Aero-Engine Research and Demonstration Programmes under CleanSky

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CLEAN SKY

Donderdag 13 Juni 2019, 20:00

Innovation Takes Off

von KARMAN INSTITUTE for FLUID DYNAMICS

72 WATERLOOSE STEENWEG, 1640 SINT GENESIUS RHODE

www.cleansky.eu

Clean Sky 2

Outline

1. Clean Sky,
   a quick, general overview.

2. Introduction,
   back to the basics …

3. Aero-Engines,
   end of the story … ?

4. What's next ?
   A roadmap to 2050 …

Part I
- Clean Sky ? -

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The Aviation Vision

1. **Meeting societal & market needs**
   - managing the effects of growth of air travel
2. **Maintaining and extending industrial leadership**
   - delivering greater competitiveness
3. **Protecting the environment and the energy supply**
   - achieving decarbonisation; reducing emissions/noise
4. **Ensuring safety and security**
   - introducing revolutionary modes of travel
5. **Prioritising research, testing capabilities & education**
   - pioneer enabling research

To <u>deliver this vision</u> and <u>meet these challenges</u> new technical solutions will be required

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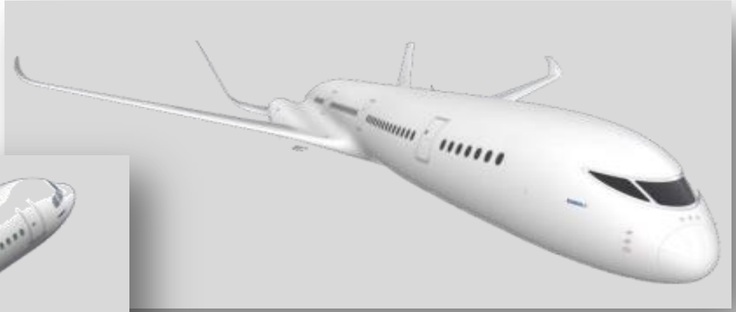
Environmental Targets …



Reduce perceived external noise by

- 50% by 2020
- 65% by 2050

Reduce NO_X emissions by

- 80% by 2020
- 90% by 2050

Reduce fuel consumption and CO_2 emissions by

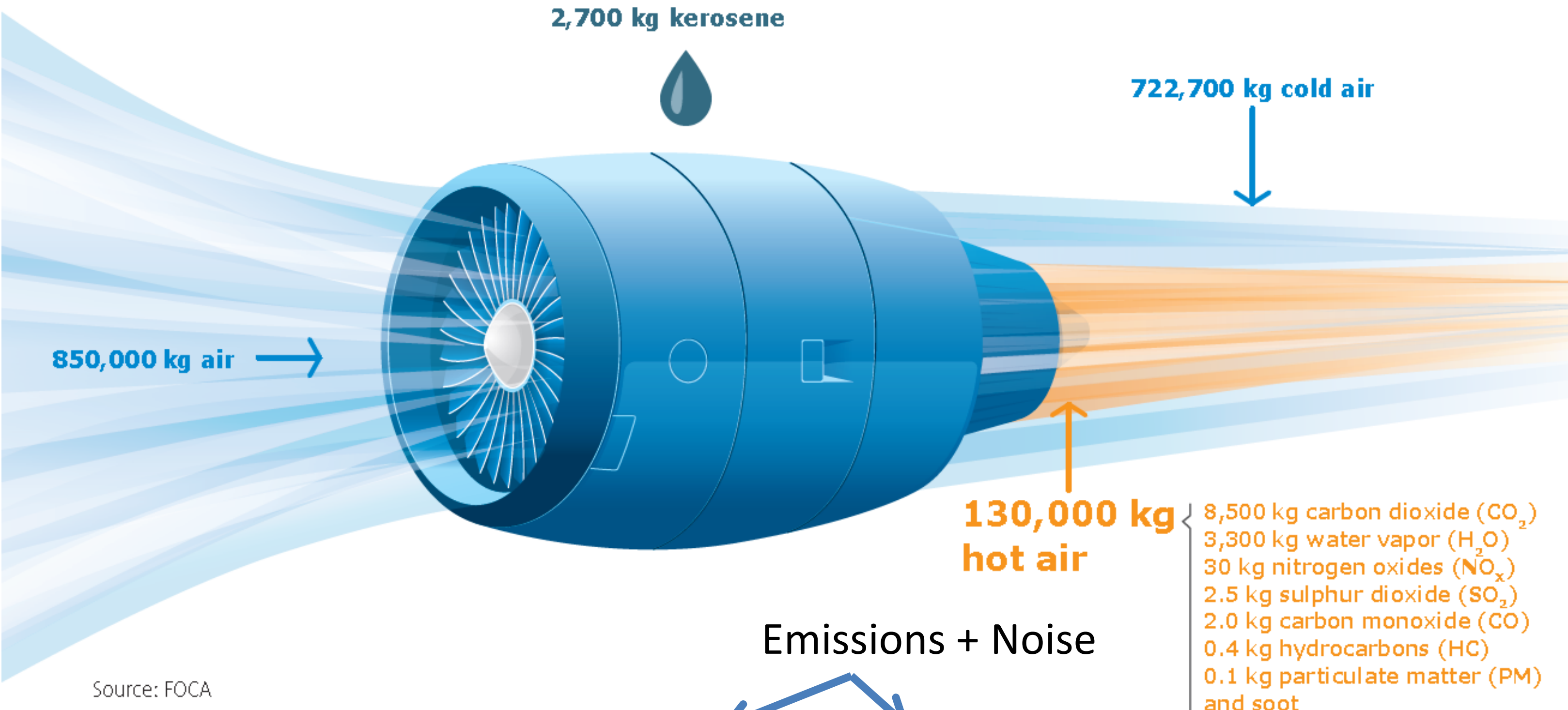
- 50% by 2020
- 75% by 2050

Vision 2020 and Flightpath 2050 targets are for new aircraft technology relative to 2000 performance

Environmental Targets

- Decarbonisation. CO2 effects only ?
- Climate Impact / Global Warming ?

Figure 1.8 Emissions from a typical two-engine jet aircraft during 1-hour flight with 150 passengers



Source: European Aviation Environmental Report 2019

Emissions + Noise

CO2 + non-CO2 effects

Clean Sky 2 tackling key environmental challenges

Environmental Objectives*

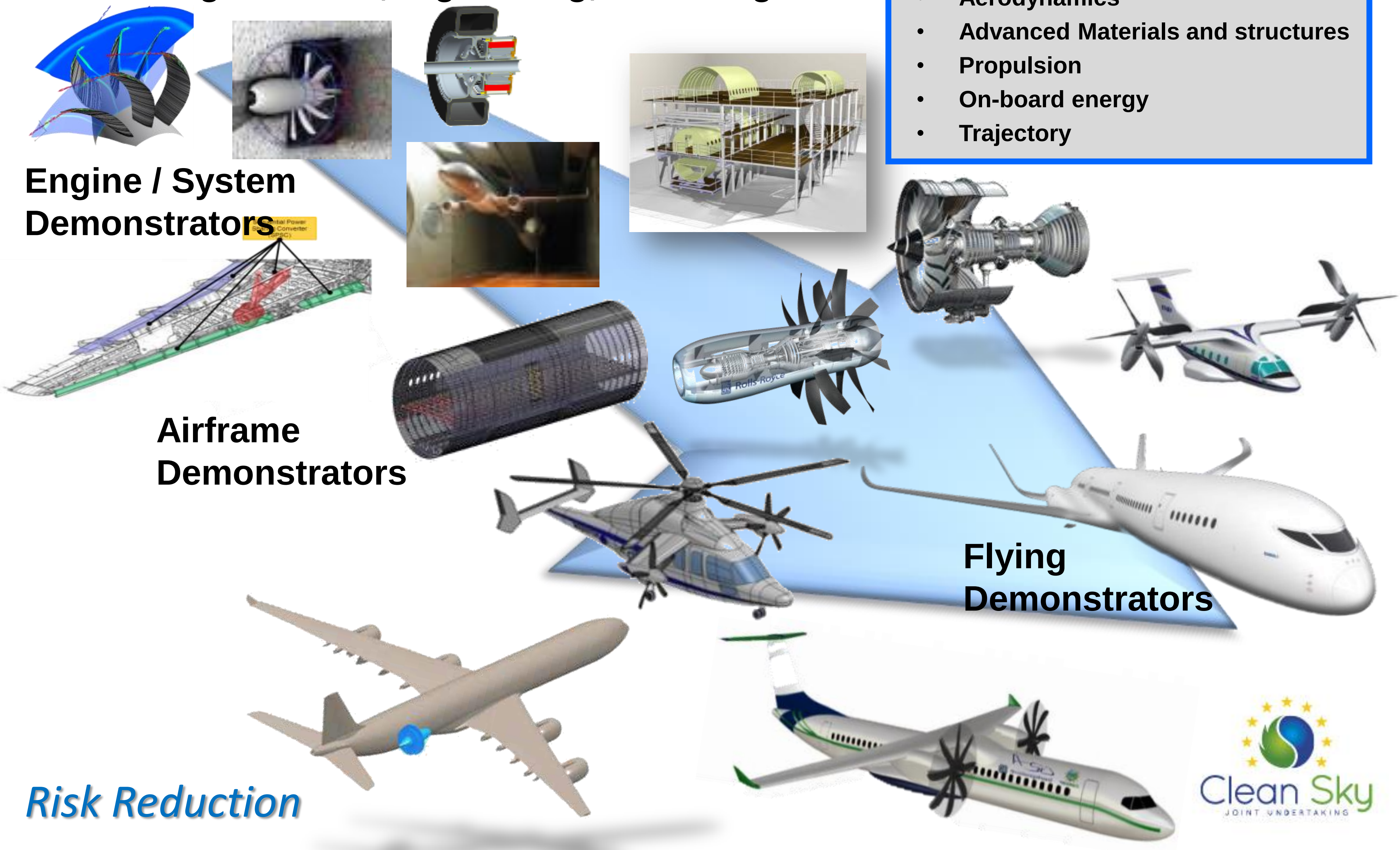
$-CO_2$	-20% TO -30%
$-NO_x$	-20% TO -30%
(noise)	-20% TO -30%

** vs today's best aircraft (ref 2014)*

…while building industrial leadership and ensuring mobility

Taking Technology to Full-Scale Demonstration

- Aerodynamics
- Advanced Materials and structures
- Propulsion
- On-board energy
- Trajectory



Clean Sky and Europe’s Aeronautical Industry

AIRBUS AN EADS COMPANY

AIRBUS HELICOPTERS

AgustaWestland A Finmeccanica Company

Alenia Aermacchi A Finmeccanica Company

DASSAULT AVIATION

DLR

AIRBUS DEFENCE & SPACE

evektor

Fraunhofer

LIEBHERR

MTU Aero Engines

PIAGGIO AERO

Rolls-Royce

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SAAB

THALES

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Clean Sky 2 Facts and Figures to date

334
INDUSTRY MEMBERS

420
SMES

373
RESEARCH CENTRES

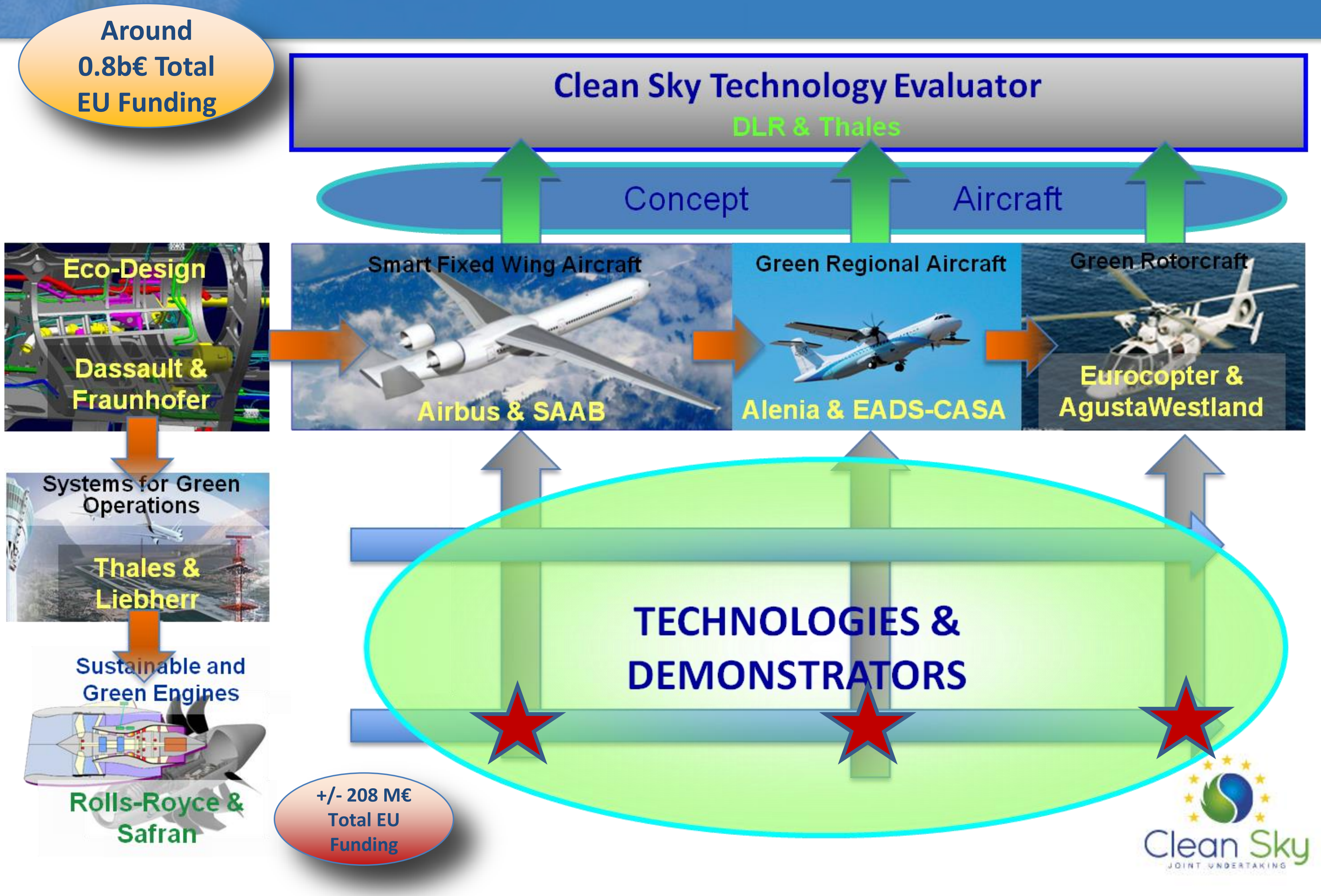
350
UNIVERSITIES

28
COUNTRIES

110
REGIONS

466
GRANTS

Clean Sky (1) Integrated Program Structure



Clean Sky 2 Programme Set-up (H2020)

Around 1.75b€
Total EU Funding

Vehicle
IADPs

Fast Rotorcraft
Agusta Westland
Eurocopter

Large Passenger Aircraft
Airbus

Regional Aircraft
Alenia Aermacchi

Large
Systems
ITDs

Eco-Design
Fraunhofer Gesellschaft

Airframe ITD
Dassault – EADS-CASA – Saab

Engines ITD
Safran – Rolls-Royce – MTU

+/- 290 M€
Total EU
Funding

Systems ITD
Thales – Liebherr

Small Air Transport
Evektor – Piaggio

Technology Evaluator (TE)
German Aerospace Center (DLR)

Building on Clean Sky, going further into integration at full aircraft level
And developing new technology streams for the next generations of aircraft

Clean Sky & Clean Sky 2 - Engines

- Clean Sky : 0.8 Bn € funding – 2008-2017
- Clean Sky 2 : 1.8 Bn € funding – 2014-2024

	Funding (M€)	Budget (M€)
CS1 – SAGE		
Leaders	154	308
CfPs (80 projects)	54	81
Total	**208**	**390**
CS2 – ENG		
Leaders	203	286
CfPs	87	122
Total	**290**	**410**
Grand Total :	**498**	**800**

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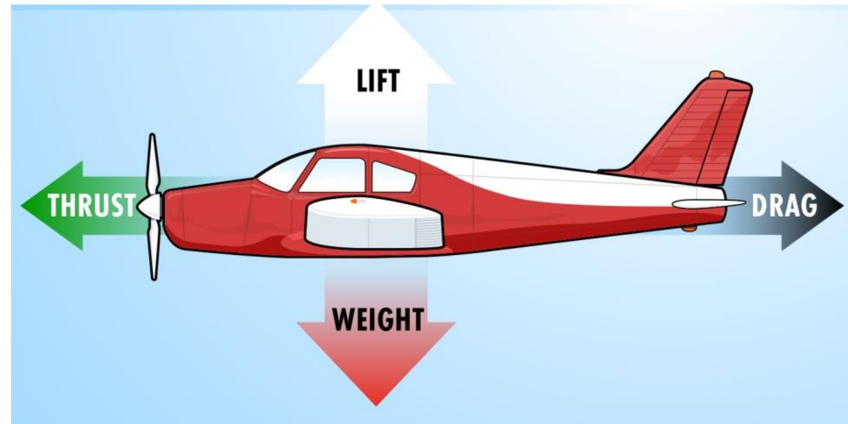
Part II
- Introduction -
Back to the basics …

Breguet's Range Equation

$$\text{Range} = \frac{h}{g}\,\frac{L}{D}\,\eta_{overall}\,\ln\frac{W_{initial}}{W_{final}}$$

Fluids (Aero) · Propulsion · Structures + Materials



$$\textit{overall efficiency} = \frac{\text{what you get}}{\text{what you pay for}} = \frac{\text{propulsive power}}{\text{fuel power}}$$

$$\textit{propulsive power} = \text{thrust} \cdot \text{flight velocity} = T.V$$

$$\textit{fuel power} = \text{fuel mass flow rate} \cdot \text{fuel energy per unit mass} = \dot{m}_f h \quad (\text{J/s})$$

$$\eta_{overall} = \frac{T.V}{\dot{m}_f h}$$

$$\text{Range} = \frac{V(L/D)}{g \cdot SFC}\ln\left(\frac{W_{initial}}{W_{final}}\right)$$

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How far can a plane fly ?

Breguet's equation tells us it depends on :

- How much energy is contained in the **fuel** it carries ?
- How aerodynamically efficient it is (Lift-to-Drag Ratio)

  -> ***Fluid Mechanics/Aerodynamics Lectures***
- How efficiently energy from the fuel is turned into useful work (Thrust x Distance travelled) which is used to oppose the drag force

  -> ***Thermodynamics & Propulsion Lectures***
- How "light-weight" is the structure, relative to the amount of fuel and payload it can carry.

  -> ***Materials and Structures Lectures***

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Improving Propulsion Systems Efficiency

1. Improving **Powerplant Efficiency**

2. Improving Powerplant **System Integration into Airframe**

3. Improving **Propulsive and Non-Propulsive Energy Generation** over flight mission

1. Improving Powerplant Efficiency

Thermopropulsive efficiency

$$\eta_{thp} = \frac{PW_{aircraft}}{PW_{fuel}}$$

Thermal efficiency

$$\eta_{th} = 1 - \frac{1}{OPR^{\frac{\gamma-1}{\gamma}}\left(1+\frac{\gamma-1}{2}M_0^2\right)}$$

→ Increase **OPR**

→ Modify **engine cycle**

→ Modify **burner operation**

Propulsive efficiency

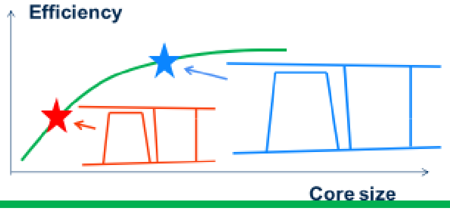
$$\eta_{pr} = \frac{2}{1+\frac{V_{out}}{V_{in}}}$$

→ Decrease **fan pressure ratio** (→ decrease exhaust velocity)

Thermal Efficiency

Increase OPR

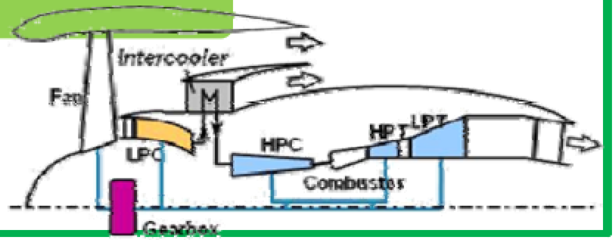
- Challenge on materials (temperature, pressure)
- Challenge on aerodynamics and coolings
- Challenge on combustor emissions



(FP7-Lemcotec)

Modify engine cycle

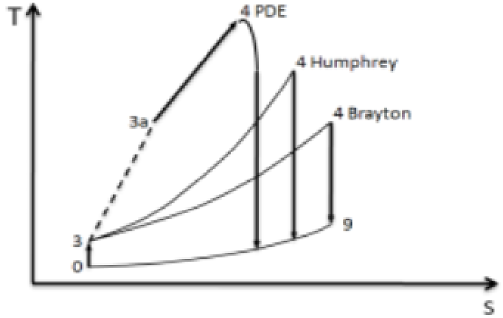
- Introduce additional features (ex : intercooled compressor, cooled cooling engine)



(FP7-Enoval)

Modify burner operation

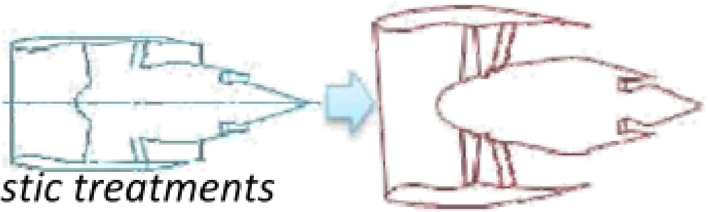
- Constant volume compressor
  - *Challenges on weight, off-design behavior*
- Detonation combustor
  - *Low TRL concept, off-design behavior to be understood, compatibility with kerosene fuels TBC*



Propulsive Efficiency

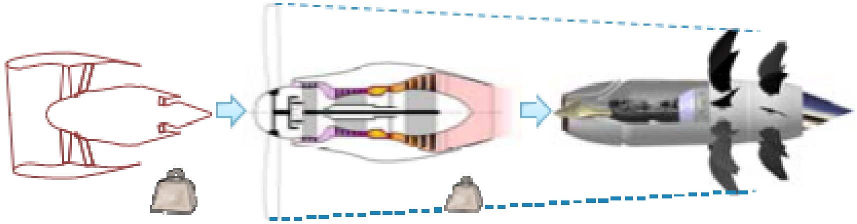
Decrease Fan Pressure Ratio

- Requires higher secondary airflow to deliver thrust
  - *Challenge on secondary duct dimensions, drag and weight, acoustic treatments*



Further decrease Fan Pressure Ratio and remove secondary duct

- Unducted configurations maximize propulsive efficiency while alleviating weight constraints
- Additionnally, counter-rotating propellers help keeping dimensions at a reasonable level



  - *Unducted configuration noise and installation still a challenge*

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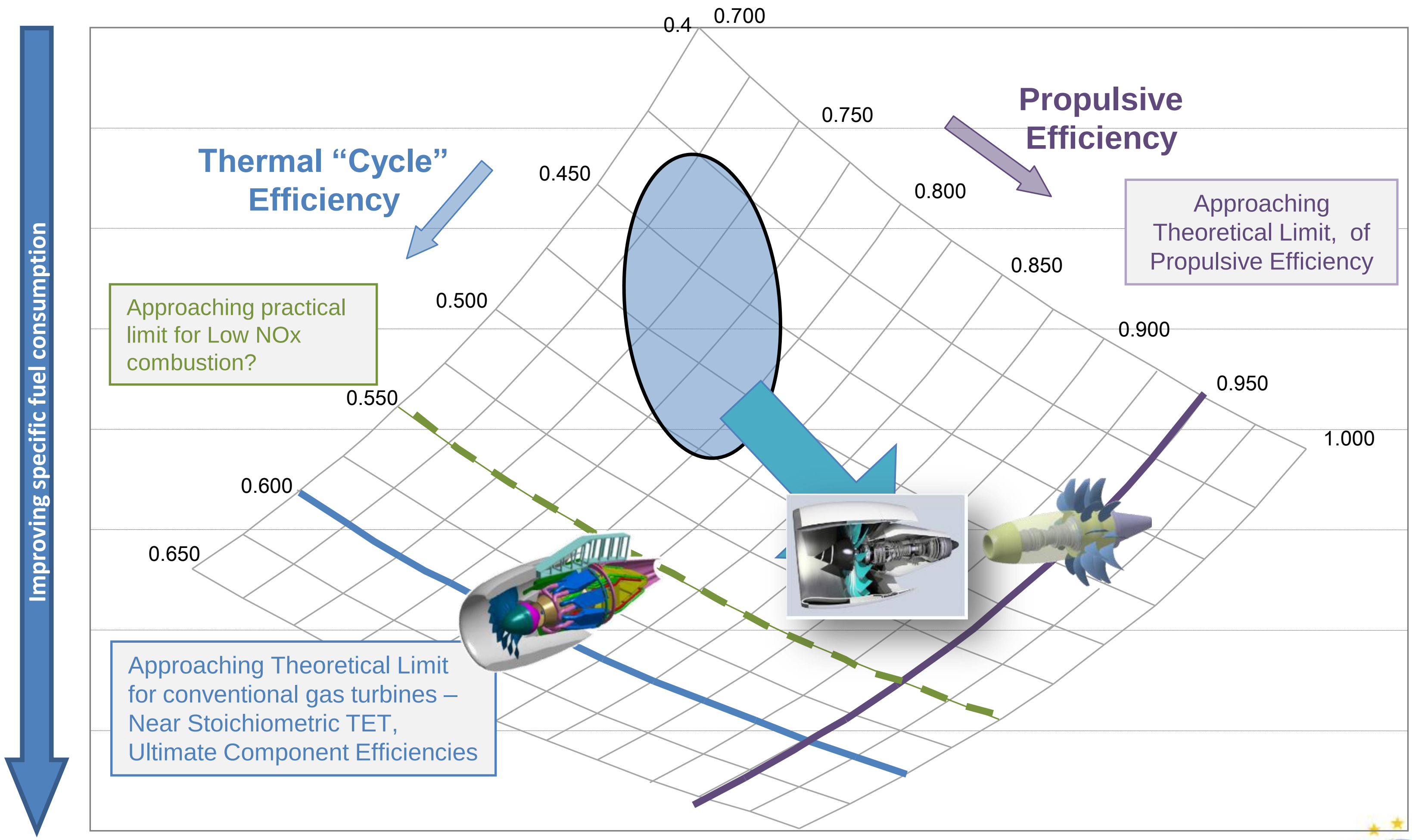
Propulsive Efficiency



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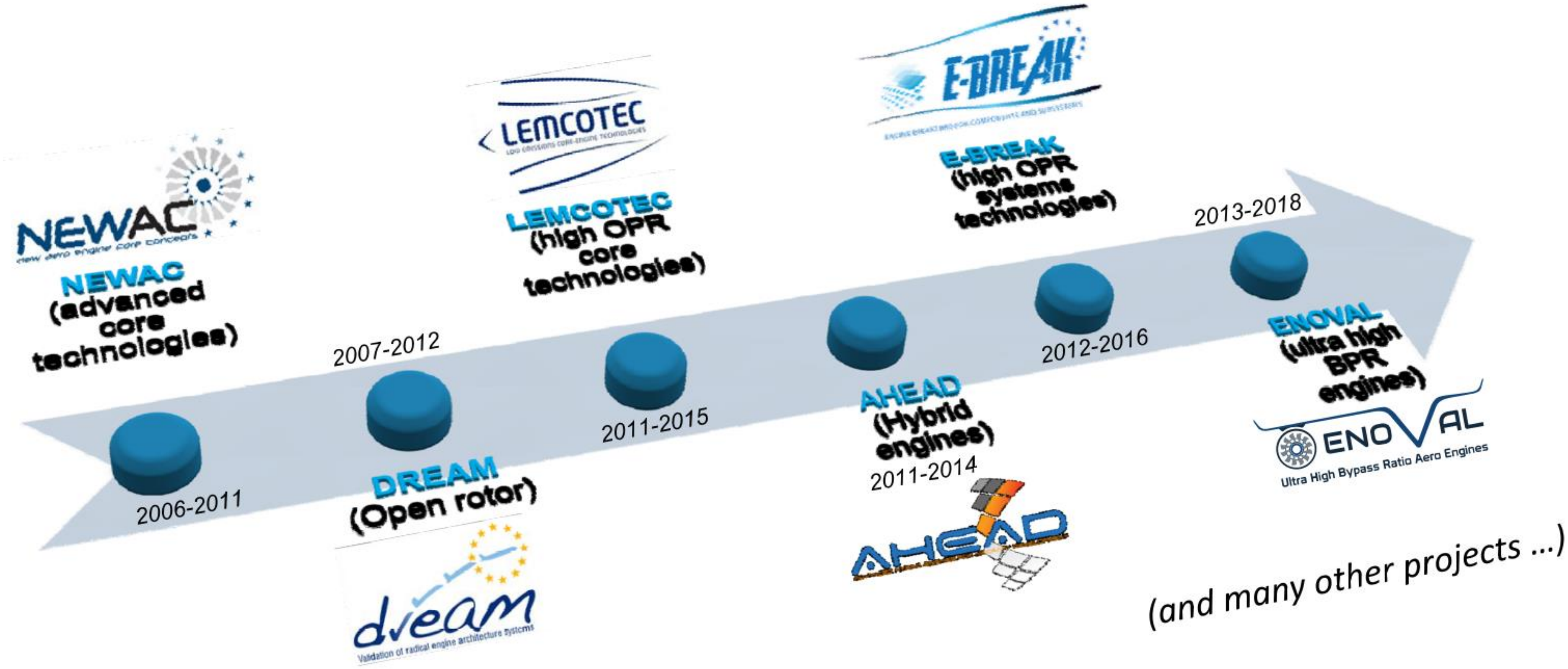
Support from EU funded projects



- Up to TRL 3-4
- Clean Sky -> Demonstrators at TRL 5-6

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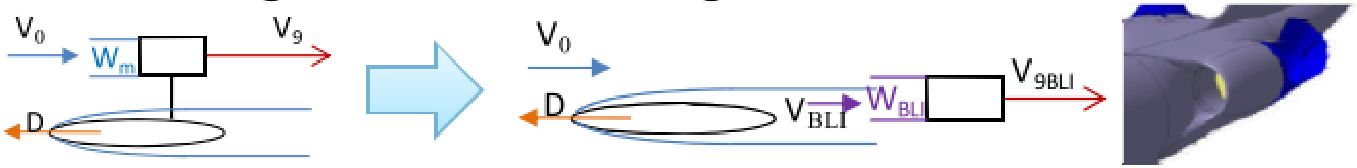
Propulsive Efficiency

Take benefit from fuselage boundary layer

- Rear fuselage semi-buried BLI configurations



- *Challenges on distorsion, installation*

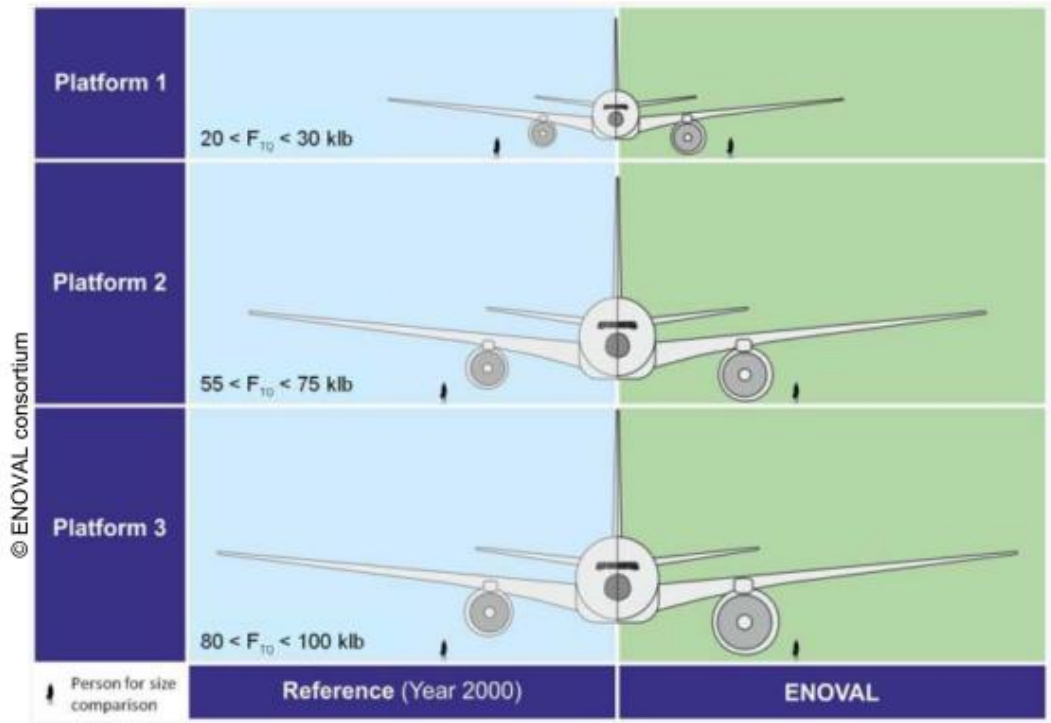
Distribute propulsion effectors

- De-couple low pressure components design from core constraints
- Improve flexibility to locate thrust generators on airframe
- Opens room for hybrid concepts

2. Improving Powerplant System Integration

Installation challenges

Highly efficient high bypass ratio engines result in high dimensions powerplants :



→ Additional challenge on integration constraints

→ Drag, weight for ducted configurations

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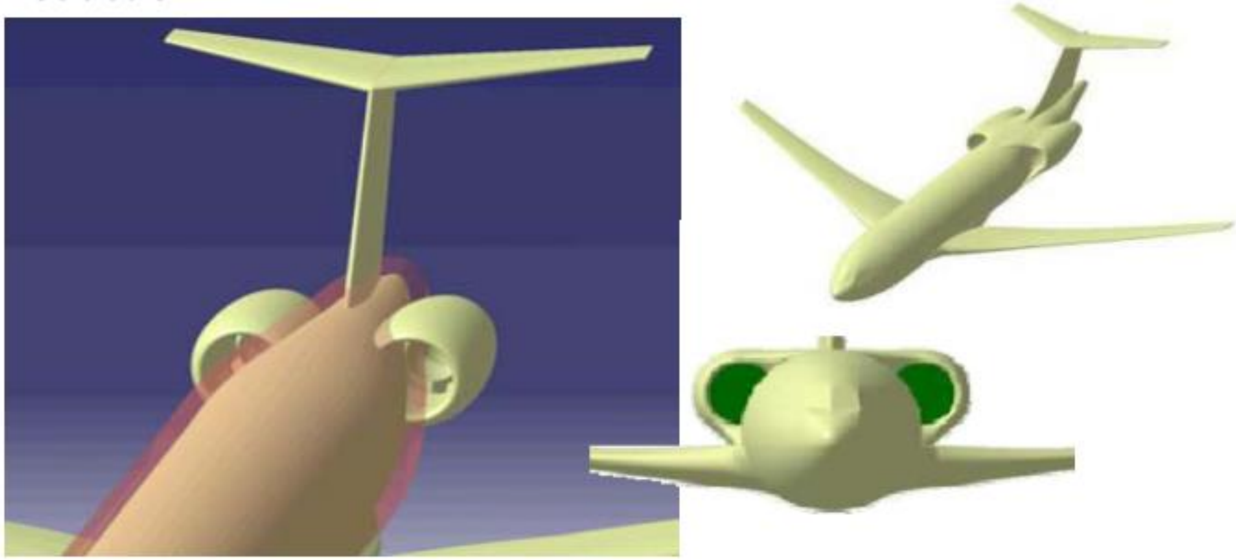
2. Improving Powerplant System Integration

Aerodynamical benefit for closer airframe / powerplant coupling

Interest for boundary layer ingestion / airframe drag reduction



These advanced installations features show their maximum benefit only if combined with **best energy-efficient** powerplants …

Example of Advanced Aircraft Integration

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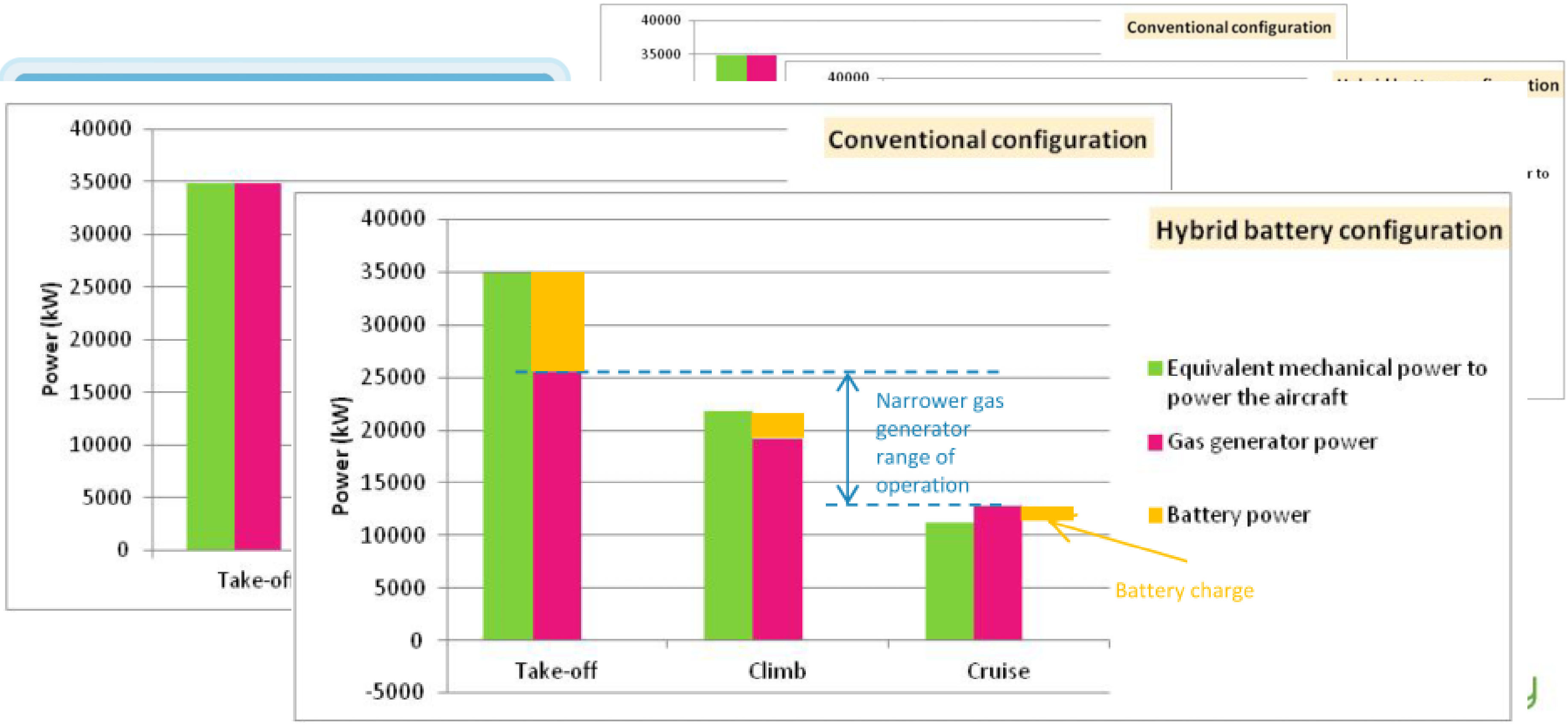
3. Improving Propulsive and Non-Prop. Energy

Identify needs per flight phase

- Propulsive energy dependent on airframe characteristics and mission, usually known
- Non propulsive energy dependent on aircraft technology and airline practices, significant scatter

Optimize energy recuperation

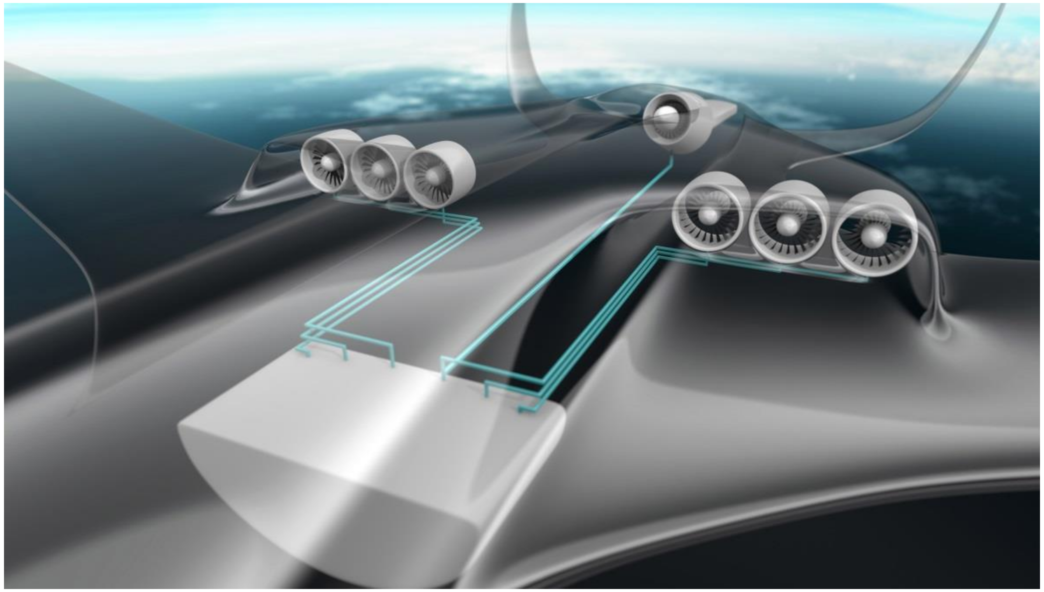
Ex : Windmilling energy recuperation during descent phase ; close link with aircraft L/D, operational descent flight path

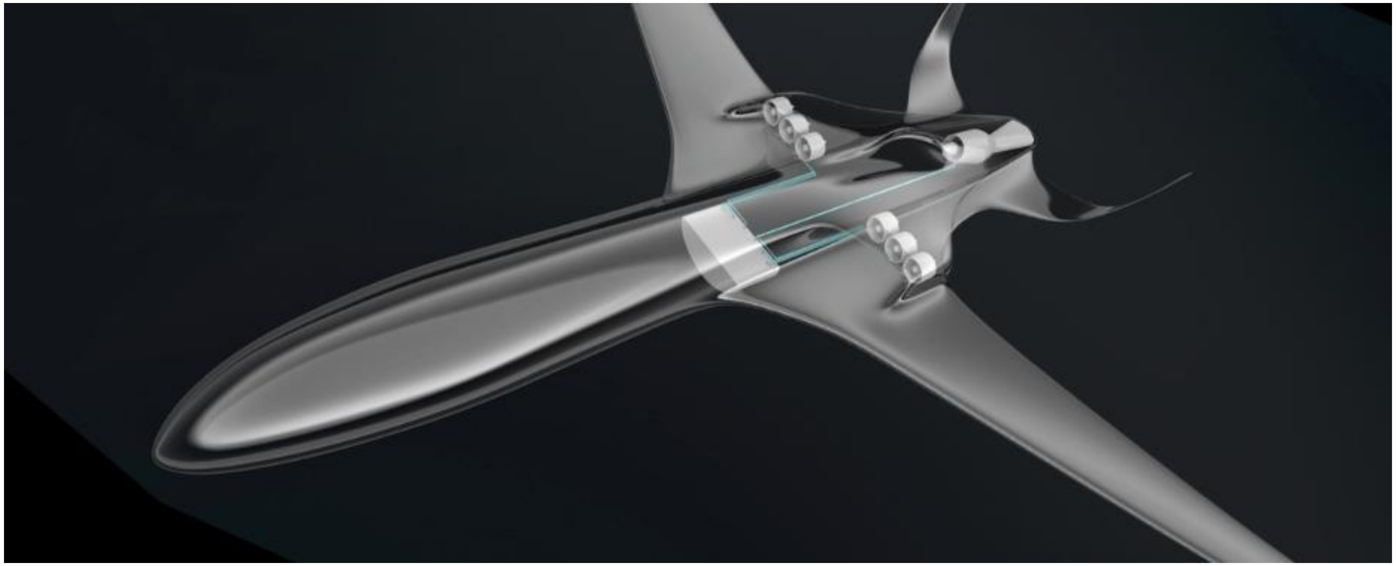


System Integration and Hybrid Propulsion

An example : E-Thrust Concept

Airbus Innovation Group & RR





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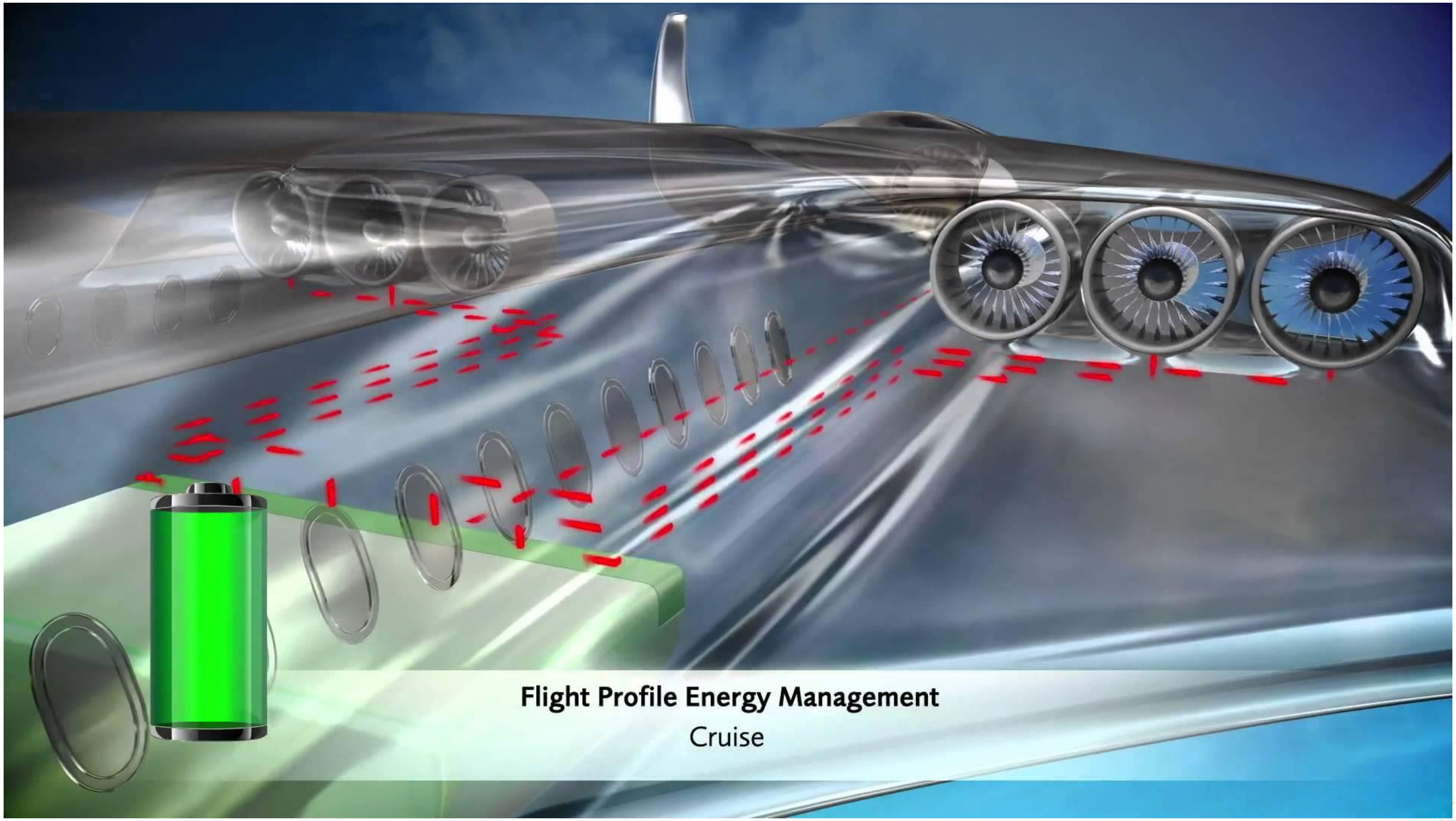
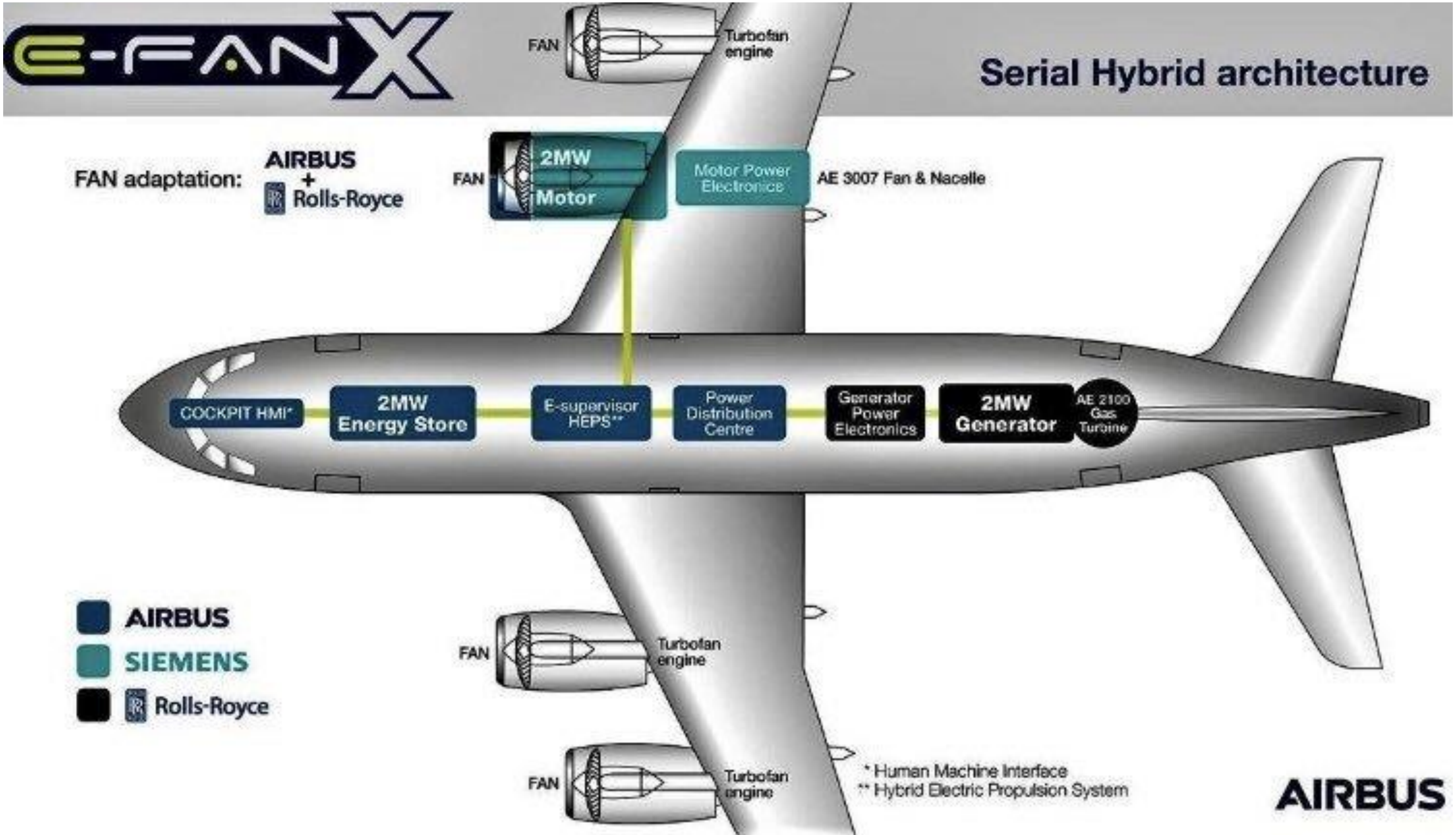
System Integration and Hybrid Propulsion



E-Fan & E-Fan X

System Integration and Hybrid Propulsion



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Part III
Aero-Engines
Here we go …

Outline

1. **Open-Rotor Architectures**
   - CS1-SAGE1 – RRUK
   - CS1-SAGE2 – SNECMA
   - CS2-LPA-(ENG-WP1) - SNECMA
2. **Large VHBR Turbofans Architectures – LR Aircraft**
   - CS1-SAGE3 – RRUK
   - CS1-SAGE6 – RRUK (Lean Burn)
   - CS2-ENG-WP5 – RRUK
   - CS2-ENG-WP6 – RRUK
3. **VHBR Turbofans – SMR Aircraft**
   - CS2-ENG-WP2 – SNECMA - UHPE
4. **Geared Turbofans – SMR Aircraft**
   - CS1-SAGE4 – MTU
   - CS2-ENG-WP4 – MTU
5. **Turboshaft Engines - Helicopters**
   - CS1-SAGE5 - TURBOMECA
6. **TurboProp Engines – Regional/SAT**
   - CS2-ENG-WP3 TURBOMECA
   - CS2-ENG-WP8 GE Avio
7. **Small Piston Engines – Small Air Transport (SAT)**
   - CS2-ENG-WP7 - SMA

1. Open Rotor Architectures

Outline

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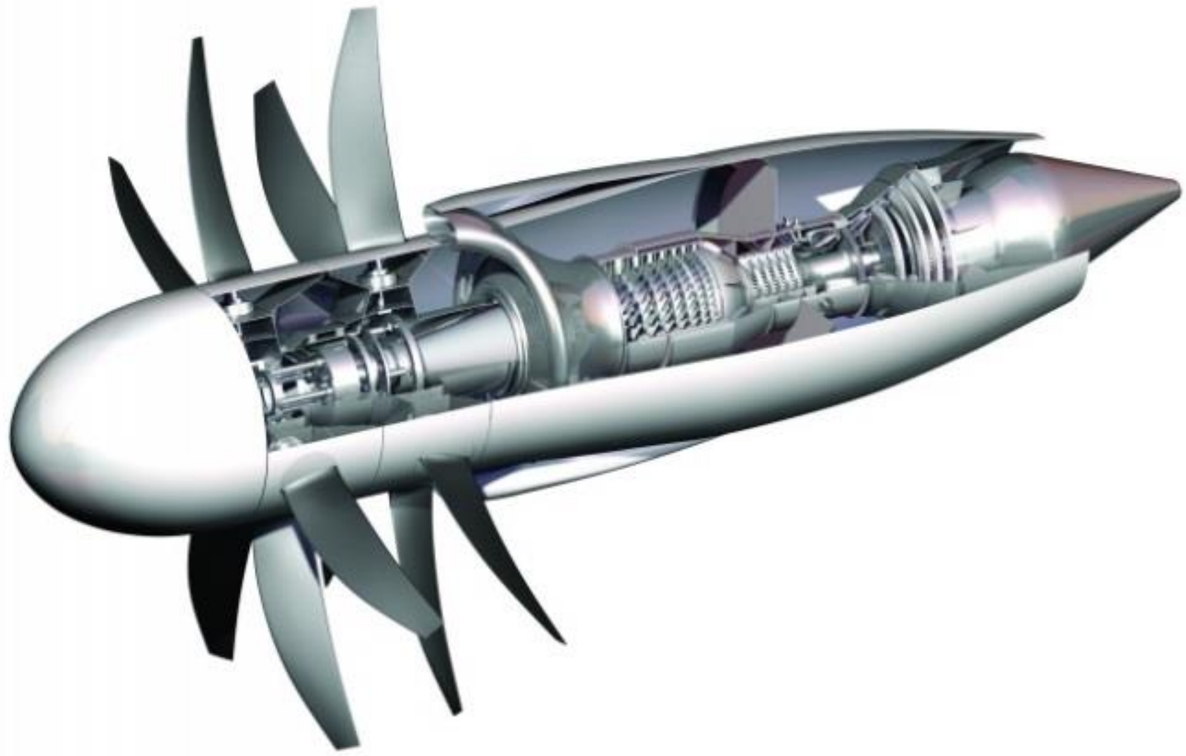
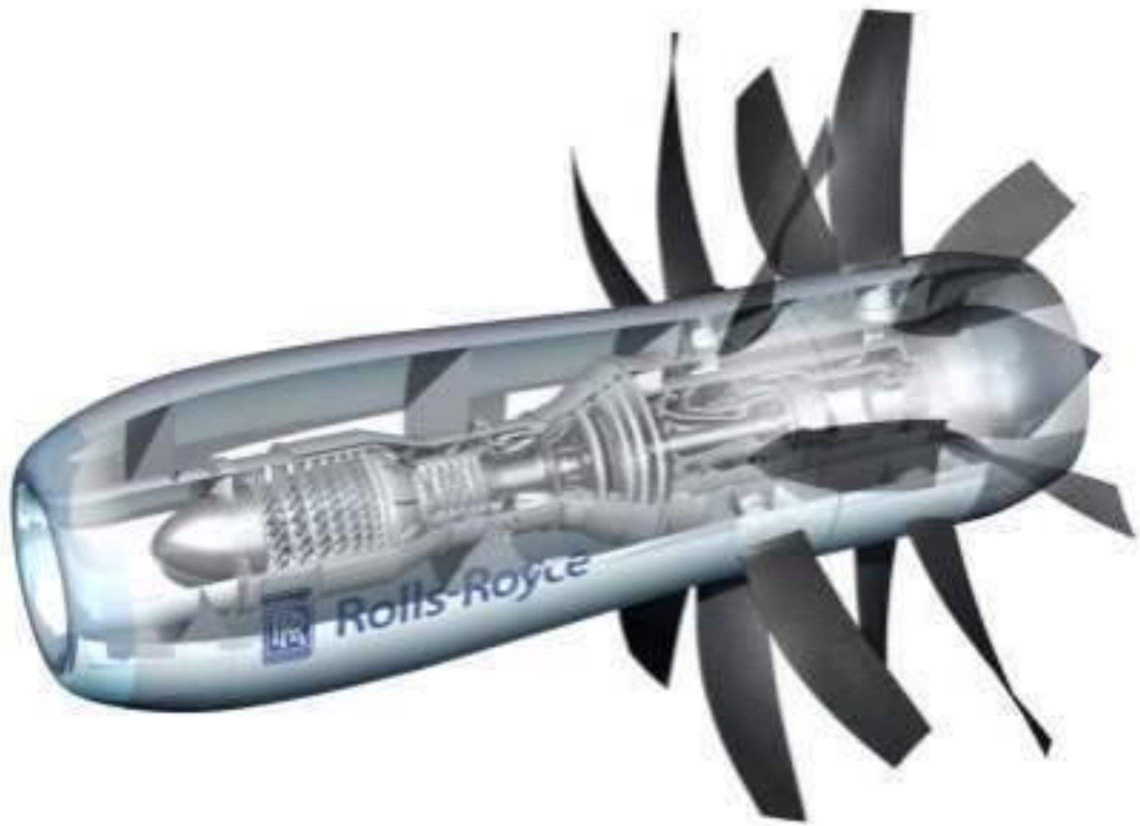


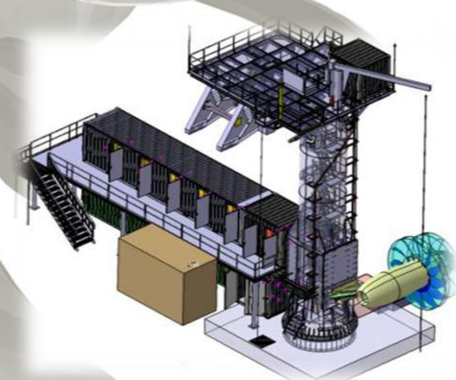

Rolls-Royce

CS1 – SAGE 2 – Snecma

- <u>Objective :</u> to build and ground test a **full-scale Geared Pusher Open Rotor engine**

- <u>Main benefit of the Open Rotor concept :</u>

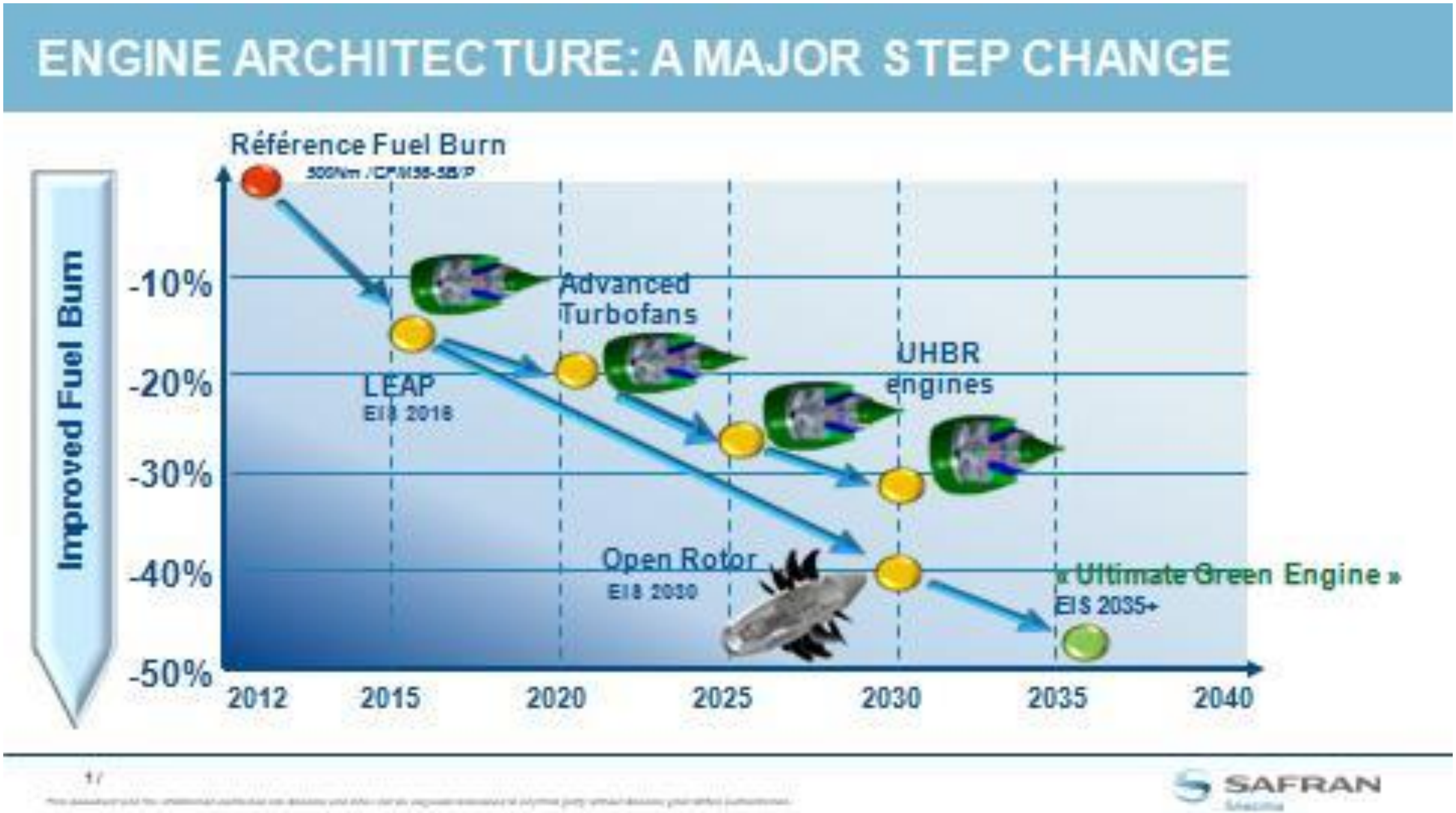
  30 % CO_2 emissions reduction compared to the CFM56®* engine



Snecma proprietary information

Plus several CfP partners …

** CFM56 engines are a product of CFM International, a 50/50 joint company between Snecma (Safran) and GE.*


ENGINE ARCHITECTURE: A MAJOR STEP CHANGE
Référence Fuel Burn
Improved Fuel Burn
-10%
-20%
-30%
-40%
-50%
Advanced Turbofans
LEAP
EIS 2016
UHBR engines
Open Rotor
EIS 2030
« Ultimate Green Engine »
EIS 2035+
2012
2015
2020
2025
2030
2035
2040
SAFRAN

Objectives and technical challenges

Technical challenges

- **Noise Certification** ✔

Several design optimizations → intensive aero-acoustic wind tunnel tests → Chapter 14 COMPLIANT

- **Whole Propulsion System Integration** ✔

- **State of the Art Propulsive Efficiency and Module Efficiency** ✔

** CFM56 engines are a product of CFM International, a 50/50 joint company between Snecma (Safran) and GE.*

SAGE2 Geared Counter Rotating Open Rotor

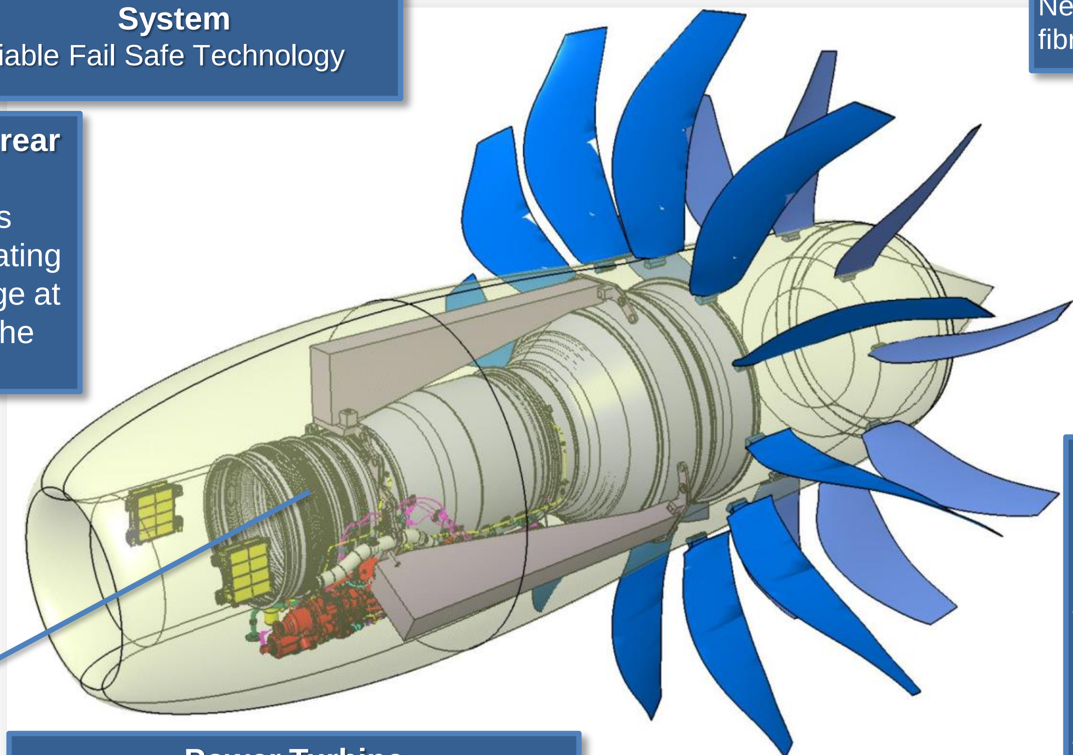
Key technologies …

Multi-variable power control, adaptative pitch actuation and active thermal management

Propeller Pitch Control System
Reliable Fail Safe Technology

Lightweight Counter-rotating propellers
Next generation 3D woven carbon fibre

Lightweight front and rear rotating frames
Robust design to address certification issues of rotating casing, controlling leakage at interfaces and reducing the weight.



M-88 Core Engine
Used for GTD

Power Gear Box
Enabling technologies to achieve reliability and power/envelope ratios required to the counter-rotating reduction gearbox for the installation on Open Rotor Architectures.

Power Turbine
Embedding new technologies in order to reduce module weight and increase efficiency

Nacelle Components
Allowing rotating nacelles
Oil Cooling System

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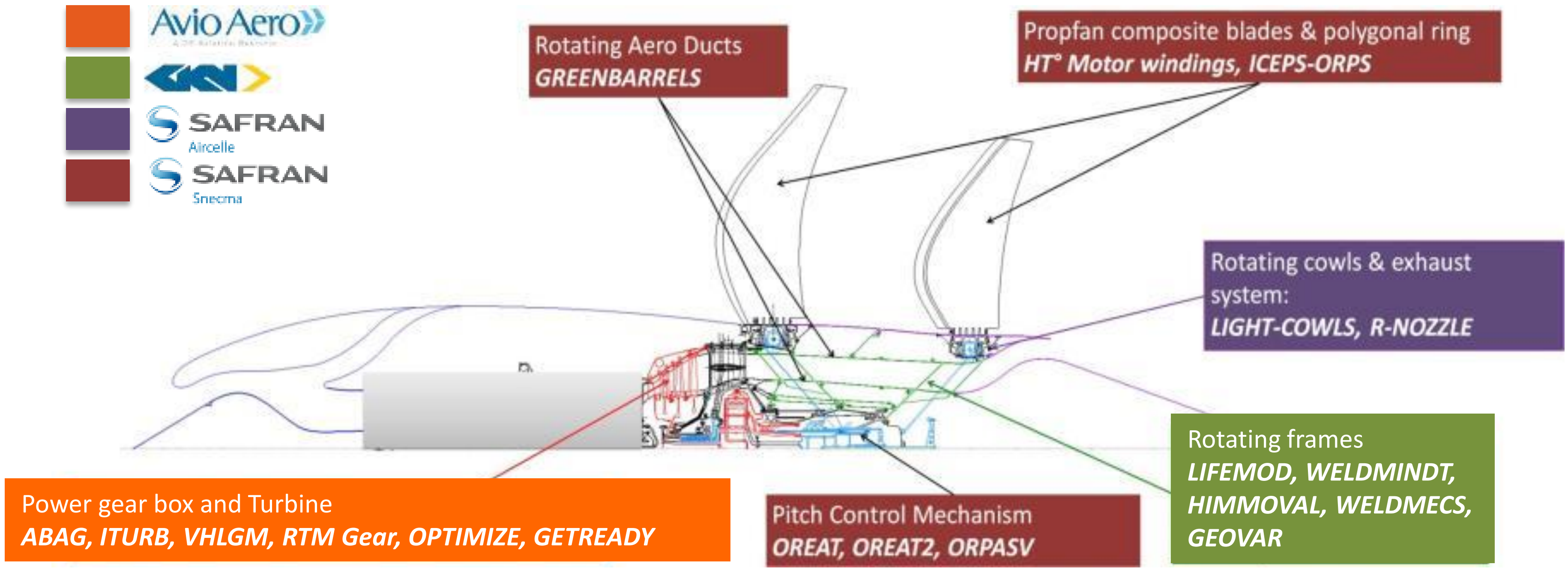
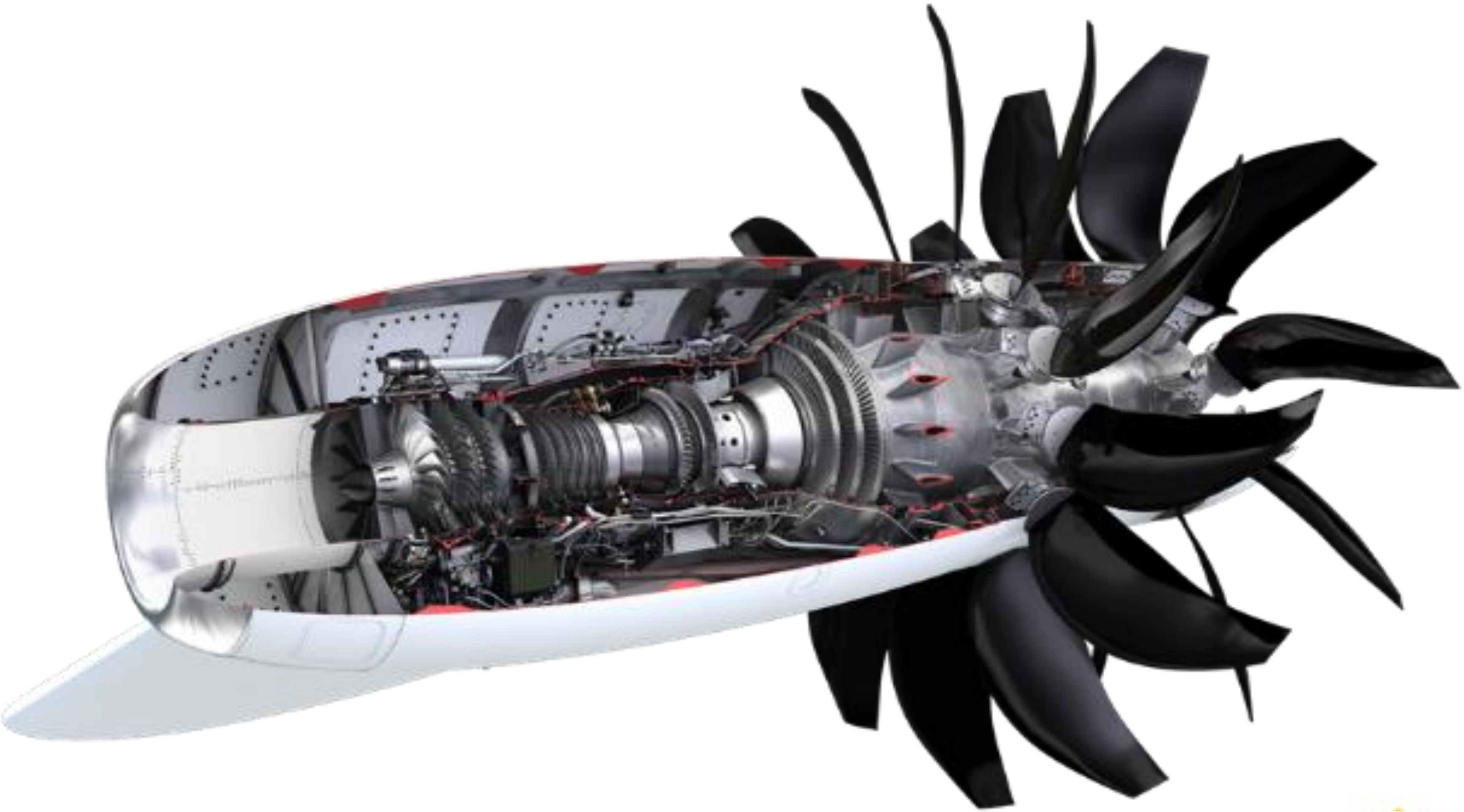
CfP projects included in SAGE 2 Demo



- **Systems & Equipments**:
  - Hispano Suiza: **COTEM, ADONIS**
  - Techspace Aero: **GILD, LubEST**
- **Bearings:**
  -Snecma: **SNRPBEARING**
- **Mounts**:
  - Snecma: **Lord OpenRotor**
- **Health monitoring:**
  - Snecma: **HITEAS**

Clean Sky

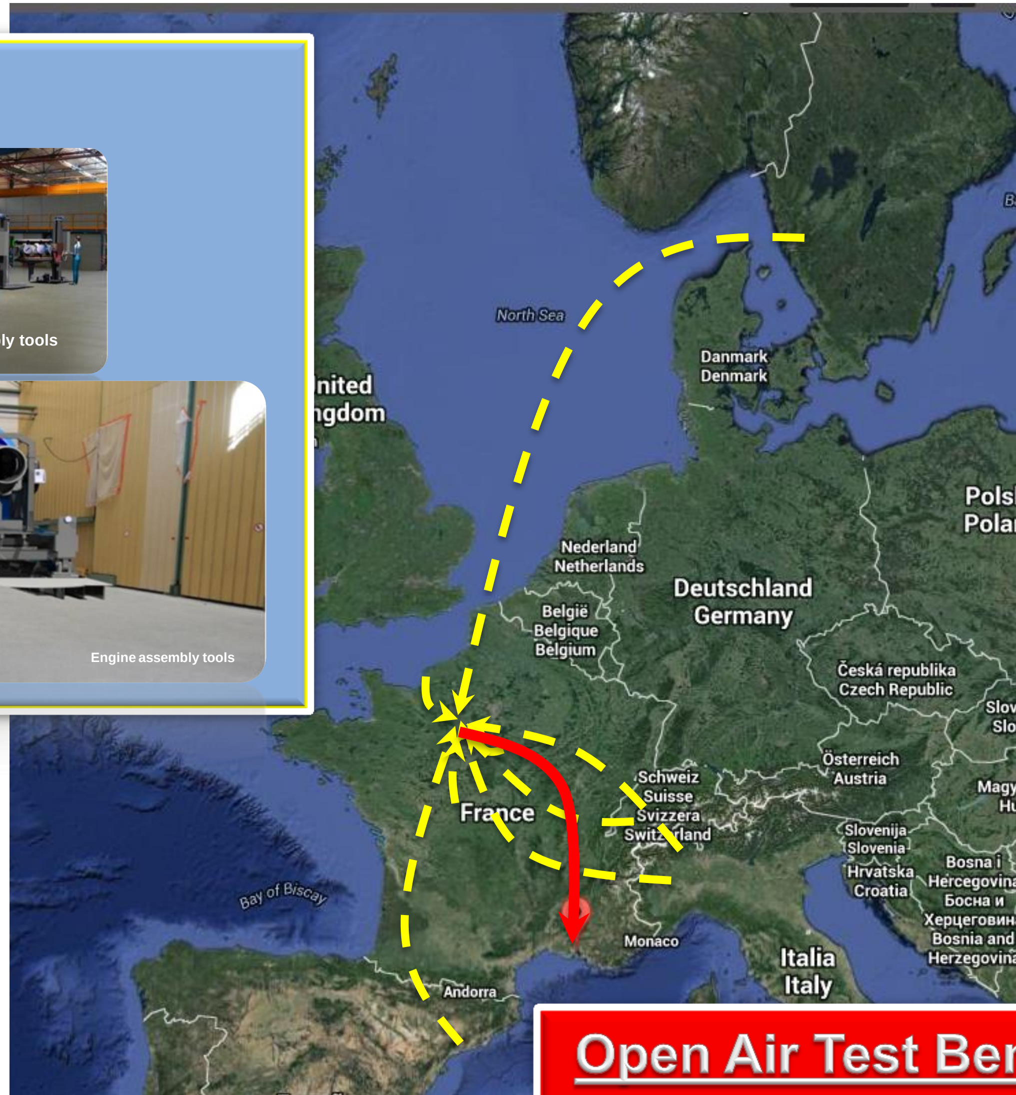


New Dedicated Assembly and Test Facilities

Assembly Shop


Module assembly tools


Engine assembly tools



Open Air Test Bench


Foundations

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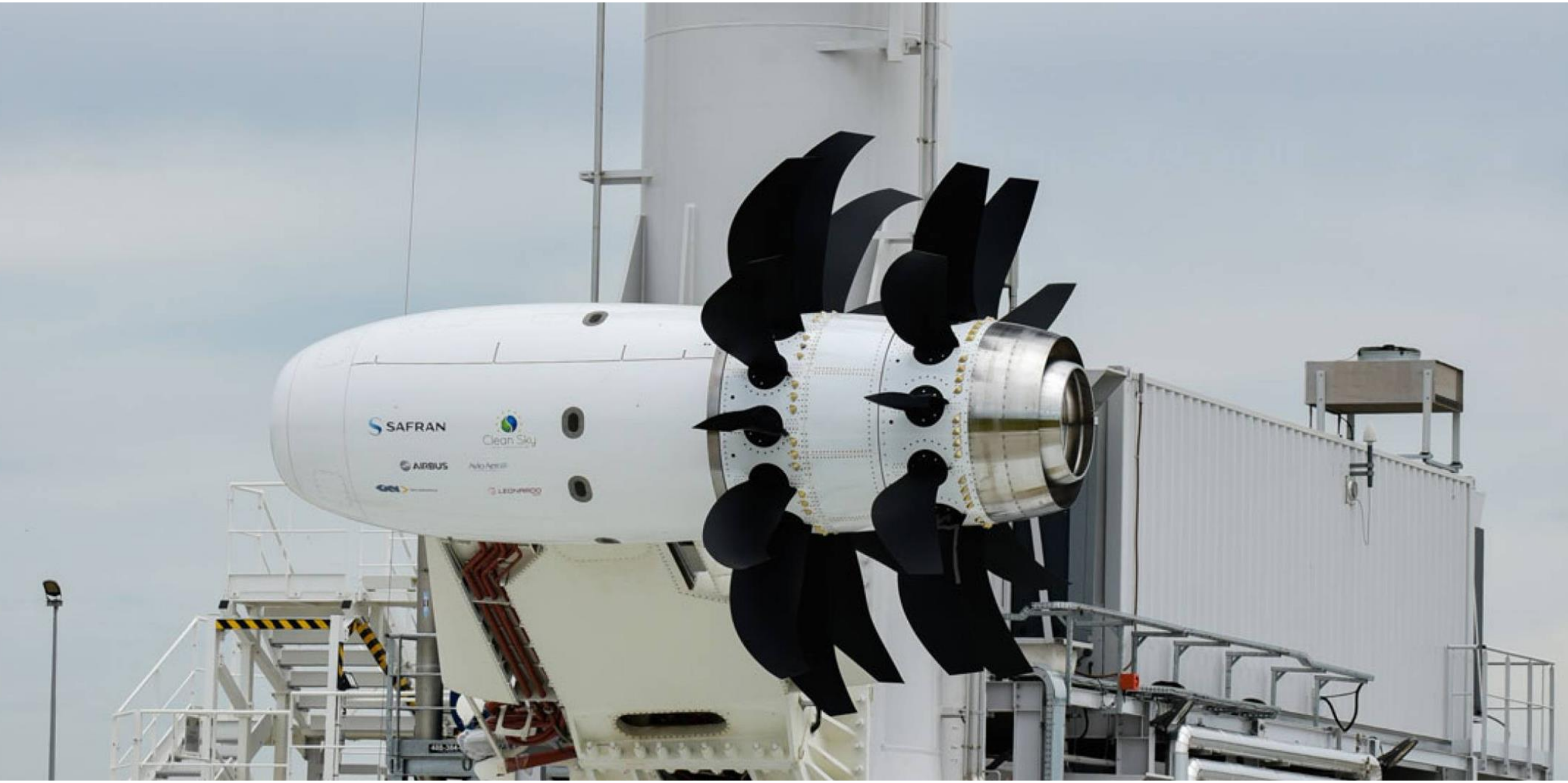
SAFRAN
Clean Sky
AIRBUS

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AEROSPACE · DEFENCE · SECURITY

Clean Sky

SAGE2 - Conclusion

- Clean Sky SAGE2 Team has delivered in 2017/2018 a Full-Scale Open Rotor Ground Test Demo
- This test has validated:
  - Propulsion System Integration
  - Key Technologies that will enable Breakthrough Ultra High Efficiency Engine Architectures
- And will offer:
  - Key Learnings on modules performance and Noise

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Clean Sky

2. Large Turbofan Architectures

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CS1 – SAGE3 – Rolls-Royce

GKN AEROSPACE

the power of talent
25 YEARS

Delivered both Ground and Flight Tests

Subsystem	Environmental targets (wrt reference)	
	CO2 [%]	Noise [EPNdB]
Composite fan system	-1 to -3	-1 to -3
Advanced integrated externals	-0.5 to -1.5	0
Low weight low pressure turbine	-1 to -2	0

A wealth of Hardware delivered through the Rolls-Royce led SAGE 3 – Advanced Low Pressure System engine programme

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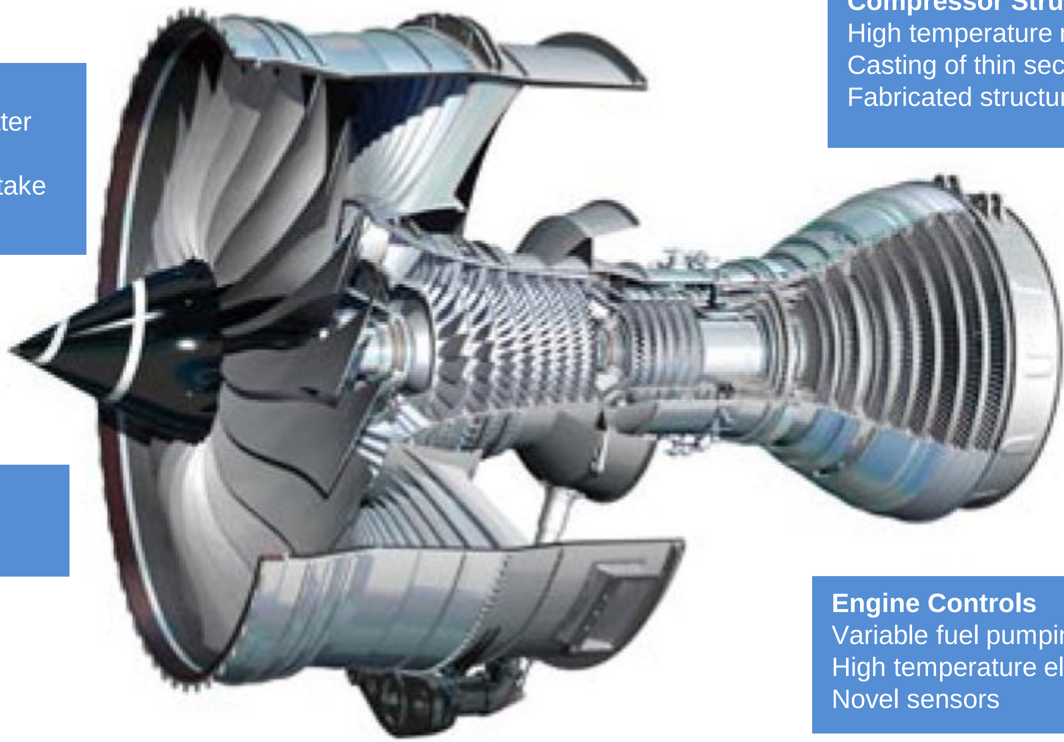
SAGE3 key technologies

Composite Fan System
Composite fan blades
Composite annulus fillers
Composite containment case
High temperature composite materials

Lightweight Advanced Dressings
High temperature printed circuit boards
Non-metallic pipes

Compressor Structures
High temperature materials
Casting of thin sections
Fabricated structures

Novel Liners
Integrated acoustic and flutter liners
Micro-perforate acoustic intake liners

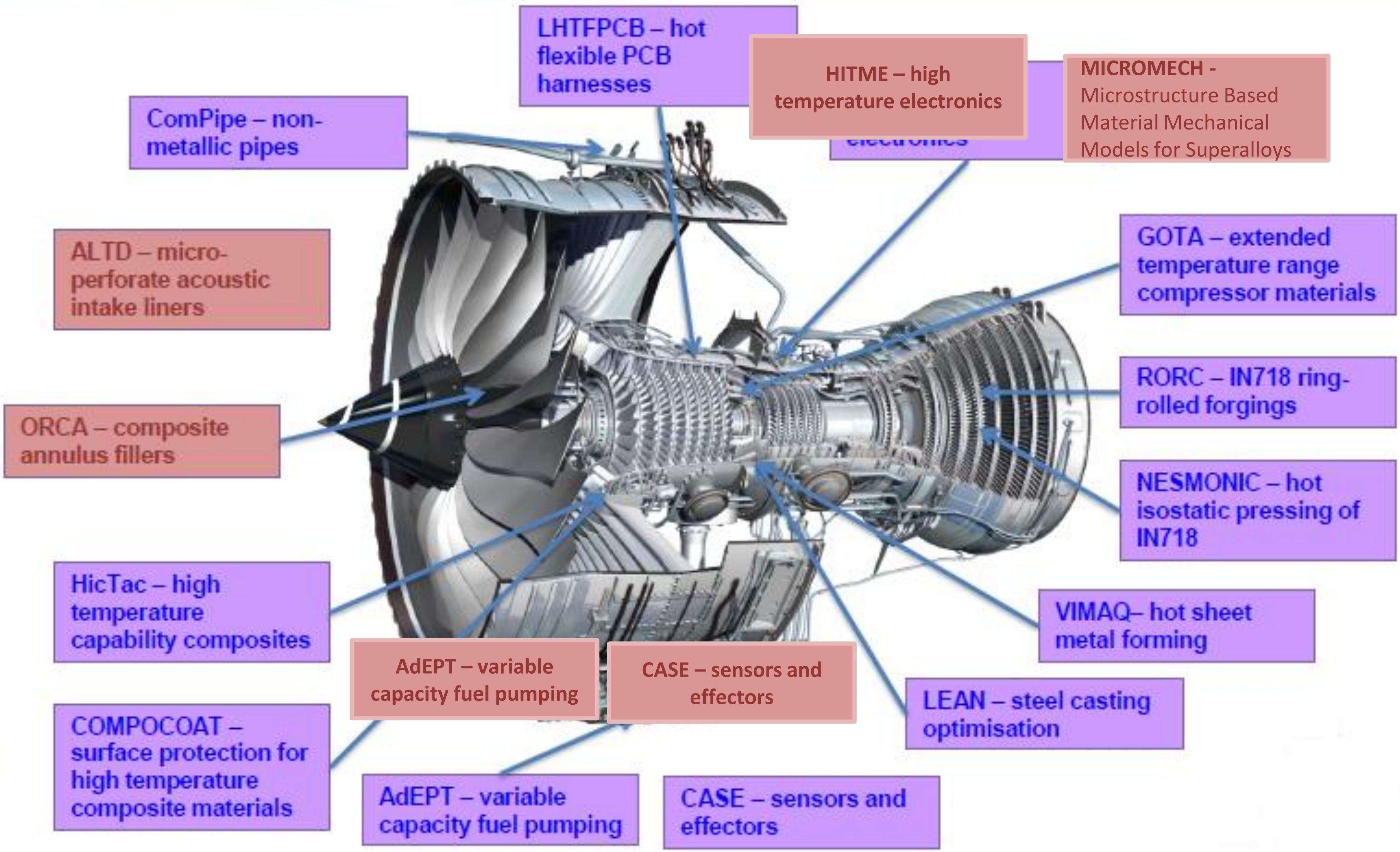


Low Pressure Turbine
Thermal management
High temperature materials
Blade retention
Damped blades
Tip clearance

Seals
Large diameter leaf seals

Engine Controls
Variable fuel pumping
High temperature electronics
Novel sensors

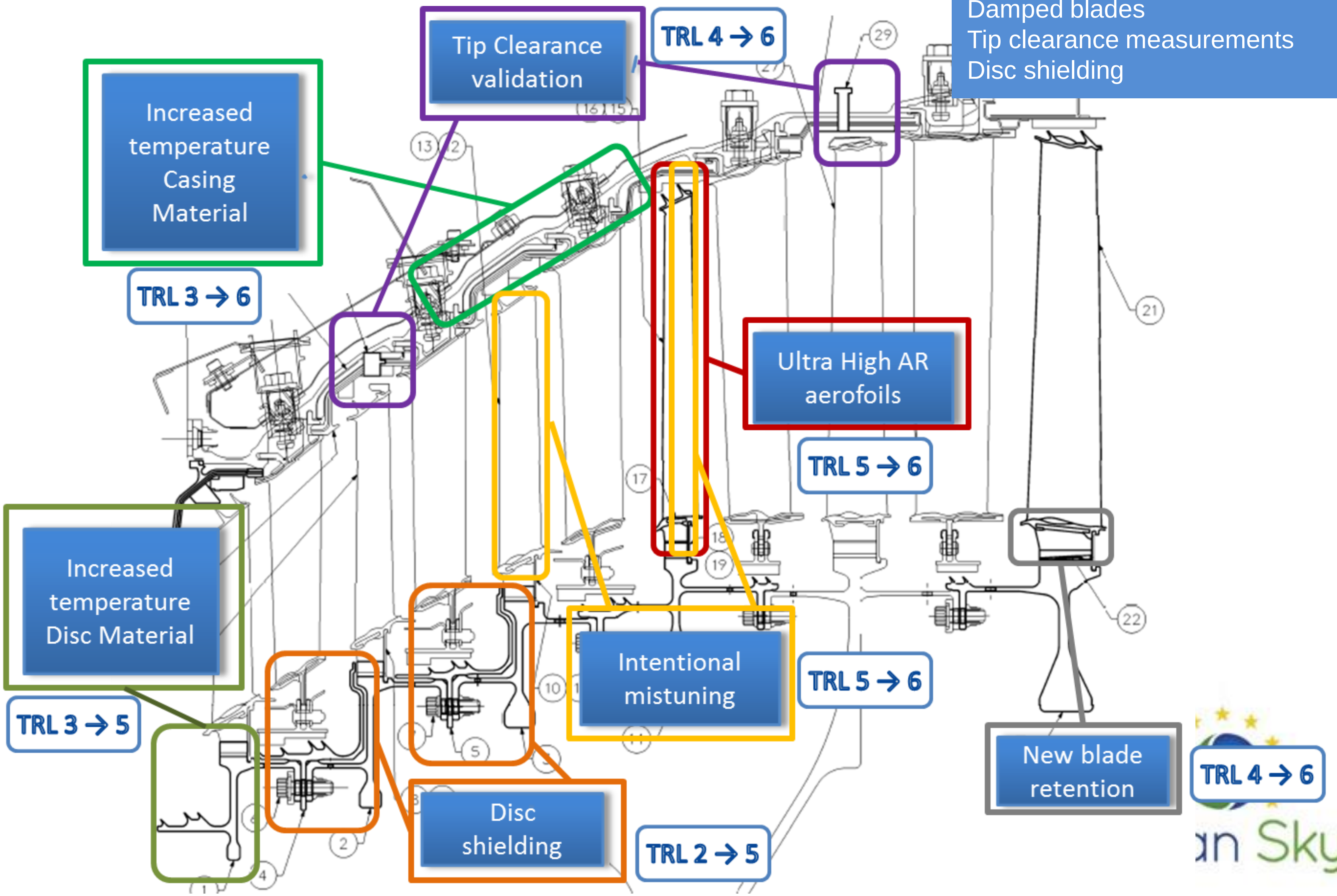
CfP projects included in SAGE 3 Demo



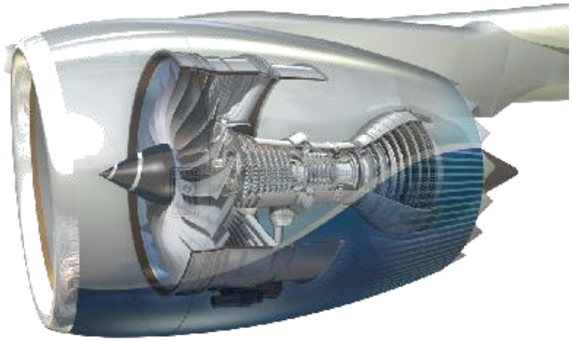
CS1: SAGE 3 LPT1

Low Pressure Turbine

Thermal management
High temperature materials
Blade retention
Damped blades
Tip clearance measurements
Disc shielding

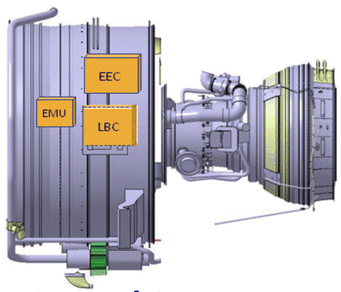


CS1 – SAGE6 – Rolls-Royce



NO_x Emissions Targets

NOx LTO <40% CAEP6
Cruise EINOx <12g/kg



Advanced/Active Control System

Hardware delivered for both Ground and Flight Tests of the Advanced Low Emissions Combustion System Engine programme

2017/2018 delivered both Ground and Flight Tests

SAGE 6

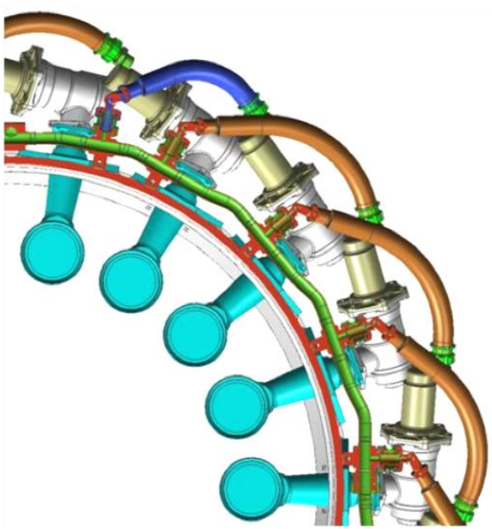
Advanced Low Emissions Combustion Systems

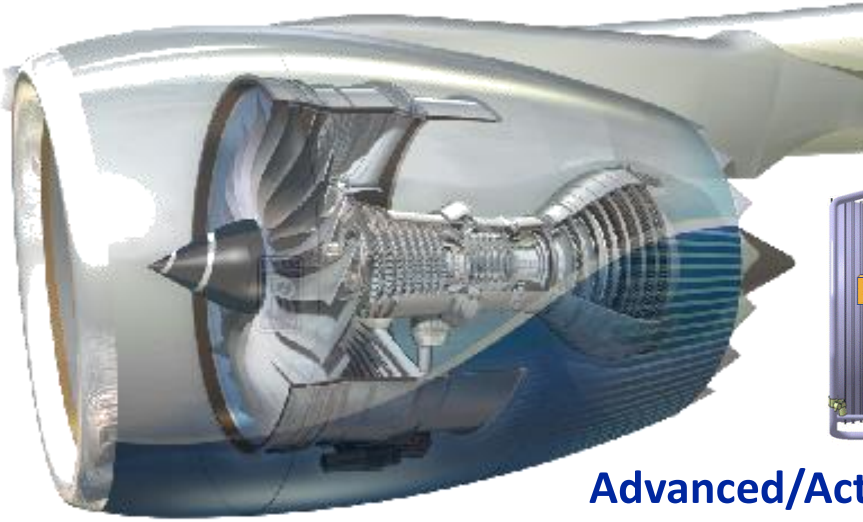
Rolls-Royce

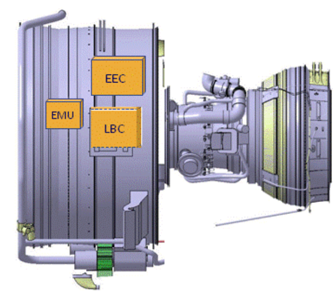
Aero Engine Controls

Combustor

- Multi-Injection Fuel Spray Nozzles (Pilot and Main)
- Improved Combustor designs and cooling







Advanced/Active Control System

- Lean burn control and fuel metering
- Fault and health monitoring

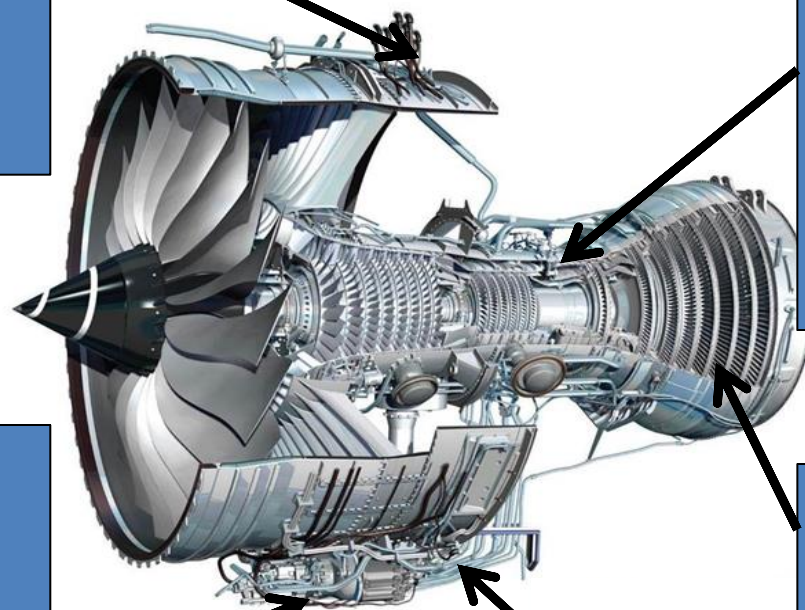
Lean Burn Combustor System

- Operability and full system validation over the full operating envelope
- Supported by EFE and E3E

SAGE6 Lean Burn Key Technologies

Engine Controls
- Lean burn control laws
- System safety functions
- Rumble detection
- Staging system fault accomodation

Combustor
- Internally staged fuel spray nozzles (pilot & main)
- Tiled combustor (symmetric, canted, increased vol, imping. effusion cooled)
- Multi-manifolds



Lean Burn Staging
- Fuel supply
- Fuel staging and splitting
- Lean blow out protection

Turbines
- Combustor Interaction (flat traverse, high swirl and high turbulence)

Installations
- Unit Placement
- Dressings/Harnesses

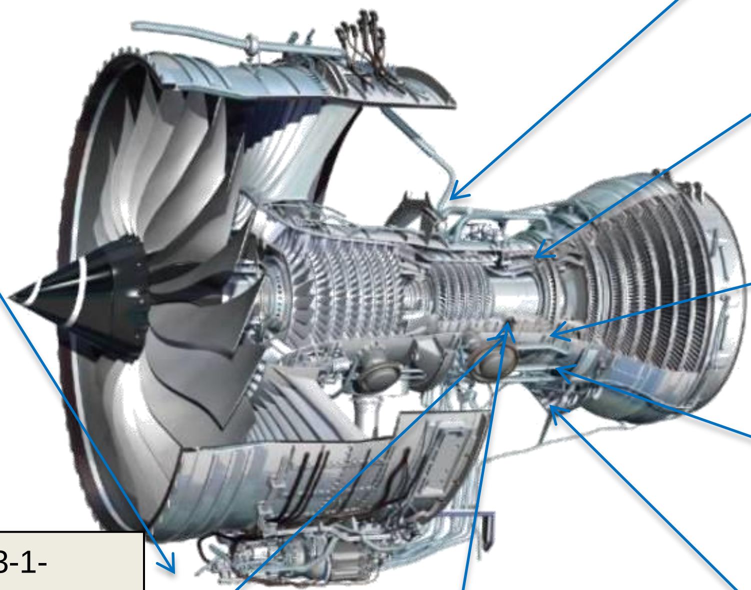
CfP projects links to SAGE6 Demo

Call #15 JTI-CS-2013-1-SAGE-06-03 AEC : Development of materials, processes, and means to enable the application of piezoelectric materials in aero engine controls (CfP kicked off) 1 500 000€ *

Call #8 JTI-CS-2011-1-SAGE-01-01 RRUK: Lean Burn Control System Verification (CfP in work) 761 335€

Call #15 JTI-CS-2013-1-SAGE-06-07 RRUK 900 000€ Validated Design Methodology for Fuel Manifold Systems (CfP kicked off)

Call #13 JTI-CS-2012-3-SAGE-06-02 RRUK: Economic manufacture of lean burn combustion liner tiles (CfP kicked off) 2 500 000€ **



Call #14 JTI-CS-2013-1-SAGE-06-04 RRUK: Design methods for low emissions (CfP kicked off) 1 300 000€

Call #14 JTI-CS-2013-1-SAGE-06-05 RRUK : Design methods for durability and operability of low emissions combustors (CfP kicked off) 850 000€

Call #16 JTI-CS-2013-1-SAGE-06-009 RRUK 950 000€ Advanced methods for prediction of lean burn combustor unsteady phenomena (CfP Successful)

Call #16 JTI-CS-2013-1-SAGE-06-011 RRUK 1 500 000€ Design methods for accurate combustor wall temperature (CfP Successful)

Call #14 JTI-CS-2013-1-SAGE-06-06 RRUK : Advanced materials for lean burn combustion system components using Laser- Additive Layer Manufacturing (CfP Kicked off) 1 000 000€ **

SAGE 3 – Ground Tests

SAGE 3 – Flight Test

Clean Sky

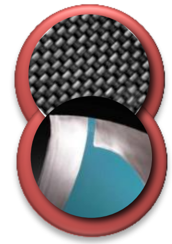
CS2 – ENG-WP5 & 6 – Rolls-Royce

Aim: System integration and delivery of whole-engine demonstration through ground and flight-based testing


Composite Containment Casing

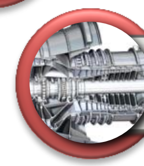

Optimised Powerplant & Nacelles

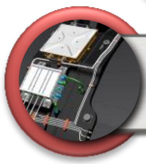

Lean Burn Combustor


Lightweight Cti Fan blades


Lightweight High Efficiency Compressors


Controls, EHM & Systems Integration


Advance Core Architecture


Lightweight Externals


Power gear box


Lightweight High Efficiency Turbines

Enabling Technologies

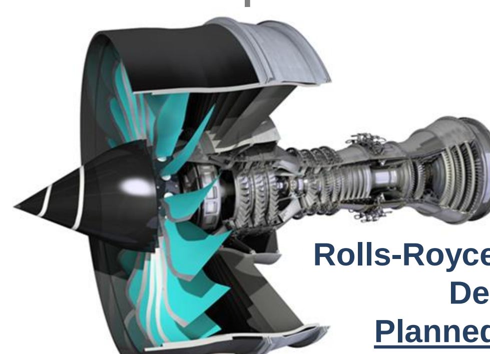
2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024

Demonstrators

Building on the success of the ALPS Engine from Clean Sky SAGE 3

Advance3 Core for the UltraFan™
Demonstration in 2018

Efficiency relative to Trent 700	20%+



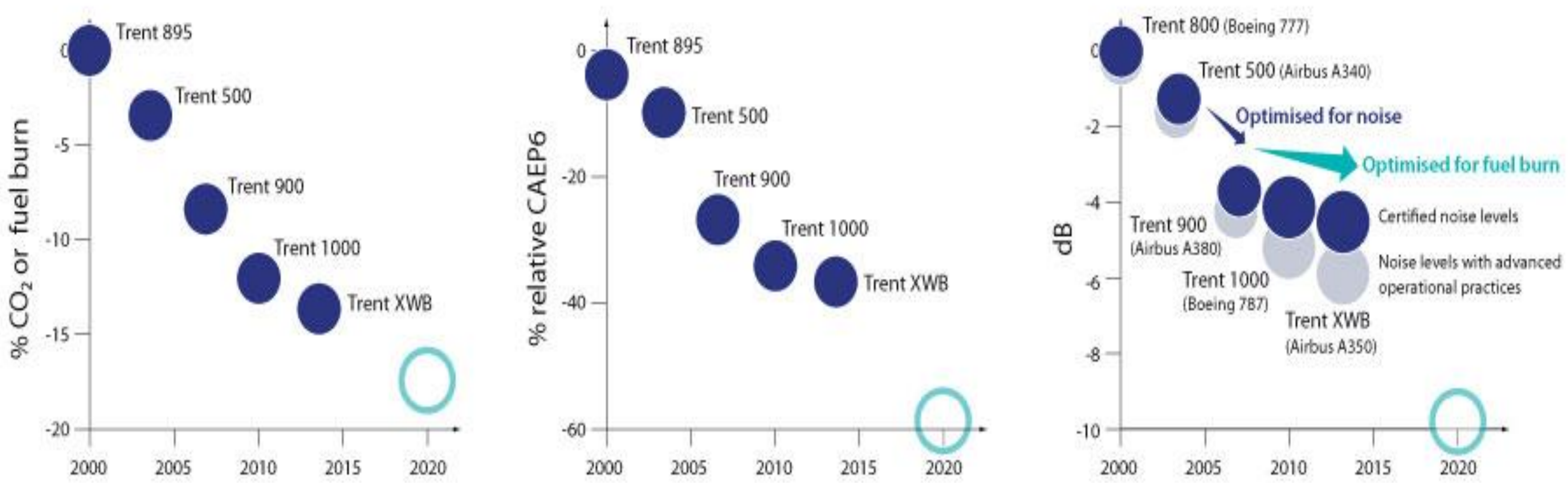
Rolls-Royce Ultrafan™ Demonstrator
Planned EIS 2025+

Efficiency relative to Trent 700	25%+
ByPass Ratio	15+

Clean Sky JOINT UNDERTAKING

Why UltraFan™?

Reducing environmental impact



Target 50% CO_2 overall reduction:
- 15-20% from engine
- 20-25% from airframe
- 5-10% from operations

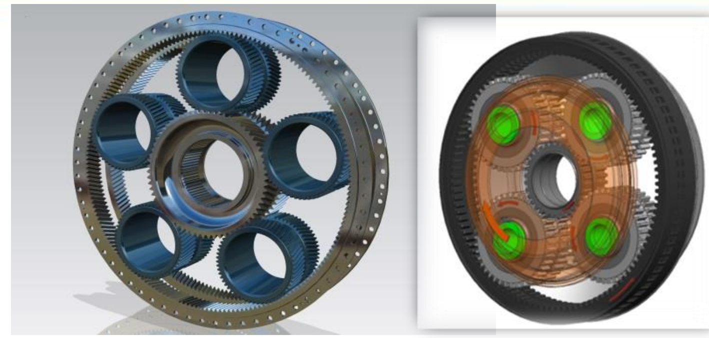
Target 80% NOx overall reduction:
- 60% from engine technology
- 20% from operational efficiency improvements

Target 50% aircraft noise reduction:
- 30dB cumulative
- 10dB average at each condition

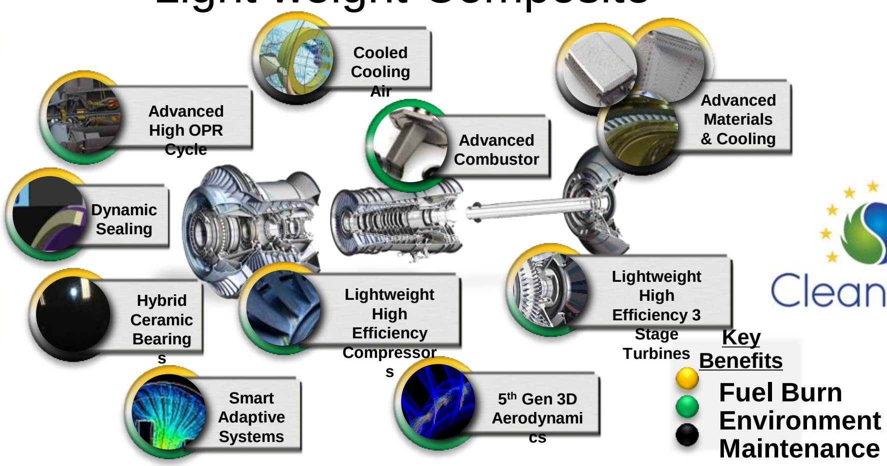
Trent family ACARE target (Advisory Council for Aeronautics Research in Europe)

UltraFan™ Foundations

Light weight Composite



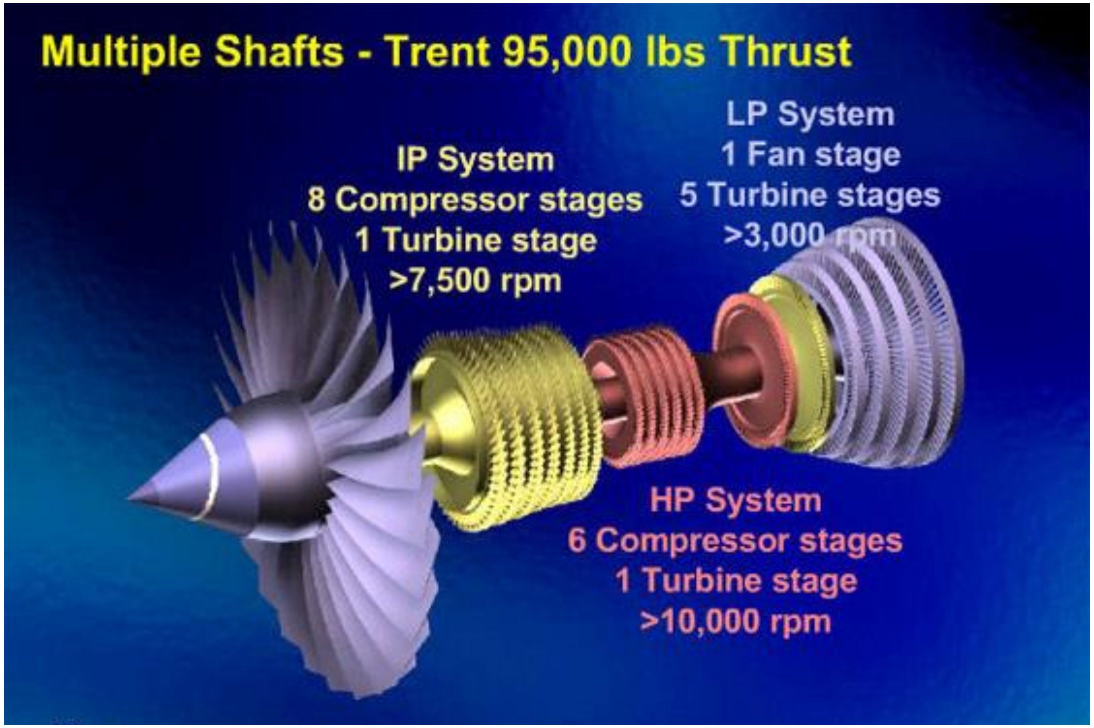
Efficient power gearbox

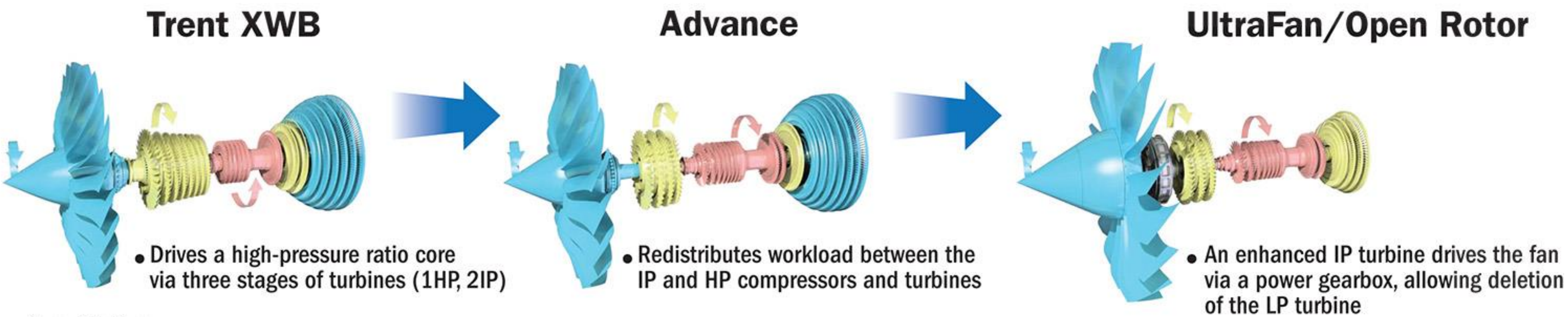


Advance – High efficiency Core

Lean Burn Combustor

3-shaft-engines -> 2 ½ shaft





Source: Rolls-Royce

The road to UltraFan™

Trent XWB	Advance	UltraFan™
Rich Burn	Lean Burn	Lean Burn
Integrated Propulsion System	Integrated Propulsion System	Integrated Slim Line Nacelle (No Thrust Reverser)
Lightweight LPT System	Lightweight LPT System	Geared Multi Stage IPT System
Hollow Ti Fan System	CTi Fan System	Variable Pitch CTi Fan System
3 Stage Turbine Core	Advance Core	Advance Core

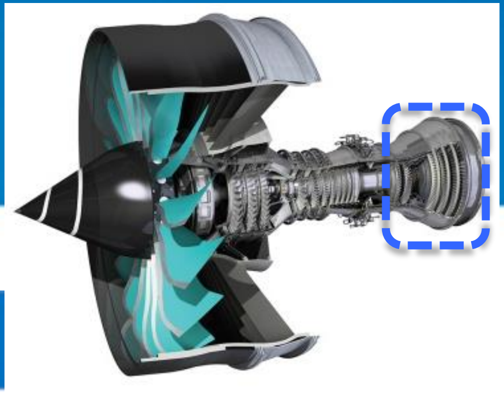
Clean Sky

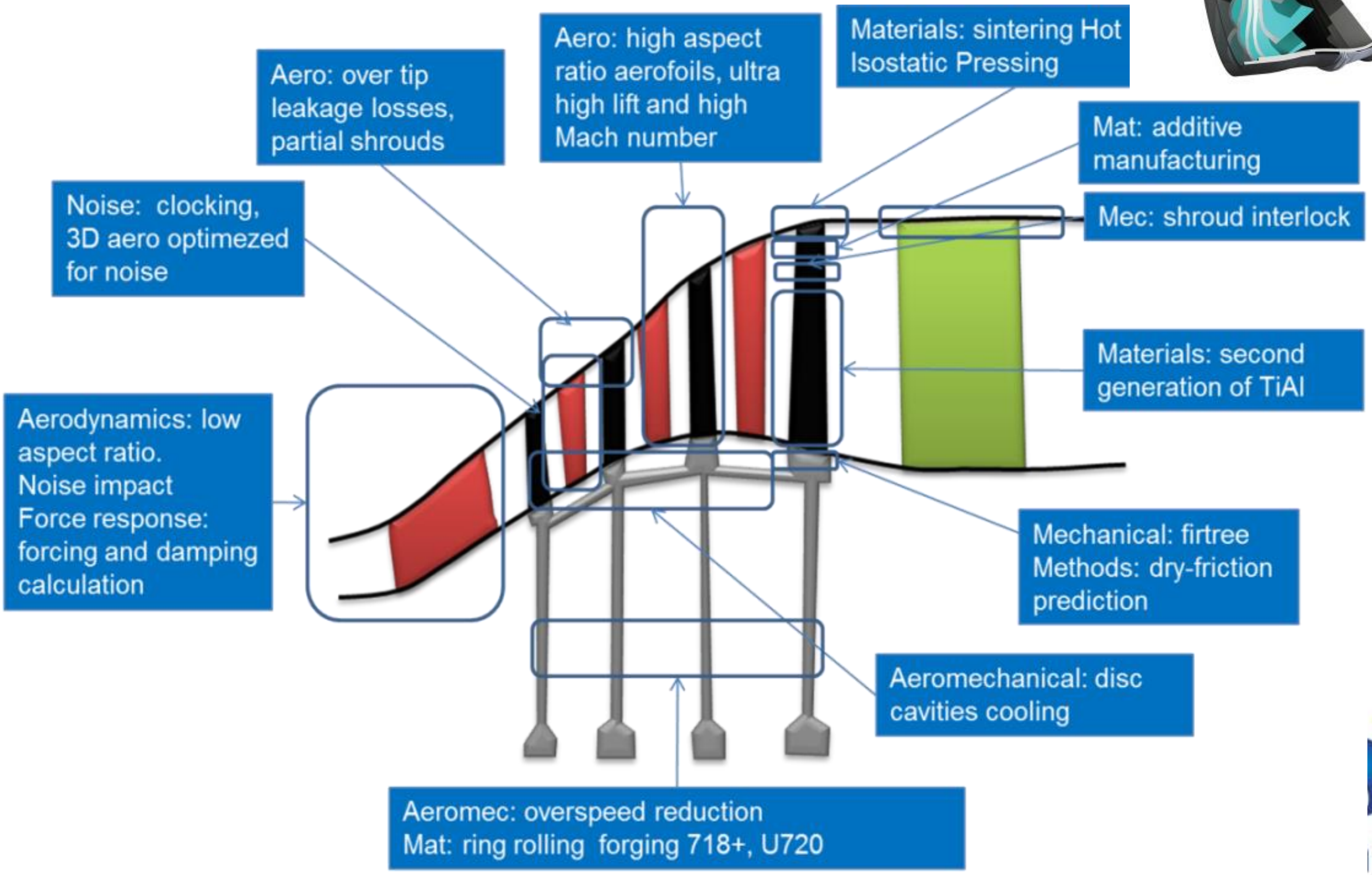
World‘s most powerful Aerospace gearbox

Successful Power Rig First Turn - May 2017

Rolls-Royce

CS2: Ultrafan™ IPT





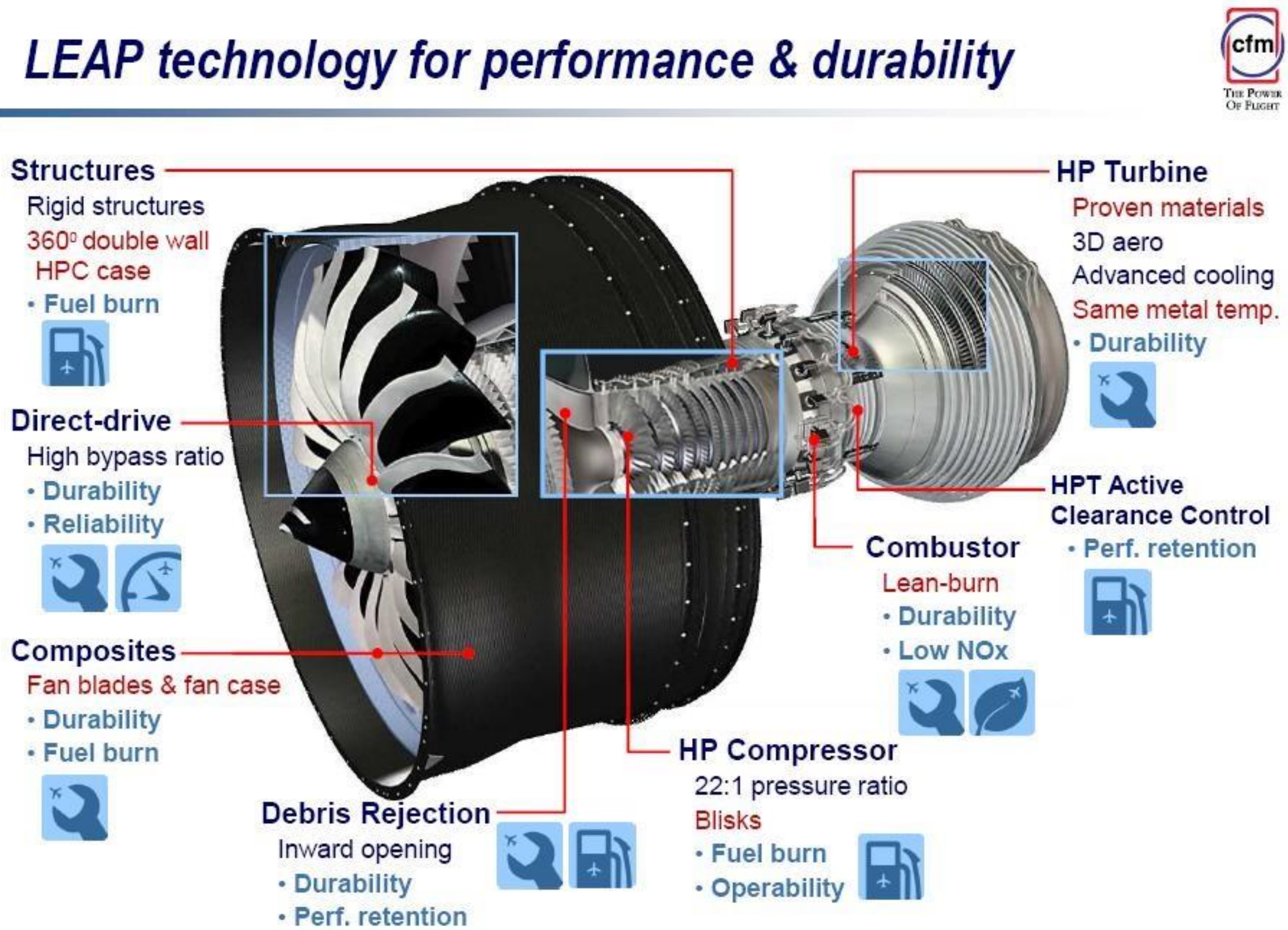
3. VHBR Turbofans

Outline

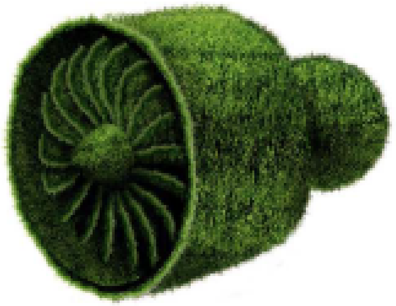
1. **Open-Rotor Architectures**
   - CS1-SAGE1 – RRUK
   - CS1-SAGE2 – SNECMA
   - CS2-LPA-(ENG-WP1) - SNECMA
2. **Large VHBR Turbofans Architectures – LR Aircraft**
   - CS1-SAGE3 – RRUK
   - CS1-SAGE6 – RRUK (Lean Burn)
   - CS2-ENG-WP5 – RRUK
   - CS2-ENG-WP6 – RRUK
3. **VHBR Turbofans – SMR Aircraft**
   - **CS2-ENG-WP2 – SNECMA - UHPE**
4. **Geared Turbofans – SMR Aircraft**
   - CS1-SAGE4 – MTU
   - CS2-ENG-WP4 – MTU
5. **Turboshaft Engines - Helicopters**
   - CS1-SAGE5 - TURBOMECA
6. **TurboProp Engines – Regional/SAT**
   - CS2-ENG-WP3 TURBOMECA
   - CS2-ENG-WP8 GE Avio
7. **Small Piston Engines – Small Air Transport (SAT)**
   - CS2-ENG-WP7 - SMA

CS2 – ENG-WP2 – Snecma

LEAP technology for performance & durability



Reference Technology Evaluator
Year 2014



9% for a new UHBR configuration

⇒ Transmission system = enabler for this architecture

⇒ Overall integration in the UHPE demo of the low speed fan, high-speed booster and turbine while reducing losses on the transmission system

Additional up to 3% thanks to new technos (WP2.1.3 & WP2.1.4)

⇒ Nacelle= ~0.6%

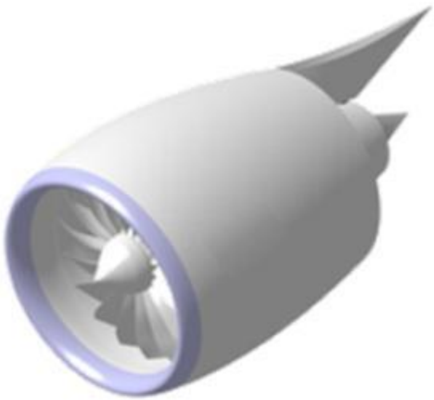
⇒ Casings GKN= ~0.2%

⇒ ~2% thanks to new techno as additive manufacturing, more electric…

Contribute to achieve NO_X emission ACARE 2020 target (- 80% vs 2000 baseline)

CS2 – ENG-WP2 – Snecma

- Ultra High Propulsive Efficiency for SMR aircraft :
  towards enhanced performance



UHBR turbofan for
SMR aircraft

Main Technology Objectives

- to validate LP modules & nacelle technologies

Key Technologies

- Low pressure ratio fan / variable area fan nozzle
- Low weight / low drag fixed or rotating structures and nacelle.
- High power gear box
- High efficiency LP turbine & LP compressor
- Engine / aircraft specific integration

Potential Partner participation:

- Fixed structures in propulsive system, low pressure turbine components, controls and systems components, shafts, bearings

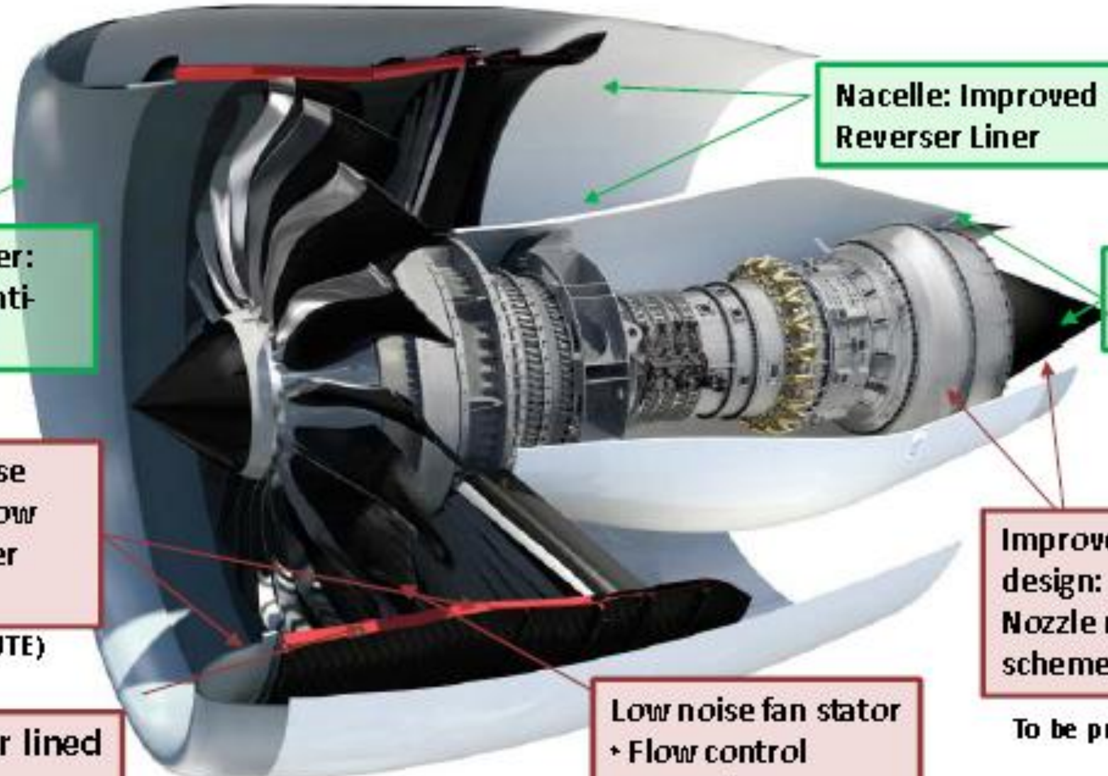
Snecma proprietary data

Clean Sky JOINT UNDERTAKING

Propulsion System: Overview of Noise Reduction Technologies

TRL 5-6

TRL 4



Nacelle: Improved Reverser Liner

Nacelle Lip Liner: Acoustic and anti-icing concept

- Treated Composite Plug and Nozzle

Engine Fan Case &Fan Frame Low Frequency liner concept

ENG – CfP07 (SALUTE)

Improved Plug and Nozzle design: Integrated Comb /Tu / Nozzle noise prediction scheme

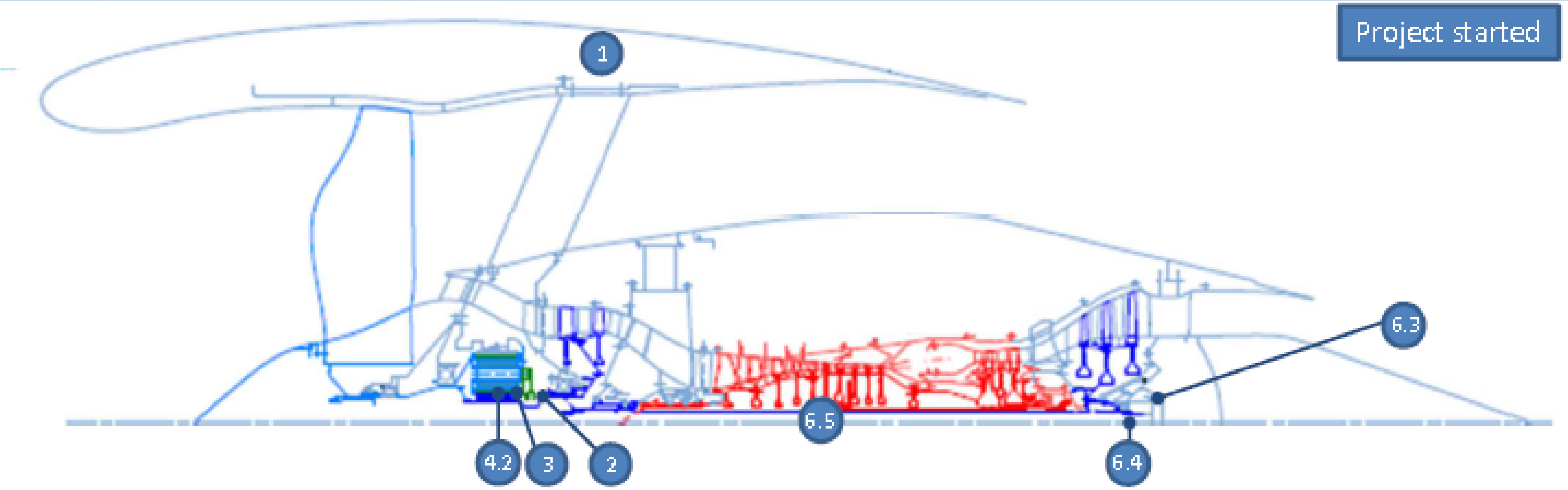
To be proposed in future LPA – CfP

Over the rotor lined panel

Low noise fan stator
- Flow control concept
- Treated OGV
- Low Count penalty offset

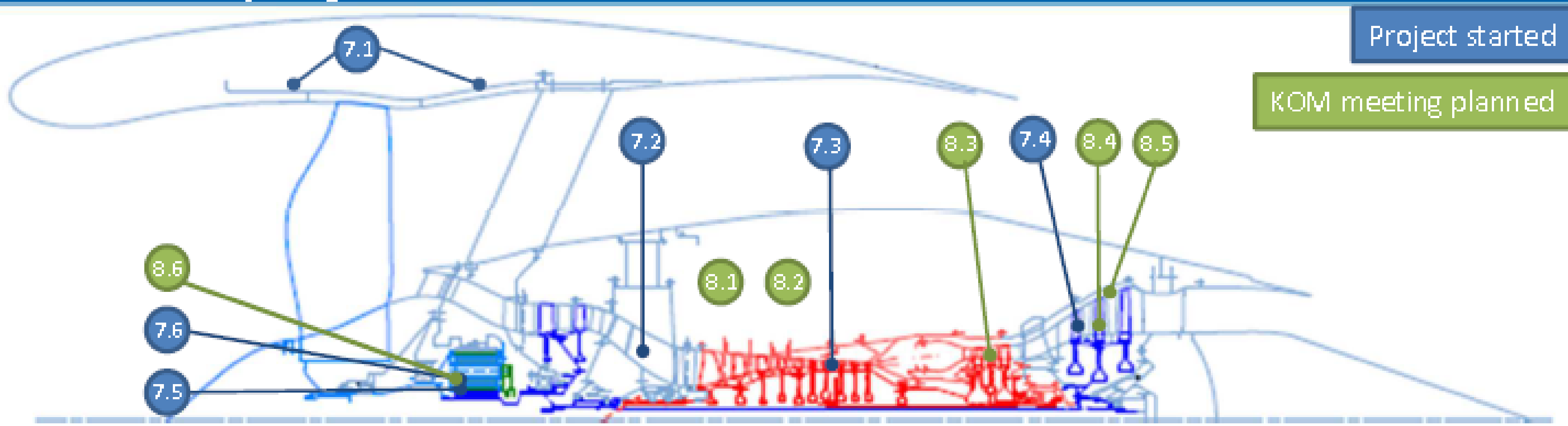
LPA – CfP09

WP2 CfP projects



N°	Title	WP	Lead	Project	leader	country	status
1	Engine Mounting System (EMS) for Ground Test Demo	2.5.6	Safran AE	EMS UHPE	LORD	Switzerland	●
2	Conventional and Smart Bearings for Ground Test Demo	2.3.5	Safran AE	UHPE	FAG	Germany	●
3	High loaded planet bearings techno	2.3.4	GE Avio	PROBATE	SKF	France	●
4.2	High load gear and bearings materials	2.3.4	GE Avio	HILOGEAR	AM Testing	Italy	●
6.3	Advanced turbine system performance improvement through dual-spool rig tests	2.4.1	GE DE	TRAVIATA	TECHNISCHE UNIVERSITAET GRAZ	Austria	●
6.4	Bearing chamber in hot environment	2.3.6	Safran AE	AMBEC	STCU	Ukraine	●
6.5	Development of innovative methods and tooling for machining of slender shafts	2.3.3	GKN	BBT	TEKNIKER	Spain	●

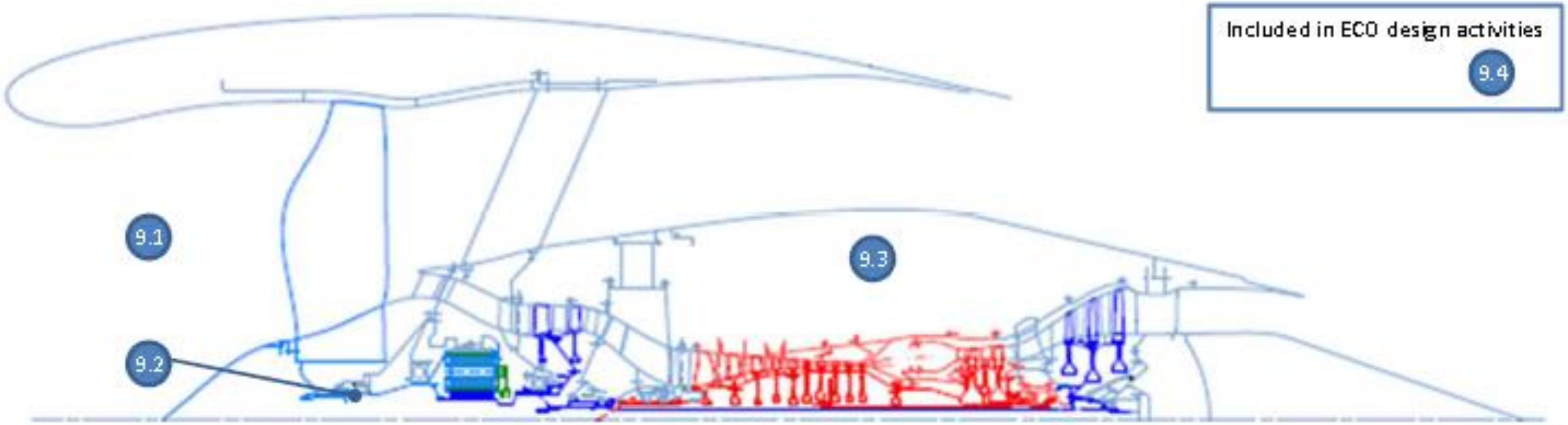
WP2 CfP projects



Nº	Title	WP	Lead	Project	Leader	Country	Status
7.1	Innovative acoustic fan frame liners technologies for UHBR	2.2.1	Safran AE	SALUTE	ECL	France	●
7.2	Composite process modelling, net-shape, complex geometry RTM tool design	2.2.6	GKN	ProTHIC	Swerea SICOMP	Sweden	●
7.3	Innovative HPC Flow Treatment Technologies	2.6.1	GE DE	FloCoTec	TUM	Germany	●
7.4	Improvement of LP Turbine performance	2.4.2	Safran AE	SPLEEN	VKI	Belgium	●
7.5	Crowned spline surface treatment and modelling	2.2.3	Safran TS	CROSSONT	WZL der RWTH Aachen	Germany	●
7.6	Gearbox bearing design and testing	2.2.3	Safran TS	BREATHE	SKF	France	●
8.1	Variable restrictions for pressure control	2.5.1	Safran AE				
8.2	Oil flow 4 channels regulation valves	2.5.1	Safran AE				
8.3	Optimized UHPE flow path cooling design and testing using advanced manufacturing techniques	2.4.1	GE DE				
8.4	Characterization of flow through rotating labyrinth seals	2.4.2	Safran AE				
8.5	Optimizing impingement cooling	2.4.2	Safran AE				
8.6	Analysis of high frequency vibrations from a Gear Box in an Engine env. by SEA	2.3.6	Safran AE				

Implementation agreements under preparation

WP2 CfP projects



Nº	Title	WP	Lead	Project	Leader	Country	Status
9.1	Ground vortex caracterization & simulation	2	Safran AE	Call 9 => Call open on CS2JU website			
9.2	Measurement of rotor vibration using tip timing for high speed booster certification and quantification of associated uncertainties	2	Safran AB				
9.3	Turbulence modelling of heat exchange and roughness impact	2	Safran AB				
9.4	Additive manufacturing boundary limits assessment for Eco design process optimization (ECO)	2	Safran AB				

Clean Sky

4. Geared Turbofans

Outline

1. **Open-Rotor Architectures**
   - CS1-SAGE1 – RRUK
   - CS1-SAGE2 – SNECMA
   - CS2-LPA-(ENG-WP1) - SNECMA
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   - CS2-ENG-WP4 – MTU
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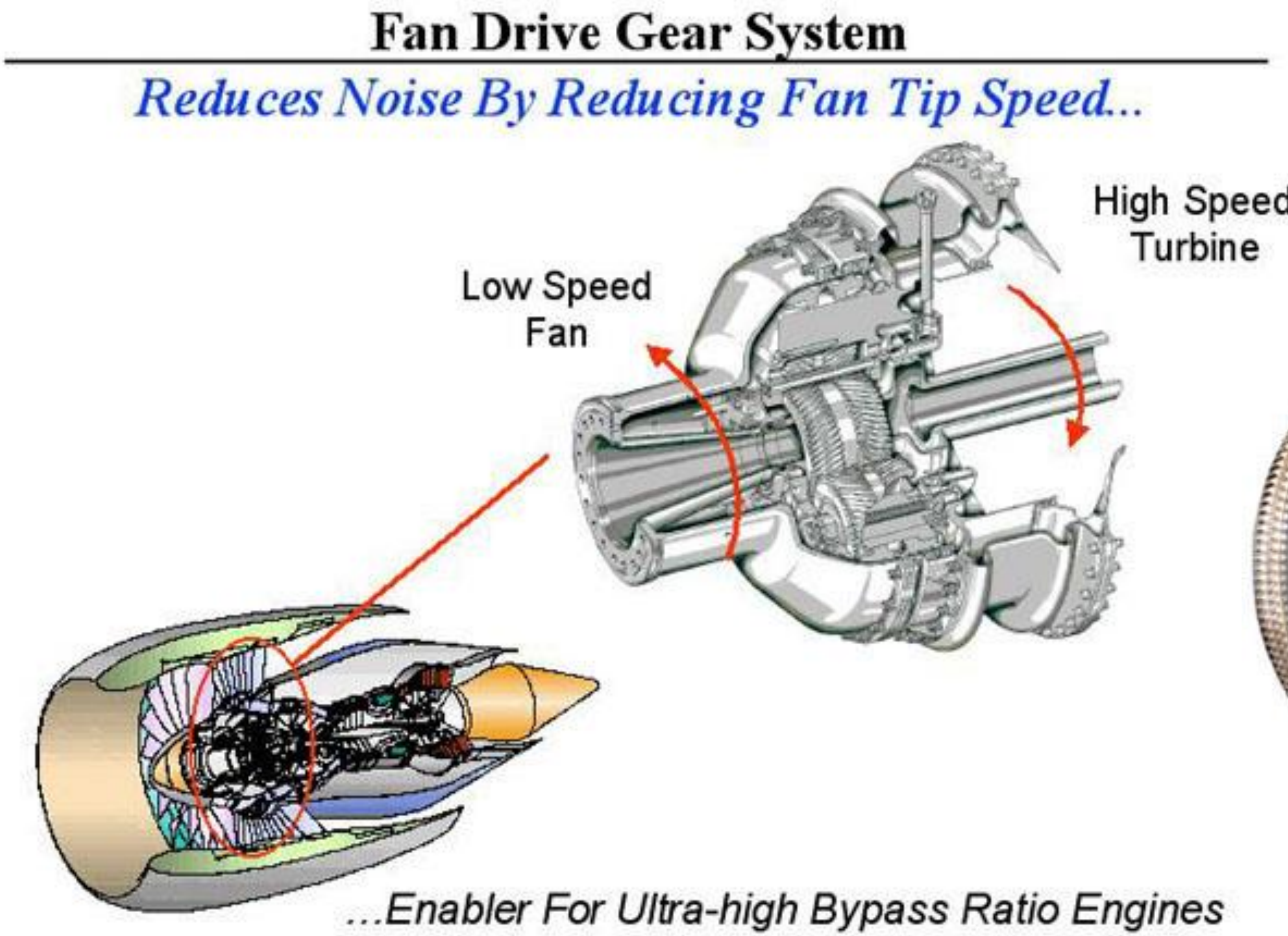
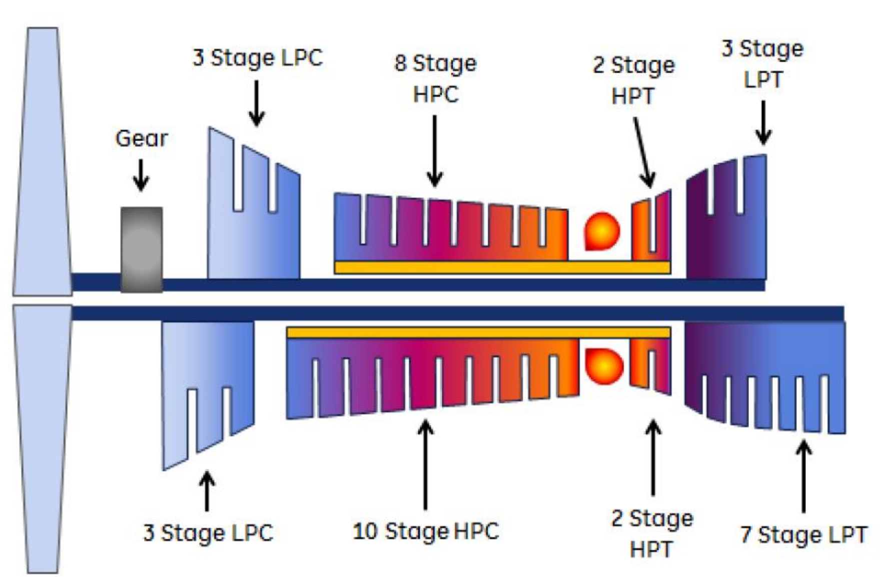
   - CS2-ENG-WP3 TURBOMECA
   - CS2-ENG-WP8 GE Avio
7. **Small Piston Engines – Small Air Transport (SAT)**
   - CS2-ENG-WP7 - SMA

Reduction Gear Box



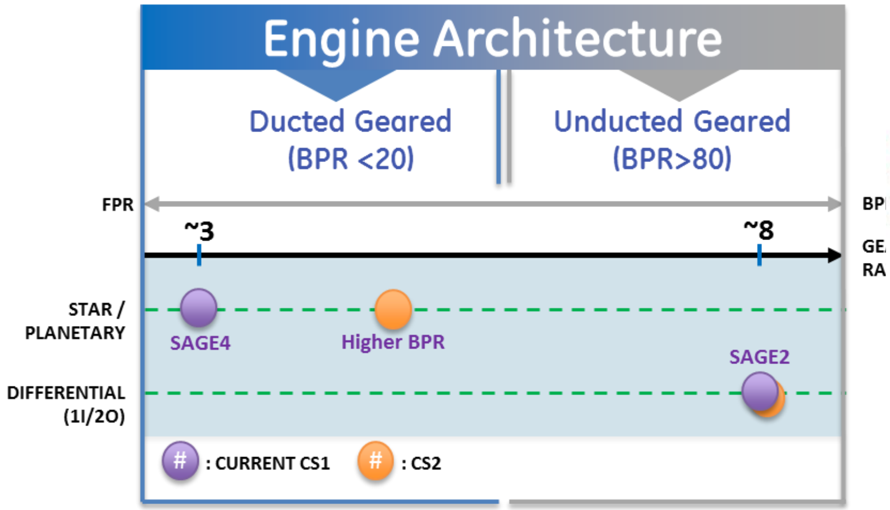
Next Generation Engines – Gear Box

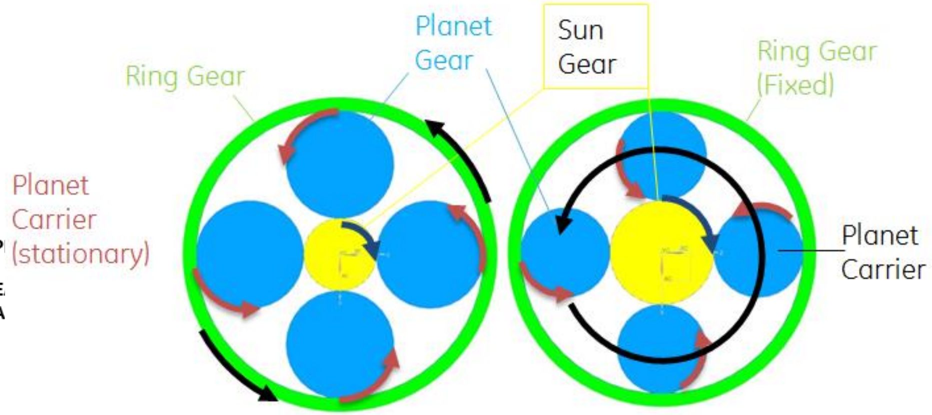


Architectural Change

(decoupling of LPT – Propulsive Element speeds)

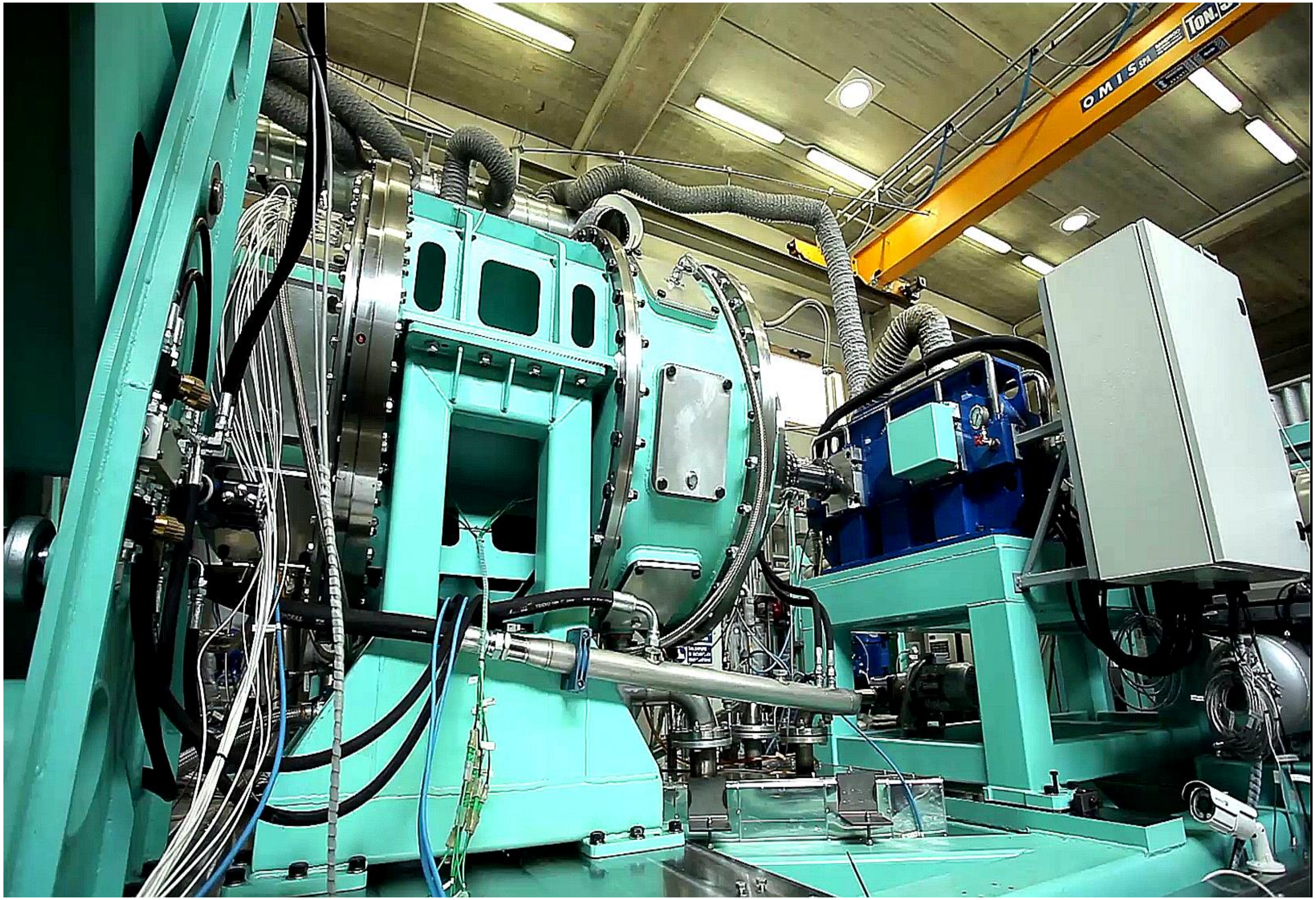
- Enables higher BPR than conventional solutions
- Lower number of HPC & LPT stages → better Life Cycle Cost
- Gearbox is a new enabling core module
- Speeds optimization includes gearbox module (Gear Ratio → size, weight)





Star (Left) and Planetary (Right)

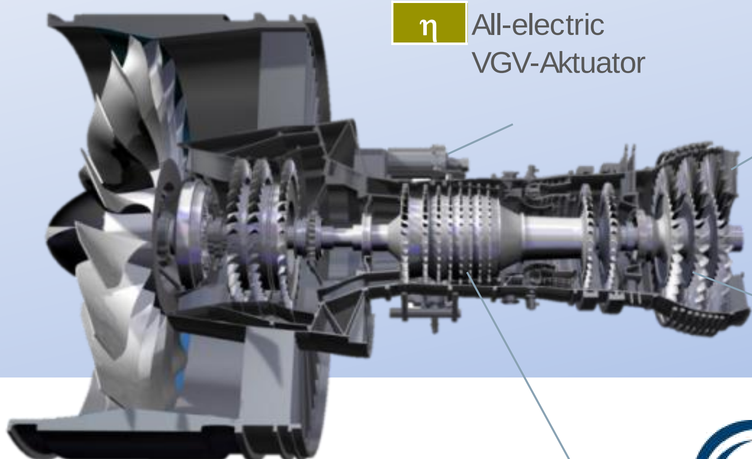
Differential: both ring and Carrier rotates



Clean Sky
JOINT UNDERTAKING

CS1 – SAGE4 – MTU

Clean Sky SAGE 4 Demonstrator testing successfully completed in Dec-2016



η All-electric VGV-Aktuator

Life leightweight TEC
dB Acoustic liner

GKN AEROSPACE

MTU Aero Engines

Turbine Technology

η	improved outer cavity design
η	advanced case design
η	new IAS designs
η	smart ACC
η	optimized airfoil shape
η	improved trim balancing
lb	frequency mistuned airfoils
lb	CMC segments
Life	TiAl blade technology

Avio Aero
A GE Aviation Business

η Integrated Drive System Technology
tested on a specific transmission test bench

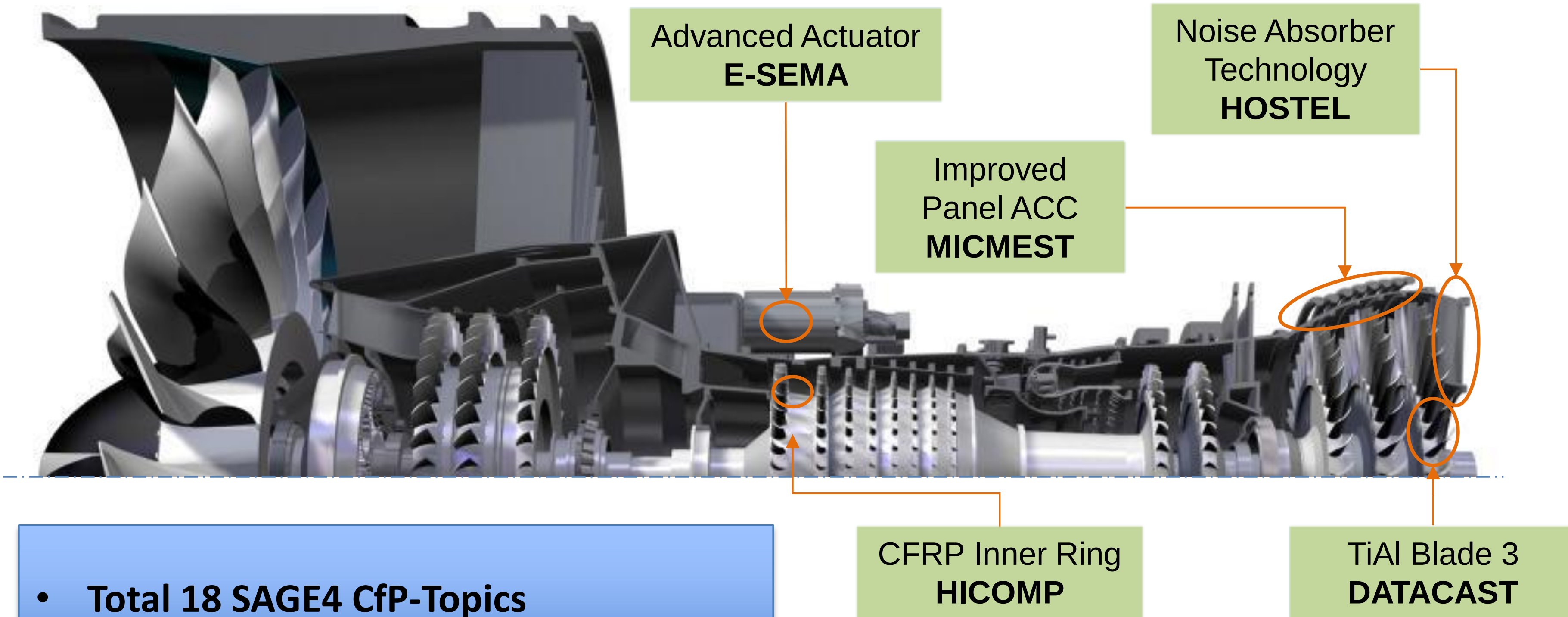
Compressor Technology

η	Surface treament
Life	Erosion protection
€	new Materials (CFRP)
€	Additive Maufacturing
€	New measurement methods

MTU Aero Engines

Clean Sky

CfP projects included in SAGE 4 demonstrator



- **Total 18 SAGE4 CfP-Topics**
- **28 Partner (Unis, RI, SMEs)**

CS1 SAGE4 CfP – HIGHCOMP

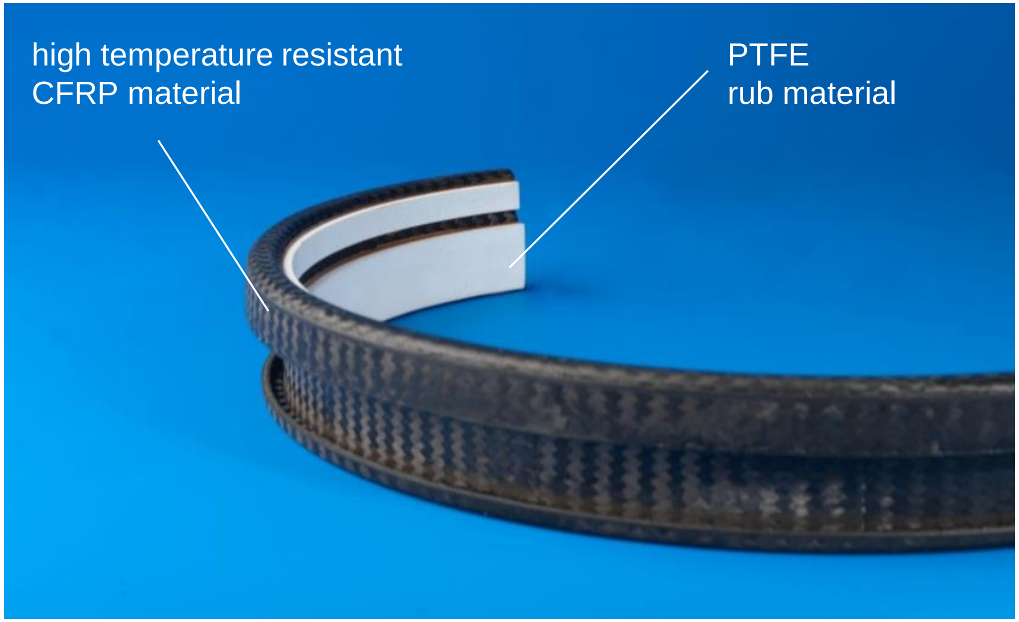
Lightweight CFRP design of HPC inner air seals CfP project HICOMP in cooperation with Cobham, UK

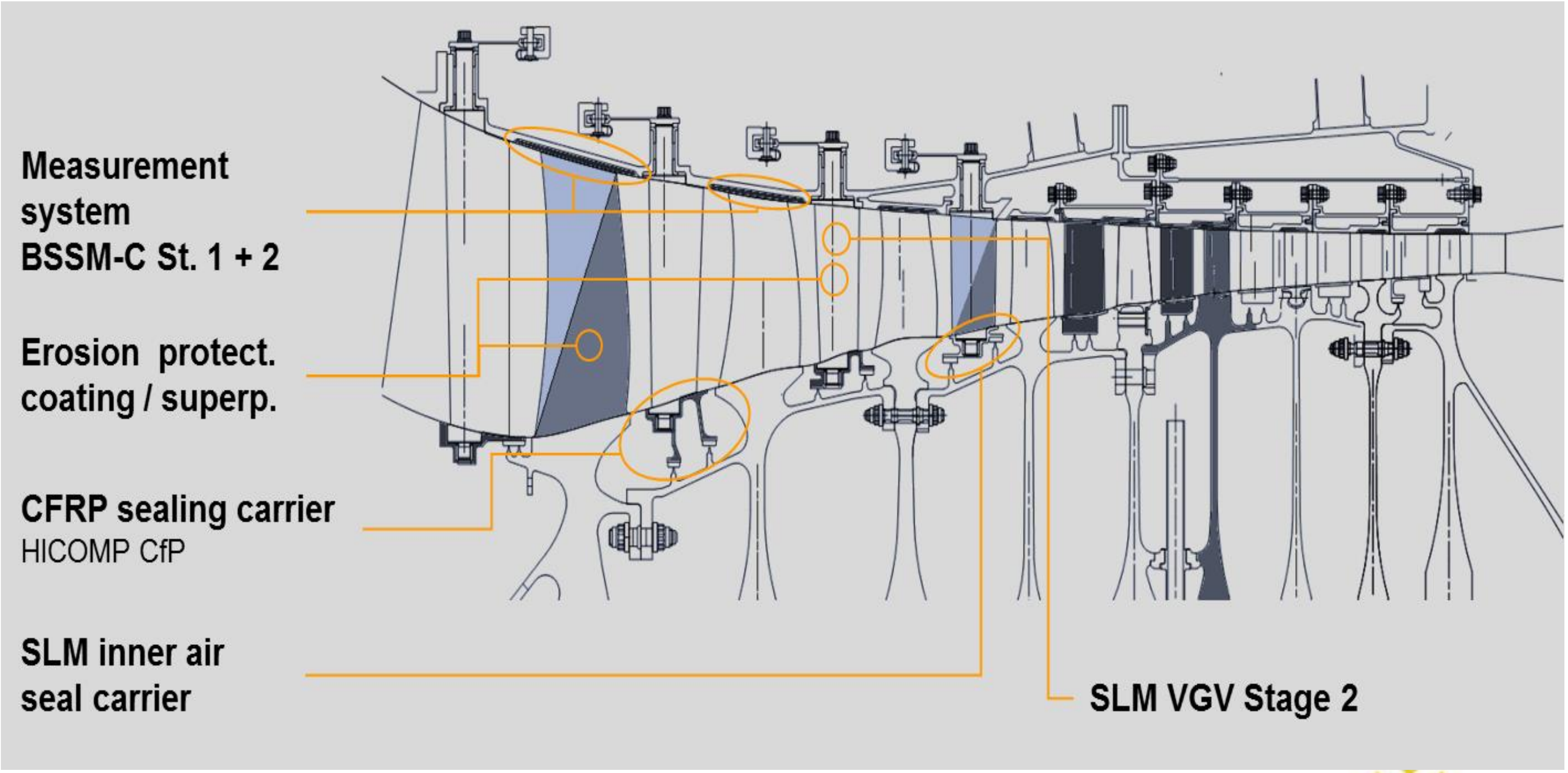
Targets:

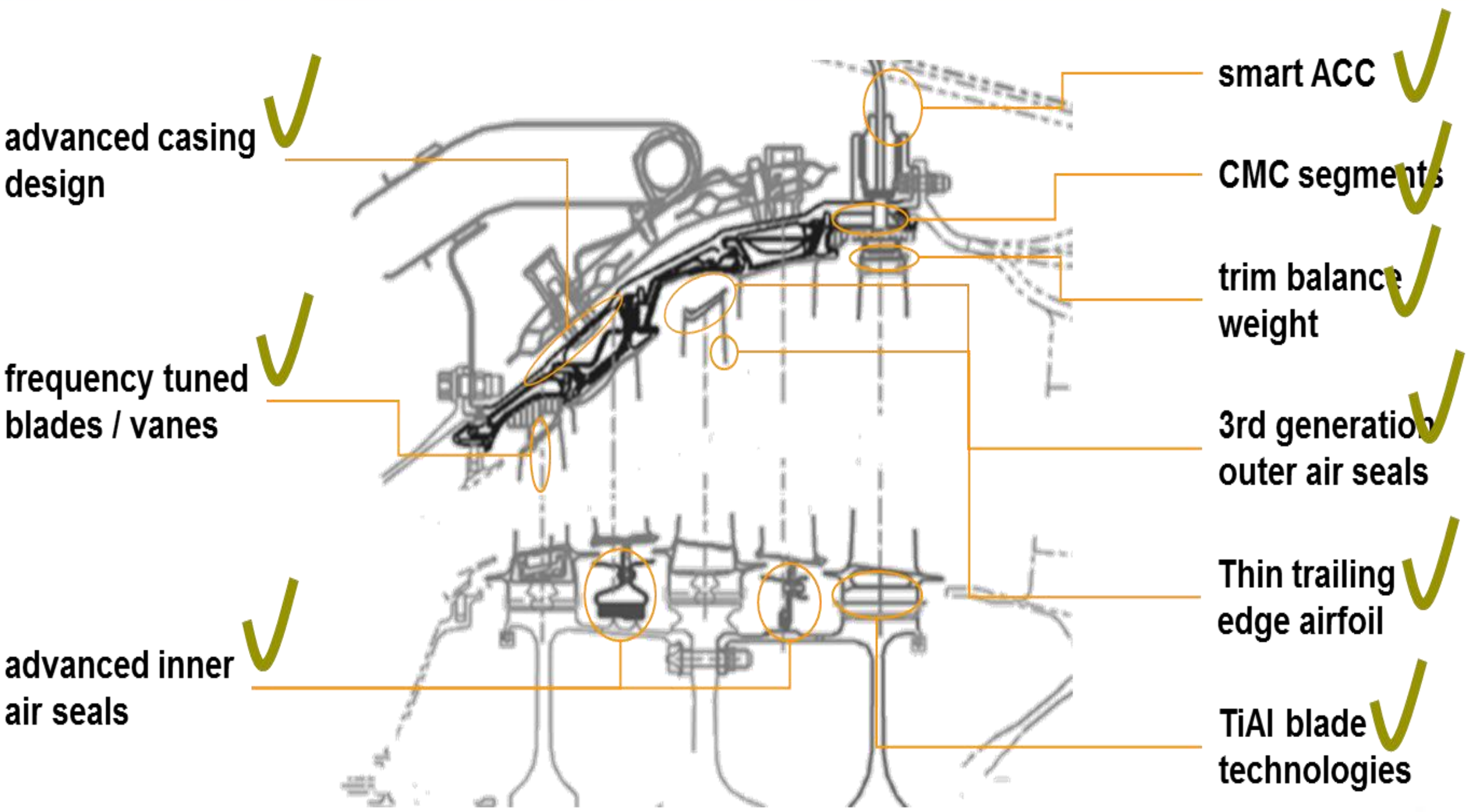
- Significant reduction of the weight of the static inner air seals
- Improvement of the vibrational behavior of the coupled variable guide vane - IAS system

Result:

- ultra light, high temperature resistant seal carrier design
- geometry adapted to the peculiarities of the CFRP material




Measurement system BSSM-C St. 1 + 2
Erosion protect. coating / superp.
CFRP sealing carrier
HICOMP CfP
SLM inner air seal carrier
SLM VGV Stage 2



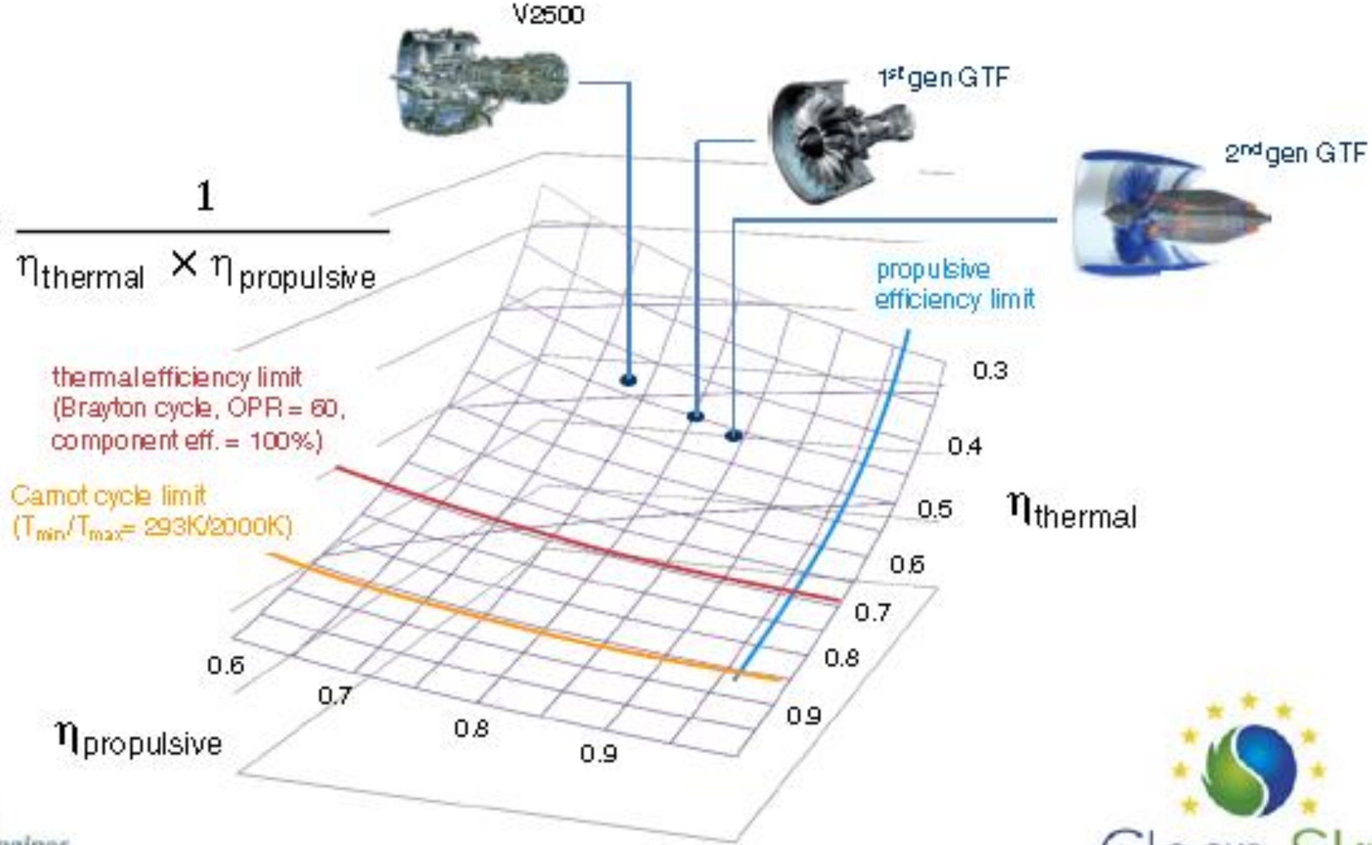
MTU Aero Engines

Clean Sky


MTU
Aero Engines

Clean Sky SAGE 4 technologies will be included in all upcoming engine developments leading to a 2nd gen GTF engine

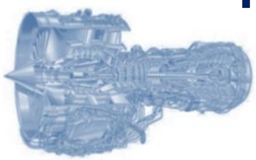
$$SFC \approx \frac{1}{\eta_{thermal} \times \eta_{propulsive}}$$



CS2 – ENG-WP4 – MTU

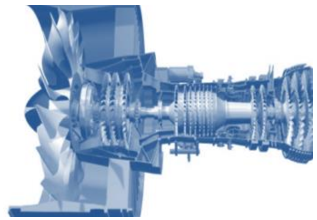
Technology maturation for future engine generations …

BPR 5
OPR 36
V2500



- 15%

BPR 12
1st gen GTF



ΔSFC %
ΔCO_2 %

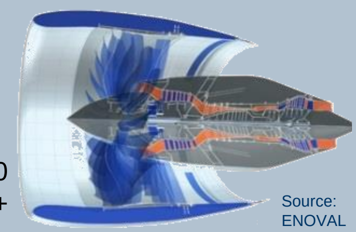
- 25%

Future Geared Fan Engines

Performance Parameters

η	lb	Life	€	dB

Clean Sky 2
Notional Engine Concept



BPR 14-20
OPR 60+

Source: ENOVAL

WP 4 Partner

MTU Aero Engines
GKN AEROSPACE
DLR

Clean Sky 2
Advanced Technology Projects

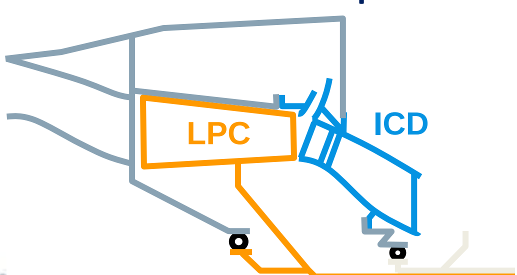
Compression System

Expansion System

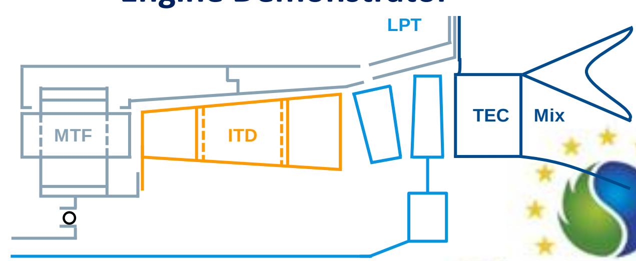
Design
Materials
Manufacturing

Technology Validation →

2 Shaft Compression Rig



Engine Demonstrator



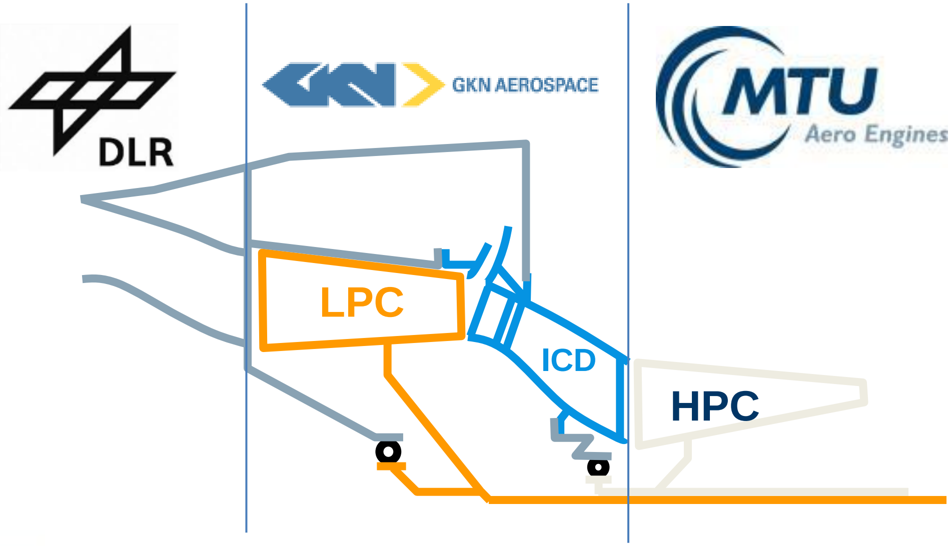
MTU Aero Engines

Clean Sky

ENG WP4 Compression System

Integrated development of technologies for compression systems

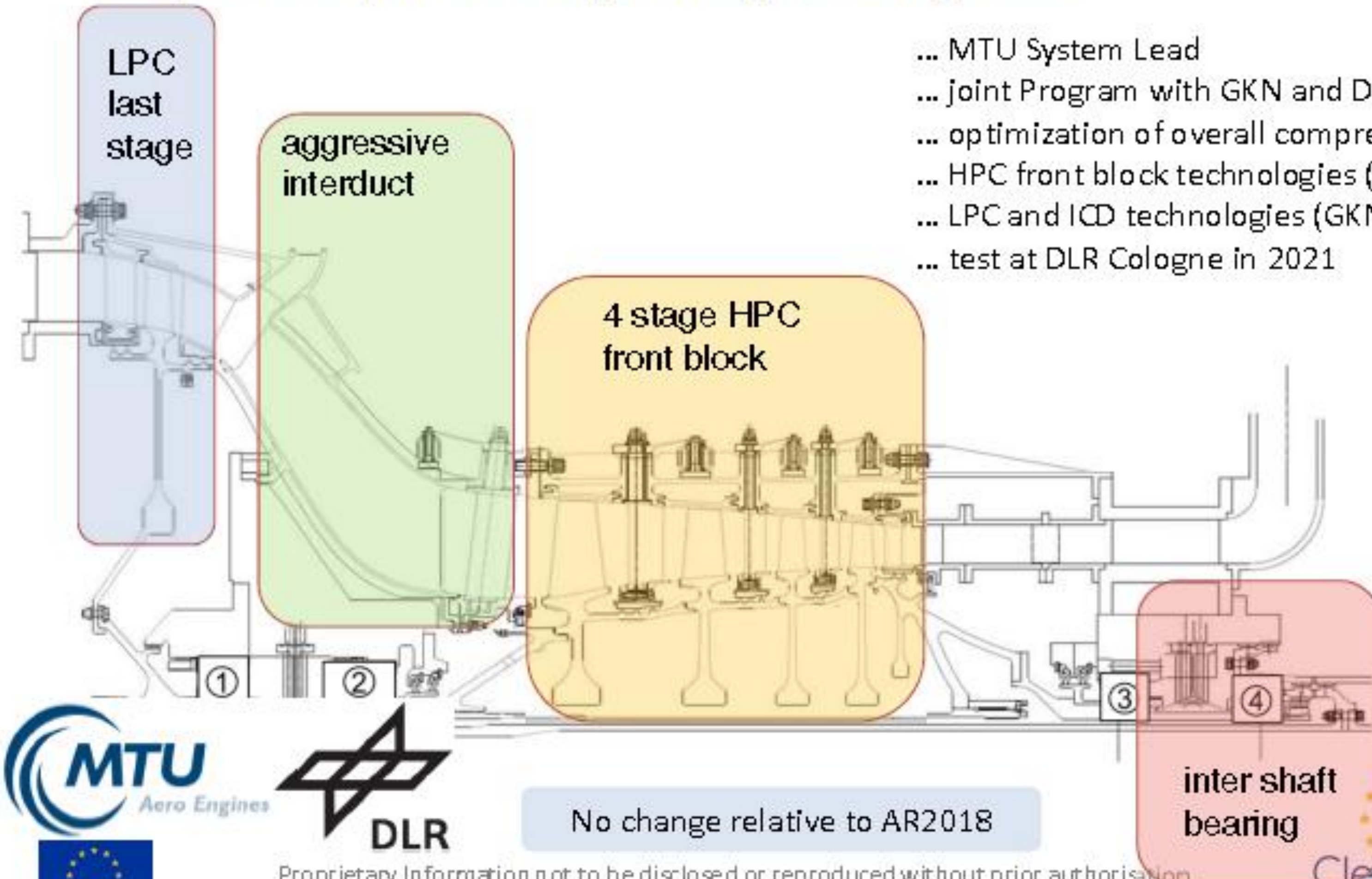
- Enable future geared fan engines with significantly improved performance parameters
- Main Focus: integrated optimization of LPC, ICD and HPC
- Technologies are demonstrated through campaigns at DLR, GKN and MTU



WP4.2 and WP4.3 - Compressor and Rig Design

2-Spool Compressor Rig concept – At a glance

- ... MTU System Lead
- ... joint Program with GKN and DLR
- ... optimization of overall compression system
- ... HPC front block technologies (MTU)
- ... LPC and ICD technologies (GKN)
- ... test at DLR Cologne in 2021



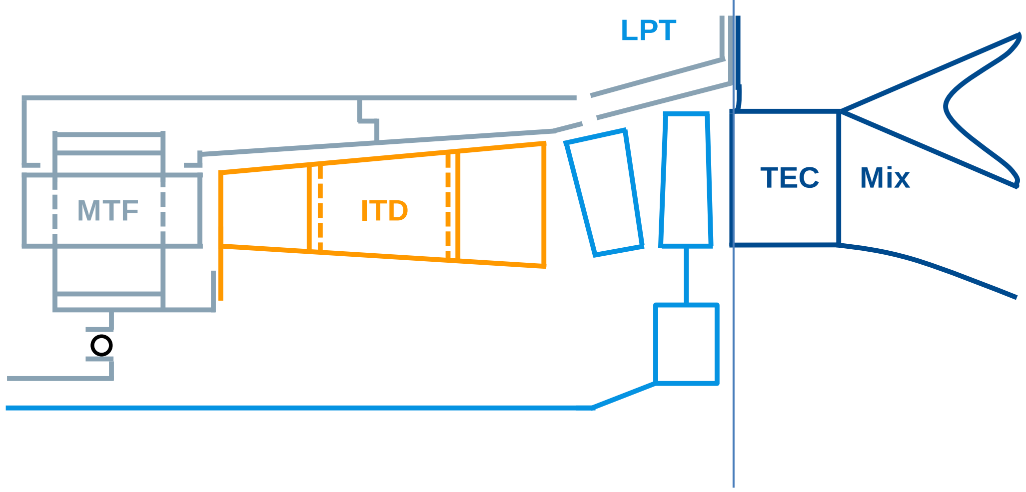
No change relative to AR2018

WP4 Expansion System Demo.

Engine demonstrator for validation …

… of developed hot section technologies

- validation of advanced designs and materials
- validation of new manufacturing technologies



WP4.4 and WP4.5 - Demonstrator Engine

Demonstrator Engine
MTR390-2C

- Initial Review (Start Concept Phase) passed in February 2016
- Concept Review (Mid Concept Phase) passed in November 2017
- Preliminary Design Review (End of Concept Phase) passed in May 2018
- Critical Design Review (End of Detail Design) rescheduled for Q3 2019

GKN AEROSPACE

GKN Technology portfolio:

- Durability of alternative materials
- Durability of different types of joints
- Durability of additive manufactured engine structural components

MTU Aero Engines

η		HTSX – Blade
€		AD730 - Disc
η		Adv. Brush Seal
€		AM Inconel
Ib	η	CMC - ITD (CfP)

Technologies and level 1 plan unchanged relative to AR2018

Clean Sky 2

5. Turboshaft Engines

Outline

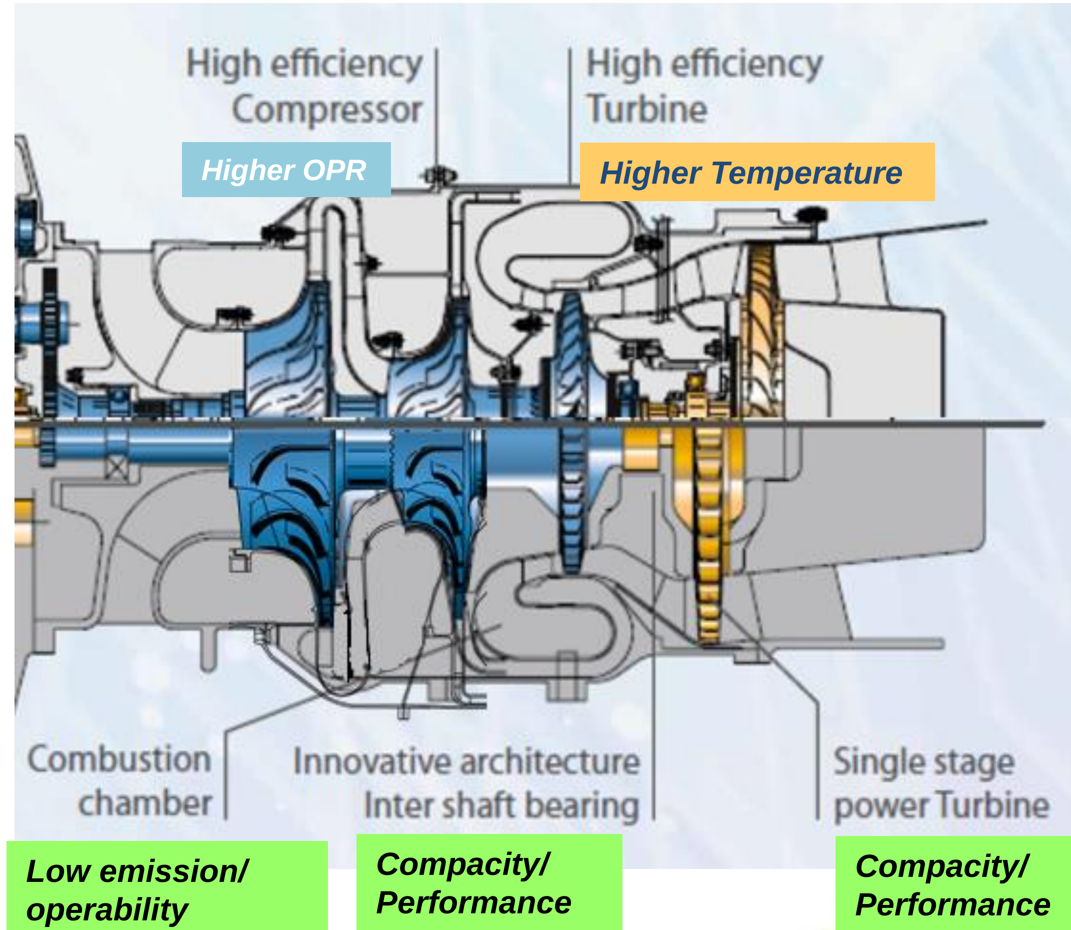
1. **Open-Rotor Architectures**
   - CS1-SAGE1 – RRUK
   - CS1-SAGE2 – SNECMA
   - CS2-LPA-(ENG-WP1) - SNECMA
2. **Large VHBR Turbofans Architectures – LR Aircraft**
   - CS1-SAGE3 – RRUK
   - CS1-SAGE6 – RRUK (Lean Burn)
   - CS2-ENG-WP5 – RRUK
   - CS2-ENG-WP6 – RRUK
3. **VHBR Turbofans – SMR Aircraft**
   - CS2-ENG-WP2 – SNECMA - UHPE
4. **Geared Turbofans – SMR Aircraft**
   - CS1-SAGE4 – MTU
   - CS2-ENG-WP4 – MTU
5. **Turboshaft Engines - Helicopters**
   - **CS1-SAGE5 - TURBOMECA**
6. **TurboProp Engines – Regional/SAT**
   - CS2-ENG-WP3 TURBOMECA
   - CS2-ENG-WP8 GE Avio
7. **Small Piston Engines – Small Air Transport (SAT)**
   - CS2-ENG-WP7 - SMA

CS1- SAGE 5 DEMONSTRATOR - INNOVATIVE CORE ENGINE

- **Project launched in 2008**

- **Design a totally new core engine called TECH800 for 800-1000 kW range allowing to :**
  - **Reduce by 15% Fuel Consumption**
  - **Reduce overall dimension and weight**
  - **Highlight possible production and maintenance cost reduction axis**

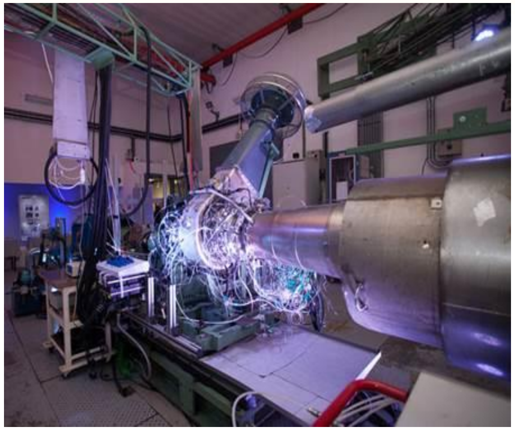
- **REACH TRL 6**



Clean Sky

CS1- SAGE 5 - DEMONSTRATOR PLAN

A demonstration in 3 steps:



- Components Partial Rig tests
  - Compressor, combustion chamber, HP turbine, LP turbine and dynamic shaft architectures
- Engine test in build 1 configuration : partial Turbine Entry Temperature
  - Validation of the mechanical architecture
  - Validation of starting phase
  - Performance test

FETT in February 2013

- Engine test in build 2 configuration : Max Turbine Entry Temperature
  - Performance test
  - New equipment (more electric) validation
  - Pollutant emission measures

FETT in June 2014

Clean Sky

From Demonstrator to Market !

Arrano

1 100 à 1 300 shp

L'Arrano est le nouveau moteur de Safran Helicopter Engines positionné sur une gamme de puissance allant de 1 100 à 1 300 shp. Il a été conçu pour équiper les monomoteurs de 2 à 3 tonnes et les hélicoptères bimoteurs de 4 à 6 tonnes.

Réduction de 10 à 15% de la consommation de carburant

L'un de ses principaux avantages est de permettre une réduction de la consommation spécifique de carburant de 10 à 15 % par rapport aux moteurs de la précédente génération.

L'Arrano contribue ainsi significativement à une augmentation des performances, en matière d'autonomie et de charge utile, des hélicoptères de nouvelle génération, et à une réduction de leur empreinte environnementale. L'Arrano se distingue également par un encombrement réduit et par une conception qui facilite et minimise les opérations de maintenance et de réparation.

10 à 15 %

DE RÉDUCTION DE LA CONSOMMATION EN CARBURANT

2019 : entrée en service

Clean Sky

L'Arrano, un descendant du programme Clean Sky

Le moteur Arrano intègre de nombreuses innovations techniques, validées en partie par le biais du démonstrateur technologique Tech 800 qui est le précurseur du coeur thermodynamique de l'ARRANO.

Le Tech 800 est le fruit d'un programme de recherche qui a reçu des financements de la Commission Européenne, par le biais de Clean Sky, un partenariat public-privé entre l'Europe et l'Industrie Aéronautique Européenne.

Pour le développement du Tech 800, Safran Helicopter Engines *a travaillé en coopération avec 34 partenaires, dont 18 PME et 12 universités et centres de recherche, issus de dix pays européens.*

Ce démonstrateur technologique de 1 100 shp a réalisé ses premiers essais au banc en avril 2013.

Clean Sky

Création de pièces par fabrication additive

L'Arrano est également l'un des premiers moteurs d'hélicoptère à utiliser des pièces réalisées en fabrication additive. Les moteurs de série disposeront ainsi d'une chambre à combustion dont les injecteurs sont réalisés par fusion laser sur lit de poudre métallique. Ce procédé permettant d'obtenir des pièces de forme complexe en un temps record.

Premier vol en 2016

L'Arrano a réalisé son premier essai au banc, dans l'usine de Bordes, en février 2014.Il a réalisé son premier vol, le H160 d'Airbus Helicopters en juin 2016.

L'Arrano est le moteur le plus innovant et performant de sa catégorie. Il incarne l'expertise de pointe et le savoir-faire technologique développé par Safran Helicopter Engines depuis des années, et est à ce jour sans équivalent.

Arrano 1A


H160 POWERED BY Arrano
9 February 2018 – Bordes
80 ans
AIRBUS
SAFRAN

6. Turboprop Engines

Outline

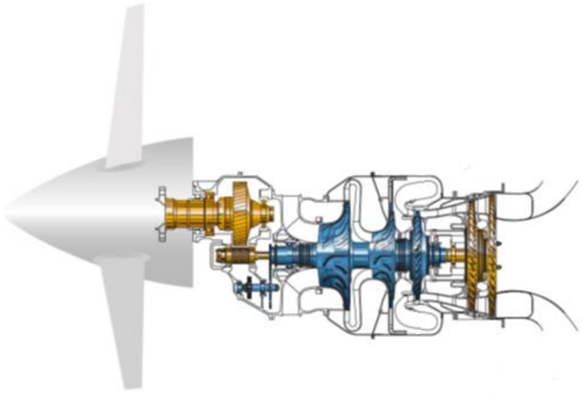
1. **Open-Rotor Architectures**
   - CS1-SAGE1 – RRUK
   - CS1-SAGE2 – SNECMA
   - CS2-LPA-(ENG-WP1) - SNECMA
2. **Large VHBR Turbofans Architectures – LR Aircraft**
   - CS1-SAGE3 – RRUK
   - CS1-SAGE6 – RRUK (Lean Burn)
   - CS2-ENG-WP5 – RRUK
   - CS2-ENG-WP6 – RRUK
3. **VHBR Turbofans – SMR Aircraft**
   - CS2-ENG-WP2 – SNECMA - UHPE
4. **Geared Turbofans – SMR Aircraft**
   - CS1-SAGE4 – MTU
   - CS2-ENG-WP4 – MTU
5. **Turboshaft Engines - Helicopters**
   - CS1-SAGE5 - TURBOMECA
6. **TurboProp Engines – Regional/SAT**
   - CS2-ENG-WP3 TURBOMECA
   - CS2-ENG-WP8 GE Avio
7. **Small Piston Engines – Small Air Transport (SAT)**
   - CS2-ENG-WP7 - SMA

Clean Sky
JOINT UNDERTAKING

CS2 – ENG-WP3 – Turbomeca

- Ground demonstration of a full Integrated Power Plant System
  - Including Air Intake & nacelle
  - Taking advantage of the FADEC for enhanced system controls capabilities

- The core generator is derived from the ARDIDEN 3 Turboshaft engine
  - Engine adaptations will be studied for matching TP usage



- New propeller and Power Gear Box will be designed

Clean Sky
JOINT UNDERTAKING

WP3 Technology Roadmap

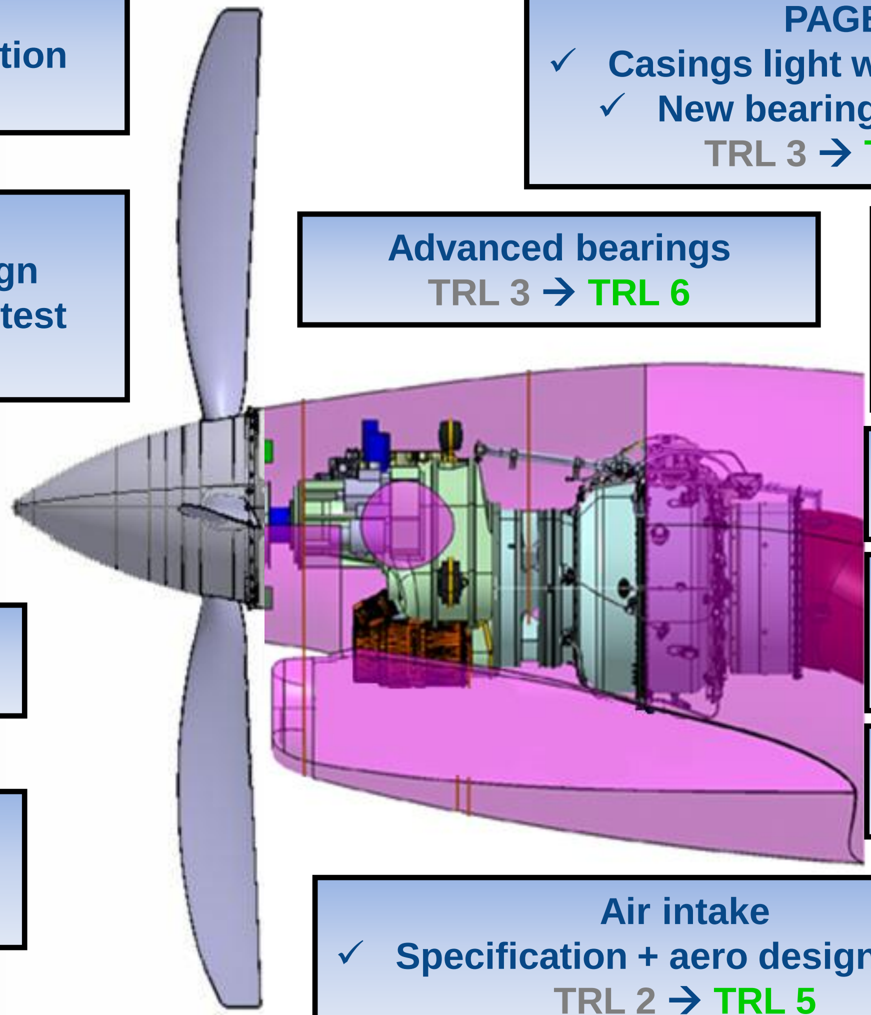
Propeller
✓ Integration & specification
TRL 3 → TRL 6

PAGB
✓ Casings light weight material
✓ New bearings materials
TRL 3 → TRL 6

Propeller
✓ New advanced design
✓ Windtunnel + Engine test
TRL 3 → TRL 6

Advanced bearings
TRL 3 → TRL 6

Nacelle
✓ Aero design
✓ LCA
TRL 3 → TRL 6



Exhaust system
TRL 3 → TRL 6

HPT materials for TP applications
TRL 4 → TRL 6

Propeller controls
TRL 2 → TRL 6

New Compressor design
TRL 3 → TRL 4

Advanced mechatronic system
TRL 2 → TRL 6

Air intake
✓ Specification + aero design + IPS
TRL 2 → TRL 5

Air Intake + Nacelle Mock-up
✓ Windtunnel test

Current TRL → Target TRL

Clean Sky JOINT UNDERTAKING

CS2 – ENG-WP8 – GE Avio

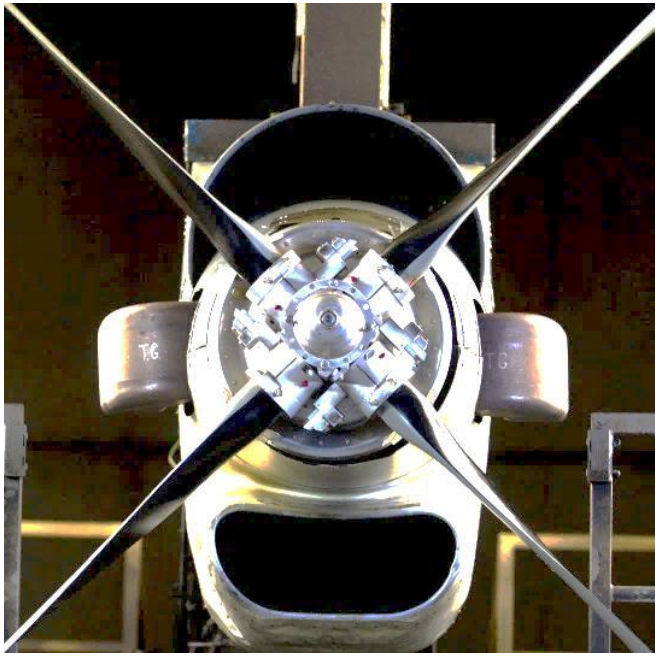
Integrated Collaborative Partnership to Strengthen European Competitiveness in **Small Air Transport** Turboprop Engines Market

High Level Objectives (vs 2014 ref. engine)

+ 15% Fuel Efficiency

- 10% Total Operating Costs

- 10 dB Noise Reduction (contrib.)



Sub-systems Technology Development and Validation on

- Advanced Core with High OPR
- Low Re Turbine Design
- Integrated Low Noise Propulsive System
- Affordable Low Emission Combustor

Clean Sky JOINT UNDERTAKING

Aircraft Level

Engine Level

Combustor Module Level

REDUCED FUEL BURN (SFC)

- HIGHER OVERALL PRESSURE RATIO (OPR)
- INCREASED INLET TURBINE TEMPERATURE (ITT)

- ULTRA COMPACT COMBUSTOR ARCHITECTURE (Reverse flow combustor)
- ADVANCED COOLING AND DILUTION TECHNOLOGY
  New cooling system to cope with the increased ITT

REDUCED LIFE CYCLE COST

- ENGINE SIMPLE ARCHITECTURE
- NO HOT SECTION INSPECTION

- ADDITIVE MANUFACTURING
  use of AM for mature selected components (swirlers)
- RQL CONSOLIDATED TECHNOLOGY
- IMPROVEMENTS OF COMBUSTOR LIFE
  New cooling technology to improve liners life

NOx EMISSION REDUCTION

- LOW EMISSION COMBUSTOR

- ADVANCED COMBUSTOR TECHNOLOGY to reduce NOx emission

Clean Sky 2

7. Small Piston Engines (Jet-fuel Diesel cycle Engines)

Outline

1. **Open-Rotor Architectures**
   - CS1-SAGE1 – RRUK
   - CS1-SAGE2 – SNECMA
   - CS2-LPA-(ENG-WP1) - SNECMA
2. **Large VHBR Turbofans Architectures – LR Aircraft**
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   - CS1-SAGE6 – RRUK (Lean Burn)
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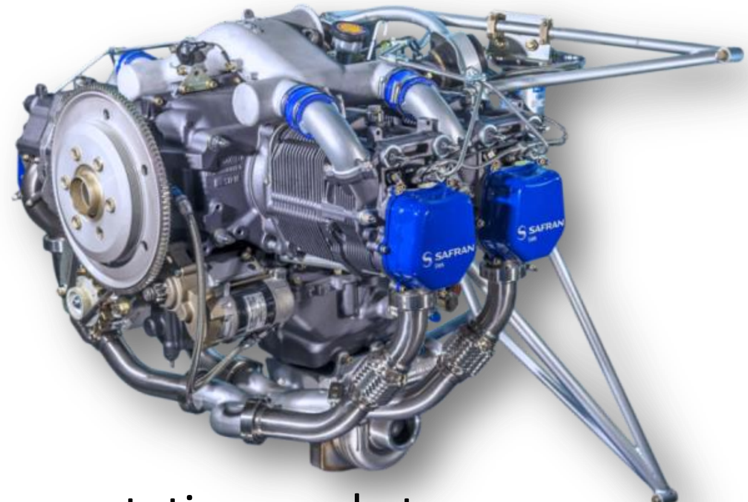
6. **TurboProp Engines – Regional/SAT**
   - CS2-ENG-WP3 TURBOMECA
   - CS2-ENG-WP8 GE Avio
7. **Small Piston Engines – Small Air Transport (SAT)**
   - **CS2-ENG-WP7 - SMA**

CS2 – ENG-WP7 – SMA

Improve Jet fuel reciprocating engines specifically designed for Small Aviation Transportation (SAT)

Technical objectives

- **Lead free** reciprocating engines fuel
- **30% - 60% of CO_2** emission reduction vs. 2000 aircraft
- **High Payload & long range** (twice)
- **Low noise** due to low speed of rotation



Competitiveness objectives

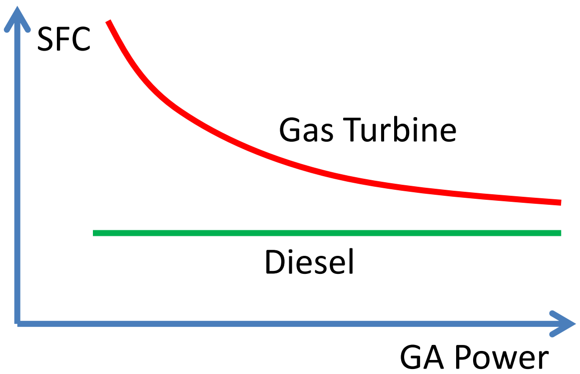
- Develop the European and worldwide small transportation market
- Develop European competiveness for small aeronautical engines

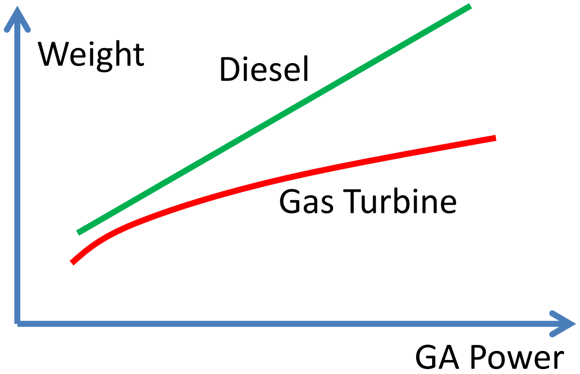
WP7 Programme Overview

- **Regular reciprocating engines** burn the 100LL AvGas, a dedicated gasoline for piston engine aviation.
  In many countries this gas is not available or not affordable.
  In addition, it is a leaded gas associated with high fuel burn and rich mixture technologies providing unburnt gas at exhaust and particules.

- **Turbine engines** burn jet A an affordable and worldwide available fuel.
  Their power density is attractive, but in the low end of power, the Specific Fuel Consumption is dramatically high in addition to high ownership costs.

SFC and power density trends



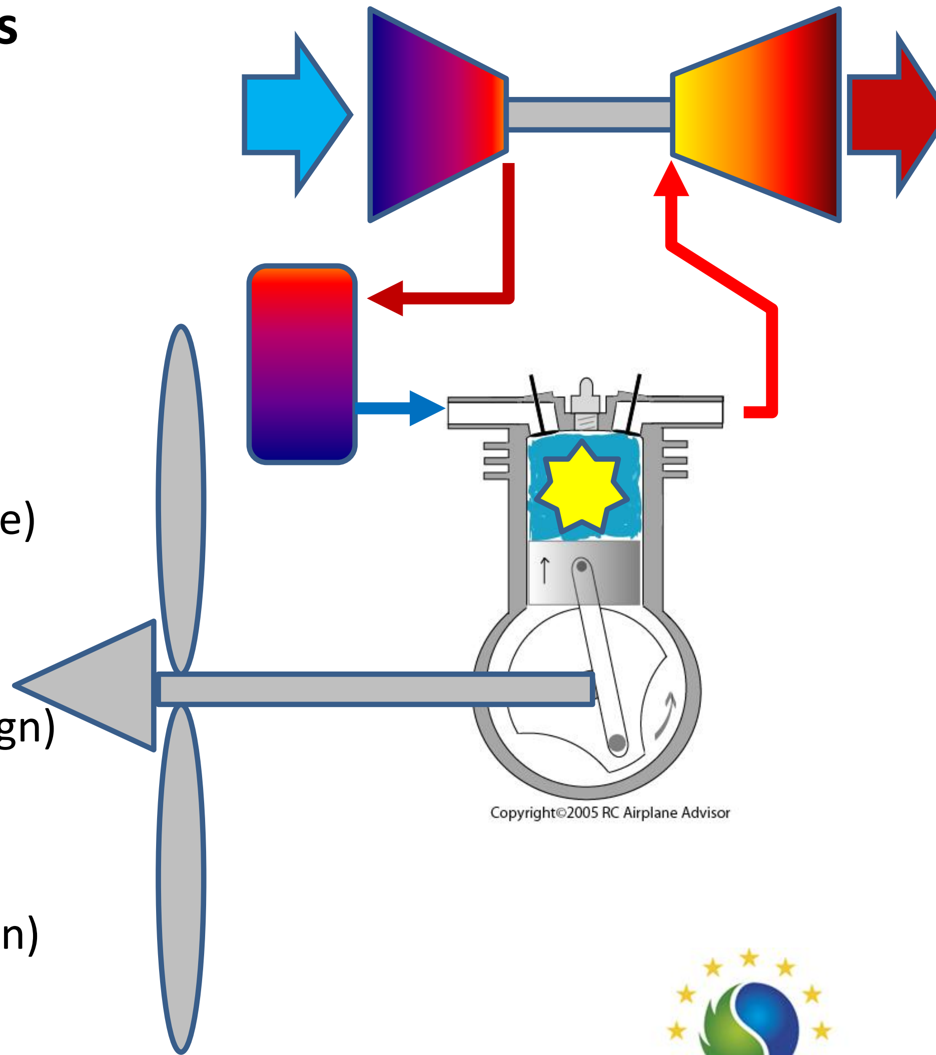


- **Jet-fuel turbo reciprocating engines** can be the compromise.
  The main challenge is to increase their power density.

WP7 Programme Overview

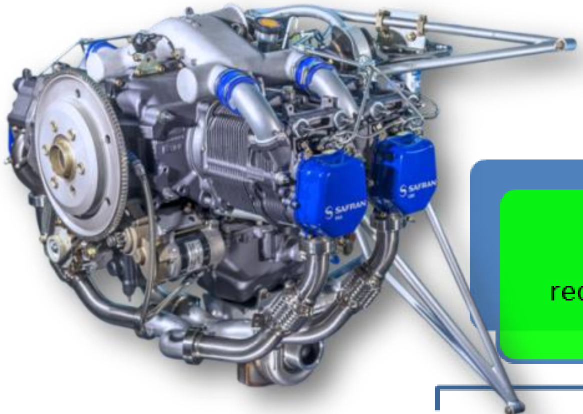
- **Jet-fuel turbo reciprocating engines**
  - Jet A fuel
  - HPC / HPT (turbocharger)
  - Intercooler & cylinder head cooling
  - Diesel cycle / compression ignition

- **Technologies**
  - Turbochargers (altitude, long endurance)
  - Coolers (efficiency / compactness)
  - Combustion chamber (power density)
  - Core engine part design (material, design)
  - Engine architecture (compactness)
  - Propeller adaptation (torque pulse)
  - Aircraft integration (system optimization)



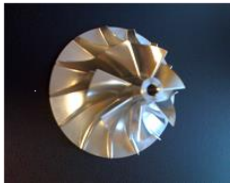
Clean Sky 2

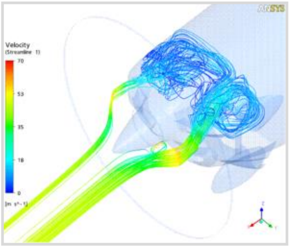
WP7 Work Breakdown structure: topics



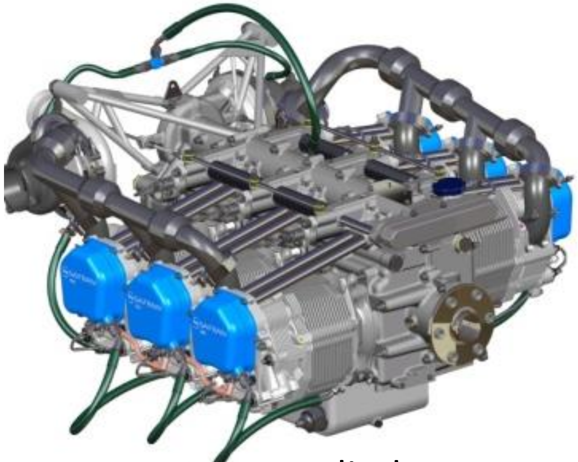
WP7
Jet-fuel reciprocating engine

- WP7.1 Core engine power density improvement
  - WP7.2 Turbocharger improvement
    - WP7.3 Propeller adaptation
- WP7.4 High Power density architectures
  - WP7.5 On wing engine installation optimization
    - WP7.6 Control Syst.

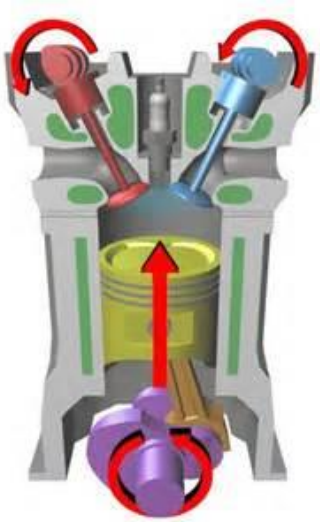




Multi-cylinder architecture

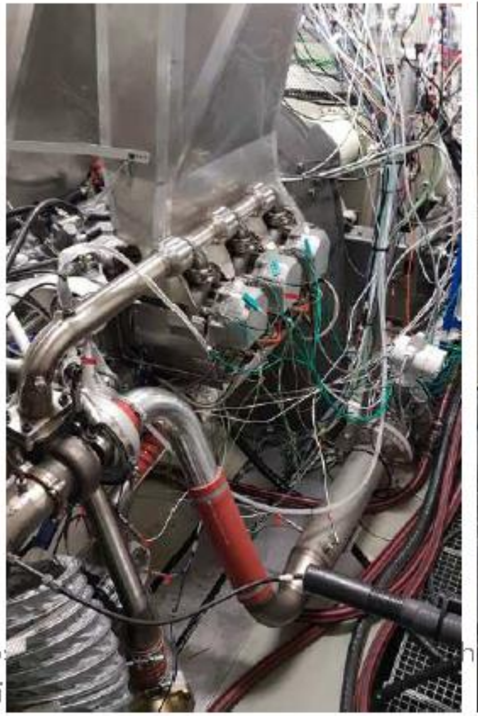


Mono-cylinder architecture



Not legally binding

- Design & Manufacturing **almost done**
- Testing phase 1 **done**
  - FETT @ driven bench
  - FETT @ test bench n°1



Engines characteristics comparison

	SR 305-230E	SR305-260E	SR 460 (demo CS2)	HPDE concept (TRL3)	Lycoming TEO540	Arrius 2F
Power output	170 kW (**230 hp**)	195 kW (**260 hp**)	MCP: 300 kW (**400 hp**) Cruise: 225 kW (300 hp)	Up to 600 kW (**800 hp**)	MCP : 280 kW (**375 hp**) Cruise : 195 kW (262 hp)	TOP: 375 kW (500 shp) MCP: 335 kW (**450 shp**)
Architecture	4-cylinder flat 5 L (305 cu in)		6-cylinder flat 7.5 L (460 cu in)	6-cylinder line / flat 3.6 L	6-cylinder 8.9 L (542 cu in)	1 Comp centrifuge 2 Turb axiales
Recommend TBO	2400 hrs	Expected min. 1600 hrs (@EIS)	Expected 2000 hrs (@EIS)	-	2000 hrs	3000 hrs
Dry engine Weight	207 kg (456 lbs)	~ 210 kg (463 lbs)	~ 290 kg (< 275kg expected)	~ 250 kg (545 lb)	~ 270 kg (592 lbs)	103 kg (227 lbs)
Power / Weight	**.81 kW/kg** (.5 hp/lb)	**.93kW/kg** (.56 hp/lb)	**> 1 kW/kg** expected	**2.5 kW/kg** (1.5 hp/lb)	**~ 1 kW/kg**	**~ 3 kW/kg**
SFC vs RPM	**215 g/kWh** @ 2200 rpm			**210 g/kWh** @ 3600 rpm, 80% MCP	**250g/kWh** @ 2400/Cr **300g/kWh** @ 2700/TO	**~335 g/kWh (MCP)**
Nominal mean torque	740 N.m @ 2200 rpm	850 N.m @ 2200 rpm	~ 1300 N.m @ 2200 rpm	~ 1600 Nm @ 3600 rpm ~ 1300 Nm @ 4500 rpm		
Air charging system	SAE turbocharger (boost pressure ~2.5 @SL / ~3.5 @10kft)		SAE turbocharger	SMA / Safran Power Unit (boost pressure > 4 bar @SL)	Turbocharger (altitude compensation)	
Injection system	Mechanical inline pump (< 1000 bar)		Mechanical unit pumps (< 1000 bar)	Common Rail (> 2000 bar)	Injection (< 300 bar)	Hydromechanical
Cooling system	Air / Oil cooling		Oil / Air cooling	Water cooling	Air cooling	
Engine control system	Electronic main mode / Mechanical back-up mode			FADEC	FADEC (under development)	FADEC
TRL	9	8	6 (expected after CS2)	6 (SCE) / 3 (MCE)	7/8	9
Fuel compatibility	Jet A, Jet A1, JP4, JP8, TS1, #3, Diesel				100LL / UL100	Jet fuels

Part IV
What's next ?
A roadmap to 2050 …

The Aviation Vision

1. **Meeting societal & market needs**
   - managing the effects of growth of air travel
2. **Maintaining and extending industrial leadership**
   - delivering greater competitiveness
3. **Protecting the environment and the energy supply**
   - achieving decarbonisation; reducing emissions/noise
4. **Ensuring safety and security**
   - introducing revolutionary modes of travel
5. **Prioritising research, testing capabilities & education**
   - pioneer enabling research

To deliver this vision and meet these challenges new technical solutions will be required

Clean Sky 2

Energy Conversion and

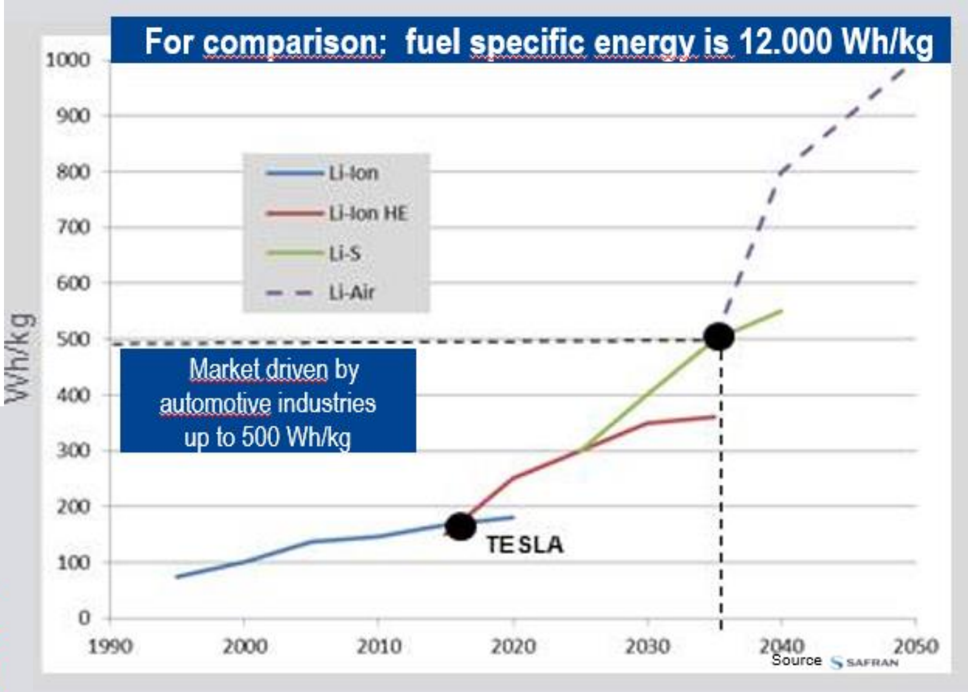
Thrust requires conversion of energy

- **There is no single solution to achieve decarbonisation across all categories of aircraft size and range**
- **Hence, diversification and transition is required across three areas**

Clean Sky 2

Ultra High Efficiency Gas Turbine – Why?

1. Energy Density
   - Medium to long range aircraft will still require a gas turbine either as part of a hybrid-electric system or direct thrust



Automotive

Assumption: Evolution of battery energy density within next decades

MTOW A320 neo = 77 T

Even with 1000 Wh/kg batteries, an All-Electric Airbus A320 requires **170 T** of batteries, compared to **20T of fuel** today

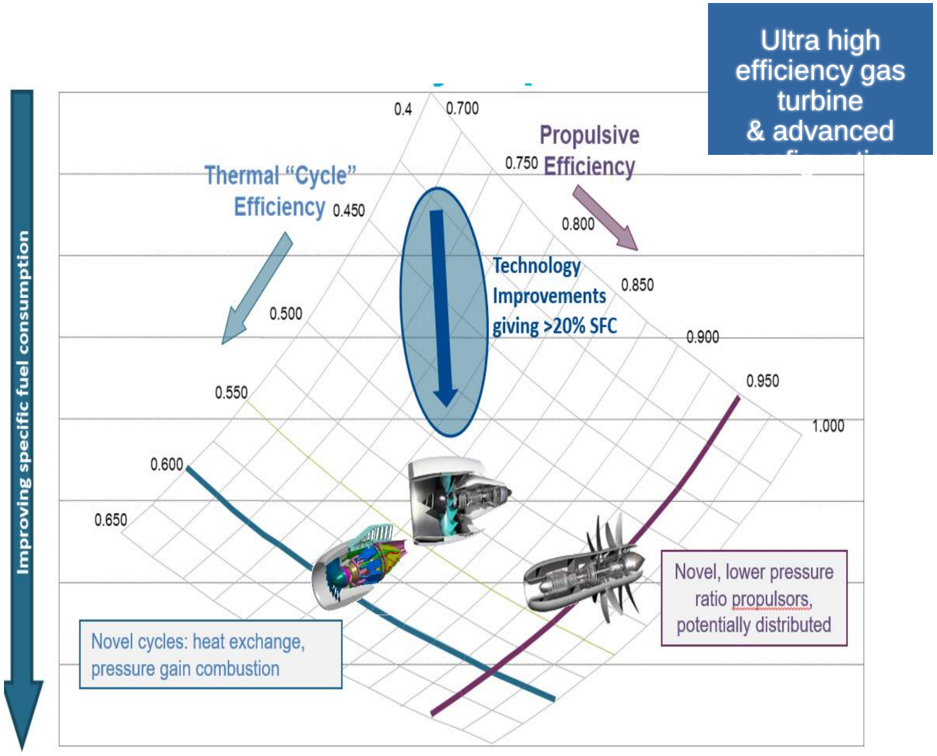
Clean Sky 2

Ultra High Efficiency Gas Turbine – Why?

1. Energy Density
   - Medium to long range aircraft will still require a gas turbine either as part of a hybrid-electric system or direct thrust

2. Efficiency Gains
   - Gains in propulsive/thermal efficiency still achievable

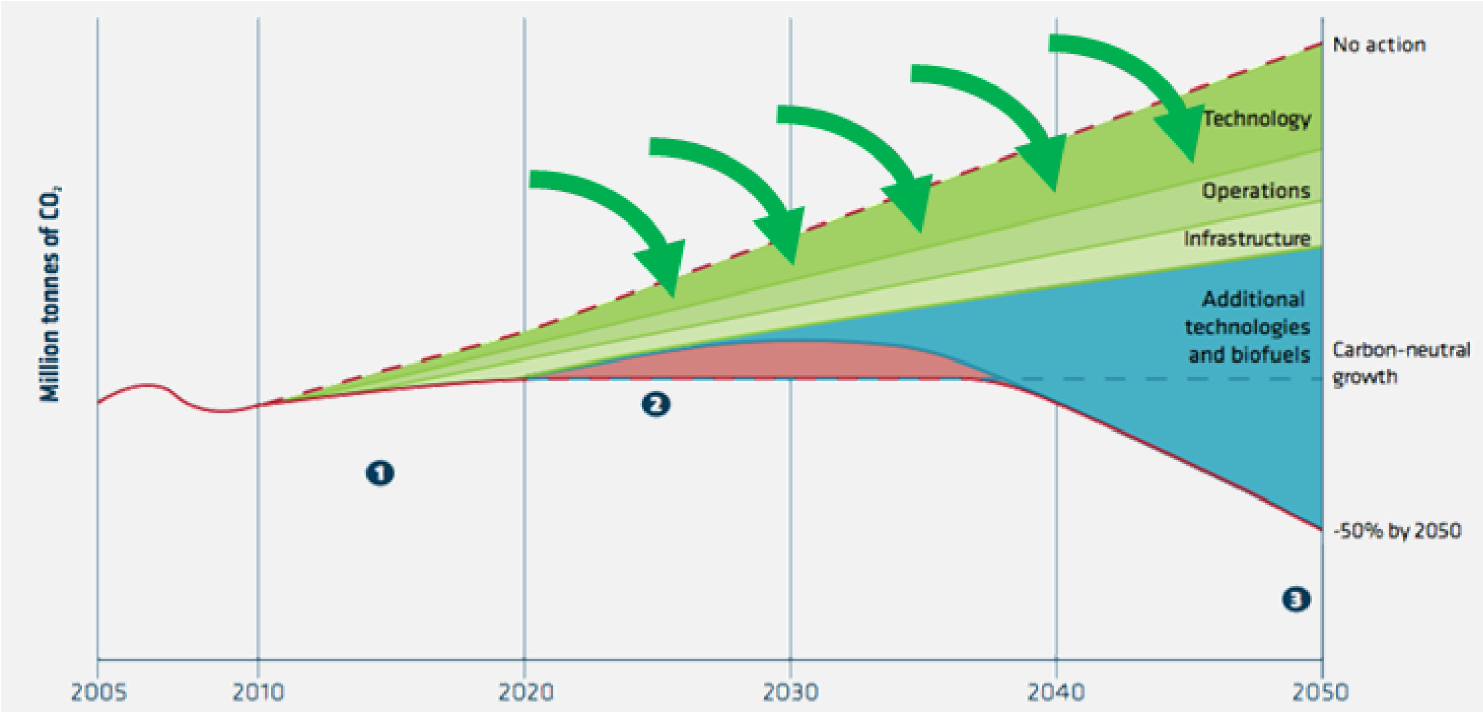
3. Timing
   - Architecture changes and technology insertion can impact decarbonisation earlier



Further reduction in gaseous emissions: identified novel cycles and architectures – additional research needed to increase TRL

Clean Sky 2

Ultra High Efficiency Gas Turbine – Why?



Ultra high efficiency gas turbine & advanced

3. Timing
   - Architecture changes and technology insertion can impact decarbonisation earlier

- Improved efficiency engines will penetrate the market earlier and faster.
- Hence utilising less fuel will contribute earlier to decarbonisation

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Ultrahigh Efficiency Gas Turbine & advanced Configuration

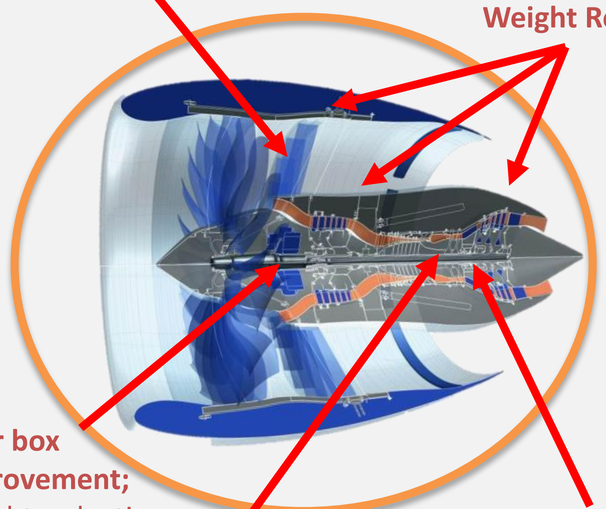
Ultra high efficiency gas turbine & advanced

- **Evolution**

- Revolution

Introduce Variable Pitch Fan; Noise & Fuel Burn Reduction

Increased Composites [Carbon; Ceramic Matrix; Metal Matrix]; Weight Reduction



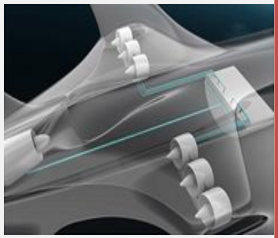
Gear box improvement; Weight reduction

Lean Burn Enhancement; Emissions Reduction

New Metallic Alloys; Weight & Fuel Burn Reduction

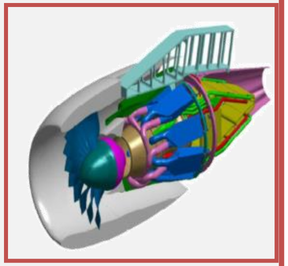
Electric-Hybrid solutions requires power generation

- novel application/adaption of existing turboprop/shaft



Change in installation paradigm opens Propulsion Design Space

Novel engine cycles



Hybridisation / Electrification– Why?

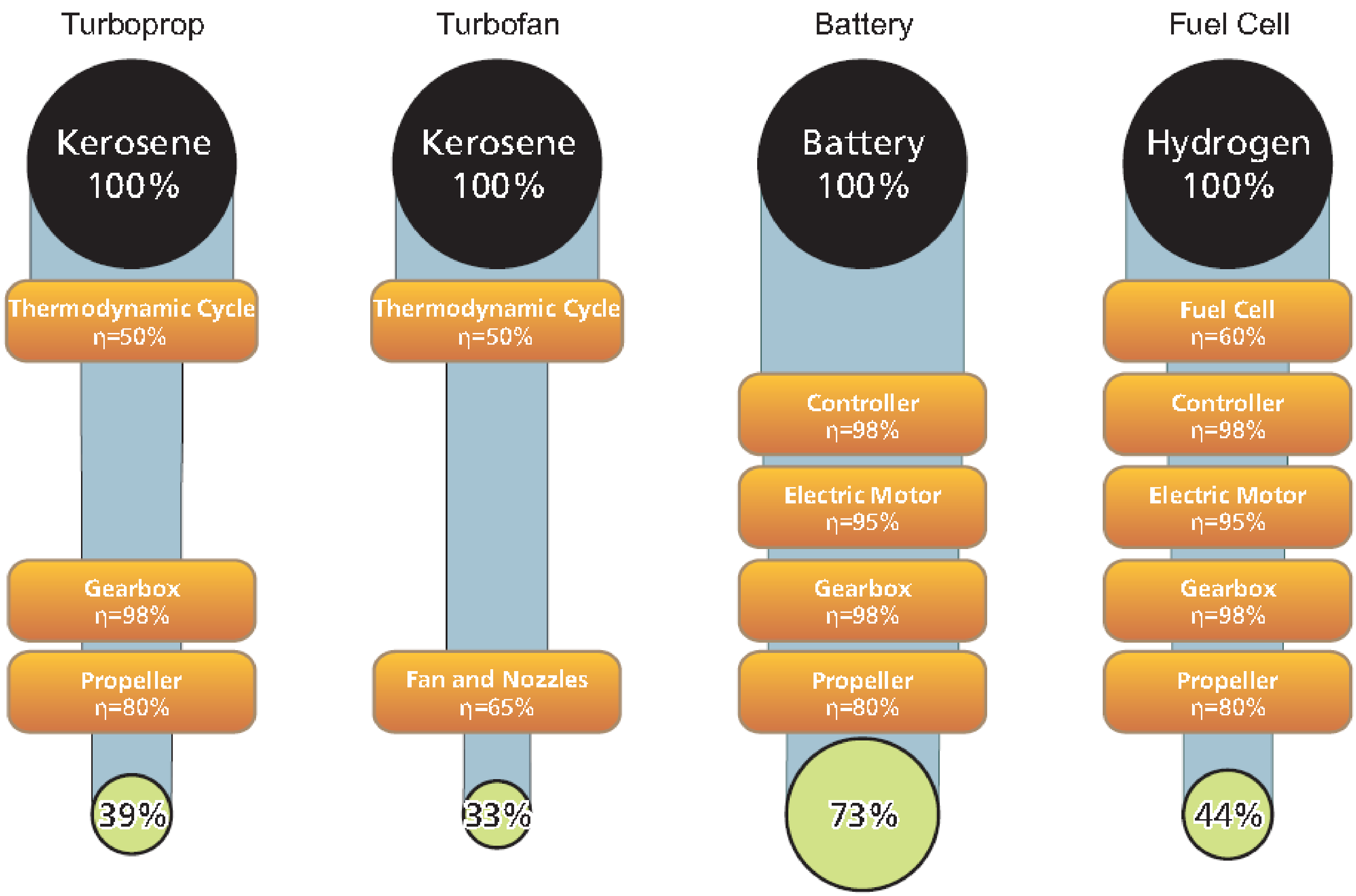
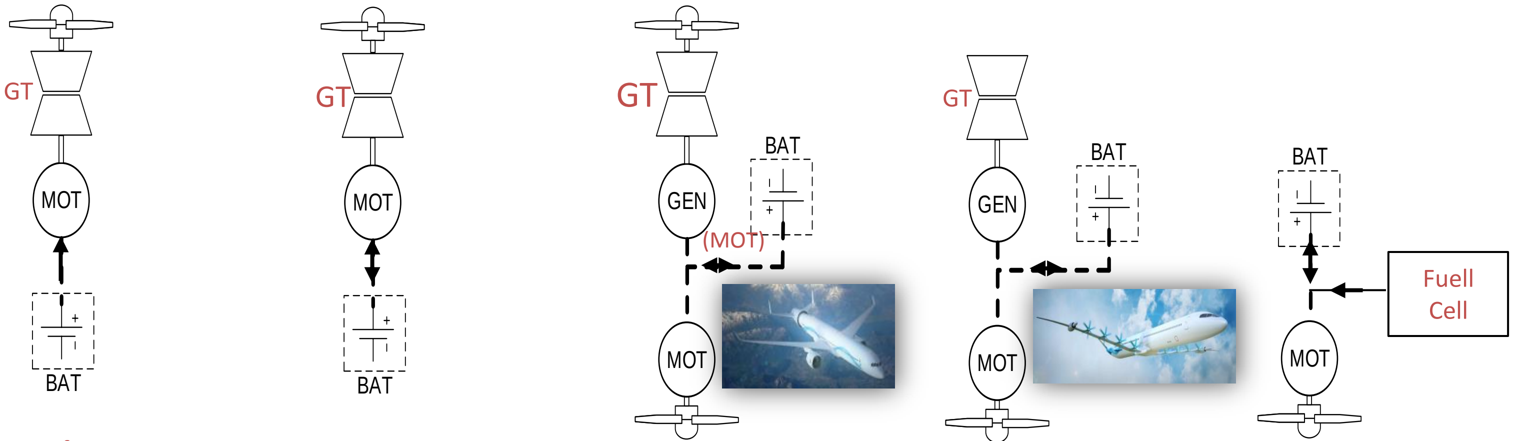


Figure 7 Typical on-board conversion chains with typical component efficiencies and total chain efficiency.

M. Hepperle, DLR

Hybridization, Electrification & Energy management

Electric energy at stake	~300 kW	~600 kW	~1 MW	~2 MW	~few MW **A/C 0% emissions**



Electricity for Engine start & Bleedless only	5% e-Propulsion	20% e-Propulsion	100% e-Propulsion 100% thermal energy	100% e-Propulsion Batteries + other sources
More electrical aircraft	Micro-Hybrid propulsion	Hybrid distributed propulsion	Electric distributed propulsion	
	Parallel Hybrid Architecture	Series/Parallel Partial Hybrid Architecture	Series Hybrid Architecture	All Electric Architecture

Numerous configurations/architectures for hybrid/electrical propulsion to be investigated

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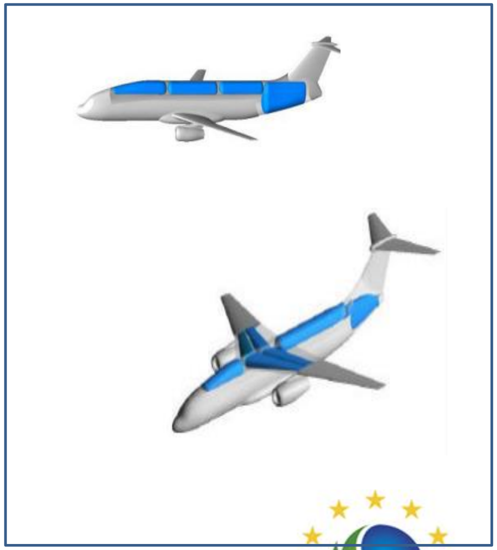
Substitute fossil fuels with sustainable alternative fuels for low CO2 emission and carbon neutral aviation.

Drop in fuels	Sustainable alternative fuels for carbon neutral aviation	✓ Current/new Aircraft configurations ✓ same infrastructure and logistics – Production capacity needed (carbon life cycle assessment)

Non drop in fuels	Liquid Natural Gas (LNG)
	
	H2 for CO2 low or free aviation
		– Aircraft technology development
		  – New Aircraft Configuration
		  – Fuel system & tank
		  – Engine optimization,
		  – Thermal/cryogenic system management
		– New Infrastructure and logistics needed
		– Production capacity needed

Sustainable Alternative Fuels



AFRAN

European Commission

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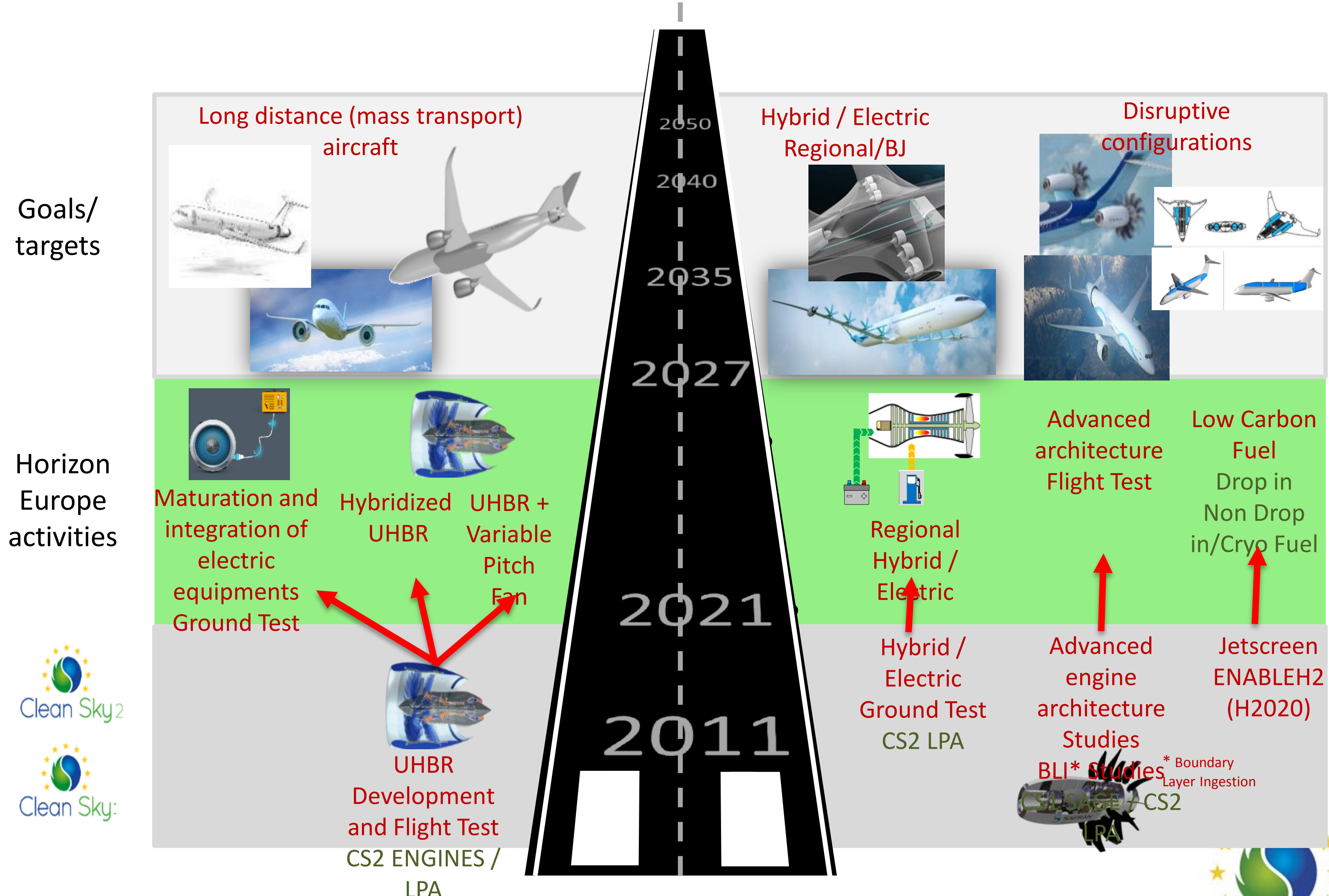
What's next ?

Achieving the vision.. explore new Technologies and Concepts



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Summary

- Societies demand for increasing mobility is now and not in 40-50 years
- Continued aviation growth and urgency to reduce CO2 requires ongoing technology insertion
- All-electric commercial aircraft is a long term solution; electrification will be introduced stepwise, provided that increasing complexity on propulsion system side can be managed on the overall platform.
- In a short/medium timeframe: evolutionary technologies are necessary for medium and long range aircraft.
- BUT at the same time we also need to create disruptive technologies for short and medium range aircraft
- Sustainable alternative fuel would complement these technologies to support decarbonisation.

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Thank You for your Attention