2nd CDF Workshop

Fabian Klausmann
Technical University of Darmstadt
Institute of Gas Turbines and
Aerospace Propulsion

Technical University of Darmstadt

Institute of Gas Turbines and Aerospace Propulsion

TECHNISCHE UNIVERSITÄT DARMSTADT

GLR

MASCHINENBAU
We engineer future

Institute of
Gas Turbines and Aerospace Propulsion

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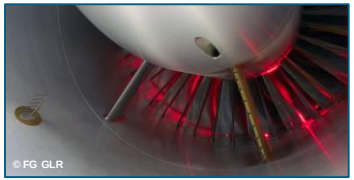

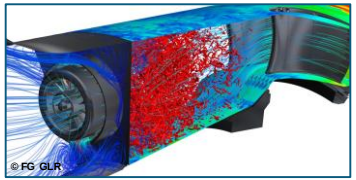

- Department of Mechanical Engineering
- Chair: Prof. Dr. H.-P. Schiffer
- 18 researcher & in-house mechanical workshop
- ~25 student research assistants per year
- ~25 Bachelor & ~15 Master thesis students per year

- Rolls-Royce University Technology Center
- research with application focus, both numerically and experimentally
- Test facilities
  - 2 transonic axial compressor rigs
  - 2 scaled axial turbine rigs
  - Turbo charger laboratory
  - Measurement design, calibration & validation

Research Partners and Funding

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ROLLS ROYCE

MTU Aero Engines

SIEMENS

GKN AEROSPACE

SAFRAN

Federal Ministry for Economic Affairs and Energy

European Union
Research and Innovation

CONTENT

Facility Introduction

Open Test Case

Technology Readiness Level Classification

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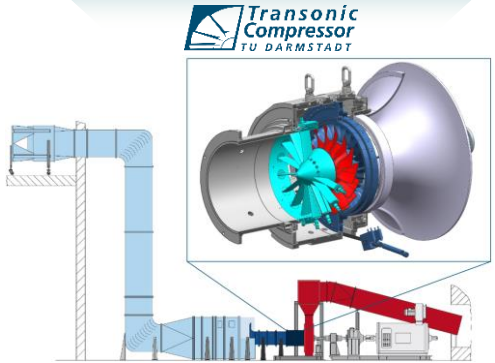
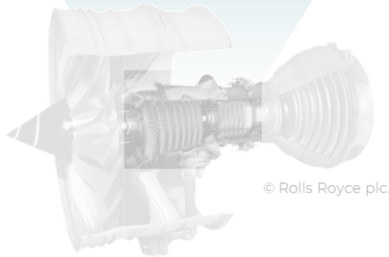
TRL 1	TRL 2	TRL 3	**TRL 4 - 5**	TRL 6 - 7	TRL 8 - 9
Basic Principles Observed and Reported	Potential Application Validated	Proof-of-Concept Demonstrated	**Component Test Facilities & Validation**	System Prototype Demonstration in Operation Environment	System Test, Launch & Operations

- Good accessibility for instrumentation
- Isolated investigation
- Industrially relevant environment
- Focus on understanding the underlying phenomena





Transonic Compressor Rig
Facility Design

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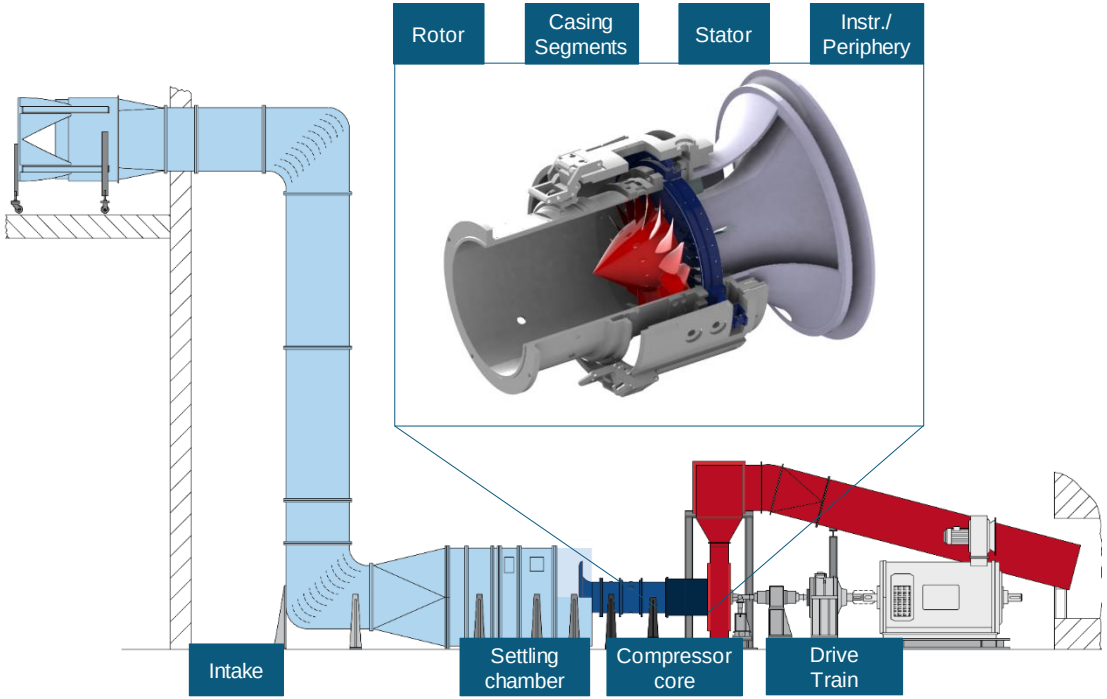
Modular stage design



Single-stage or 1.5-stage axial compressor setups (representative for a HPC front stage)

Capacity	
In /out flow	axial-axial
Electr. Power	800 kW
Max. Torque	350 Nm
Max. speed	20 500 rpm
Max. rotor diameter	0.38 m
Hub to tip ratio	~ 0.5
Rel. Ma-Number @ tip	~ 1.4

Research Focus

Performance, Aerodynamics, Aeroelasticity

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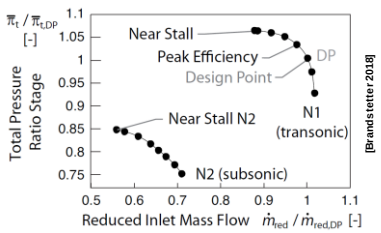
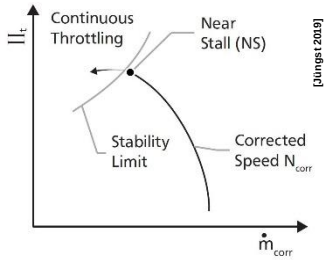
Performance Measurements

- Analyzing global effects
- Influencing parameters



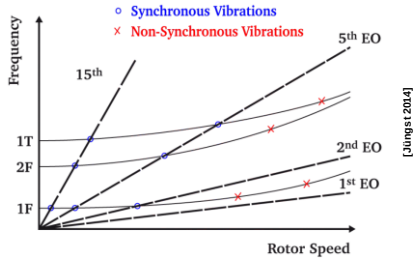
Unsteady Aerodynamics

- Stall inception mechanisms
- Pre-stall disturbances



Aeroelasticity

- Non-synchronous vibration
- Forced response



Interaction & fluid-structure coupling mechanisms

Countermeasures / influences

CONTENT

Facility Introduction

Open Test Case

Darmstadt Transonic Compressor
Stage Design **OPEN TEST CASE**

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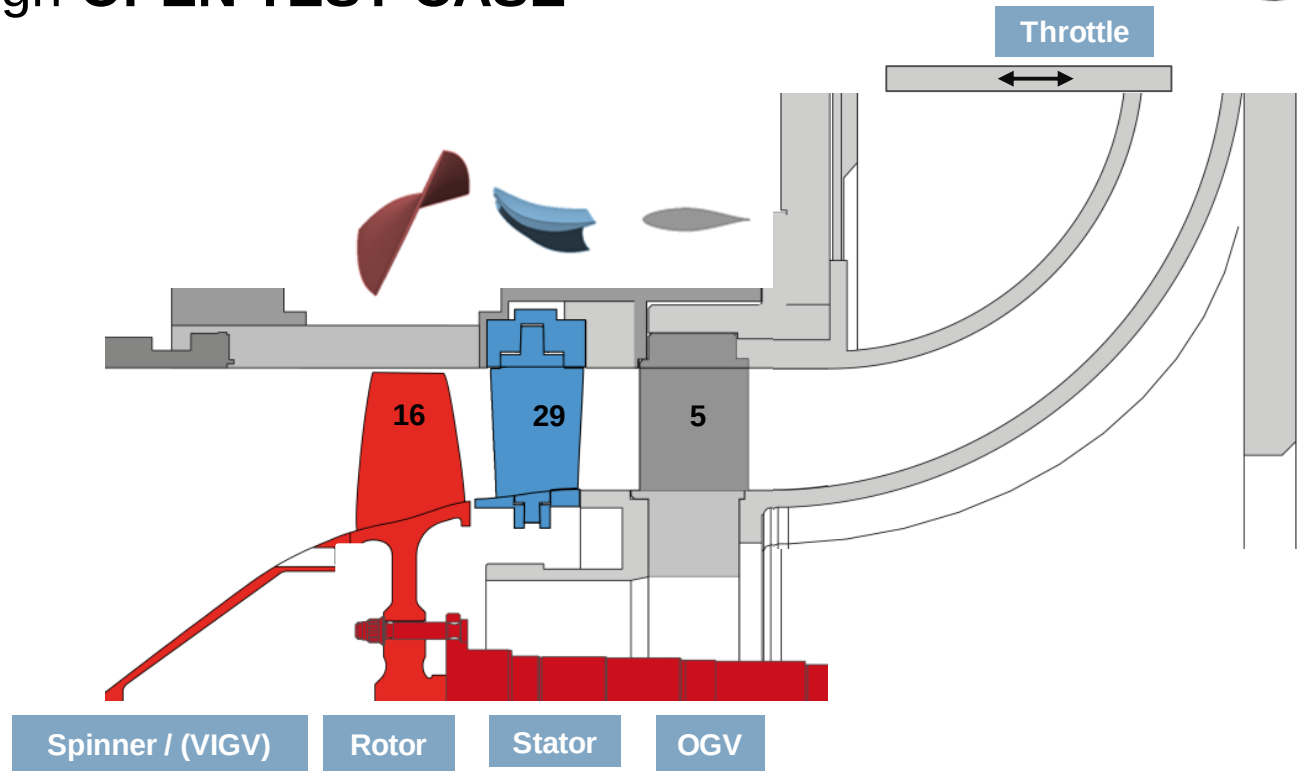

TUDa-GLR-OpenStage
Geometry

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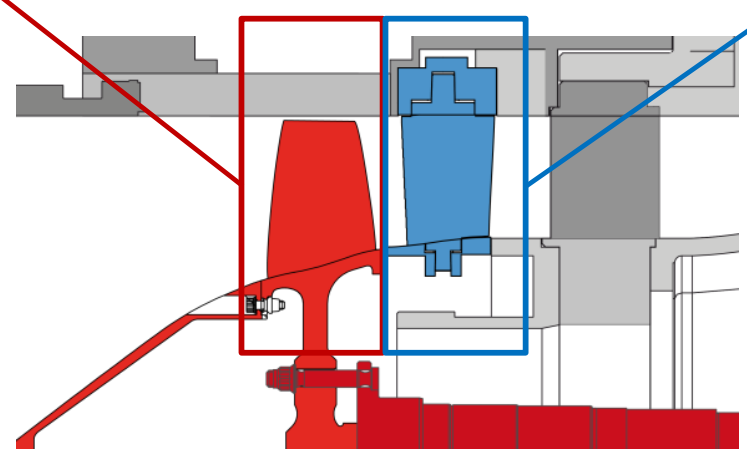
Rotor 1

Designed by *MTU Aero Engines*
- First run 1994
- Broad availability of literature
- open test case



Stator opt. (7)

CFD optimized Stator
- Design and optimization conjointly realized by ***DLR*** and ***GLR*** (see *Bakhtiari, 2015*)
- Suppression of flow separation
- Manufacturing within EU funded H2020 Project ***ARiAS***

Measurement Systems & Instrumentation

Overview

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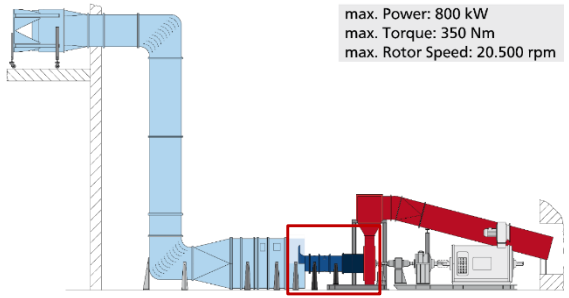
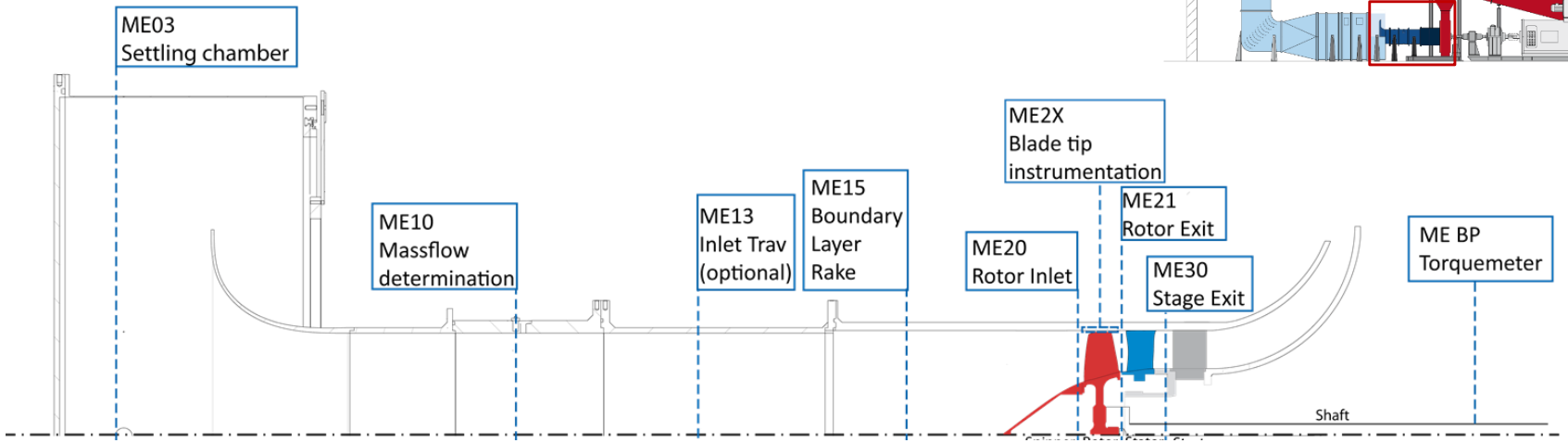
max. Power: 800 kW
max. Torque: 350 Nm
max. Rotor Speed: 20.500 rpm





Measurement Techniques
Performance and Stationary Instrumentation

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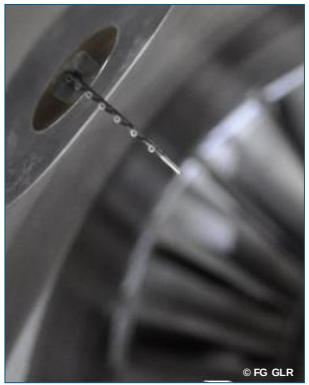
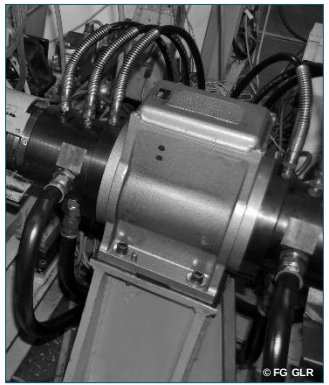
Combined total pressure and temperature rakes

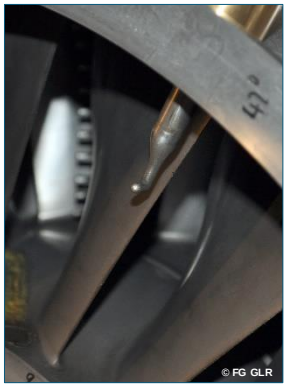
Combined inlet instrumentation



Boundary layer rake



Torque and shaft speed measurements



Traversable five-hole probe

Performance

2D flow field
(p, v, α, etc.)

Measurement Systems & Instrumentation

Time-resolved Instrumentation

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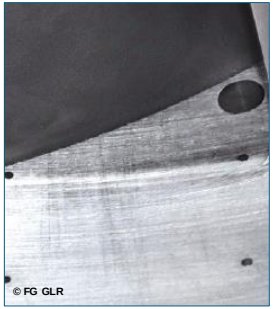
Strain gauges

Blade vibration



Capacitive BTC / BTT system

Only tip clearance

Time-resolved pressure transducer in rotor casing

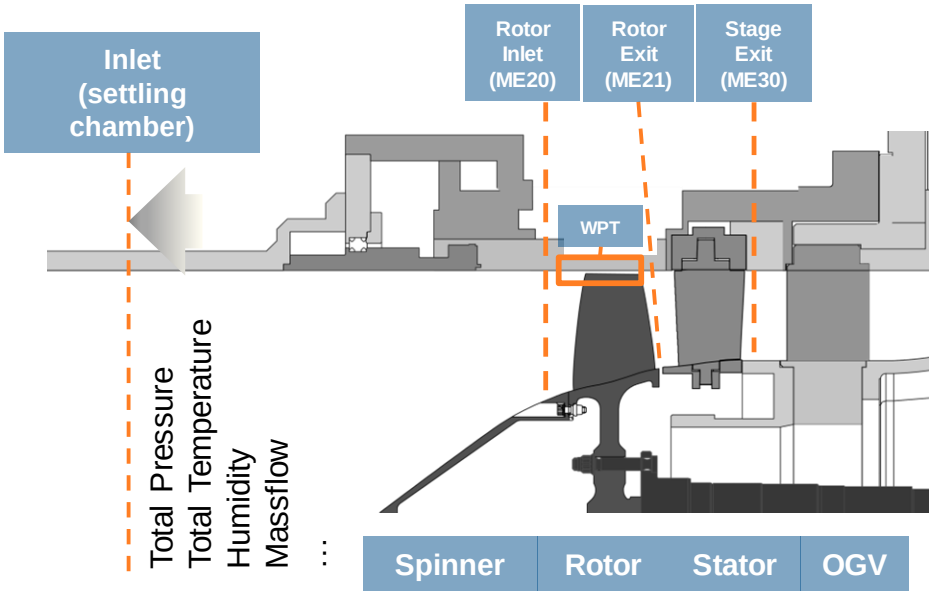
Unsteady aerodynamics within the rotor tip region

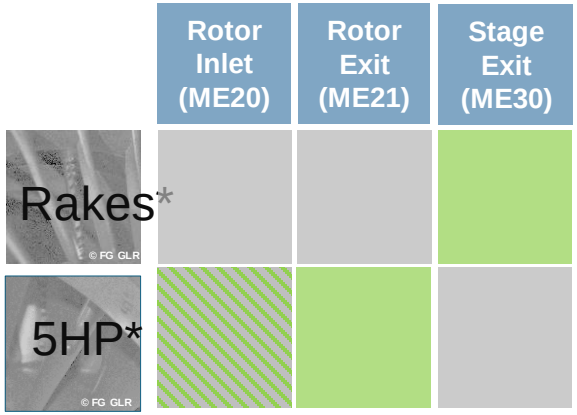
Traversable unsteady pressure probes (virtual multi-hole probe)

Unsteady 2D flow field within the rotor / stage exit plane

Transonic Compressor Rig Introduction

Instrumentation – Compressor Core (Open Test Case)



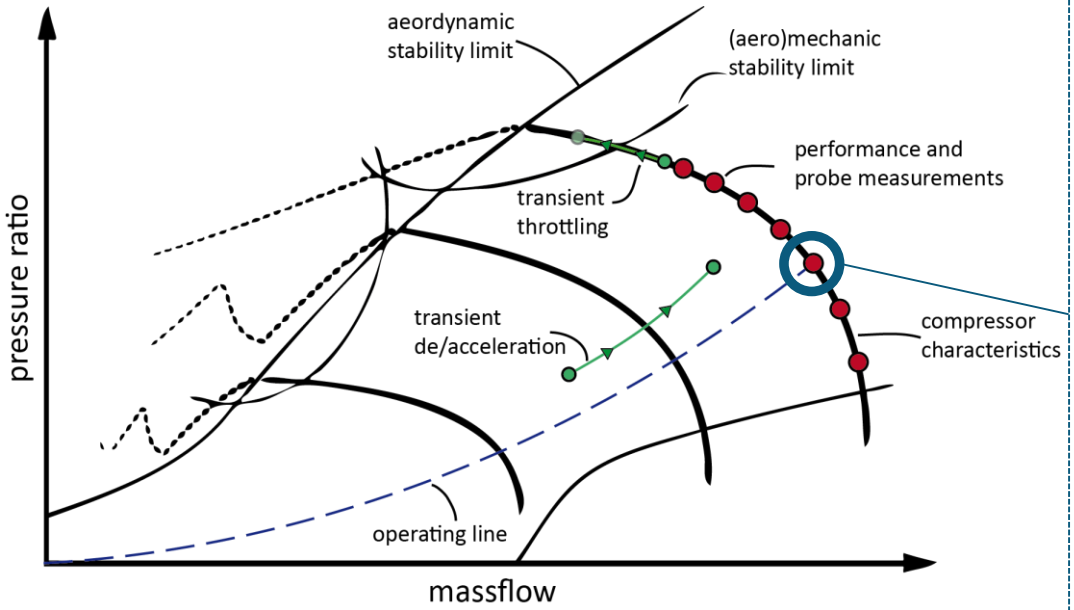


Measurement of static pressure in all sections (casing)

Rakes*: Total Temperature and Pressure
5HP*: Mach numbers and flow angles – stationary frame of reference

Measurement Systems & Instrumentation

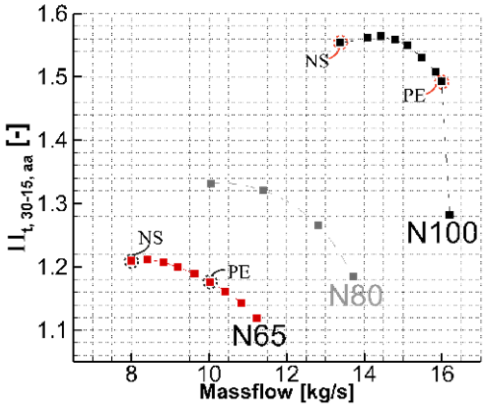
Test Procedure, Data Acquisition & Processing

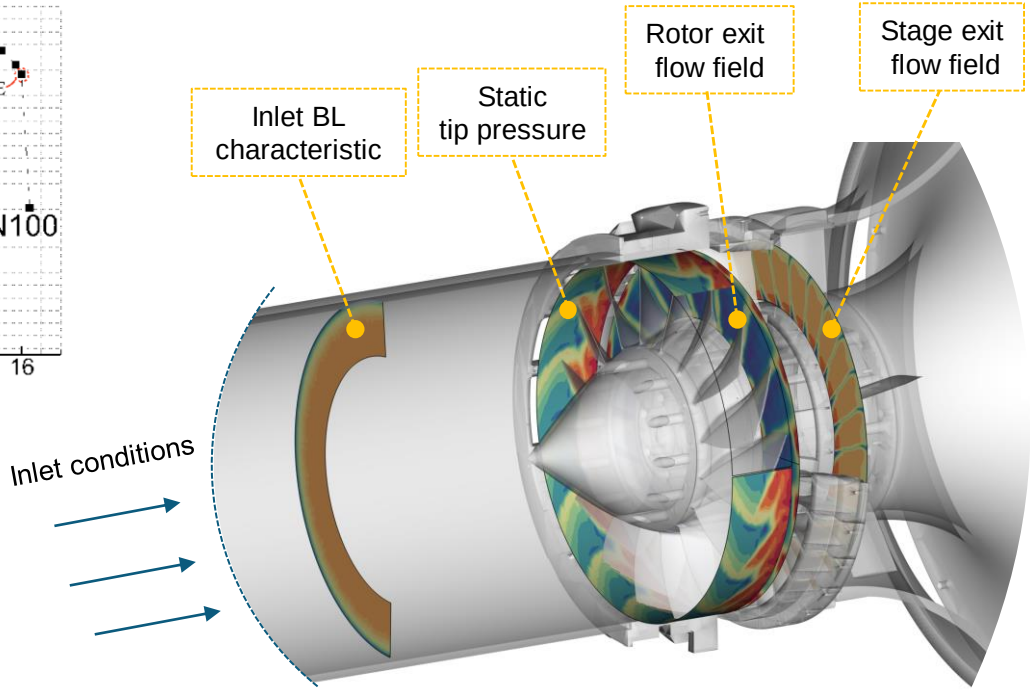


Steady-state Operating Point

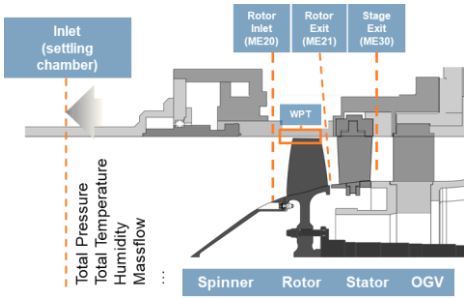
- Defined by:
  - **Reduced massflow**
  - **Reduced speed**
- Measurements:
  a. Stage exit flow field (exit rakes) – at all shared OPs
  b. Probe measurements at **PE** and **NS** conditions
  c. Unsteady wall pressure measurements
  d. Blade tip clearance at all shared OP

Data Set





Data Set - OUTLOOK



Repro 2022

- Detailed 5HP measurements in ME30
- Detailed v4PH measurements in ME21/ME30
- Included IM OP
- Included stator cavity leakage variation

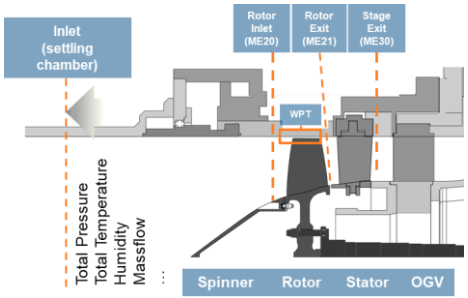
2020

	Rotor Inlet (ME20)	Rotor Exit (ME21)	Stage Exit (ME30)
Rakes*			
5HP*			

2022

	Rotor Inlet (ME20)	Rotor Exit (ME21)	Stage Exit (ME30)
Rakes*			
5HP*			
v4HP*			

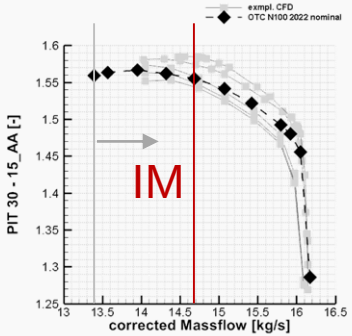
Data Set - OUTLOOK



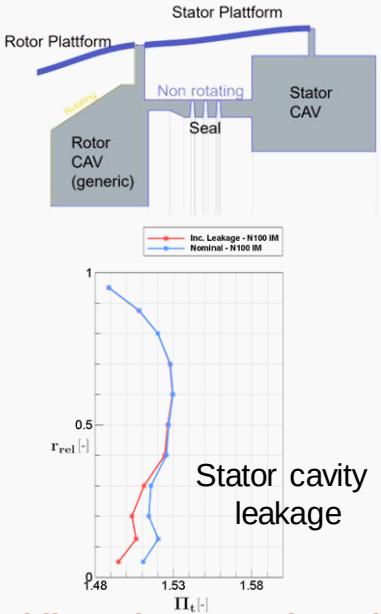
Repro 2022

- **Detailed 5HP measurements in ME30**
- **Detailed v4PH measurements in ME21/ME30**
- **Included IM OP**
- **Included stator cavity leakage variation**

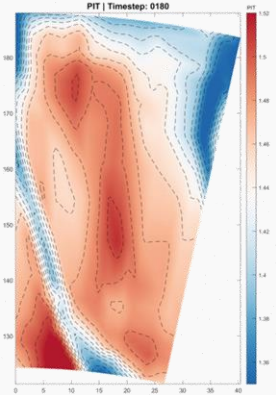
2022



Additional OP for probe data In all sections



Stator cavity leakage



Virtual probe in ME30

available in bilateral cooperation with TUDa

GPPS Global Power & Propulsion | CHANIA 2022 12th-14th September

Next Speaker

Xiao He

Imperial College London

Department of Aeronautics

Comparison – Mingmin Zhu SJTU
CFX SST fine

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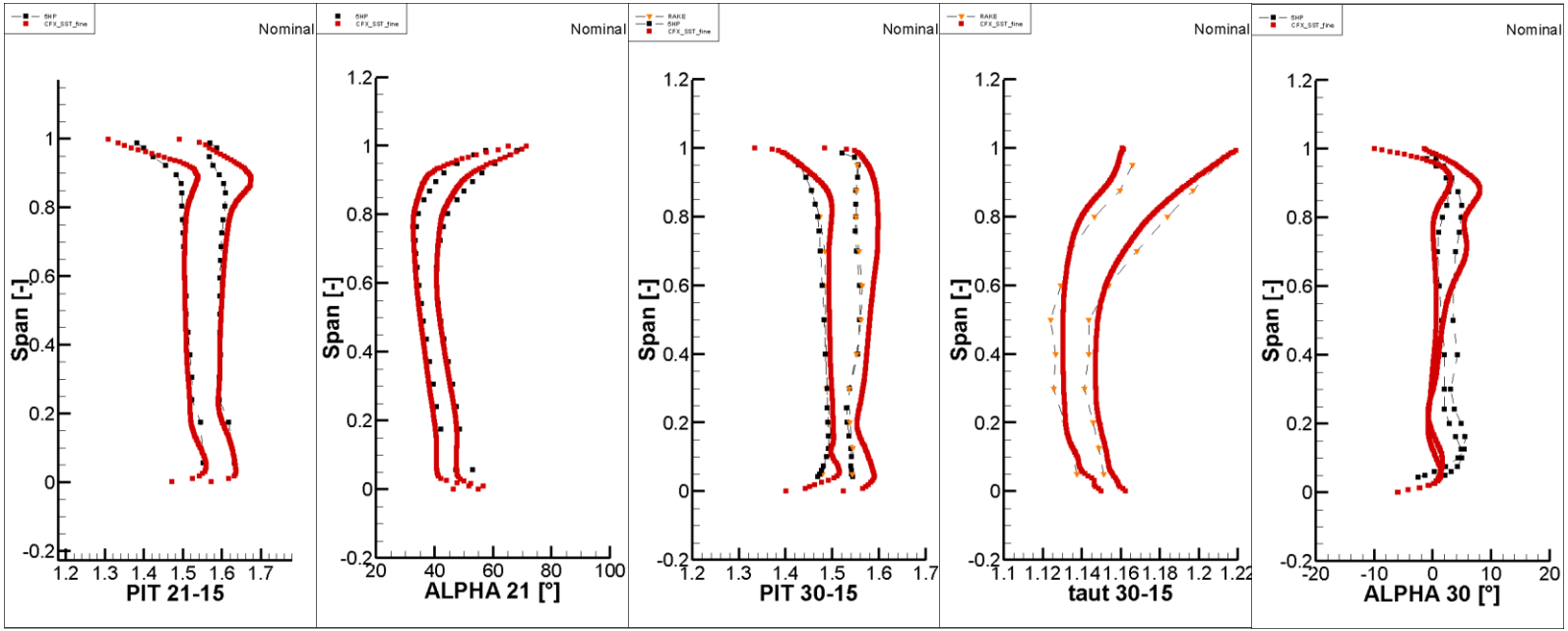

Comparison – Bruni Giuseppe Siemens Turbostream_SA_inhouse_N100

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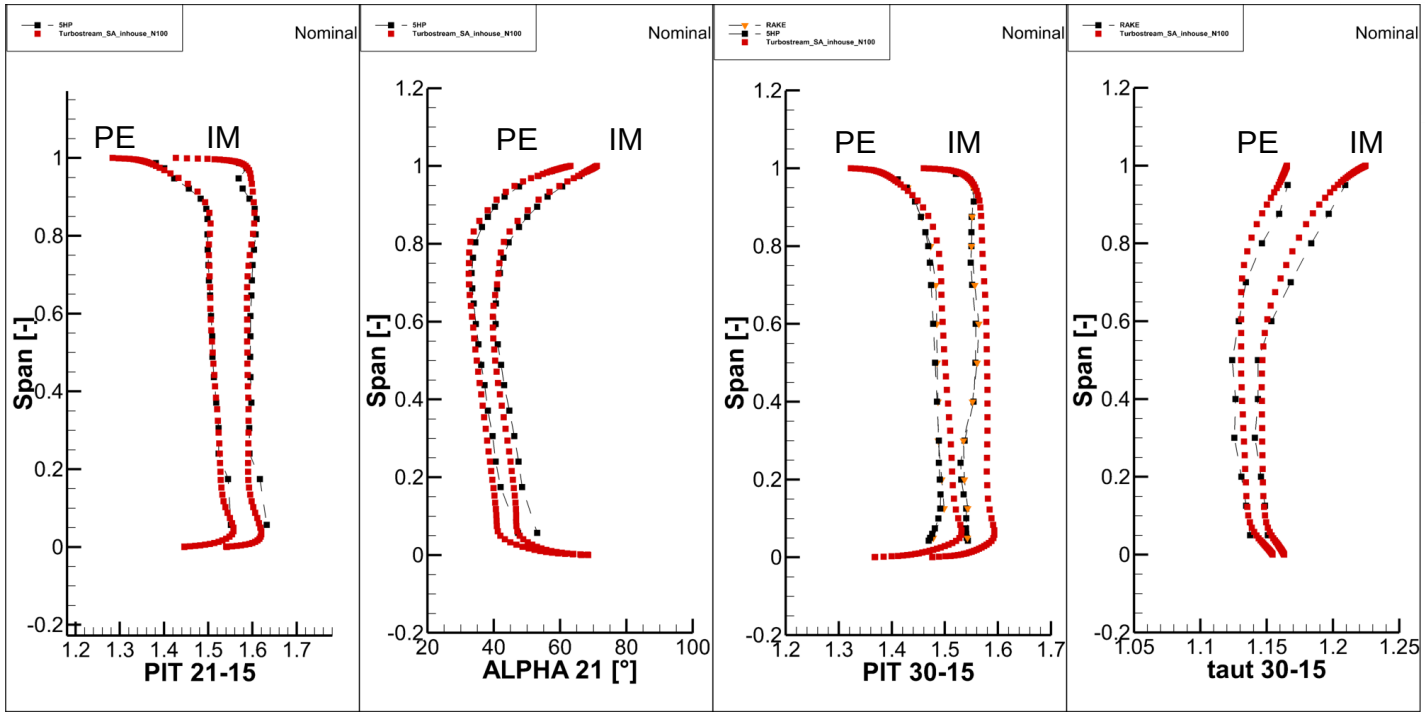
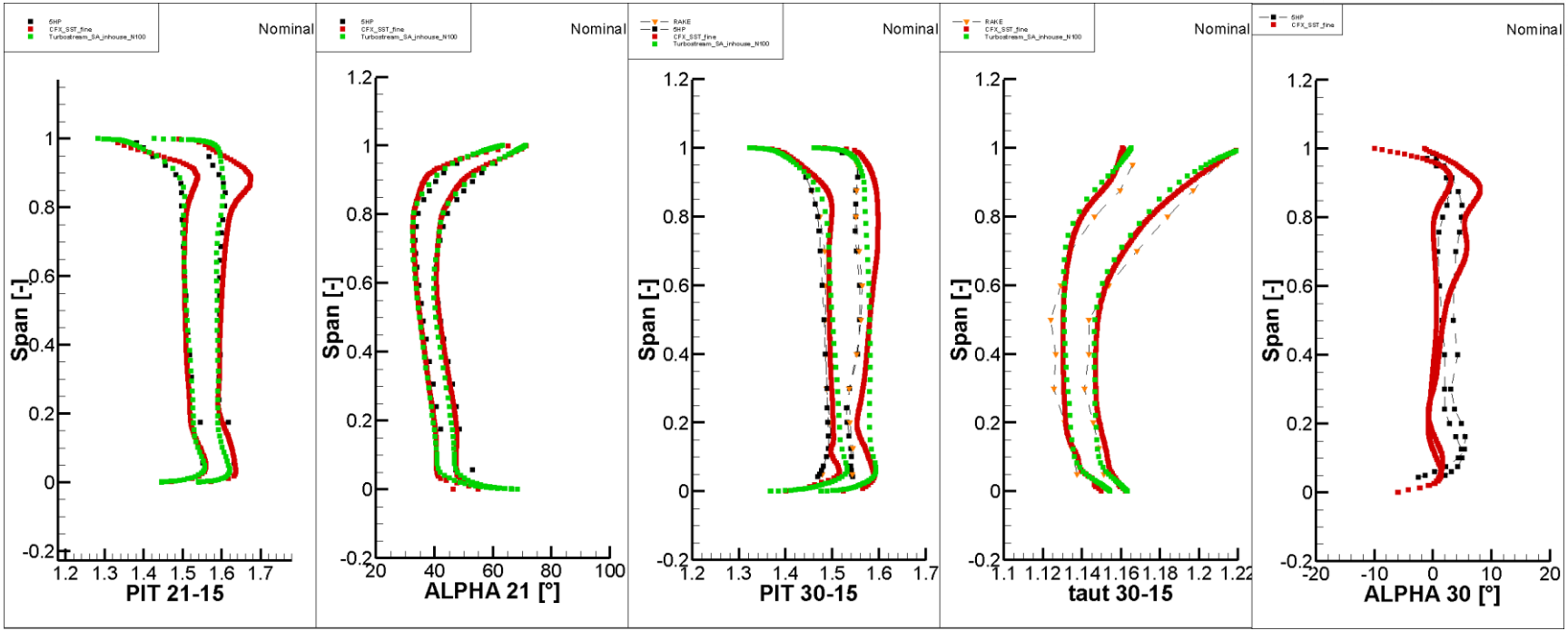


CFX SST fine - Turbostream



Comparison – Mendicino Domenico Cadence Fine Turbo EARSM

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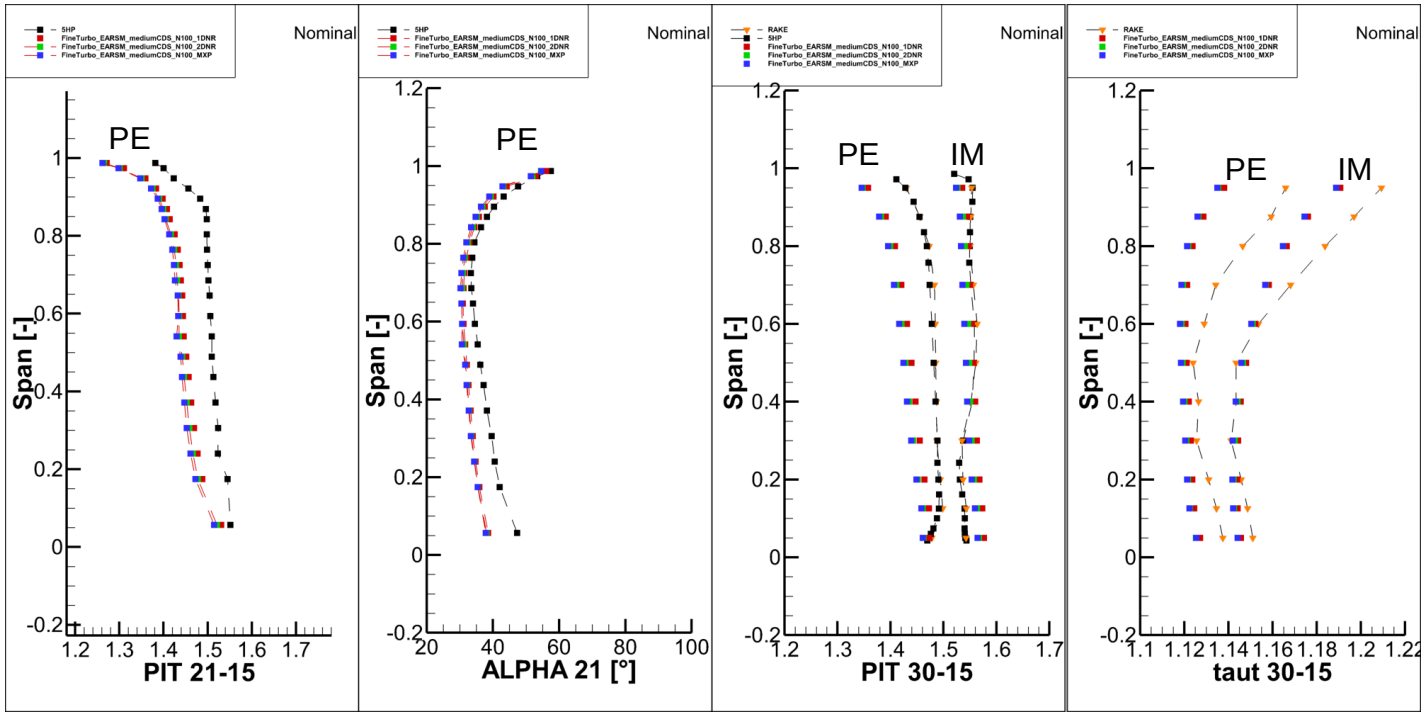

Backup

CONTENT

Facility Introduction

Measurement Techniques

Test Procedures, Data Acquisition and Dataset

Conclusion

Measurement Systems & Instrumentation
Overview

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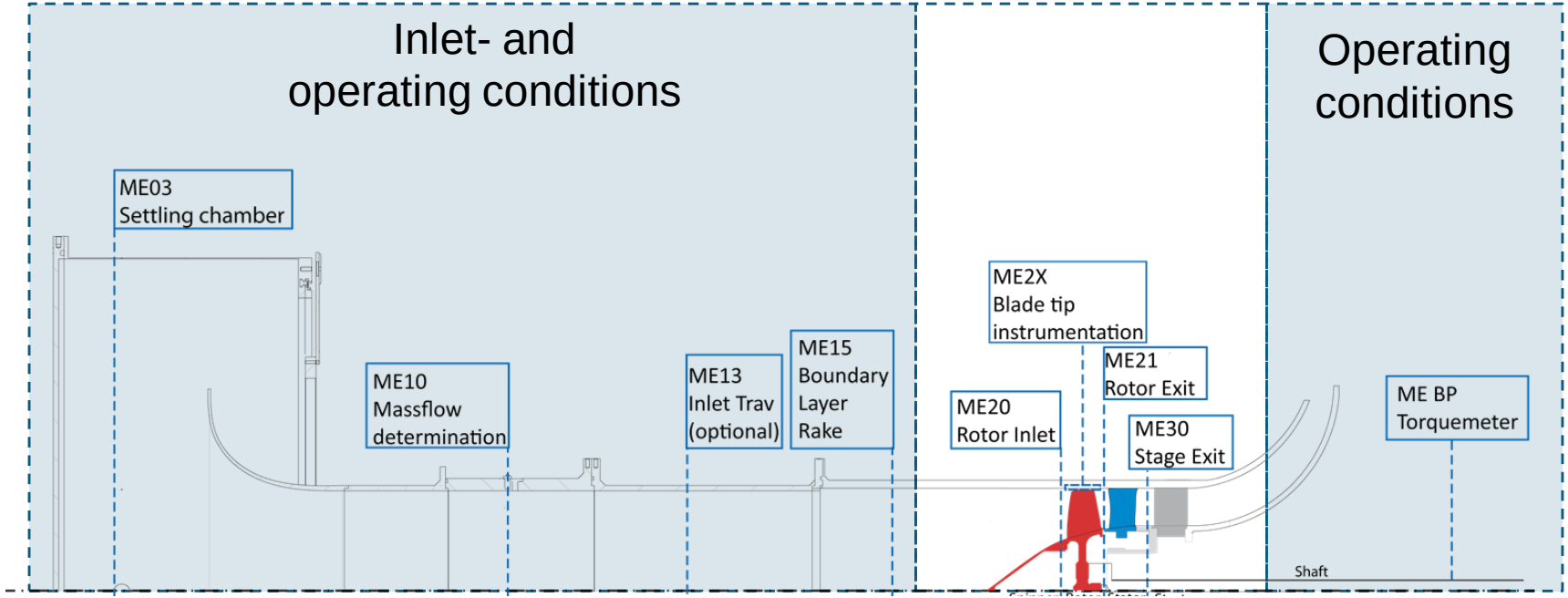

Measurement Techniques
Performance and Stationary Instrumentation

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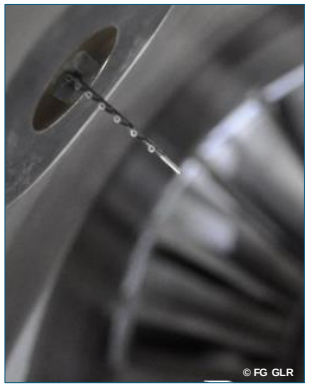
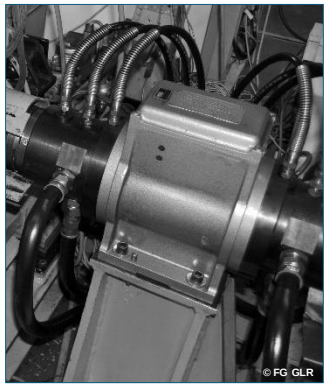
Combined total pressure and temperature rakes

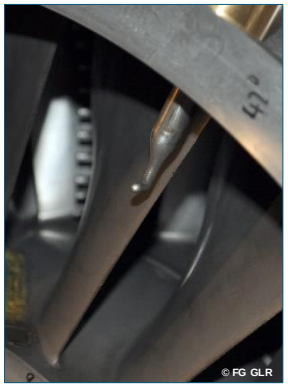
Combined inlet instrumentation



Boundary layer rake



Torque and shaft speed measurements



Traversable five-hole probe

Performance

2D flow field
(p, v, α, etc.)

Measurement Systems & Instrumentation
Time-resolved Instrumentation

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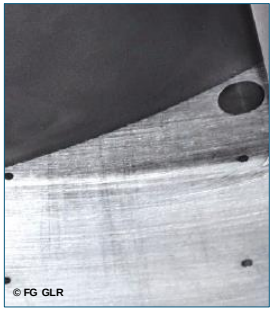
Strain gauges

Blade vibration



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Only tip clearance

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Unsteady aerodynamics within the rotor tip region

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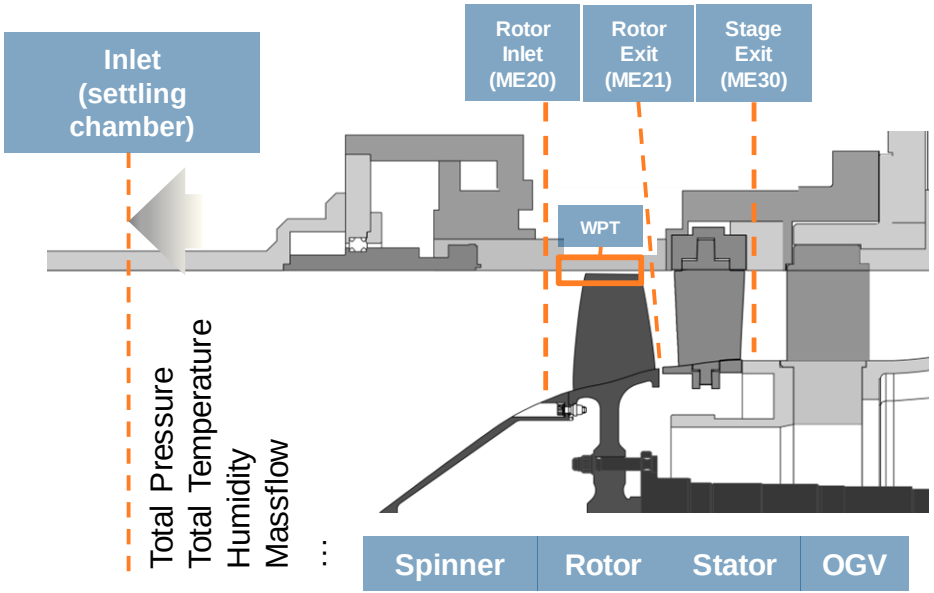
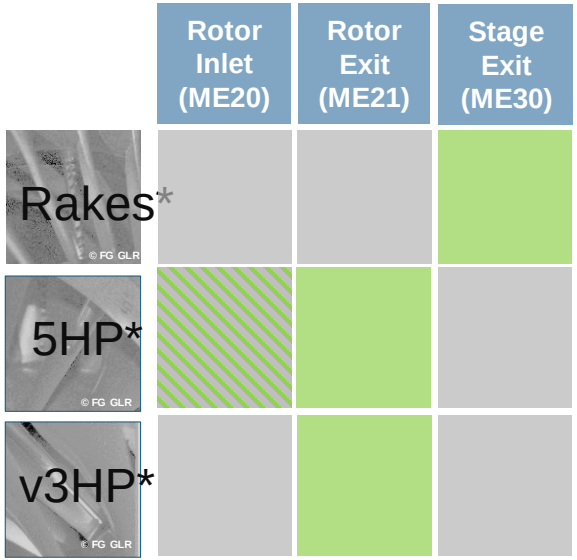
Transonic Compressor Rig Introduction

Instrumentation – Compressor Core (Open Test Case)





Rakes*: Total Temperature and Pressure
5HP*: Mach numbers and flow angles – stationary frame of reference
v3HP*: Mach numbers and flow angles – rotating frame of reference

Measurement of static pressure in all sections (casing)

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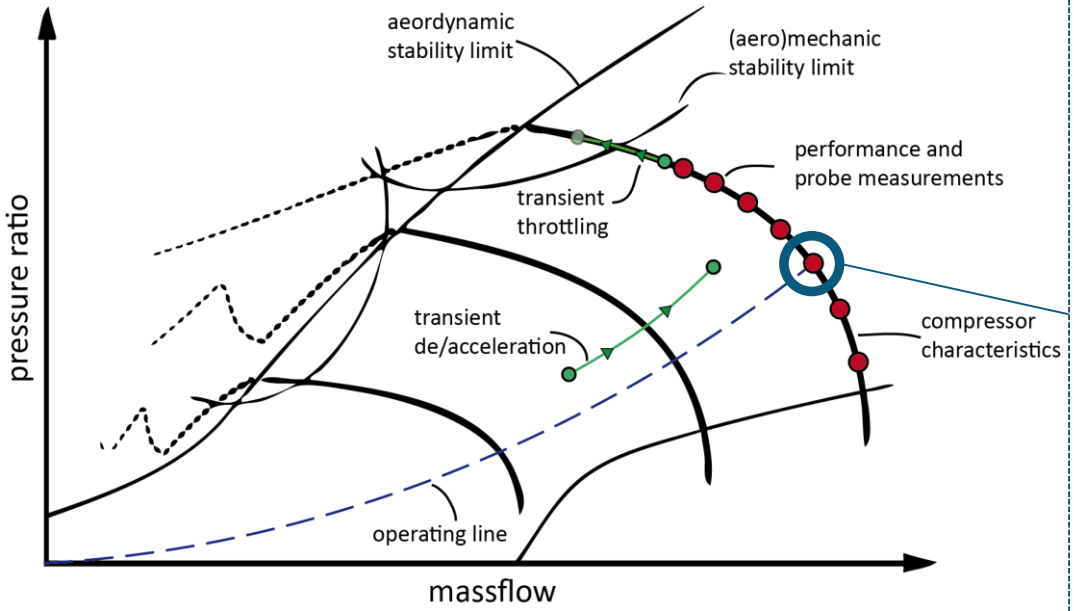
Test Procedure, Data Acquisition & Processing



Steady-state Operating Point

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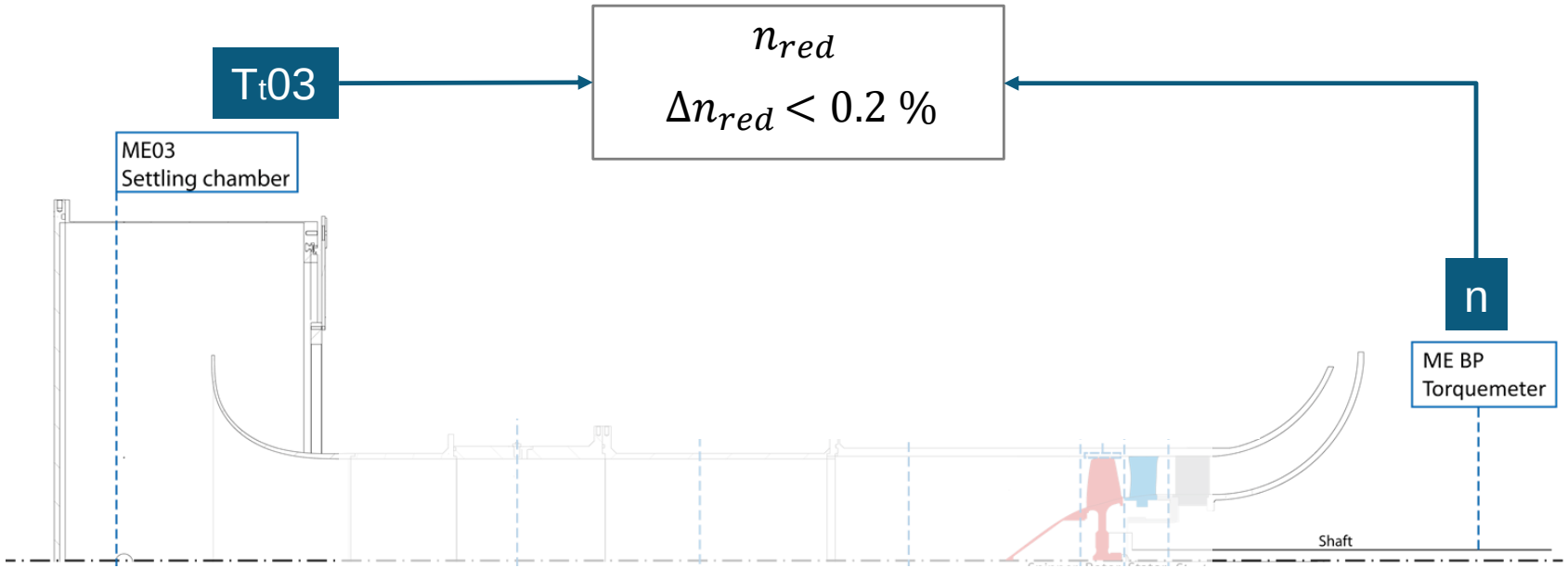
Measurement Systems & Instrumentation

Massflow Determination / Operating Point Definition



Measurement Systems & Instrumentation

Massflow Determination / Operating Point Definition

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P_{t03} / P_{s03}

T_{t03}

$$\dot{m} = \alpha \epsilon A_{in} \sqrt{2 \rho_{03} \Delta p}$$

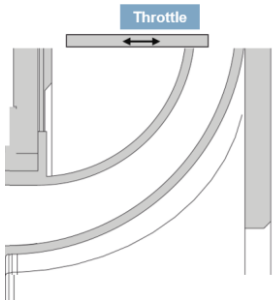
$$\Delta \dot{m} < 0.2\%$$

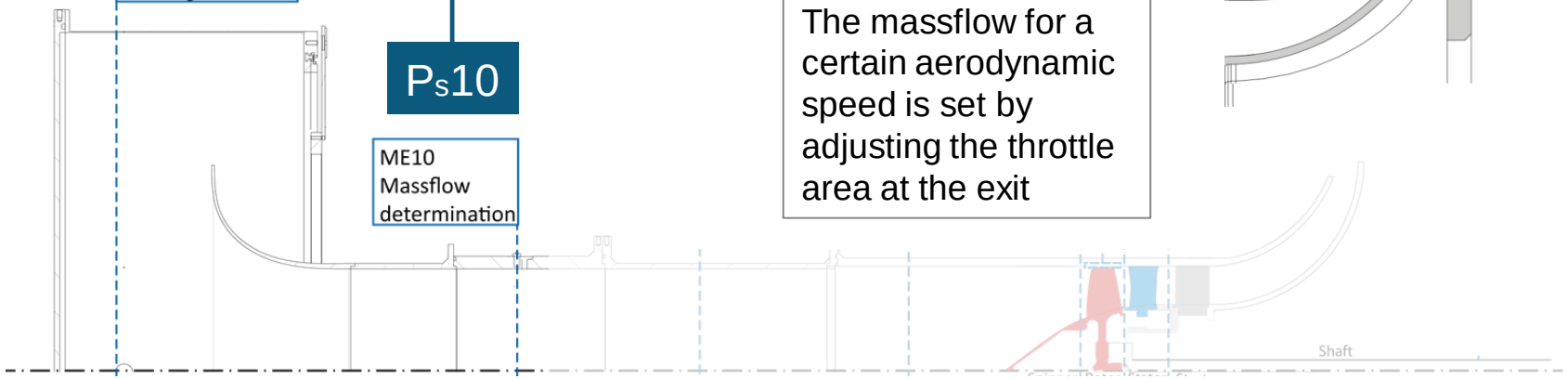
ME03
Settling chamber

P_{s10}

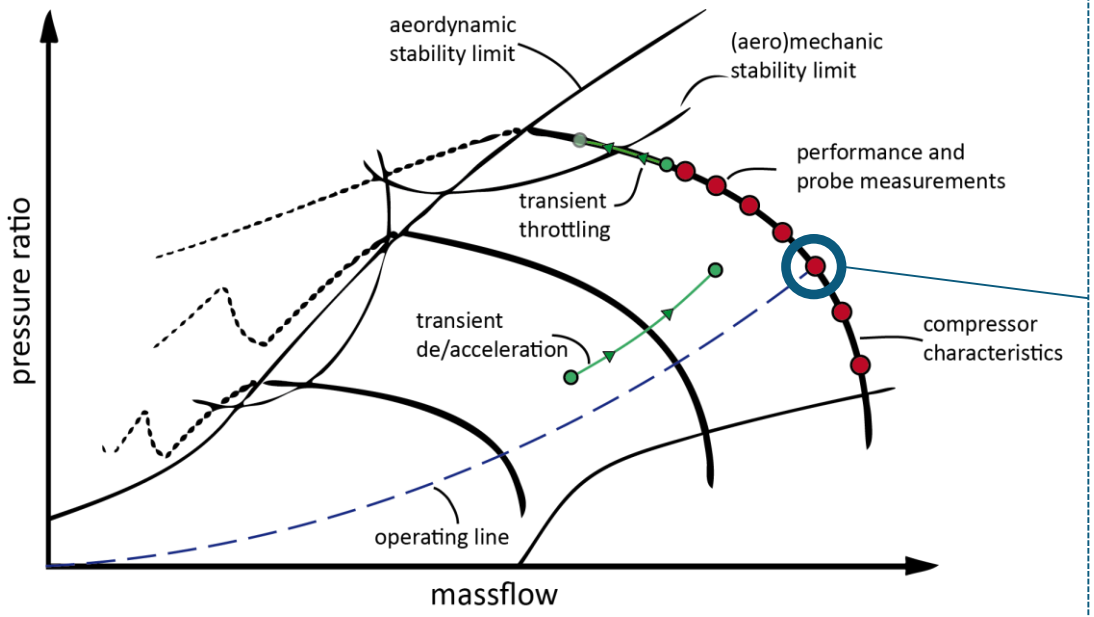
ME10
Massflow
determination

The massflow for a certain aerodynamic speed is set by adjusting the throttle area at the exit

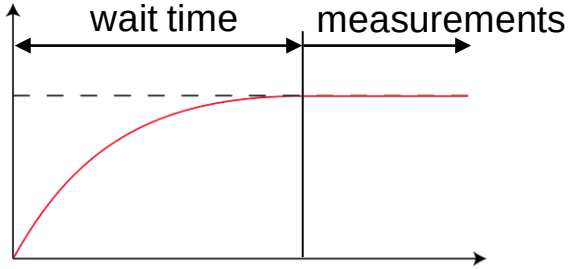




Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing



Steady-state Operating Point



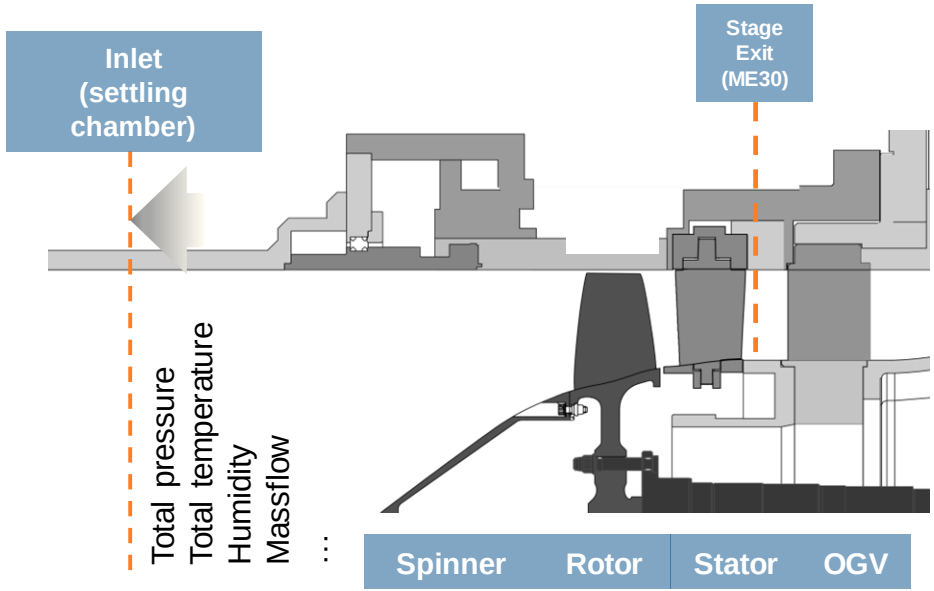
- Wait time until all measurement systems related to operating conditions converge (e.g. tip gap, temperatures …)
- Afterwards, rig is ready for stationary measurements

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

(a) Stage exit flow field (exit rakes)



Combined total pressure and temperature rakes

Measurement of:

- Total pressure
- Total temperature

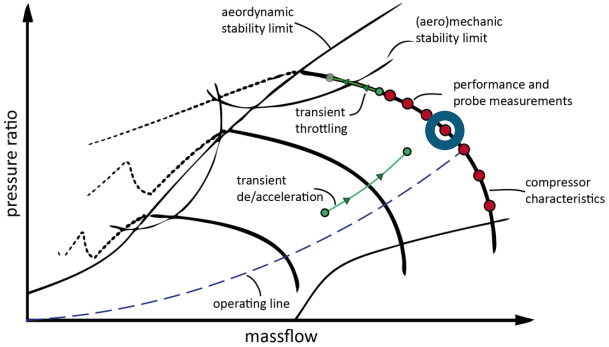
Determination of

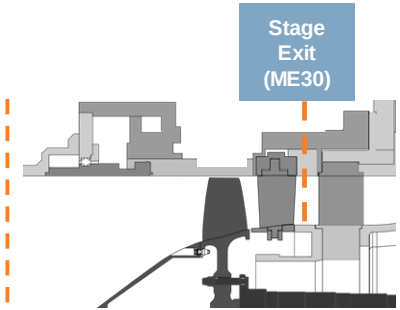
- Total *pressure/temperature* ratio
- isentropic efficiency

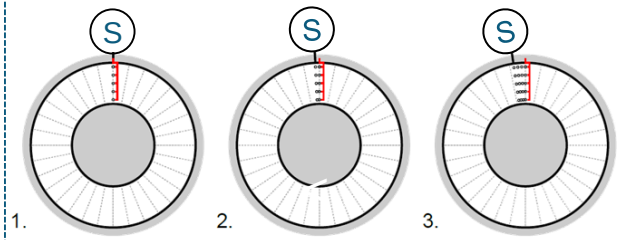
Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

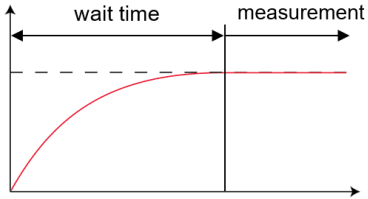
(a) Stage exit flow field (exit rakes)







Traversing of stationary parts
(15 positions per stator passage)



P_{t30} T_{t30}

Stepwise clocking of stator module:

- In between each clocking position waiting for convergence of relevant parameters
- Measurement time is set, thus number of uncorrelated measurements varies

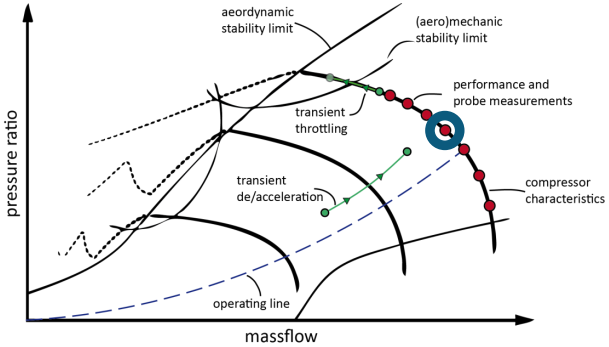
Waiting time open test case = 20s
Measurement time open test case = 6s

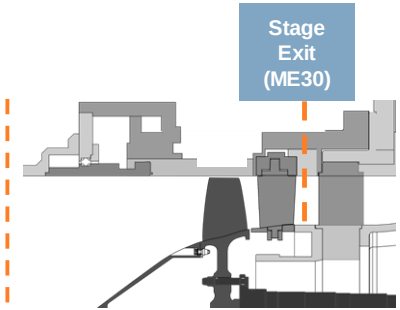
Measurement Systems & Instrumentation

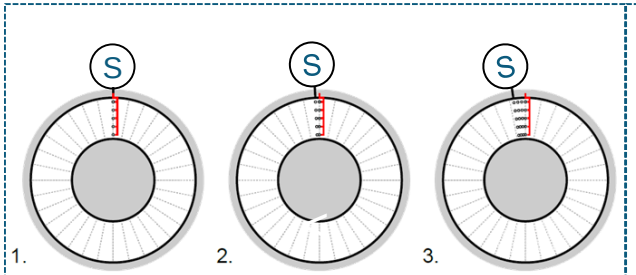
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

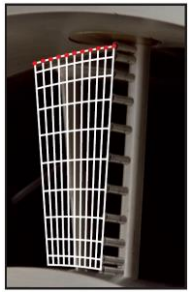
(a) Stage exit flow field (exit rakes)





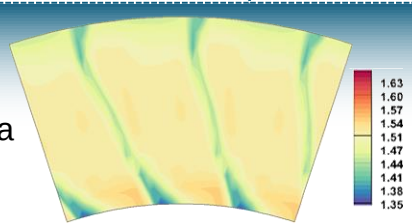


Traversing of stationary parts (15 positions per stator passage)



2 dimensional measurement grid

Exit flow field data



Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

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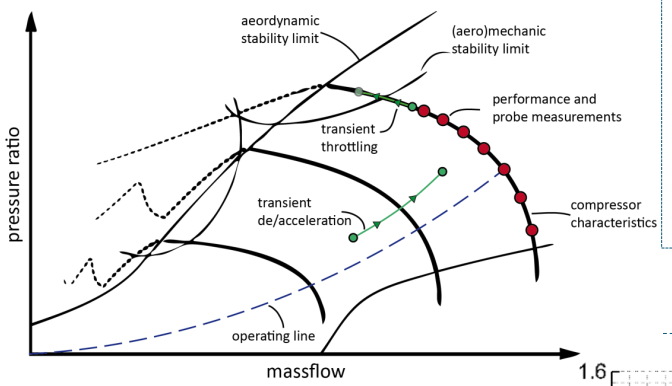
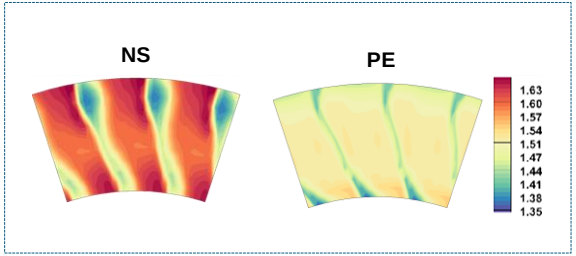
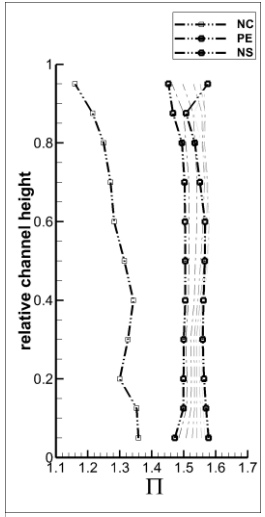
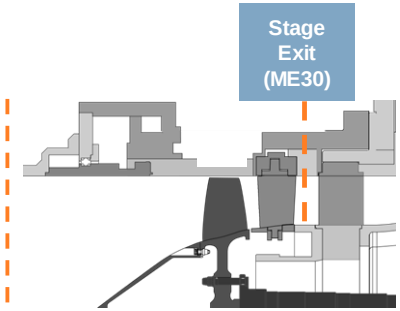
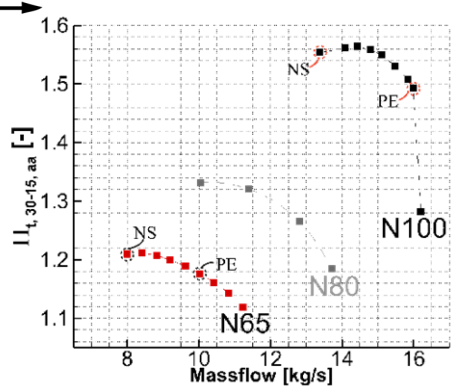
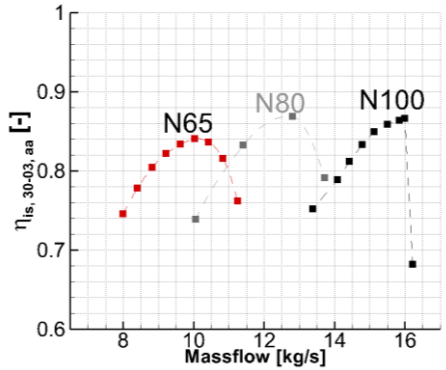












Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

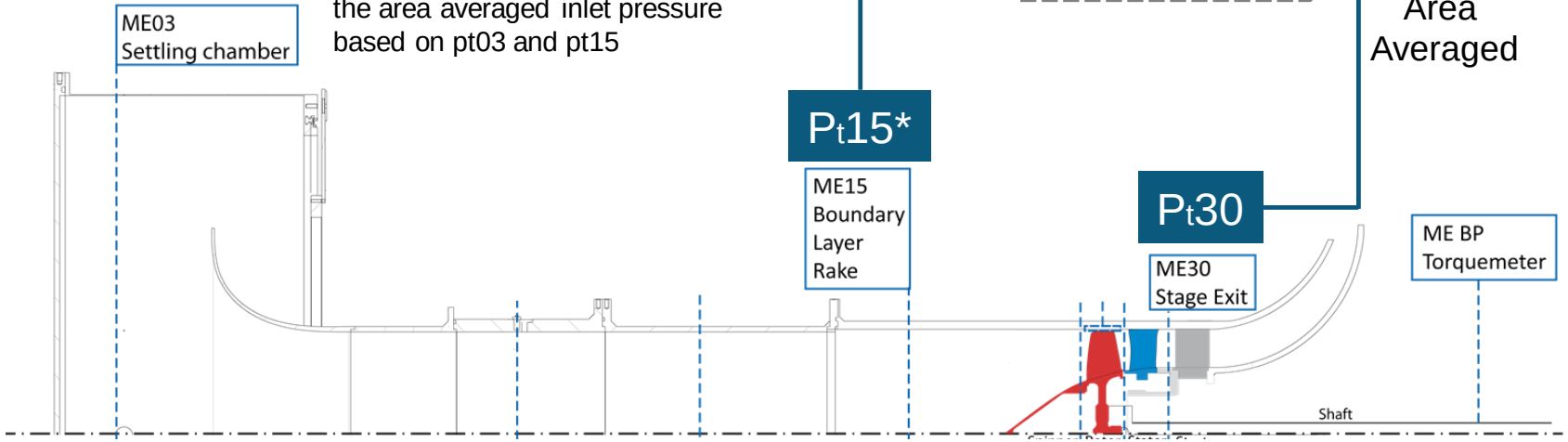
(a) Stage exit flow field (exit rakes)

$$\Pi_t = \frac{P_{t,out}}{P_{t,in}}$$

P_t03 / P_s03

All total pressure ratios are determined with the area averaged inlet pressure based on pt03 and pt15

Area Averaged



*considers pressure loss in inlet duct

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

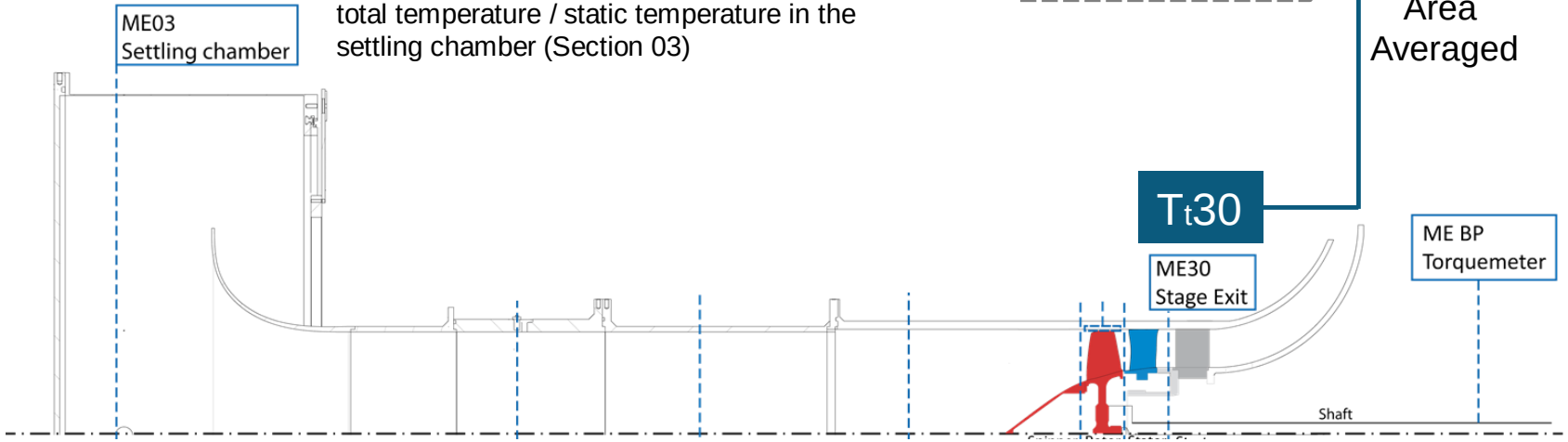
(a) Stage exit flow field (exit rakes)

$$\tau = \frac{T_{t,out}}{T_{t,in}}$$

T_t03^*

All temperature ratios are determined with the total temperature / static temperature in the settling chamber (Section 03)

Area Averaged

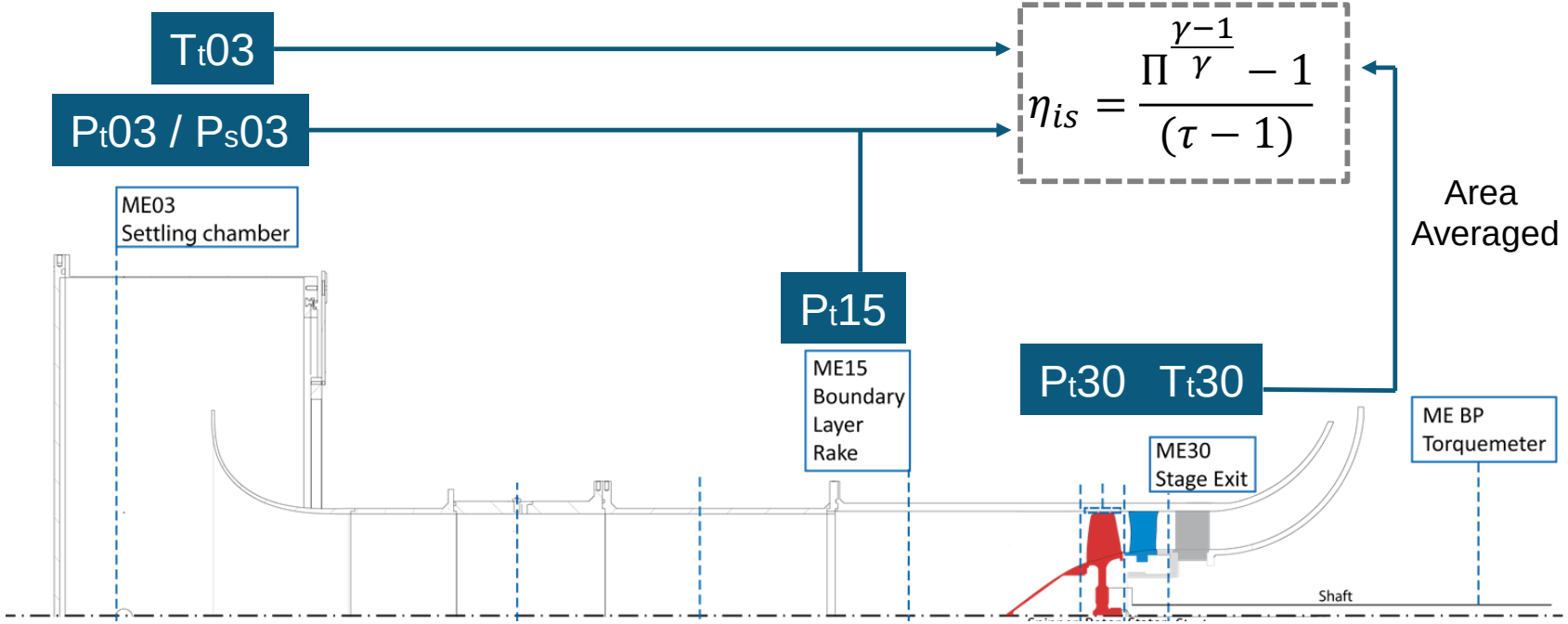


*Inlet duct assumed to be adiabatic

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

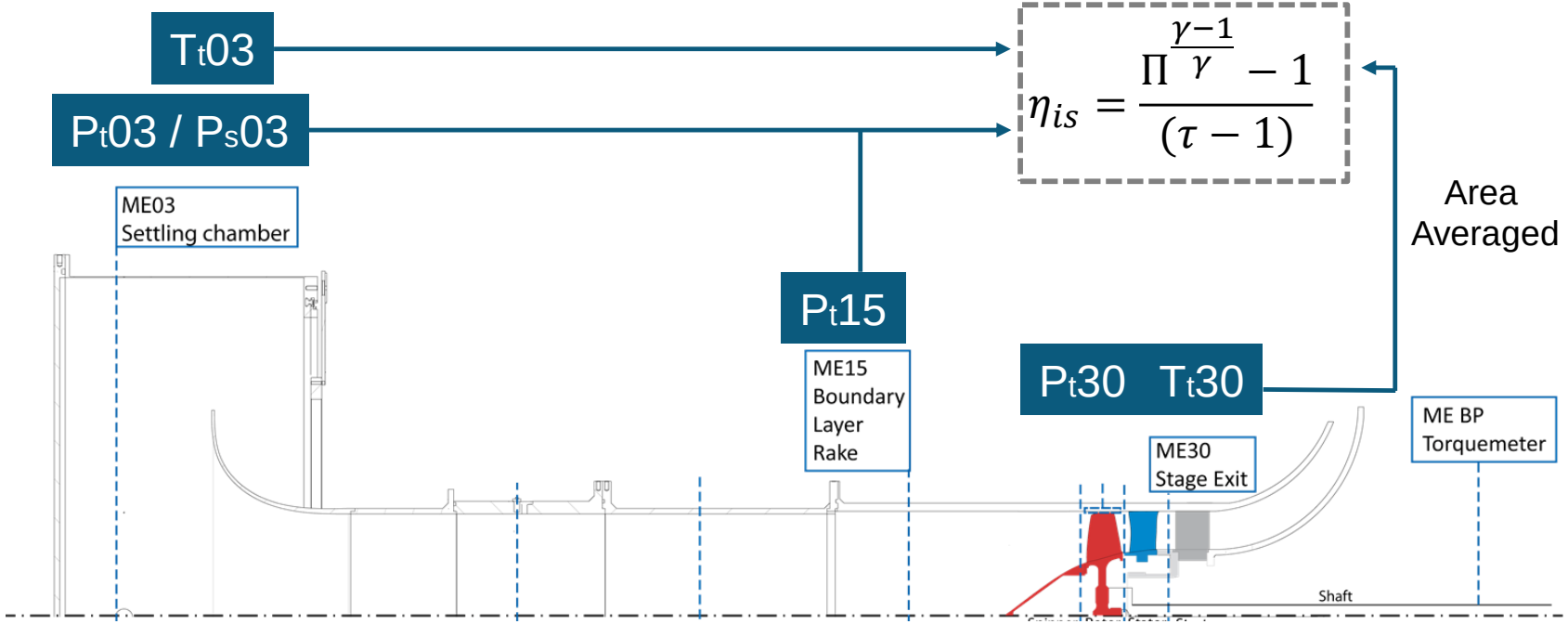


*change of γ due to changing inlet conditions is considered

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT



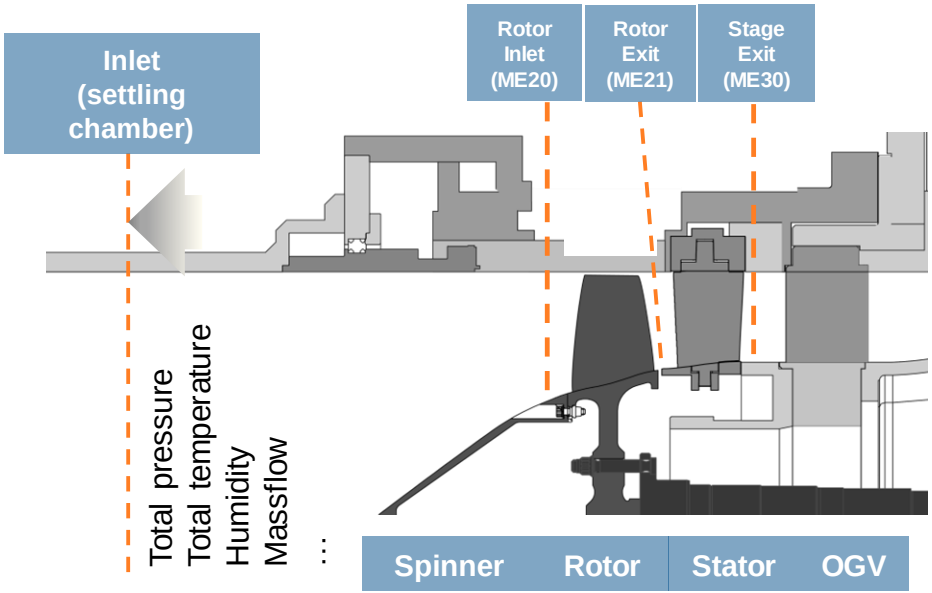
*change of γ due to changing inlet conditions is considered

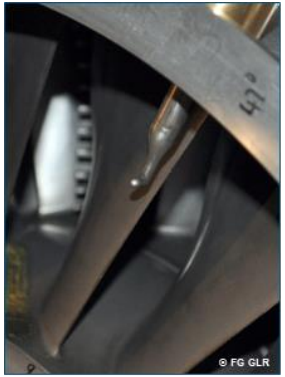
Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

(b) Probe measurements





Traversable five-hole probe

Stationary frame of reference

- Total pressure
- Flow angles
- Local flow velocities

Traversable unsteady pressure probes (virtual multi-hole probe)

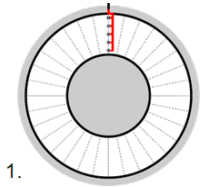
Rotating frame of reference

- Total pressure
- Flow angles
- Local flow velocities

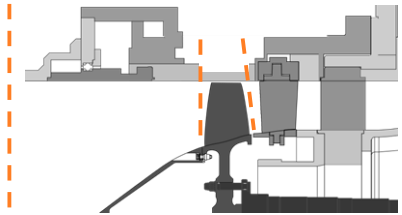
Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

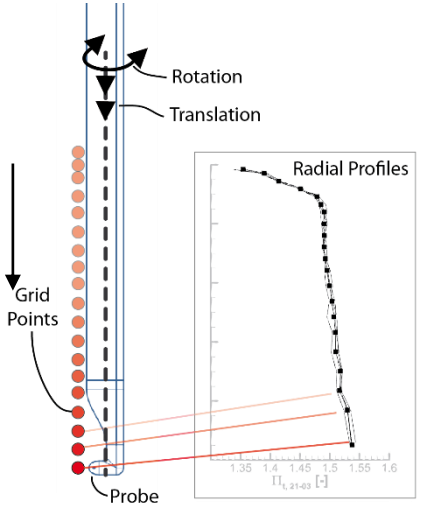
TECHNISCHE UNIVERSITÄT DARMSTADT

(b) Probe measurements

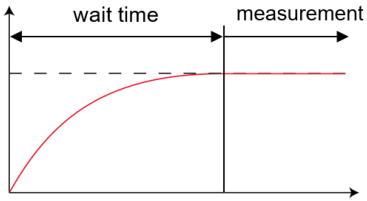


Conditions:
- » Operating conditions are set
- » Stator clocking is set





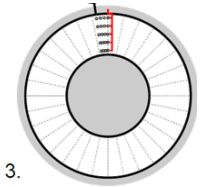
Stepwise radial traversing of probe:
- » In between each clocking position waiting for convergence of relevant values
- » Measurement time is set, thus number of uncorrelated measurements varies



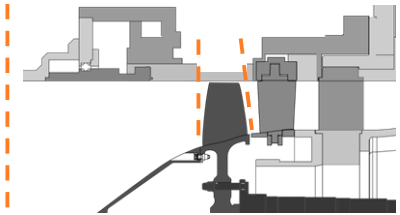
Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

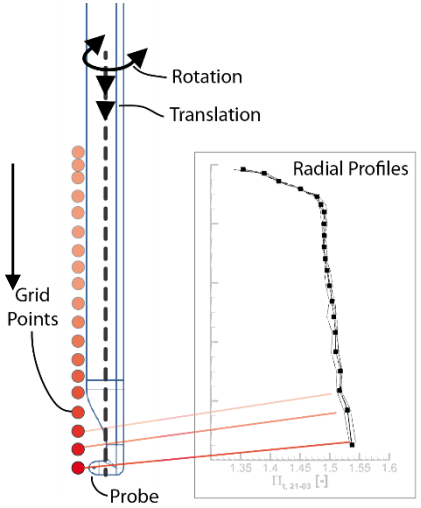
TECHNISCHE UNIVERSITÄT DARMSTADT

(b) Probe measurements



Conditions:
- » Operating conditions are set
- » Stator clocking is set





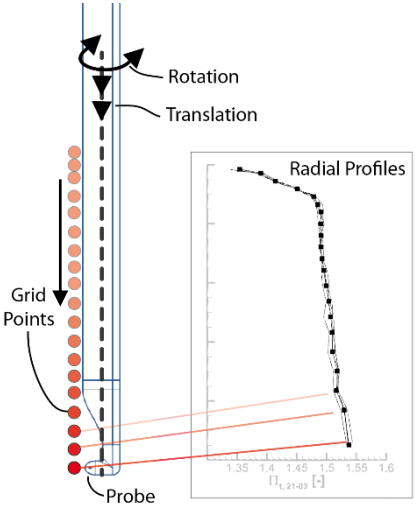
Stepwise radial traversing of probe:
- » In between each clocking position waiting for convergence of relevant values
- » Measurement for set time, thus number of uncorrelated measurements varys
- » Several stator relative radial profiles are measured

Open test case data considers 4 stator clocking positons for rotor inlet (ME20) and exit (ME21) to consider stator influence (e.g. potential field) and 15 for stage exit (ME30)

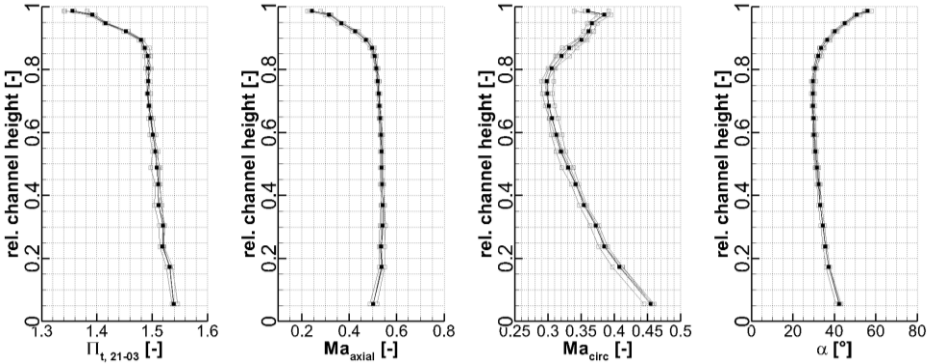
Measurement Systems & Instrumentation

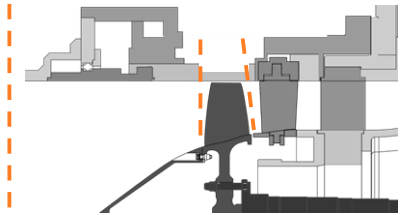
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

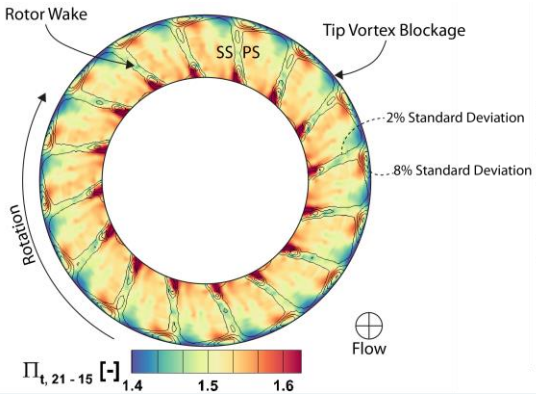


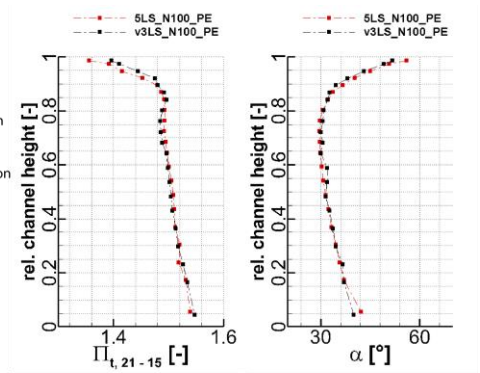
5HP





v3HP





Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

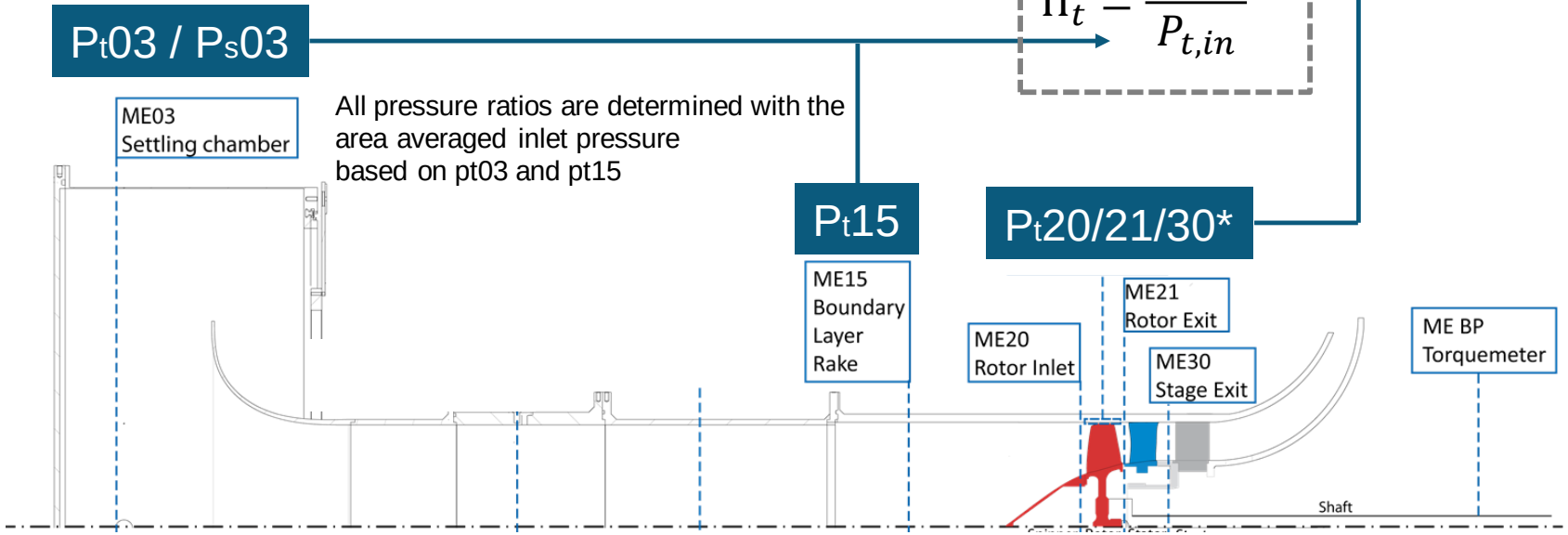
TECHNISCHE UNIVERSITÄT DARMSTADT

(b) Probe measurements

$$\Pi_t = \frac{P_{t,out}}{P_{t,in}}$$

P_t03 / P_s03

All pressure ratios are determined with the area averaged inlet pressure based on pt03 and pt15



*depending on probe location

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

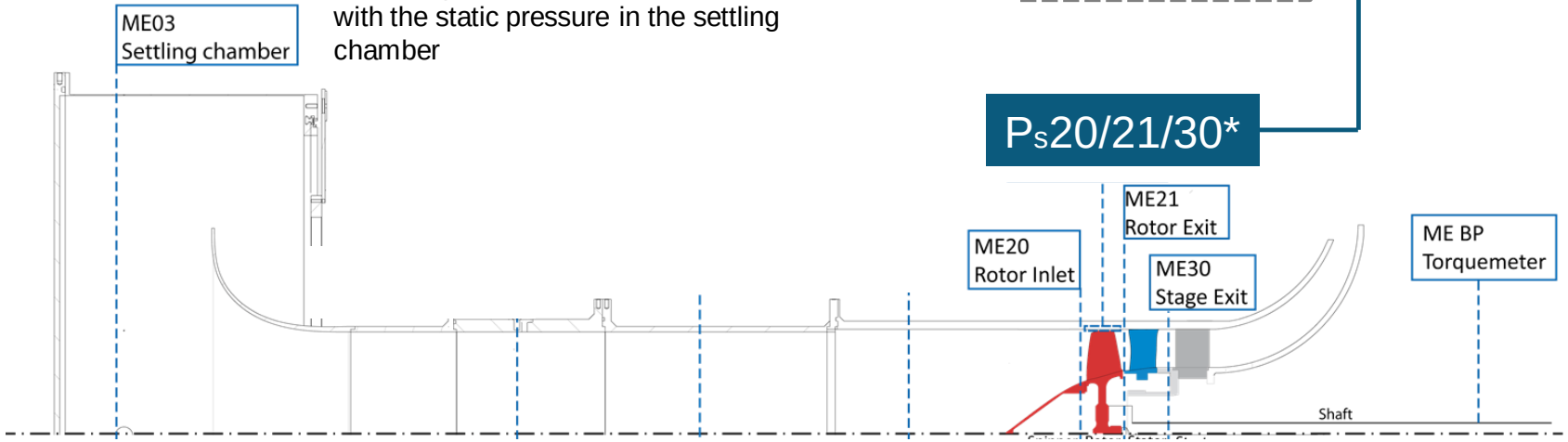
TECHNISCHE UNIVERSITÄT DARMSTADT

(b) Probe measurements

$$\Pi_s = \frac{P_{s,out}}{P_{s,in}}$$

P_s03

All static pressure ratios are determined with the static pressure in the settling chamber



*depending on probe location

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

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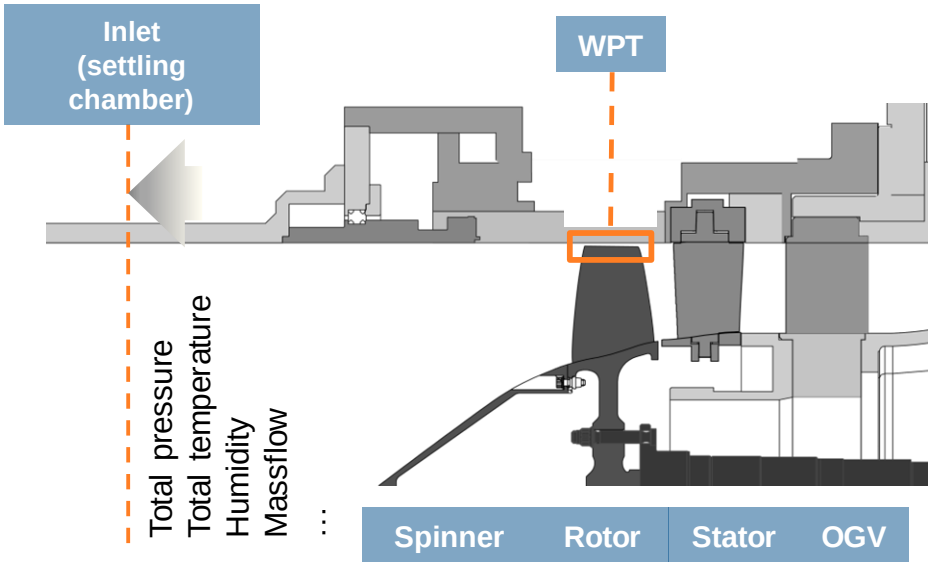
(c) Unsteady wall pressure measurements

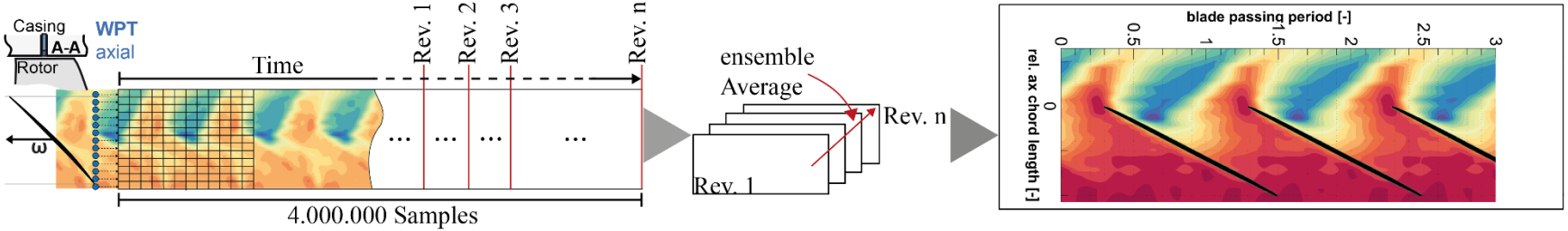


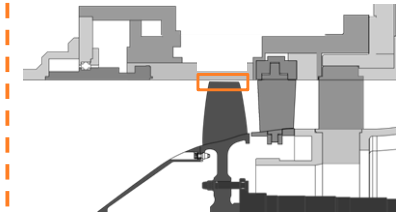
Time-resolved pressure transducer in rotor casing

- Static pressure rise at rotor tip
- Static pressure field in rotating frame of reference
- Analysis of unsteady tip flow field

Measurement Systems & Instrumentation

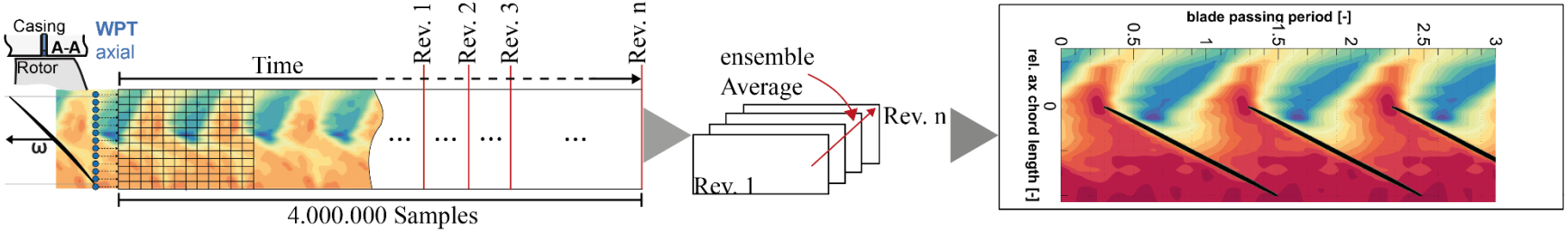
Test Procedure, Data Acquisition & Processing

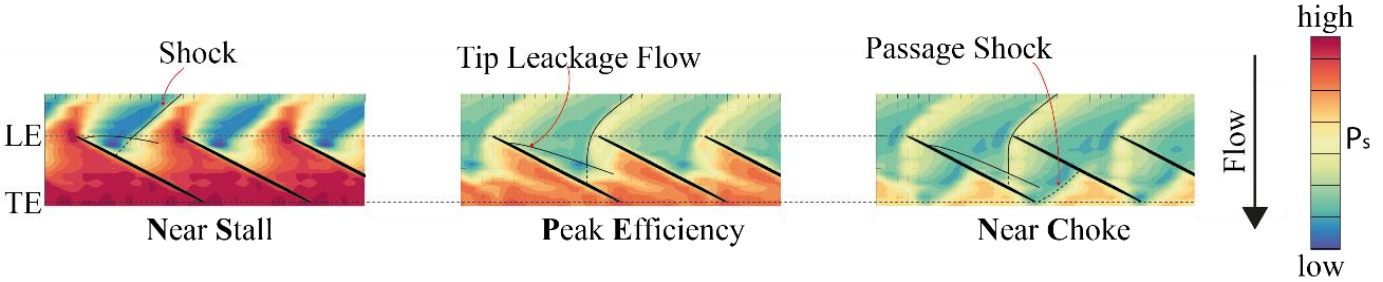


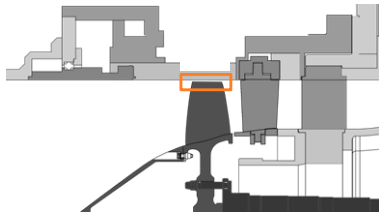


Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing







- 8 second measurements with kulite system
- $4 * 10^6$ samples / >1200 rotor revolutions (at nominal speed)
- Open test case includes static pressure ratio (normalized to settling chamber pressures)

Comparison SST Fine 5HP / Rakes

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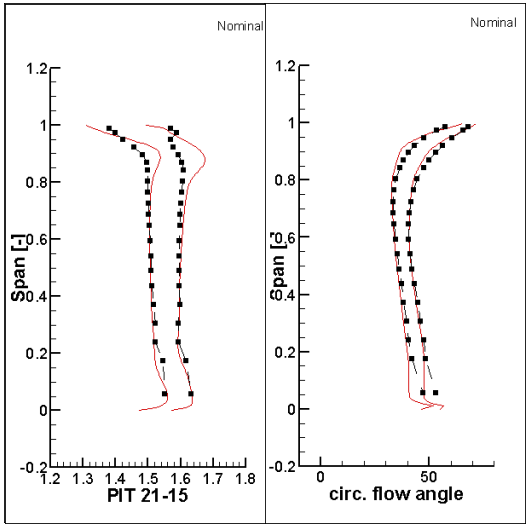
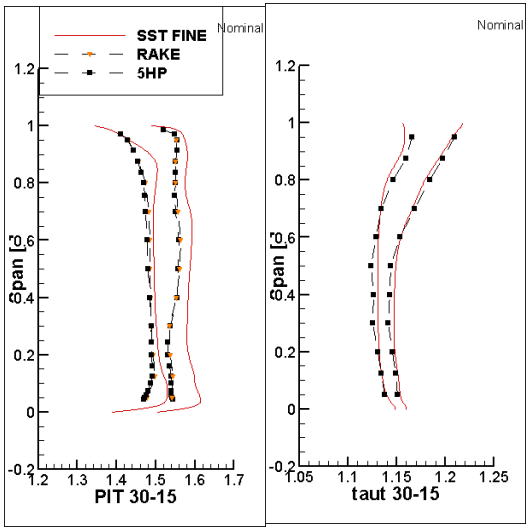
N100 PE / IM Rotor Exit



N100 PE / IM Stage Exit



Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

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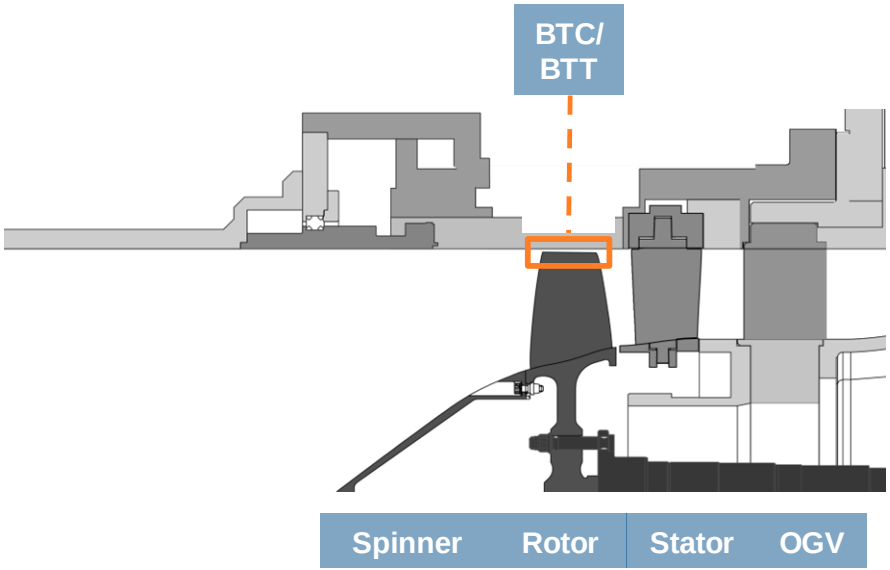
(d) Blade tip clearance (/blade vibration)



Capacitive BTC / BTT system

- In operation tip clearance
- Blade vibration (synchronous/ non-synchronous vibration)
- Blade untwist

Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

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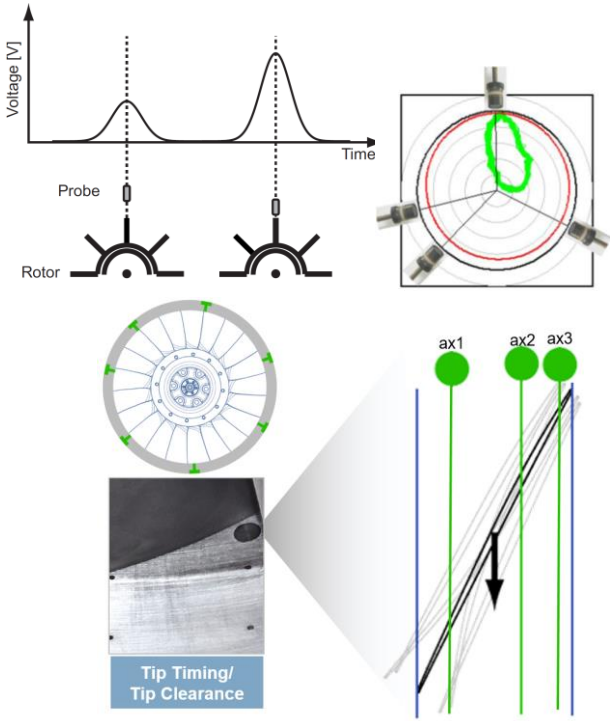
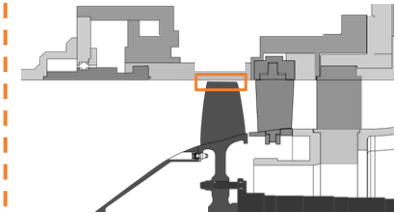
(d) Blade tip clearance (/blade vibration)

- Tip clearance, rotor orbiting and center line shift
  - +/- 50µm, meas. range 2/3 of probe diameter
  - Absolute values depending on calibrated voltage
  - Determination of vibration and blade untwist due to several axial measuremet locations





CONTENT

Facility Introduction

Measurement Techniques

Test Procedures, Data Acquisition and Dataset

Conclusion

Comparing CFD and Experiment

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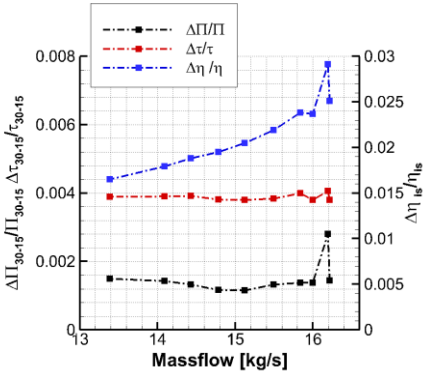
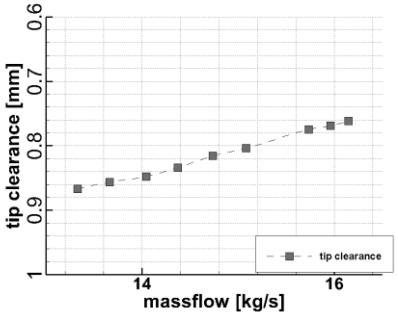
Inconsistencies due to measurement data

- Consider measurement system uncertainty
- Consider low spatial resolution (use measurement grid points)
- Consider data acquisition procedure
- Consider measured operating conditions

Inconsistencies due to geometry

- Consider differences between real compressor geometry and model
  - Different tip gaps at every operating point
  - Different blade untwist at every operating point
  - Gaps and cavities
  - Additional objects in flow path (e.g. probes)





Conclusion

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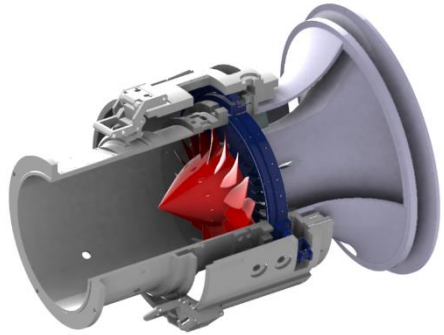
Initial dataset

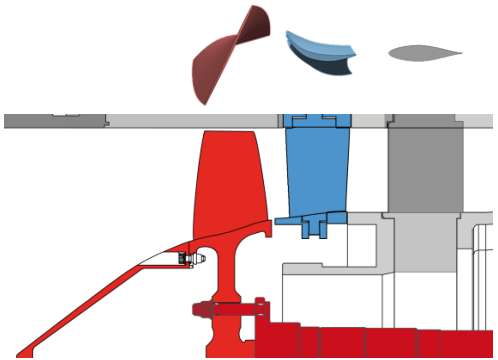
- For comparison of steady flow simulations
- Solver validation
- Turbulence model validation
- …

→ Test Case is WIP and will be extended in the upcoming years



High TRL experiments crucial

- Validation of unsteady flow phenomena
- Investigation of aeroelastic phenomena
- Investigation of aeroacoustic phenomena



GPPS Test Cases: ETH Zurich, Seoul National University, Beihang University
https://gpps.global/gpps-data-sets-2021/

CATANA Open test case (EC Lyon)
http://catana.ec-lyon.fr/#OTC

…

THANK YOU!

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GLR

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Transonic Compressor TU DARMSTADT

GPPS Global Power & Propulsion | XI'AN21 CFDWorkshop

Open Discussions

Presentations

Validation and Verification of RANS Solvers for TUDa-GLR-OpenStage Transonic Axial Compressor
Mingmin Zhu (Shanghai Jiaotong University)

Capabilities of Open-source Code SU2 on Turbomachinery Application
Chuanxiang Yan (Tsinghua University)

ASPAC and its validation on TUDa-GLR-OpenStage
Ziwei Wang (CARDC)

Simulation of TUDa-GLR-OpenStage by HGAE
Qingzhe Gao (Beihang University)

Steady RANS Simulations of the TUDa-GLR-OpenStage Using an In-house Code MAP
Haowei Zhou (Beihang University)

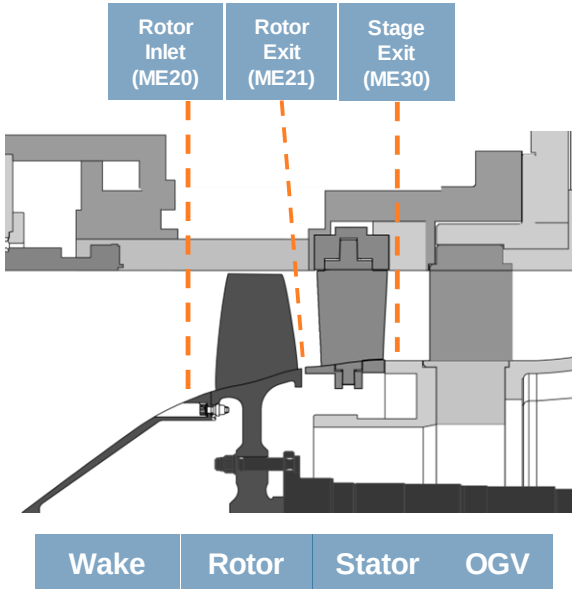
SU2 Analysis of Flow Field within the TUDa Transonic compressor
Qinglin Zhou (Northwestern Polytechnical University)

Validation and Verification of a RANS Solver for TUDa-GLR-OpenStage
Dongming Cao (Northwestern Polytechnical University)

Validation and Verification of RNAS Solver with the Space-Time Gradient Method for TUDa-GLR-OpenStage Transonic Axial Compressor
Boqian Wang (Northwestern Polytechnical University)

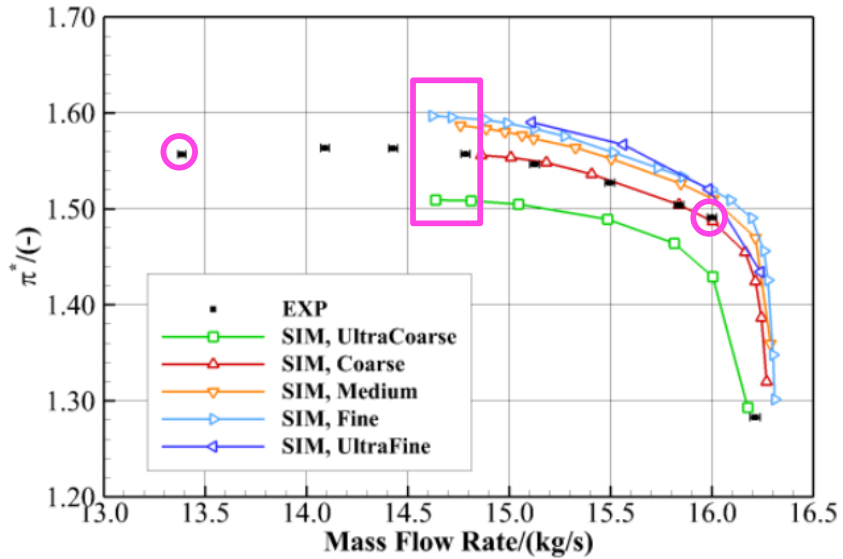
Measurment Scope 2022

Open Stage 2022



- What the current data set lacks:
  - Reliable inlet turbulence (source and measurement technique unclear) **(1)**
  - Detailed Rotor Inlet Probe Data **(2)**
- GLR internal measurement focus
  - Repro measurements of 2020
  - Repro measurements to evaluate system accuracy (repeated measurements of single OPs)
  - Detailed Probe investigation of Stator Inlet (ME21) and Exit (ME30) (Perfomance of in-house developed Stator vanes – probe grid with high special resolution)

Intermediate OP



- Intermediate OP for probe measurements
  - Currently probe data (ME20, 21 and 30) is only available for PE and NS
  - Proposal: Add intermediate OP within the range of last cfd convergence
  - Corresponding mass flow has to be determined

TCD Publications

Update!

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GLR

F. Holzinger
Coupling of tip leakage flow and blade vibration in transonic compressors – Mechanism and countermeasures. Dissertation, 2017. Darmstadt

C. Brandstetter, M. Jüngst, H.-P. Schiffer
Measurements of radial vortices, spill forward and vortex breakdown in a transonic compressor. Journal of Turbomachinery, 2018. ISSN 0889-504X. Doi: 10.1115/1.4039053

M. Jüngst, S. Liedtke, H.-P. Schiffer, B. Becker
Aerodynamic effects in a transonic compressor with nonaxisymmetric tip clearance. Proceedings of the ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition, Oslo, 2018. GT2018-75404

M. Jüngst, D. Franke, H.-P. Schiffer, T. Giersch
Aeroelastic effects in a transonic compressor with nonaxisymmetric tip clearance. Proceedings of GPPS Forum 18. Montreal, 2018. GPPS-NA-2018-0041

M. Jüngst
The transonic compressor with non-uniform tip clearance: Effects on aerodynamics and aeroelasticity. Dissertation, 2019. Darmstadt

D. Möller, M. Jüngst, F. Holzinger, C. Brandstetter, H.-P. Schiffer and S. Leichtfuss
Numerical investigation of tip clearance flow induced flutter in an axial research compressor. Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition, 2016. GT2016-56956

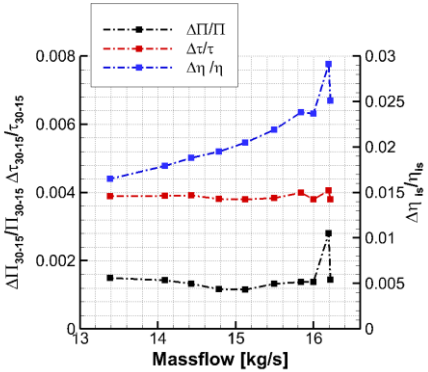
D. Möller, M. Jüngst, H.-P. Schiffer, T. Giersch and F. Heinichen
Influence of rotor blockage on near stall blade vibrations in an axial compressor rig. Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition, 2017

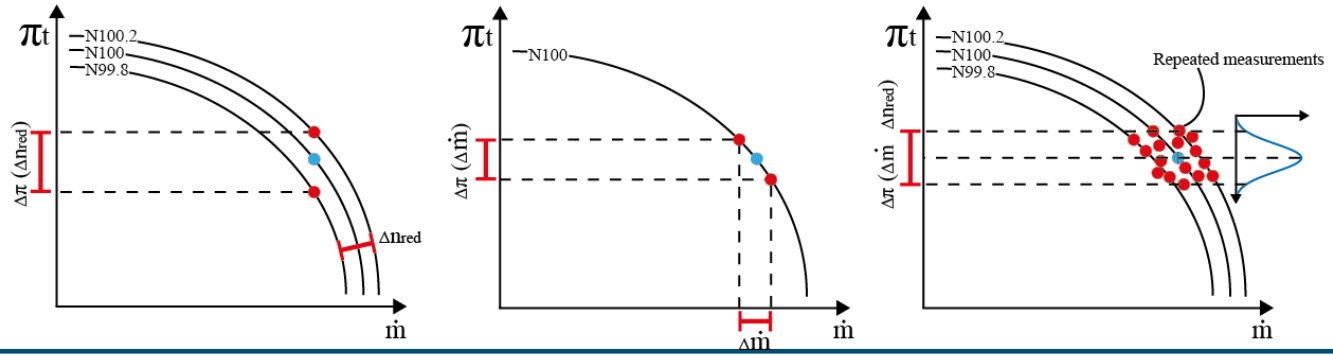
D. Möller
Zum aerodynamischen und aeroelastischen Verhalten des Axialverdichters an der Stallgrenze. Dissertation, 2019. Darmstadt

BACKUP

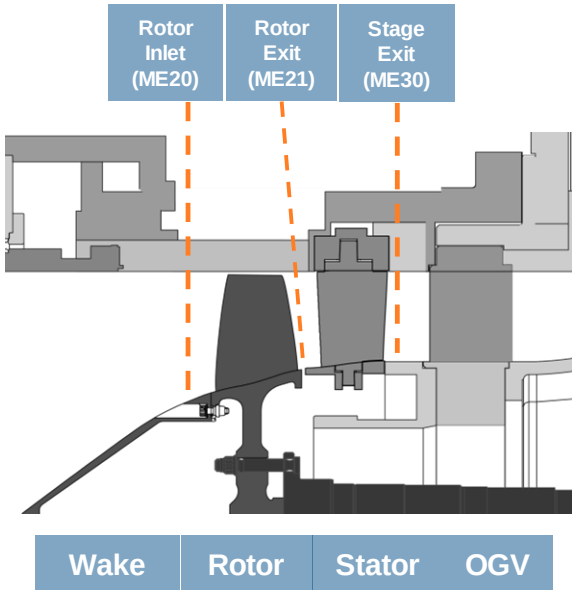
Comparing CFD and experiment

- Consider measurement system uncertainty
- Consider low spatial resolution





Planned Measurement scope Open Stage Test Campaign 2022



Rotor Inlet (ME20)	Rotor Exit (ME21)	Stage Exit (ME30)
N65 / N100 • 2/3 OPS Radial profiles /2D fields of: • Flow angles • Total pressure • Static pressure • Mach number	N65 / N100 • 2/3 OPS Radial profiles /2D fields of: • Flow angles • Total pressure • Static pressure • Mach number • Stationary frame of reference • Rotating frame of reference	N65 / N100 • 2/3 OPS Radial profiles /2D fields of: • Flow angles • Total pressure • Static pressure • Mach number N65 / N80 / N100 Radial profiles /2D fields of: • Total pressure • Total temperature

Planned Measurement Scope Open Stage Test Campaign 2021

Turbulence measurements

- Probe that is capable to measure all velocity components time resolved
- Virtual probe only measures total pressure time resolved (and radial angle)

→Usage of 3-Wire hot fiber probe

Hot Fiber Probe

- Probe availability bound to turbine rig measurement plans
- Measurement of inlet turbulence for different massflows