10 MW HTS Generator für hybrid-elektrische Flugzeugantriebe

TELOS – LuFO V

Dr. Martin Boll & Dr. Lars Kühn - Rolls Royce Deutschland

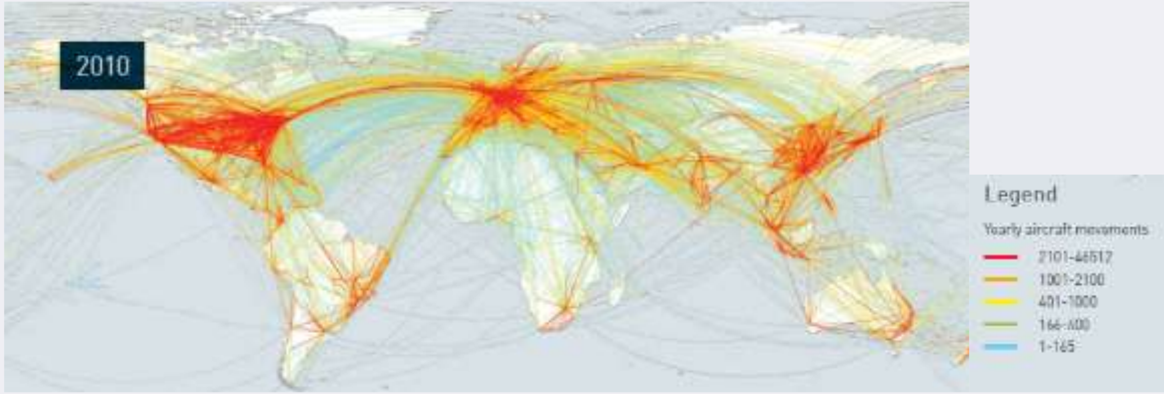
Ziehl VII Workshop- Berlin, 06. März 2020

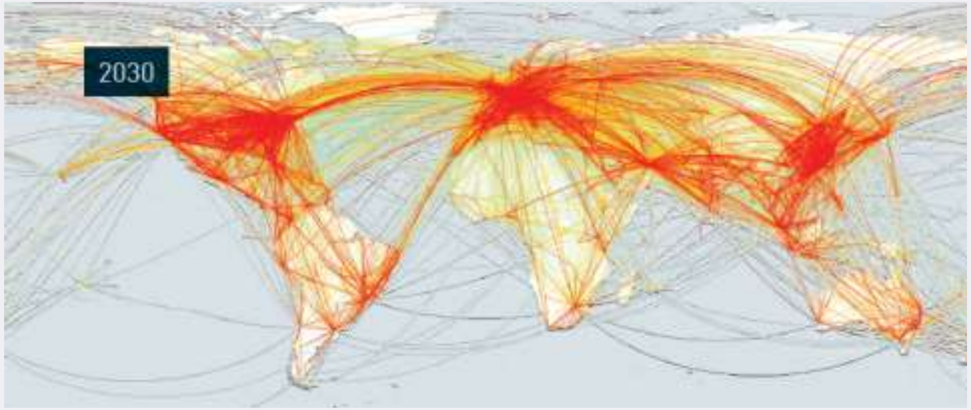
Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Air traffic
2010 and 2030

Airbus Global Market Forcecast 2019 (> 100 PAX):

- 2038: Doubling # of passengers
- ~ 4 % increase/year





Source: ICAO, 2016 [1]

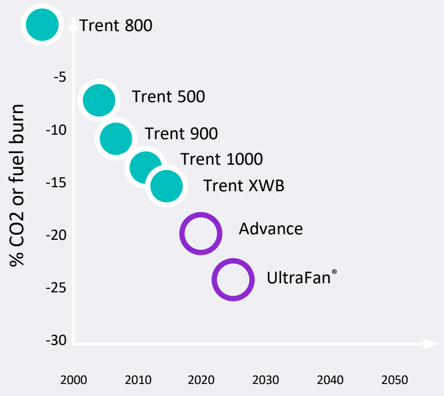
Working towards our FP2050 goals

Trent family

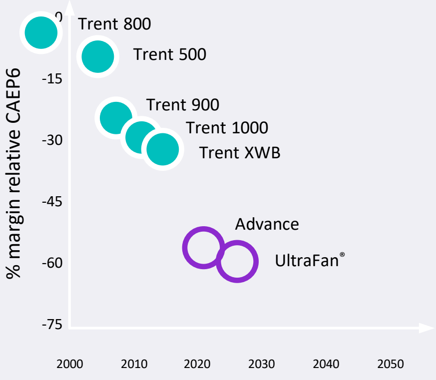
Technology demonstrator engine targets

ACARE (Advisory Council for Aviation Research and Innovation in Europe) Flightpath 2050 target

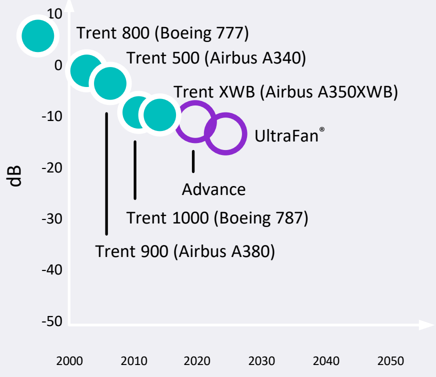
CO_2 (Engine)



NOx (Engine)



Noise (Aircraft)



ACARE Flightpath 2050 targets

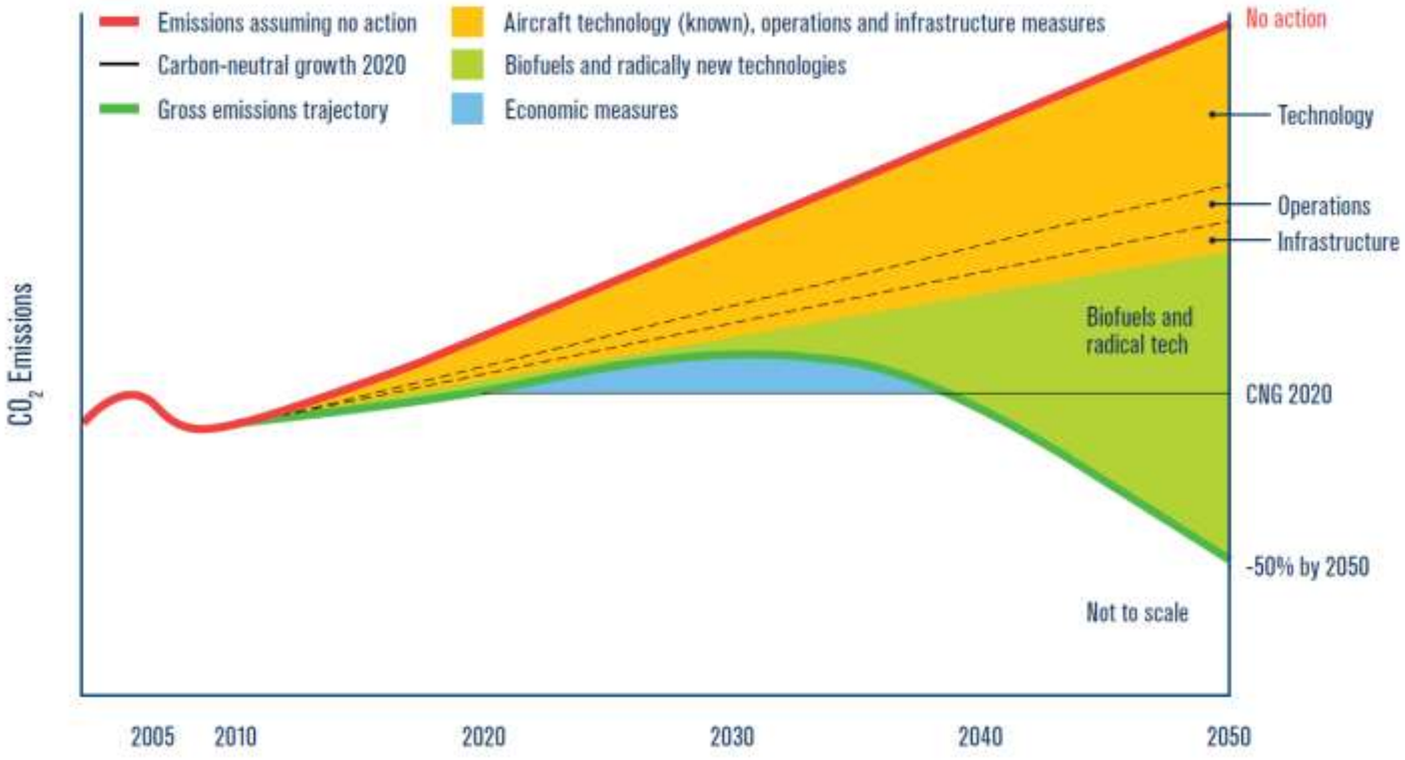
75%

90%

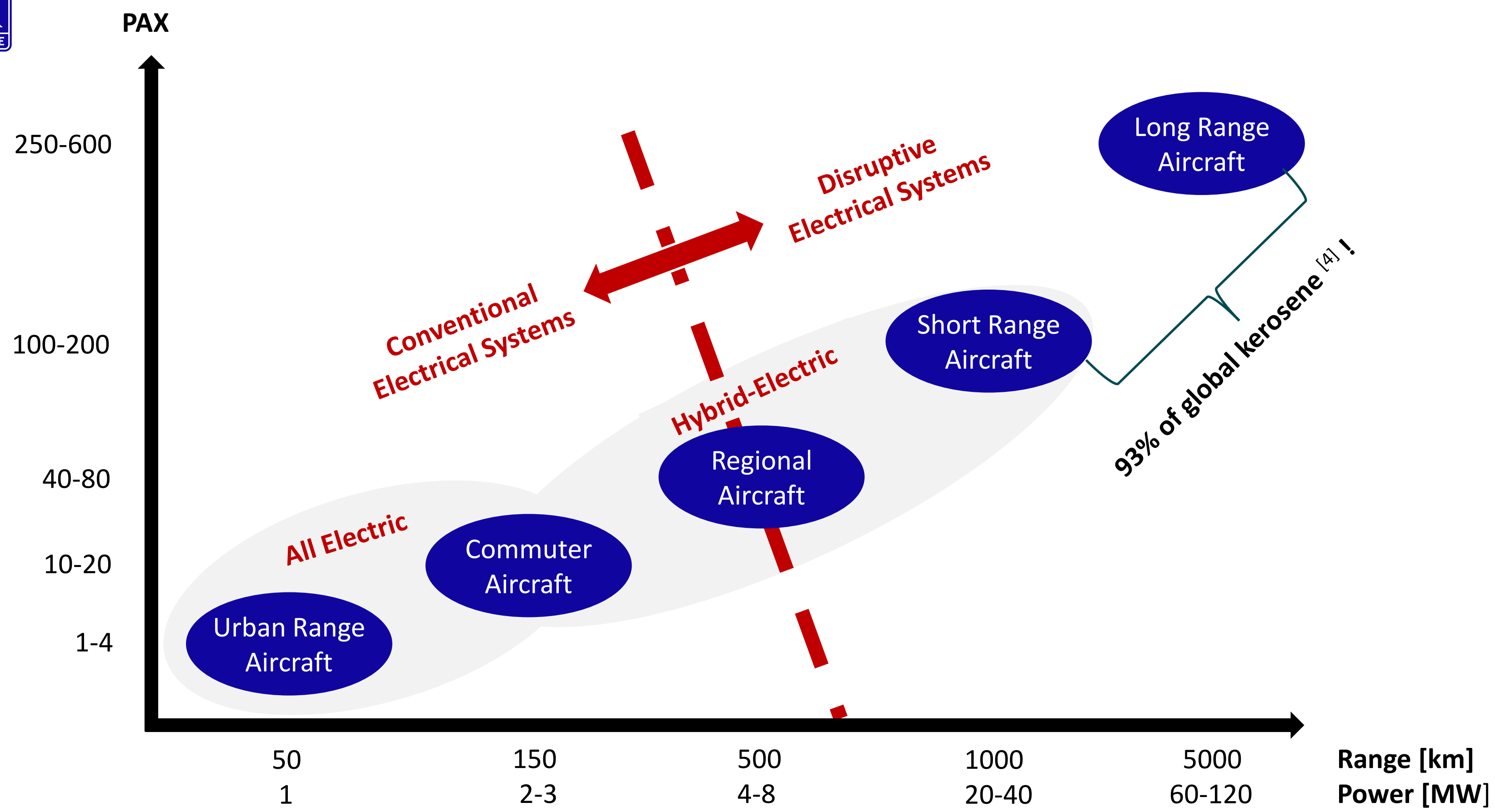
65%

Continuing to deliver competitive, efficient, environmentally friendly aircraft

Source: IATA Technology Roadmap, 2013 [3]



We need to evaluate disruptive approaches!



Sources: Discussion with Airbus in TELOS, [4]: Epstein, JOURNAL OF PROPULSION AND POWER Vol. 35, No. 3, May–June 2019

TELOS

Airbus
Rolls Royce (Siemens)
KIT
TU München
Neue Materialien Bayreuth

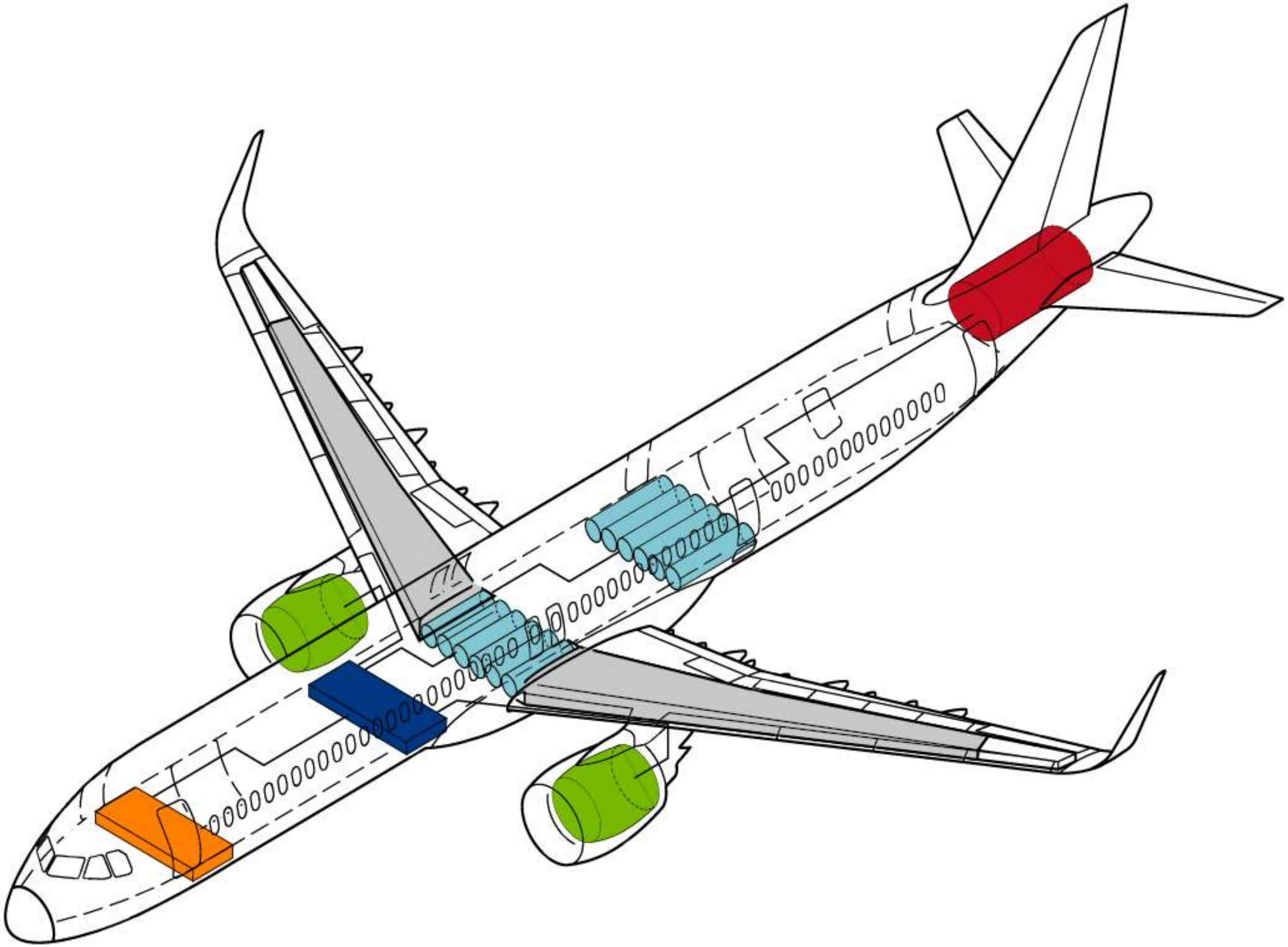
I. **Feasibility Study**
II. 10 MW HTS Generator

Source: Airbus: https://www.airbus.com/aircraft/passenger-aircraft/a320-family/a321ceo.html [5]

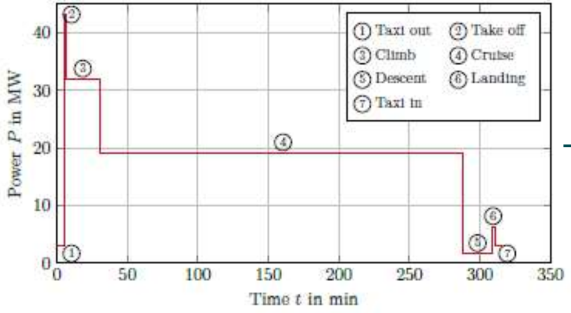
Feasability Study

Re-equipped aircraft:

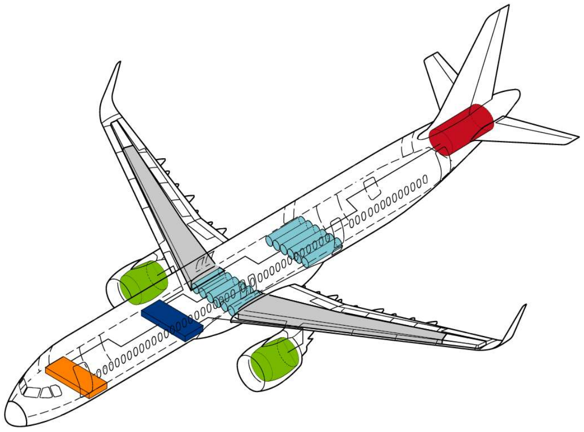
- Serial turboelectric
- 220 passengers
- Electric propulsion units at wings
- Liquid hydrogen tanks replace center tanks
- Kerosene in wing tanks



Methodology



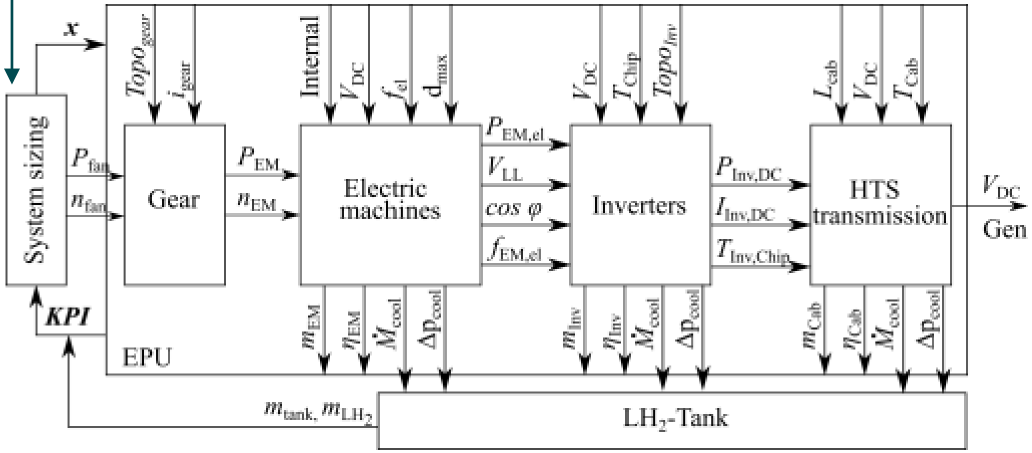
CS 25 Certification



Requirements

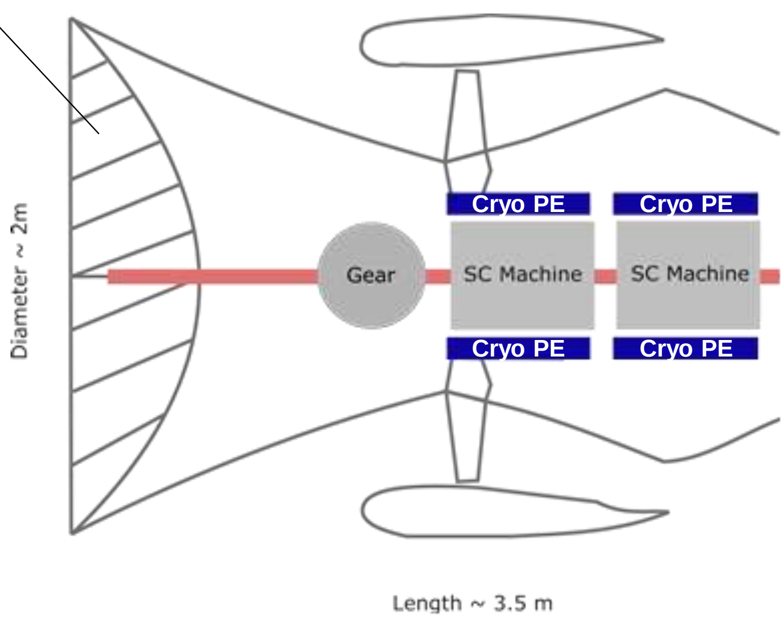
Analytical model for system optimisation

- Components are sized with respect to requirements
- Global parameters as voltage level, electric frequency or topology are varied
- Internal component parameters/materials are scanned
- System KPIs as mass, efficiency, installation space are computed

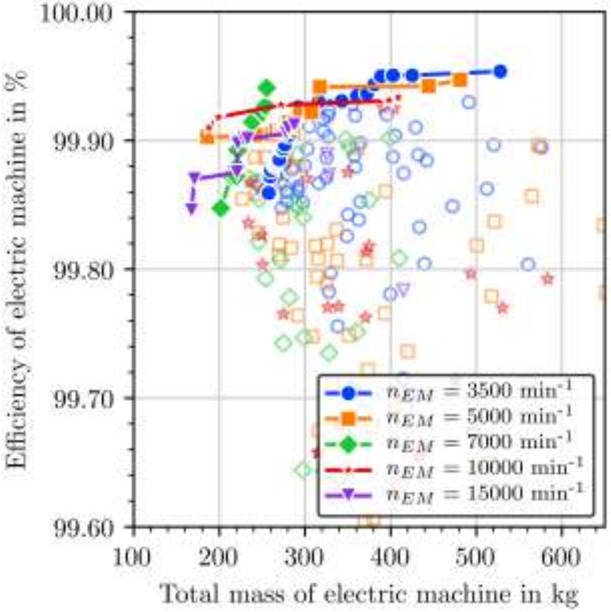


Cryogenic Electric Propulsion System (CEPS)

Fan: 3500 rpm



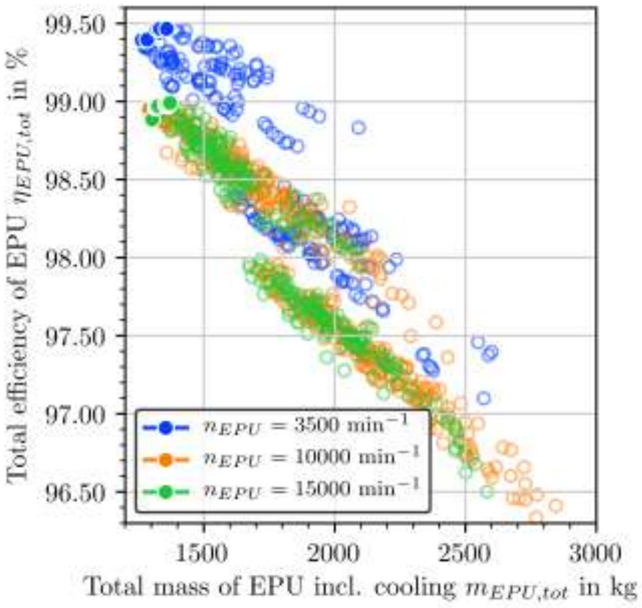
10 MW SC Machine



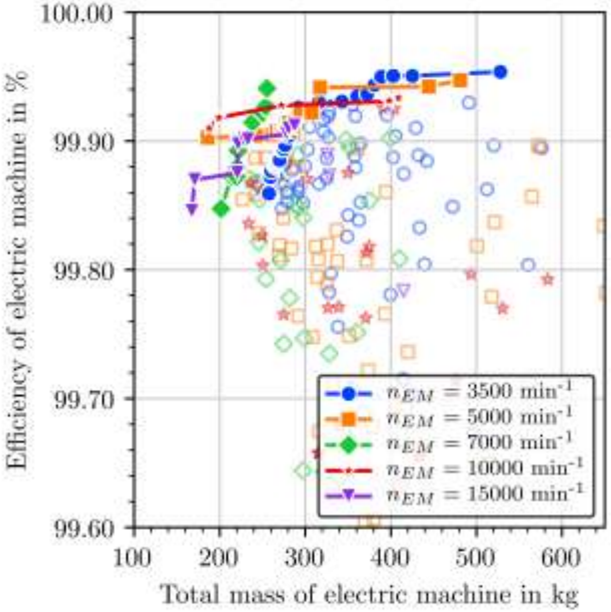
Sources: Boll et al., A holistic system approach for short range passenger aircraft with cryogenic propulsion system, SUST, 2020 (accepted)
Corduan et al., Topology comparison of superconducting AC machines for hybrid-electric aircraft, IEEE Trans On Appl SC 30 (2), 1-10, 2020

Cryogenic Electric Propulsion System (CEPS)

20 MW EPU incl. cooling for mission profile



10 MW SC Machine



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Cryogenic Electric Propulsion System (CEPS)

- Actual AC loss and cryogenic power electronics favours direct drive solutions (due to lower electric frequencies)
- Better SC will require higher saturation field of the iron yoke
- Research focus on cryo PE will be required (temperature reliability, cosmic radiation)
- Feasability propulsion system only if cryogenic cooling liquid acts as energy source

Type	Symbol	Unit	Value	Value	Value
Global	V_{DC}	V	1500	3000	4000
	M_{Sys}	kg	8355	8432	8417
	η_{Sys}	%	98.27	98.71	98.75
	m_{equi}	kg	3900	2744	2618
	M_{eff}	kg	4455	5688	5799
EPU	f_{el}	Hz	350	350	350
	n_{EM}	$\min^{-1}$	3500	3500	3500
	P_{EM}	MW	10.5	10.5	10.5
	d_{EM}	m	0.52	0.55	0.54
	l_{EM}	m	0.54	0.63	0.62
	m_{EM}	kg	287	304	303
	η_{EM}	%	99.90	99.92	99.92
	$B_{S,EM}$	T	1.17	0.91	0.90
	$Q_{S,EM}$	W	4378	2393	2396
	$Q_{Fe,EM}$	W	5077	5653	5680
	m_{Inv}	kg	479	545	554
	η_{Inv}	%	99.65	99.76	99.77
Gen	f_{el}	Hz	500	500	500
	P_{EM}	MW	21.0	21.0	21.0
	n_{EM}	$\min^{-1}$	10000	10000	10000
	d_{EM}	m	0.37	0.36	0.37
	l_{EM}	m	1.02	1.21	1.02
	m_{EM}	kg	376	398	375
	η_{EM}	%	99.87	99.92	99.90
	$B_{S,EM}$	T	0.82	0.73	0.81
	$Q_{S,EM}$	W	2645	2062	2640
	$Q_{Fe,EM}$	W	6740	6461	6730
	m_{Inv}	kg	886	1096	1114
	η_{Inv}	%	99.63	99.74	99.76
Cool	m_{Tank}	kg	947	663	632
	m_{LH_2}	kg	1187	831	793
	V_{LH_2}	l	16765	11737	11200

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Source: Airbus: https://www.airbus.com/aircraft/passenger-aircraft/a320-family/a321ceo.html [5]

Requirements and boundary conditions

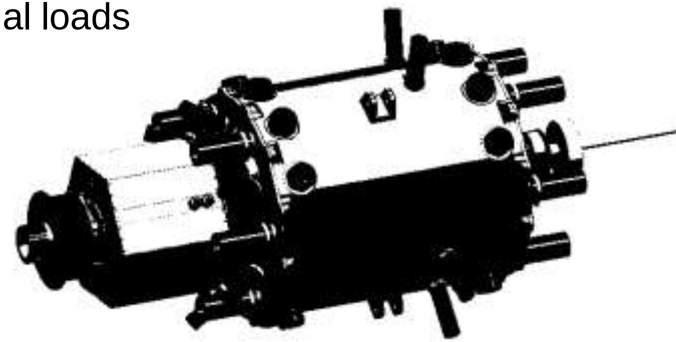
Goal

Develop a 10 MW generator using DC coils made of 2G HTS to provide a new technology for motors and generators with high power densities.

Target parameters

• Power:	10 MW
• Power density:	>20 kW/kg
• Speed:	7000 rpm
• Voltage:	3 kV
• Efficiency:	97 %

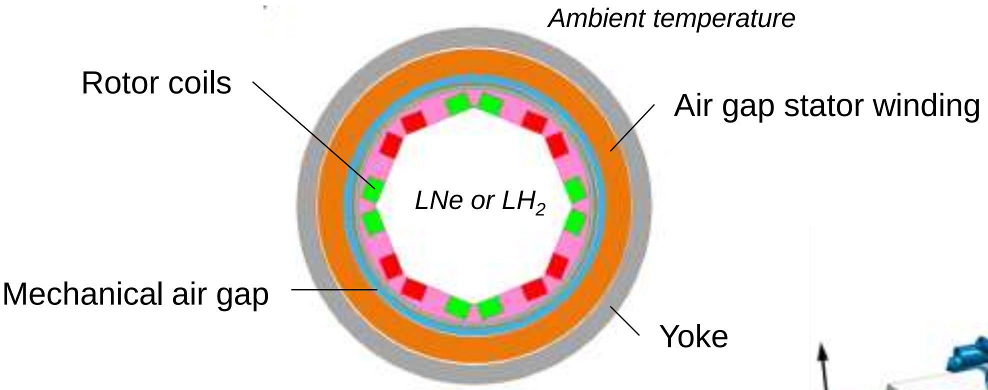
- Prototype with the essential feature ***Proof-of-concept*** (TRL 3)
- **3 h Operation / 0.5 h Care**
- Generator provides **continuous Power of 10 MW** within the **3 hours** (peaks are compensated by an onboard energy storage)
- **(Constant) Operation speed is 7000 rpm** (→ compromise between generator, transmission and gas turbine)
- Power density > **20 kW/kg → < 500 kg** total weight
- Lifetime **2000 h**
- Load cases to be considered: torque, electromagnetic forces, thermal expansion, gravity, pressure and centrifugal loads
- Load-free coupling to turbine

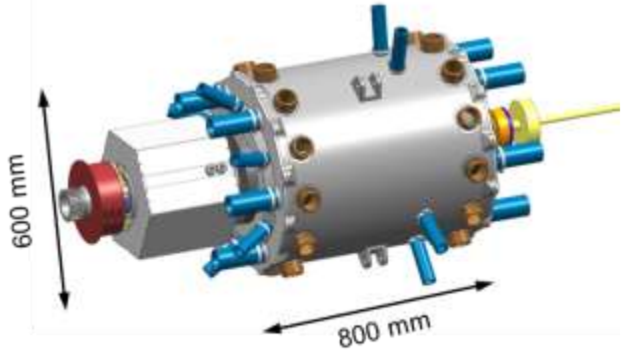


Synchronous machine with HTS DC coils

Requirements: 10 MW | 7000 rpm | 20 kW/kg | > 97%

Basic design





Rotor

- 4 Pole pairs
- DC coils made of 2G HTS tapes
- Operated at 20 to 28 K
- Cooled with LNe or LH_2

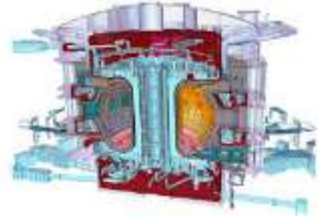
Stator

- Air gap winding made of Cu litz wire
- Operated at 370 K
- Liquid cooled
- Yoke to guide the magnetic flux and for shielding

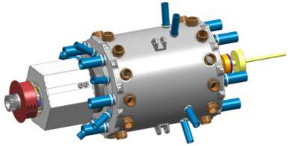
Challenges

10.000 g corresponds to maximum piston acceleration of Formula One engines

MMF > 200 kA corresponds to plasma confinement coils in fusion power plants

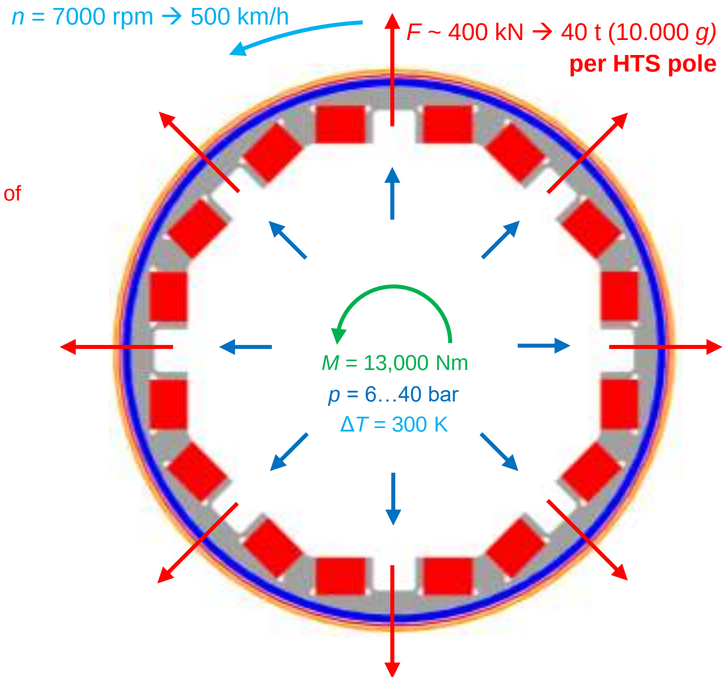


7.5 K/mm corresponds to temperature gradient in fusion power plants (15.000 K / 2 m)



p corresponds to about 400 m water depth → diving depth of military submarines

ΔT corresponds to temperature difference day/night on the Moon

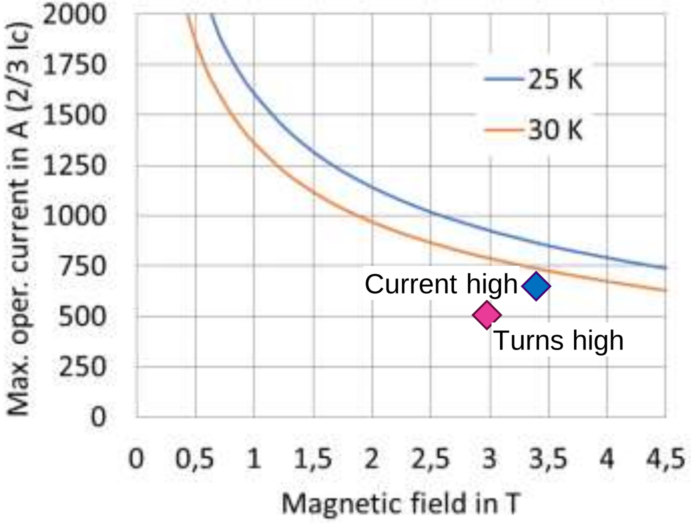


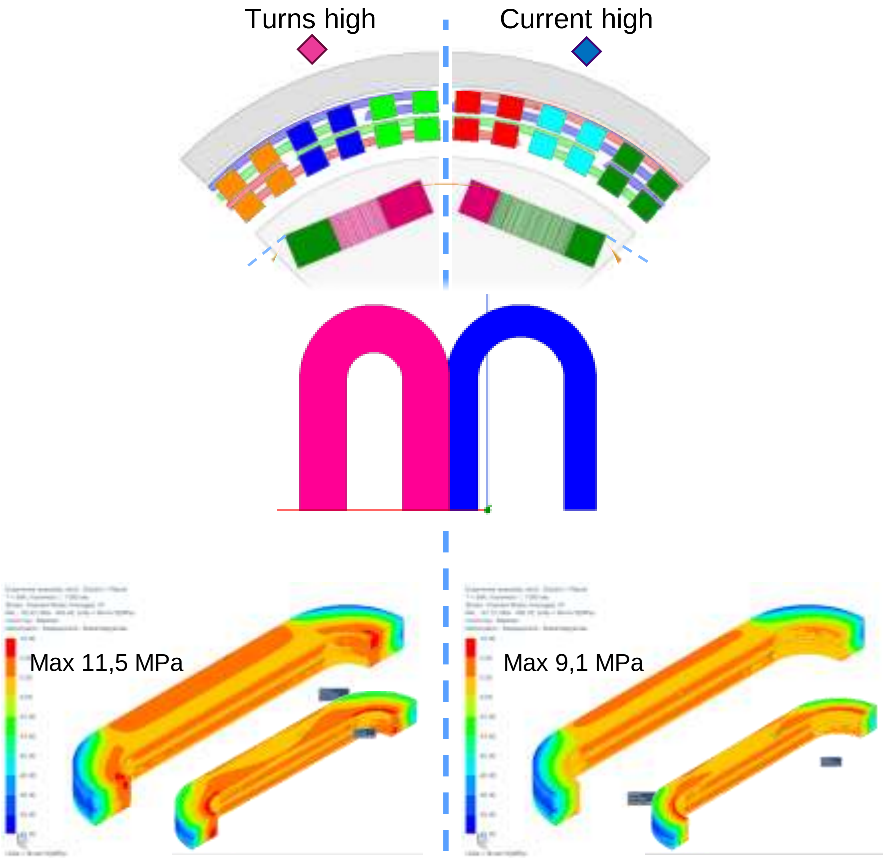
Loads on rotor	
Strain from bandage to coil carrier	Press-fit
Thermal contraction	Operating @ 20 K
High centrifugal load	Rotational speed
Torque transmission	20 K to RT over 40 mm (7.5 K/mm)
High magnetomotive force	Pole MMF > 200 kA

Design space HTS poles

Option	Turns	I [A]	M [kNm]	$B_{\perp}$ max [T]
Turns high	250	530	15,6	2,97
Current high	150	685	15,8	3,33

Tape F (12mm)





Margin to superconducting limits

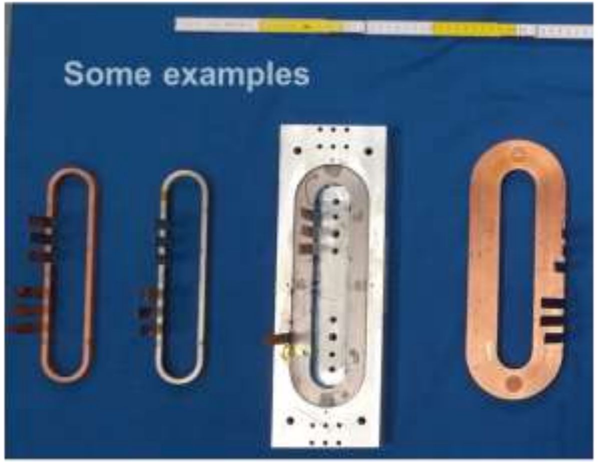
Turns

Current

Margin to mechanical stress limits

HTS tapes → Coils → Single poles → Multi Poles for high speed rotating machines

Single coils tested

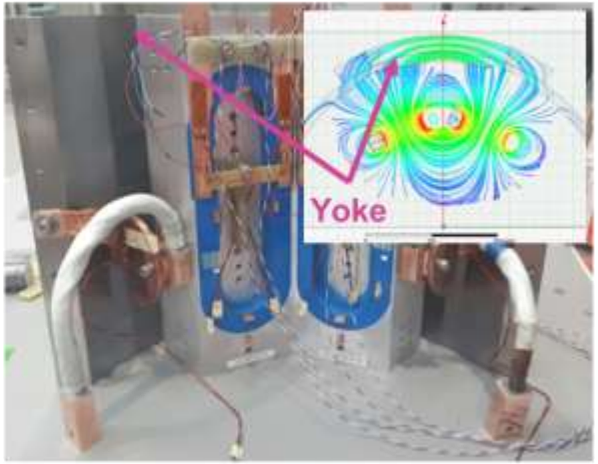


Ic 280A @77K	Ic 180A @77K	Ic 150A@77K 900A@24K	Ic 175A@77K 165A@77K
45 turns	35 turns	130 turns	240 turns
Not insulated			Insulated
Tape F	Tape A	Tape T	Tape F

Single pole tested (dry-cooled)

Ic 195A@77K Ic 560A@52K Ic 1050A@23K [3.1T]
2 x 160 turns (stacked)
Insulated
Tape F

Double pole tested (dry-cooled)



Operated at 700A @21K | Expected Ic 1100A
Pole left: 2 x 160 turns (stacked)
Pole right: 2 x 160 turns (stacked)
Margin factor 1.5
Tape F
Experimental results support design values.

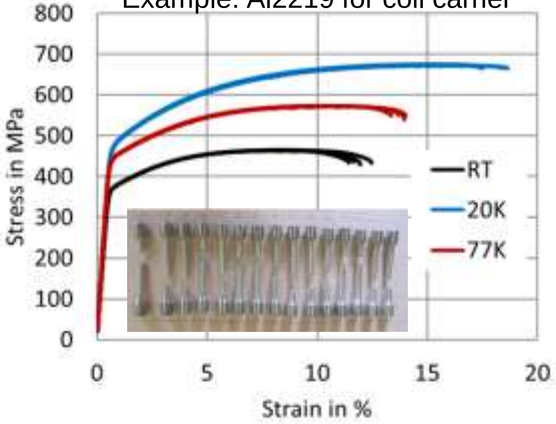
New materials and manufacturing methods were needed

90% of the components require materials that are unusual in electrical machines.

„Battle of material“

Identified materials for all components

Example: Al2219 for coil carrier



- Developed electron beam welding process and validated the quality with tensile tests at 77 K

Developed and validated processing and assembling of the generator

Sleeve (Inconel)
Processing 300 h

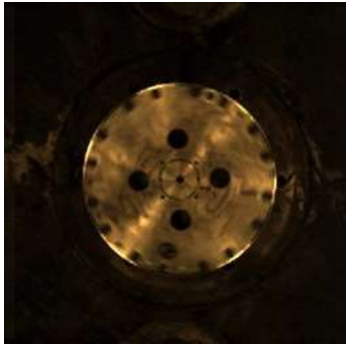
Shrinkage test
Sleeve on coil carrier
Scale 1:1

Demonstrated efficient manufacturing of the generator

- 3D printing of large structural components with required tolerances

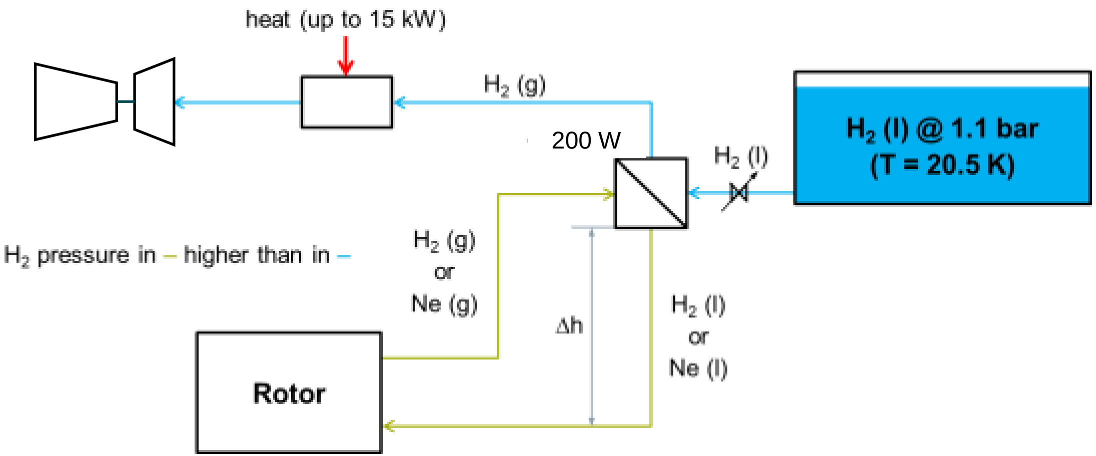
Printed Inconel

Printed Al-alloy



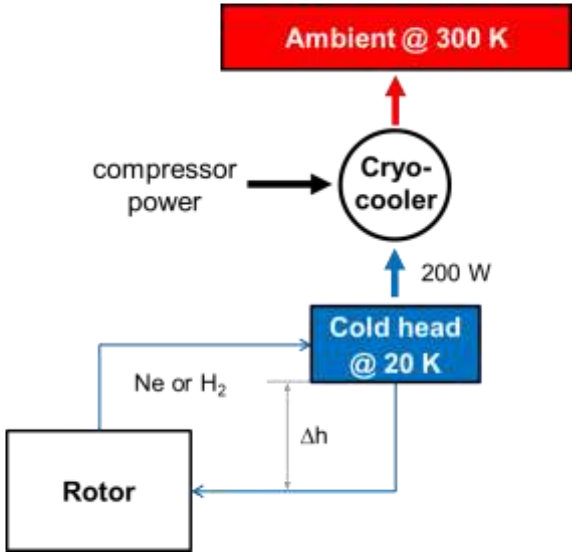
burst speed 25500 rpm

Aircraft cooling concept: LH_2 tank



Cooling capacity	200 W
Operational time	5 h
Amount of LH_2	8 kg
LH_2 tank (115 L)	approx. 80 kg
Total mass	approx. 88 kg

Lab cooling concept: Cryo cooler



Cooling capacity	300 W
Total mass	> 1000 kg

Stator winding

Simulation cooling

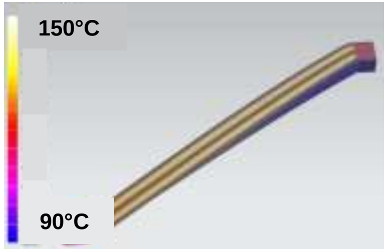
T_{max} coils: 155°C

T_{max} support structure: 130 °C

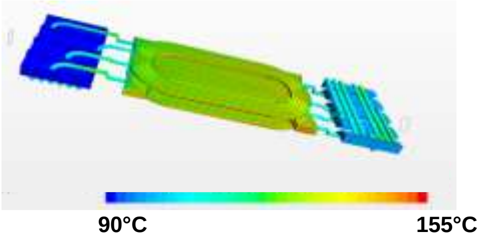
Pressure drop: 1 bar

T_{inlet}: 90°C

T distribution helical



T distribution flat coils



Manufacturing (Scale 1:1)

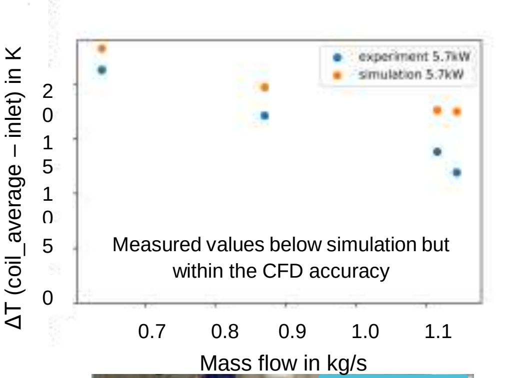
- Manufacturing of helical and flat coil
- Filling factor > 75% (both concepts)
- Dimensionally stable geometry
- Successfully connected
- No insulation damages

Helical

Flat coil

Cooling Test

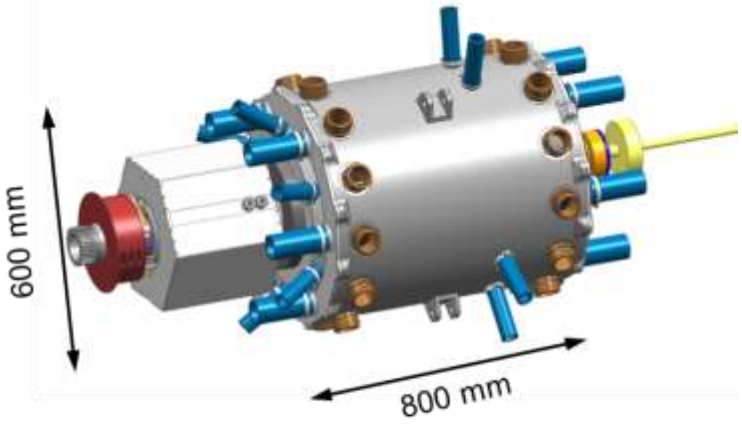
- All parameters adjustable
- Original sized cooling channels
- Flow rate: 42 l/min (Coolant FC3283)
- Cooling concept confirmed up to 6 kW (5.8 kW per coil in HTS-Geno expected)



At a glance

Rated load operation parameters	
Effective power	10 MW
Apparent power	11.3 MVA
Power factor	-0.89 (under-excited)
Torque	13.9 kNm
Speed	7000 rpm
Pole pair	4
Rated effective coil current stator	384 A
Stator effective current density	27.5 A/mm^2
Rated rotor current	500 A
Line-line peak voltage	3 kV
Power density (for active parts only)	43 kW/kg
Torque density (for active parts only)	58.6 Nm/kg
Weight	476 kg
Power density total	21 kW/kg
No-load peak magnetic flux density at rotor surface / middle of stator winding	1.82 T / 1.11 T

- Developed a resilient design of a 10 MW HTS Generator
- Achieved a gravimetric power density above 20 kW/kg
- Set up digital twins for all relevant disciplines
- Validated the relevant mechanical material characteristics
- Verified hydrogen compatibility
- Multiple manufacturing and mounting tests
- Finalized a multi-physics model of the HTS Generator (integration of HTS tape pending)



Source: M. Filipenko, L. Kuehn, et al., Concept Design of a High Power Superconducting Generator for Future Hybrid-Electric Aircraft, SUST, 2020 (DOI:10.1088/1361-6668/ab695a).

Learnings

Combination of superconductors and hydrogen show potential for decarbonization of passenger aircrafts (> 100 PAX)

Holistic system approach

i. Generic mission profile
ii. System architecture
iii. Safety and Reliability
iv. Modelling of all components

Demonstrators

i. As early as possible
ii. Functional proof
iii. Manufacturing proof
iv. Test infrastructure

Material and design

i. Low AC-loss
ii. Cryo compatibility (H_2)
iii. High mechanical strength
iv. Tailored thermal conductivity
v. Cryo database
vi. Availability and traceability
vii. Cryogenic power electronics

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Acknowledgments

Team

Martin Boll[1], Lars Kühn[1], Matthias Corduan[2], Stefan Biser[1], Marijn Oomen[2], Sonja Schlachter[3], Bernhard Holzapfel[3], Matthias Noe[3], Andreas Westenberger[4], Peter Rostek[4], Marc Lessmann[1], Thomas Gleixner[1], Stefan Moldenhauer[1], Jörn Grundmann[2], Matthias Böhm[1], Markus Wilke[2], Peter Gröppel[1], Martin Thummet[1], Sunil Sreedharan[2], Johannes Richter[2], Christian Weidermann[2], Vladimir Danov[3], Manfred Wohlfart[3], Klaus Dennerlein[2], Christian Triebel[2], Peter van Haßelt[2], Peter Kummeth[2], Joachim Hubmann[2], Michael Frank[2], Dirk Möller[1], Andreas Schröter[1], Otto Batz[2], Dietmar Bayer[2], Mykhaylo Filipenko[1], Kerstin Häse[1]

1) Rolls-Royce RRE Bavaria
2) Siemens AG
3) Karlsruhe Institut für Technologie KIT
4) Airbus Operations & Electric Aircraft Systems

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Thank you.

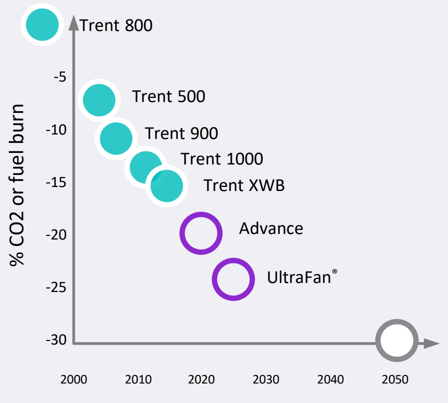
Working towards our FP2050 goals

Trent family

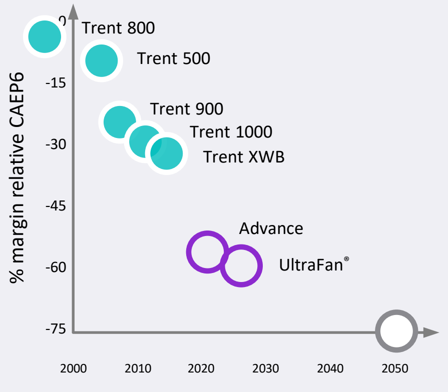
Technology demonstrator engine targets

ACARE (Advisory Council for Aviation Research and Innovation in Europe) Flightpath 2050 target

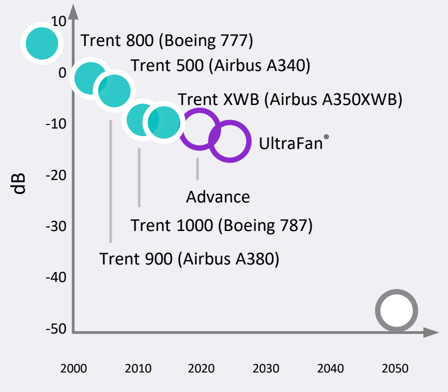
CO_2 (Engine)



NOx (Engine)



Noise (Aircraft)



ACARE Flightpath 2050 targets

75%

90%

65%

Continuing to deliver competitive, efficient, environmentally friendly aircraft

Airbus Forcecast

- Aircraft (>100 PAX)
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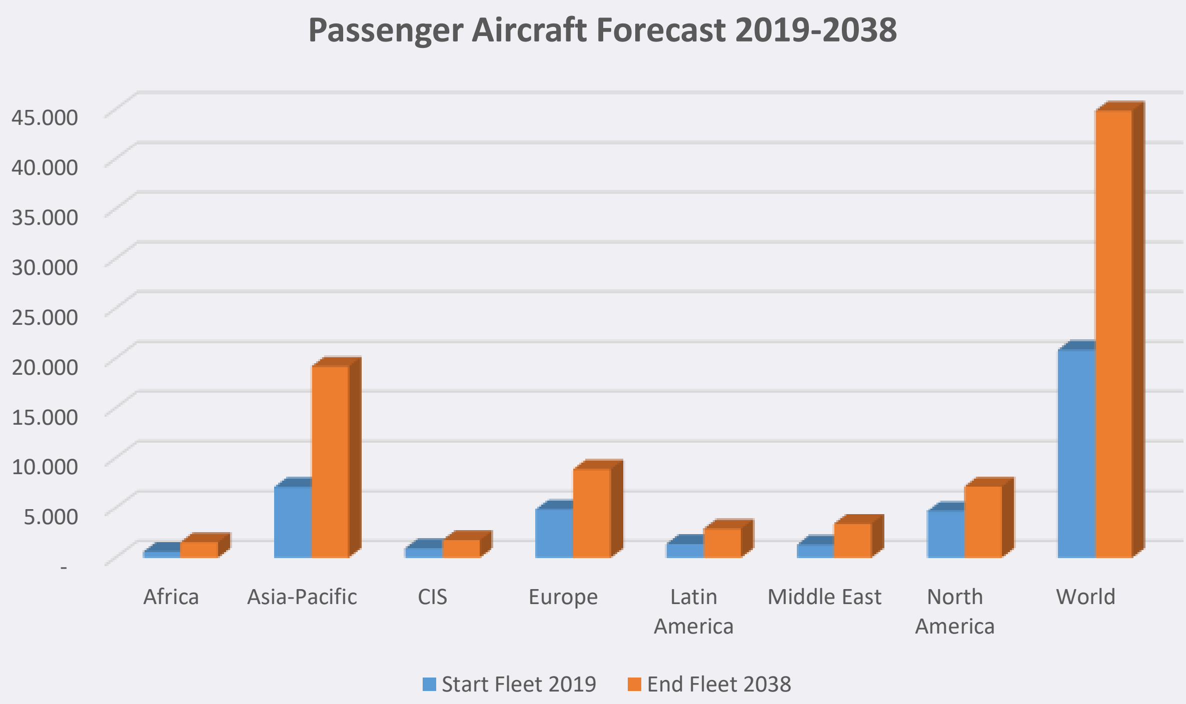
- ~ 4 % increase/year

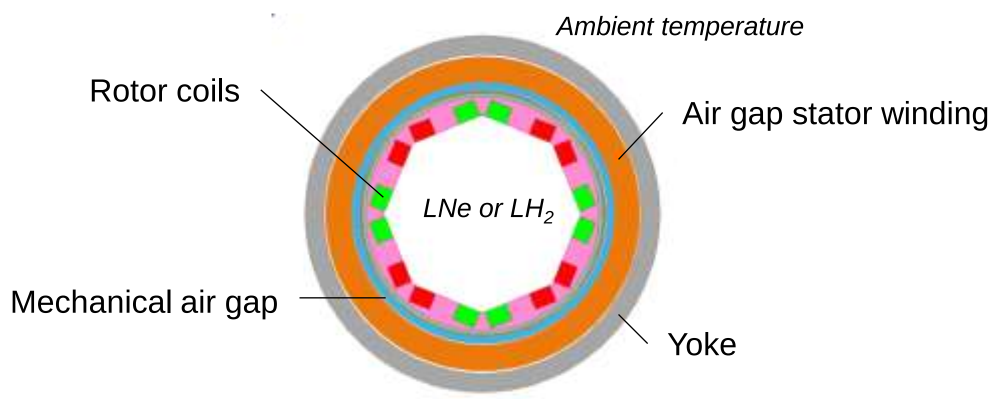


Source: Airbus Global Market Forcecast, 2019 [2]

Synchronous machine with HTS DC coils

Requirements: 10 MW | 7000 rpm | 20 kW/kg | > 97%

Basic design



Rotor:

- 4 Pole pairs
- DC coils made of 2G HTS tapes
- Operated at 20 to 28 K
- Cooled with LNe or LH_2

Stator:

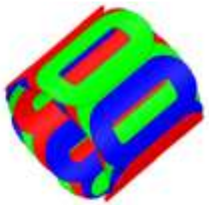
- Air gap winding made of Cu litz wire
- Operated at 370 K
- Liquid cooled
- Yoke to guide the magnetic flux and for shielding

Air gap stator winding options

Helical

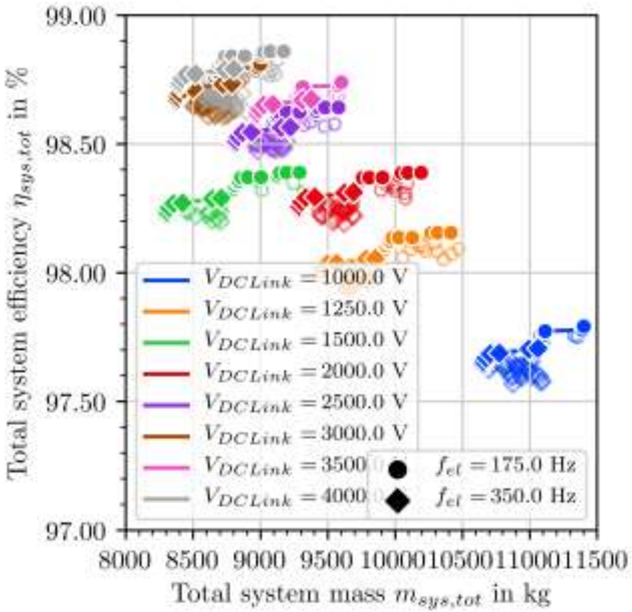
- Successful manufactured bar shaped elements with filling factor >75 %
- Loop current losses due to crimped litz wire hard to predict

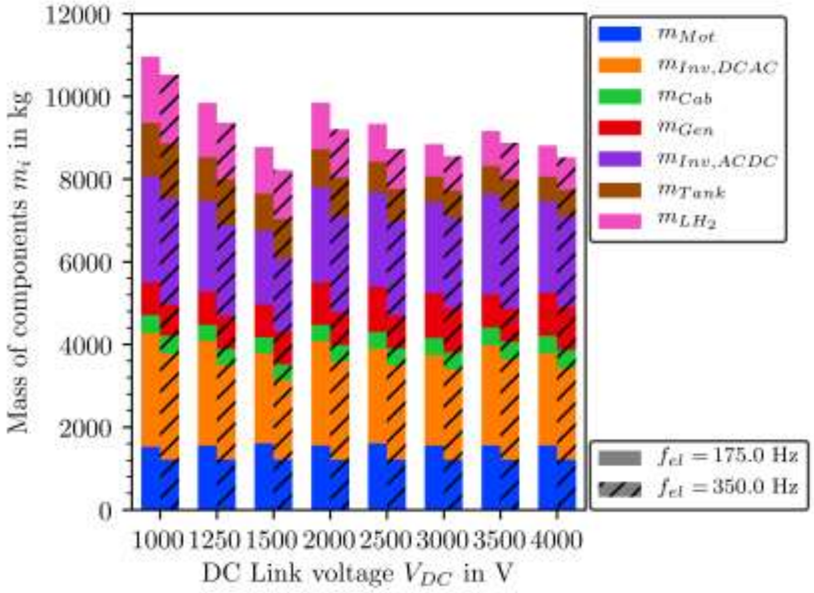
Flat coil



- Manufacturing with high filling factor and exact shape is challenging
- Less unpredictable losses

Cryogenic Electric Propulsion System (CEPS)

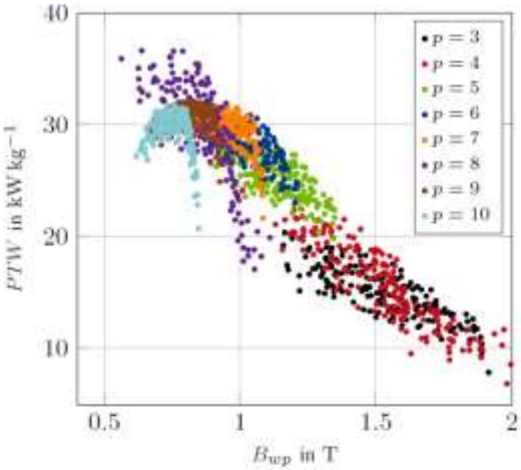




Sources: Boll et al., A holistic system approach for short range passenger aircraft with cryogenic propulsion system, SUST, 2020 (accepted)
Corduan et al., Topology comparison of superconducting AC machines for hybrid-electric aircraft, IEEE Trans On Appl SC 30 (2), 1-10, 2020

Cryogenic Electric Propulsion System (CEPS)

- Not the lightest component leads to the best system
- In re-equiped aircraft only 14.000l of LH2 fit
- The combined mass of inverter and its required cooling system has the highest influence.
- Low electric frequencies still favoured.
- Operational fields of the machine‘s stator/rotor are moderate



Type	Symbol	Unit	Value	Value	Value
Global	V_{DC}	V	1500	3000	4000
	M_{Sys}	kg	8355	8432	8417
	η_{Sys}	%	98.27	98.71	98.75
	m_{equi}	kg	3900	2744	2618
	M_{eff}	kg	4455	5688	5799
EPU	f_{el}	Hz	350	350	350
	n_{EM}	$\min^{-1}$	3500	3500	3500
	P_{EM}	MW	10.5	10.5	10.5
	d_{EM}	m	0.52	0.55	0.54
	l_{EM}	m	0.54	0.63	0.62
	m_{EM}	kg	287	304	303
	η_{EM}	%	99.90	99.92	99.92
	$B_{S,EM}$	T	1.17	0.91	0.90
	$Q_{S,EM}$	W	4378	2393	2396
	$Q_{Fe,EM}$	W	5077	5653	5680
	m_{Inv}	kg	479	545	554
	η_{Inv}	%	99.65	99.76	99.77
Gen	f_{el}	Hz	500	500	500
	P_{EM}	MW	21.0	21.0	21.0
	n_{EM}	$\min^{-1}$	10000	10000	10000
	d_{EM}	m	0.37	0.36	0.37
	l_{EM}	m	1.02	1.21	1.02
	m_{EM}	kg	376	398	375
	η_{EM}	%	99.87	99.92	99.90
	$B_{S,EM}$	T	0.82	0.73	0.81
	$Q_{S,EM}$	W	2645	2062	2640
	$Q_{Fe,EM}$	W	6740	6461	6730
	m_{Inv}	kg	886	1096	1114
	η_{Inv}	%	99.63	99.74	99.76
Cool	m_{Tank}	kg	947	663	632
	m_{LH_2}	kg	1187	831	793
	V_{LH_2}	l	16765	11737	11200