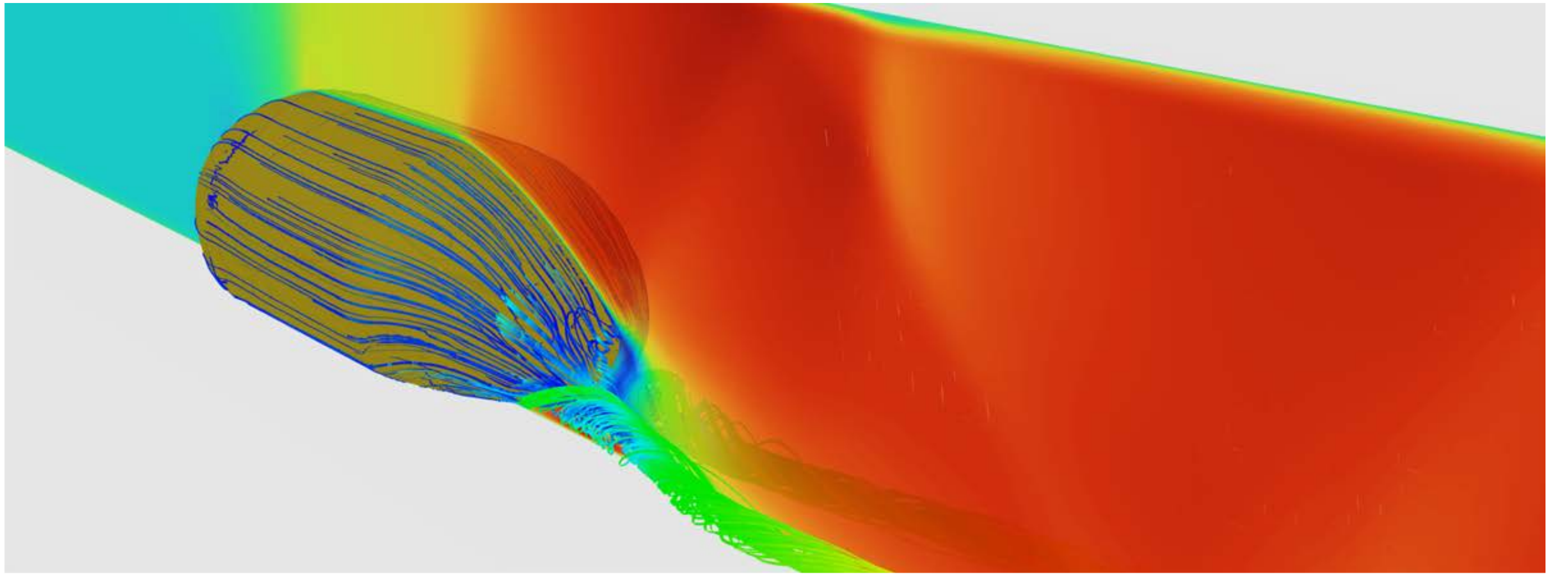

AERODYNAMICS OF VEHICLES IN VACUUM TUBE SYSTEMS

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Théo Mercat, Christian Pinas-salles, Mathias Widmer, Assistants

HEPIA Geneva Wind Tunnels

Vacuum Transport Seminar
November 21, 2022

L'avenir est à créer

hepia
Haute école du paysage, d'ingénierie et d'architecture de Genève

Hes·so Genève
Haute Ecole Spécialisée de Suisse occidentale

1. INTRODUCTION – VACUUM TUBES, WHY?

Challenges : « High speed with less resistance ». However, in Switzerland other aspects are also interesting:

- Less surface on the ground. Less objections for project applications!
- Less noise pollution
- Environementally friendly(?) → Depend on project choices!

History : Not a new idea! Some projects are:

1960	Office for High Speed Ground Transportation (USA), projects at the Jet Propulsion Lab (CalTech), MIT, Illinois Institute of Technology, ecc.
1974	Institut Battelle « The quiet Tube Train »
1975	Illinois Institute of Technology, « Pneumatic air vacum propulsion system »,
1994	EPFL, Swissmetro SA, Prof. Marcel Jufer
2013	Hyperloop, SpaceX, Hyperloop Alpha Description, then student competition, several projects in the world.
2015	Actually projects exist in numerous countries, also in Switzerland. Delft, Canada, EPFL, Eurotube Foundation, ecc.

1. INTRODUCTION

HES-SO PROJECT OBJECTIVES

Complete the work done by the actual actors, on subjects not completely coverred, and in the competences of university of applied sciences:

- Integration in the Swiss transport policy
- Socio-cultural acceptance
- Industrial dimensioning (maintenance, costs, investments)
- Safety (in regard of the operation of a vacuum train?)
- Developement of methodology for aerodynamics, thermal aspects, electricity management, sustentation, propulsion, composite structure.
- Support for Eurotube Foundation projects

Offer these knowledge in a vaccum tube transport project.

→ **HES-SO Project GRIPIT**

1. INTRODUCTION - HES-SO PROJECT GRIPIT

Groupe de Recherche Interdisciplinaire en Projets Innovants de Transport (GRIPIT)

- Prof. Samuel Chevailler, HES-SO//Valais (magnetic levitation, motors)
  Electromagnetism and electrical energy, project manager
- Prof. Joël Cugnoni, HEIG-VD (ex. Hyperloop EPFL)
  Multifunctional structure, composite materials
- Prof. Carole Baudin, HE-ARC
  Anthropotechnology, socio-cultural context
- Prof. Vincent Bourquin, HEIA-FR (ex. Swissmetro SA 1990, Prof. Jufer)
  Systemic model, safety
- Prof. Patrick Haas, HEPIA (ex. ARD SA, Bombardier Inc., Eurotunnel)
  Aerodynamic, thermal, safety

2. AERODYNAMICS

Demystifying beliefs! Physics tells us:

- The vacuum is not enough to go fast!
- The drag is proportional to the density in subsonic regime.
- In supersonic (high blocking ratio, i.e. small tunnel) :

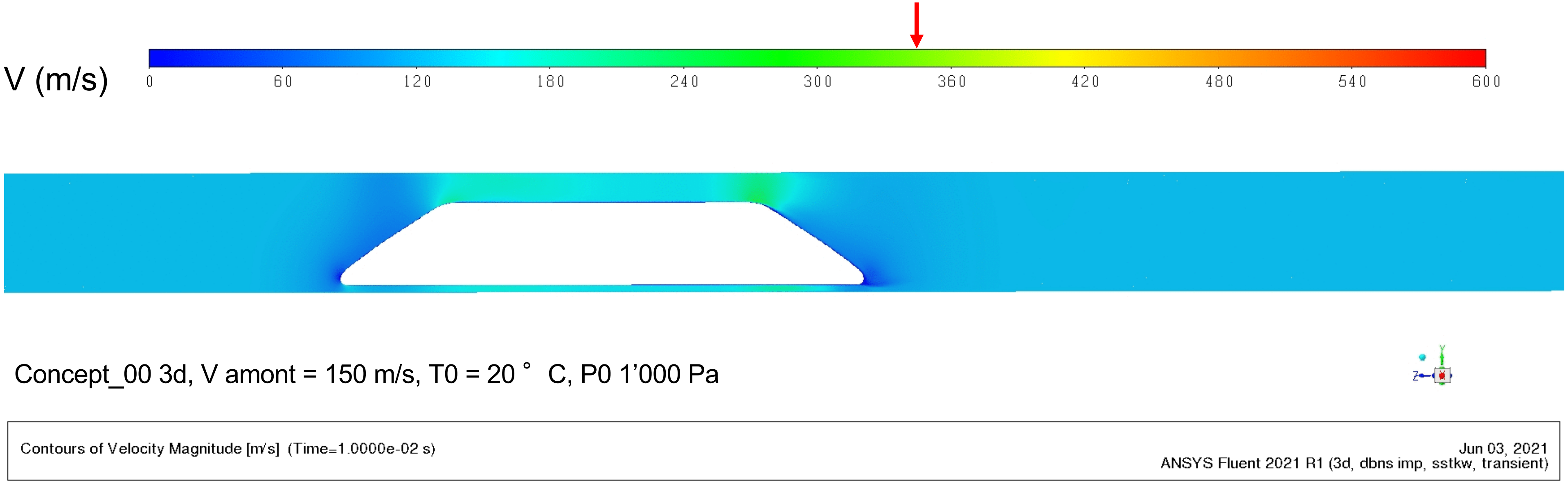
→ Sonic blocking appears!

- The speed of sound is then the sensitive parameter. It is not possible to go much beyond this one.
- Thermal ? How to cool a machine dissipating 50 to 500 kW in vacuum? At 100 Pa (1 mbar), ΔT are multiplied by 1'000 !

2. AERODYNAMICS

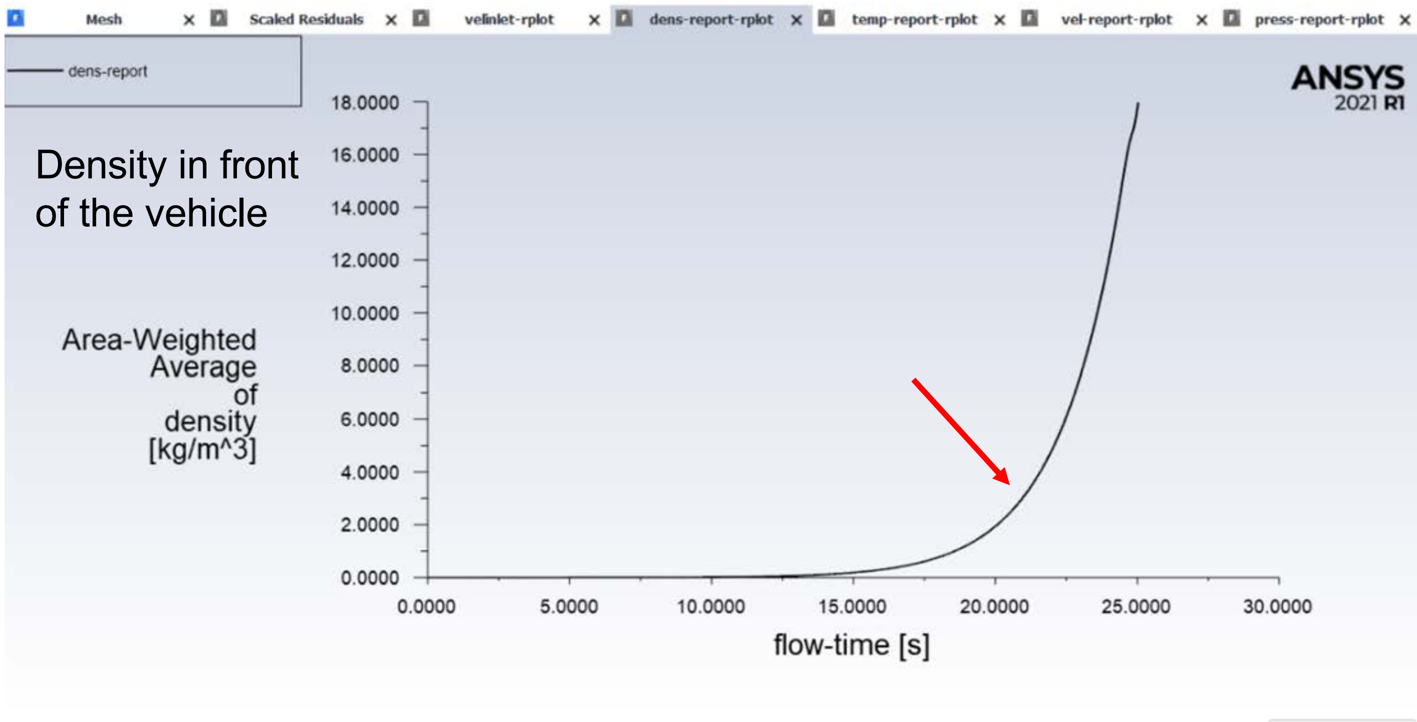
MOTION OF VEHICLES IN TUNNELS

Speed of sound (343 m/s)



- The speed of sound is reached in the annular section
- Presence of shock waves and expansions downstream of the vehicle (supersonic regime)
- Constancy of the Mach number in the annular section (Ma 1.0)
- The speed does not evolve significantly whatever the upstream pressure !

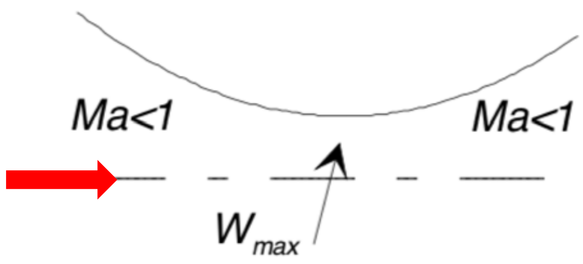
2. AERODYNAMICS
EVOLUTION OF VARIABLES AND SONIC BLOCKING



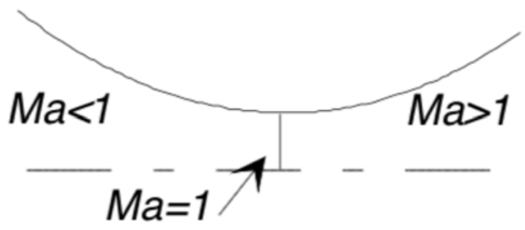
→ **Sonic blocking**

2. AERODYNAMICS

FLOW IN A CONVERGENT - DIVERGENT SECTION



Subsonic Subsonic



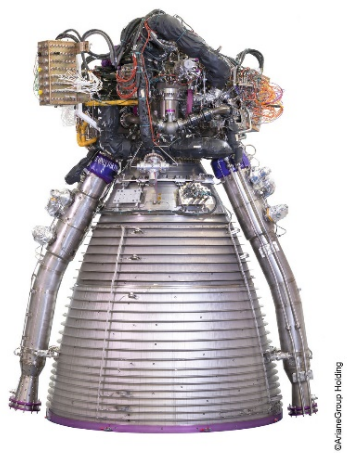
Subsonic Supersonic

Soyouz rocket

Hugoniot theorem

$$(Ma^2 - 1) \cdot \frac{dW}{W} = \frac{dS}{S}$$

→ Relation between Ma and section S



Vulcain motor - Ariane

2. AERODYNAMICS – SONIC BLOCKING

Hugoniot theorem

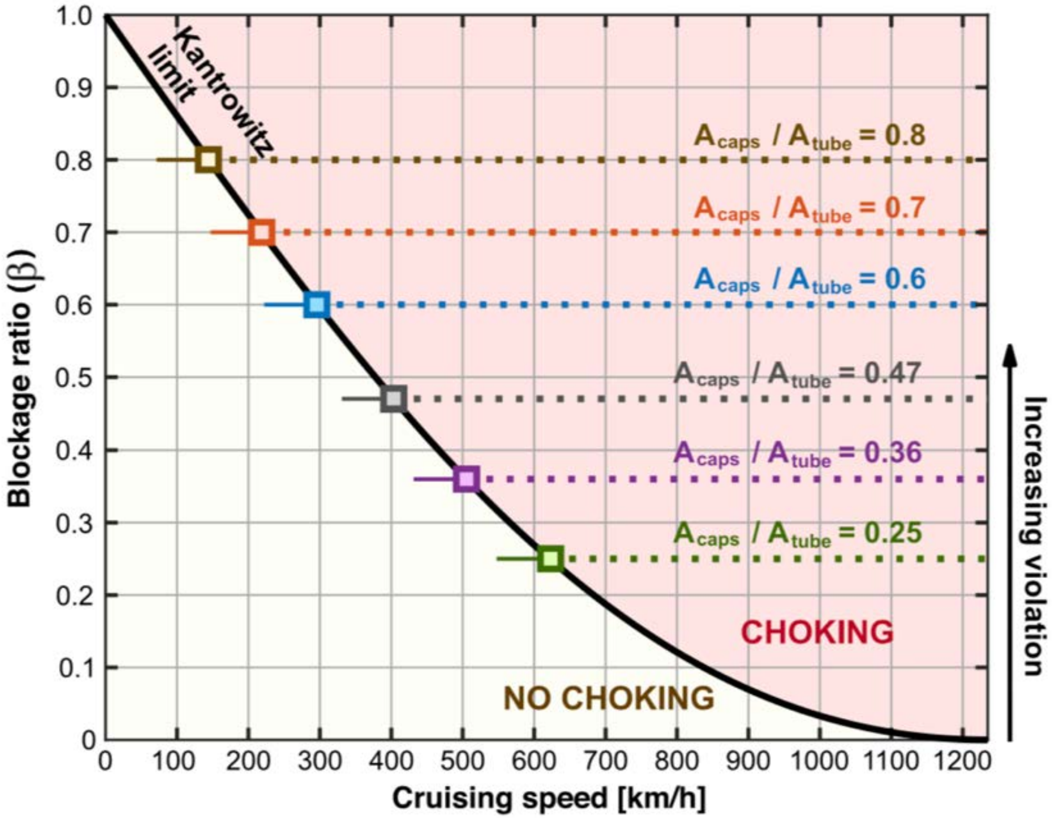
$$(Ma^2 - 1) \cdot \frac{dW}{W} = \frac{dS}{S}$$

$$Ma = \frac{W}{a} \qquad a = \sqrt{\kappa\, r\, T}$$

- When the speed W reaches the speed of sound a in the annular section, the vehicle is "blocked"! The supersonic regime starts.
- At the nozzle throat dS = 0 and therefore Ma = 1.0. W = a (speed of sound) always!
- The speed of sound is not influenced by the pressure! It is a function of the gas characteristics κ, r and temperature.
- So the pressure is not the determining criterion if you want to go fast!
- It only reduces the drag in subsonic regime. The problem is that the sonic limit is obtained soon for a high blockage ratio (> 0.40).

2. AERODYNAMICS – SONIC BLOCKING

When we use a blocking ratio, we introduce the Kantrowitz limit:



$$\frac{1}{1-\beta} = \frac{1}{\mathrm{Ma}}\left(\frac{1+\left[\frac{\gamma-1}{2}\right]\mathrm{Ma}^2}{1+\left[\frac{\gamma-1}{2}\right]}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

Blockage ratio:

$$\beta = \frac{Vehicle\ section\ area}{Tunnel\ section\ area}$$

(J.K. Noland, NTNU, Values at 15 degC)

3. DISCUSSION ON THE TUNNEL ENVIRONEMENT

Our argument is as follows:

1. We should come back to the hypothesis regarding the environment. If a closed environment is realized, it is necessary to go further than making the vacuum. We should act on the sensitive parameters who are the characteristics of the gas (Cp and Cv) and the temperature !

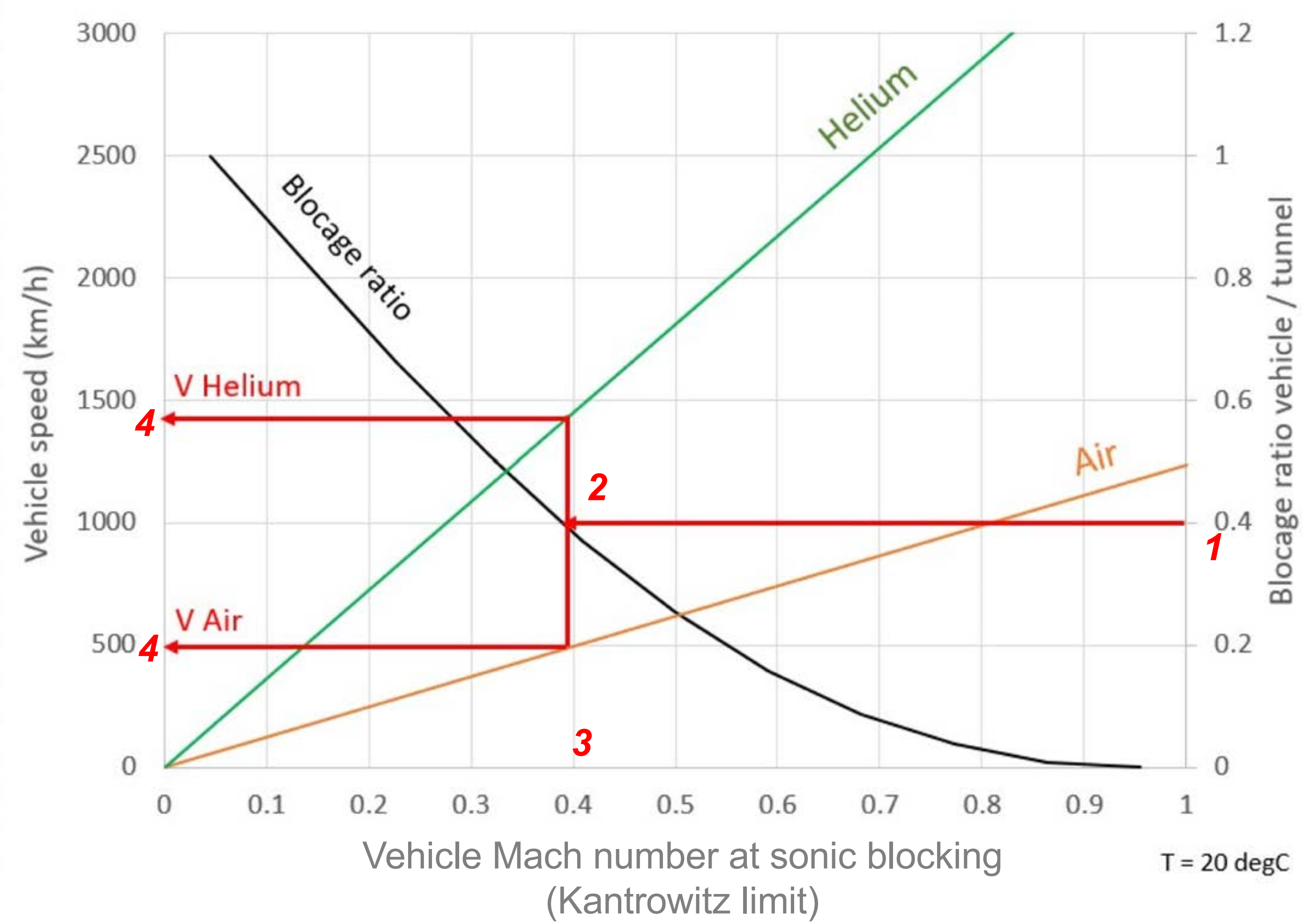
2. Our objective is to increase the speed of sound (> 800 m/s)

   → Allow the use of smaller tunnels (high blockage ratio)

3. Our research is directed beyond the use of air under vacuum at room temperature:

   - We look for other gases: Helium, Hydrogen, mixtures
   - Higher temperatures
   - Two-phase fluid (cooling by evaporation/condensation, water evaporates at about 7 ° C at 1’000 Pa).

3. DISCUSSION ON THE TUNNEL ENVIRONEMENT



Example:

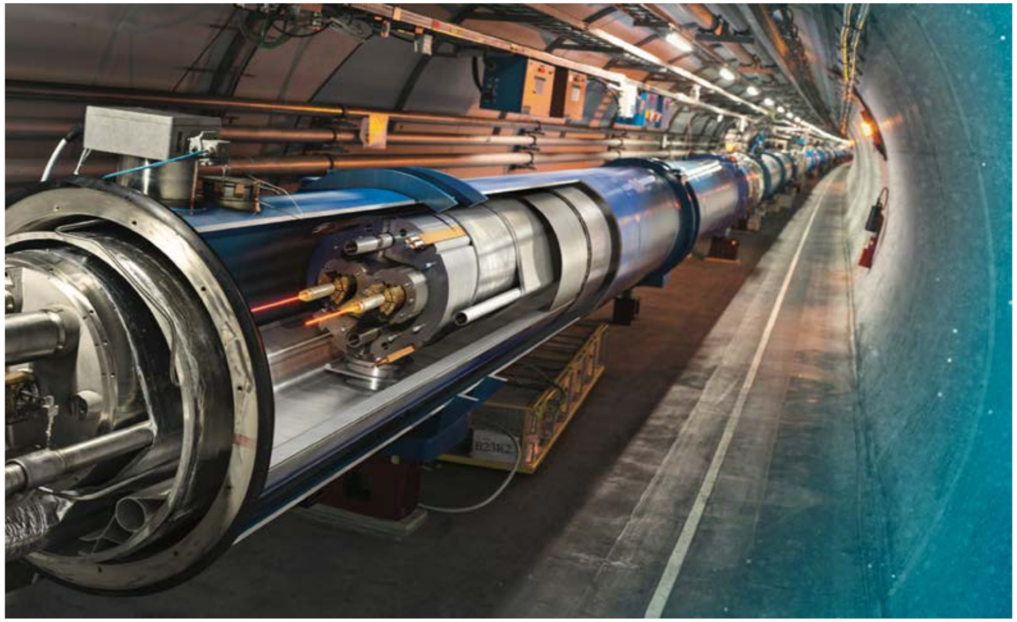
Si A_v / A_t = 0.40
Kantrowitz: Ma 0.40

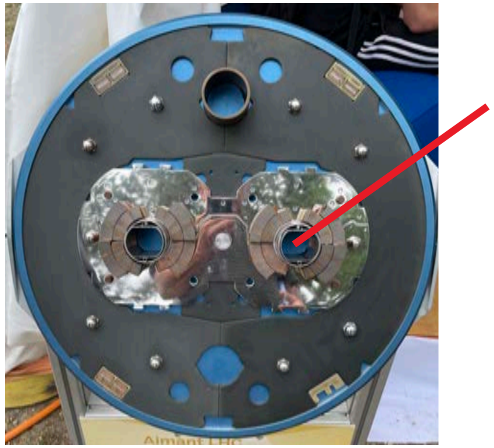
Air : 500 km/h
Helium : 1'400 km/h

EXPLORE THE USE OF HELIUM !

3. DISCUSSION ON THE TUNNEL ENVIRONEMENT

Is it reasonable to use helium? Large industrial projects exist. CERN surely has things to show.





P = 10^{-13} bars
T = 1.9 K
L = 27 km

CERN LHC

- A better vacuum than on the moon! They know how to extract fluid particles from a tube!
- Imagined in 1980, work started in 1994! Operational in 2010 !
- More difficult things: Helium disponibility for industry?

4. METHODOLOGY USED AT HEPIA-CMEFE

Our group develops multidisciplinary methodologies of CFD simulations and experimental works in parallel.

Chapter 1: CFD

Calculation tools:

With UNIGE :

Baobab HPC : 4'200 CPU, 95 GPU, 10 Tb RAM
Intel Sandy Bridge, Broadwell and Cascade Lake,
Yggdrasil HPC : 4'300 CPU, 52 GPU, 10 Tb RAM,
Intel Gold

Group Workstations:

EoleC6: Dell, 96 CPU, 512 Gb RAM
Workstations: 1 x WS of 48 CPU, 384 Gb et 8 x WS of 16 CPU, 126 Gb RAM
Storage (NAS): 2 x 120 Tb = 240 Tb, managment of confidentiality
CFD software: ANSYS CFD Associate (« industrial »), Research and Teaching – ANSYS Academic Partner

4. METHODOLOGY USED AT HEPIA-CMEFE

Chapter 2: Experimental – AEROTUBE

A supersonic wind tunnel for the aerodynamics of vehicles in tunnels:

GRIPIT Concept_00
diam. 47 mm

- Air tank: 20 m^3, 16 bars, 100 degC, blasts of 60 sec
- Test section 8 x 12 cm^2
- 0.8 < Ma < 2.4
- Measurement of Ma, pressures and temperatures
- Test done in Ma similitude, scale approx. 1:50

5. CFD ANALYSIS

Validity of a finite volumes CFD approach in vacuum

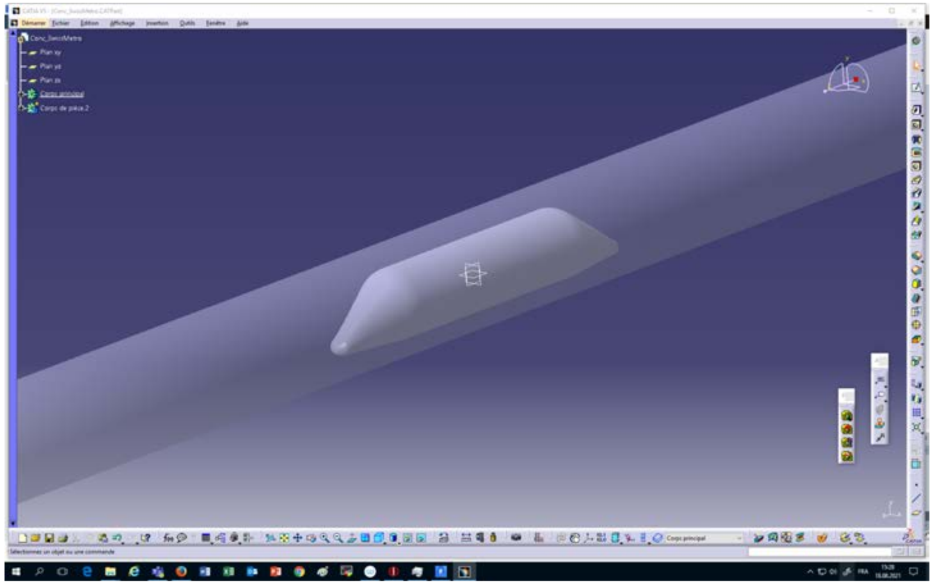
Knudsen number: $Kn = \frac{\lambda}{L}$ $\lambda = \frac{\mu}{P}\sqrt{\frac{\pi RT}{2M}}$

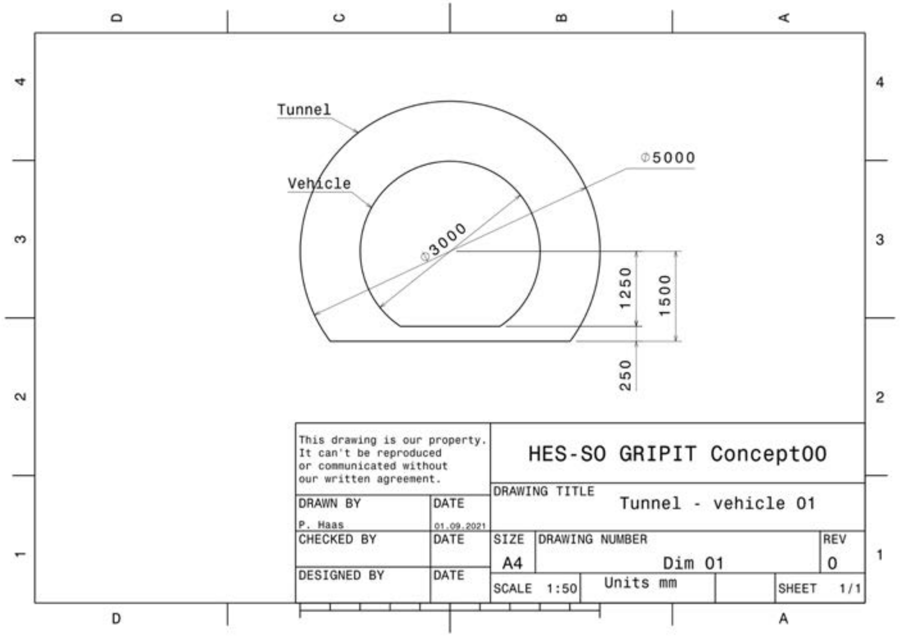
L	Length characteristic
λ	Free movement length of a particle
μ	Dynamic viscosity Pa.s
P	Pressure Pa
R	Gaz constant 8,314 $J.K^{-1}.mol^{-1}$
M	Molecul mass $kg.mol^{-1}$

- The medium is said to be continuous, and a finite volume solver usable, if $Kn<0.01$. This is the case!
- Remark: In Fluent, the "Low-pressure boundary slip" model in "Turbulence / Laminar", allows to work between 0.01 < Kn < 0.1.

5. CFD ANALYSIS

Vehicle geometry, base case





Concept_00 (simple, inspired Swissmetro 1990)
Section vehicle : 6.8 m^2
Section tunnel : 16.8 m^2
Blockage ratio : 0.40

5. CFD RESULTS

Preliminary results with Concept_00 to understand the evolution of some quantities (Fluent solver, k-w SST model, compressible, unsteady).
Computing time: About 1/2 day, 48 cores.

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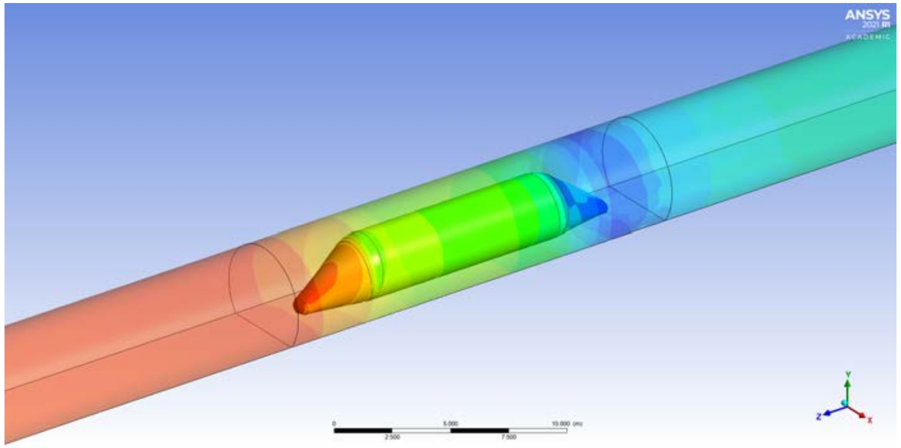


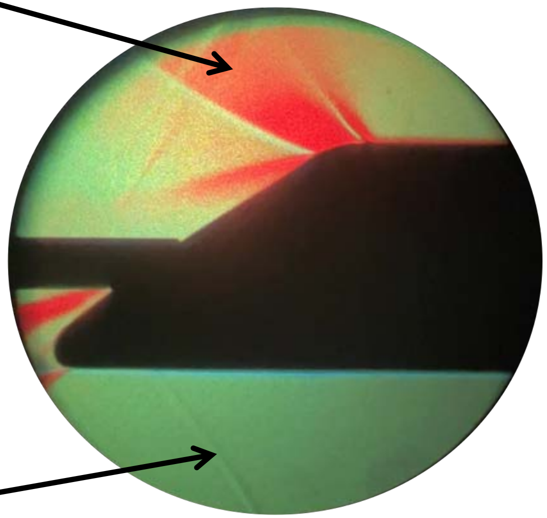
- Forces and moments
- Convection
- Pressures (distribution)
- Unsteady phenomena

→

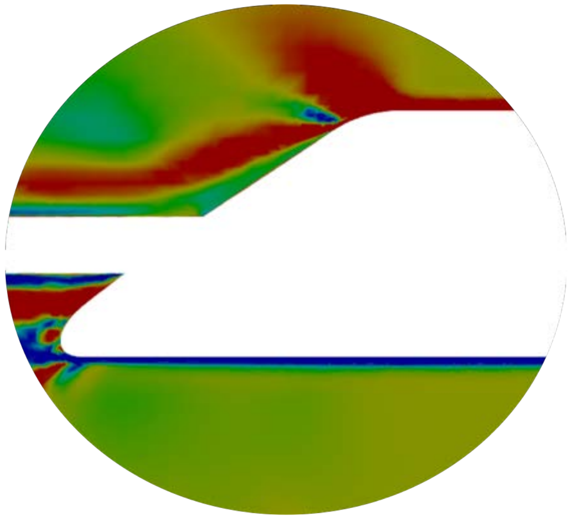
Vehicle dynamic study
Thermal study
Structure design
Tunnels, fatigue, installations

5. CFD - RESULTS

CFD Validation using Aerotube results



Aerotube experiment
Schlieren optical system

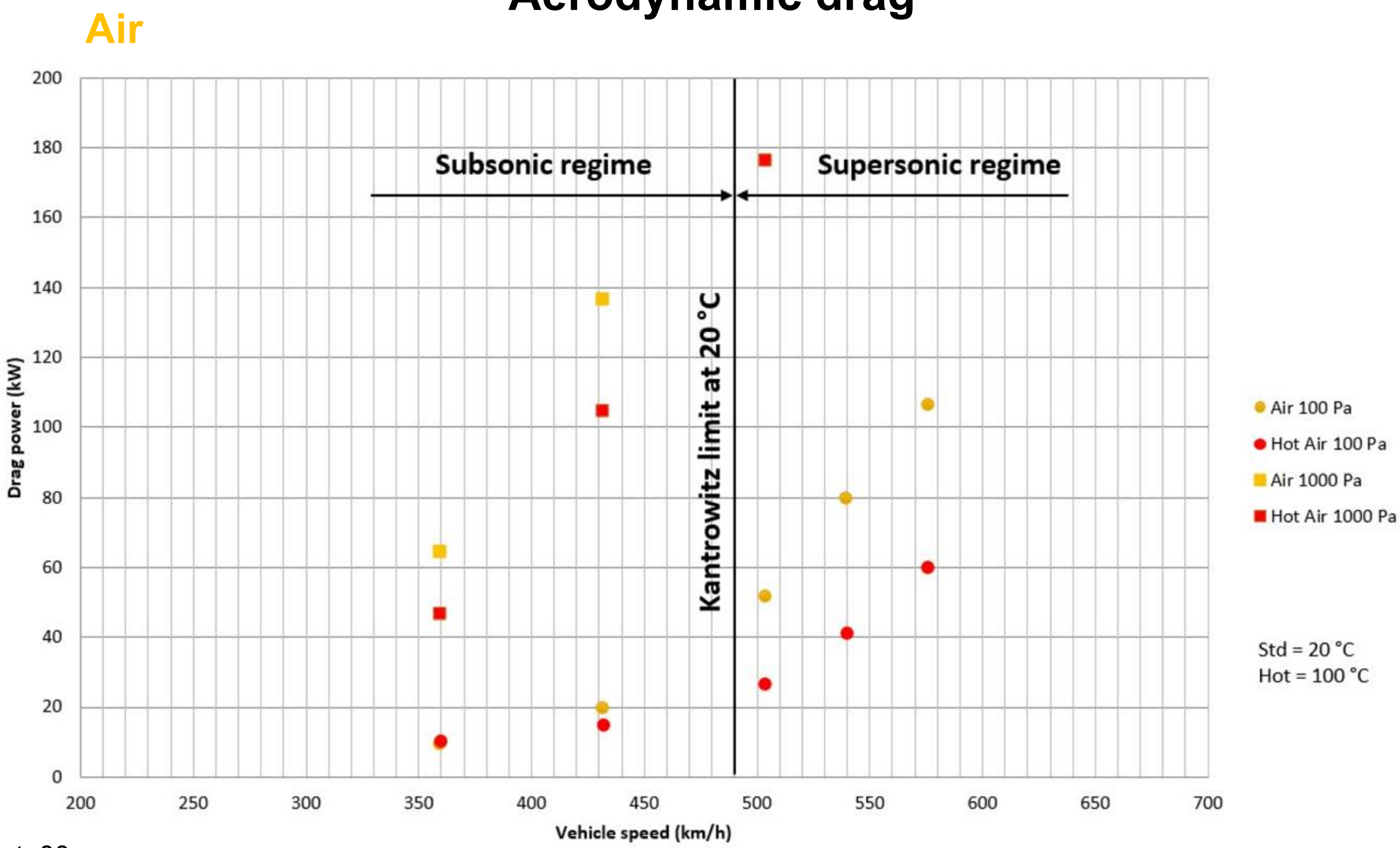


CFD simulation
Air density gradient

Concept_00
Blockage ratio: 0.40

5. CFD - RESULTS

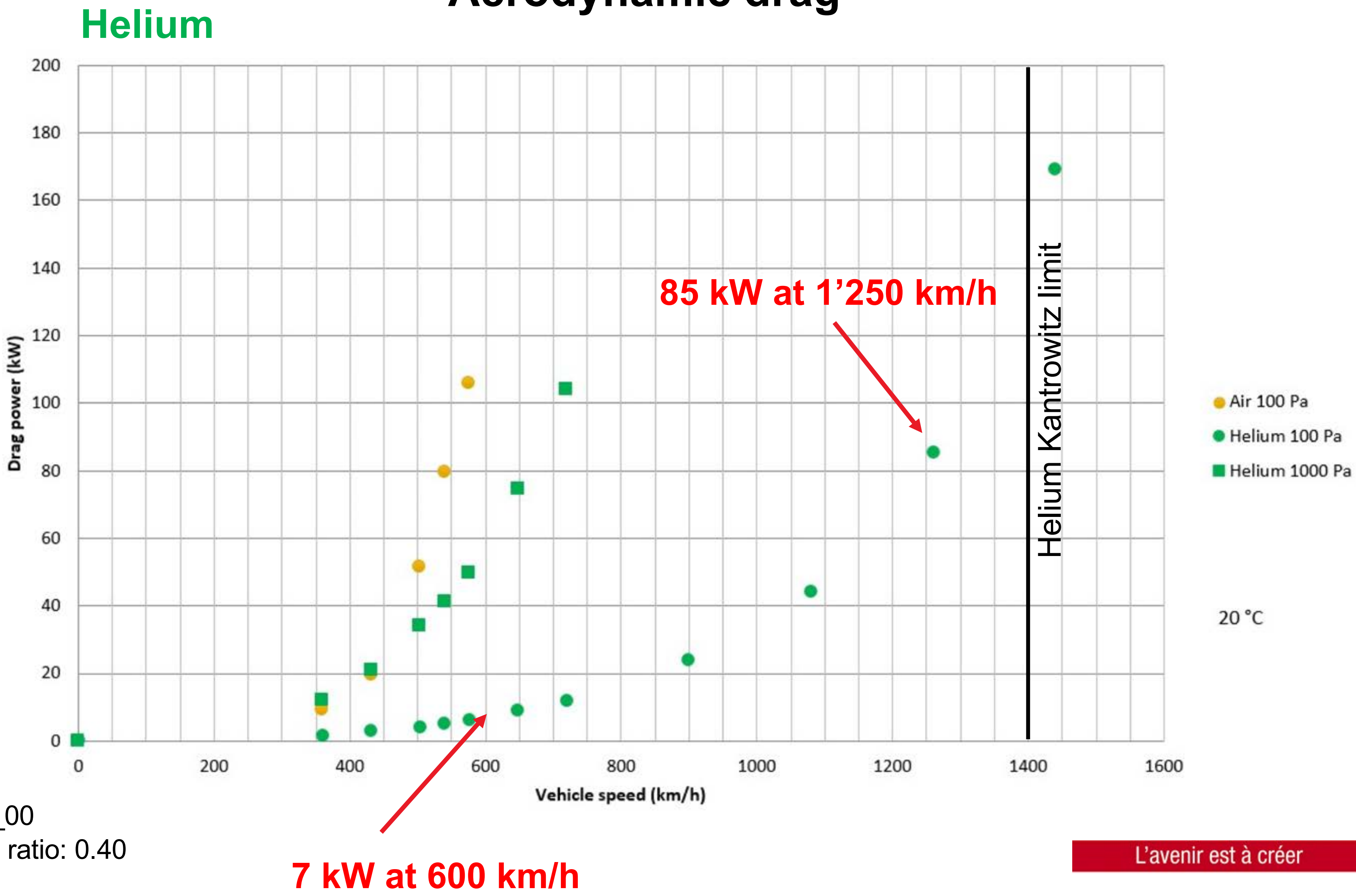
Aerodynamic drag



Concept_00
Blockage ratio: 0.40

5. CFD - RESULTS

Aerodynamic drag



Concept_00
Blockage ratio: 0.40

6. WHAT SOLUTION TO CHOOSE?

We can imagine the following projects:

1. « Classical » air project:

V = 600 km/h
Blockage ratio: 0.40 (tunnel diameter 5.0 m)
Aerodynamic power: 130 kW

2. High speed helium project and small tunnel (low investment):

V = 1'000 km/h
Blockage ratio: 0.60 (tunnel diameter 4.4 m)
Aerodynamic power: 100 kW

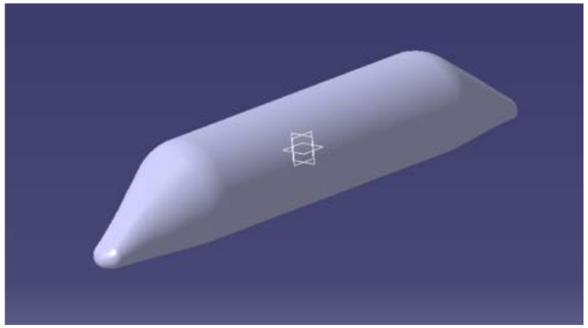
3. Low energy helium project:

V = 600 km/h
Blockage ratio: 0.40 (tunnel diameter 5.0 m)
Aerodynamic power: 7 kW
Magnetic drag of sustentation ? Wheels?

(These values are for 100 Pa and 20 ° C)

7. CFD RESULTS – GEOMETRY OPTIMISATION

Concept_00
Swissmetro 1990



Step 1

Concept_01
Haack's ogive

Haack's ogive

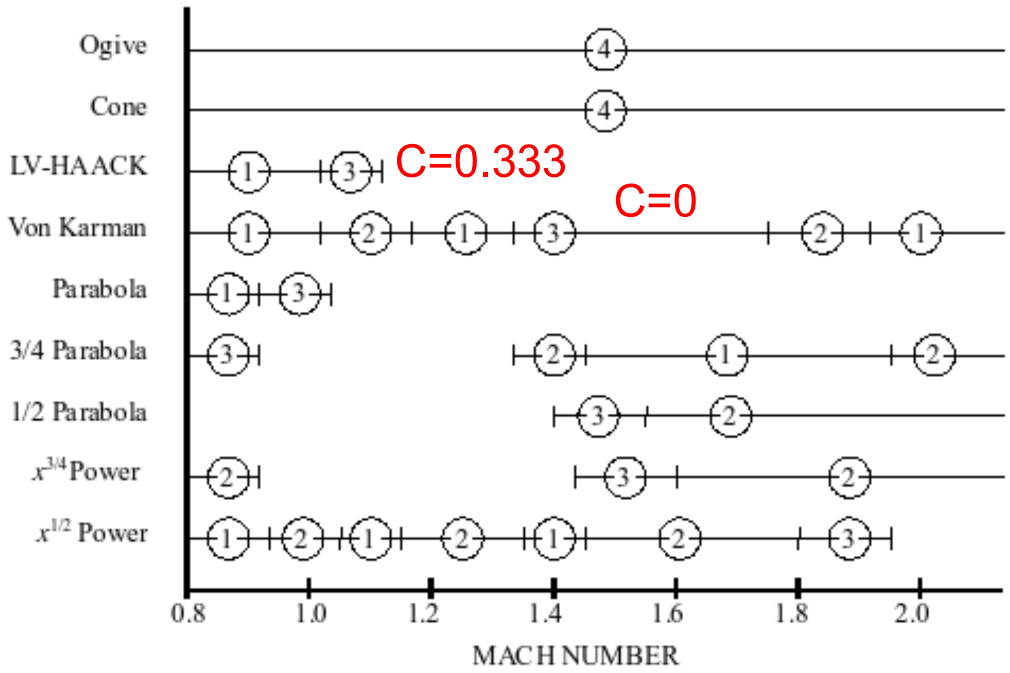
7. CFD RESULTS – GEOMETRY OPTIMISATION

<u>Haack's theory</u>:

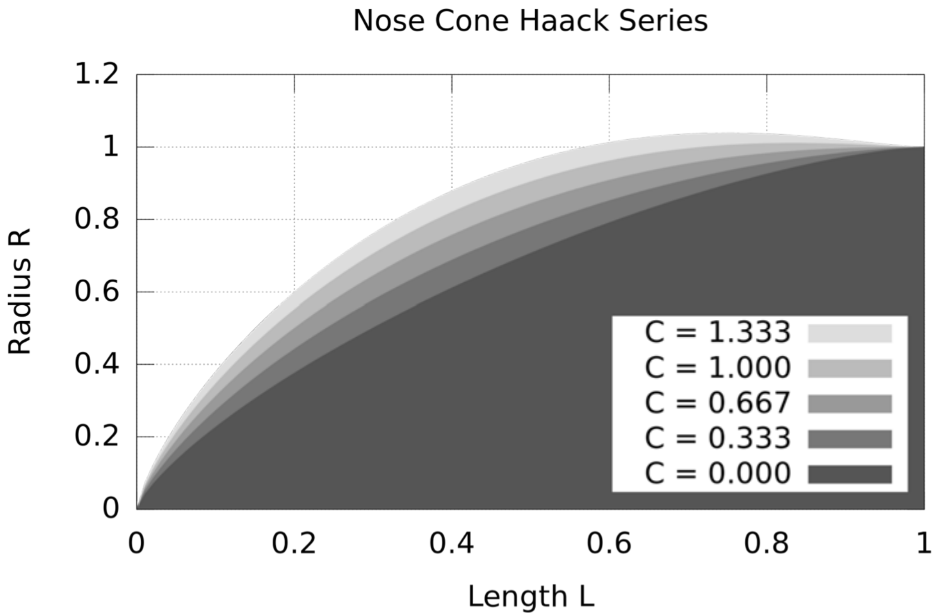
We choose the von Karman one with C = 0 for best performances in transonic regime

$$\theta = \arccos\left(1 - \frac{2x}{L}\right)$$

$$y = \frac{R}{\sqrt{\pi}}\sqrt{\theta - \frac{\sin(2\theta)}{2} + C\sin^3(\theta)}$$



(Performance parameter: 1 good to 4 bad)



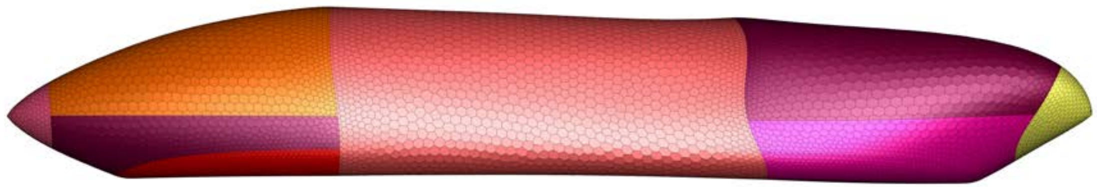
7. CFD RESULTS – GEOMETRY OPTIMISATION

Concept_01
Haack's ogive
(C = 0 von Karman,
two ends)

Step 2

CFD automatic optimisation using a gradient based model

Concept_02
HES-SO ogive

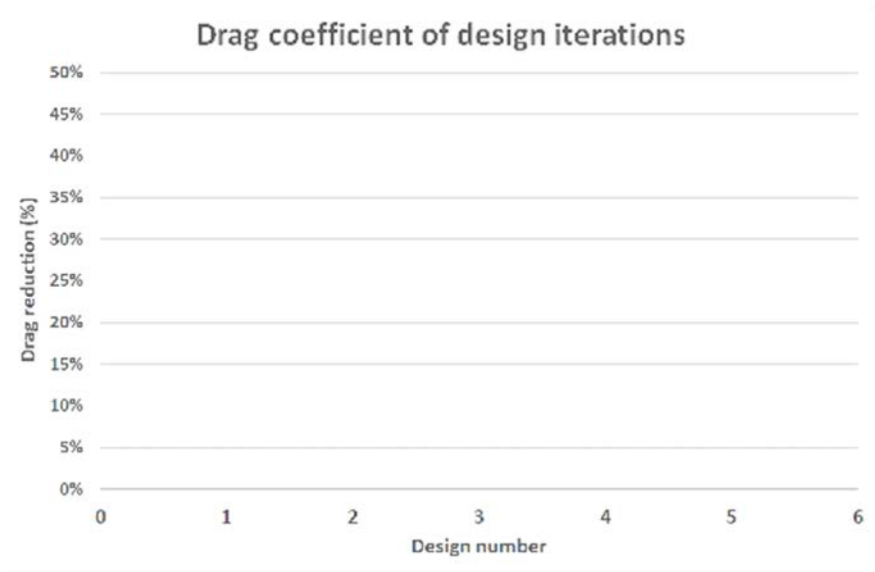


Optimized geometry

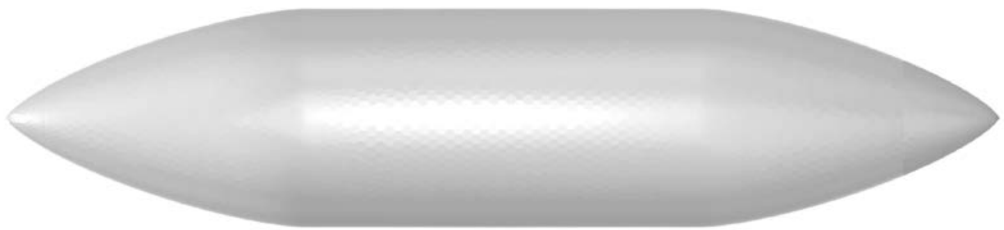
7. CFD RESULTS – GEOMETRY OPTIMISATION

- The changes reflect 3D effects: The Haack's ogive is 2D axisymetrical
- Our vehicle has two ends: The Haack's ogive second end is flat (projectile)

V = 600km/h
P = 100 Pa
Blockage = 0.25
Mach col = 0.95



- Gradient based optimizer
- Second order: pressure and movement
- Ideal gas



L'avenir est à créer

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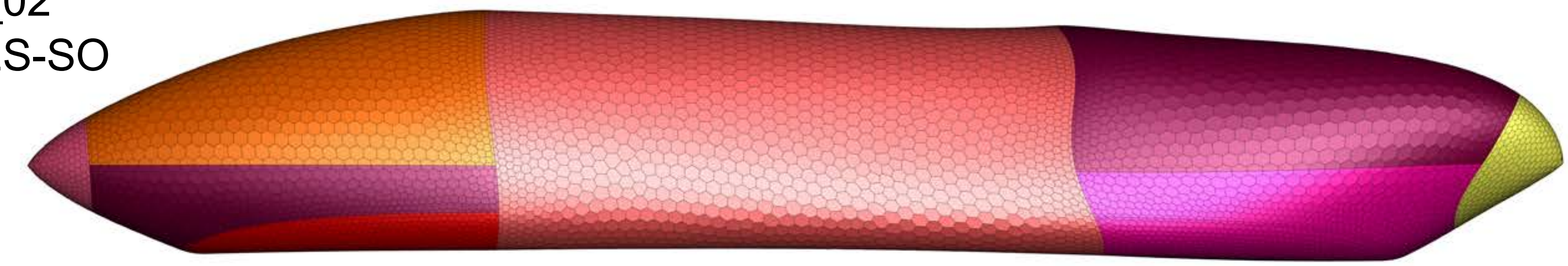
7. CFD RESULTS – GEOMETRY OPTIMISATION

Concept_01
Haack's ogive

Concept_02
Ogive HES-SO



Front end with
small changes

Rear end with
important changes

Optimized geometry

Aerodynamic drag reduction about 40%

L'avenir est à créer

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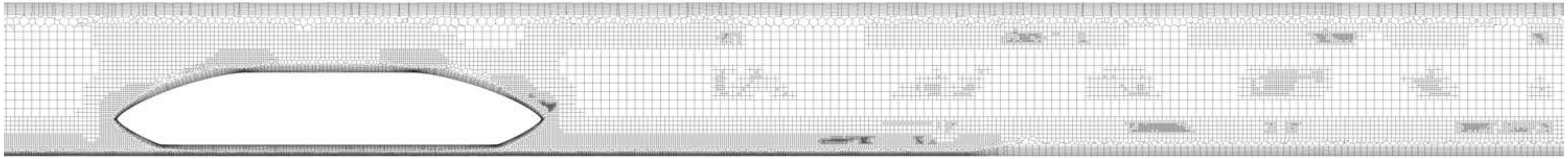
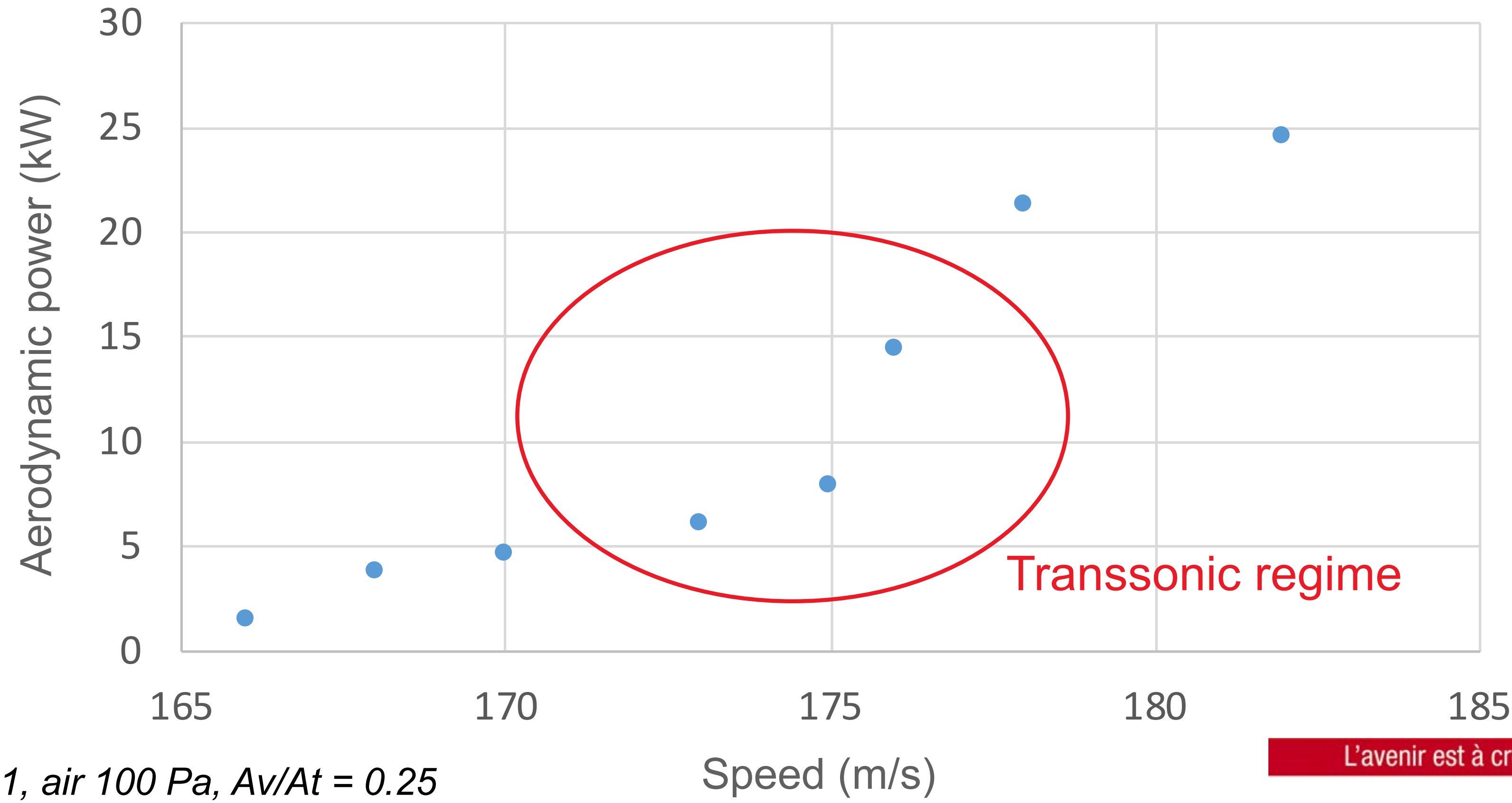
8. TRANSSONIC REGIME

3.5 Mio de mailles, hex-core adaptative, grad(P) model, kw-SST modified, compressible





Concept_01, air 100 Pa, Av/At = 0.25

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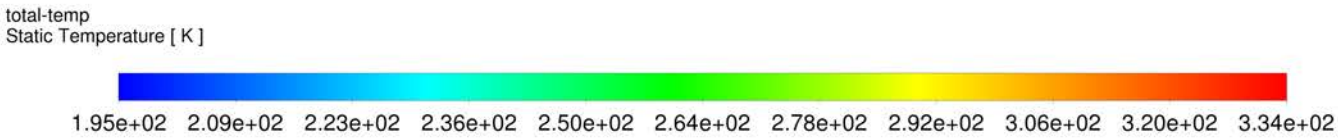
8. TRANSSONIC REGIME



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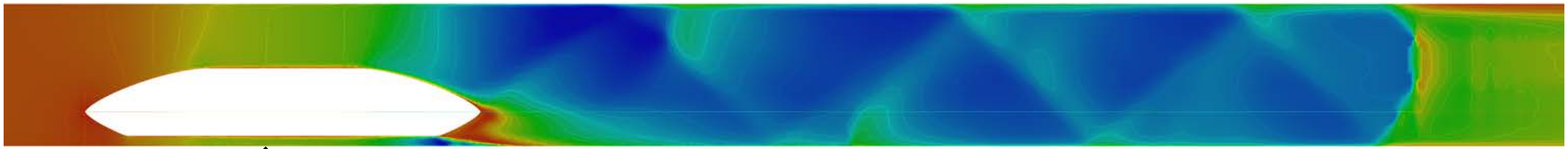
Increase of P, T

Static temperature (K)

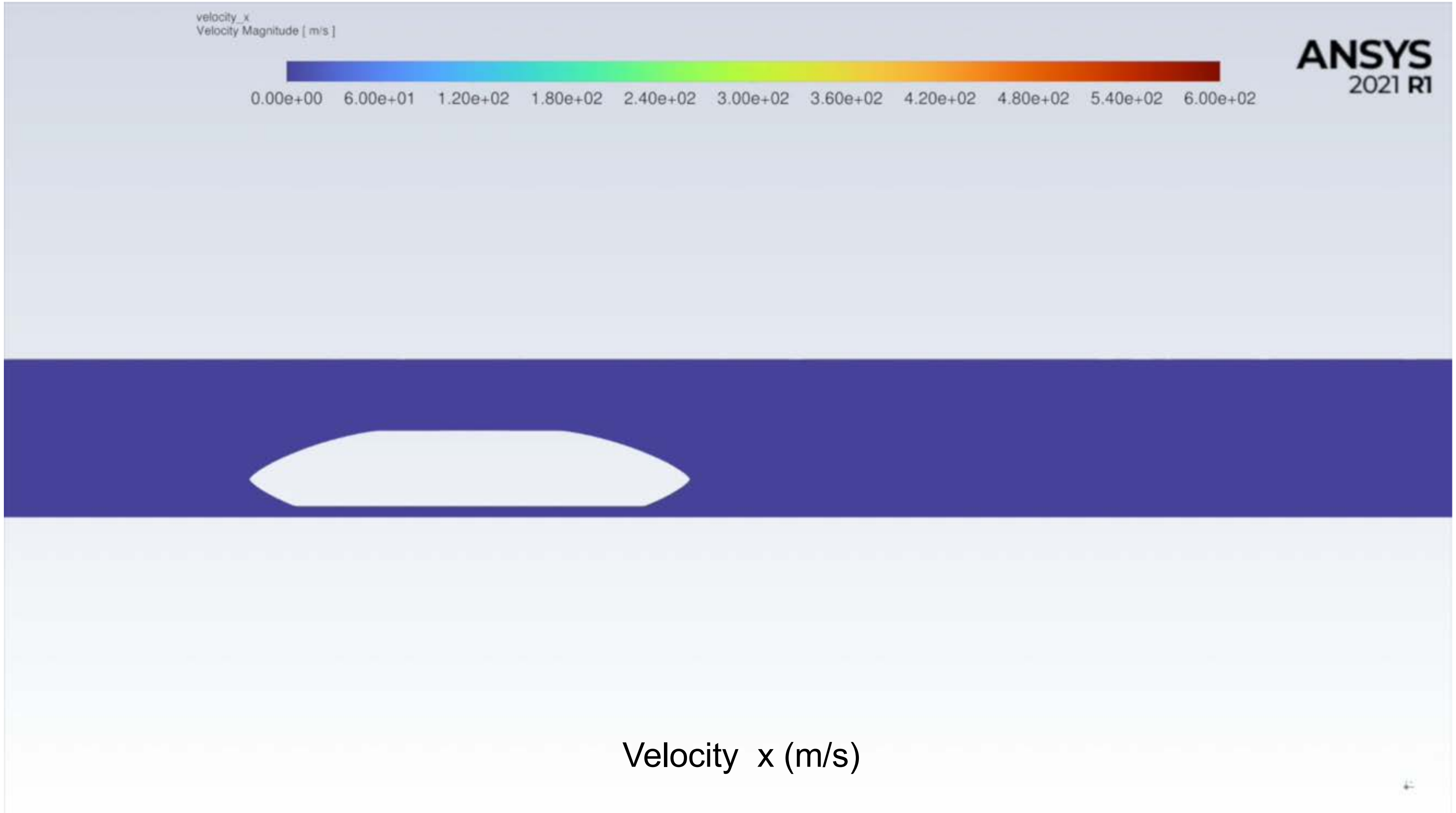


Ma = 1

Supersonic region with shocks and Prandtl-Meyer expansion waves reflected on the walls

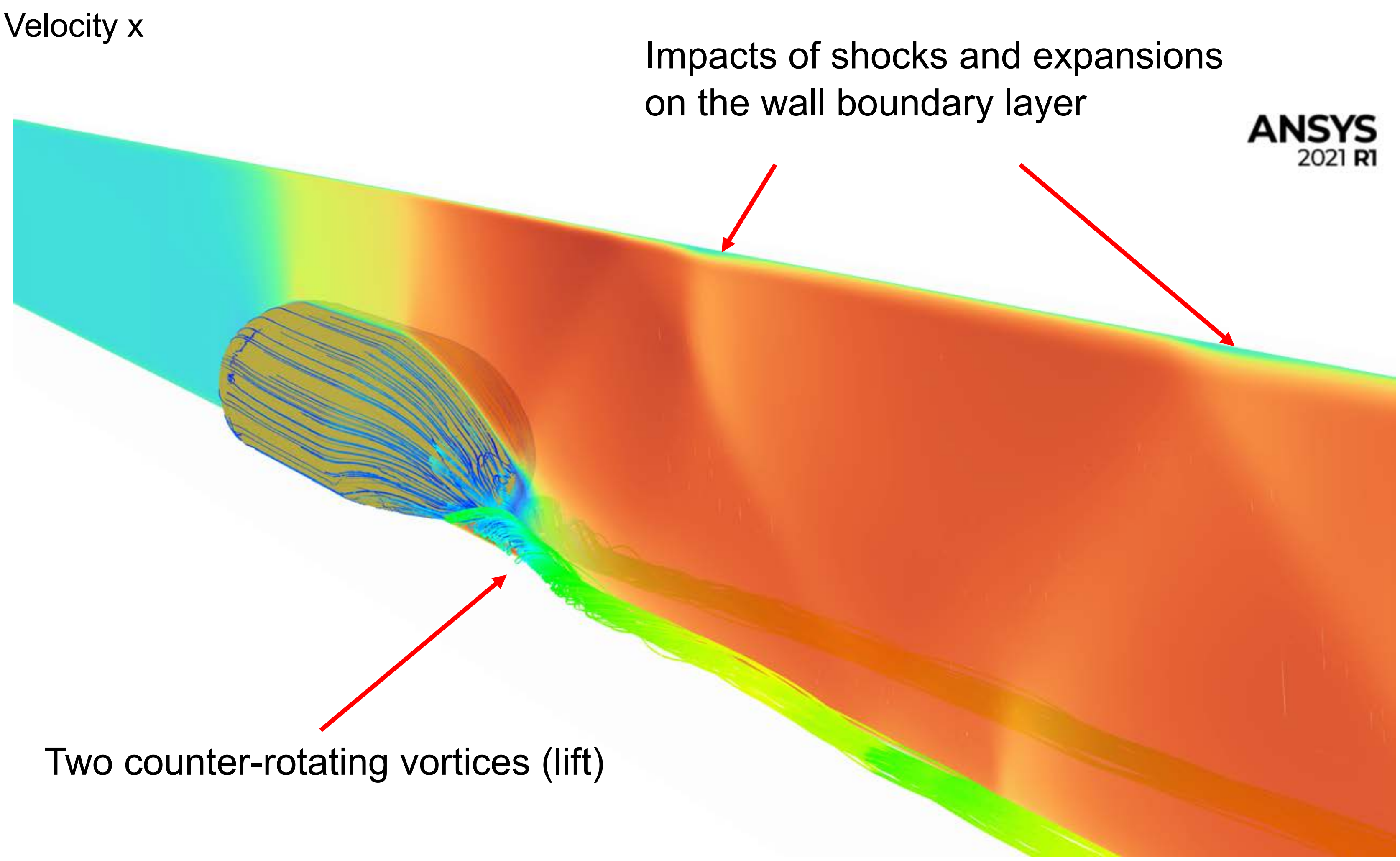
Concept_01, air 100 Pa, Ma 0.65 (178 m/s or 640 km/h)

8. TRANSSONIC REGIME



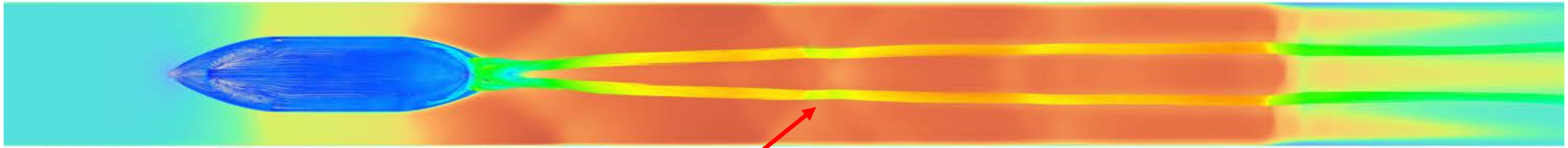
Concept_01, air 100 Pa, Ma 0.0-0.8, RB 0.25

8. TRANSSONIC REGIME



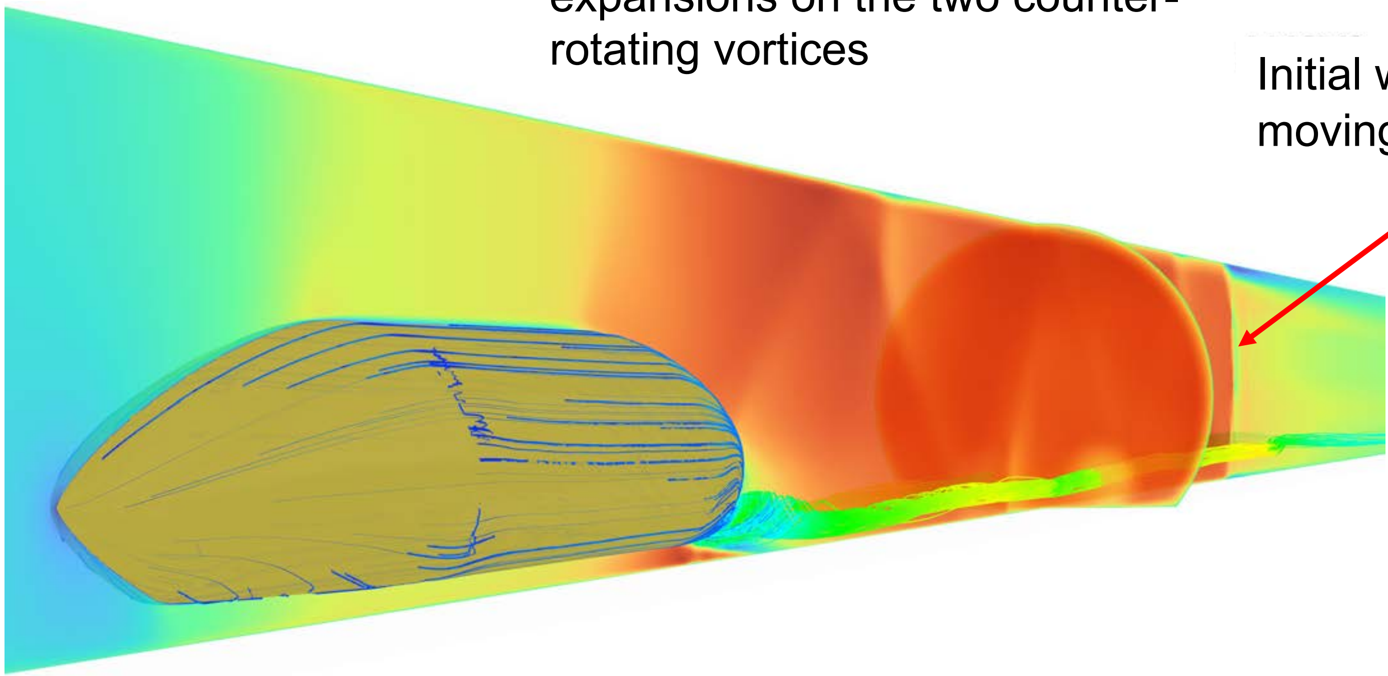
Concept_01, air 100 Pa, Ma 0.65 (178 m/s or 640 km/h)

8. TRANSSONIC REGIME



Impacts of the shocks and expansions on the two counter-rotating vortices

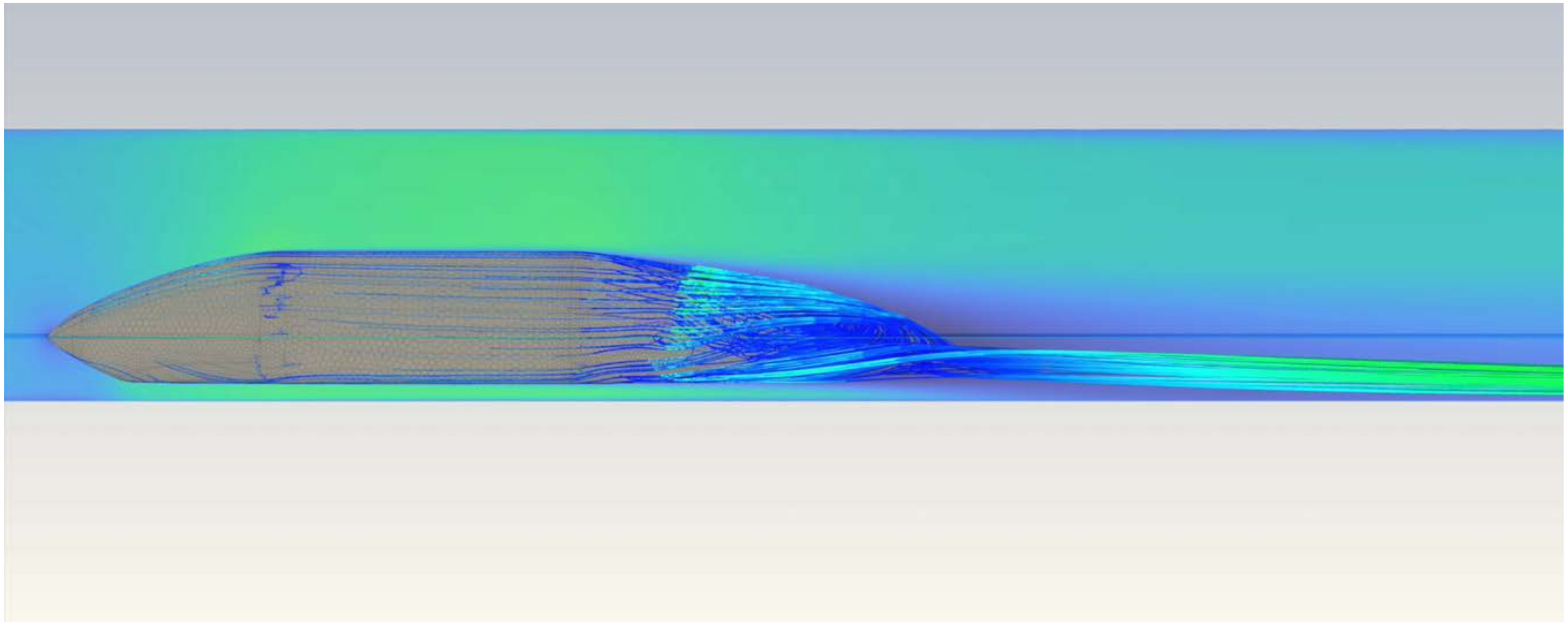
Initial wave (sonic speed) moving to tunnel extremity



Concept_01, air 100 Pa, Ma 0.65
(178 m/s or 640 km/h)

8. TRANSSONIC REGIME

Vehicle moving from Ma 0 to 0.8

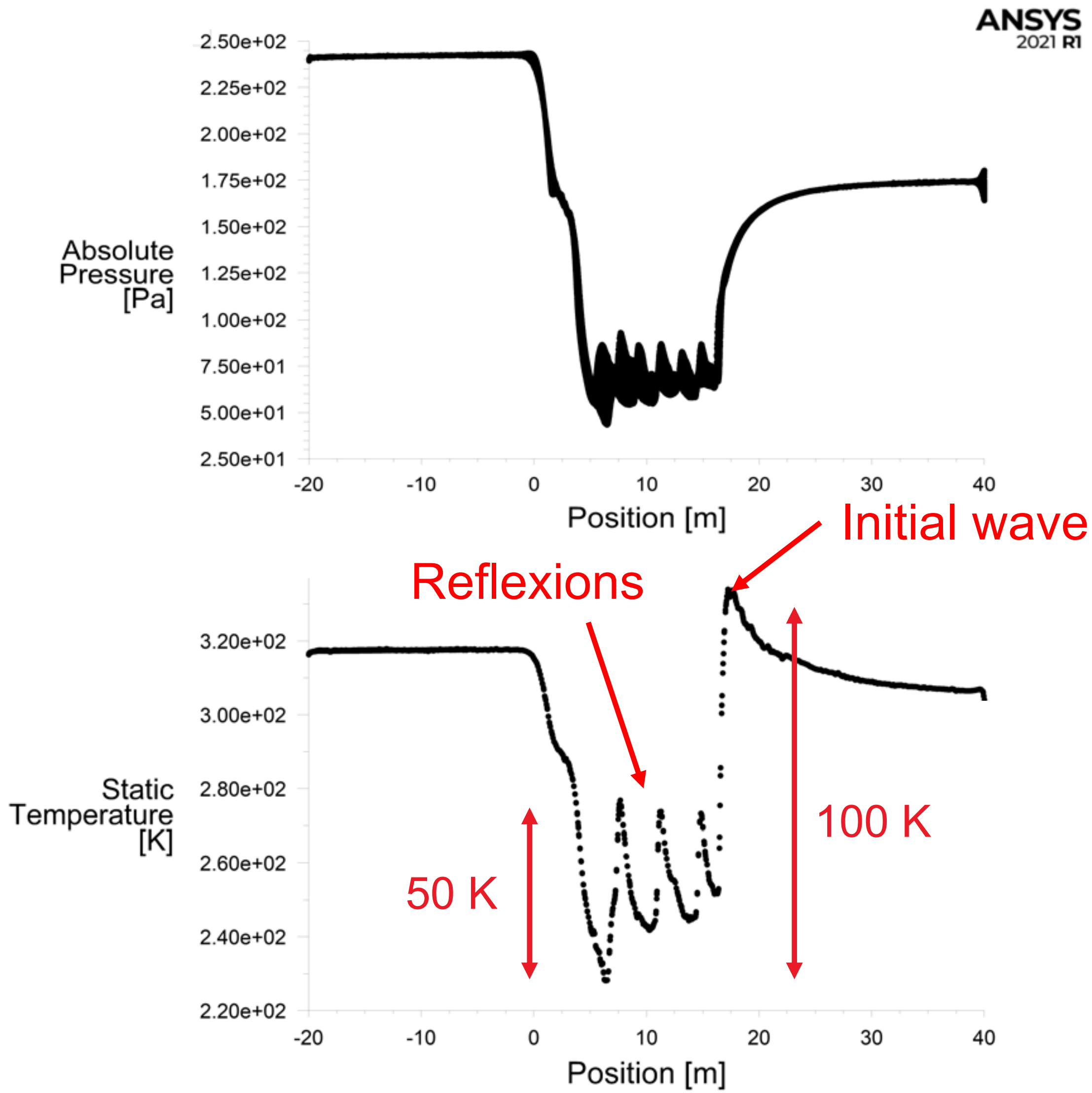


Streamlines colored by velocity (m/s)

Concept_01, air 100 Pa, Ma 0.0-0.8, RB 0.25

8. STRESSES ON THE TUNNEL WALLS

In the vicinity of the reflections of the waves on the walls:



Pressures and temperatures on the tunnel walls in transonic regime.

→ Highlight of the mechanical and thermal stresses

Fatigue loading cases

9. FINAL COMMENTS

OPTIMAL VEHICLE SPEED DEFINITION

Remark :

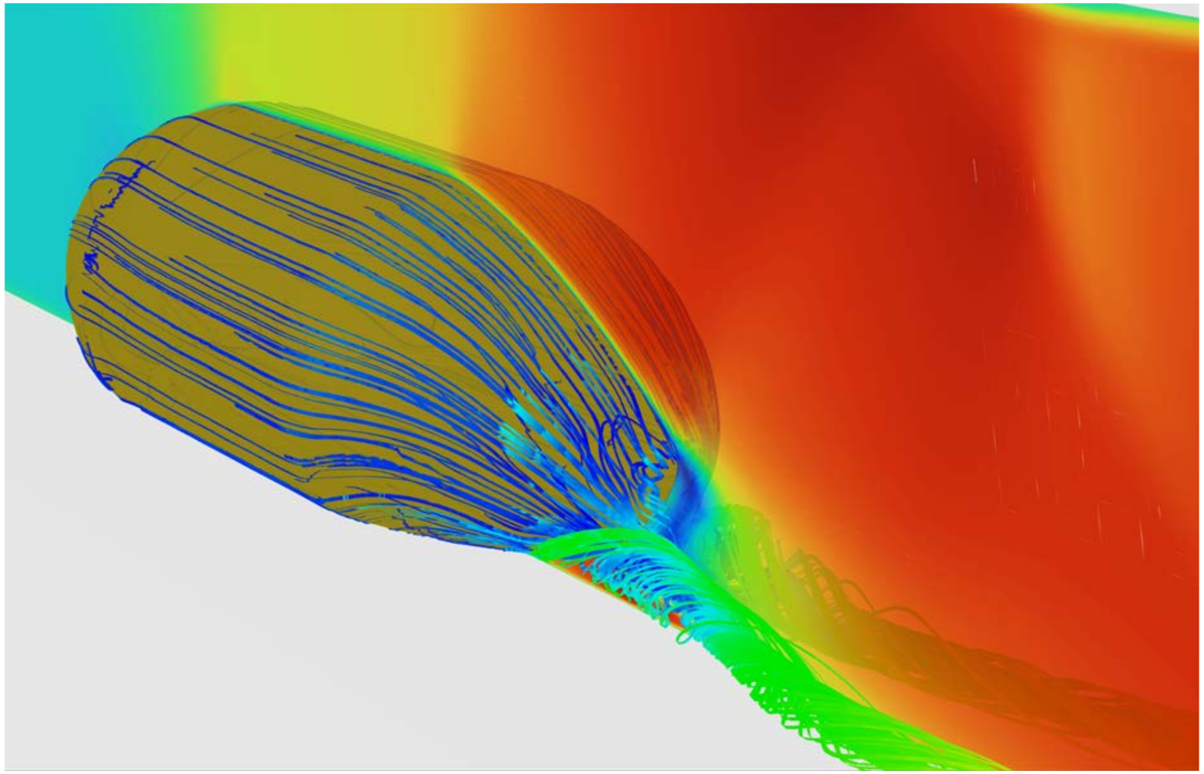
- For magnetically supported systems, there is a strong magnetic drag up to 800 km/h (10 x the aerodynamic drag)
- An optimization « aerodynamics + magnetic resistance » shall be done

→ The optimal speed is a little beyond the Kantrowitz limit

Limitations:

Supersonic effects: Strong temperature and pressure variations in the fluid!

- Can lead to the solidification of the moisture in the gas
- Small ice particles at 1'000 km/h in the tunnel!



THANKS! COMMENTS?

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www.cmefe.ch

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