FACTOR
Insight on
combustor-turbine
interactions

SEVENTH FRAMEWORK PROGRAMME

Project co-funded
by the European Commission

# Full Aero-thermal Combustor-Turbine interactiOn Research (FACTOR)

## Final Publishable Summary Report (1 December 2010 to 31 August 2017)

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| DATE | 31/08/2017 |
| PROJECT | Full Aero-thermal Combustor-Turbine interactiOn Research (FACTOR) |
| START DATE AND DURATION | 1 December 2010 – 81 months |
| ABSTRACT | This final report comprises three separate parts: a final publishable summary report covering results, conclusions and socio-economic impact of the project, a plan for use and dissemination of foreground and a report covering the wider societal implications of the project. It also includes the final report on the distribution of the European Union financial distribution |
| AUTHOR, COMPANY | Matthieu Chevrier (SAFRAN AE) and Herman Bertrand (ARTTIC) |
| FILING CODE | FACTOR_Final_Publishable_Summary_Report |
| KEYWORDS | Final publishable summary report, final distribution, results, conclusions, socio-economic impact, use and dissemination, foreground, societal implications |

DOCUMENT HISTORY

| Version | Date | Reason of change | Status | Distribution |
|---|---|---|---|---|
| 0.1 | 30/07/2017 | First draft | Draft | ALL |
| 1.0 | 07/11/2017 | Final | Final | ALL |

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# PROJECT FINAL REPORT

**Grant Agreement number:** 265985

**Project acronym:** FACTOR

**Project title:** FULL AERO-THERMAL COMBUSTOR-TURBINE INTERACTION RESEARCH

**Funding Scheme:** CP

**Period covered:** From 1 December 2010 to 31 August 2017

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# Abbreviations Used in this Document

| **Abbreviation / acronym** | **Description** |
|---|---|
| BC | Boundary Condition |
| CA | Consortium Agreement |
| CAD | Computer Aided Design |
| CDR | Critical Design Review |
| CFD | Computational Fluid Dynamics |
| CS | Combustor Simulator |
| DMU | Digital Mock-Up |
| DoW | Description of Work |
| EC | European Commission |
| FAV | Fast Acting Valve |
| FDR | Final Design Review |
| FEA | Finite Element Analysis |
| FGA | FACTOR General Assembly |
| FPMT | FACTOR Project Management Team |
| FRS | Filtered Rayleigh Scattering |
| GA | Grant Agreement |
| HP | High Pressure |
| HPT | High Pressure Turbine |
| IR | Infra-red |
| NGV | Nozzle Guide Vane |
| LE | Leading Edge |
| LES | Large Eddy Simulation |
| LP | Low Pressure |
| LPT | Low Pressure Turbine |
| SFC | Specific Fuel Consumption |

# 1. Final Publishable Summary Report

## Executive summary

To reduce fuel consumption and CO2 / NOx emissions, modern turbo-machineries operate at high velocities and high temperature conditions. The lack of confidence in the prediction of combustor-turbine interaction leads to apply extra safety margins on components design.

Consequently, the understanding of combustor-turbine flow field interactions is mandatory to preserve high-pressure turbine (HPT) life and performance when optimising the design of new HPT and combustors (e.g. lean burn combustors).

The main objective of the FACTOR project is to optimise the combustor-HPT interaction design. This will be achieved through a better understanding of the interaction between the coolant system, the transport and mixing mechanisms enabling a Specific Fuel Consumption (SFC) reduction of about 2%.

To achieve this purpose a new turbine has been designed. This turbine has the same characteristic as a current engine turbine. This turbine has been designed by the most important European aeronautical actors and has been manufactured to be setup on the DLR rig. To be representative of an engine environment, a combustor simulator has been designed in order to produce a flow which has the same characteristic and the same hot point that may be found in real engine.
This turbine has been specially designed to allow high precision measurements which are not available in a real engine measurement, but which are mandatory to have a better understand of the fluid structure and behaviour.

Optical access has been designed to allow non-intrusive measurements in the turbine, optical measurements have enabled to measure heat-transfer coefficient on both stator and rotor blades which are not measurable inside a real engine because of accessibility.
Once the test database has been available, new CFD calculations have been performed to see if the calculations are enough representative to reproduce the behaviour seen during tests. The objective was to find a suitable configuration and calculation parameters that may be used during future design to better predict the hot-point migration.

All these measurements have been concatenated to create a new test database which is available for all the FACTOR partners and will be used for the future design of turbine. This database is very complete because it contains different clocking positions that enable to better understand how the hot point interacts with the turbine. It also contains detailed measurements in all interfaces which will be available and used for at least 10 years to better understand the fluid structure inside the turbine. It will also be used to be more predictive in future design to achieve higher efficiency engines.

# Summary description of project context and objectives

To reduce fuel consumption and CO2 / NOx emissions, modern turbo-machineries operate at high velocities and high temperature conditions. The lack of confidence in the prediction of combustor-turbine interaction leads to apply extra safety margins on components design.

Consequently, the understanding of combustor-turbine flow field interactions is mandatory to preserve high-pressure turbine (HPT) life and performance when optimising the design of new HPT and combustors (e.g. lean burn combustors).

Previous projects have investigated combustor technologies to improve combustor volume, cooling, emissions and exit temperature profiles (INTELLECT and TIMECOP) and others addressed the challenge of understanding the behaviour of hot flow structures in the HPT (TATEF2 and AITEB2). All those projects gave a better understanding of the physical behaviour of the combustor and the turbine and brought improvements on the designs of both modules.

However industrial experience demonstrates that the separate optimisation of the two modules - combustor and turbine - does not necessarily ensure that the system in which they are embedded will also be optimum. This understanding is even more crucial to develop new combustion technologies (e.g. lean burn combustion) where there is a lack of industrial experience.

The link between the combustor and the turbine in an engine is very tight and all engine manufacturers are putting a strong effort to master this interface: extremely hot gases, variable boundary layers, turbulence effects and inherent unsteadiness are some of the phenomena making this region of the engine a difficult interface. This interface still requires strong improvements as gas turbine designers are lacking the experimental data needed to optimise its design.

The main objective of the FACTOR project is to optimise the combustor-HPT interaction design. This will be achieved through a better understanding of the interaction between the coolant system, the transport and mixing mechanisms enabling a Specific Fuel Consumption (SFC) reduction of about 2%.

To get a detailed understanding of the combustor-HPT interactions, FACTOR will set up an experimental test infrastructure using most advanced measurement techniques. These measurement techniques will be adapted to FACTOR specific requirements and all combined to ensure that an all-encompassing and comprehensive database of measurements is obtained together, respecting exactly the same boundary conditions. This unique test infrastructure involves two complementary European turbine test rigs:

- A new continuous flow facility hosted by DLR (Deutsches Zentrum für Luft- und Raumfahrt). Fed by hot and cold air, this module will supply realistic flow field to the downstream HPT and thus enable experimentalists to explore the aerodynamic and thermal interactions between combustor and turbine.
- A complementary blow-down turbine facility hosted by Oxford University (the Oxford Turbine Research Facility O-TRF) that will be used to supplement the analysis of the DLR continuous flow test rig.

The turbine modules which have been plugged on the DLR rig have been designed and manufactured during the first part of the project.

Before starting any detailed design, the first objective of the project was to choose main parameters of the future with three requirements:

- The rig has to be representative of current engine technology
- The rig must be compatible with most advanced measurements technics
- The tests have to be reproducible
- The comparison with calculation has to be easiest as possible

These three requirements have been declined in design objectives for all parts of the turbine:

- Well-chosen periodicity of each part of the turbine enables to perform representative high-fidelity CFD without computing the entire turbine. The objective was to design a turbine with a 2Pi/20 periodicity which enables to make high accuracy CFD at a reasonable cost.
- The operating point of the turbine will be a high subsonic one which is representative of current high-pressure turbine.
- The combustor simulator must be “clockable” to change the position of the hot point relatively to the NGV grid.
  This enables to investigate two different configurations. A leading-edge configuration, in which the hot point will hit the leading edge of the NGV grid. A passage configuration, in which the hot point will be targeted between two NGV to prevent it from blowing up and see how it interacts with the rotor.

To achieve this purpose a one-stage and half HP turbine has been designed. The challenge of this kind of project is to design a facility which is representative of a real engine module but in which high precision measurements can be easily performed. That’s why the temperature has been lowered to a level that makes intrusive measurements possible (around 500K-700K). Even-if the temperature is much lower than in an engine, the aerodynamic behaviour of the turbine is representative of the most recent engines. The design of the FACTOR required also to design a combustor simulator which produces an exit flow which is representative of a real engine in term fluid structure and temperature gradient. The objective is to be representative of a real combustor without burning any fuel.

So the temperature is raised by an electrical device which enables to easily control the temperature level at the exit of the combustor simulator.

The turbine was not the only part which had to be designed in the project, as matter of fact suitable instrumentation devices had to be designed to be compatible with the rig:

- Traverse measurements in each plane. This measurement enables to have a detailed mapping of the flow in a given plane
- Optical access to the rig :
  - Performing RAMAN measurements
  - Performing heat-transfer measurements

The combustor simulator was the first part of the rig which has been designed in detailed. As this part is very important to have a turbine which is representative of a real engine, the decision has been made to setup a facility at the University of Florence (UNIFI). This facility enables to measure the flow produced by the combustor simulator. As the measurements have been available during the module design, the measurement results have been used to control that the HP module will correctly respond to the inlet flow.

To simplify the experiment, only three sectors have been mounted on the rig. Later it was also decided to add Nozzle Guide Vane after the combustor simulator to measure how the hot point will go through the NGV stage. This rig was also useful to perform measurement formerly scheduled on the DLR rig which have been removed from the test campaign in order to save time.

The design of the turbine was also made to allow operating at different points:

- Design operating point : high subsonic point
    - Both passage and Leading-edge clocking
- Isothermal conditions
- Uncooled conditions
- Off-design operating point : supersonic point

The test campaign aims at obtaining producing results which will be used for comparison with calculations. For this purpose, the measurements should satisfy these requirements:

- Enough detailed results to allow an easy comparison the continuous CFD
- Under-control uncertainty to be confident in the comparison
- The results of the campaign will give strong information about:
    - The inlet condition at the inflow of the NGV
    - Detailed results in all the interface planes
- Good control of the turbine parameters
    - Main stream massflow
    - Accurate measurement of the cooling massflow
    - Accurate measurement of secondary massflow (cavity for example)

By satisfying all these requirements, the FACTOR rig will allow to setup a strong experimental database which will be used for detail comparison with CFD.
Once the experimental results are available, the second objective of the project is to compare the design calculations to see if the predicted behaviour of the turbine is similar to the one observed during tests.

Then, the final objective is to perform CFD with different configuration to find the better way to predict the migration of the hot point through the turbine. At this stage, the CFD won’t be performed on preliminary operating point with theoretical boundary conditions, but some results of the rig will be used to update CFD boundary conditions.

So, the main objectives of the project may be summarized this way:

- See how the hot point migrate through the turbine on a well-controlled environment.
- Find a good calculation setup which enables to reproduce the behaviour seen on the rig.
- Apply this calculation setup on future engine design to optimize the engine consumption.

# Description of the main S&T results / foregrounds

## Work Package 1 – Component design and manufacturing

The work-package 1 is related to the design of component design and the manufacturing of the parts of the rig. The design is not supported by only one partner but by many partners:

- Combustor Simulator Design (Safran Helicopter Engines)
    - Injection System (Avio)
- Turbine Flow Paths Design (ITP)
- Cooled HP Turbine Components Design:
    - Design of the HP NGV (RRUK)
    - Design of the HP rotor blades (Safran Aircraft Engines)
    - Design of the HP rotor disk (RRD)
- LP Inter-duct Design (VAC)
- Secondary Air System (MTU)

At the beginning of the project, Activities in WP1 have not progressed as expected. The choice that was made at the start of the project of a “design loop process” to optimize the design tasks (meaning that progressing through the turbine, each design leader would wait for the upstream component to be designed to obtain the right boundary conditions) proved to be inappropriate since internal resource problems of any partner was affecting all the others, hence blocking the design process. To mitigate the delay, partners have then agreed to design components in parallel, accepting the risk of additional work/re-work when putting all elements together in the end.

### Combustor simulator design

The combustor simulator will produce targeted swirl and temperature profile upstream from the turbine stage. There is not any combustion process in the simulator and the temperature profile is obtained by the mixing of hot and cold air streams. It has been agreed by the partner that the combustor simulator key design features should be representative of a lean burn combustor.

The combustor architecture is described as follows:

- Full annular axial combustor
- Equipped with 20 swirlers, leading to 18° sector
- The swirlers can have two clocking positions
    - Aligned with NGV leading edge
    - Aligned with centre of NGV passage
- The combustor produces a targeted temperature profile by mixing two different air flows
    - Cold air (~300K ie ambient temperature)

  - Hot air which maximal temperature is 700K

For the design of the combustor simulator, RANS and LES calculations have been performed, the design of the combustor simulator is detailed in deliverable 1.1.

The design of the combustor simulator has been tested on UNIFI tri-sector rig. These activities are detailed in task 2.5 and the results are detailed in D2.3 : “Aerodynamic and thermodynamic characteristics of combustor simulator”.

## Turbine flow path design

The flow paths design is a very important step in the design of the rig. In fact, all the partners have to agree on the main parameters of the rig and the operating point of the turbine.

Flow path Specifications document provides necessary initial inputs for the following

FACTOR module components & systems detailed design:

- The FACTOR module components
  - HP Turbine NGV (task 1.3)
  - HP Turbine Rotor (task 1.3)
  - Inter Turbine Duct, including Strut/NGV (task 1.4)
- The FACTOR module systems:
  - Secondary Air System (task 1.3)

The consortium has chosen a high subsonic operating point for the turbine. 6 iterations have been made during the first period to find a good compromise between partners. The 6 iterations are detailed in D1.2: “Flow paths specifications” (FACTOR-ITP-019-R1.2).

## Cooled HP turbine components design

The cooled HP turbine of four different parts:

- The HP vane blades
- The cooling system for the HP Nozzle Guide Vane
- The HP rotor blades
- The HP disk
- The Secondary air system
- The LP vane

*HP Vane blades design:*

The HP vane blades have been designed by RR, with the following process:

- Use 2D tools to create hub, mid-span and casing sections.
- Create 21 sections to assemble complete aerofoil.
- Use CFD program JA63 to run single-row calculation; flowfield extends from turbine inlet to position of leading edge of rotor.

- Use results of CFD to modify the vane so as to obtain the right capacity and present the right distribution of flow to the rotor.
- Create further versions of the vane as necessary if the flowfield is too far from specification.
- Use CFD to analyze each version of the vane.
- When the vane was found to be aerodynamically

The vane has been designed to meet the aerodynamic requirements (to accept the flow from the combustor and to present the correct flow to the following rotor) and the geometric requirements (to be sufficiently straight and to have sufficient volume to accommodate the cooling plenums).

*NGV cooling system design:*

The design requirements of the HP NGV cooling system They are categorized in two sorts, the first one is based on the geometry (manufacturing capabilities, sub-system integration) and the second one on the performance of the cooling system (mass flow, blowing rate, pressure ratio).

The Geometry includes 2 cooling passages or ducts called Leading Edge (LE) passage and Trailing Edge (TE) passage. The passages feed the different film rows with the cooling flow. Due to manufacturing capabilities, the cooling passage shape cannot be designed as real engine component. The ducts will be drilled from the hub so their shape must be uniform in the span direction. Moreover, the passage do not got through the entire component and there should be at least 3mm wall between the tip end wall and the end of the ducts.

The total cooling flow passing through the NGV is close to engine conditions. It was first agreed to deal with 10%w40 with 7.5%w40 pre-throat and 2.5%w40 post-throat area. However, as the TE film configuration was abandoned, the total mass flow is finally fixed at 7.5%w40.

*HP disc design:*

The design of the disc has been done by RRD. The disc will rotate with around 9,000 revolutions per minute (RPM) and will hold 60 blades. The fatigue analysis was run with the target to get over 10,000 life cycles, which results in the required life of the research rig. Iterations have been done between RRD and Safran Aircraft Engines which design the rotor blades.

Two concepts have been studied for the blade attachment, a “two fingers” architecture and a three fingers strategy which has the advantage to decrease the binding displacement of the lower pin.

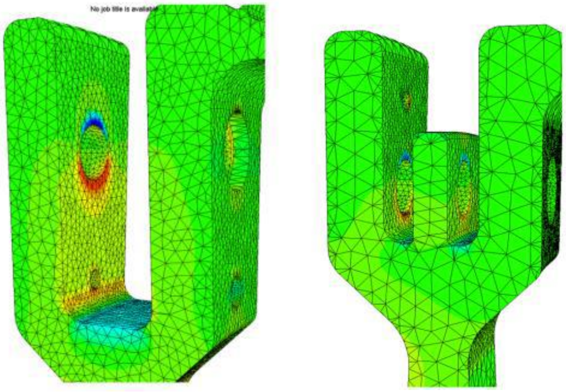


**Figure 1 : Two and Three fingers attachment**

*HP rotor blades design:*

The design has been subdivided in two parts:

- The aerodynamic design which aims at achieving the operating point requirements given by the through flow model
- The mechanical design which aims at verifying that the rig can run safely on both operating and off-design point.

Two operating points were initially discussed among the partners:

- Subsonic as design OP
- Supersonic as off-design OP

The subsonic OP is the main design point and all components are designed to comply with the specifications/conditions of it. The purpose of the supersonic OP is to study the effect of high Mach numbers on the interaction between the combustor generated structures and the heat transfer on the airfoils. Although the design of all components is going to be performed based on the subsonic point, all components have to be able to work at the supersonic point.

One point to consider for the aerodynamic design was to obtain a robust design that could deal with variations in the inlet swirl angle profile (caused for instance by updates of the HP vane geometry, which was being designed in parallel). The starting point of this design was the BRITE/TATEF blade scaled in ITP through-flow. The number of blades was set early to 60 in order to provide a simpler CFD case. RANS calculations have been performed to modify the blade to fulfil the through flow requirements. The conception process is detailed in D1.3: Cooled HP turbine design.

Mechanical analyses were achieved on the operating regime with margins displayed for target speed. Centrifugal forces, thermal conditions and aerodynamic loads were taken into account for the simulation. The preliminary analyses performed by Safran Aircraft Engines were on the initial geometry using Jethete M152 material for both the blade and the disc.

Dynamic FE simulation results were provided by WSK on two models where either only the blade or both the disc and the blade were modelled, using the final material combination.

On the blade, no resonance is expected to occur within +/-5% of the HPT nominal speed (8500 rpm), however when the disc is implemented into the model, the resonance of 4th mode with 40E line is very close to the upper margin (+5% from nominal speed).

A similar assessment was performed as well by Safran Aircraft Engines and WSK (mechanical static and dynamic analyses) on a configuration with a hybrid blade designed by UCAM, where the blade consists of the tongue in Titanium Ti64 and the cap in Torlon material. Results are described in D1.3 – "Cooled HP turbine design".

These results have been investigated by Safran Aircraft Engines with the support of WSK, by comparing SN calculations and WSK ones. Safran Aircraft Engines calculations predicted higher risks of resonance than WSK results for both metal and Torlon blade when modelled as mounted onto the disc. Consequently, some design changes have been performed on the blade root finger to soften it and therefore shift the coincidence point away from the operating nominal speed (i.e. 8500rpm).

As a result, coincidences are shifted outside of the +/-15% area and therefore fulfil with Safran Aircraft Engines safety criterion. Softening the blade root fingers has been successful on the rotor model with metal blade. However, on the Torlon blade, the outcome of this design change was not satisfying and did not really shift the risk of coincidence away from operating point.

In order to make sure DLR rig operates within safety criteria, Safran Aircraft Engines has set up the following risk management measures for the dynamic situation:
Ping-tests: Characterize natural frequencies with a "hammer type" excitation to evaluate frequency dispersion regarding material and geometry on an adequate number of samples. The result of the ping test done by Safran Aircraft Engines is detailed in the fourth period report and has been enough to consider that the predicted margin is enough to run the rig safely.

### *Torlon blade design*

In order to perform infrared measurements hybride blades (metal and torlon) have been added on both HP stator and rotor grid. The composite turbine blade will increase the signal to noise ratio of the heat transfer measurements by a factor of ~10 (when compared to a solid Titanium blade only).

Torlon 7130 was identified as a suitable material for the following reasons:

- It has a low thermal diffusivity (0.1 x Titanium 6,4 value)
- It has a high specific strength (0.7 x Titanium 6,4 value)
- It can be injection moulded and easily machined
- It has a high fracture toughness – making it tolerant to any manufacturing imperfections/cracks
- It has good fatigue and creep resistant properties
- It has a matched coefficient of linear thermal expansion with Titanium 6,4

### *Infrared windows design*

To perform heat-transfer measurement on blades, optical access to the flow path has been designed. The IR windows must be able to withstand the operating temperatures of the FACTOR test rig. Sufficient mechanical and optical properties need to be retained at temperatures across the range of 300 to 500K.

A specific tip seal has also design the torlon NGV. The design of this tip seal has been validated with tests which are detailed in D1.3.

Mechanical calculations have also been performed to verify that both HP and LP windows can resist to both thermal and pressure loads.

### *LP vane design*

In the VAC vane design system, each vane is constructed from a number of stacked 2D profiles. For this design, these profiles were stacked at the position of maximum thickness for each profile along a straight line. Different designs were explored but for the final design, it was decided to keep the leading and trailing edges straight. This, mainly for simplicity of the geometry and because no gains were observed with the alternatives evaluated.

The number of vanes was set early to 20 in order to match the number of combustors and provide a simpler CFD case.

A check for robustness respect to the inlet swirl angle was done by varying the inlet angle ± 5 degrees. No flow separation was detected.

It has also been checked that the LP vane can operate at off-design point (ie supersonic point) without flow separation.

The detailed design is described in D1.4 – LP vane in turbine duct design.

### *Test rig manufacturing*

The manufacturing of the Rig parts has been mostly managed by PROGESA. The manufacturing was very challenging because of the wide range of pieces.

Some of them were very large and heavy, but the required precision was very small. As a matter of fact the final assembly is made on an existing test RIG at DLR. It requires to manage manufacturing tolerances to be sure that the designed module will perfectly fit with the DLR device.

The NGV manufacturing required high precision for the cooling system, the objective is to avoid dispersion in the cooling flow which is introduced in the turbine. A too high geometrical dispersion would have led to high uncertainties on the cooling massflow which is introduced on the studied NGV.

Some parts have also been subcontracted to specialized supplier. The most important parts were the two Infrared windows. These windows required a huge experience and a good technical command of the industrial process to be able to manufacture such windows. Find a supplier who accepts to manufacture the windows was difficult and many suppliers had refused to manufacture the part when they say the complex shape of the part. The supplier also broke one window at the final stage of the process and he needed to restart the process from the beginning.

# Work Package 2 – Instrumentation design & manufacturing and rig adaptation

This WP2 targeted the preparation of the two rigs used for the most important measurement campaigns in FACTOR, namely the Combustor Simulator Rig or ‘trisector rig’ at UNIFI in Florence (Italy) and the continuous rotating turbine rig to operate in the NG-Turb test facility at DLR Göttingen (Germany). It is reasonable to separate the two rigs concerning summarizing reporting.

## UNIFI Trisector Rig

During the first 18 months of the project, UNIFI collaborated with other partners in the Task 2.4 (Instrumentation design and manufacturing). In detail, UNIFI contributed to the design of the access for the instrumentation in the test rig, both in terms of holes and slots for the probes and windows for the optical access, in the view of performing PIV measurements on DLR rig within WP4. This activity was then canceled further in the project and it was decided to extend the activities at the trisector rig (see WP4 for more information).

UNIFI was asked to design a dedicated test rig, complementary to the main facility at DLR. The test rig reproduced 3/20 of the geometry of the DLR rig combustion chamber. Vanes and blades were not included. UNIFI was involved in the whole design of the test rig, both in terms of instrumentation and the requirement to reproduce the geometry of the main facility. This activity was performed in close collaboration with Turbomeca, the partner involved in the combustor chamber design, and with Progesa, the rig manufacturer.

During the second project period, UNIFI was involved in Task 2.1 (Lab development of measurement techniques and 2.5 (Validation of the combustor simulator at UNIFI). Within the first task, two borescopes and a laser-arm were provided; additionally, a borescope cooling system was also designed. Within the second task, the trisector test rig was installed in the test facility and its characterization was carried out. Four different sizes of the swirler duct were tested and the resulting flow field on Plane 40 was measured by means of a 5-hole probe; both the probe and the traverse system were provided by Turbomeca. The configuration with a 55mm duct gave the best results, which however presented some discrepancies with the expected (i.e. target) values. In particular the measured hot streak consists in a wavy shape, with a distortion factor less enhanced than for the target pattern. A good matching was found, on the other hand, for the swirl pattern, as long as the duct55 configuration is concerned (Fig. 2).

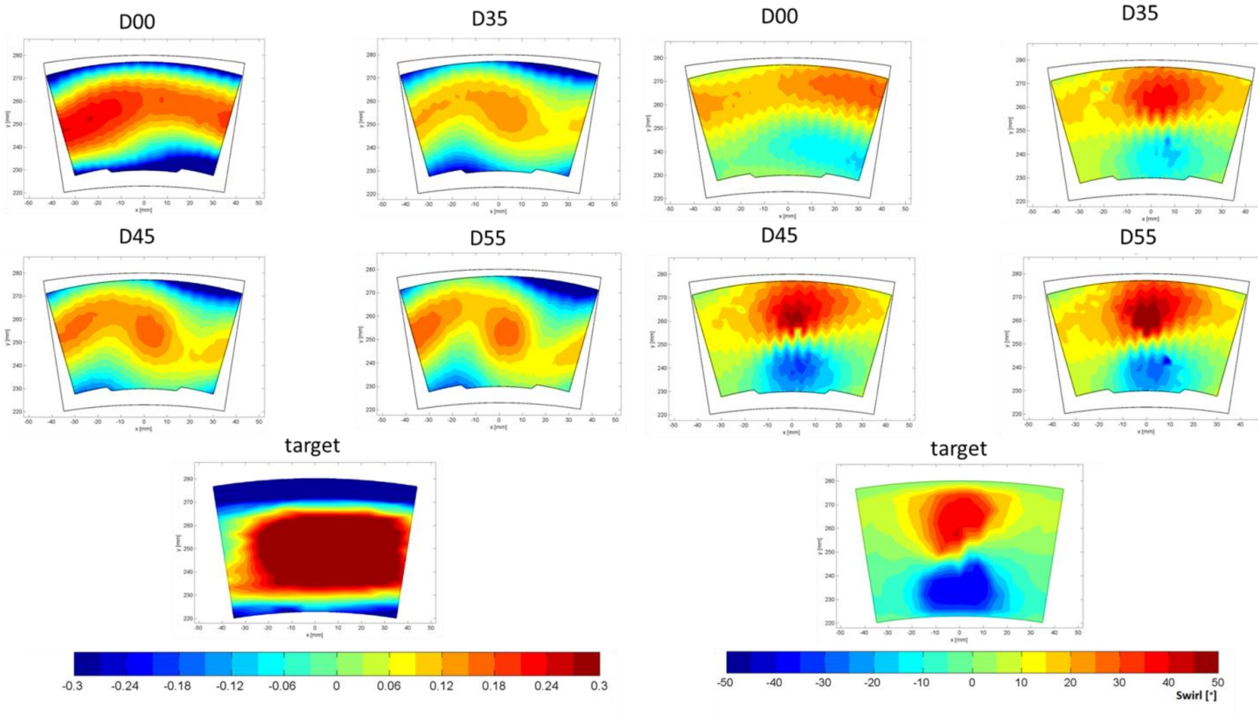


**Figure 2: Temperature and swirl pattern: effect of duct size and comparison with target profiles**

Additional tests with different operating conditions were also performed in order to try to achieve a better match with the target profile. Conditions with different main-to-coolant flow splits, different inner-to-outer coolant flow split and with different combustion chamber pressure were tested: since no relevant improvement was found in the comparison with the target, it was decided to stick with the original operating conditions, with duct55 configuration.

A fast response thermocouple, provided by Turbomeca, was used to investigate the unsteady thermal field on Plane 40. While the probe cut-off frequency was found to be too low for a proper characterization of the temperature fluctuations, the investigation of the mean thermal field gave similar results to the five hole probe investigation.

The first preliminary PIV measurements in the combustion chamber, in cold conditions, were also carried out.

The third period started with task 2.5 and measurements using five hole probe and unsteady thermocouple that have been repeated on Plane 40+ (Fig. 3) in order to evaluate the hot streaks transport between the chamber exit and the NGVs virtual position. These measurements have been performed for configurations D00, D45 and D55 only, as decided following the analysis of the previous results. While the hot spot shape and the temperature field morphology is quite similar to the one measured on Plane 40 (compare Fig. 2), it is possible to note a hot spot temperature reduction due to the interaction between main flow and coolant, that leads to a less distorted temperature profile. This reduction can be estimated as about the 2% of the measured dimensional values on Plane 40 for the ducted configurations and even higher than 4% for D00, since the mixing is less bounded and it influences more the hot streak zone. Concerning the swirl pattern, the effect of the interaction between main and coolant between Plane 40 and Plane 40+ is to weaken the swirl angle distribution. This reduction of flow angles is also caused by the axial acceleration of the flow because of the smaller section. From a comparison with Figure 2 a reduction of swirl angles intensity up to 30% can be noted, for D55 configuration, in the zones of the section in which the tangential momentum is maximum.

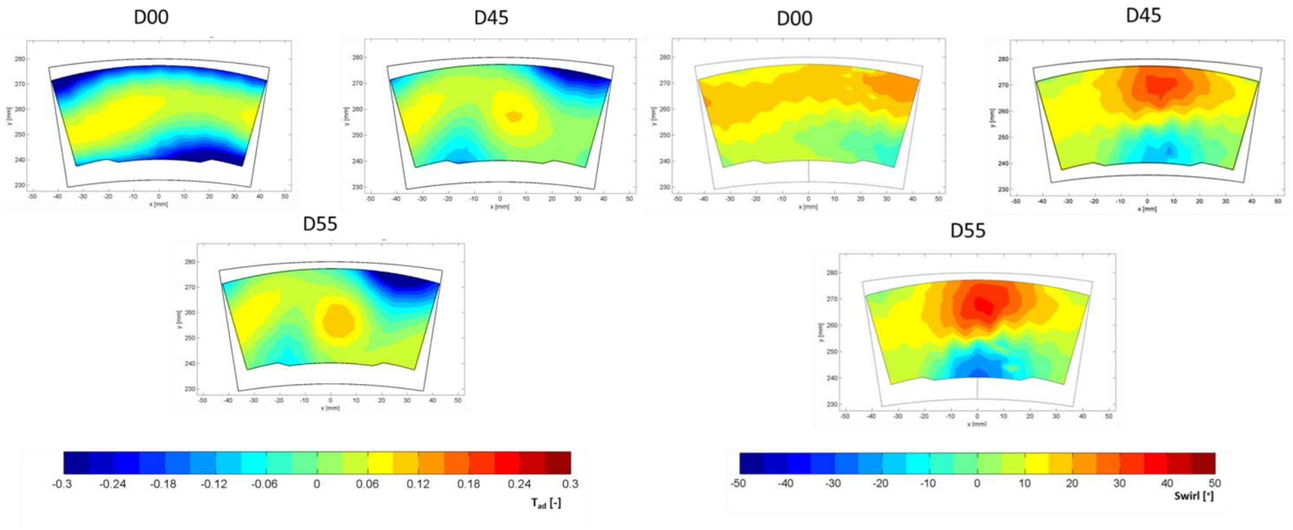


**Figure 3: Temperature and swirl patterns on Plane 40+**

PIV measurements on combustion chamber symmetry plane were also completed for configuration D00 and D55 (Fig. 3). Measurements highlighted some typical flow structures of a modern swirl-stabilized combustor, which are the corner vortex (under the inner jet) and the central recirculation zone (CRZ) generated by the vortex breakdown. They also allowed to understand the flow field evolution within the chamber. For the duct00 configuration, the jet opening at the swirler exit generates a large hot zone which covers, in the proximity of the swirler plate, almost the whole chamber height, while it rapidly becomes confined in the central area of the chamber due to the coolant injection. In the first part of the chamber, the swirling flow dissipates a great part of its tangential momentum: therefore, the closure of the hot recirculation zone is quite far from Plane 40. On the other hand, due to the presence of the duct, the CRZ is narrower, but its closure is nearer to the combustor exit. Consequently, the hot swirling flow is conserved up to the measurement plane, while the region of mixing with the coolant is more bounded. This results in a more marked hot spot and enhanced flow angles, as measured by the five hole probe.

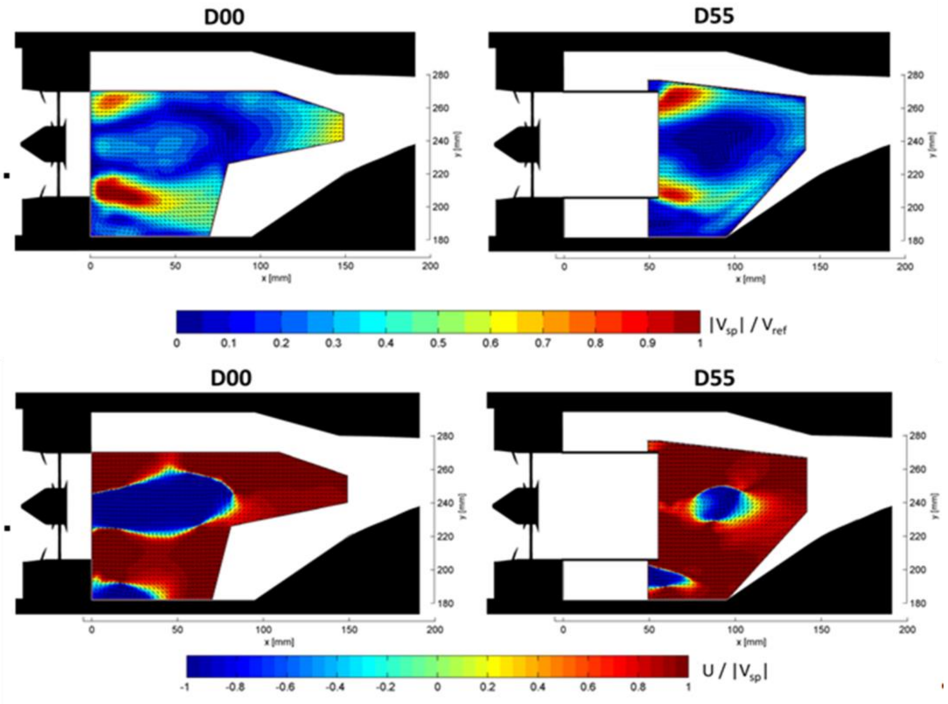


**Figure 4: Normalized 2D (top) and axial (bottom) velocity magnitude on combustion chamber symmetry plane**

PIV measurements on Plane 40 were postponed because a system upgrade was necessary, but turbulence measurements on Plane 40 and 40+ were carried out by means of hot wire anemometry, for configurations D00, D45 and D55 (see Fig. 4). The approach pursed to retrieve the 3D turbulence flow field on the P40 is based on combining measured performed on two different experiments characterize by traversing two different Dantec split fiber probes. Each probe is provided with two sensors, made by nickel films deposited on a quartz fiber with diameter of 200 µm; the two selected Dantec probes 55R56 and 55R57 have their quartz fibers perpendicular to each other so they allow to measure velocity on two perpendicular planes. In order to evaluate the three-dimensional flow field is, therefore, necessary to repeat each test point twice, in order to investigate it with both the probes and then combine the results. For the ducted configurations, the highest values, up to 28 %, are reached in the rotating core generated by the swirlers that is conserved up to the measurement planes; this is a typical behavior of the swirl-dominated flow fields, like the ones encountered in Lean Burn chambers. For the unducted configuration, such values are slightly lower since the vortex is almost completely dissipated, due to the enhanced interaction between main flow and coolant caused by the absence of the duct. Reduction of 25-30% of these values can be observed for all the configurations moving from Plane 40 to Plane 40+.

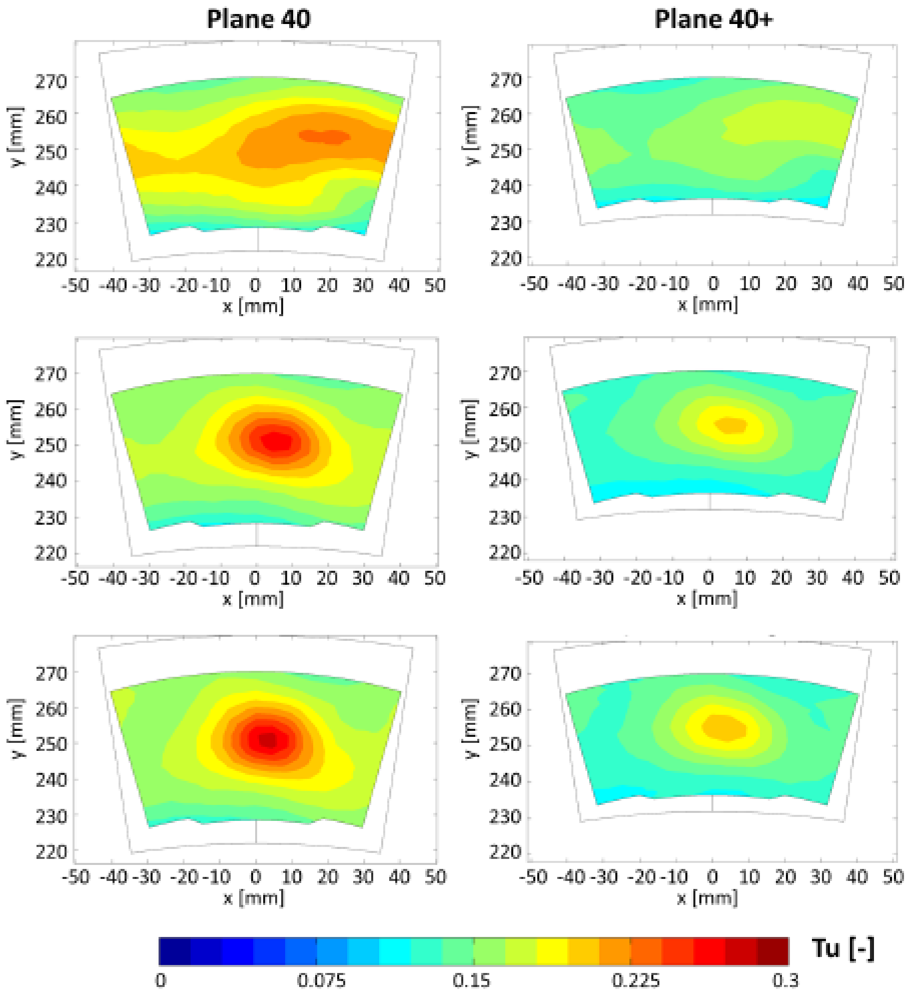


**Figure 5: Turbulence intensity maps on Plane 40 and 40+**

During the fourth period the last missing tests for the complete combustor simulator characterization (within task 2.5) were carried out. Additionally, PIV measurements on the duct55 configuration have been carried out on the rig symmetry plane, to get a whole view of the flow field evolution on the centerline, and on three axial planes, in order to highlight details and displacements of the swirling structure promoted by the swirlers. Tests have been repeated both for isothermal conditions and heating the mainstream to appreciate how the main-coolant density ratio affects the overall flow field evolution. Due to the presence of the rig pyrex walls, the mainstream temperature had to be kept at 180°C for the hot tests. The application of PIV was made challenging by both the operating conditions and the complex geometry, in terms of optical accesses; despite some drawbacks, mainly related to reflections and optical issues, borescopic PIV have been exploited to achieve a description of the flow field evolution which is both reliable and accurate. Results on the axial planes have been used to demonstrate how the tangential momentum of the rotating structure is modified up to combustor exit. An important role on the resulting flow field at plane 40 is due to the typical converging shape of the inner liner. In particular, the inner liner pushes up the center of the swirling structures and generates a non-uniform tangential momentum distribution of the flow field approaching the turbine inlet. The temperature ratio between mainstream and coolant generates significant differences on the main flow field in the combustor chamber, mainly reducing the jet opening angle and increasing the tangential velocity on the outer liner. Despite that, on Plane 40 its influence is reduced, and the isothermal and warm velocity profiles are almost comparable probably due to the flow acceleration prompted by the inner liner.

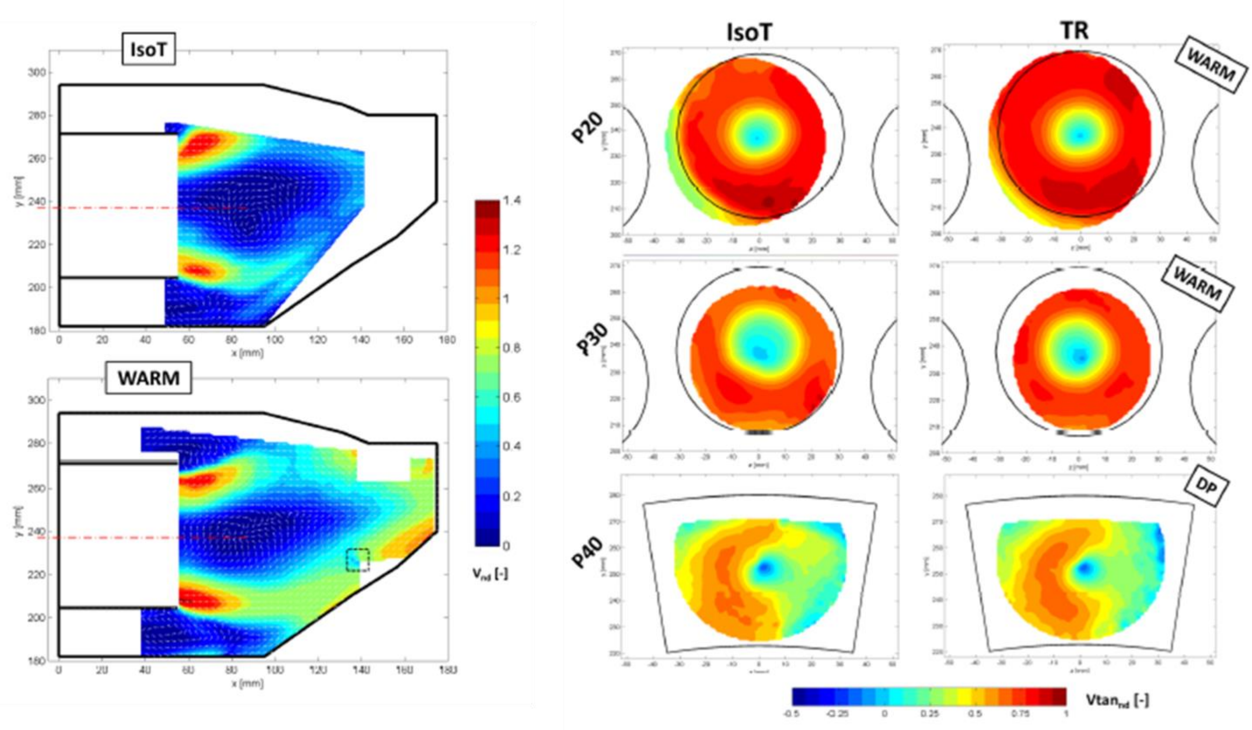


**Figure 6: 2D velocity on symmetry plane (left) and tangential momentum of the swirling structure on three consecutive axial planes (right)**

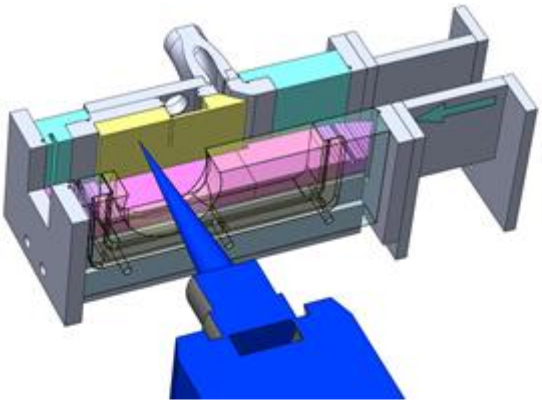
<u>DLR rotating rig at NG-Turb facility</u>

The NG-Turb facility was built and erected during the project runtime of FACTOR and the decision to adapt the FACTOR rotating turbine rig to this new facility was on one hand the reason for various additional risks, cost and time delay, but on the other hand enabled a combustor-turbine-design and rig configuration including potential measurement technique access that are unrivalled and had otherwise been impossible to achieve. It was therefore a critical task to successfully develop and implement the pneumatic, electric and optical system and techniques for the rotating rig at NG-Turb in due time and to verify the successful mechanical integration by initial runs of commissioning activity.

During the first project phase DLR started to develop the fast electric heater concept and control strategy for it, since it was clear from the UCAM specification and planning, that the heat transfer measurements in the rotating rig would be most challenging but also potentially, in terms of technical and scientific advance, the most promising measurement technique. This technique was developed and planned in detail by UCAM.

Another aspect of these heat transfer measurements required the ability to switch not only main flow temperature virtually instantly (via fast heater) but also modulate the NGV film coolant air. That is why UCAM started to specify and develop fast acting valves (FAV) to be placed below the NGV vanes that would enable to switch between a cold and a hot coolant flow.

In parallel the work on the official CAD mock-up started and DLR took responsibility for it, evolving the design together with partners input and merging their individual CAD parts. The assembly sequence was defined in that early phase, with a basically two-sided rig that would be closed at an interface in between. The downstream side can be translated to the back, resting on the NG-Turb facility rail system together with the complete shaft and braking generator arrangement. It was decided that the combustor would belong to the upstream side and the NGV blades together with the rest of the turbine stage would be part of the downstream section. The design of the specific location and type / size of all access for the different measurement techniques (probes, infrared, laser, PIV seeding and borescope) were preliminary planned and integrated into the CAD model.



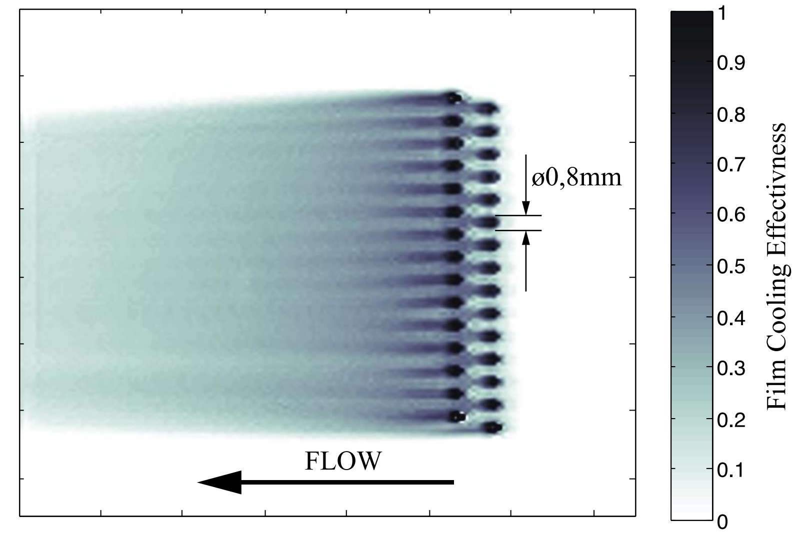


**Figure 7: UCAM film cooling effectiveness measurement taken at FACTOR NGV conditions**

In the second project phase UCAM was able to conduct basic experiments in their own lab at relevant conditions to prove the concept of their HT and film cooling effectiveness measurements technique and function of the IR camera setup by looking at a plate with adequately sized coolant holes (see Figure 7). Also the selected low thermal conductivity material Torlon with sufficient mechanical strength was used to mimic the expected conditions in the rig.

At DLR the heater mesh solution for fast main flow heating were confirmed and the control software for a fast step was developed in a first version. In a set-up over an air blower and using a fast wire anemometer for temperature measurement, it was possible to verify the capability of creating sufficiently fast temperature steps (see Figure 8). DLR also evolved the heater design for rig application during that period and decided for three sequential rows of slightly folded meshes to enable the fit into a round annulus of square-cut meshes.

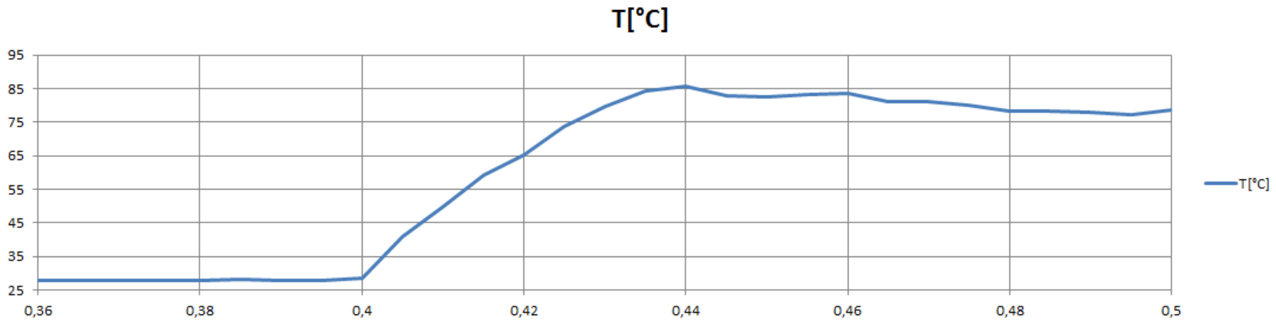


**Figure 8: DLR measured temperature step achieved with basic heater mesh and control software**

At the partner ONERA the planned RAMAN laser-optical technique was prepared for application in a running rig and beside the FACTOR turbine at DLR NG-Turb facility. The definition of the three important planes in front, in between and aft of the HP turbine stage was important for the RAMAN laser optics planning (Figure 9). The close vicinity of the rig was required to be accessible at least with the laser optics and the huge spectrometer and traverse set-up of ONERA would have to be placed further away.

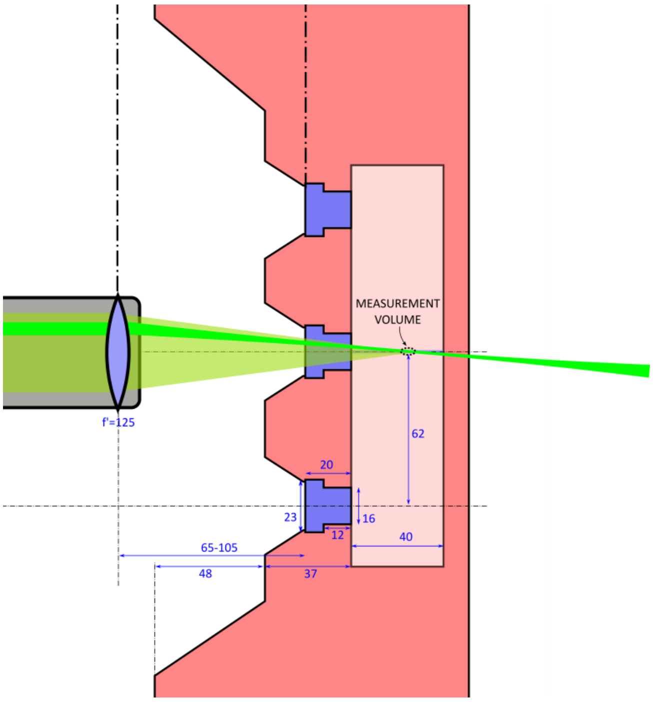


**Figure 9: Three planned RAMAN laser windows in FACTOR rig main casing, laser optics access**

It was decided to replace the planned (laser) vibrometry measurements for Filtered Rayleigh Scattering technique (FRS) that would be applied by partner ILA with assistance from DLR, that developed this technique from lab to rig application already. Frequency Filtered Rayleigh Scattering was chosen as the measurement technique to be employed for density and temperature fluctuations in FACTOR as it has no problems with test rig vibrations, moreover, it can use the same optical access as for the Particle Image Velocimetry (PIV) measurements already planned in CAD. Further advantages of FRS are high spatial resolution and the possibility to perform near-wall measurements in high pressure environments. Finally, the accuracy of the measurements depends on suppression ad correction of the background and stray light. The Figure 10 shows a typical spectrum and the FRS signal to be processed and the physical Rayleigh scattering.

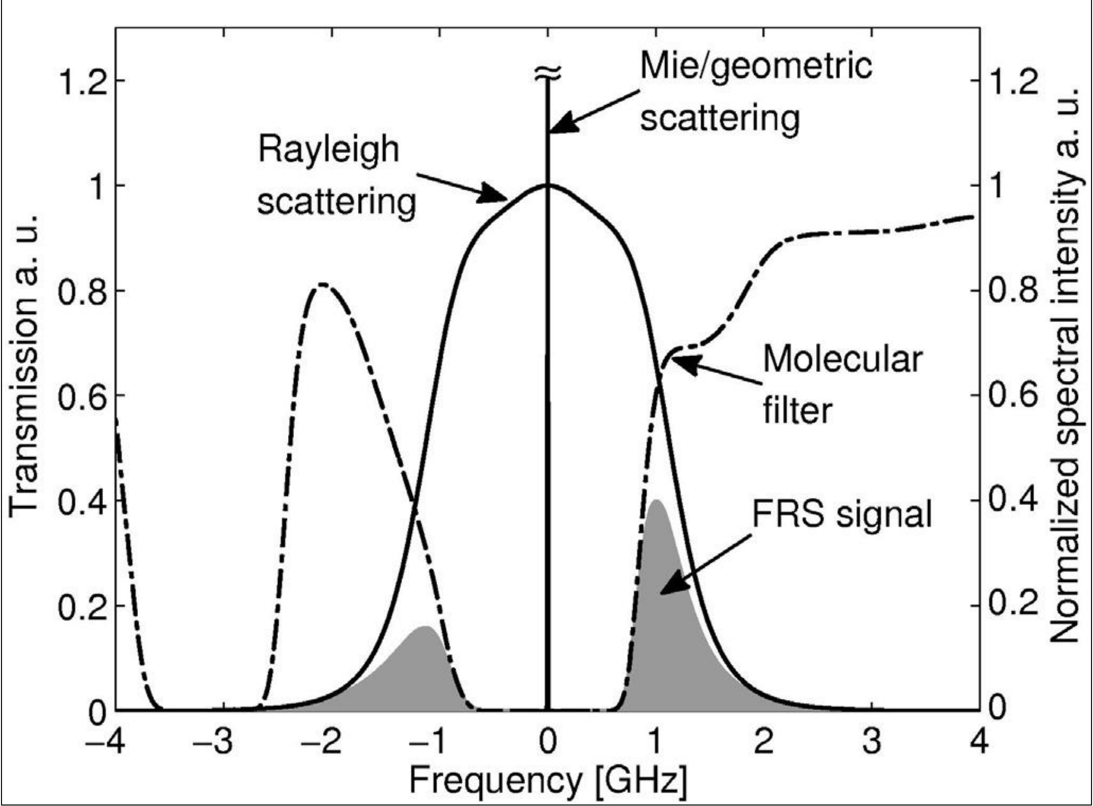


**Figure 10: Typical FRS technique spectrum and signal, molecular filter needed**

The conventional pneumatic probe measurements were also prepared by designing and manufacturing of probe heads for intended use in the rotating FACTOR rig at DLR NG-Turb facility. DLR itself was responsible for the static area traverses using 5-hole-probes (5HP), that were manufactured by 3D printing including all pressure channels and geometric features. On Figure 11 left, the DLR 5HP head can be seen in size comparison with a Euro cent and the cut-out prepared for the placement of a thermocouple to enable additional flow temperature measurement above the head can be seen. On the same Figure 11 right is a CAD drawing of a fast response aerodynamic probe (FRAP) head with a single Kulite pressure sensor shown, that was prepared by VKI for rig application. This FRAP will enable to do unsteady pressure measurements and capture fluctuations, complementing the time-averaged results by the DLR 5-hole-probe. For all probes radial traverse systems (already existing at DLR) as well as a special circumferential traverse system to fit dedicated huge slots in the FACTOR main casing were developed by DLR. In this phase the first CAD models and studies for the circumferential traverse were created.

**Figure 11: Picture of DLR 5-hole-probe (left) and drawings of VKI FRAP Kulite probe heads (right)**

During the this phase, the preparation of the heat transfer measurements required extensive calculation, CAD design, manufacturing and tests by UCAM. The requirement for a mechanically strong and durable but still plastic (low thermal conductivity) rotor blade led to a hybrid design with a titanium core and a Torlon mould around to form the aero surface. This was manufactured and tested as a specimen to prove the required material properties (see Figure 12). Additionally the detailed design and determination of size of the IR windows to be integrated into the FACTOR rig main casing was done. These windows depicted in Figure 13 left are unmatched in size for a rotating rig of this configuration and enable almost every possible viewing angle onto the HP stage (NGV and rotor, window 1) as well as the huge LP-strut stator (window 2). Finally also the design of the fast acting valves (FAV) to switch the NGV film cooling flows was advanced and detailed to enable a CAD integration as well as the further analysis by numerical flow simulation (see Figure 13 right). The design was reduced in size from existing 3-way valves and optimised for fast actuation as well as robustness in the harsh rig environment.

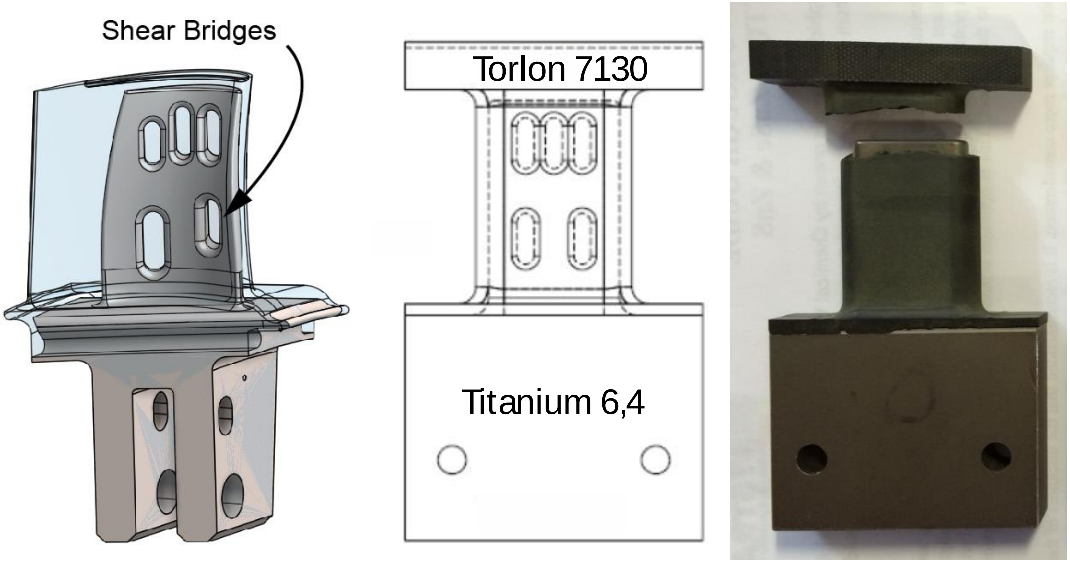


**Figure 12: UCAM plastic (Torlon) rotor blade design and mould testing specimen**

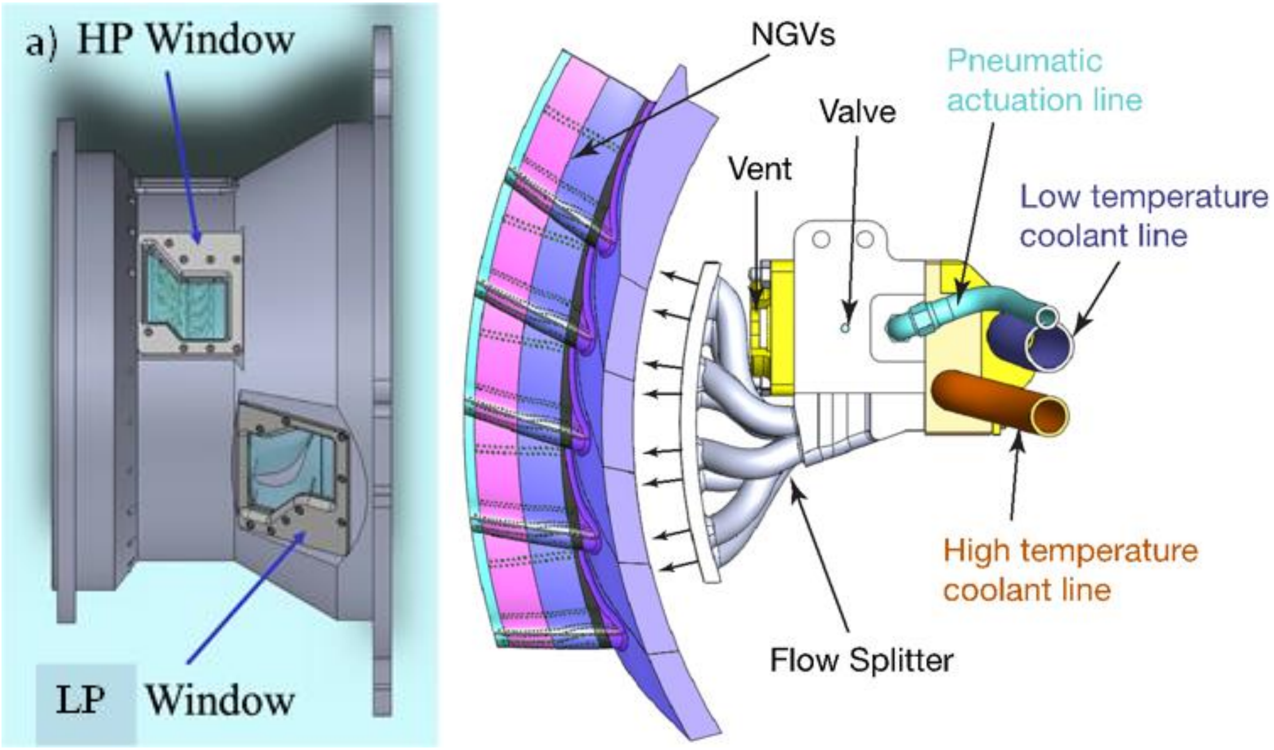


**Figure 13: UCAM IR window main casing CAD integration (left) and FAV design & logic (right)**

DLR carried out pre-manufacturing tests of the fast heater in the final configuration to be integrated into the rig, which will be six segments forming a complete ring that fills the annulus in front of the combustor swirlers. The use of ceramic material to withstand heat and at the same time isolating electrically was tested and finally decided after promising results. Additionally the mentioned circumferential traverse system was finally designed and ready for manufacturing. The Figure 14 shows this CAD design on the left and the future end result after successful manufacturing to compare on the right.

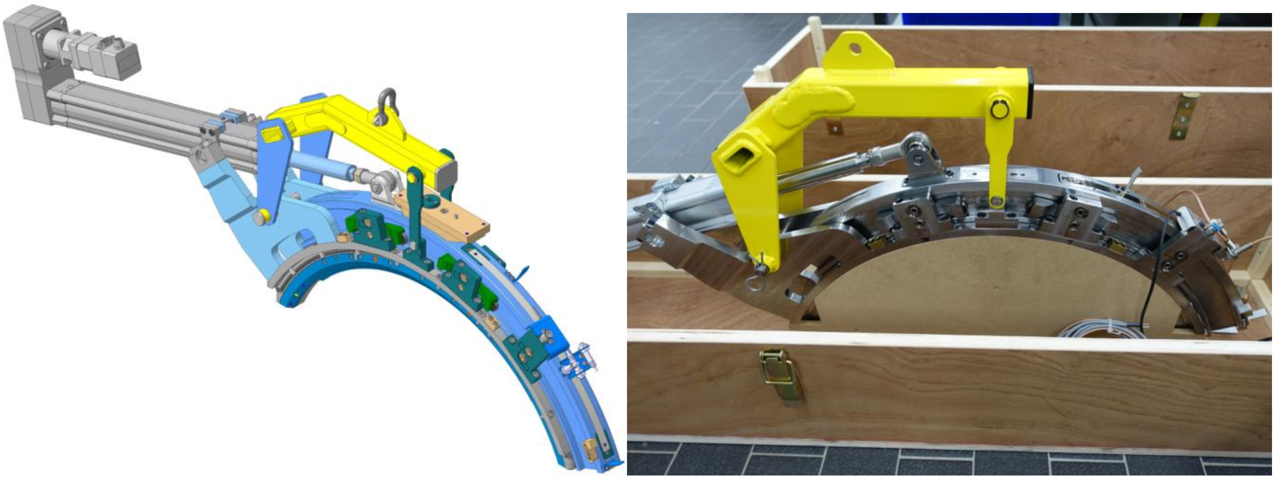


**Figure 14: Circumferential traverse system by DLR in final CAD (left) and as manufactured part (right)**

During the fourth period a detailed description of the RAMAN hardware setup to be integrated at DLR NG-Turb including CAD of parts was created by ONERA. Due to the decision of DLR to implement a burst protection containment around the rig, that normally would restrain the physical access to the vicinity of the rig, which was however required by RAMAN technique (compare Figure 9), a discussion was started between DLR and ONERA to find a solution. This was finally defined and implemented in form of a hole or more precise, a tunnel, in the containment, providing access to a very limited area at and around the RAMAN laser windows in the FACTOR main casing. This tunnel was designed and calculated to still contain turbine parts in case of an accident. The partner ONERA specified the size of the tunnel such as it would still be possible to design an optical arm that could be inserted through, coming from the spectrometer box or table set-up now standing apart from the rig and outside of the protecting containment structure (see Figure 15).

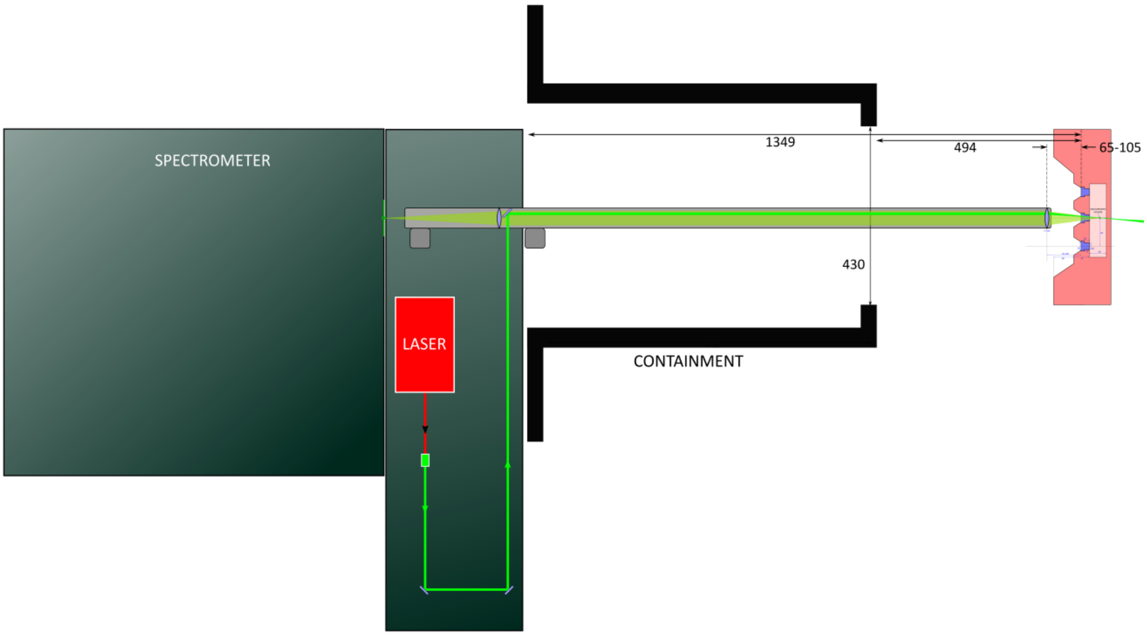


**Figure 15: RAMAN spectrometer placement at DLR NG-Turb facility with containment tunnel**

DLR completed successfully the manufacturing of the fast main flow heater segments from metal and ceramics. The final segments were again tested on an air blower with metal meshes and electrical connections installed to prove again the temperature step ability.

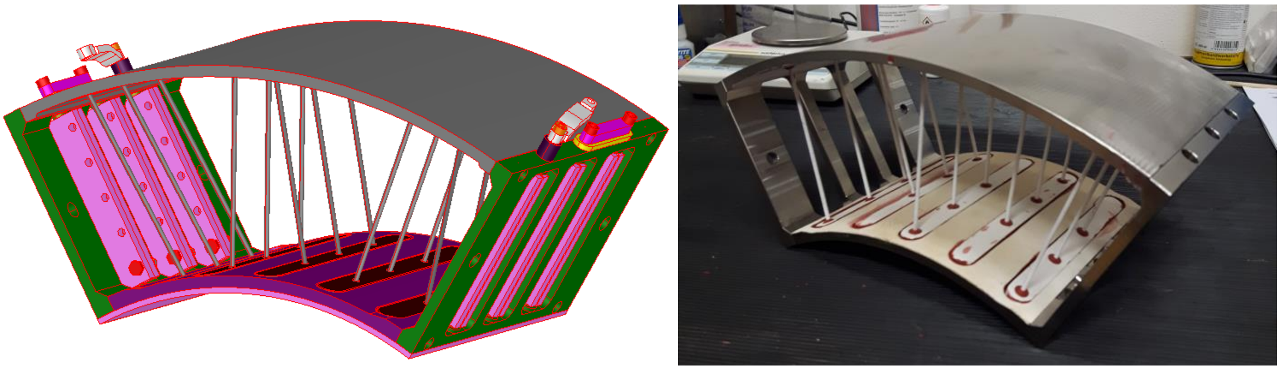


**Figure 16: DLR fast main flow heater segment CAD (left) and manufactured part (right)**

DLR also started to integrate temperature and pressure instrumentation into the already delivered first rig parts like the main casing or NGV ring (see Figure 17 for example). These instrumentation work being stated and the FACTOR turbine rig parts being delivered to DLR Göttingen one after the other marked the transition to the final, fifth project phase.

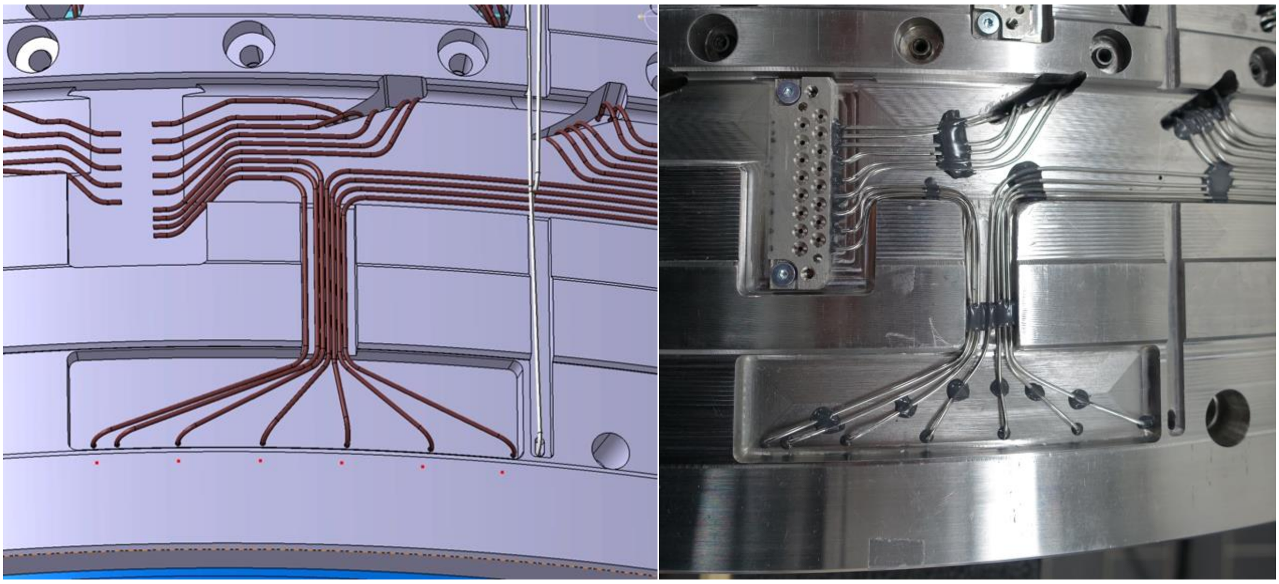


**Figure 17: Comparison of CAD NGV instrumentation design (left) & application to real part (right)**

In the fifth project period the completion of the WP2 was achieved by instrumenting and assembling all FACTOR rotating turbine rig parts at and into DLR NG-Turb test facility. The following compilation of pictures documents the successful rig integration:

- At the upstream side the densely packed UCAM fast acting valves under the rig closure interface of the NGV and the combustor simulator view in Figure 18
- At the downstream side the already mounted main casing and insertion of the rotor followed by the NAGV ring using a dedicated mounting device in Figure 19
- The complete instrumentation of the rig and connection of sensor to acquisition systems beside the rig, exemplarily represented by thermocouple and pressure connectors on main casing in Figure 20
- The successfully integrated RAMAN box measurement setup with cooled laser, spectrometer and adjusted optics as well as a 3-axis traverse system close to the rig but in front of the NG-Turb containment (optical arm through the tunnel getting access to the laser windows in main casing) in Figure 21
- The fully assembled FACTOR rig with all sensors connected and coolant supply tubes mounted in a closed state ready to run in Figure 22
- The mounting of the containment structure weighing 5 tons around the fully instrumented and closed rig using the NG-Turb facility hall crane in Figure 23

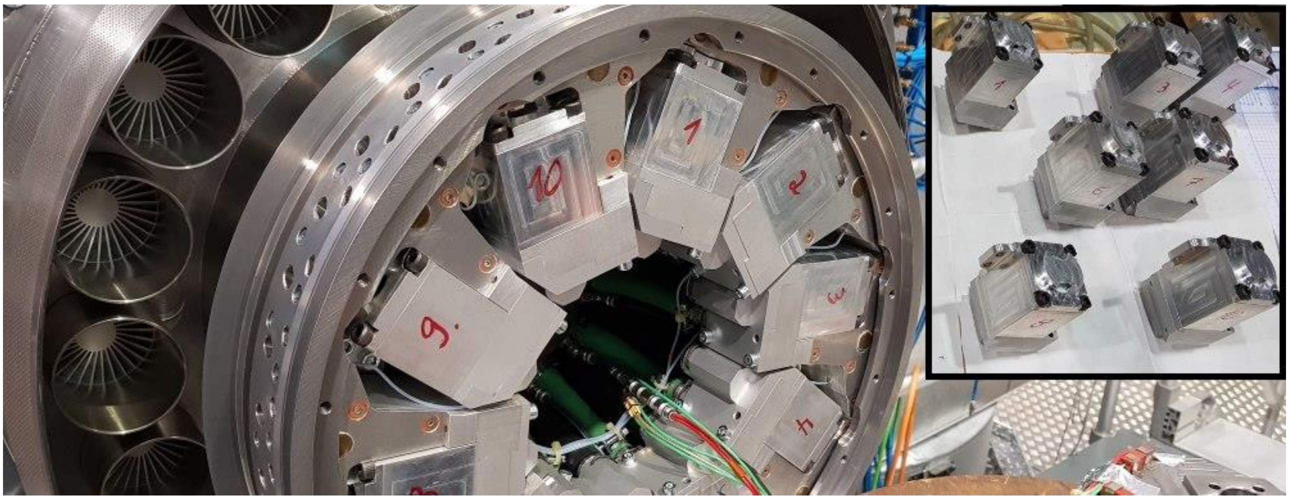


**Figure 18: FACTOR rig integration - FAVs alone (top) and assembled into the rig, combustor swirlers**

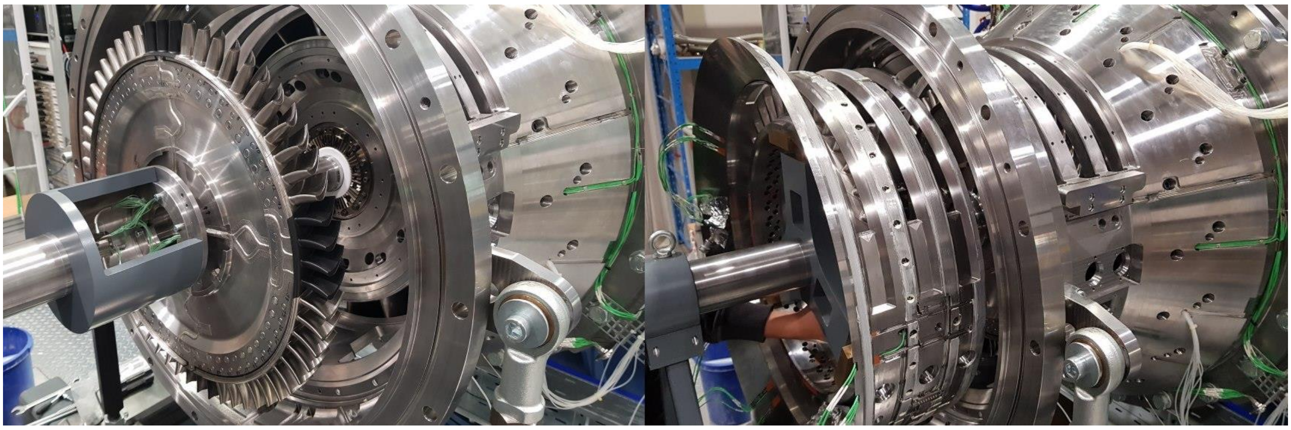


**Figure 19: FACTOR rig integration - mounting of rotor and NGV on downstream side into main casing**

**Figure 20: FACTOR rig integration - main casing instrumentation with tubes, connectors and sensors**

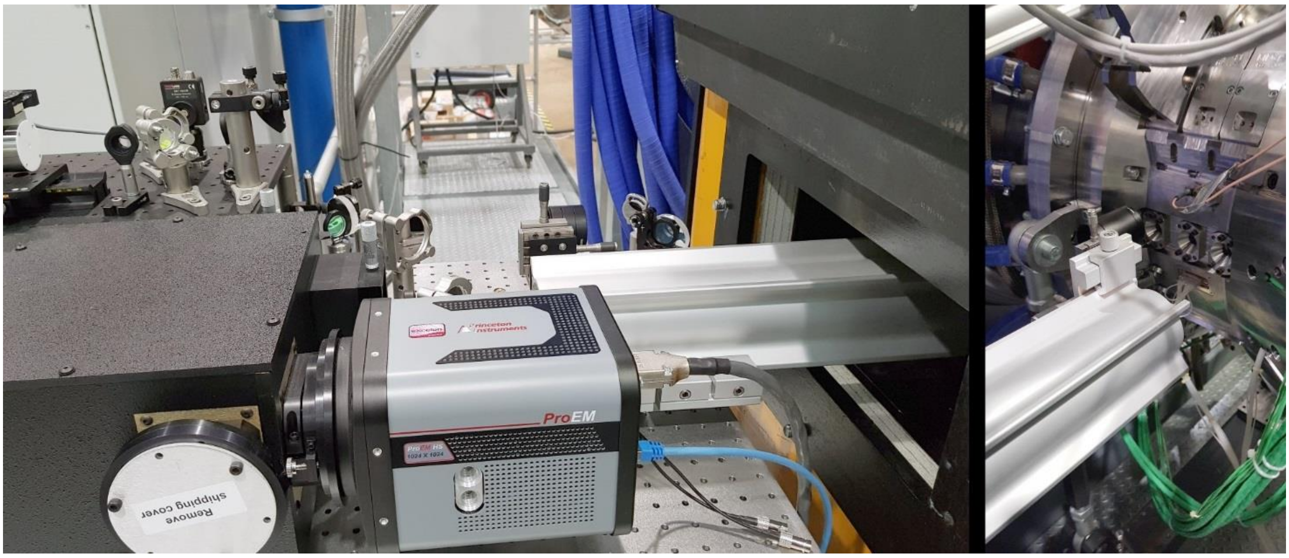


**Figure 21: FACTOR rig integration - RAMAN set-up with optical arm through containment tunnel**

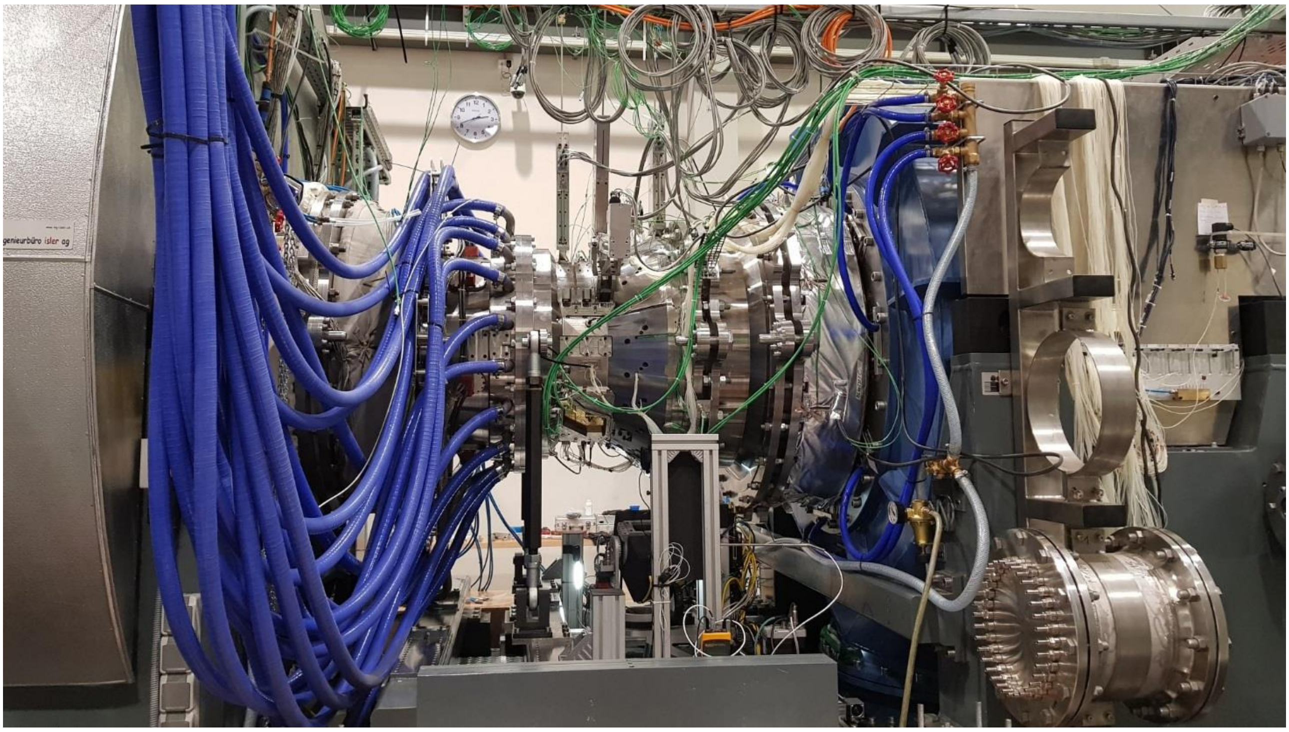


**Figure 22: FACTOR rig integration - fully assembled and closed rig with UCAM IR traverse below**

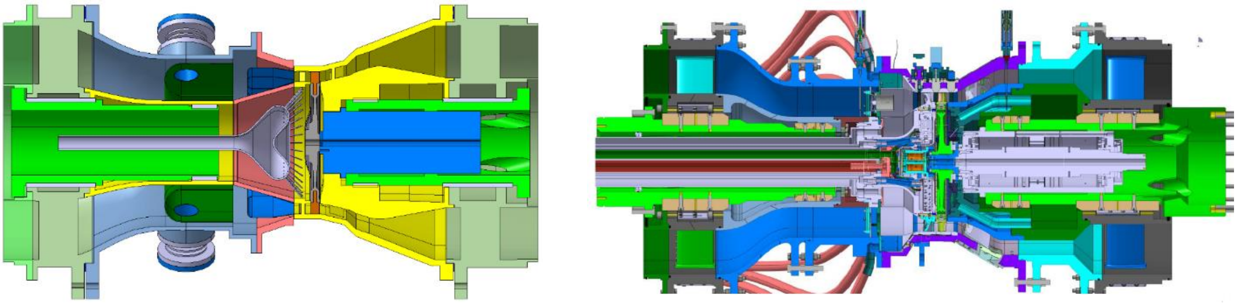
Figure 23: FACTOR rig integration - mounting the containment around the closed & instrumented rig

# Work Package 3 – Integration

The objective of WP3 is to ensure the integration of all parts designed by partners into the DLR rig, along with the proper inclusion of the instrumentation. The WP3 activities thus extend from the beginning of the project (set-up of the first CAD mock-up) until the end of manufacturing when assembly begins within WP2. This work package activities involve at some point any partner in charge of the design of a component (WP1) or a measurement technique (WP2), under the lead of SafranHE and DLR crews.

The first activity is the supply detailed rig specifications in terms of main rig architecture, interfaces, overall operating conditions, instrumentation requirements and interaction with the NGTurb facility hosting the FACTOR rig… Such specifications were frozen at the end of period 1 and reported in D3.1, allowing to start detailed design of the individual components. At the end of the day, a comparative summary between rig specifications and achieved design is provided in D3.4.

The second activity of WP3 is the development and continuous upgrade of the CAD mock-up with the parts given by the partners as well as DLR internally designed components. This task, led by DLR has three objectives : insure that all parts fit well into the module and if necessary propose solutions ; make sure that instrumentation and components interact well ; give green light for manufacturing when a component and its interfaces are frozen. In total, 27 releases of the rig mock-up were published, as illustrated in Figure 24 between the first and last versions. At the end of the day, the manufactured CAD model contains more than 500 parts, which underlines the complexity of the module. Deliverables D3.2 (organization of the CAD assembly), D3.5 (final CAD to be manufactured) and mock-up v3.0 constitute the outcomes of this task.



Initial CAD mock-up

Final CAD mock-up

**Figure 24 - Evolution of FACTOR test rig CAD models**

The last task of WP3 is to validate the design of the fully assembled rig by using simulation tools to assess the expected performances (aero-thermo-mechanical) of different parts of the rig. Such analysis complement the isolated computations of the components performed for design activities (WP1).

First, SafranHE ran a 2-D thermomecanical analysis of the overall rig by means of finite elements (Figure 25). This allowed to better understand the full temperature field of the module, obtain thermo-mechanical displacement values for interfaces & hot2cold aspects, verify that all parts are within the material stress limits and verify tip clearance aspects in particular for transient regime.

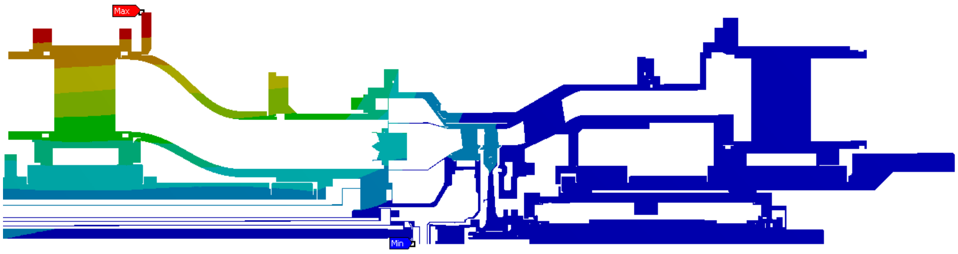


**Figure 25 - 2D Thermomecanical analysis of the test rig**

Second, various partners focused on CFD assessment of different groups of components of the rig to ensure that interactions between modules are in line with the design target. Figure 26 reports the performed simulations.

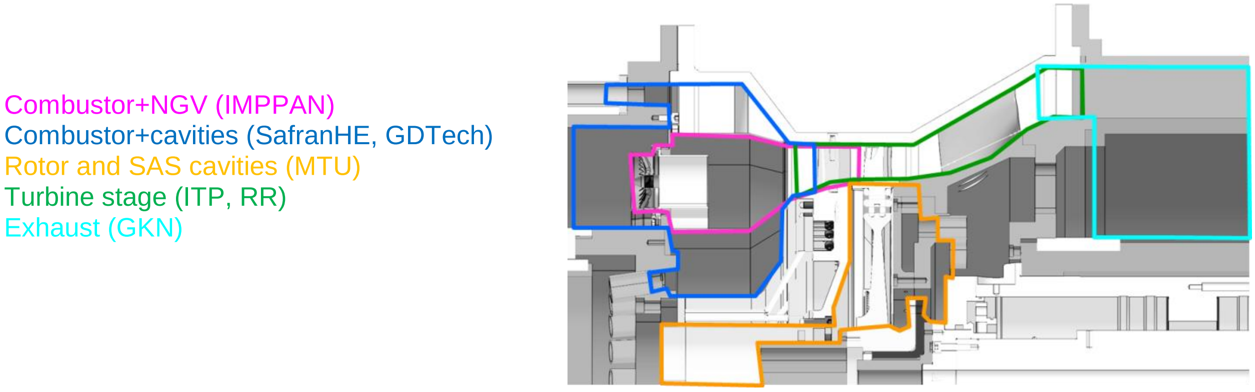
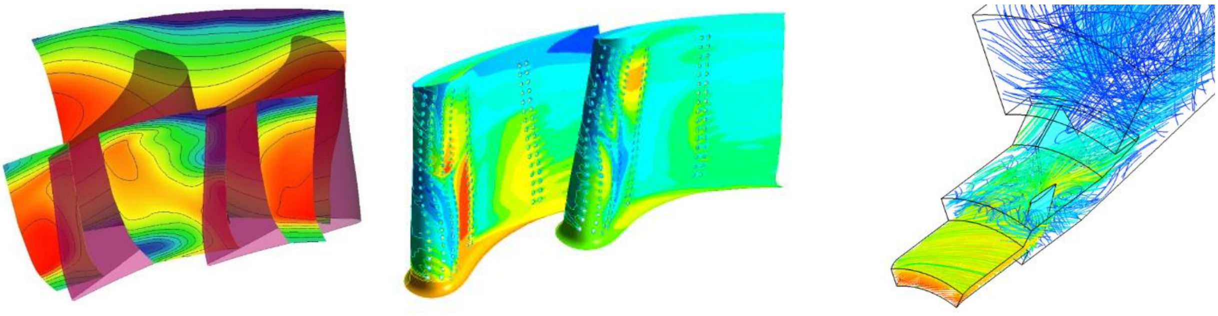


**Figure 26 – Summary of the CFD investigations**

SafranHE and GDTech together computed the combustor simulator featuring an explicit mesh of the liner cooling holes to comfort the design of this module. IMPPAN performed fully integrated CFD of the combustor and NGVs using RANS and URANS approaches to highlight the impact of the swirler/vanes clocking and hot streak transport. MTU established several CFD models (RANS) of the rotor cavities plus the NGV and HP rotor blades to assess the behaviour of the full turbine stage. This allowed to validate the design of fins on the disk and rim seals and confirmed the presence of a hot streak still visible at the rotor exit. Such analysis were completed by simulations of the HP turbine stage main gas path performed by ITP and RR. Finally, GKN numerically assessed the interactions between the LP vane and the exhaust of the rig by means of transient CFD and confirmed the design choices.
All the results from these integration assessment analyses, illustrated in Figure 27, are reported in D3.3.

Combustor cavities (Safran) Clocking combustor/NGVs (IMPPAN) Turbine stage with cavities (MTU)



HP stage main stream (ITP) NGV cooling (MTU) Exhaust (GKN)

**Figure 27 - Overview of the CFD dedicated to the integration digital assessment**

# Work Package 4 – Measurement campaign

The following report will summarize the individual measurement tasks to be carried out at UNIFI tri-sector-rig and at the DLR NG-Turb facility rotating turbine rig in order to complete the result database for FACTOR.

## *Task 4.1 – Area probe traverses and steady measurements (DLR)*

As the pneumatic probe measurement results were considered most critical to enable the real rig vs. CFD computation comparison it was decided to start the measurement campaign at NG-Turb with them.

The available measurement planes (MP) feature at least one type of access for probes or rakes. With the exception of the more restricted planes 43 and 44 around the LP stator, all MPs enable a radial probe traverse at least in one circumferential position. The most interesting planes around the HP stage MP40, 41 & 42 enable the mounting of the DLR circumferential traverse system that itself can connect the radial traverse system on top. This is required to perform the desired 2D area traverses using the DLR 5-hole-probes (5HP). Except the fifth back pressure hole, the Figure 28 shows the frontal hole configuration of this probe type, that additionally features a thermocouple on top of the probe head to also measure flow temperature.

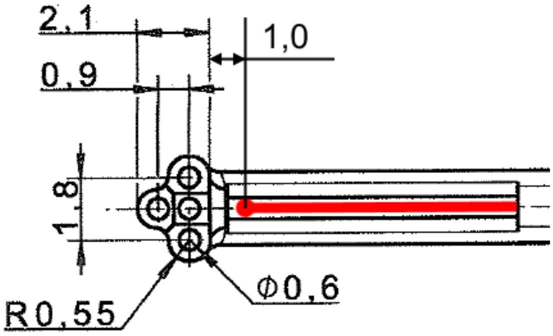


**Figure 28: DLR 5-hole-probe head dimensions, frontal view**

The post-processing of the probe holes pressure data yields not only radial and circumferential flow angles, but also corrected main flow Mach number and associated total pressure. The temperature measured by the probe's thermocouple is taken into account and could also be plotted to have a planar temperature distribution.

The area traverse measurements were planned to be taken at least for the two relevant combustor clocking positions, that would also be simulated by CFD software and are two extreme positions concerning their effect on turbine blades aerodynamics and interaction. The orientation of the combustor flow swirler center to the passage was the first position, followed by the orientation to the lower leading edge tip of the first stator row (NGV). The  Figure 29 is showing a basic sketch and the principle of aligning the combustor swirler with the NGV blades upstream.

Within the fifth period, just the commissioning and the very first test measurements could be carried out. However shortly after all 5HP measurements were completed successfully. The results are presented in detail and full scope in the deliverable D4.1. The results were used to initialize the CFD simulations to enable a comparison with numerical results within WP6.

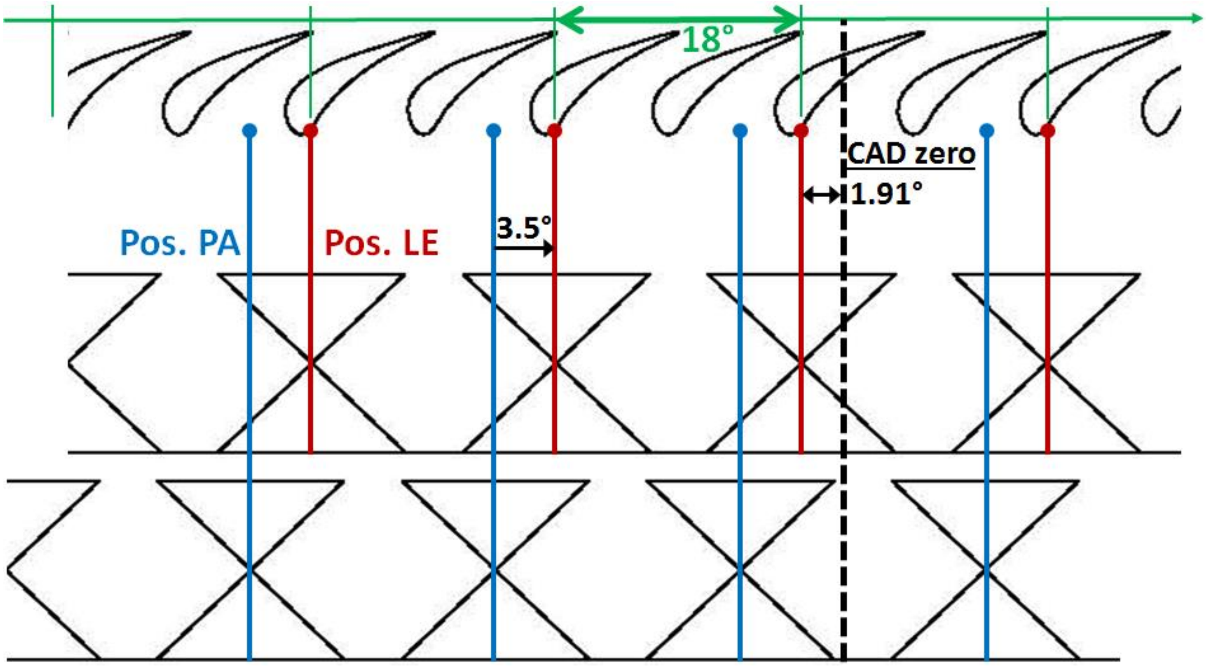


**Figure 29: Schematic drawing of the realised combustor-NGV clocking and positioning vs. CAD**

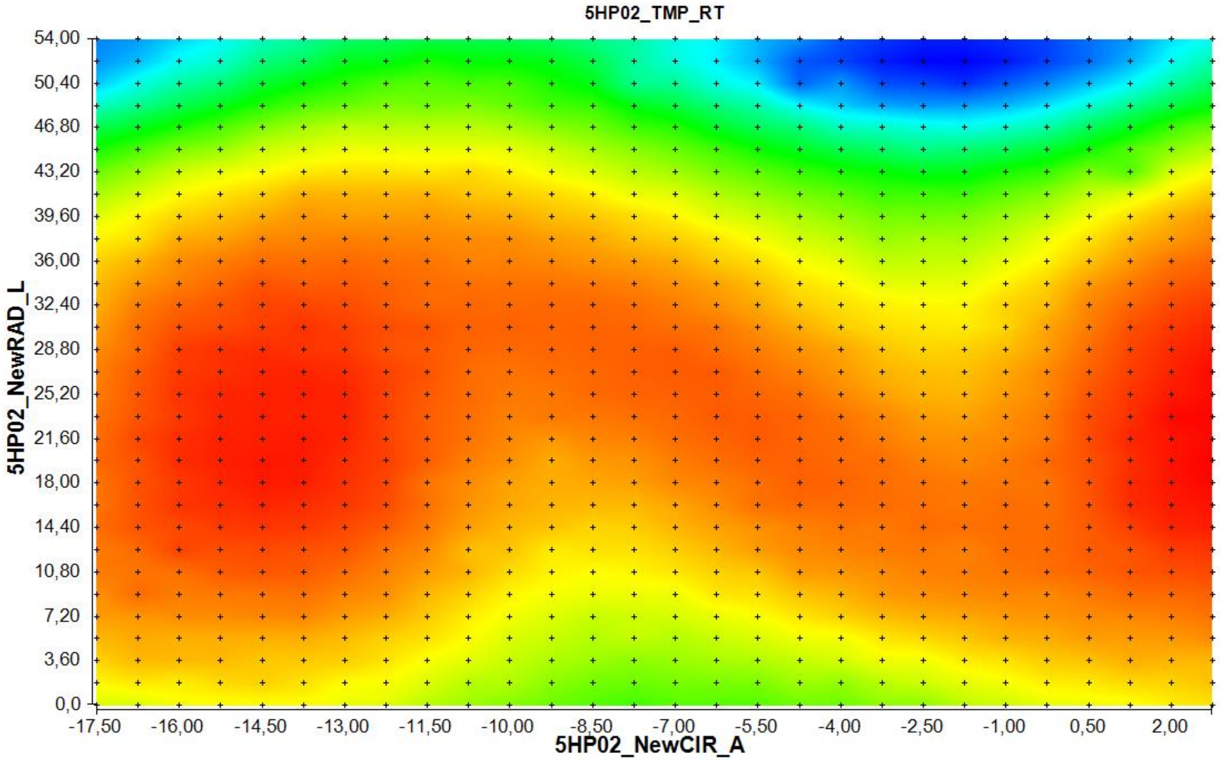


**Figure 30: Planar temperature distribution in MP40, passage clocking (PA)**

The expected and desired characteristic temperature and velocity field at the turbine inlet could be demonstrated and was verified; see Figure 30 for temperature distribution at inlet measured with the 5HP head thermocouple. Due to its positioning above the pressure holes (compare Figure 28) especially the bottom, near-hub data is physically (by probe construction) cut-away. At the hub, also cold wall flow is expected to be present (compare results in WP2 from UNIFI tri-sector-rig). It was proved that the combustor simulator in the continuous turbine rig at NG-Turb facility was working exactly as desired and produced the formerly designed strong temperature (and swirl) profile at the turbine inlet for realistic boundary conditions comparable with an aero engine.

As an additional highlight result from the completed probe area traverses, the significant influence of the combustor clocking positon on the total pressure distribution behind the NGV (MP41) is shown in Figure 31. The strongly asymmetrical result at the bottom clearly identifies the passage clocking centered to the viewable left NGV passage. Some artifacts in the data, also viewable partly in Figure 31, were accountable to local probes traverse system malfunctions or probe calibration limitations. These are also discussed in deliverable D4.1 which concludes the overall successful measurements. The complete results of this task were used to support the CFD simulations carried out and described under WP6.

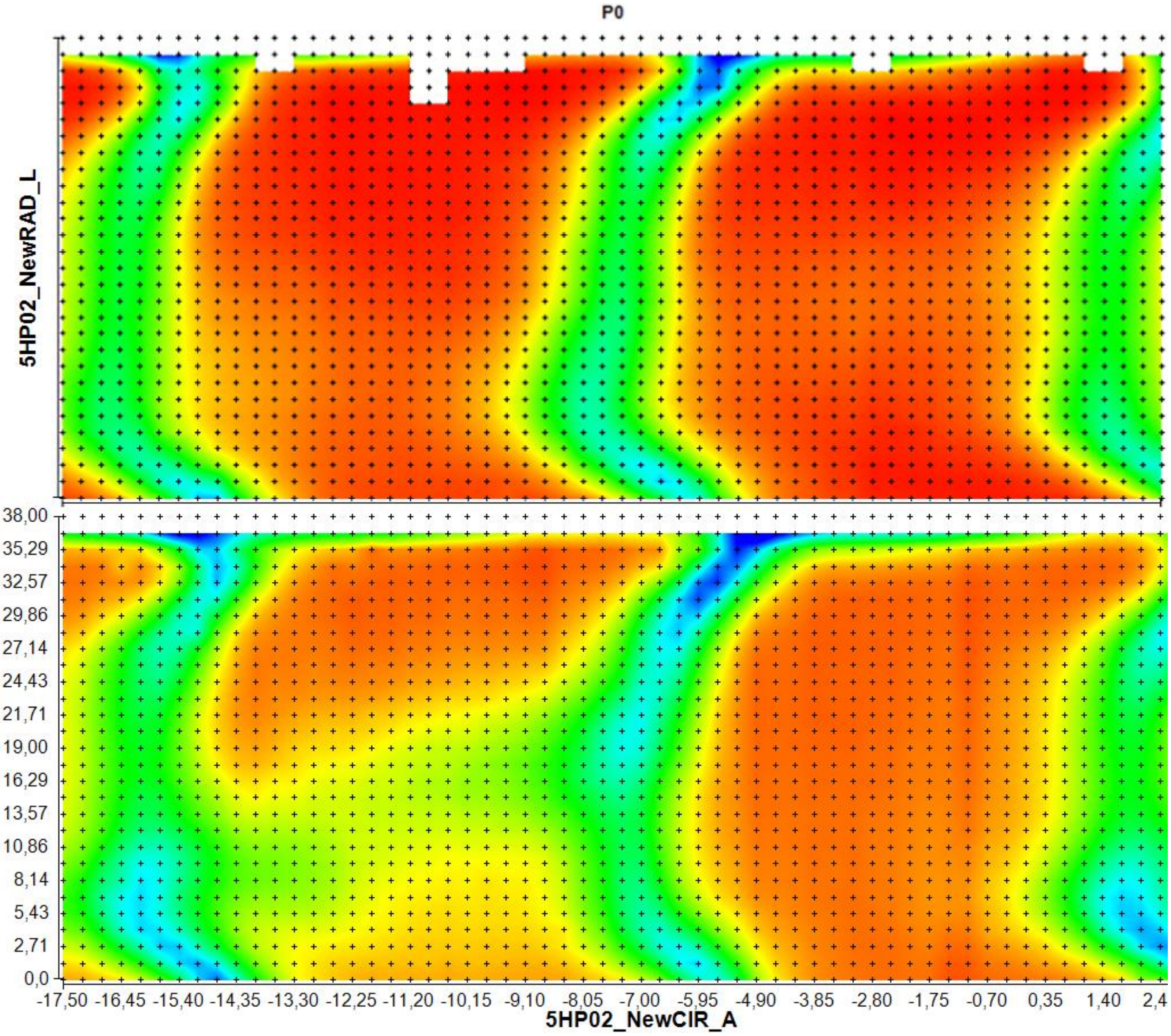


**Figure 31: Total pressure distribution behind the NGV (MP41), Clocking PA (bottom) vs. LE (up)**

## *Task 4.2 – Aerothermal measurements (ONERA, UCAM, VKI)*

Waiting for inputs

## *Task 4.3 - Unsteady measurements and preparation (ILA)*

### 1. Instrumentation design and Manufacturing & Rig Adaption

In the first periods of the FACTOR project the activities of ILA concentrated on WP2 Instrumentation design and Manufacturing & Rig Adaption. Initially 3 measurements techniques were under discussion:

- Vibrometry
- Interferometry and
- BOS ( Background Orientated Schlieren Method)

After evaluation of the pros and cons together with the project partners it was decided to develop a new measurement device based on an interferometer (see Figure 32).

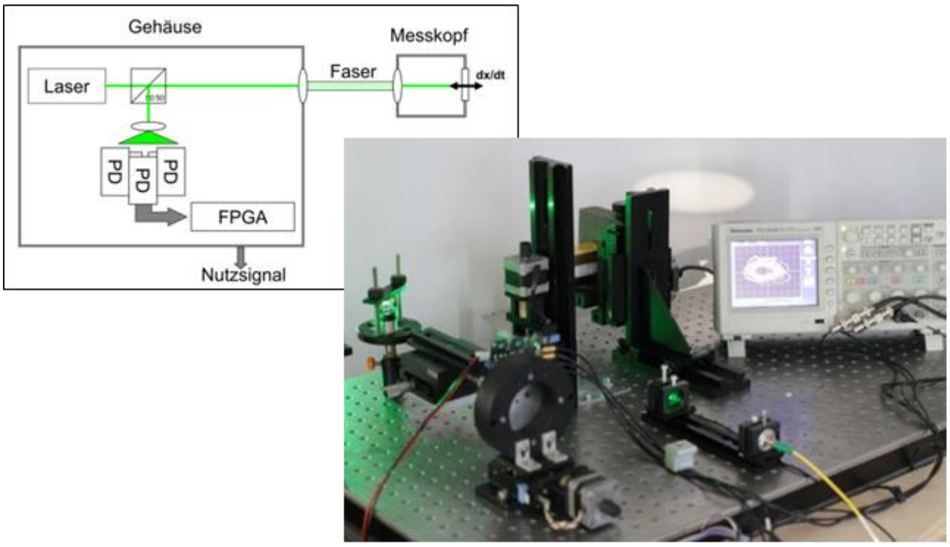


**Figure 32: Measurement principle and realized test rig of the interferometer**

The modification and adaption of a new measuring technology was carried out in cooperation with DLR Berlin. After several pre-investigations the test rig was realized and measurements were carried out in the laboratory of ILA. The hardware components and the algorithms have been tested successfully. Measurements with a Piezo oscillating system to simulate temperature fluctuations were carried out. Unfortunately the stability of the laser was a problem. Furthermore no optical sensor was available to be suitable for measurements under practical environmental conditions. Hence, the project partners and the EC coordinator agreed to look for another approach.

After several discussions about the opportunity to use PIV the common decision was made to use FRS Filtered Rayleigh Scattering instead. In this case the optical access is much easier and there are no particles needed.

2. FRS measurements in the UNIFI Test Rig

A first FRS test campaign in the test rig at UNIFI in Florence, Italy was carried out in May 2015. After some problems with the optical access promising investigations could be made. The test campaign was carried out in cooperation with the DLR in Cologne, which has specialized on FRS measurement in engines and combustion chambers. Because of the window issues a borescope was used to have optical access. Hence the test duration to obtain a 2-dimensional temperature distribution was such long that the results were disturbed by the pollution of the window. This led to a decreased accuracy.

But it has to be stated that there was a good qualitatively agreement between FRS and UNIFI results and the topology of the temperature field was very similar.

After several discussions with the work package leader and the EC coordinator a new test campaign was planned to avoid the problems described above. These measurements have been carried out in June 2017 in the UNIFI test-rig in Florence again. The measurements refer to the plane 41 just downstream of the stator blades (see Figure 33).

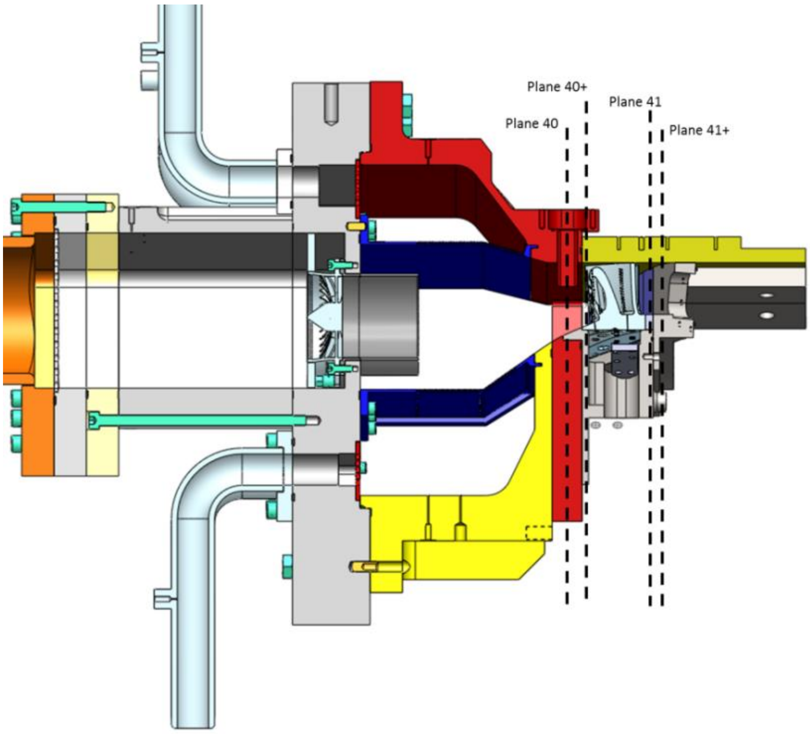


**Figure 33: Schematic of the UNIFI test-rig, actual configuration (Source UNIFI)**

The measurements were done at three operation points: Isothermal conditions (prove of principle), OP 250 degree (factor operation point), OP 150 degree.

The measured temperatures are showing a good agreement compared to the probe measurements and the calculations carried out by UNIFI, if the temperature is inside the calibrated range.

Also for 250 degree a good agreement between FRS-temperature measurements and probe measurements concerning level and distribution could be reached.

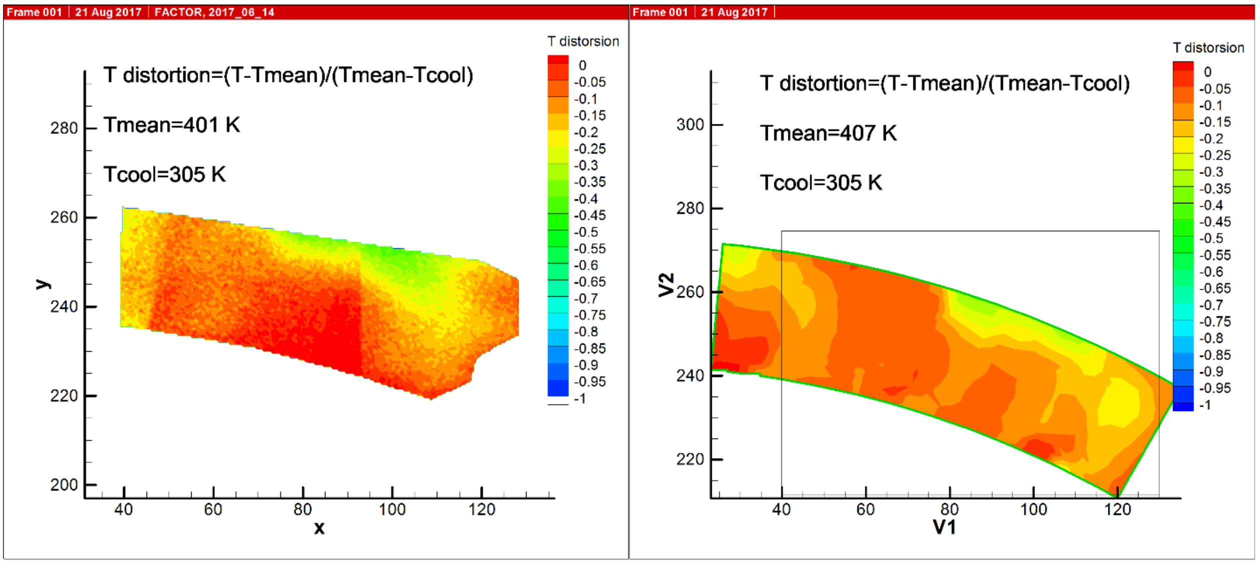


**Figure 34: Comparison FRS-Probe measurements OP 250l, P41 (14.06.2017, left), distortion temperatures compared to Measurement UNIFI June 2017 (right)**

There is a good agreement between the measurements some differences between probe and FRS measurements can be observed.

- For the isothermal case the FRS temperature distribution is like expected
- For the Factor OP 250 case, the FRS temperature distribution with shows a good agreement to the probe measurements and to the CFD calculations
- For OP 150 the highest FRS data quality is reached because of the use of calibration model in data evaluation, probe measurements are planned

The deviations observed are caused by several circumstances which should be regarded in further investigations:

- Adverse influence of the probe onto the flow field
- Different spatial resolution of the measurement methods
- Movement of the test section due to thermal heating (therefore no pressure results from FRS can be obtained)
- Temperature and pressure of the factor OP 250 is outside FRS calibration model, extension of the calibration model is planned by DLR

As a general conclusion it should be stated that FRS measurements in a hot turbine is a very powerful technique to gather local temperature-, density- and velocity-distributions. The optical method has the big advantage that the flow is not disturbed by any probe and the spatial resolution is very high. And FRS temperature measurements can be done at high temperatures were probe measurements are not possible. The measurements carried out in FACTOR have been very limited because of budget restrictions and also by the near project end. But the huge capabilities of this technology could have been demonstrated. Hence, in a follow-up project FRS measurements should be considered to improve the quality and value of flow data.

### *Task 4.4 – Particle image velocimetry PIV @ NG-Turb (UNIFI)*

Test were cancelled for NG-Turb rig for campaign duration and costs reasons. The effort was spent with more intensive work on PIV investigations at the UNIFI tri-sector-rig. Therefore, see Task 4.5 for results.

### *Task 4.5 – Measurements @ sector test rig (UNIFI)*

Whereas no activity was done in the first period, the UNIFI WP4 activity was then moved mainly to within the second period with the new planning. Many results can be therefore be found in this document above under WP2. However, in the third period, as an upgrade an new part of WP4, a preliminary design of the sector rig upgraded with the NGV cascade was carried out and the first drawings were sent to the manufacturing partner Progesa for quotations. In the fourth period the design of the upgraded rig has been completed and the manufacturing activity has been followed, in order to cooperate with Progesa in some manufacturing choice.

The test rig components and the NGVs needed for the campaign, had been manufactured and delivered to UNIFI in November 2016. The test rig has been assembled and it was ready to be installed in the test facility. Figure 35 shows some details of the test rig upgraded with the NGV cascade.

**Figure 35: Pictures of the upgraded UNIFI test rig**

In the fifth period the experimental campaign on the upgraded test rig was carried out. Five hole probe tests and hot wire tests have been repeated in Plane 40. Five hole probe tests were repeated to double-check the old results with a new probe. Results provided a good matching with the previous measurements. Figure 36 reports the results of five hole probe and HWA test, in that a highly swirling flow field with relevant turbulence and hot streaks can be identified.

Five hole probe tests and hot wire tests have also been carried out in order to evaluate both the overall aerothermal field and the turbulence at NGV exit plane:

- o five hole probe tests have been carried out in both DP conditions (heated mainstream and ambient temperature coolant) and isothermal ones (all the flows at ambient temperature)
- o HWA tests were performed only in isothermal conditions

Concerning the aero-field, results showed that the swirling structure, observed on Plane 40, is mainly convected in the right passage, where it interacts with end wall flows and determines local zones with high pressure losses. Figure 37 reports a pressure loss coefficient map, with secondary flows vectors overlapped on it. The shape of the residual swirling structure is easily recognizable in the right passage, while reduced secondary flows are present in the left one.

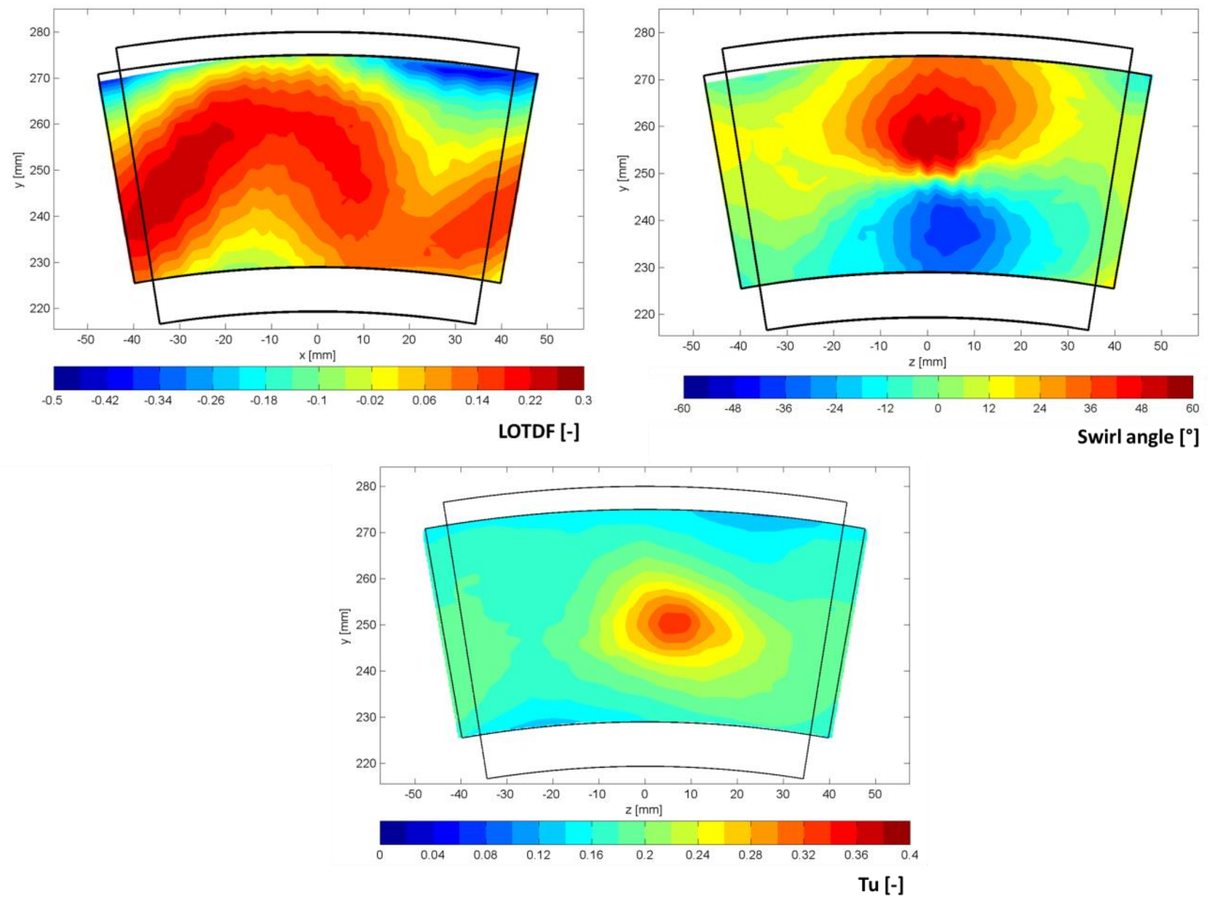


**Figure 36: 5-hole probe and HWA results at combustor exit**

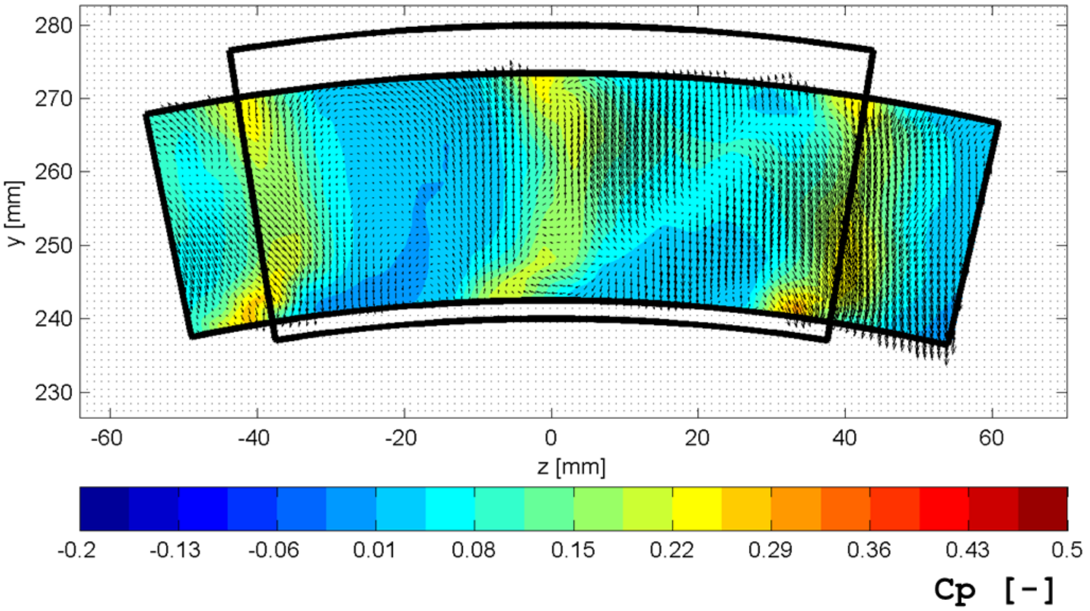


**Figure 37: Pressure loss coefficient measured on Plane 41**

Concerning the hot streaks migration an important reduction in the hot spot, with respect to Plane 40 was observed. The temperature field is dominated by the effect of the residual swirl that bleed some of the outer liner coolant inside the right passage, making the temperature pattern, in this passage, very distorted. The hot streak is segregated towards the inner liner. Figure 38 shows a LOTDF (Local Overall Temperature Distortion Factor) map on Plane 41.

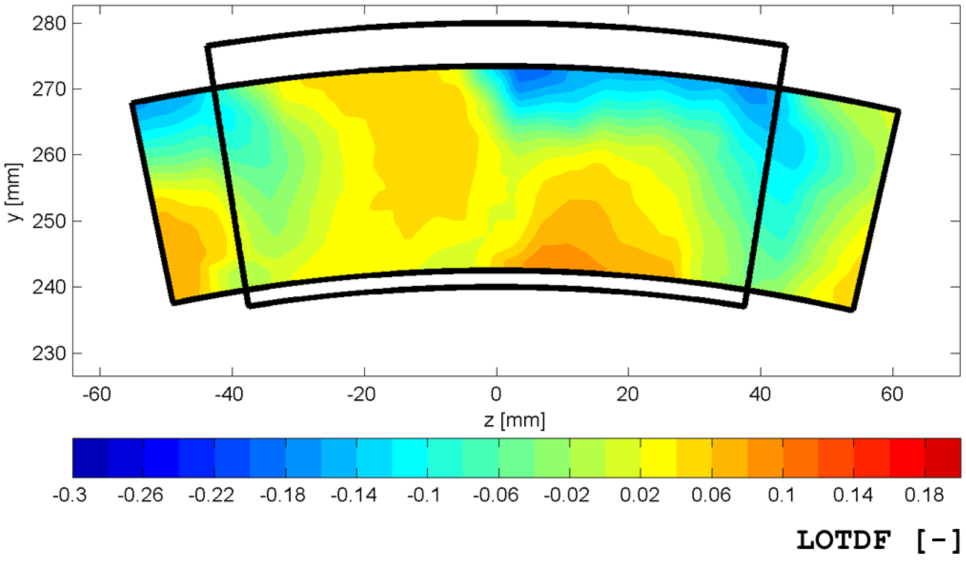


**Figure 38: LOTDF measured on Plane 41**

Moreover, HWA results showed that a residual turbulent spot is present in the right passage, in agreement with the other results. Important contributions also came from the zones close to the inner liner, where high pressure losses were detected. Figure 39 shows the turbulence intensity contour plot on Plane 41.

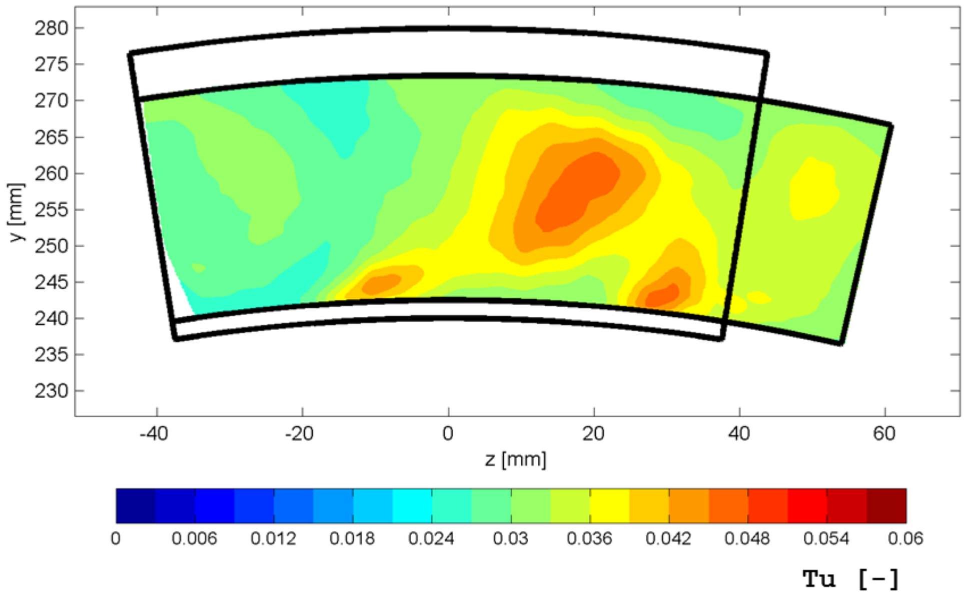


**Figure 39: Turbulence intensity measured on Plane 41**

In addition to these tests, PSP measurements in isothermal conditions have been performed on the cooled NGV airfoils in order to evaluate the adiabatic effectiveness in the presence of the highly swirling inflow. It was found that the inlet swirl affects the cooling performance due to three different phenomena: first of all it influence the stagnation line positions on the LE; it also determines a zone of local low mainstream pressure in its core; furthermore, it creates relevant coolant upwash on the pressure side of the central airfoil, so that the zone close to the inner end wall remains almost uncovered. Fig. 36 reports the adiabatic effectiveness measured through three different camera setups.

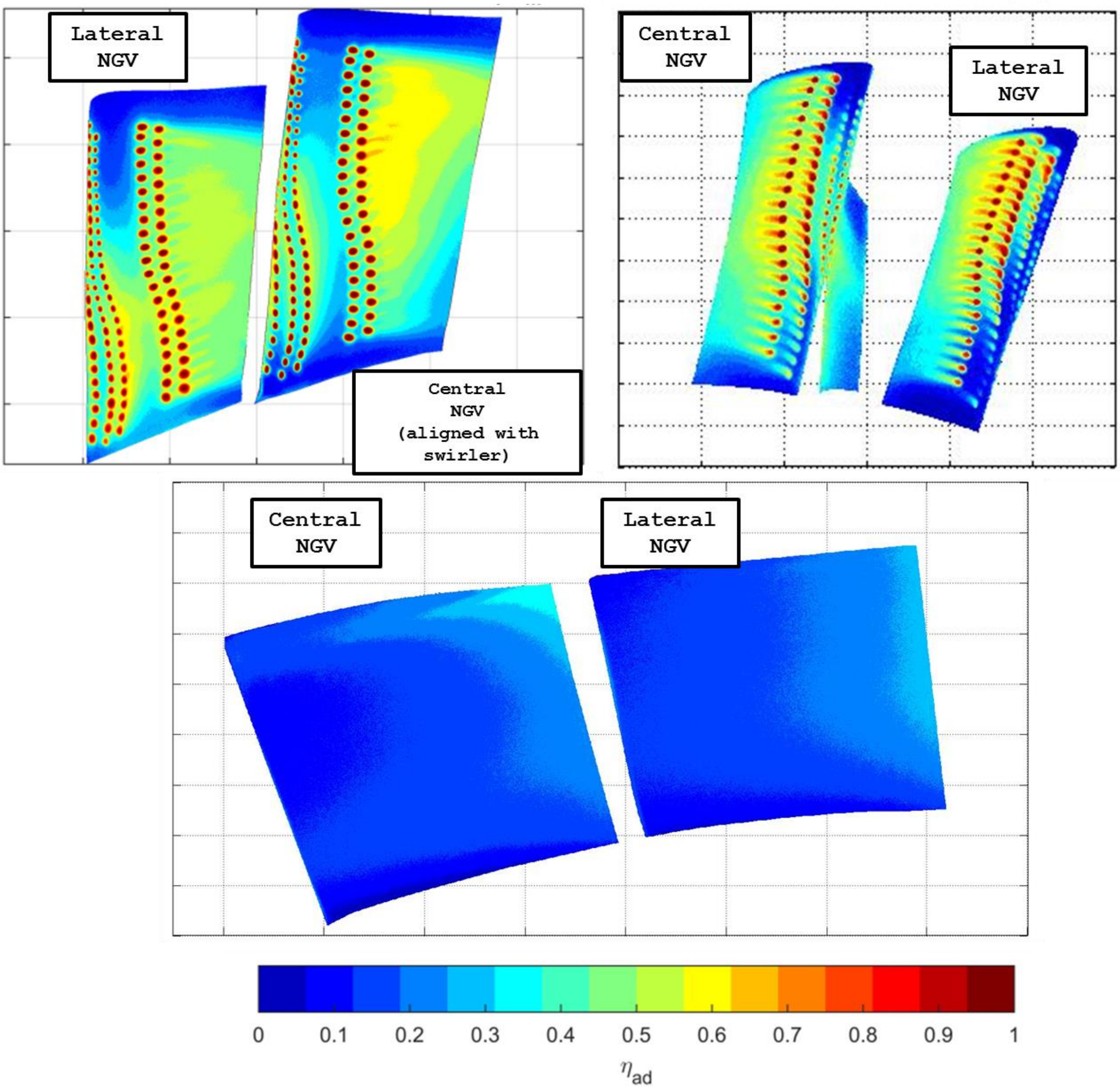


**Figure 40: Adiabatic effectiveness measured through PSP campaign**

All the tests have been carried out for three different film cooling mass flow rates, in order to assess the its impact on all the investigated phenomena. All the results reported above are taken in the nominal coolant conditions (7.5% of mainstream).

Finally, the deliverable D4.8, together with a results database, summarizes all the results of this experimental campaign and it has been released at the end of the project.

### *Task 4.6 – Facility (NG-Turb) operation (DLR)*

Directly after completing the rig installation at DLR NG-Turb facility, the commissioning started with dynamic in-situ rotor balancing as well as tip clearance calibration runs.

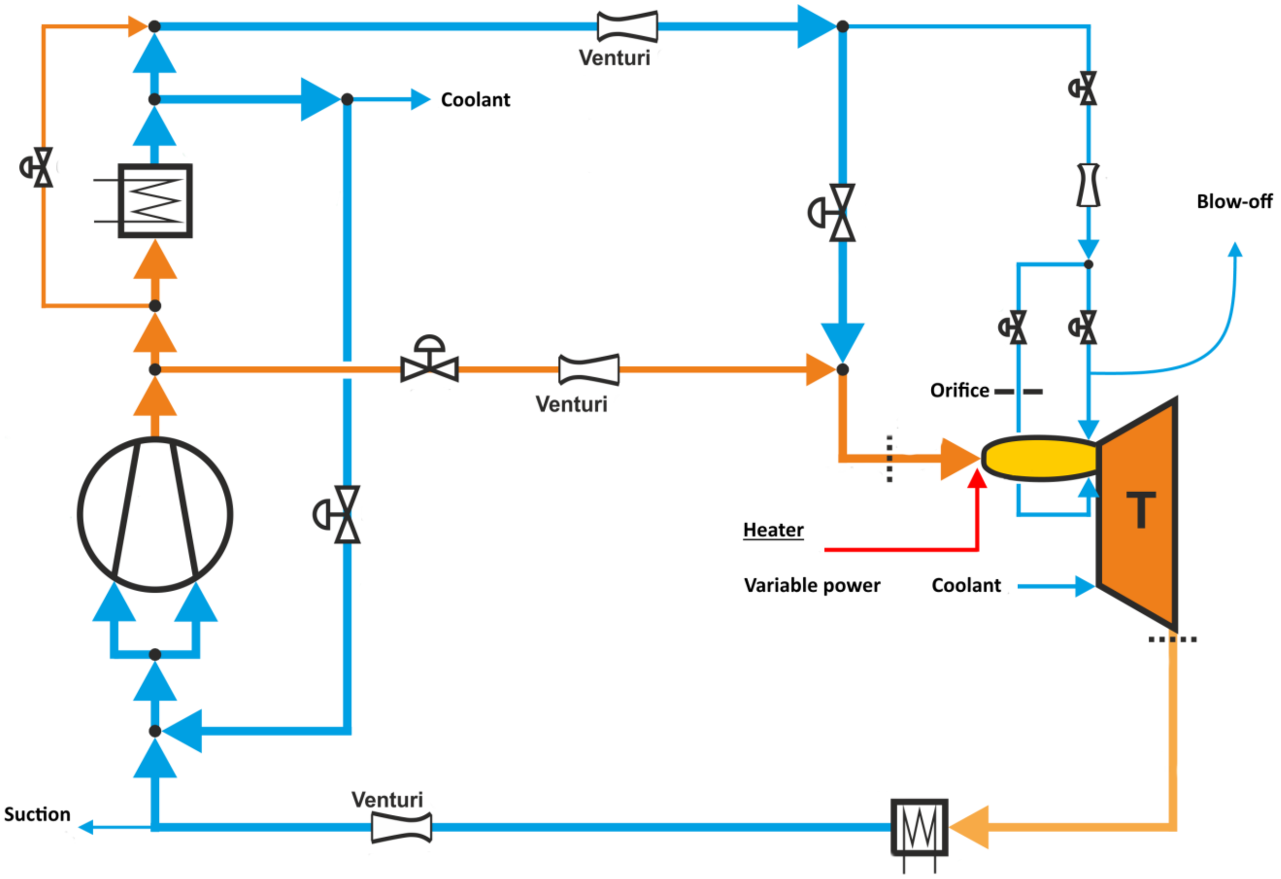


**Figure 41: NG-Turb circuit diagram (simplified) with FACTOR turbine**

The Figure 41 shows the NG-Turb closed facility circuit diagram in a simplified basic sketch with the FACTOR turbine rig connected and supplied with hot, cold and coolant air flows. All details about the integration and detailed OP description including facility operation procedures can be found in the deliverables D2.4 and D4.1.

While still defining procedures for rig operation and finding the aerothermal operating point in commissioning, the following data in Figure 42 was acquired during a running up of the turbine. Each measurement point from the x-Axis corresponds to 5 seconds of elapsed time. The inlet temperature evolution (no scale) recorded by the DLR-designed temperature rake in front of the NGV (see Figure 20 on the right) is shown in Figure 42 from the moment of starting the acquisition system with the rig still shut-off up to a moment where design RPM and pressure were almost reached. Various characteristic phases and events can be identified looking at the graphs, showing the temperature read-out from the four thermocouples at different radial positions angular across the annulus in front of the NGV:

0) Start of acquisition system, all shut-off, no flow, radial temperature gradient due to varying inner- and outer wall temperature and sensor positioning. Then start of evacuation phase with filling up the circuit using dry shop air on one side and sucking on the other. Temperature decreasing and matching better.
1) Start of the main compressor at low sub-atmospheric pressure (wind on), in hot main flow the thermocouples give almost identical, higher values. After that, the mass flow and pressure is constantly increased giving a linear temperature rise, because the compressor outlet temperature is rising.

2) Activation of cold main flow feeding the combustor simulator cavities with effusion coolant, results immediately in an (expected and desired) strong radial temperature profile (compare Figure 30). Hot main flow temperature continues to rise.
3) Setting valves and thus flow split and distribution of the combustor coolant feed to nominal (already tested in previous runs), Especially the T40_4 sensor close to the hub influenced by combustor inner cavity cold feed is now taking its correct position amongst the other sensors, where the two inner ones give the highest temperature read-out (sitting mid-channel close to hot spot). Close-to-shroud T40_1 is expectedly the coldest being influenced by the cold casing film. Then temperature is rising linearly, at some point more slowly where progression is reduced to wait for the facility inlet casing struts to adjust to the temperature gradients.
4) First power-on of the fast main flow heater with an idle power of 2%, expected and virtually instant temperature rise. Compressor driven temperature rise for some time after that to check heater control software and heater behaviour.
5) Beginning of manually controlled rising of heater power (step by step) clearly influencing main flow temperature, but keeping characteristic (i.e. radial temperature profile) unchanged as desired. With dozens of kilowatts in, this proves the function of the heater also as a constant operation device.
6) At last, usage of the DLR heater software by switching from manual to automatic temperature control based on a single Pt100 sensor directly downstream of the heater. Everything worked as intended. In the following it was possible to keep turbine inlet temperature constant, independent of any temperature fluctuation of the facility during the whole measurement day.

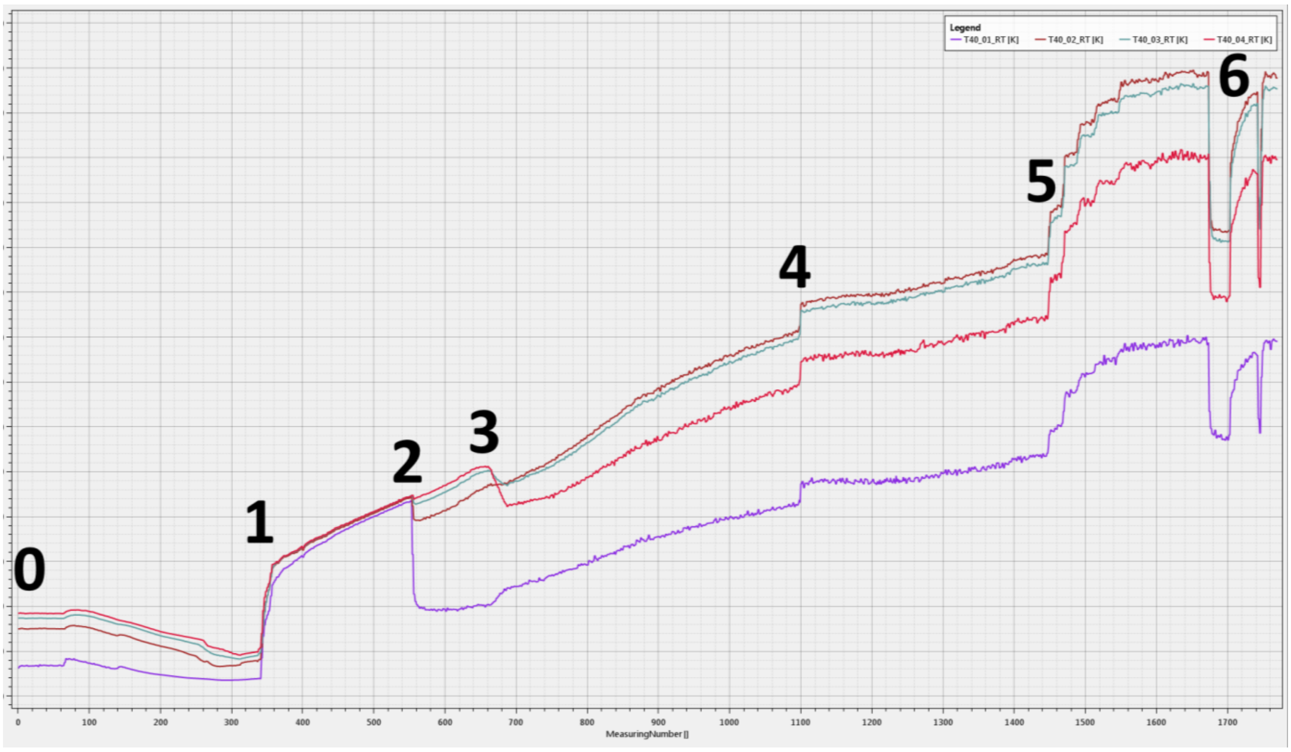


**Figure 42: Inlet temperature T40 (four TCs radially distributed) while running up the FACTOR rig**

This facility operation described above during one of the first runs was optimised and standardised in the following to reach design point quickly and stable on every measurement day and maximize measurement time for the probe traverse campaign as well as other measurement techniques to be applied.

# Work Package 5 – Lean burn influences on low turning strut heat transfer

## Introduction

WP5 contains an investigation using the O-TRF (Oxford Turbine Research Facility) and is thus separated from the other WP’s in the FACTOR project. In WP5, the O-TRF rig with existing MT1 turbine stage was equipped with a new low turning IP vane and turbine duct, representative for a counter rotating engine configuration. In earlier O-TRF project (TATEF) only a high turning IP vane, for a co-rotating configuration, had been studied. Partners within WP5 were; GKN (WP leader, aero design, CFD), RRUK (through flow analysis, CFD) and Oxford (experiments). Connected to WP5 was a Swedish funded PhD student (Martin Johansson), who contributed significantly to the work. In the end, MTU supported WP5 doing some CFD.

## Design and instrumentation

The design work was split between the partners. RRUK was responsible for flow path layout and through flow analysis. GKN did the detailed aero design and analysis of the new IP vane and turbine duct, which was reviewed and approved by RRUK. Oxford was responsible for the mechanical design and specifications (drawings) for the manufacturing of parts and rig assembly. Since the new IP vane turn the flow in the opposite direction vs earlier/TATEF design, a new de-swirl vane had to be designed and manufactured. Figure 39 shows pictures of the O-TRF rig and the new IP vane.

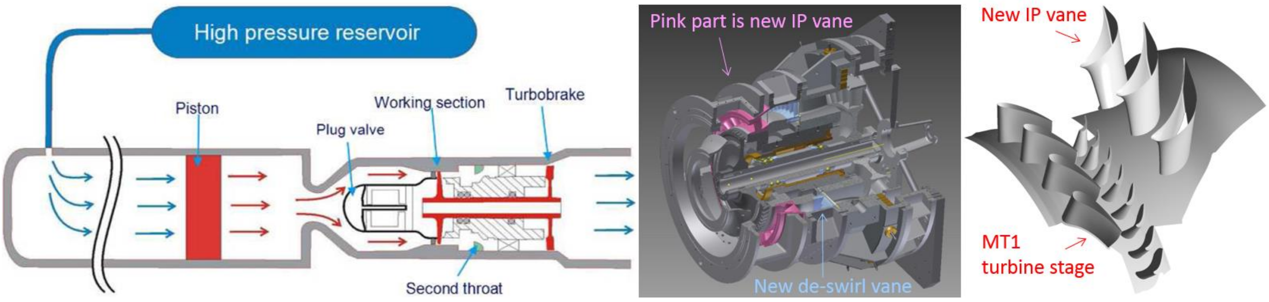


**Figure 43: The O-TRF rig and the new IP-vane.**

Based on initial (pre-test) unsteady analysis by GKN, it was found that the clocking effect between NGV’s and IP vanes were significant, so it was decided to instrument at 3 nearby IP-vanes to capture this clocking effect. Instrumentation for pressure and heat transfer at 3 different spans (10%, 50% and 90%) and shroud resulted that all (24) IP vanes hardwares had some kind of instrumentation. In addition to the instrumentation on the vanes, pressures and heat transfer were measured on the endwalls. Flow field was captured by rakes and a traverse downstream of the IP vane. The additional instrumentation caused some delays, due to instrumentation work and challenging rig assembly. The heat transfer was measured using Oxford manufactured thin film heat transfer gauges (TFHTG). The instrumentation layout and examples of instrumented IP-vanes are shown in Figure 40.

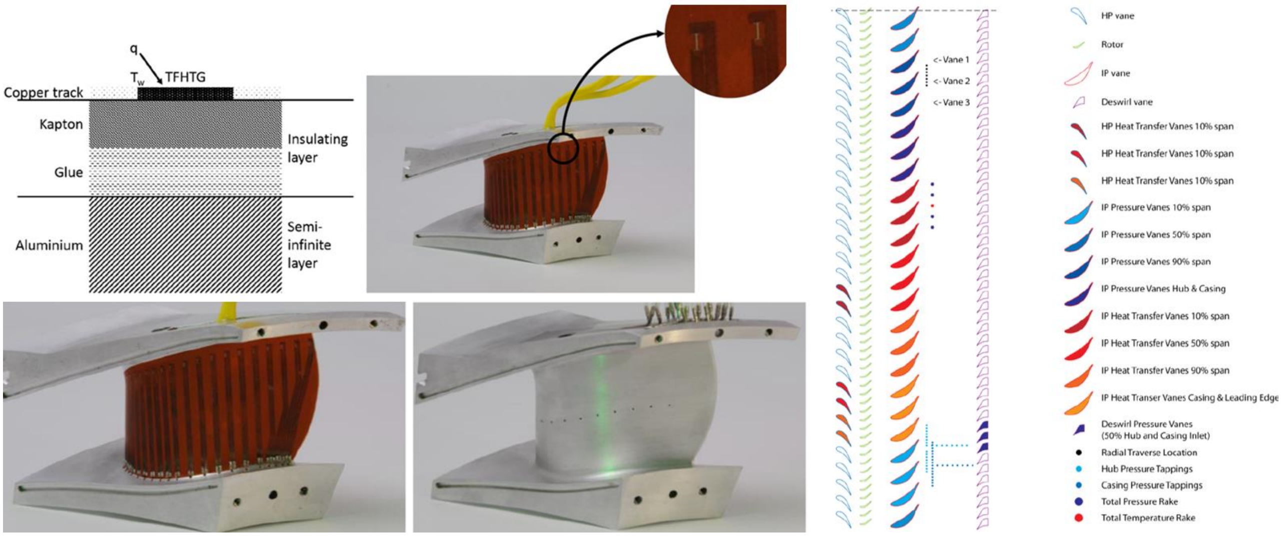


**Figure 44:: Instrumentation.**

Rig build and problems

The rig assembly started in Sept 2012 and finished in Nov 2012, with some challenges due to the extensive instrumentation. Pictures of the assembly and rig is shown in Figure 41. During the commissioning and operation of the (existing/old) rig, several problems occurred, which caused some challenges and delays:

- A damaged rotor bearing, which needed repair.
- Problems with vacuum, a broken vacuum pump and leakages.
- Oscillations in pressure due to a sticking plug valve, due to a worn seal.
- Repair of blade tip abradable.
- Cracks in turbobreak and following repair and re-commissioning.

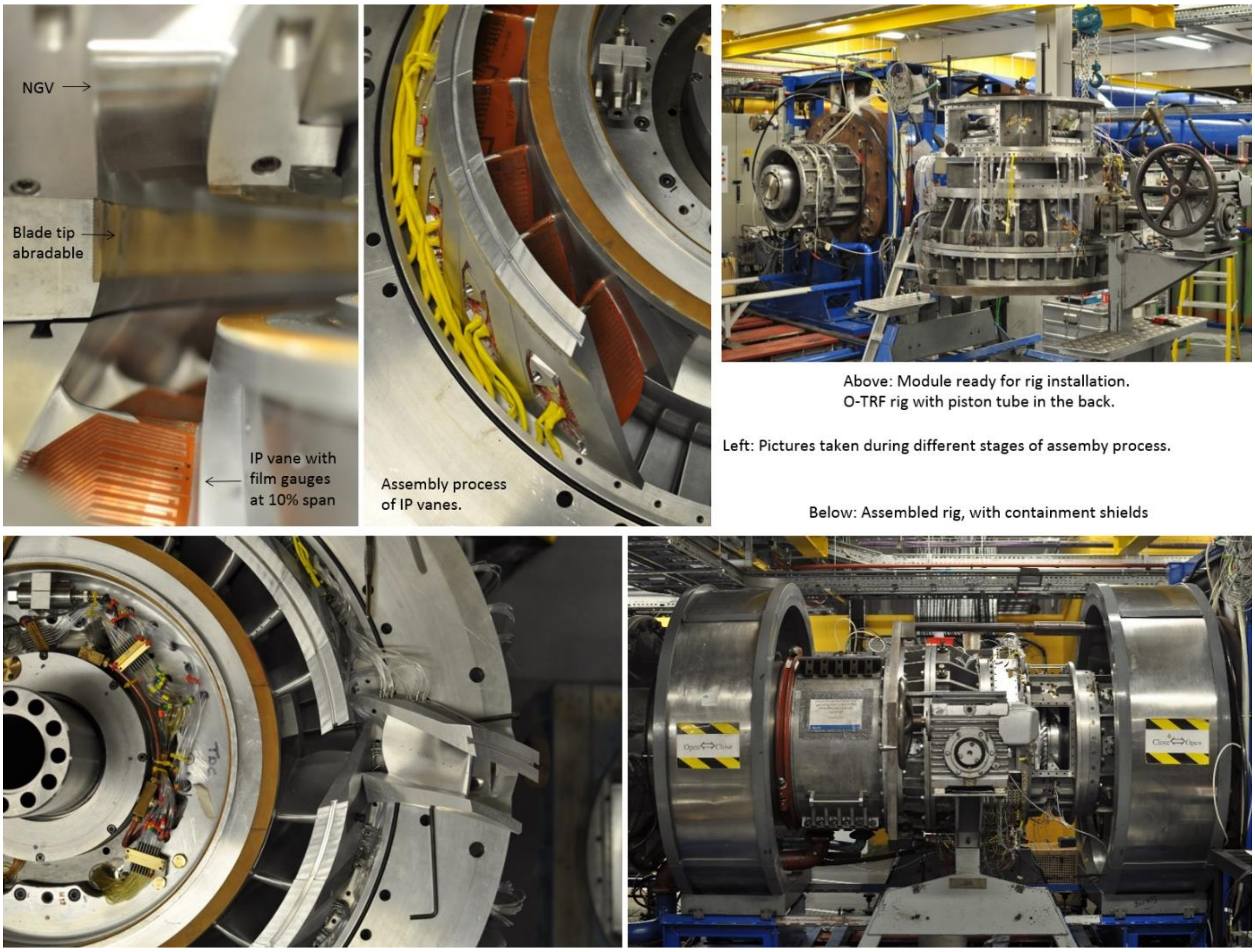


**Figure 45: The O-TRF rig and hardware.**

### Measurements and evaluation

Measurements has been performed for different inlet conditions to the turbine. Initial measurements were performed for uniform inlet conditions (D5.1). After this the inlet condition was changed to a temperature profile (EOTDF, D5.2), swirl condition (D5.3) and finally clocked swirl condition (D5.4). The difference to the DLR rig measurements, the temperature and swirl conditions were not combined in WP5. WP5 used the O-TRF rig in 23 months, between Sept 2012 (start of installation) and July 2014 (measurements finished), for installation, commissioning and measurements of the 4 inlet conditions.

The evaluation work started in spring 2013 when the first uniform measurements were available. The evaluation of the adiabatic wall temperature was a challenge, due to the low temperature step behind the MT1 stage and short measuring window. It was needed to improve the heat transfer evaluation (regression) method by combining several rig runs and to extend the measurement window using some colder air at end of run, including a correction for the reduced flow. The final evaluation method was agreed in Jan 2015, when final evaluations were done for all operating conditions.

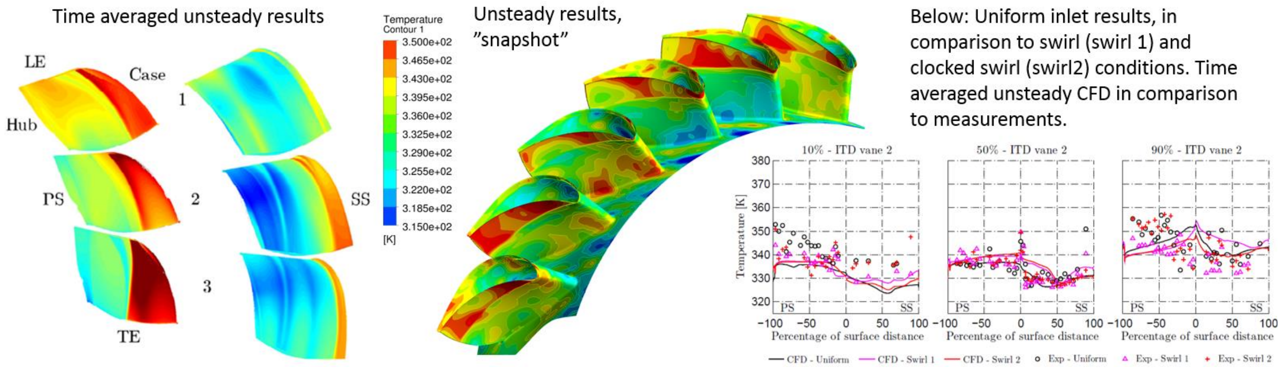
### CFD

CFD work was performed by GKN and RRUK, as WP5 partners. In the end, also MTU did some CFD work for WP5. Some of the CFD work has been done by students. CFD analysis has been performed using; different CFD codes, different turbulence models, steady and unsteady analysis, different CFD domains, different meshes and different inlet conditions. The CFD work split:

- GKN: CFX, kw-SST turbulence model, steady and unsteady analysis, 90 deg “full” domain (8-15-6, i.e. 8 NGV, 15 blades, 6 IP vanes), coarse (wall function) HPT stage mesh, different inlet conditions.
- RRUK: Hydra, kw-SST turbulence model, steady analysis, well resolved meshes, different inlet conditions.
- MTU: CFX, transition turbulence model, steady and unsteady analysis, different “reduced” domains (3-5-2, 2-3-1, 4-7-3) with profile and time transformation, well resolved HPT stage mesh, different inlet conditions.

Results

A lot of results, measurements and CFD, have been presented at meetings and are included in periodic reports, deliverables and papers. Here only a few examples of results are shown, in Figures 42 to 45. Figure 42 shows the adiabatic wall temperature, which shows the very complex temperature and flow field, with effect of warmer tip leakage flow, impinging on the IP-vane pressure side. The measurement results is from the used regression evaluation technique.

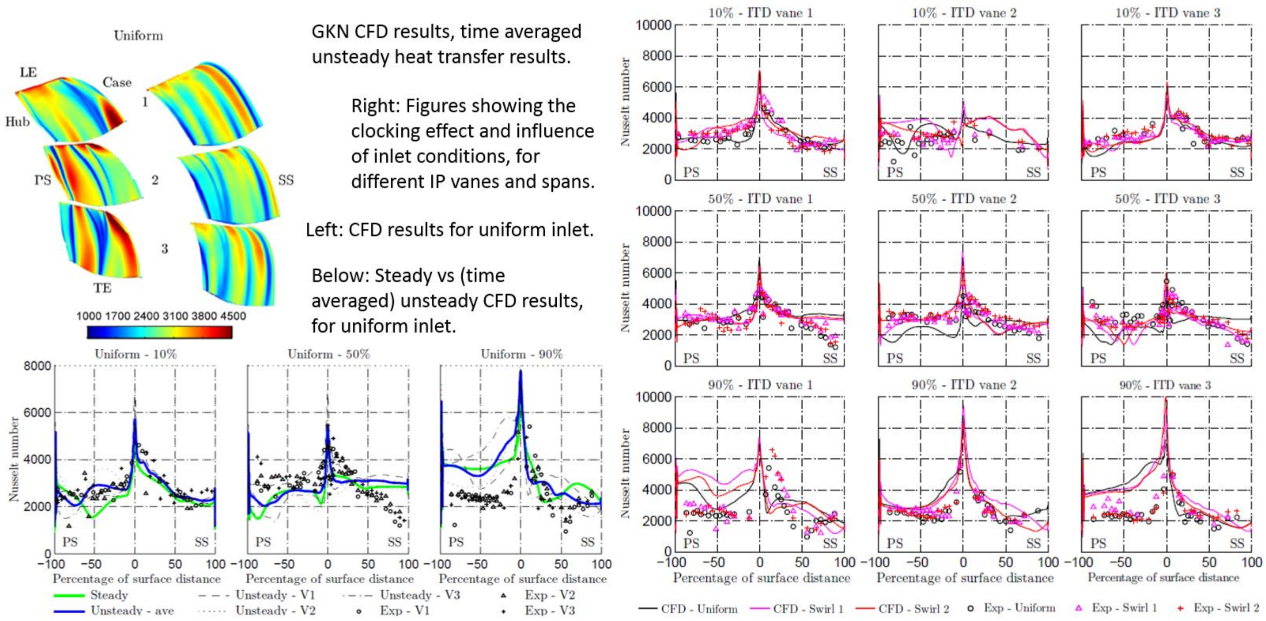

Time averaged unsteady results

Unsteady results, ”snapshot”

Below: Uniform inlet results, in comparison to swirl (swirl 1) and clocked swirl (swirl2) conditions. Time averaged unsteady CFD in comparison to measurements.

**Figure 46: GKN CFD results for uniform inlet conditions. Adiabatic wall temperature.**

GKN heat transfer CFD results are shown in Figure 43, in comparison to measurements. The right figure shows the effect of the different inlet conditions and the clocking effect, which shows that the measured clocking effect is larger than the effect of different inlet conditions. It is also noticed that the CFD predicts a larger clocking effect vs shown in the measurements. Comparisons of a steady CFD analysis and a time averaged unsteady analysis shows similar results. Largest difference between CFD and measurements are found on the 90% span pressure side. Comparison of heat transfer results for the new low turning IP vane with previous/TATEF high turning vane shows that the new low turning vane has higher heat transfer level, probably due to the tip leakage impinging effect on the IP vane pressure side.



GKN CFD results, time averaged unsteady heat transfer results.

Right: Figures showing the clocking effect and influence of inlet conditions, for different IP vanes and spans.

Left: CFD results for uniform inlet.

Below: Steady vs (time averaged) unsteady CFD results, for uniform inlet.

**Figure 47: GKN CFD results for uniform inlet conditions. Heat transfer results.**

MTU CFD results for uniform inlet are shown in Figure 44. MTU used a transition turbulence model, and some signs of transition is shown at 10% span. MTU run their unsteady CFD with “reduced” CFD domains and profile or time transformation techniques. MTU “3-5-2” capture a clocking effect, of same order as GKN’s “8-15-6” analysis. The difference between steady state CFD or unsteady analyses are small, and similar to GKN’s unsteady results.

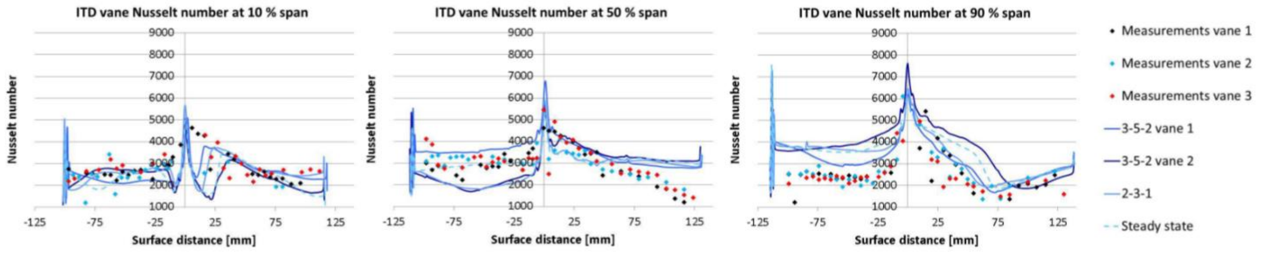


**Figure 48: MTU CFD analyses for uniform inlet conditions, steady state and unsteady analysis for different CFD domains.**

RRUK CFD results are shown in Figure 45, which includes steady CFD for all different inlet conditions. RRUK final CFD analysis used a very refined mesh of the HPT stage, which improved the results significantly at the 90% span on pressure side.

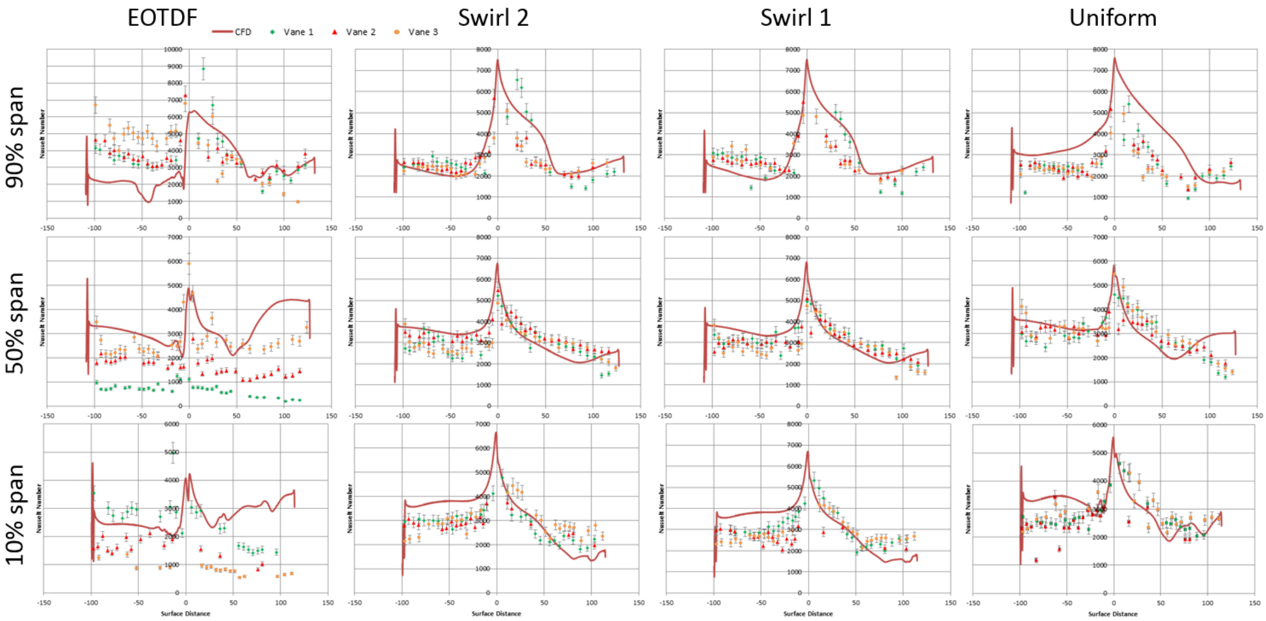


**Figure** 49**: RRUK final CFD calculations for different inlet conditions. Steady CFD analysis using Hydra and refined meshes. Swirl 1 = swirl. Swirl 2 = clocked swirl.**

Conclusions

From the results, measurements and CFD calculations, the following major conclusions can be drawn:

- The influence of inlet condition (uniform, swirl, clocked swirl) on IP vane heat transfer is not so large, and smaller than NGV clocking effect.
- The new low turning IP vane has somewhat higher heat transfer vs earlier/TATEF high turning vane.
- It was a challenge to evaluate IP vane heat transfer, due to low temperature step at HPT stage exit and short run time. A novel evaluation method has been developed, to improve the used regression technique, using data after stable aero period, with cold slug of air close to piston. Impossible to use regression technique for EOTDF, since fluctuations too large.
- CFD heat transfer predictions agree fairly well with measurements and GKN, RRUK and MTU’s CFD results are similar. Steady CFD agrees well with averaged unsteady CFD.
- NGV clocking effects for IP-vane heat transfer is larger in CFD vs measurements.
- CFD predicts too high heat transfer on pressure side 90% span, probably linked to tip leakage effect. Important to have a good mesh resolution (tip leakage). Probably better with a better resolved steady analysis, vs coarse unsteady analysis.

# Work Package 6 – Synthesis of experiments and computations

The main objective of the FACTOR project is to optimise the combustor-HPT interaction design. This is achieved through a better understanding of the interaction between the coolant system, the transport and mixing mechanisms enabling a Specific Fuel Consumption (SFC) reduction of about 2%.

A major aspect of this objective is the synthesis of experiments and computations, which involves the numerical prediction of fluid dynamic with respect to the combustor, the High Pressure Turbine (HPT), the secondary air system (SAS) of the HPT as well as characteristics of Lean Burn combustion concepts. In order to get a detailed understanding of the combustor-HPT interactions, numerical results compared to measurement data is key in

(1) understanding predictive capabilities of current numerical methods,

(2) understanding flow phenomena related to combustor turbine interaction in depth and

(3) developing guidelines on how to model key features of combustor turbine interaction.

More generally, FACTOR is targeting the understanding of combustor-turbine interactions that will lead to increase thermal efficiency by optimising the coolant flows and reducing risks for the integration of lean burn combustors with turbine modules. Improvements of testing and modelling capabilities will finally allow the engine manufacturers to obtain more thermally efficient gas turbines. The FACTOR project test infrastructure will enable further research in combustor-turbine understanding and allow the study of state-of the-art combustor concepts to be used in the next generation of aero-engines.

Since the synthesis of experiments and computations finally relies to 100% on measurement data and its quality, the FACTOR project set up an experimental test infrastructure using most advanced measurement techniques, which have been adapted to FACTORs specific requirements.

This unique test infrastructure involves two complementary European turbine test rigs:
- A new continuous flow facility hosted by DLR (Deutsches Zentrum für Luft- und Raumfahrt).
- A complementary blow-down turbine facility hosted by Oxford University (the Oxford-Turbine Research Facility O-TRF)

The continuous flow facility is fed by hot and cold air -as in an aero engine-, this module will supply realistic flow field to the downstream HPT and thus enable experimentalists and their numerical counterpart to explore the aerodynamic and thermal interactions between combustor and turbine.

The latter rig facility will be used to supplement the analysis of the DLR continuous flow test rig.

WP6, which coordinates the synthesis of experiments and computations, is structured in four main tasks each associated with a respective deliverable.

- Task/Deliverable D6.1: Database definition, set-up and maintenance
- Task/Deliverable D6.2: Conduct Pre-Test CFD (aid the rig design process including instrumentation support)
- Task/Deliverable D6.3: Conduct Post-Test CFD (involves all CFD based on experimentally obtained rig boundary conditions in order to validate numerical methods applied)
- Task/Deliverable D6.4: Derive best practice guidelines on modelling combustor-turbine interaction phenomena and related features

During the first month into the FACTOR project WP6 focused onto setting up the required infrastructure for large amounts of Data associated with Computational Fluid Dynamics (CFD). During the first reporting period of the FACTOR program a CFD-database was defined, setup and tested. This database covering Task 6.1 is an important tool to the consortium partners to share and collect information regarding the geometry, meshes, boundary conditions as well as the generated numerical and experimental results. Post project start, the consortium partners decided as a consequence of the size limitation of the FACTOR general website to create the database as a separate web-based one, that can be accessed from any Web browser connected to the internet. Thus, the sufficient storage of experimental and numerical results and its fast and platform-independent transfer could be ensured even before the exchange of pre-test CFD data was requested. On the other hand, this change management following the stated size limitations caused a 2-month delay compared to the originally planned Description of Work (DoW). The CFD-database has a capacity of 3TB and is accessible to all FACTOR partners to ensure the exchange of data such as stated above. Its physical location is at IMP PAN, since this consortium partner additionally volunteered to realise the maintenance of this database during the project runtime and until one year past the project end.

Furthermore, WP6 quickly assumed its role to aid the design process by taking over work packages within the realm of Task 6.2 (Pre-Test CFD). While during the first reporting period predominately the design of the combustor simulator has been supported, further work of pre-test CFD covered parts of the HPT components, the Secondary Air System of the rig, the full 1.5 Stage HPT aerothermal design, supporting calculations for the thermo-mechanical model of the rig, etc. These computational models are described in the periodic reports of the project as “Meta-models”. Especially during the 2nd reporting period, significant results have been achieved by the WP6 partners towards the final design of the rig by aiding it with CFDs performed. Even more important, the work carried out by CERFACS (LES-simulations), was already a first step towards scientifically contributions of the FACTOR project in the field of Combustor-Turbine-Interaction. Moreover, it was an early contribution to the final Tasks 6.3 and 6.4, since it is necessary to validate the RANS methodology with LES, while URANS/RANS can be considered as a state-of-the-art industrial approach. During the 2nd reporting period WP6 delivered multiple 3D-CFD models of the 1.5 Stage HPT including one fully featured (incl. all cooling and sealing flows) as a part of WP3. Nevertheless, not all objectives planned of the 2nd reporting period could be achieved on time. With respect to the Description of Work (DoW), the scientifically related Task 6.3 and 6.4 should have started at M36 to enable both tasks to be finished at M48. This target could not be achieved, since the design of the FACTOR rig already faced a significant delay which manifested in missing rig measurement data for all downstream related tasks. Especially Task 6.3 as well as Task 6.4 relies to 100% on the availability of measurement data, which requires the commissioning of the FACTOR rig prior to its start.

This situation triggered the request for a project extension, which has already been discussed during M30 and M36 Meetings and is explained from WP6 in the respective periodic reports.

During the 3rd and 4th reporting period the massive delay of the FACTOR project forced WP6 to alter the initially planned Post-Test CFD work, such that some of the future planned work was shifted in the presence. While initially 12-Month (post-test) of work have been planned for Tasks 6.3 and Task 6.4, WP6 now prepared to do most of the CFD work in parallel with the upcoming measurement campaign of WP4.

This required the WP6 Partners to start setting up their 3D-CFD Models prior to test, in order to allow a parallel start with the measurements immediately at the beginning of the 5th reporting period. In a first step, a common CFD geometry based on the final rig geometry has been generated and distributed to all WP6 partners at the end of the 3rd reporting period. This geometry enabled all partners to choose their respective domain or domain-combination of choice, depending on which component of the rig they are focused on.  A schematic drawing of the 18deg sector FACTOR Rig CAD Model of post-test CFD is shown in Figure 46.

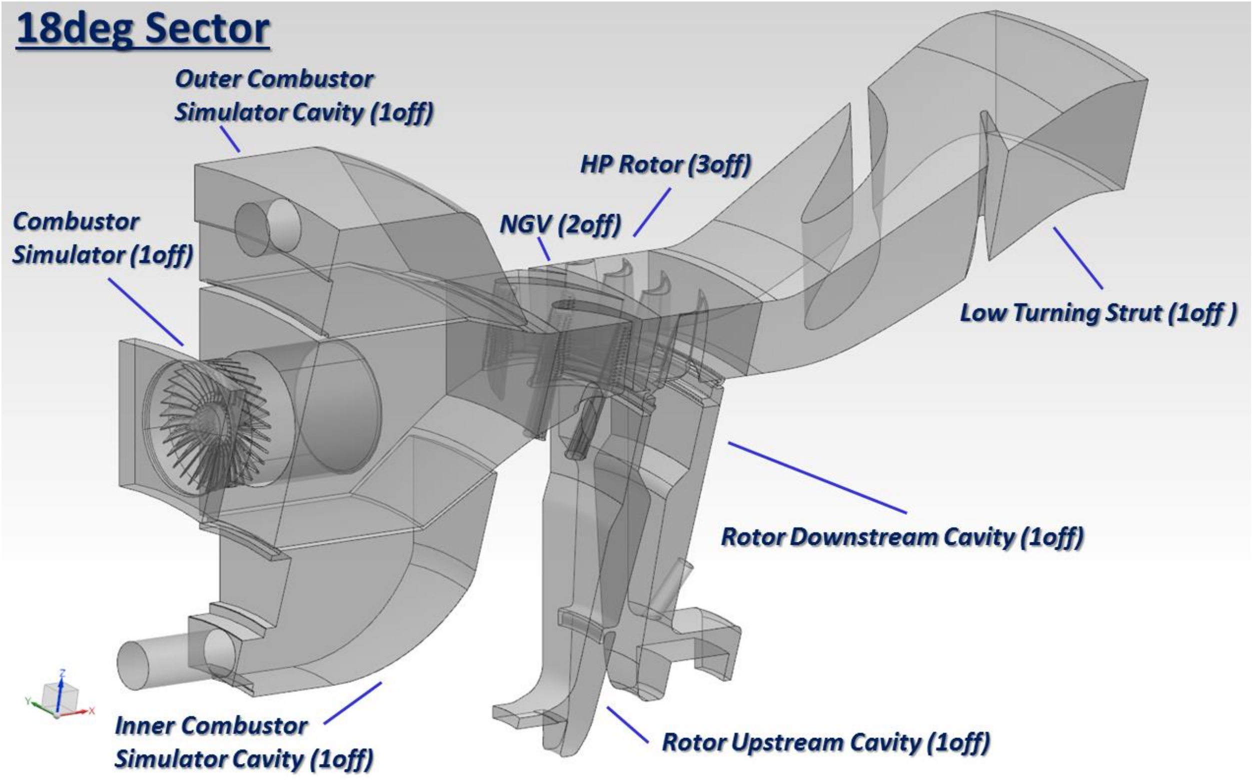


**Figure 50: Schematic drawing of the 18deg sector FACTOR Rig CAD Model for post-test CFD**

In a second step a CFD strategy has been worked out by WP6, detailing the roadmap from Task 6.3 (Post-Test CFD) to the derivation of guidelines for combustor / turbine interaction (Task 6.4). Based on this roadmap a five key-study has been identified, which allow to work out the required guidelines. The respective five key studies are listed below.

| Study # | WP6 partners involved | Focus of investigation |
|---|---|---|
| **1** | MTU, TM, SIT,RRD | Comparisons of Traverse prediction (Plane40) and adiabatic wall temperatures (NGV) between different Simulation Types |
| **2.1** | IMP-PAN | Comparisons of Traverse prediction between Domain Types: CS incl. NGV vs. CS w/o NGV |
| **2.2** | TM, CERFACS | Comparisons of Traverse prediction and hot spot migration between Domain Types: CS incl. 1st Stage vs. 1st Stage w/o CS |
| **3** | GE Avio, RRUK | Comparisons of Traverse prediction and hot spot migration through the 1.5 Stage HPT between different turbulence models |
| **4** | IMP-PAN | Comparison of Cooling Hole Modelling - Generalized BC vs. explicitly modelled holes on Combustor Liner and NGV Cooling |
| **5** | SIT,MTU | Cavity Modelling (simplified or full cavity modelling w.r.t. upstream, and downstream effects |

| **Table 1** |
|---|

In addition, three more studies are carried out to capture the effect of clocking on the two downstream blade rows of the NGV (HP Blade and LPNGV) and to compare the Through Flow Model solution to the CFD.

| **Study #** | **WP6 partners involved** | **Focus of investigation** |
|---|---|---|
| **1** | GKN | CS Clocking Effect on LPNGV |
| **2** | SN | CS Clocking Effects on Rotor 1 |
| **3** | ITP | Comparison of Through Flow Model vs. CFD |
| **Table 2** | | |

Unfortunately, the overall project delay and additional technical issues during commissioning of the FACTOR rig prevented the availability of post-test CFD at the time the project officially ended. However, while the measurement data is still being acquired and the present report is written, WP6 partners are working on post-test CFD required for the studies listed in Table 1 and Table 2.

Even though, the final Deliverable 6.4 (Derive best practice guidelines on modelling combustor-turbine interaction phenomena and related features) has not acquired a state of final knowledge, WP6 can give a detailed overview, which phenomena are under investigation and consequently will be fed into the best practice guidelines on modelling combustor-turbine interaction.

Task 6.4 will clarify, which is the best practice simulation type (RANS, URANS, SAS, LES, etc.) in order to predict the combustor outlet profile at Plane 40. Differences w.r.t. the measurement will be assessed and linked to respective simulation type capabilities. It is intended to give a clear recommendation, which features/phenomena of the flow can be sufficiently captured at what cost (numerical resources and time) in order to classify the different simulation types for practice.

Moreover Task 6.4, investigates the effect of the downstream NGV on the traverse prediction at Plane 40. It is well know, that the potential field of the NGV does have an upstream effect on the combustor flow field thus introducing a difference compared to the case without the downstream NGVs. Even though, in most practical applications this effect can be neglected (as it is current State of the Art in industrial applications), in remains to be investigated, how the upstream effect of the NGVs influences the lean burn characteristic features of the traverse. This valuable knowledge is addressed in post-test CFD of Task6.3 and will subsequently be fed into the guidelines of Task 6.4. In addition and depending on the outcome of these investigations, Task 6.4 might suggest a new method of handling the interface of combustor and turbine w.r.t. the upstream effects of the NGV.

Hot Spot Migration through the 1st Stage of the rig is another big topic addressed in Task6.4. Depending on the Domain type (whether the combustor simulator is included or not) of simulation, a different behaviour of hot-spot migration might be expected. The underlying physics are explained by differences in capturing of the mixing process. This becomes clear by recalling, that the mixing of hot and cold air is initiated in the Combustor Simulator. However, by starting the CFD Domain at Plane 40, all information about the history of the turbulent mixing process is lost, which can significantly affect the behaviour of the turbulent quantities of the flow downstream this plane leading to a different prediction of hot spot migration.

In this realm the effect of different turbulence models on the hot spot migration through the three blade rows is also assessed. This will lead to a recommendation of WP6, which turbulence Model shall be used for different aspects for Hot Spot Migration in order to give the best solution.

Another aspect of combustor turbine interaction guidelines targets the use of simplified boundary conditions, such as generalised boundary condition / source terms for cooling flows and simplified geometries for rim seal leakage flows. Such approaches can significantly reduce the resources required for a given CFD investigation. However, the large degree of simplification on the one hand and the physical/numerical influence of these simplified flows on the main flow on the other hand can impact the solution of a given problem significantly. Therefore, especially the source term approach for cooling holes is assessed w.r.t. the combustor liner cooling and traverses prediction. Since this approach has sometimes been suspected in the past of unphysically altering the main gas flow, this technique shall be investigated w.r.t. combustor turbine interaction.

Furthermore, it is very common in turbomachinery industry to simplify the rim seal cavity flows by reducing the cavity geometry to the very closest annulus features. However, saving the resources for the whole lower part of the cavity also reduces details of the flow, which might be insufficient – especially in annulus flows, which are dominated by a high amount of residual combustor swirl.

In the realm of Turbomachinery the term ‘Clocking’ is generally understood as the circumferential displacement of a blade row with respect to another component (blade row or combustor). The FACTOR rig is capable of realising the two most common clocking positions of the combustor relative to the NGV leading edge. Both measurement series will provide data to compare numerical solutions capturing the effects of this Combustor Simulator (CS) clocking on the all three blade rows. While the effect is most pronounced between CS and the NGV, which is already captured with the investigations focusing the traverse predictions, the two downstream blade rows (Blade and Low Pressure Nozzel Guide Vane) are subject of two separate studies. Those will detail the effect of clocking on the respective component and give recommendations on the respective numerical modelling.

# Work Package 7 – Dissemination and exploitation

## Work Packages Objectives

The objectives for the work package were as follows:

- To ensure the uptake of project results in a large range of “appropriate” applications
- To identify necessary work to further develop the technology.
- To disseminate appropriate information into the design cycle to realise the technology benefits on production engines.
- To communicate to the wider world appropriate information on the technology generated (with the benefits) that this EU supported research has created.
- To disseminate knowledge within the member companies.

To achieve these objectives 3 tasks were defined in the Description Of Work (DOW) for the programme, these are summarised below, with the activities undertaken to address them:

### Task 7.1 – Dissemination of Selected Information

Disseminate information outside the consortium. In order to communicate efficiently with the project partners and the scientific and business community, the following actions will be undertaken :

- Dissemination of technical performance and results through papers in technical reviews, specialised press and web pages, without revealing sensitive information.
- Communication with existing clusters like the turbo machinery cluster that will help identify areas where complementary technology from on-going projects can be exploited alongside the results from FACTOR project.

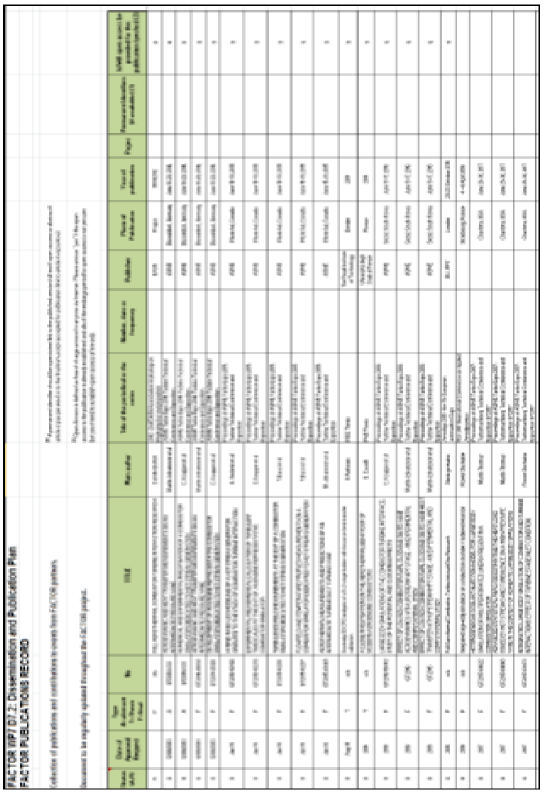
These are the prime vehicles for dissemination of knowledge within the academic and industrial research community. Papers will be encouraged from all engineers involved in the programme. This will raise awareness among a greater community and encourage the use of the technology within other industry sectors.

Technical forums will be sought to publicise the programme and encourage take-up of the programme results.

Realisation

A activities of tasks was undertaken in support of this task. Firstly, a public website was created with the support of the management team to be the internet presence of the project, its role would be provide a worldwide means of communication & information resource for the project to a scientific and technical audience as well as the general public.

Secondly, a publications tracker and database was created as a resource for the consortium members and technical parties, at the end of the project the 20 refereed papers had been produced. The tracker is shown below.

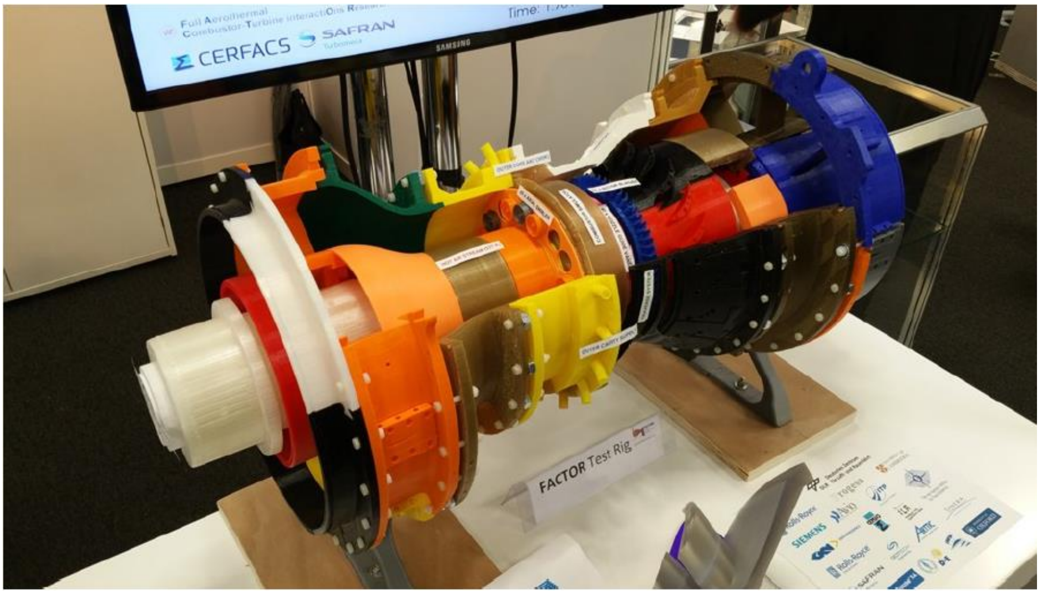


FACTOR WP7 D7.2: Dissemination and Publication Plan
FACTOR PUBLICATIONS RECORD

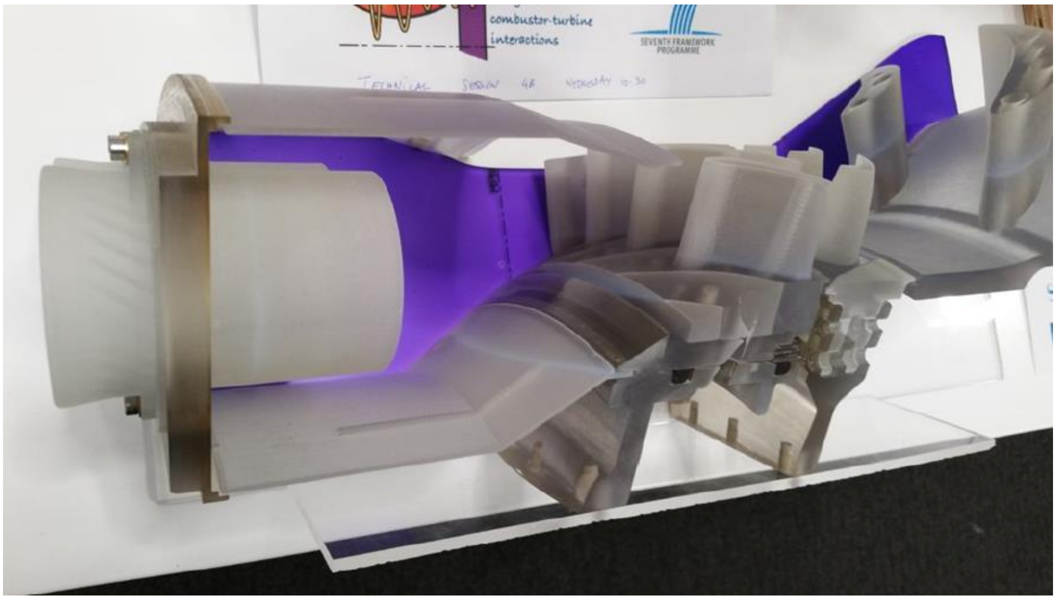
Image of the publication tracker

Thirdly, as part of the dissemination work package a team {A.Germain (SAFRAN), C.Koupper (SAFRAN HE), M.Stokes (RRUK)}, from the FACTOR project supported the 7th European Aeronautics Days 2015. This event was held in London on the 20-23 October 2015.

The team exhibited scale models and printed materials on an exhibition display promoting the project during the event, the models are shown below.



Whole Rig model displayed at AERODAYS



Working Section Model displayed at AERODAYS

A.Germain gave a presentation on ‘Combustor-Turbine Interaction Research - FACTOR’ in the session on ‘Competitiveness in the Aviation Industry’, describing the project which was well received.

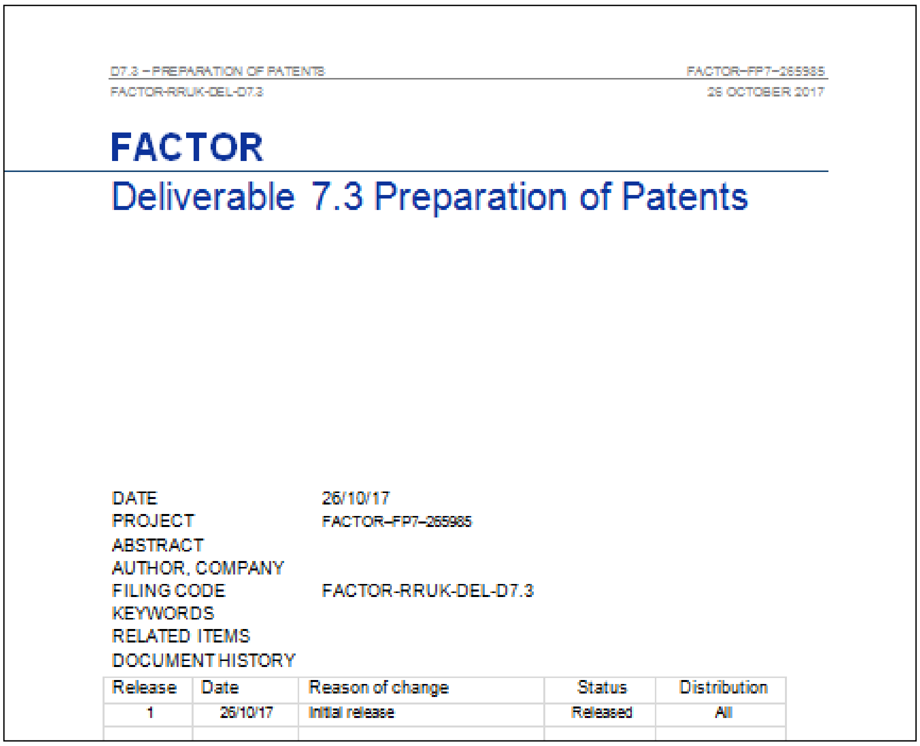
### Task 7.2 – Preparatory measures for patent deposition

Monitor main FACTOR results in order to identify new innovative components, prototypes or modules and tools for patent. Innovation reporting will be established in order to inform partners about the new innovative elements. Benchmarking studies have to be foreseen. The General Assembly will be responsible for assessing innovative elements to protect. The IP departments of partner organisations will be involved in this task in order to negotiate property rights and patent costs according to the consortium agreement signed at the beginning of the project.

Address any IPR issue connected to the exploitation of the project results: licensing, further developments, etc.

Realisation

The patent application process was monitored using the same spreadsheet system as for technical publications. The potential for patent generation within the project was limited by the focus of the project. This being CFD validation and experimental data gathering. Whilst both activities were performed using state of the art techniques this does not necessarily yield new patents. This issue is explored in detail in ‘D7.3 Preparation of Patents’, shown below.



D7.3 – PREPARATION OF PATENTS
FACTOR-RRUK-DEL-D7.3
FACTOR-FP7-265985
26 OCTOBER 2017

**FACTOR**

Deliverable 7.3 Preparation of Patents

| | |
|---|---|
| DATE | 26/10/17 |
| PROJECT | FACTOR–FP7–265985 |
| ABSTRACT | |
| AUTHOR, COMPANY | |
| FILING CODE | FACTOR-RRUK-DEL-D7.3 |
| KEYWORDS | |
| RELATED ITEMS | |
| DOCUMENT HISTORY | |

| Release | Date | Reason of change | Status | Distribution |
|---|---|---|---|---|
| 1 | 26/10/17 | Initial release | Released | All |
| | | | | |

### Task 7.3 – Exploitation plan

Undertake the required steps to produce an Exploitation Plan with the cooperation of all partners to move the FACTOR technology to higher TRLs. The Exploitation Plan will encompass the following activities:

- Helping plan and implement exploitation with partners
- Demonstrating the benefits of the research
- Documenting the ownership of results
- Publishing the results

Prepare the Exploitation Plan, as part of the mid-term assessment, each work package will identify where the technology that has been generated can be used, with timescales and any possible applications. This will be recorded in a report/plan. It will be re-assessed at the end of the project and the report/plan formally issued

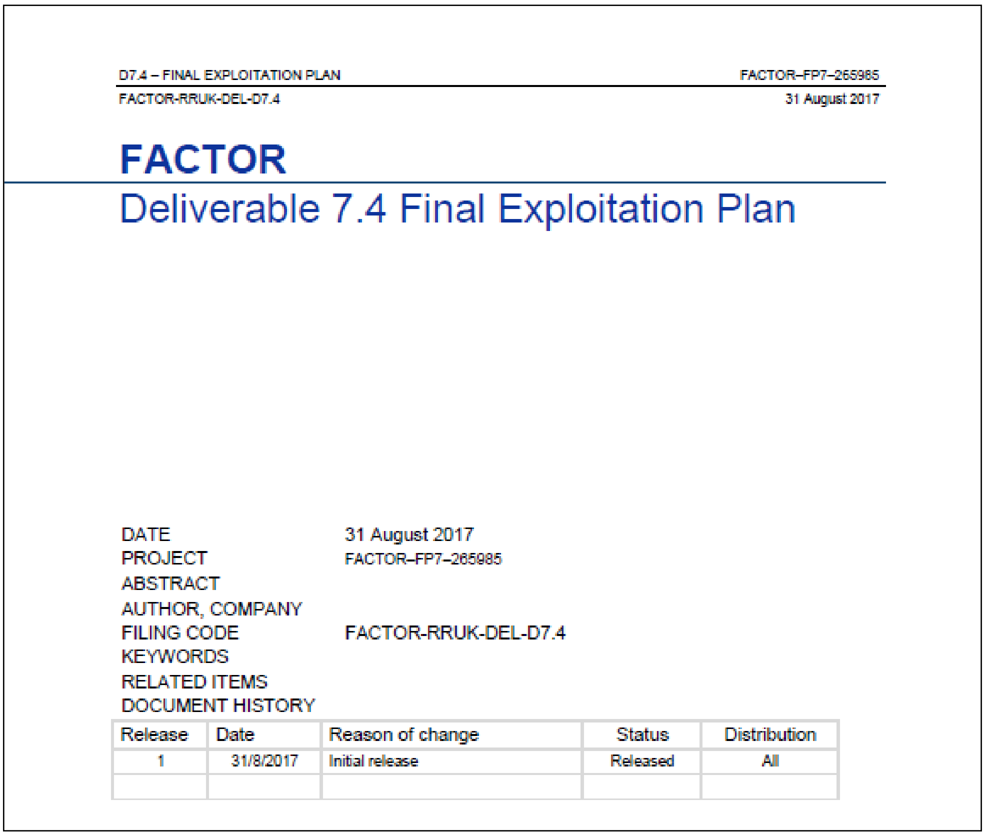
Develop technology transfer plans with CLEAN SKY SAGE ITD: as part of the exploitation, contribute whenever possible to the design of the five SAGE engine platforms

Realisation

Deliverable ‘D7.4 Final Exploitation Plan’ gives a comprehensive review of how the data generated in the project is to be used by the individual consortium members to improve their processes. It is in this way that the aerospace community represented by the consortium members will benefit from the programme.

These improvements will help to increase the competitiveness of the individual members to the benefit of the EU.

Evidence of the increased understanding from the programme are seen in the review of all 20 refereed technical publications within the report. The material covers various subject areas from advanced CFD modelling to fundamental aspects of heat transfer.



D7.4 – FINAL EXPLOITATION PLAN FACTOR–FP7–265985
FACTOR-RRUK-DEL-D7.4 31 August 2017

**FACTOR**

Deliverable 7.4 Final Exploitation Plan

DATE 31 August 2017
PROJECT FACTOR–FP7–265985
ABSTRACT
AUTHOR, COMPANY
FILING CODE FACTOR-RRUK-DEL-D7.4
KEYWORDS
RELATED ITEMS
DOCUMENT HISTORY

| Release | Date | Reason of change | Status | Distribution |
|---|---|---|---|---|
| 1 | 31/8/2017 | Initial release | Released | All |
| | | | | |

Front Sheet for the Final Exploitation Plan

# Work Package 8 – Management

During the project the management has been adapted to better fit the partners needs and to be able to manage issues and risks.

At each step, weekly task force meeting has been scheduled to create an exchange area with all required partners:

- During the design phase these weekly task forces were dedicated to the WP1 and WP3 partners.
- During the manufacturing phase, weekly phone call has been organised with PROGESA to follow the manufacturing process and to be sure that the milestones are fulfilled, and the parts are compliant with partners requirements.
- The assembly and commissioning phase weekly task-force were focused on DLR work to help them solving issues with the Interturb rig.
- Before the start of the campaign and all along the tests, weekly task force has been focused on coordination for the test campaign and first analysis of the test results.

Specialists meeting have also been scheduled during the design phase in order to accelerate the design process and to exchange on the design interfaces.

Consortium meetings have been also scheduled to keep the consortium as a real project team and to follow project

# Potential impact

## Competitiveness & Innovation

The majority of the anthropogenic CO2 emissions stem from power generation, heavy industries and transport. European power companies and their suppliers are among the most efficient in the world. Considerable RTD efforts are ongoing in the areas of developing the energy systems of the future: clean power generation, transport systems, fuels cells, hydrogen production etc. The FACTOR project is one of the contributing projects focusing on lean burn combustion, one of the most promising next generation efficient combustion concepts. More detailed the FACTOR project targets the optimisation of combustor-HP turbine interaction design. This is achieved through a better understanding of the interaction between the coolant system, the transport (secondary flows) and mixing mechanisms enabling an SFC reduction of about 2.0%. Indeed, the optimization of the coolant mass-flows will allow more of the core-flows to pass through the combustor of a stationary gas turbine or a flying aircraft engine. The purpose of the post-test CFD carried out in WP6 is run computational analysis using the boundary conditions measured on the Goettingen FACTOR- rig in WP4 and compare the numerical results to the measured data. These comparisons are invaluable for the European turbomachinery community, especially the industrial partners, since the direct comparison between numerical predictions and measured data allow the derivation of practical guidelines on how to model the phenomena of combustor-HP Turbine interaction. Moreover, these comparisons give valuable insights on the behavior of numerical codes w.r.t. a lean burn characteristic flow, and enables code developers of CFD prediction methods to adjust their tools on future combustor-turbine concepts. In General, the FACTOR WP6 work served to increase the current knowledge on the physics of combustor-turbine interaction. The comparisons provided additional insights into the accuracy of the various numerical approaches and codes.

## European Added-value

The FACTOR project would not have been possible to carry out in the national sphere. It is a project resulting from the joint European policies on Climate Change, and the subsequent joint EU Kyoto commitment of reducing average EU greenhouse gasses by 8%. The FACTOR project directly addressed one of the main institutional issues of the ACARE SRA related to the development of research infrastructure objectives. In fact, the FACTOR project aimed at upgrading an existing facility to gather engine manufactures and academic partners from turbo-machinery and combustion expertise fields around a new unique experimental test infrastructure. WP6 consisted of twelve European partners from eleven different nations - truly Trans-European, bringing together relevant skills, national data, and other competencies (e.g. cooperative and human skills). Due to this, numerous scientific papers –grown in WP6– have been presented internationally.

Furthermore, the FACTOR project addressed two of the six activities fixed in the ACARE Strategic Research Agenda summarized in the work programme 2010:

- Greening of Air Transport
- Improving cost efficiency

# Address of the project public website

The FACTOR public website is www.factor-fp7.eu

Below is the list of the Beneficiaries:

| Partner number | Partner name | Partner short name | Contact person | Email |
|---|---|---|---|---|
| P1 | SAFRAN AIRCRAFT ENGINES | SAFRAN AE | Jerome Dagruma | jerome.dagruma@snecma.fr |
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|---|---|---|---|---|
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| P18 | THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY<br>OF OXFORD | UOXF | Gill Wells | ecresearch@admin.ox.ac.uk |
| P19 | GKN AEROSPACE SWEDEN | GKN | Robert Lundberg | robert.lundberg@gknaerospace.com |
| P20 | INSTITUT VON KARMAN DE DYNAMIQUE DES FLUIDES | VKI | Bernard Schaballie | bernard.schaballie@vki.ac.be |
| P21 | PRATT & WHITNEY RZESZOW SPOLKA AKCYJNA | PWR | Pawel Winiarz | pawel.winiarz@wskrz.com |
| P22 | ARTTIC | ART | Martin Dietz | dietz@arttic.eu |
| P23 | GE AVIO | GE AVIO | Massimo Negro | massimo.negro@avioaero.com |

# 2. Use and dissemination of foreground

# Section A (public)

## TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

| No | TITLE | Main author | Title of the periodical or the series | No, date | Publisher | Place of Publication | Year of publication |
|---|---|---|---|---|---|---|---|
| 1 | FULL AEROTHERMAL COMBUSTOR TURBINE INTERACTION RESEARCH | Camille Battisti | 2012 - 2nd EASN Association Workshop on Flight physics and propulsion | | EASN | Prague | 31/10/2012 |
| 2 | AERODYNAMIC AND HEAT TRANSFER MEASUREMENTS ON AN INTERMEDIATE PRESSURE VANE | Martin Johansson et al | ASME Turbo Expo 2014: Turbine Technical Conference and Exposition | | ASME | Düsseldorf, Germany | June 16-20, 2014, |
| 3 | NUMERICAL AND EXPERIMENTAL INVESTIGATION OF A COMBUSTOR SIMULATOR DEDICATED TO HOT STREAK GENERATION | C. Koupper et al | ASME Turbo Expo 2014: Turbine Technical Conference and Exposition | | ASME | Düsseldorf, Germany | June 16-20, 2014, |
| 4 | AERODYNAMIC AND HEAT TRANSFER MEASUREMENTS ON AN INTERMEDIATE PRESSURE VANE | Martin Johansson et al | ASME Turbo Expo 2014: Turbine Technical Conference and Exposition | | ASME | Düsseldorf, Germany | June 16-20, 2014, |
| 5 | DEVELOPMENT OF AN ENGINE REPRESENTATIVE COMBUSTOR SIMULATOR DEDICATED TO HOT STREAK GENERATION | C. Koupper et al | ASME Turbo Expo 2014: Turbine Technical Conference and Exposition | | ASME | Düsseldorf, Germany | June 16-20, 2014, |
| 6 | HYBRID RANS-LES MODELING OF A HOT STREAK GENERATOR ORIENTED TO THE STUDY OF COMBUSTOR-TURBINE INTERACTION | A. Andreini et al | Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition | | ASME | Montréal, Canada | June 15–19, 2015 |
| 7 | EXPERIMENTAL AND NUMERICAL CALCULATION OF TURBULENT TIMESCALES AT THE EXIT OF AN ENGINE REPRESENTATIVE COMBUSTOR SIMULATOR | C.Koupper et al | Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition | | ASME | Montréal, Canada | June 15–19, 2015 |
| 8 | TURBULENCE FIELD MEASUREMENTS AT THE EXIT OF A COMBUSTOR SIMULATOR DEDICATED TO HOT STREAKS GENERATION | T.Bacci et al | Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition | | ASME | Montréal, Canada | June 15–19, 2015 |
| 9 | FLOWFIELD AND TEMPERATURE PROFILES MEASUREMENTS ON A COMBUSTOR SIMULATOR DEDICATED TO HOT STREAKS GENERATION | T.Bacci et al | Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition | | ASME | Montréal, Canada | June 15–19, 2015 |
| 10 | AEROTHERMAL MEASUREMENTS AND PREDICTIONS OF AN INTERMEDIATE TURBINE DUCT TURNING VANE | M. Johansson et al | Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition | | ASME | Montréal, Canada | June 15–19, 2015 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 11 | Unsteady 3D CFD analysis of a 11=2-stage turbine with focus on heat transfer validation | A.Axelsson | MSC Thesis | | The Royal Institute of Technology | Sweden | 2014 |
| 12 | A CLOSE INVESTIGATION ON THE AEROTHERMAL BEHAVIOUR OF MODERN AEROENGINE COMBUSTORS | G. Caciolli | PhD Thesis | | Università degli Studi di Firenze | Firenze | 2014 |
| 13 | LARGE EDDY SIMULATIONS OF THE COMBUSTOR TURBINE INTERFACE: STUDY OF THE POTENTIAL AND CLOCKING EFFECTS | C. Koupper et al | Proceedings of ASME Turbo Expo 2016: Turbine Technical Conference and Exposition | | ASME | Seoul, South Korea | June 13-17, 2016 |
| 14 | EFFECT OF LOW-NOX COMBUSTOR SWIRL CLOCKING ON ITD VANE AERODYNAMICS WITH UPSTREAM HPT STAGE - AN EXPERIMENTAL AND COMPUTATIONAL STUDY | Martin Johansson et al | Proceedings of ASME Turbo Expo 2016: Turbine Technical Conference and Exposition | | ASME | Seoul, South Korea | June 13-17, 2016 |
| 15 | EFFECT OF LOW-NOX COMBUSTOR SWIRL CLOCKING ON ITD VANE HEAT TRANSFER WITH UPSTREAM HPT STAGE - AN EXPERIMENTAL AND COMPUTATIONAL STUDY | Martin Johansson et al | Proceedings of ASME Turbo Expo 2016: Turbine Technical Conference and Exposition | | ASME | Seoul, South Korea | June 13-17, 2016 |
| 16 | Full Aerothermal Combustor-Turbine interactiOns Research | Alexis germaine | Aerodays 2015 - the 7th European aeronautics Days | | EU - FP7 | London | 20-23 October 2015 |
| 17 | Integrated large eddy simulation of combustion chamber / turbine interaction | Florent Duchaine | 51st 3AF International Conference on Applied Aerodynamics | | | Strasbourg, France | 4 – 6 April 2016 |
| 18 | HETEROGENEOUS COOLANT INJECTION MODEL FOR LARGE EDDY SIMULATION OF MULTIPERFORATED LINERS PRESENT IN A COMBUSTION SIMULATOR | Martin Thomas | Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition GT2017 | | | Charlotte, USA | June 26-30, 2017 |
| 19 | ADVANCED STATISTICAL ANALYSIS ESTIMATING THE HEAT LOAD ISSUED BY HOT STREAKS AND TURBULENCE ON A HIGH-PRESSURE VANE IN THE CONTEXT OF ADIABATIC LARGE EDDY SIMULATIONS | Martin Thomas | Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition GT2017 | | | Charlotte, USA | June 26-30, 2017 |
| 20 | INTEGRATED LARGE EDDY SIMULATION OF COMBUSTOR AND TURBINE INTERACTIONS: EFFECT OF TURBINE STAGE INLET CONDITION | Florent Duchaine | Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition GT2017 | | | Charlotte, USA | June 26-30, 2017 |

**TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES**

| No | Type of activities | Main leader | Title | Date | Place | Type of audience | Additional type of audience | Size of audience | Countries addressed |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Presentation | Camille Battisti | 2012 - 2nd EASN Association Workshop on Flight physics and propulsion | 31/10/2012 | Prague | Industrial | | | |
| 2 | Exhibition / Presentations | Dr M.R..Stokes | 7th European Aeronautics Days 2015. | 20-23 October 2015 | London | Industrial | Technical | 1000 | Global |

# Section B (Confidential or public: confidential information to be marked clearly)

## Part B1

### TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.

| Type of IP Rights[1]: | Confidential Click on YES/NO | Foreseen embargo date dd/mm/yyyy | Application reference(s) (e.g. EP123456) | Subject or title of application | Applicant (s) (as on the application) |
|---|---|---|---|---|---|
| | | | | | |

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[1] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

## Part B2

Please complete the table hereafter:

| Type of Exploitable Foreground[2] | Description of exploitable foreground | Confidential Click on YES/NO | Foreseen embargo date dd/mm/yyyy | Exploitable product(s) or measure(s) | Sector(s) of application[3] | Timetable, commercial or any other use | Patents or other IPR exploitation (licences) | Owner & Other Beneficiary(s) involved |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |

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[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[3] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

# 3. Report on societal implications

## A General Information *(completed automatically when **Grant Agreement number** is entered.*

| | |
|---|---|
| **Grant Agreement Number:** | 265985 |
| **Title of Project:** | Full Aero-thermal Combustor-Turbine interactiOn Research (FACTOR) |
| **Name and Title of Coordinator:** | Matthieu Chevrier |

## B Ethics

| | |
|---|---|
| **1. Did your project undergo an Ethics Review (and/or Screening)?**<br>• If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports?<br>Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'* | ***0Yes 0No*** |
| **2. Please indicate whether your project involved any of the following issues (tick box) :** | ***YES*** |
| **RESEARCH ON HUMANS** | |
| • Did the project involve children? | No |
| • Did the project involve patients? | No |
| • Did the project involve persons not able to give consent? | No |
| • Did the project involve adult healthy volunteers? | No |
| • Did the project involve Human genetic material? | No |
| • Did the project involve Human biological samples? | No |
| • Did the project involve Human data collection? | No |
| **RESEARCH ON HUMAN EMBRYO/FOETUS** | |
| • Did the project involve Human Embryos? | No |
| • Did the project involve Human Foetal Tissue / Cells? | No |
| • Did the project involve Human Embryonic Stem Cells (hESCs)? | No |
| • Did the project on human Embryonic Stem Cells involve cells in culture? | No |
| • Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos? | No |
| **PRIVACY** | |
| • Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)? | No |
| • Did the project involve tracking the location or observation of people? | No |

| | |
|---|---|
| **RESEARCH ON ANIMALS** | |
| - Did the project involve research on animals? | No |
| - Were those animals transgenic small laboratory animals? | No |
| - Were those animals transgenic farm animals? | No |
| - Were those animals cloned farm animals? | No |
| - Were those animals non-human primates? | No |
| **RESEARCH INVOLVING DEVELOPING COUNTRIES** | |
| - Did the project involve the use of local resources (genetic, animal, plant etc)? | No |
| - Was the project of benefit to local community (capacity building, access to healthcare, education etc)? | No |
| **DUAL USE** | |
| - Research having direct military use | No |
| - Research having the potential for terrorist abuse | No |

## C Workforce Statistics

### 3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

| Type of Position | Number of Women | Number of Men |
|---|---|---|
| Scientific Coordinator | | |
| Work package leaders | | |
| Experienced researchers (i.e. PhD holders) | | |
| PhD Students | | |
| Other | | |

| | |
|---|---|
| **4. How many additional researchers (in companies and universities) were recruited specifically for this project?** | |
| Of which, indicate the number of men: | |

## D Gender Aspects

|  |  |  |
|---|---|---|
| **5. Did you carry out specific Gender Equality Actions under the project?** | ○<br>● | Yes<br>No |

**6. Which of the following actions did you carry out and how effective were they?**

|  |  | **Not at all effective** … **Very effective** |
|---|---|---|
| ☐ | Design and implement an equal opportunity policy | ○ ○ ○ ○ ○ |
| ☐ | Set targets to achieve a gender balance in the workforce | ○ ○ ○ ○ ○ |
| ☐ | Organise conferences and workshops on gender | ○ ○ ○ ○ ○ |
| ☐ | Actions to improve work-life balance | ○ ○ ○ ○ ○ |
| ○ | Other: |  |

**7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?**

○ Yes- please specify

● No

## E Synergies with Science Education

**8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?**

○ Yes- please specify

● No

**9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?**

○ Yes- please specify

● No

## F Interdisciplinarity

**10. Which disciplines (see list below) are involved in your project?**

○ Main discipline[4]:

○ Associated discipline[4]:

○ Associated discipline[4]:

## G Engaging with Civil society and policy makers

|  |  |  |
|---|---|---|
| **11a Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)* | ○<br>● | Yes<br>No |

**11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?**

○ No
○ Yes- in determining what research should be performed
○ Yes - in implementing the research
○ Yes, in communicating /disseminating / using the results of the project

| | | |
|---|---|---|
| **11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?** | ○<br>○ | Yes<br>No |

**12. Did you engage with government / public bodies or policy makers (including international organisations)**

○ No
○ Yes- in framing the research agenda
○ Yes - in implementing the research agenda
○ Yes, in communicating /disseminating / using the results of the project

**13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?**

○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
○ No

**13b If Yes, in which fields?**

| | | | | | |
|---|---|---|---|---|---|
| Agriculture<br>Audiovisual and Media<br>Budget<br>Competition<br>Consumers<br>Culture<br>Customs<br>Development Economic and Monetary Affairs<br>Education, Training, Youth<br>Employment and Social Affairs | | Energy<br>Enlargement<br>Enterprise<br>Environment<br>External Relations<br>External Trade<br>Fisheries and Maritime Affairs<br>Food Safety<br>Foreign and Security Policy<br>Fraud<br>Humanitarian aid | | Human rights<br>Information Society<br>Institutional affairs<br>Internal Market<br>Justice, freedom and security<br>Public Health<br>Regional Policy<br>Research and Innovation<br>Space<br>Taxation<br>Transport | |

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[4] Insert number from list below (Frascati Manual).

**13c If Yes, at which level?**

○ Local / regional levels
○ National level
○ European level
○ International level

## H Use and dissemination

| | |
|---|---|
| **14. How many Articles were published/accepted for publication in peer-reviewed journals?** | **20** |
| **To how many of these is open access[5] provided?** | |
| **How many of these are published in open access journals?** | |
| **How many of these are published in open repositories?** | |
| **To how many of these is open access not provided?** | |
| **Please check all applicable reasons for not providing open access:** | |
| ☐ publisher's licensing agreement would not permit publishing in a repository<br>☐ no suitable repository available<br>☐ no suitable open access journal available<br>☐ no funds available to publish in an open access journal<br>☐ lack of time and resources<br>☐ lack of information on open access<br>☐ other[6]: …………… | |

| | | |
|---|---|---|
| **15. How many new patent applications ('priority filings') have been made?** *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).* | | **0** |
| **16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).** | Trademark | **0** |
| | Registered design | **0** |
| | Other | **0** |
| **17. How many spin-off companies were created / are planned as a direct result of the project?** | | **0** |
| ***Indicate the approximate number of additional jobs in these companies:*** | | |

**18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:**

| | |
|---|---|
| ☐ Increase in employment, or | ☐ In small & medium-sized enterprises |
| ☐ Safeguard employment, or | ☐ In large companies |
| ☐ Decrease in employment, | ■ None of the above / not relevant to the project |
| ■ Difficult to estimate / not possible to quantify | |

| | |
|---|---|
| **19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:** | *Indicate figure:* |
| Difficult to estimate / not possible to quantify | ■ |

## I Media and Communication to the general public

**20. As part of the project, were any of the beneficiaries professionals in communication or media relations?**

○ Yes ● No

**21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?**

○ Yes ● No

**22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?**

☐ Press Release
☐ Media briefing
☐ TV coverage / report
☐ Radio coverage / report
☐ Brochures /posters / flyers
☐ DVD /Film /Multimedia
■ Coverage in specialist press
☐ Coverage in general (non-specialist) press
☐ Coverage in national press
☐ Coverage in international press
☐ Website for the general public / internet
☐ Event targeting general public (festival, conference, exhibition, science café)

**23 In which languages are the information products for the general public produced?**

☐ Language of the coordinator
☐ Other language(s)
■ English

***Question F-10***: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

### FIELDS OF SCIENCE AND TECHNOLOGY

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[5] Open Access is defined as free of charge access for anyone via Internet.

[6] For instance: classification for security project.

## 1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

## 2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

## 3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

## 4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

## 5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

## 6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]

# 4. FINAL REPORT ON THE DISTRIBUTION OF THE European Union FINANCIAL CONTRIBUTION

## Report on the distribution of the European Union financial contribution between beneficiaries

| Name of beneficiary | Final amount of EU contribution per beneficiary in Euros |
|---|---|
| 1. | |
| 2. | |
| | |
| n | |
| | |
| Total | |