DESIGN, INTEGRATION AND OPERATION OF A ROTATING COMBUSTOR-TURBINE-INTERACTION TEST RIG WITHIN THE SCOPE OF EC FP7 PROJECT FACTOR

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ABSTRACT

Following the industrial trend of increasingly integrative design and analysis of the combustor-turbine interface, the EC FP7 project FACTOR was launched many years ago. The project ended in late 2017 after successful completion of the experimental test campaign involving blank-sheet design rotating turbine rig hardware, which was assembled, integrated and operated in DLR's turbine test facility NG-Turb in Göttingen, Germany.
This paper highlights the DLR contribution to FACTOR including the 1.5 stage turbine rig's mechanical design, instrumentation and integration as well as final part assembly to a working rig. Additionally, DLR was responsible for rig operation and overall measurement campaign fulfilment including the acquisition of static pressure and temperature data as well as aerothermal 5-hole-probe traverses in different measurement planes. The implemented combustor simulator created a characteristic flow profile to and through the turbine with strongly varying flow angles and temperatures, that posed a challenge for the applied measurement techniques.

NOMENCLATURE

5HP	Five-hole probe	IR	Infra-red	PA	Passage (clocking)
CS	Combustor simulator	LE	Leading Edge (clocking)	TC	Thermocouple
CTI	Comb. Turbine Interaction	MP	Measurement plane	TCL	Tip clearance
HT	Heat transfer	OP	Operating point	TE	Trailing Edge

INTRODUCTION

The project EC FP7 FACTOR, for **F**ull **A**ero-Thermal **C**ombustor-**T**urbine Interacti**O**n **R**esearch, was set-up at the beginning of this decade and addresses the need for a future integral approach when designing and analysing the hot core of aero engines and gas turbines. Previous work on CTI was done in EC FP6 using turbine inlet flow profile generators and focussing not only on aerodynamics but also thermal aspects (i.e. heat transfer) analysis, e.g. in project TATEF II (Chana et al., 2009) and (Povey and Qureshi, 2009). Again for FACTOR, a large consortium (see on www.factor-fp7.eu) was formed to ensure relevance of the commonly designed hardware and shared experimental as well as numerical results; now with a title and content that was not concentrating on the turbine alone but integrating the combustor and its effects for CTI research.
In the first project phase, the FACTOR combustor simulator was designed (Koupper et al., 2014) involving extensive numerical simulations, e.g. by (Andreini et al., 2016) or (Koupper et al., 2016) which were validated against data from a dedicated tri-sector test rig set-up in Florence, Italy (Bacci et al., 2018). Also early in the project, the LPT strut was designed and tested (Johansson et al., 2016).

The ultimate goal of FACTOR was to gain more insight into CTI flow phenomena and to validate CFD methods by comparing with and validating against data from testing a completely new 1.5 stage rotating turbine rig with non-reacting combustion simulator. This rig was supposed to enable continuous operational testing at relevant Reynolds and Mach numbers and at the same time provide broad optical access for application of different measurements techniques to complement probe traverses and stationary instrumentation. The impact of hot streaks and according vortices from the combustor on aerodynamics as well as heat transfer is a key question in turbine design. FACTOR intended to contribute to that field by comparing diverse industrial and academic CFD methods and approaches capturing the mentioned effects, and at the same time create validation data from a relevant and highly-accessible new rig, designed especially for the task of CTI investigations.
An early general description of the project's full scope was given by (Battisti et al., 2012). This current paper will focus on the rotating rig and in detail on the DLR work associated with it, that included mechanical design, manufacturing, instrumentation, assembly, facility operation and acquisition of experimental data.
The FACTOR rig was planned to fit the turbine test facility NG-Turb (Rehder et al., 2017) from DLR Institute of Propulsion Technology in Göttingen, Germany. The NG-Turb enables many hours of continuous testing in closed-loop for high resolution probe traverses and complex optical measurements. An example of another modern turbine test rig in this facility is given by (Wolf et al., 2017).

MECHANICAL DESIGN

The FACTOR turbine rig is a clean-sheet design that every project partner contributed to. The competence split for individual parts, especially their design, was extremely fine. That increased anyway expectable challenges during a rig design even more for FACTOR, as everything depended on joint decisions and a converging professional discussion to freeze certain features and parts. With many different experimental techniques involved, the interdependencies to design & make proved complex, however they helped shape the rig into its final configuration. One key aspect was the CAD supremacy given to DLR, where all partner's models were integrated into one digital mock-up. Finally the manufacturing was also distributed, with a major share by *Progesa s.r.l.* in Italy, but also involving other partners.
Looking at Fig.1 for a detailed mechanical design overview, the colouring additionally indicates part competence split among several partners. The combustor simulator featuring 3D-printed swirlers and

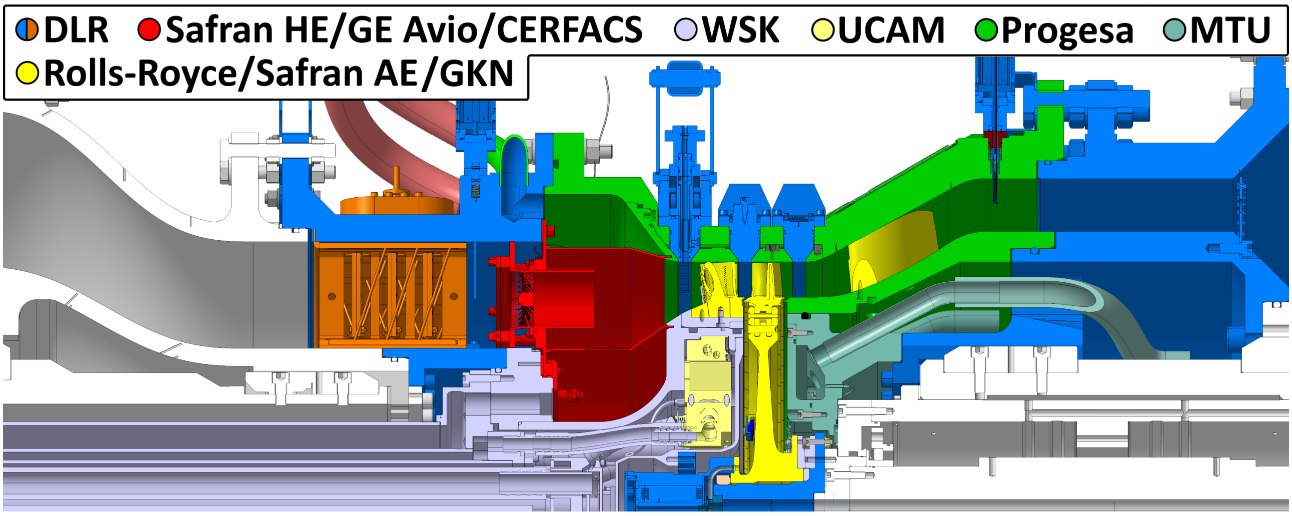

Figure 1: **FACTOR rig CAD mock-up in NG-Turb facility (white) with 'political' part coloring**

effusion cooling liners can be seen (red). The big, one-part main casing (green) with many features to provide probe as well as optical access is characteristic for the design. The hot main flow heater in front of the swirlers (orange) as well as the fast acting valves (pale yellow) below NGV blading hint at some special abilities of this rig with respect to heat transfer investigations.

Casings

With the exception of the main casing, all other casing parts connecting to the NG-Turb facility inlet/outlet ducts, were designed and manufactured by DLR.
On the upstream side, the flanged outer casing as well as the inner part were designed to mount, house, electrically connect and seal the main flow heater (see below for details). Additionally, they enable pre-swirler radial probe traverse and combustor outer cavity coolant supply.
Downstream of the turbine HP-LP interduct, two casing parts create a constant cross-section flow path that suddenly diffuses and connects to the bigger NG-Turb outlet casing. As can be seen in Fig.1, the inner part is quite complex and extends axially upstream below the interduct to sit on the spindle (white) and route the rotor back cavity purge air supply (grey).

Fast Main Flow Heater

From the requirement by UCAM to generate a fast temperature step ($\Delta T \geq 25K$ in $< 1s$) for turbine blade and end wall surface heat transfer investigations, a complete system was designed comprising of an electrical heater ring to be placed directly in front of the CS swirlers, electrical connection and wiring, power supply cabinet, hardware and dedicated software for control as well as secure operation up to the already mentioned heater casing of the rig.
Since the UCAM requirement had to be fulfilled at measurement location (i.e. blade surfaces), even for the second (LP) stator, and due to the mixing with colder air in the CS, the swirler inlet temperature would have to be modulated with a significantly bigger and sharper step by the heater system. With a swirler mass flow of $> 3\ kg/s$, it was planned for an overall electrical power of $350\ kW$.
It was chosen to design three sequential layers of fine stainless steel meshes and connect each mesh to one of the three-phases current supply, insulated against each other. Typically behind an annular cross-section cut-out mesh, there is a strong radial gradient in temperature (wire length + resistance varying). For FACTOR, a way was found to integrate a rectangular mesh into the annular heater ring by angled folding around small rods in analogy to an accordion instrument. In Fig.2 the concept can be reviewed, where white color indicates ceramics (coating and solid), while the blue is for the stainless steel structure, yellow for current-carrying parts like the clamping of the mesh in copper and finally red for high-temperature silicone to insulate smaller parts and house the coated rods in the brittle ceramic shingles inserts. The Fig.3 shows six segments forming a full-annular heater ring with three mesh layers, mounted to the upstream side of the rig.

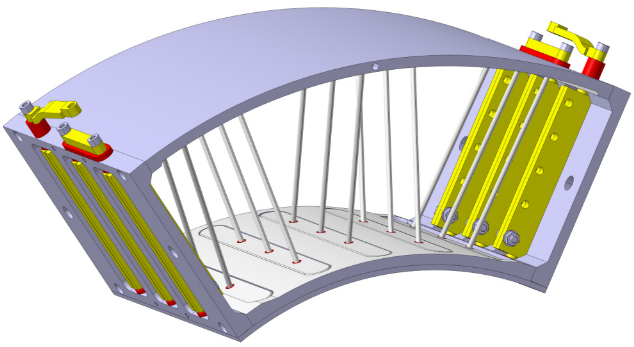

Figure 2: **CAD heater segment without mesh**

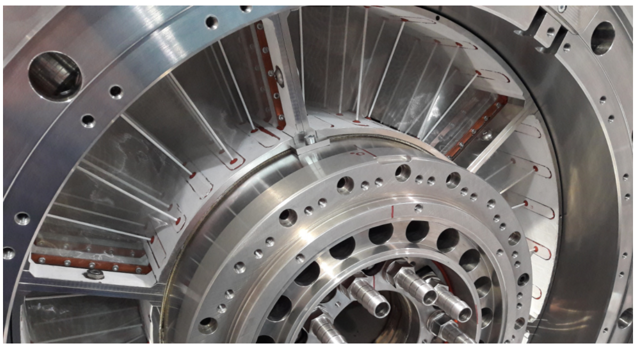

Figure 3: **Rig-integrated heater ring with mesh**

Beside the general heater design, also the power supply & control system incl. software interface was part of a bachelor thesis at DLR. The overall layout using thyristor hardware and phase angle control (leading-edge) was complemented by a programmed smart control. This featured initial ultra-short power overshoot to sharpen the step and a fast emergency power cut-off mode triggered by a mesh rupture initialisation detection. This function was based on second derivation of resistance against power monitoring and was tested to successfully prevent full mesh rupture in operation. Such a failure would lead to a catastrophic short-circuit of the ruptured mesh touching the neighbouring (folded) intact mesh layer and resulting in flying sparks that could damage the rig hardware. Finally, an up to $80K$ temperature rise at the heater was achieved, with a time constant of just $0.1s$. Additionally, the heater played a far more central role in regular rig operation than initially planned, as a mean to virtually 'freeze' the rig inlet temperature while the facility was still heating up over the day.

Circumferential Probe Traverse Gear

For radial probe traversing, already existing gear units from DLR were used in FACTOR. However, to realise inter-blading 2D area traverses, a circumferential traverse would be needed. The alternative solution of rotatable stator rings with a circumferentially fixed probe is elegant and advantageous concerning studying additional clocking effects, see (Wolf et al., 2017). For FACTOR that was excluded due to the extremely complex one-part main casing structure needed to provide optical access to all three blade rows. This defined the design task for a circumferential traverse gear with top mounted radial traverse (see Fig.4). It even influenced early FACTOR flow path design, as the constant tip HPT section was chosen mainly to keep outer radius constant and enable the application of the same traverse gear part in all core measurement planes. The size constraints were extremely challenging as the width of the traverse gear insert for the slotted casing is small. The design uses an internal chain structure to fill the circumferential gap. External rollers and rails help accurately position the probe and top-mounted radial traverse gear. The device is driven by a linear motion unit with connected geared servo motor.
A single circumferential traverse gear was built and the two remaining casing slots were closed with dummies that are instrumented and also feature a radial traverse gear connection port to do 1D traverses in parallel. As can bee seen on Fig.5, mounting is only possible with a special spreader to be inserted into one casing slot, since the three $\pm 20°$ cut-outs are that close to each other and thus structurally weakening to the casing, that a deformation would prevent the traverse gear to be inserted.

INSTRUMENTATION

While not to the highest density seen in other rigs (sensor count), the FACTOR rig is instrumented diversely and provides access for many techniques. An overview will be given in the following.

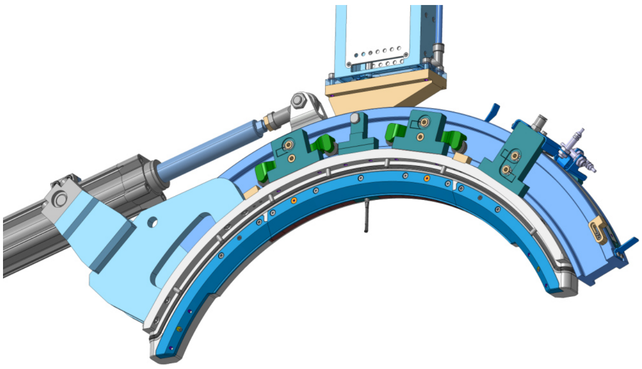

Figure 4: **Probe traverse gears (radial on CTG)**

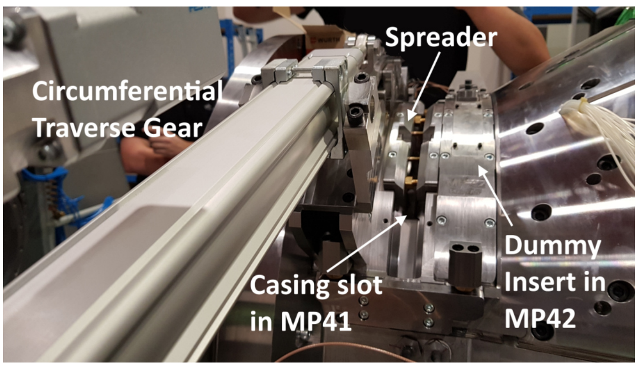

Figure 5: **Mounting of CTG & dummy inserts**

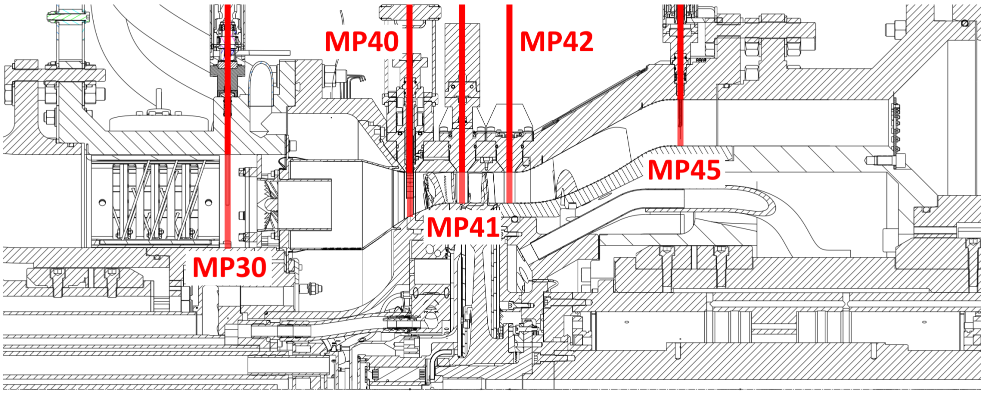

Figure 6: **FACTOR rig CAD cut-away view, probe access MPs**

A technical drawing, cut-away view of the FACTOR rig can be seen on Fig.6 with the measurement planes highlighted. The core planes in HP turbine MP40-42 provide circumferential traverse gear access and thus planar probe measurement capability. Only radial traversing is available in the other MPs shown, where the heater casing and the main casing feature radial traverse gear connection ports. For MP30 there is just one access (top dead center) to measure in front of the CS swirler and behind the DLR fast heater. In MP45, behind the interduct, there are three access ports on the upper circumference at $0°$ and $\pm 48°$. There was no implementation of rakes or even a circumferential traversing in MP45. This prioritisation in instrumentation clearly shows the character of the FACTOR rig as a highly accessible multi-technique, cross-validation rig to study effects rather than absolute efficiency. The usage of NG-Turb facility instrumentation (sensors installed in the exit casing) would have been an option but due to operational requirements the installation of a perforated plate at rig exit was necessary, which (deliberately) changes exit conditions.

Static Pressure Tappings

More than 180 static pressure tappings on end walls and blades as well as in the CS and in cavities were connected to DLR pressure scanners close to the rig. These were calibrated before to achieve at least OEM spec. accuracy of 0.15% up to $1\,psi$ and 0.05% up to $15\,psi$ respectively.

Especially the NGV sub-assembly with glued-in vanes, that themselves were used to route instrumentation additionally to existing coolant channels, had to be instrumented prior to the campaign. Before finalising the design in global CAD mock-up, every single routing path was detailed and checked, not just for the NGV. This work resulted in several part design decisions and adaptations, sometimes leading to either sensor cancellation or mechanical constraints. This was key for an achieved $\sim$99% rate of instrumentation availability during rig testing. The Fig.7 shows the mentioned preparation of pressure tube routing in CAD vs. executed instrumentation on NGV ring and their high resemblance.

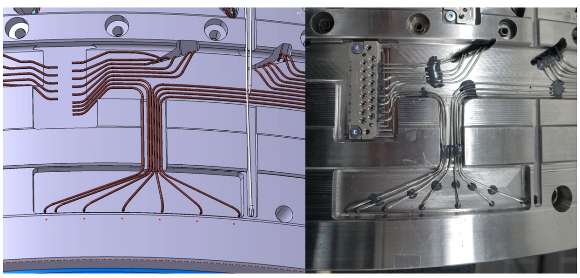

Figure 7: **Routing of tubes, CAD vs. real**

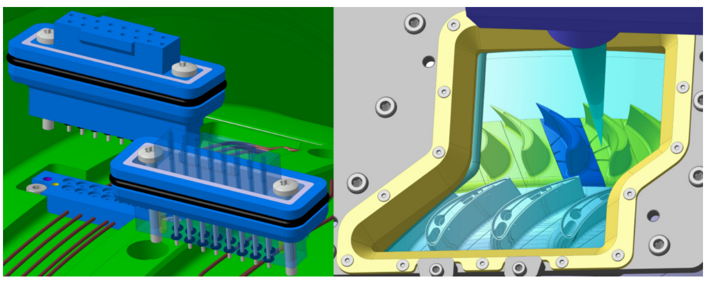

Figure 8: **CAD connector & HP IR window view**

Thermocouples in static parts and inlet temperature rake

Analogous to the pressure tappings described above, a total of 261 thermocouples were distributed in static rig parts, especially over all casing walls on the inner and outer sides around the circumference. About 85% of them were routed to commercially available connectors, placed on supports to guarantee a surrounding temperature level of less than $350\ K$ which helps keeping erroneous influence low (additional thermoelectric voltage). The remaining TCs had to be routed directly out of the rig, bundled and connected to the DLR acquisition system nearby. The TCs were calibrated using a thermal bath to yield an overall, temperature-dependent uncertainty (expanded, 95% probability) of $0.25 - 0.48\ K$ in the relevant range of $283 - 530\ K$.

Pressure Connectors

Due to the rig design philosophy of inserting the NGV ring into the main casing, the size (i.e. depth) of pockets at the NGV ring circumference for instrumentation was limited (review Fig.7) and anything sticking out of these pockets would be sheared-off when mounting the NGV sub-assembly to the main casing. A handful of flexible pressure tubes were routed directly out of the rig. But especially on the NGV, the vast majority had to be routed using small metal tubes. This led to the problem of commercially available pressure connectors being too big to fit into the pockets and anyway the connection density, i.e. ratio of plug size to number of connections, was too small. Therefore, special pressure connectors were designed and custom-built using in-house 3D metal printing (SLM) manufacturing technique. On Fig.8 left, the connector CAD can be seen in detail, where especially the flat female connector part fitting inside the pockets can be seen (compare also Fig.7 right).

Aerothermal Five-Hole Probes

DLR Göttingen developed and applied aerodynamic probes regularly. The current design used for FACTOR features 3D printing to create an integral probe head with small size, reduced frontal area, defined angles and integrated channels, that can be mounted to shafts of different size (Fig.9). Its dimensions and layout can be reviewed in Fig.10. The probe calibration procedure using a dedicated wind tunnel was developed by (Kost, 2009) in DLR using soldered probes, introducing the processing of data from a back pressure hole behind the probe head (Fig.10 top right) in eddy water to enhance accuracy especially in transonic flow.
For FACTOR, this 4+1 hole design was implemented with the new probes depicted in Fig.9 and 10. Additionally, a TC is applied on top of the 5HP head. As in FACTOR no dedicated temperature probe traverse was planned, the DLR 5HP TC data was used to acquire 2D temperature fields (see results below). The probe used for core MPs 40-42 was calibrated to an uncertainty in temperature (expanded, 95% probability) in relevant operating range of less than $0.3\ K$.

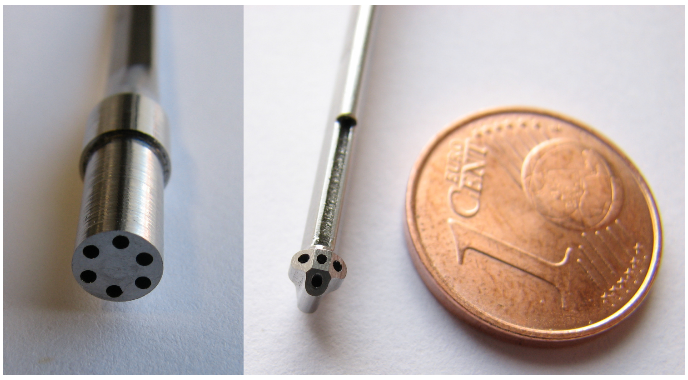

Figure 9: **5HP shaft interface & head size photo**

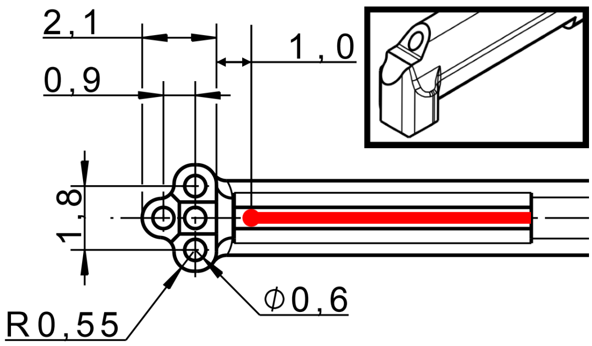

Figure 10: **5HP head dimensions, TC in red, back pressure hole behind head (top right)**

Tip Clearance Sensors

Tip clearance measurement over the rotor at the LE and TE (3x2 sensors) was provided by DLR using an existing capacitive system. It proved capable of decent repeatability and dependable relative distance changes, while the absolute accuracy was compromised. The reason was a combination of calibration setup, rotor tip geometry, sensor mounting through casing and NGV ring, rotor blade material and data processing. This experience led to the procurement of a new system after the project.

Other Instrumentation

Instrumentation and measurement equipment of the techniques described below was completely under responsibility of the individual FACTOR partner. During the campaign, DLR as rig operator provided any help needed with integration and setup as well as acquisition if reasonable and requested.

Infra-red Surface Temperature and Heat Transfer

The FACTOR rig design was heavily influenced by the requirements from IR HT measurements to be carried out by UCAM. The fast heater as one major element was described above, creating sharp steps or even continuous waves of varying flow temperature to detect the answer of the wetted surfaces in the turbine. Since the NGVs feature film cooling that deliberately insulates certain parts of its surface from outer main flow temperature, increasing the latter would not be effective there. Thus, another system comprising of a second NGV coolant feed line, custom-built fast acting valves (Fig.1 pale yellow) and an additional heater was designed to enable fast coolant temperature modulation. By two big IR windows, over the HP turbine stage (Fig.8) and the LP-Strut in the interduct, almost all wetted surfaces were optically accessible by the UCAM IR camera traverse below the rig. In order to approach adiabatic wall conditions, one LP strut, three NGVs and two rotor blades were moulded from plastics of low thermal conductivity rather than being made from titanium.

Laser - Raman Scattering

Another optical access was implemented in horizontal direction by small porthole-like laser windows for MP40-42. A laser spectrometer on an externally mounted traverse & table was used by ONERA to conduct Raman Scattering measurements that yield point-wise data of static temperature.

Fast Response Aerodynamic Probes and Rotating Instrumentation

Complemental to the 5HP traverses, VKI provided fast response aerodynamic probes (Kulite) to capture pressure fluctuations. The probes were adapted to fit DLR's traverse gears and adjusting procedure on the rig. VKI was also responsible for instrumentation of the rotating system, where TCs had to be placed not only on the disc but also into rotor blades (see TC grooves in Fig.8 right).

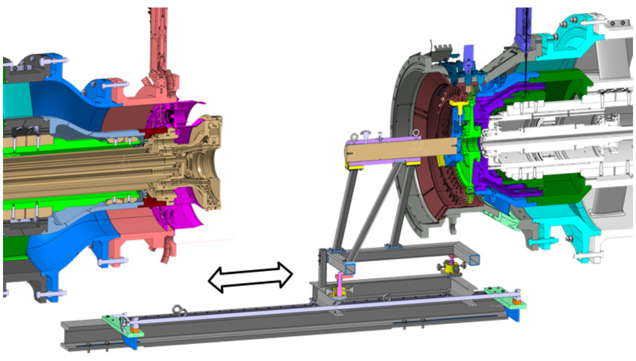

Figure 11: **Mounting device usage in CAD view**

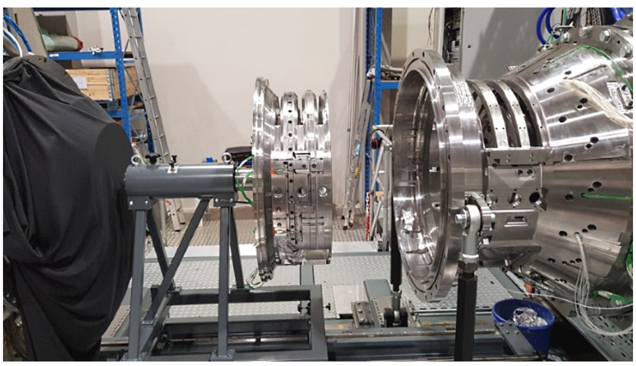

Figure 12: **Mounting device + NGV ring at rig**

ASSEMBLY & FACILITY INTEGRATION

The current mounting concept of rigs to the NG-Turb is definied by placing the complete breaking shaft assembly including spindle (rotor mount) on a rail system, so that it can be traversed back from the inlet casing, see also (Rehder et al., 2017). This requires the rig to be separated at a defined interface (here: below NGV), where it opens up and enables access to upstream and downstream side, see Fig. 11. A special mounting device can be seen in use on Fig.12, cantilevering the NGV assembly while the rotor was already put into the main casing and fixed to the spindle. The adjustment procedure was challenging, as was the whole design concept of a co-axial ring/casing for the NGV requiring perfect alignment due to the traverse slots and other access features going through both parts. However once adjusted, the actual mounting itself was quick, straightforward and secure with the axially traversable device on rails.

The fully mounted, closed and instrumented rig including IR camera traverse below can be seen in Fig.13. The complete facility integration until test readiness took 23 weeks. Several weeks were spent waiting for parts to be delivered to the facility with effectively no mounting action done. This was due to delays with manufacturing and instrumentation of the parts as well as sometimes required re-work or adaptation of certain features and even some additional parts needing to be procured.

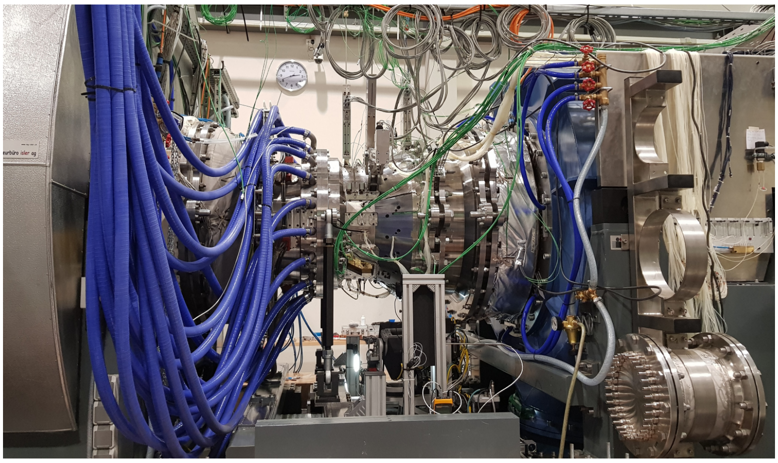

Figure 13: **FACTOR rig assembled & instrumented at NG-Turb**

COMMISSIONING & OPERATION

The commissioning phase started with the check of all sensors and security devices both in the rig as well as in the NG-Turb facility. First data acquisition and low-speed rotation tests with closed rig were carried out. The commissioning phase took a rather lengthy four weeks. This was mainly due to initial problems achieving the high-speed operating point and some electronic malfunctions leading to checks and part replacements.

Looking at the FACTOR-specific NG-Turb circuit scheme in Fig.14, it can bee seen that some adaptations had to be done and thus, managed in operation; compare also (Rehder et al., 2017). The additional coolant compressor sucking from ambient air to feed nominal NGV coolant mass flow (high resistance due to valves for HT, i.e. pressure loss) blew up the closed circuit. As standard vacuum pump suction at low pressure side was not able to extract enough mass (volume flow limitation), a controllable blow-off on the high pressure side in CS outer cavity feed had to be installed during commissioning. Also, the heating-up of the facility tubing influencing hot main flow feed temperature for hours had to be eliminated to start long-duration probe traverses as early as pressure level was stable. This required the electrical main flow heater, against original planning, to be operated all the time under automatic control in order to freeze swirler inlet temperature at the nominal (high) level.

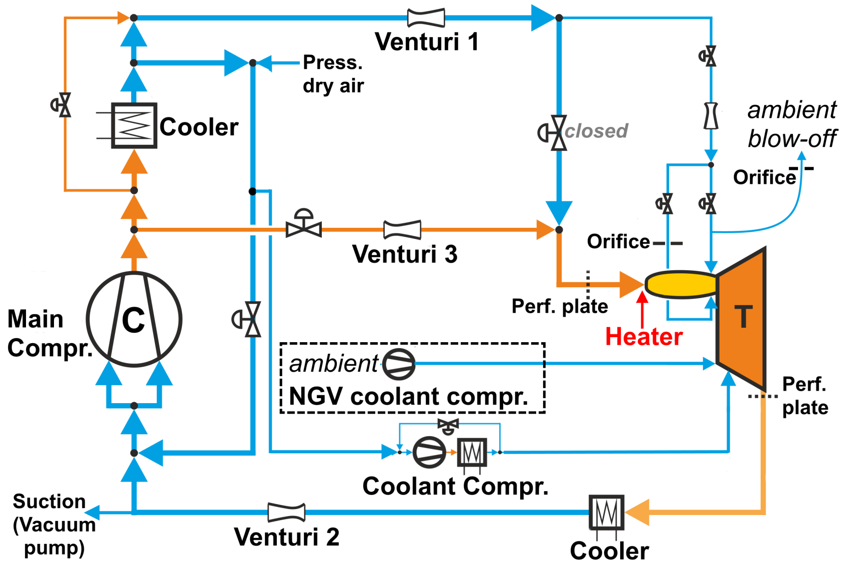

Figure 14: **NG-Turb facility circuit in FACTOR configuration**

Parameter description	Value	Unit	Measure
Inlet pressure (static ≈ total)	149	kPa	Tapping
Outlet static pressure	53	kPa	Tapping
Pressure ratio (total-to-static)	2.7	-	-
Swirler mass flow (Venutri 3)	3.09	kg/s	Venturi 3
CS coolant feed mass flow	1.88	kg/s	Venturi 1
CS outer coolant mass flow	0.95	kg/s	-
CS inner coolant mass flow	0.67	kg/s	Orifice
Upstream blow-off	0.26	kg/s	Orifice
Rotor front cavity purge flow	72	g/s	Orifice
Rotor back cavity purge flow	72	g/s	Orifice
NGV coolant (ext.) mass flow	0.36	kg/s	Orifice
Swirler air temperature	512	K	Pt100
Coolant temperature (all)	298	K	TC
Turbine rotor RPM	7700	rpm	Magnetical
Turbine rotor power	395	kW	-
Turbine rotor torque	490	Nm	Torsion

Figure 15: **FACTOR OP table**

The finally achieved and fixed operating point is detailed in Fig.15. The campaign took eleven weeks to complete including mounting and configurational breaks of about five weeks in between. Starting with the probe traverses (DLR & VKI) as first-to-deliver data for waiting post-test CFD partners, the Laser Raman measurements were taken afterwards followed by a longer installation phase until finally the IR HT measurements (UCAM) were conducted. In between, the CS was clocked several times from leading edge to passage alignment of swirler center, changing the hot spot position and the flow scheme as desired for CTI investigations (see also Fig.17 right).
The flow temperature and its non-uniform scheme was characteristic for the rig and also dominating the operational constraints with the facility. Therefore a typical probe measurement day is described in the following by looking specifically at the evolution of turbine inlet total temperature, measured by a round and grooved TC rake of 6mm in diameter, all depicted in Fig.16:

a) Starting from shut-off state where temperature equilibrium was reached, the main compressor is activated at $20 kPa$ closed circuit ambient pressure (wind on). Mass flow and pressure is constantly increased resulting in a linear temperature rise at rig inlet as the compressor outlet temperature is also rising. Only the hot line (Venturi 3) is used, i.e. only CS swirler flow at start-up.

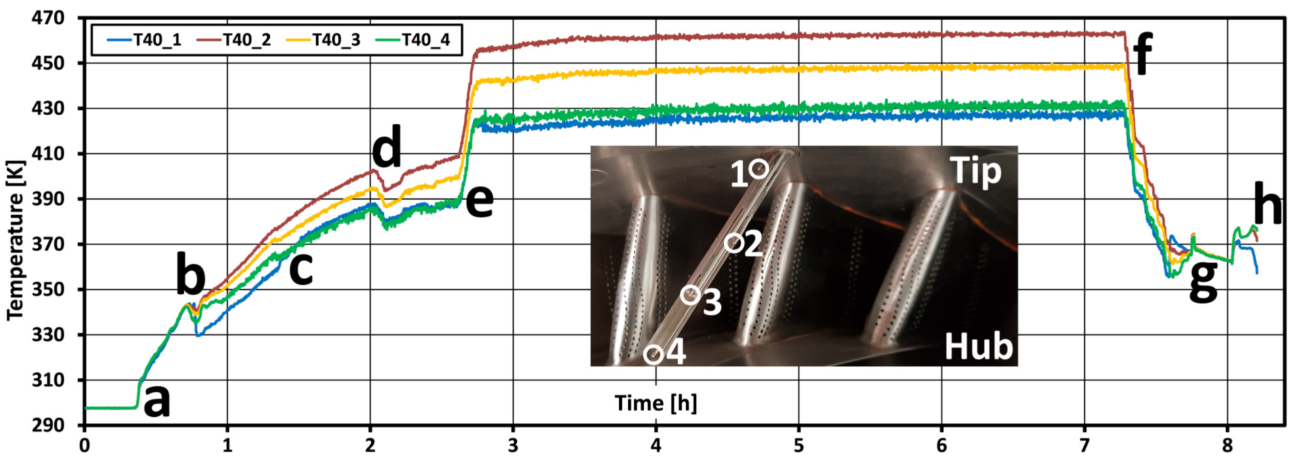

Figure 16: **MP40 flow temperature evolution on a typical probe measurement day (single OP)**

b) Activation of cold main flow (Venturi 1) feeding the CS cavities with effusion cooling, results in a strong radial temperature profile. Hot main flow and thus overall temperature continues to rise.

c) Start of setting valves, flow split and distribution of the CS coolant feed to nominal. Especially the close-to-hub `T40_4` and close-to-tip `T40_1` sensors temporarily switch positions, as the changing cold flow influences temperatures near the end walls. Expectedly, the two inner sensors give the highest temperature read-out (mid-channel close to hot spot).

d) Kink in global temperature rise caused by a quick valve setting to final configuration which redistributes a significant amount of air from hot to cold line initially, then falling back to a constant level (still higher than before) that lets overall (i.e. mixed in CS) temperature rise again.

e) Activation of main flow heater, boosting hot line flow temperature in front of CS swirlers by $80\,K$, resulting in MP40 as increase of about $50\ K$ overall, desired strong radial and circumf. gradients.

f) After several hours of constant operation, made possible by heater control lowering the electrical power such that CS swirler inlet air temperature is kept constant even if facility is still heating-up. Probe traverse program is completed and shut-down of facility begins. Pressure and mass flow are lowered, strongly affecting the temperature while the electrical heater is turned off.

g) Analogous to b) now the flow over Venturi 1, i.e. the cold line feeding the CS coolant cavities, is turned off. The `T40` rake temperatures fall together as just a swirl profile is preserved without any temperature gradients. The sudden temperature increase is explained by the absence of cold line flow, eventually being compensated shortly after when the hot line temperature is lowered further.

h) Main compressor switched off, no flow. The slight up and down before is caused by almost no flow other than the pressurized dry (and cold, $300\ K$) air being used to blow up the circuit to atmospheric pressure influencing the `T40` rake in combination with conduction of casing heat.

EXEMPLARY RESULTS

Being an introductory paper giving an overview of the rig configuration and the campaign, no processed results other than the exemplary comparison of the two CS clocking positions' influence on the temperature field behind the NGV in Fig.17 shall be presented here. The results were obtained by 5HP planar traversing in MP41 using the hardware described herein. The view is upstream as the TC on the probe was oriented. The automatic yaw aligns the 5HP head and therefore the TC on top, with main flow direction (here: NGV outflow). Consequently, the bowed NGV trailing edge (influence) can be clearly seen in Fig.17 as a colder zone from hub to tip, separating the hot areas.
A slight difference in circumferential span of the measurement between PA and LE clocking can be observed in Fig.17, however both were $> 18°$ to cover more than one swirler / two NGV pitches. Small dots indicate the probe locations where data was acquired, giving an idea about the planar resolution of the interpolated contour. The pronounced hot spot in the left passage for PA case is clearly visible, as is the almost equal and broad transport of the obviously split-apart hot spot to both passages in LE case, with a slightly higher peak temperature in the right passage. Due to the position of the TC on top of the 5HP head (review Fig.10) and the programmed traverse matrix keeping a safety distance from the hub, it is clear that the temperature distribution shown in Fig.17 is somewhat cut-off at the bottom, where also colder flow zones (like at the tip) are expected.

CONCLUSIONS AND OUTLOOK

The FACTOR rotating turbine rig design, instrumentation, integration and operation was described with a focus on DLR work and responsibility. The measurement campaign yielded valuable data that was either distributed directly during the campaign to all partners and/or was started to be

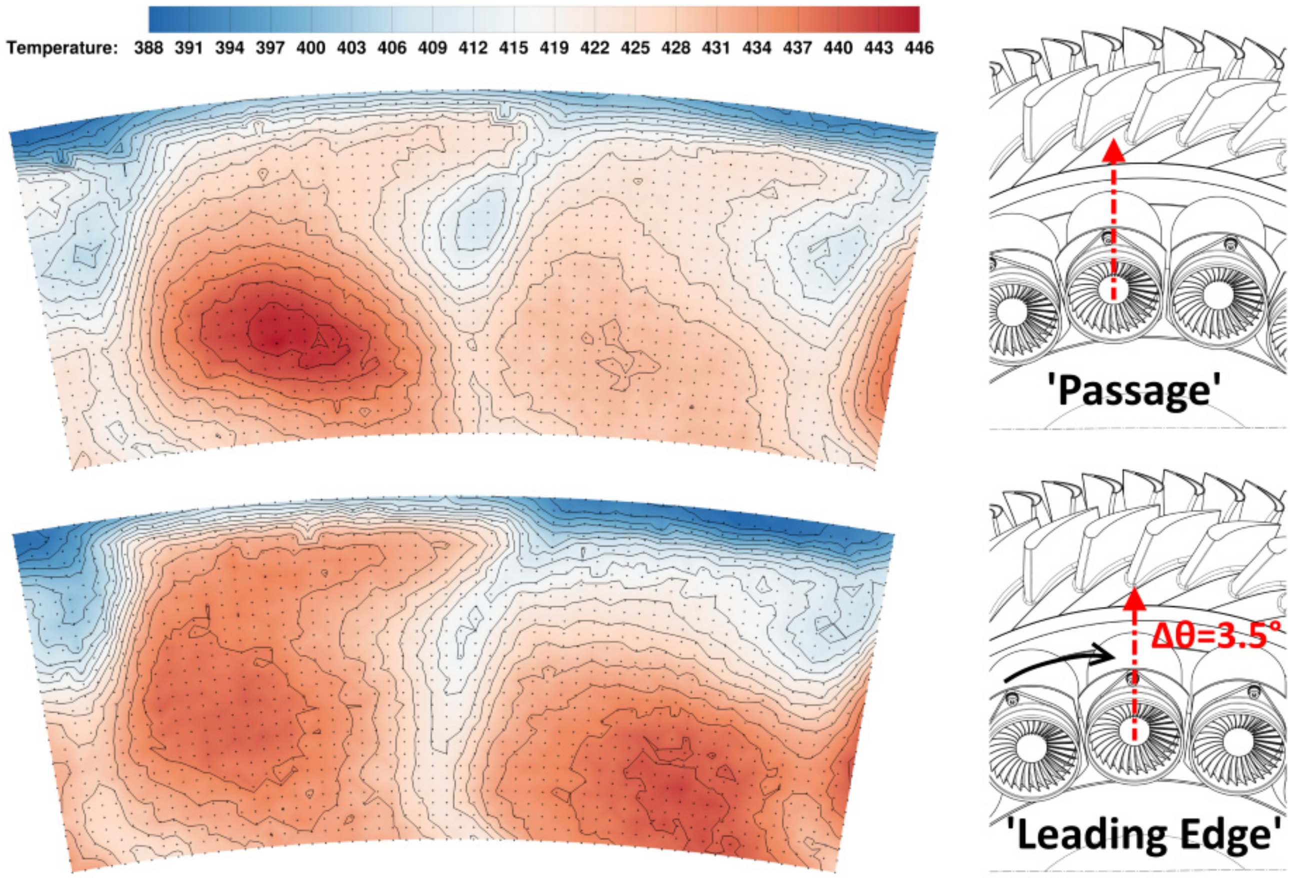

Figure 17: **Temperature field behind NGV looking upstream (MP41) for CS clocking PA vs. LE**

post-processed. As of today, various results and comparisons are about to be published by FACTOR partners, many of which were also engaged in post-test CFD work. Especially the results from 5HP traverses are about to be processed and presented later in 2019.
Concerning modern turbine rig design and operation, the FACTOR campaign enables to draw some conclusions, that are valuable for future approaches:

1) Distributed design of a complex rig involving numerous and different CAD systems is possible, however requires significant resources to create and manage an overall virtual mock-up with highest grade of detail possible. The latter proved to be of great use in accurately predicting the limits as well as in finding solutions for instrumentation routing and integration.
2) A powerful and quick main flow heater proves exceptionally helpful in achieving constant operating conditions in a large closed-loop facility, as long as it features automated control and is positioned close to the actual rig inlet. The NG-Turb facility was upgraded with a heater device in the inlet tubing after FACTOR, based on the positive experience made.
3) The operation of a multi-feed combustor simulator in front of a rotating turbine rig is delicate and ideally requires a set of fix instrumentation that is not too obtrusive but enables to characterize the highly non-uniform turbine inlet flow independent of traverse action with an adequate accuracy to base facility control on it (T40 rake as shown herein is a bare minimum in this respect).

FACTOR rig assembly and operation proved to be very challenging, but all partners stayed not only committed and supportive but keep working today on analysis and dissemination even after the official end; they still actively seek new opportunities to further investigate CTI using the existing and commonly designed rig hardware.

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