IMOTHEP

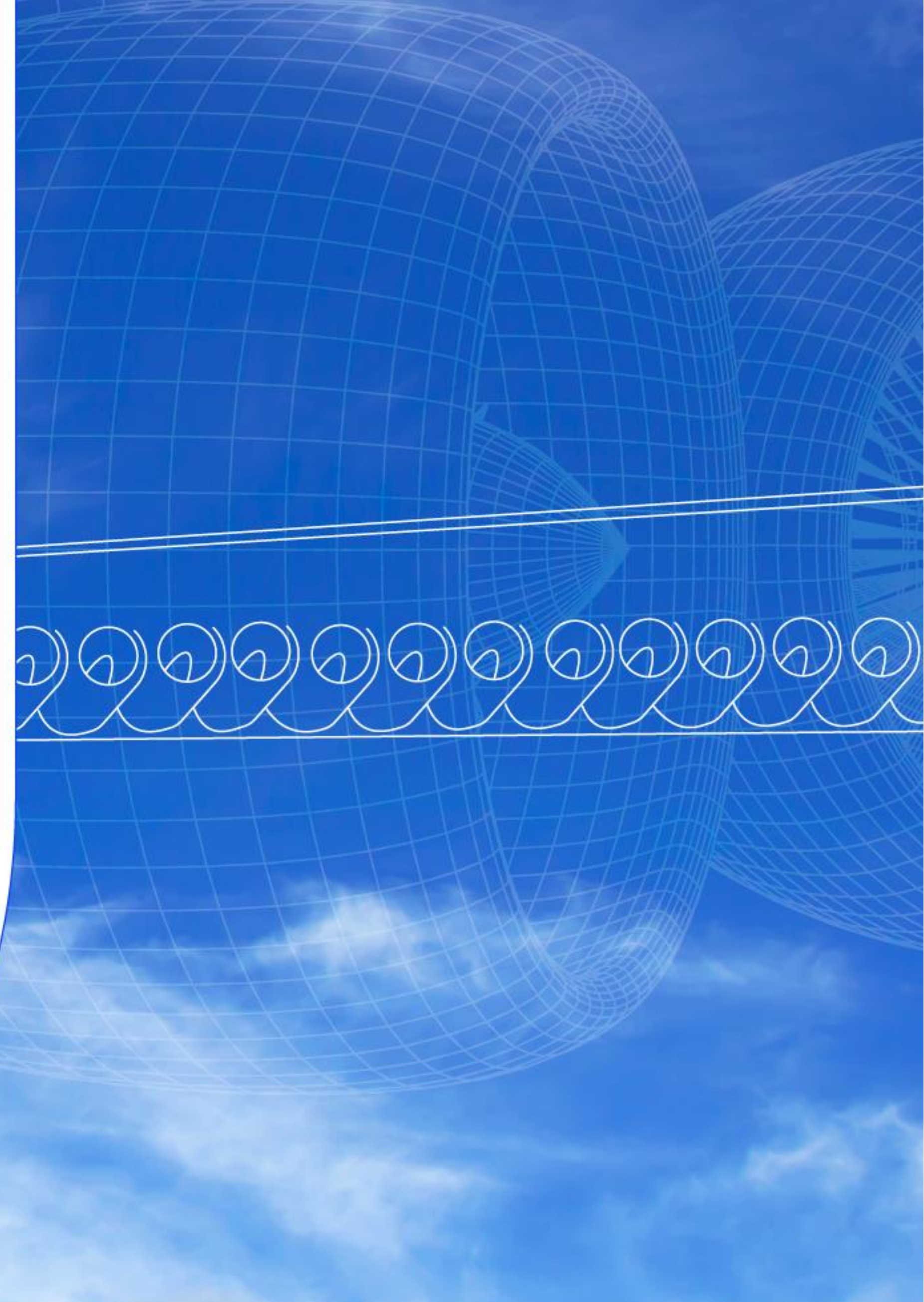
GETTING HYBRID ELECTRIC

IMOTHEP: towards hybrid propulsion for commercial aviation

Project Overview

Ph. Novelli, ONERA – Project coordinator

AIAA Aviation 2021 Forum– 02/08/2021



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875006

Project's context

European Research and Innovation Framework Program H2020

Call 2019 "Mobility for Growth"

Future propulsion and integration: towards a hybrid/electric aircraft

- **Background**
  - Aligning commercial aviation with the COP21's target: **ΔT < 2°C**
  - ⇨ Critical need for disruptive technologies beyond incremental technology improvements
- **Challenge**
  - Developing hybrid-electric and full-electric propulsion and integration technologies
  - Developing a roadmap for key enabling technologies

IMOTHEP in figures

- **Four-year research project**
- **33 partners**
  - 9 European countries
  - 6 international partners from Russia and Canada
- **1311 person.month effort** (~27 full time equivalent)
- **10.4 M€ EC funding + 7,8 M€ contribution of international partners**

IMOTHEP's top level ambition

Imhotep - Egyptian architect, doctor and philosopher
A great and innovative builder…

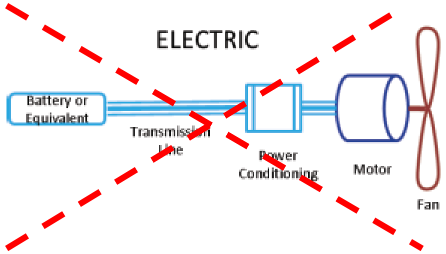
"Investigation and Maturation of Technologies for Hybrid Electric Propulsion"

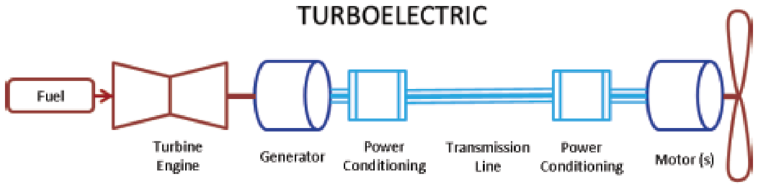
- **Achieving a key step in assessing potential benefits of HEP for emissions reductions of commercial aircraft**
- **Building the overall European development roadmap for HEP**

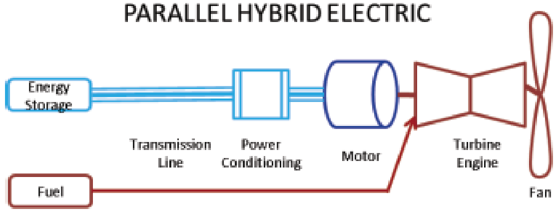
- **First level objectives**
  - Identifying HEP architecture & aircraft concepts benefiting from HEP
  - Investigating technologies for HE power train architecture and components
  - Analysing required tools, infrastructures, demonstrations and regulatory adaptations for HEP development
  - Synthesising results through the elaboration of the development roadmap for HEP

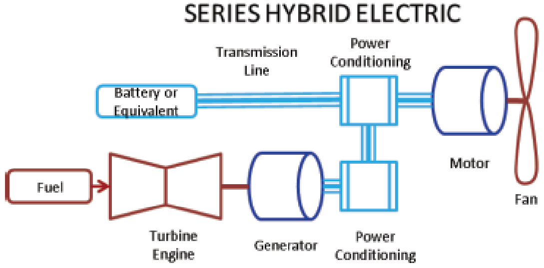
Hybrid electric propulsion

A broad variety of possibilities and concepts…

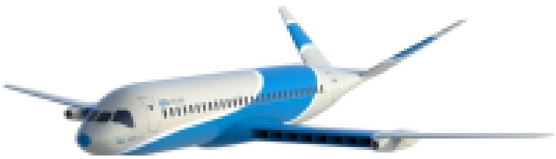






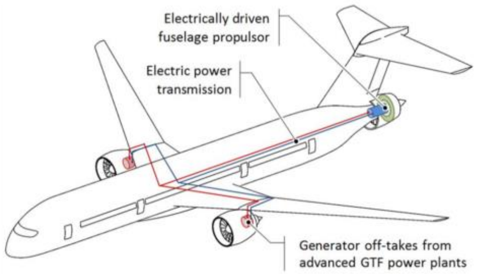


NASA N3-X
DEP + BLI + Superconductivity



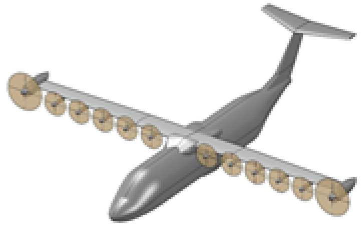
EPS ECO150-300
Distributed propulsion

Boeing Sugar Volt
Electrically Assisted turbofan



CENTRELINE (H2020)
BLI turboelectric tail fan

NASA Pegasus
Parallel hybrid



ONERA/SAFRAN
Distributed propulsion
Blown wing

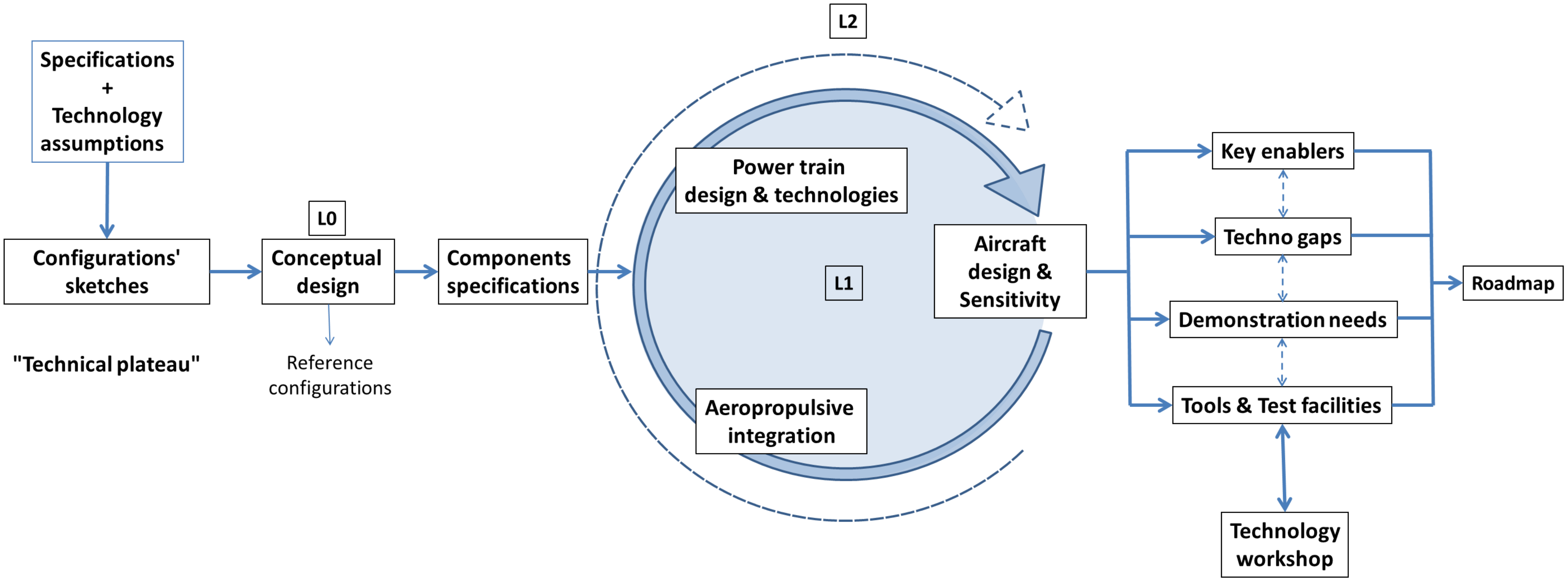
IMOTHEP GETTING HYBRID ELECTRIC

IMOTHEP's overall approach

Investigating HEP energy system

- **In close connection with propulsion integration in the vehicle**
  - Specifications for power chain components derived from conceptual design of aircraft concepts
- **At a meaningful scale**
  - Representative of technological challenges in the power range of commercial aircraft (3 - 80 MW)
- **With a major effort on investigating technologies for hybrid electric power train**
- **Synthesised through integrated aircraft performance analysis**
  - To identify technological gaps and key enablers
  - Architectures and configurations best benefiting from HEP
- **To issue a roadmap for HEP development**

IMOTHEP's methodological approach



IMOTHEP GETTING HYBRID ELECTRIC

Project's targets

- **Reference missions**
  - **Short/medium range:** minimum segment for a significant impact on aviation emissions
  - **Regional:** more accessible, potential intermediate step toward SMR

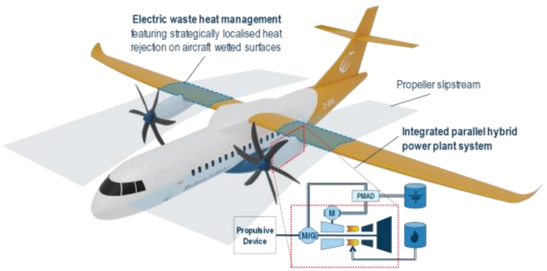
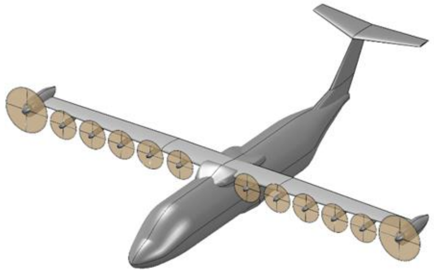
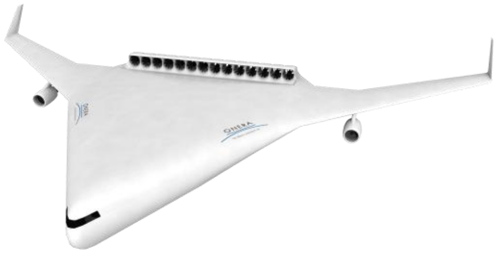
Mission	PAX	Speed	Range
Regional	40	Mach 0,4	600 nm (typ. 200 nm)
SMR	150	Mach 0,78	>= 1200 nm (typ. 800 nm)

  - EIS: 2040+
- **Technological scope**
  - Central focus on thermal hybrid with drop-in fuel
    + some investigations on fuel cells at conceptual level (aircraft + fuel cell specific issue for aircraft)
  - Main focus on conventional conductivity
    + Exploration of superconductivity as a potential enabler
- **Performance target: 10%** more emissions reduction than Clean Sky 2 targets for 2035
  - **Regional: -45% to -50%** fuel burn
  - **SMR: -40%** fuel burn

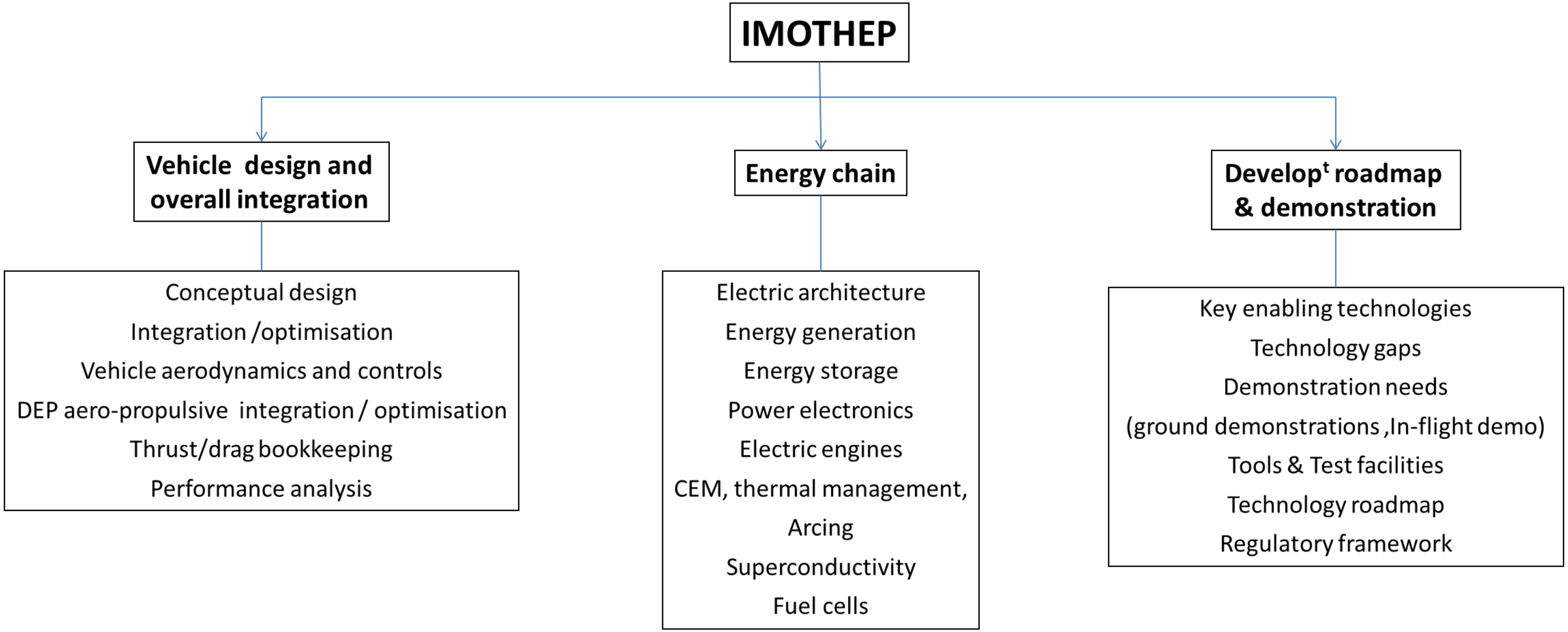
  } compared to 2014 technology

Project's suporting configurations

- Build-on / complement existing studies (e.g. CS2, CENTRELINE,etc.)
- Explore a range of architectures

	Conservative	**Radical**
Regional	 Electrically assisted turboshaft	 Turboelectric + DEP + wing-tip propeller
SMR	 Tube & wing, turboelec, DEP (from CS2)	 BWB, turboelectric, DEP, BLI

Project's technical scope



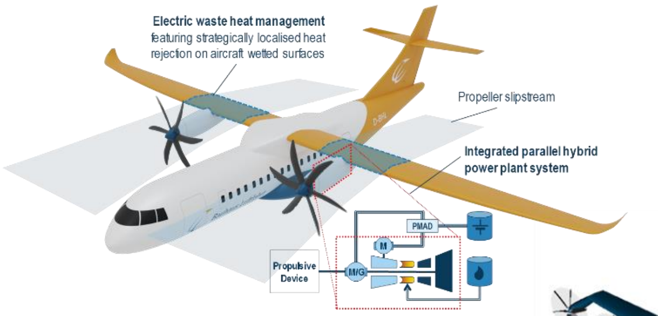
TRL 2 to 4 conceptual studies

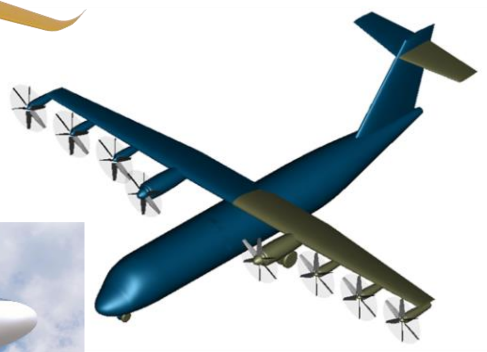
Vehicle design

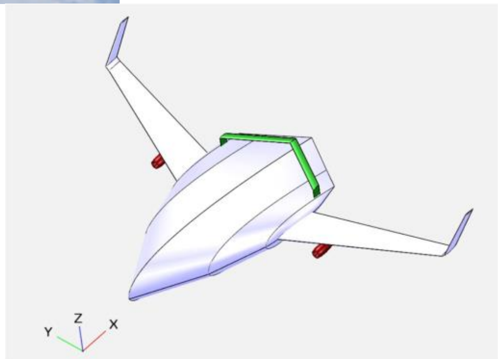
- **Top level requirements from airframers**

  AIRBUS   LEONARDO AIRCRAFT

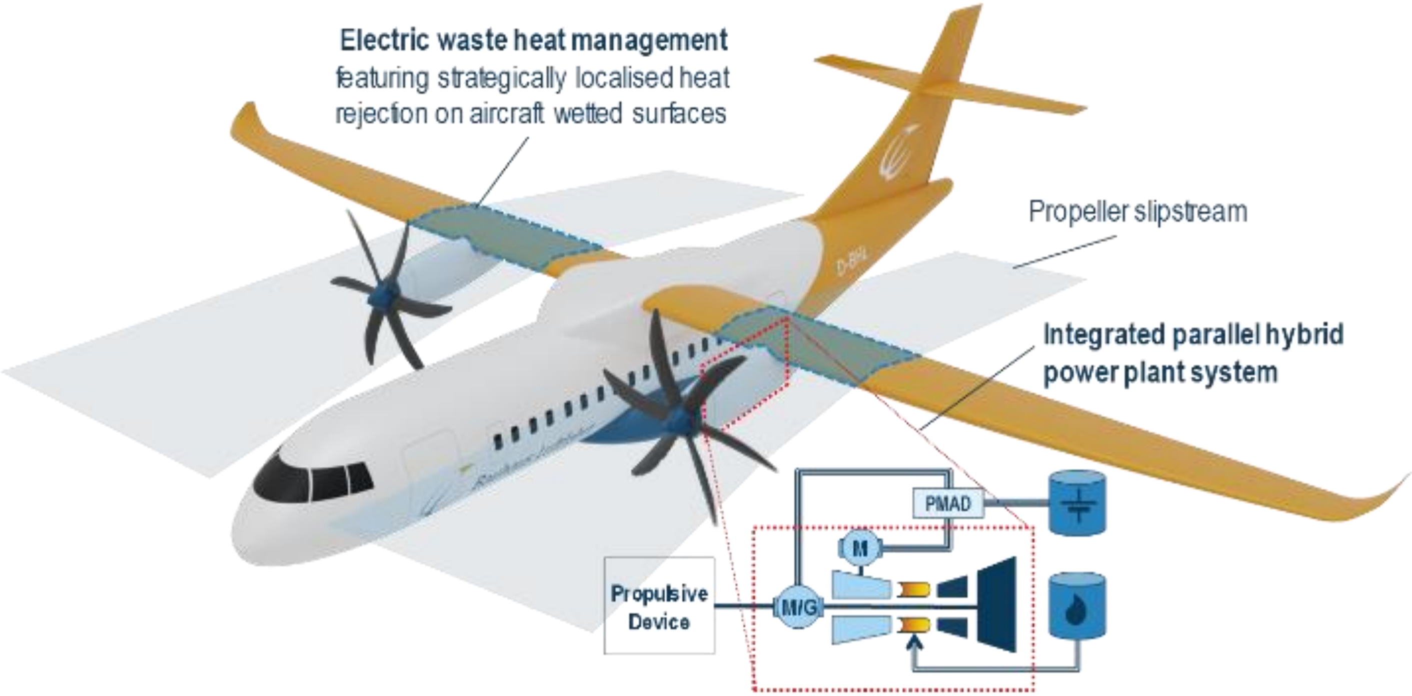
- **First design loop achieved**
  - **Based on projection of components' performances to 2035**
  - **4 initial configurations defined with consistent technology assumptions**
  - **Initial performance evaluated** (no optimisation)
  - **Specifications / targets for electric subsystems issued**
- **Next steps**
  - **Refined design loop with higher fidelity model**
  - **Inclusion of the outcomes of first component design studies and aeropropulsive integration studies**
  - **Optimisation of aircraft configurations**







Vehicle initial design



Conservative regional: parallel hybrid

- Based on ATR 42-600 adapted to IMOTHEP TLAR
- Battery energy used for mechanical and cycle assistance to two turboshaft engines
  - Indicative preliminary design values
    - ~3600 kg batteries
    - 550 kW assistance /engine
    - 540 DC voltage
- Forced convection cooling via propeller slipstream over wing wetted surfaces

➢ **Optimisation of the hybridisation strategy is key**

Vehicle initial design

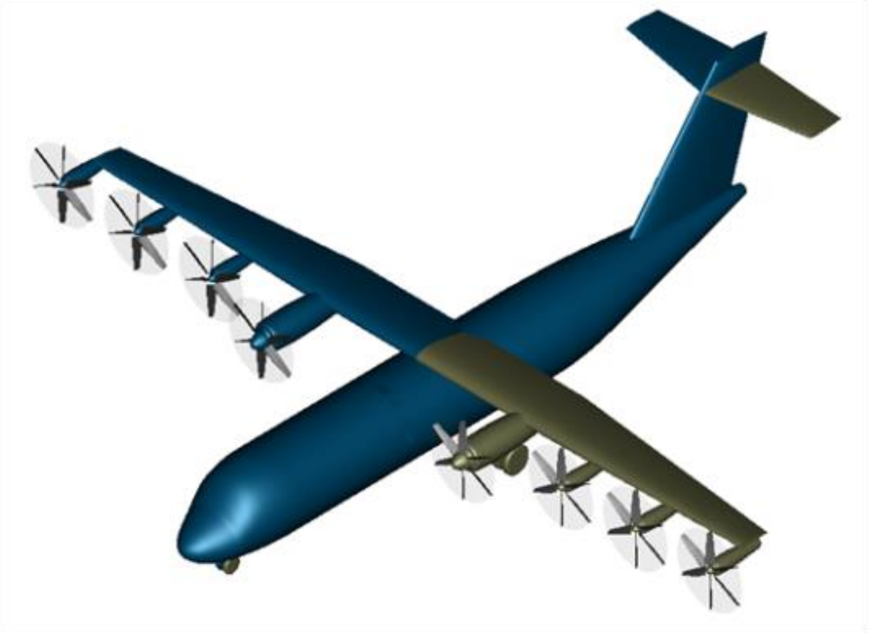
DLR

Radical regional: turboelectric + distributed propulsion

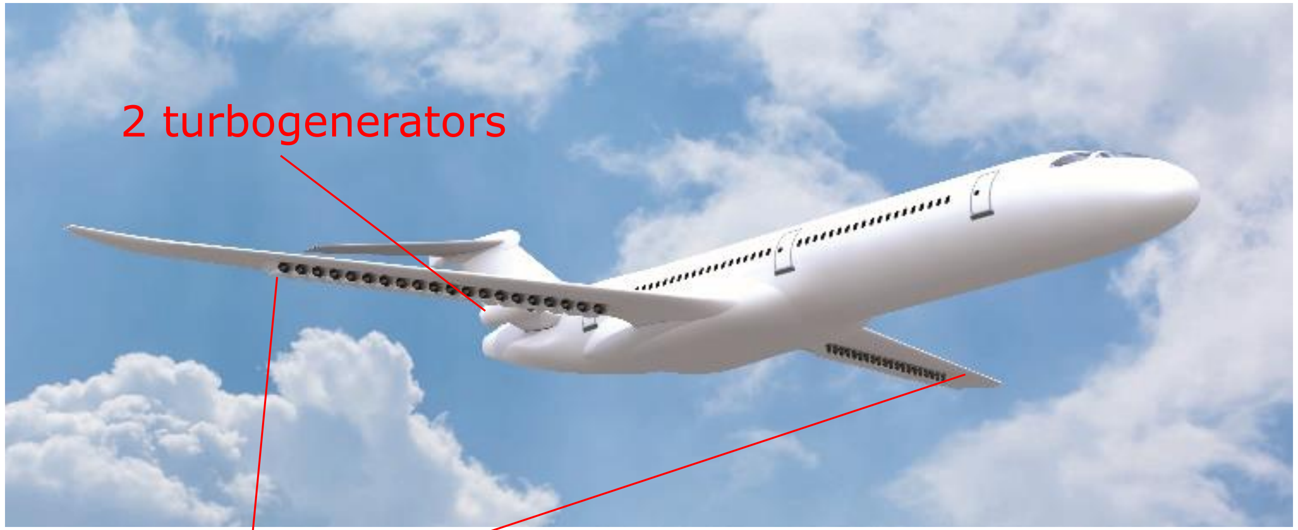
- 6 electric engines (300 kW each)
- 2 turboshafts driving 2 electric generators
- 800 V DC voltage

➢ **Increased propulsive efficiency thanks to DEP**

➢ **Mass reduction of electric power chain is key**



Vehicle initial design



Conservative SMR: turboelectric with DEP (DRAGON configuration)

- 24 electric fans, 820 kW each
- 2 turbogenerators : 2 x 11 KW
- 3000 V DC voltage

- ➢ **Increased propulsive efficiency thanks to DEP**
- ➢ **Performance dependant on the efficiency of electric machines**

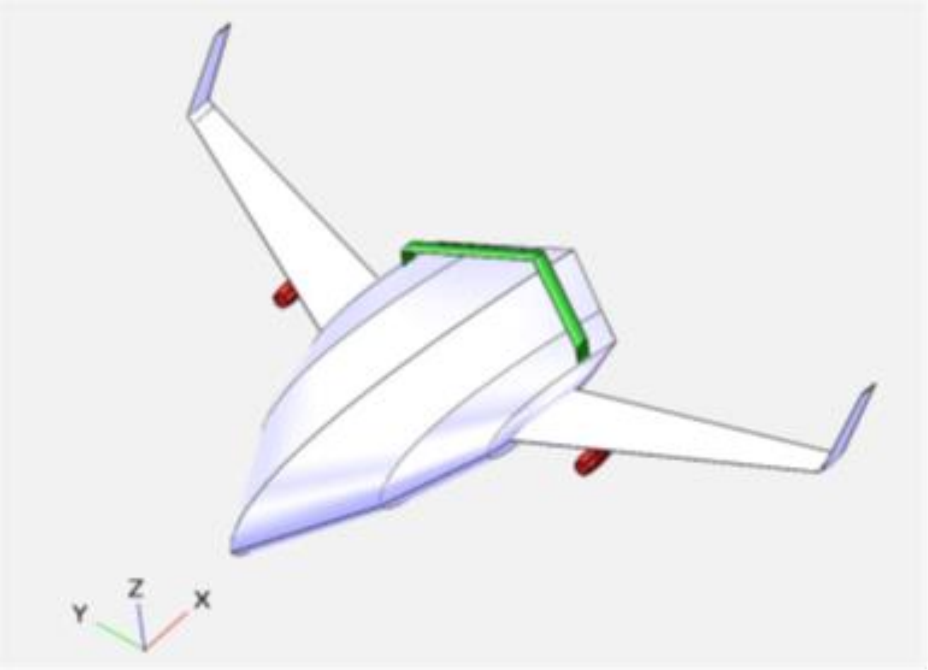
Vehicle initial design

Radical SMR: turboelectric + DEP + BLI + BWB

- 18 electric fan, 1100 kW each
- 2 turbogenerators : 2 x 11 KW
- 3000 V DC voltage

➢ **Need for further shape optimisation & higher fidelity analysis for BLI**

➢ **Significant influence of turbogenerator efficiency (PSFC)**



Aeropropulsive integration studies

- **Key for a meaningful evaluation of the benefit of HEP**
  - Benefit through careful optimisation of efficiency and airframe / propulsion integration
  - Need for a precise modelling for a precise evaluation of benefits
  - Applied to Radical configurations
- **Design and integration of propellers for distributed propulsion**
  - Design of propellers
  - Propellers location on the wing
- **Design and benefit evaluation of wing-tip propellers**
- **Aerodynamic optimisation of BLI integration for BWB**
  - Aerodynamic integration
  - Impact on fan design and performances
- **Thrust / drag bookkeeping for BLI configuration**
- **Noise assessment (post-design)**

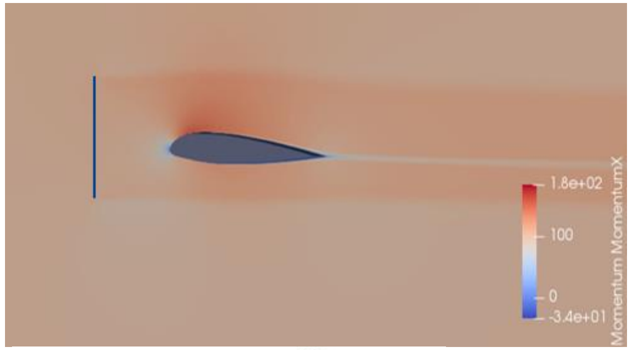
On-going :
low fidelity method for Loop 1

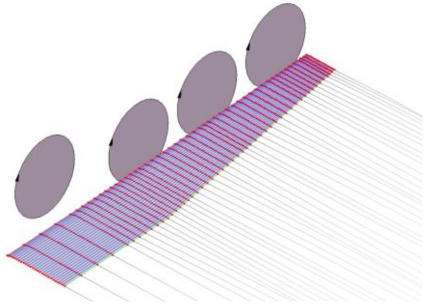
Next step:
Detailed analysis in loop 2

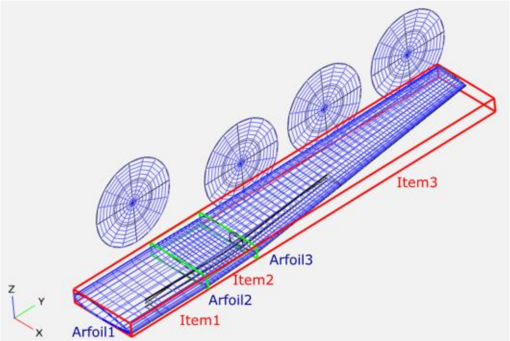
Aeropropulsive integration studies

On the Regional-radical configuration :

- Propeller conceptual design studies for orienting parametric design space exploration
  - Optimization for propeller efficiency / blowing efficiency
  - Wing tip propellers
  - Including wing interaction
- 2D CFD of power-on / power-off wing behavior
  - Including high lift devices
  - For low speed and high speed conditions
- Surrogate model of propulsive efficiency
  - Taking into account propellers number, high lift devices, propellers performances, wing geometry and airfoils
  - Covering propellers slipstream effect on wing performance in both cruise and low speed conditions



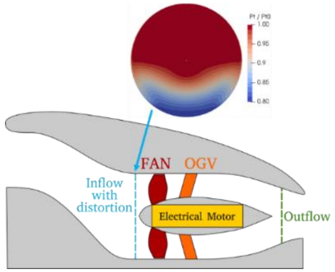


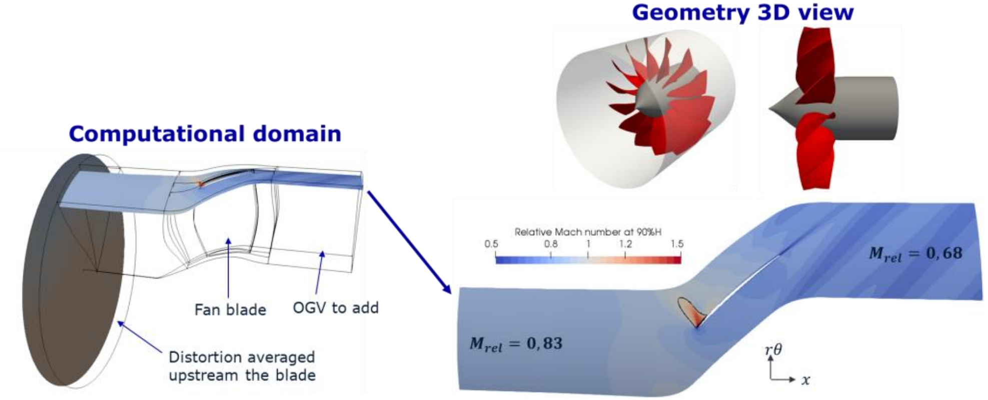


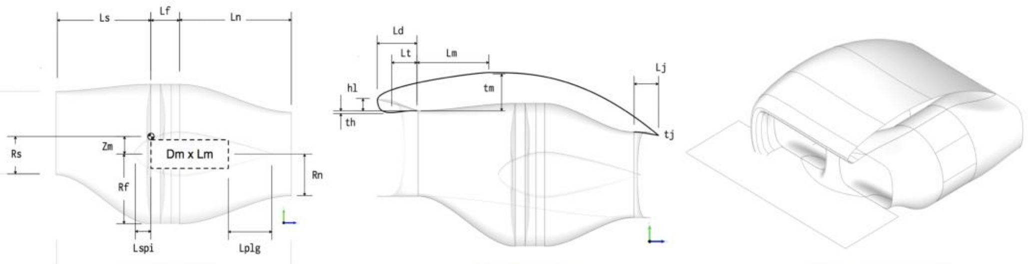
Aeropropulsive integration studies

On the SMR-radical configuration :

- Accounting for BLI effect in propulsive performance
  - Set up of a low fidelity toolchain, based on parallel compressor approach and power balance methods
- Design of ducted thrusters under BLI effect
  - Preliminary parametric exploration of top level sizing parameters (fan pressure ratio, rotational speed …) to be linked with electric machine performances
  - Inclusion of airframe integration constraints (available space, integration of high lift devices …) and electrical chain design features (motors rotational speed …).
- Parametric inlet geometry models for numerical optimization in order to achieve best coupling between S-duct BLI inlet and ducted thruster





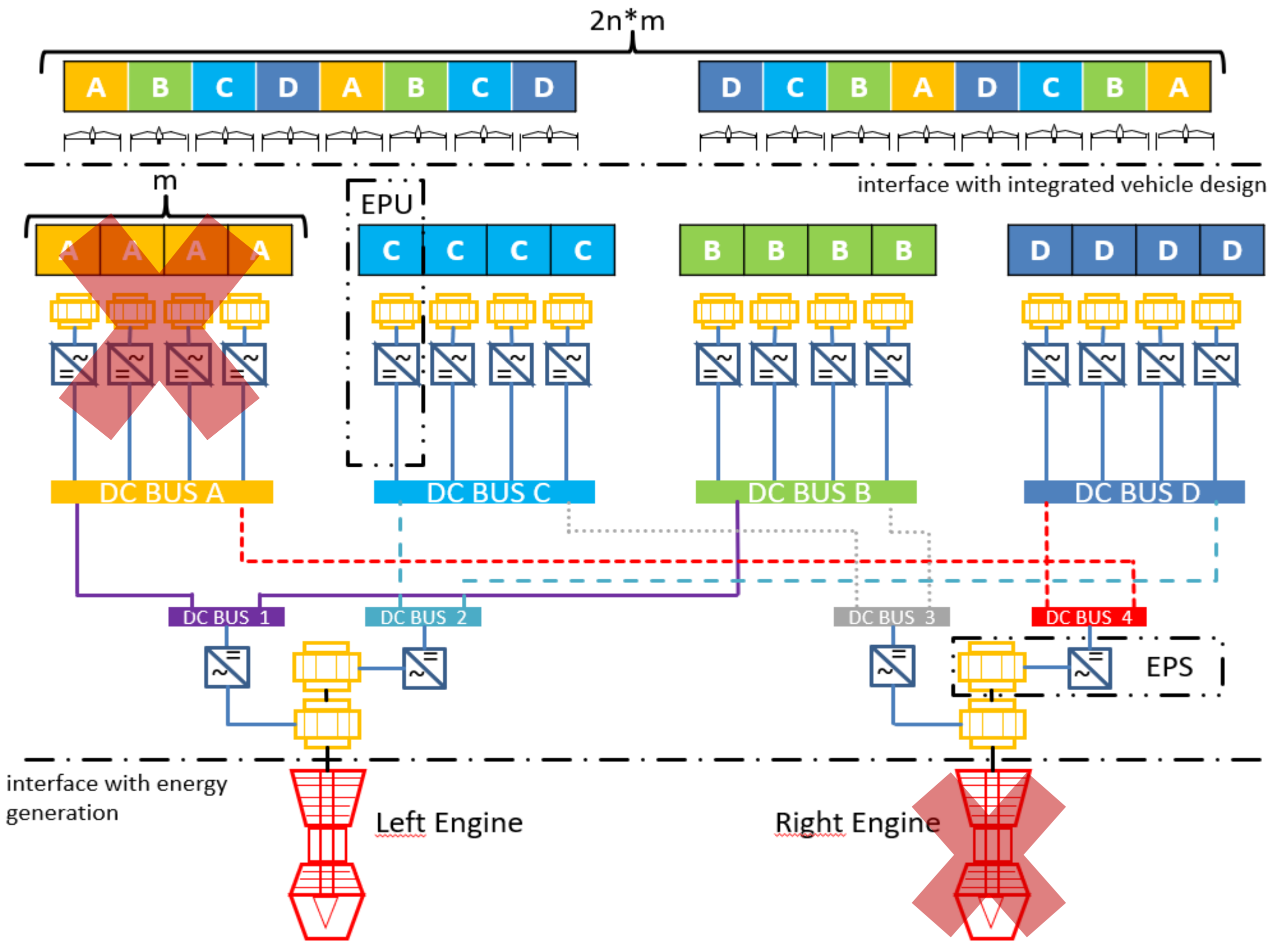


Propulsor ducts Nacelle profile General arrangement

Electric architecture

- **Scope : Electric architecture definition and management**
  - Components selection and interfaces
  - Power management & fault analysis
  - Thermal management
  - EMC and discharges
- **Achieved during Loop 0 (“conceptual design”)**
  - Collection of technology assumptions
  - Preliminary architecture design for turboelectric propulsion chain
  - Specifications for electric components
- **On going:**
  - Thermal management architecture definition
  - Failure cases analysis (in connexion with configuration design)
  - Detailed SMR architecture analysis, extension to REG architectures

Electric architecture



Architecture for Conservative SMR

- **Identification of critical failure cases**

  1 EPU bus inoperative and one engine inoperative

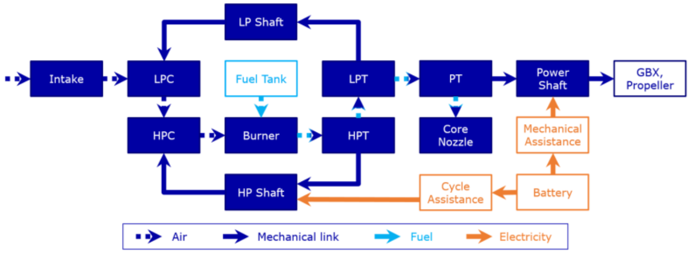
- **Sizing of components for max normal operation requirement + oversizing margin**
- **Safety & reliability analysis :**
  - stochastic model for reliability, availability and repair, mainly for supply failure
  - Low probability of aggregate EPUs failures, in line with safety requirements.
  - Individual failures of a single EPU might not be uncommon

Hybrid electric power train

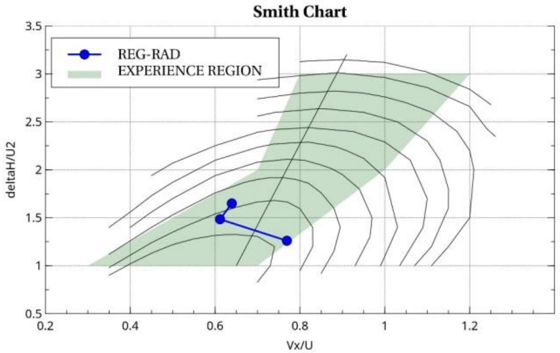
- **Technology investigation of all the components of the power train**
- **Energy sources**
  - Turbogenerator : turbine architecture and sizing, generator design, integration & dynamic aspects
  - Batteries: coin-cell demonstrator and modelling of all-solid-state Li-metal anode battery
  - Fuel cells: investigation of fuel cell technologies for a commercial aircraft environment
- **Electric machines**
  - Topology studies and pre-design
  - Interaction of electric machines and power electronics
- **Power electronics**
  - Investigation of Power Electronics topologies and pre-design of inverters and converters
  - Inverter control concepts for optimized motor application
  - Power distribution : choice of DC voltage, high voltage components and thermal release
- **Superconductivity:** exploration of potential benefits on electric machines, power electronics and distribution

Energy generation

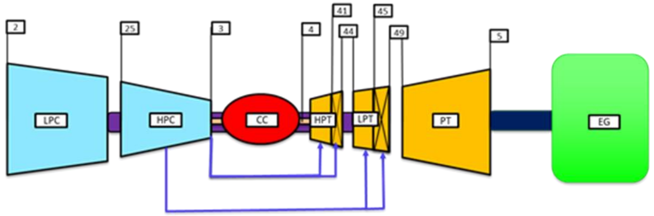
- **Turbomachinery**
  - Component sizing and performance maps for the 4 concepts
- **Electric generator**
  - Surface mounted Permanent Magnets Synchronous Machine
  - For regional : 1.25 MW power class, 25000 rpm
  - For SMR : 11 MW power class, 8-10000 rpm
- **Batteries**
  - Characterization of coin cell electrolytes
  - ASSB parameters optimization



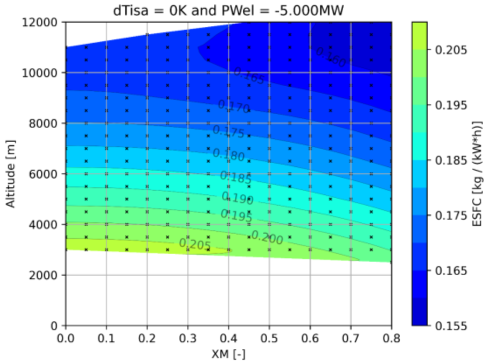
REG-CON assisted turboshaft (1.2 MW class)



REG-RAD turbine operating domain

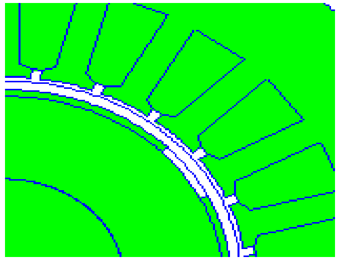


SMR-CON turboshaft (10 MW class)

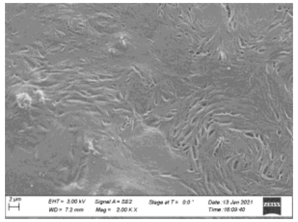


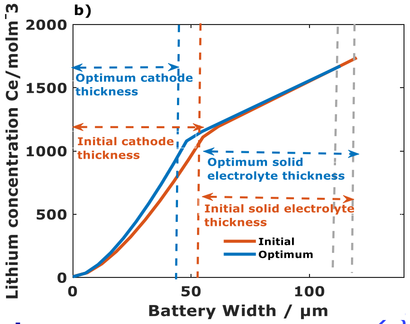
SMR-RAD off-design studies

Generator modelling



Coin cell electrolyte



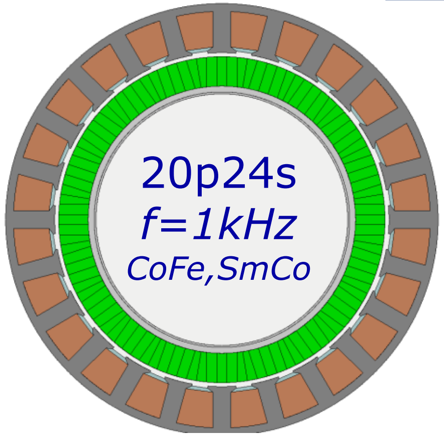


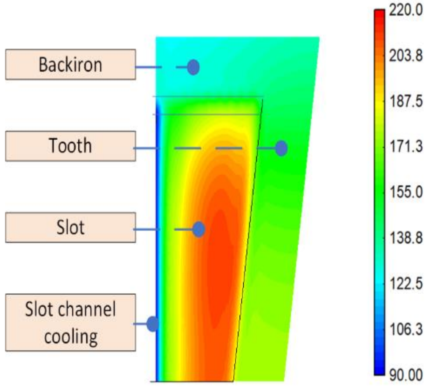
5C battery parameters

Electric power unit

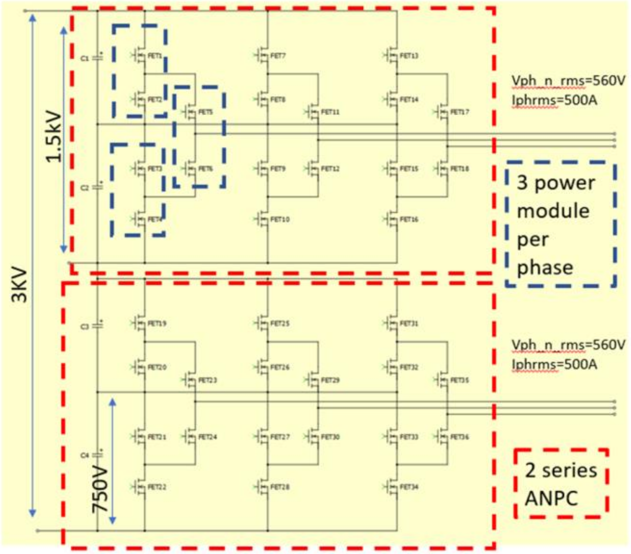
- **Requirement identification and refinement from aircraft and electrical system concept**
  - First applied to SMR turboelectric concept
- **Preliminary requirement allocation to the different electrical component that compose the powertrain**
  - Electric machines, EWIS, power electronics
- **First evaluation of the electrical components key characteristics**
  - Initial sizing to be fed back to aircraft level
  - Superconductivity initial evaluation
- **Integration of the electrical components predesign in preliminary EPU concept**

SAFRAN | University of Nottingham UK | CHINA | MALAYSIA | UNIVERSITÉ DE LORRAINE

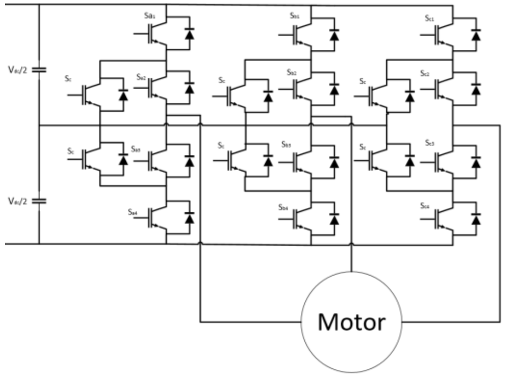




Electric motor : 820kW continuous, 5700rpm, target >10kW/kg, oil-cooling and air-cooling investigated



EPU key challenge : 3000 V DC voltage



Superconductivity:
Power Electronic @ 50K
Superconducting motor @ 20K

IMOTHEP GETTING HYBRID ELECTRIC

Conclusion : the ambition of IMOTHEP

- **A consolidated estimate of HEP potential**
  - Aircraft concept & performance built on consolidated technology data for power train components
  - Harmonised technology assumptions and design methodology
  - Key enablers & techno gaps identified from components' performance integration at aircraft level
- **A holistic approach of electric systems integrated in a propulsion architecture**
  - Preliminary solutions for components in the targeted range of performances
  - Consolidated components' model
  - Integration in a whole electric architecture
  - Analysis of failure cases, EMI, electric discharge
- **A roadmap for HEP development**
  - R&T priorities with timely objectives and milestones
  - Needs for tools, facilities and demonstrations for HEP maturation
  - Preliminary analysis of needs for certification adaptation

The IMOTHEP team

ONERA
THE FRENCH AEROSPACE LAB

AIRBUS

CIRA
Centro Italiano Ricerche Aerospaziali

DLR

LEONARDO
AIRCRAFT

SAFRAN

Avio Aero
A GE Aviation Business

UP L

AIT AUSTRIAN INSTITUTE OF TECHNOLOGY

GKN AEROSPACE

AVANCEZ 1829
CHALMERS
UNIVERSITY OF TECHNOLOGY

Łukasiewicz
Institute of Aviation

INCAS
National Institute for Aerospace Research "Elie Carafoli"

ITP Aero

nlr

MTU
Aero Engines

Bauhaus Luftfahrt
Neue Wege.

UNIVERSITÉ DE LORRAINE

isae
Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

KIT
Karlsruhe Institute of Technology

University of
Strathclyde
Glasgow

Politecnico di Bari

University of Nottingham
UK | CHINA | MALAYSIA

EUROCONTROL

ЦАГИ

CIAM

ГосНИИ АС

NATIONAL RESEARCH CENTER
ZHUKOVSKY INSTITUTE

МАИ

NRC·CNRC

IMOTHEP
GETTING HYBRID ELECTRIC

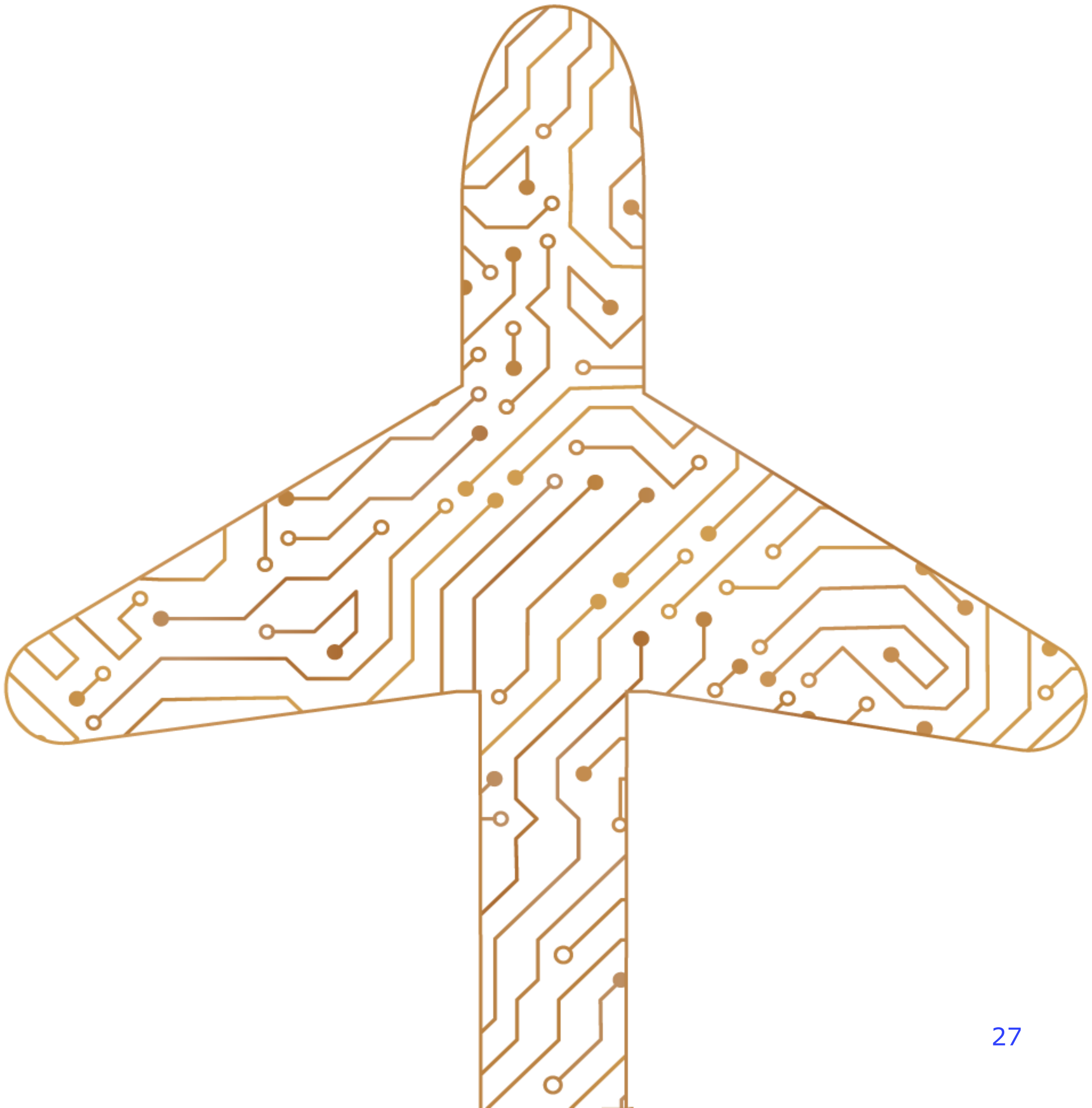
THANK YOU !

Contact points for any question:

- Project Coordinator
  - Philippe NOVELLI (ONERA)
  - Email: philippe.novelli@onera.fr
  - Office: +33 1 80 38 69 14

- PMO
  - Peggy FAVIER (L-UP)
  - Email : peggy.favier@l-up.com
  - Office: +33 4 78 41 44 47
  - Mobile: +33 6 75 64 10 78

- www.imothep-project.eu



This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 875006