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Design Aspects for DC-HTS Cables in Hybrid-Electric Propulsion Systems for Aircraft

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INSTITUTE OF TECHNICAL PHYSICS (ITEP) - SUPERCONDUCTING MATERIALS AND ENERGY APPLICATIONS (SUPRA)

Why do we need electric or hybrid-electric aircraft?

<u>**Goals of „FLIGHTPATH 2050“:**</u>

- Protecting environment and energy supply
  - Reduction of carbon footprint of aviation sector.
    - 75%* reduction in CO_2 emissions per passenger kilometer
    - 90%* reduction in NO_x emissions
    - Aircraft movements are emissions-free when taxiing
  - Reduction of noise emission of flying aircraft is by 65%.

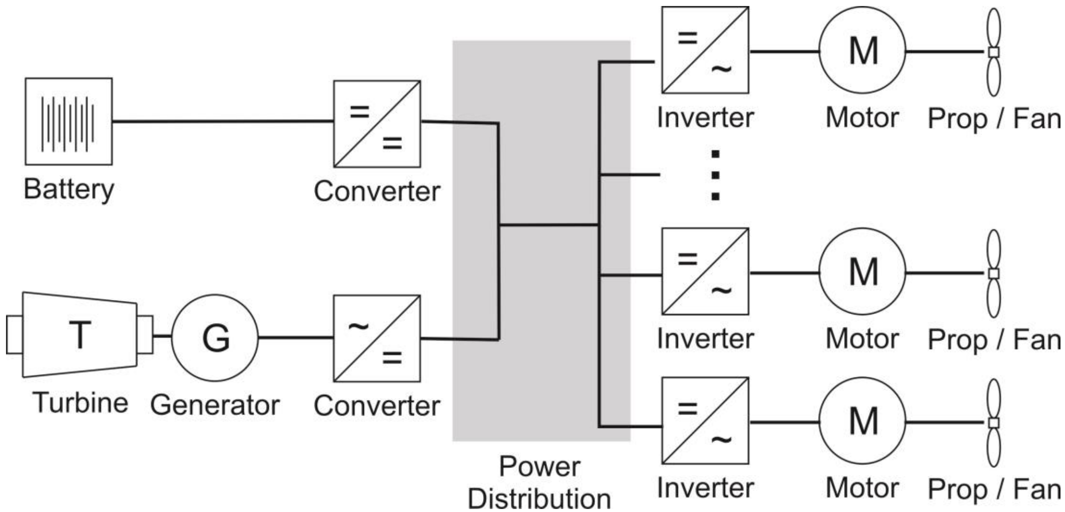
➢ Electrical and hybrid-electrical engines have entered the aviation market.

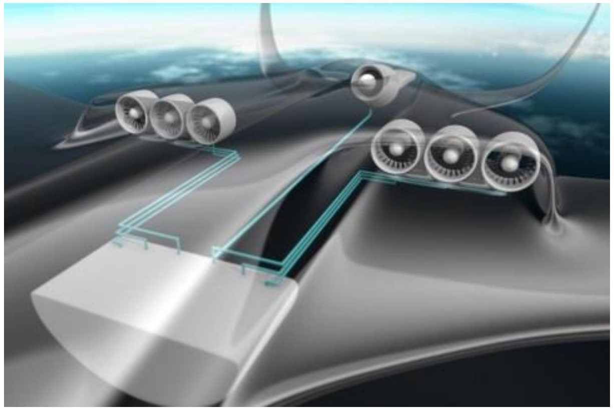
* These are relative to the capabilities of typical new aircraft in 2000.

Source: Flightpath 2050 - Europe’s Vision for Aviation
http://ec.europa.eu/transport/modes/air/doc/flightpath2050.pdf - doi: 10.2777/50266

Hybrid-electric propulsion system

Purely electric propulsion not feasible for larger aircraft due to high battery weight
→ hybrid-electric propulsion with battery and gas power unit





http://img.welt.de/img/wirtschaft/crop127296741/4926936553-ci3x2l-w900/E-Thrust-2-.jpg

- Thrust generation decentralized
  → design space for aircraft
- Already applied in ships, trains, mining trucks
  <u>but:</u> different boundary conditions for aviation !

TELOS - Project

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- TELOS - Thermo-Electrically Optimised Aircraft Propulsion Systems
- Goals:
  - Exploration of technical aspects of hybrid-electric propulsion system
  - Development and test of demonstrators
- Funding: Federal Ministry of Economic Affairs and Energy
- Duration: 01/2016 – 03/2019
- Partners:
  - Airbus Group Innovations, München
  - Airbus Operations GmbH, Hamburg
  - Siemens AG, Erlangen → HTS Generator
  - Karlsruhe Institute of Technology → **DC HTS Cables**
  - New Materials Bayreuth GmbH
  - Technical University of Munich

Boundary conditions for superconducting DC cables in hybrid-eletric aircraft

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Requirements of other components of hybrid-electric propulsion system

Required power level for aircraft:
1 - 10 MW range

Voltage level
1 - 10 kV

Current
0.1 – 10 kA

SUPERCONDUCTING DC CABLE

SC Material
MgB_2, REBCO, BSCCO

Cryogenic system / Operating Temperature

Cable Length / joints

Installation and operation

Safety and redundancy

Aircraft and duty cycle

Cooling of Superconducting Cable System

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Cooling Options:

- Cryo cooler
  → high weight
  → additional electric power required for cooling system
- Liquid Cryogens (LN_2, LH_2, GHe)
  → advantage: „leave Carnot outside the aircraft"
  → infrastructure required for storage and refilling
- Combination of Cryo cooler and liquid cryogen
  → Liquid cryogen for pre-cooling (reduce T_{hot})
  → LH_2 or LCH_4 could be used for propulsion

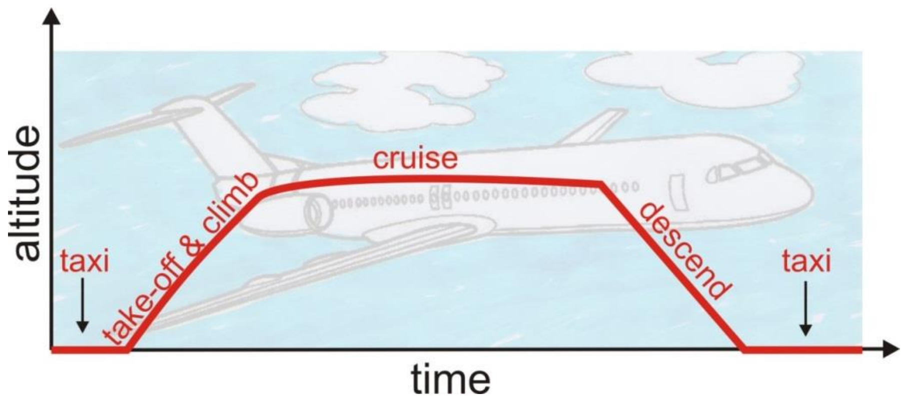
→ F. Berg et al., IEEE TAS 27 (2017) 3600307, **DOI:** 10.1109/TASC.2017.2652319

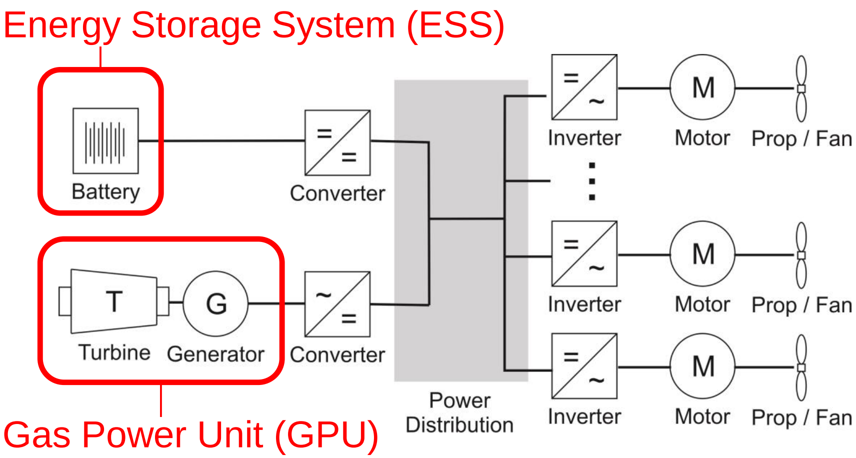
Important issues:

- For cable: lower T → lower conductor cost ($I_c(T)$), higher cryostat weight
- Temperature required for other superconducting components (generator, motor, SMES, …) → weight optimization
- Temperature of connections between sc components (Current Leads!)

→ Cooling of TELOS Demonstrator Cable: LN_2

Flight Profile Energy Management





- ***Taxi:*** energy from energy-storage system (ESS)
- ***Take-off and climb:*** energy from gas power unit (GPU) and ESS
- ***Cruise*:** energy from GPU, charging of ESS
- ***Descend:***
  - Gliding: GPU switched off, ESS powers on-board systems
  - Windmilling: fans might be windmilling producing electric power which will be stored in ESS
- ***Landing:*** GPU producing electric power on a low level

Source: „E-Thrust - Electrical distributed propulsion system concept for lower fuel consumption, fewer emissions and less noise", Brochure by Rolls Royce and Airbus Group

Current Lead Design for DC HTS Cable:

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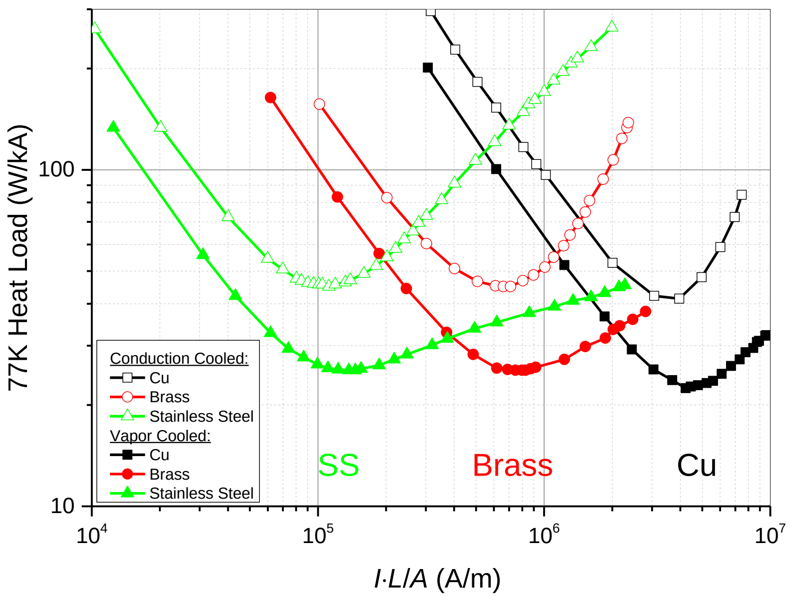
- Maximum power/ current only during short periods, e.g. during take-off / climb
- Lower power consumption / current during cruise, landing and taxiing
- $I \approx 0$ while aircraft is on ground

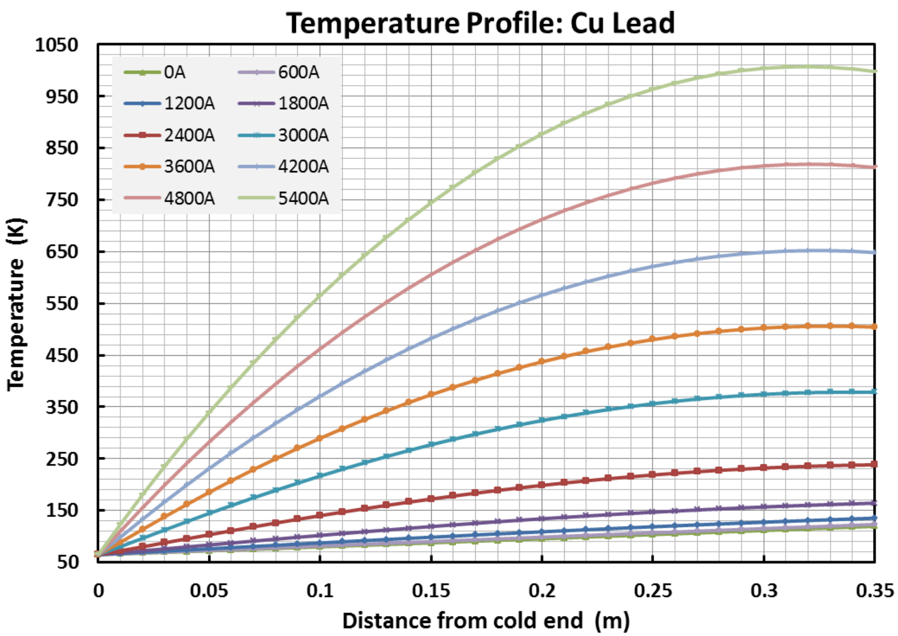
Losses of conduction and vapor cooled current leads (RT ←→ 77 K):

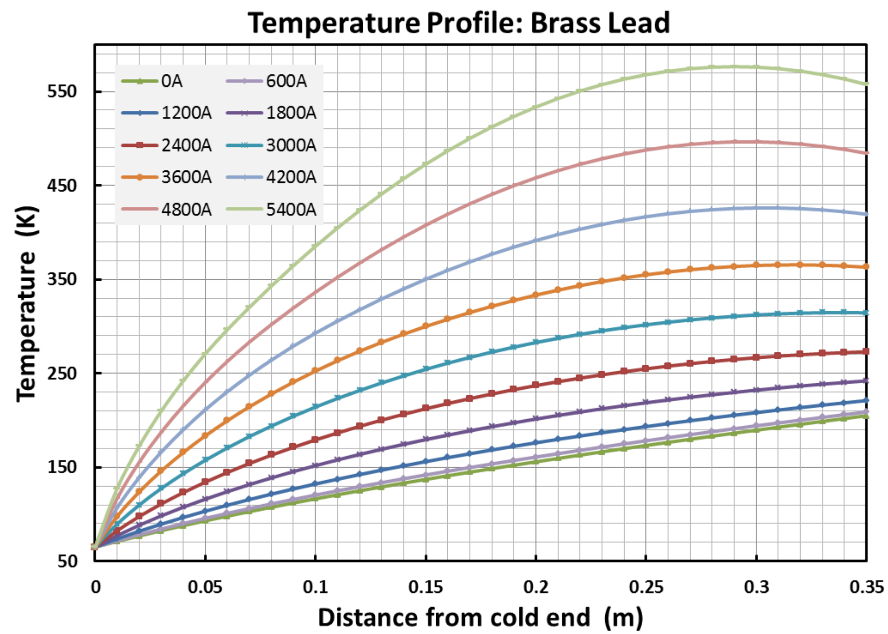


P.F. Herrmann, „Current Leads for cryogenic Applications“, in „Handbook of Applied Superconductivity, ed. By Bernd Seeber, IOP Publishing Ltd. (1998), ISBN 0750303778

Material choice for current leads (CL)

CL temperatures at different operating currents (Design Current: I = 3000 A):





Static heat load at I = 0:

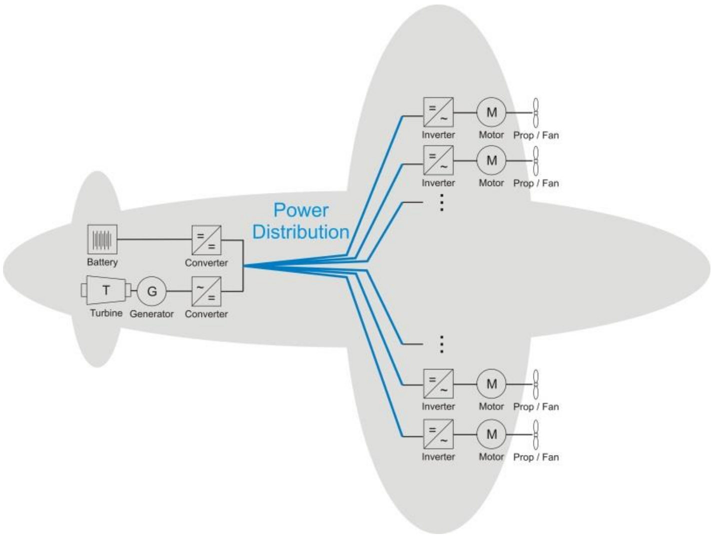
- Optimized conduction cooled Cu current lead: $Q_{I=0}$ = 68.6 W
- Underdesigned brass current lead with A/A_{opt} = 0.5: $Q_{I=0}$ = 18.6 W

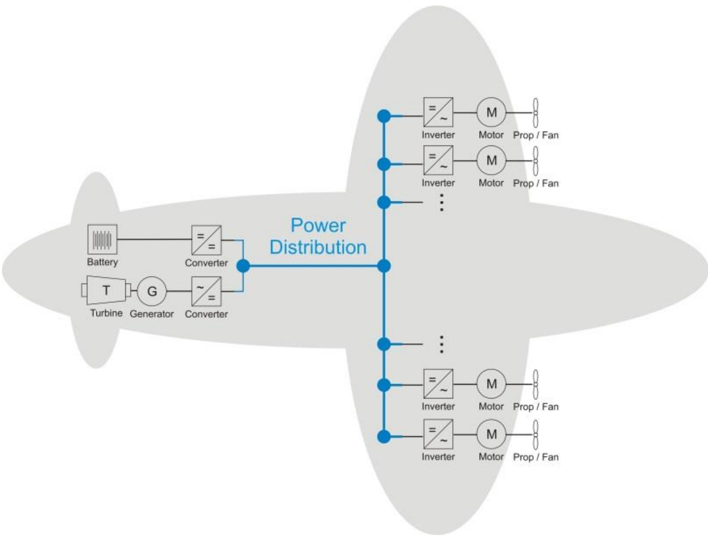
→ > 70 % reduction of losses

Power Distribution in Aircraft

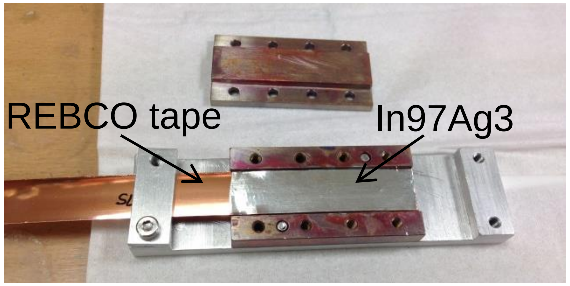
Star or busbar topology ?

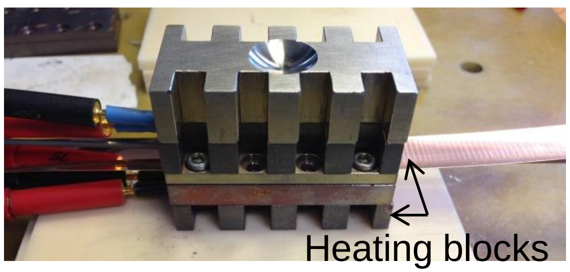
- Star topology:
  - Redundancy concerning cable failure
  - Cables in separate cryostats
    → more weight
    → cryogenic redundancy
  - Separate Cables in one cryostat
    → weight optimization
    → no cryogenic redundancy
- Busbar topology:
  - No redundancy for cable and cryogenic failure
  - Joints necessary
  - Weight optimization





Cable Joints: first experiments with lap joints

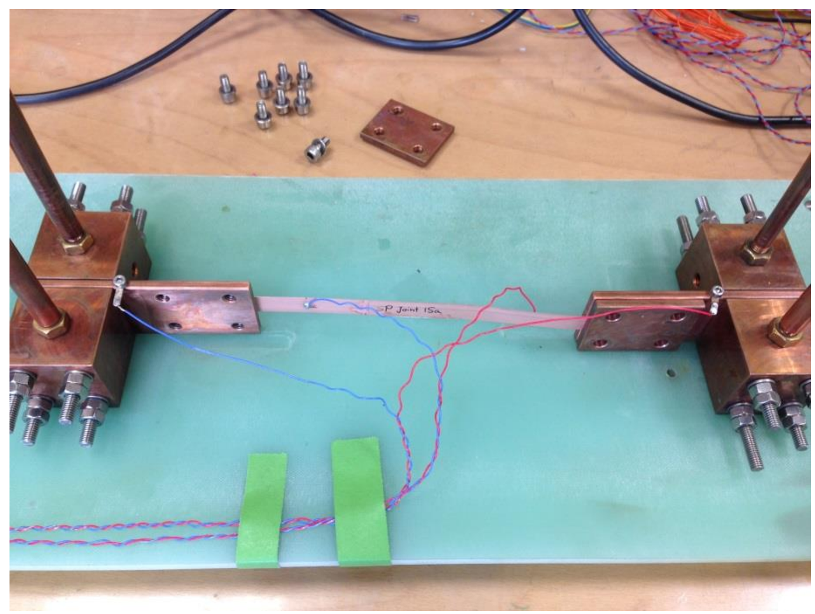




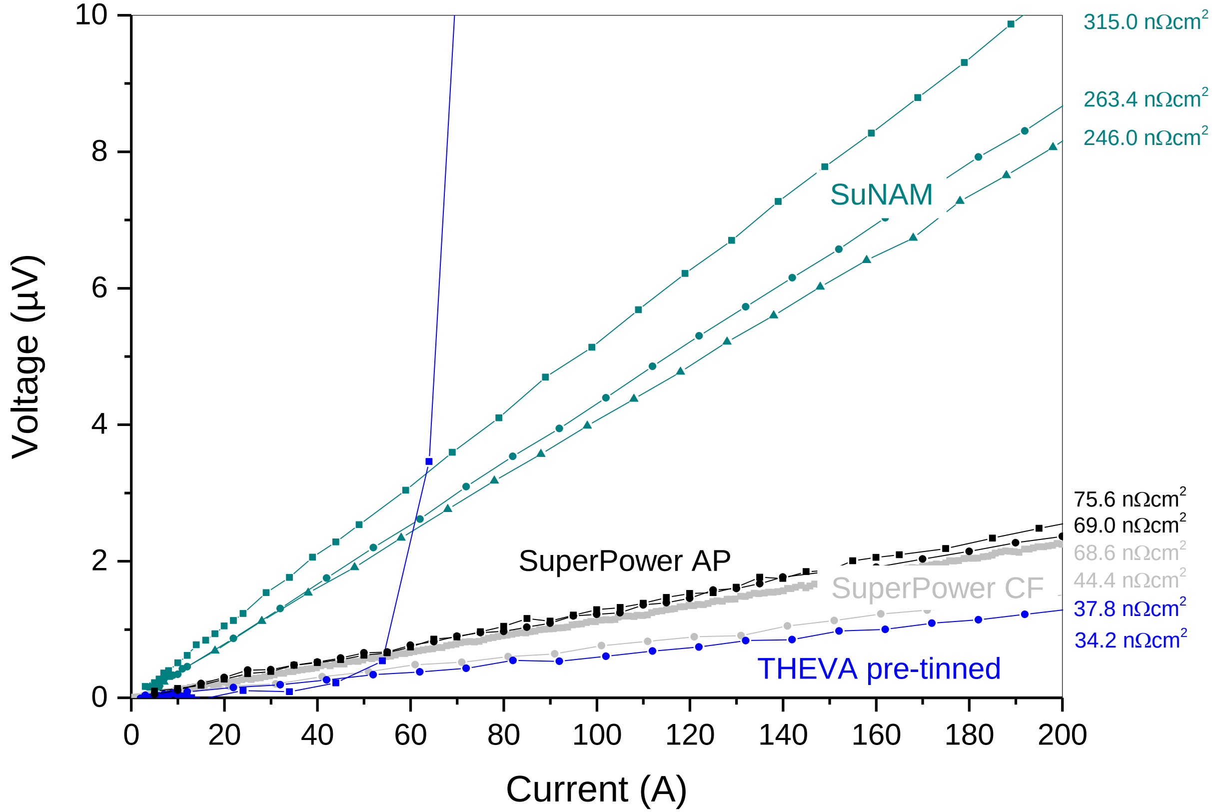
Simple and reliable process required:

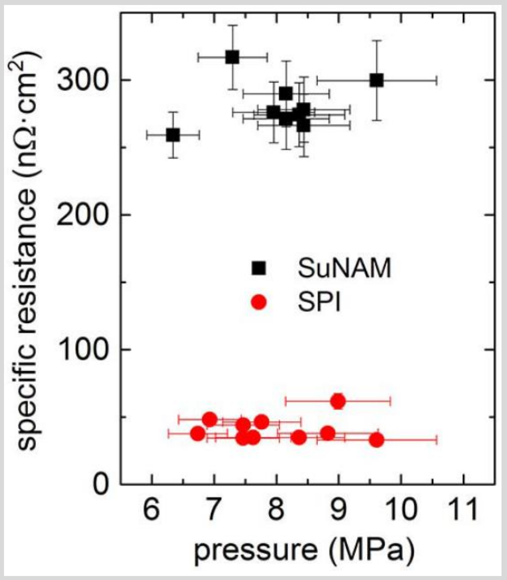
- „Cleaning“ of joint area“ with soft solder flux
- Insertion of In97Ag3 foil (thickness = 50 µm)
- Low soldering temperatures → In97Ag3 (T_m= 143 °C)

→ Joints for tapes from different suppliers



Joints with tapes from different suppliers

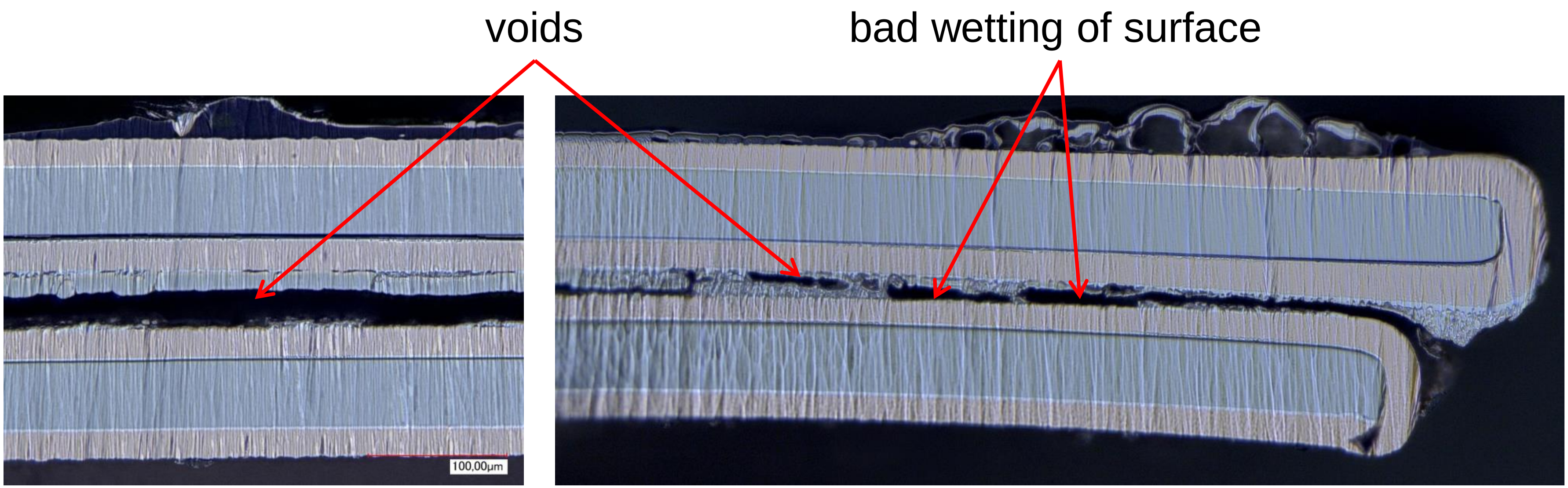




N. Bagrets, A. Augieri, G. Celentano, G. Tomassetti, K.-P. Weiss, and A. della Corte, IEEE-TAS 25 (2015) 6602705

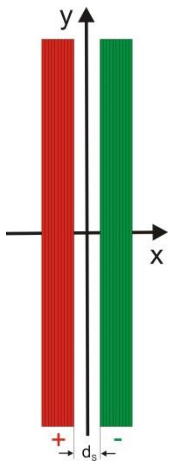
→ Joints with SuNAM tapes show much higher resistances

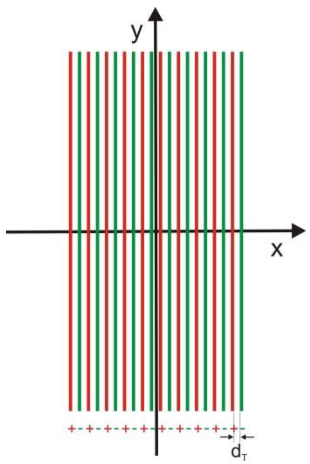
Joint with SuperPower Tapes ($R \cdot A = 69.0\ \mathrm{n\Omega \cdot cm^2}$)

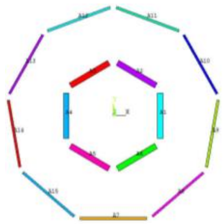


- Thickness of solder layer ~ 12 µm
- Sections with bad wetting visible

Self-fields in CC-Cables (2x 3 kA)

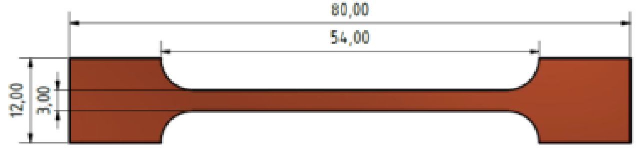


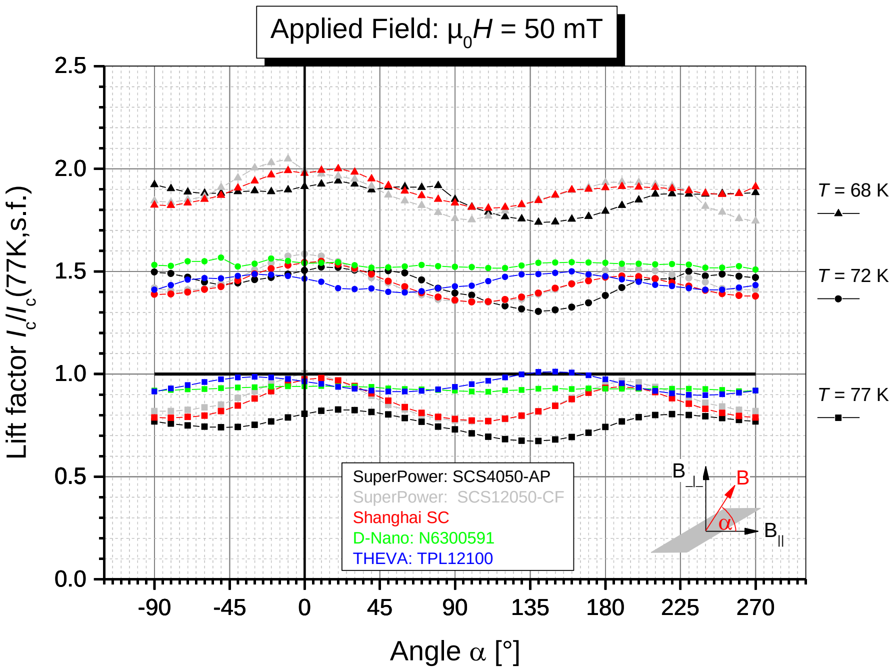


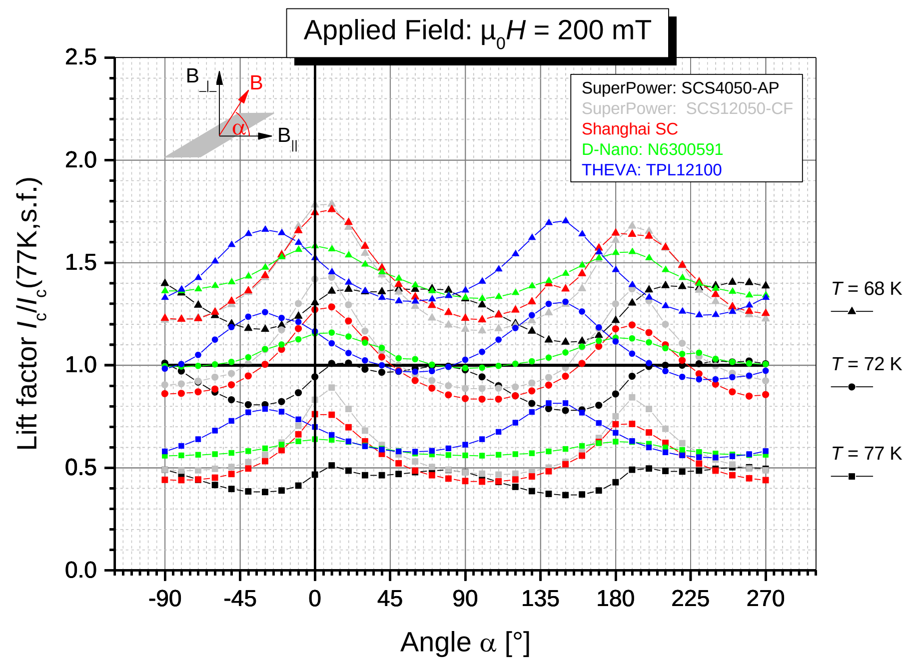


	Stack Cable Type A (+ -) Distance between 2 poles					Stack Cable Type B (+ - + -…..+ -) Distance between tapes					Coaxial Cable (CORC-type)	
	1 mm	2 mm	3 mm	4 mm	5 mm	0.1 mm	0.2 mm	0.4 mm	0.8 mm	1 mm	Inner pole	Outer pole
B_{max} [10^{-3} Tesla]	281.4	266.4	253.1	241.5	231.7	28.4	27.4	26	24.9	24.4	139.3	73
$B_{\parallel max}$ [10^{-3} Tesla]	281.4	266.4	253.1	241.5	231.7	28.4	27.4	26	24.9	24.4	139.2	73
$B_{\perp max}$ [10^{-3} Tesla]	119.4	138.4	151.4	161.1	167.4	16	18.9	21.2	23.7	23.5	46.7	28

Angular dependence of I_c at different temperatures and fields







- Large differences for tapes from different suppliers

Conclusion

- Complex parameter space for optimization of power distribution in aircraft with hybrid-electric propulsion systems:
  - e.g.: Voltage level, weight, losses, air pressure, reliability, maintainability, aircraft environment
  - ➢ ***Optimization of the whole propulsion system necessary***
- KIT contribution to TELOS project: DC-HTS cable
  - Design of current leads according to strongly varying currents during different flight phases or on ground
  - Development of simple and reliable joints
  - Optimization of cable layout
  - Building of short demonstrator cable and test cryostat:
    - I = 3 kA
    - LN_2-cooling
  - Analysis of impact of parameter changes on propulsion system (temperature, current, …)

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