von KARMAN INSTITUTE
FOR FLUID DYNAMICS

Turbo Expo 2023
Turbomachinery Technical Conference & Exposition

Adaptation of VKI's isentropic compression tube facility for High-Speed Low-Pressure Turbines testing

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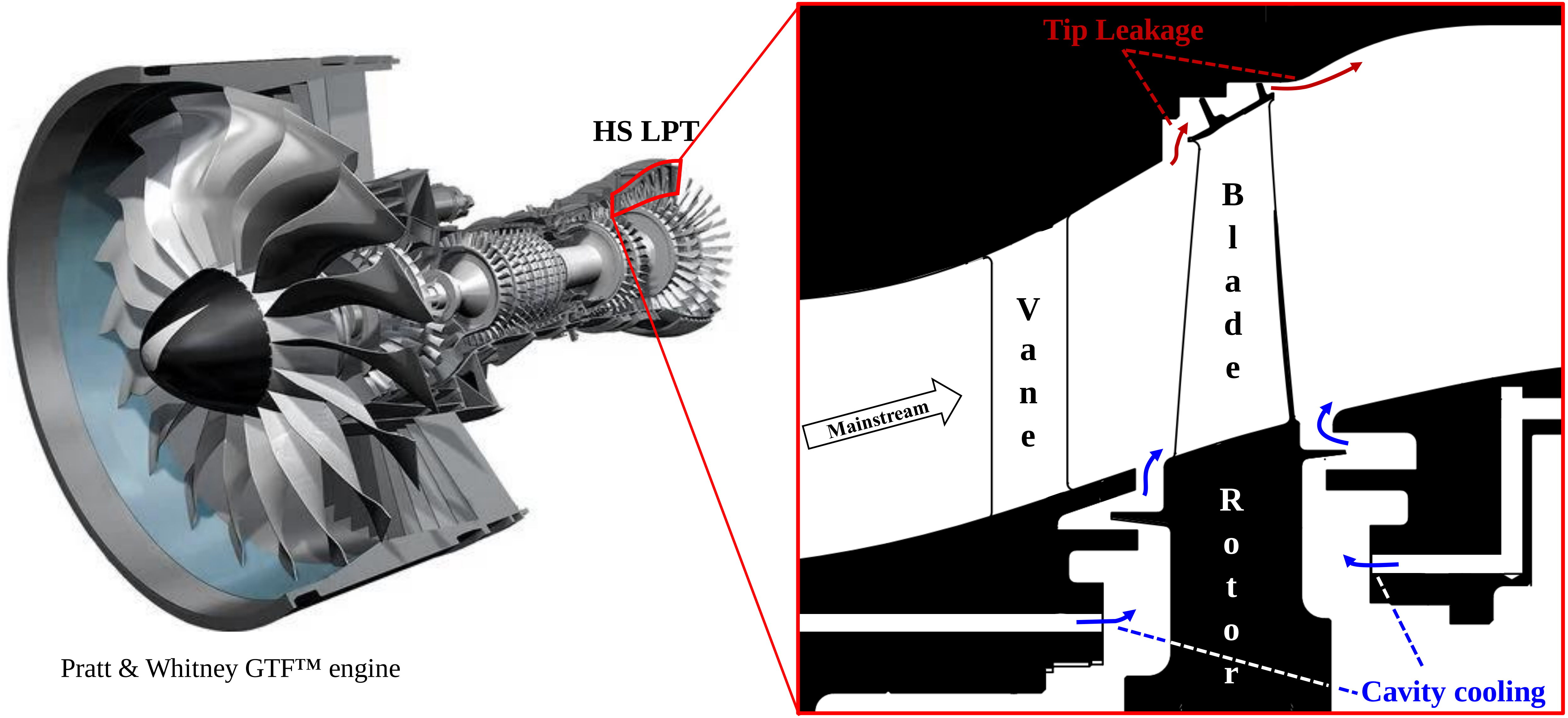
Motivation



Pratt & Whitney GTF™ engine

Full-scale HS LPT stage testing at VKI

Clean Sky 2 JOINT UNDERTAKING

SPLEEN

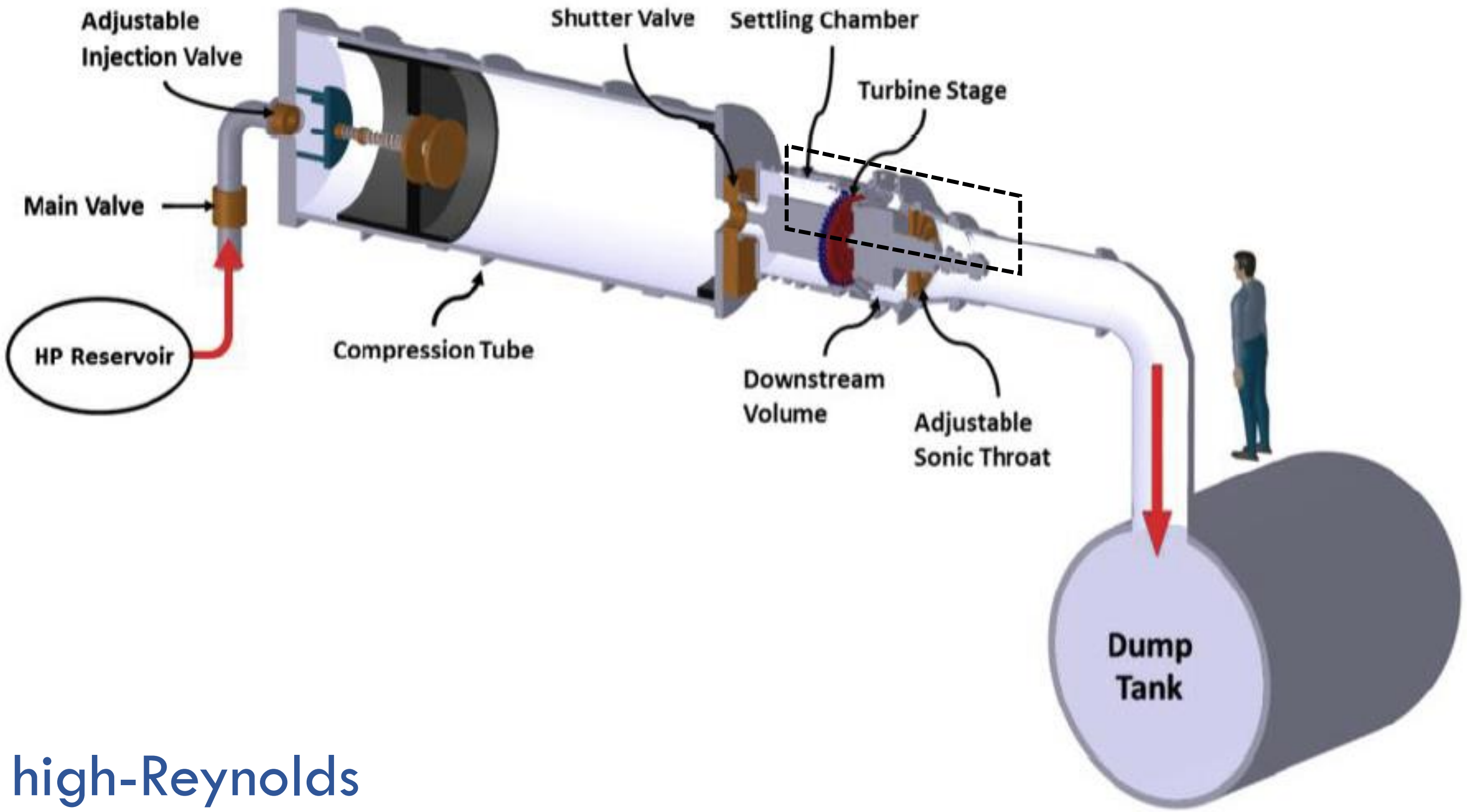
SECONDARY AND LEAKAGE FLOW EFFECTS IN HIGH-SPEED LOW PRESSURE TURBINES

Design objectives

- Engine representative single-stage HSLPT
- CFD-friendly stage (open-access database)
- Engine-realistic hub and shroud cavities
- Adjustable purge flow rate

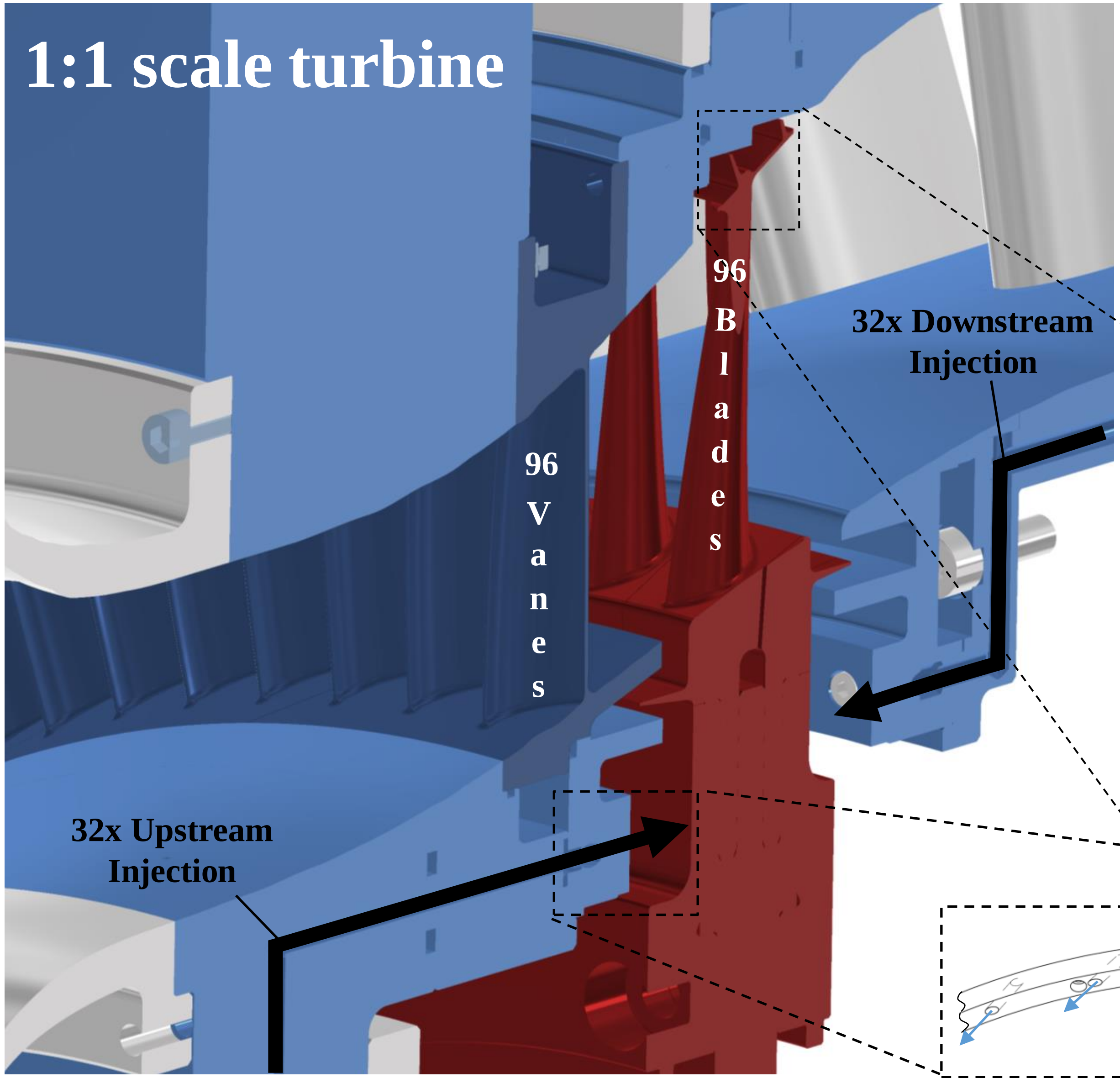
VKI short-duration rotating rig (CT3)

Parameter	Value
Testing time	~0.250 [s]
Rotational Speed	4500-7000 [RPM]
Reynolds number	0.5 - 3.4 x 10^6
$M_{vane,exit}$	0.8-1.05
T_{gas}/T_{wall}	~1.5
Pressure ratio	2-4

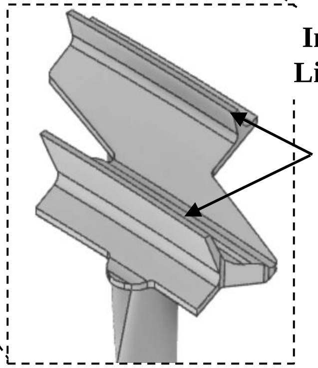


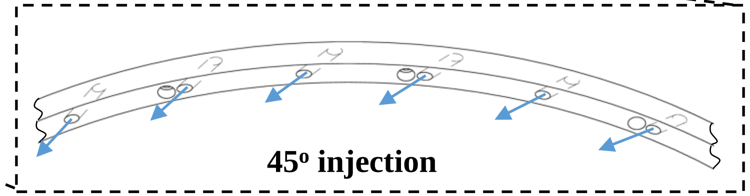
- Geometrical constraints
- Typically used for HPT testing and high-Reynolds
- Rig operating at LPT testing conditions: High capacity flows→ quick un-chocking of the adjustable sonic throat

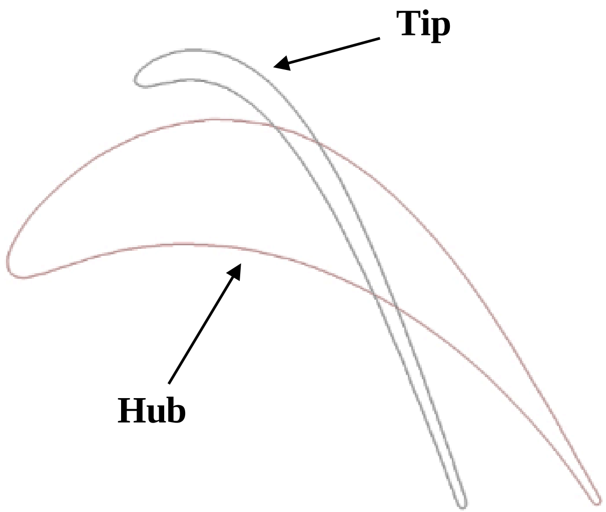
Design of the research turbine



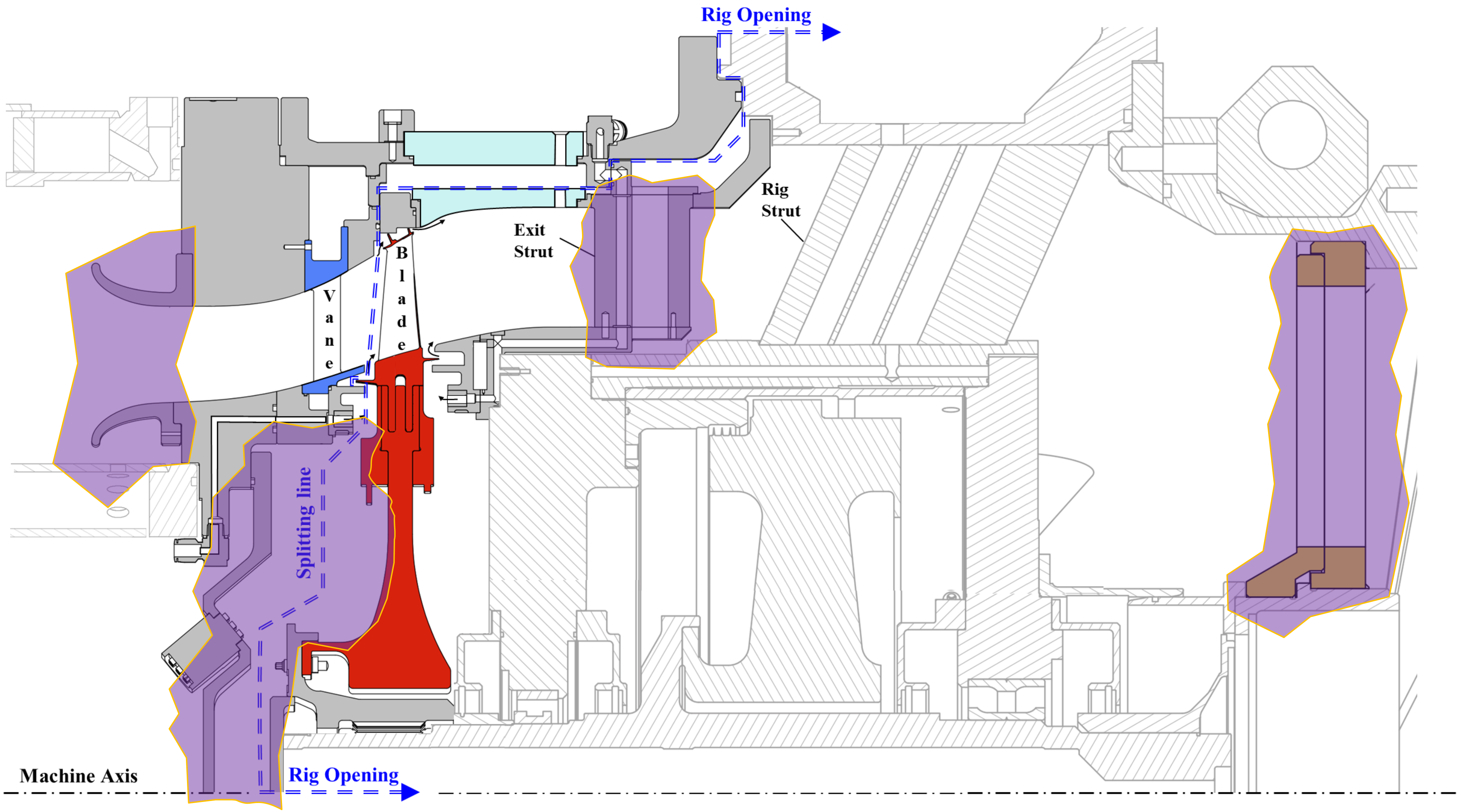
Parameter	Value
Flow Coefficient	0.6
Blade loading	1.8
Total-to-static pressure ratio	2.10
Gas-to-wall temperature ratio ($T_{0,1}/T_w$)	1.11
Relative rotor exit Mach number	0.82
Reynolds number	2.21 x 10^5
Purge-to-mainstream mass flow ratio	0.5%
Rotational speed (RPM)	4466



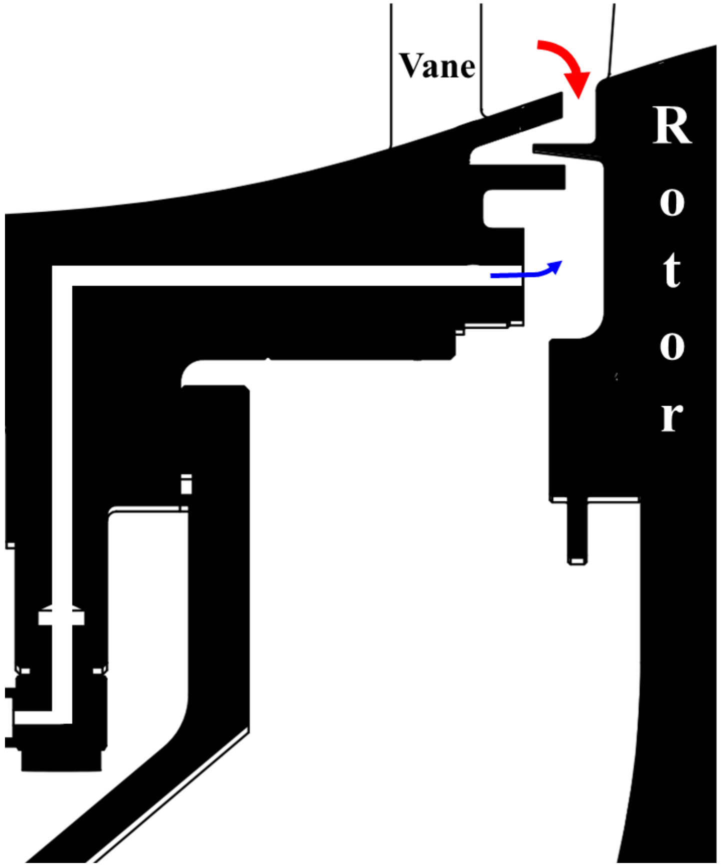


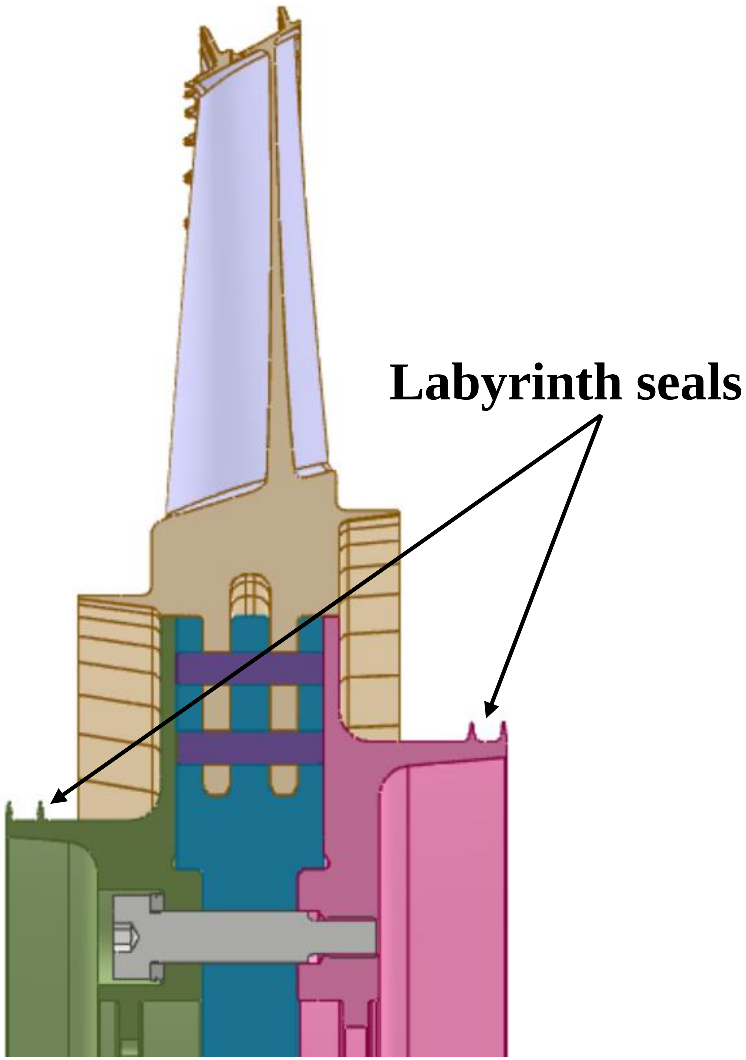


VKI short-duration rotating rig

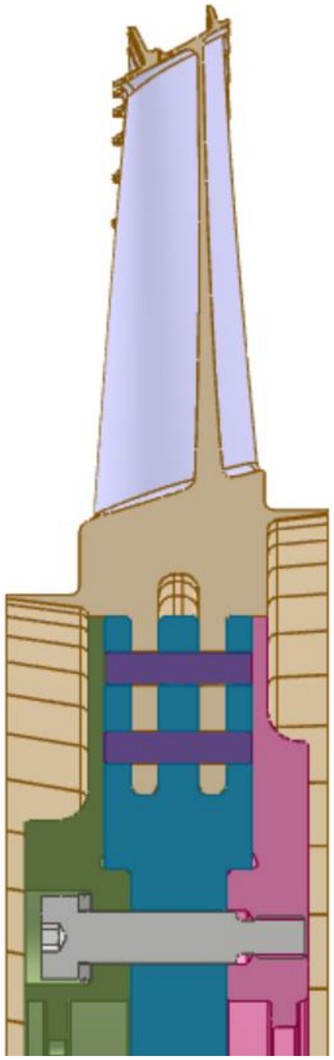


Cavity filling – design solutions



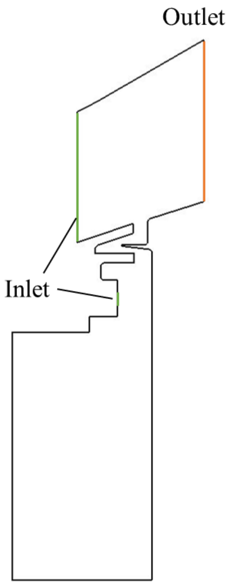


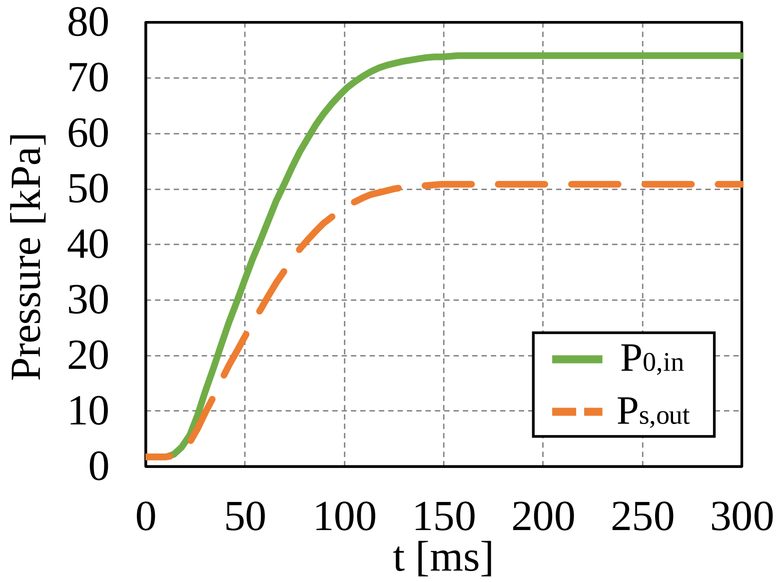
Labyrinth seals configuration



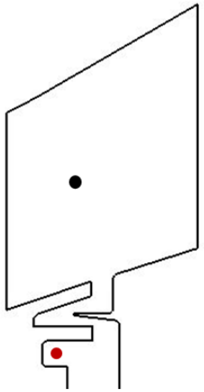
No-labyrinth seals configuration

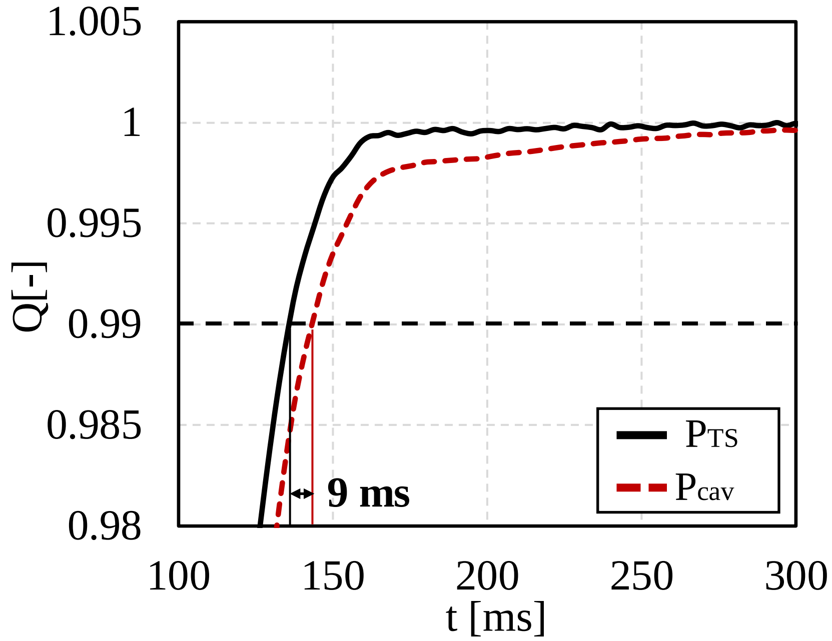
Upstream cavity filling – CFD





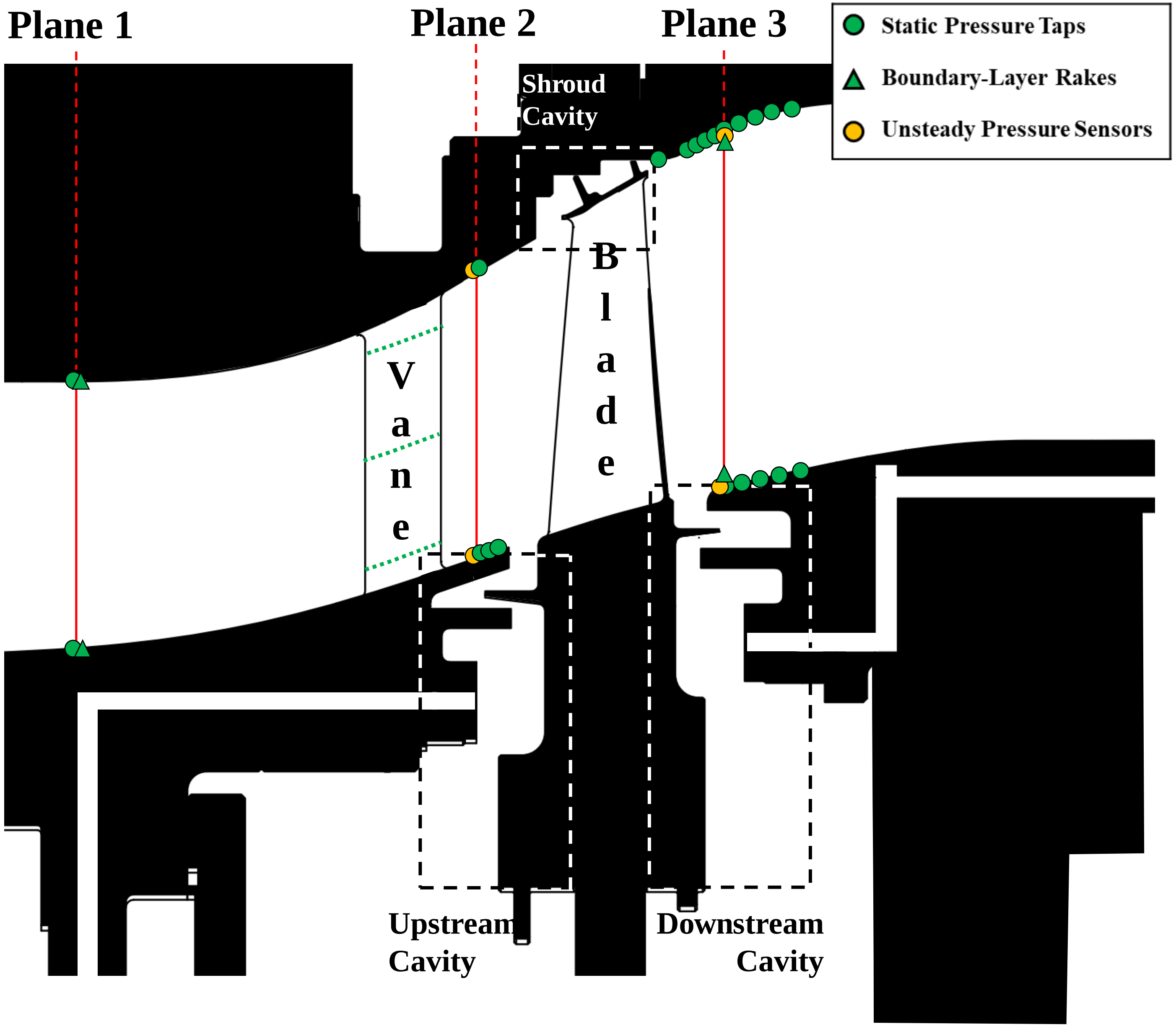
- 3D annular sector of 1 injection hole
- Mesh size = 9.4M cells, y+<1
- Unsteady fully turbulent simulations K-ω SST
- Normalized quantities: $Q = \frac{P(t)}{P_{end}}$



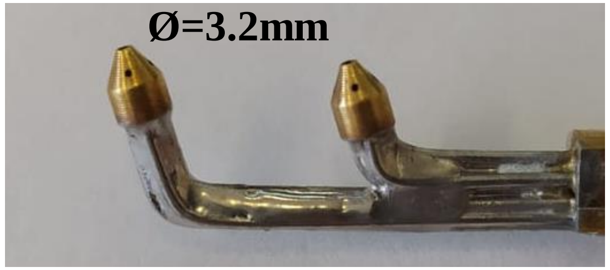


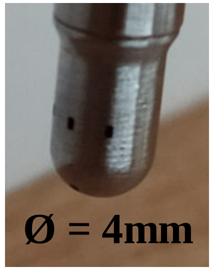
- Cavity filling time in time 3% of the testing time
- No-labyrinth seals configuration is validated

Mainstream instrumentation

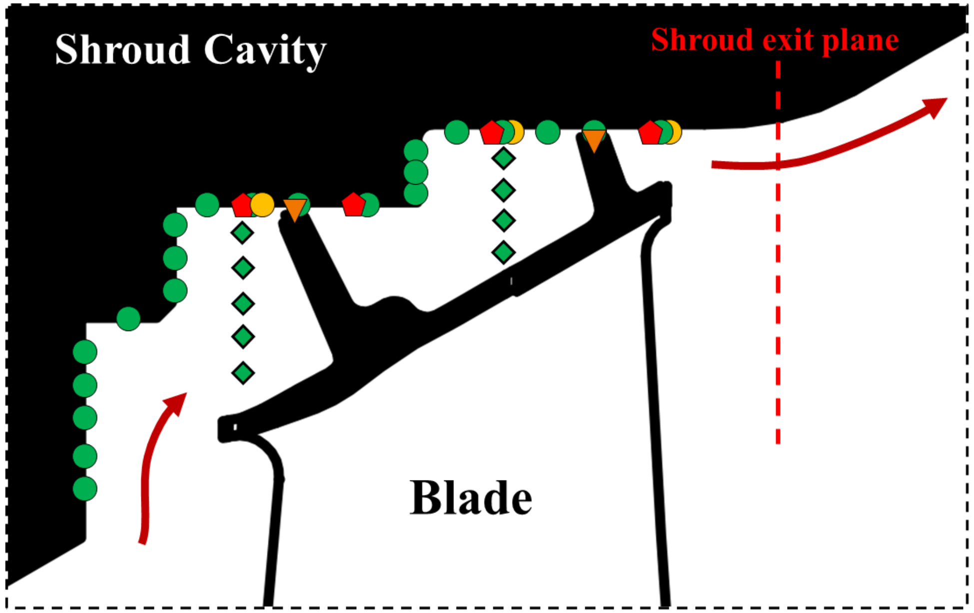


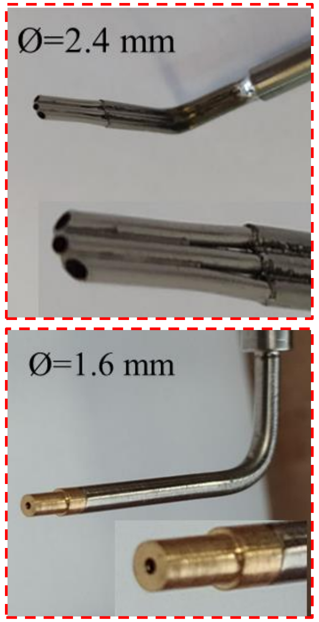
- Turbine-inlet characterization (P0,T0,TI)
- Vane outlet aerodynamics + cavity effects
- Rotor outlet cavity purge and tip leakage impact on mainstream
- Stage efficiency measurements



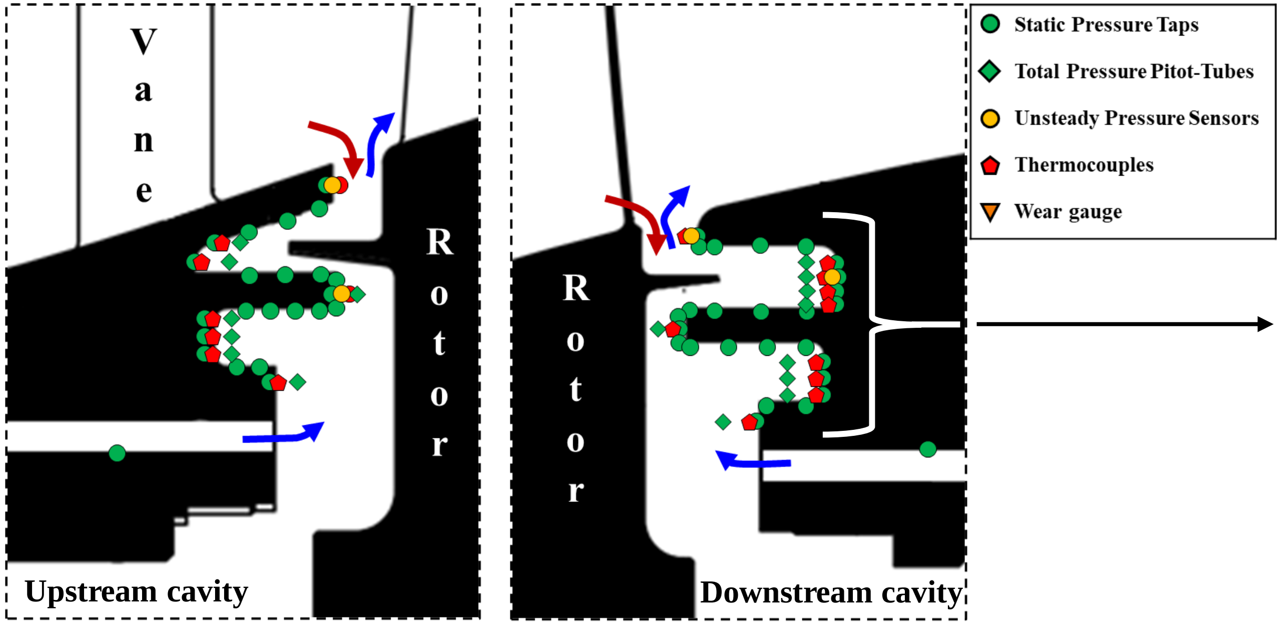


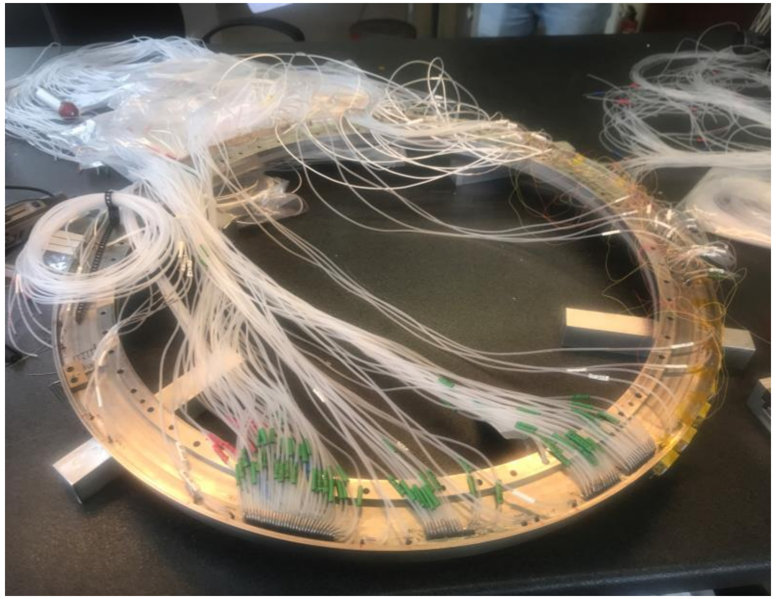
Cavity-regions instrumentation

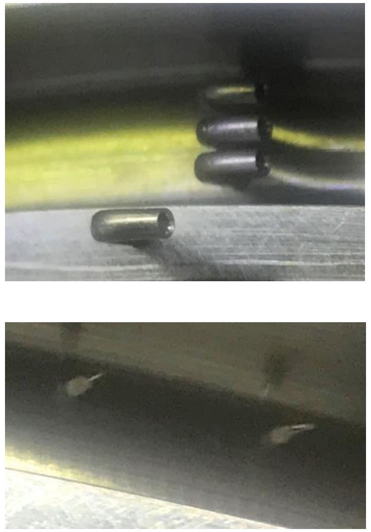




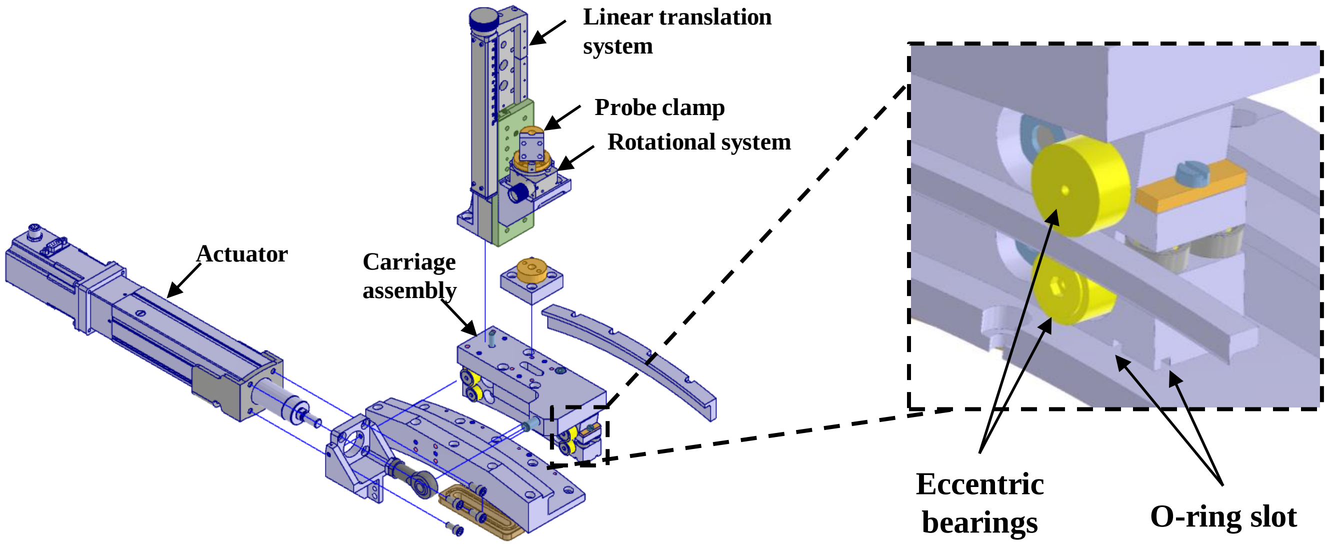
- Cavities full characterization
- Unsteady flow structures
- Tip clearance
- Tip leakage flow and unsteadiness
- Injection uniformity

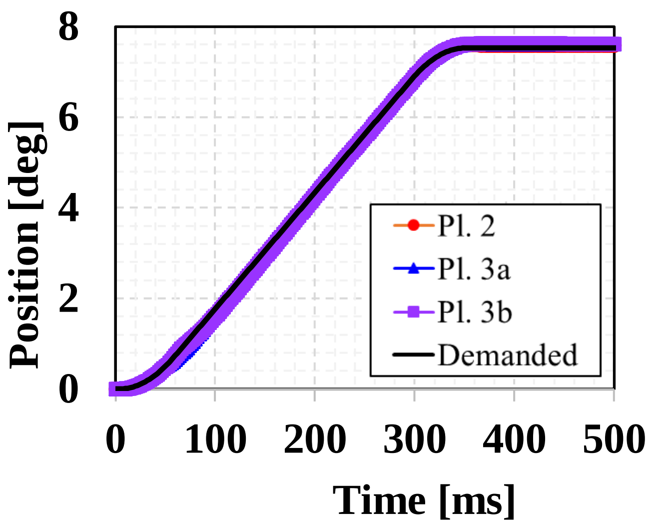


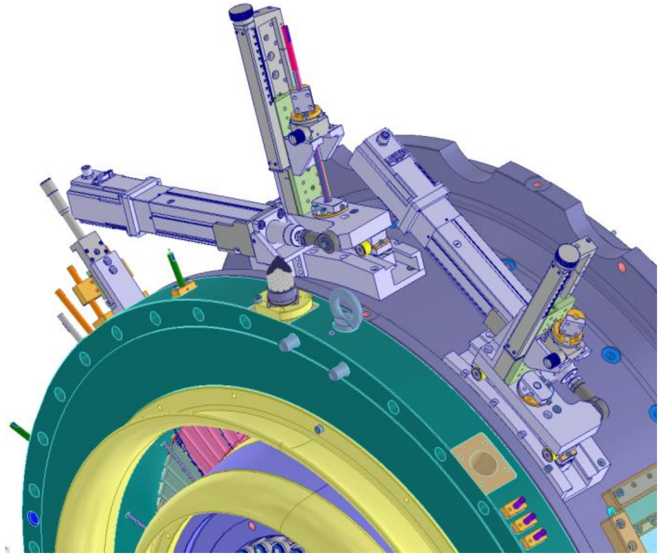




Traversing system design and commissioning







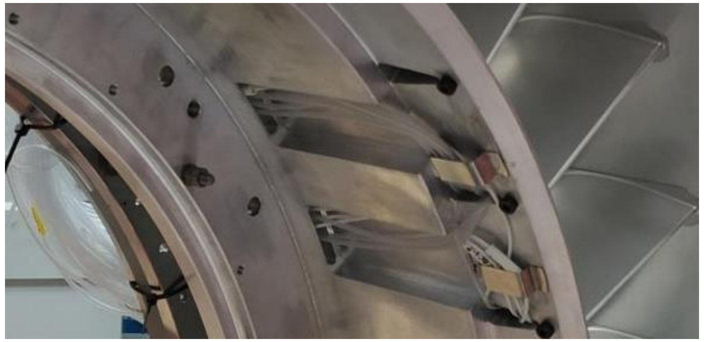
- In-house traversing system design
- Reduction of test matrix
- Maximum traversing speed of 600 mm/s
- Adjustable velocity and position
- High spatial resolution
- Test Section kept sealed during the traverse

Integration

Upstream assembly

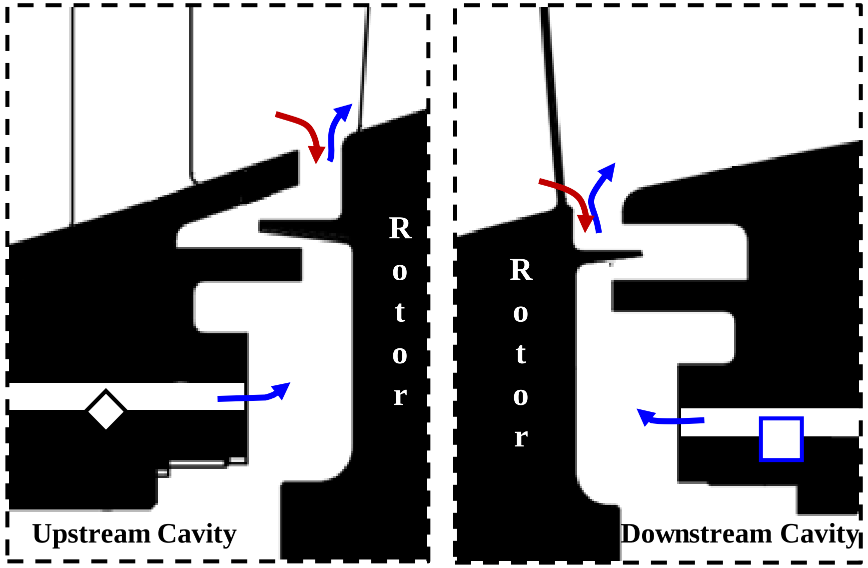
Rotor assembly

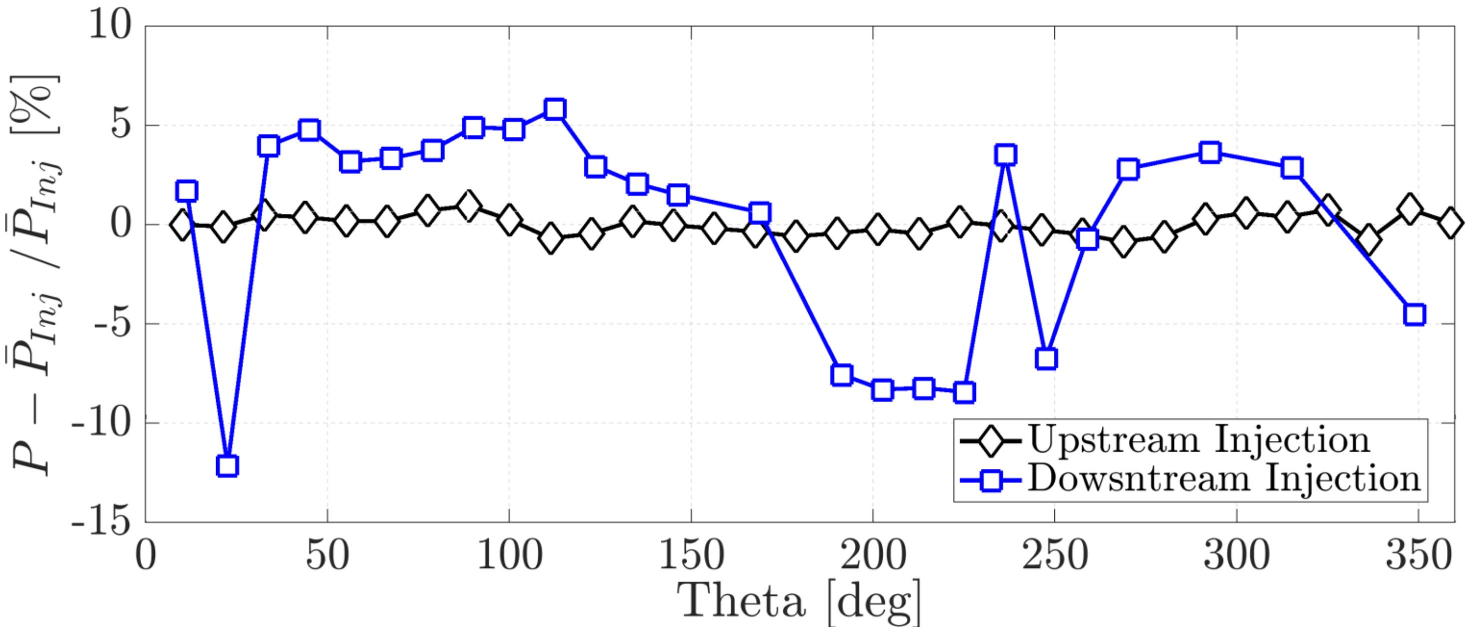
Stage outlet assembly



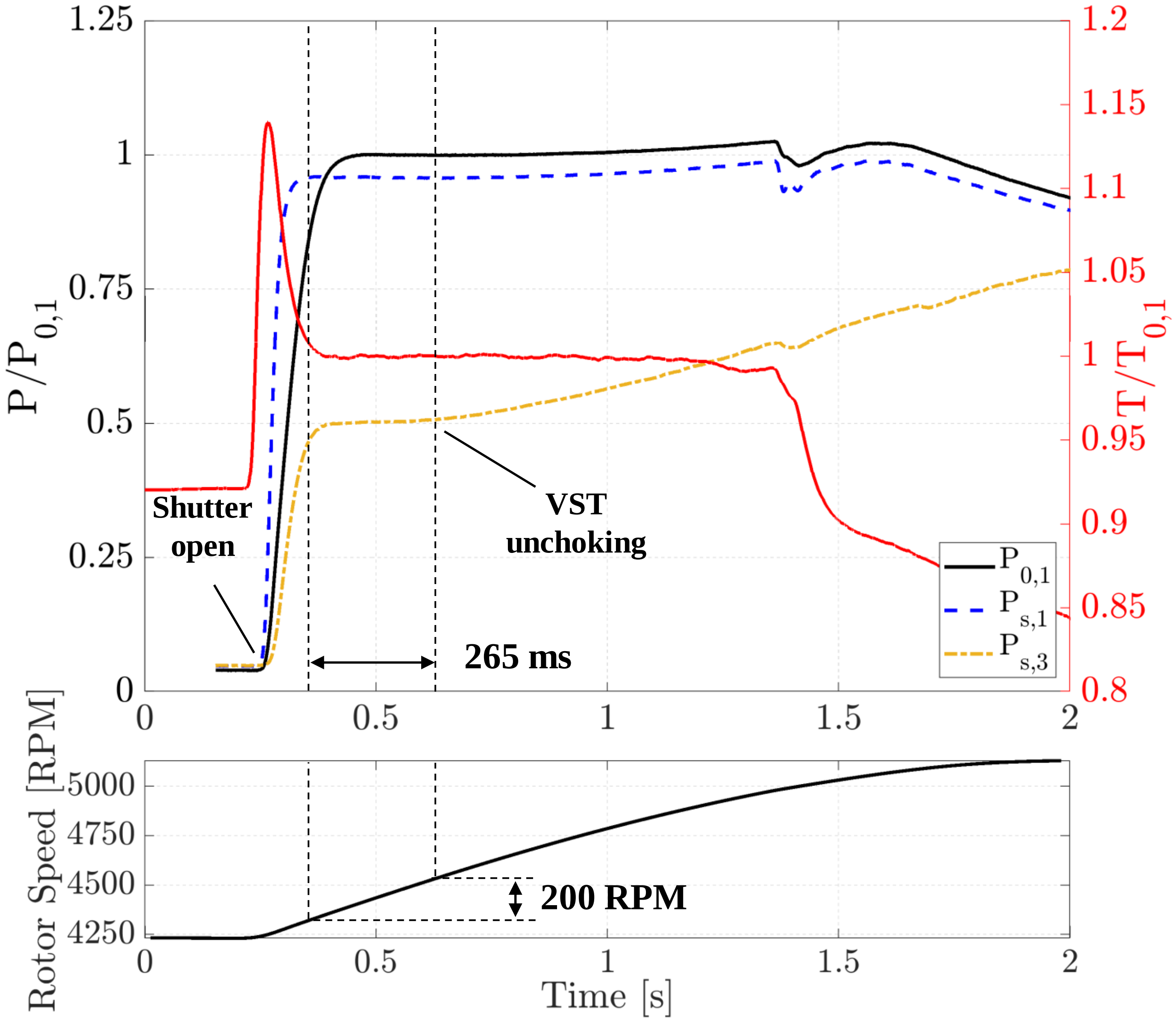
Test commissioning – Injection uniformity

- Upstream injection variation within ±1%
- Downstream injection variation -10% to +5%
- Possible leakage located in the internal injection supply line
- All test campaign without downstream purge injection



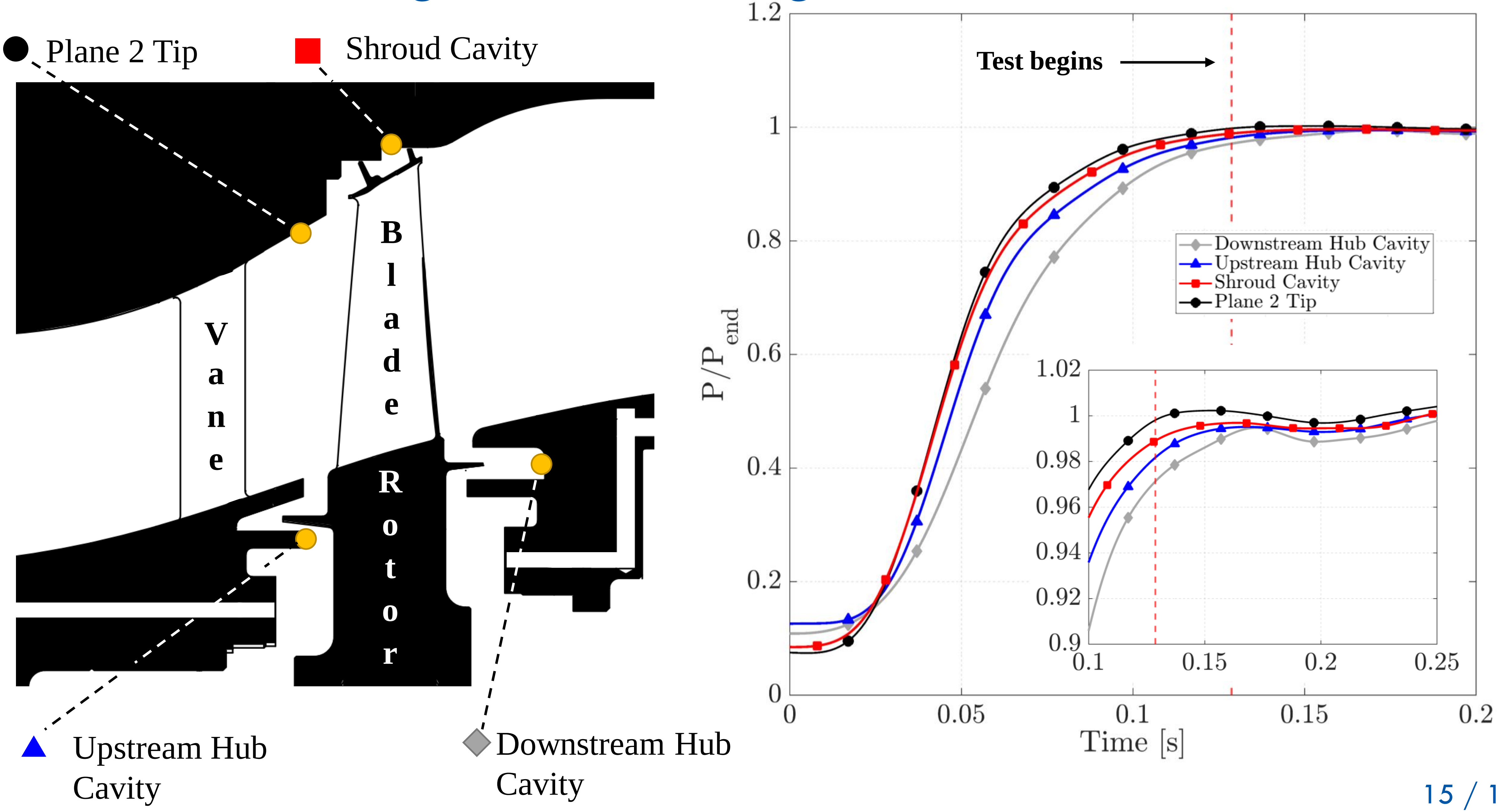


Test commissioning – Aerothermal parameters



Quantity	Mean	95 % CI [%]
P01/PS3h	2.12	0.42
T01/T03	1.18	0.36
Velocity [rpm]	4460	0.17
Purge flow [kg/s]	0.05	1.73

Test commissioning – Cavities filling time



Conclusions

- New research turbine stage SPLEEN representative of modern High-Speed LPT
- Redesign and upgrade of the VKI turbine rig to test at HS LPT conditions
- Electro-mechanic fast-traverse system proven in operation
- Verified capability to test at the intended operating conditions for about 250 ms
- Turbine stage operated without downstream hub-cavity injection
- Test campaign completed in February 2023

Acknowledgements

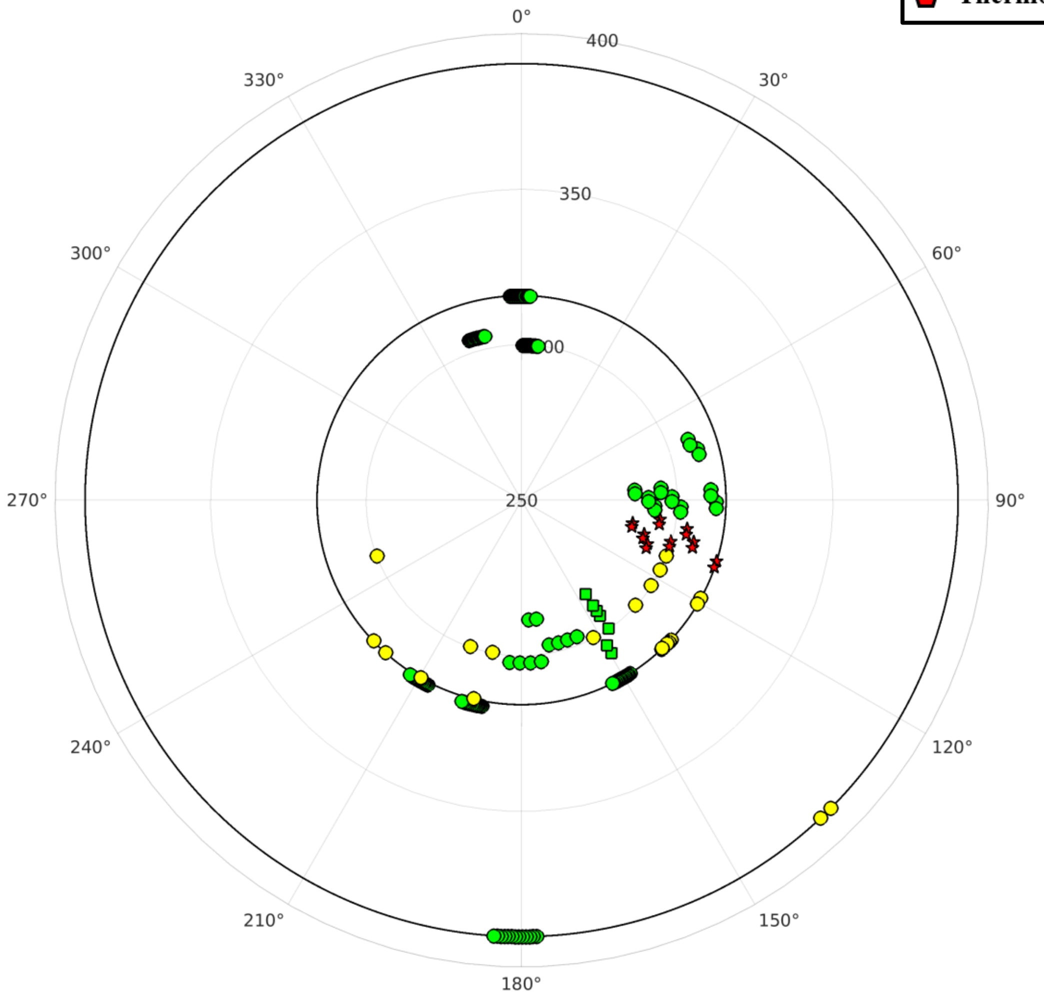
The **SPLEEN** project is found by the **Clean Sky 2 Joint Undertaking** (grant agreement 820883) under the European Union's **Horizon 2020** research and innovation program

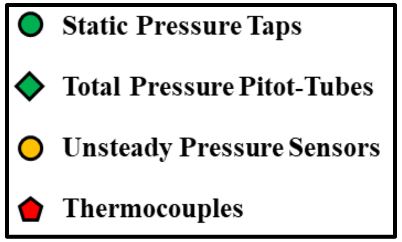
SPLEEN is an open test case. Stage results coming up soon!

Backup slides

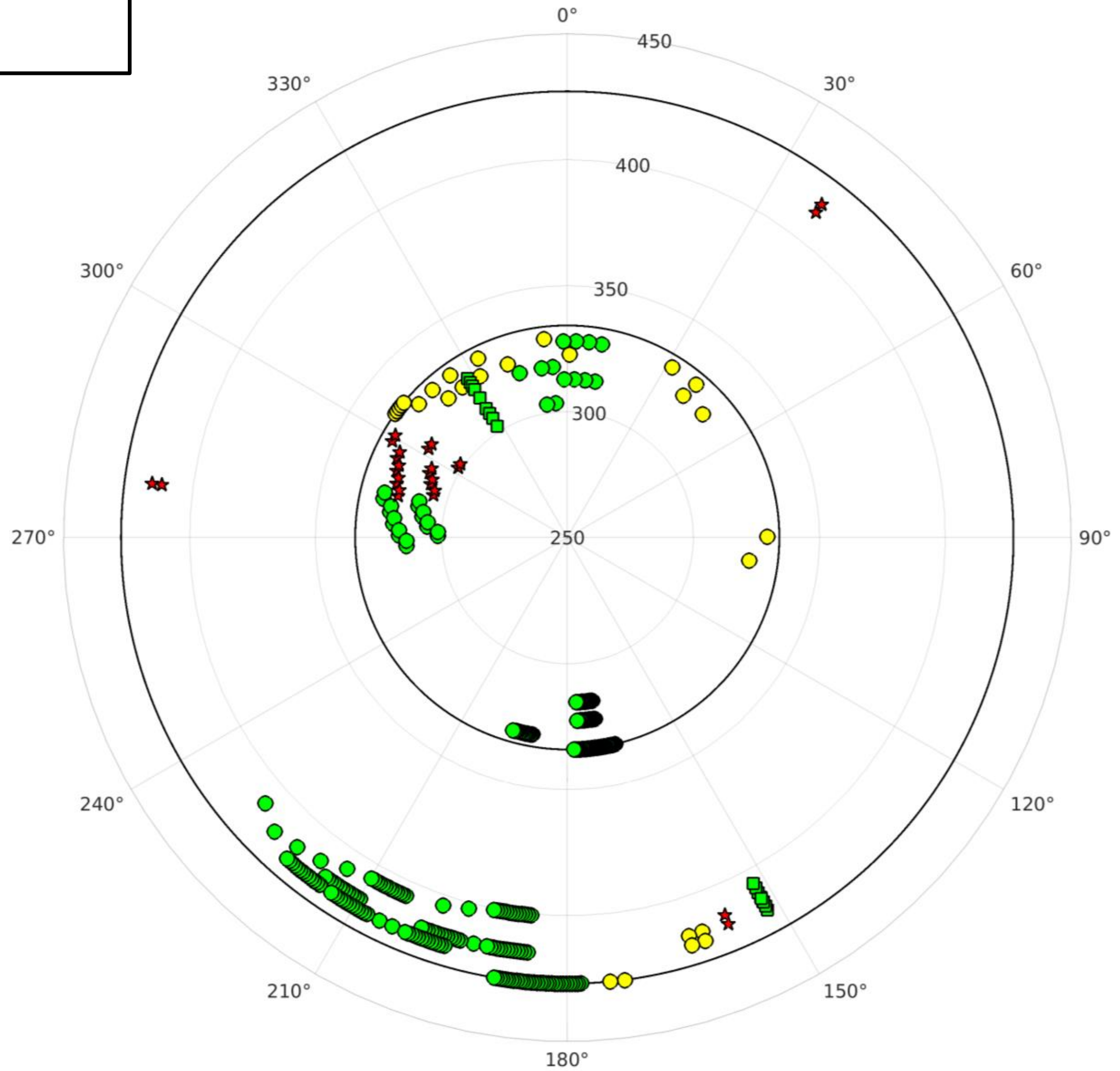
Instrumentation

Plane 2 and Upstream Cavity

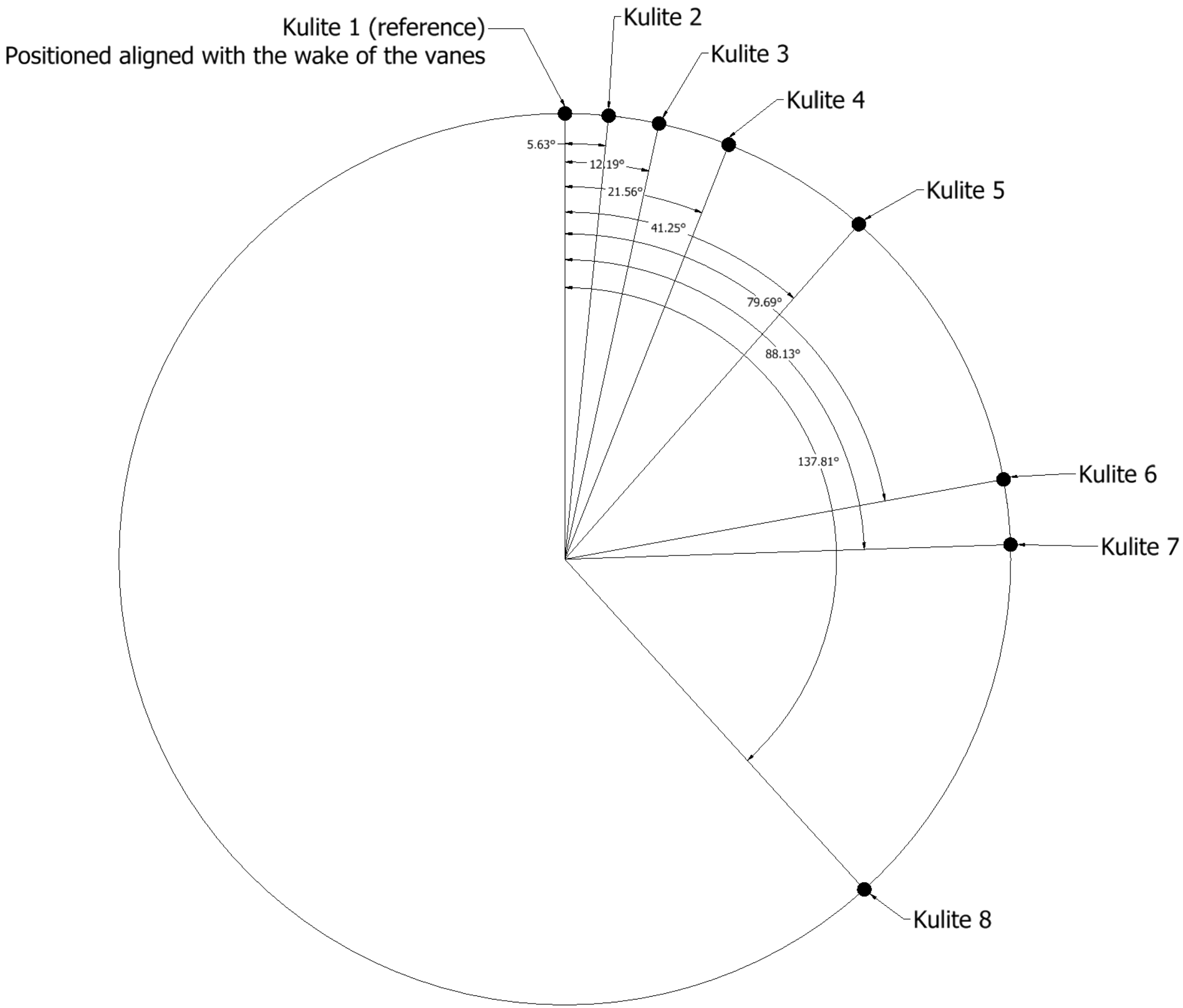




Plane 3, downstream and shroud cavities

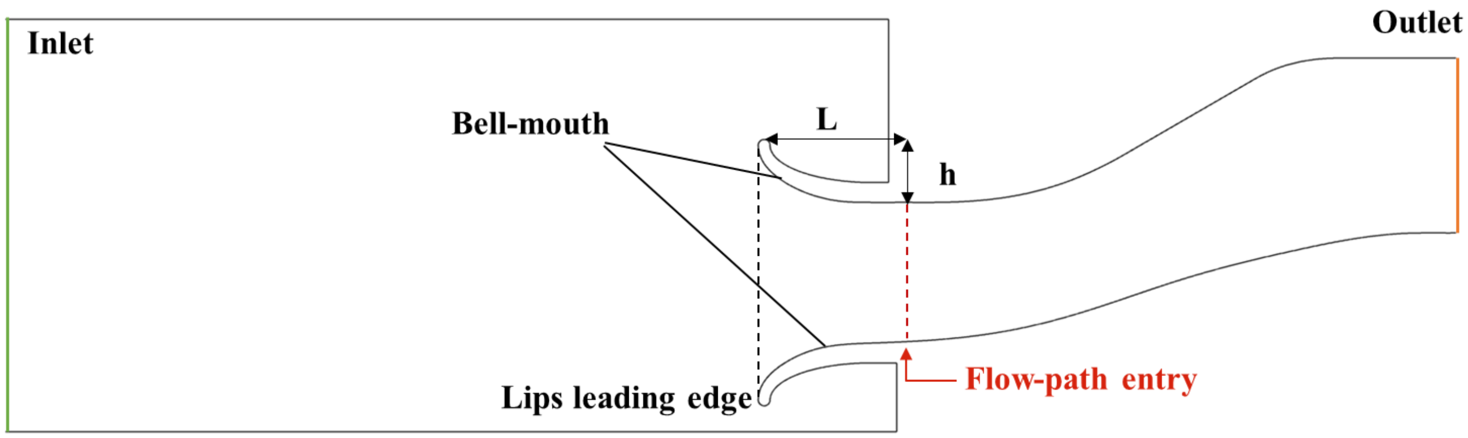


Kulites positioning



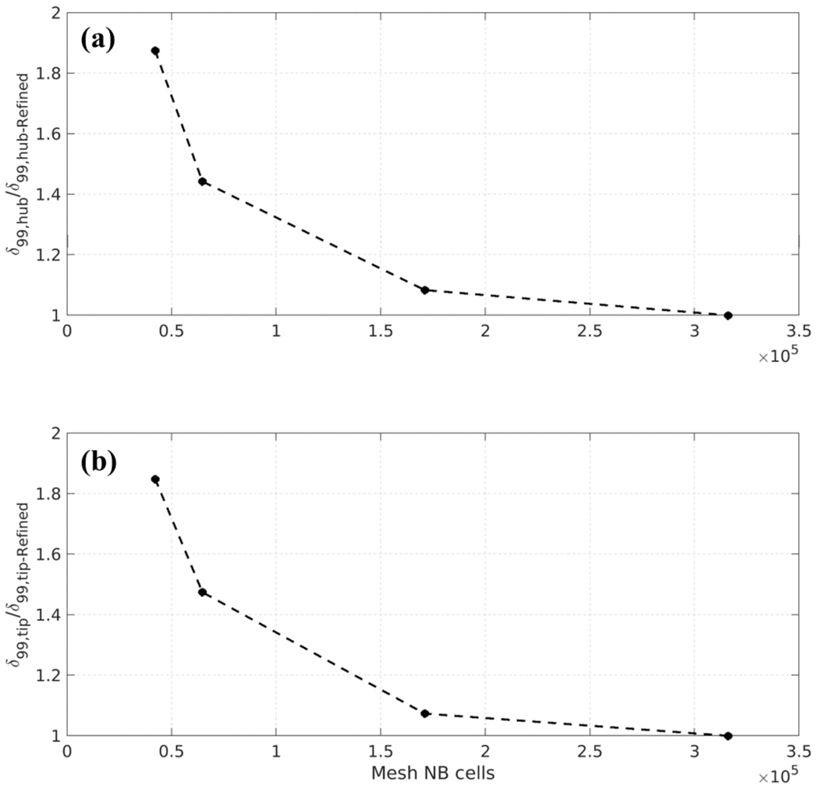
Sensor Number	Position relative to vane pitch
1	0 /1
2	0.5
3	0.25
4	0.75
5	0/1
6	0.25
7	0.5
8	0.75

Bellmouth design

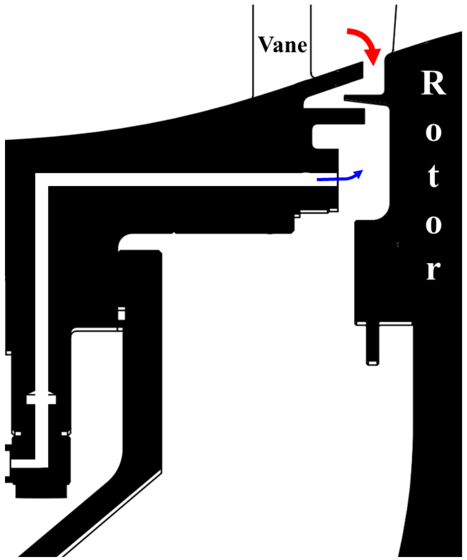


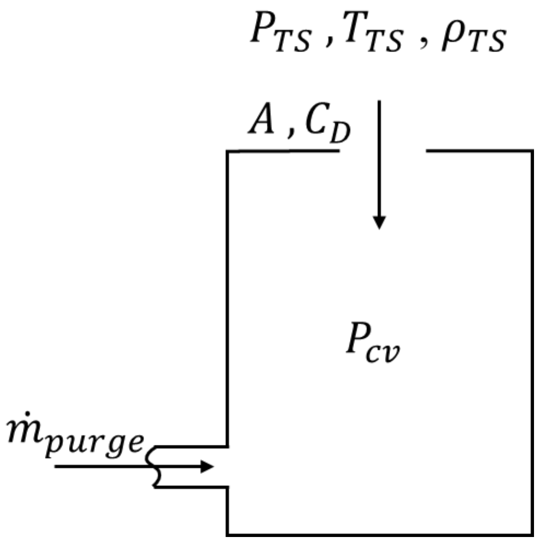
At the hub endwall $\delta_{99} = 2.91$ mm

At the tip endwall $\delta_{99} = 2.78$ mm



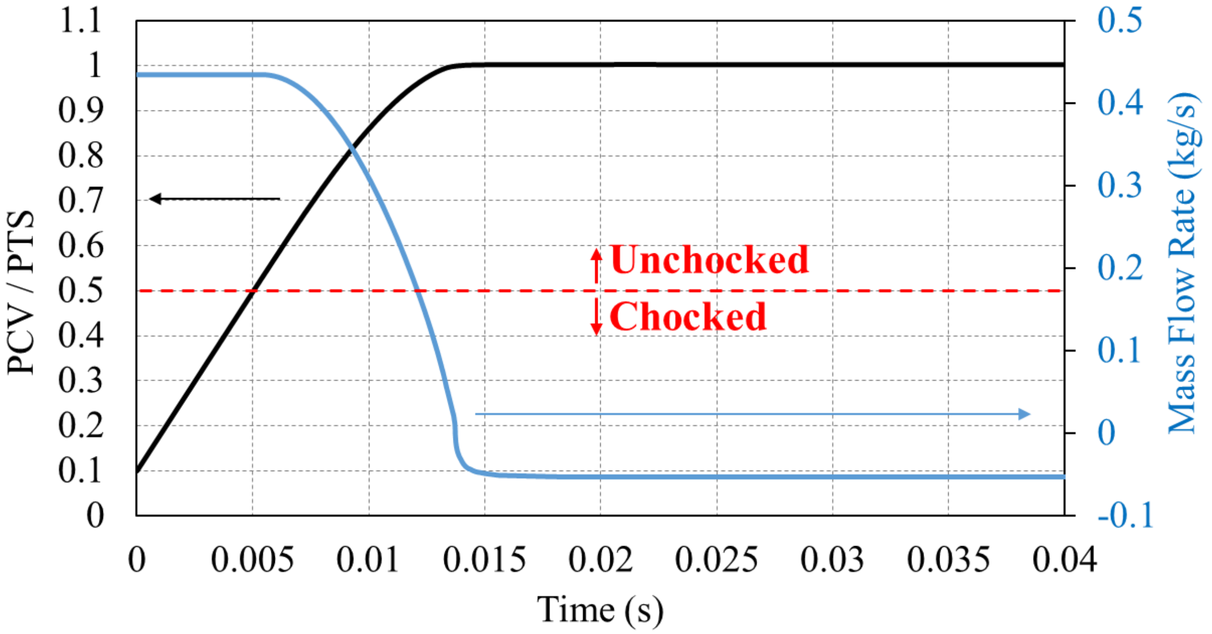
Upstream cavity filling – 0D model





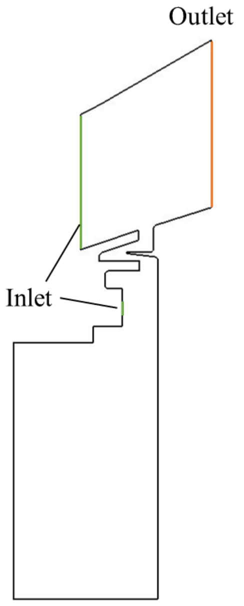
$$\dot{m}_{net} = \frac{V}{a_{TS}^2}\frac{dP}{dt}$$

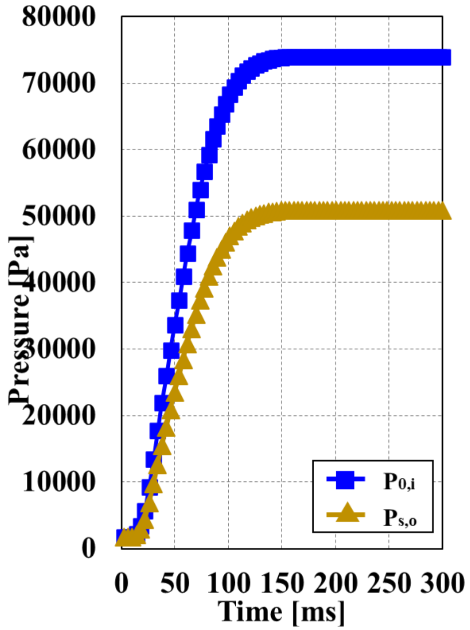
$$\dot{m}_{net} = \dot{m} + \dot{m}_{purge}$$



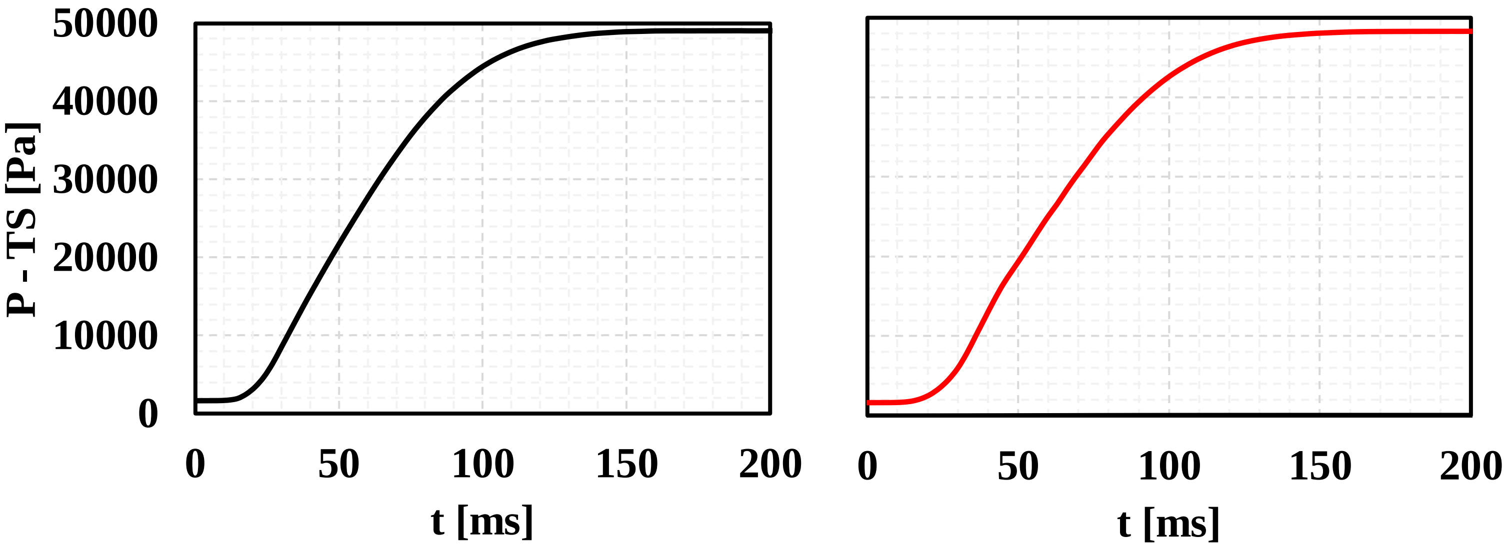
- Cavity initially at vacuum and suddenly opened the test-section conditions
- $\dot{m}$ through an orifice (chocked/unchocked)
- Pressure equilibrium achieved after 13 ms

Upstream cavity filling – CFD

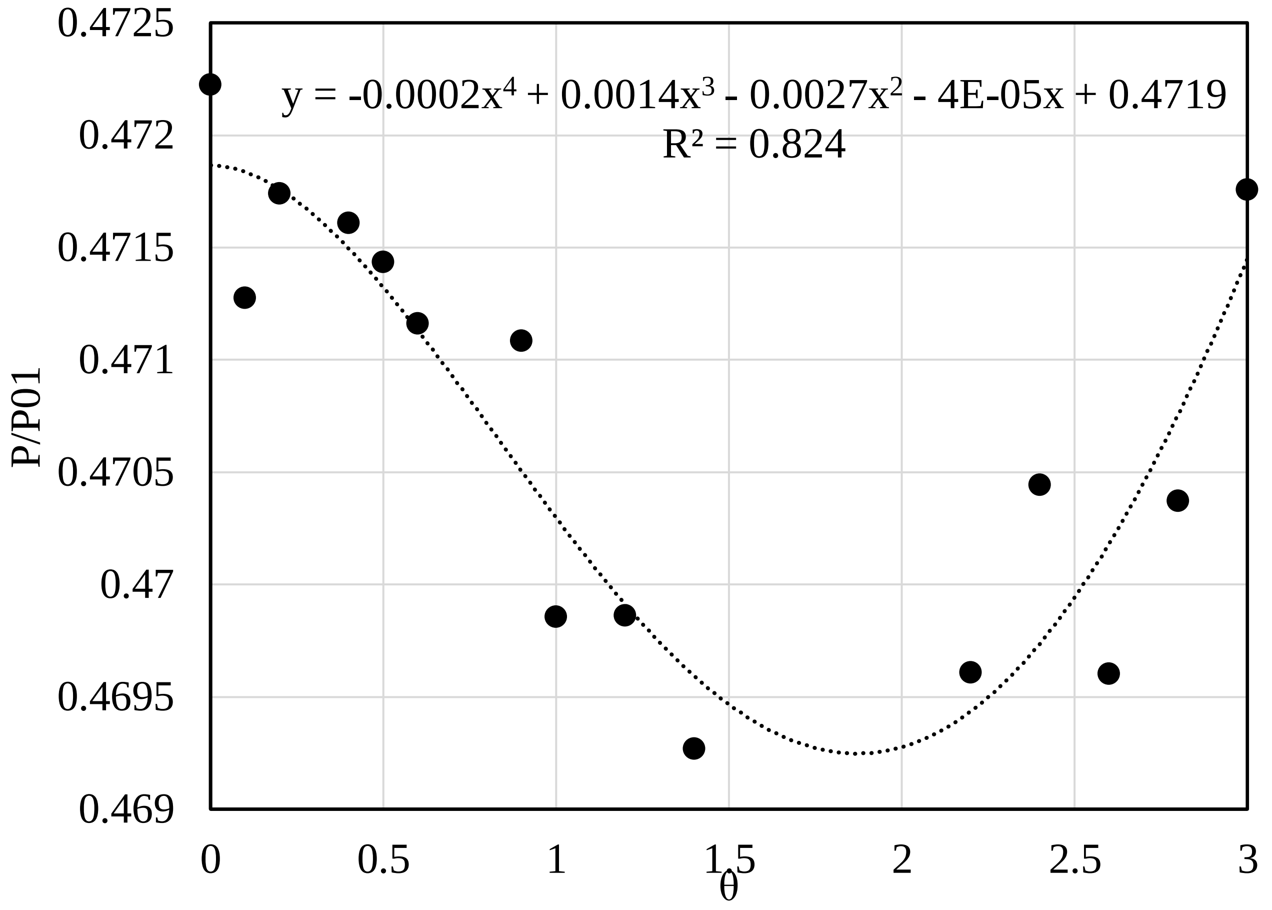




- 3D annular sector of 11.25° (1 injection hole = 3 vane passages
- Mesh size = 9.4M cells, y+<1
- Unsteady fully turbulent simulations K-ω SST
- Variable boundary conditions

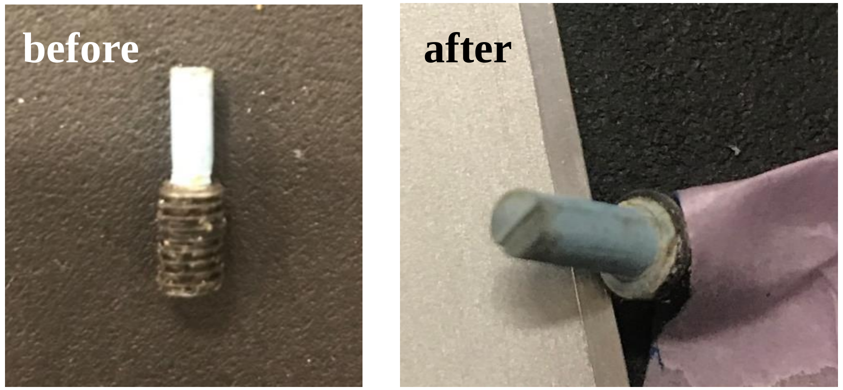


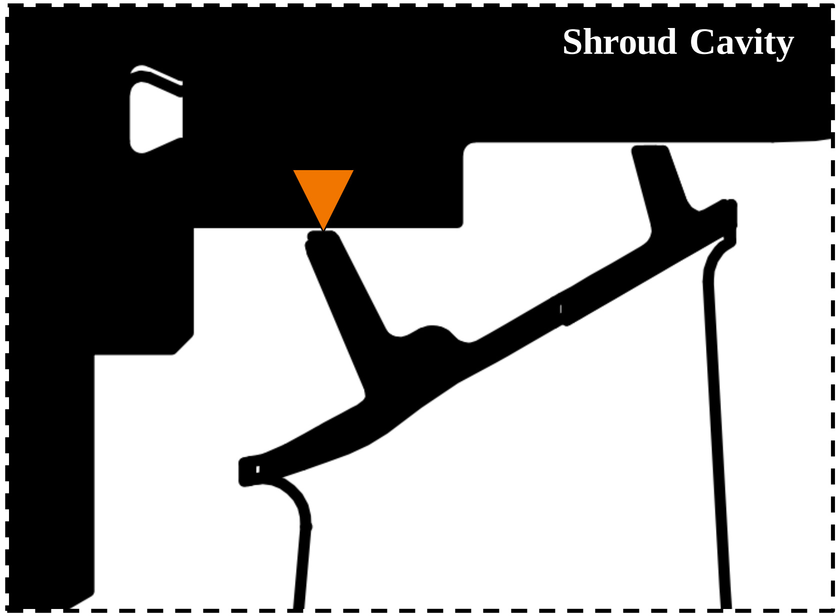
Struts Effect - hub

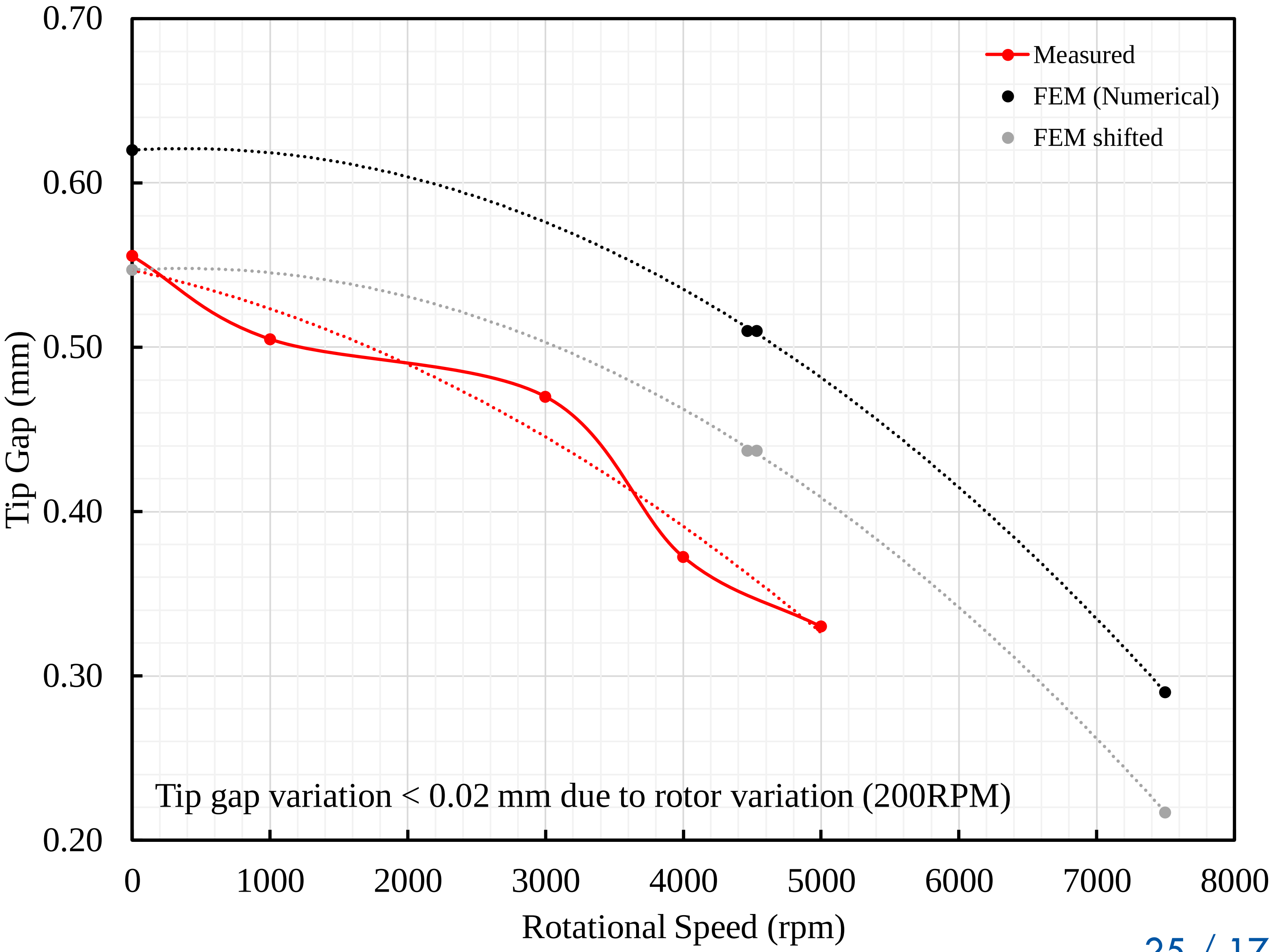


Tip clearance

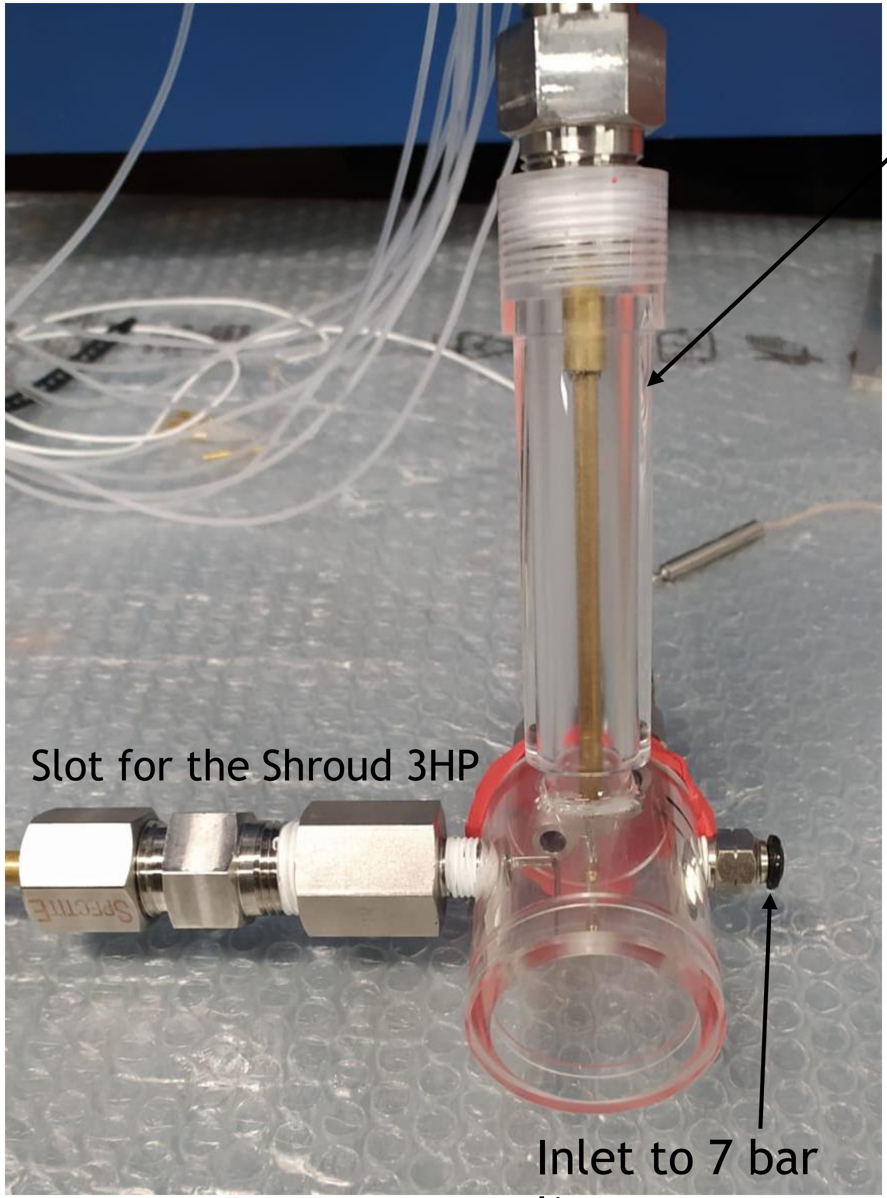
Wear gauge measurements

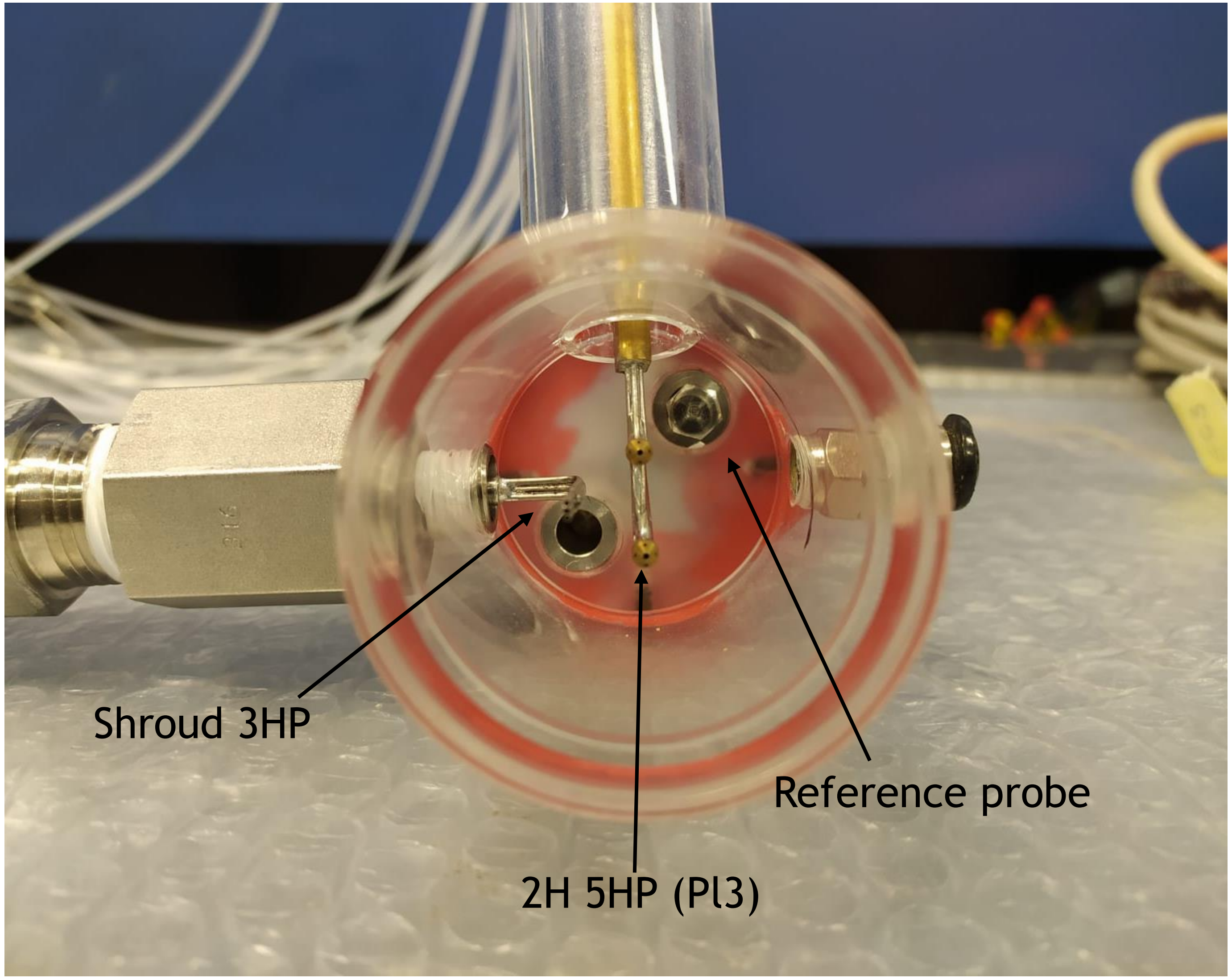




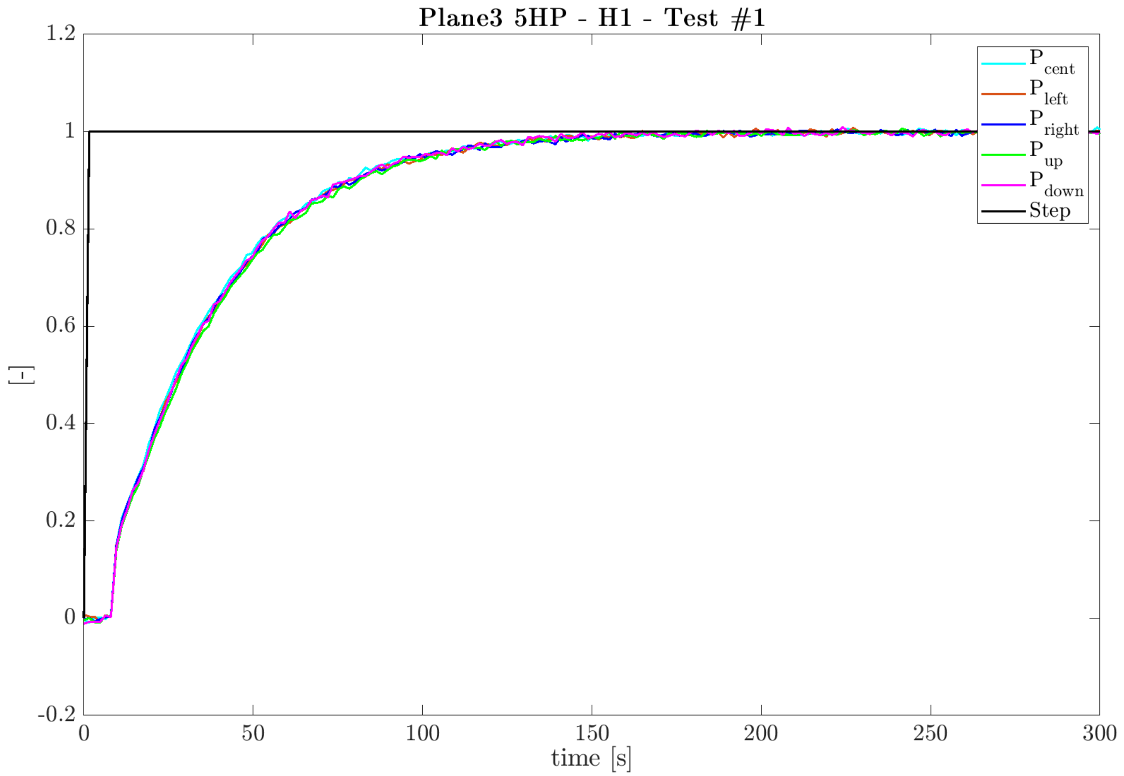


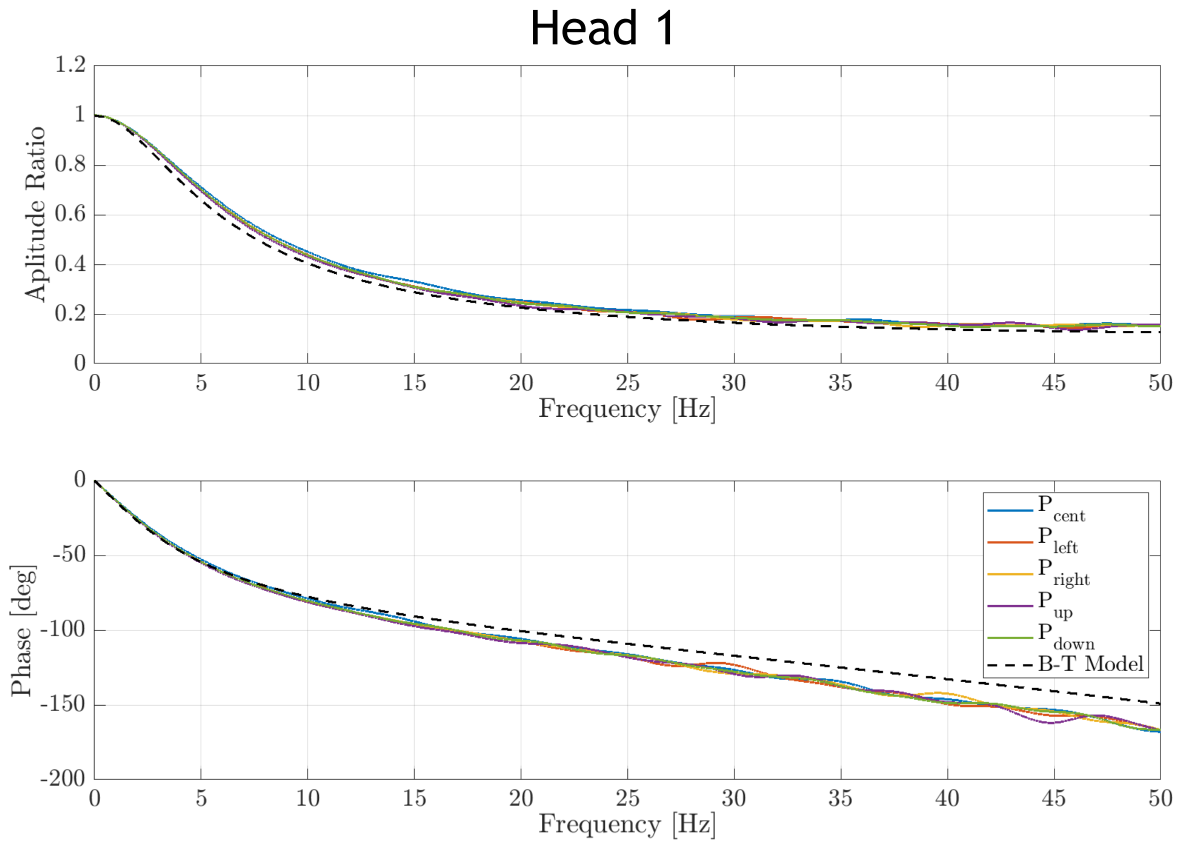
Balloon test dynamic calibration



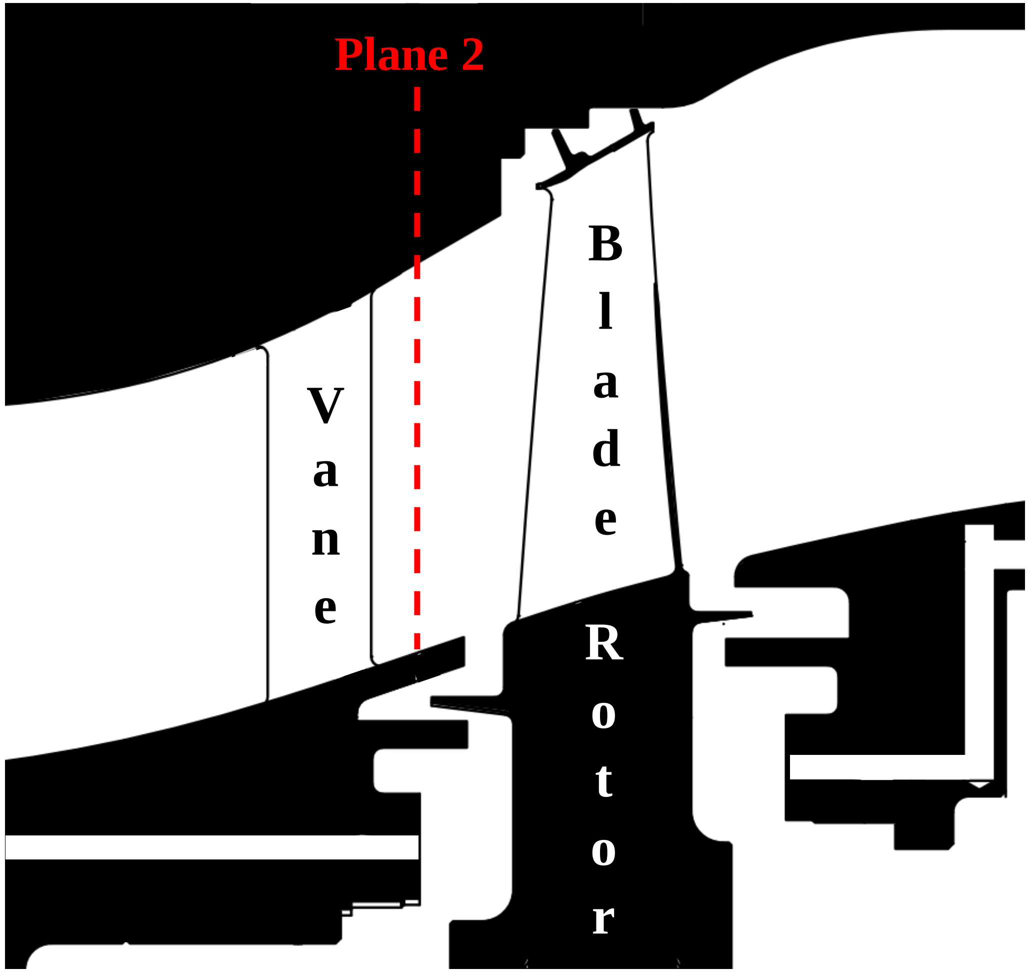


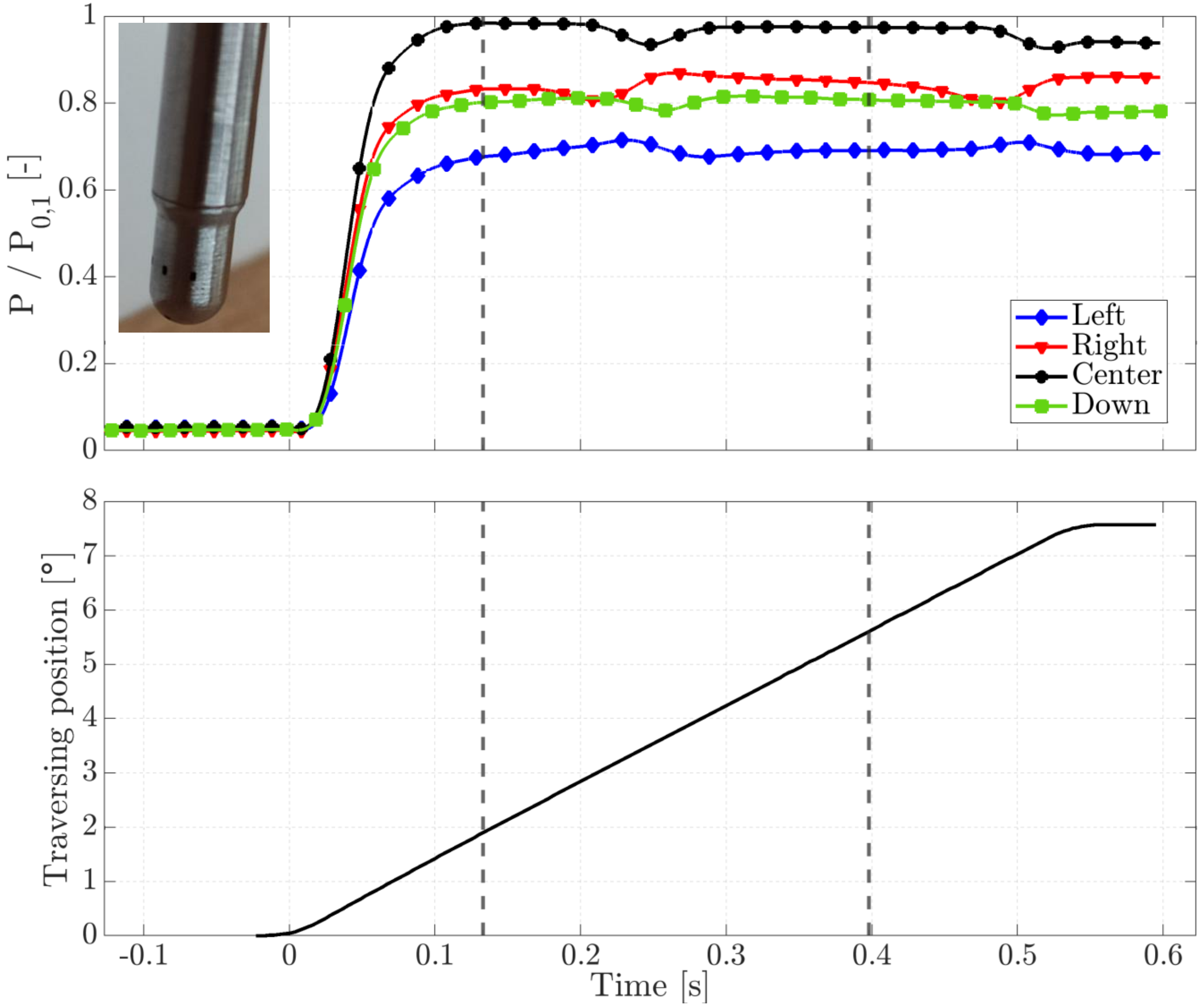
Balloon test dynamic calibration





Test commissioning – Probe traversing



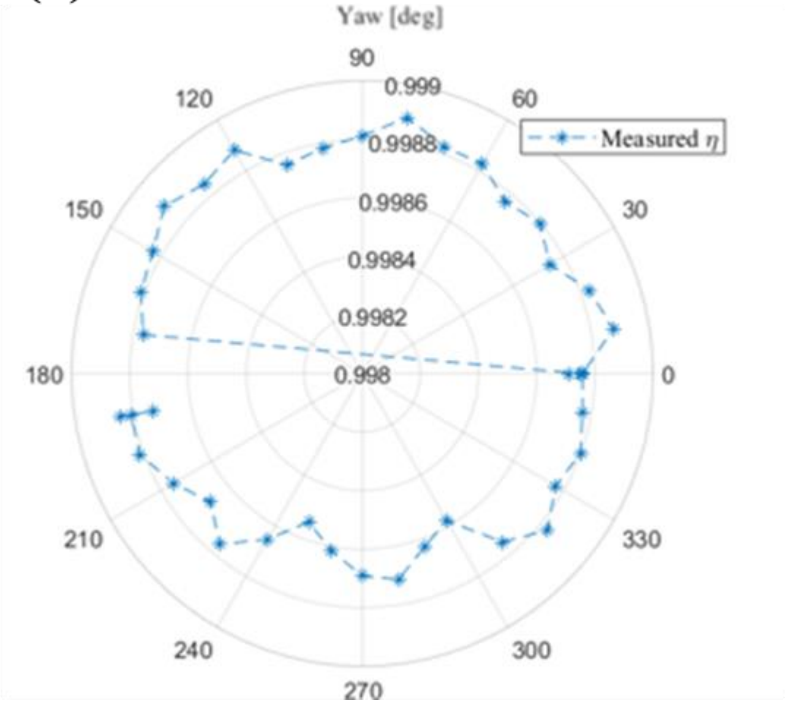


Measurement uncertainty

Quantity	Sensor	Total Uncertainty 95% CI
Pressure – pneumatic	Scanivalve	±1 mbar
Total temperature	TC type K	±0.35 K
Pressure – fast response	Kulite	±3 mbar
Yaw – Pneumatic 5HP	Scanivalve	±0.40^{o}
Pitch – Pneumatic 5HP	Scanivalve	±0.43^{o}
Mach – Pneumatic 5HP	Scanivalve	±0.005
Yaw – FR4HP	Kulite	±0.43^{o}
Pitch – FR4HP	Kulite	±0.78^{o}
Mach – FR4HP	Kulite	±0.009

Thermocouple recovery factor

(a)



(b)

Injection uniformity