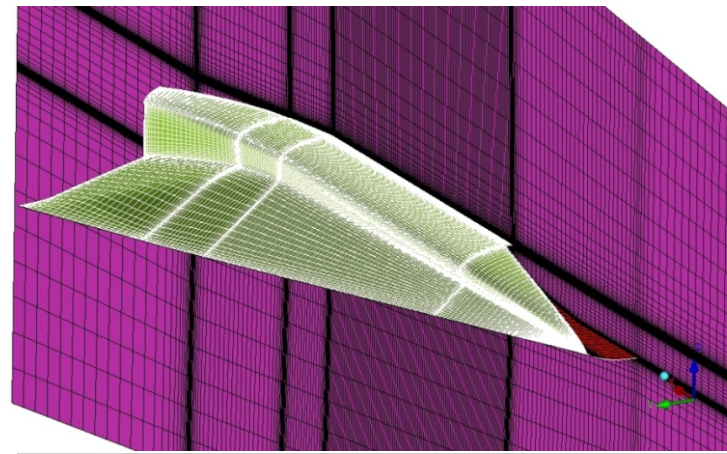
- Nozzle: analysis of plume/external flow interaction, configuration trade-off study, performance prediction, bypass and core nozzles detailed internal fluid dynamics
- Nozzle: CFD analysis and rebuilding of propulsive nozzle experiment at GDL



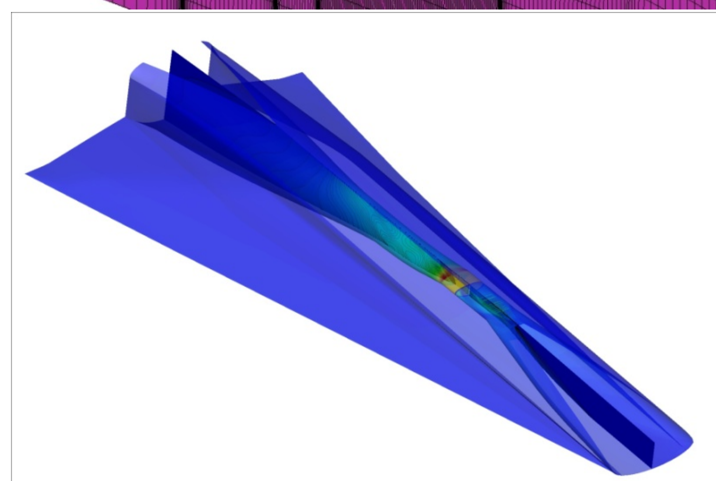
Scramjet Propulsion: Analysis of a Mach 8 concept vehicle

- Nose-to-Tail simulation of a full-scale vehicle by using a CFD 3D code for both internal (scramjet operating mode) and external flow

Courtesy by ESA/ESTEC



- Cruise condition: Mach Number 8 at an altitude of 32÷33 km
- Grid: 3.5 million cells, 174 blocks
- Detailed CFD analysis of the vehicle
  - ✓ Grid sensitivity analysis (3 levels)
  - ✓ Combustion chemistry model sensitivity
  - ✓ Analysis of local phenomena inside the scramjet path

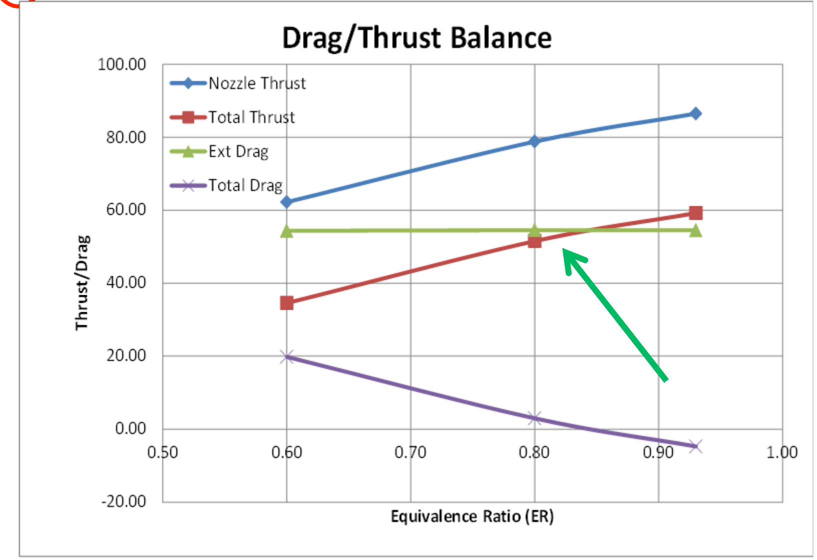


Scramjet Propulsion: Analysis of a Mach 8 concept vehicle

- Aero-propulsive balance of the scramjet vehicle in fuel-off and fuel-on conditions: the balance is positive (D_{prop}<0) for laminar and turbulent hypothesis in fuel-on conditions

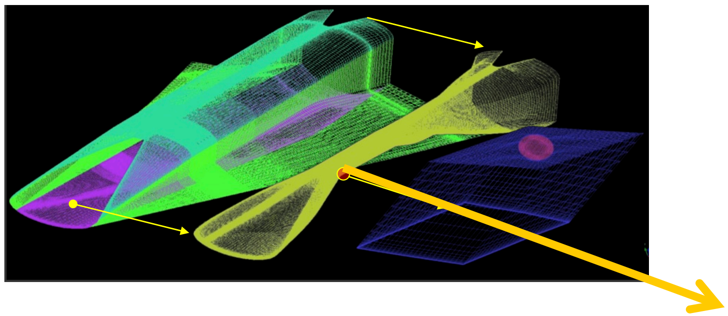
Grid level	Engine state	Flow regime	L	D_{tot} (ext + int)	D_{body} (ext)	D_{prop} (int)	D_{intake}	D_{cc}	D_{nozzle}	Eff Aer
[-]	[-]	[-]	[tons]	[tons]	[tons]	[tons]	[tons]	[tons]	[tons]	[-]
L_3	ON	LAM	**347.81**	**-26.88**	**34.08**	**-60.95**	18.01	1.44	-80.41	10.21
L_3	ON	TURB k-e	**341.69**	**-17.25**	**37.23**	**-54.49**	20.62	3.41	-78.51	9.18
L_3	ON	TURB-SA	**347.12**	**11.82**	**58.78**	**-46.96**	23.79	4.47	-75.21	5.91
L_3	ON	TURB-SA0	**343.76**	**4.48**	**52.11**	**-47.63**	22.87	4.32	-74.81	6.60

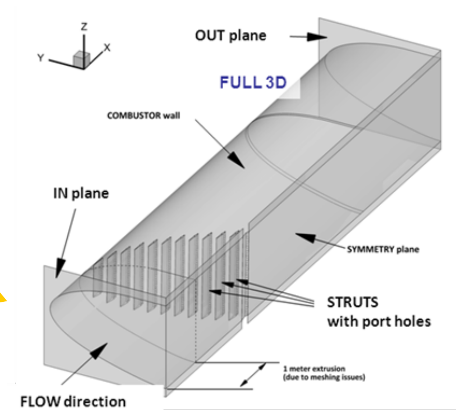
- Contribution to aero-propulsive database of the vehicle
- Aerodynamic performance at the cruise conditions (L≥W, T≥D)
- Lift-to-drag ratio (external) around 6 for more reliable CFD simulations
- Sensitivity analysis to find the exact value of ER assuring aero-propulsive balance (T≥D) necessary for cruise (T=D for ER ≈ 0.84)



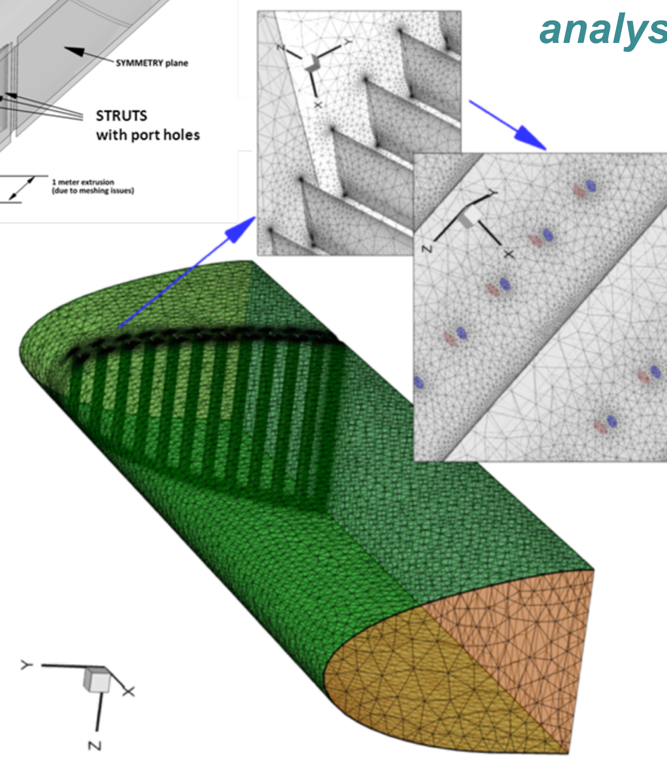
Scramjet Propulsion: Analysis of a Mach 8 concept vehicle

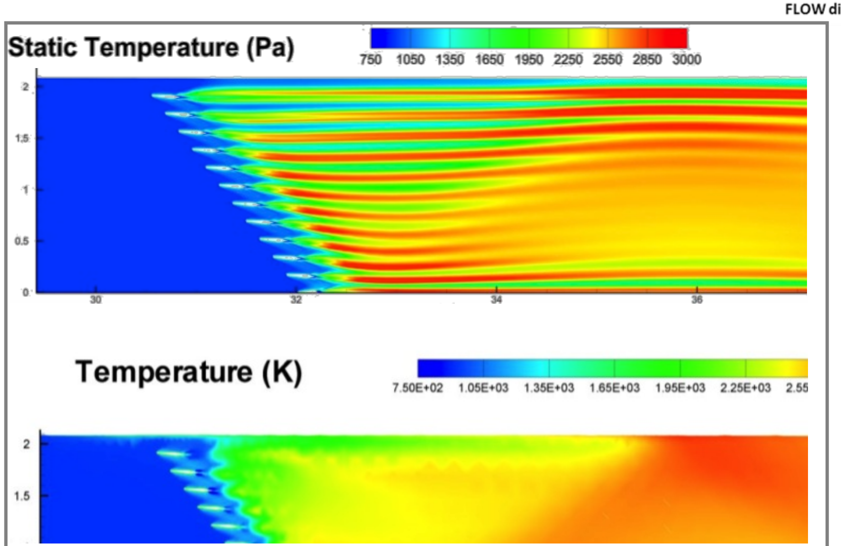
- 2D and simplified (slices instead of port holes) 3D geometry: structured mesh
- 3D detailed geometry: unstructured mesh (11M cells) and use of FLUENT v13





LAPCAT MR2.4 combustor 3D detailed analysis





Scramjet Propulsion: Analysis of a Mach 8 concept vehicle

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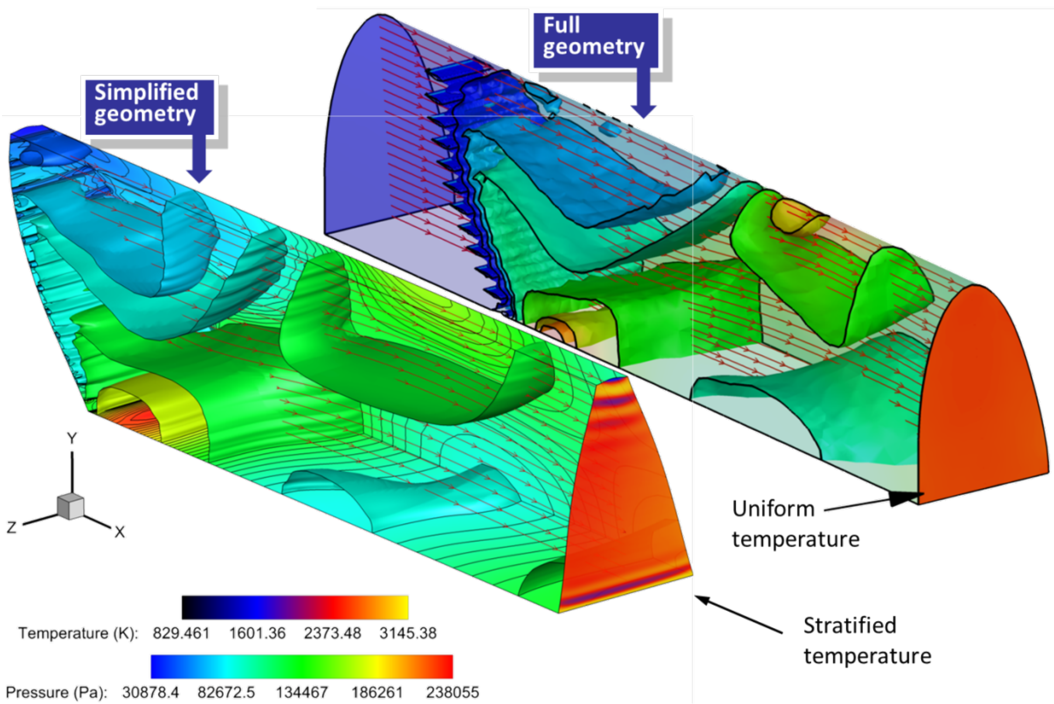
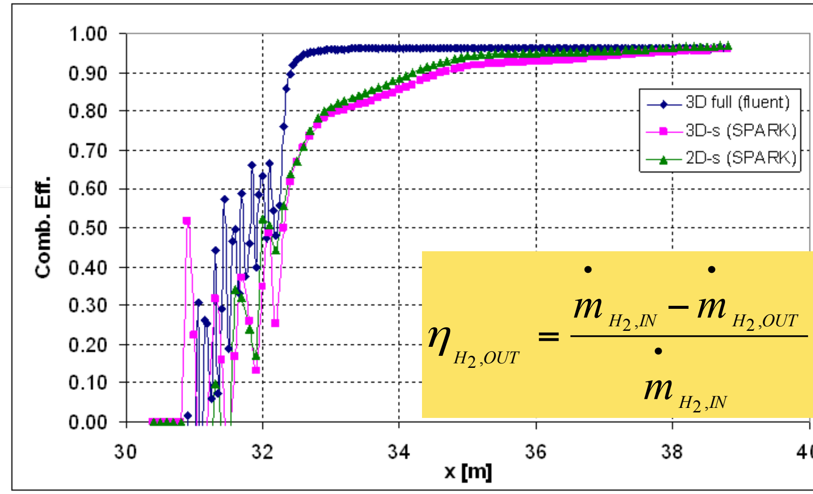
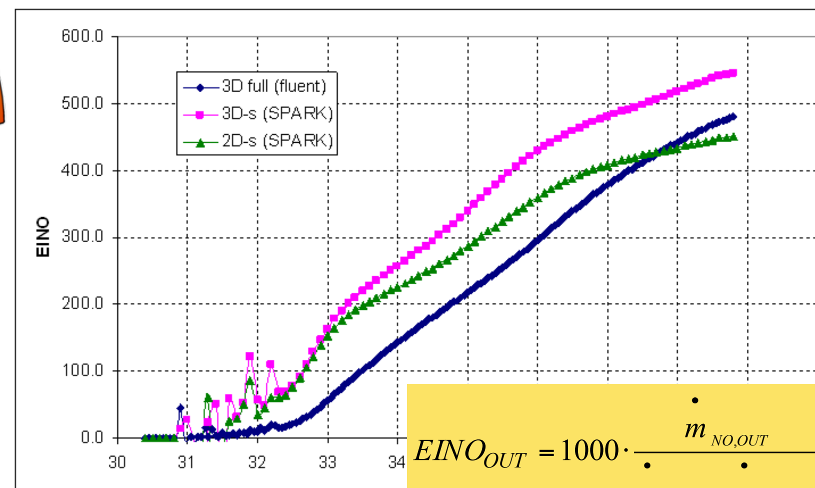
Pressure iso-surfaces





$$\eta_{H_2,OUT} = \frac{\dot{m}_{H_2,IN} - \dot{m}_{H_2,OUT}}{\dot{m}_{H_2,IN}}$$



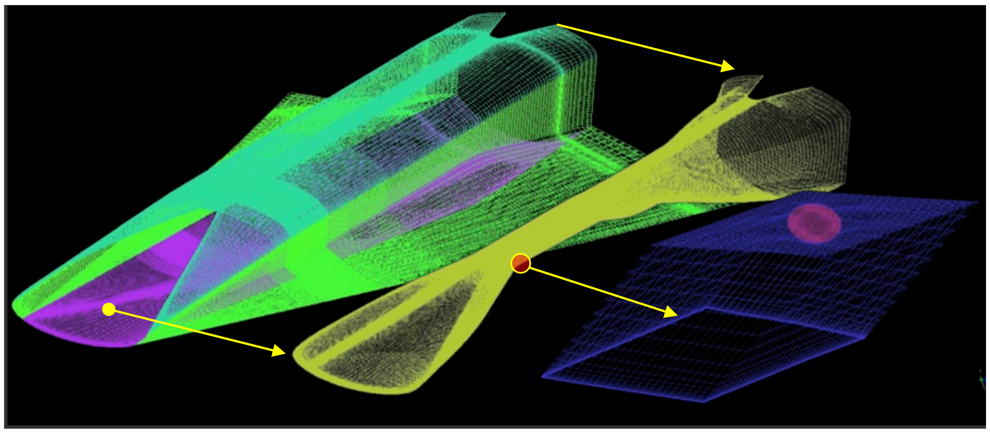
$$EINO_{OUT} = 1000 \cdot \frac{\dot{m}_{NO,OUT}}{\dot{m}_{H_2,IN} - \dot{m}_{H_2,OUT}}$$

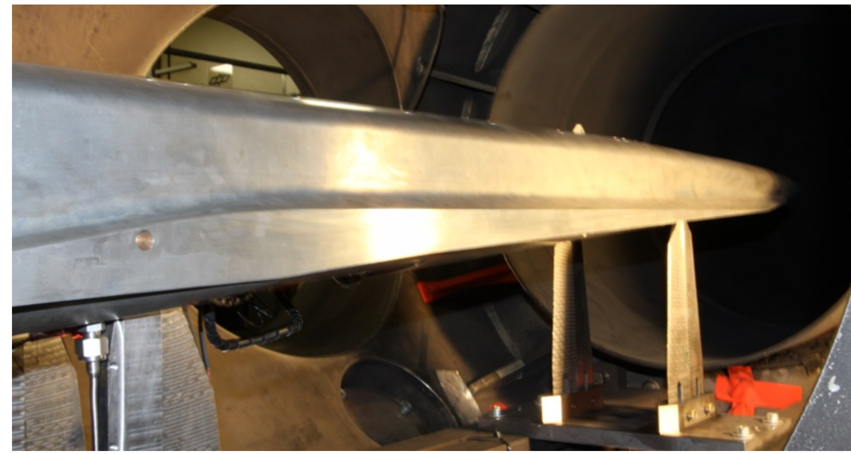
LAPCAT MR2.4 combustor 3D detailed analysis

Scramjet Propulsion: Analysis of a Mach 8 concept vehicle in WT

APCAT II
Long-term Advanced Propulsion Concepts And Technologies II

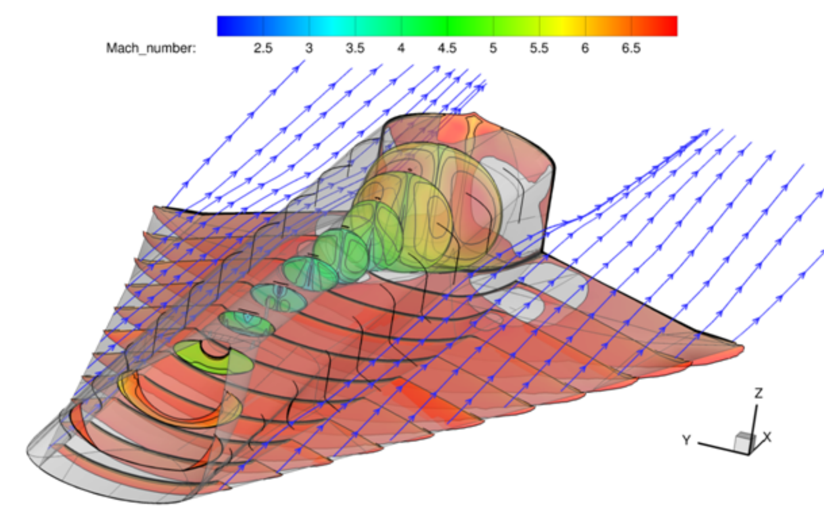
- CFD support to experimental test campaigns (small scale, L=1.44 m)



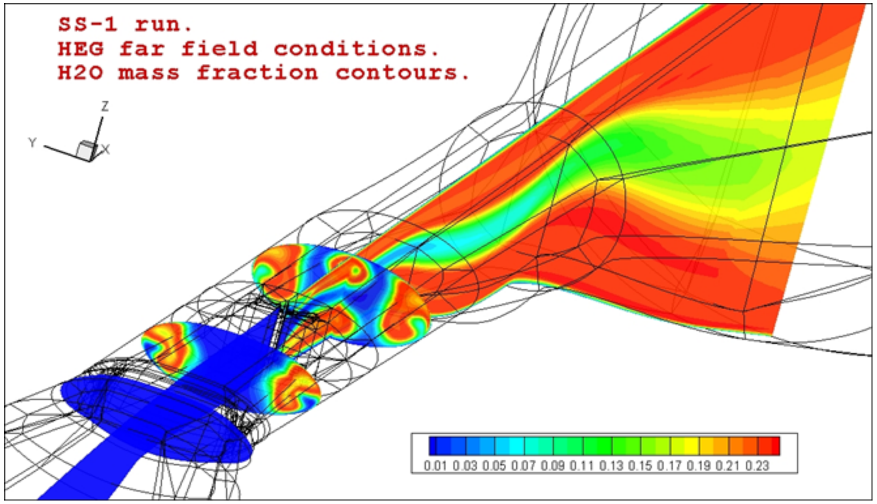


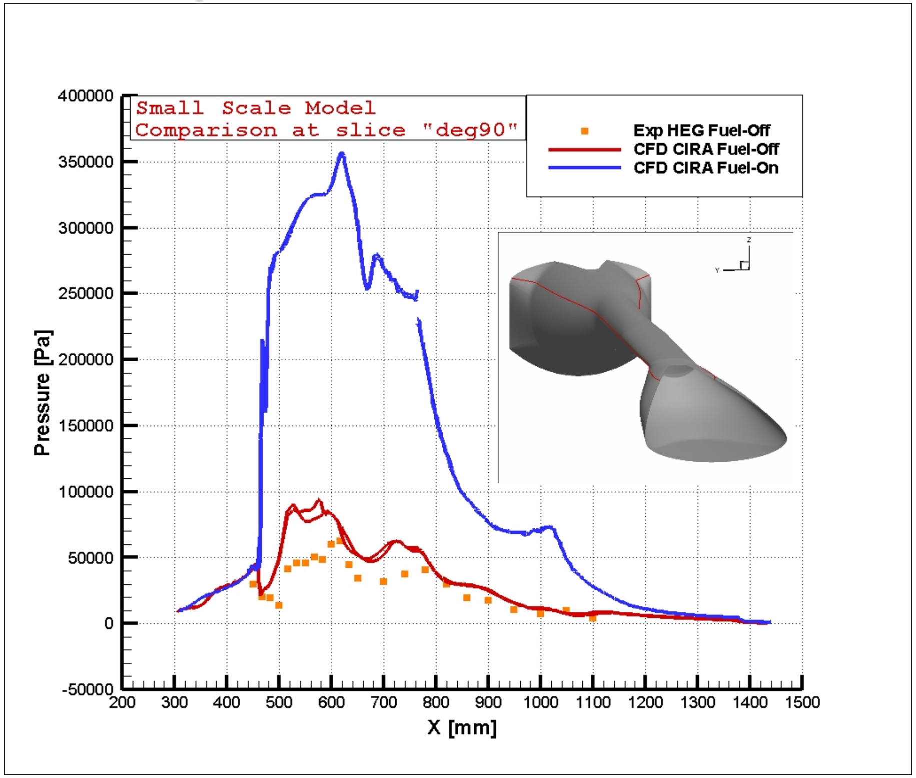
- 11M cells structured grid (use of SPARK code)
- **DLR HEG** test chamber flow conditions
- Inviscid and viscous flow simulations
- Fuel-on

P_∞ = 2051,18 Pa
M_∞ = 7,355
ρ_∞ = 0,02717 kg/m^3
T_{wall}= 300 K
Standard air model provided



Scramjet Propulsion: Analysis of a Mach 8 concept vehicle in WT





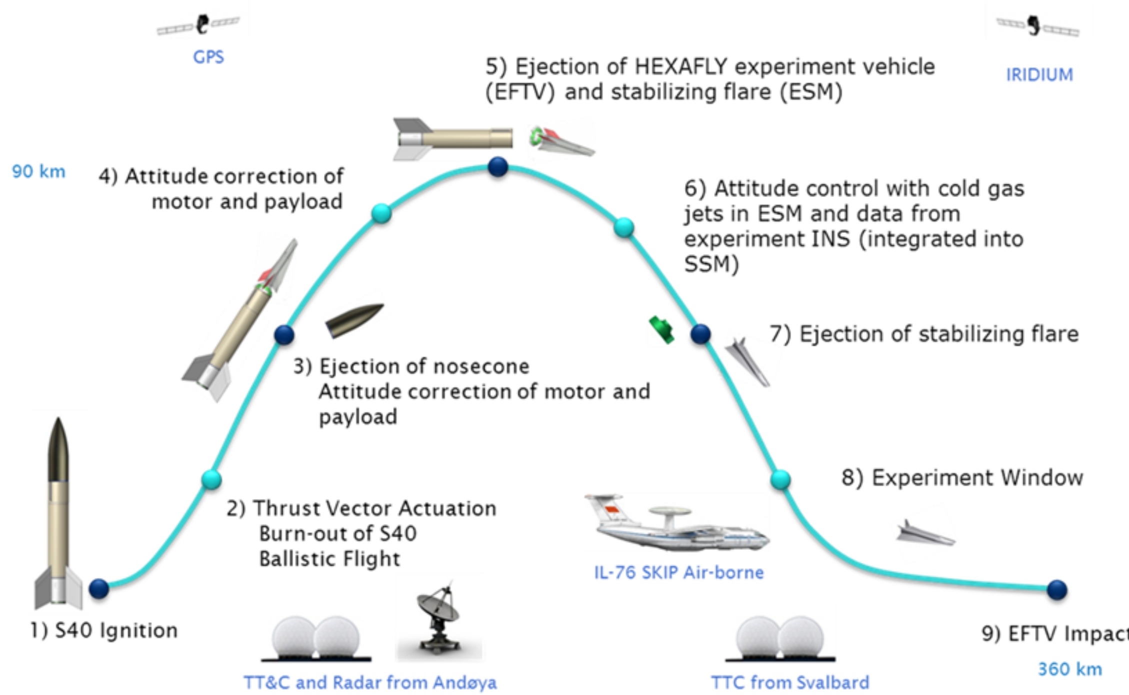
- Split approach for viscous simulations
- Good evaluation of aero-propulsive balance (comparison with experiments)

Test	Regime	Dtot	Dext	Dint	Doff - Don
[-]	[-]	[N]	[N]	[N]	[N]
CFD CIRA	OFF	592.00	380.00	213.00	NA
CFD CIRA	ON	189.00	380.00	-191.00	NA
CFD CIRA					**404.00**
CFD DLR					**436.00**
EXP HEG					**525.00**

	Eff.	EINO
EUL	58.92	27.34
NS	90.78	24.03

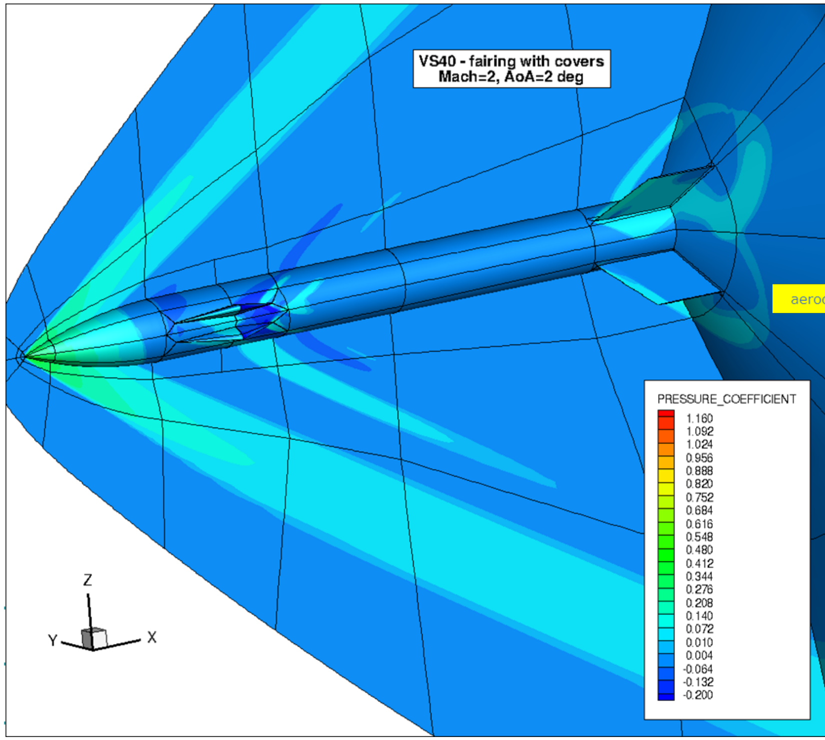
Scramjet Propulsion: Flight experiment of a scramjet propulsion system

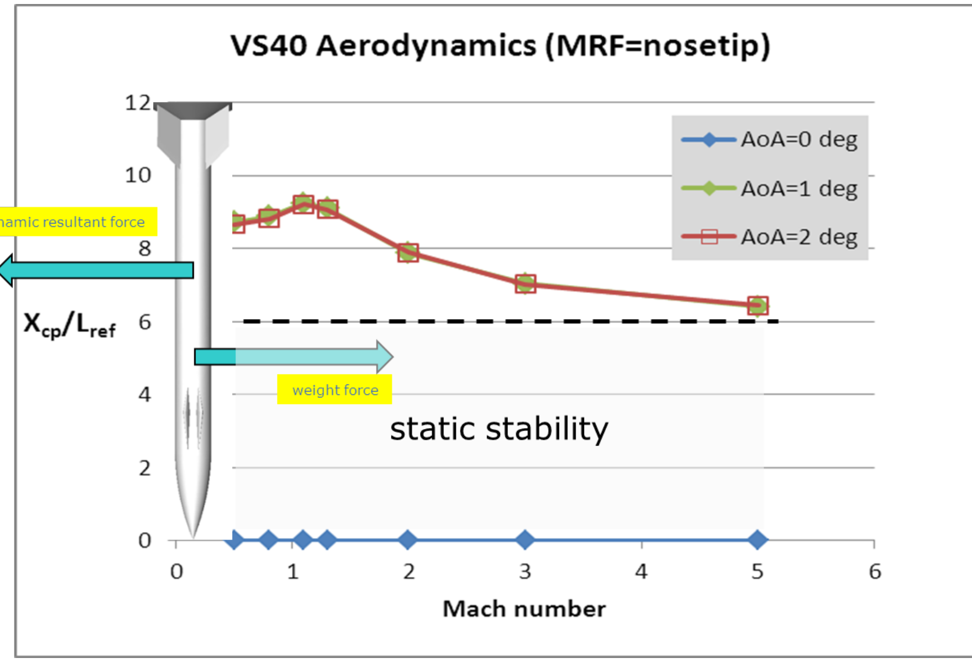
- ❑ Contribution to the development of the scramjet vehicle, launch vehicle and mission
- ❑ Aero-propulsive characterization of different scramjet vehicle configurations, setup and analysis of AEDB in nominal propelled flight condition
- ❑ Sizing of ailerons (shape, span, length) and vertical tail (shape, size, toe-angle)
- ❑ Analysis of longitudinal trimming conditions
- ❑ Assessment of static stability analysis in clean and trimmed configuration
- ❑ Assessment of dynamic stability analysis with a focus on Dutch-Roll
- ❑ Flight Control equipment
  - ✓ Inertial Measurement Unit
  - ✓ Magnetometer
  - ✓ Flight Control Computer
  - ✓ Aileron servo-actuators
  - ✓ Aileron actuation lane

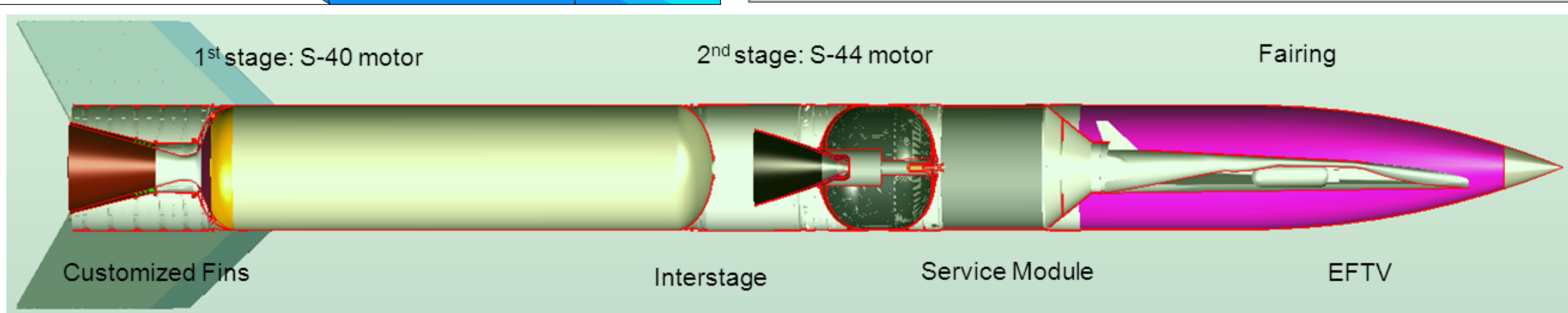


Scramjet Propulsion: Flight experiment of a scramjet propulsion system

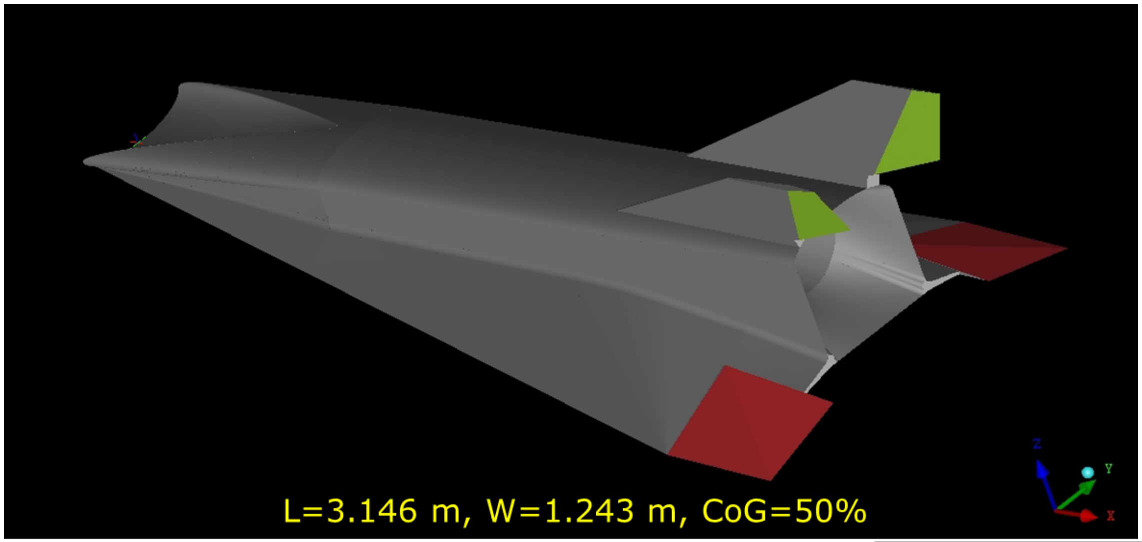
HEXAFLY

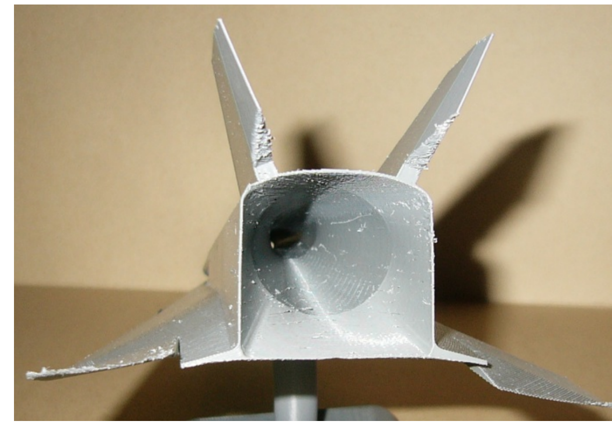






Scramjet Propulsion: Flight experiment of a scramjet propulsion system





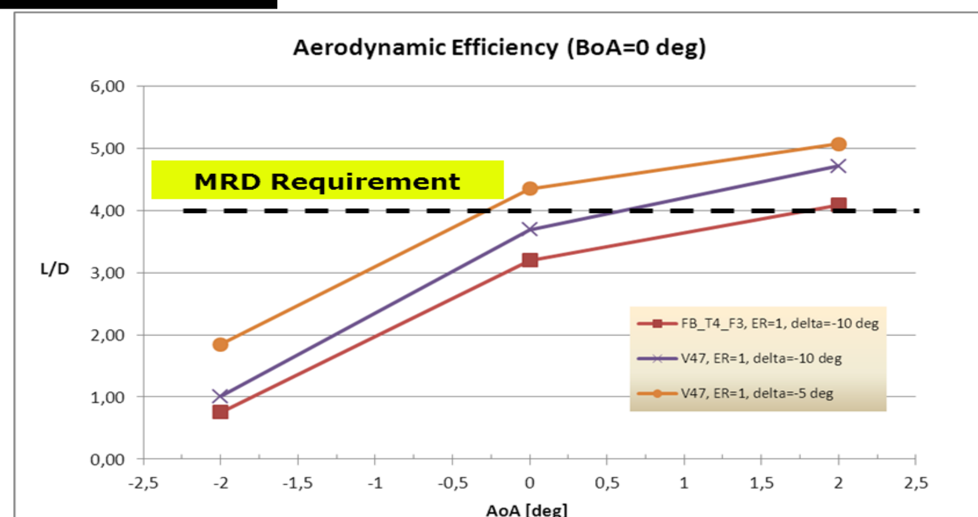
Experimental Flight Test Vehicle

Vehicle's length 3 m

Flight speed M=7.4

Altitude 28÷33 km

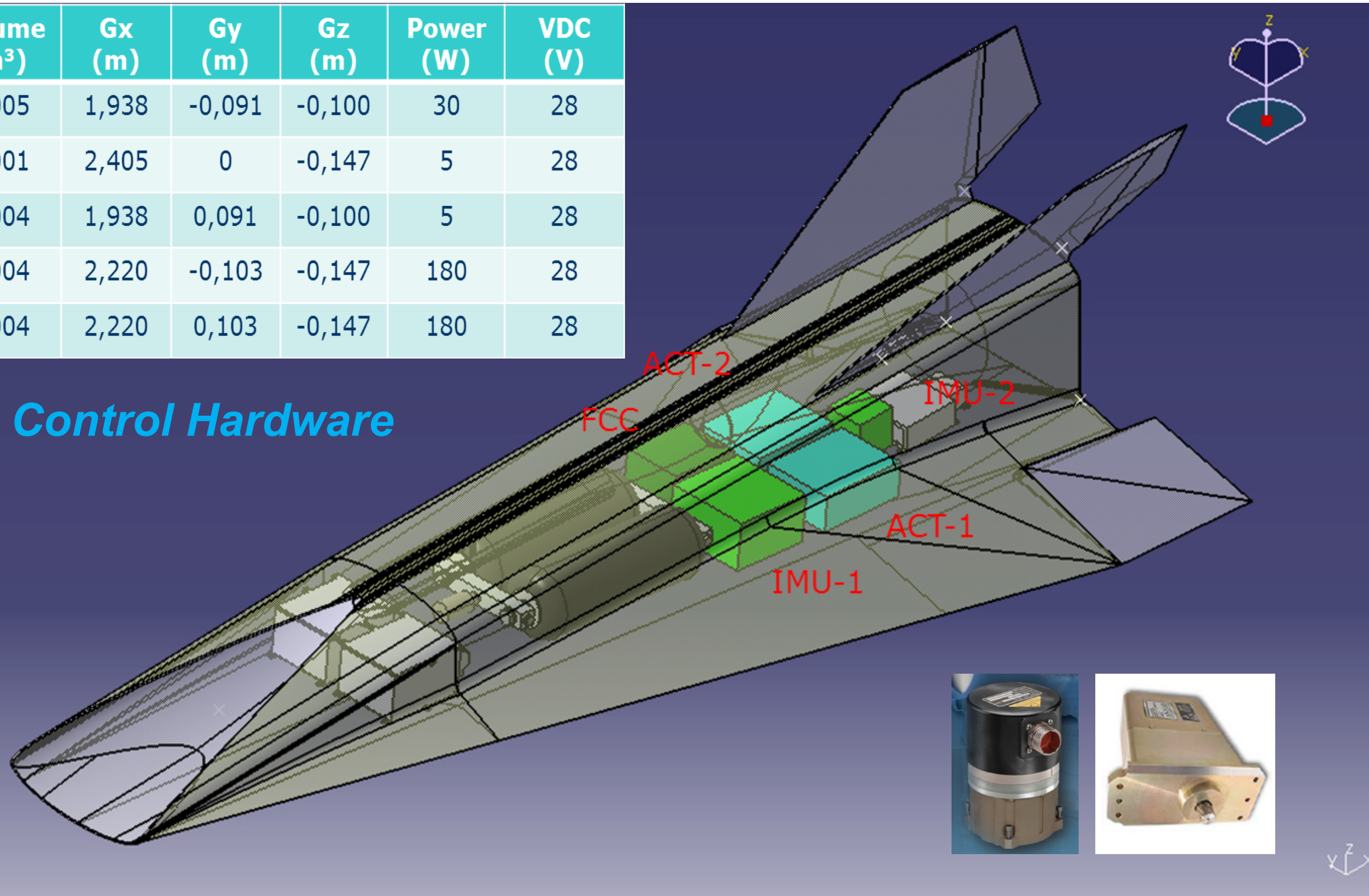
Scramjet operation 10÷15 sec



Scramjet Propulsion: Flight experiment of a scramjet propulsion system

#	Part name	Mass (kg)	Volume (m³)	Gx (m)	Gy (m)	Gz (m)	Power (W)	VDC (V)
1	IMU-1	2	0,005	1,938	-0,091	-0,100	30	28
2	IMU-2	0,5	0,001	2,405	0	-0,147	5	28
3	FCC	2	0,004	1,938	0,091	-0,100	5	28
4	Act. Moog 1	4,6	0,004	2,220	-0,103	-0,147	180	28
5	Act. Moog 2	4,6	0,004	2,220	0,103	-0,147	180	28

EFTV Flight Control Hardware

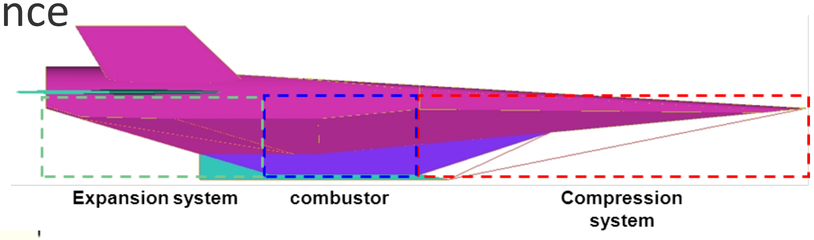


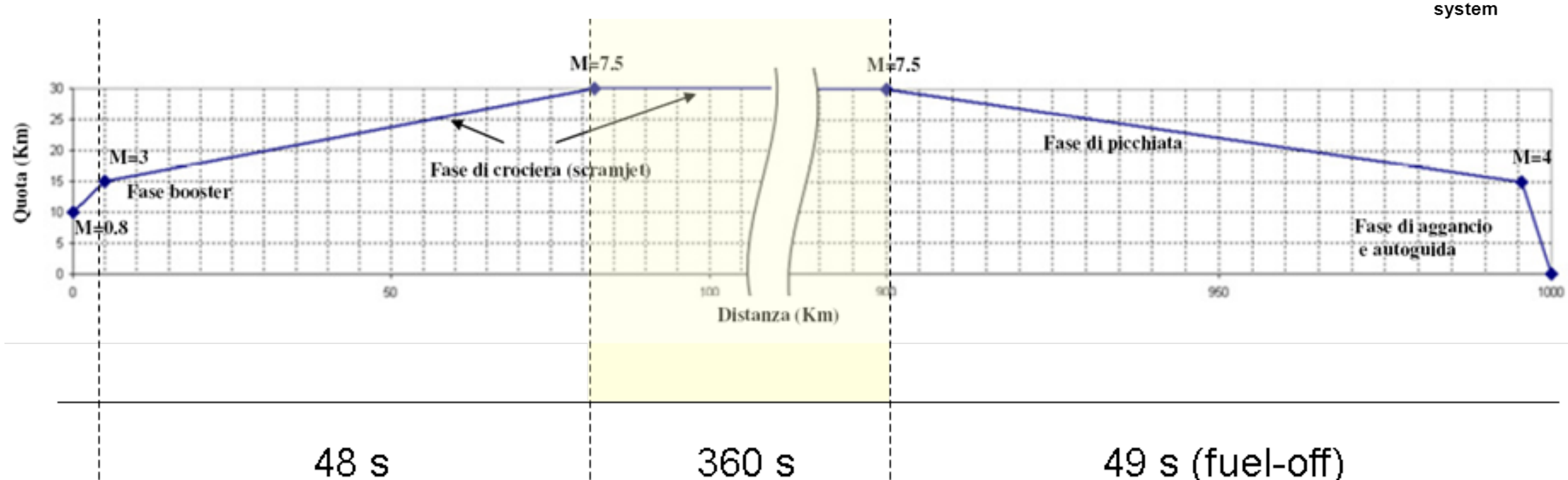
Scramjet Propulsion: Design of propulsive system of a hypersonic tactical missile (HYTAM)

- ❑ Preliminary design of a scramjet propulsive system (by using an engineering tool and simplified CFD) to match mission requirements
- ❑ Air/H_2 combustion with 1-D SPREAD code (detailed kinetic scheme by Jachimowski)
- ❑ Critical issues: mixing of reactants, injection modalities, ignition delay, combustion development and stability, thruster performance

Design cruise conditions: H=30 Km; M=7,5

Fuel=LH$_2$ ($P_{storage}$=3,5 bar; $T_{storage}$=20K; ρ_{LH2}=70 Kg/m^3)

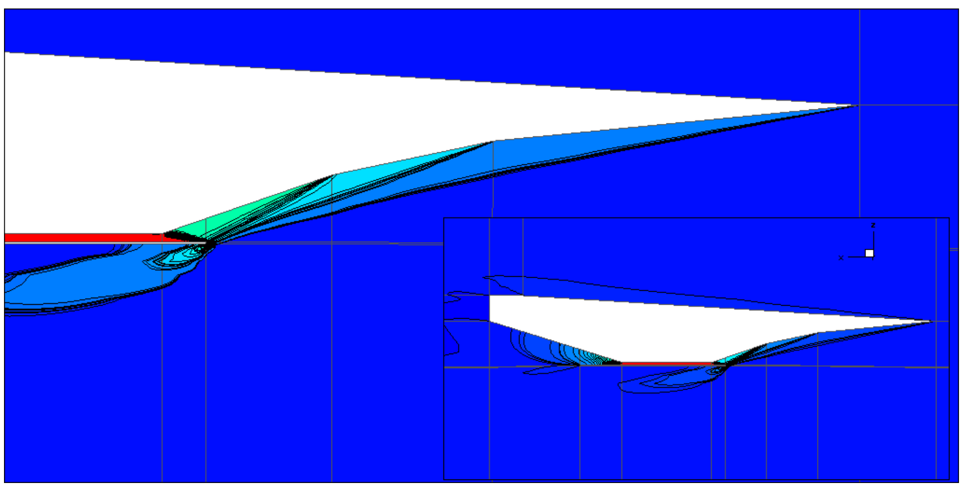


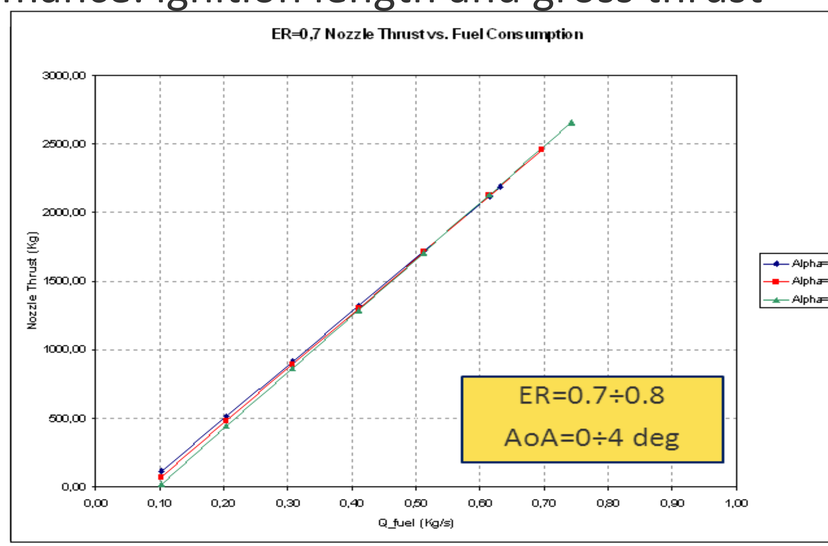


Scramjet Propulsion: Design of propulsive system of a hypersonic tactical missile (HYTAM)

- Multi-ramp inlet to achieve P and T values to properly ignite combustion
- Effects of P and T on ignition delay
- To limit combustion chamber size the optimum fuel is LH_2
- Need for a strong fuselage/propulsive system integration: aerothermodynamics and propulsion disciplines are not separable
- Sizing of scramjet propulsive system and performance: ignition length and gross thrust

Property	Kerosene	CH4	H2
Heat of combustion (MJ/Kg)	44	55	118,1
Specific heat Cp at 300 K(KJ/Kg/K)	2,01	2,24	14,3
Liquid density (Kg/m^3)	800	422	70
Boiling temperature at 1 atm (K)	420	112	20



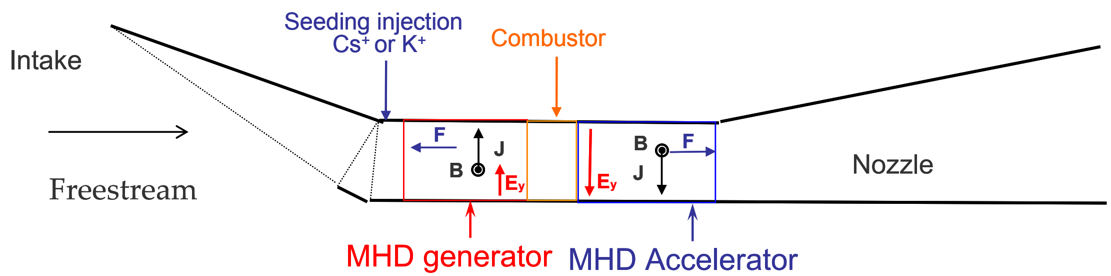


$$T = \dot{m}_{air}\left(V_e - V_i\right) + \dot{m}_f V_e + S_e\left(P_e - P_\infty\right) - S_i P_i$$

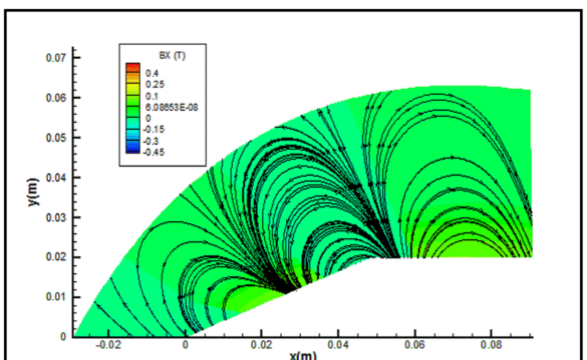
Scramjet Propulsion: MHD Bypass technique

A strategy to improve scramjet performances is the **MHD bypass technique** proposed in the past by Bruno, Park et al.

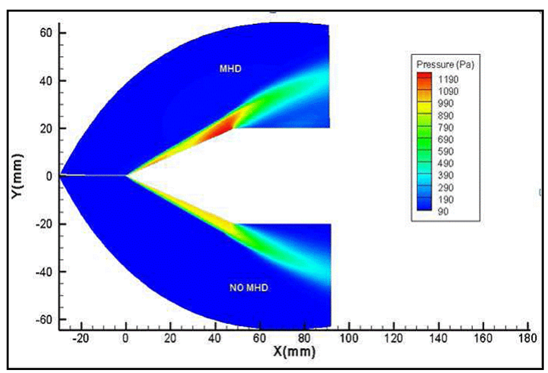
Operation principles:



- **MHD generator** slows down the flow to the desiderated value of M, and recovers energy (E_y/uB<1)
- **MHD accelerator** after combustion accelerate the flow throughout **F** ponder-motive force. (E_y/uB>1)



Magnetic field generated by permanent magnets in a sharp body (by EMC3NS)



Effect of the magnetic field on the pressure distribution over the sharp body (by EMC3NS)

- The seeding injection system (Cs+ or K+) gives to the flow a certain value of electrical conductivity.

Scramjet Propulsion: MHD Bypass technique

<u>Advantages</u> :

- Increase of combustion efficiency and stability with a more compact design of the scramjet propulsive system (i.e. limit the combustion chamber size)
- With an efficient electric accumulator and a good ionization level (5%) is possible to gain thrust throughout the accelerator
- Under inviscid hypothesis, from preliminary calculations (by assuming a 60% generator efficiency) it has been estimated a gain in terms of total force with MHD bypass

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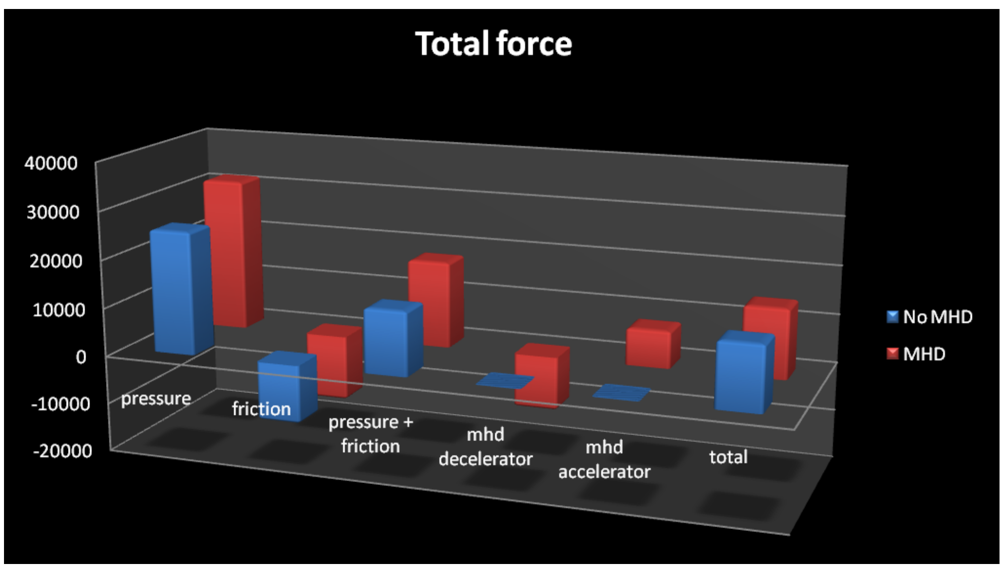


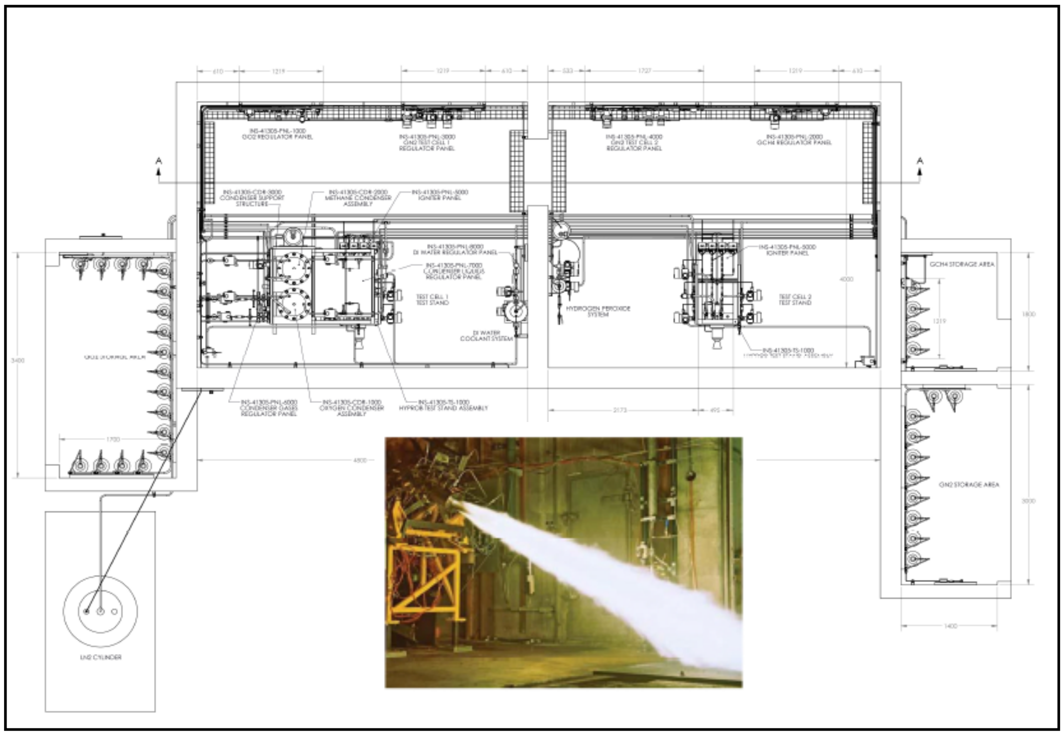
<u>Drawbacks</u> :

- Off-design conditions difficult to be handled
- MHD generator efficiency is a critical issue to guarantee an effective gain on thruster performance
- Feasibility of high-efficiency MHD generator not still been proven
- Increase of aerodynamic drag ?
- Necessity of means to handle the radioactivity of Cs+ or K+ used for the seeding injection system

Experimental Capabilities for Ramjet Propulsion

The existing CIRA rocket engine ground test facility will be updated by including:

- fuel line (JP4);
- air heater;
- ramjet engine test cell;
- specific non-intrusive diagnostics.



CIRA rocket engine ground test facility: present layout

- ❑ Freestream Mach conditions ranging from 2.5 to 5
- ❑ Altitude of nearly 30 Km
- ❑ Both JP4/Air and Methane/Air as propellants
- ❑ Thrust chamber max diameter 20÷30 cm
- ❑ Thrust chamber max length 120÷150 cm
- ❑ Chamber pressure 8÷10 bar

Conclusions

- During the last years CIRA has matured competencies in airbreathing propulsion systems for hypersonic vehicles by participating to European and National projects
- The following topics have been/are being developed:
  - ✓ Physical modelling of combustion
  - ✓ Development, verification and validation of engineering tools and CFD codes
  - ✓ Support to design of airbreathing engine components
  - ✓ Support to design of experimental test campaigns and test rebuilding
  - ✓ Analysis of a complete scramjet vehicle configurations
  - ✓ Feasibility study of a flight experiment of a scramjet propulsion system mounted on a hypersonic vehicle
  - ✓ Contribution to design of mission, launch vehicle and scramjet propelled vehicle
  - ✓ Feasibility study of a scramjet propulsive system of a hypersonic tactical missile
  - ✓ Feasibility study of a MHD bypass for a scramjet engine
  - ✓ Feasibility study of future experimental capabilities for ramjet propulsion

Other Slides

Scramjet Propulsion: code development and validation (LAPCAT-I)

- Study of the main thermo-fluid dynamics phenomena in this type of engines
- Trade-off analysis of kinetic models for Air/H_2 combustion
- Typical supersonic combustion features: mixing process in a normal-injection configuration; mixing and combustion in a parallel-injection configuration; scramjet combustor in fuel-off and fuel-on conditions
- C3NS code validation

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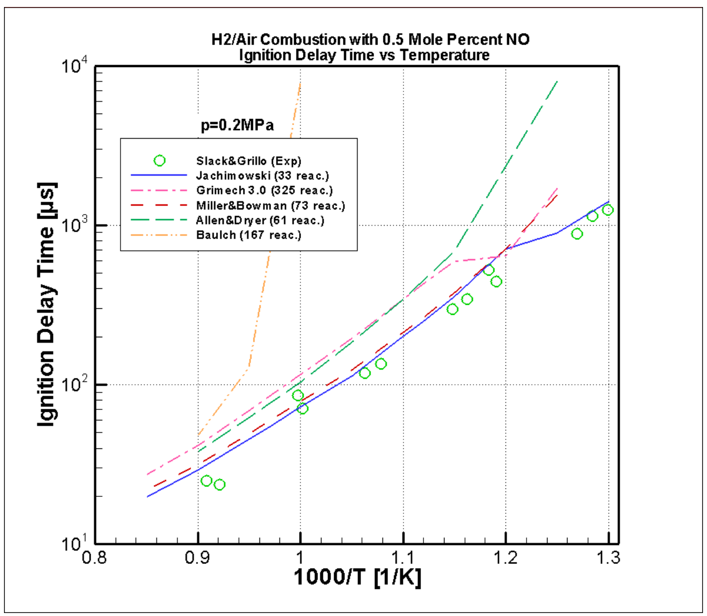
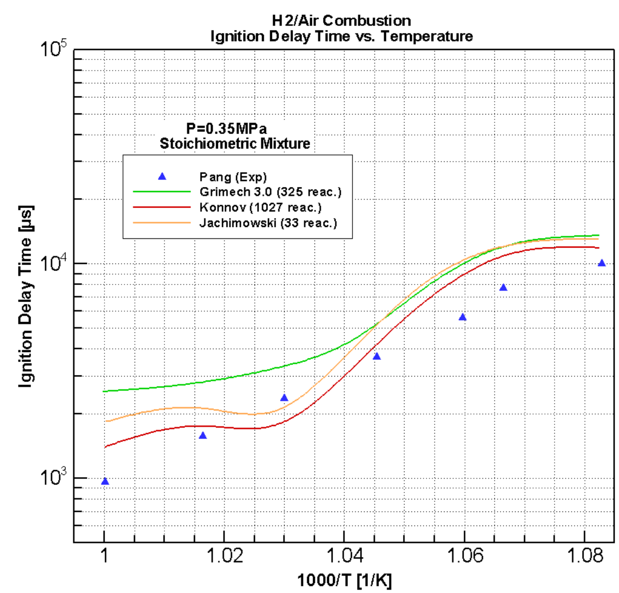
Ram/Scramjet Propulsion: combustion modelling (LAPCAT-II)

LAPCAT II Long-term Advanced Propulsion Concepts And Technologies II

- Detailed and reduced kinetic schemes for Air/H_2 combustion in presence of NO_x
- A detailed reference scheme has been selected and its results have been compared with available literature experimental data in different p and T ranges
- A proper reduced scheme has been selected able to predict NO_x emissions in the typical operating and off-design conditions of the Mach 5 and Mach 8 vehicles propulsion systems, suitable to be embedded into a CFD code

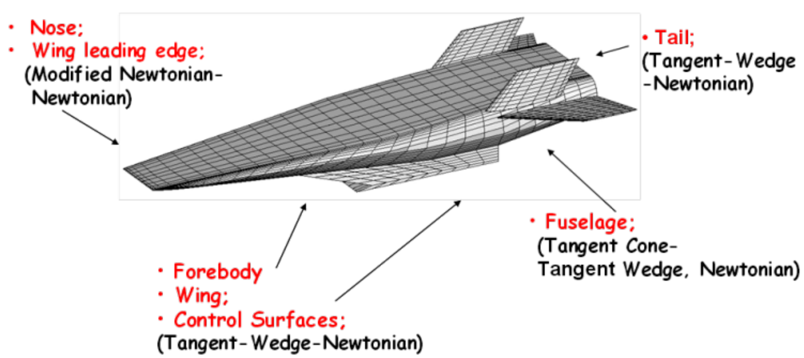


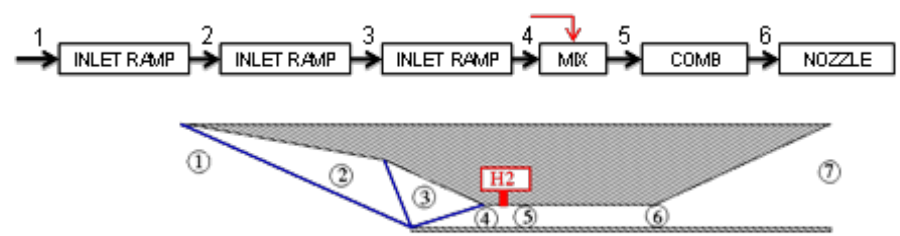
- *Validation in terms of predicted and measured ignition delay times for scramjet and ramjet working conditions*
- *Necessary inclusion of effective pressure history (shock tube)*



Ram/Scramjet Propulsion: engineering tool development, demonstration and validation (LAPCAT-II)

- SPREAD engineering tool development, demonstration and validation activities of both engine module and aerothermodynamic module
- Engine module: multi-ramp inlet, mixer, combustor, nozzle with different geometry assumptions (constant, linear, tabulated geometries), detailed and reduced combustion chemistry, viscous effects
- Aerothermodynamic module: 3-D Supersonic-Hypersonic Panel Method based on surface inclination methods, viscous corrections
- High flexibility for quick prediction of aerodynamic performance and aero-heating
- Good comparison with available CFD/EXP/AEDB data, assessment of error margins

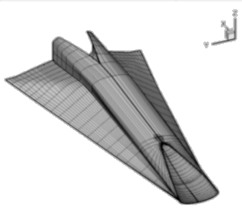


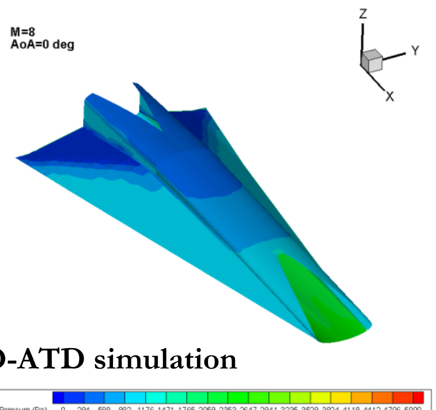


Ram/Scramjet Propulsion: engineering tool application to nose-to-tail analysis of MR2.4 vehicle (LAPCAT-II)

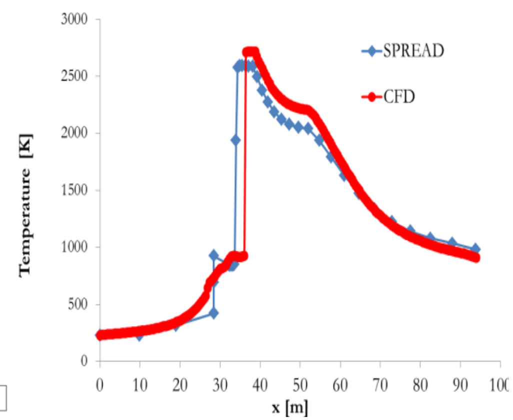
Mach	8
A.o.A. (deg)	0
Altitude (km)	31.95
P_∞ (Pa)	896.09
T_∞ (K)	228.46
E.R.	0, 0.6
T_{H2} (K)	500

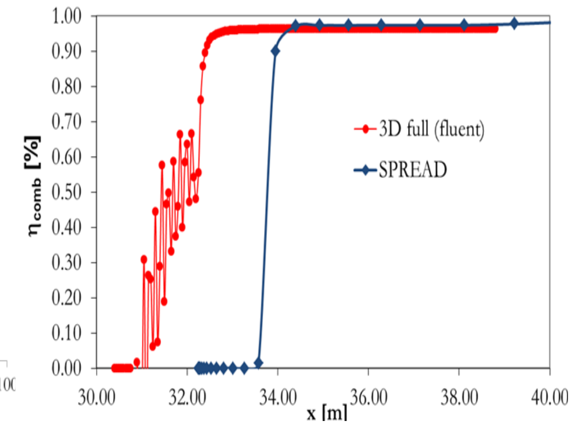
- Weak coupling between propulsive and aerothermodynamic modules
- Full application to MR2.4 vehicle (L=94 m) in flight condition
- Analysis of external aerothermodynamics and internal engine's flowpath



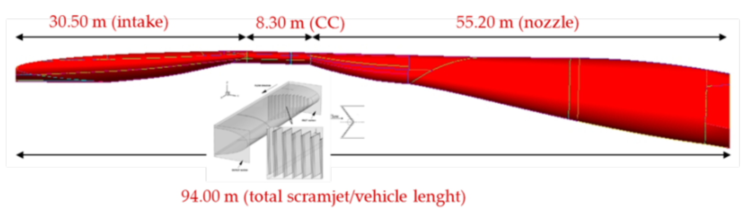


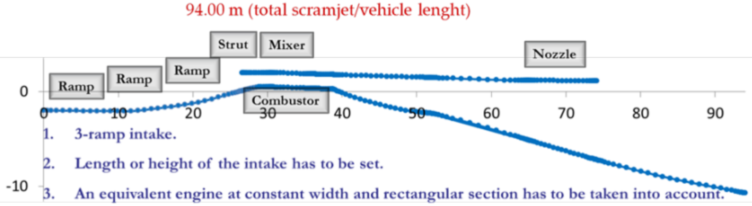
SPREAD-ATD simulation





SPREAD-ENGINE simulation





- Good general prediction of external aerodynamics and engine's internal flowpath (w.r.t. CFD reference)

$$APB = D_{ext} + D_{int} = D_{ext} - T_{prop}$$

Simulation	Comb. Coupling	Owner	ER	L (kN)	APB (kN)	D_{ext} (kN)	D_{int} (kN)	D_{pres} (kN)	D_{visc} (kN)	L/D
CFD TURB SA0	1D/3D	ESTEC	0	3453,00	643,00	467,00	176,00	337,00	306,00	7,39
SPREAD+SIM	*ATD module*	*CIRA*	*0*	*3095,97*	*664,40*	*409,63*	*254,77*	*373,26*	*291,14*	*7,56*
CFD TURB SA0	1D/3D	CIRA	0,6	3372,30	44,00	511,20	-467,20	-364,00	408,00	6,60
CFD TURB SA0	3D/3D	CIRA	0,6	3438,00	195,00	534,00	-339,00	-251,00	446,00	6,44
SPREAD+SIM	*ATD+ENG modules*	*CIRA*	*0,6*	*2971,92*	*143,72*	*525,25*	*-381,53*	*-179,44*	*323,16*	*5,66*