Aerodynamic, aerothermodynamic and propulsive characteristics of the STRATOFLY vehicle

M. Marini, P. Roncioni, L. Cutrone, P. Natale (CIRA)
B.H. Saracoglu, A.C. Ispir (VKI)
R. Fusaro, N. Viola (Pol. Torino)

3rd International Symposium on Hypersonic Flight

Air Force Academy (Pozzuoli), Italy, May 30-31, 2019

AAA – Sez. Roma Due "Luigi Broglio"

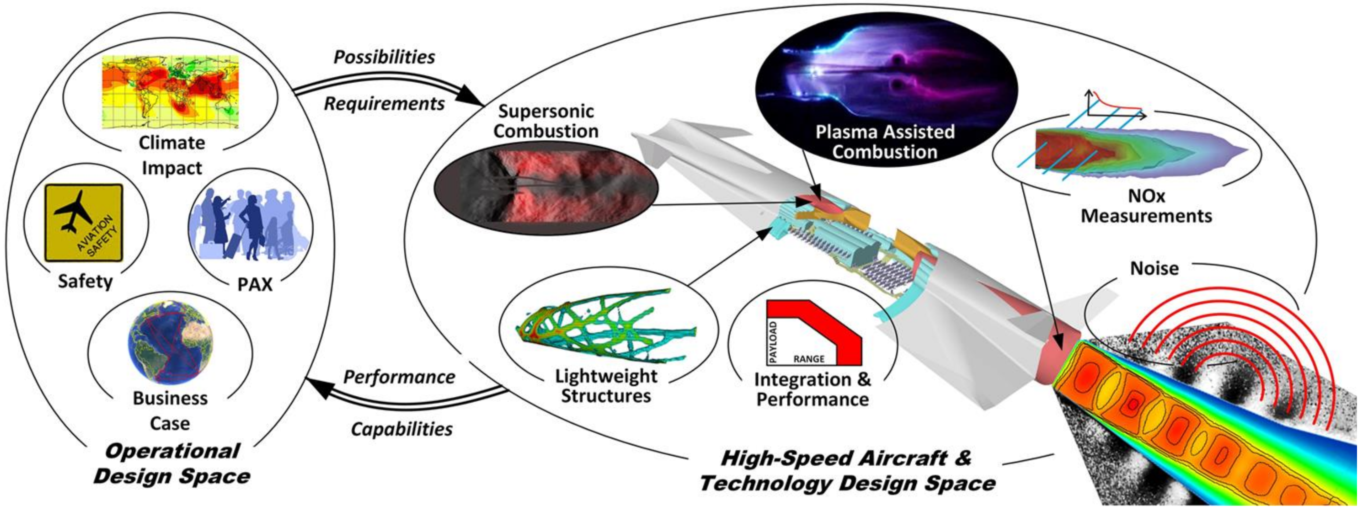
The STRATOFLY Project

- Continuation of a series of EC-funded projects (LAPCAT, ATTLAS, FAST20XX, HEXAFLY, HEXAFLY-INT), STRATOFLY is a highly multidisciplinary project combining technological and operative issues for hypersonic civil aircrafts studying the feasibility of high-speed passenger stratospheric flight

- Technological, environmental, operational and economic factors are taken into account, allowing global sustainability of new air space’s exploitation and drastically reducing transfer time (antipodal flights in less than 2÷4 hours), emissions and noise, and guaranteeing the required safety

- Main objectives:
  - *to refine design and CONOPS of the LAPCAT-II MR2.4 vehicle*
  - *to reach TRL=6 by 2035 for the concept*

- STRATOFLY crucial technologies may represent a step forward for future reusable space transportation systems



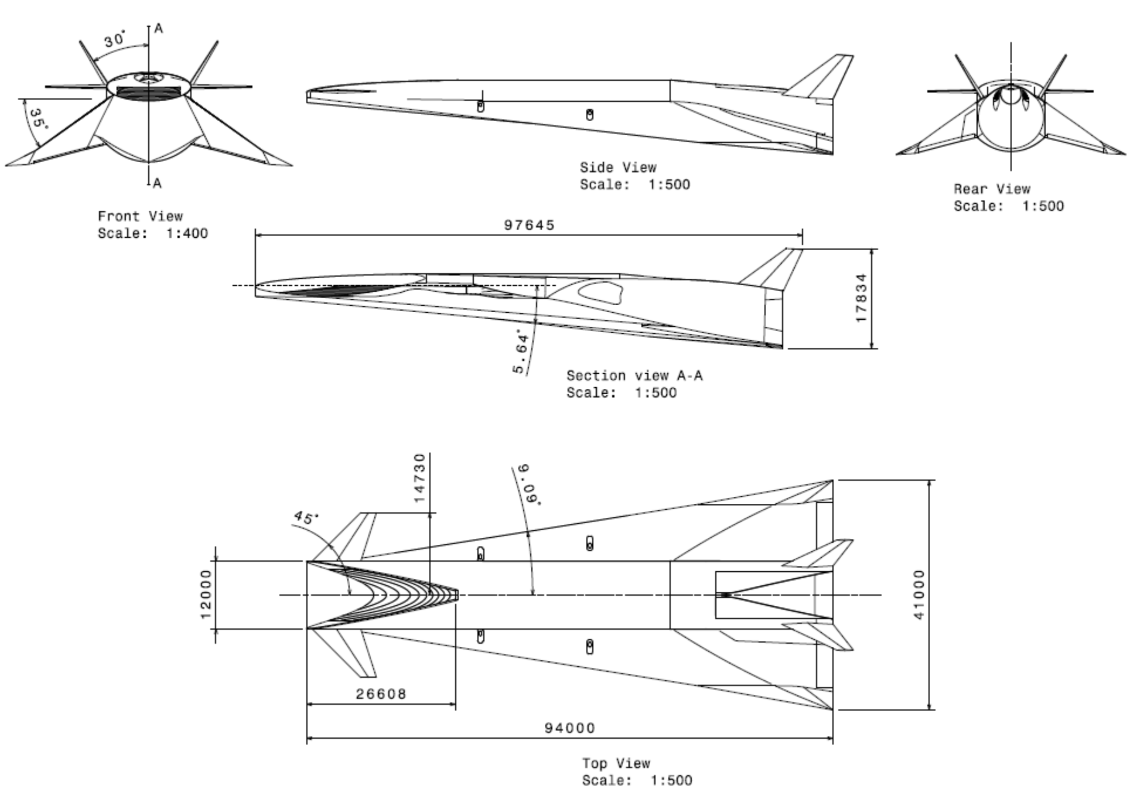
The STRATOFLY Vehicle

LAPCAT II Long-term Advanced Propulsion Concepts And Technologies II

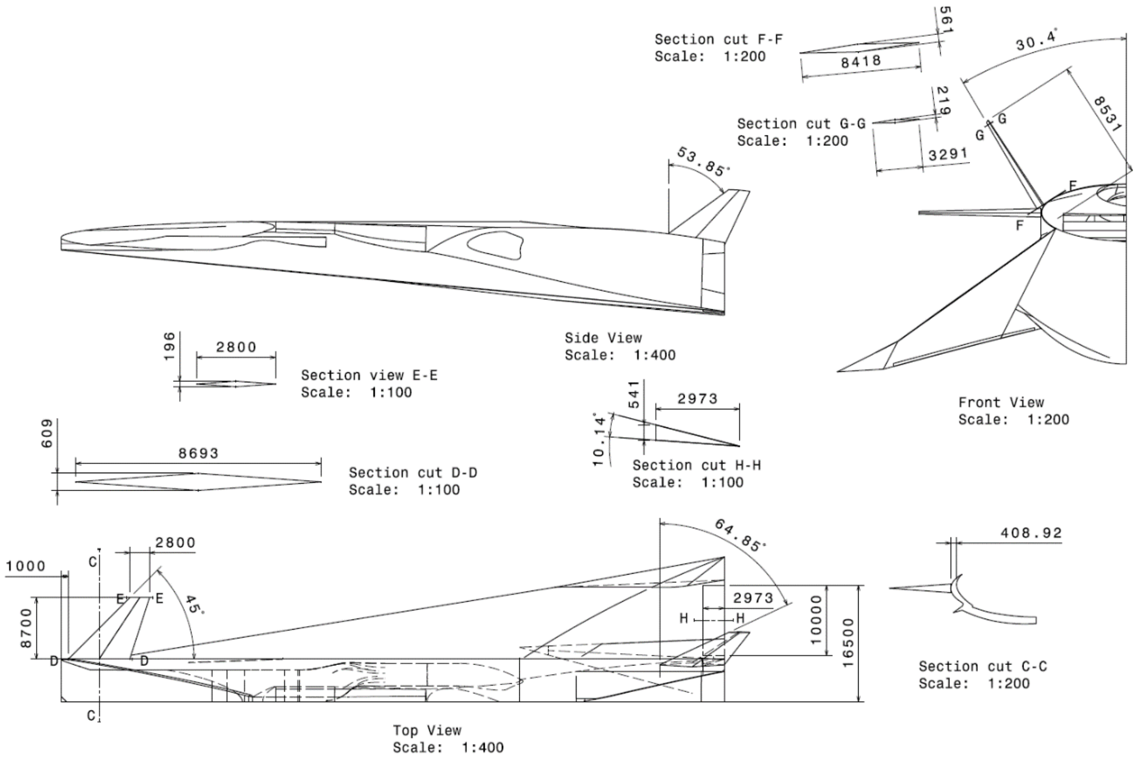
esa

- L=94m, GTOW=400 tons
- 300 PAX transportation
- Cruise: Mach=8 @ 32÷33 km
- Waverider aeroshape with dorsal mounted engine
- Combined propulsion system merging Air-Turbo-Rockets (Mach=0÷4.5) and Dual-Mode-Ramjet (Mach=4.5÷8)

The STRATOFLY Vehicle



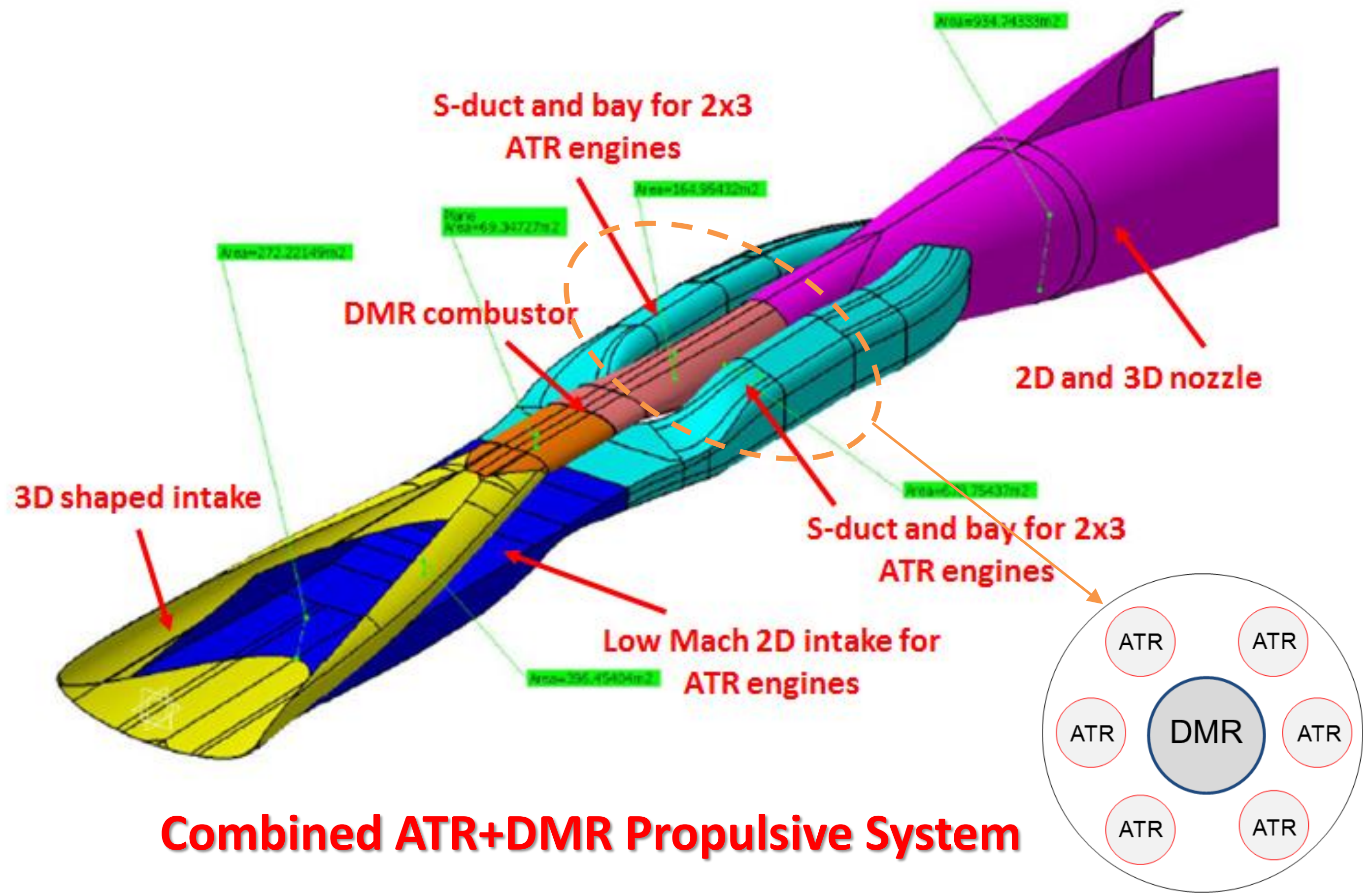
OML – Main Views



FCS - Control Surfaces

- The reference hypersonic propelled vehicle is the LAPCAT-II MR2.4

The STRATOFLY Vehicle

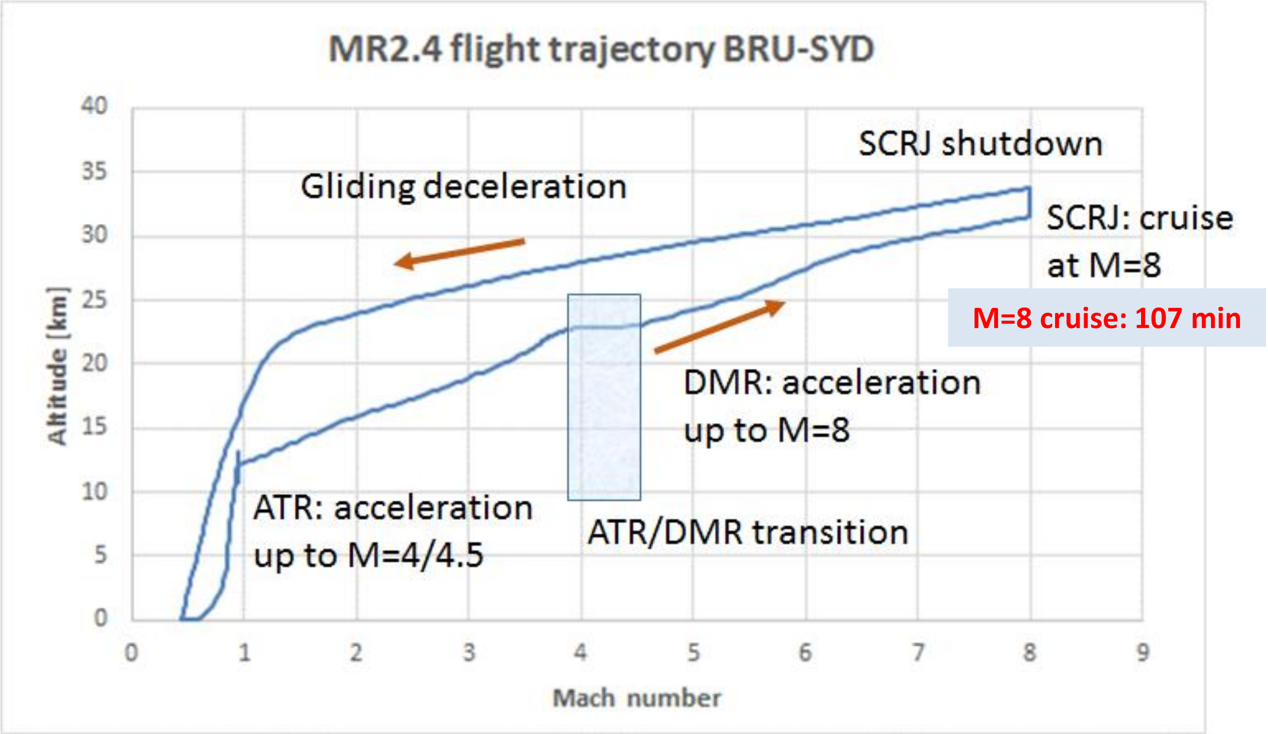


Combined ATR+DMR Propulsive System

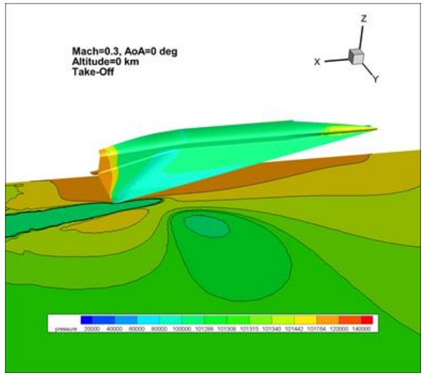
- The sophisticated dorsal-mounted combined propulsion plant of the vehicle enables take-off, cruise, approach and landing solely with airbreathing systems
- 6 Air-Turbo-Rocket engines: 2x3 ATR engines based on an expander cycle mounted laterally, operating from take-off to Mach=4/4.5
- 1 Dual-Mode-Ramjet: central DMR engine operating from Mach=4.5 to Mach=8

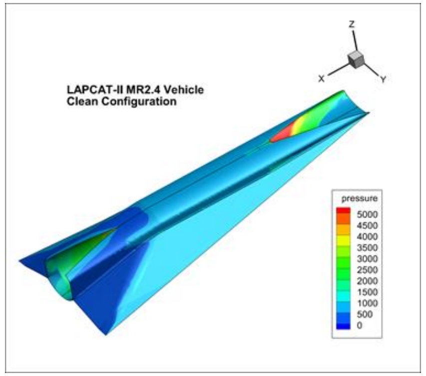
- The reference hypersonic propelled vehicle is the LAPCAT-II MR2.4

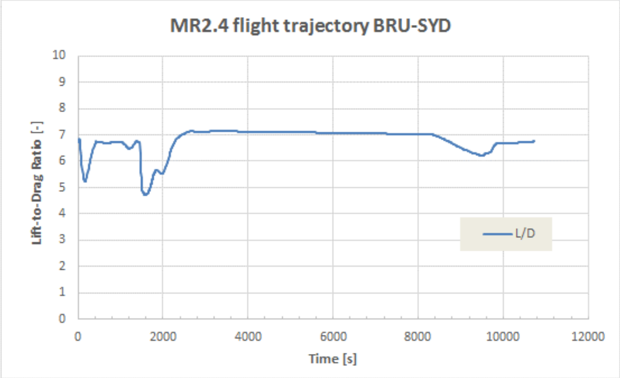
The STRATOFLY Reference Flight: BRU-SYD

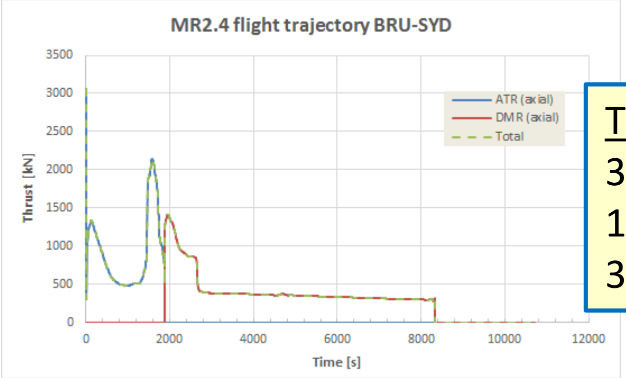


- Cruise: Mach 8, AoA≈0°, Alt=32÷33.5 km
- Flight duration: 2h 58’ (10715s)
- Distance flown: 18734 km
- Load factors not critical
- MTOW: 400 t (180 t propellant)
- MLW: 231 t (12,5 t of propellant left)
- L/D≈7 in hypersonic cruise
- DMR shutdown at 33.8 km, Mach 8







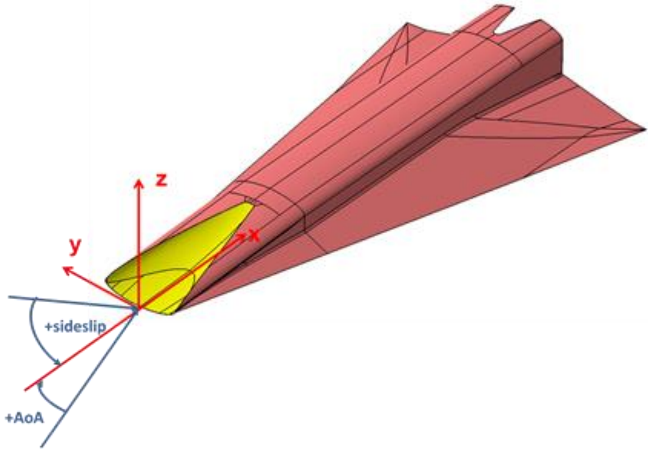


Thrust levels
3070 kN @ T.O.
1370 kN @ transition
300÷400 kN @ cruise

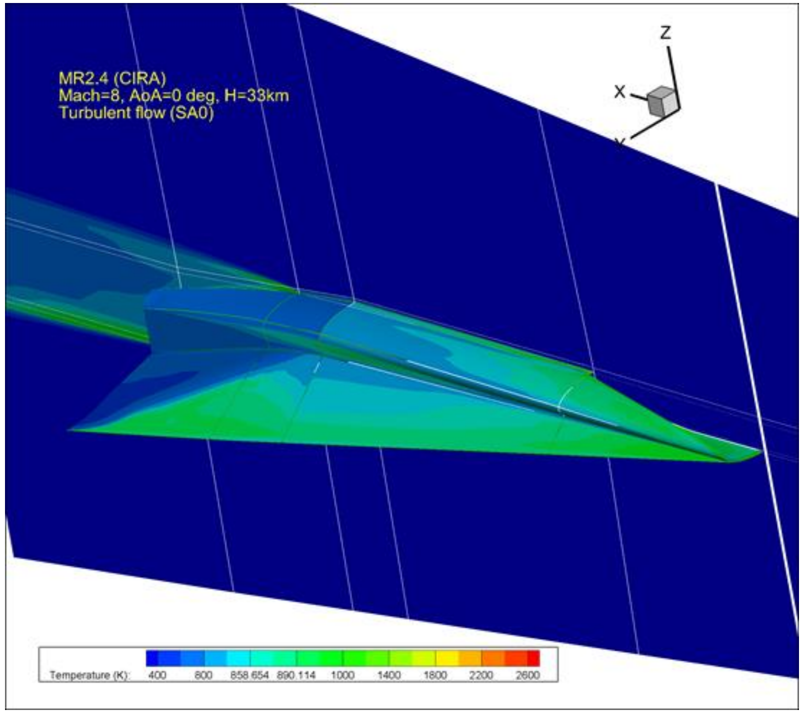
STRATOFLY Aerodynamics

- Aerodynamic behaviour by analysing detailed CFD nose-to-tail aero-propulsive simulations (Mach=0.3, 0.5, 0.75, 4, 6, 8; different AoA values; clean configuration)
- Effect of engine (on/off)
- Effect of CoG movement during flight, longitudinal static stability

	LAPCAT-II - MR2.4
L_{ref} (m)	94
S_{ref} (m^2)	2365
b_{ref} (m)	41
CoG (m) from nosetip	49.98 (53.2%) 20% fuel 52.95 (56.3%) 100% fuel
Vertical Tail	no
Horizontal Tail	undeflected*
Available Data	CFD (ESA, CIRA)
Flight Conditions (also M=0.3, 0.5, 0.75 with ATR engine)	M=4, 6, 8 AoA(°)=-2, 0, 2 fuel-on/off

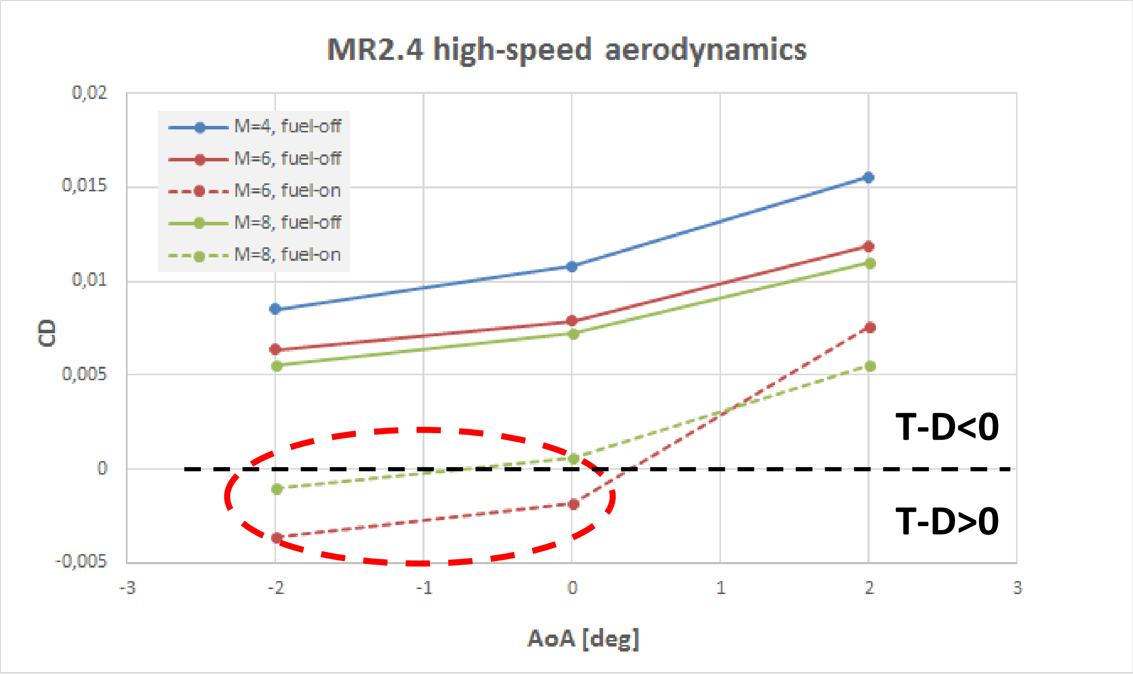


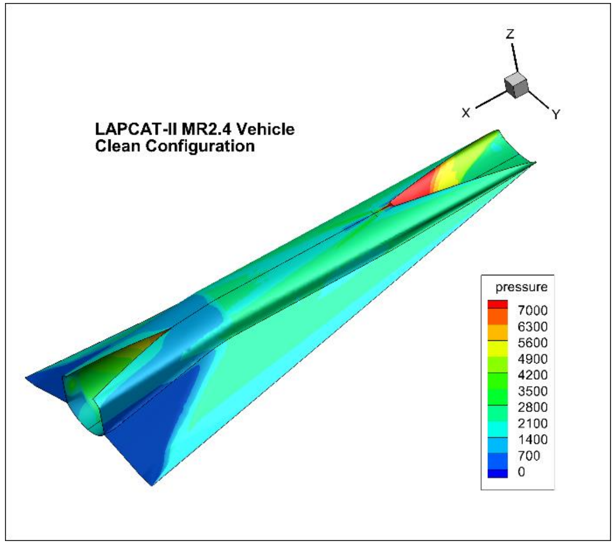
*no canards



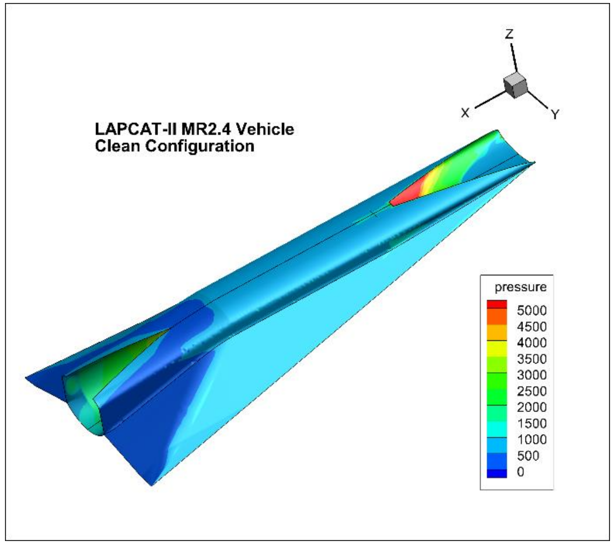
STRATOFLY High-Speed Aerodynamics

- Aero-Propulsive analysis of the MR2.4 vehicle (AEP-DB provided by ESA)
- High supersonics/hypersonics: Mach=4, 6, 8; AoA=-2°, 0°, 2°; AoS=0°
- Hypothesis: DMR thrust action line coincides roughly with X-axis of vehicle
- X_{COG} 49.98m (53,2%, most forward, 20% fuel) and 52.95m (56,3%, most backward, 100% fuel) from nosetip





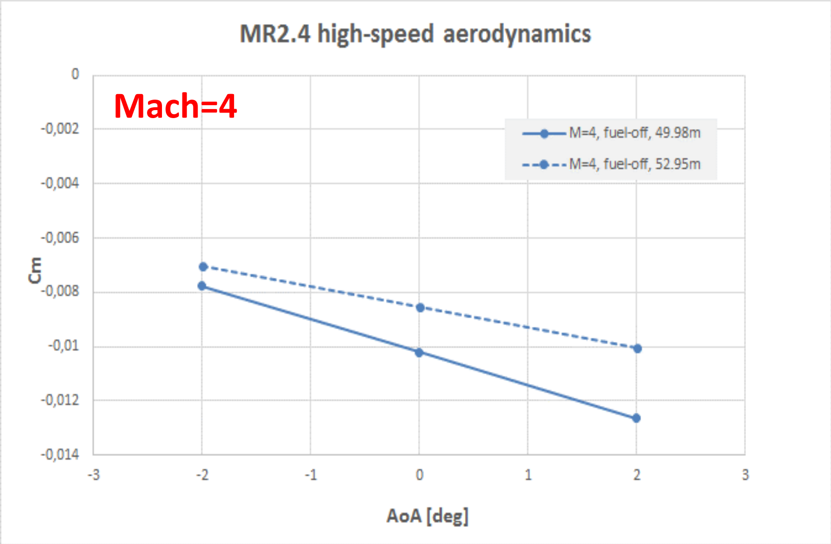
Mach=6, AoA=0°

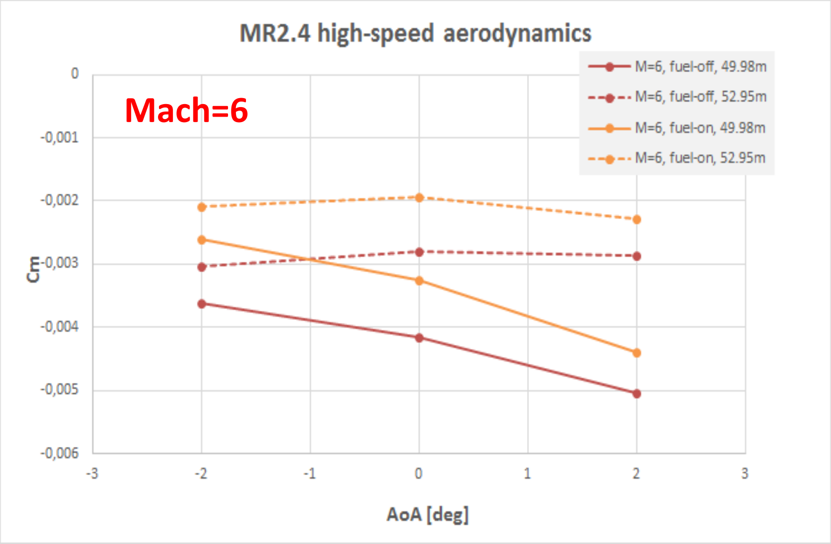


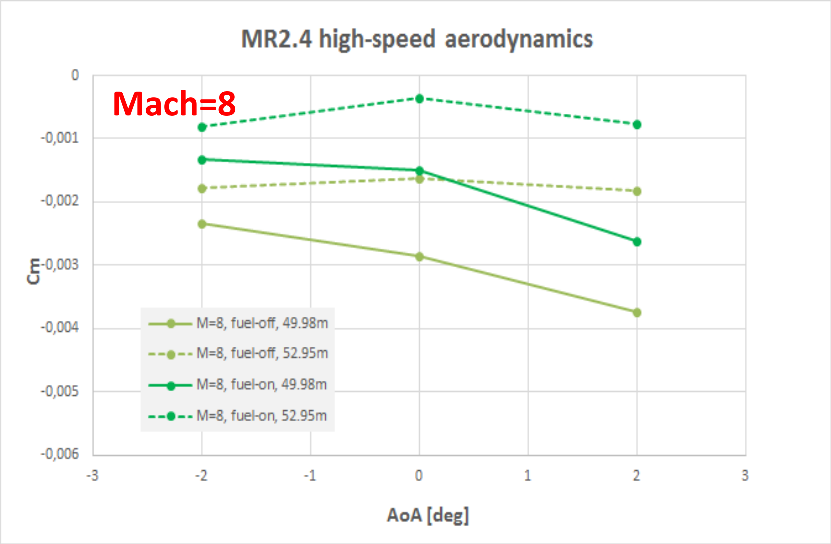
Mach=8, AoA=0°

- Propulsive thrust for AoA=-1°÷0° at Mach=6 and AoA=-2° at Mach=8

STRATOFLY High-Speed Aerodynamics







- Beneficial effect of engine for all flight conditions → upshift of Cm curve → reduction of aileron deflection for trim
- Clear stability for CoG at 53.2% at all Mach numbers, neutral stability or incipient instability for CoG at 56.3%
- Need for trimmability with negative aileron deflection for all flight conditions (large ΔCm to null)
- Conflicting requirements: stability vs. trimmability → find optimum!

$$C_z = C_L\,cos\alpha + C_D\,sin\alpha$$

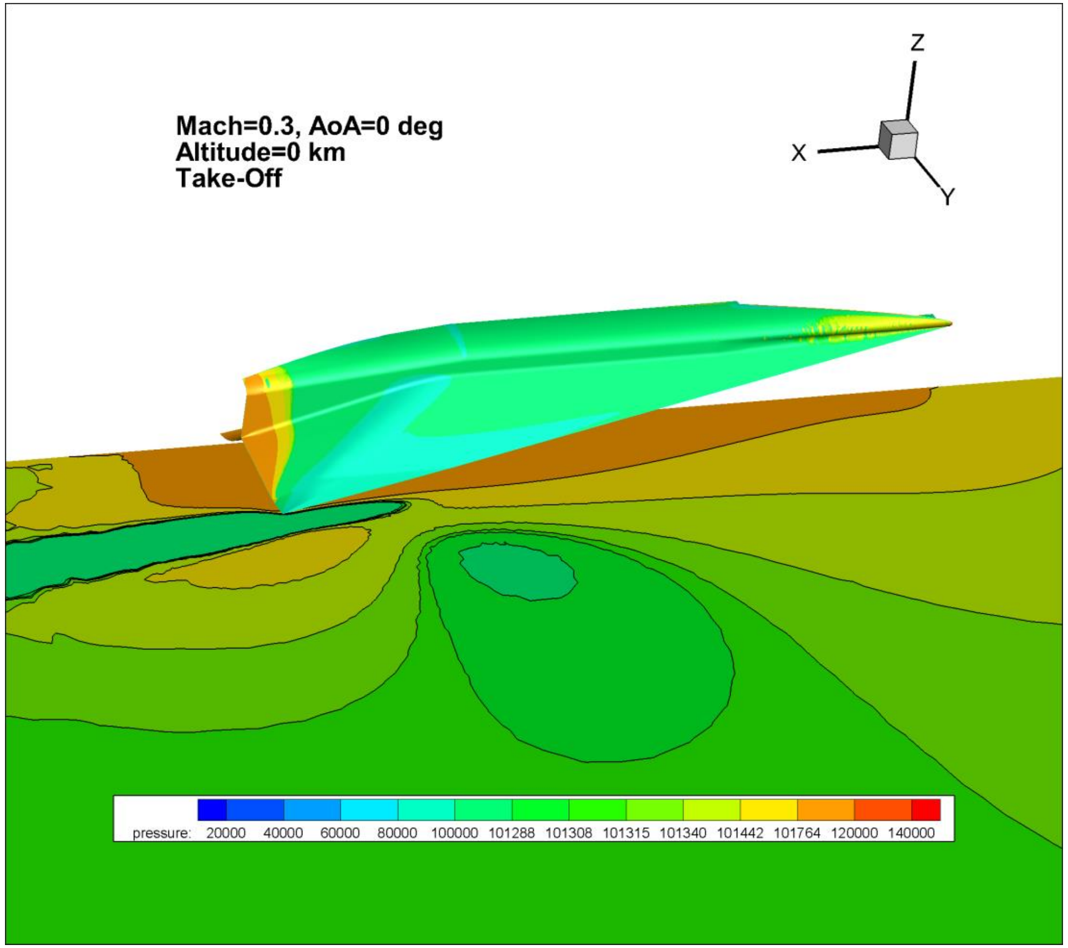
$$Cm_1 = Cm_0 + C_z\frac{(X_1 - X_0)}{L_{ref}}$$

Cm,alpha			
Mach	DMR	XCoG (m)	
		49,98	52,95
4	OFF	-0,00122	-0,000758984
6	OFF	-0,00036	4,11344E-05
6	ON	-0,00045	-4,88087E-05
8	OFF	-0,00035	-9,55412E-06
8	ON	-0,00032	1,1102E-05

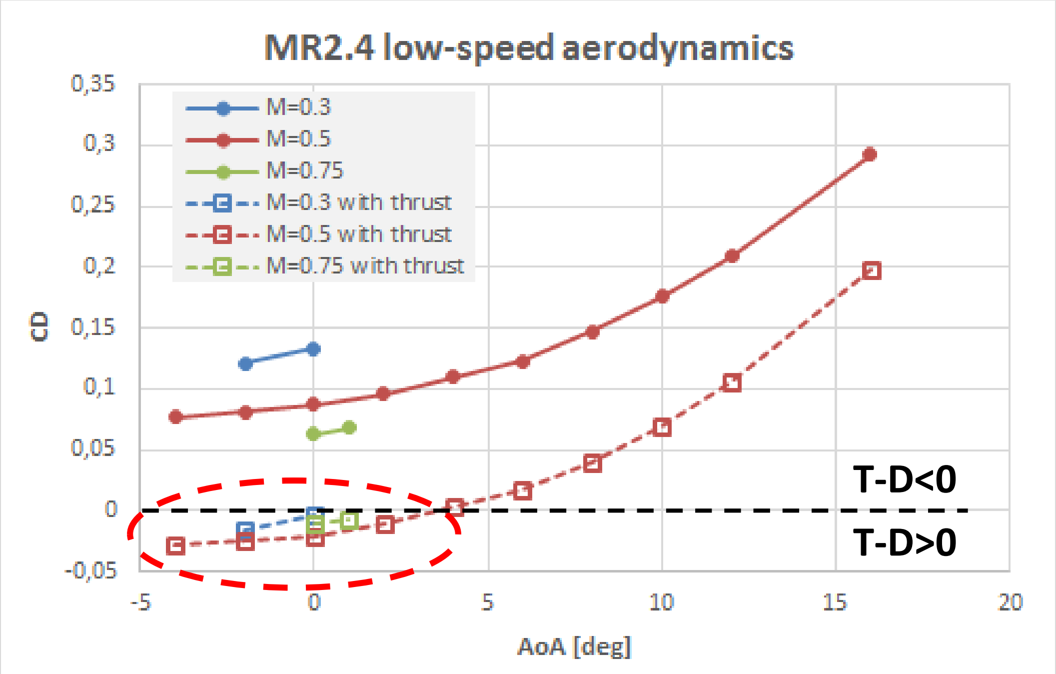
STRATOFLY Low-Speed Aerodynamics

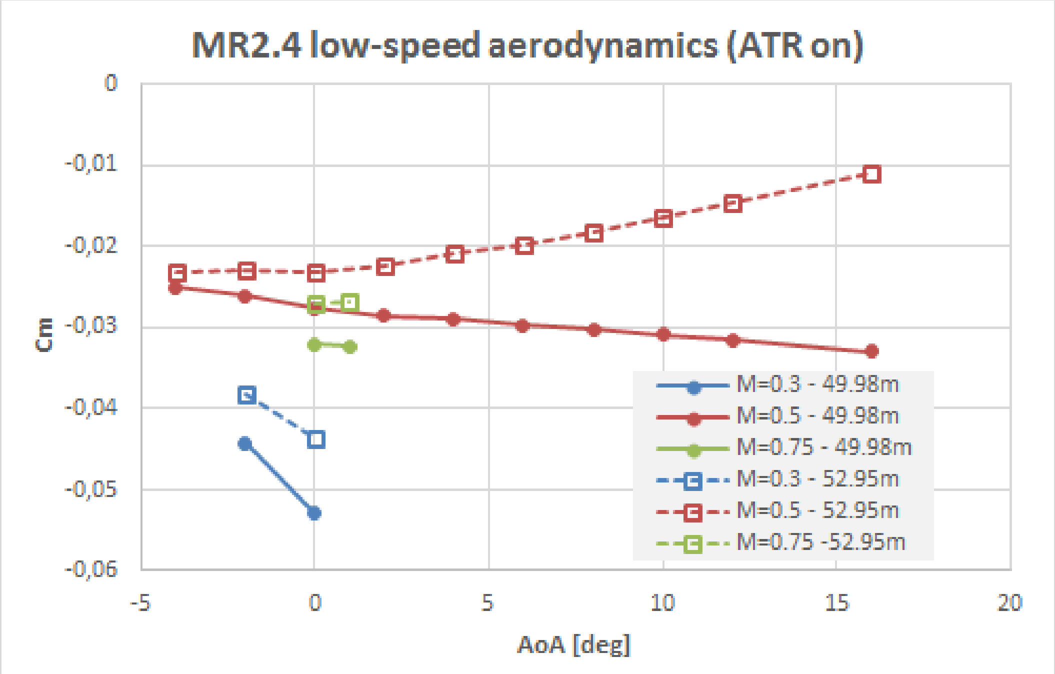
- Aero-Propulsive analysis of the MR2.4 vehicle (AEP-DB provided by ESA)
- Subsonics: Mach=0.3, 0.5, 0.75; different AoAs; AoS=0°
- Hypothesis: ATR thrust action line coincides roughly with X-axis of vehicle
- X_{COG} 49.98m (53,2%, most forward, 20% fuel) and 52.95m (56,3%, most backward, 100% fuel) from nosetip

Mach	Altitude (km)	AoA (°)
0.3	0	-2, 0
0.5	7	-4,-2, 0, 2, 4, 6, 8, 10, 12, 16
0.75	10.6	0, 1



STRATOFLY Low-Speed Aerodynamics





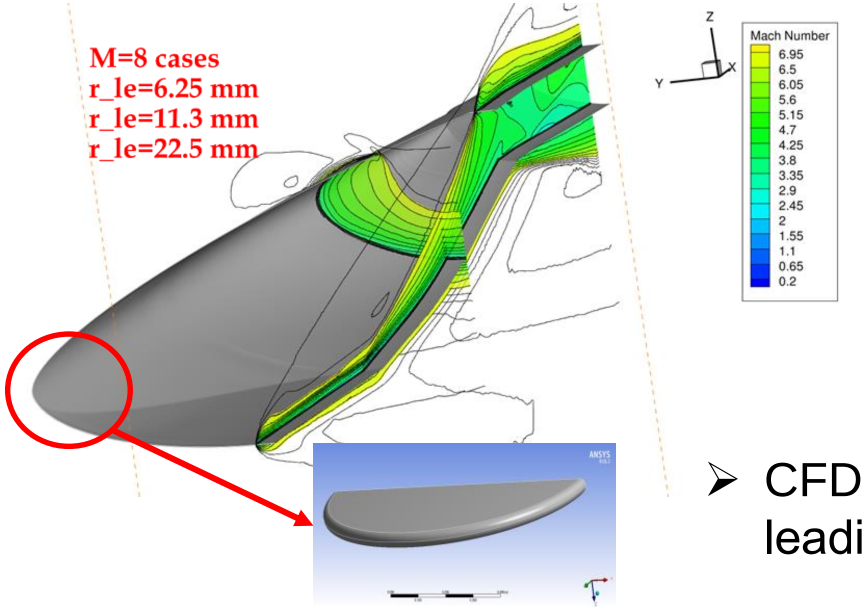
$$C_z = C_L\, cos\alpha + C_D sin\alpha$$

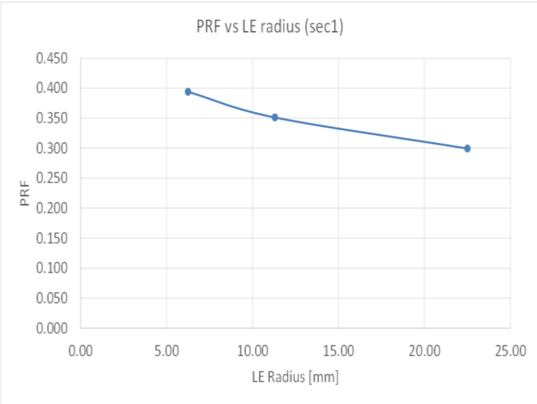
$$Cm_1 = Cm_0 + C_z \frac{(X_1 - X_0)}{L_{ref}}$$

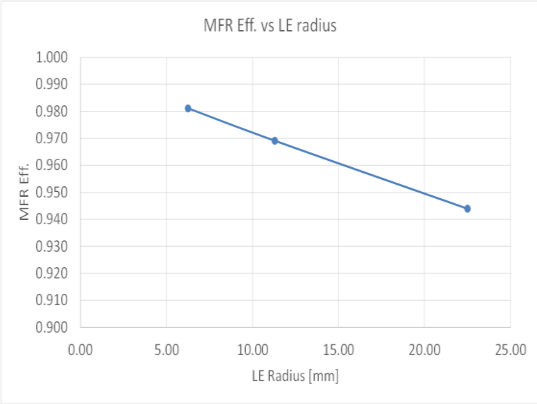
- Take-off possible conditions with higher thrust for AoA=-2°
- T-D > 0 for both Mach=0.5 (-4°<AoA<4°) and Mach=0.75
- Clear stability with CoG at 53.2%, neutrally stable (Mach=0.75) or unstable (Mach=0.5, AoA>0°) with CoG at 56.3%
- Need for trimmability at all conditions, especially at take-off (Mach=0.3)

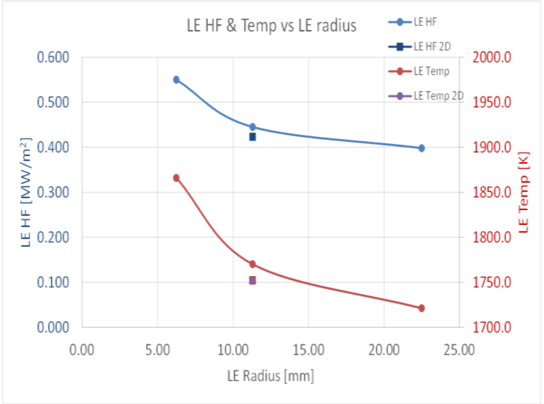
Cm,alpha			
Mach	ATR	XCoG (m)	
		49,98	52,95
0.3	ON	-0,00433	-0,00269
0.5	ON	-0,00038	0,000629
0.75	ON	-0,00036	0,000437

STRATOFLY Aerothermodynamics





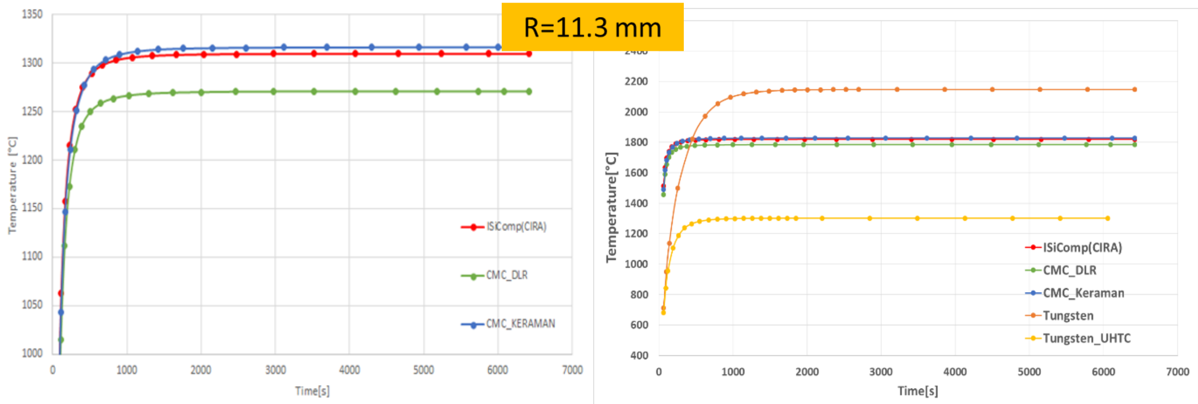




- CFD simulations on a reduced domain to select the proper rounding at intake leading edges through evaluation of intake's performance and local heat fluxes

- Thermal analysis along the Mach 8 flight slag trajectory to evaluate the time-dependent temperature of the structure for the different materials at the intake and crotch

R_{LE} (mm)	HF_{LE} [kW/m²]	HF_{CR} [kW/m²]
6.25	550	1140
11.3	445	1092
22.5	398	1136

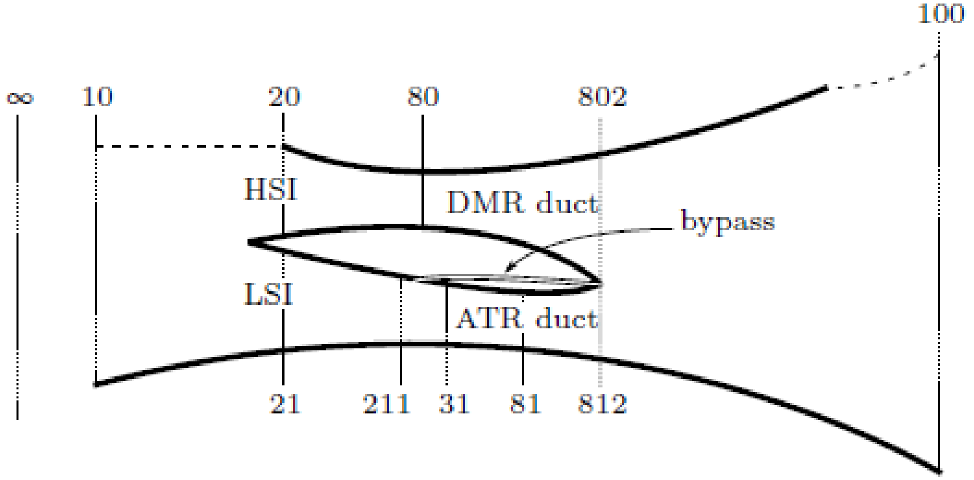


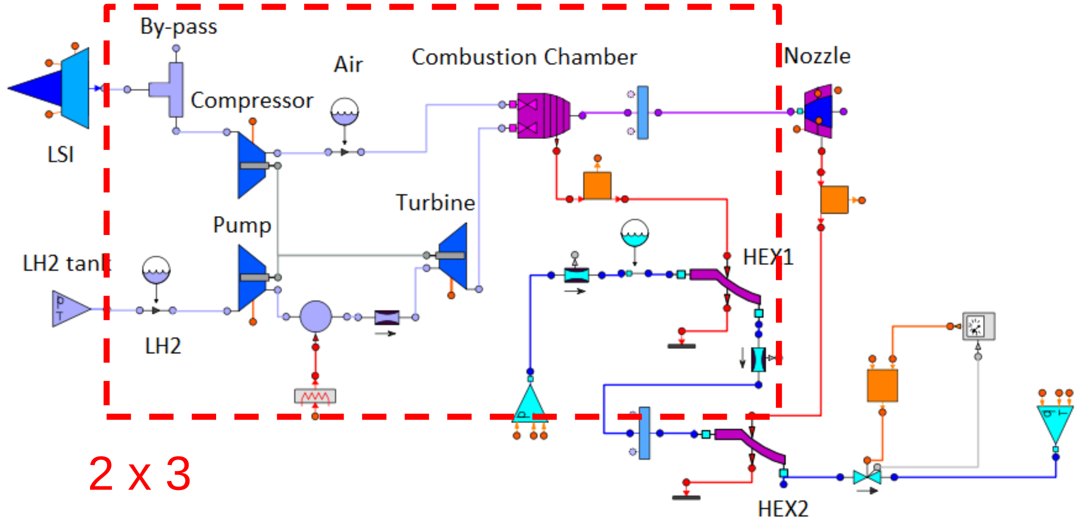
Sample Thickness (mm)	R (mm)	$T_{ISiComp}$ @ LE / Crotch	T_{CMC_DLR} @ LE / Crotch	$T_{Keraman}$ @ LE / Crotch	$T_{Tungsten}$ @ Crotch	$T_{Tungsten + UHTC}$ @ Crotch
12.5	**6.25**	1314 / 1745 °C	1268 / 1697 °C	1312/ 1739 °C	1929 °C	1171 °C
22.6	**11.3**	1309 / 1820 °C	1271 / 1785 °C	1316 / 1829 °C	2147 °C	1302 °C
45.0	**22.5**	1329 / 1896 °C	1301 / 1871 °C	1320 / 1885 °C	2488 °C	1504 °C

- Suggestions for vehicle's material layout
- Need for active cooling system

STRATOFLY Propulsive System

Engine installation along the propulsive duct:





2 x 3

DMR Unit

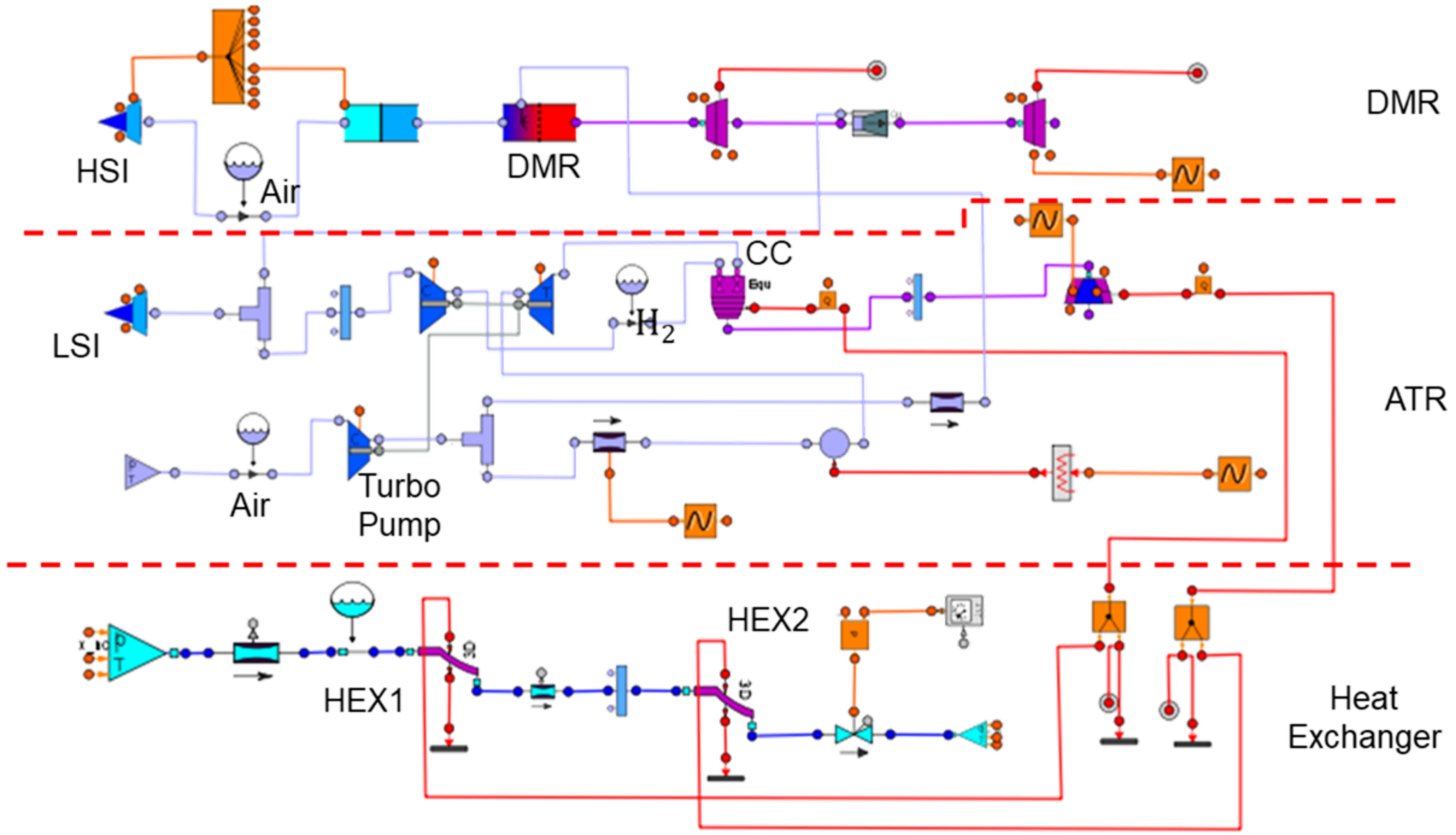
10 – 20: Supersonic intake (HSI)
20 – 80: DMR intake region
80 – 802: DMR isolator + combustion chamber + + nozzle + by-pass out
802 – 100: Common nozzle

ATR Unit

10 – 21: Supersonic intake (LSI)
21 – 211: Air-compressor
31 – 81: ATR combustion chamber
81 – 812: Flow combination of six ATR engines
812 – 100: Common nozzle

STRATOFLY Propulsive System

Ecosimpro layout of the complete propulsion system for the cruise speeds of Mach 0 ÷ 4.5:



***Air Turbo Rocket (ATR)*:**

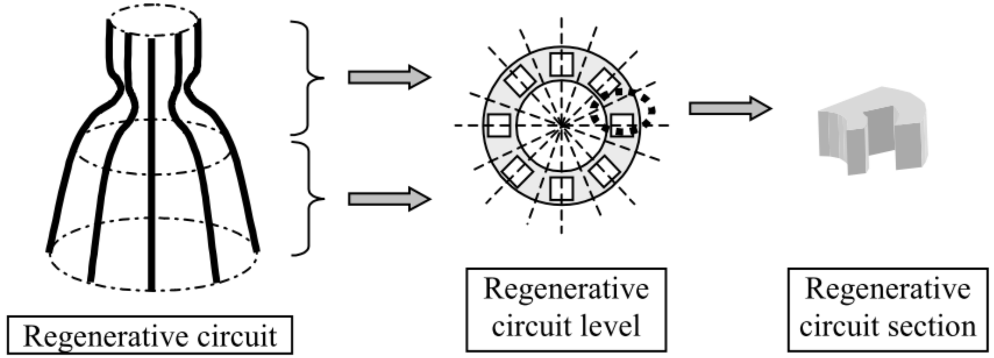
- ✓ Mach 0 ÷ 4.5
- ✓ Hydrogen turbine driving air compressor and fuel pump
- ✓ Constant pressure combustion in a pre-burner
- ✓ Bypass line to boost the DMR thrust

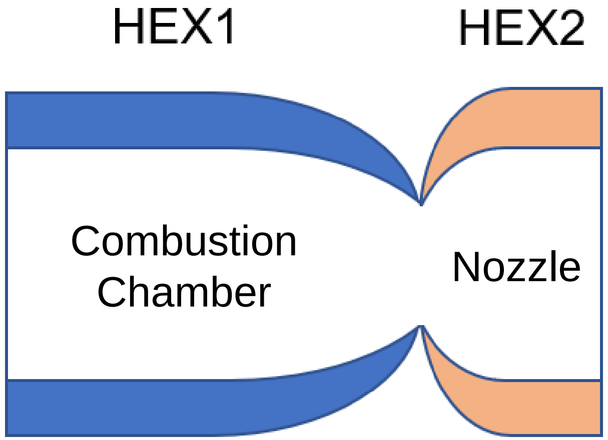
Dual Mode Ramjet (DMR):

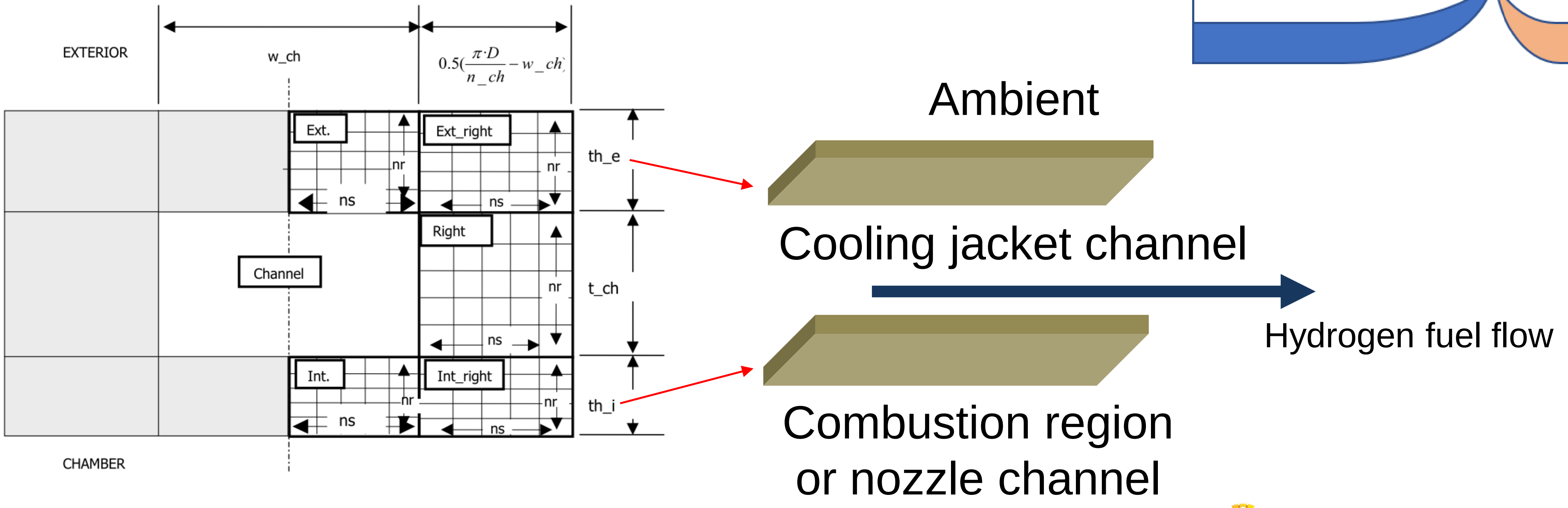
- ✓ Mach 1.5 ÷ 4.5 (Ramjet Mode)
- ✓ Subsonic combustion and acceleration to supersonic speeds with diverged nozzles

STRATOFLY Propulsive System

Heat pick-up system from heat sinks used to increase the enthalpy of turbine flow:

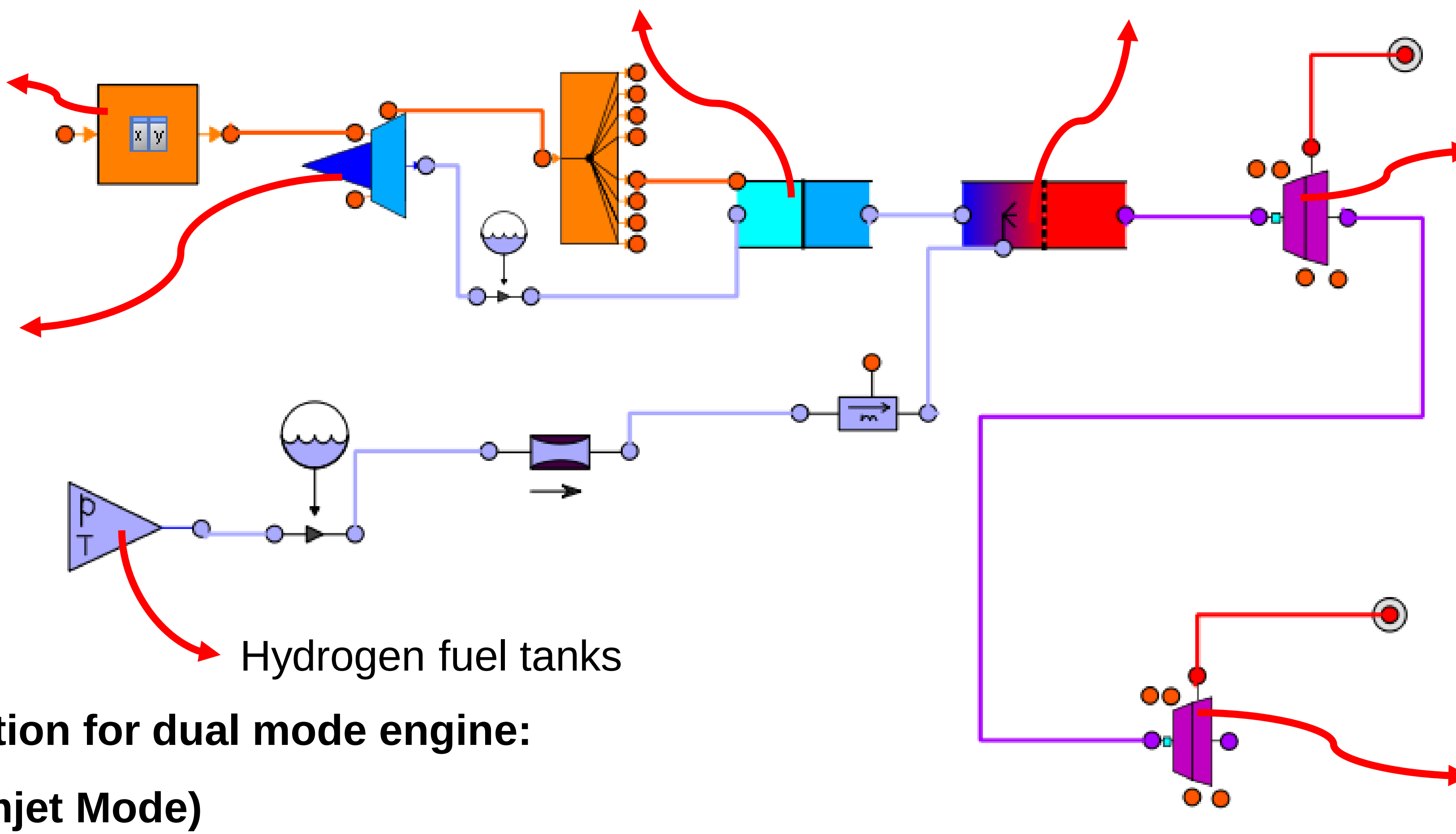






STRATOFLY Propulsive System

Ecosimpro layout of the dual mode ramjet engine for the cruise speeds of Mach 5 ÷ 8:



Operational prediction for dual mode engine:

- ✓ **Mach 5 ÷ 6 (Ramjet Mode)**
- ✓ **Mach 6 ÷ 8 (Scramjet Mode)**

STRATOFLY Propulsive System

Design strategy

Creation of 0D model of combined propulsion plant in Ecosimpro

↓

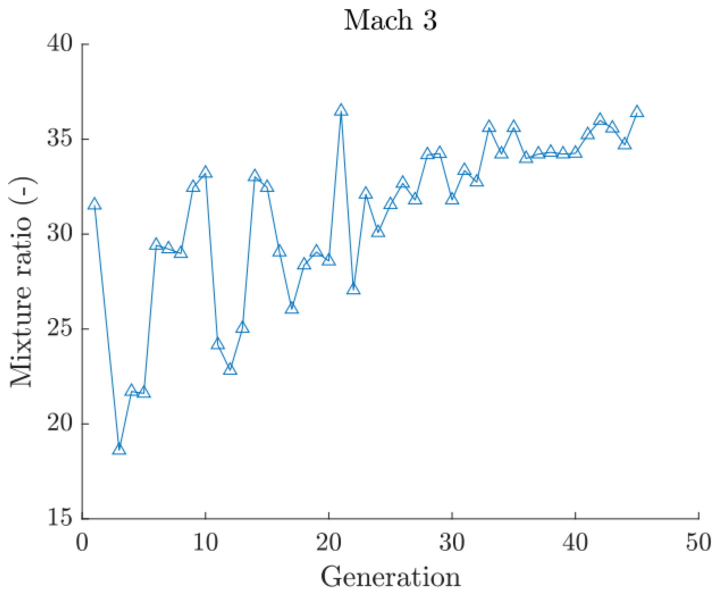
1D transient thermodynamic simulations to calculate ATR engine performance

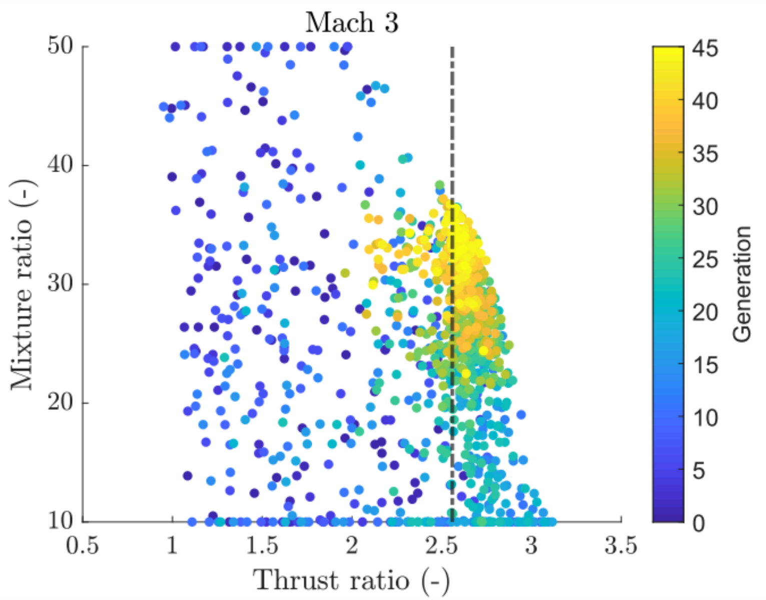
↓

Optimization study to determine ATR engine operational conditions for best performance

↓

1D transient thermodynamic simulations for DMR engine at cruise speeds of Mach 4.5 – 8



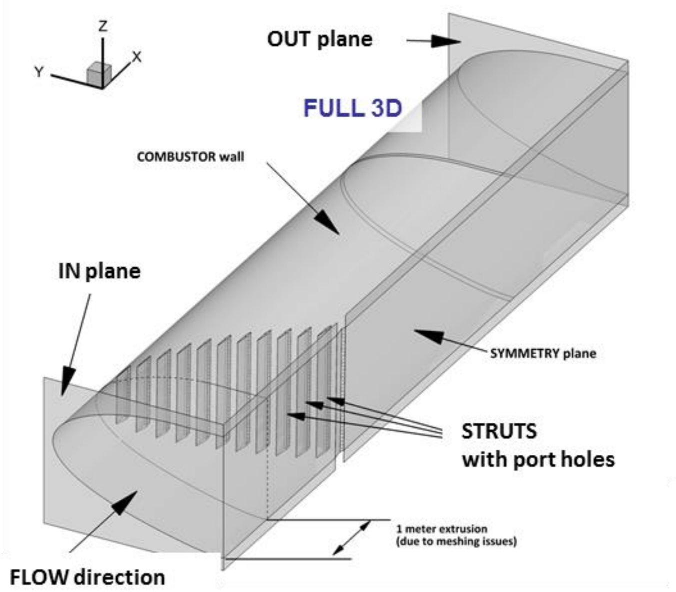


<u>Example</u>

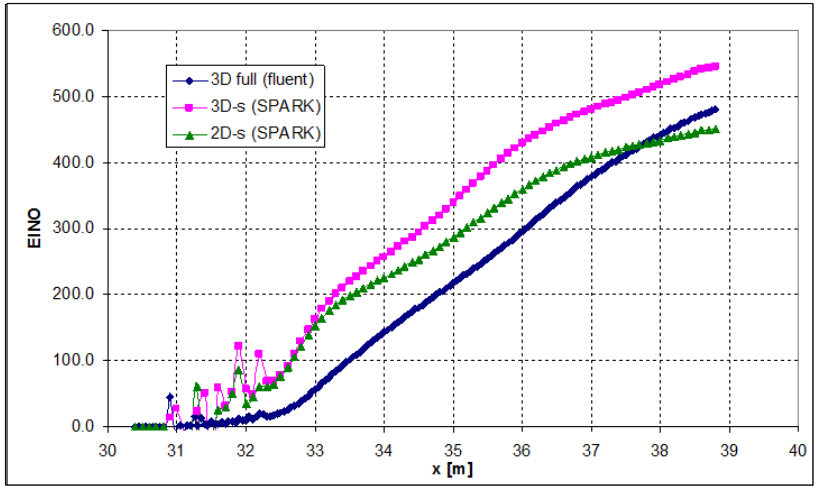
Optimization study to determine air-fuel mixture for Mach=3 flight speed

$$\text{Mixture ratio: } \frac{m_{air}}{m_{fuel}} \qquad \text{Thrust ratio: } \frac{F_{ATR}}{F_{cruise}}$$

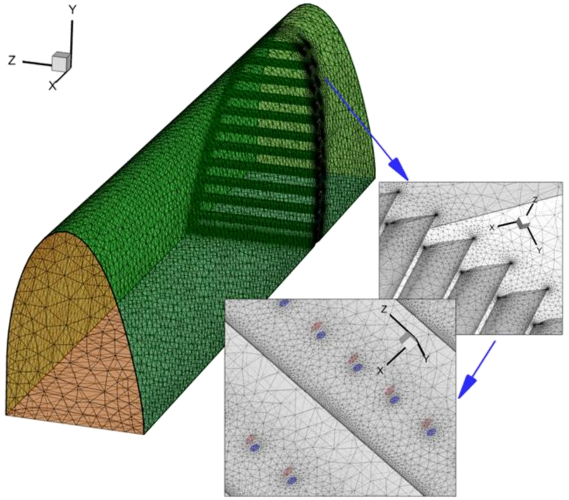
STRATOFLY Propulsive System

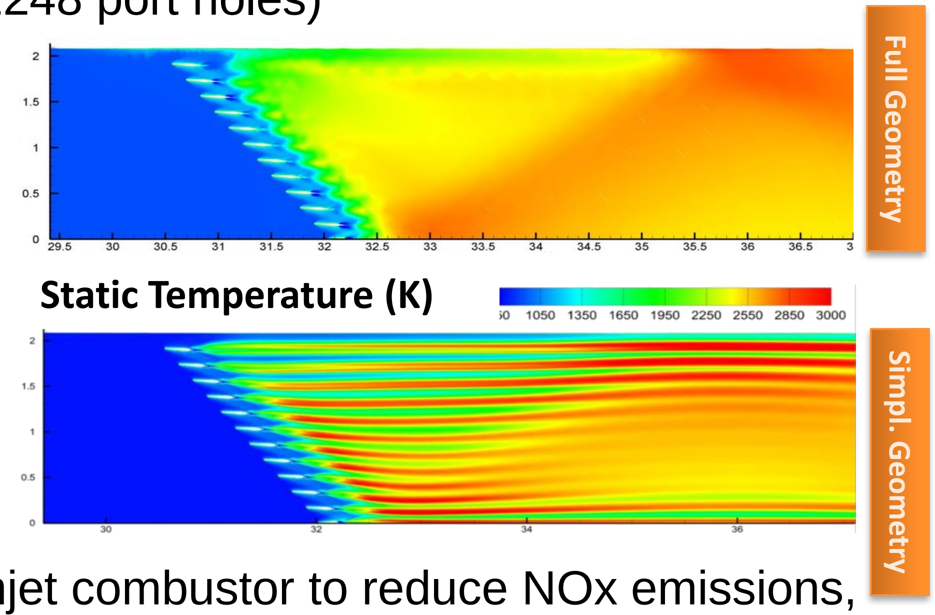


MR2.4 DMR Combustor



- Detailed CFD analysis of DMR full-scale combustor in scramjet mode, Air/H_2 turbulent combustion
- Geometry modelling: simplified 2D, simplified 3D, full configuration with 11M cells unstructured grid (23 struts, 1248 port holes)





- Optimization of MR2.4 scramjet combustor to reduce NOx emissions, with different injection strategies, strut layouts, lengths of the combustion chamber, etc.
- Use of CIRA's SPREAD engineering code and CFD detailed methodology, both validated with experiments at DLR-HEG

Conclusions

- Aero-propulsive characterization of the STRATOFLY vehicle along the whole flight reference mission, with an assessment of aero-propulsive balance, longitudinal stability and trimming requirements in the different phases of flight

- Assessment of system requirements in terms of CoG position, AoA for maximum thrust, AoA for maximum L/D, deflection for longitudinal trim

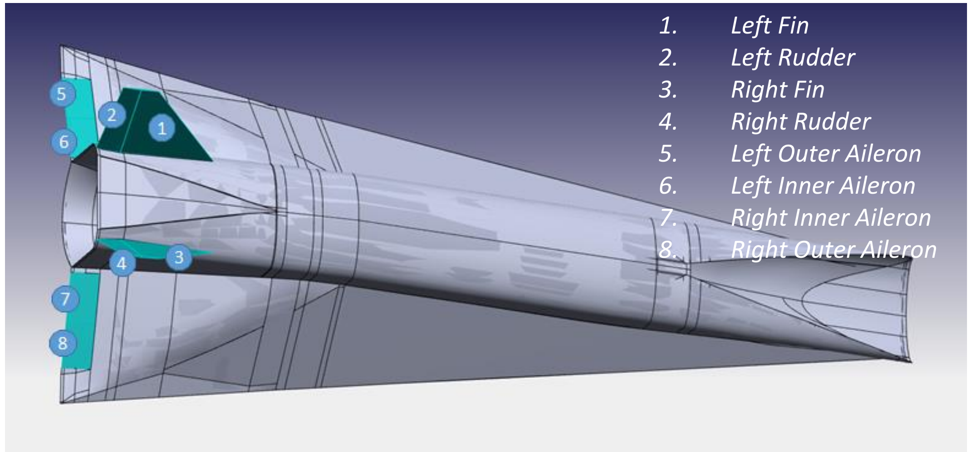
- STRATOFLY aeroshape evolution on-going, in particular concerning:
  - refinement of the main intake design with adding of rounded leading edges, to reduce locally the thermal loads while keeping the same intake's performance
  - suggestions for vehicle's material layout and need for active cooling
  - design and analysis of flight control system, i.e. sizing of ailerons/elevons and vertical tail

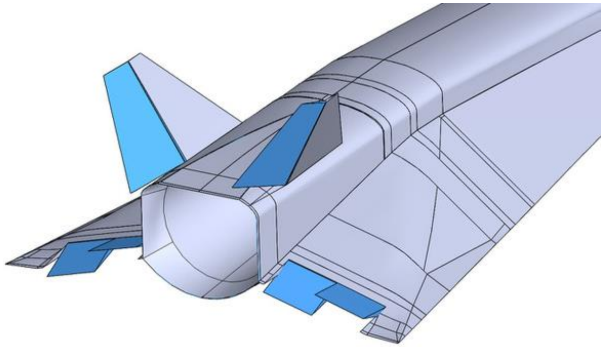
- Two different types of engines combined to form STRATOFLY propulsion plant for take-off, supersonic acceleration and hypersonic cruise

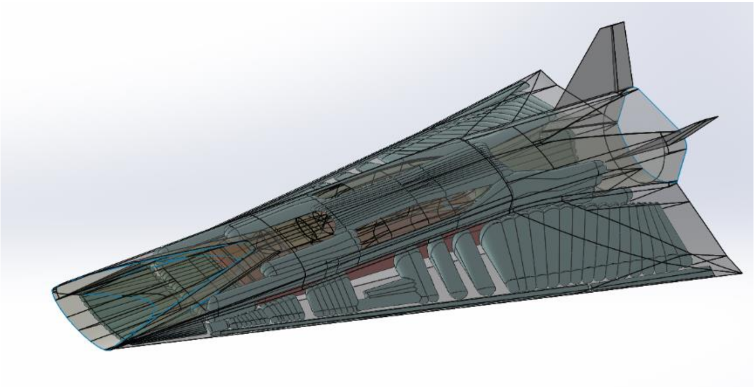
- Thermodynamic model of the propulsion system for 1D transient simulations and for extensive optimization study done to determine the conditions for reliable operation with best performance

Future Work

- Assessment of AEDB (external surfaces only) by engineering methods (different for Mach no. ranges) with the effect of deflected control surfaces as ailerons, rudders, etc.
- Flight Mechanics analysis (longitudinal and lateral-directional static stability, roll-yaw coupling, trimmability)
- New flight trajectory generation and optimization (with updated MCI data and AEDB)
- Optimization of ATR heat exchangers and expander elements to achieve right sizing for the propulsion system components, optimization of the DMR combustor







THANKS FOR YOUR ATTENTION !

STRATOFLY MR3 1:100 model exhibited at AEROdays 2019 (Bucharest)