Minutes of meeting

German-Dutch Wind Tunnels

Subject	Visit to Airbus Defence and Space to present supersonic assessment HST
Author	Frenk Wubben, Andreas Bergmann
Date of Meeting	12 June 2019
Place of Meeting	Manching, Germany

Participants

Luis Ruiz Calavera	(Head of CoC Flight Physics)
Roland Bacher	(Program Manager EF) *acting as deputy of Achim Pittner (Head of Portfolio management & Combat Growth)*
Juergen Reimann	(Head Wind Tunnel Tests Aerodynamics – TEAGA)
Rick Lohmann	(Aerodynamic Engineer Wind Tunnel Tests - TEAGA)
Herbert Collins	(Aerodynamic Engineer Wind Tunnel Tests – TEAGA)
Bernd Schiefer	(Head Aero Data)
Daniel Stolle	(Model Design)
Frank Helber	(Measurement Techniques)
Alexander Allen	(Chief Engineer EF office)
Mauro Molino	(Integration Manager EF Flight Physics) *– in a four-eye conversation with AB prior the meeting*
Andreas Bergmann	(Director DNW)
Stefan Melber	(DLR Institute AS)
Frenk Wubben	(Project Aerodynamics DNW)

Distribution

Participants

Susana Calvo
Andreas Hövelmann
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Roy Gebbink
Sinus Hegen
Christophe Hermans
Kerstin Huber
Cor Jutten
Kees Kapteijn
Carsten Lenfers
Stefan Melber
Jan Takens
Henri Vos

Subject	Action
The following agenda was followed 1. Intro (all) 2. Airbus EF midterm high speed test requirements (Airbus) 3. General presentation HST (DNW) 4. Airbus EF past experience in HST -TP25 (Airbus) 5. Motivation for investigation of supersonic flow conditions HST (DNW) 6. HST Supersonic flow investigations by CFD (DLR) 7. HST Supersonic flow investigations by experiment (DNW) 8. Wider overview on Airbus Defence & Space wind tunnel planning (Eurofighter) 9. Wider overview on Airbus Defence & Space wind tunnel planning (including non-EF and low speed) (Airbus) 10. DNW capabilities other than HST (DNW) 11. Closure	
1 Introduction The meeting is organized at Airbus Defence and Space in Manching. The main goal for ADS is to assess whether HST can be a suitable candidate for testing the Eurofighter model in the period of 2020-2023. The goal for DNW is to find out what volume of testing is planned for and what services are requested. So far, ADS has tested in CALSPAN with the EF FC5-HS-Model (owned by NETMA). Political conditions as well as the currently very high capacity utilization of the CALSPAN tunnel with other customers than ADS mean that ADS is looking for alternatives in Europe. ARA is	

seen as the competitor for HST. It is under investigation, whether this situation is now suitable to come to a successful and sustainable cooperation with ADS. See also presentation, ref. [2].	
2 Airbus EF midterm high speed test requirements Jürgen Reimann presents the midterm and high-speed test requirements. ADS envisages a test volume of 40,000 polars (2 x 5,000 per year) in the period of 2020-2023 in the framework of a next enhanced Eurofighter evolution plan. 0.4 < Ma < 1.3. Apart from that tests are envisaged within the framework of the Airbus & Dassault cooperation for development of a New Generation Fighter (NGF), agreed upon in 2017 between France and Germany. These tests might come on top of the high work load with FC5. For these developments, ADS is asking for a suitable wind tunnel facility that is agile, flexible and quick. Total pressure requirements are 0.3 < Pt < 3 bar. 3 bar to achieve Re for 1:4 scale (FC5) at Ma = 0.4. Requirements for angle of attack are subdivided by the tasks ▪ Air-to-Air: -10° < AoA < 40° depending on Ma (ARA might be suitable because of the larger test section size) - Max AoA @ Ma=1.05: 26° - Max AoA @ Ma=1.2: 22° ▪ Air-to-Surface: -10° < AoA < 29° depending on Ma (HST might comply) - Max AoA @ Ma=1.05: 22° - Max AoA @ Ma=1.2: 19° HST is interesting for ADS to do measurements. See also presentations, ref. [2] and [3]. In ref. [3] plots are shown during the meeting, however plots cannot be provided due to security restrictions.	
3 General presentation HST Frenk presents a brief overview of the DNW organization.	
4 Airbus EF past experience in HST Jürgen Reimann presents the past experiences of ADS in HST, ref [3]. The Eurofighter model was tested in HST during a demonstration test in 2002. After that, ADS decided to execute the production tests at ARA and CALSPAN. Wind tunnel test results of ARA and CALSPAN were compared with flight test results and appeared to be in good agreement. Comparison with HST results appeared to be marginally acceptable between Ma=0.85 and 0.9. At Ma=0.9, the pitching moments results of HST appeared to be higher than the other wind tunnels (~0.008). In some cases, the HST results appeared to better than the other two tunnels (e.g. yaw stability in general, pitch at low Mach). HST results @ M1.05 far off. The experiences of ADS in 2002 showed the following main problems at HST: 1. At Ma=1.05, pitching moment and rolling moment derivative to sideslip is deviating (above alpha 10 deg) from expectations for the FC5 test in HST (2002) 2. Angle of attack range at supersonic Mach numbers is too limited (for larger models)	

5 Motivation for investigation of supersonic flow conditions HST

Frenk Wubben presents the motivation for a supersonic assessment of HST by two approaches:
- CFD assessments by DLR
- Experimental assessments by DNW

Referring also to feedback from former ADS FC5 test (TP25)
- AoA limit partly too low
- Sweep rate too low
- Unexpected results at Ma 1.05 in Cm and Cl_beta

6 HST Supersonic flow investigations by CFD

Stefan Melber presents an overview of the flow physics in HST based on CFD assessments for MA number 1.2. The CFD results contributed to a better understanding of the flow control in the wind tunnel as well as the advantages of plenum suction on the flow quality.

EF FA5 geometry provided by ADS for the simulation, not FC5 model due to restrictions.
- Simulation at Ma 1.05 ongoing, results expected within two weeks
- Total wind tunnel pressure for simulation around 50kPa
- Jürgen Reimann: in reality rather at 65kPa
- Simulation done for free flight and wind tunnel
  - Significant differences for critical case (high AoA, flaps deflected) due to overpressure in plenum
  - Plenum pressure not corresponding to initially set static pressure
- Conclusion:
  - Passive plenum suction at HST not sufficient
  - Possible solution: installation of active plenum suction

See also presentation, ref. [5].

7 HST supersonic flow investigations by Experiment (DNW)

Frenk Wubben presents an overview of experimental assessments that were performed. The main conclusions are:

- The MA-number versus Alpha envelope can be extended by changing the re-entry geometry of the HST.
- Although the available model sweep rate of the model is in the order of 0.9 deg/s, it cannot be used due to constraints in the hydraulic system of the compressor blade angle system that is limiting the Mach number control during a model sweep. This can be solved by an upgrade of the blade angle system.
- At Ma=1.05, subsonic flow is observed at the upper and lower wall near the model location. For angles of attack above 16 deg, the model shock impingement point at the wall is moving forward indicating that the model bow shock is moving forward also.

Conclusions:

- Alpha-Ma envelope increase:
  - Change of re-entry geometry (available)
  - Active plenum suction (requires high investment and calibration effort)
  - Second throat to control terminating shocks
- Model sweep rate increase:
  - Modification of hydraulic blade pitch system or installation of electrical system
  - If feasible and fast response possible active plenum suction
- Results at Ma 1.05:
  - More ventilation

- Boundary layer removal by suction
- Smaller model

See also presentation, ref. [4].

ADS (Luis Ruiz) very much appreciates the large effort that has been spent by DNW / DLR.

8 Wider overview on Airbus Defence & Space wind tunnel planning (Eurofighter)

Based on the presentations, it is concluded that a demonstration test in HST is not opportune at this moment due to the uncertainties in flow physics at Ma=1.05 at higher angles of attack. ADS states that Mach number 1.05 is a very important Mach number as bridge between subsonic and supersonic flow conditions. Due to the earlier mentioned differences at Ma=0.9, there is no way to circumvent this. In addition, angle of attack levels up to at least 22 deg in supersonic flow are mandatory but cannot be guaranteed at the moment in HST. **It is mandatory for a switch to HST that DNW solves the Ma = 1.05 problem.**

DNW/DLR

It is agreed that the uncertainties at Mach number 1.05 will be further studied with CFD by DLR. **Half of July 2019, a meeting will be organized by DNW to provide feedback to ADS concerning the status.**

ADS has planned eight campaigns with Eurofighter model in the period 2020-2023, starting the first entry early to mid-next year. Two campaigns are already ordered at CALSPAN for 2020 because the suitability of HST is not clear at the moment and the deadline for orders in 2020 is due, but ADS seeks clarity on HST as soon as possible. So a maximum of six campaigns may take place in HST. Program wise it is planned to implement first EF Air-to-Air, later Air-to-Surface capabilities. Separate testing of these phases might be possible. Consistent data over AoA range is necessary, cutting AoA range is not an option.

DNW states that updates in the HST facility are envisaged in case a business case exists. The decision has to be made this year. ADS confirmed that a letter of intent can be issued to show the interest in testing at HST. Based on the NA2 test in HST, ADS experiences a higher productivity. Improvements shall be in place mid of 2020 latest.

DNW states that differences at Ma=0.9 might also be due to differences in wind tunnel corrections (support interference effects, wall effects and internal duct drag corrections). **DNW will check which corrections were applied for the FC5 test in 2002 and whether improvements are possible.** For the test a short sting was used but it was postulated that corrections for a longer sting version were applied. Effects of support interference might also be assessed with CFD.

DNW

ADS is willing to perform support interference calculations for the articulated boom. Stefan Melber will provide the geometry of the articulated boom in IGES format to ADS.

ADS
DLR

Feedback concerning the NA2 test in HST in 2018 will be shifted to a later moment.

9 Wider overview on Airbus Defence & Space wind tunnel planning (including non-EF and low speed)

Jürgen Reimann and Luis Ruiz Calavera present a brief overview of non-Eurofighter high speed programs.

- NGWS
  - Contract German – French
  - Concept (demo) study
  - Planning 6/8 weeks high speed testing (within 18 months from now)
  - Planning 6/8 weeks low speed testing (within 18 months from now)

- Low speed model will be simple and will be tested in a cheap wind tunnel (not LLF), University is envisaged but NWB is a good alternative. Test will take place in 2020 / 21.

▪ EuroDrone
  - The „EuroDrone“ is a project of the German, French and Italian governments, to which Spain later also joined. The drone can be equipped with both rockets and surveillance technology. The development is to be finally decided before the end of this year.
  - Test in low speed wind tunnel
  - Propeller propulsion
  - LLF is candidate
  - Project will start early 2020.
  - Test will be executed in 2020-2021
  - There is no model available yet
  - Contrary to Talarion model, it is anticipated that this model will be a full model
  - Short preparation phase is a challenge
  - If possible, components from the past will be re-used.

▪ Eurofighter low speed
  - Currently nothing planned (no FC3 in LLF) in the upcoming years
  - Maybe maximum one week

▪ R&T/R&D projectd Diabolo and WeaponBay
  - Approximately five campaigns in TWG over the next three years

10 DNW capabilities other than HST

Andreas Bergmann explains the main capabilities of DNW that could be of interest for ADS:

▪ Acoustic testing
▪ Propulsion integration testing
  - Substantial infrastructure updates at NWB for TPS testing
  - Promising feasibility study for electrically powered simulators
▪ Near ground testing
  - Moving belt (80 m/s) at LLF
▪ Non-intrusive testing techniques
  - PIV
  - SPR for wing deflection and twist
  - Helium filled soap bubbles
▪ ADS should decide whether the RTD (Test rig for quasi-steady rolling and spinning motion) at NWB is necessary for the upcoming programs, otherwise it might be scraped — **Action: ADS**

After this overview, Juergen Reimann closes the meeting.

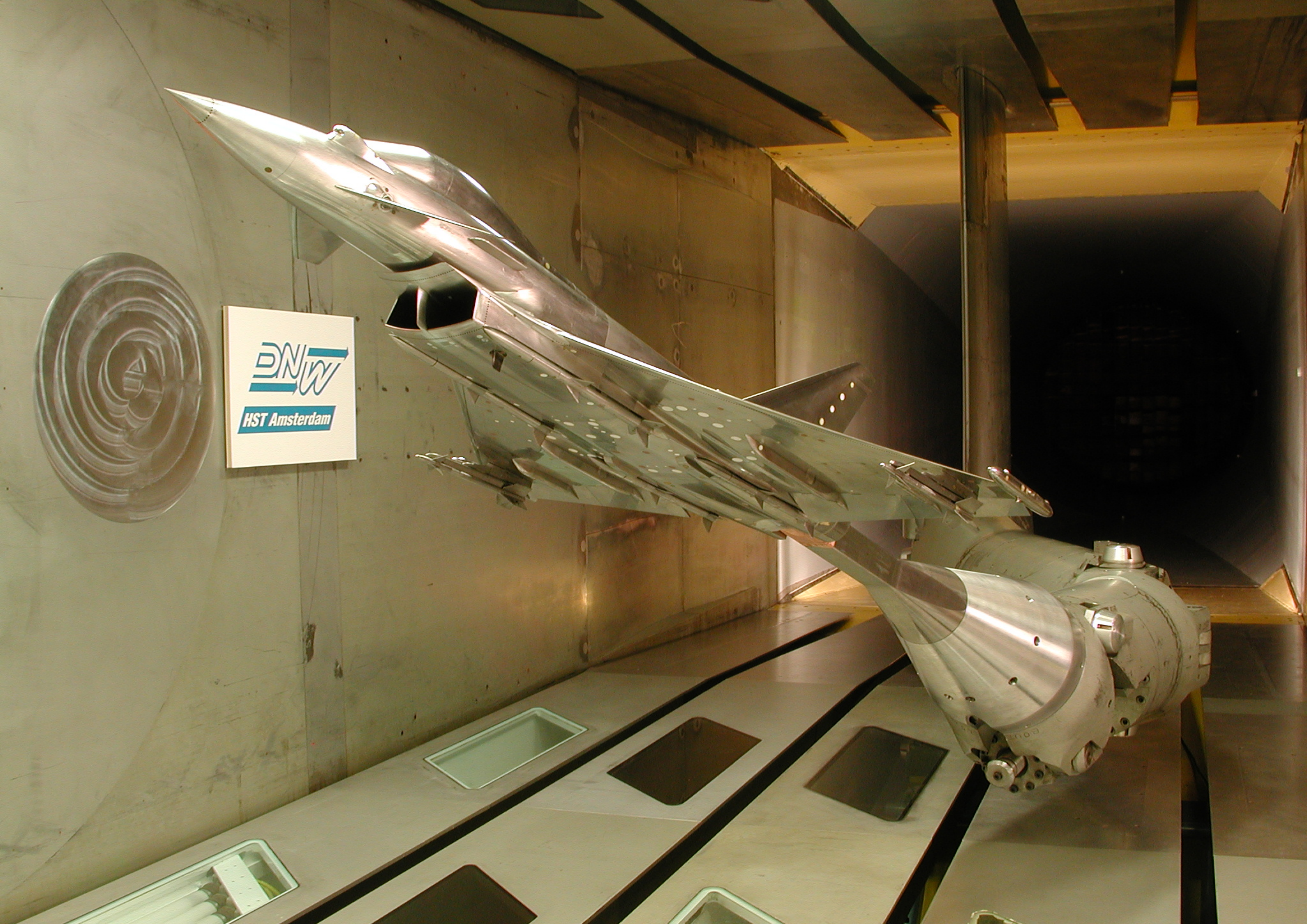
Activities after the meeting

Andreas Bergmann discusses the contents of a Letter of Intent with Luis Ruiz Calavera. After this discussion, Stefan Melber and Andreas Bergmann have to leave for the airport.

Frenk Wubben pays a visit to the Eurofighter model and the 1.5 inch TASK balance. ADS is considering to buy a 2 inch TASK balance for eventual testing in HST. Another possibility is to use the existing 1.5 inch TASK balance. In order to mount it to the model, a sleeve will be necessary. In that case, it seems to be necessary to make a new sting for proper mounting to the balance. Frenk presents a brief overview of the intended control updates in HST.

Juergen Reimannn strongly encourages to start working on these updates in order to be ready in case the supersonic flow physics are settled.

REFERENCES	
[1] "Agenda", Agenda.pptx; ADS: JR; 12.06.2019 [2] "Introduction", Intro.pptx; ADS: JR; 12.06.2019 [3] "Airbus EF Past Experience in HST", EF past experience (wo NR data).pptx; ADS: JR; 12.06.2019 [4] "Assessment of the HST supersonic performance", EXP_HST_investigations_short.pdf; DNW: R. Gebbink, F. Wubben; received 14.06.2019 [5] "Results of HST CFD Simulations", hst_final_Airbus_v2.pdf; DLR: SM; received: 13.06.2019	
ABBREVIATIONS	
DNW: German-Dutch Wind Tunnels HST: High-Speed Tunnel, Amsterdam DLR: German Aerospace Centre ADS: Airbus Defence and Space MAN: Manching WT: Wind Tunnel WTT: Wind Tunnel Test Ma: Mach number kPa: kilo Pascal AoA: Angle of attack	


DNW
HST Amsterdam

Airbus Defence & Space „Wind Tunnel Roadmap“
Evaluation of High Speed Tunnels for Fighter Testing

Visit of DNW-HST to Manching 12.6.2019

Agenda

TEAGA-TL3, June 2019

Agenda

1. Introduction / Airbus EF high speed test requirements (Airbus)
2. General presentation DNW-HST high speed tunnel (DNW)
3. Airbus EF past experience in HST (Airbus)
4. Motivation for investigation of supersonic flow conditions HST (DNW)
5. HST Supersonic flow investigations by CFD (DLR)
6. HST supersonic flow investigations by Experiment (DNW)
7. HST performance (time, cost, quality) including review of Airbus NGWS test from 2018 (all)
8. Discussion on potential EF evaluation test program (program proposal will come from Airbus)
9. Open technical issues (balance, sting etc) (all)
10. Time schedule / milestones for way forward (all)

Optional, if time permits:

11. Wider overview on Airbus D&S wind tunnel planning (including non-EF and low speed) (Airbus)
12. DNW capabilities other than HST (DNW)

Airbus Defence & Space „Wind Tunnel Roadmap“ Evaluation of High Speed Tunnels for Fighter Testing

Visit of DNW-HST to Manching 12.6.2019

Introduction

TEAGA-TL3, June 2019

Motivation

With the continuing development of the **Euro Fighter** („EF“) capabilities in the framework of …

- Serving future **core and export customer** requirements (EF Long Term Evolution, „LTE“)
- Potential capability enhancements with the replacement of aging **GE** „Tranche 1“ EF aircraft
- Preparation to offer EF as a **GE** Tornado replacement
- **Airbus D&S internal** initiatives

… Airbus Defence & Space as major provider of EF high speed wind tunnel data forsees the need of testing up to **40.000 polars** in the M=0.4..1.3 range in **2020-23** (typically in campaigns of ≈ 5000 polars each)

(German-French **FCAS/NGF** development work might come on top of that.)

High work load and long lead slot reservation times in suitable facilites world wide have impact on …

➢ **… Airbus D&S targets**
- Agile, quick and flexible response to customer requirements
- Significant reduction of capability enhancement implementation times

To gain additional flexibility in supplier selection,
Airbus D&S currently evaluates facilities up to now not regularly in use with EF

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Target

"To gain additional flexibility in supplier selection Airbus D&S currently evaluates facilities up to now not regularly in use with EF…"

In general DNW-HST has been identified as a suitable facility

However

- during a 2002 EF campaign in HST ("TP25") severe shortfalls were found in
  - data quality
  - tunnel performance
    - agenda item 3
- during 2016-18 Mephisto and Diabolo tests in HST, Airbus D&S identified potential for tunnel performance improvements
    - agenda item 7

DNW-HST reports to have analysed past problems and **found solutions**

- agenda items 4, 5, 6

Airbus DS **target** for todays meeting is to

Gather and compile all information necessary to come to a timely decision on whether an EF evaluation campaign in DNW-HST seems sensible.

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Airbus Defence & Space „Wind Tunnel Roadmap“ Evaluation of High Speed Tunnels for Fighter Testing

Visit of DNW-HST to Manching 12.6.2019

Airbus EF Past Experience in HST

TEAGA-TL3, June 2019

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Overview

In 2002 Airbus D&S had a short campaign in HST with the EF FC5 high speed model („FC5 TP25“)

- **Compared to the results from 2 similar facilities** (widely matching flight test) from the same time (same model build standard) in some aeras **significant differences were found in HST**
- In supersonics requested **maximum AoA was not reached in HST**

Data Reliability

Compared to the results from 2 similar facilities significant differences were found in HST

Only a limited number of control settings is suitable for comparison
All comparisons in „baseline“ configuration (6 light air-to-air missiles, no tanks, no air-to-surface weapons)

Starting from **M=0.85** (differences marginally acceptable) up to **M=1.05**
(outside this Mach range data compare well)

Pitch

- Higher level in pitch
- At M=1.05 different pitch characteristics
- Effect increases with positive flap
- slight dependency from leading edge setting
- (no canard data available)

Roll

- Loss in roll stability, coincident with pitch

Lift

- Minor order of magnitude, but different characteristics

Whole envelope

- Slightly less **directional stability** (here HST compares better to flight test)
- 10% less **flap pitch power**

HST performance

In supersonics requested maximum AoA was not reached in HST during TP25

- The effect seems to be flap dependent
- Could also be leading edge dependent
- The effect is not store configuration dependent
- (There is no indication, that the effect could be loads driven)

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EF high speed testing requirements

AoA limits

	current serial EF		future enhanced EF („AMK“)		
	Air-Air	Air-Surface	Air-Air	3 Tanks	Air-Surface
Mach	**Alpha max**	**Alpha max**	**Alpha max**	**Alpha max**	**Alpha max**
0.4	29°	27°	40°	34°	29°
0.6	27°	23°	37°	31°	27°
0.7	27°	22°	36°	30°	26°
0.8	27°	20°	34°	30°	24°
0.85	27°	20°	33°	30°	24°
0.9	26°	20°	32°	30°	24°
0.93	26°	20°	31°	29°	24°
0.95	26°	20°	29°	27°	23°
0.975	25°	20°	29°	26°	23°
1.05	24°	20°	26°	23°	22°
1.1	23°	20°	25°	22°	21°
1.2	20°	19°	22°	19°	19°
~~1.3~~	~~20°~~	~~18°~~	~~22°~~	~~18°~~	~~18°~~

target

abs. min. requirement

Reynolds Number

typically: **10mio/m = const**

i.e. H≈1.3bar @ M=0.4
H≈0.7bar in supersonics

Total Pressure Requirements

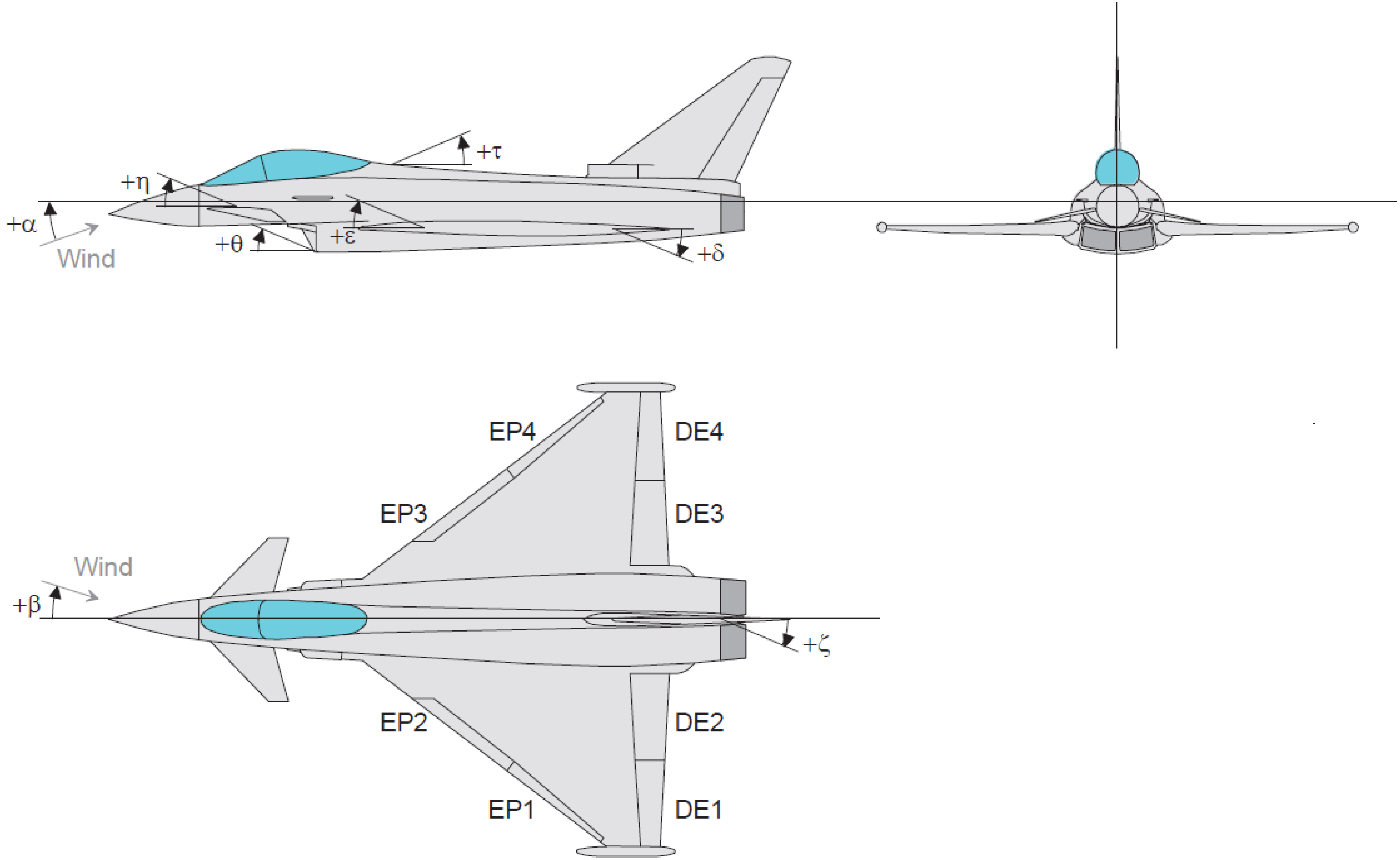
ocasionally:

H≈3.0bar @ M=0.4
to achieve Re-No of 1:4 model @ LLF

H<0.7bar (downto 0.3) @M=0.85
to overcome external stores vibrations

PLOTS

EF FC5 control surfaces overviewq



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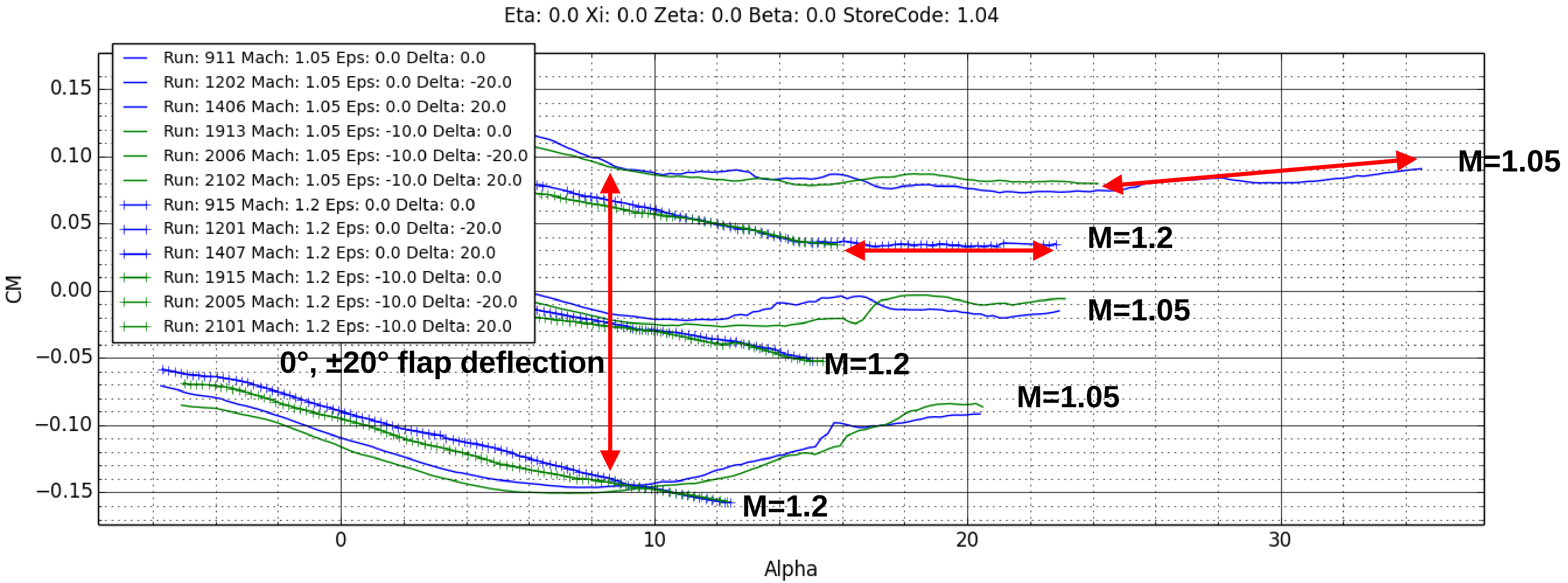
HST, lacking high AoA capability, leading edge dependency

All data HST
blue: le 0°
green: le -10°



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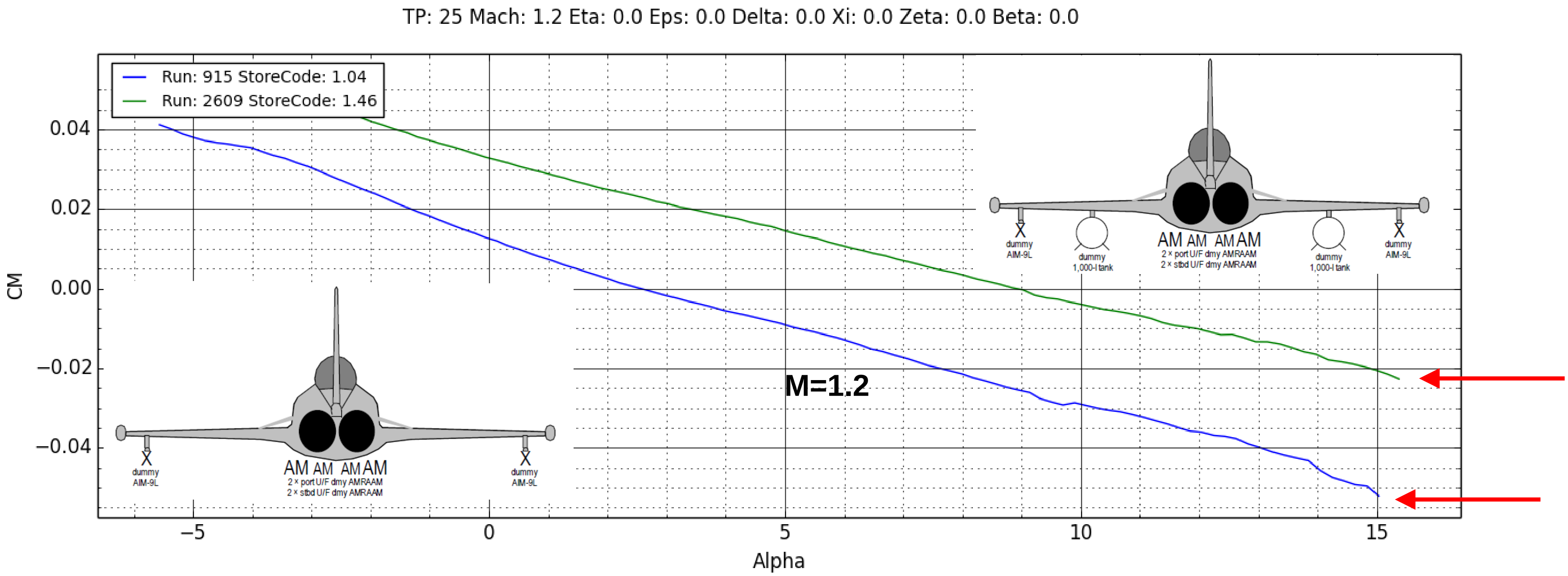
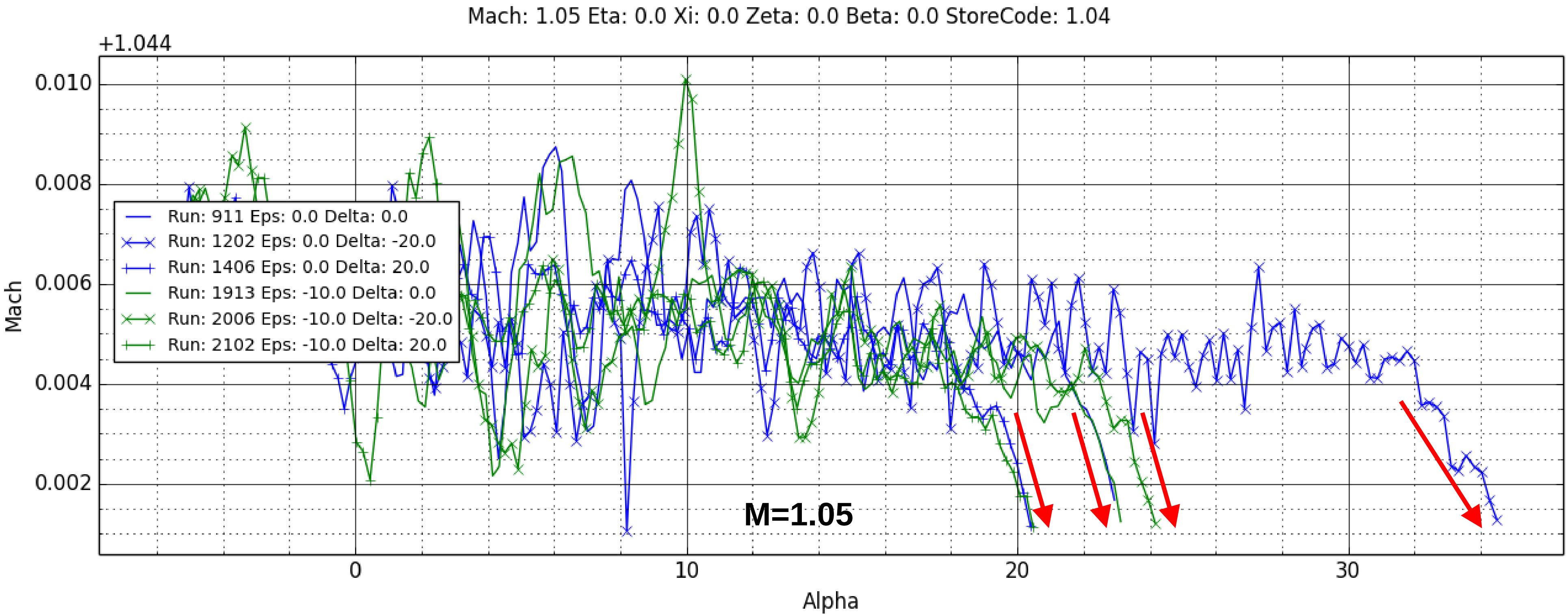
HST, lacking high AoA capability, store configuration (in)dependency

All data HST
blue: baseline
green: 2 under-wing 1000l external fuel tanks



HST, lacking high AoA capability

All data HST



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Assessment of the HST supersonic performance

12 June 2019

German-Dutch Wind Tunnels

Roy Gebbink and Frenk Wubben
Project managers DNW

Contents

- **Motivation**
- Facility
- CFD assessments
- Experimental assessments
  - Extension Alpha – Mach number envelope
  - HST versus CFD
  - Model sweep rate extension
  - Results at Ma=1.05
- Conclusions

Motivation

Feedback ADS, concerning the **FC5** test at HST:

1. **Maximum ALPHA** too low
   - 35° desired for all Mach numbers

   or at least:
   - 25° at M=1.05;
   - 20° at M=1.20

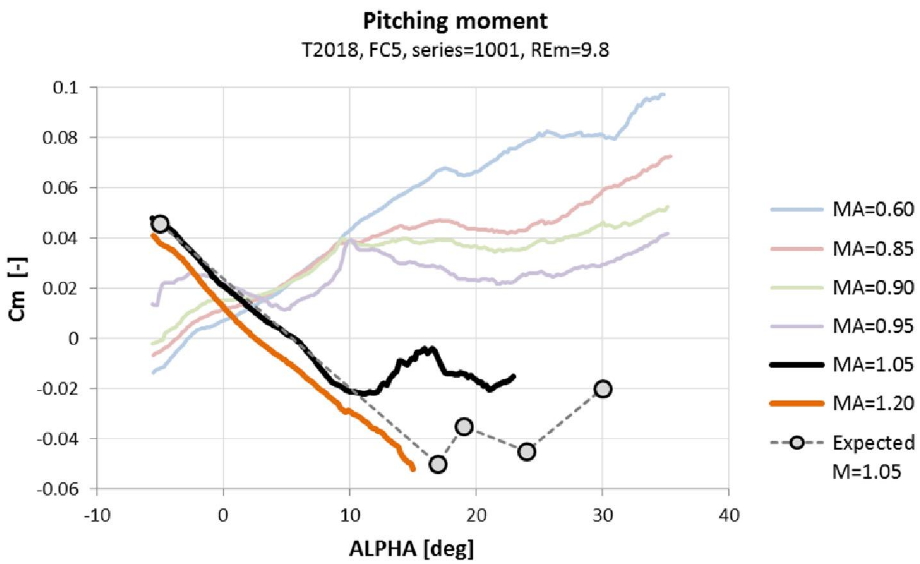
2. **Model sweep rate versus tunnel "eigenvalues"** too slow
   - Actual sweep rate 0.2°/s at supersonic conditions
   - Desired sweep rate 1.0°/s

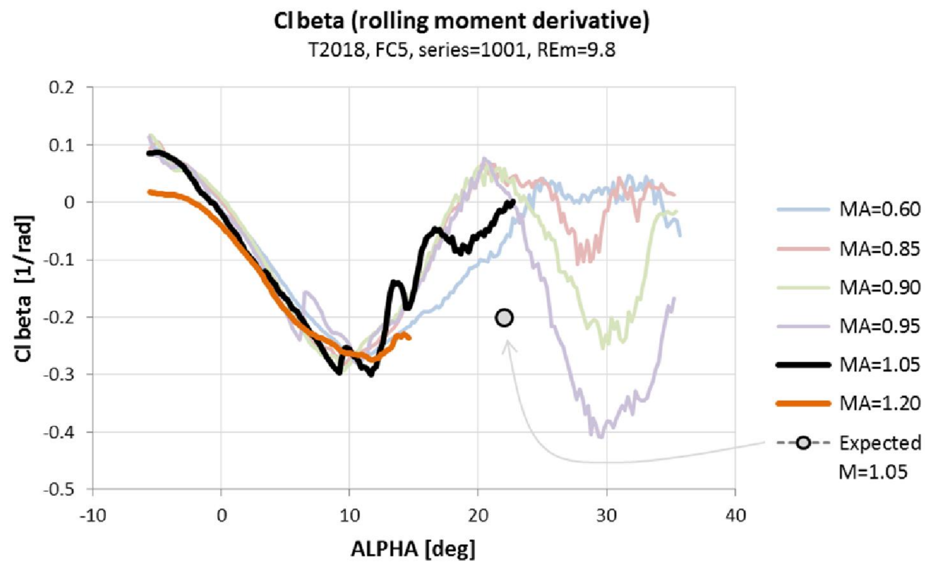
Motivation

Feedback ADS, concerning the **FC5** test at HST:

3. **Unexpected results at Ma=1.05**
   - **Cm** at ALPHA>10°
   - **Clbeta** at ALPHA>10°

$$Clbeta = \frac{Cl(\alpha, \beta 2 = 5\ deg) - Cl(\alpha, \beta 1 = -5\ deg)}{\beta 2 - \beta 1}$$





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German-Dutch Wind Tunnels

Motivation

- Assessment of HST's supersonic performance
  - Via **CFD** (by DLR)
    - Develop insight in the test section's behavior
    - In-tunnel vs free flight comparisons
    - MA=1.05 and 1.20, ALPHA 0° and 20°
  - Via an **experiment** (T9016)
    - Identify test envelope and limits (multiple MA, ALPHA)
    - Variation of the tunnel's re-entry geometry (diffusor height and setting of the slat extensions)
    - Provide validation data for CFD

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- **Facility**
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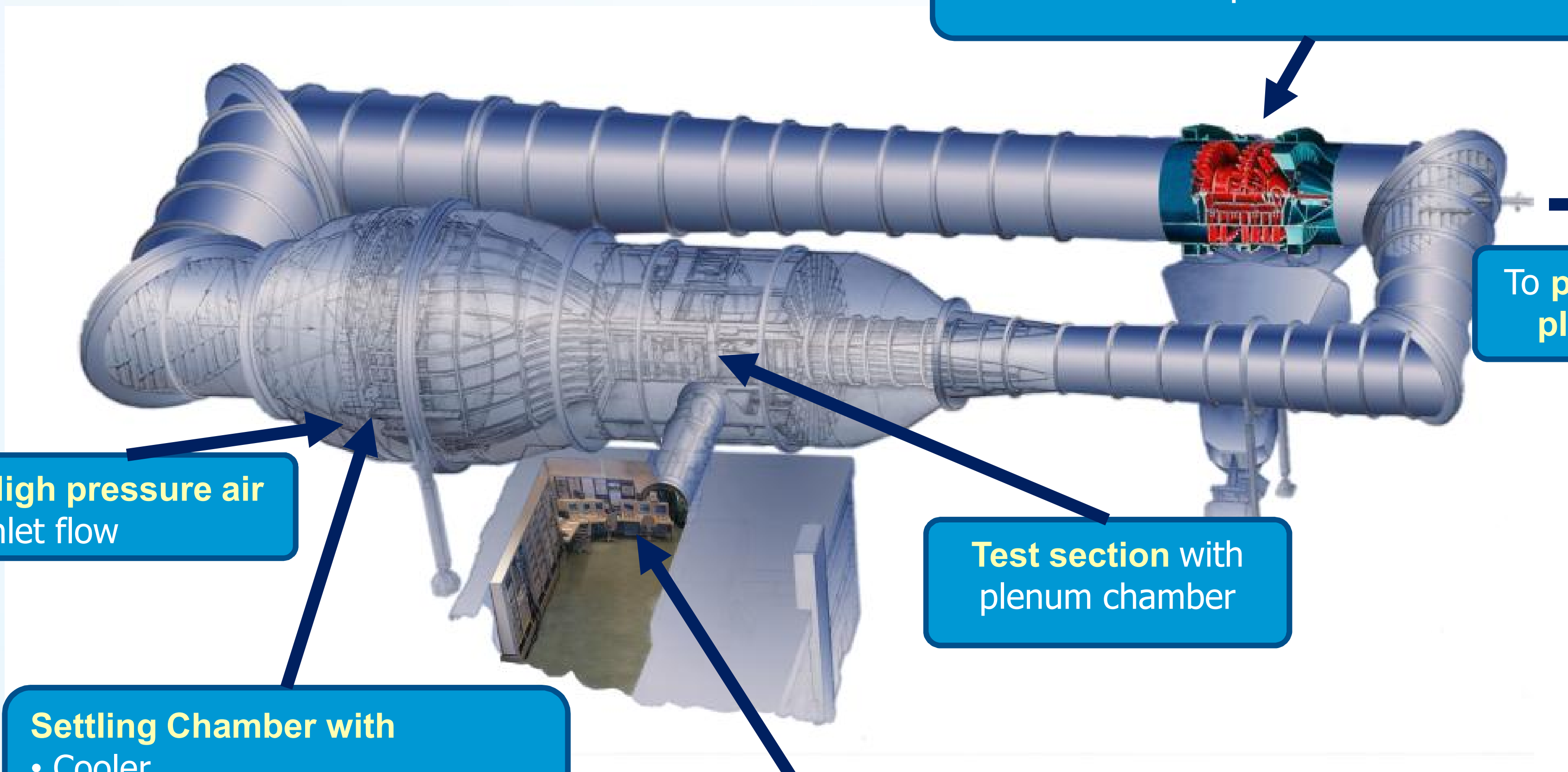
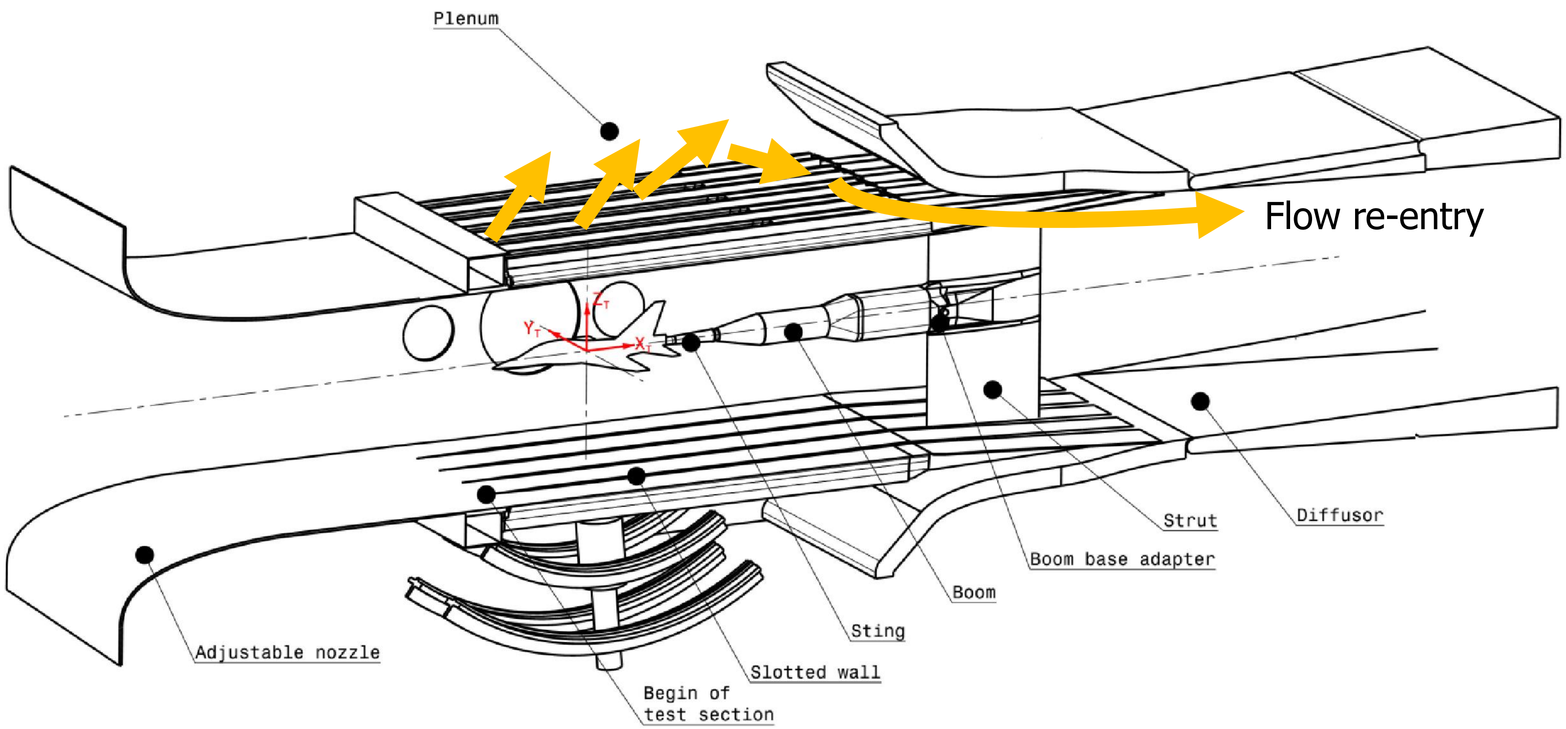
HST facility



DNW-HST test section

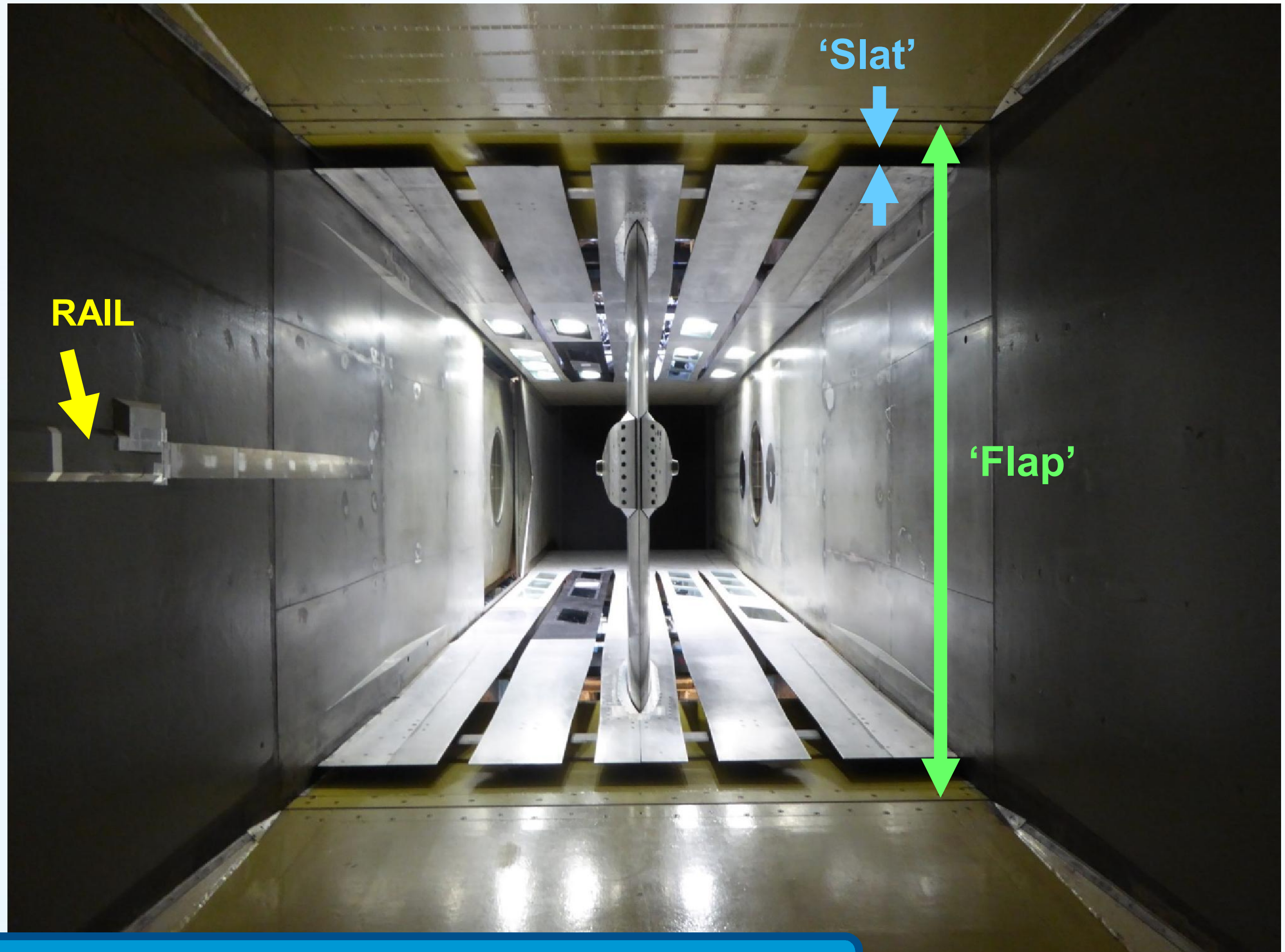


Ma-range: 0.2 – 1.3
P0-range: 25 – 390 kPa

Height: 1.6/1.8 m
Width: 2.0 m

Slotted upper/lower walls
Openness ratio: 12%

Re-entry zone / start diffusor



Wall pressure measurements, into diffusor

German-Dutch Wind Tunnels

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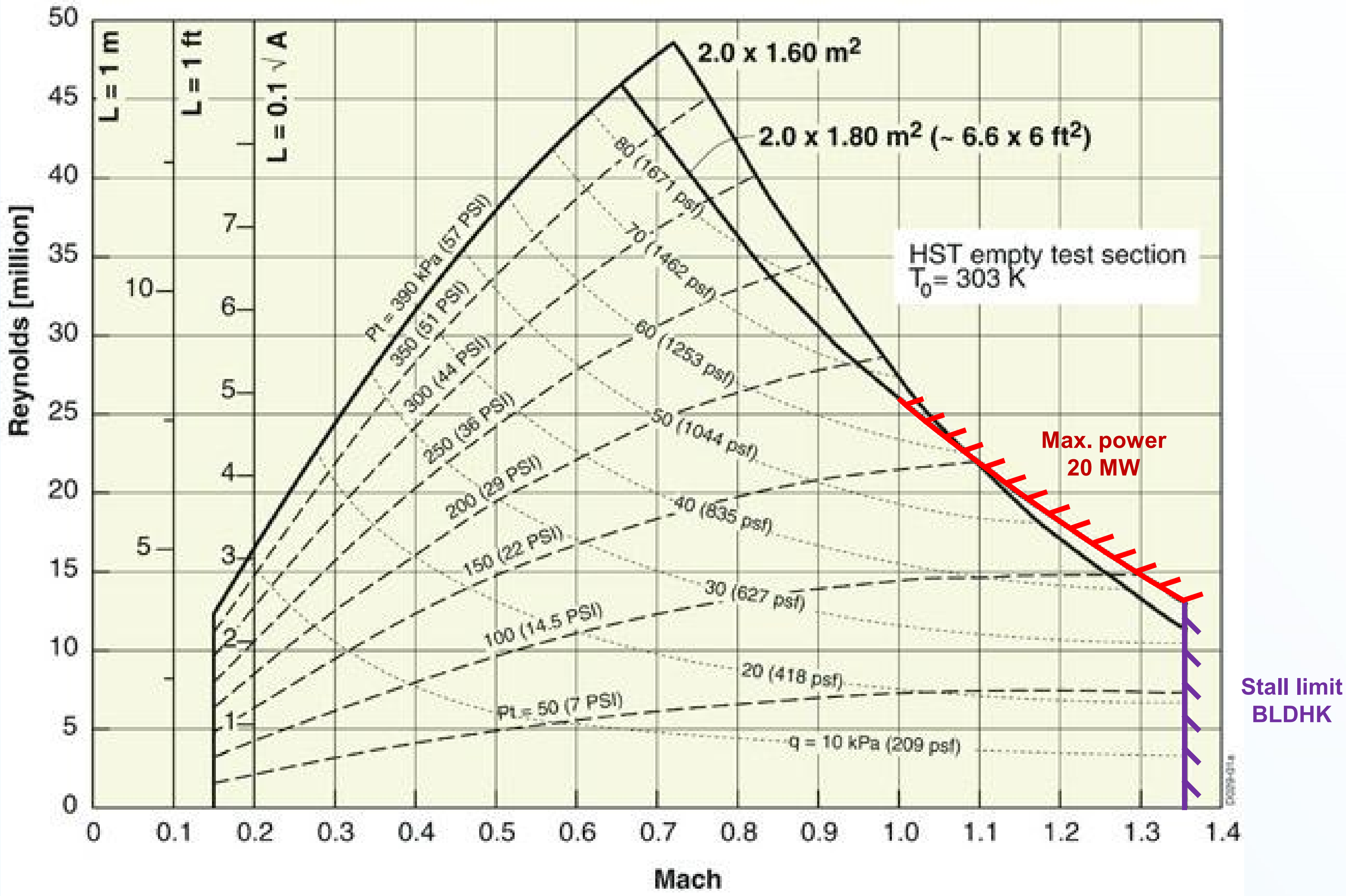
Test envelope



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- Motivation
- Facility
- **CFD assessments → Stefan Melber**
- Experimental assessments
  - Extension Alpha – Mach number envelope
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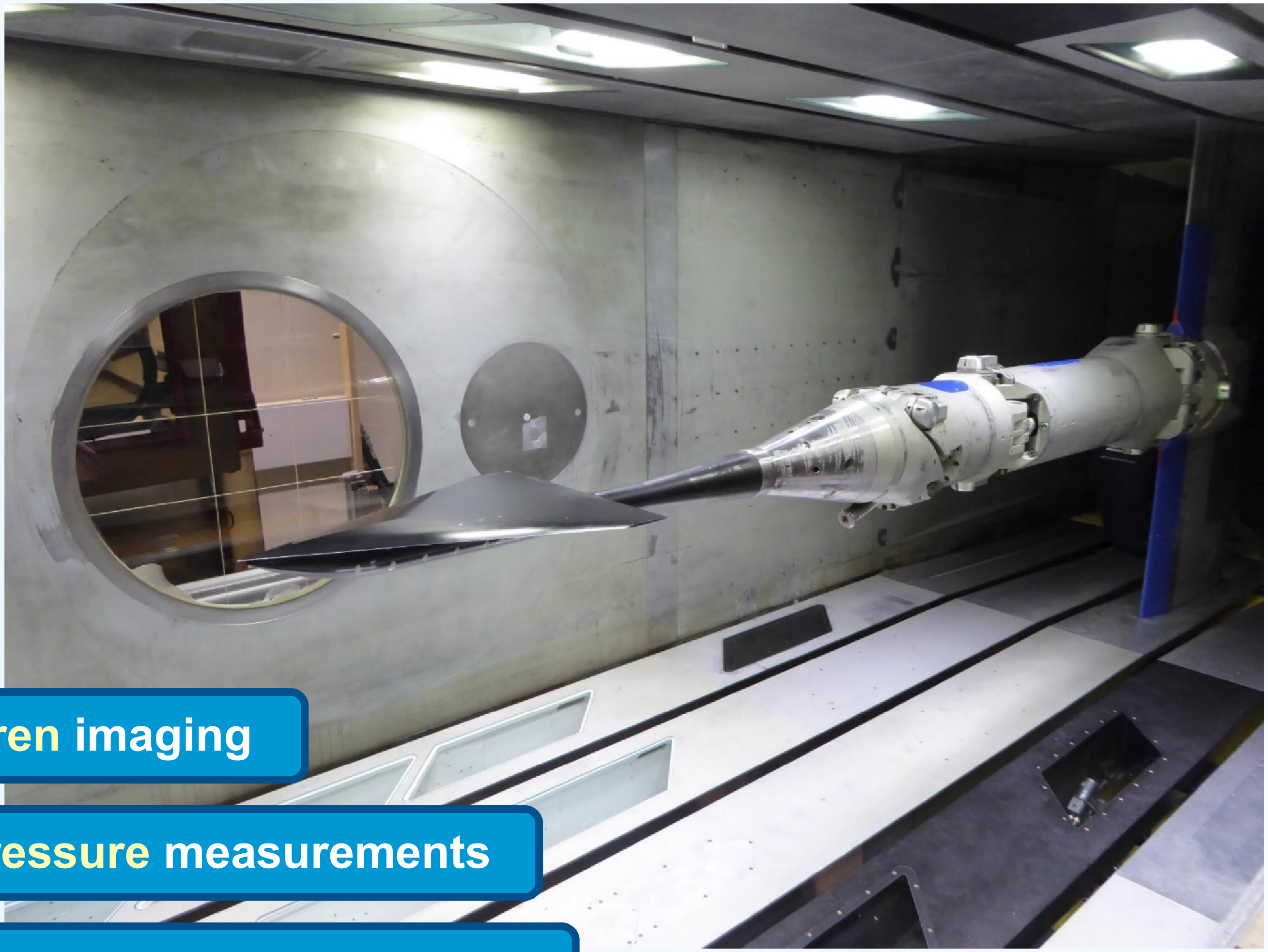
T9016 Test set-up

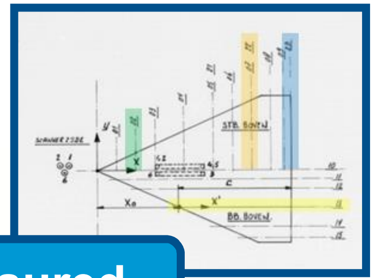


Schlieren imaging

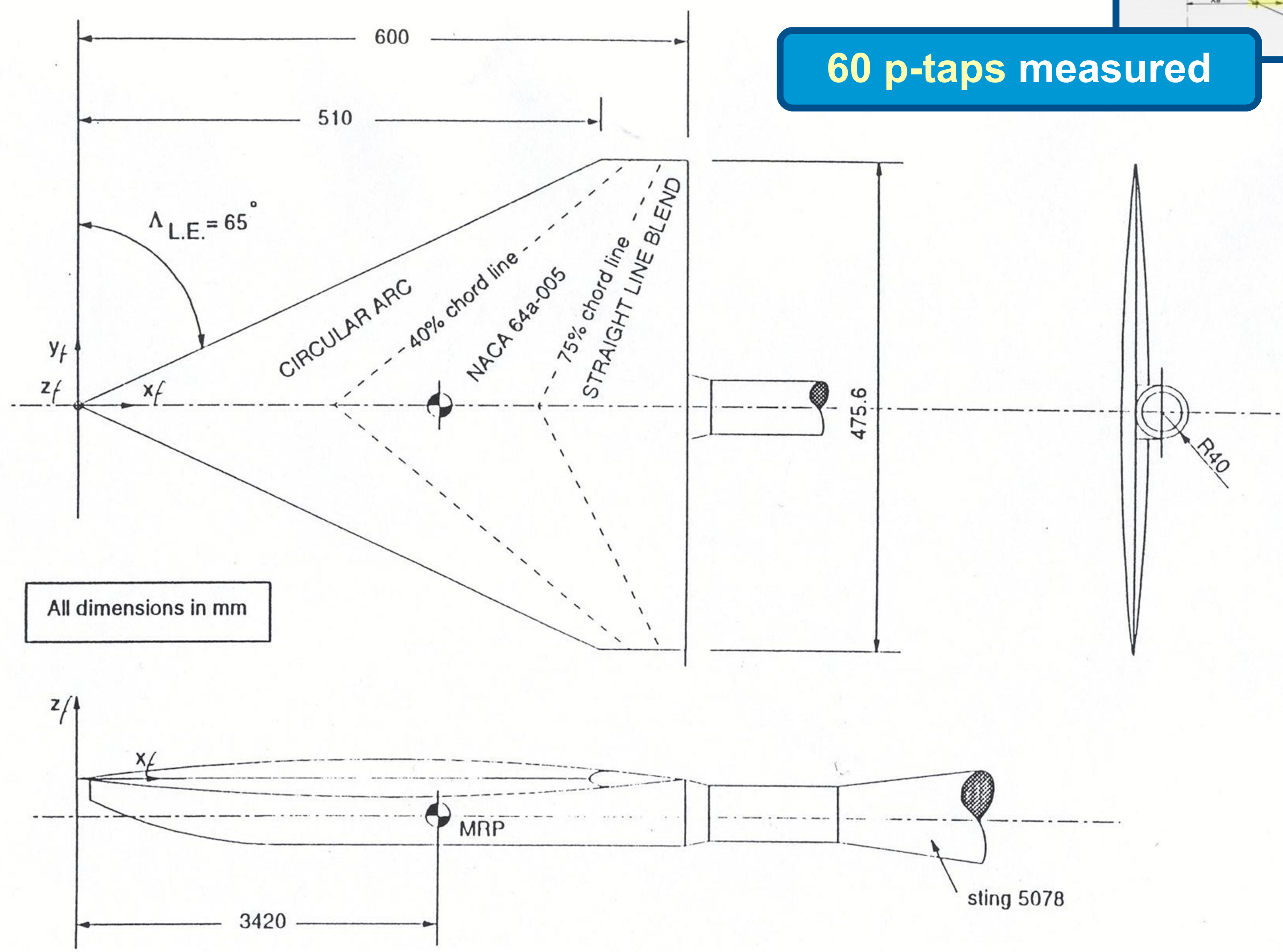
Wall pressure measurements

Model pressure measurements

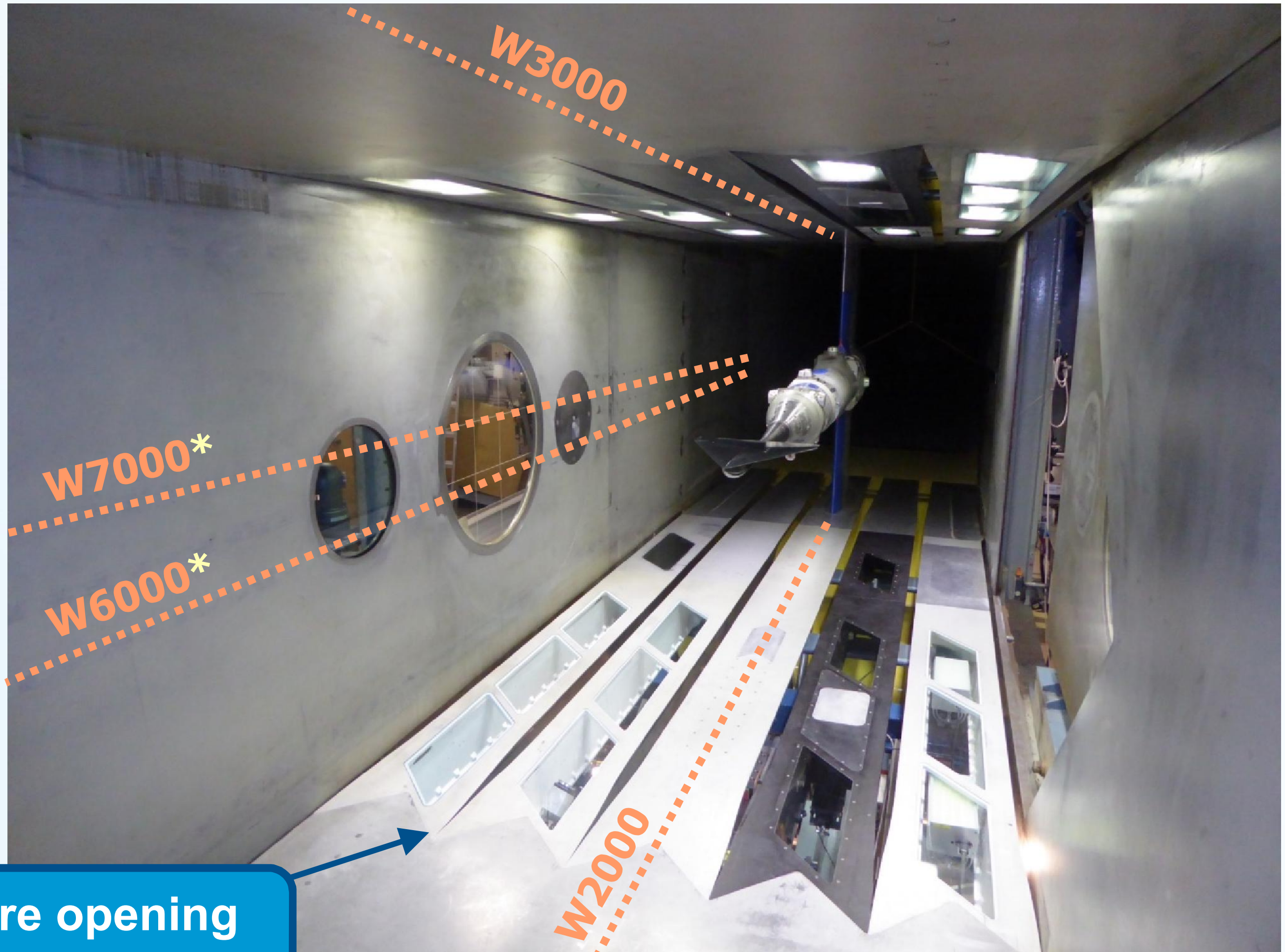
Delta wing model



60 p-taps measured



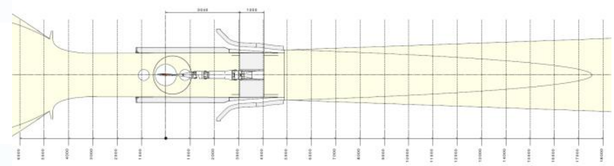
Location of slots and wall pressures

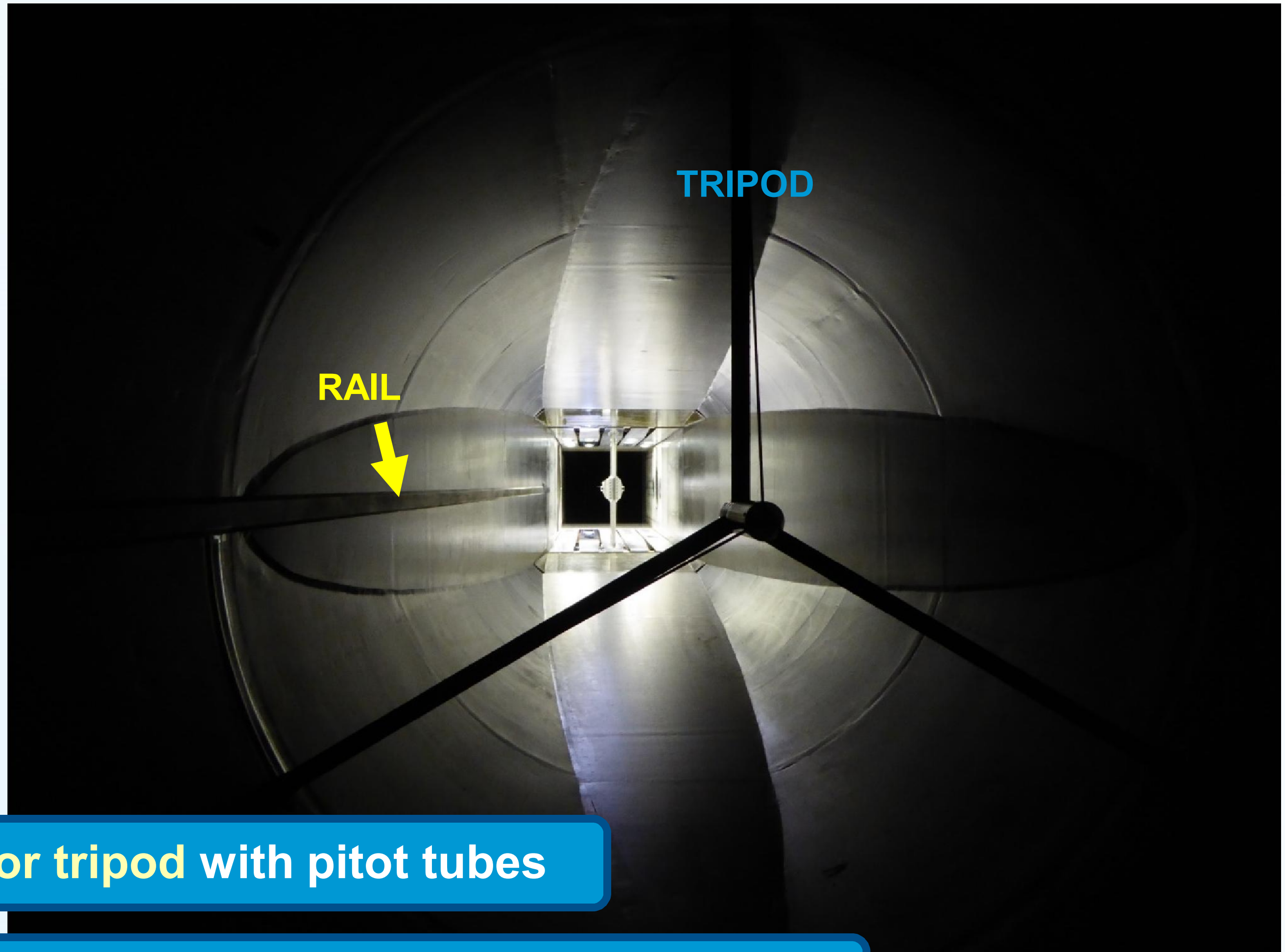


Slots are opening as of XT > -1.225m

* In reality W6000 and W7000 are located on the oppositie wall

Diffusor, viewing upstream





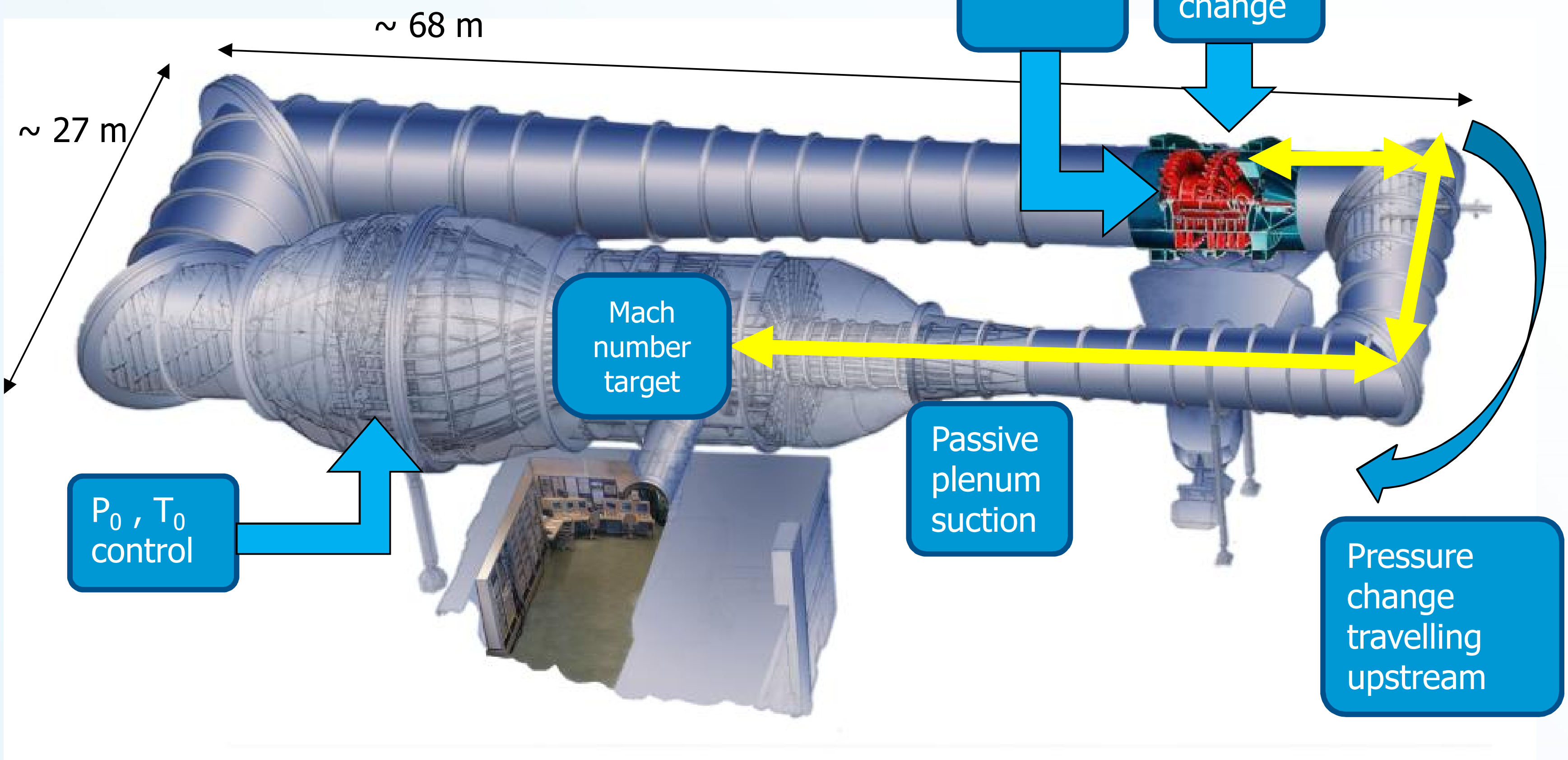
Diffusor tripod with pitot tubes

Wall pressure measurements into diffusor

Overview T9016

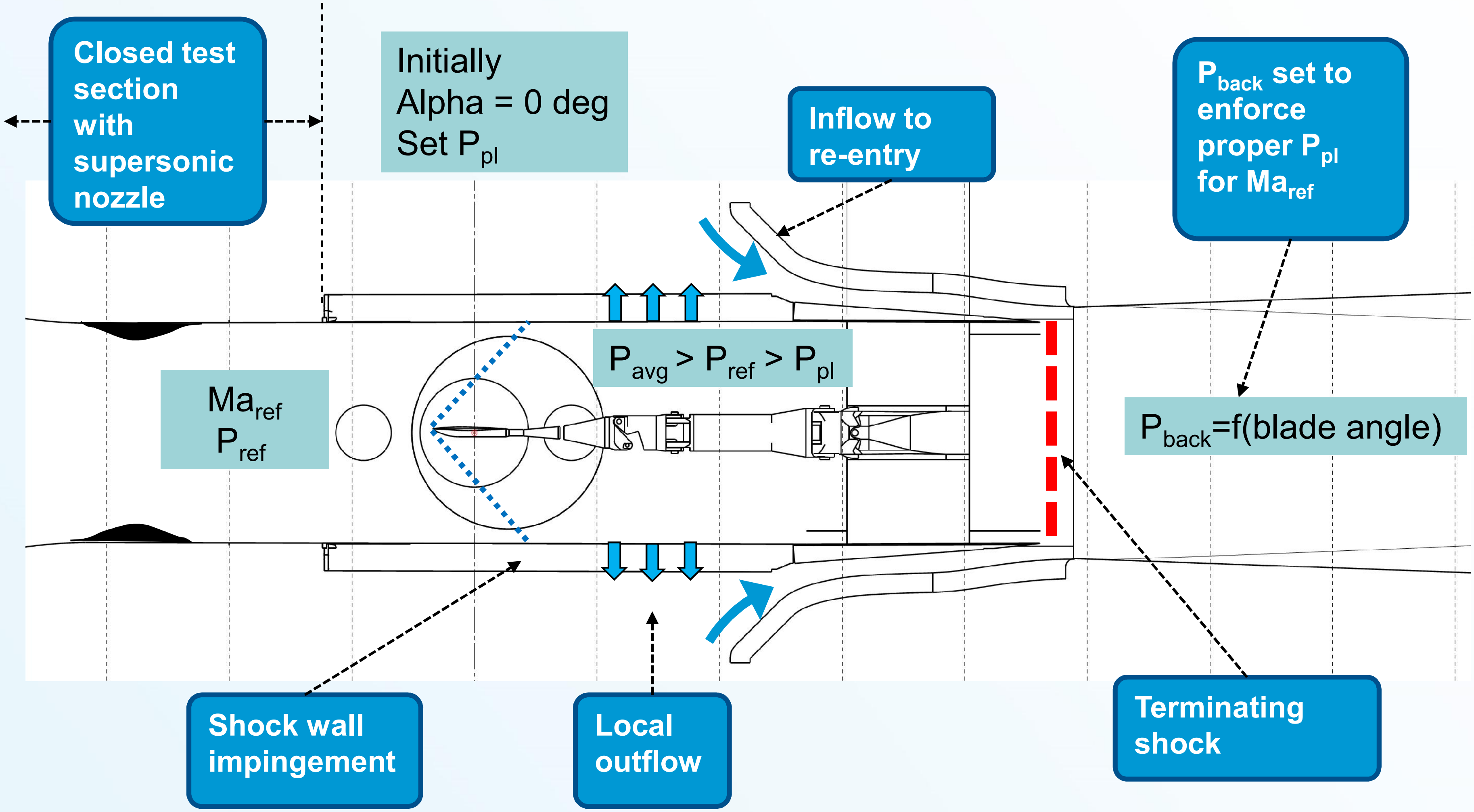
- Type of test:
  - Model pressure measurements
  - Test section wall pressure measurements
  - Diffusor wall pressure measurements (RAIL)
  - Diffusor stagnation pressure measurements (TRIPOD)
  - Plenum distributed pressure measurements
  - Schlieren imaging
  - Variation of tunnel Flap/Slat settings

Tunnel operation

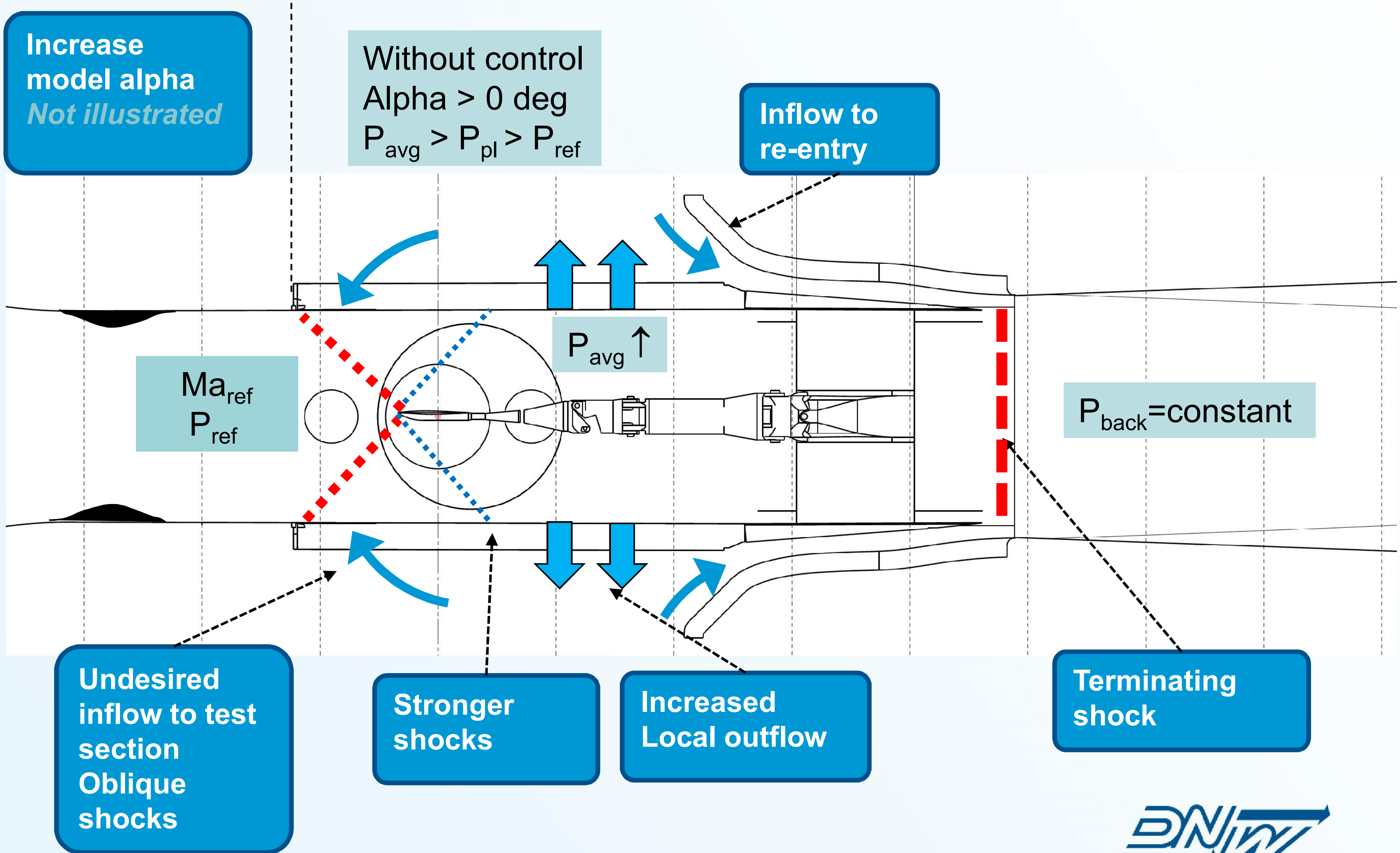


About 60 m distance between test section and fan blade control.
Travelling time = f(Ma) ≈ 0.2-0.3 s

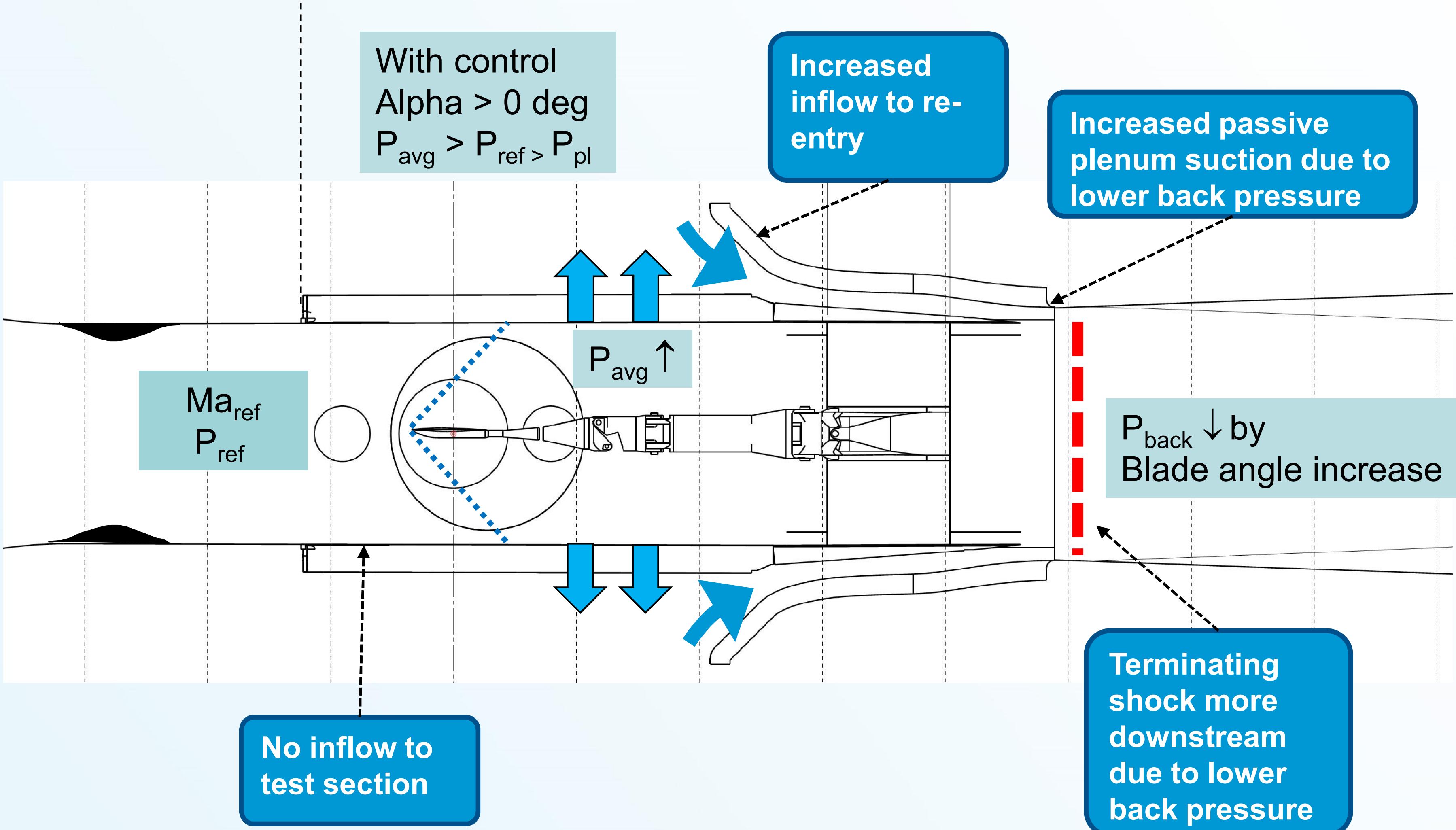
Supersonic initial flow setting



No Mach control at alpha>0 deg



With Mach control at alpha>0 deg



German-Dutch Wind Tunnels

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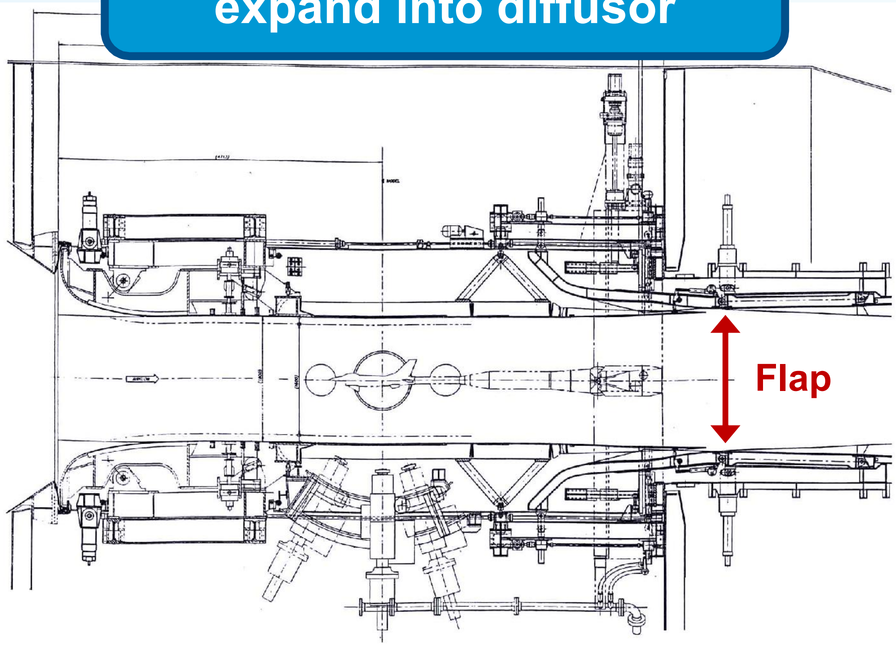
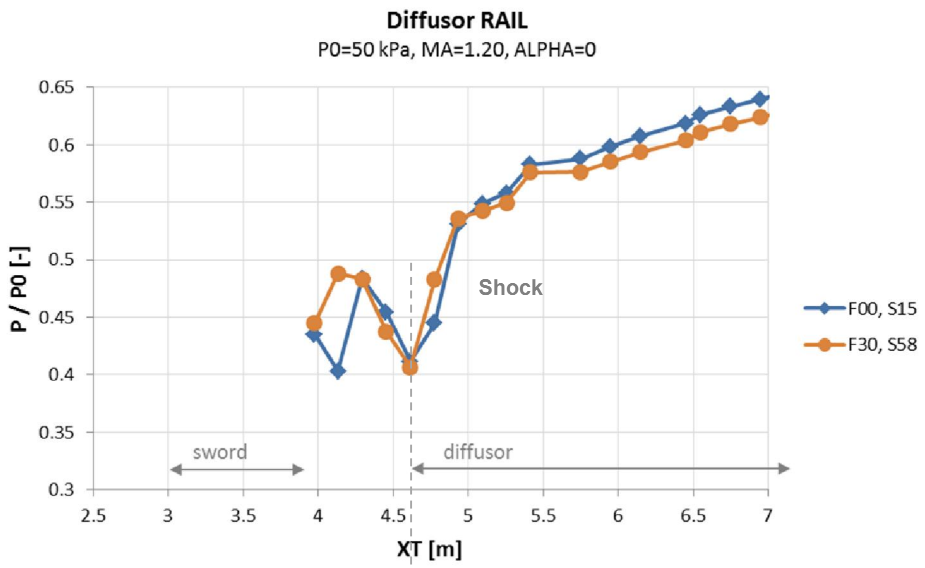
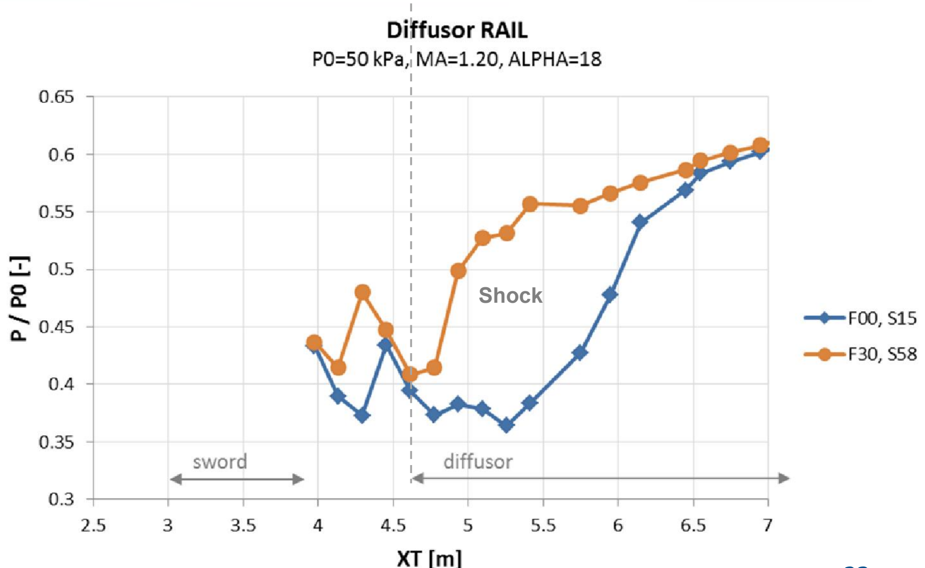
Baseline vs alternative Flap/Slats

With increasing ALPHA, the final shock moves aft as BLDHK increases to maintain constant MA

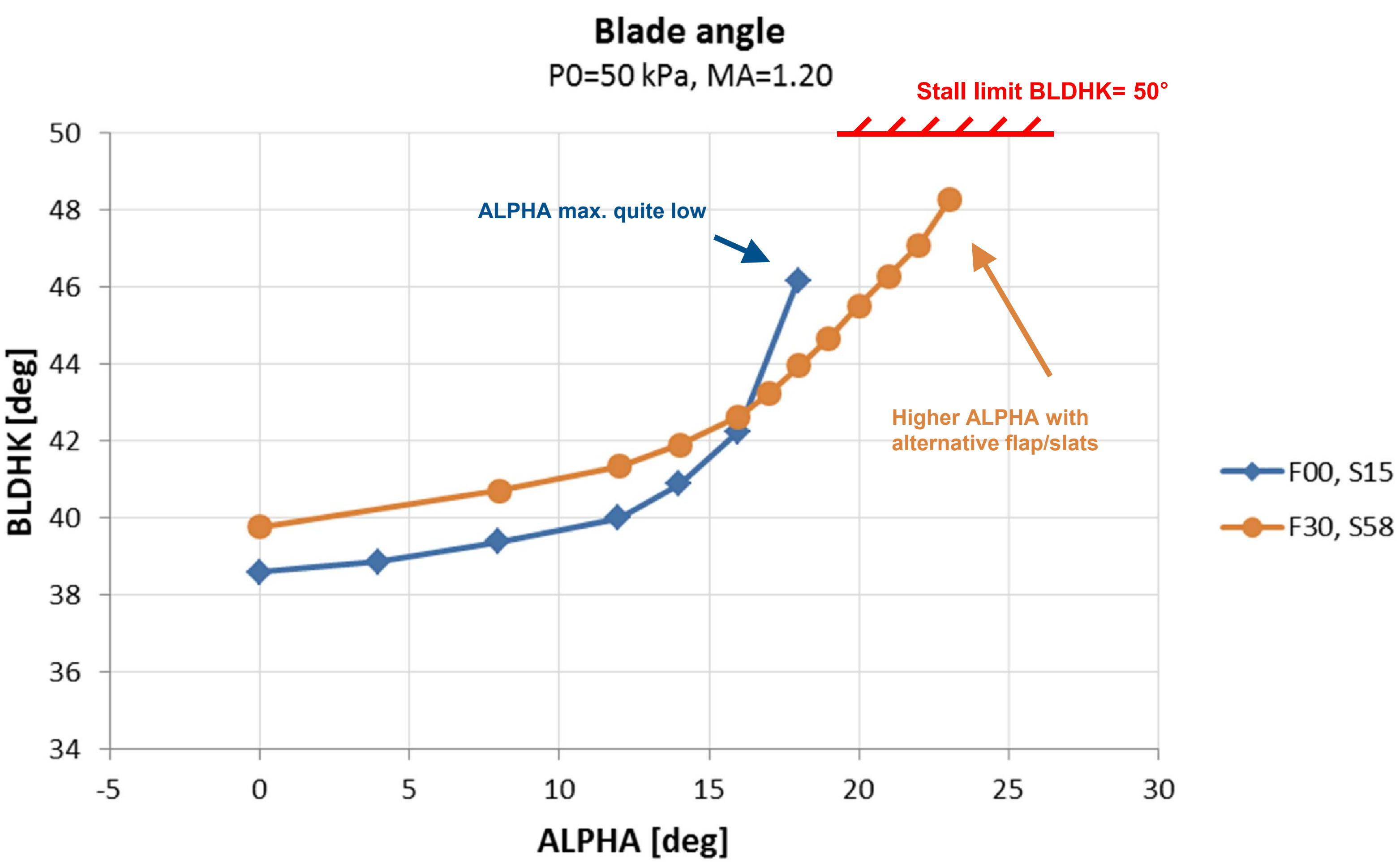
Increasing 'Flap' reduces tendency of the flow to expand into diffusor



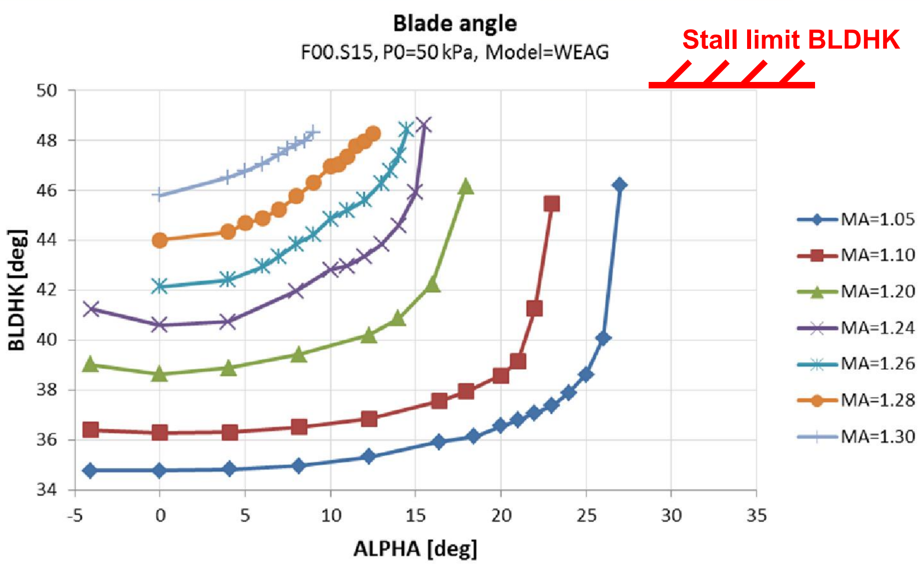


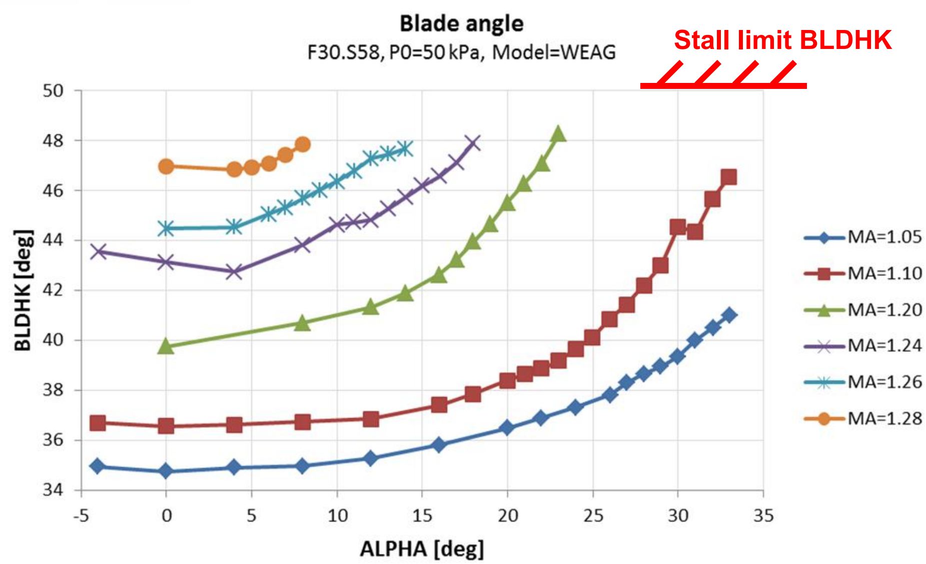


Baseline vs **alternative** Flap/Slats

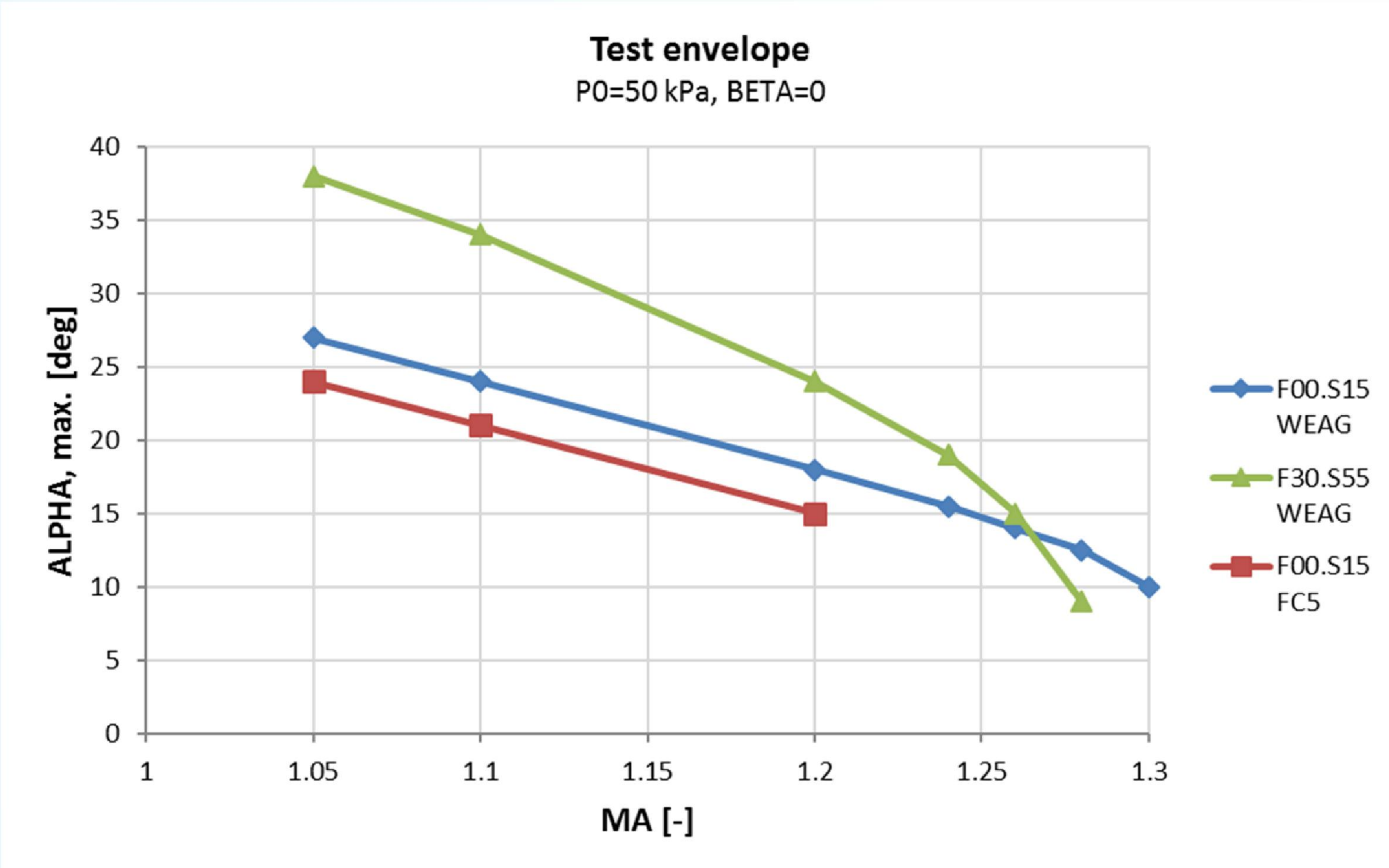


Baseline vs **Alternative** Flap/Slats





Max Alpha - Mach number envelope



German-Dutch Wind Tunnels

Company confidential

Intermediate conclusions

- PPL is a good indicator for the in/out flow through slots
- PPL can be controlled via BLDHK, but control diminishes the further the shock moves into the diffusor
- Flap/slat setting change allows for testing higher ALPHA

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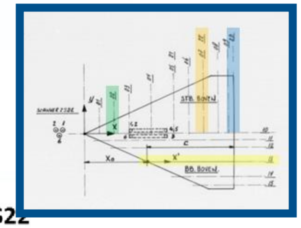
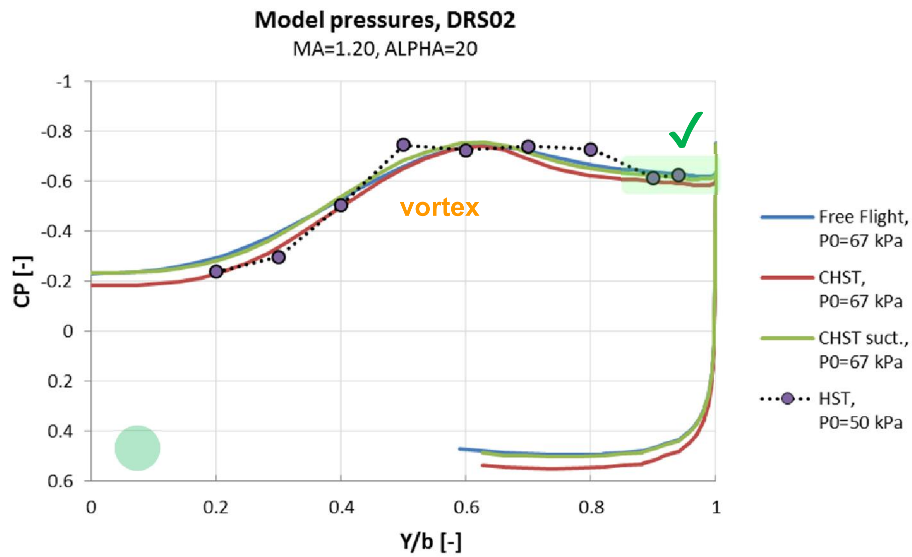
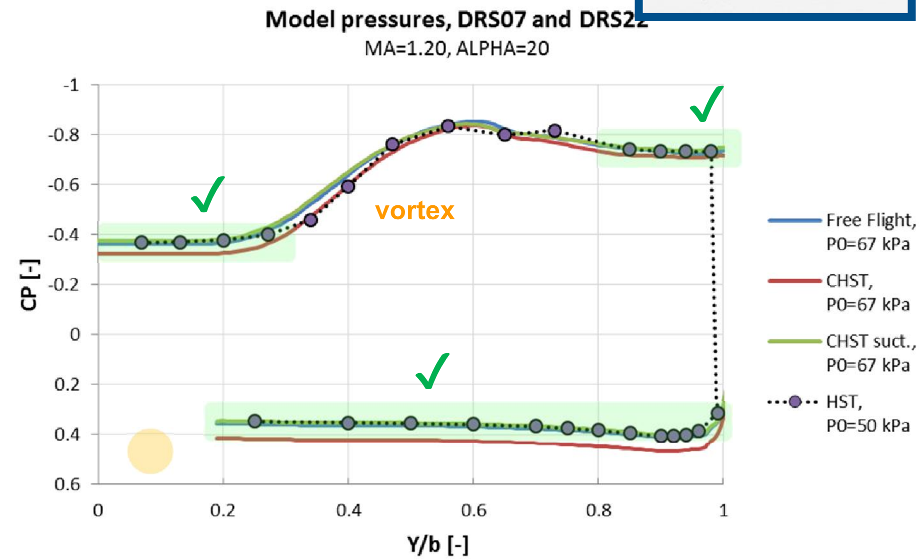
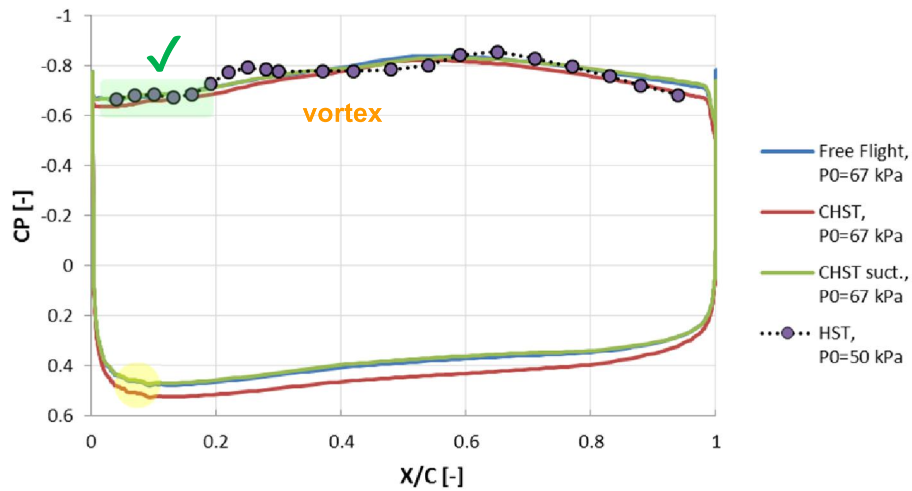
HST vs CFD: model pressures

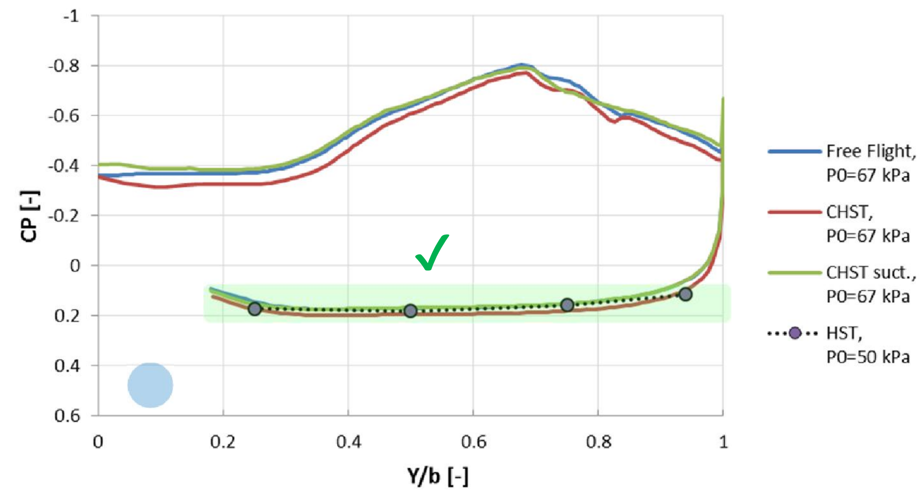






HST matches with Free Flight (and CHST with suction ON)





Intermediate conclusions

- Current HST results (MA=1.20, step-by-step) are in good agreement with free flight CFD, at both ALPHA 0° and 20°
- During execution of the project, it was realized that the re-entry geometry as provided for CFD modelling is not in accordance with the actual HST geometry
  - This might be the reason for differences in behavior (e.g. back pressure effects on plenum pressure) between CHST and HST
  - Active plenum suction circumvents this problem in CHST

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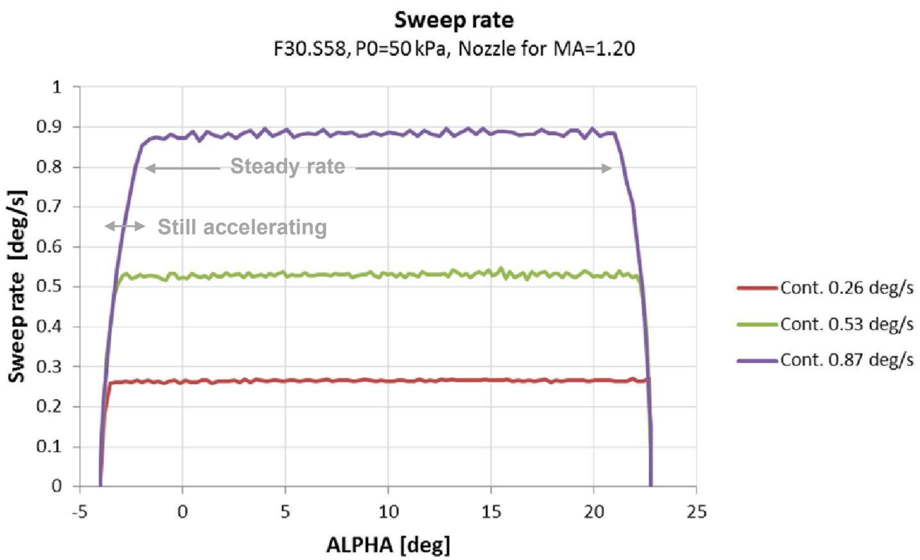
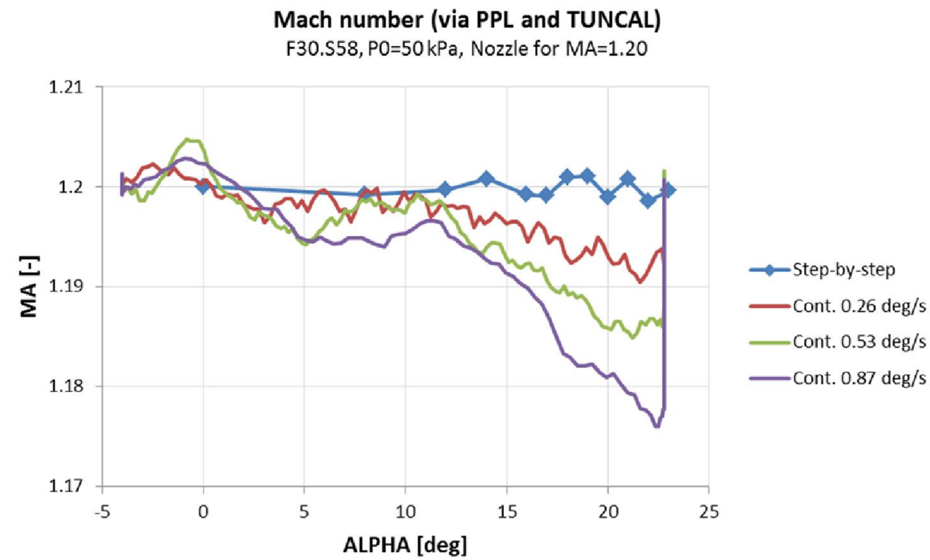
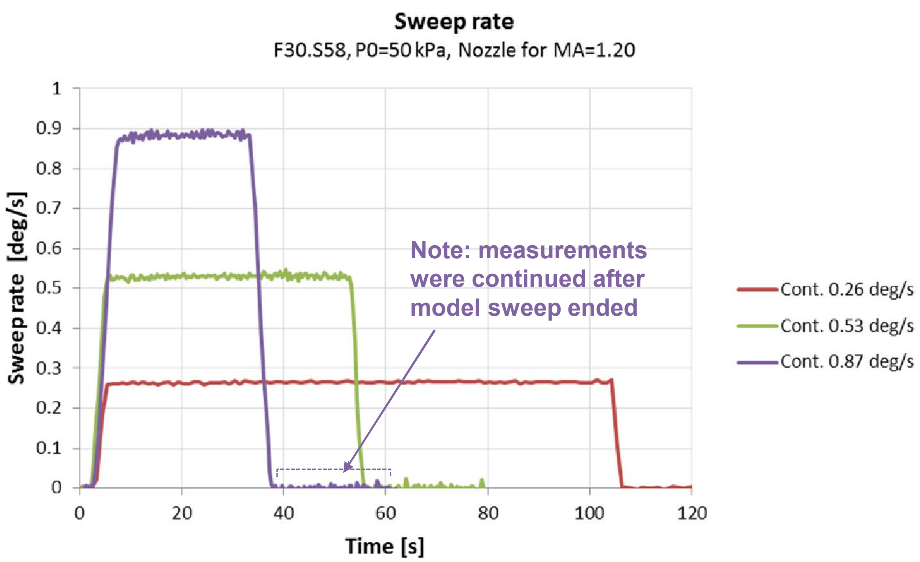
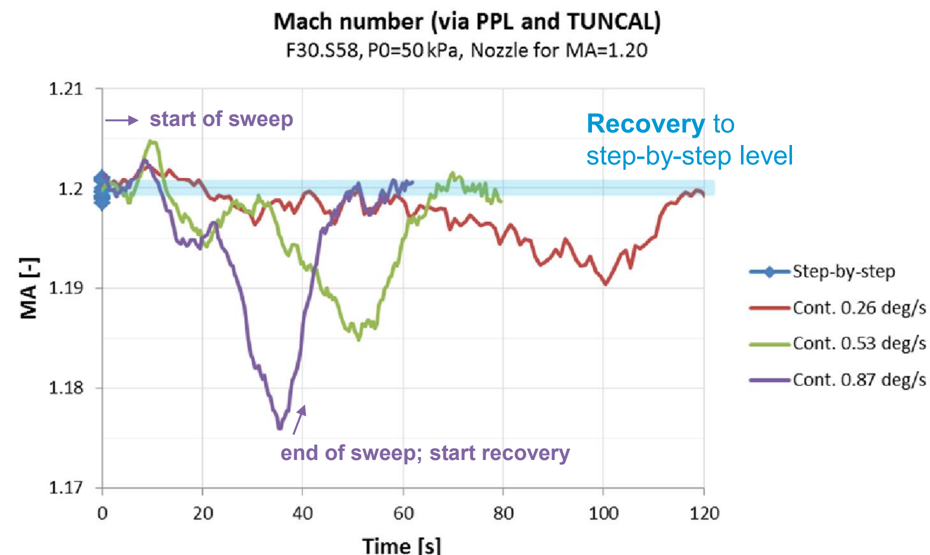
Controller cannot keep MA constant



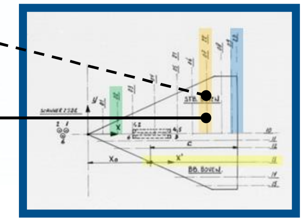


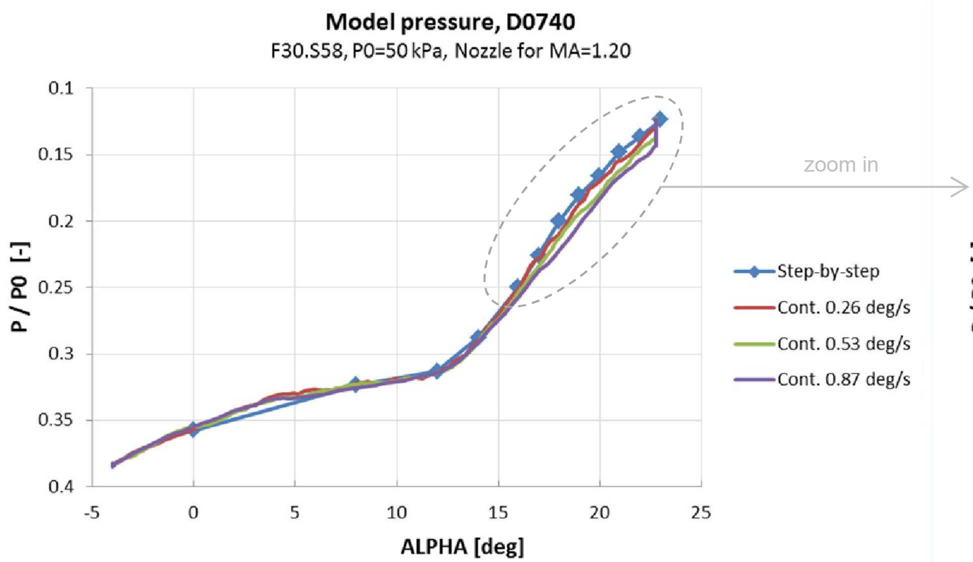


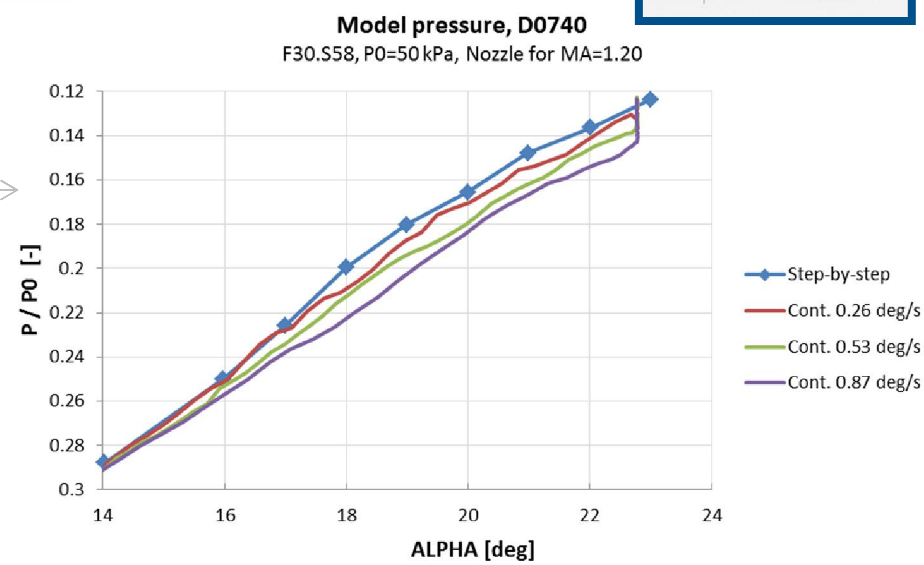


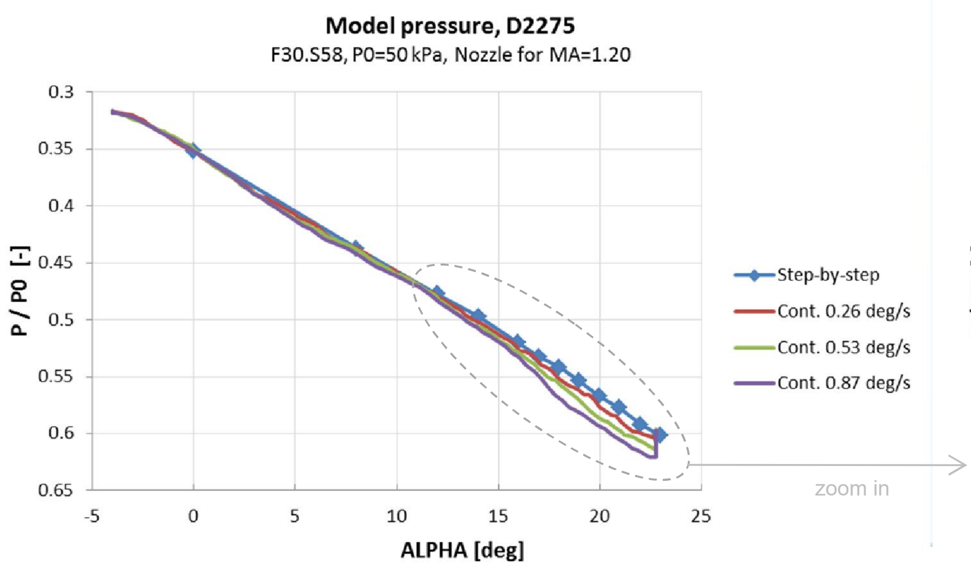
Company confidential

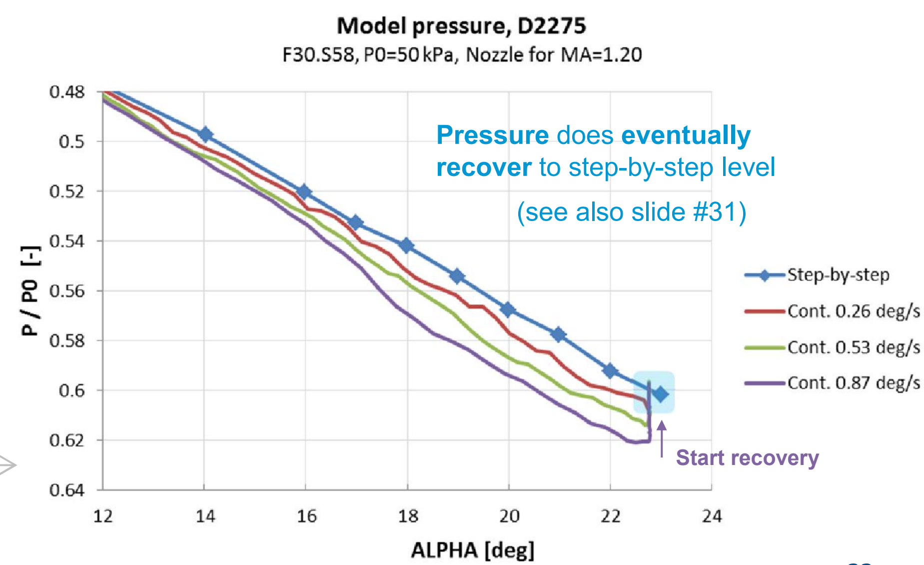
Impact on model results









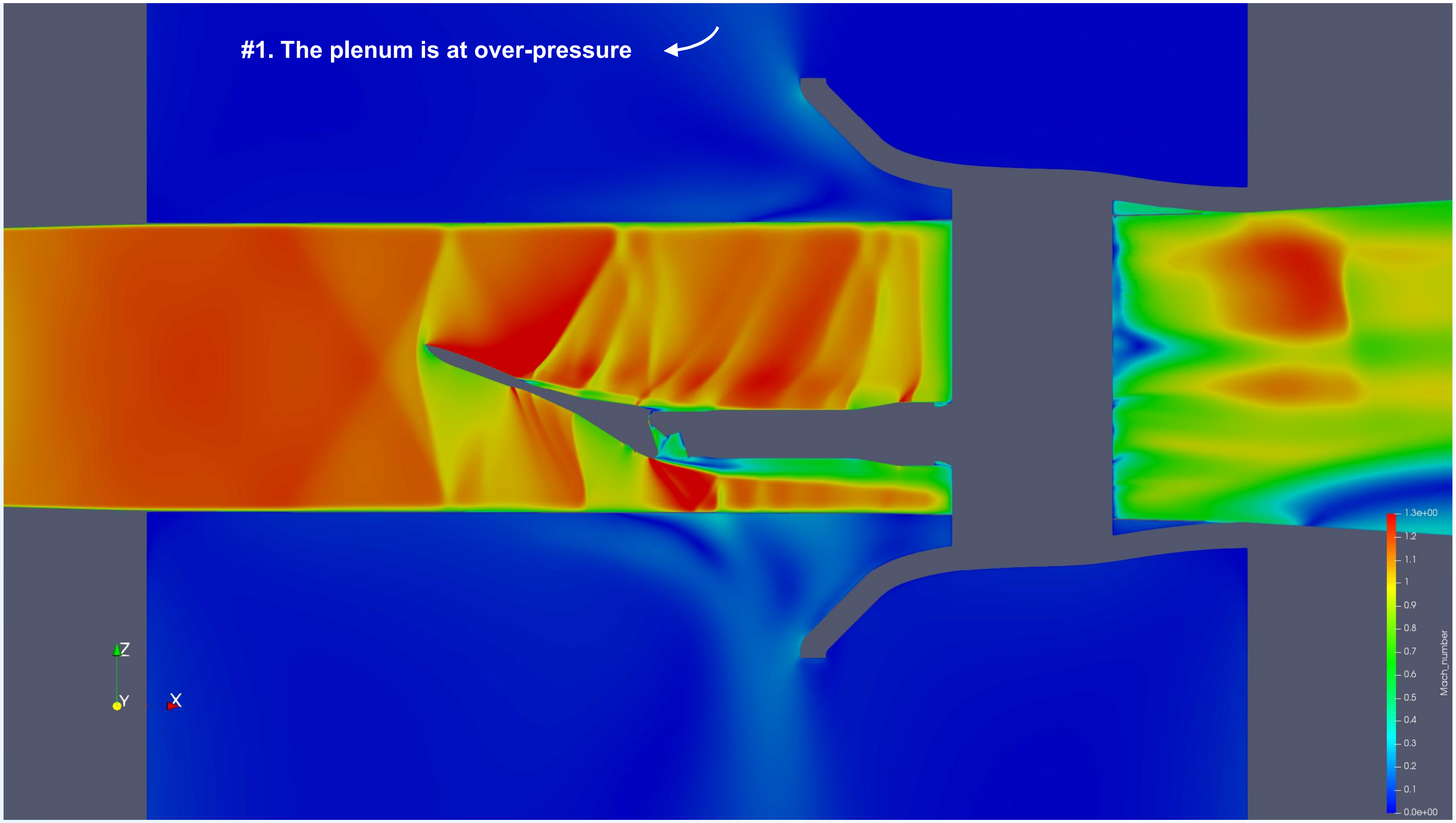


What about the oncoming flow field?

- The nozzle dictates the oncoming flow field, but… when MA is lagging behind:
  - The plenum is effectively at over-pressure
  - Causing air to enter the test section through the slots
  - Meaning the effective cross section reduces
  - Meaning a shock occurs -upon opening of the slots
  - Meaning a rise of static pressure should be visible across / aft of the shock

Just like what happens in CHST…

Case WEAG	pb	Pref	P0	Ma	AOA	p_suct	mp_suc	PPL	PPL-Pref	DLRs CaseName
Tunnel (ptot = 50kPa)	35.7k	20k	48499	1.20	20	-	-	21590	+1590	KANAL_v07finalGeom_Ma_1_2_mitSupport_undWEAG_finalGlatt_Alpha20_v2_ptot50k



German-Dutch Wind Tunnels

Just like what happens in CHST...

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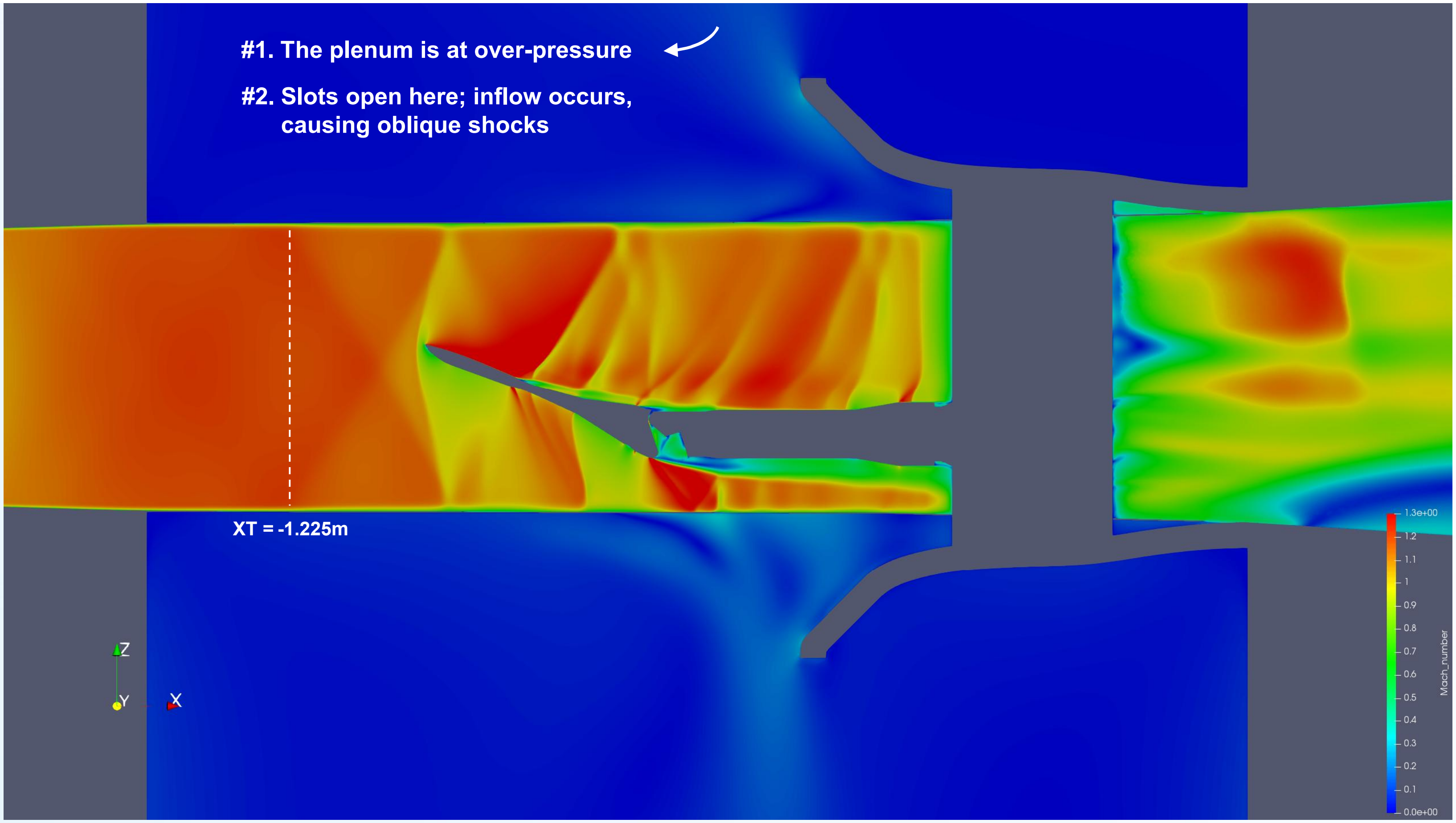

Note: for this CHST example (with the WEAG model) the plenum is much more over-pressured than in the HST

Just like what happens in CHST…

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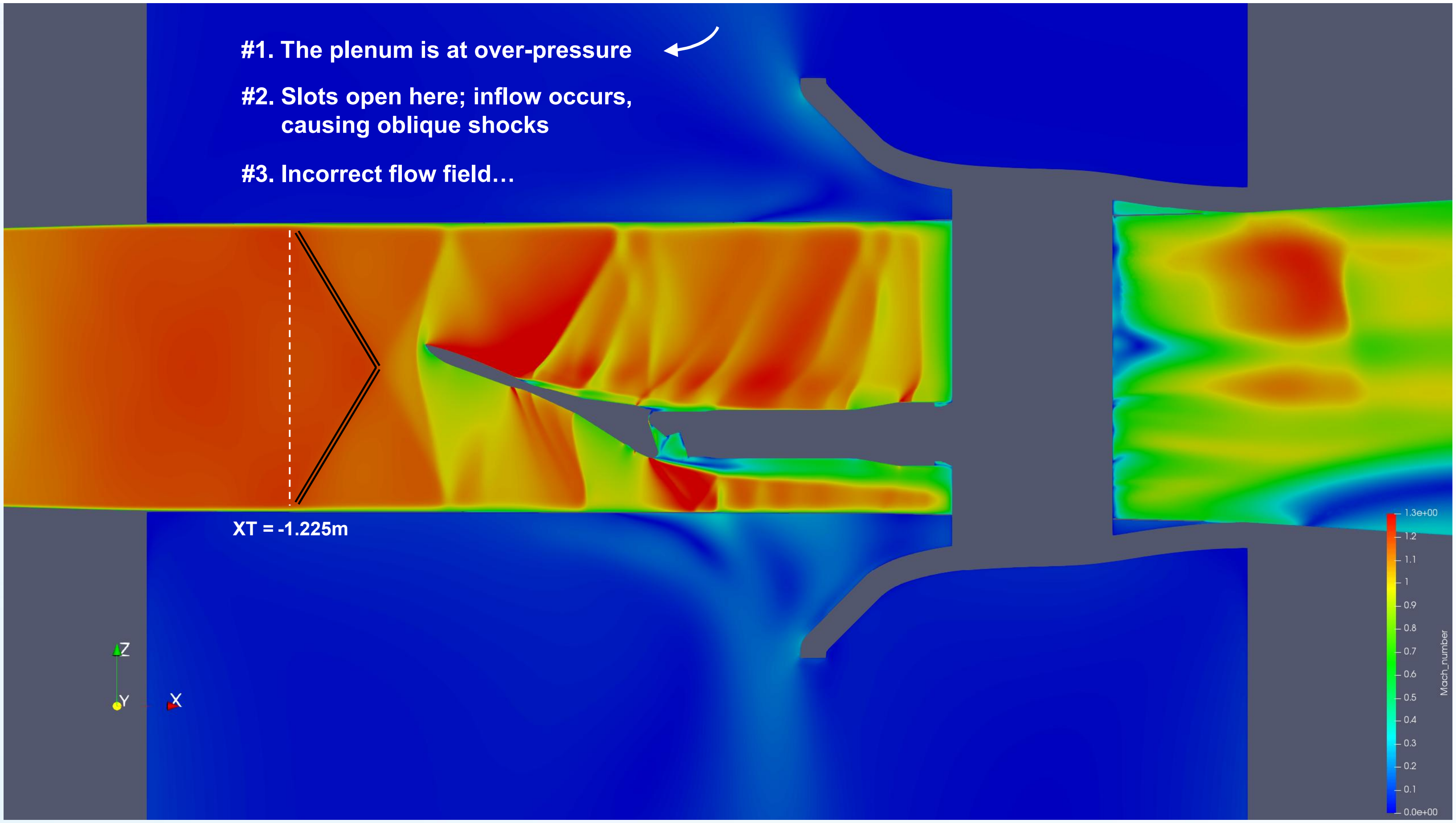

Note: for this CHST example (with the WEAG model) the plenum is much more over-pressured than the HST

Intermediate conclusions

- It is essential to keep the plenum at the correct pressure
  - Otherwise air enter (or leaves) the test section
  - Which changes the oncoming flow field and model results
  - AGARD AG-49: a zero pressure difference from plenum to test section is furthermore needed to be shock reflection free on the walls
- The plenum pressure can be adjusted via the BLDHK, but the controller is unable to keep the plenum pressure constant during continuous sweep testing
  - The amount and speed at which BLDHK changes seems to be the limiting factor –currently.

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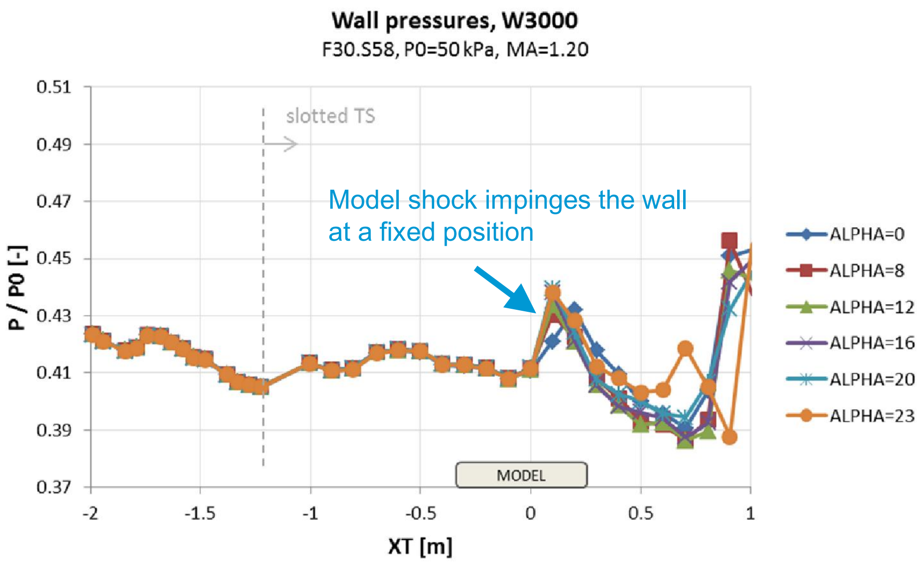
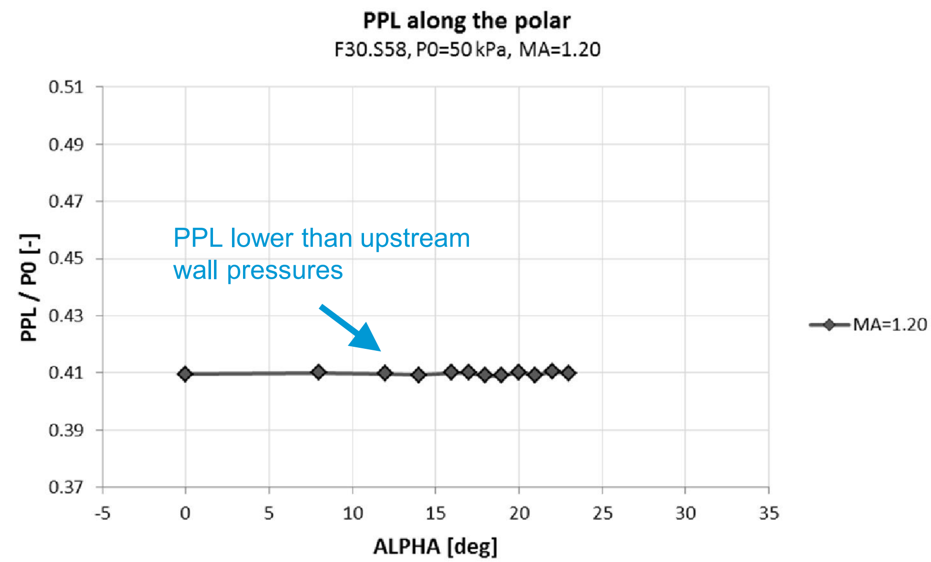
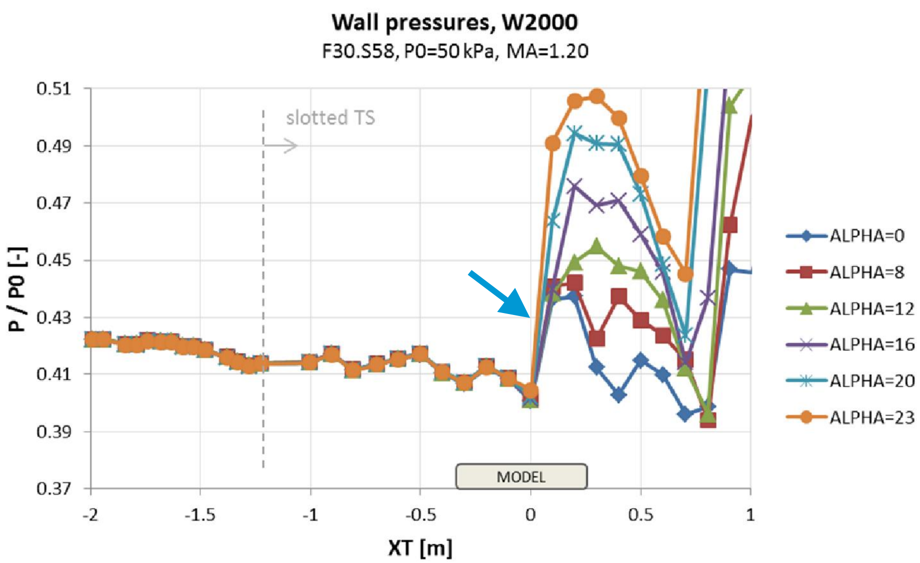
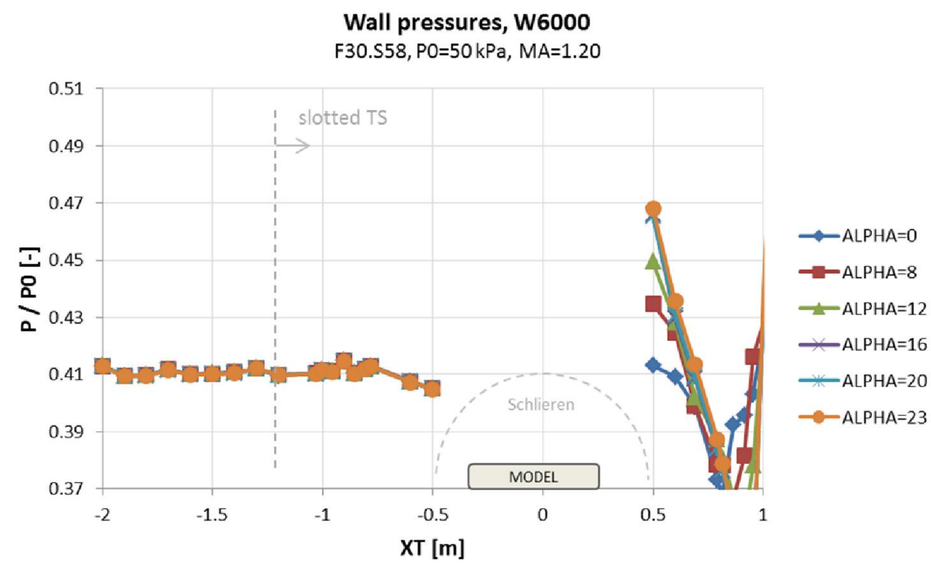
Wall pressures: Model=WEAG, **MA=1.20**

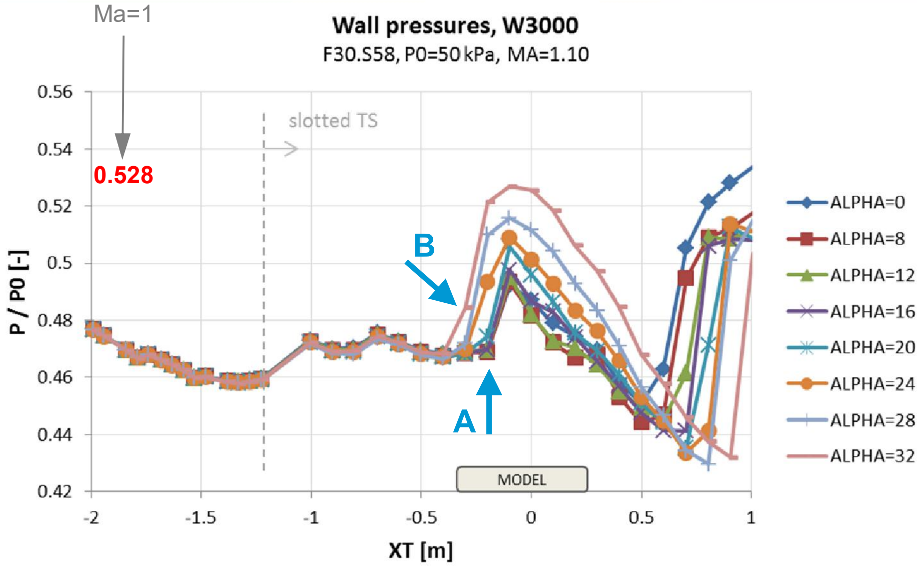








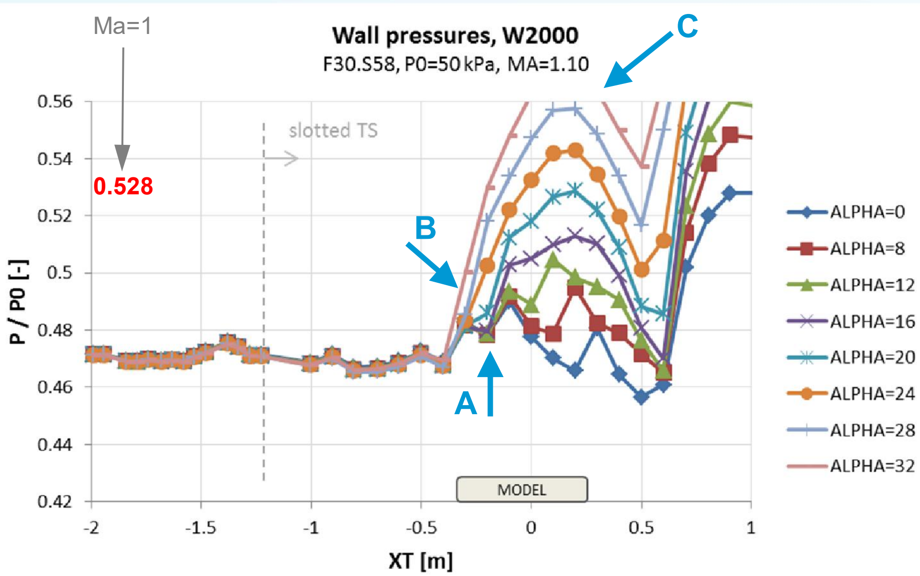
Wall pressures: Model=WEAG, **MA=1.10**

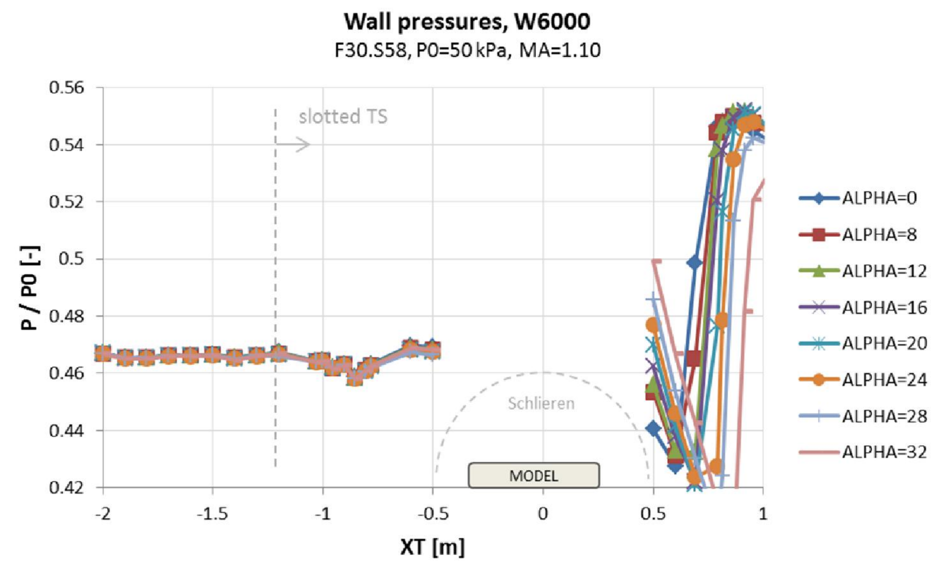


A. Model shock impinges at the same X-position up to ALPHA ~16° (on both upper and lower wall)

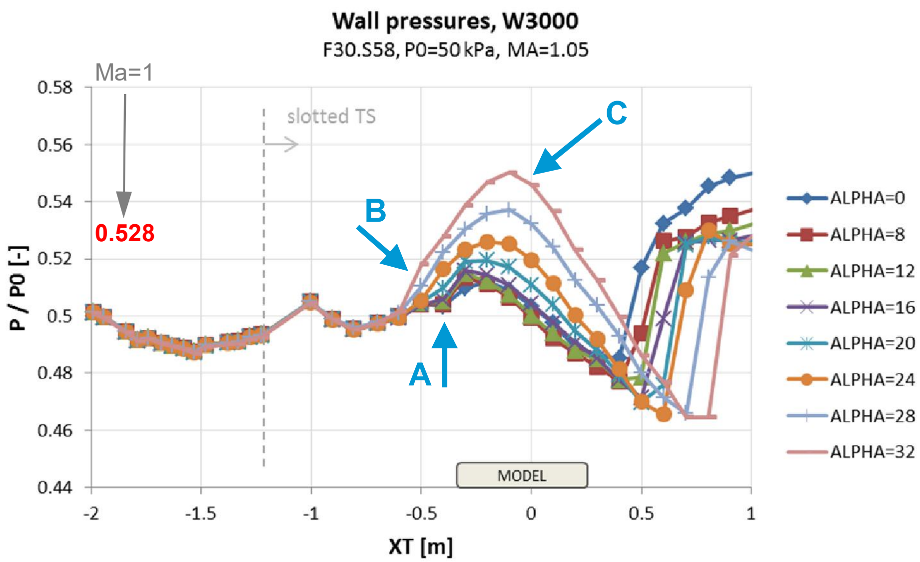
B. Beyond ALPHA 16~20° the model shock starts moving forward with increasing ALPHA

C. Subsonic flow region





Wall pressures: Model=WEAG, **MA=1.05**

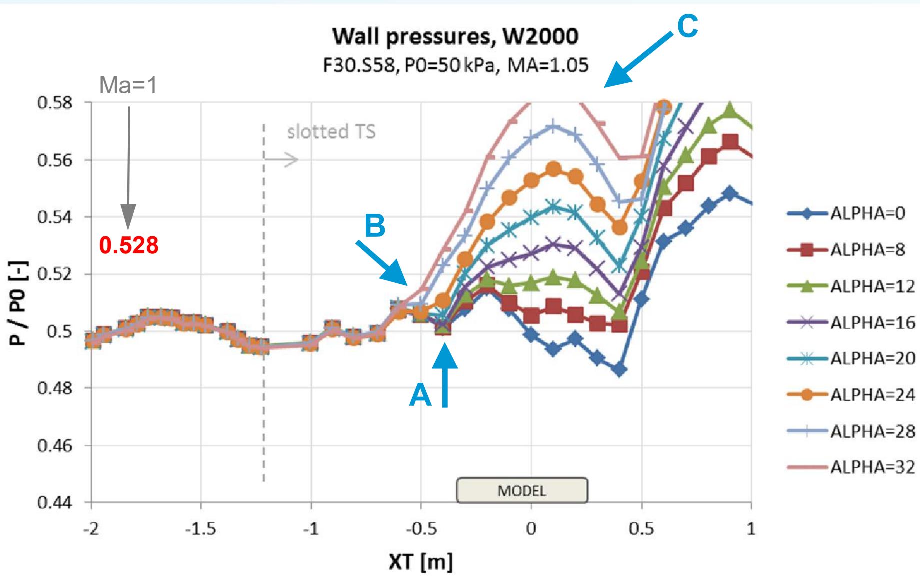


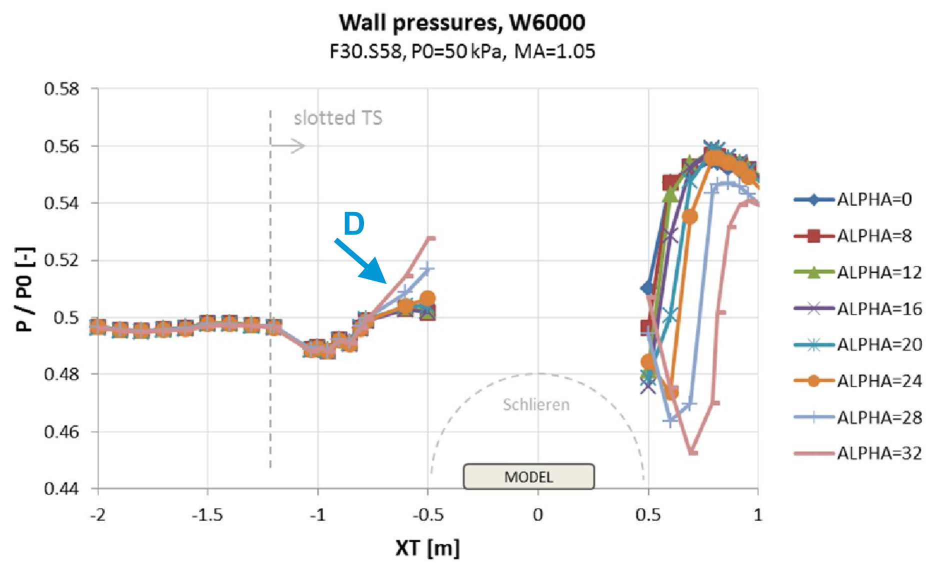
A. **Model shock impinges at the same X-position up to ALPHA ~12° (on both upper and lower wall)**

B. **Beyond ALPHA 12~16° the model shock starts moving forward with increasing ALPHA**

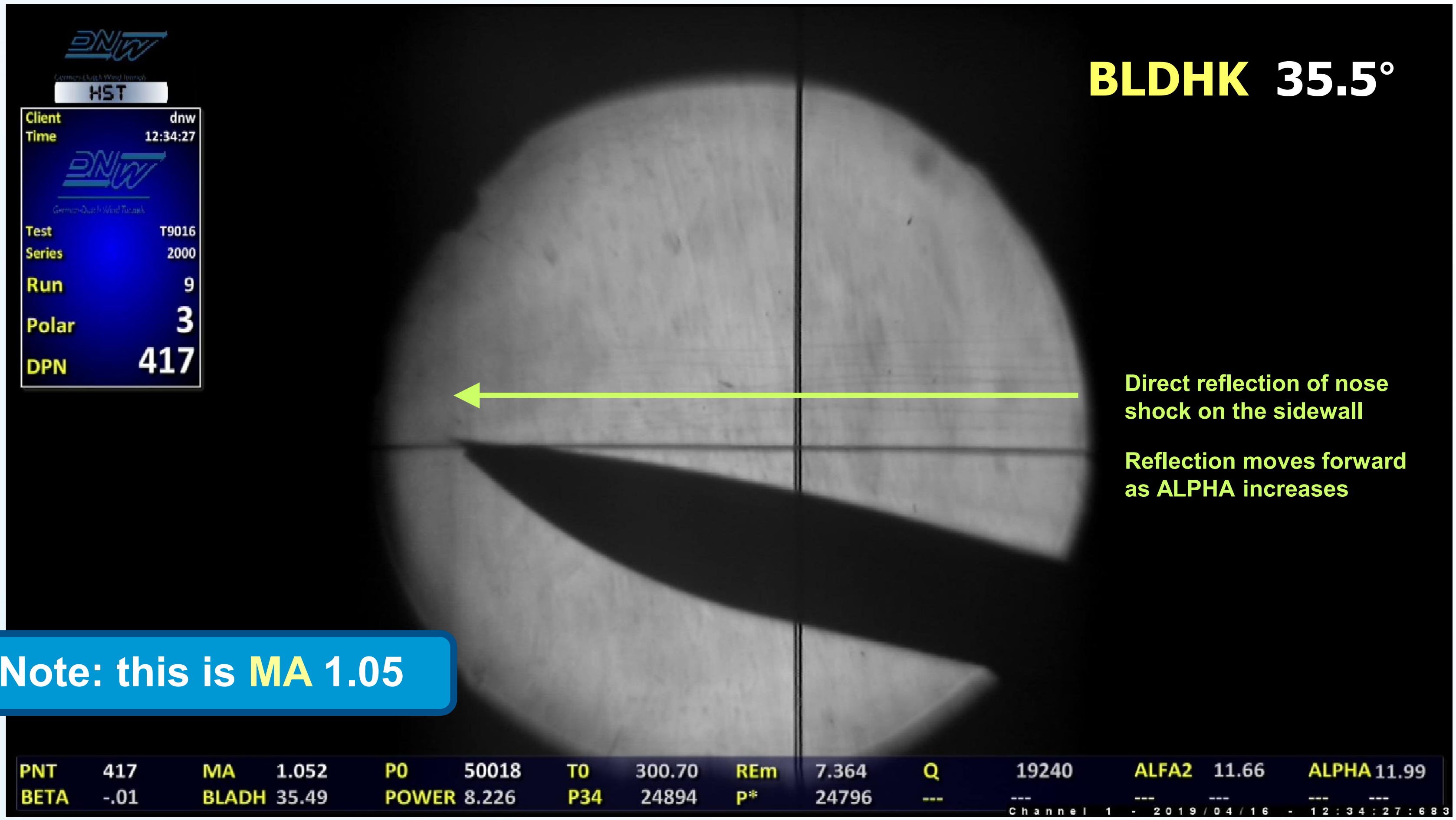
C. **Subsonic flow region**

D. **Same is visible on the sidewall, though the shock seems already further upstream than on the upper and lower walls**



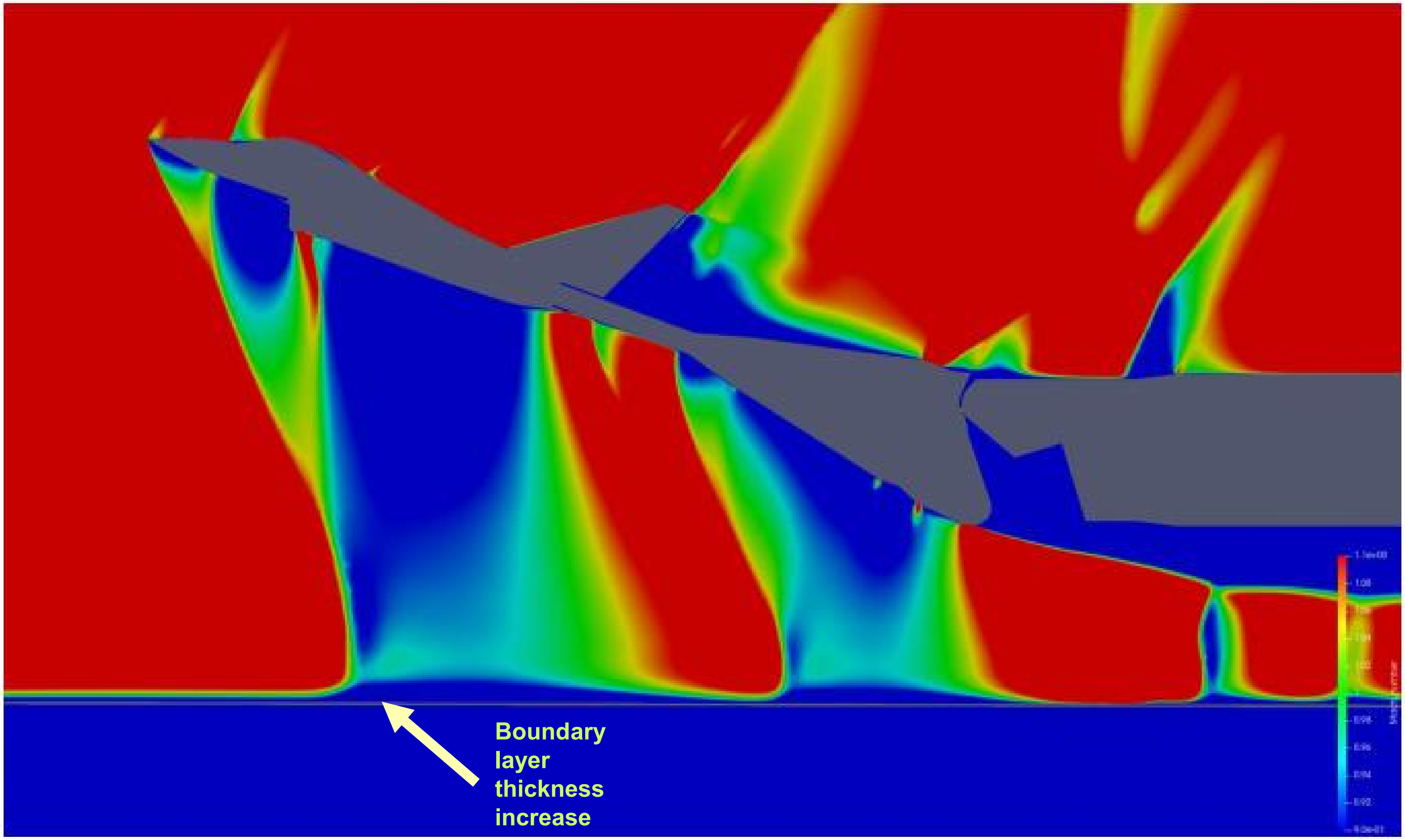


Schlieren: Nozzle for MA=1.05, ALPHA=12



Note: this is MA 1.05

Shock impingement: MA=1.20, Alpha=12

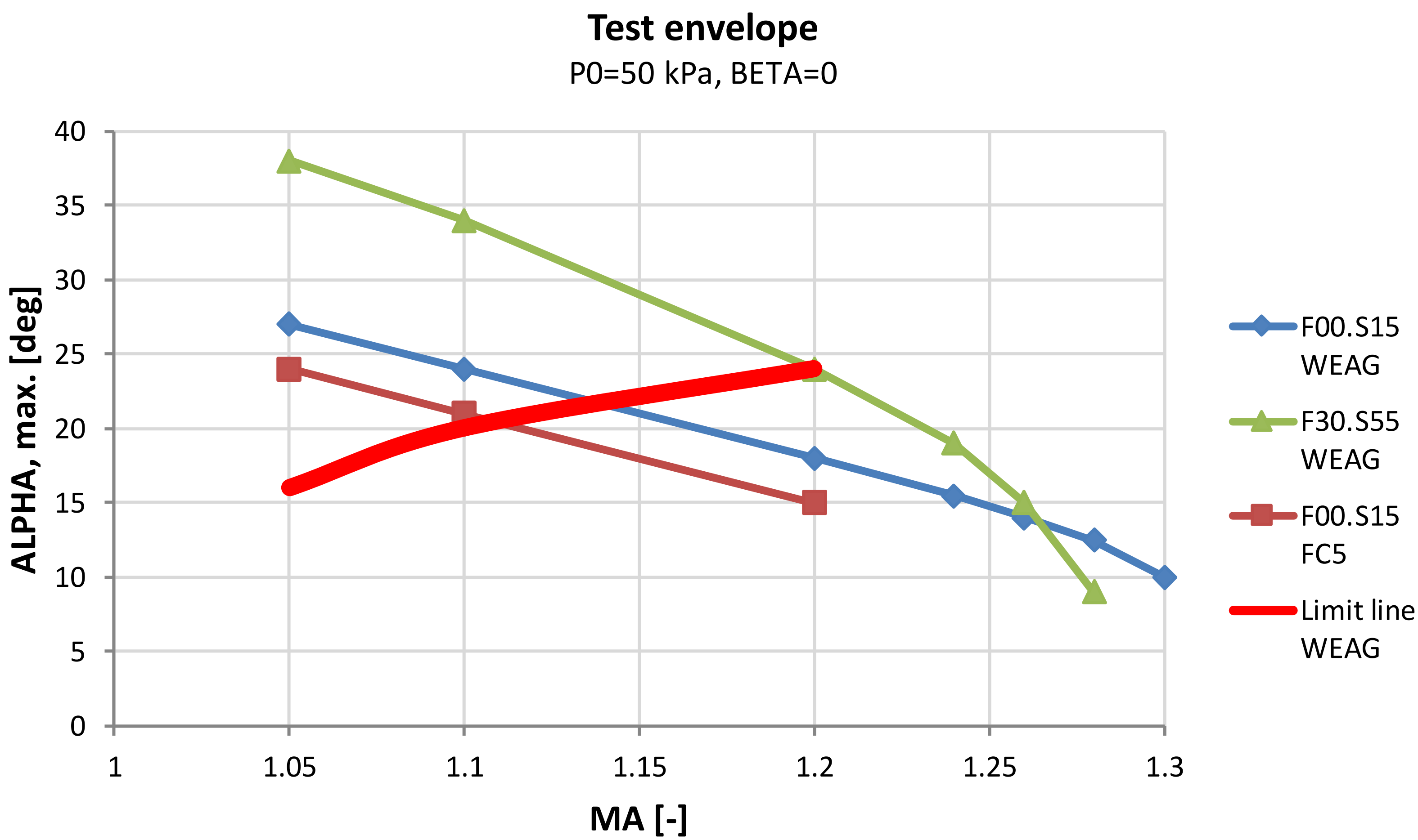


Boundary layer thickness increase, adds to reduction in effective area → local subsonic flow

Intermediate Conclusions/Remarks

- The model shock impinges each wall at a constant position (per wall) with increasing ALPHA – initially
- From a certain higher ALPHA the shock impingement point starts moving forward in HST
- The ALPHA at which this movement starts depends on MA
  - At MA=1.05 near ALPHA~16; at MA=1.10 near ALPHA ~20; at MA=1.20 it is not visible (up to ALPHA=23)
- This phenomenon is not visible in TWG for other model
- Hypothesis: Local subsonic flow due to boundary layer growth
- CFD calculations for CHST at MA=1.05 are running

Max Alpha - Mach number envelope



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Final Conclusions (1/3)

1. Alpha – Mach number envelope

Alpha – Mach number envelope should be expanded

Current limitation

- Maximum blade pitch angle
- Re-entry geometry

Possible solutions

- Change re-entry geometry (available)
- Second throat to control terminating shock position
- Active plenum suction

Final Conclusions (2/3)

2. Model sweep rate extension

Mach controller not fast enough to keep Mach number constant during model sweep rate

Current limitation

- Blade pitch rate is limiting factor

Possible solutions

- Modification of hydraulic blade pitch system or replacement with electrical control system
- Active plenum suction (not sure whether this is fast enough for control)

Final Conclusions (3/3)

3. Results at Ma=1.05

Unexpected results at Ma=1.05 for Alpha> 10 deg

Current limitation

- Local subsonic flow due to shock – boundary layer interaction (?)

Possible solutions

- More ventilation by
  - Slots in side walls
  - Perforated walls with 60 deg slanted holes
- Boundary layer removal by suction
- Smaller model (blockage < 1%)

Possible next steps

- Simulation of flow phenomena at Ma=1.05 for CHST
  - Updating re-entry geometry
  - Grid refinements at wall boundary layers
  - Simulation perforated walls
- Upgrading/replacement of blade angle hydraulic system
- Implementing plenum/boundary layer suction system
- Change wall ventilation

Results of HST CFD Simulations

S. Melber-Wilkending

Institute of Aerodynamics an Flow Technology

DLR Braunschweig

Introduction

- Problem: Measurement results of Eurofighter Aircraft model at higher angles of attack / higher flap angles are off the expected results during measurements in HST wind tunnel at Ma = 1.2
- Research support for DLR to answer:
  - Question I: Identification of the problem
  - Question II: Ideas for modifications to resolve the problem?

Introduction

- Problem: Measurement results of Eurofighter Aircraft model at higher angles of attack / higher flap angles are off the expected results during measurements in HST wind tunnel at Ma = 1.2
- Research support for DLR to answer:
    - Question I: Identification of the problem
    - Question II: Ideas for modifications to resolve the problem?
- Approach by numerical simulation of big part of HST including aircraft model, support and plenum → "Computational"HST → CHST
- Because of unsymmetrical effects in measurement: simulation of "left" and "right" side necessary

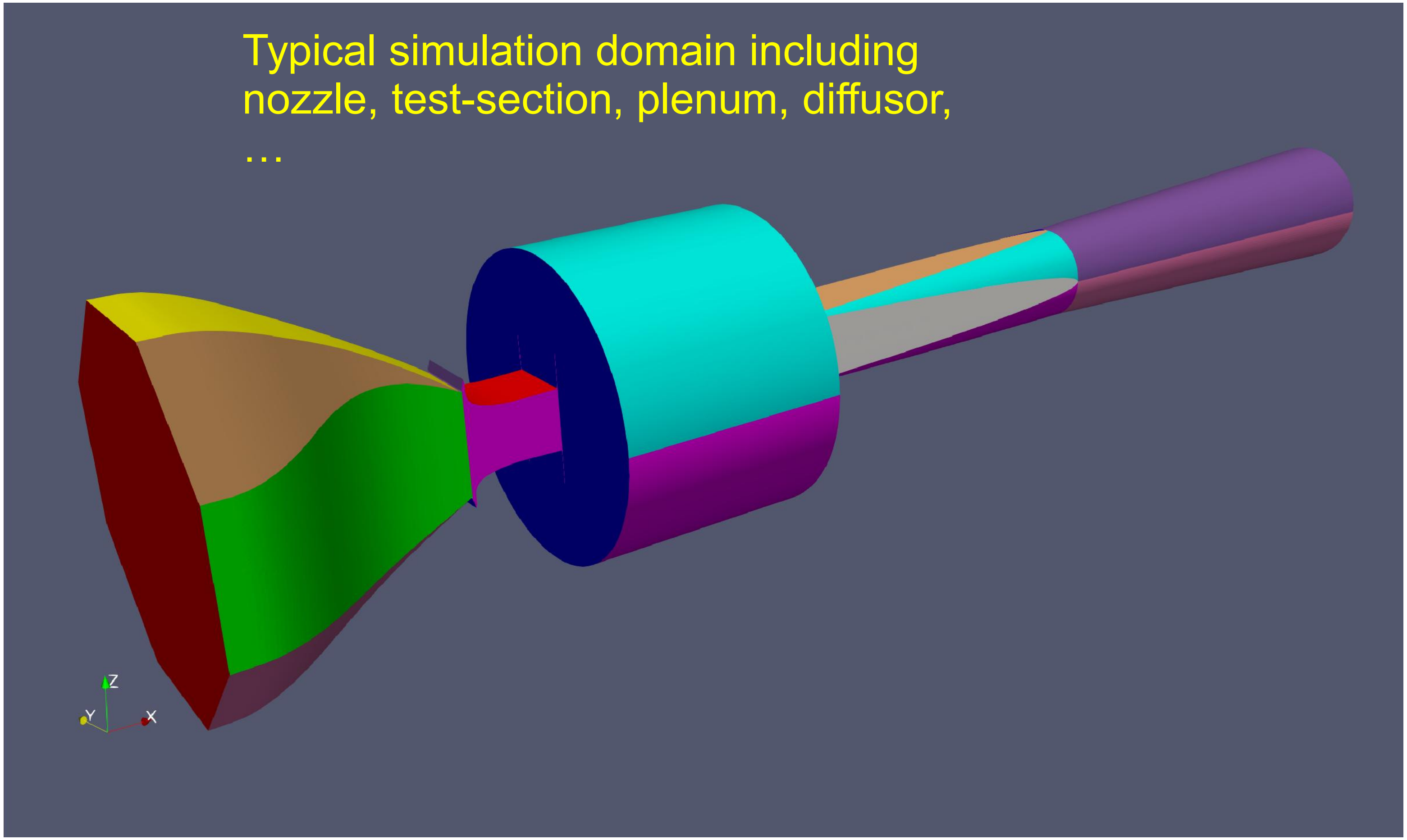
Flow Solver & Grids

- Because of complexity of geometry → mesh generation with DLR-Solar mesh generator (hybrid unstructured, structured dominant)
- Numerical flow simulation with DLR-TAU Code (hybrid unstructured finite volume code)
- Reference data:
  - Mach number = 1.2
  - Static pressure = 28000 Pa
  - Temperature = 236 K
  - Density = 0.41 kg/m^3
- Typical simulation time of one configuration on 384 Cores on CASE-Cluster with mesh size around 170 – 200 million points → two weeks
- Overall 60 configurations calculated (test-simulations not included) up to now …

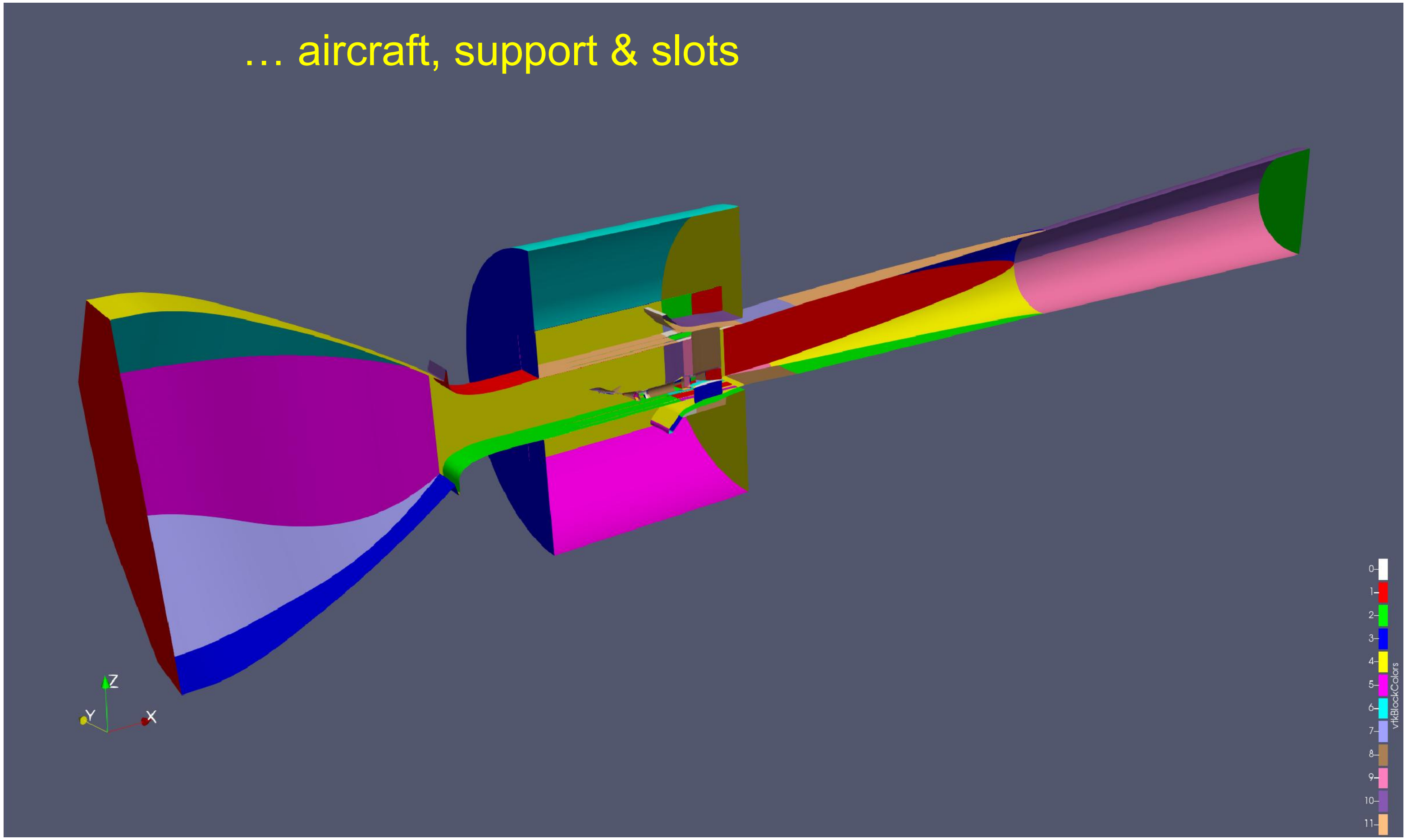
Cases

Case EuroFighter	p_out	AOA/ Flap	p_suct	mp_suc	Slots SideW	p_pl	p_pl- p_stat	DrivePower@ T12 [MWatt]	Diffusor@ T12 [MWatt]	T12 [K]	dE_inout [%]	CL	CD	CM	Remarks
Tunnel empty & support	50k	-/-	-	-	-	28093	+93	-	-	-	-	-			ok
Tunnel empty & support	51k	-/-	-	-	-	28400	+400	-	-	-	-	-			Exit pressure to high
Tunnel empty & support	52k	-/-	-	-	-	28274	+274	-	-	-	-	-			Exit pressure to high
Tunnel empty & support	53k	-/-	-	-	-	28799	+799	-	-	-	-	-			Exit pressure to high
Tunnel empty & support	54k	-/-	-	-	-	29714	+714	-	-	-	-	-			Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-	-	-	28596	+596	-	-	-	-	-			
Tunnel	50k	00/00	-	-	-	27930	-70	12.9	6.8	301.8	0.18	-0.0115	0.0072	0.0028	
Tunnel	50k	00/20	-	-	-	27973	-27	11.9	7.1	301.8	0.01	0.0368	0.0153	-0.0104	
Tunnel	50k	20/00	-	-	-	29761	+1761	11.4	6.8	302.0	0.10	0.2498	0.0913	-0.0287	
Tunnel	50k	20/20	-	-	-	30488	+2488	12.7	6.8	301.8	0.02	0.2846	0.1186	-0.0394	
Tunnel (MarkerMod)	50k	20/20	-	-	-	30509	+2509	10.4	6.8	301.8	0.34	0.2829	0.1178	-0.0392	
Tunnel (FullMarkerMod)	50k	20/20	-	-	-	30485	+2485	14.6	6.7	301.8	0.29	0.2834	0.1180	-0.0391	
Tunnel (without support)	50k	00/00	-	-	-	30428	+2428	10.9	7.6	301.9	0.02	-0.0166	0.0087	0.0037	Removed Support --> strong shock there
Tunnel (without support)	50k	20/20	-	-	-	29181	+1181	11.6	6.4	301.8	0.04	0.2866	0.1184	-0.0389	Removed Support --> strong shock there
Tunnel & slots closed	50k	20/20	-	-	-	-	-	12.0	9.2	302.4	0.03	0.2169	0.0857	-0.0239	Too strong shock in diffusor --> Ma<1
Tunnel & slots closed	40k	20/20	-	-	-	-	-	18.5	15.7	301.0	0.01	0.2169	0.0857	-0.0239	Too strong shock in diffusor --> Ma<1
Tunnel & slots closed (red. diffusor)	50k	20/20	-	-	-	-	-					0.2170	0.0857	-0.0239	Ma < 1
Tunnel & slots partly closed to nose	50k	20/20	-	-	-	30412	+2412	13.2	6.9	301.8	0.02	0.2840	0.1161	-0.0380	
Tunnel & slots partly closed to cone	50k	20/20	-	-	-	29119	+1119	14.7	7.1	301.8	0.31	0.2660	0.1055	-0.0346	Ma < 1
Tunnel & suction	50k	20/20	27.7k	2.49%	-	27630	-370	13.3	6.7	302.0	1.55	0.2913	0.1189	-0.0403	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27.8k	2.35%	-	27731	-269	12.9	6.3	302.0	1.54	0.2913	0.1189	-0.0402	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27.9k	2.31%	-	27828	-172	13.6	7.1	302.0	1.39	0.2913	0.1189	-0.0401	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27.95k	2.37%	-	27882	-118	13.1	6.7	302.0	1.40	0.2913	0.1188	-0.0400	ok
Tunnel & suction	50k	20/20	28k	2.21%	-	27933	-67	13.5	7.0	302.0	1.32	0.2913	0.1189	-0.0400	ok: No Regulation! --> p_plenum right!
Tunnel & suction (MarkerMod / without support)	50k	0/0	28k	0%	-	27956	-44	10.8	7.1	301.8	0.59	-0.0108	0.0072	0.0026	
Tunnel & suction (MarkerMod)	50k	20/20	28k	2.79%	-	27941	-59	13.5	6.9	302.0	1.79	0.2911	0.1188	-0.0399	
Tunnel & suction & SideSlots	50k	20/20	28k	4.33%	x	27738	-262	13.4	6.1	302.2	3.48	0.2892	0.1190	-0.0405	
Tunnel & suction (reentry off)	50k	20/20	28k	9.87%	-	28404	+404	8.0	0.16	303.3	9.73	-			
Tunnel & conehat	50k	00/-	-	-	-	30263	+2263	-	-	-	-	-			Removed Support --> strong shock there
Tunnel & conehat	50k	20/-	-	-	-	26877	-1123	-	-	-	-	-			Removed Support --> strong shock there
Tunnel & conehat (rot. source)	50k	20/-	-	-	-	26630	-1370	-	-	-	-	-			Removed Support --> strong shock there
Tunnel & double conehat	50k	20/-	-	-	-	31762	+3762	-	-	-	-	-			Removed Support --> strong shock there
Tunnel & double conehat & Support	50k	00/-	-	-	-	28209	+209	12.0	7.0	301.6	0.01	-			
Tunnel & double conehat & Support	50k	20/-	-	-	-	28579	+579	11.8	6.4	301.6	0.01	-			
Tunnel	40k	00/00	-	-	-	26778	-1222	25.1	13.9	300.7	0.92	-0.0099	0.0073	0.0024	
Tunnel	40k	00/20	-	-	-	26869	-1131	19.1	14.2	300.9	0.00	0.0351	0.0151	-0.0100	
Tunnel	40k	20/00	-	-	-	29543	+1563	21.2	14.5	300.8	0.27	0.2521	0.0923	-0.0289	
Tunnel	40k	20/20	-	-	-	30321	+2321	20.1	14.2	300.6	0.03	0.2839	0.1183	-0.0393	
Tunnel	50k	20/20	-	-	-	30488	+2488	12.7	6.8	301.8	0.02	0.2846	0.1186	-0.0394	
Tunnel	49k	20/20	-	-	-	30414	+2414	13.6	7.5	301.7	0.03	0.2843	0.1185	-0.0394	
Tunnel	48k	20/20	-	-	-	30363	+2363	14.4	8.3	301.6	0.03	0.2841	0.1184	-0.0393	
Tunnel	47k	20/20	-	-	-	30352	+2352	15.2	9.1	301.5	0.03	0.2840	0.1184	-0.0393	
Tunnel	46k	20/20	-	-	-	30351	+2351	15.9	9.9	301.4	0.03	0.2840	0.1184	-0.0393	
Tunnel	45k	20/20	-	-	-	30351	+2351	16.3	10.3	301.2	0.02	0.2840	0.1184	-0.0393	
Tunnel	44k	20/20	-	-	-	30351	+2351	17.0	11.0	301.1	0.03	0.2840	0.1184	-0.0393	
Tunnel	30k	20/20	-	-	-	30333	+2333	26.6	20.7	299.7	0.03	0.2839	0.1184	-0.0393	
Tunnel	50k	20/20	-	-	-	43431	+15431	6.5	2.3	302.7	0.12	0.1978	0.0771	-0.0211	Ma < 1
Tunnel	50k	20/20	-	-	-	31113	+3113	15.1	7.6	302.0	0.10	0.2865	0.1189	-0.0392	
Tunnel & suction	50k	20/20	x	x	-	27502	-498	12.8	5.8	301.7	0.04	0.2911	0.1187	-0.0400	
Tunnel & suction	50k	20/20	x	x	-	28241	+241	11.5	4.8	302.0	0.20	0.2901	0.1188	-0.0394	
Tunnel & Flap 50mm open	50k	20/20	-	-	-	27738	-262	16.35	8.71	302.2	0.42	0.2908	0.1188	-0.0402	
Tunnel & Flap 50mm open & Slat partly closed	50k	20/20	-	-	-	32920	4920	12.84	5.24	301.6	0.096	0.2813	0.1153	-0.0377	
Free Flight	-	00/00	-	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	
Free Flight	-	00/20	-	-	-	-	-	-	-	-	-	0.0381	0.0151	-0.0107	
Free Flight	-	20/00	-	-	-	-	-	-	-	-	-	0.2509	0.0917	-0.0298	b is not critical in free flight because no slots!
Free Flight	-	20/20	-	-	-	-	-	-	-	-	-	0.2863	0.1187	-0.0401	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b is not critical in free flight because no slots!

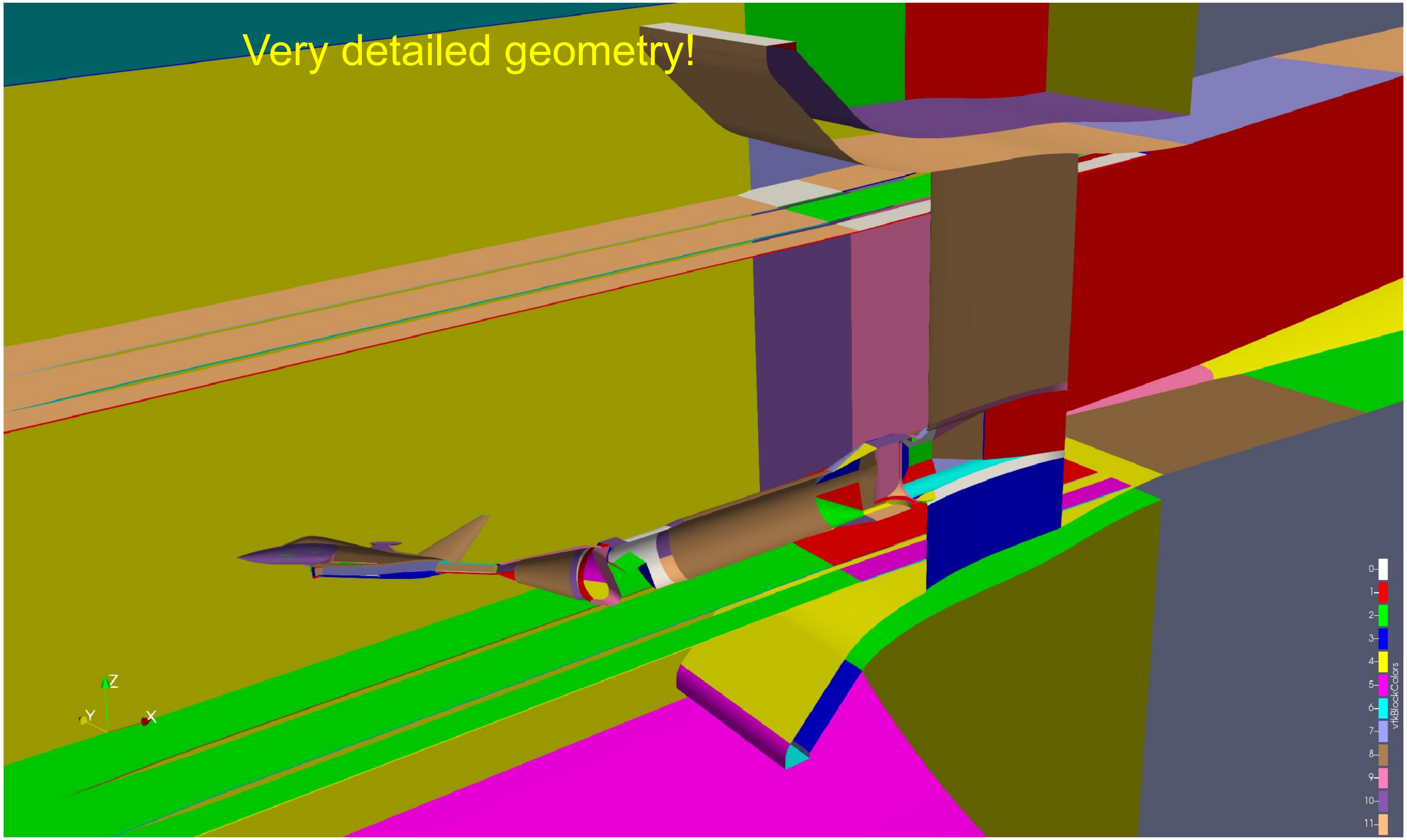
Flow Solver & Grids



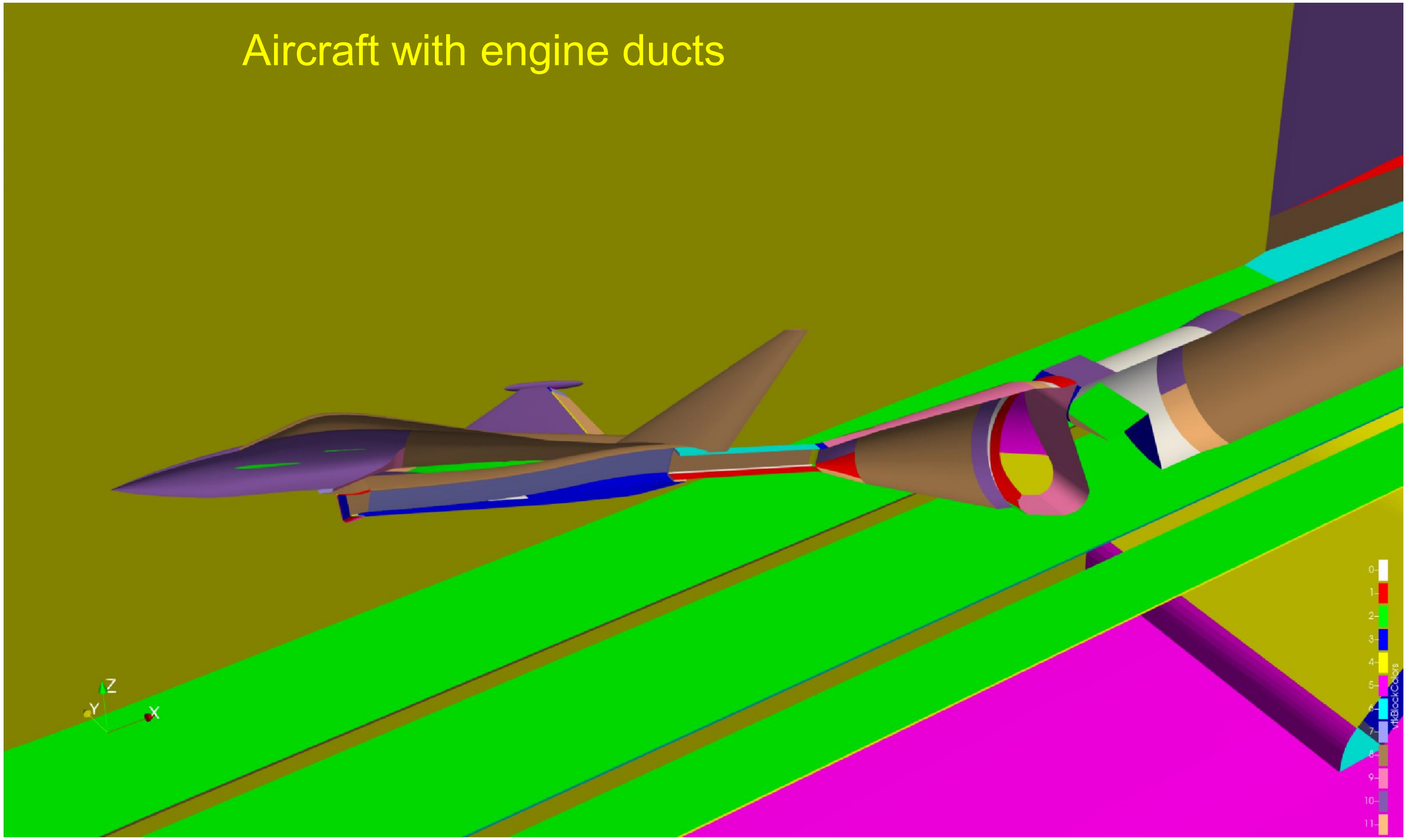
Flow Solver & Grids



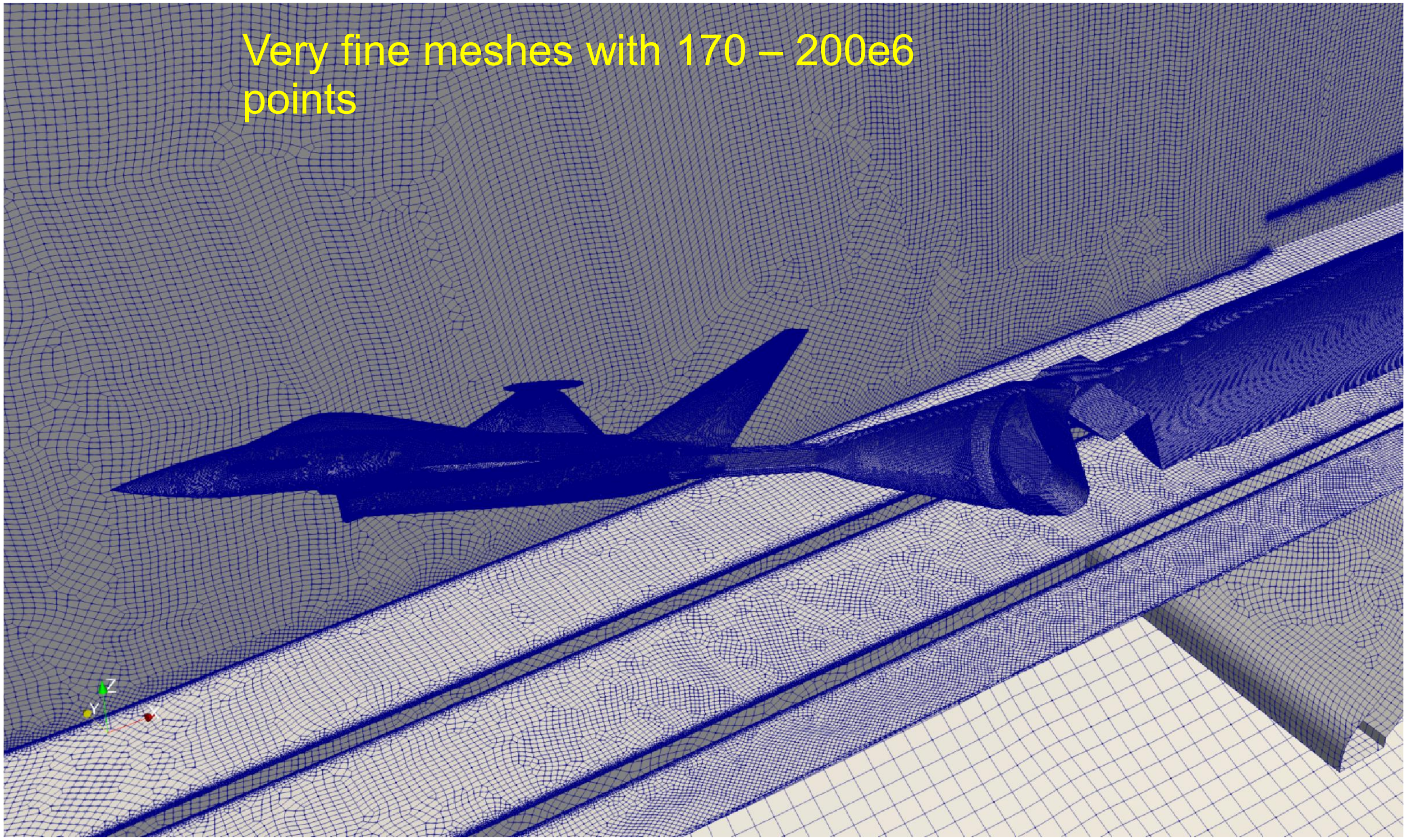
Flow Solver & Grids



Flow Solver & Grids



Flow Solver & Grids



Tunnel regulation in HST & CHST

Tunnel regulation

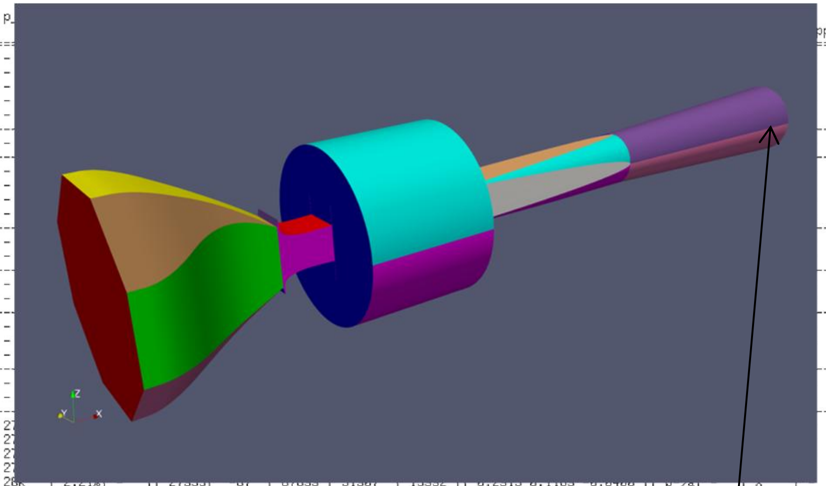
- Real tunnel (HST):
  - Measurement of plenum pressure
  - If plenum pressure differ from static pressure in test section → change in blade angle of drive → change of backpressure at the end of the diffusor

- Numerical wind tunnel (CHST):
  - Constant backpressure – no regulation
  - Before simulation: variation of backpressure to find range in which Ma = 1.2 in test section can be reached

Influence of back pressure

Influence of back pressure

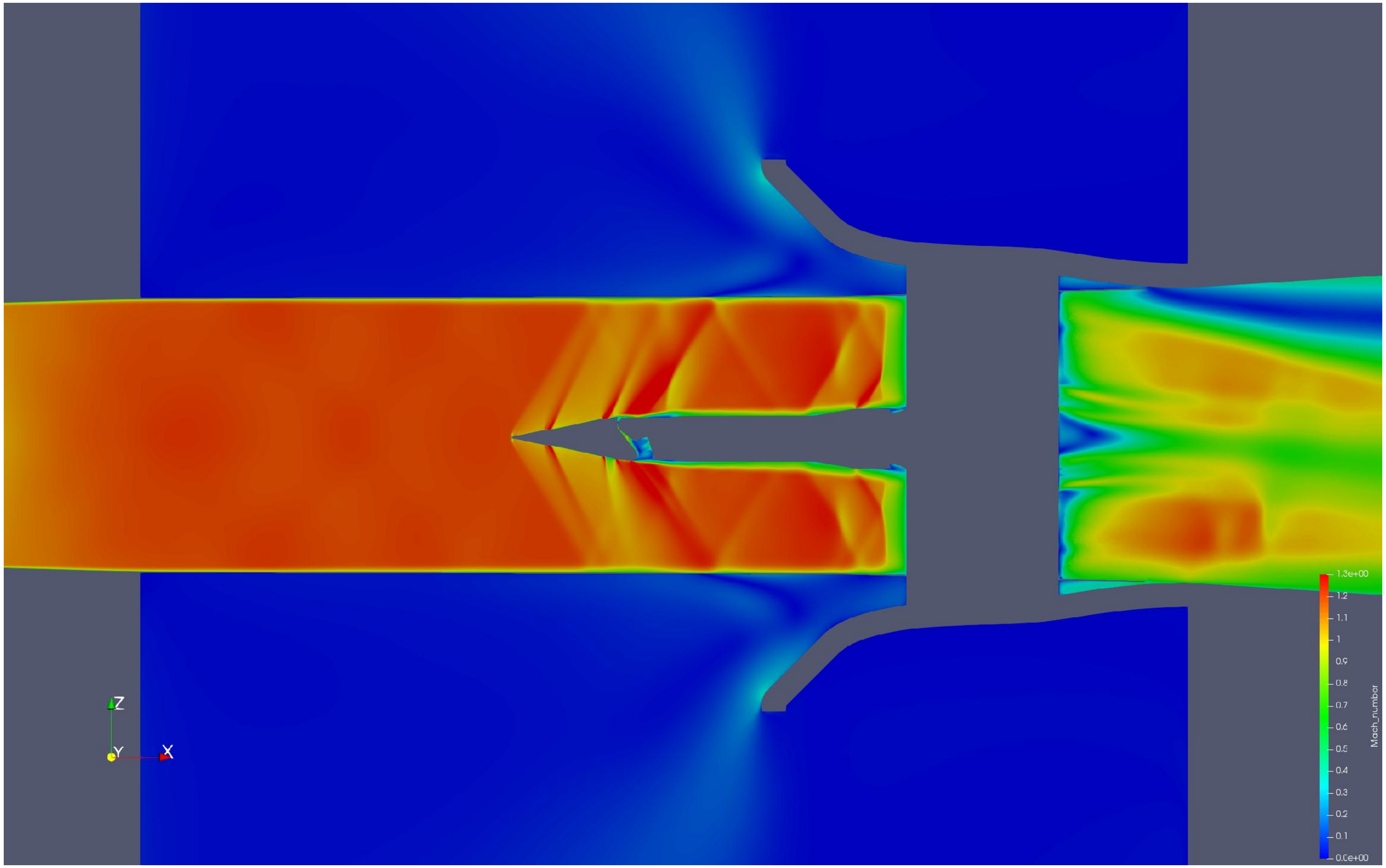
Case	p_out	AOA/ Flap	p_														pp	Remarks
Tunnel empty & support	50k	-/-	-															ok
Tunnel empty & support	51k	-/-	-															Exit pressure to high
Tunnel empty & support	52k	-/-	-															Exit pressure to high
Tunnel empty & support	53k	-/-	-															Exit pressure to high
Tunnel empty & support	54k	-/-	-															Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-															
Tunnel	50k	00/00	-															
Tunnel	50k	00/20	-															
Tunnel	50k	20/00	-															
Tunnel	50k	20/20	-															
Tunnel (MarkerMod)	50k	20/20	-															
Tunnel (FullMarkerMod)	50k	20/20	-															
Tunnel (without support)	50k	00/00	-															Removed Support --> strong shock there
Tunnel (without support)	50k	20/20	-															Removed Support --> strong shock there
Tunnel & slots closed	50k	20/20	-															Too strong shock in diffusor --> Ma<1
Tunnel & slots closed	40k	20/20	-															Too strong shock in diffusor --> Ma<1
Tunnel & slots closed (red. diffusor)	50k	20/20	-															Ma<1
Tunnel & slots partly closed to nose	50k	20/20	-															
Tunnel & slots partly closed to cone	50k	20/20	-															Ma < 1
Tunnel & suction	50k	20/20	27															Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27															Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27															Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27															ok
Tunnel & suction	50k	20/20	28k															ok: No Regulation! --> p_plenum right!
Tunnel & suction (MarkerMod / without support)	50k	0/0	28k	0%	-	27956	-44	67899	52332	15567	-0.0108	0.0072	0.0026	a	-	x	-	
Tunnel & suction (MarkerMod)	50k	20/20	28k	2.79%	-	27941	-59	67899	51870	16029	0.2911	0.1188	-0.0399	b->a	-	x	-	
Tunnel & suction & SideSlots	50k	20/20	28k	4.33%	x	27738	-262	67899	51813	16086	0.2892	0.1190	-0.0405	b->a	-	~	-	
Tunnel & conehat	50k	00/-	-	-	-	30263	+2263	67899	52309	15590	-			sup	-	-	x	Removed Support --> strong shock there
Tunnel & conehat	50k	20/-	-	-	-	26877	-1123	67899	52356	15543	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & conehat (rot. source)	50k	20/-	-	-	-	26630	-1370	67899	52297	15602	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat	50k	20/-	-	-	-	31762	+3762	67899	52160	15739	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat & Support	50k	00/-	-	-	-	28209	+209	67899	52311	15588	-			a				
Tunnel & double conehat & Support	50k	20/-	-															
Tunnel	40k	00/00	-															
Tunnel	40k	00/20	-															
Tunnel	40k	20/00	-															
Tunnel	40k	20/20	-															
Tunnel	30k	20/20	-															
Free Flight	-	00/00	-															
Free Flight	-	00/20	-															
Free Flight	-	20/00	-															free flight because no slots!
Free Flight	-	20/20	-															free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a	-	x	x	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b	-	x	x	b is not critical in free flight because no slots!



What happens in the flow field when the back pressure at diffusor outlet is changed?

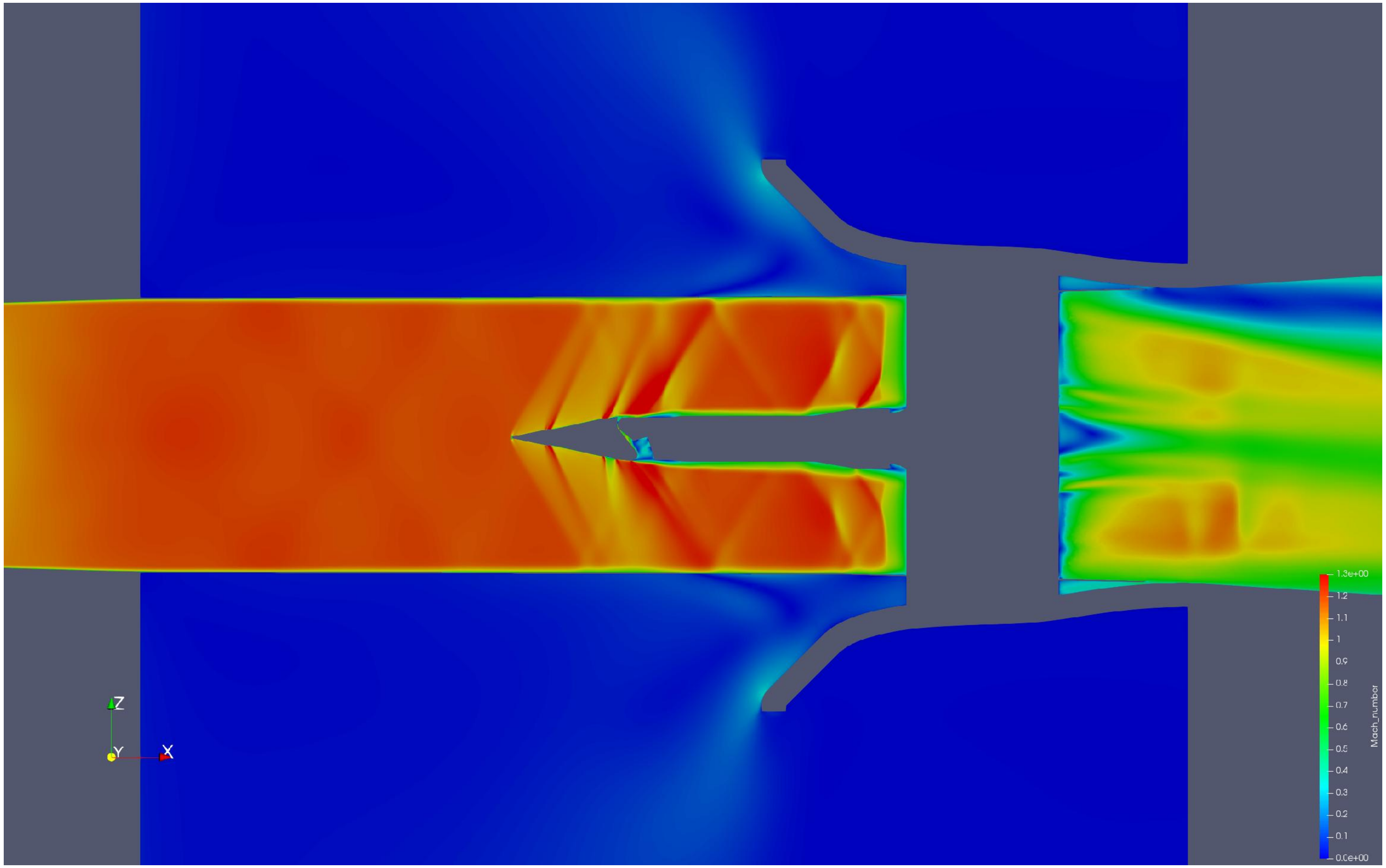
Influence of back pressure

Empty test section / p = 50k



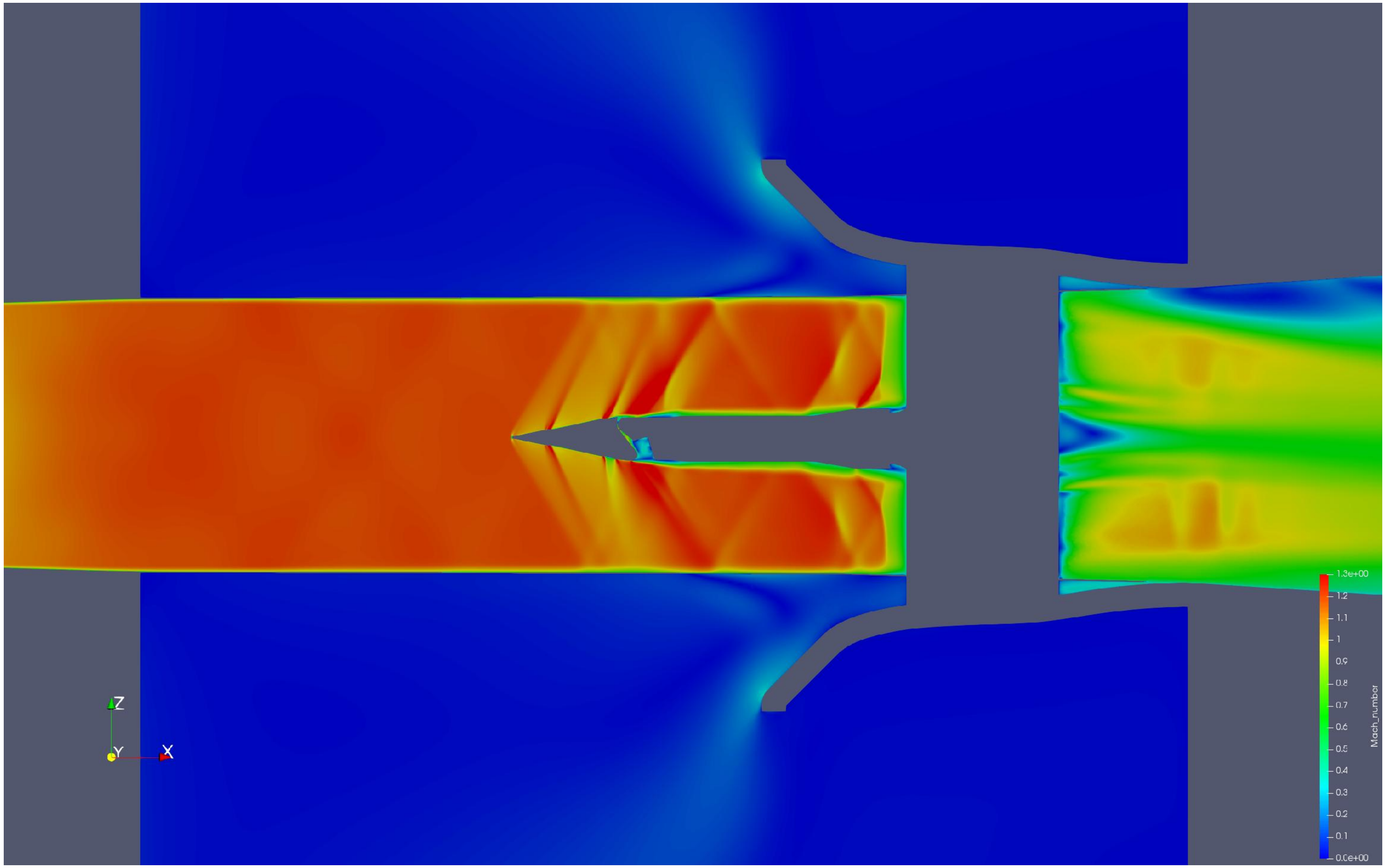
Influence of back pressure

Empty test section / p = 51k



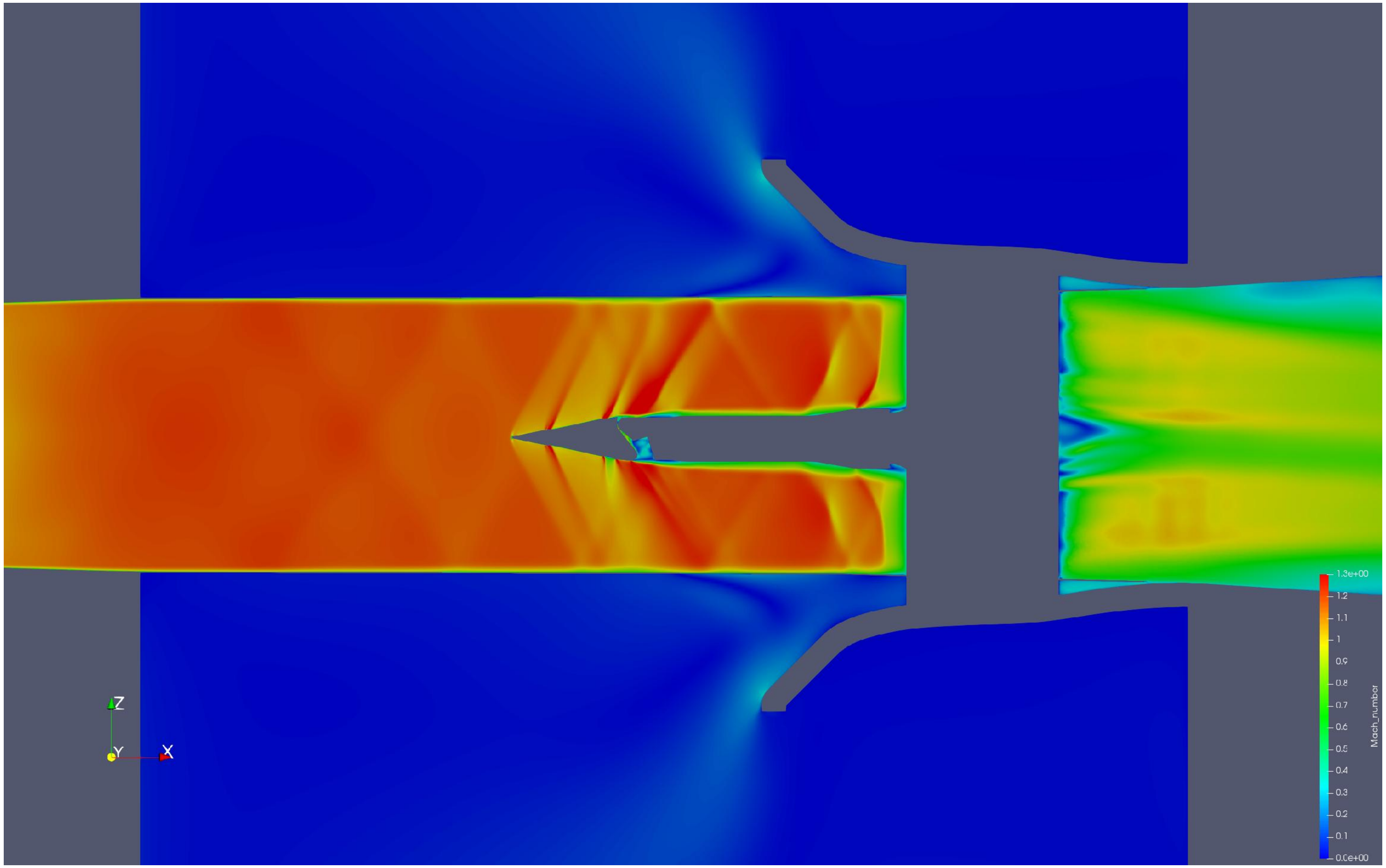
Influence of back pressure

Empty test section / p = 52k



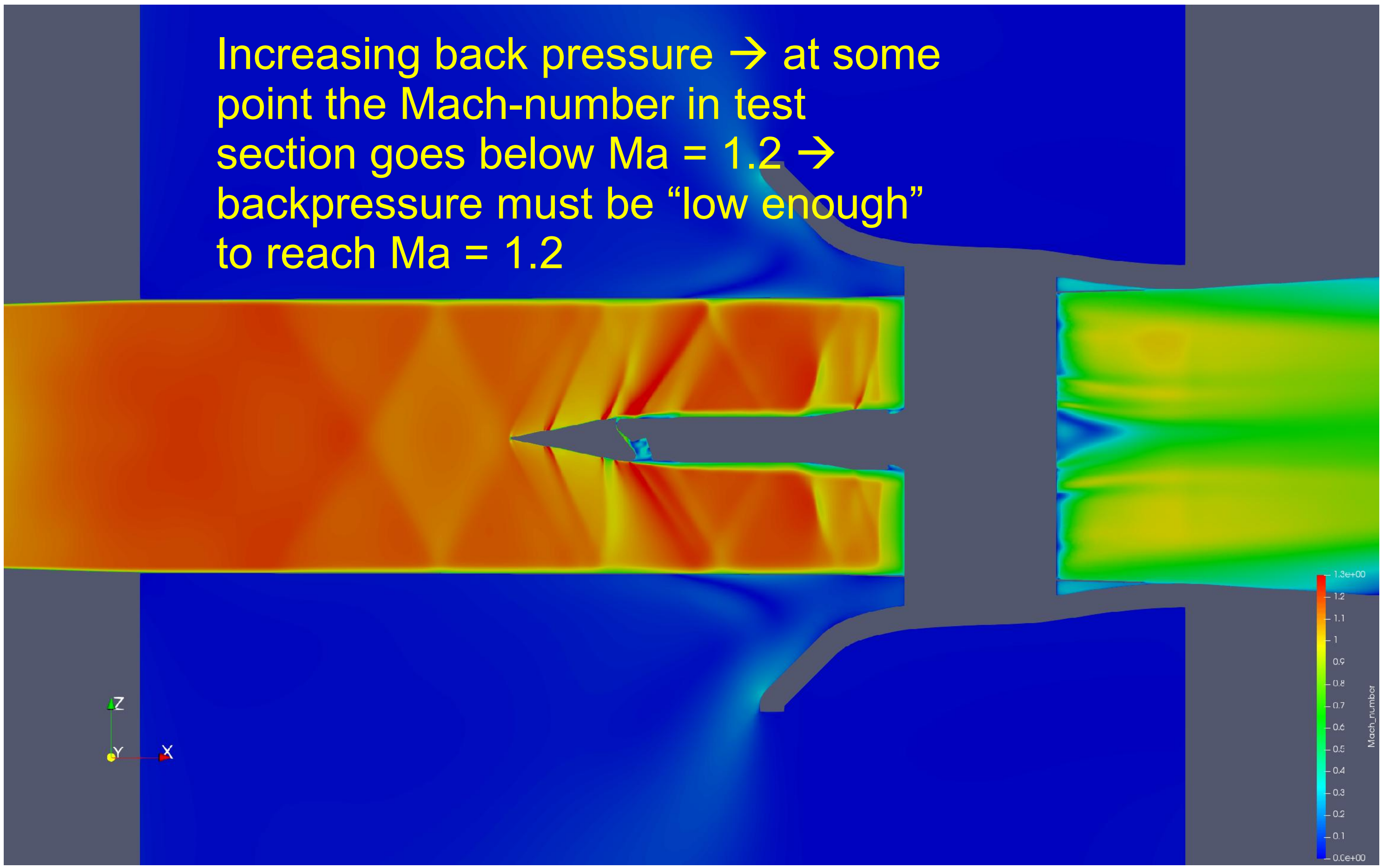
Influence of back pressure

Empty test section / p = 53k



Influence of back pressure

Empty test section / p = 54k



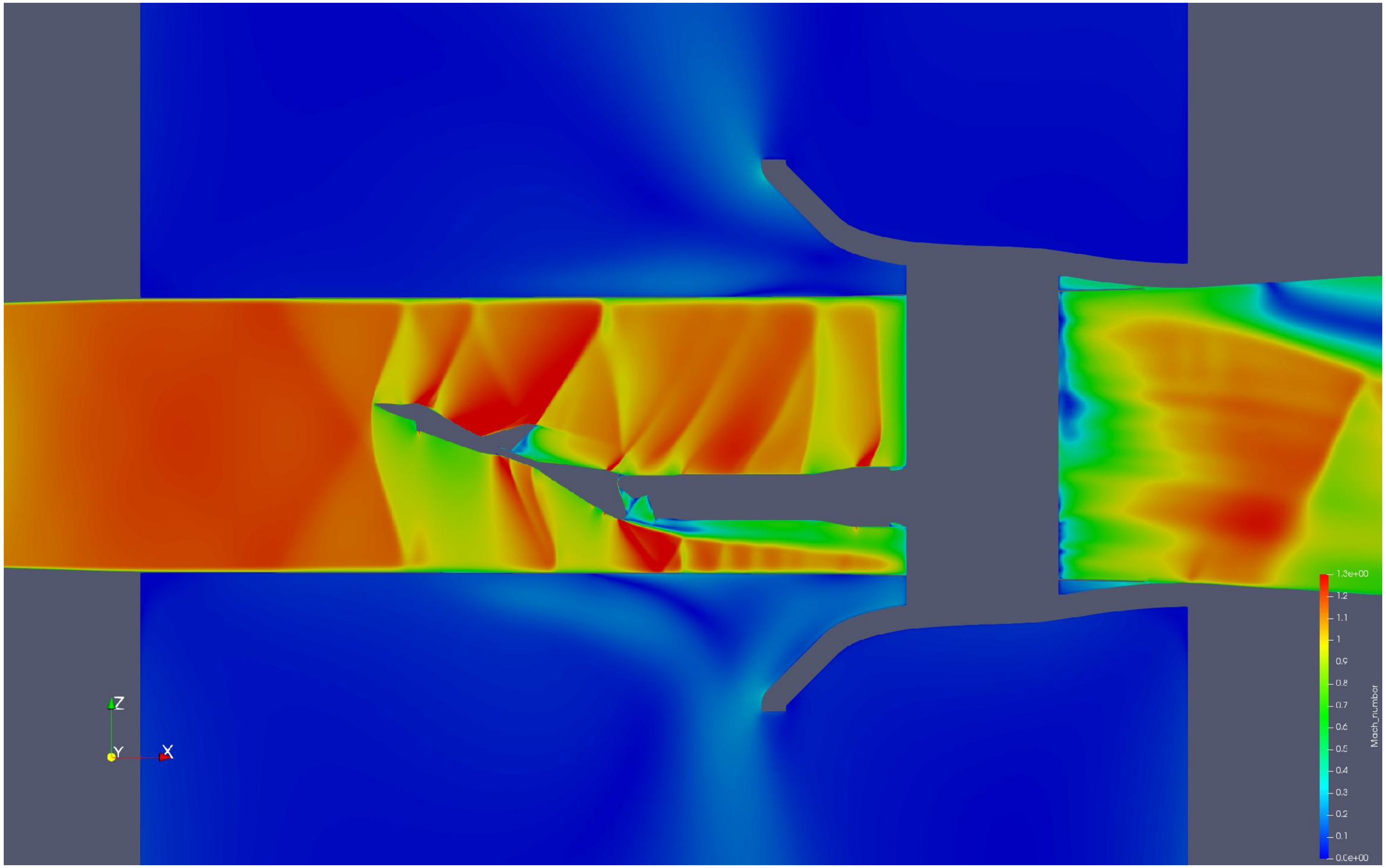
Influence of back pressure

Case	p_out	AOA/ Flap	p_suct	mp_suc	Slots SideW	p_pl	p_pl- p_stat	ptot_in	ptot_out	dptot_ out_in	CL	CD	CM	Case	Ma- Waves	p_pl= p_stat	No Supp	Remarks
Tunnel empty & support	50k	-/-	-	-	-	28093	+93	67899	52312	15587	-			-	-	x	-	ok
Tunnel empty & support	51k	-/-	-	-	-	28400	+400	67899	53231	14668	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	52k	-/-	-	-	-	28274	+274	67899	54135	13764	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	53k	-/-	-	-	-	28799	+799	67899	54994	12905	-			-	x	-	-	Exit pressure to high
Tunnel empty & support	54k	-/-	-	-	-	29714	+714	67899	55902	11997	-			-	x	-	-	Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-	-	-	28596	+596	67899	52303	15596	-			b	x	-	-	
Tunnel	50k	00/00	-	-	-	27930	-70	67869	52240	15629	-0.0115	0.0072	0.0028	a	-	x	-	
Tunnel	50k	00/20	-	-	-	27973	-27	67899	52218	15681	0.0368	0.0153	-0.0104	a	-	x	-	
Tunnel	50k	20/00	-	-	-	29761	+1761	67899	52030	15869	0.2498	0.0913	-0.0287	b	x	-	-	
Tunnel	50k	20/20	-	-	-	30488	+2488	67899	52006	15893	0.2846	0.1186	-0.0394	b	x	-	-	
Tunnel (MarkerMod)	50k	20/20	-	-	-	30509	+2509	67899	52009	15890	0.2829	0.1178	-0.0392	b	x	-	-	
Tunnel (FullMarkerMod)	50k	20/20	-	-	-	30485	+2485	67899	52012	15887	0.2834	0.1180	-0.0391	b	x	-	-	
Tunnel (without support)	50k	00/00	-	-	-	30428	+2428	67899	52315	15584	-0.0166	0.0087	0.0037	sup	x	-	x	Removed Support --> strong shock there
Tunnel (without support)	5																	moved Support --> strong shock there
Tunnel & slots closed	5																	o strong shock in diffusor --> Ma<1
Tunnel & slots closed	4																	o strong shock in diffusor --> Ma<1
Tunnel & slots closed (red. diffusor)	5																	<1
Tunnel & slots partly closed to nose	5																	
Tunnel & slots partly closed to cone	5																	< 1
Tunnel & suction	5																	o much suction --> p_plenum to low
Tunnel & suction	5																	o much suction --> p_plenum to low
Tunnel & suction	5																	o much suction --> p_plenum to low
Tunnel & suction	5																	
Tunnel & suction	50k	20/20	28k	2.21%	-	27933	-67	67899	51907	15992	0.2913	0.1189	-0.0400	b->a	-	x	-	ok: No Regulation! --> p_plenum right!
Tunnel & suction (MarkerMod / without support)	50k	0/0	28k	0%	-	27956	-44	67899	52332	15567	-0.0108	0.0072	0.0026	a	-	x	-	
Tunnel & suction (MarkerMod)	50k	20/20	28k	2.79%	-	27941	-59	67899	51870	16029	0.2911	0.1188	-0.0399	b->a	-	x	-	
Tunnel & suction & SideSlots	50k	20/20	28k	4.33%	x	27738	-262	67899	51813	16086	0.2892	0.1190	-0.0405	b->a	-	~	-	
Tunnel & conehat	50k	00/-	-	-	-	30263	+2263	67899	52309	15590	-			sup	-	-	x	Removed Support --> strong shock there
Tunnel & conehat	50k	20/-	-	-	-	26877	-1123	67899	52356	15543	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & conehat (rot. source)	50k	20/-	-	-	-	26630	-1370	67899	52297	15602	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat	50k	20/-	-	-	-	31762	+3762	67899	52160	15739	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat & Support	50k	00/-	-	-	-	28209	+209	67899	52311	15588	-			a	-	-	-	
Tunnel & double conehat & Support	50k	20/-	-	-	-	28579	+579	67899	52307	15592	-			a	-	-	-	
Tunnel	40k	00/00	-	-	-	26778	-1222	67899	43124	24775	-0.0099	0.0073	0.0024	a	-	-	-	
Tunnel	40k	00/20	-	-	-	26869	-1131	67899	43103	24796	0.0351	0.0151	-0.0100	a	-	-	-	
Tunnel	40k	20/00	-	-	-	29543	+1563	67899	42975	24924	0.2521	0.0923	-0.0289	b	x	-	-	
Tunnel	40k	20/20	-	-	-	30321	+2321	67899	42946	24953	0.2839	0.1183	-0.0393	b	x	-	-	
Tunnel	30k	20/20	-	-	-	30333	+2333	67899	34643	33256	0.2839	0.1184	-0.0393	b	x	-	-	
Free Flight	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0151	-0.0107	a	-	x	x	
Free Flight	-	20/00	-	-	-	-	-	-	-	-	0.2509	0.0917	-0.0298	b	-	x	x	b is not critical in free flight because no slots!
Free Flight	-	20/20	-	-	-	-	-	-	-	-	0.2863	0.1187	-0.0401	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a	-	x	x	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b	-	x	x	b is not critical in free flight because no slots!

Increasing backpressure leads to higher plenum pressure → influence on flow in test section

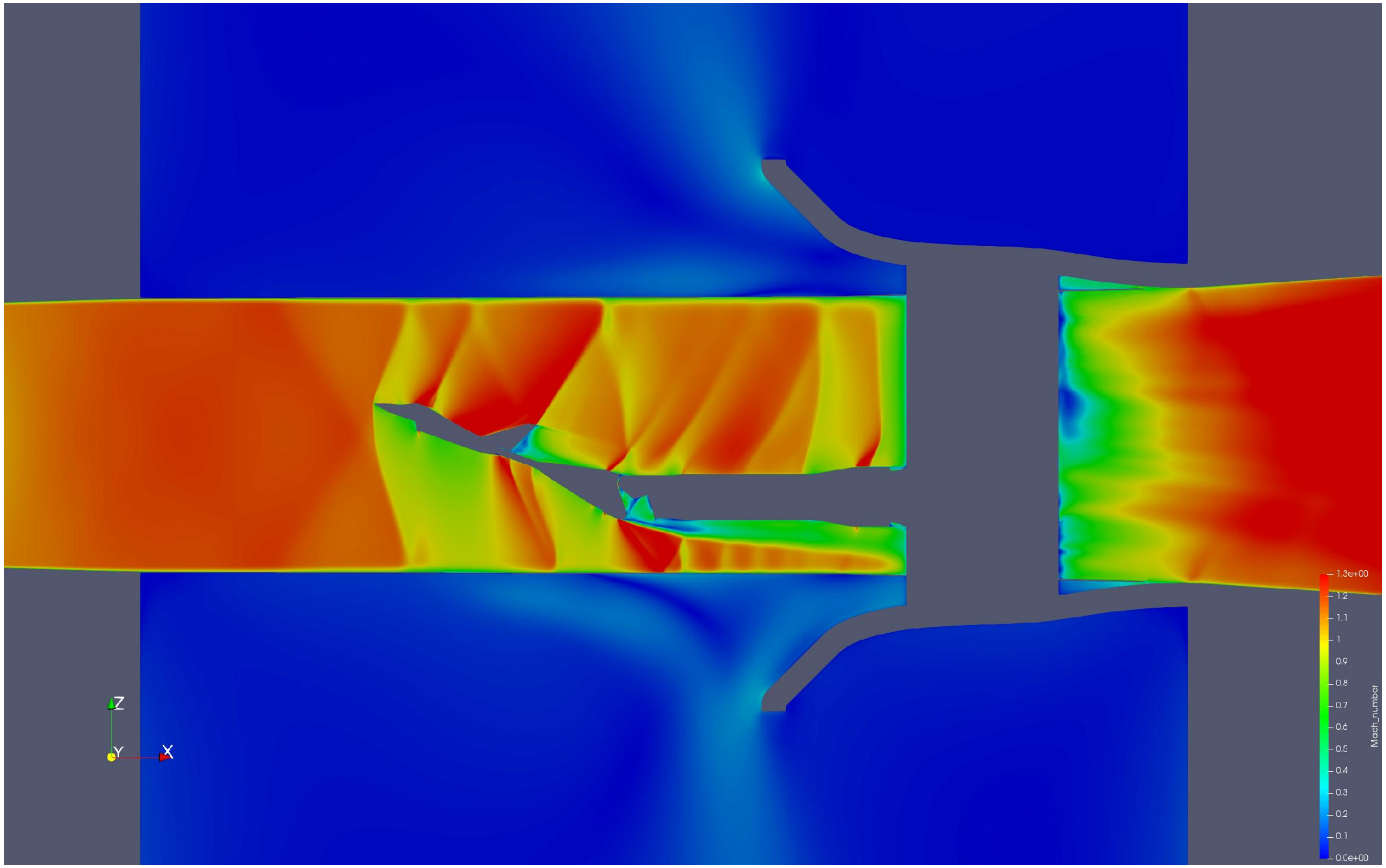
Influence of back pressure

AOA 20 / Flap 20 / p = 50k



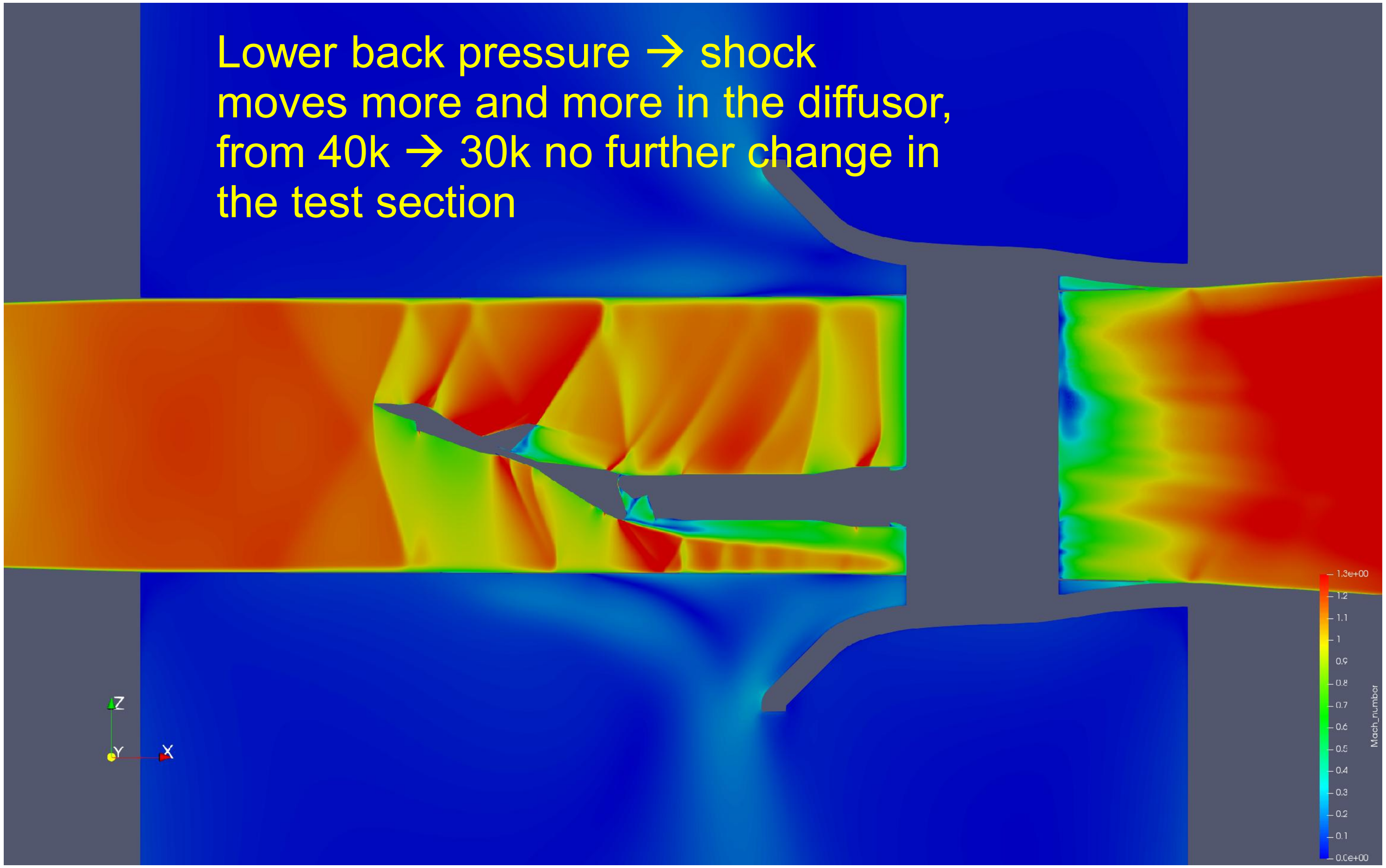
Influence of back pressure

AOA 20 / Flap 20 / p = 40k



Influence of back pressure

AOA 20 / Flap 20 / p = 30k



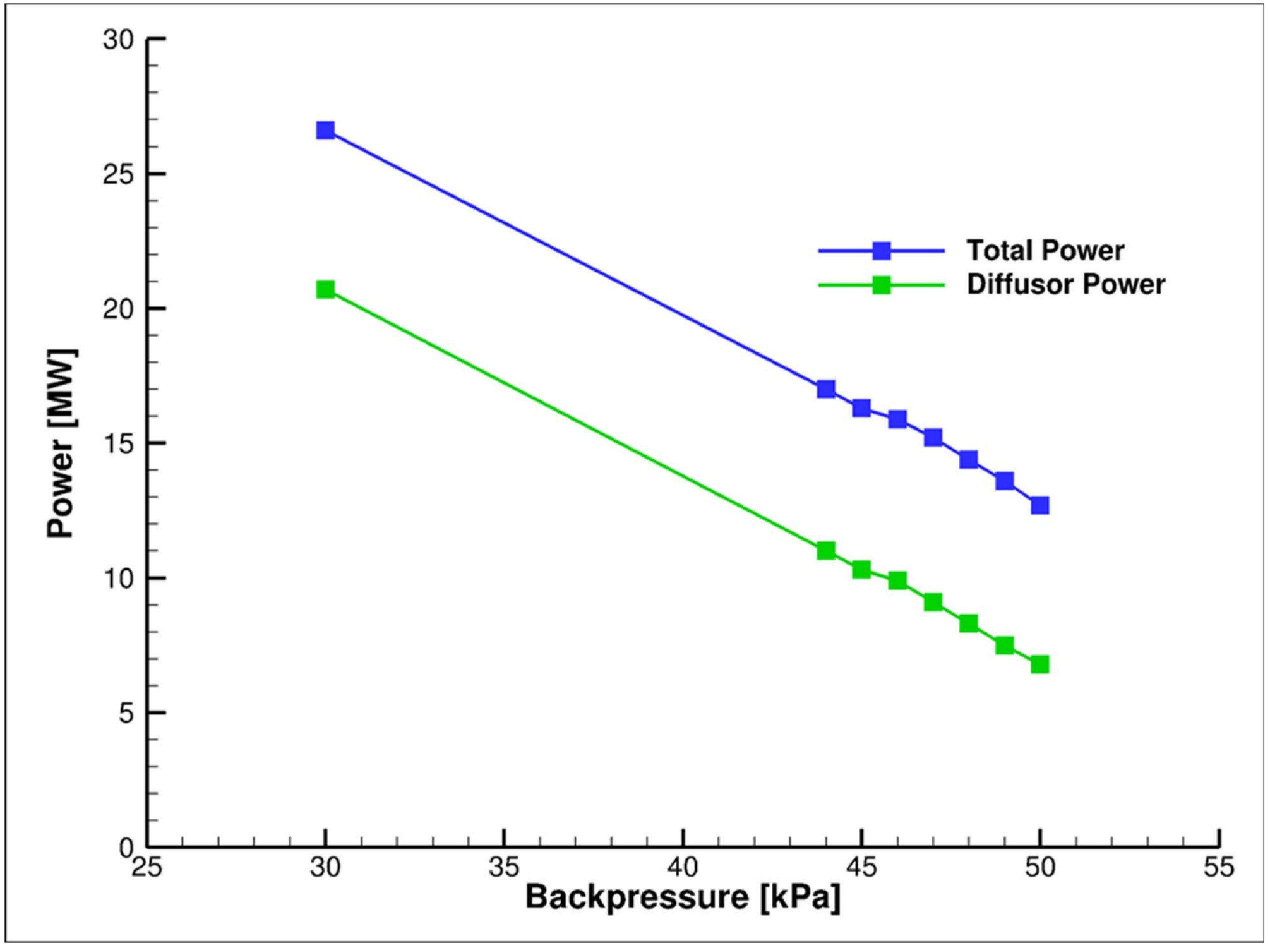
Influence of back pressure

Case	p_out	AOA/ Flap	p_suct	mp_suc	Slots SideW	p_pl	p_pl- p_stat	ptot_in	ptot_out	dptot_ out_in	CL	CD	CM	Case	Ma- Waves	p_pl= p_stat	No Supp	Remarks
Tunnel empty & support	50k	-/-	-	-	-	28093	+93	67899	52312	15587	-			-	-	x	-	ok
Tunnel empty & support	51k	-/-	-	-	-	28400	+400	67899	53231	14668	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	52k	-/-	-	-	-	28274	+274	67899	54135	13764	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	53k	-/-	-	-	-	28799	+799	67899	54994	12905	-			-	x	-	-	Exit pressure to high
Tunnel empty & support	54k	-/-	-	-	-	29714	+714	67899	55902	11997	-			-	x	-	-	Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-	-	-	28596	+596	67899	52303	15596	-			b	x	-	-	
Tunnel	50k	00/00	-	-	-	27930	-70	67869	52240	15629	-0.0115	0.0072	0.0028	a	-	x	-	
Tunnel	50k	00/20	-	-	-	27973	-27	67899	52218	15681	0.0368	0.0153	-0.0104	a	-	x	-	
Tunnel	50k	20/00	-	-	-	28761	+1761	67899	52030	15869	0.2498	0.0913	-0.0287	b	x	-	-	
Tunnel	50k	20/20	-	-	-	30488	+2488	67899	52006	15893	0.2846	0.1186	-0.0394	b	x	-	-	
Tunnel (MarkerMod)	50k	20/20	-	-	-	30509	+2509	67899	52009	15890	0.2829	0.1178	-0.0392	b	x	-	-	
Tunnel (FullMarkerMod)																		
Tunnel (without support)																		
Tunnel (without support)																		
Tunnel & slots closed																		
Tunnel & slots closed																		
Tunnel & slots closed (red.																		
Tunnel & slots partly close																		
Tunnel & slots partly close																		
Tunnel & suction																		
Tunnel & suction																		
Tunnel & suction																		
Tunnel & suction																		
Tunnel & suction																		
Tunnel & suction (MarkerMod																		
Tunnel & suction (MarkerMod)																		
Tunnel & suction & SideSlots																		
Tunnel & conehat																		
Tunnel & conehat																		
Tunnel & conehat (rot. sourc																		
Tunnel & double conehat																		
Tunnel & double conehat & Su																		
Tunnel & double conehat & Su																		
Tunnel																		
Tunnel																		
Tunnel	40k	20/00	-	-	-	29543	+1563	67899	42975	24924	0.2521	0.0923	-0.0289	b	x	-	-	
Tunnel	40k	20/20	-	-	-	30321	+2321	67899	42946	24953	0.2839	0.1183	-0.0393	b	x	-	-	
Tunnel	30k	20/20	-	-	-	30333	+2333	67899	34643	33256	0.2839	0.1184	-0.0393	b	x	-	-	
Free Flight	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0151	-0.0107	a	-	x	x	
Free Flight	-	20/00	-	-	-	-	-	-	-	-	0.2509	0.0917	-0.0298	b	-	x	x	b is not critical in free flight because no slots!
Free Flight	-	20/20	-	-	-	-	-	-	-	-	0.2863	0.1187	-0.0401	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a	-	x	x	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b	-	x	x	b is not critical in free flight because no slots!

Reducing backpressure (below critical value for Ma = 1.2)
→ plenum pressure is constant as the final shock is behind the reentry section & first part of diffusor goes supersonic
→ Backpressure cannot “change” plenum pressure any more
→ tunnel “regulation” with backpressure in 20/20 case not possible!
→ Reducing backpressure further → only power-consumption goes up because of stronger final shock & diffusor losses

Influence of back pressure

- Power consumption for case 20/20 (in the numerical domain)



Comparison to free flight

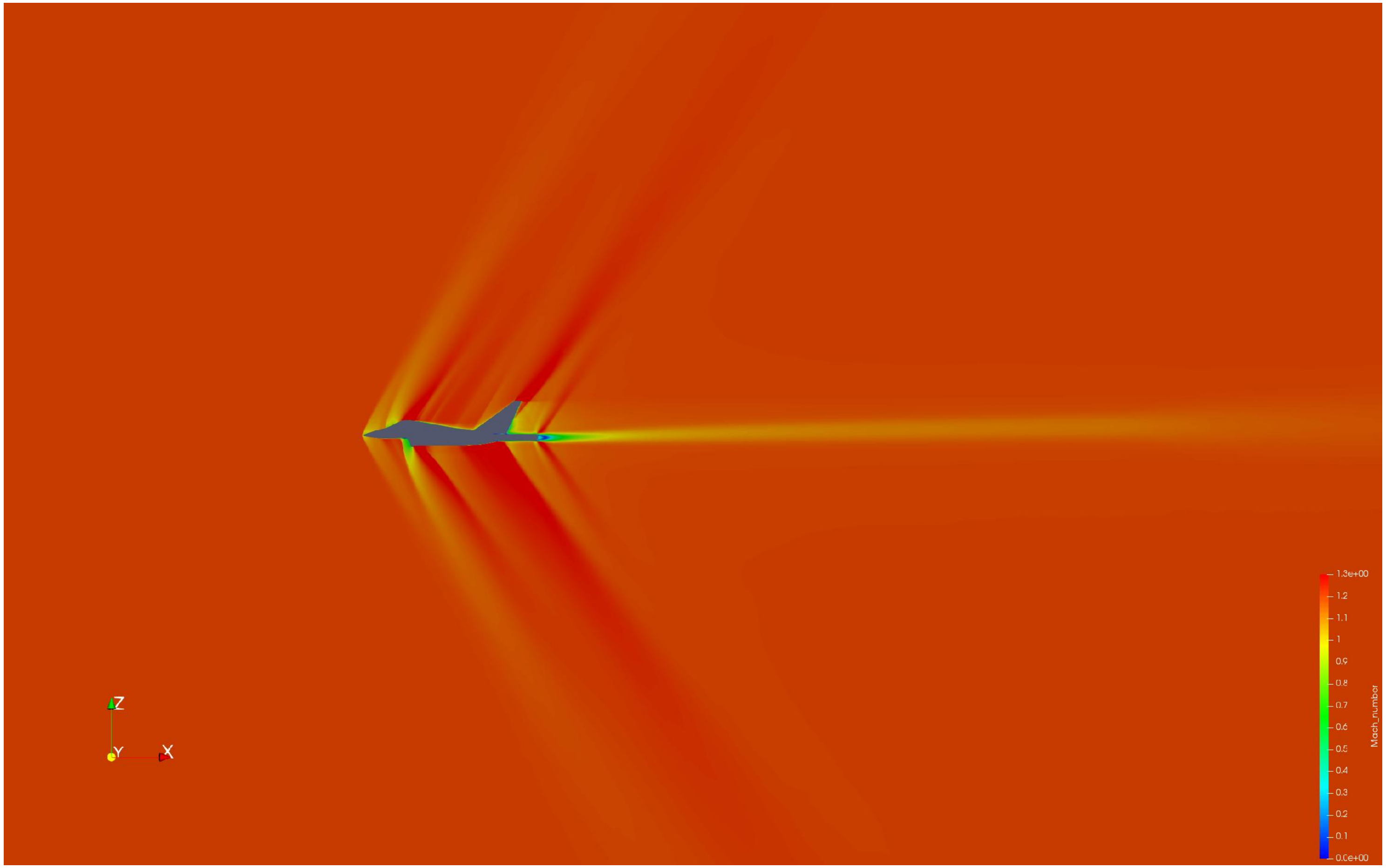
Comparison to free flight

Case	p_out	AOA/ Flap	p_suct	mp_suc	Slots SideW	p_pl	p_pl- p_stat	ptot_in	ptot_out	dptot_ out_in	CL	CD	CM	Case	Ma- Waves	p_pl= p_stat	No Supp	Remarks
Tunnel empty & support	50k	-/-	-	-	-	28093	+93	67899	52312	15587	-			-	-	x	-	ok
Tunnel empty & support	51k	-/-	-	-	-	28400	+400	67899	53231	14668	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	52k	-/-	-	-	-	28274	+274	67899	54135	13764	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	53k	-/-	-	-	-	28799	+799	67899	54994	12905	-			-	x	-	-	Exit pressure to high
Tunnel empty & support	54k	-/-	-	-	-	29714	+714	67899	55902	11997	-			-	x	-	-	Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-	-	-	28596	+596	67899	52303	15596	-			b	x	-	-	
Tunnel	50k	00/00	-	-	-	27930	-70	67869	52240	15629	-0.0115	0.0072	0.0028	a	-	x	-	
Tunnel	50k	00/20	-	-	-	27973	-27	67899	52218	15681	0.0368	0.0153	-0.0104	a	-	x	-	
Tunnel	50k	20/00	-	-	-	29761	+1761	67899	52030	15869	0.2498	0.0913	-0.0287	b	x	-	-	
Tunnel	50k	20/20	-	-	-	30488	+2488	67899	52006	15893	0.2846	0.1186	-0.0394	b	x	-	-	
Tunnel (MarkerMod)	50k	20/20	-	-	-	30509	+2509	67899	52009	15890	0.2829	0.1178	-0.0392	b	x	-	-	
Tunnel (FullMarkerMod)	50k	20/20	-	-	-	30485	+2485	67899	52012	15887	0.2834	0.1180	-0.0391	b	x	-	-	
Tunnel (without support)	50k	00/00	-	-	-	30428	+2428	67899	52315	15584	-0.0166	0.0087	0.0037	sup	x	-	x	Removed Support --> strong shock there
Tunnel (without support)	50k	20/20	-	-	-	29181	+1181	67899	52338	15561	0.2866	0.1184	-0.0389	sup	x	-	x	Removed Support --> strong shock there
Tunnel & slots closed	50k	20/20	-															in diffusor --> Ma<1
Tunnel & slots closed	40k	20/20	-															in diffusor --> Ma<1
Tunnel & slots closed (red. diffusor)	50k	20/20	-															
Tunnel & slots partly closed to nose	50k	20/20	-															
Tunnel & slots partly closed to cone	50k	20/20	-															
Tunnel & suction	50k	20/20	2[illegible]															--> p_plenum to low
Tunnel & suction	50k	20/20	2[illegible]															--> p_plenum to low
Tunnel & suction	50k	20/20	2[illegible]															--> p_plenum to low
Tunnel & suction	50k	20/20	2[illegible]															
Tunnel & suction	50k	20/20	2[illegible]															[illegible]! --> p_plenum right!
Tunnel & suction (MarkerMod / without support)	50k	0/0	28k	0%	-	27956	-44	67899	52332	15567	-0.0108	0.0072	0.0026	a	-	x	-	
Tunnel & suction (MarkerMod)	50k	20/20	28k	2.79%	-	27941	-59	67899	51870	16029	0.2911	0.1188	-0.0399	b->a	-	x	-	
Tunnel & suction & SideSlots	50k	20/20	28k	4.33%	x	27738	-262	67899	51813	16086	0.2892	0.1190	-0.0405	b->a	-	~	-	
Tunnel & conehat	50k	00/-	-	-	-	30263	+2263	67899	52309	15590	-			sup	-	-	x	Removed Support --> strong shock there
Tunnel & conehat	50k	20/-	-	-	-	26877	-1123	67899	52356	15543	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & conehat (rot. source)	50k	20/-	-	-	-	26630	-1370	67899	52297	15602	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat	50k	20/-	-	-	-	31762	+3762	67899	52160	15739	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat & Support	50k	00/-	-	-	-	28209	+209	67899	52311	15588	-			a	-	-	-	
Tunnel & double conehat & Support	50k	20/-	-	-	-	28579	+579	67899	52307	15592	-			a	-	-	-	
Tunnel	40k	00/00	-	-	-	26778	-1222	67899	43124	24775	-0.0099	0.0073	0.0024	a	-	-	-	
Tunnel	40k	00/20	-	-	-	26869	-1131	67899	43103	24796	0.0351	0.0151	-0.0100	a	-	-	-	
Tunnel	40k	20/00	-	-	-	29543	+1563	67899	42975	24924	0.2521	0.0923	-0.0289	b	x	-	-	
Tunnel	40k	20/20	-	-	-	30321	+2321	67899	42946	24953	0.2839	0.1183	-0.0393	b	x	-	-	
Tunnel	30k	20/20	-	-	-	30333	+2333	67899	34643	33256	0.2839	0.1184	-0.0393	b	x	-	-	
Free Flight	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0151	-0.0107	a	-	x	x	
Free Flight	-	20/00	-	-	-	-	-	-	-	-	0.2509	0.0917	-0.0298	b	-	x	x	b is not critical in free flight because no slots!
Free Flight	-	20/20	-	-	-	-	-	-	-	-	0.2863	0.1187	-0.0401	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a	-	x	x	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b	-	x	x	b is not critical in free flight because no slots!

Analysis of the “question I”: comparison of free flight and in-tunnel simulation

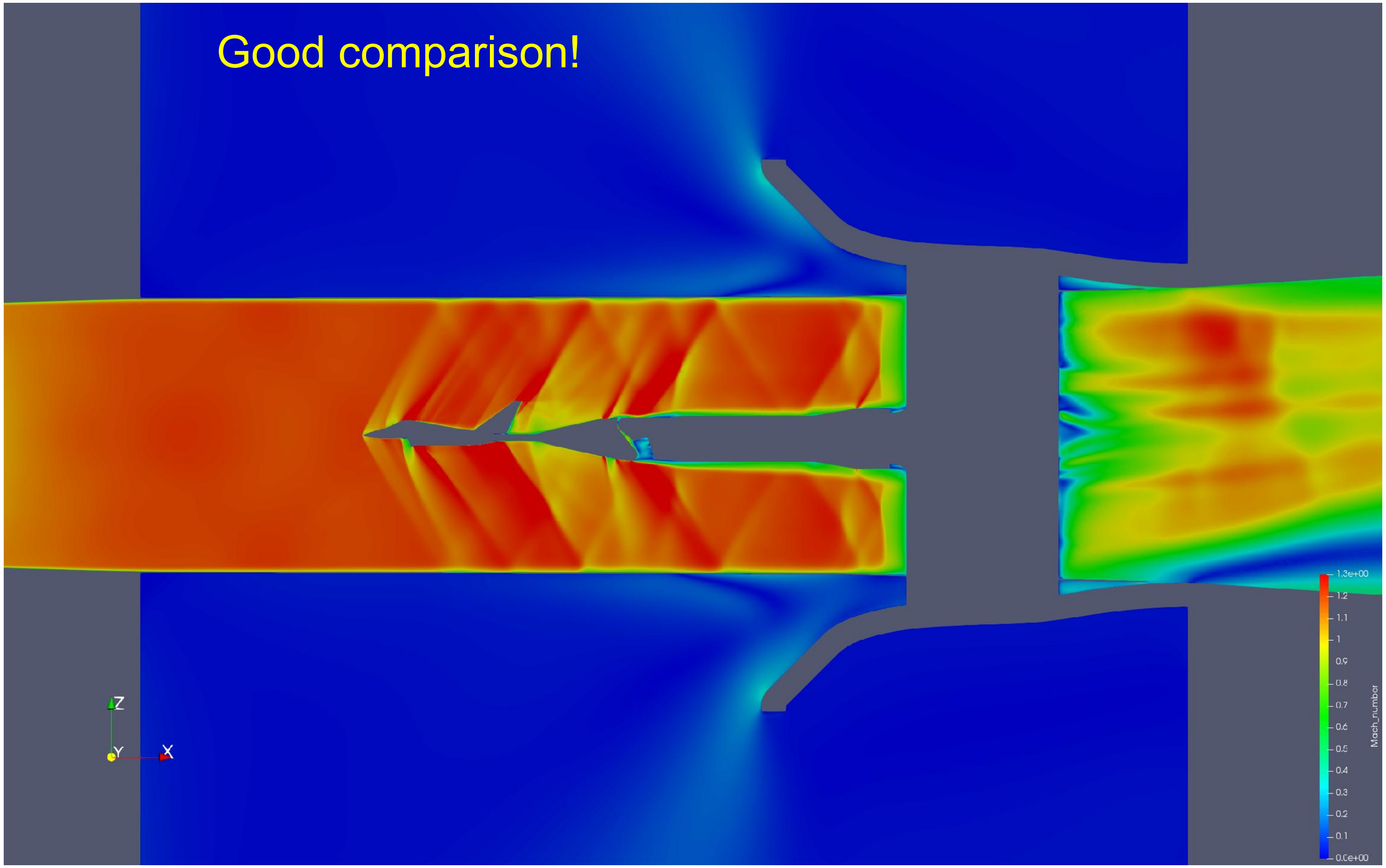
Comparison to free flight

AOA 00 / Flap 00 / Free Flight



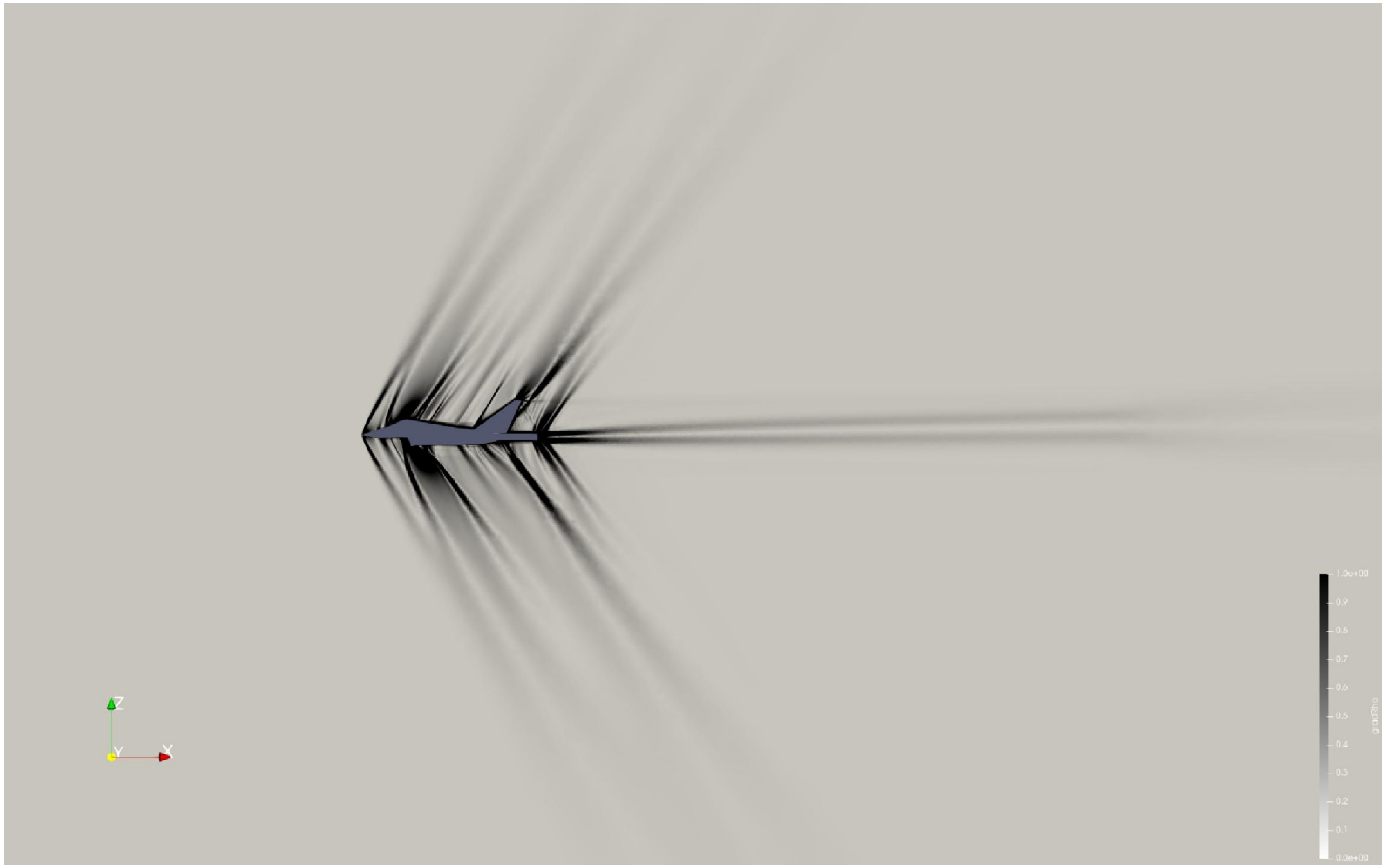
Comparison to free flight

AOA 00 / Flap 00 / p = 50k



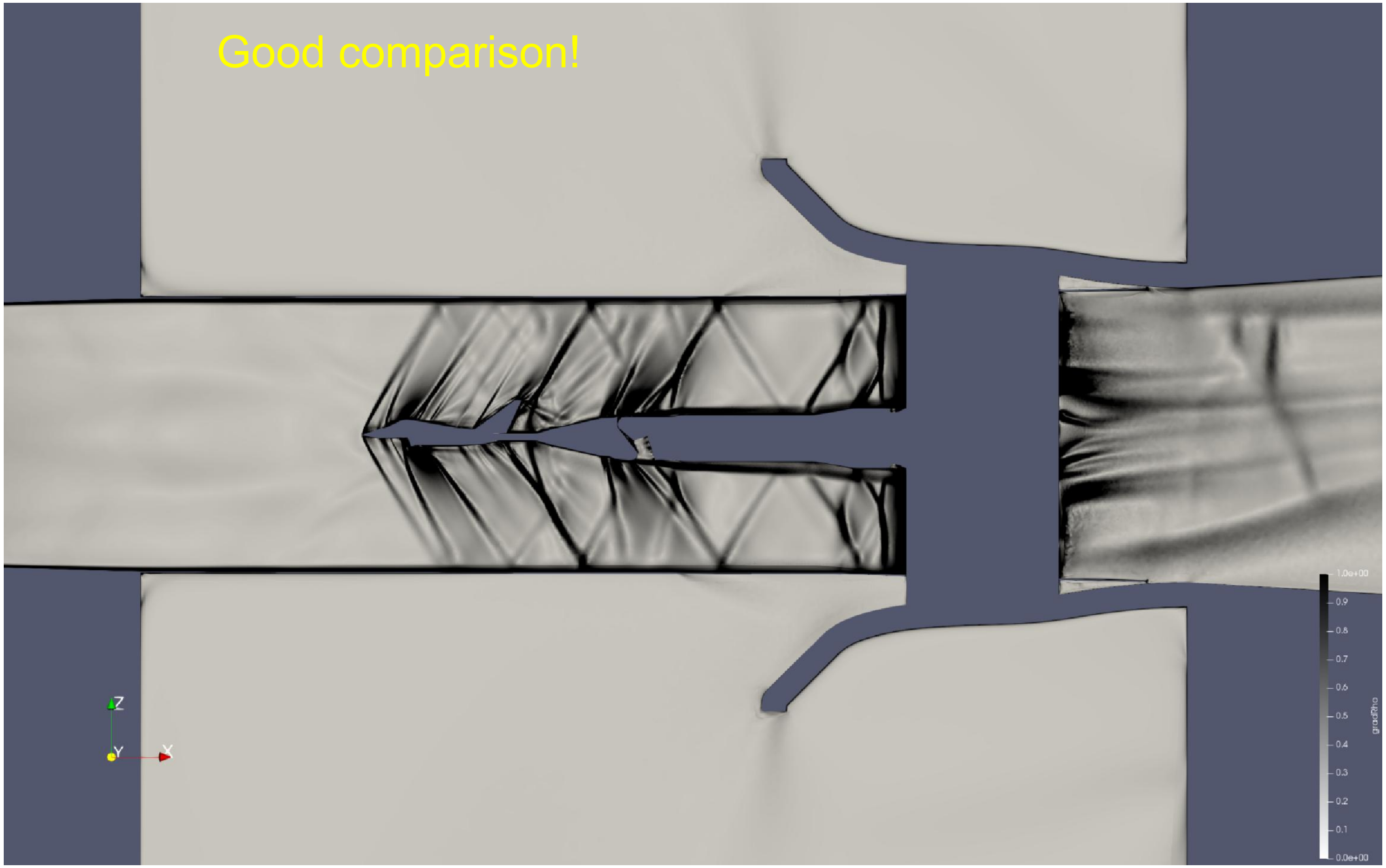
Comparison to free flight

AOA 00 / Flap 00 / Free Flight

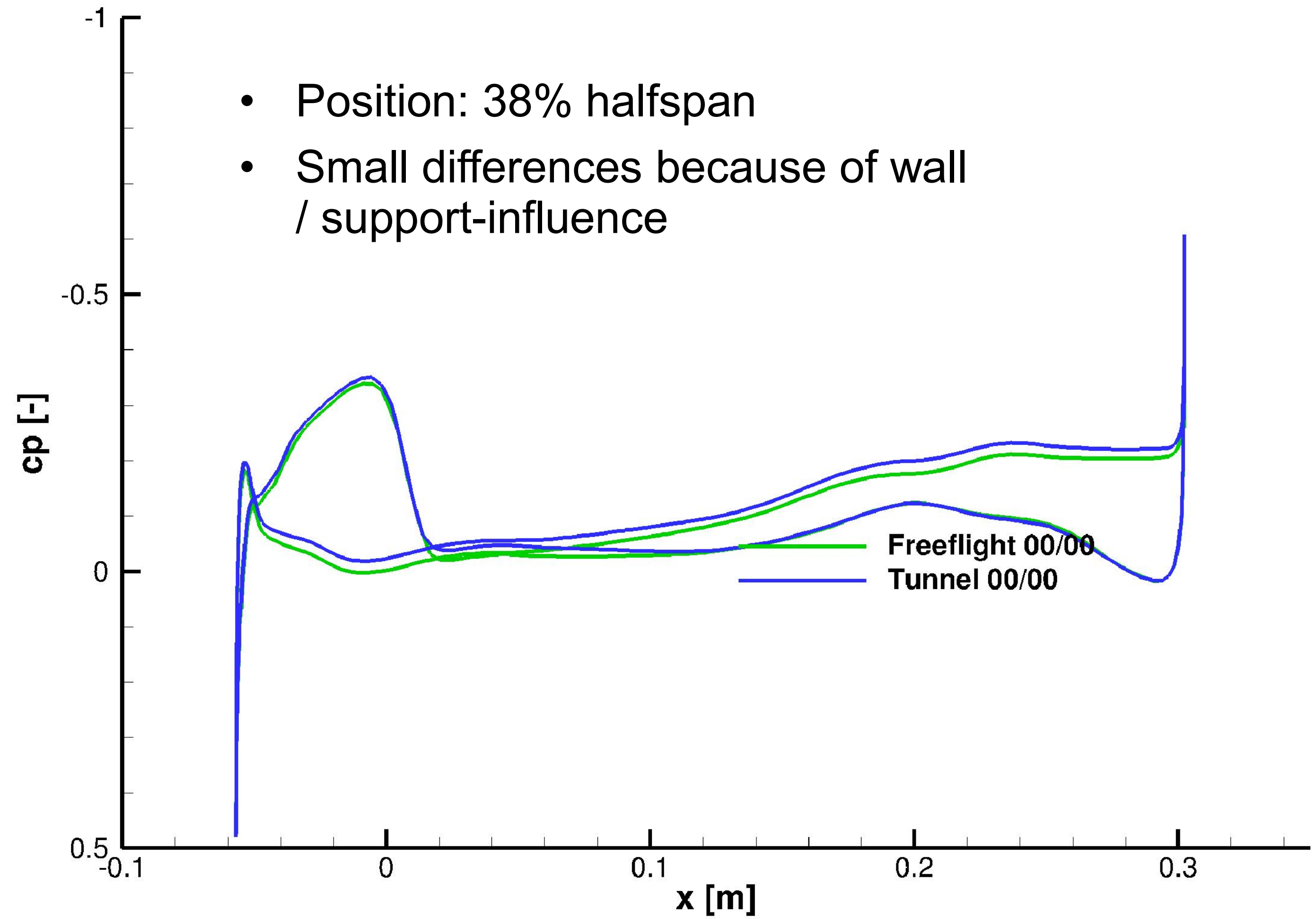


Comparison to free flight

AOA 00 / Flap 00 / p = 50k

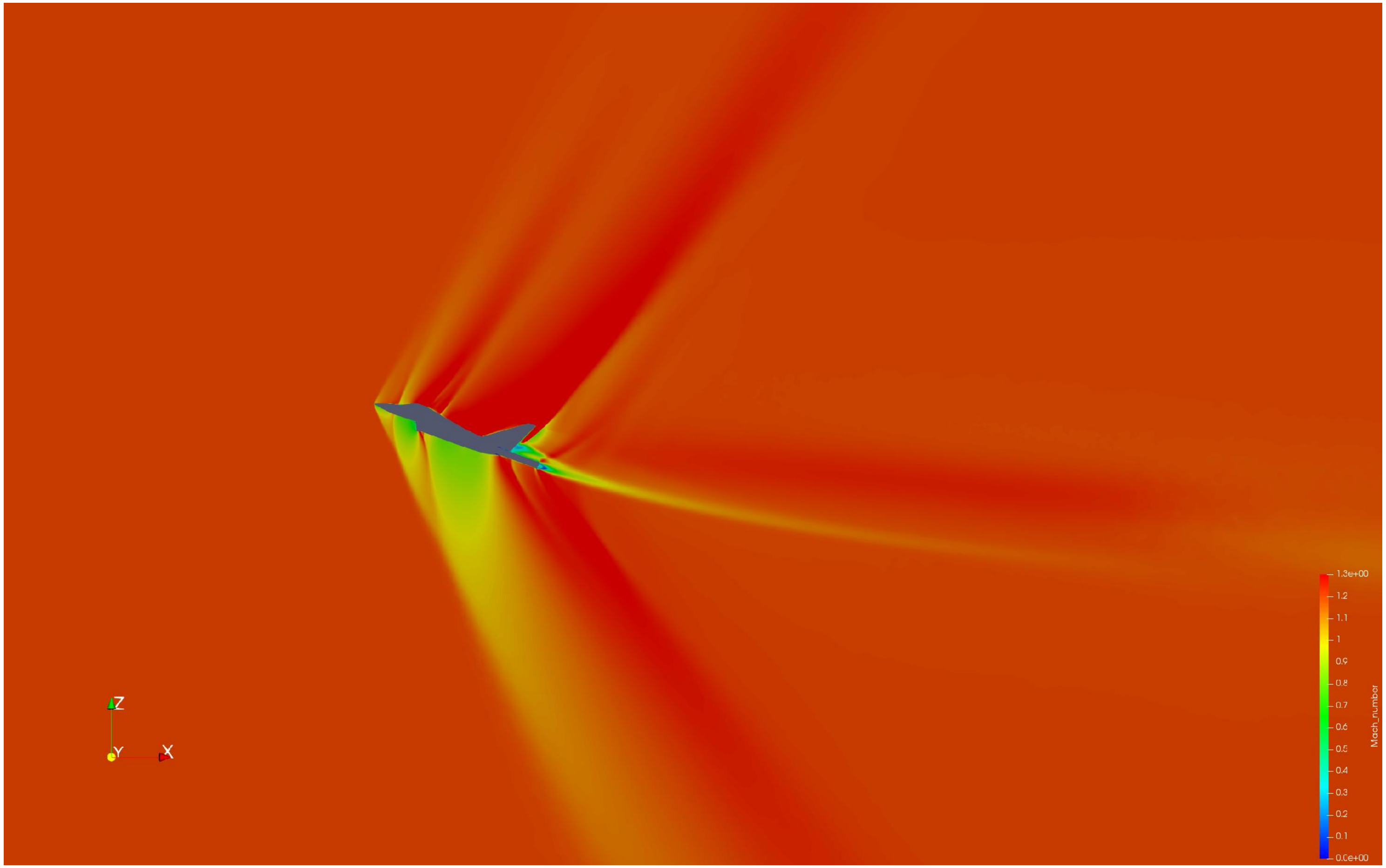


Comparison to free flight



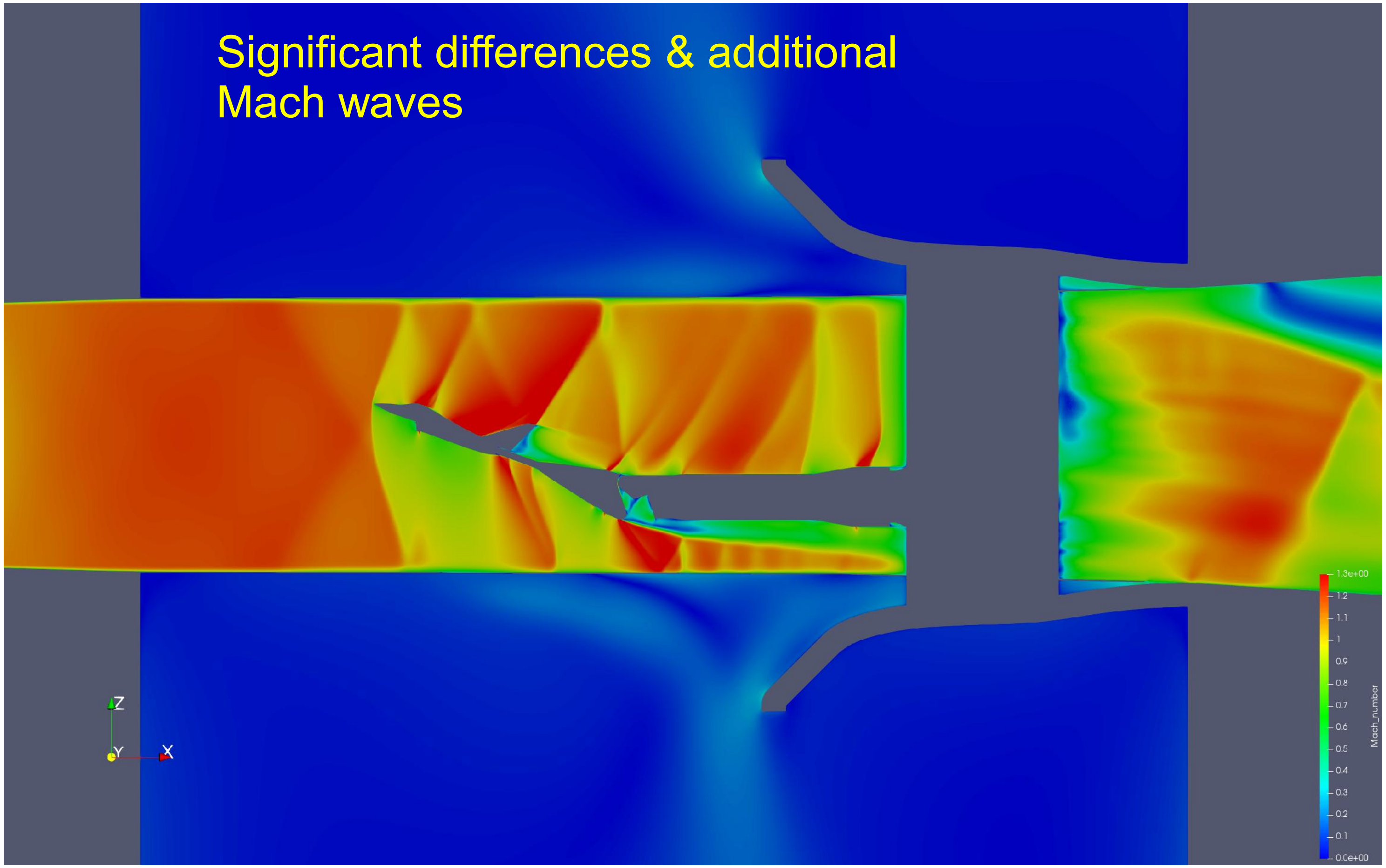
Comparison to free flight

AOA 20 / Flap 20 / Free Flight



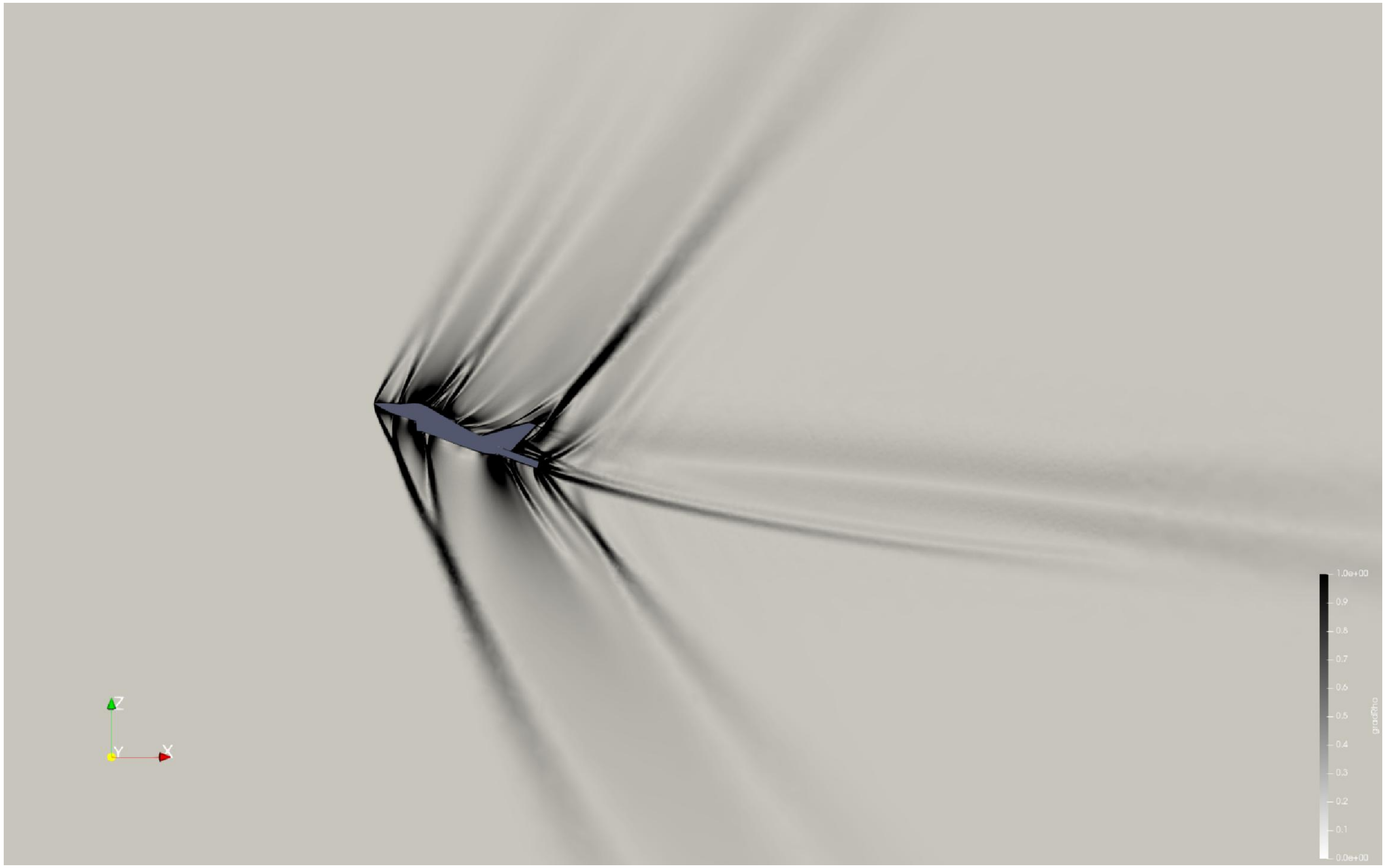
Comparison to free flight

AOA 20 / Flap 20 / p = 50k



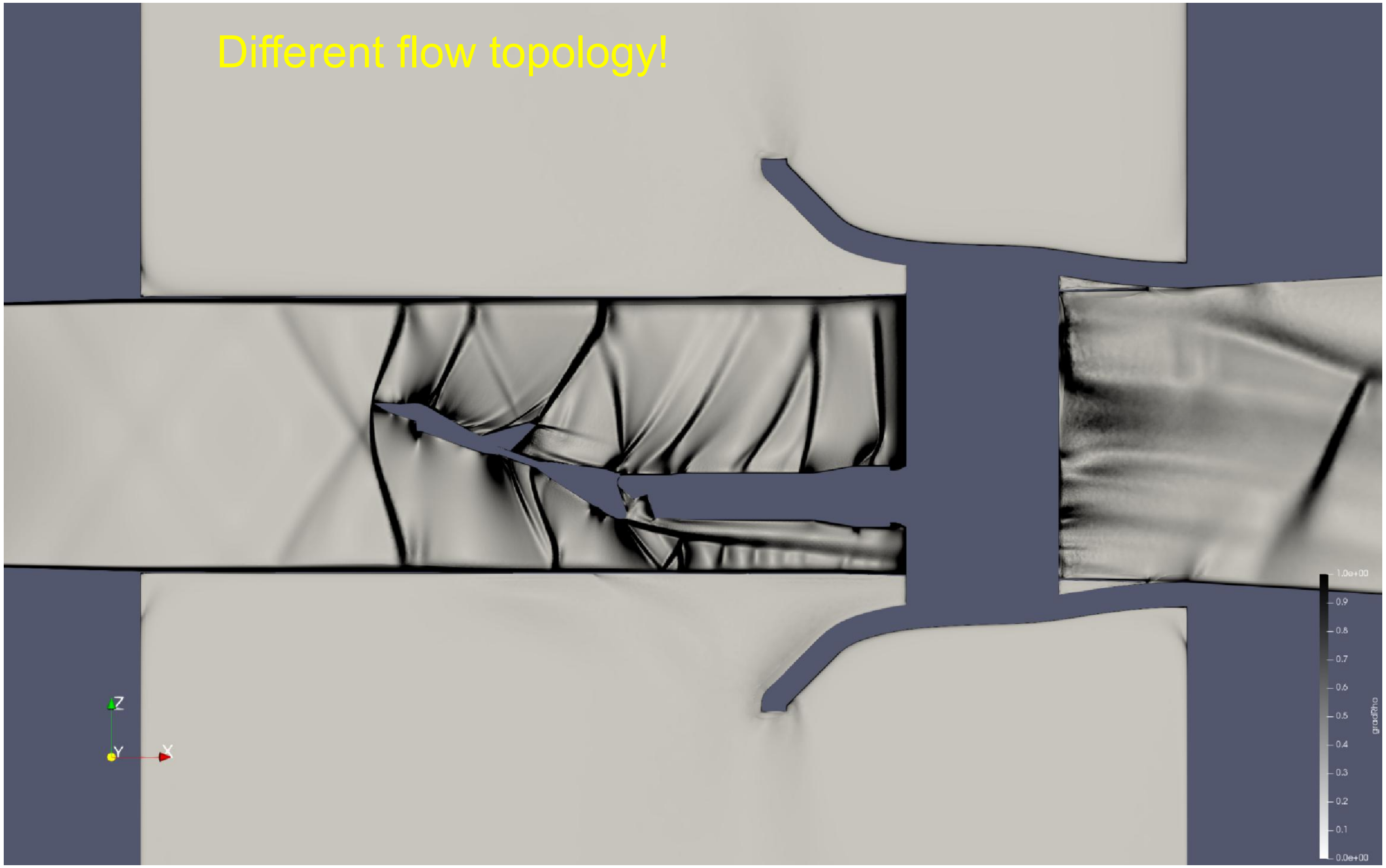
Comparison to free flight

AOA 20 / Flap 20 / Free Flight

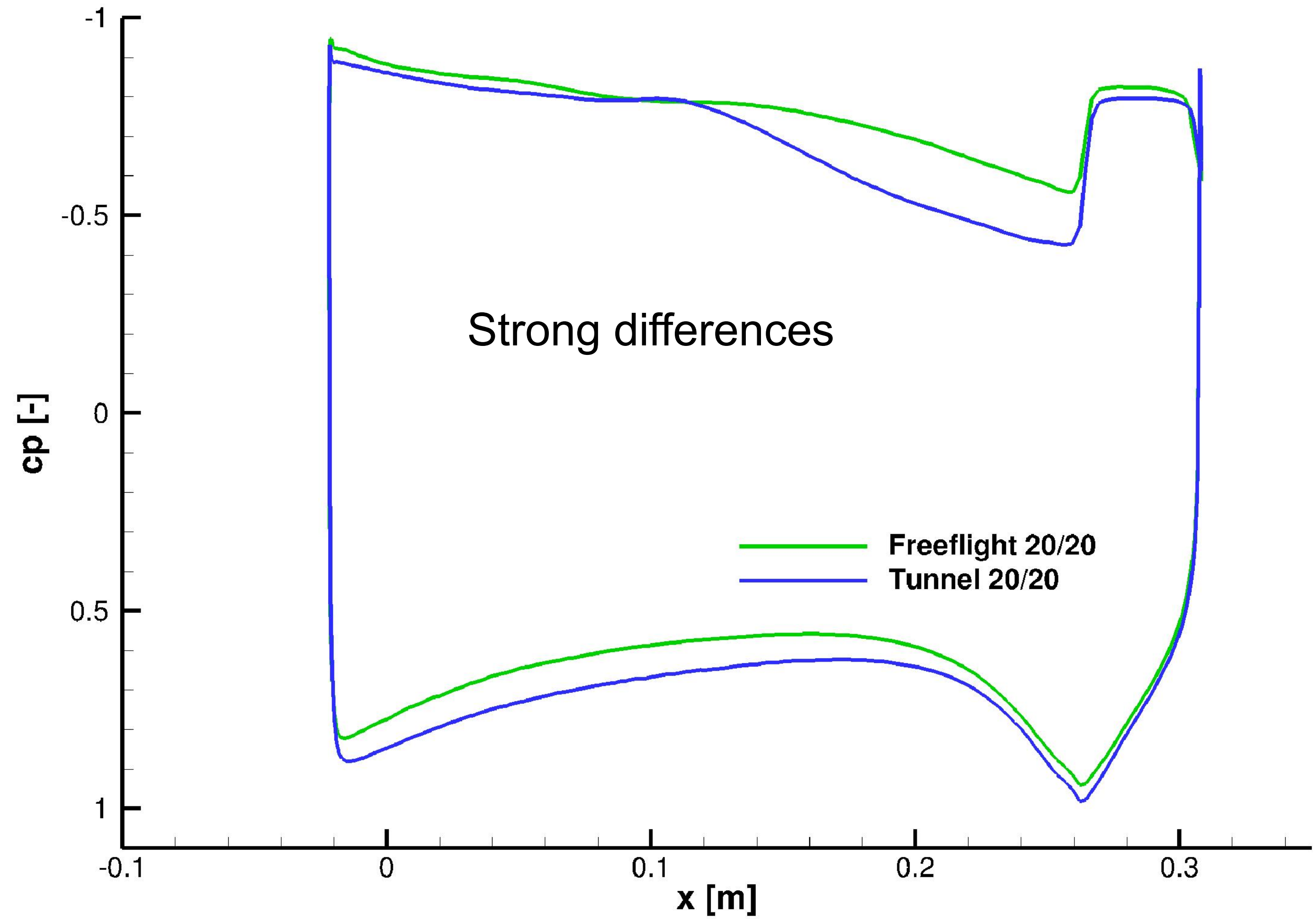


Comparison to free flight

AOA 20 / Flap 20 / p = 50k



Comparison to free flight



Comparison to free flight

Case	p_out	AOA/ Flap	p_suct	mp_suc	Slots SideW	p_pl	p_pl- p_stat	ptot_in	ptot_out	dptot_ out_in	CL	CD	CM	Case	Ma- Waves	p_pl= p_stat	No Supp	Remarks
Tunnel empty & support	50k	-/-	-	-	-	28093	+93	67899	52312	15587	-			-	-	x	-	ok
Tunnel empty & support	51k	-/-	-	-	-	28400	+400	67899	53231	14668	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	52k	-/-	-	-	-	28274	+274	67899	54135	13764	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	53k	-/-	-	-	-	28799	+799	67899	54994	12905	-			-	x	-	-	Exit pressure to high
Tunnel empty & support	54k	-/-	-	-	-	29714	+714	67899	55902	11997	-			-	x	-	-	Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-	-	-	28596	+596	67899	52303	15596	-			b	x	-	-	
Tunnel	50k	00/00	-	-	-	27930	-70	67869	52240	15629	-0.0115	0.0072	0.0028	a	-	x	-	
Tunnel	50k	00/20	-	-	-	27973	-27	67899	52218	15681	0.0368	0.0153	-0.0104	a	-	x	-	
Tunnel	50k	20/00	-	-	-	29761	+1761	67899	52030	15869	0.2498	0.0913	-0.0287	b	x	-	-	
Tunnel	50k	20/20	-	-	-	30488	+2488	67899	52006	15893	0.2846	0.1186	-0.0394	b	x	-	-	
Tunnel (MarkerMod)	50k	20/20	-	-	-	30509	+2509	67899	52009	15890	0.2829	0.1178	-0.0392	b	x	-	-	
Tunnel (FullMarkerMod)	50k	20/20	-	-	-	30485	+2485	67899	52012	15887	0.2834	0.1180	-0.0391	b	x	-	-	
Tunnel (without support)	50k	00/00	-	-	-	30428	+2428	67899	52315	15584	-0.0166	0.0087	0.0037	sup	x	-	x	Removed Support --> strong shock there
Tunnel (without support)	50k	20/20	-	-	-	29181	+1181	67899	52338	15561	0.2866	0.1184	-0.0389	sup	x	-	x	Removed Support --> strong shock there
Tunnel & slots closed	50k	20/20	-	-	-	-	-	-	-	-	0.2169	0.0857	-0.0239	-	Ma<1	-	-	Too strong shock in diffusor --> Ma<1
Tunnel & slots closed																		Too strong shock in diffusor --> Ma<1
Tunnel & slots closed (red. diffusor)																		Ma<1
Tunnel & slots partly closed to nose																		
Tunnel & slots partly closed to cone																		Ma < 1
Tunnel & suction																		Too much suction --> p_plenum to low
Tunnel & suction																		Too much suction --> p_plenum to low
Tunnel & suction																		Too much suction --> p_plenum to low
Tunnel & suction																		ok
Tunnel & suction																		ok: No Regulation! --> p_plenum right!
Tunnel & suction (MarkerMod / without suppor																		
Tunnel & suction (MarkerMod)																		
Tunnel & suction & SideSlots																		
Tunnel & conehat																		Removed Support --> strong shock there
Tunnel & conehat	50k	20/-	-	-	-	26877	-1123	67899	52356	15543	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & conehat (rot. source)	50k	20/-	-	-	-	26630	-1370	67899	52297	15602	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat	50k	20/-	-	-	-	31762	+3762	67899	52160	15739	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat & Support	50k	00/-	-	-	-	28209	+209	67899	52311	15588	-			a	-	-	-	
Tunnel & double conehat & Support	50k	20/-	-	-	-	28579	+579	67899	52307	15592	-			a	-	-	-	
Tunnel	40k	00/00	-	-	-	26778	-1222	67899	43124	24775	-0.0099	0.0073	0.0024	a	-	-	-	
Tunnel	40k	00/20	-	-	-	26869	-1131	67899	43103	24796	0.0351	0.0151	-0.0100	a	-	-	-	
Tunnel	40k	20/00	-	-	-	29543	+1563	67899	42975	24924	0.2521	0.0923	-0.0289	b	x	-	-	
Tunnel	40k	20/20	-	-	-	30321	+2321	67899	42946	24953	0.2839	0.1183	-0.0393	b	x	-	-	
Tunnel	30k	20/20	-	-	-	30333	+2333	67899	34643	33256	0.2839	0.1184	-0.0393	b	x	-	-	
Free Flight	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0151	-0.0107	a	-	x	x	
Free Flight	-	20/00	-	-	-	-	-	-	-	-	0.2509	0.0917	-0.0298	b	-	x	x	b is not critical in free flight because no slots!
Free Flight	-	20/20	-	-	-	-	-	-	-	-	0.2863	0.1187	-0.0401	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a	-	x	x	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b	-	x	x	b is not critical in free flight because no slots!

At 20/00 and 20/20 the plenum pressure is significantly higher then 28kPa and cannot lowered due to backpressure variation (in CHST)!

Comparison to free flight

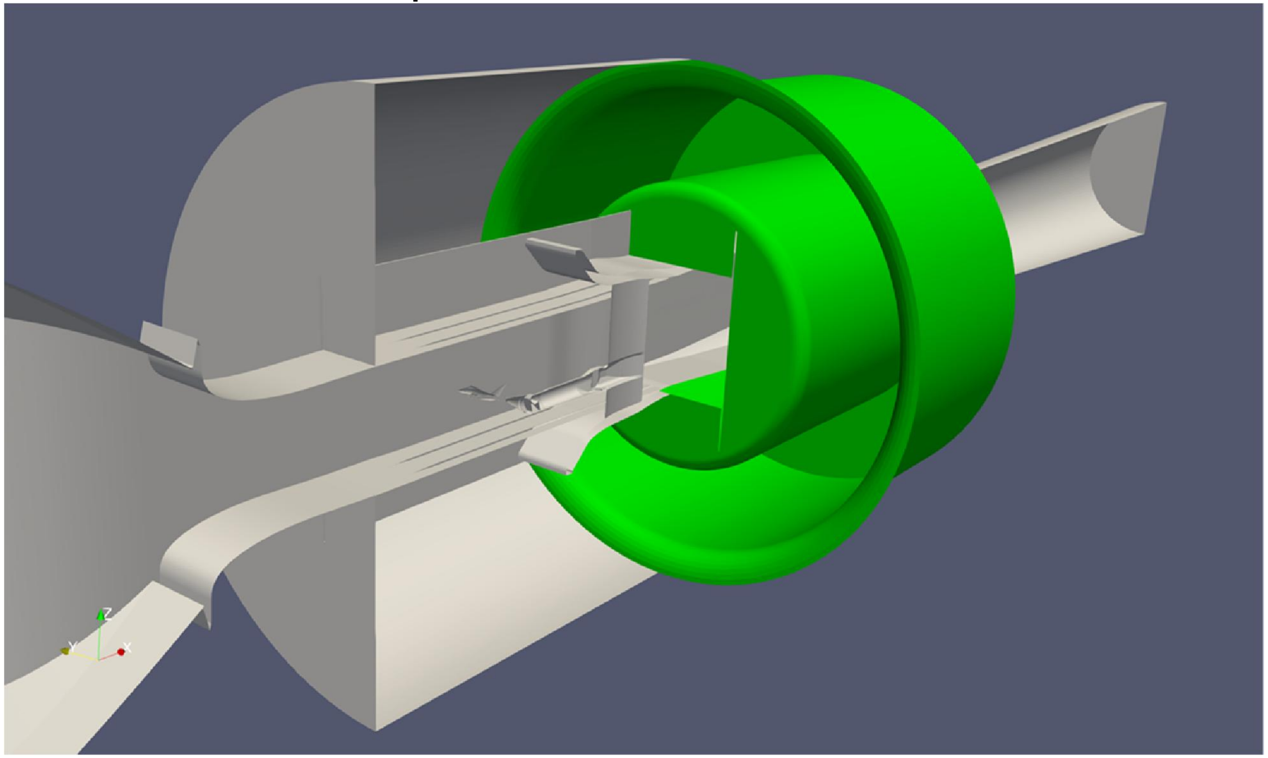
Case	p_out	AOA/ Flap	p_suct	mp_suc	Slots SideW	p_pl	p_pl- p_stat	ptot_in	ptot_out	dptot_ out_in	CL	CD	CM	Case	Ma- Waves	p_pl= p_stat	No Supp	Remarks
Tunnel empty & support	50k	-/-	-	-	-	28093	+93	67899	52312	15587	-			-	-	x	-	ok
Tunnel empty & support	51k	-/-	-	-	-	28400	+400	67899	53231	14668	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	52k	-/-	-	-	-	28274	+274	67899	54135	13764	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	53k	-/-	-	-	-	28799	+799	67899	54994	12905	-			-	x	-	-	Exit pressure to high
Tunnel empty & support	54k	-/-	-	-	-	29714	+714	67899	55902	11997	-			-	x	-	-	Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-	-	-	28596	+596	67899	52303	15596	-			b	x	-	-	
Tunnel	50k	00/00	-	-	-	27930	-70	67869	52240	15629	-0.0115	0.0072	0.0028	a	-	x	-	
Tunnel	50k	00/20	-	-	-	27973	-27	67899	52218	15681	0.0368	0.0153	-0.0104	a	-	x	-	
Tunnel	50k	20/00	-	-	-	29761	+1761	67899	52030	15869	0.2498	0.0913	-0.0287	b	x	-	-	
Tunnel	50k	20/20	-	-	-	30488	+2488	67899	52006	15893	0.2846	0.1186	-0.0394	b	x	-	-	
Tunnel (MarkerMod)	50k	20/20	-	-	-	30509	+2509	67899	52009	15890	0.2829	0.1178	-0.0392	b	x	-	-	
Tunnel (FullMarkerMod)	50k	20/20	-	-	-	30485	+2485	67899	52012	15887	0.2834	0.1180	-0.0391	b	x	-	-	
Tunnel (without support)	50k	00/00	-	-	-	30428	+2428	67899	52315	15584	-0.0166	0.0087	0.0037	sup	x	-	x	Removed Support --> strong shock there
Tunnel (without support)	50k	20/20	-	-	-	29181	+1181	67899	52338	15561	0.2866	0.1184	-0.0389	sup	x	-	x	Removed Support --> strong shock there
Tunnel & slots closed	50k	20/20	-	-	-	-	-	-	-	-	0.2169	0.0857	-0.0239	-	Ma<1	-	-	Too strong shock in diffusor --> Ma<1
Tunnel & slots closed	40k	20/20	-	-	-	-	-	-	-	-	0.2169	0.0857	-0.0239	-	Ma<1	-	-	Too strong shock in diffusor --> Ma<1
Tunnel & slots closed (red. diffusor)																	-	Ma<1
Tunnel & slots partly closed to nose																	-	
Tunnel & slots partly closed to cone																	-	Ma < 1
Tunnel & suction																	-	Too much suction --> p_plenum to low
Tunnel & suction																	-	Too much suction --> p_plenum to low
Tunnel & suction																	-	Too much suction --> p_plenum to low
Tunnel & suction																	-	ok
Tunnel & suction																	-	ok: No Regulation! --> p_plenum right!
Tunnel & suction (MarkerMod / without																	-	
Tunnel & suction (MarkerMod)																	-	
Tunnel & suction & SideSlots																	-	
Tunnel & conehat																	x	Removed Support --> strong shock there
Tunnel & conehat																	x	Removed Support --> strong shock there
Tunnel & conehat (rot. source)	50k	20/-	-	-	-	26630	-1370	67899	52297	15602	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat	50k	20/-	-	-	-	31762	+3762	67899	52160	15739	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat & Support	50k	00/-	-	-	-	28209	+209	67899	52311	15588	-			a	-	-	-	
Tunnel & double conehat & Support	50k	20/-	-	-	-	28579	+579	67899	52307	15592	-			a	-	-	-	
Tunnel	40k	00/00	-	-	-	26778	-1222	67899	43124	24775	-0.0099	0.0073	0.0024	a	-	-	-	
Tunnel	40k	00/20	-	-	-	26869	-1131	67899	43103	24796	0.0351	0.0151	-0.0100	a	-	-	-	
Tunnel	40k	20/00	-	-	-	29543	+1563	67899	42975	24924	0.2521	0.0923	-0.0289	b	x	-	-	
Tunnel	40k	20/20	-	-	-	30321	+2321	67899	42946	24953	0.2839	0.1183	-0.0393	b	x	-	-	
Tunnel	30k	20/20	-	-	-	30333	+2333	67899	34643	33256	0.2839	0.1184	-0.0393	b	x	-	-	
Free Flight	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0151	-0.0107	a	-	x	x	
Free Flight	-	20/00	-	-	-	-	-	-	-	-	0.2509	0.0917	-0.0298	b	-	x	x	b is not critical in free flight because no slots!
Free Flight	-	20/20	-	-	-	-	-	-	-	-	0.2863	0.1187	-0.0401	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a	-	x	x	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b	-	x	x	b is not critical in free flight because no slots!

A good comparison from free flight to tunnel experiment correlates with minimum static pressure difference between test section and plenum

Plenum suction

Plenum suction

- Case 20/20: plenum pressure to high (compared to static pressure in test section) → how to reduce it?
- Some other supersonic tunnels have plenum suction installed → solution for HST?
- Suction: a ring in the backwall of the plenum

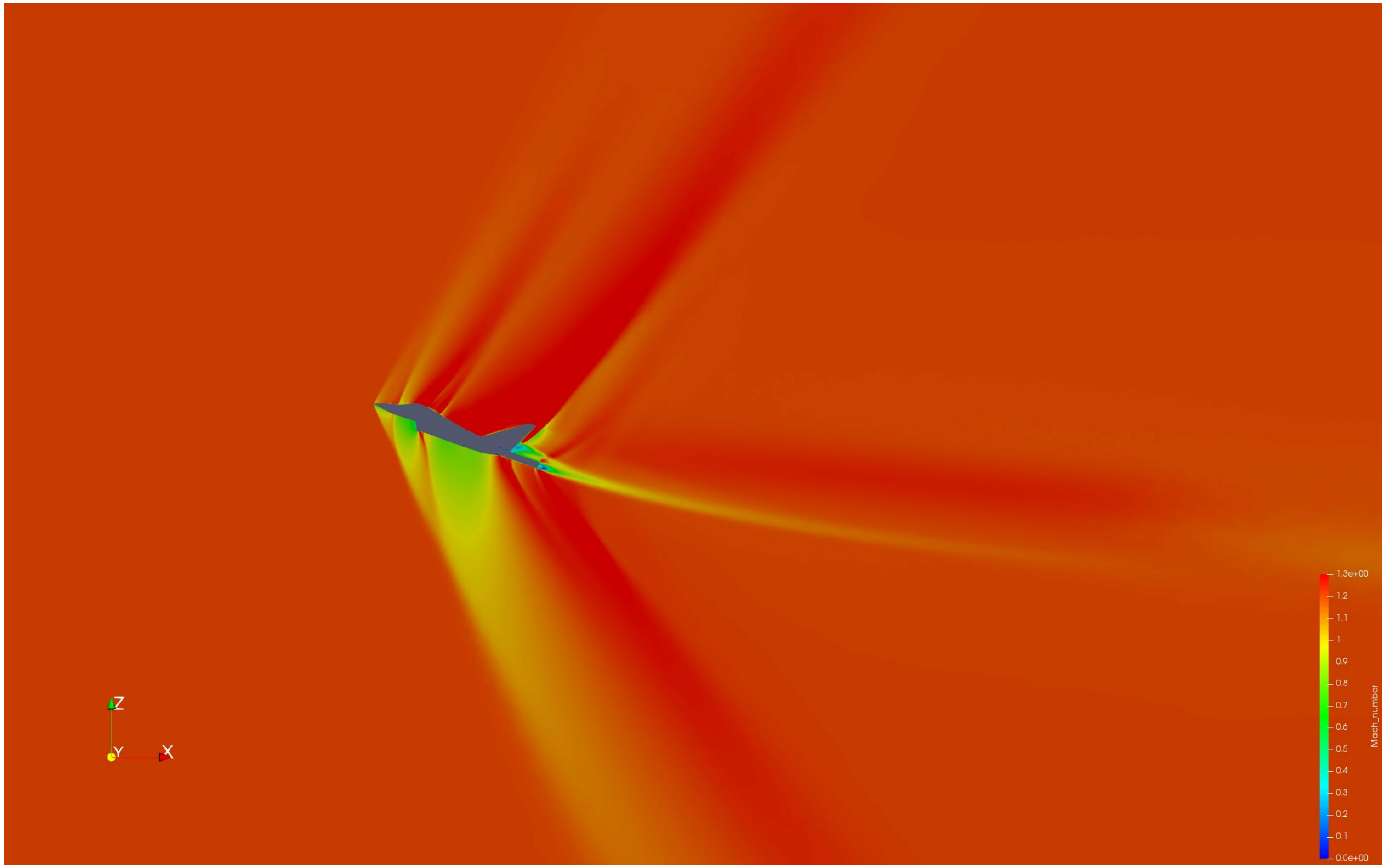


Plenum suction

Case	p_out	AOA/ Flap	p_suct	mp_suc	Slots SideW	p_pl	p_pl- p_stat	ptot_in	ptot_out	dptot_ out_in	CL	CD	CM	Case	Ma- Waves	p_pl= p_stat	No Supp	Remarks
Tunnel empty & support	50k	-/-	-	-	-	28093	+93	67899	52312	15587	-			-	-	x	-	ok
Tunnel empty & support	51k	-/-	-	-	-	28400	+400	67899	53231	14668	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	52k	-/-	-	-	-	28274	+274	67899	54135	13764	-			-	-	-	-	Exit pressure to high
Tunnel empty & support	53k	-/-	-	-	-	28799	+799	67899	54994	12905	-			-	x	-	-	Exit pressure to high
Tunnel empty & support	54k	-/-	-	-	-	29714	+714	67899	55902	11997	-			-	x	-	-	Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-	-	-	28596	+596	67899	52303	15596	-			b	x	-	-	
Tunnel	50k	00/00	-	-	-	27930	-70	67869	52240	15629	-0.0115	0.0072	0.0028	a	-	x	-	
Tunnel	50k	00/20	-	-	-	27973	-27	67899	52218	15681	0.0368	0.0153	-0.0104	a	-	x	-	
Tunnel	50k	20/00	-	-	-	29761	+1761	67899	52030	15869	0.2498	0.0913	-0.0287	b	x	-	-	
Tunnel	50k	20/20	-	-	-	30488	+2488	67899	52006	15893	0.2846	0.1186	-0.0394	b	x	-	-	
Tunnel (MarkerMod)	50k	20/20	-	-	-	30509	+2509	67899	52009	15890	0.2829	0.1178	-0.0392	b	x	-	-	
Tunnel (FullMarkerMod)	50k	20/20	-	-	-	30485	+2485	67899	52012	15887	0.2834	0.1180	-0.0391	b	x	-	-	
Tunnel (without support)	50k	00/00	-	-	-	30428	+2428	67899	52315	15584	-0.0166	0.0087	0.0037	sup	x	-	x	Removed Support --> strong shock there
Tunnel (without support)	50k	20/20	-	-	-	29181	+1181	67899	52338	15561	0.2866	0.1184	-0.0389	sup	x	-	x	Removed Support --> strong shock there
Tunnel & slots closed	50k	20/20	-	-	-	-	-	-	-	-	0.2169	0.0857	-0.0239	-	Ma<1	-	-	Too strong shock in diffusor --> Ma<1
Tunnel & slots closed	40k	20/20	-	-	-	-	-	-	-	-	0.2169	0.0857	-0.0239	-	Ma<1	-	-	Too strong shock in diffusor --> Ma<1
Tunnel & slots closed (red. diffusor)	50k	20/20	-	-	-	-	-	-	-	-	0.2170	0.0857	-0.0239	-	Ma<1	-	-	Ma<1
Tunnel & slots partly closed to nose	50k	20/20	-	-	-	30412	+2412	67899	51981	15918	0.2840	0.1161	-0.0380				-	
Tunnel & slots partly closed to cone	50k	20/20	-	-	-	29119	+1119	67899	52067	15832	0.2660	0.1055	-0.0346	-	Ma<1	-	-	Ma < 1
Tunnel & suction	50k	20/2	27.7k	2.49%	-	27630	-370	67899	51893	16006	0.2913	0.1189	-0.0403	b->a	-	-	-	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/2	27.8k	2.35%	-	27731	-269	67899	51896	16003	0.2913	0.1189	-0.0402	b->a	-	-	-	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/2	27.9k	2.31%	-	27828	-172	67899	51900	15999	0.2913	0.1189	-0.0401	b->a	-	~x	-	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/2	27.95k	2.37%	-	27882	-118	67899	51903	15996	0.2913	0.1188	-0.0400	b->a	-	x	-	ok
Tunnel & suction	50k	20/2	28k	2.21%	-	27933	-67	67899	51907	15992	0.2913	0.1189	-0.0400	b->a	-	x	-	ok: No Regulation! --> p_plenum right!
Tunnel & suction (MarkerMod / without support)	50k	0/0	28k	0%	-	27956	-44	67899	52332	15567	-0.0108	0.0072	0.0026	a	-	x	-	
Tunnel & suction (MarkerMod)	50k	20/20	28k	2.79%	-	27941	-59	67899	51870	16029	0.2911	0.1188	-0.0399	b->a	-	x	-	
Tunnel & suction & SideSlots	50k	20/20	28k	4.33%	x	27738	-262	67899	51813	16086	0.2892	0.1190	-0.0405	b->a	-	~	-	
Tunnel & conehat	50k	00/-	-	-	-	30263	+2263	67899	52309	15590	-			sup	-	-	x	Removed Support --> strong shock there
Tunnel & conehat	50k	20/-	-	-	-	26877	-1123	67899	52356	15543	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & conehat (rot. source)	50k	20/-	-	-	-	26630	-1370	67899	52297	15602	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat	50k	20/-	-	-	-	31762	+3762	67899	52160	15739	-			sup	x	-	x	Removed Support --> strong shock there
Tunnel & double conehat & Support	50k	00/-	-	-	-	28209	+209	67899	52311	15588	-			a	-	-	-	
Tunnel & double conehat & Support	50k	20/-	-	-	-	28579	+579	67899	52307	15592	-			a	-	-	-	
Tunnel	40k	00/00	-	-	-	26778	-1222	67899	43124	24775	-0.0099	0.0073	0.0024	a	-	-	-	
Tunnel	40k	00/20	-	-	-	26869	-1131	67899	43103	24796	0.0351	0.0151	-0.0100	a	-	-	-	
Tunnel	40k	20/00	-	-	-	29543	+1563	67899	42975	24924	0.2521	0.0923	-0.0289	b	x	-	-	
Tunnel	40k	20/20	-	-	-	30321	+2321	67899	42946	24953	0.2839	0.1183	-0.0393	b	x	-	-	
Tunnel	30k	20/20	-	-	-	30333	+2333	67899	34643	33256	0.2839	0.1184	-0.0393	b	x	-	-	
Free Flight	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0151	-0.0107	a	-	x	x	
Free Flight	-	20/00	-	-	-	-	-	-	-	-	0.2509	0.0917	-0.0298	b	-	x	x	b is not critical in free flight because no slots!
Free Flight	-	20/20	-	-	-	-	-	-	-	-	0.2863	0.1187	-0.0401	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a	-	x	x	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b	-	x	x	b is not critical in free flight because no slots!

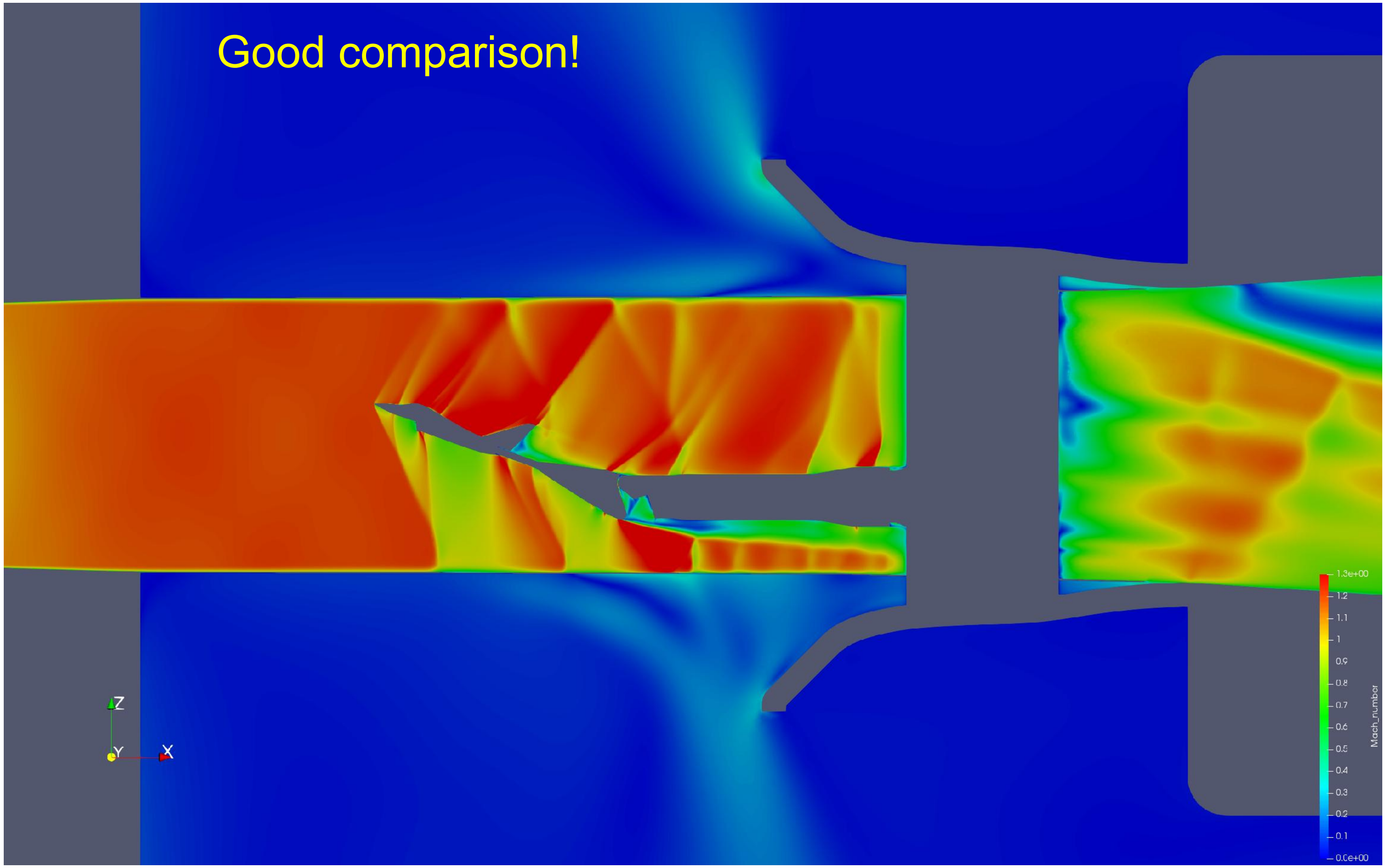
Plenum suction

AOA 20 / Flap 20 / Free Flight



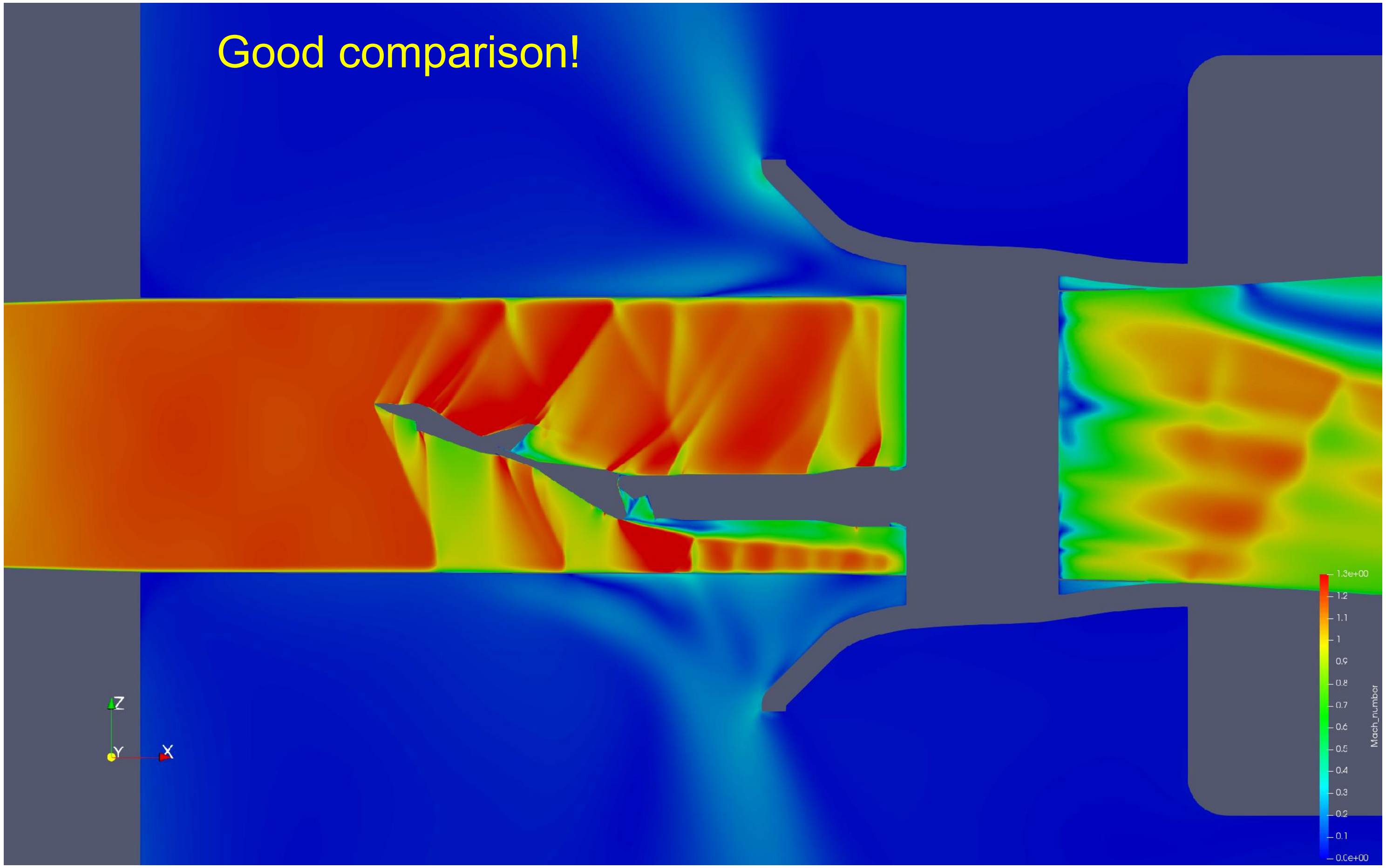
Plenum suction

AOA 20 / Flap 20 / p = 50k / suction p = 27.7k



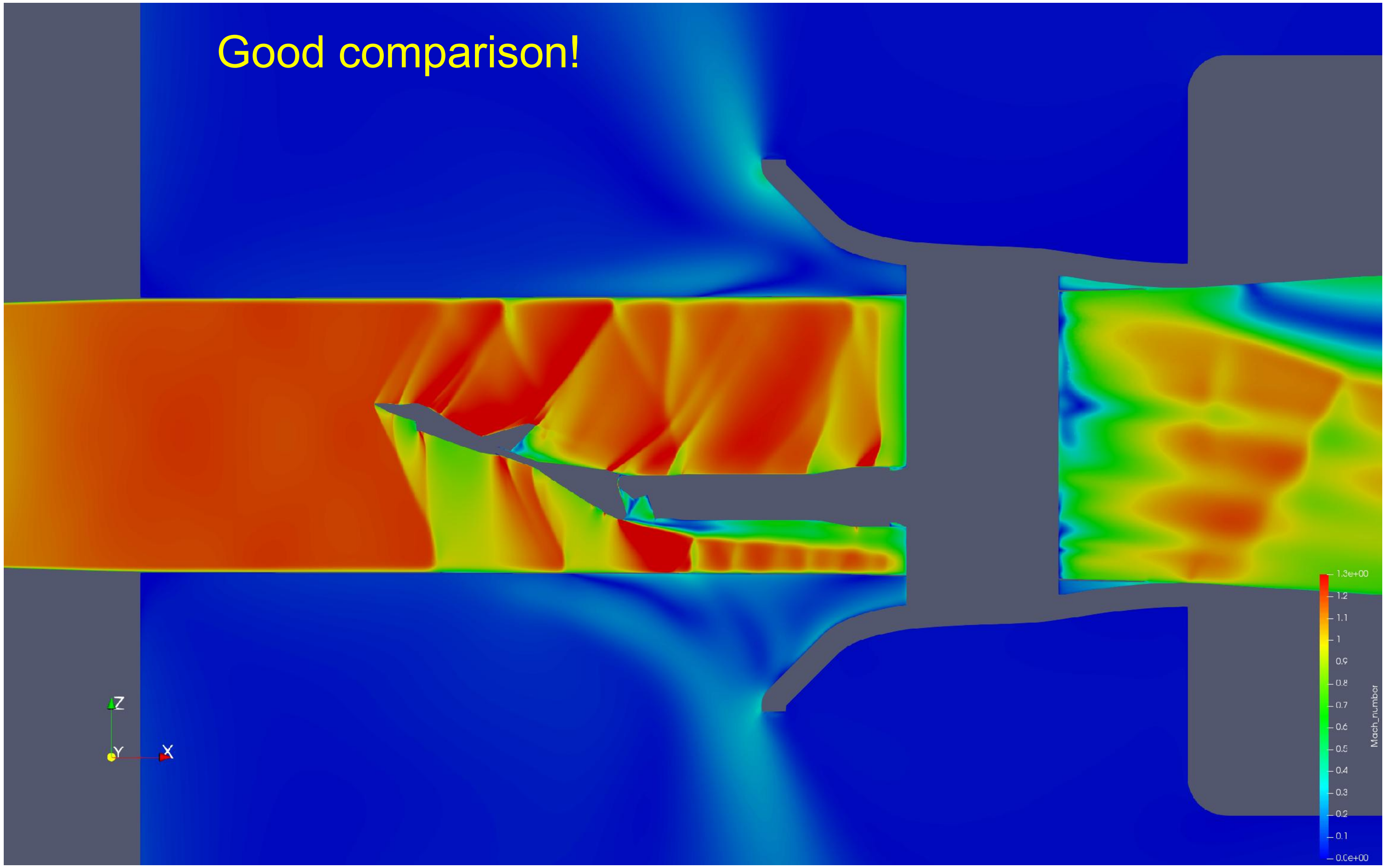
Plenum suction

AOA 20 / Flap 20 / p = 50k / suction p = 27.8k



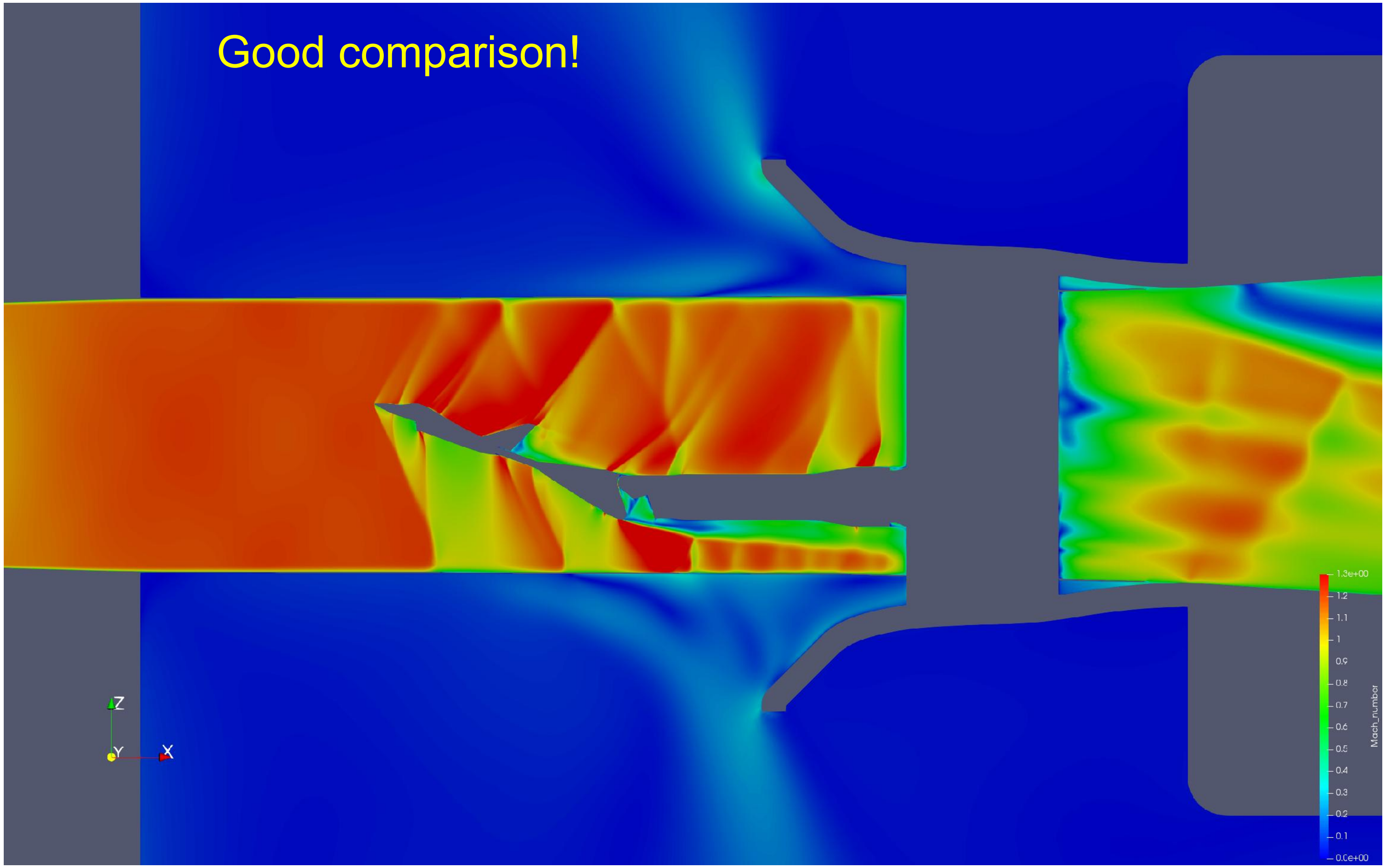
Plenum suction

AOA 20 / Flap 20 / p = 50k / suction p = 27.9k



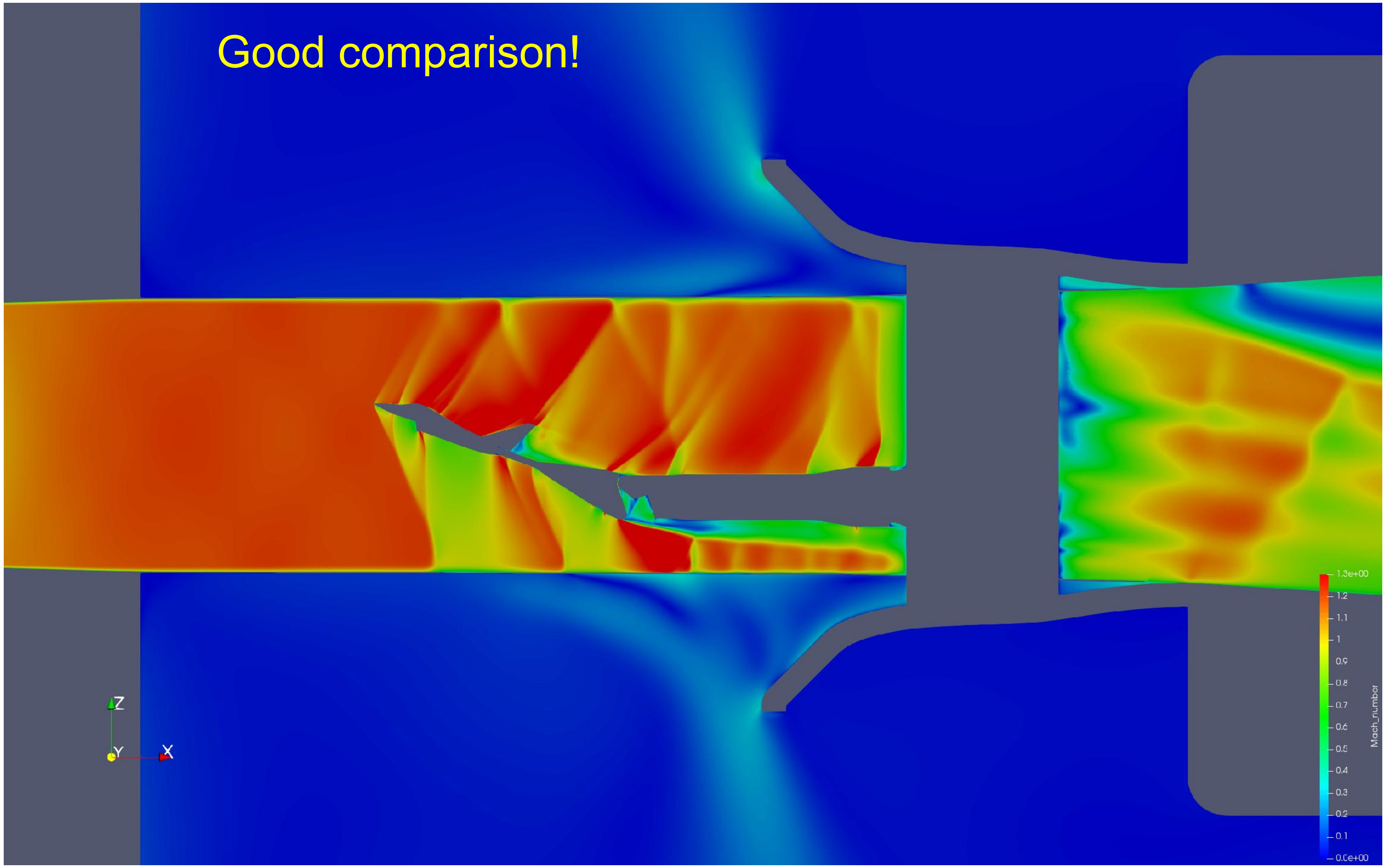
Plenum suction

AOA 20 / Flap 20 / p = 50k / suction p = 27.95k



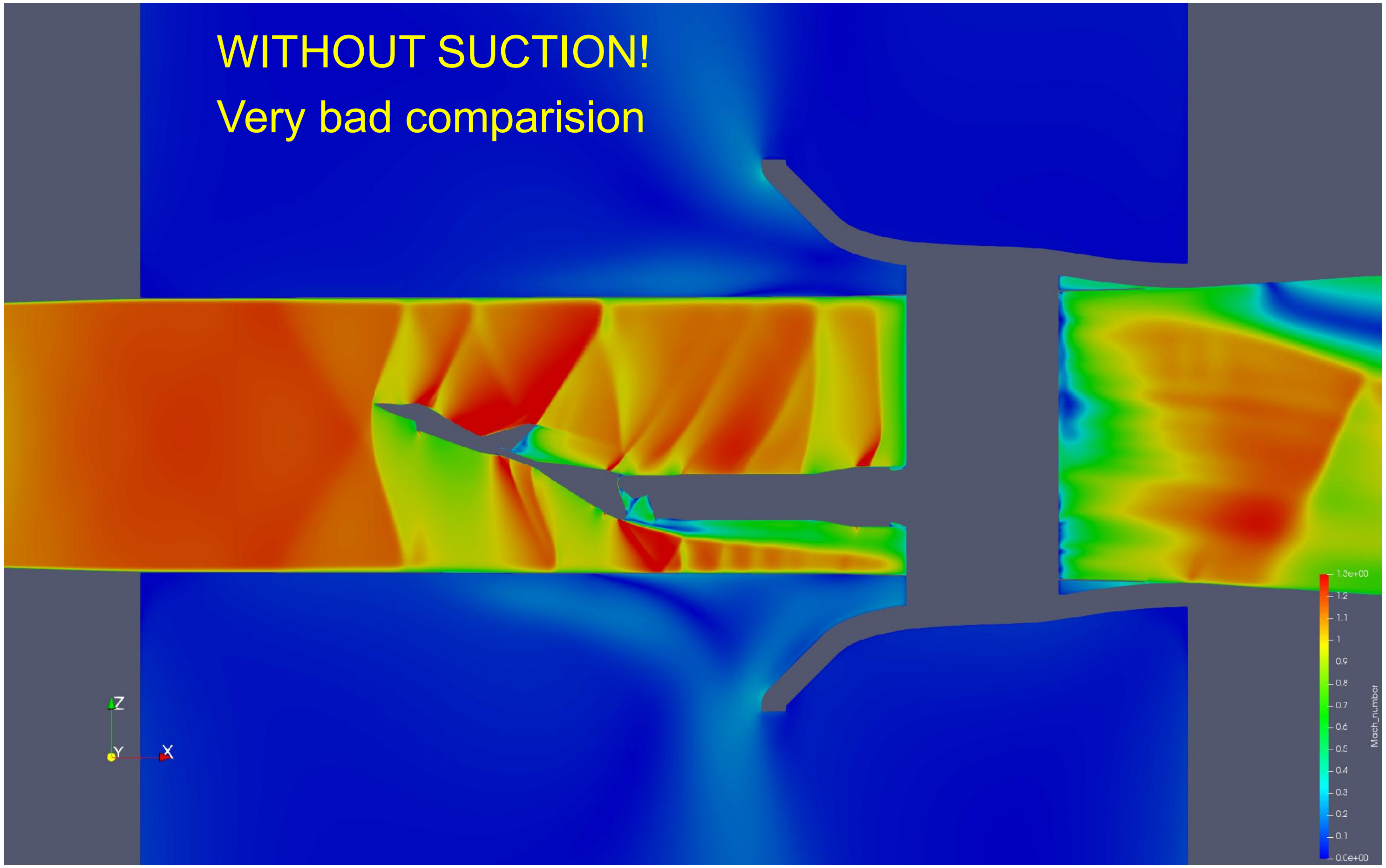
Plenum suction

AOA 20 / Flap 20 / p = 50k / suction p = 28k



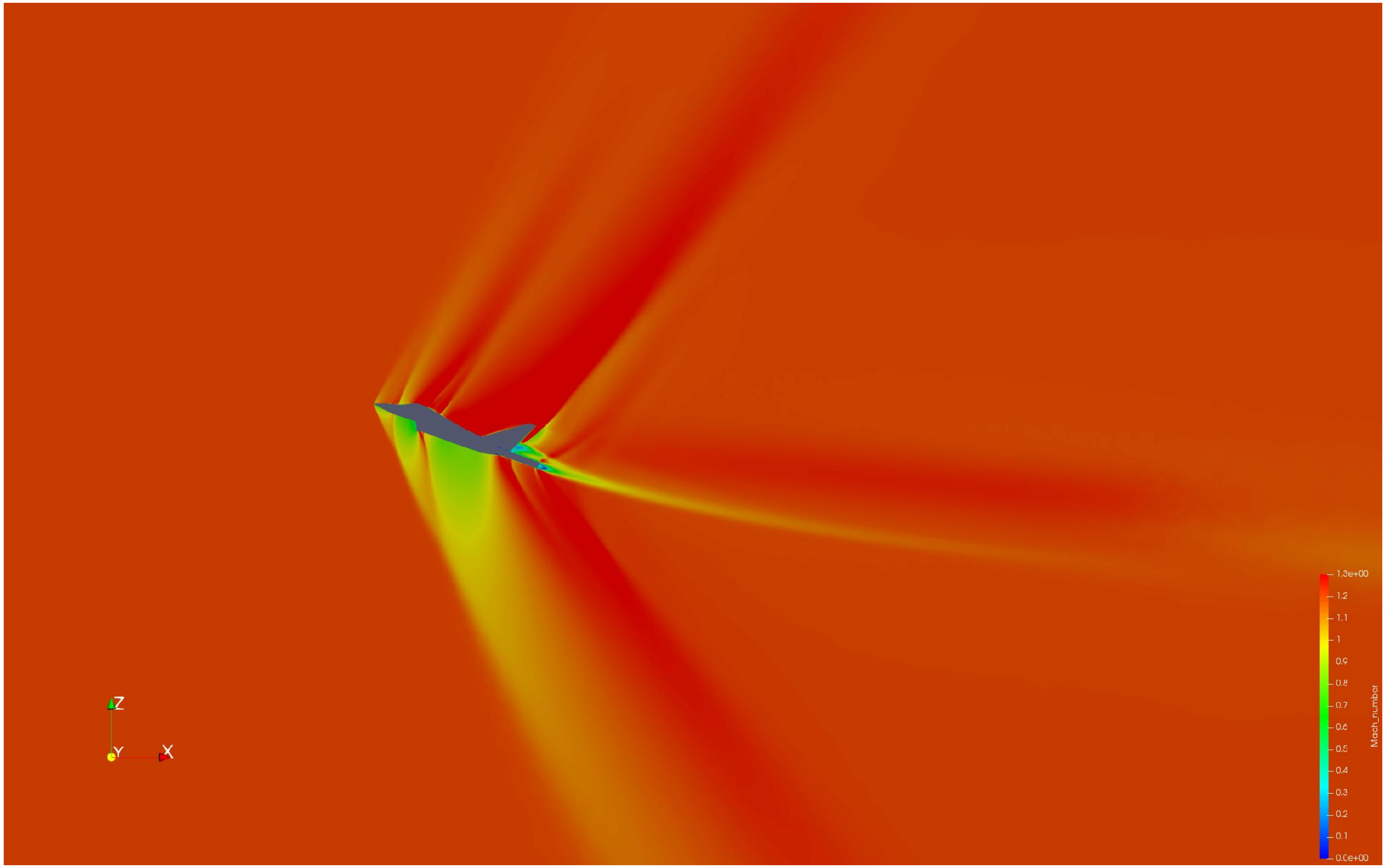
Plenum suction

AOA 20 / Flap 20 / p = 50k

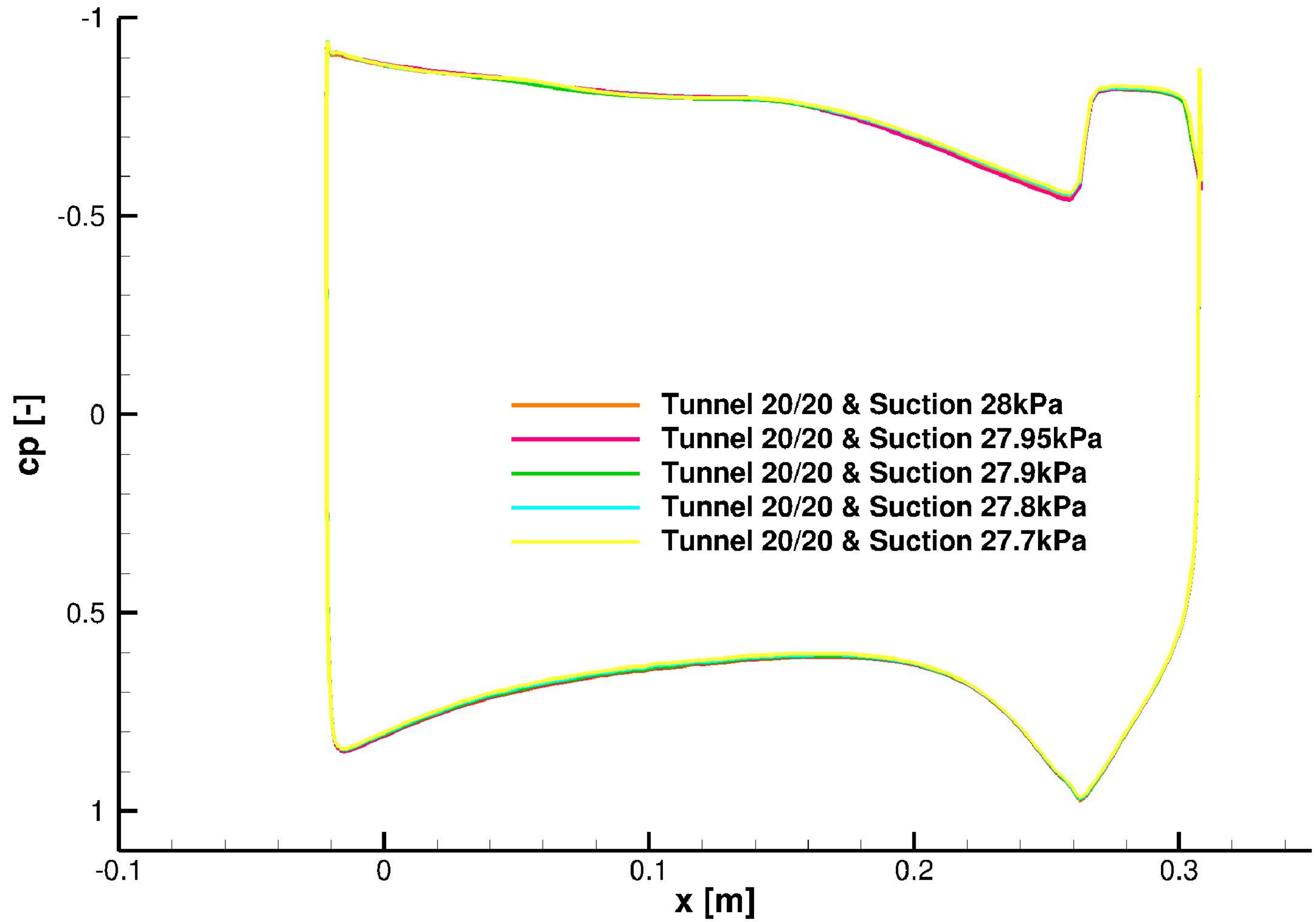


Plenum suction

AOA 20 / Flap 20 / Free Flight

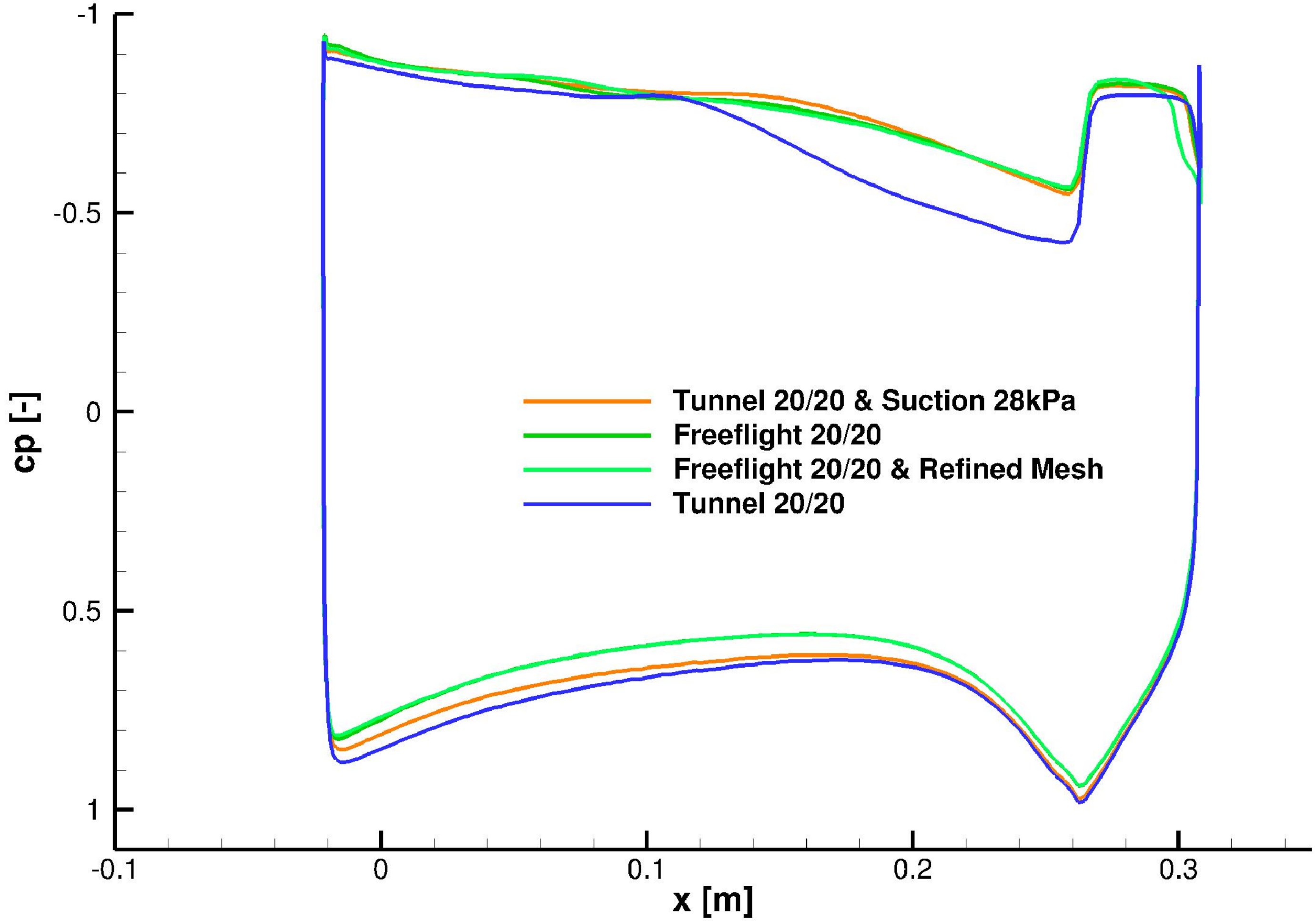


Plenum suction



Plenum suction

- Suction → cp closer to free flight
  - Very small difference on suction side
  - Small difference on pressure side → wall influence?



Plenum suction

Case	p_out	AOA/ Flap	p_suct	mp_suc	Slots SideW	p_pl	p_pl- p_stat	ptot_in	ptot_out	dptot_ out_in	CL	CD	CM	Case	Ma- Waves	p_pl= p_stat	No Supp	Remarks
Tunnel e														-	-	x	-	ok
Tunnel e														-	-	-	-	Exit pressure to high
Tunnel e														-	-	-	-	Exit pressure to high
Tunnel e														-	x	-	-	Exit pressure to high
Tunnel e														-	x	-	-	Exit pressure to high
Tunnel empty & support (at 20deg pos.)	50k	-/-	-	-	-	28596	+596	67899	52303	15596	-			b	x	-	-	
Tunnel	50k	00/00	-	-	-	27930	-70	67869	52240	15629	-0.0115	0.0072	0.0028					
Tunnel	50k	00/20	-	-	-	27973	-27	67899	52218	15681	0.0368	0.0153	-0.0104					
Tunnel	50k	20/00	-	-	-	29761	+1761	67899	52030	15869	0.2498	0.0913	-0.0287					
Tunnel	50k	20/20	-	-	-	30488	+2488	67899	52006	15893	0.2846	0.1186	-0.0394					
Tunnel (MarkerMod)	50k	20/20	-	-	-	30509	+2509	67899	52009	15890	0.2829	0.1178	-0.0392					
Tunnel (FullMarkerMod)	50k	20/20	-	-	-	30485	+2485	67899	52012	15887	0.2834	0.1180	-0.0391					
Tunnel (without support)	50k	00/00	-	-	-	30428	+2428	67899	52315	15584	-0.0166	0.0087	0.0087					
Tunnel (without support)	50k	20/20	-	-	-	29181	+1181	67899	52338	15561	0.2866	0.1184	-0.0389					
Tunnel & slots closed	50k	20/20	-	-	-	-	-	-	-	-	0.2169	0.0857	-0.0239					
Tunnel & slots closed	40k	20/20	-	-	-	-	-	-	-	-	0.2169	0.0857	-0.0239					
Tunnel & slots closed (red. diffusor)	50k	20/20	-	-	-	-	-	-	-	-	0.2170	0.0857	-0.0239					
Tunnel & slots partly closed to nose	50k	20/20	-	-	-	30412	+2412	67899	51981	15918	0.2840	0.1161	-0.0380					
~~Tunnel & slots partly closed to cone~~	50k	20/20	-	-	-	29119	+1119	67899	52067	15832	0.2660	0.1055	-0.0346	-	Ma<1	-	-	Ma < 1
Tunnel & suction	50k	20/20	27.7k	2.49%	-	27630	-370	67899	51893	16006	0.2913	0.1189	-0.0403	b->a	-	-	-	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27.8k	2.35%	-	27731	-269	67899	51896	16003	0.2913	0.1189	-0.0402	b->a	-	-	-	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27.9k	2.31%	-	27828	-172	67899	51900	15999	0.2913	0.1189	-0.0401	b->a	-	~x	-	Too much suction --> p_plenum to low
Tunnel & suction	50k	20/20	27.95	2.37%	-	27882	-118	67899	51903	15996	0.2913	0.1188	-0.0400	b->a	-	x	-	ok
Tunnel & suction	50k	20/20	28k	2.21%	-	27933	-67	67899	51907	15992	0.2913	0.1189	-0.0400	b->a	-	x	-	ok: No Regulation! --> p_plenum right!
Tunnel & suction (MarkerMod / without support)	50k	0/0	28k	0%	-	27956	-44	67899	52332	15567	-0.0108	0.0072	0.0026	a	-	x	-	
Tunnel & suction (MarkerMod)	50k	20/20	28k	2.79%	-	27941	-59	67899	51870	16029	0.2911	0.1188	-0.0399	b->a	-	x	-	
Tunnel & suction & SideSlots	50k	20/20	28k	4.33%	x	27738	-262	67899	51813	16086	0.2892	0.1190	-0.0405	b->a	-	~	-	
Tunnel & conehat	50k	00/-	-	-	-	30263	+2263	67899	52309	15590	-			sup	-	-	x	Removed Support --> strong shock there
Tunnel & conehat	50k	20/-	-	-	-	26877	-1123	67899	52356	15543	-			sup				
Tunnel & conehat (rot. source)	50k	20/-	-	-	-	26630	-1370	67899	52297	15602	-			sup				
Tunnel & double conehat	50k	20/-	-	-	-	31762	+3762	67899	52160	15739	-			sup				
Tunnel & double conehat & Support	50k	00/-	-	-	-	28209	+209	67899	52311	15588	-			a				
Tunnel & double conehat & Support	50k	20/-	-	-	-	28579	+579	67899	52307	15592	-			a				
Tunnel	40k	00/00	-	-	-	26778	-1222	67899	43124	24775	-0.0099	0.0073	0.0024	a				
Tunnel	40k	00/20	-	-	-	26869	-1131	67899	43103	24796	0.0351	0.0151	-0.0100	a				
Tunnel	40k	20/00	-	-	-	29543	+1563	67899	42975	24924	0.2521	0.0923	-0.0289	b				
Tunnel	40k	20/20	-	-	-	30321	+2321	67899	42946	24953	0.2839	0.1183	-0.0393					
Tunnel	30k	20/20	-	-	-	30333	+2333	67899	34643	33256	0.2839	0.1184	-0.0393	b				
Free Flight	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a				
Free Flight	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a				
~~Free Flight~~	-	20/00	-	-	-	-	-	-	-	-	[illegible]	[illegible]	[illegible]					
Free Flight	-	20/20	-	-	-	-	-	-	-	-	0.2863	0.1187	-0.0401		-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	00/00	-	-	-	-	-	-	-	-	-0.0106	0.0070	0.0026	a	-	x	x	
Free Flight (RefinedMesh)	-	00/20	-	-	-	-	-	-	-	-	0.0381	0.0152	-0.0107	a	-	x	x	
Free Flight (RefinedMesh)	-	20/00	-	-	-	-	-	-	-	-	0.2511	0.0917	-0.0297	b	-	x	x	b is not critical in free flight because no slots!
Free Flight (RefinedMesh)	-	20/20	-	-	-	-	-	-	-	-	0.2860	0.1183	-0.0400	b	-	x	x	b is not critical in free flight because no slots!

Massflow is nearly constant

Aerodynamic coefficients nearly constant at different suction pressure

Compared to FreeFlight there is only a small error of 1.7% in lift

Plenum suction

- In the tested range from 27.7k to 28k there is no significant difference in the flow field, the massflow and aerodynamic forces …
- “Keep it simple”: suction with static pressure of the test section is the best solution
- If the plenum pressure is already the static pressure of the test section for e.g. smaller angle of attack the suction there will be zero → fully automatic solution → suction should be used all the time

Conclusion

Conculsion

- Problems with Eurofighter at higher angles of attack / flap angles: result of additional slot (in)flow → change in effective cross section of test section → Mach number disturbed & cannot recovered with backpressure variation

- "Simple" & fully automatic solution:
  - suction of the plenum with static pressure of the test-section → slot (in)flow is minimized → minimal Mach number disturbance → best comparison to free flight
  - Suction rate for Ma = 1.2 & Eurofighter at AOA 20 deg ~ 12 kg/s