Aerodynamics of hypervelocity bodies
Milestone 4, Final meeting

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November 13, 2019

Agenda

- 9.45 - 10.00: Overview of the GSTP activity

- 10.00 - 10.20: Automation of the VKI Longshot wind tunnel
- 10.20 - 10.40: Lagrangian modeling of the wind tunnel
- 10.40 - 11.00: State-of-the-art flow characterization
- 11.00 - 11.20: Design/testing of a Mach 14 contoured nozzle
- 11.20 - 11.40: Design/testing of a 6-components aerodynamic balance

- 11.40 - 12.00: Conclusions and outlook
- 12.00 - 13.30: Discussions
- 13.30: adjourn

Project overview, task division

Task 1:
- **WP1** *Project management*

Task 2: *Hardware and wind-tunnel development*
- **WP2.1** *Future operational map*
- **WP2.2** *New W-T instrumentation*
- **WP2.3** *Check valves removal*
- **WP2.4** *Flow characterization*
- **WP2.5** *New contoured nozzle*
- **WP2.6** *Automatic operation*
- **WP2.7** *Ease nozzle exchange*

Task 3: *Meas. techniques & methodologies*
- **WP3.1** *New probes*
- **WP3.2** *New balance*
- **WP3.3** *Flow establishment*
- **WP3.4** *Data acquisition system*

Task 4: *Numerics & data processing*
- **WP4.1** *1D modeling of wind tunnel*
- **WP4.2** *Nozzle flow modeling*
- **WP4.3** *Free-stream rebuilding*

Task 5:
- **WP 5** *Summary of findings*

Project overview, details on task 2

Task 2: *Hardware and wind-tunnel development*

- **WP2.1** *Future operational map*
- **WP2.2** *New W-T instrumentation*
- **WP2.3** *Check valves removal*
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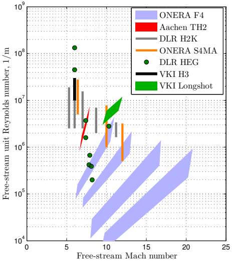
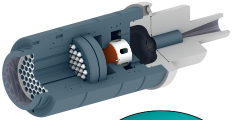
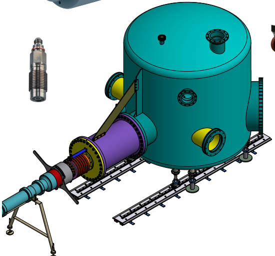
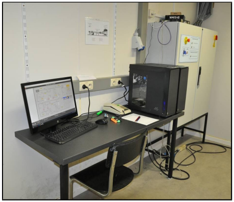
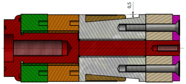
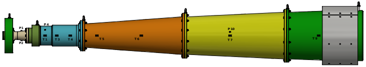






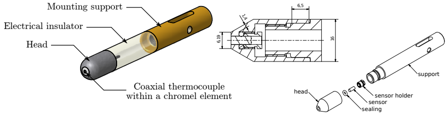


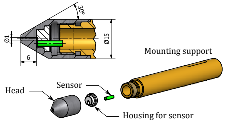


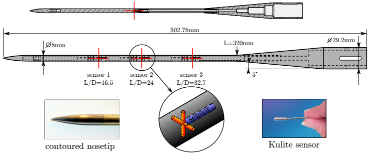


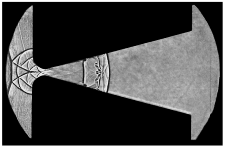
Project overview, details on task 3

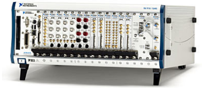
Task 3: *Meas. techniques & methodologies*	**WP3.1** *New probes*	**WP3.2** *New balance*	**WP3.3** *Flow establishment*	**WP3.4** *Data acquisition system*

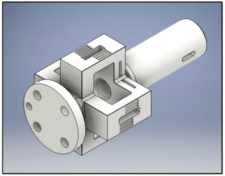


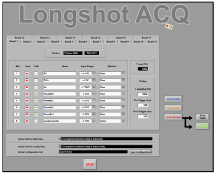












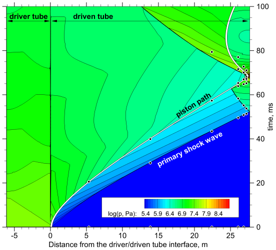
Project overview, details on task 4

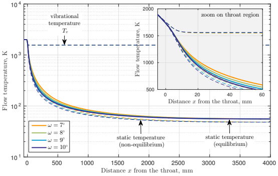
Task 4: *Numerics & data processing*

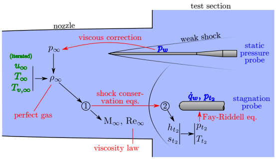
WP4.1 *1D modeling of wind tunnel*

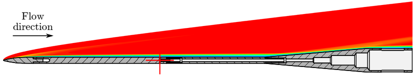
WP4.2 *Nozzle flow modeling*

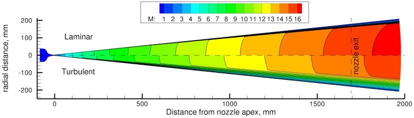
WP4.3 *Free-stream rebuilding*





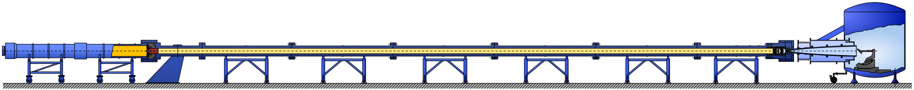






Presentation outline

1. Automation of the wind tunnel
2. Lagrangian modeling of the wind tunnel
3. State-of-the-art flow characterization
4. New Mach 14 contoured nozzle
5. 6-components aerodynamic balance



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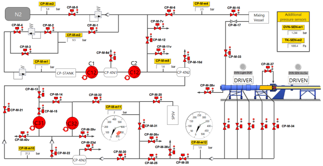
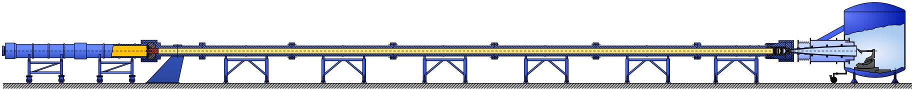


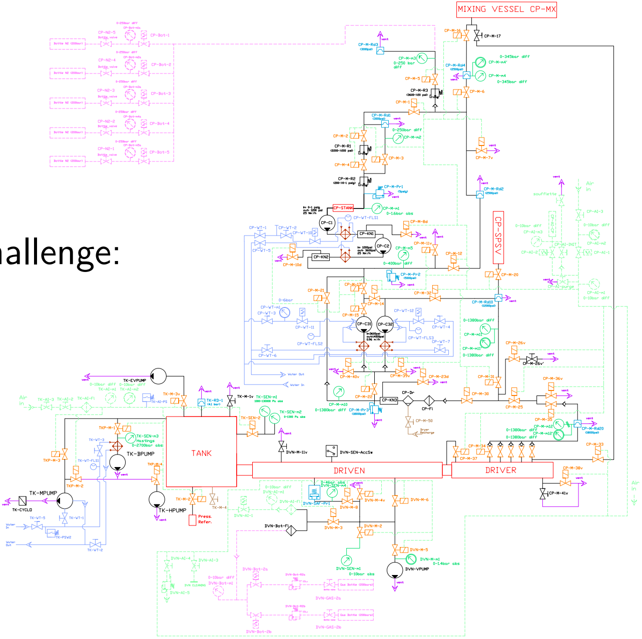


Purposes of an automation system for the Longshot

Objectives

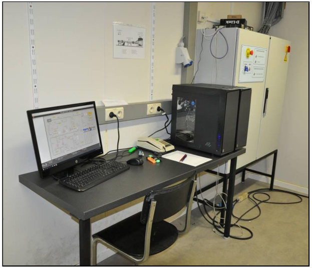
1. Reduce manual interaction
2. Automate full test procedures (“before”, “during” and “after” a run)
3. Automate individual procedures (vacuum phases, leak test...)
4. Increase system awareness (add diagnostics + feedback to operator)
5. Gain efficiency (towards two tests per day)
6. Improve test-to-test repeatability
7. Introduce emergency procedures for enhanced safety

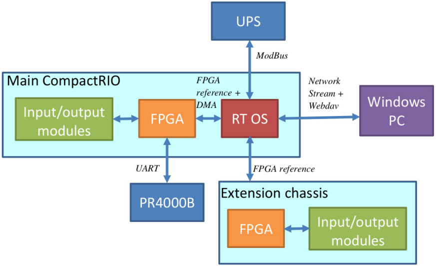
The challenge:

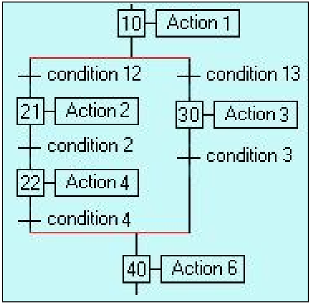


Main characteristics of the automation system

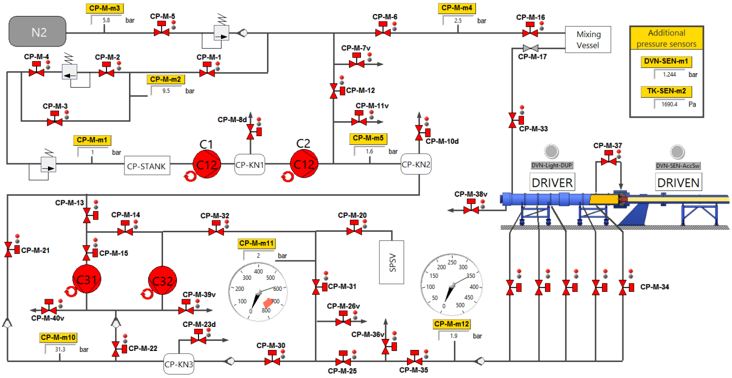
- Automat: CompactRIO technology
- Language: Labview + FPGA
- 1 control station + 2 remote displays
- Interpretation of Sequential Function Charts
- Robust emergency procedures (hard coded)
- For safety: Watchdog, UPS...







User interface, Labview



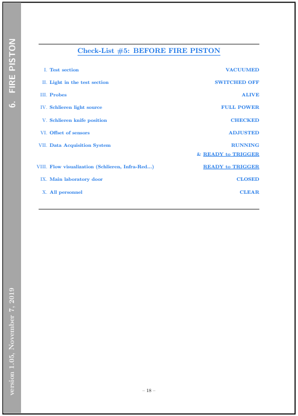
- 2 levels of accreditation: operator / administrator
- 3 modes of operation: real / simulation / manual
- Real time display, on 3 computers
- Automation logs saved for each experiment

Enhanced safety procedures

What if...?

- power cut
- loss of pressurized air
- loss of cooling system
- crash of control system
- early start of the piston
- piston cannot be released
- use of toxic gases
- pressure leak through the piston
- overpressure
- ...

Check-lists introduced


6. FIRE PISTON

Check-List #5: BEFORE FIRE PISTON

I.	Test section	VACUUMED
II.	Light in the test section	SWITCHED OFF
III.	Probes	ALIVE
IV.	Schlieren light source	FULL POWER
V.	Schlieren knife position	CHECKED
VI.	Offset of sensors	ADJUSTED
VII.	Data Acquisition System	RUNNING & READY to TRIGGER
VIII.	Flow visualization (Schlieren, Infra-Red...)	READY to TRIGGER
IX.	Main laboratory door	CLOSED
X.	All personnel	CLEAR

version 1.05, November 7, 2019

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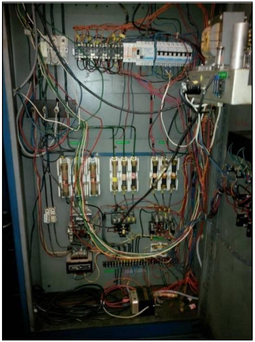
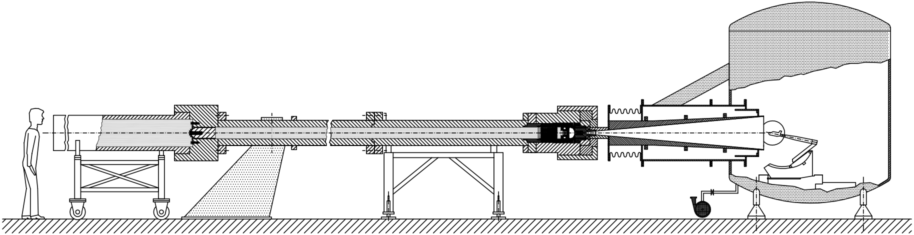
+ Emergency buttons available throughout the lab in case of emergency

Visual summary





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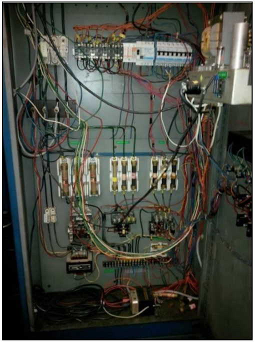
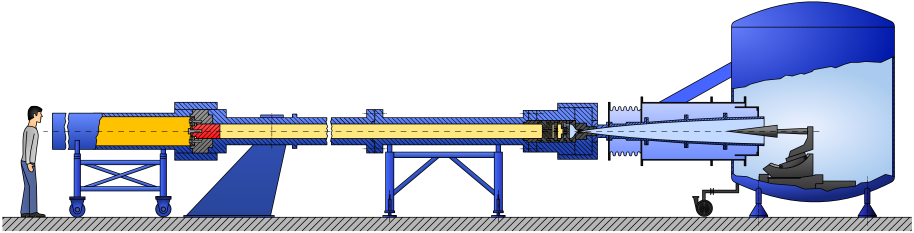




Automation facts

Some numbers...

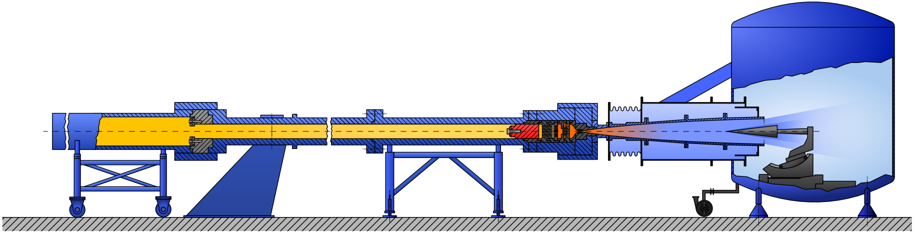
- 225 channels (sensors and actuators)
- over $4\,\mathrm{km}$ of electrical cabling ($+$ from US to European standard)
- over $50\,\mathrm{m}$ of high-pressure tubing
- 37 new high pressure valves
- 13 pressure sensors
- 4 flow switches
- 1 temperature sensor

Summary

Current status

- ✓ Automation system is operational
- ✓ Optimization phase completed
- ✓ Over 60 automated Longshot runs already achieved, many more to go!

→ Longshot operation is safer ✓, easier ✓, faster ✓, more repeatable ✓



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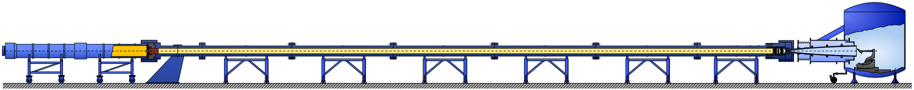

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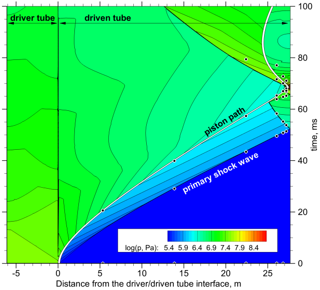
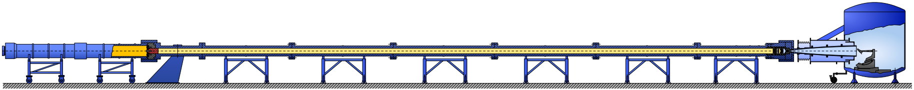


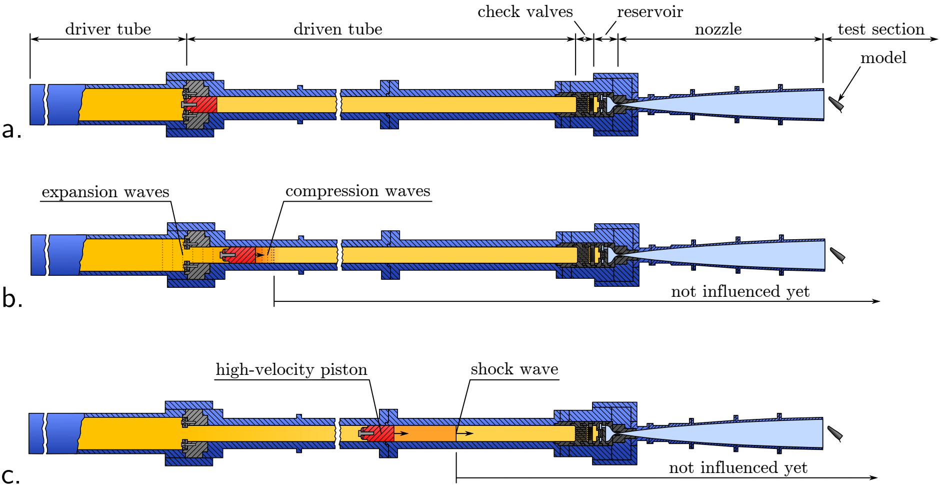


Purposes of the numerical modeling

Objectives

1. Simulate the Longshot compression process numerically
   - Accurately
   - Efficiently: using a simplified quasi-1D geometry
2. Determine sensitivity to initial flow conditions
3. Determine operational maps
4. Evaluate safety margins
   - pressure along tube
   - minimum distance left in front of piston before collision
5. Predict Longshot operation using new conditions
6. Open new perspectives: operate the tunnel with additional test gases

Description of the Longshot compression process



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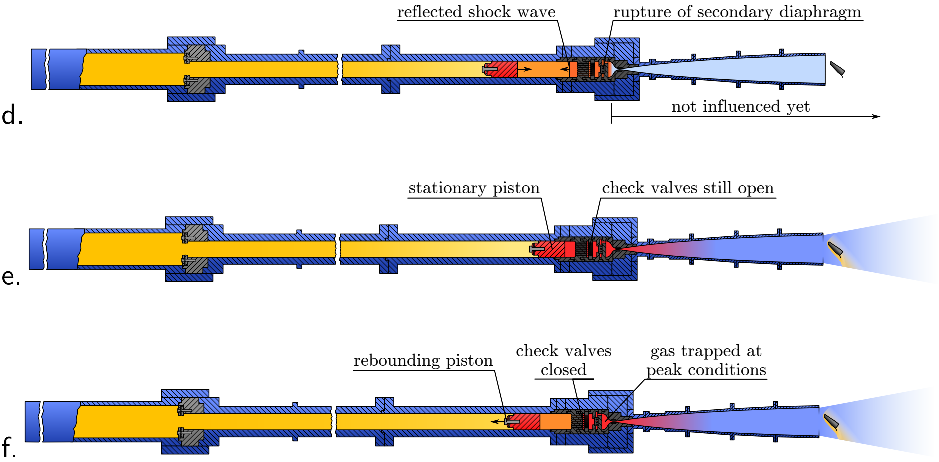
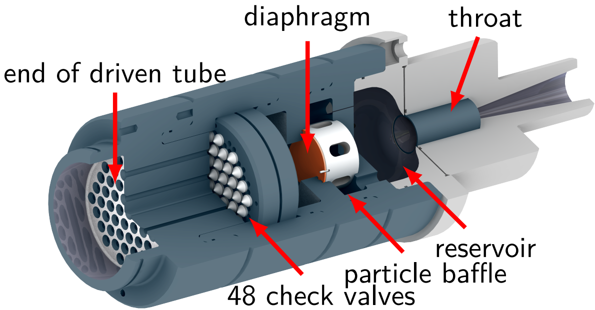
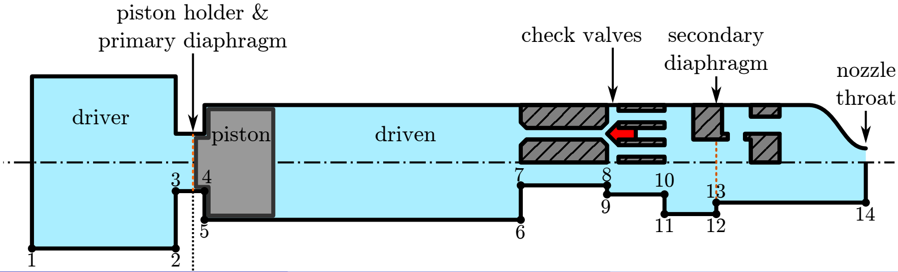


Simplification of the geometry for numerical investigations





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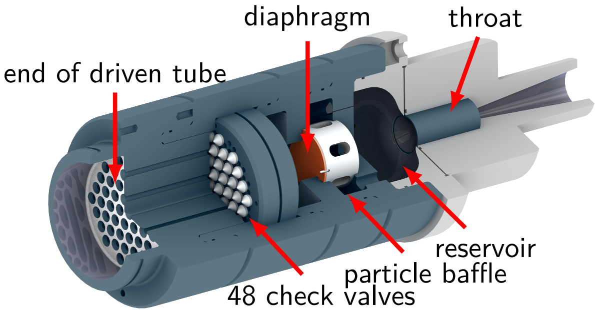
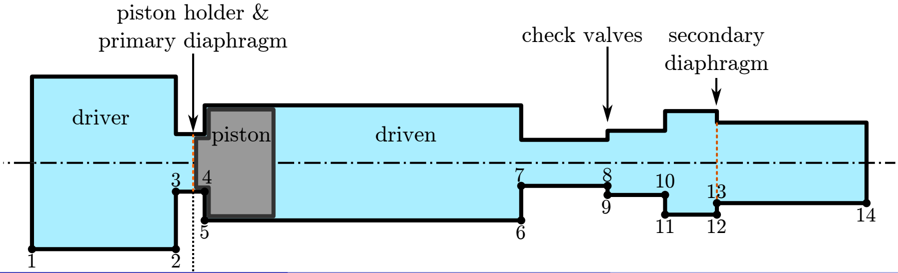




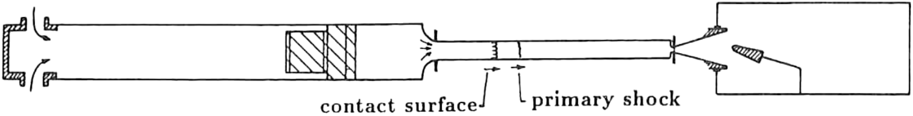
Numerical tool: L1d2

Solver developed by P. Jacobs (Uni. Queensland)

- Quasi-one-dimensional Lagrangian solver
- Second-order accuracy in both space and time
- Robust shock-capturing scheme
- Open source

Successfully applied to different tunnels

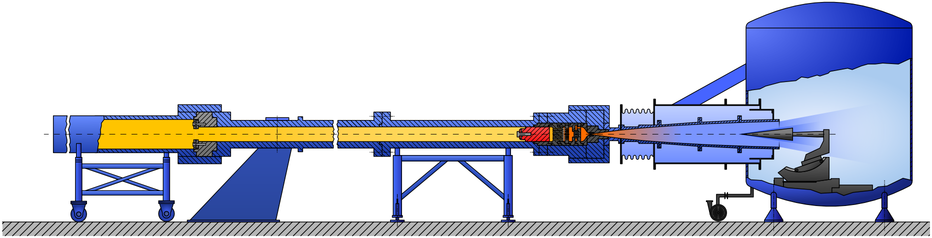
- T4 free-piston shock tunnel (Jacobs, 1994)
- HEG free-piston shock tunnel (Jacobs, 2005)
- T2 free-piston shock tunnel (McGilvray, 2013)



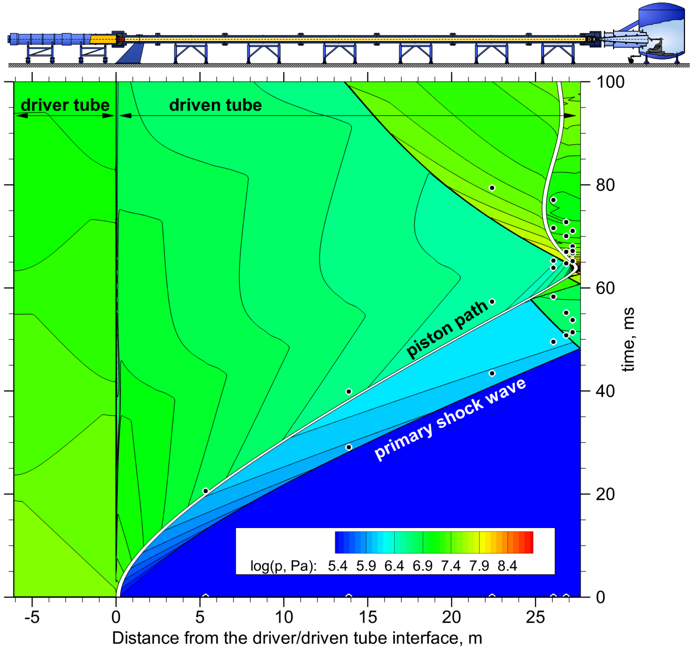
Modeling approach

Decomposition of the problem

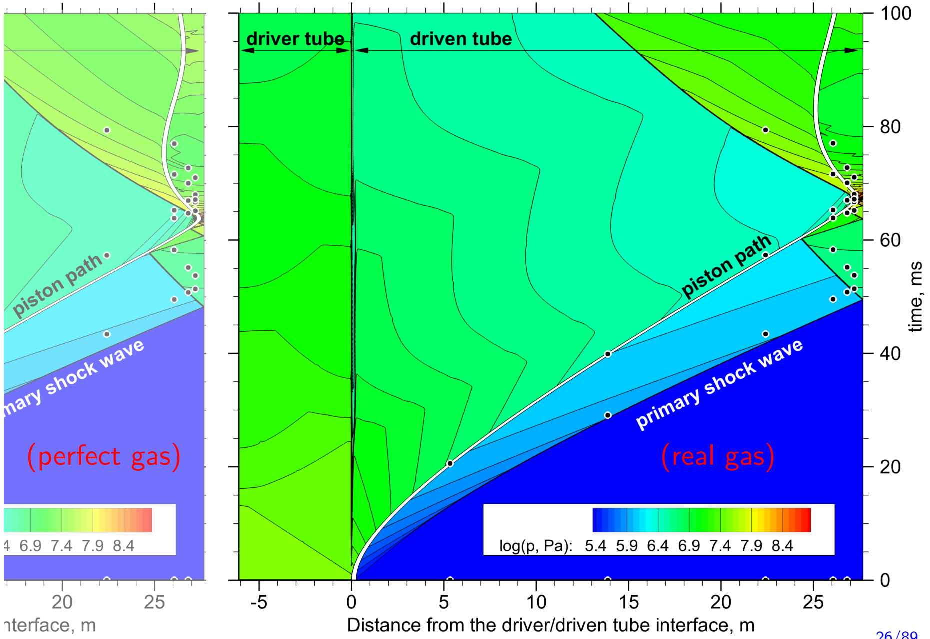
1. Initial part of the compression
   ↳ definition of relevant physical models:
   chambrage, equation of state, viscous effects, bore friction...
2. Final part of the compression
   ↳ inclusion of check valves geometry and calibration of associated losses
3. Use of the numerical model to determine operational maps



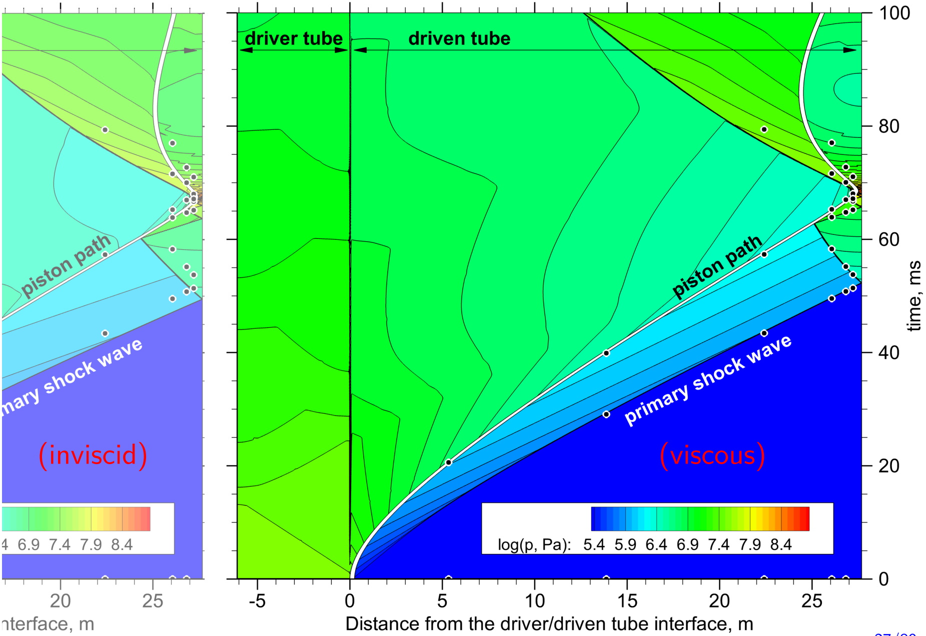
Space-time diagram, Perfect gas



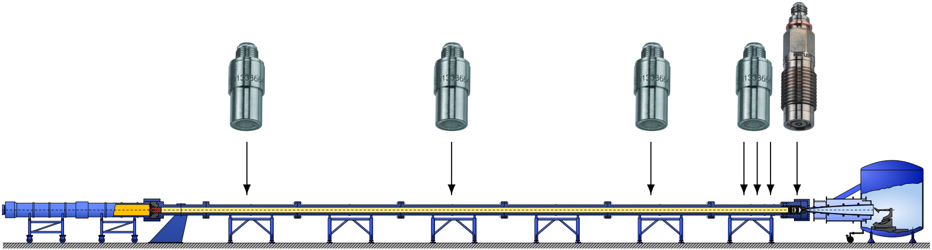
Space-time diagram, improvements with a Real gas



Space-time diagram: improvements with viscous effects



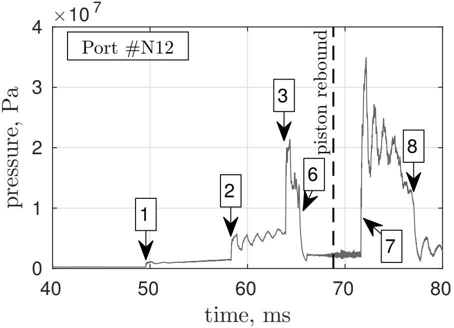
Experimental validation



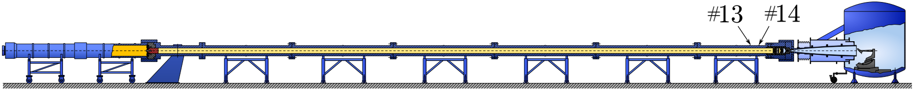
Measurements along driven tube

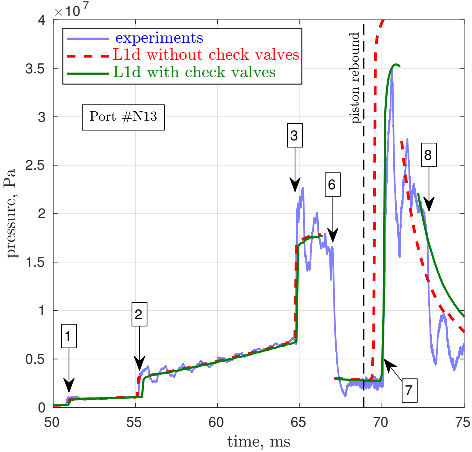
Fast-response high-pressure Kistler sensors used to identify:

- Shock waves
- Reflected shock waves
- Piston passage in front of port

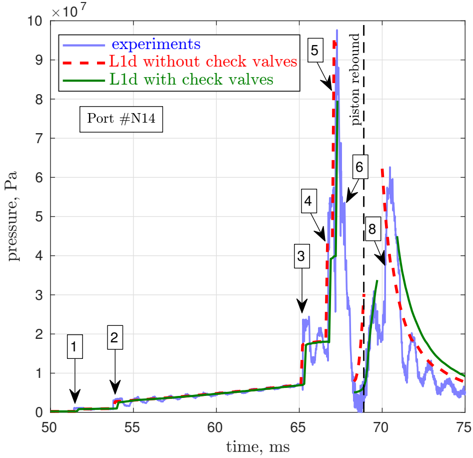


Transient pressure along the tube with/without check valves



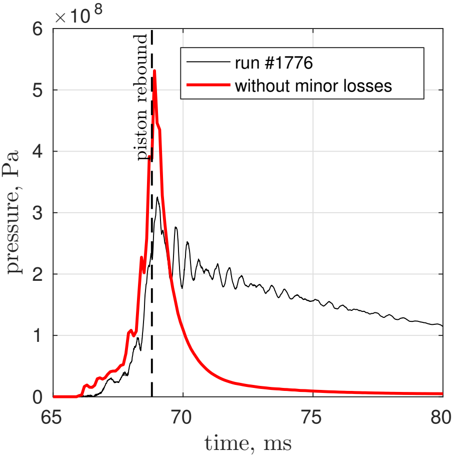


$x = 26.8\,\mathrm{m}$ (port #13)



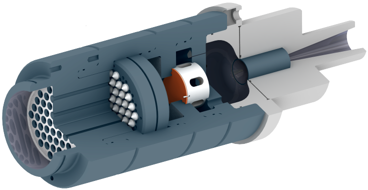
$x = 27.2\,\mathrm{m}$ (port #14)

Prediction of reservoir pressure



Losses through check valves

- Viscous losses modeled but not sufficient
- Minor losses need to be introduced to account for rapid changes of tube cross sections



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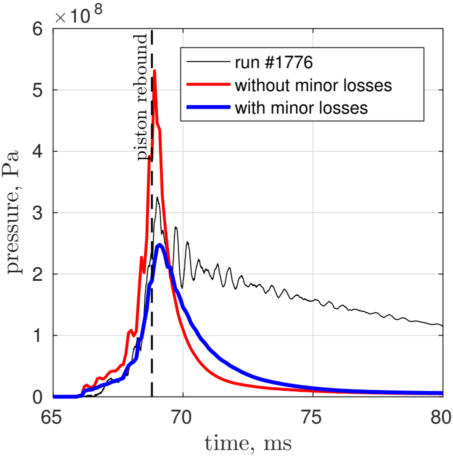

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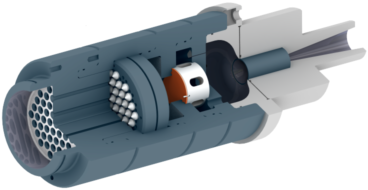
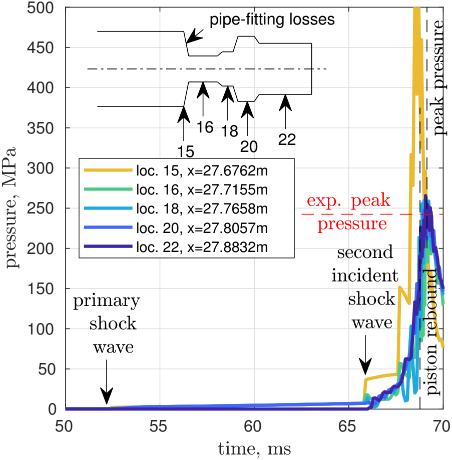
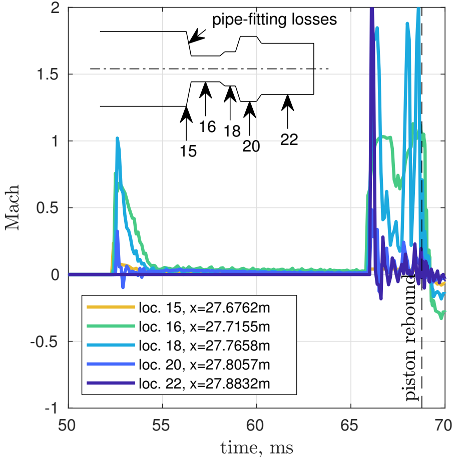
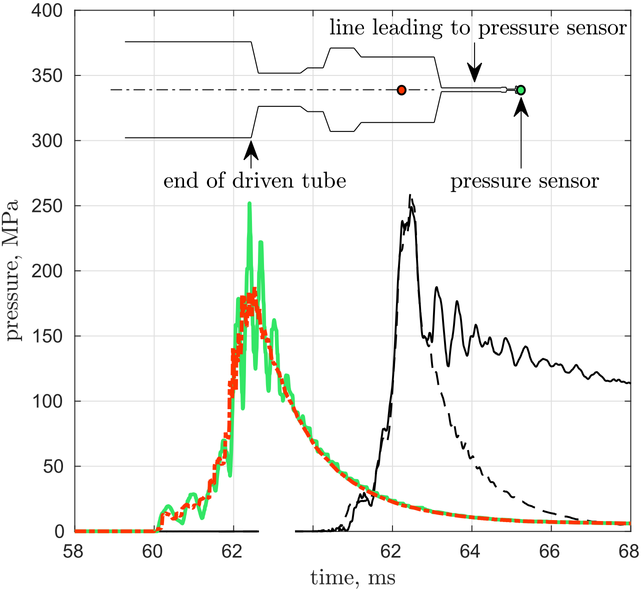


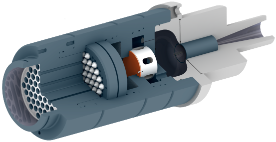
Flow through the check valves





Check valves closure and decay rates





Animation of the Longshot compression process

1-dimensional Lagrangian simulation of the Longshot compression process
Pressure contours (log-scale)

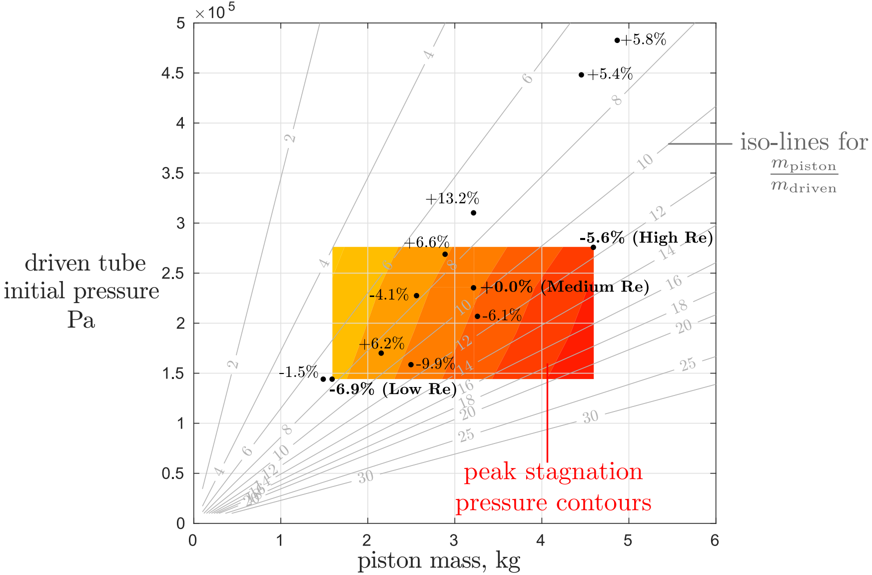
Sensitivities to initial flow conditions

Perturbation of the initial flow conditions...

... and quantification of the influence on the reservoir flow conditions

	Peak pressure p_0	Peak temperature T_0
Reference case	$242.52\,\mathrm{MPa}$	$2215.8\,\mathrm{K}$
$p_{\text{driver}} = 37.95\,\mathrm{MPa}\ (+10\%)$	$\nearrow$ +3.7%	$\nearrow$ +2.8%
$p_{\text{driven}} = 258.94\,\mathrm{kPa}\ (+10\%)$	$\searrow$ -6.4%	$\searrow$ -6.4%
$m_{\text{piston}} = 3.5365\,\mathrm{kg}\ (+10\%)$	$\nearrow$ +11.3%	$\nearrow$ +3.5%
$T_{\text{driver}} = 330\,\mathrm{K}\ (+10\%)$	$\nearrow$ +6.6%	$\nearrow$ +5.4%
$T_{\text{driven}} = 322.3\,\mathrm{K}\ (+10\%)$	$\nearrow$ +4.4%	$\nearrow$ +7.6%

Longshot operational map and prediction accuracy



Summary and perspectives

VKI Longshot modeling using L1d solver (VKI customized)

- Whole Longshot compression process modeled
  ↳ Accounts for chambrage, real gas effects & viscous effects
  ↳ Bore friction negligible
  ↳ Simplified check valves modeling
- Predictions validated with reference experimental data

Main achievements

✓ Sensitivities to initial flow conditions determined

✓ Operational maps determined

✓ New insight, improved understanding of the facility

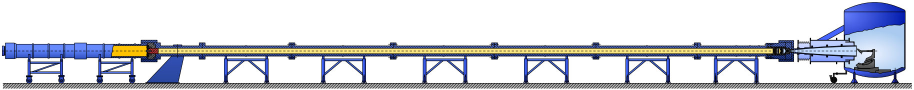
✓ Safer operation whenever using new operating conditions

Perspectives

- Extend modeling to the following nozzle
- Use different gases...

Presentation outline

1. Automation of the wind tunnel
2. Lagrangian modeling of the wind tunnel
3. State-of-the-art flow characterization
4. New Mach 14 contoured nozzle
5. 6-components aerodynamic balance



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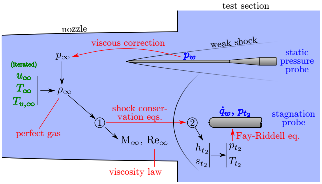
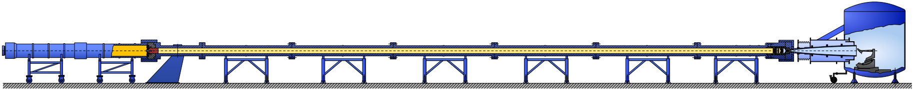




The need for accurate free-stream flow quantities

Similarity parameters with flight conditions

- Free-stream Mach number $\mathrm{M}_\infty = \frac{u_\infty}{\sqrt{\gamma r T_\infty}}$
- Free-stream Reynolds number $\mathrm{Re}_{\infty,L} = \frac{\rho_\infty u_\infty L}{\mu_\infty}$

Non-dimensionalization of experimental data

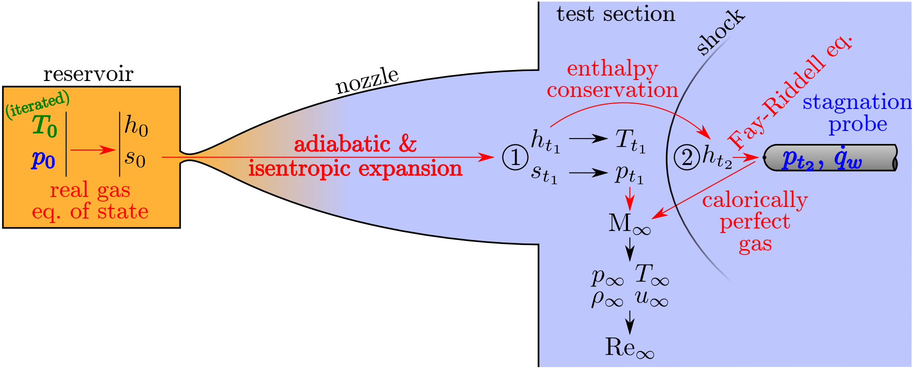
- Wall pressure coefficient $C_p = \frac{p_w - p_\infty}{\frac{1}{2}\rho_\infty u_\infty^2}$
- Wall heat transfer coefficient $St = \frac{\dot{q}_w}{\rho_\infty u_\infty (h_{aw} - h_w)}$
- Aerodynamic coefficients $C_L = \frac{L}{\frac{1}{2}\rho_\infty u_\infty^2 S}$

Purposes of the flow characterization

Objectives

1. Establish new theoretical methods for free-stream rebuilding
2. Develop new flow characterization probes
3. Determine free-stream flow properties
4. Validate predictions with independent measurement techniques
5. Quantify uncertainties on free-stream flow properties

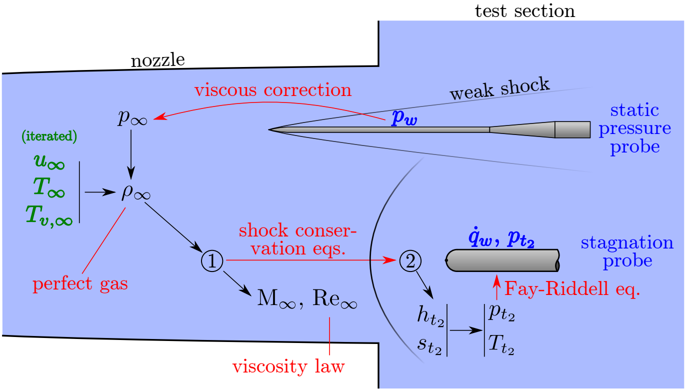
The regular flow characterization approach, its drawbacks



Drawbacks

- Requires elaborated equations of state
- Subject to severe assumptions (ideal nozzle expansion)
- Calorically perfect gas in the stagnation point region

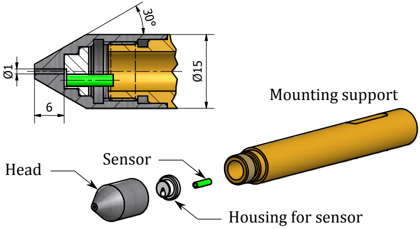
The improved flow characterization approach, its advantages

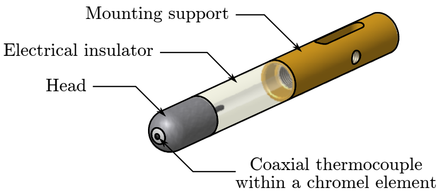


Advantages

- No need for elaborated equations of state
- No assumptions about the nozzle flow
- Rigorously solves shock conservation equations, including high-temperature effects

Existing probes, optimized designs





Pitot pressure probe

- Slender head design
  ↳ minimizes influence of flow pollutants on measurements
- Minimized internal cavity
  ↳ optimizes response time
- Sensor offset from probe axis
  ↳ Better protection of the sensor

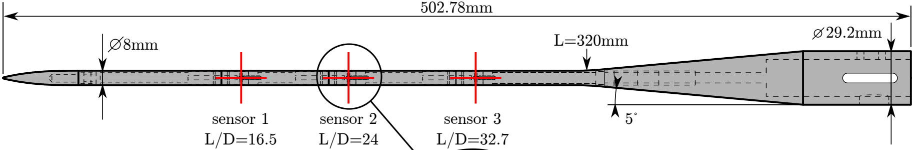
Stagnation point heat flux probe

- Smaller diameter
  ↳ larger heat flux
  ↳ enhanced sensitivity
- Plain thermocouple + Chromel insert
  ↳ 1D heat flux ensured through the probe

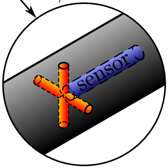
New probes for free-stream static pressure measurements

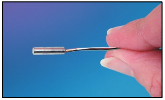
Challenges

- Low static pressures: $< 1000\,\mathrm{Pa}$
- Short test times: $20\,\mathrm{ms}$
- Transient variations during a test



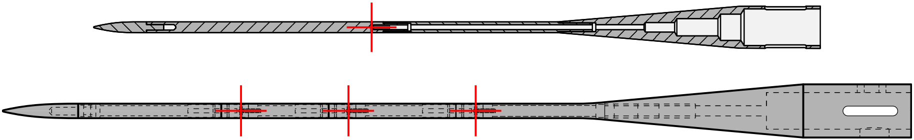
contoured nosetip





Kulite sensor

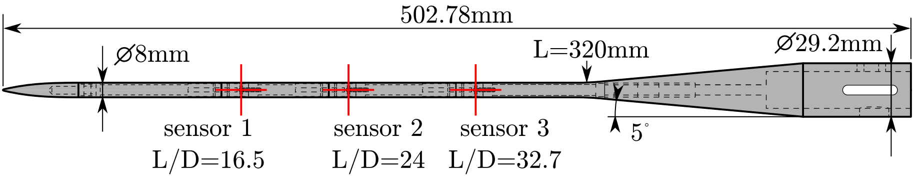
New probes for free-stream static pressure measurements



Characteristics of the probes

- Embedded instrumentation → optimizes response time
- Absolute pressure measurement → accurate even at low pressure
- Contoured nosetip → minimizes influence on measurements
- Shallow opening angle → avoids upstream influence of flow separation
- 3 instrumented locations along large probe → quantify viscous effects
- 4 taps for each location → reduces influences to flow misalignment

Static pressure measurements appear robust

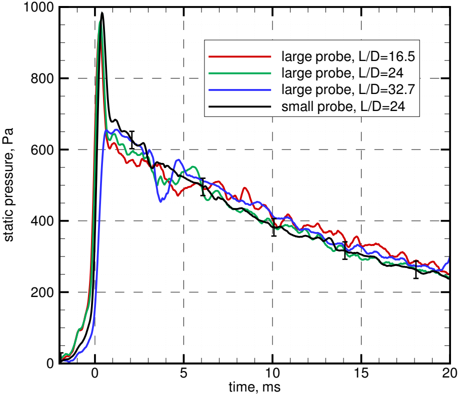


Viscous effects: weak influence along small and large probes

Instrumentation: different pressure sensors do not reveal any bias

Angle of attack of the probe: negligible influence for $\alpha < 0.33^\circ$

Probing hole geometries (straight or chamfered): negligible influence



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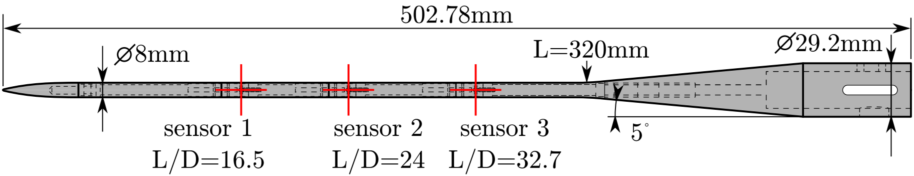

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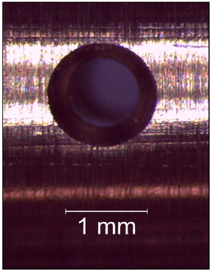
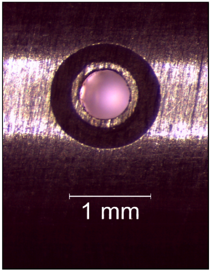
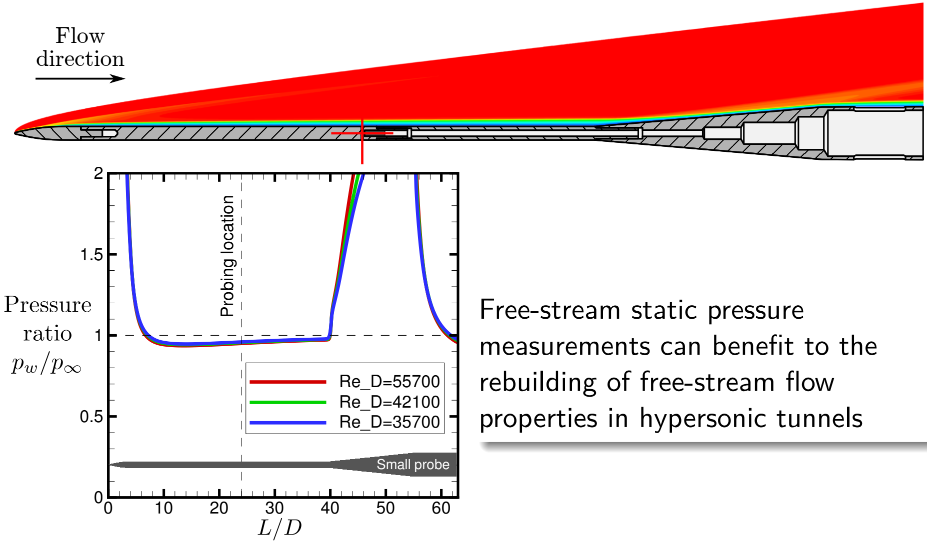




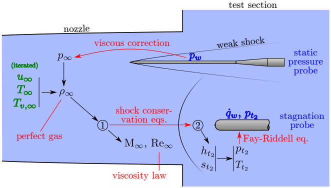
Weak viscous effects along the probe

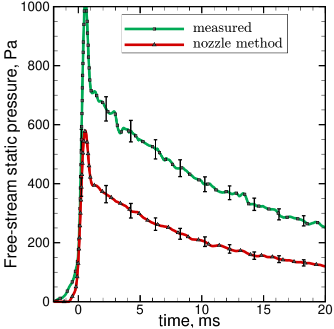


Free-stream static pressure measurements can benefit to the rebuilding of free-stream flow properties in hypersonic tunnels

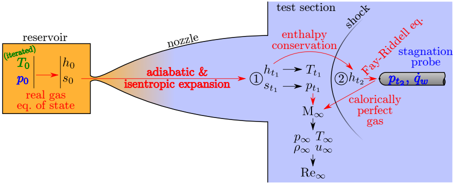
Comparing measurements against theory

Free-stream method





Nozzle method



Failure of the nozzle method:

- Underpredict p_∞
- Underpredict T_∞
- Overpredict M_∞ and Re_∞

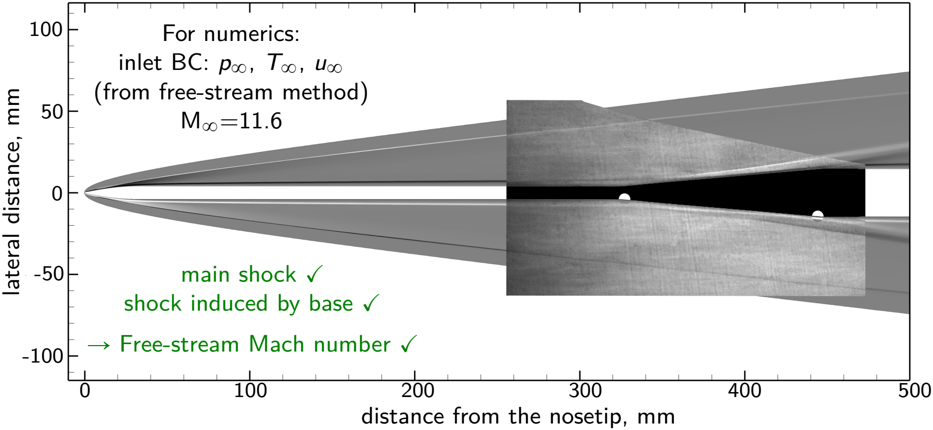
Predictions from free-stream method:

✓ Validated by independent measurement techniques

Validating free-stream Mach number using schlieren

Comparison between experiments and numerics

- Experimental flow visualization (Schlieren)



Summary

Longshot free-stream flow characterization

- 3 probes: Pitot, stagnation point heat flux, free-stream static pressure
- Free-stream rebuilding method:
  ↳ *accurately solves shock conservation equations*
  ↳ *accounts for high temperature effects (vibrational excitation)*
  ↳ *applicable to other test gases*
  → *potentially applicable to other hypersonic facilities*

Cross-checks on free-stream flow properties:

✓ Free-stream Mach number → *using Schlieren flow visualization*

✓ Free-stream static temperature → *via flow condensation experiments*

✓ Free-stream Reynolds number
✓ Free-stream velocity
$\Big\}$ → *via BLT investigations*

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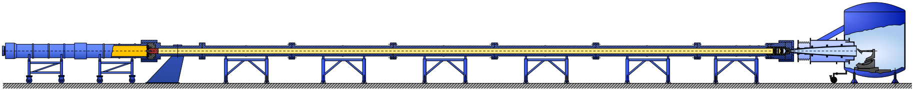

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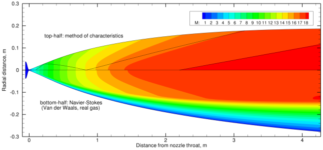
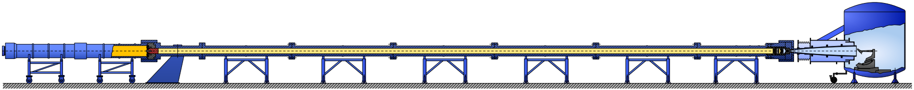




Purposes of the activity

ESA requirements

- Bring back the Longshot wind tunnel with Mach 14 capabilities

Objectives

1. Implement a methodology to design axisymmetric contoured nozzles
2. Account for real gas effects
3. Identify optimum nozzle design (parametric studies)
4. Manufacture the nozzle, instrument it
5. Run experiments and characterize the hypersonic flow

New tool: code for axisymmetric hypersonic nozzle design

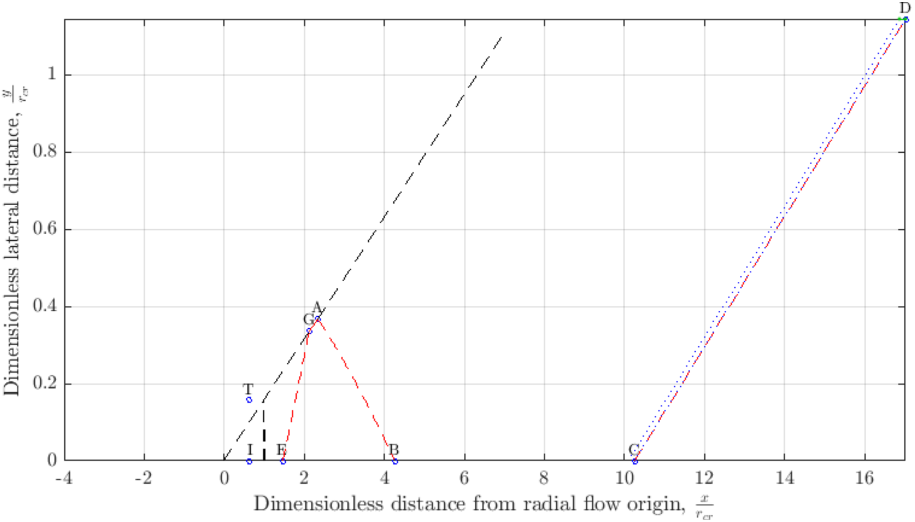
Main features of the code

- Handles Perfect gas/Real gas (via tabulated EoS) ✓
- Designs subsonic contour ✓
- Designs transonic contour ✓
- Designs supersonic/hypersonic contours (method of characteristics)✓
- Corrects for viscous effects ✓
- Optimizes nozzle length for maximum core flow diameter ✓
- Exports inviscid meshes towards numerical solvers ✓
- Includes graphical output ✓
- Accepts scripts for parametric studies ✓

Performances

- 1 design (using fine meshes) $< 1\,\mathrm{min}$

Nozzle design, illustration step by step



Inviscid nozzle design using the method of characteristics

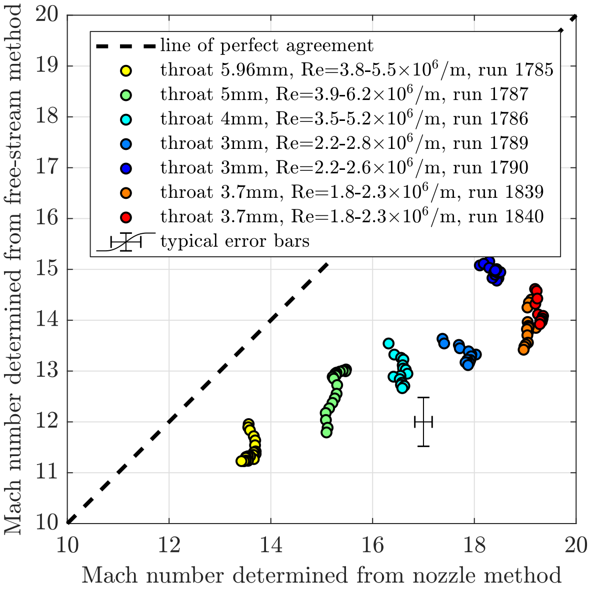
New Longshot Mach 14 nozzle

- Gas is pure nitrogen + follows a real gas equation of state (dense gas effects and high-temperature effects are accounted for)
- 6^{th} order polynomial for the convergent (reservoir volume matches existing configurations)
- Parabolic arc for the transonic region
- 5^{th} order velocity/Mach number polynomials along segments IE and BC, method of characteristics used to infer the corresponding contour

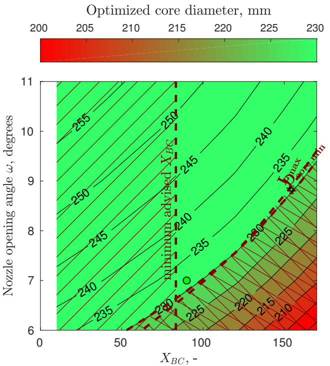
Improvement with respect to earlier design

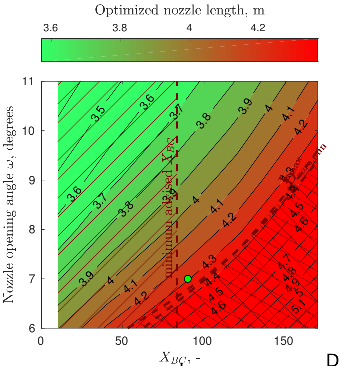
1. ✓ No more discontinuities on the first derivative of the contour
2. ✓ Better transonic design: coherent with Hall's theory
3. ✓ Longer segment AJ: avoids coalescence of compression waves
4. ✓ Second order accuracy on the method of characteristics

Definition of the design Mach number

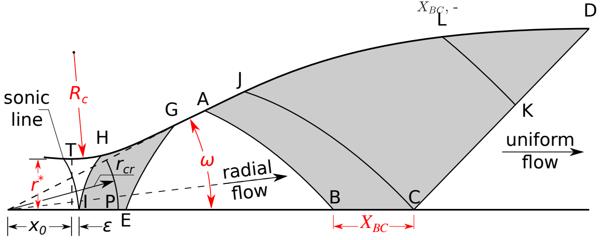


Identification of optimum design: parametric studies





- $p_0 = 166\,\mathrm{MPa}$
- $T_0 = 2400\,\mathrm{K}$
- $\omega = 7^\circ$
- $X_{BC} = 90$
- $d^* = 3.7\,\mathrm{mm}$
- $R_c = 30\frac{d^*}{2}$



Summary of the design parameters

The following initial conditions for the Longshot tunnel:

- driver tube pressure: $p_{driver} = 345 \times 10^5\,\mathrm{Pa}$
- driven tube pressure: $p_{driven} = 1.586 \times 10^5\,\mathrm{Pa}$
- piston mass: $m_{piston} = 2.5\,\mathrm{kg}$

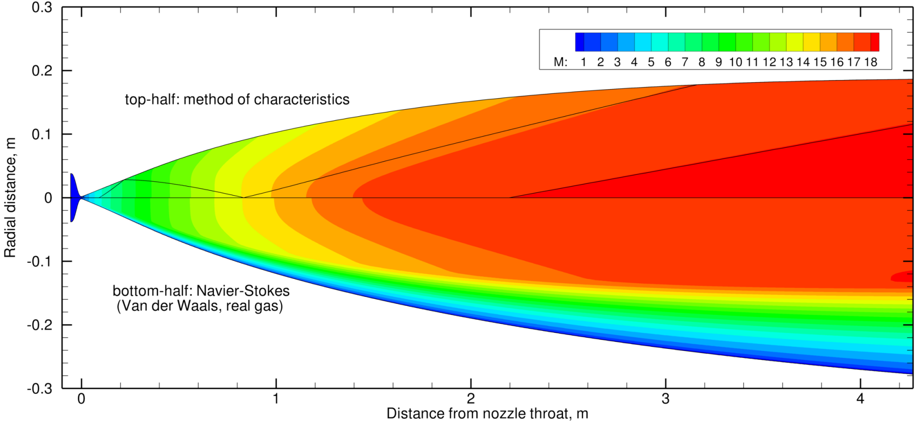
... compress the test gas up to the following reservoir flow conditions:

- stagnation pressure: $166\,\mathrm{MPa}$
- stagnation temperature: $2400\,\mathrm{K}$

... which enable to reach Mach 14 in a condensation free environment.

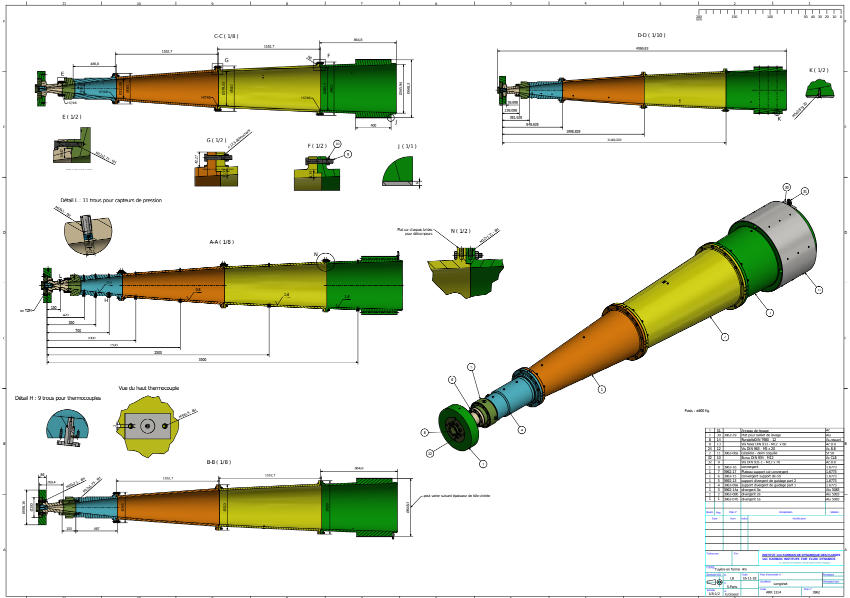
Numerical simulations

Flow Mach number:



Good agreement between inviscid predictions (top, issuing from the method of characteristics) and Navier-Stokes ones (bottom)

Technical drawings

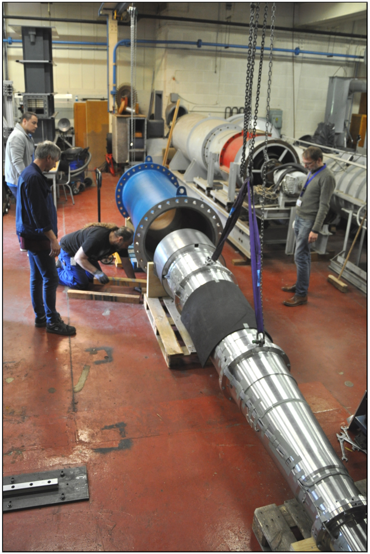


Nozzle manufacturing

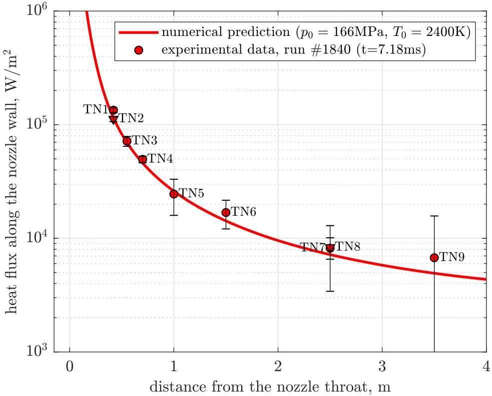
Nozzle throat: Titanium-Zirconium-Molybdenum alloy (TZM)
Other pieces: either Steel 36NiCrMo16 (close to the throat), or Alu 5083 (for the downstream sections)

Nozzle installation

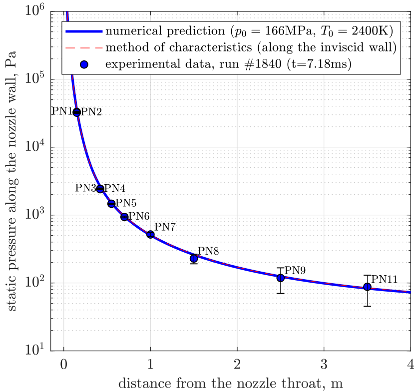
Overall nozzle length: 4.06 m
Exit diameter: 541 mm
Total weight: $\approx$ 600 kg



Measurements along the new nozzle

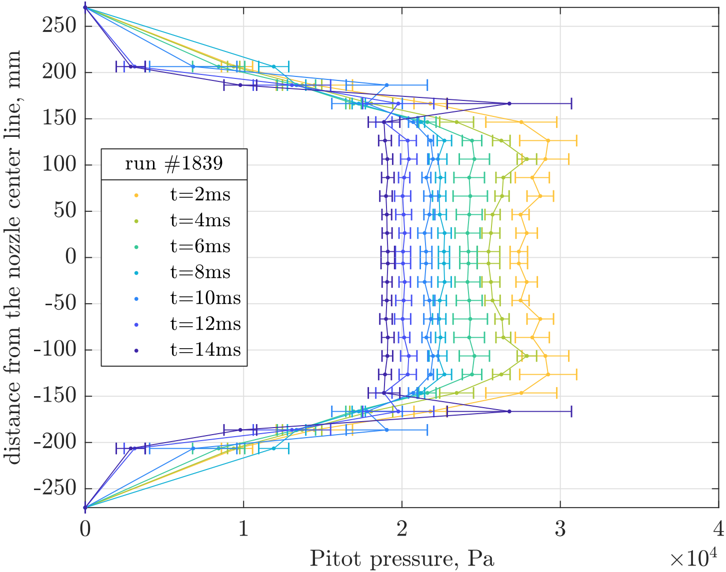


Wall heat flux measurements

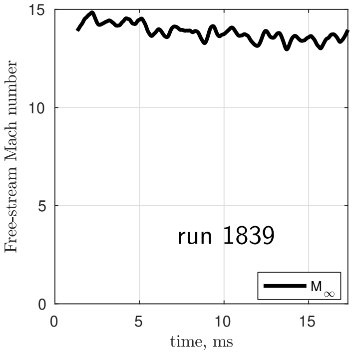


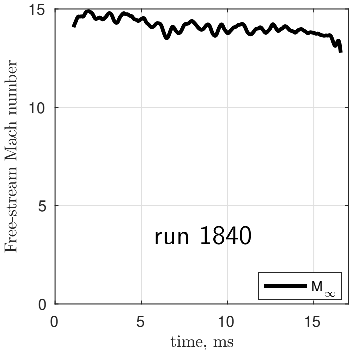
Wall pressure measurements

Flow uniformity across the new nozzle

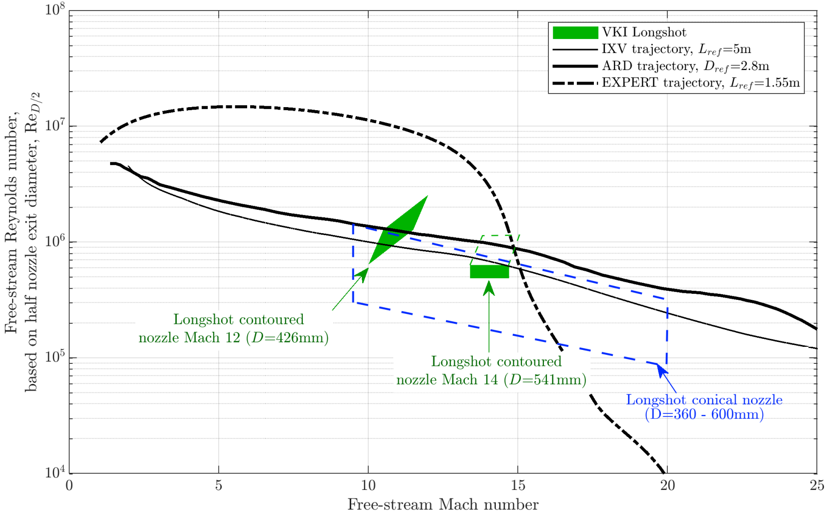


Free-stream Mach number





Longshot operational map



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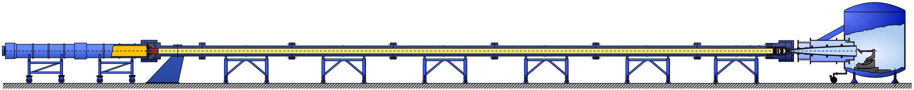

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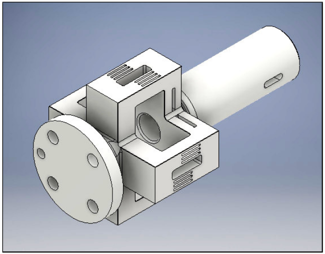
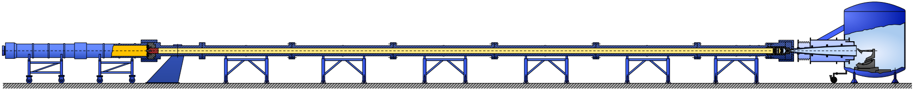




Objectives

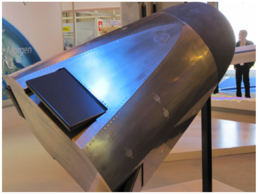
Objective: enable aerodynamic measurements on reentry capsules

1. Range definition for the 6 components balance
2. Design of the balance
3. Numerical calibration of the balance
4. Real calibration of the balance
5. Test in the Longshot tunnel

Definition of the range for the balance

Apollo	CD	1.6
	CL	0.6
	Cy	0.25
	Cmy	0.1
	Cmx	0.02
	Cmz	0.03

Expert	CD	0.4	
	CL	0.25	@10deg
	Cmy	0.08	@8 deg
	Cmx		

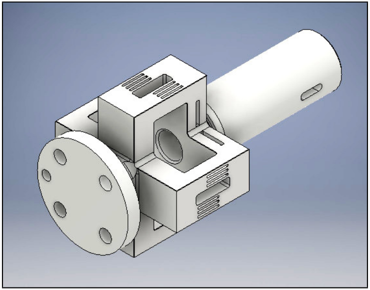


	From database	safety factor	Design range	
Fx	1800	1.5	2700	N
Fy	450	1.5	700	N
Fz	700	1.5	1050	N
Mx	3	1.5	4.5	Nm
My	15	1.5	22.5	Nm
Mz	15	1.5	22.5	Nm

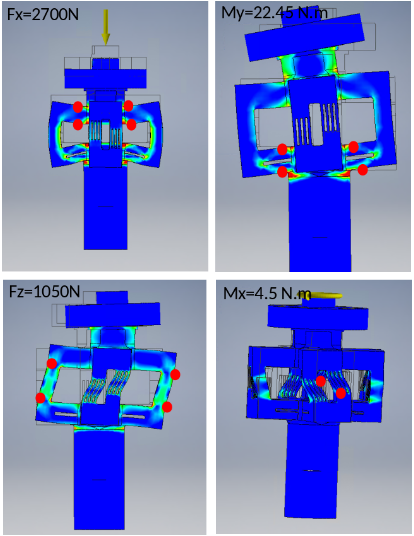
Design of the balance

Characteristics

- 6 components
- Small size: $40 \times 40 \times 24\,\mathrm{mm}^3$
- Model interface with angular positioning
- Sting interface with angular positioning
- Cables are passing inside the sting



Finite element method



The finite element method was used for:

- Optimization of the geometry
- Location of the strain gauges
- Virtual calibration
- Limitation of the interferences

Virtual calibration

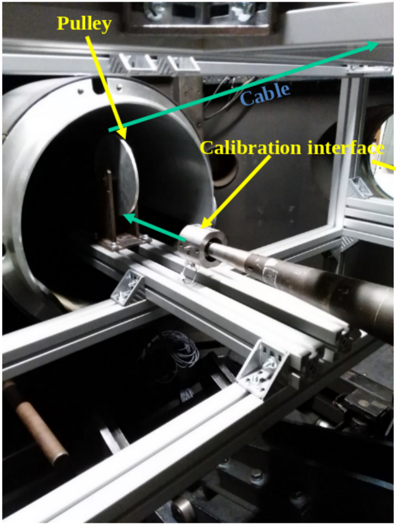
Finite element method is used to compute the stresses at the strain gauge locations for pure forces and moments

σFx		265.9	0	-0.5	-1	3.4	0.5		Fx
σFy		0.15	312.9	-0.1	8	-0.04	-154.7		Fy
σFz	=	0.3	0.1	259.4	23.1	160.2	0.07	*	Fz
σMx		-0.05	2.24	1.25	174.16	0.3	-1.94		Mx
σMy		-0.3	-0.1	2.3	-43.3	265	0.13		My
σMz		0	-3.3	-0.2	53.7	0.1	268.1		Mz

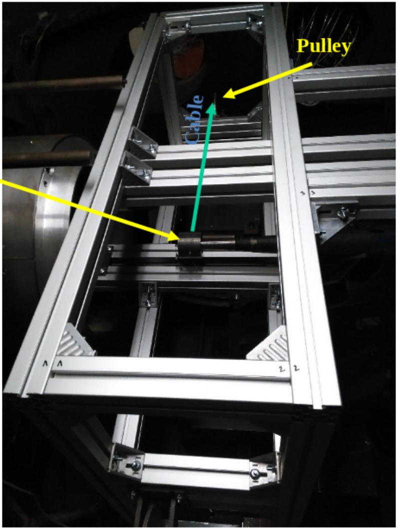
Inverted matrix allows to find the forces and moments from the stresses

Fx		10.15401	-0.00530	-0.01953	0.00309	0.01217	-0.00070		σFx
Fy		-0.00017	3.38164	0.00611	-0.04297	-0.00582	0.05024		σFy
Fz	=	0.00805	0.00648	4.07517	-0.02916	-0.04013	0.00898	*	σFz
Mx		0.00004	-0.00324	-0.00494	0.02585	0.00427	-0.00522		σMx
My		-0.00119	-0.00007	-0.05264	0.00023	0.08521	-0.00012		σMy
Mz		-0.00016	0.04160	-0.00010	0.00040	0.00004	0.08417		σMz

Real calibration

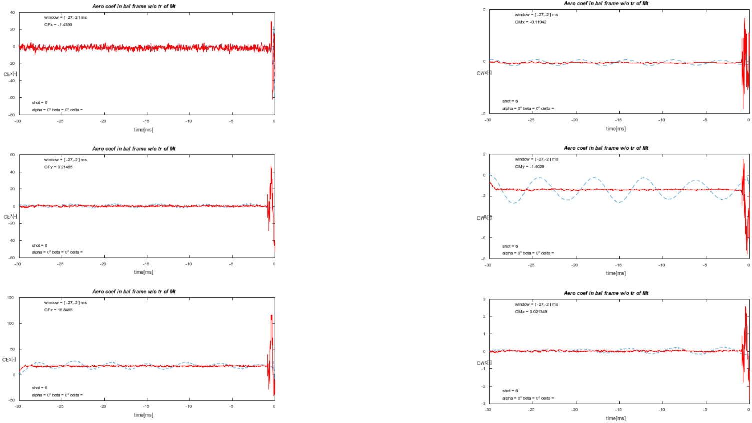


View from the back



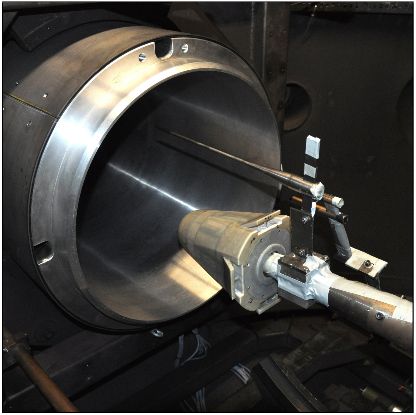
View from the top

Real calibration



Components	Approximative input	From the balance
Fz	16.71 N	16.85 N
Fx	1.46 N	1.44 N
My	1.42 Nm	1.40 Nm

Longshot tests

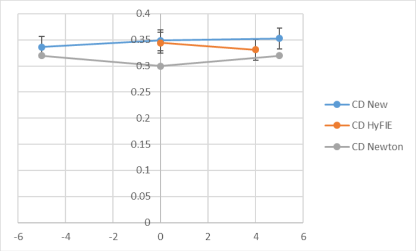


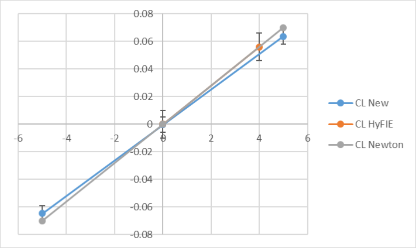
3 Longshot tests performed at Mach 14

- Balance installed at CG (58% from the nose)
- 6 accelerometers in the model
- 2 accelerometers on the sting
- Model made of resin by 3D printing
- Pressure transducer at nose tip

Longshot tests

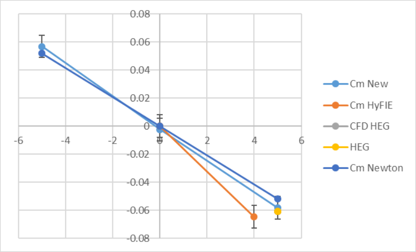
Comparison with data from HyFIE





Present results

	1841	1842	1843
AoA	0	5	-5
CD	0.3489	0.353	0.33634
Cya	-0.0033	-0.00466	0.0043
CL	-0.00049	0.0636	-0.0647
Cla	-4.00E-05	0.000526	0.00015
Cma	-0.00241	-0.0582	0.0569
Cna	0.003	0.00391	0.00123

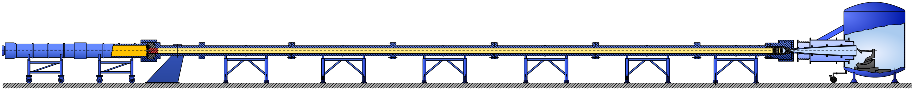


Summary

- Balance was successfully designed, build and instrumented
- Numerical calibration shows good behavior
- Real calibration confirms the good behavior
- Application of an impulse force can be measured with a good accuracy
- Tests were performed. Results are very close to the reference

Presentation outline

1. Automation of the wind tunnel
2. Lagrangian modeling of the wind tunnel
3. State-of-the-art flow characterization
4. New Mach 14 contoured nozzle
5. 6-components aerodynamic balance



Summary

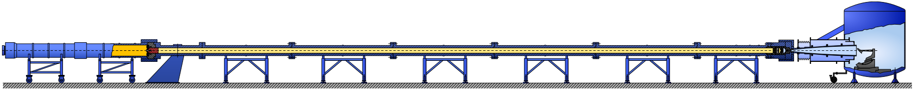
General summary

3 main axes of investigations:

1. Hardware / wind tunnel development
(wind tunnel automation, design new hypersonic nozzle...)

2. Measurement techniques and methodologies
(new flow diagnostic techniques, new aerodynamic balance...)

3. Numerical support, data processing, Uncertainty Quantification
(wind tunnel modeling, modeling of nozzle flow expansion, free-stream rebuilding...)



General summary

The greatest Longshot adventure ever written...

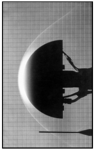
- 21 Technical Notes
  ↳ *TN3200, TN3300 & TN5000 uploaded*
- over 1400 pages
- over 900 figures
- over 250 equations
- over 50 tables

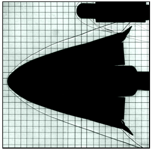
General summary

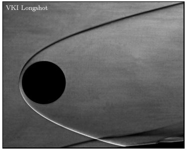
Main achievements

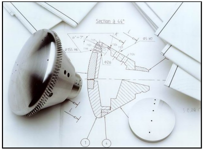
- ✓ **Highest Mach/Reynolds numbers** achievable across Europe
- ✓ **Modernized wind tunnel** for improved safety, efficiency, repeatability
- ✓ **Well-characterized free-stream environment**
  - ↳ *recommended methodology for other hypersonic facilities*
- ✓ **New numerical tools to plan future investigations**
- ✓ **Hypersonic VKI expertise** strengthened

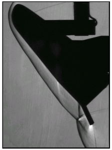
→ **Ready to support future missions**
from the European Space Agency









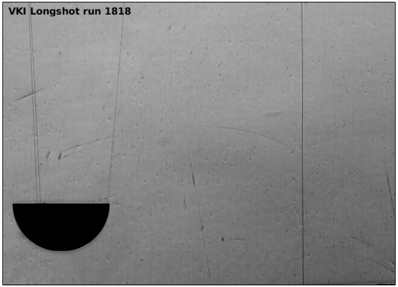


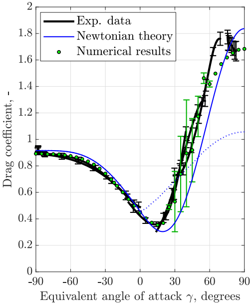
Future and perspectives

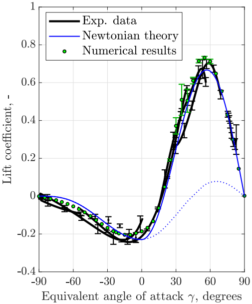
Suggestions

- Aerothermodynamics of reentry vehicles, space debris, rockets...
- Reach higher Reynolds, higher enthalpies in the Longshot
- Use different test gases (Mars, Venus, Ice giants...)

→ **What else do you have in mind?**







List of publications 1/2

Contributions to books

- G. Grossir & Z. Ilich "*Numerical modeling of the VKI Longshot compression process*", VKI Lecture Series 2018/19 [1]
- G. Grossir & B. Dias "*Flow characterization of the VKI Longshot wind tunnel*", VKI Lecture Series 2018/19 [2]

Journal articles

- G. Grossir, B. Van Hove, S. Paris, P. Rambaud & O. Chazot "*Free-stream static pressure measurements in the Longshot hypersonic wind tunnel and sensitivity analysis*" Experiments in Fluids, 2016, **57**, 1-13 [3]
- G. Grossir, B. Dias, O. Chazot & T. E. Magin, "*High temperature and thermal non-equilibrium effects on the determination of free-stream flow properties in hypersonic wind tunnels*", Physics of Fluids, 2018, **30**, 1-13 [4]

List of publications 2/2

Conference papers

- G. Grossir, Z. Ilich, S. Paris. & O. Chazot "*Theoretical considerations to extend the operational map of the VKI Longshot hypersonic wind tunnel*" AIAA paper 2016-3818 [5]
- Z. Ilich, G. Grossir & O. Chazot "*Evaluation of the stagnation-point velocity gradient in low-enthalpy hypersonic flows*" AIAA paper 2017-3984 [6]
- Z. Ilich, G. Grossir, S. Paris & O. Chazot "*Experimental investigations of the VKI Longshot gun tunnel compression process*" EUCASS 2017 [7]
- G. Grossir, Z. Ilich & O. Chazot "*Modeling of the VKI Longshot gun tunnel compression process using a quasi-1D approach*" AIAA paper 2017-3985 [8]

Technical reports

- T. Wammen "*Investigating a Photonic Doppler Velocimeter to characterize the Longshot hypersonic wind tunnel piston trajectory*", VKI TN 219, 2018 [9]
- T. Wammen "*Investigating high driven gas temperatures in the VKI Longshot hypersonic wind tunnel*", VKI TN 220, 2018 [10]
- T. Wammen "*Investigating high driver gas pressures in the VKI Longshot hypersonic wind tunnel*", VKI TN 221, 2018 [11]

Laboratory documentation

- A. Marchal-Marchant, S. Paris & G. Grossir "*Longshot Procedures*", 2018 [12]

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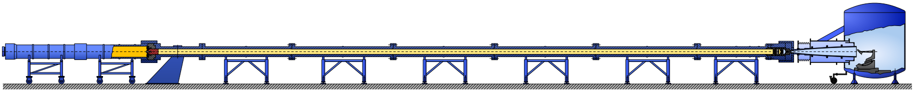
- Jose Longo
- Guillermo Ortega



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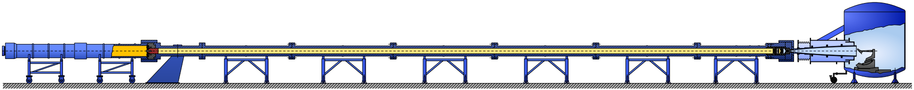
- B. Dias & A. Munafò *(nozzle flow modeling)*
- A. Marchal-Marchant *(Longshot automation)*
- R. Vostes & P. Cuvelier *(electronic support)*
- K. Bensassi *(L1d numerical modeling)*
- P. Danneels *(Longshot operator)*
- VKI workshop
- VKI staff



[1] G. Grossir and Z. Ilich. Numerical modeling of the VKI Longshot compression process. In O. Chazot and G. Grossir, editors, Flow characterization and modeling of hypersonic wind tunnels, volume VKI Lecture Series 2018/19, chapter 2. von Karman Institute for Fluid Dynamics, December 2018.

[2] G. Grossir and B. Dias. Flow characterization of the VKI Longshot wind tunnel. In O. Chazot and G. Grossir, editors, Flow characterization and modeling of hypersonic wind tunnels, volume VKI Lecture Series 2018/19, chapter 3. von Karman Institute for Fluid Dynamics, December 2018.

[3] G. Grossir, B. Van Hove, S. Paris, P. Rambaud, and O. Chazot. Free-stream static pressure measurements in the Longshot hypersonic wind tunnel and sensitivity analysis. Experiments in Fluids, 57(64):1–13, May 2016.

[4] G. Grossir, B. Dias, O. Chazot, and T. E. Magin. High temperature and thermal non-equilibrium effects on the determination of free-stream flow properties in hypersonic wind tunnels. Physics of Fluids, 30(126102):1–13, December 2018.

[5] G. Grossir, Z. Ilich, S. Paris, and O. Chazot. Theoretical considerations to extend the operational map of the VKI Longshot hypersonic wind tunnel. In 32nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, number AIAA paper 2016-3818, June 2016.

[6] Z. Ilich, G. Grossir, and O. Chazot. Evaluation of the stagnation-point velocity gradient in low-enthalpy hypersonic flows. In 33rd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, number AIAA paper 2017-3984, June 2017.

[7] Z. Ilich, G. Grossir, S. Paris, and O. Chazot. Experimental investigations of the VKI Longshot gun tunnel compression process. In EUCASS, number 155, July 2017.

[8] G. Grossir, Z. Ilich, and O. Chazot. Modeling of the VKI Longshot gun tunnel compression process using a quasi-1D approach. In 33rd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, number AIAA paper 2017-3985, June 2017.

[9] T. Wammen. Investigating a Photonic Doppler Velocimeter to characterize the Longshot hypersonic wind tunnel piston trajectory. Technical Report VKI TN 219, von Karman Institute for Fluid Dynamics, June 2018.

[10] T. Wammen. Investigating high driven gas temperatures in the VKI Longshot hypersonic wind tunnel. Technical Report VKI TN 220, von Karman Institute for Fluid Dynamics, June 2018.

[11] T. Wammen. Investigating high driver gas pressures in the VKI Longshot hypersonic wind tunnel. Technical Report VKI TN 221, von Karman Institute for Fluid Dynamics, June 2018.

[12] A. Marchal-Marchant, S. Paris, and G. Grossir. Longshot procedures. August 2018.