GPPS Global Power & Propulsion | XI'AN21 CFD Workshop

Workshop Program

16:00 Beijing / 09:00 CET	Introduction to the Workshop
16:05 Beijing / 09:05 CET	Introduction to the Test Facility & Measurement Data
16:50 Beijing / 09:50 CET	Summary of Participants' CFD Results
17:30 Beijing / 10:30 CET	Coffee Break
17:45 Beijing / 10:45 CET	Participant Presentations
19:10 Beijing / 12:10 CET	Open Discussions
19:30 Beijing / 12:30 CET	Presentation data set: Beihang University
19:50 Beijing / 12:50 CET	Presentation data set: ETH
20:10 Beijing / 13:10 CET	Wrap-up and outlook

Mingmin Zhu	Shanghai Jiaotong University
Chuanxiang Yan	Tsinghua University
Ziwei Wang	CARDC
Qingzhe Gao	Beihang University
Haowei Zhou	Beihang University
Qinglin Zhou	Northwestern Polytechnical University
Dongming Cao	Northwestern Polytechnical University
Boqian Wang	Northwestern Polytechnical University

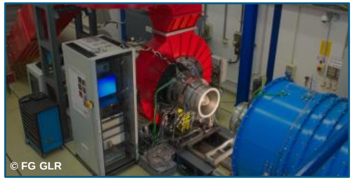
Technical University of Darmstadt

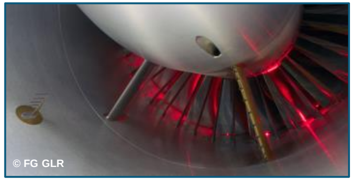
Institute of Gas Turbines and Aerospace Propulsion

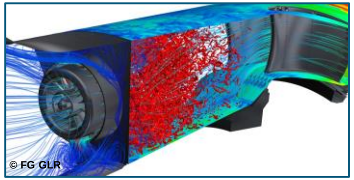
TECHNISCHE UNIVERSITÄT DARMSTADT

GLR

Institute of
Gas Turbines and Aerospace Propulsion







- 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

TECHNISCHE UNIVERSITÄT DARMSTADT

ROLLS ROYCE

MTU Aero Engines

SIEMENS

GKN AEROSPACE

SAFRAN

Federal Ministry for Economic Affairs and Energy

European Union
Research and Innovation

CONTENT

Technology Readiness Level Classification

TECHNISCHE UNIVERSITÄT DARMSTADT

TRL 1
Basic Principles Observed and Reported

TRL 2
Potential Application Validated

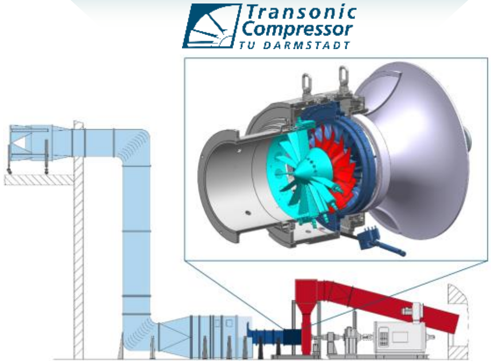
TRL 3
Proof-of-Concept Demonstrated

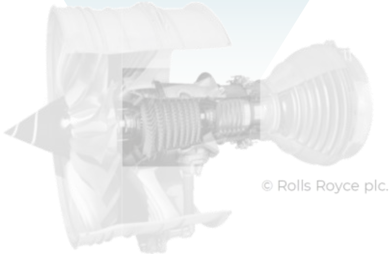
TRL 4 - 5
Component Test Facilities & Validation

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

TRL 6 - 7
System Prototype Demonstration in Operation Environment

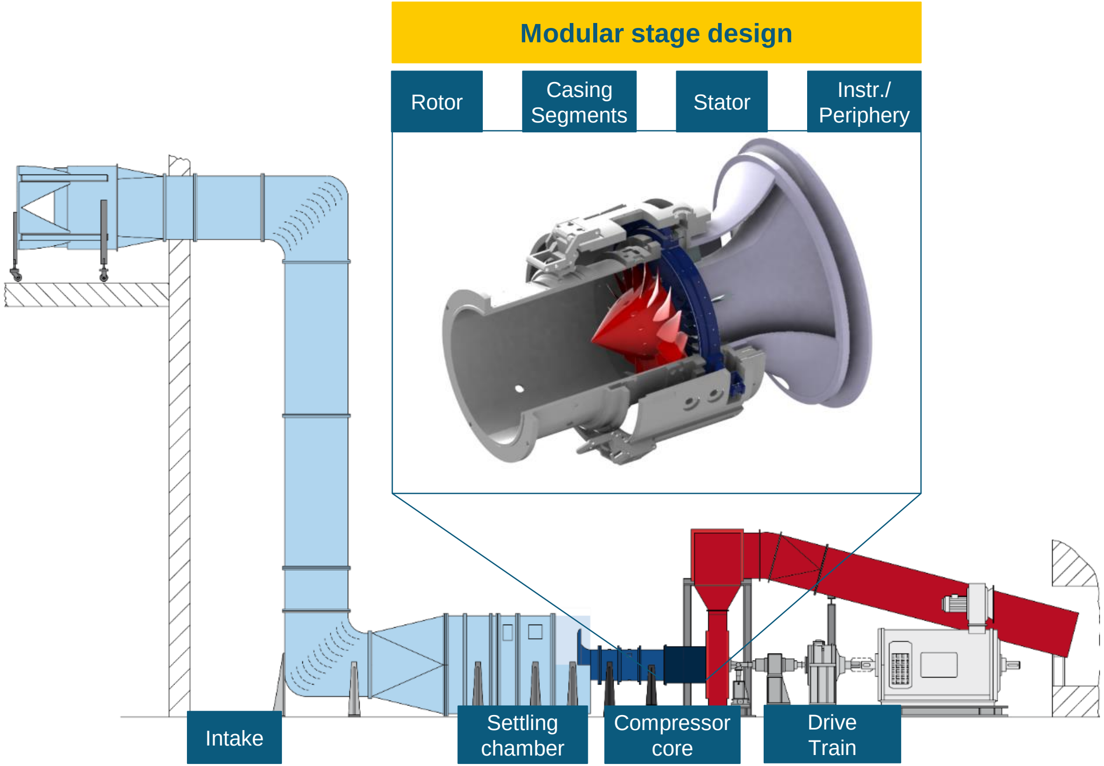
TRL 8 - 9
System Test, Launch & Operations





Transonic Compressor Rig
Facility Design

TECHNISCHE UNIVERSITÄT DARMSTADT



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

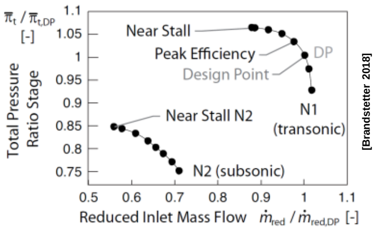
Capacity	
In /out flow	axial-axial
Electr. Power	800 kW
Max. Torque	350 Nm
Max. speed	20 500 rpm
Max. rotor diameter	0.38 m
Hub to tip ratio	~ 0.5
Rel. Ma-Number @ tip	~ 1.4

Research Focus
Performance, Aerodynamics, Aeroelasticity

TECHNISCHE UNIVERSITÄT DARMSTADT

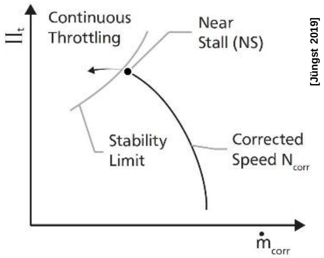
Performance Measurements

- Analyzing global effects
- Influencing parameters



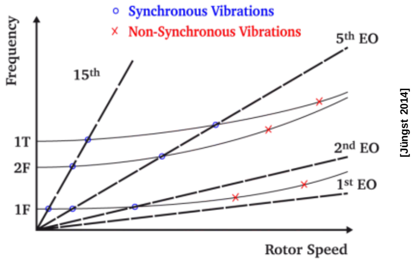
Unsteady Aerodynamics

- Stall inception mechanisms
- Pre-stall disturbances



Aeroelasticity

- Non-synchronous vibration
- Forced response



Interaction & fluid-structure coupling mechanisms

Countermeasures / influences

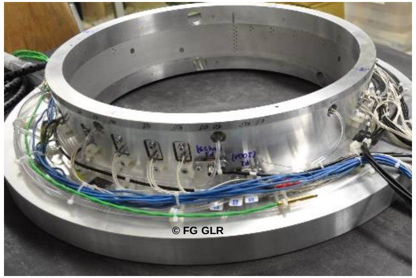
Darmstadt Transonic Compressor

Rotor

- 11 BLISKs commissioned
- Varying
  - 3D design
  - Blade count
  - Fw/bw Sweep
  - Materials
  - Instrumentation

Stator

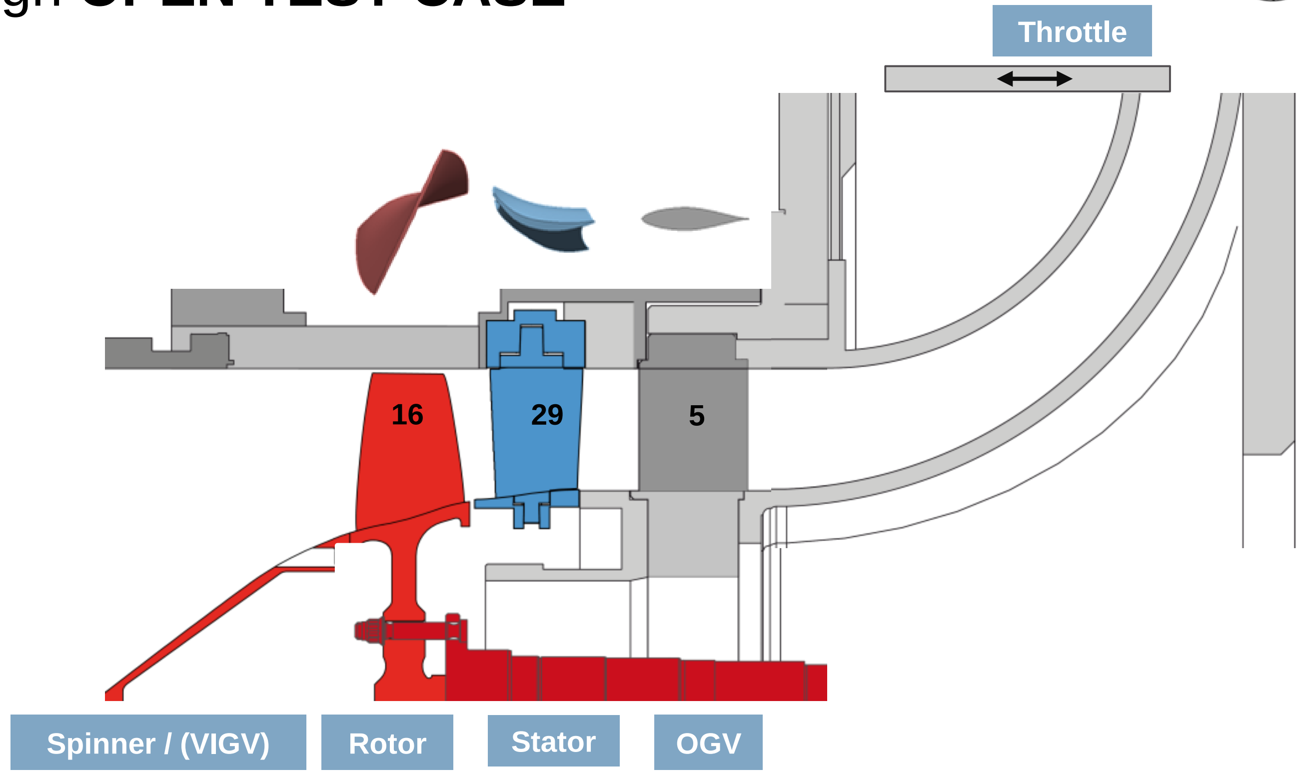
- 6 stators commissioned in several stage setups
- Varying
  - 3D design
  - Vane count
  - Variable stagger during operation
  - Materials
  - Instrumentation



Casing Segments

- Multiple variations
- Varying
  - Tip clearance
  - Eccentricity
  - Casing treatments
  - Abradable liner
  - Instrumentation

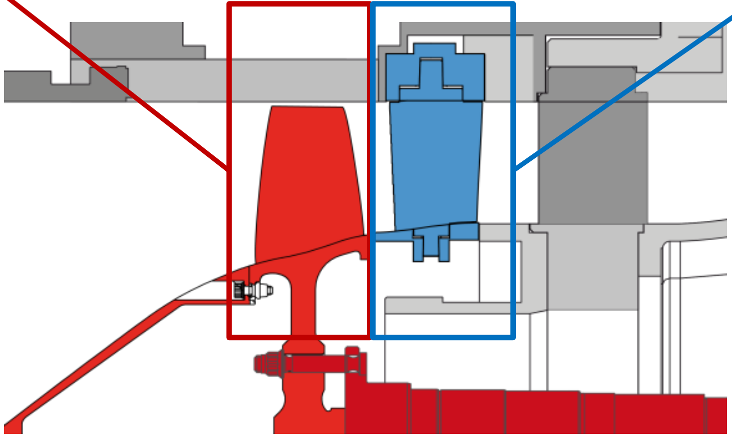
Darmstadt Transonic Compressor
Stage Design **OPEN TEST CASE**



TUDa-GLR-OpenStage

Geometry

TECHNISCHE UNIVERSITÄT DARMSTADT



Rotor 1

Designed by *MTU Aero Engines*

- First run 1994
- Broad availability of literature
- open test case

Stator opt. (7)

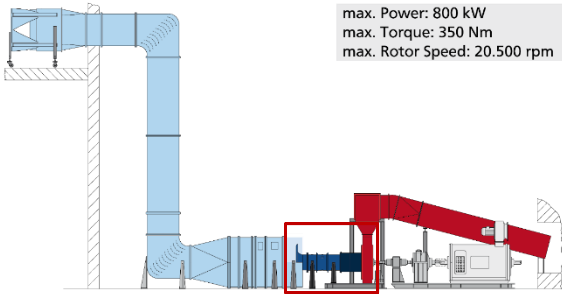
CFD optimized Stator

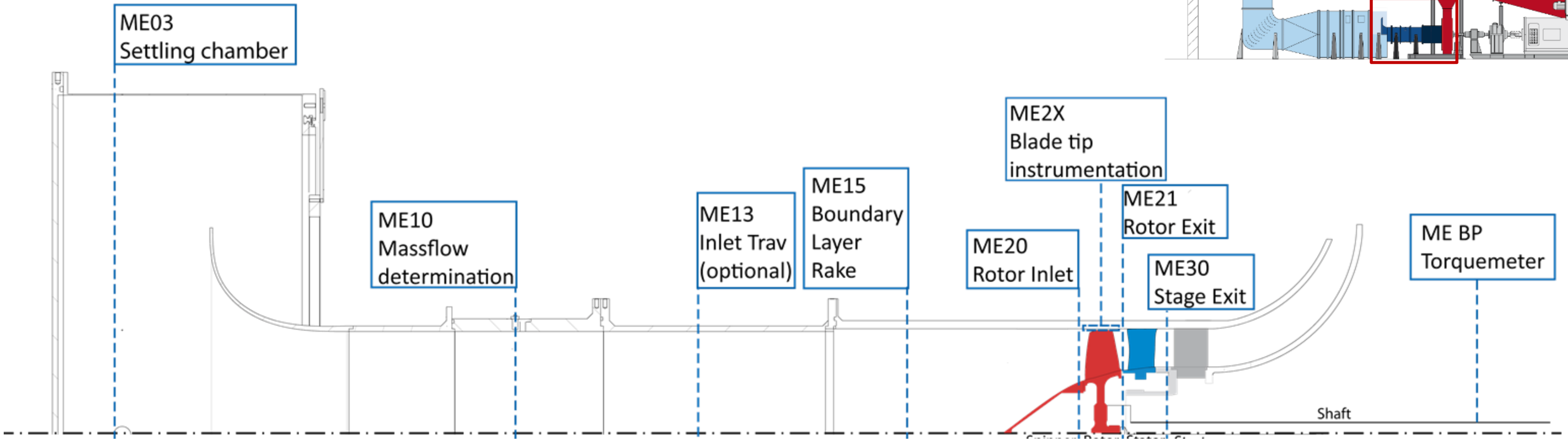
- Design and optimization conjointly realized by ***DLR*** and ***GLR*** (see *Bakhtiari, 2015*)
- Suppression of flow separation
- Manufacturing within EU funded H2020 Project ***ARiAS***

CONTENT

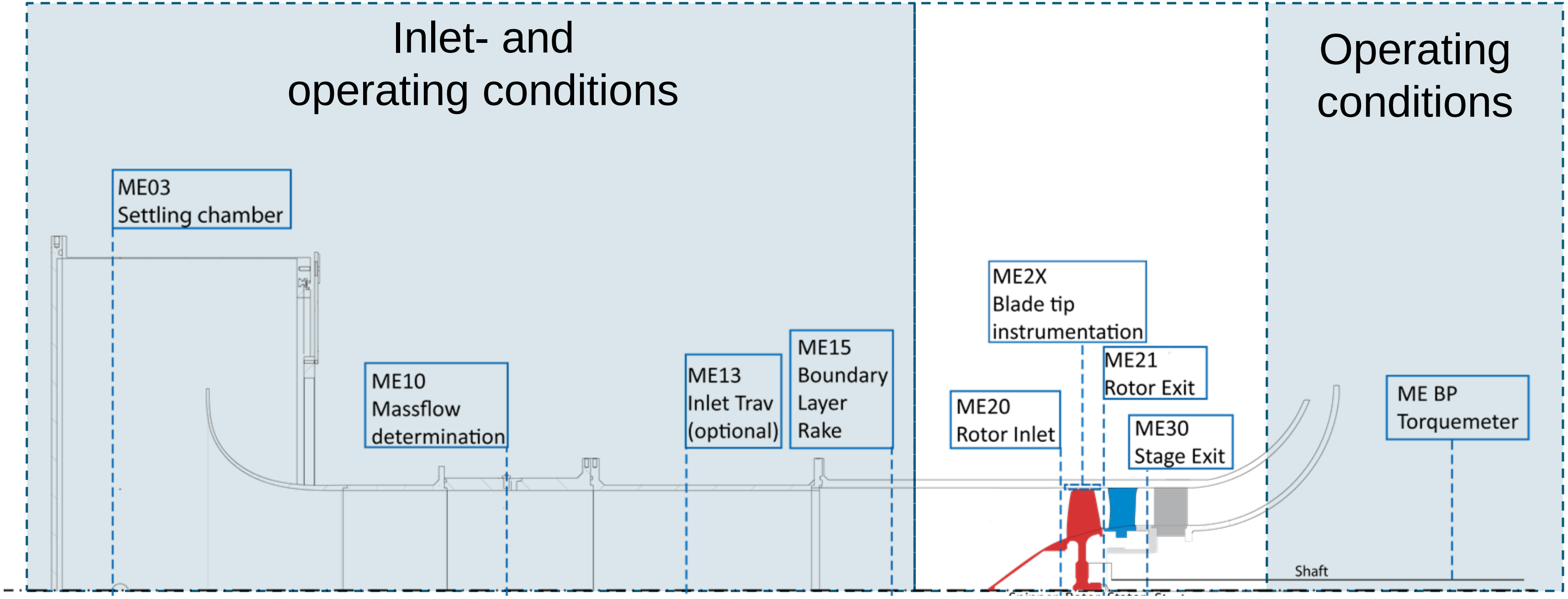
Measurement Systems & Instrumentation
Overview

TECHNISCHE UNIVERSITÄT DARMSTADT





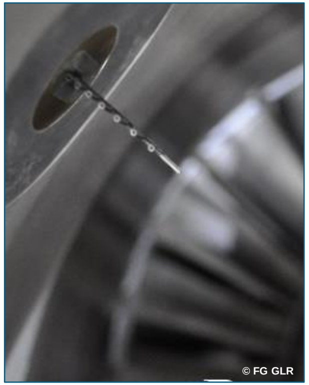
Measurement Systems & Instrumentation
Overview



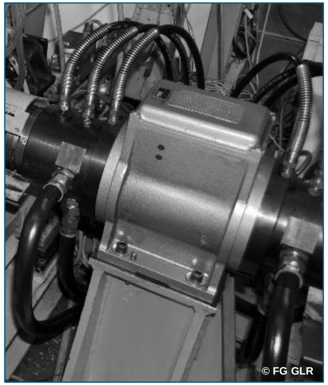
Measurement Techniques
Performance and Stationary Instrumentation

Combined total pressure and temperature rakes

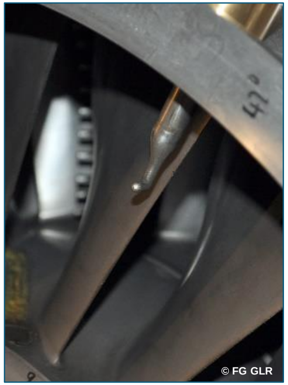
Combined inlet instrumentation



Boundary layer rake



Torque and shaft speed measurements



Traversable five-hole probe

Performance

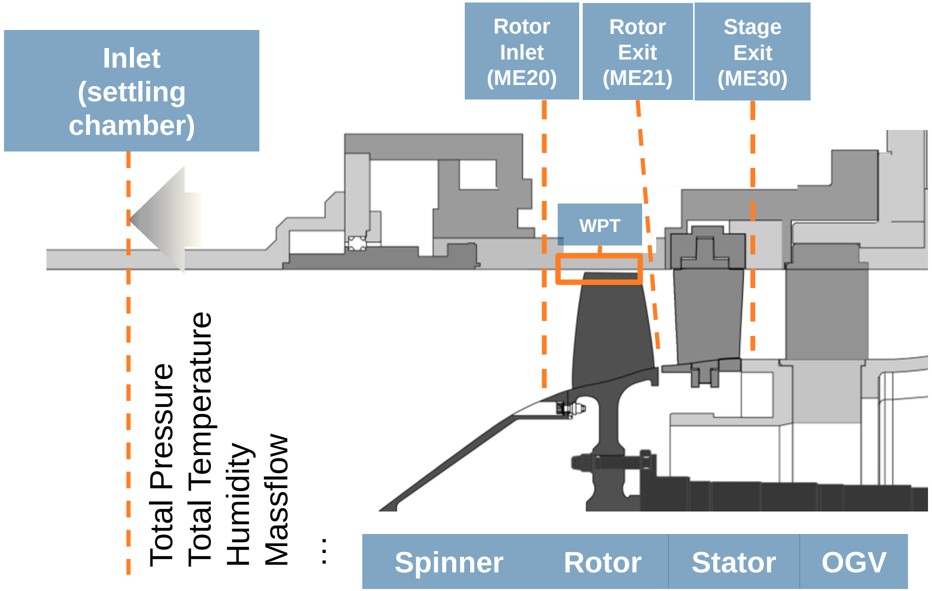
2D flow field
(p, v, α, etc.)

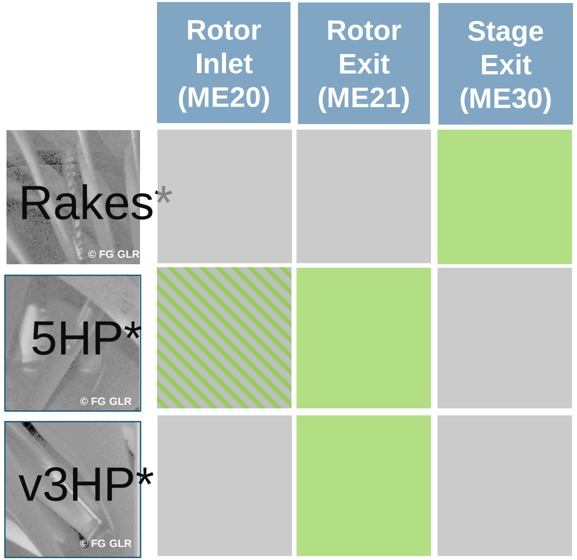
Measurement Systems & Instrumentation
Time-resolved Instrumentation

TECHNISCHE UNIVERSITÄT DARMSTADT

			
Strain gauges	Capacitive BTC / BTT system	Time-resolved pressure transducer in rotor casing	Traversable unsteady pressure probes (virtual multi-hole probe)
Blade vibration	Only tip clearance	**Unsteady aerodynamics within the rotor tip region**	**Unsteady 2D flow field within the rotor / stage exit plane**

Transonic Compressor Rig Introduction
Instrumentation – Compressor Core (Open Test Case)





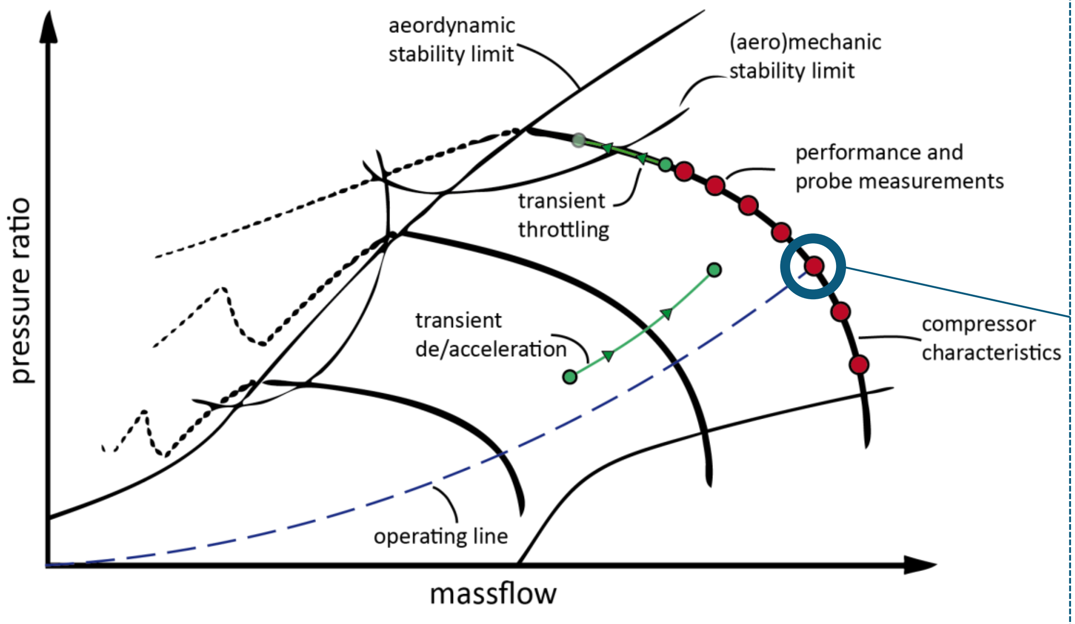
Rakes*: Total Temperature and Pressure
5HP*: Mach numbers and flow angles – stationary frame of reference
v3HP*: Mach numbers and flow angles – rotating frame of reference

Measurement of static pressure in all sections (casing)

CONTENT

Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT



Steady-state Operating Point

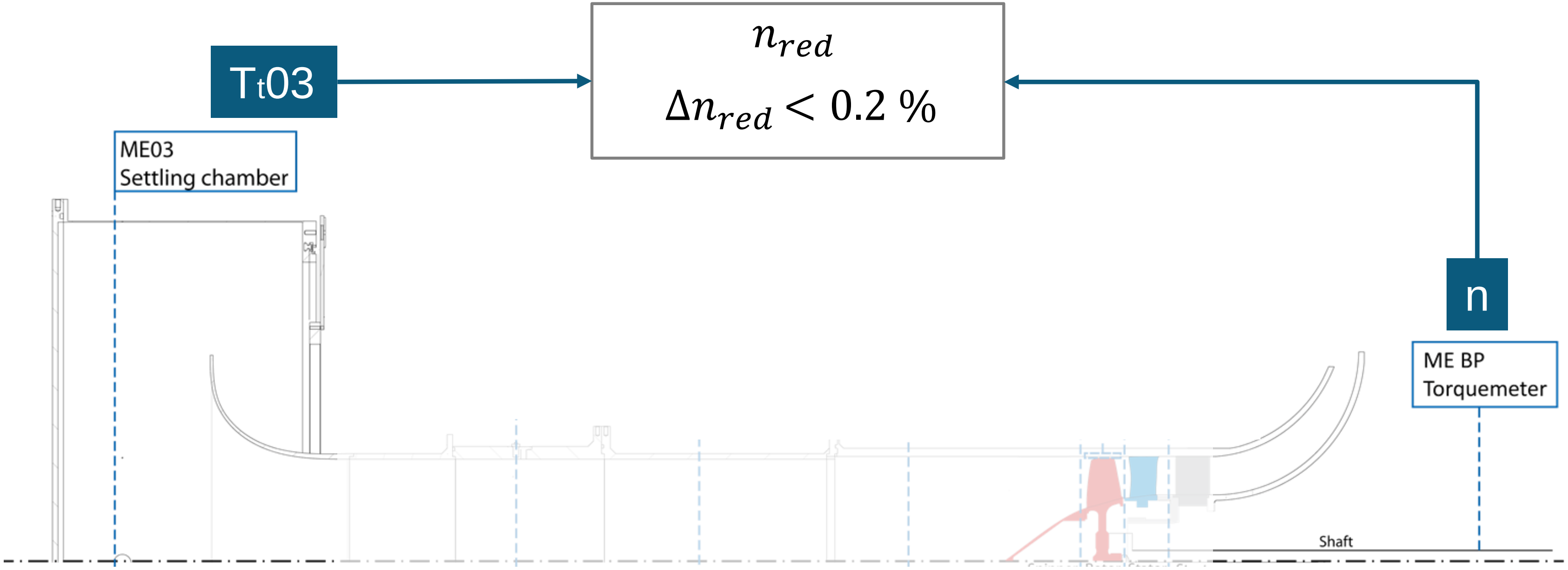
» Defined by:
  » **Reduced massflow**
  » **Reduced speed**

» 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

Measurement Systems & Instrumentation

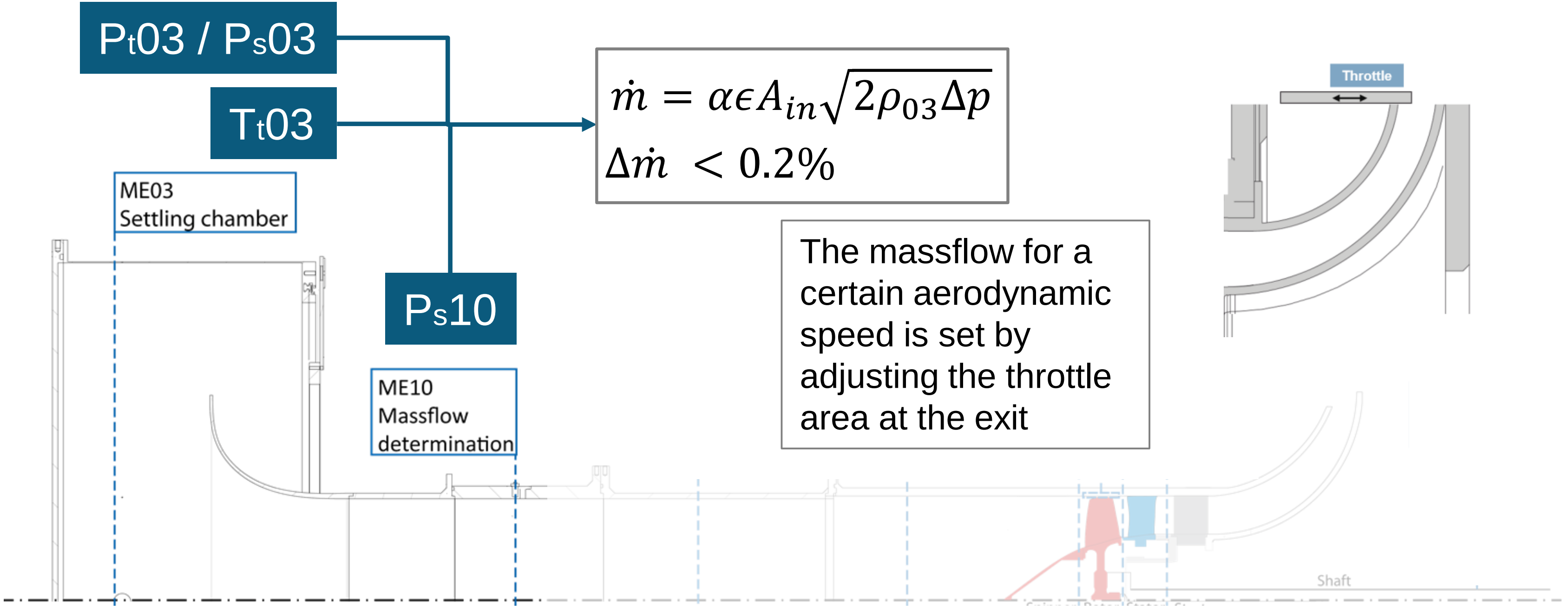
Massflow Determination / Operating Point Definition

TECHNISCHE UNIVERSITÄT DARMSTADT



Measurement Systems & Instrumentation

Massflow Determination / Operating Point Definition



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

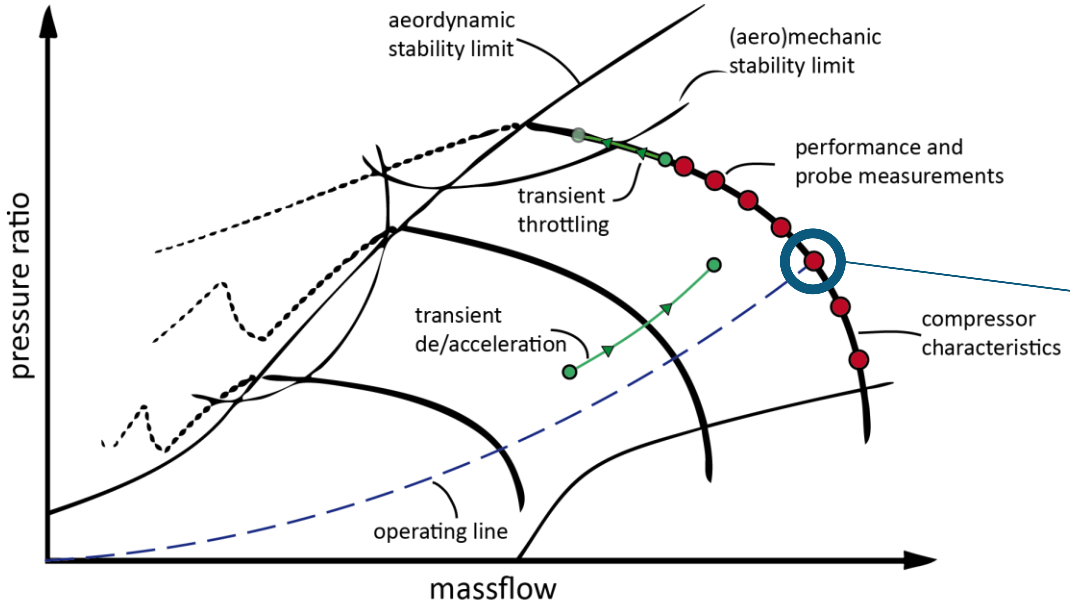
$$\Delta\dot{m} < 0.2\%$$

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

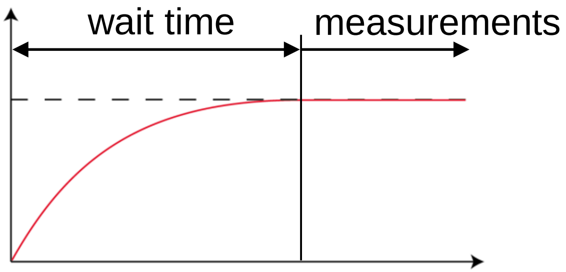
Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT



Steady-state Operating Point

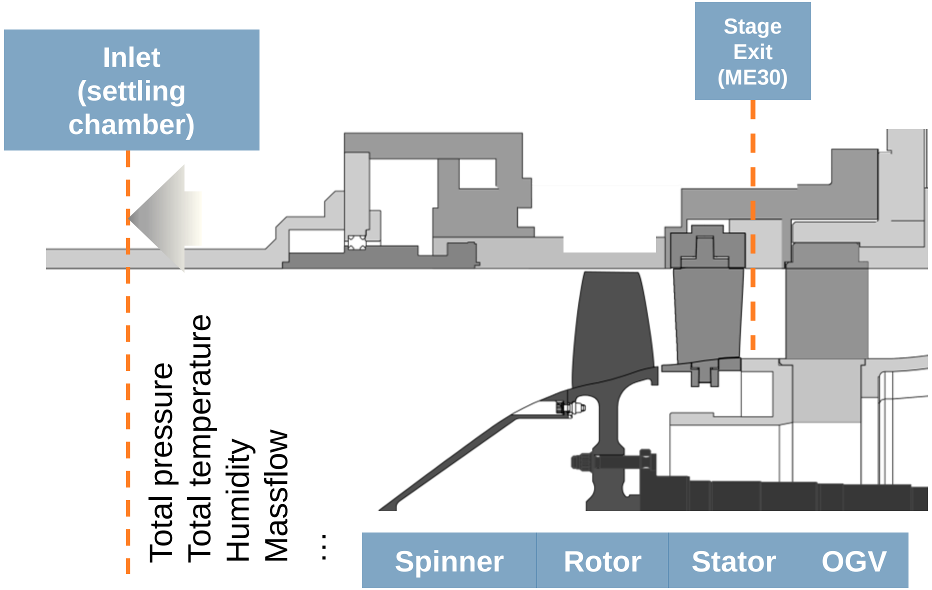


- Wait time until all measurement systems related to operating conditions converge (e.g. tip gap, temperatures …)
- Afterwards, rig is ready for stationary measurements

Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

(a) Stage exit flow field (exit rakes)



Combined total pressure and temperature rakes

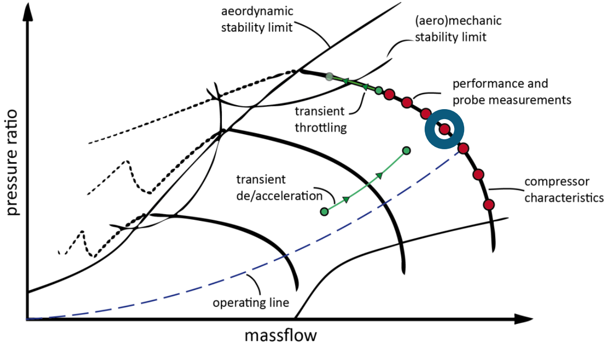
Measurement of:
- Total pressure
- Total temperature

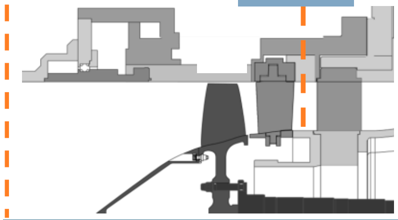
Determination of
- Total *pressure/temperature* ratio
- isentropic efficiency

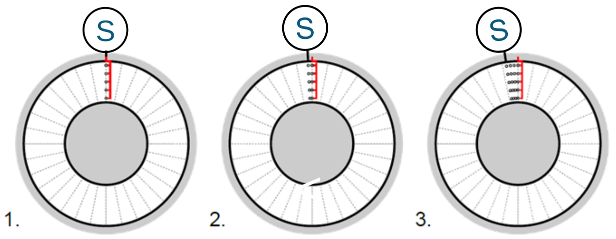
Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

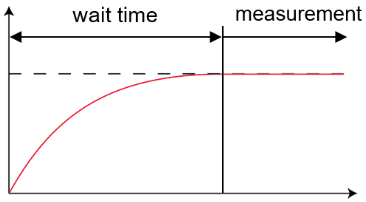
(a) Stage exit flow field (exit rakes)







Traversing of stationary parts
(15 positions per stator passage)



Pt30 Tt30

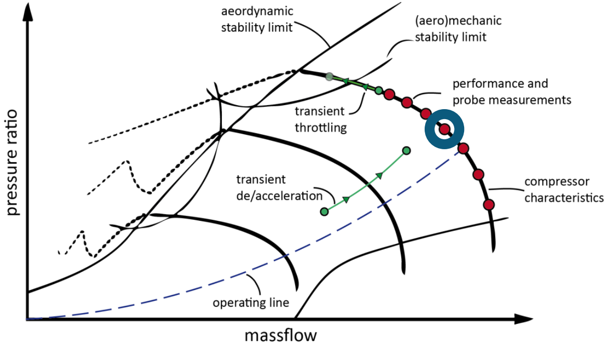
Stepwise clocking of stator module:
» In between each clocking position waiting for convergence of relevant parameters
» Measurement time is set, thus number of uncorrelated measurements varies

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

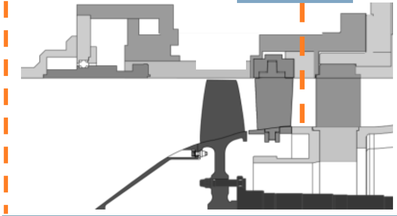
Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

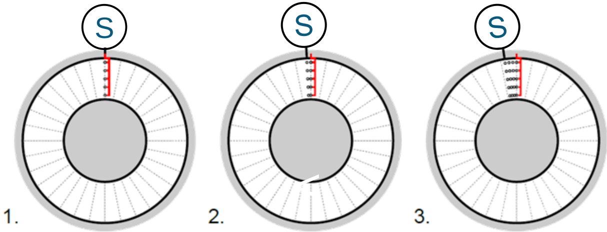
TECHNISCHE UNIVERSITÄT DARMSTADT

(a) Stage exit flow field (exit rakes)

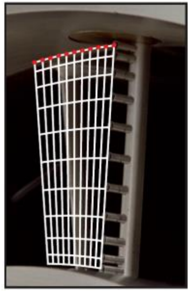


Stage Exit (ME30)



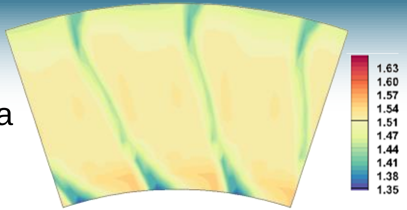


Traversing of stationary parts (15 positions per stator passage)



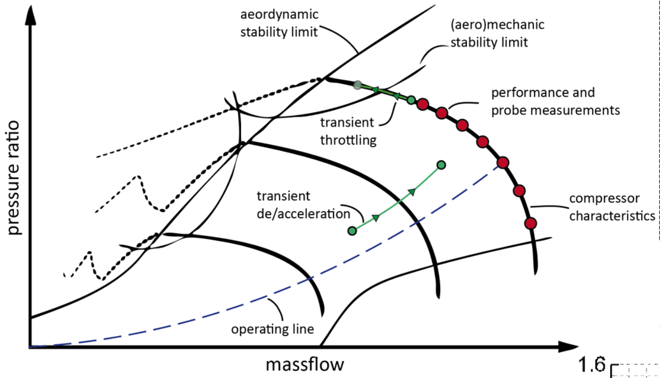
2 dimensional measurement grid

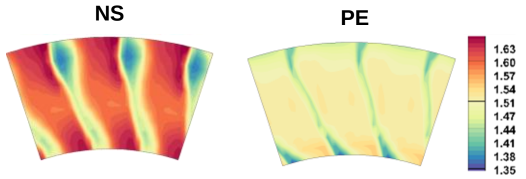
Exit flow field data



Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

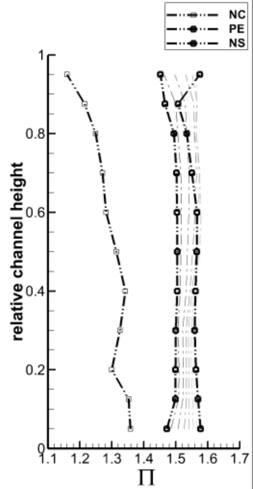
TECHNISCHE UNIVERSITÄT DARMSTADT

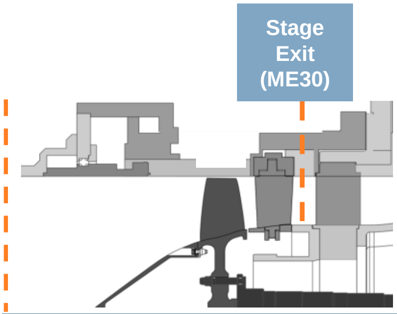


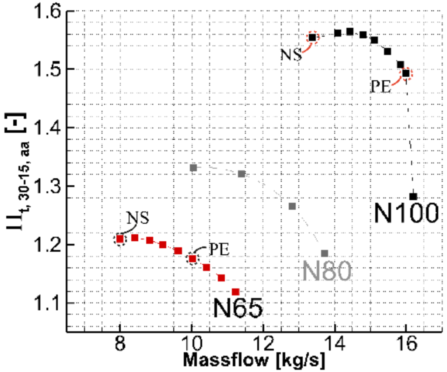


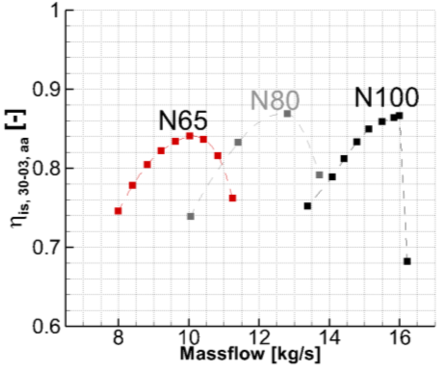
circumferential average

area average





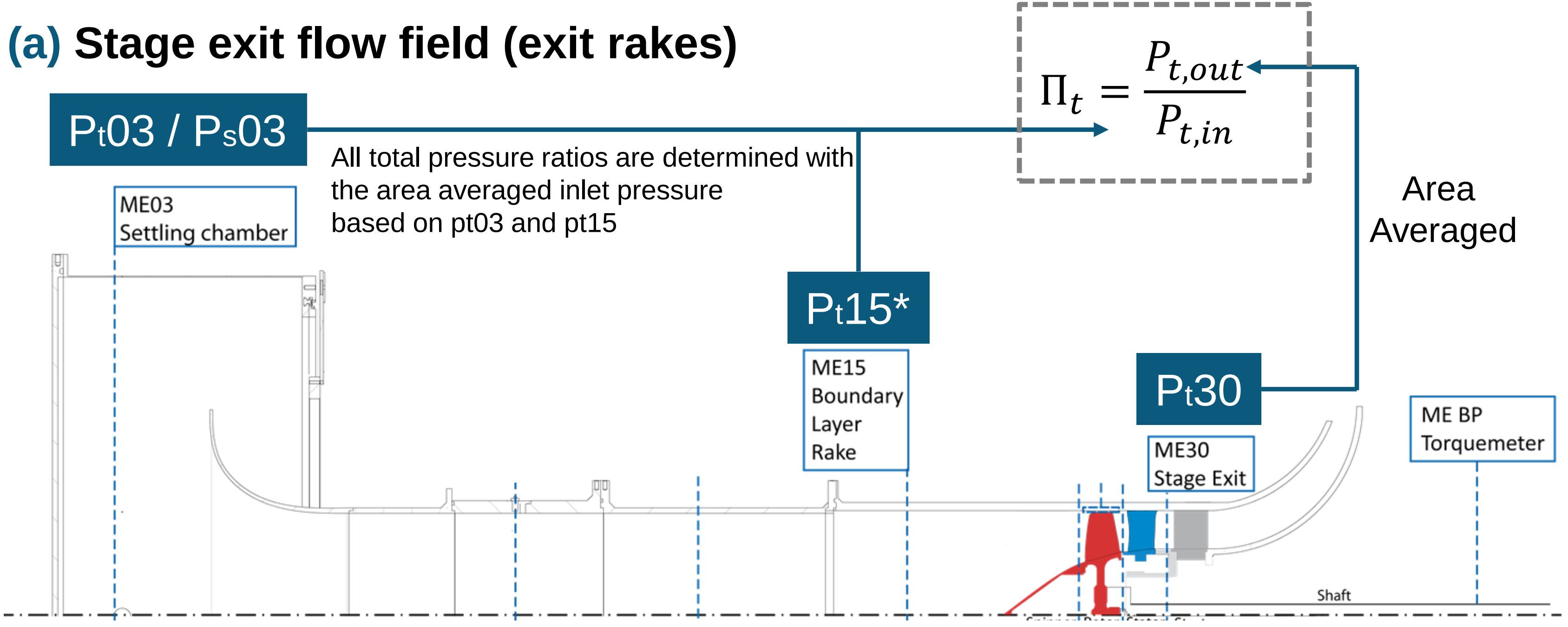




Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

(a) Stage exit flow field (exit rakes)



*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)

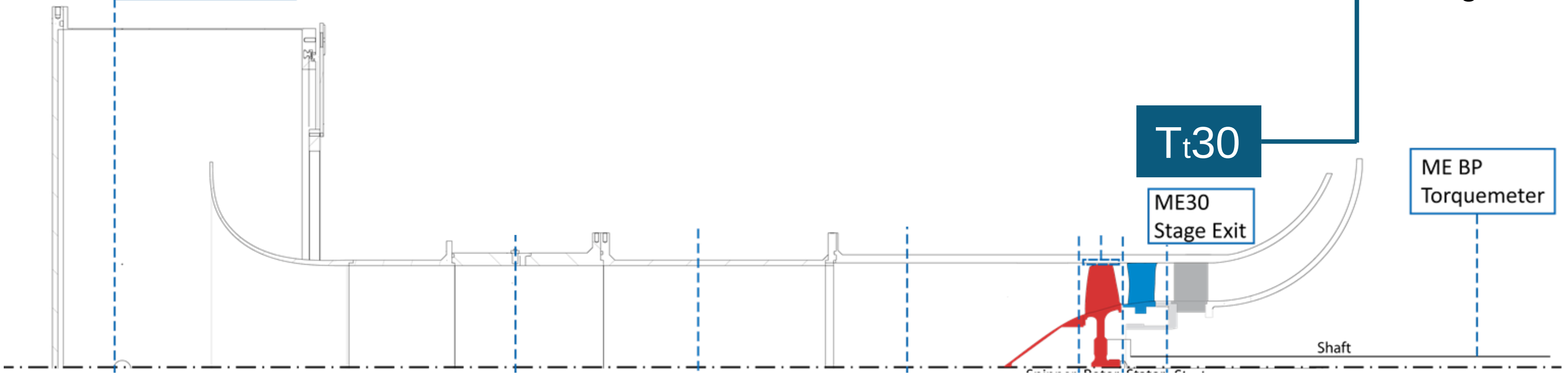
Area Averaged

ME03
Settling chamber

T_{t30}

ME30
Stage Exit

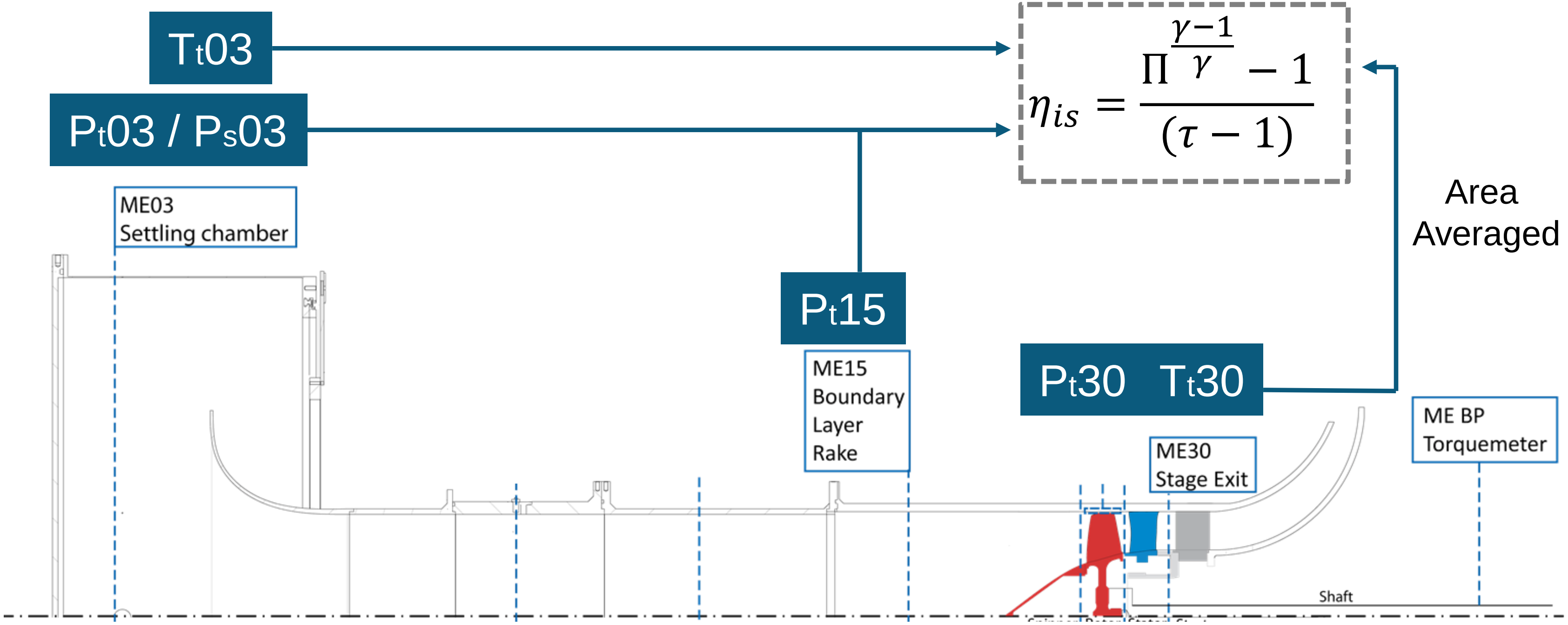
ME BP
Torquemeter



*Inlet duct assumed to be adiabatic

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing



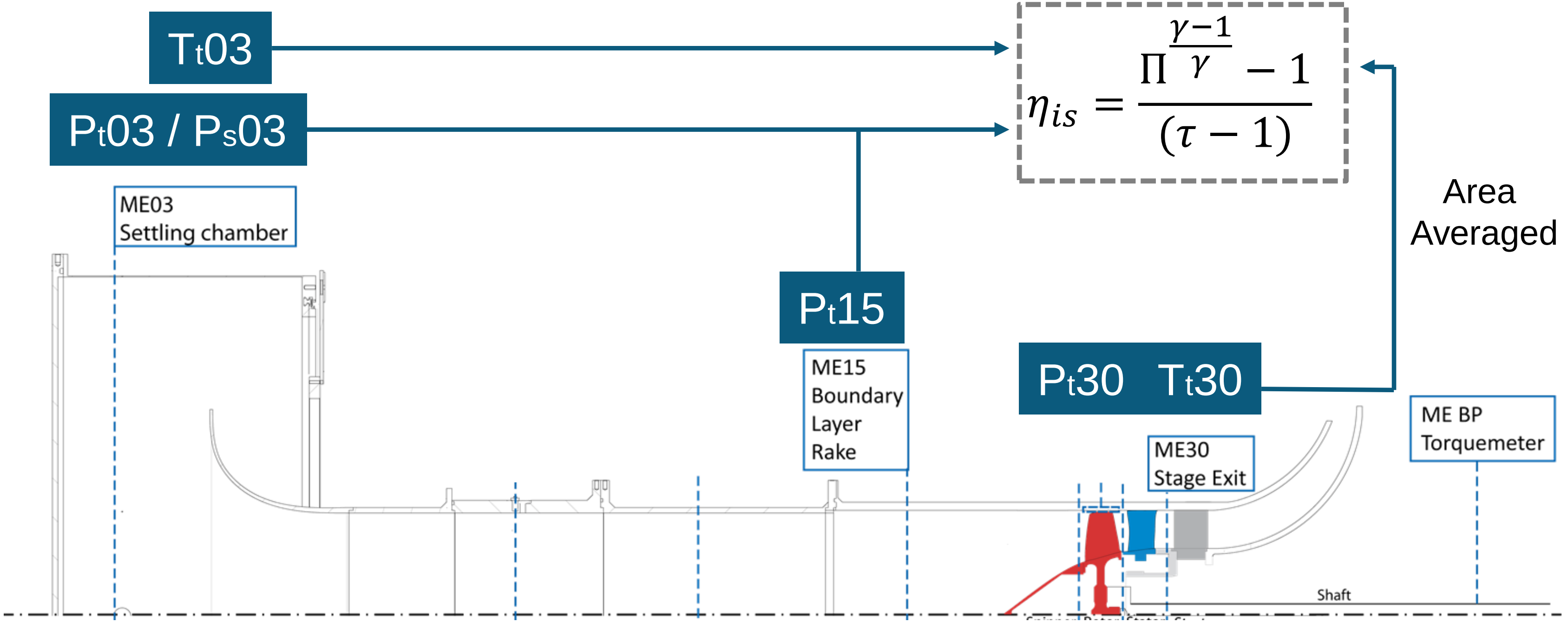
$$\eta_{is} = \frac{\Pi^{\frac{\gamma-1}{\gamma}} - 1}{(\tau - 1)}$$

*change of γ due to changing inlet conditions is considered

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

$$\eta_{is} = \frac{\Pi^{\frac{\gamma-1}{\gamma}} - 1}{(\tau - 1)}$$



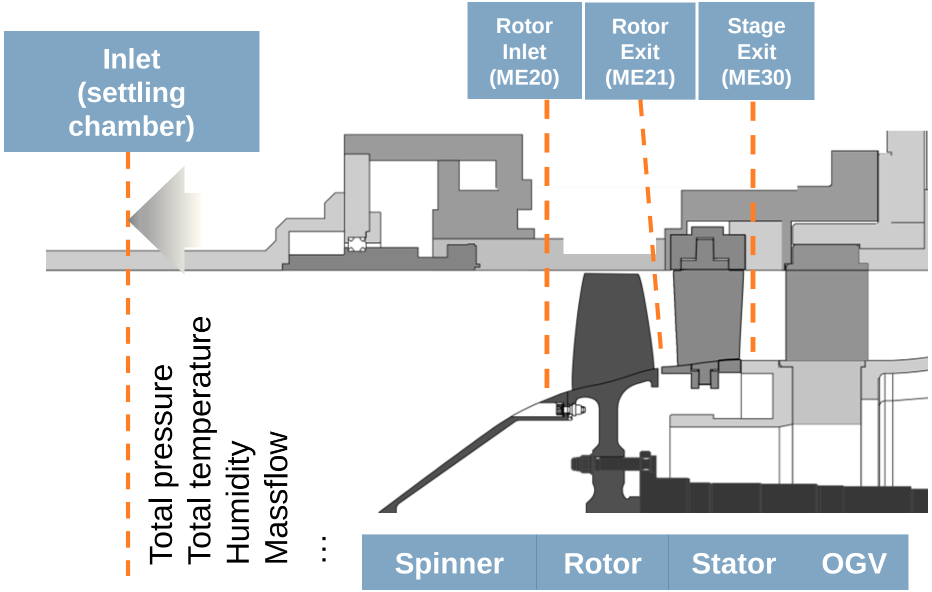
*change of γ due to changing inlet conditions is considered

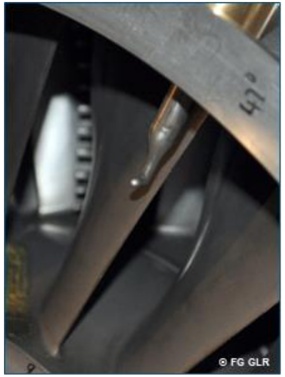
Measurement Systems & Instrumentation

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)

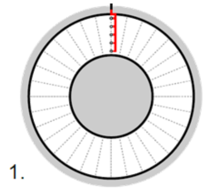
Rotating frame of reference

- » Total pressure
- » Flow angles
- » Local flow velocities

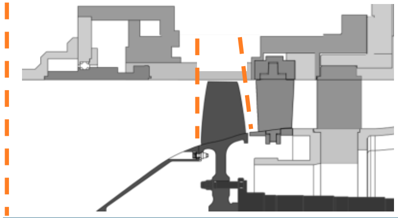
Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

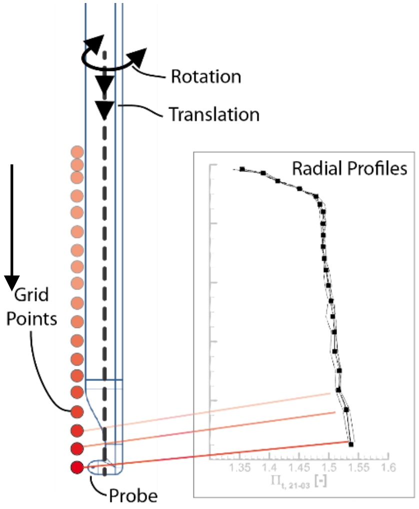
TECHNISCHE UNIVERSITÄT DARMSTADT

(b) Probe measurements

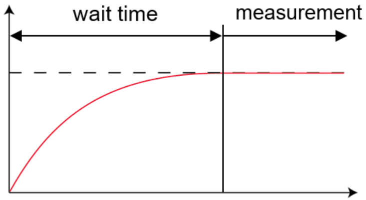


Conditions:
- Operating conditions are set
- Stator clocking is set





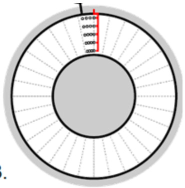
Stepwise radial traversing of probe:
- In between each clocking position waiting for convergence of relevant values
- Measurement time is set, thus number of uncorrelated measurements varies

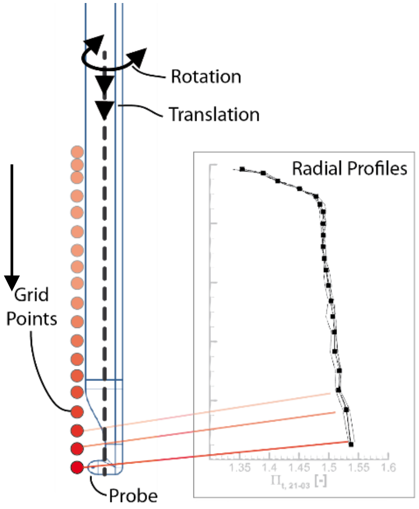


Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

(b) Probe measurements



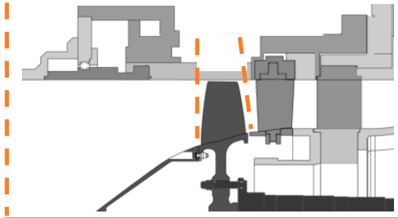


Stepwise radial traversing of probe:

- 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

Conditions:

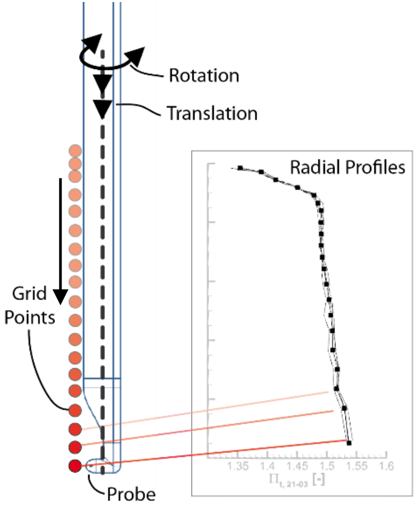
- Operating conditions are set
- Stator clocking is set



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)

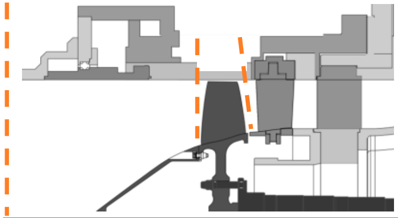
Measurement Systems & Instrumentation

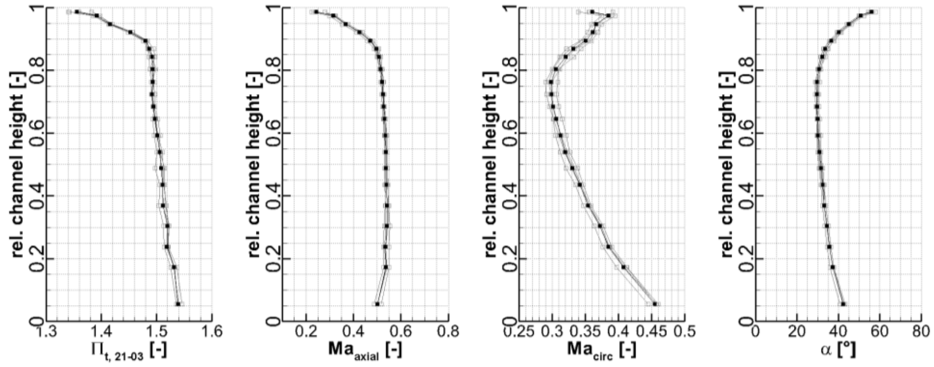
Test Procedure, Data Acquisition & Processing

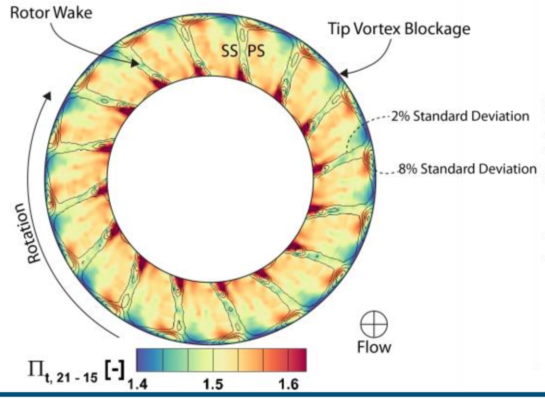


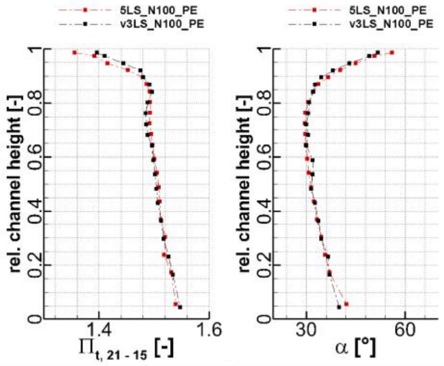
5HP

v3HP









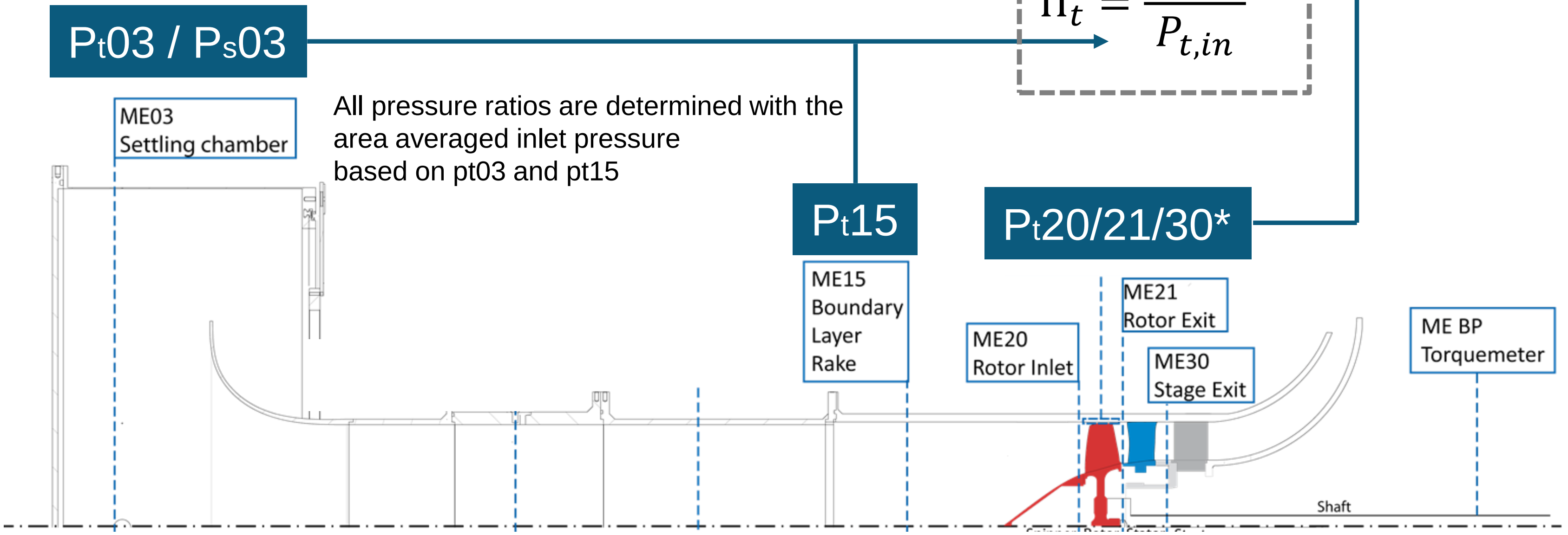
Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

(b) Probe measurements

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

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

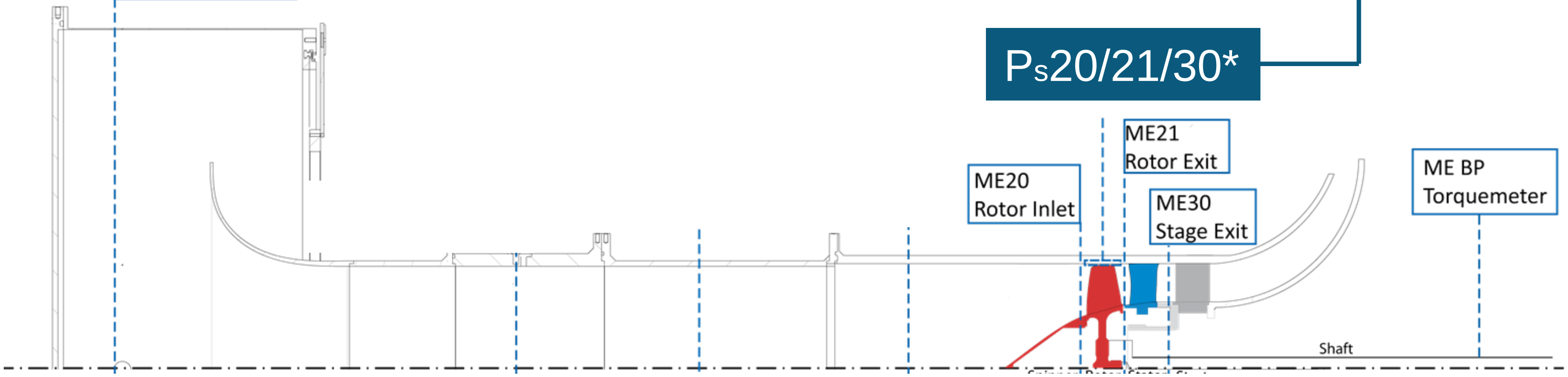
(b) Probe measurements

Ps03

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

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

Ps20/21/30*



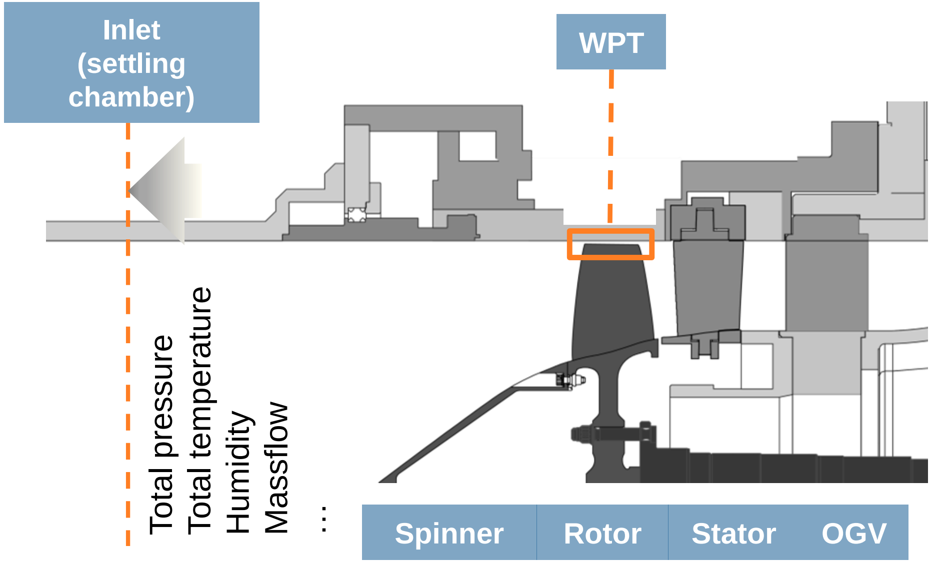
*depending on probe location

Measurement Systems & Instrumentation

Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

(c) Unsteady wall pressure measurements

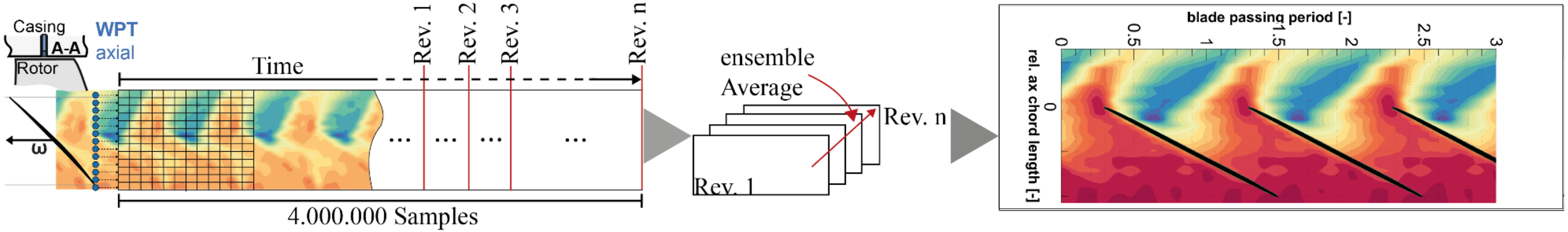


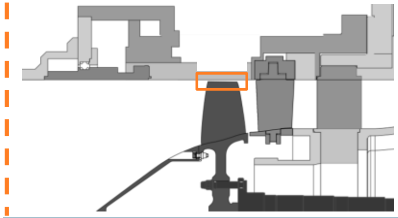
Time-resolved pressure transducer in rotor casing

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

Measurement Systems & Instrumentation

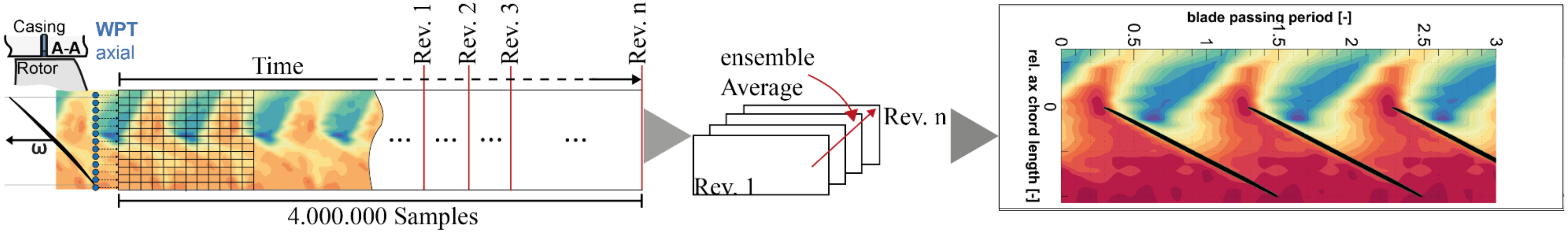
Test Procedure, Data Acquisition & Processing

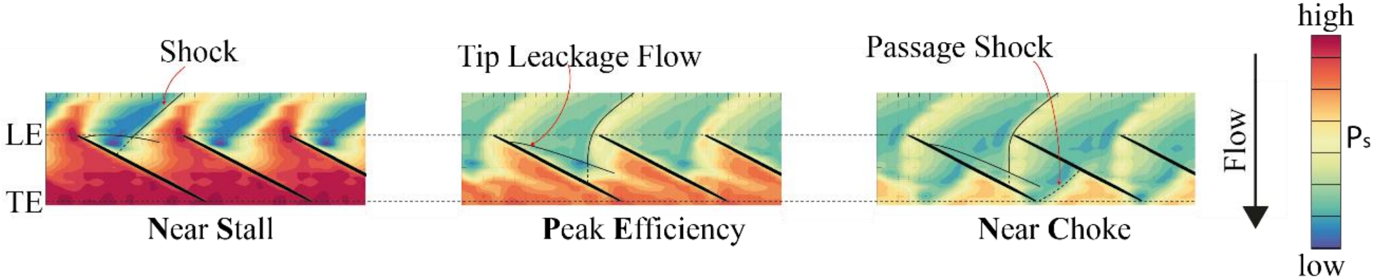


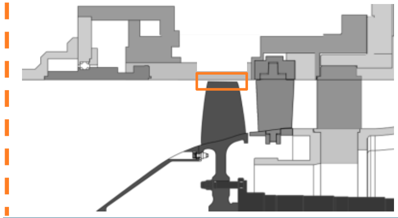


Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT





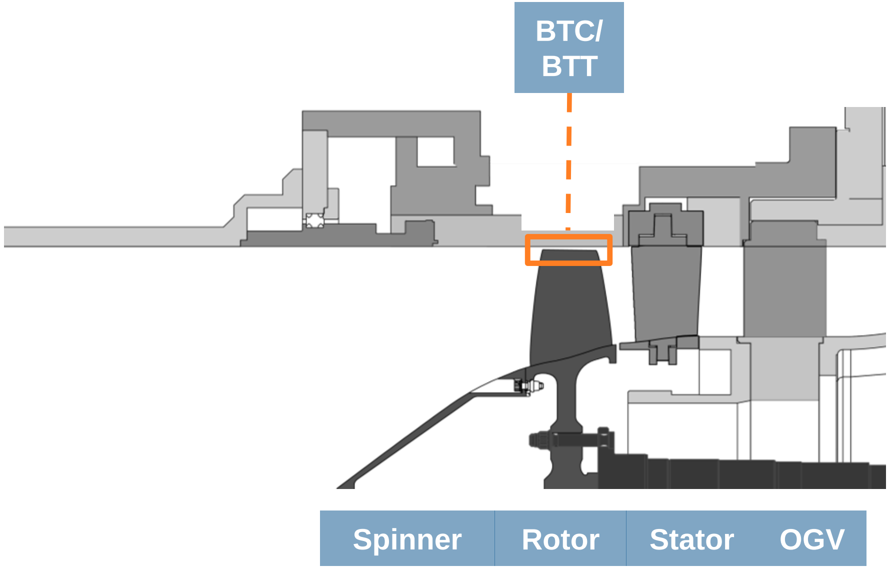


» 8 second measurements with kulite system
» $4 * 10^6$ samples / >1200 rotor revolutions (at nominal speed)
» Open test case includes static pressure ratio (normalized to settling chamber pressures)

Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

TECHNISCHE UNIVERSITÄT DARMSTADT

(d) Blade tip clearance (/blade vibration)



Capacitive BTC / BTT system

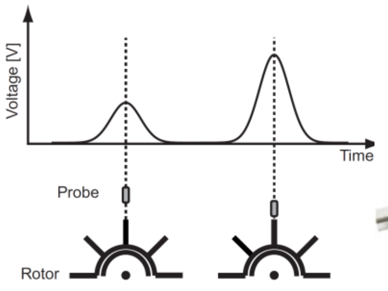
- In operation tip clearance
- Blade vibration (synchronous/ non-synchronous vibration)
- Blade untwist

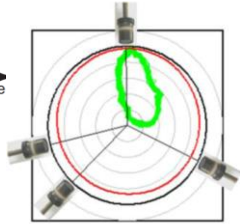
Measurement Systems & Instrumentation
Test Procedure, Data Acquisition & Processing

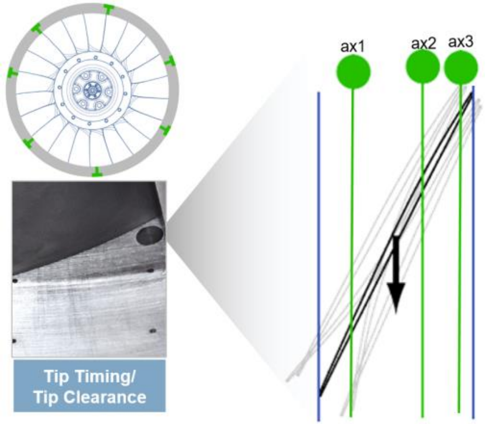
TECHNISCHE UNIVERSITÄT DARMSTADT

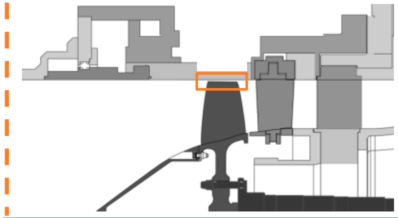
(d) Blade tip clearance (/blade vibration)

- »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



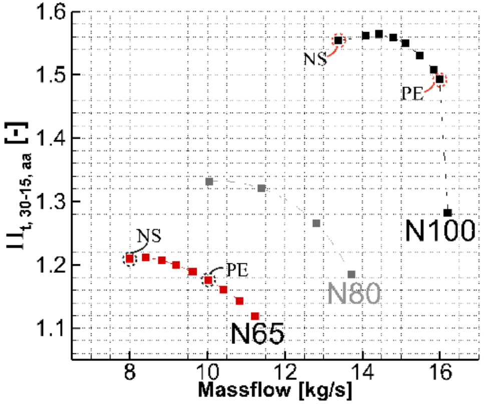


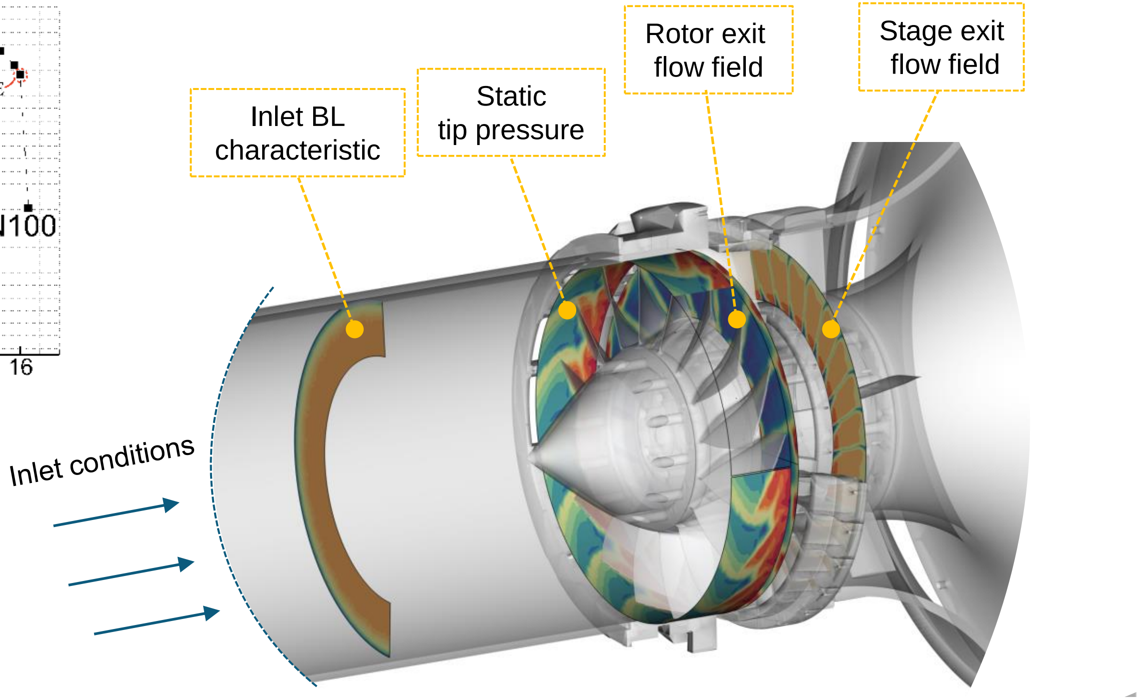




Data Set

TECHNISCHE UNIVERSITÄT DARMSTADT





CONTENT

TECHNISCHE UNIVERSITÄT DARMSTADT

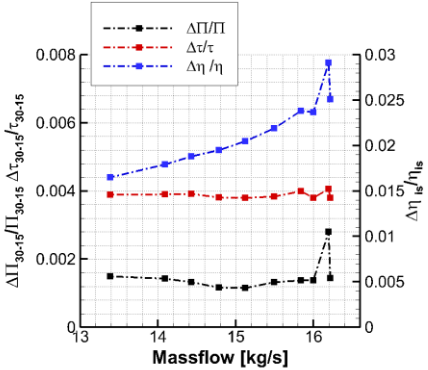
Comparing CFD and Experiment

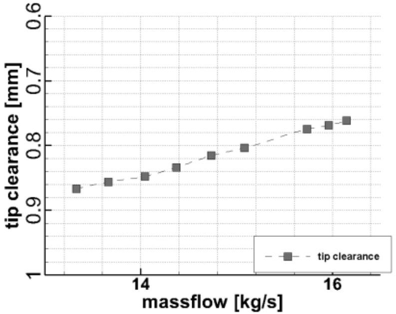
Inconsistencies due to measurement data

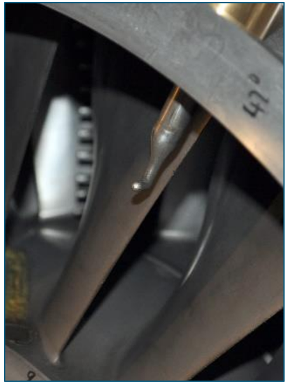
- » Consider measurement system uncertainty
- » Consider low spatial resolution (use measurement grid points)
- » Consider data acquisition procedure
- » Consider measured operating conditions

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)





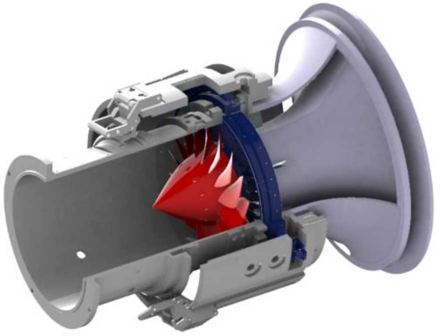


Conclusion

Initial dataset

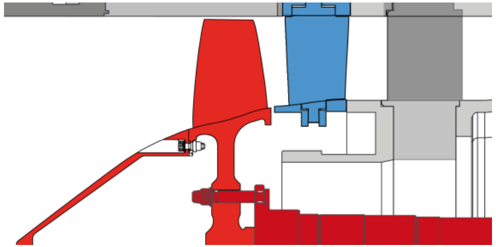
- » For comparison of steady flow simulations
- » Solver validation
- » Turbulence model validation
- » …

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!

Team:

Fabian Klausmann, Daniel Franke, Jonas Foret, Benedikt Schmidt

Contact:

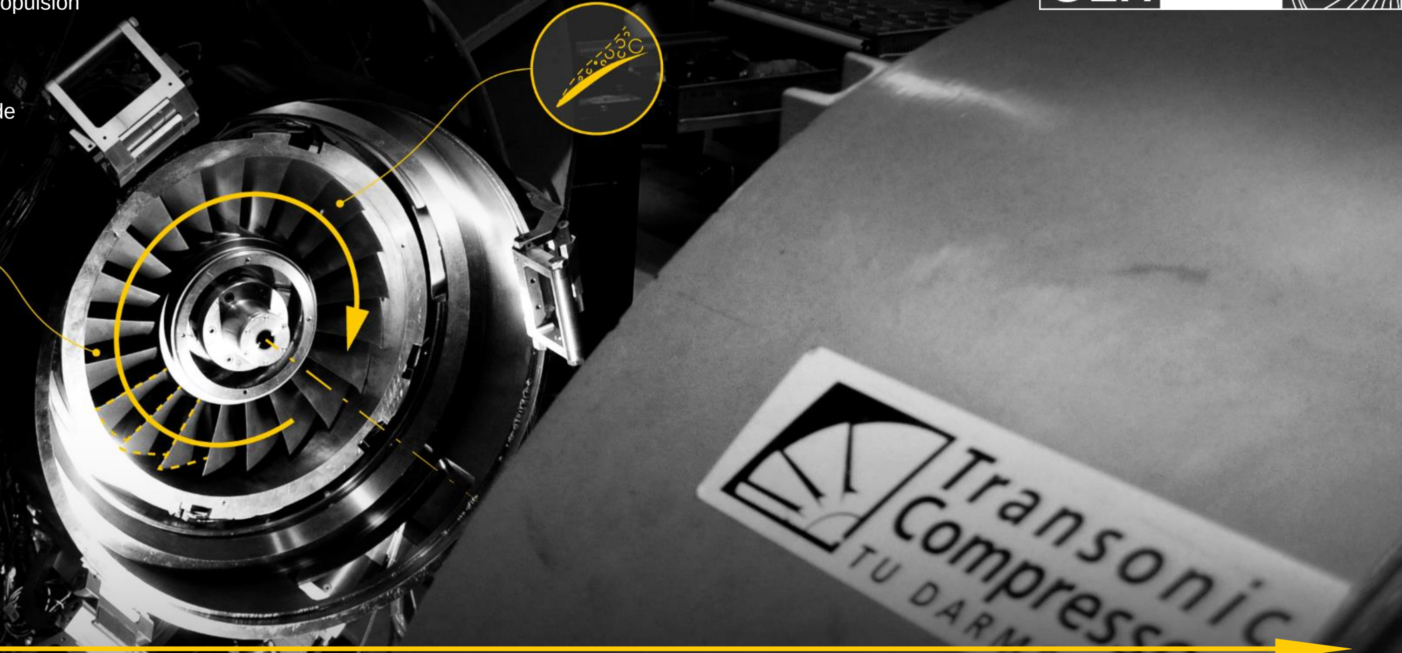
Institute of Gas Turbines and Aerospace Propulsion

64287 Darmstadt, Germany

Phone: +49 (0)6151 16-22118

Mail: compressor@glr.tu-darmstadt.de

Web: www.glr.tu-darmstadt.de



MASCHINENBAU
We engineer future

TUDa-GLR-OpenStage
Outlook

GPPS 2021 Xi'an

- 1st GPPS CFD Turbomachinery Workshop
- **After workshop** release of CFD data; submission of workshop summary to GPPS Journal
- **After conference** release of second part of dataset:
  - Probe data (rotor inlet / exit)
  - Kulite data
  - Blade tip clearance data

GPPS 2022 Chania

- Conclusion of second Open test case measurement campaign (planned for April-June 2022)
- **Second GPPS CFD Turbomachinery Workshop (F2F)**
- Conference paper regarding rig stability and measurement uncertainty (draft topic)

2023 2024 2025

Establish standard test case with reliable experimental and computational database

TUDa-GLR-OpenStage

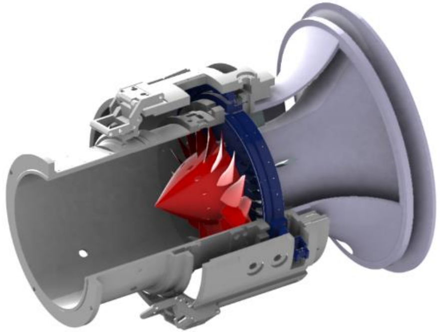
TUDa-GLR-OpenStage

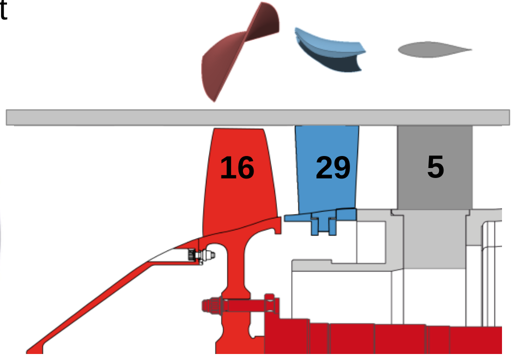
Transonic compressor stage geometry

- TU Darmstadt *Rotor 1* with *StatorOPT, OGV, radial diffusor*
- Hub & shroud contour, running tip clearance

Measurement data, exemplary

- *Steady state*: inlet conditions and 0D, 1D & 2D exit traverses
- *Dynamic*: unsteady wall pressure at blade tip (steady state & transient operating conditions, e.g. stall inception), unsteady pressure probe at rotor exit





GPPS Global Power & Propulsion | XI'AN21 CFD Workshop

Thank you