Toward Zero Emissions Electric Aircraft through Superconducting DC Distribution Network

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Content

- **Hydrogen-powered Aircraft**
- **Cryogenic Power Electronics**
- **DC Network Protection Challenges**
- **Integration of SFCL and SSCB**
- **Summary**

IAAPS Introduction

University of Bath
Institute for Advanced Automotive Propulsion (IAAPS)/
AAPS Centre for Doctoral Training

- Delivery of fundamental research and innovation programs
- Funded industrial collaborative research projects
- Training the next generation of leaders and engineers to pioneer and shape the transition to clean, sustainable and affordable mobility

IAAPS Limited
Wholly owned subsidiary of the University of Bath

- Commercial focused delivery of research, innovation and testing programmes for industry
- Supporting the University of Bath in delivery research and innovation programmes
- Regional enterprise activity

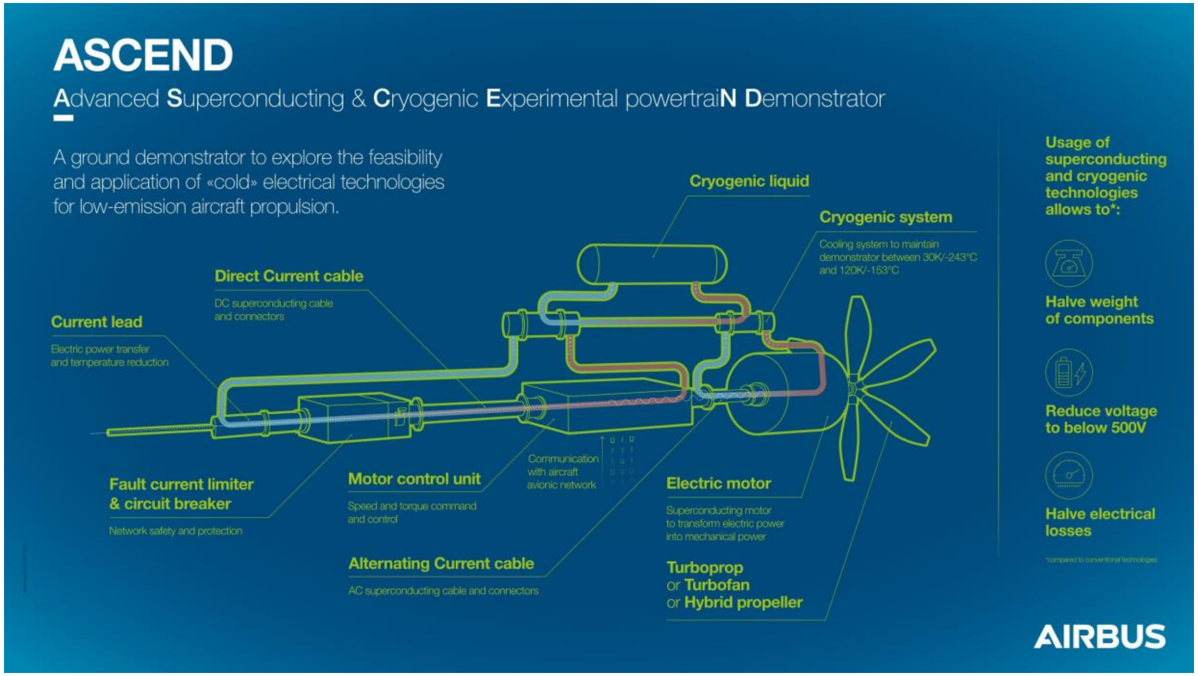
Hydrogen-powered Aircraft

Airbus' ambition is to bring to market the world's first hydrogen-powered commercial aircraft by 2035.

Source: Airbus

Hydrogen-powered Aircraft

- Zero emission aircraft powered by hydrogen address the environment impact and also opens new opportunities for superconductivity technology.
- Superconducting and cryogenic propulsion system has great potential to deliver high power density and high efficiency.



Source: Airbus

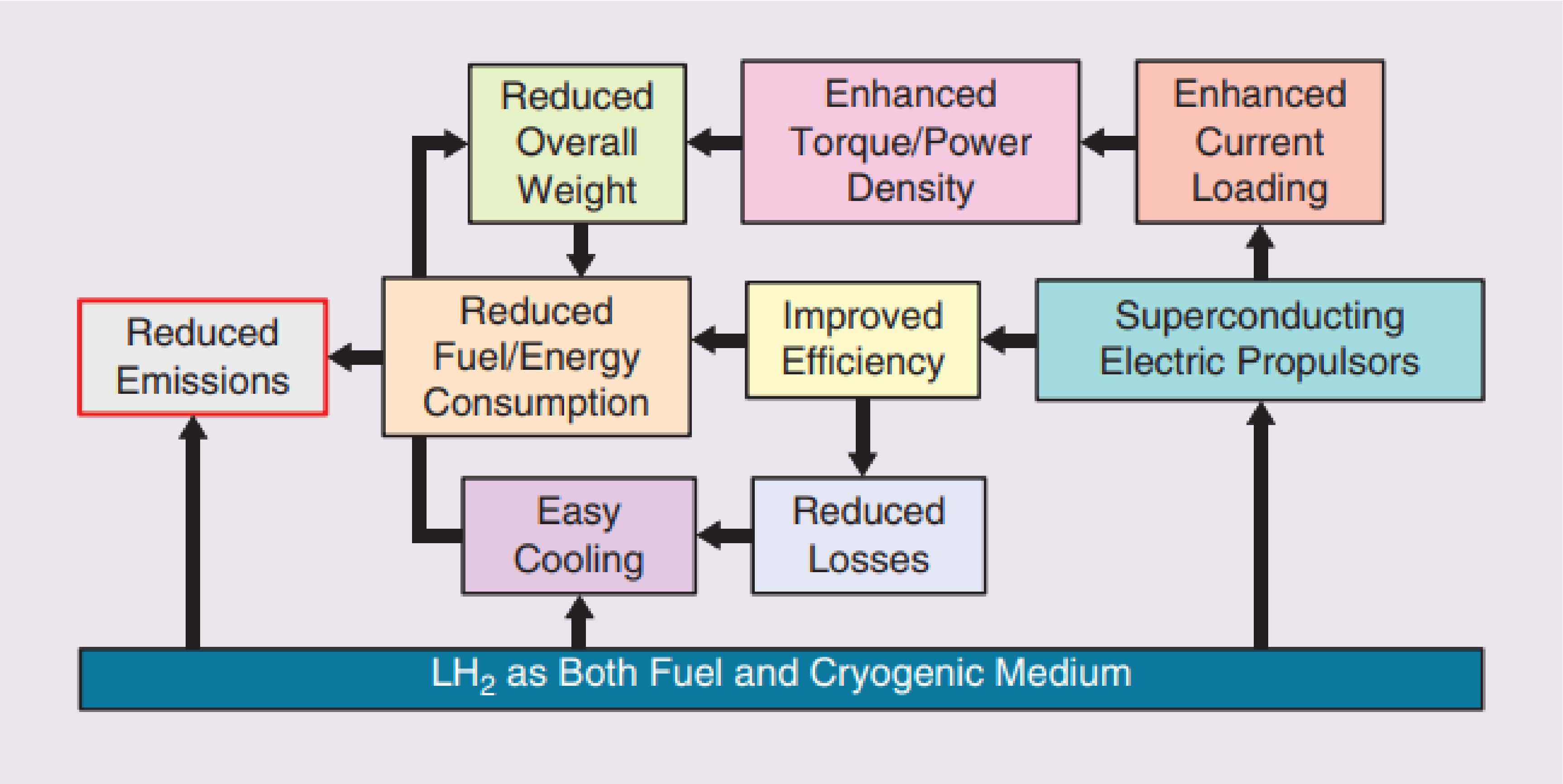
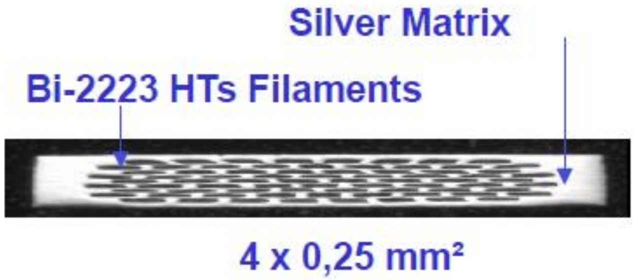


Figure 12. The overall philosophy when reducing emissions using LH_2 as a fuel and a cryocooler.

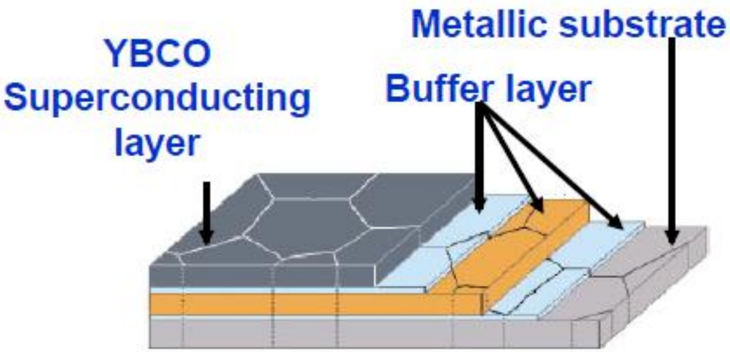
Source: J. K. Nøland, "Hydrogen Electric Airplanes: A disruptive technological path to clean up the aviation sector," in IEEE Electrification Magazine, vol. 9, no. 1, pp. 92-102, March 2021.

High Temperature Superconductor Materials

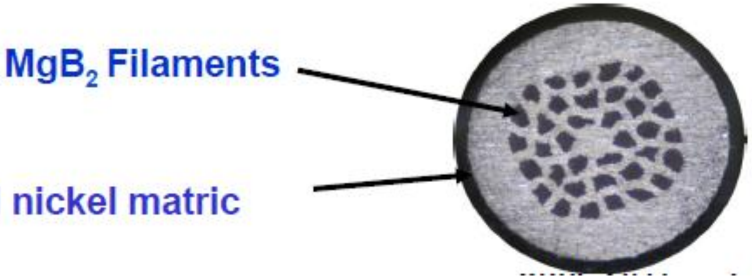
- 1st generation: Multifilamentary Bi 2223 tapes

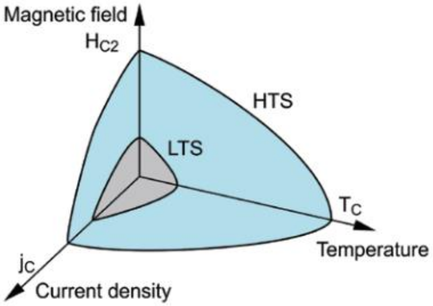


- 2nd generation: YBCO Coated conductor

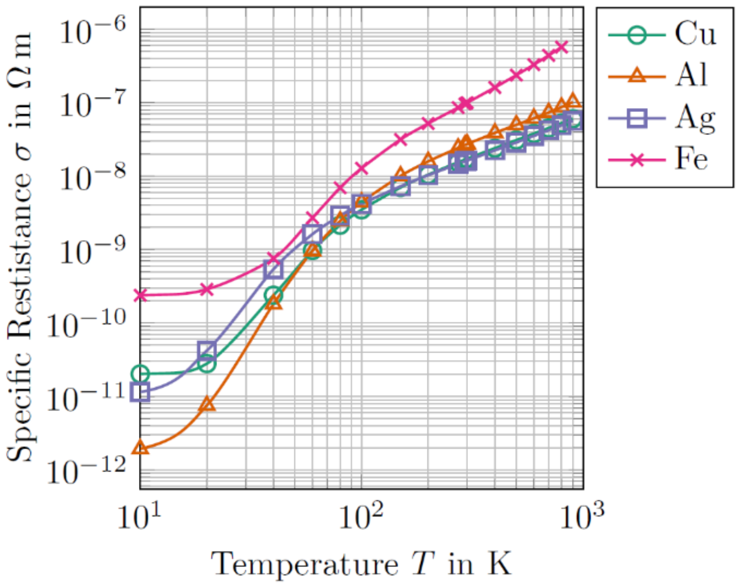


- Multi-filamentary wire (T_{op} =20-25K)

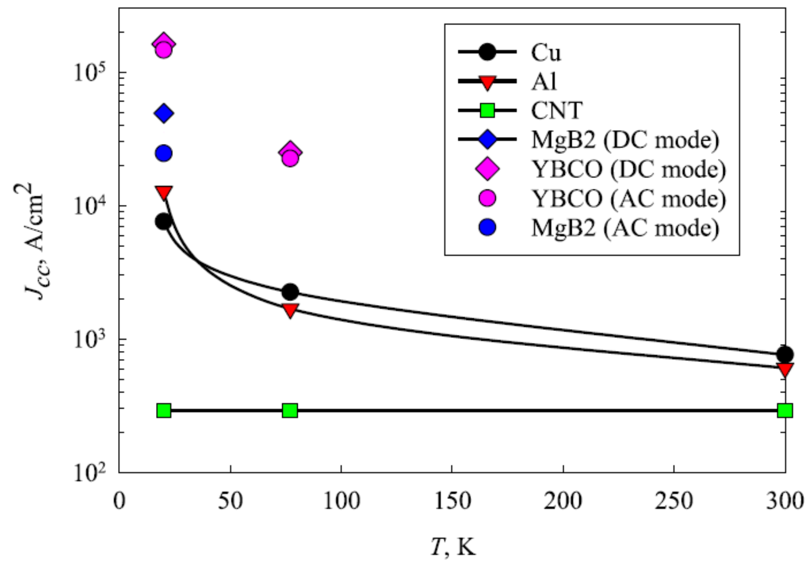




Hyperconduting



Specific Resistance vs Temperature

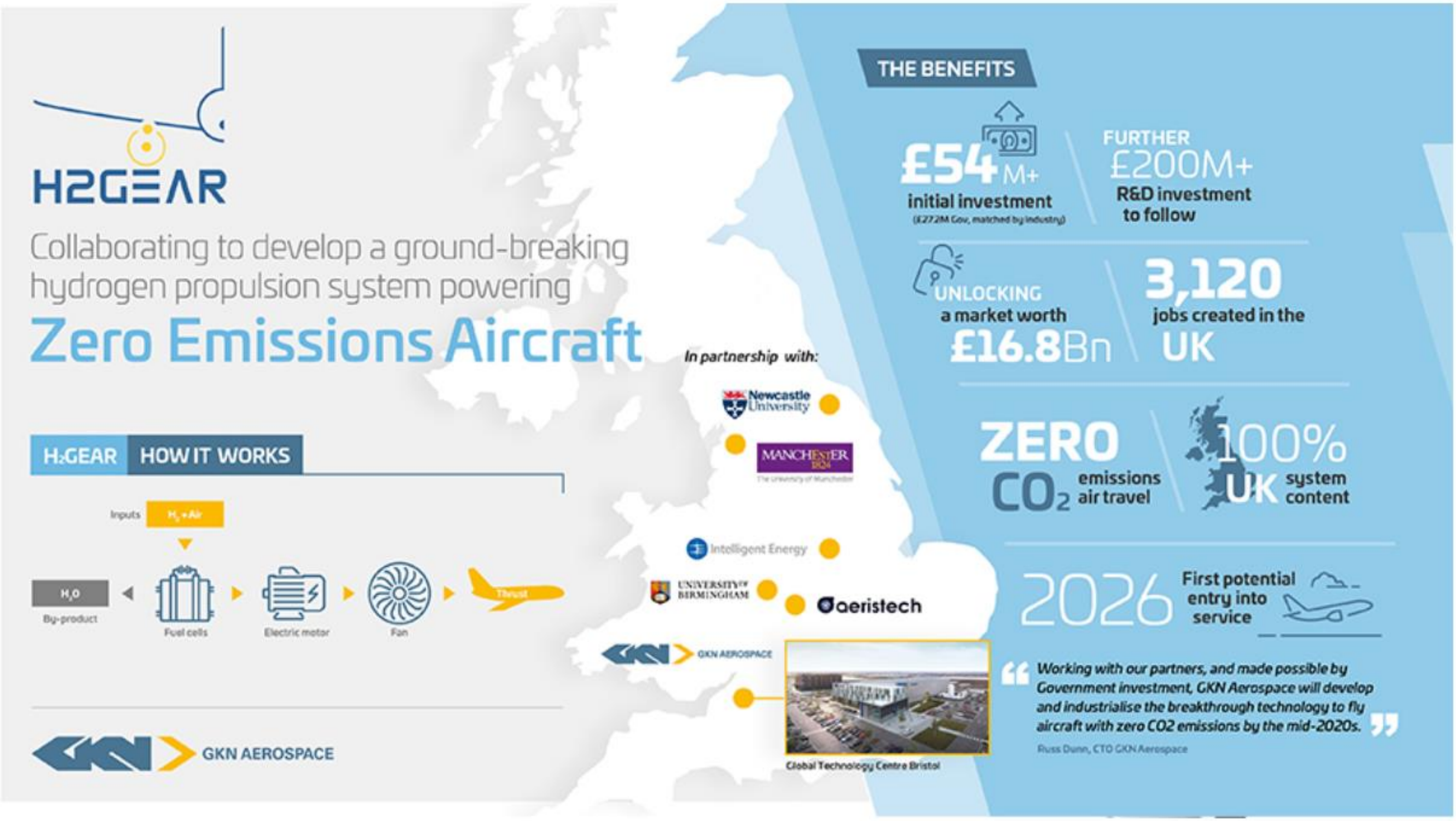


Current Density vs Temperature

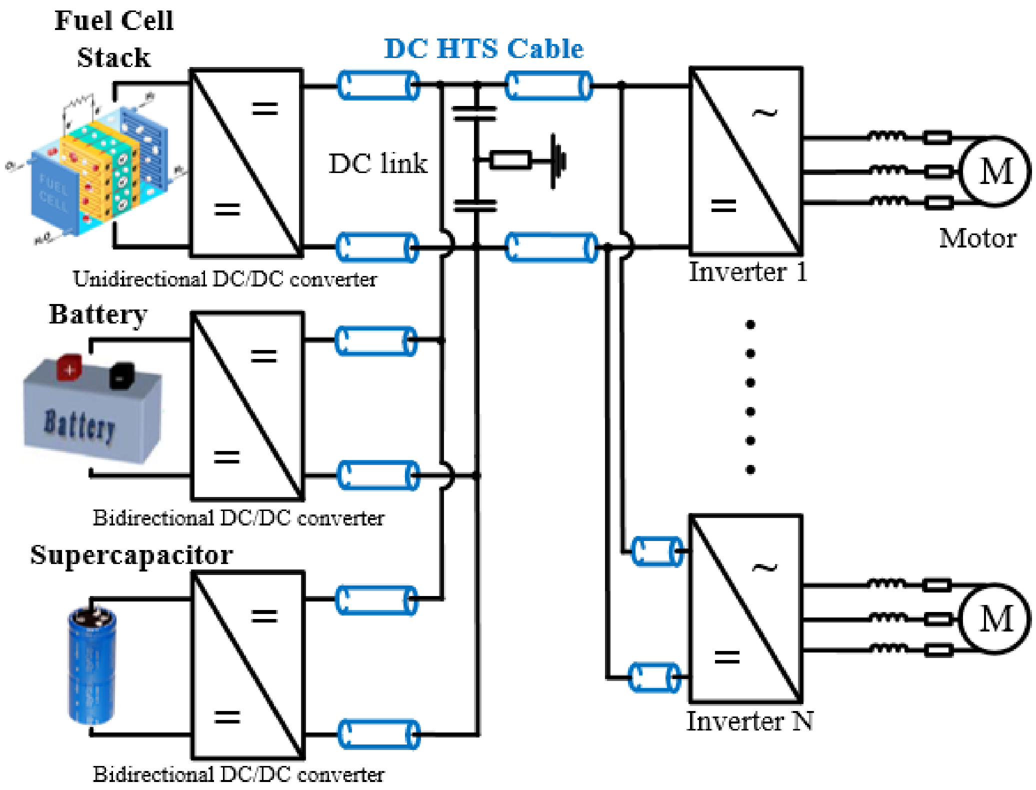
Source: David Filusch, Martin Breiteneder and Hans-Georg Herzog, Design of a Hyperconducting Synchronous Machine for High-Torque Applications".

M.D. Sumption, J. Murphy, M. Susner, T. Haugan, Performance metrics of electrical conductors for aerospace cryogenic motors, generators, and transmission cables, Cryogenics, Volume 111, 2020, 103171.

Hydrogen-powered Aircraft



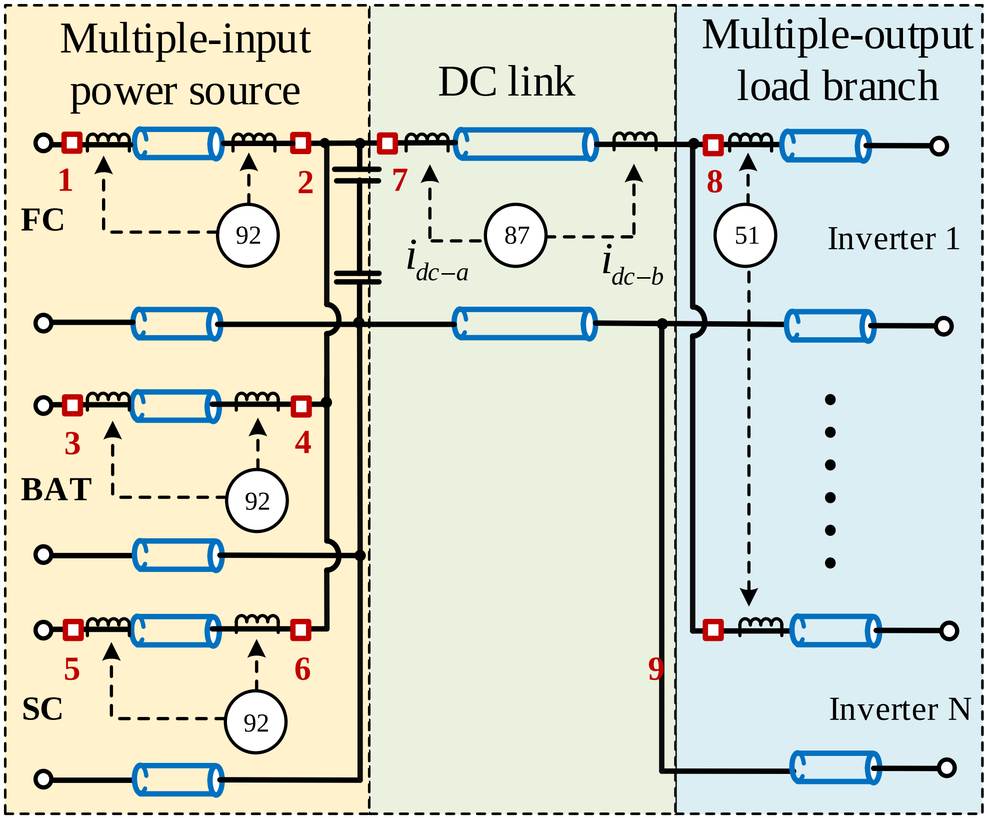
Fuel Cell Propulsion System



- DC/DC/AC system
- DC/DC converters as power controller
- Fuel cell as primary power source
- Batteries and supercapacitors as energy storage system
- DC link voltage regulated by batteries and supercapacitors

P. Liu, X. Pei, X. Zeng, R. K. Surapaneni, G. Galla, E. Nilsson, J. Rouquette, F. Berg and L. Ybanez, "Pole-to-Pole Fault Management for Electric Aircraft DC Network with HTS Cables," IEEE Transactions on Applied Superconductivity, vol. 34, no. 3, pp. 1-6, May 2024, Art no. 4803506, doi: 10.1109/TASC.2024.3363127.

Fuel Cell Propulsion System



:Current transformer :Circuit breaker (CB)

87 :Differential relay 92 :Directional relay 51 :Overcurrent relay

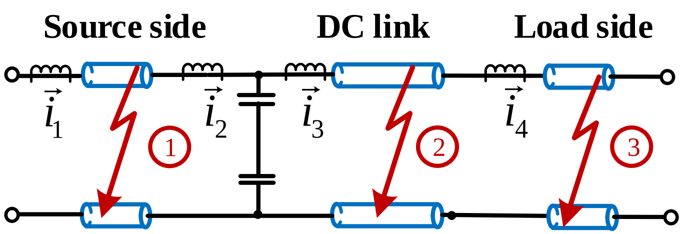
Potential fault locations and types

1. Powe source side fault

- Ground fault + Short-circuit fault

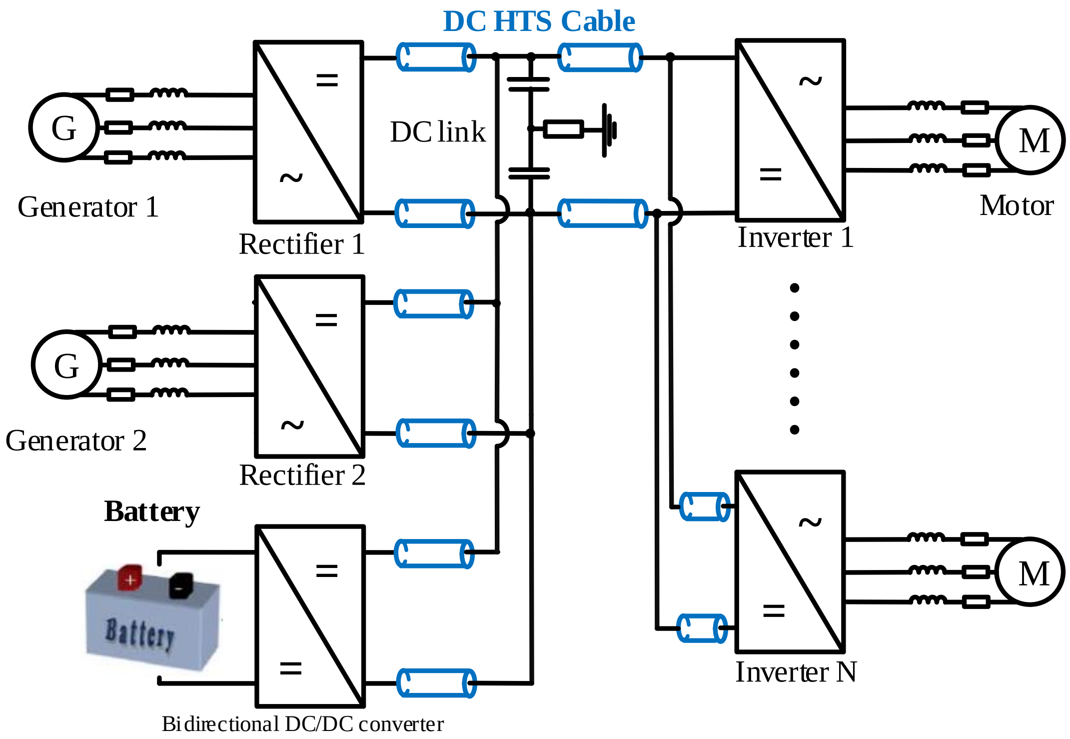
2. DC link side fault

- Ground fault + Short-circuit fault



P. Liu, X. Pei, X. Zeng, R. K. Surapaneni, G. Galla, E. Nilsson, J. Rouquette, F. Berg and L. Ybanez, "Pole-to-Pole Fault Management for Electric Aircraft DC Network with HTS Cables," IEEE Transactions on Applied Superconductivity, vol. 34, no. 3, pp. 1-6, May 2024, Art no. 4803506, doi: 10.1109/TASC.2024.3363127.

Turbo Electric Propulsion System



- AC/DC/AC system
- Distributed generations and distributed loads
- Converter based power network
- DC link voltage regulated by rectifiers

P. Liu, X. Pei, X. Zeng, R. K. Surapaneni, G. Galla and L. Ybanez, "DC Link Voltage Control Strategy for Electric Propulsion Aircraft," IEEE Transportation Electrification Conference & Expo (ITEC), Detroit, MI, USA, 2023 (Best paper award).

Power devices at cryogenic temperatures compared with room temperature

Type	**Si MOSFET**	**Si IGBT**	**GaN HEMT**	**SiC MOSFET**
On-state resistance	Lower	Lower	Lower	Higher
Switching loss	Lower	Lower	Higher	Constant
Breakdown voltage	Lower	Lower	Constant	Constant
Threshold voltage	Higher	Higher	Constant	Higher

Cryogenic Power Electronics

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Si MOSFET at cryogenic temperatures

- Lower on-state resistance
- Lower switching loss
- Reduced breakdown voltage

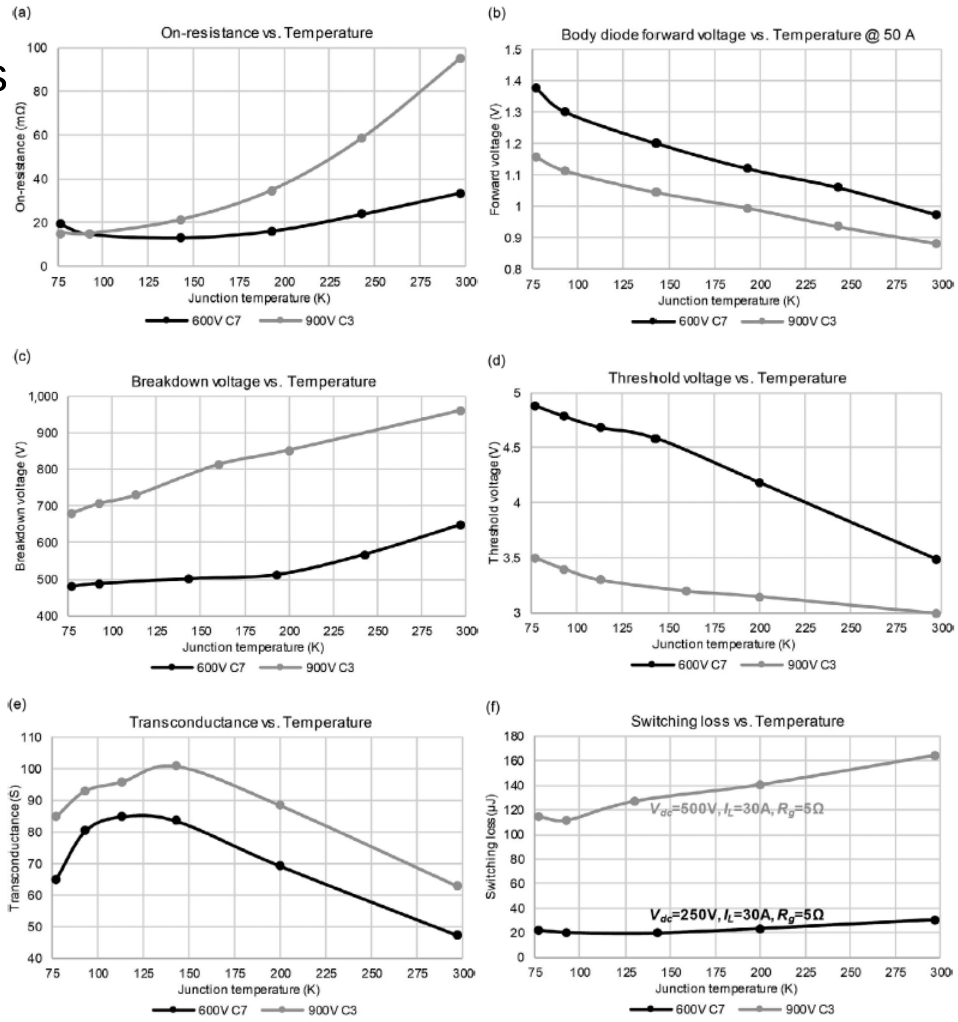

Figure 6.6 Performance of two Si MOSFET candidates at cryogenic temperature. © [2020] IEEE. Reprinted, with permission, from [26]

Source: Zheyu Zhang, Fei (Fred) Wang, Ruirui Chen, and Handong Gui, Chapter 6: Cryogenic Power Electronics, Electrified Aircraft Propulsion, 2022.

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Passive components

COMPARISON OF DIFFERENT CAPACITORS AT CRYOGENIC TEMPERATURES WITH ROOM TEMPERATURE

Material	Ceramic				Film				Mica	Electrolytic	Tantalum
	X7R	Y5V	Z5U	NP0	Polypropylene	PPS	Polyester	Polycarbonate			
Capacitance	↓↓	↓↓	↓↓	--	--	--	↓	↓	--	↓↓	↓
Dissipation factor	↑↑	↑↑	↑↑	--	↓	--	↓	↓	--	↓↓	↑↑

- NP0, metallized polypropylene, mica, and polyethylene capacitors maintain capacitances and/or have improved dissipation factors at lower temperatures.

COMPARISON OF DIFFERENT CORE MATERIALS AT CRYOGENIC TEMPERATURES WITH ROOM TEMPERATURE

Material	Powder			Ferrite	Nano-crystalline	Amorphous
	MP	High Flux	Kool Mμ			
Permeability	--	--	↓	↓↓	↑	--
Loss	↑	--	--	↑↑	↑	↑
Saturation flux density	N/A	N/A	N/A	Not clear	↑	↑

↑↑: increase significantly ↑: increase slightly –: keep constant ↓: decrease slightly ↓↓: decrease significantly

Source: H. Gui et al., "Review of Power Electronics Components at Cryogenic Temperatures," IEEE Trans. on Power Electron., May 2020.

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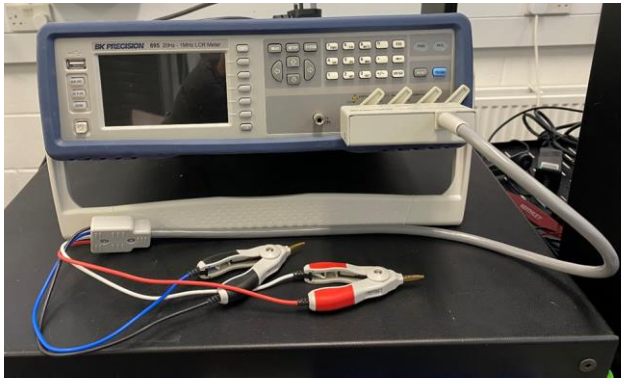
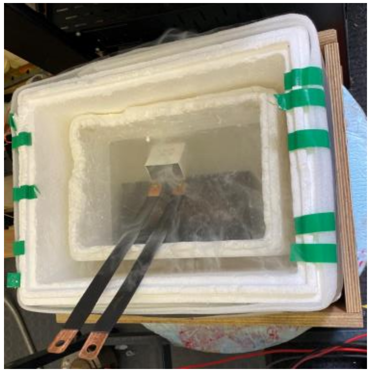
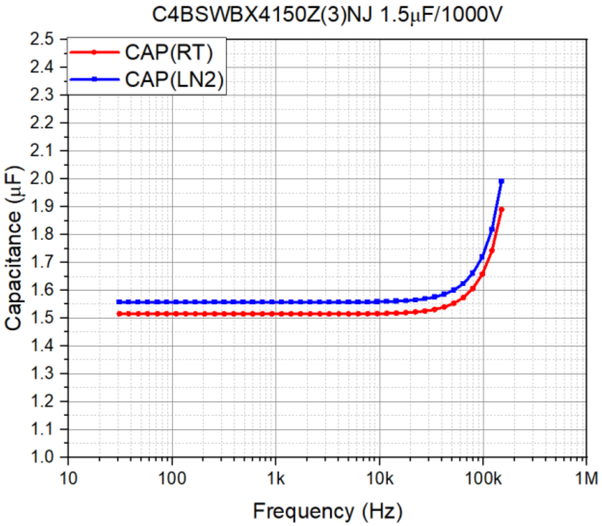
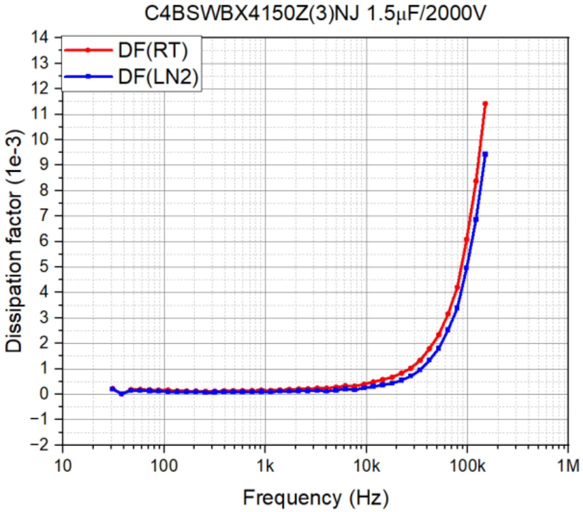
Capacitor characterisation









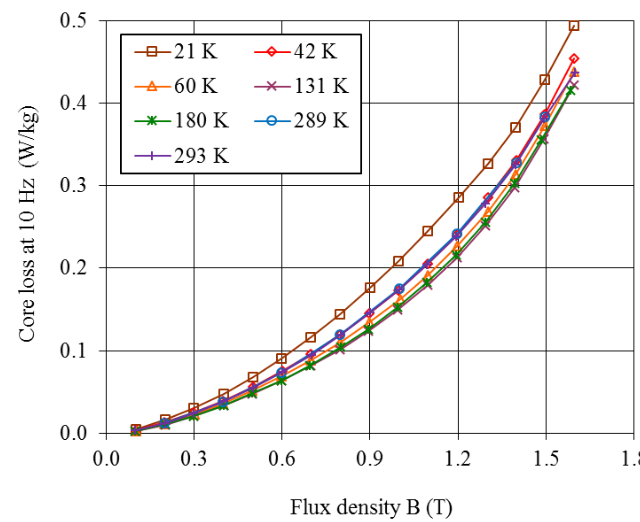
Z. Wang, X. Zeng, A. Deriszadeh, E. Nilsson, J. Rouquette, R. K. Surapaneni, G. Galla, L. Ybanez, X. Pei, "Performance of Snubber Capacitors and TVS Diodes for Cryogenic Power Electronics," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 1774-1780, doi: 10.1109/ECCE53617.2023.10362921.

Magnetic core characterisation

Fig. 1. Picture of soft magnetic ring core samples: (a) fully-processed, low loss non-oriented steel; (b) fully-processed, non-oriented steel with enhanced permeability; (c) grain-oriented steel; and (d) nano-crystalline alloy Finmet.

MAGNETIC PROPERTIES OF FOUR RING CORE SAMPLES

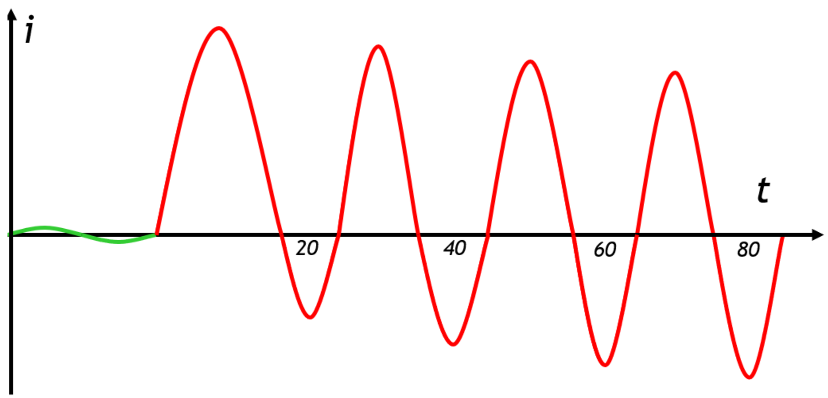
Sample	Temperature of best magnetic properties (K)	Core losses at best temperature/room temperature	Core losses at 21 K/room temperature
Low loss NO steel	131	0.93	1.12
NO steel with enhanced permeability	180	1	1.4
GO steel	289	1	1.2
Finemet	289	1	-



X. Pei, A. C. Smith, L. Vandenbossche and J. Rens, "Magnetic Characterization of Soft Magnetic Cores at Cryogenic Temperatures," in IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-6, Aug. 2019, Art no. 7800306, doi: 10.1109/TASC.2019.2901371.

DC Network Protection Challenges

- Electric aircraft has high reliability and safety requirements.
- Potentially very high fault current as the on-board power network is closely coupled.



AC

- Current crosses zero twice in each cycle.

DC

- No natural current zero.
- High fault current level.
- High rate of rise of fault current.

ASCEND Specification

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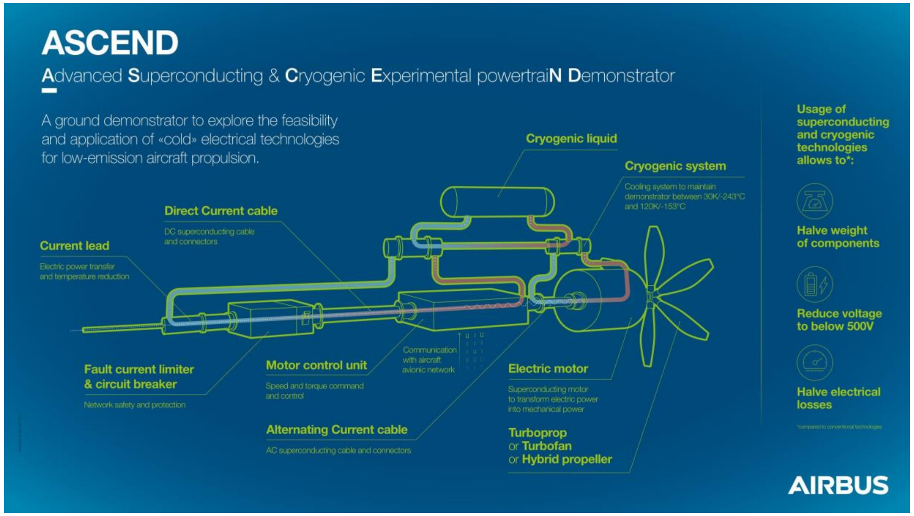
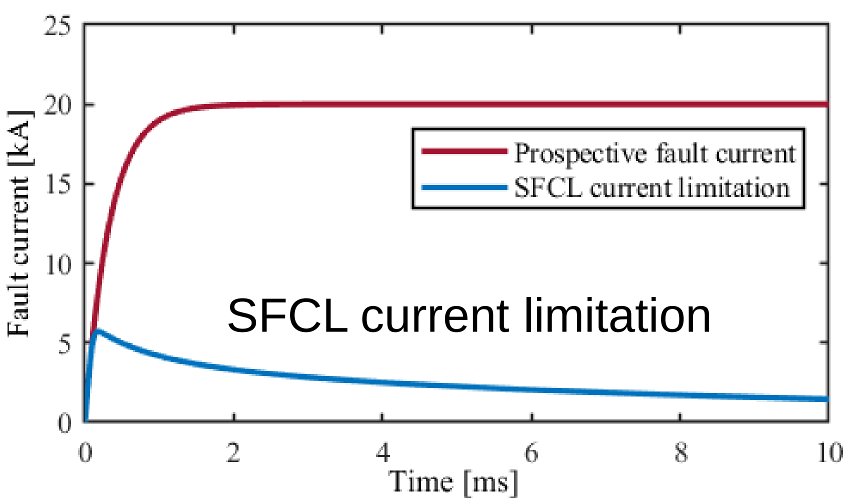
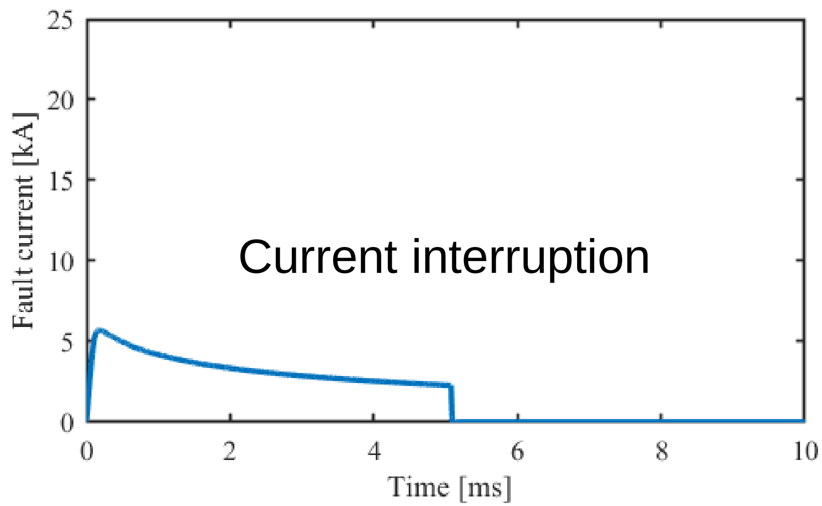


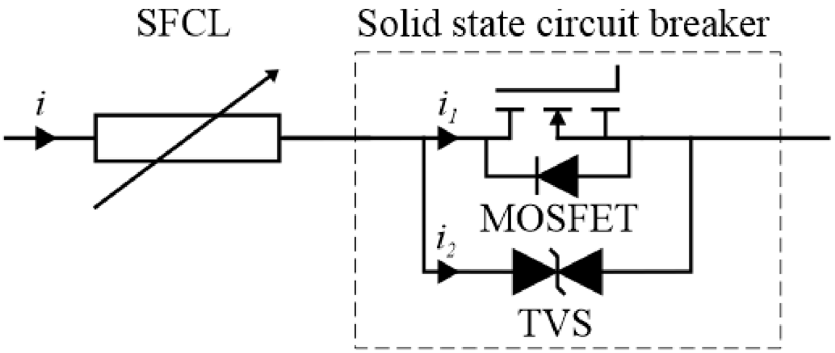
Power rating	500 kW
Nominal voltage	300 V
Nominal current	1700 A
Prospective fault current	10-20 kA
Maximum limited fault current	6800 A
Withstand voltage	2000 V
Fault interruption time	5-10 ms





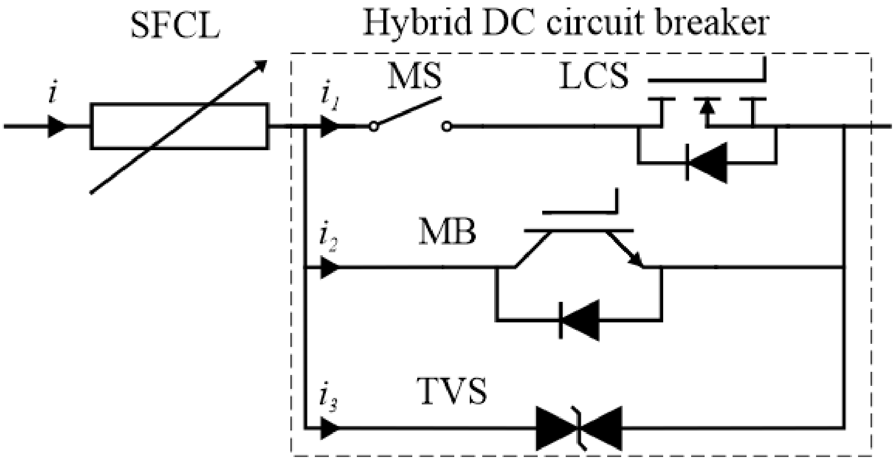
Integration of SFCL with DCCB

Technical solution 1: SFCL and solid state circuit breaker



- Faster interruption

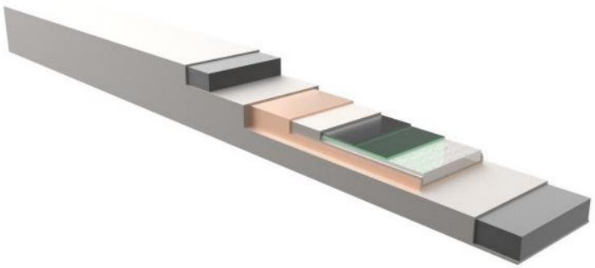
Technical solution 2: SFCL and hybrid DC circuit breaker



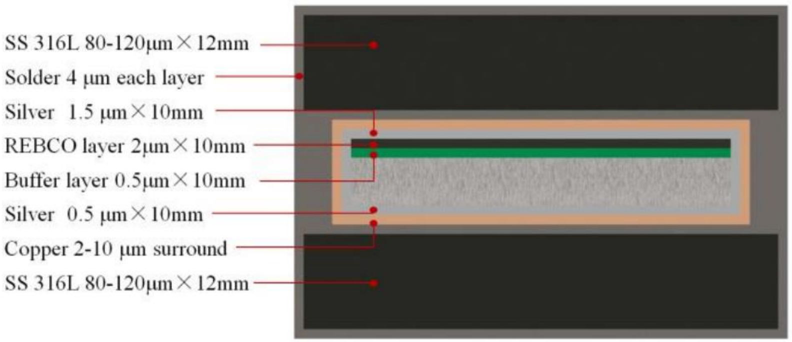
- Lower loss

J. Xi, Z. Wang, J. Hu, X. Zeng, E. Nilsson, J. Rouquette, L. Ybanez and X. Pei, "Integration of Superconducting Fault Current Limiter and DC Circuit Breaker for Electric Aircraft DC Network," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 3, pp. 1-5, May 2024, Art no. 5600205, doi: 10.1109/TASC.2023.3337054.

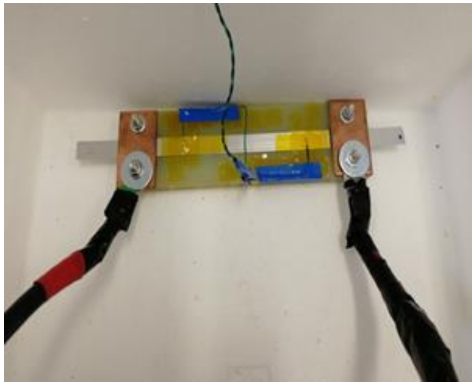
HTS Tape



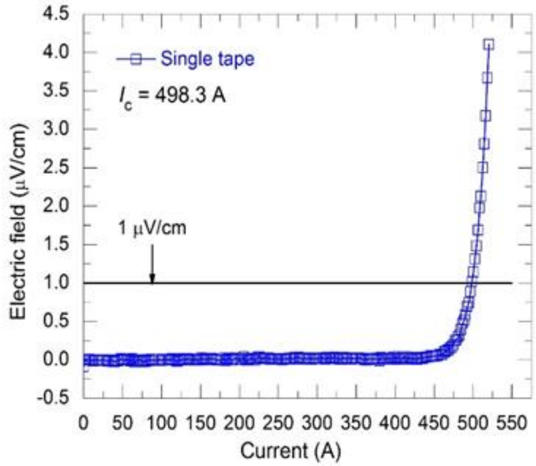
(a) A



(b) B



Short sample

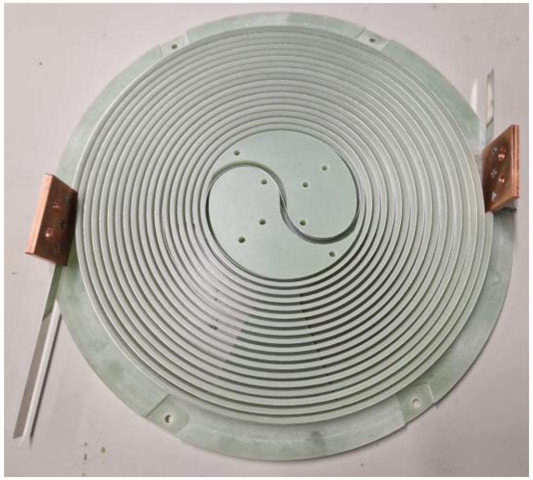


Shanghai superconductor 2G HTS tape with stainless steel lamination

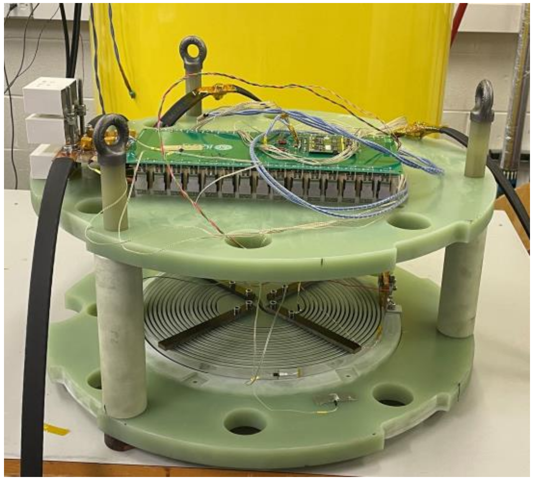
Critical current measurement

J. Hu, J. Xi, Z. Wang, X. Zeng, E. Nilsson, J. Rouquette, L. Ybanez and X. Pei, "Preliminary Design of DC Resistive Superconducting Fault Current Limiter for ASCEND," IEEE Transactions on Applied Superconductivity, vol. 34, no. 3, pp. 1-5, May 2024, Art no. 5600305, doi: 10.1109/TASC.2023.3338134.

Superconducting Fault Current Limiter



SFCL pancake coil



SFCL on the sample holder

Items	Values
Tape	ST-12-L
Lamination material	Stainless steel
Tape width	12 mm
Tape thickness	0.25 mm
Resistance @ RT	100 mΩ/m
Critical current @ 77K	533 A
Critical current @ 65K	1023 A
Tape length	11.6 m
Number of turns	10×2
Diameter of former	400 mm

J. Hu, J. Xi, Z. Wang, X. Zeng, E. Nilsson, J. Rouquette, L. Ybanez and X. Pei, "Preliminary Design of DC Resistive Superconducting Fault Current Limiter for ASCEND," IEEE Transactions on Applied Superconductivity, vol. 34, no. 3, pp. 1-5, May 2024, Art no. 5600305, doi: 10.1109/TASC.2023.3338134.

Applied Superconductivity and Cryogenic Propulsion Laboratory

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Cryogenic Cooling System

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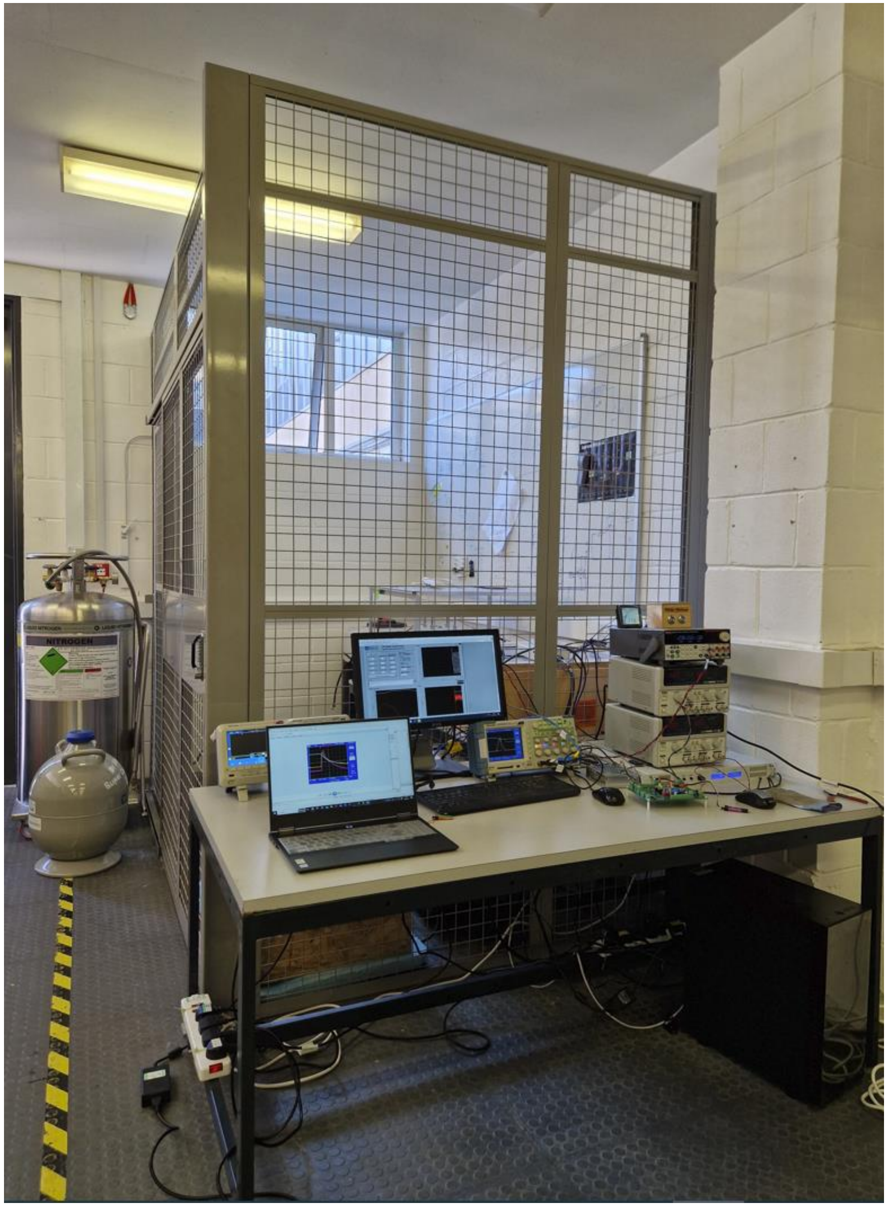
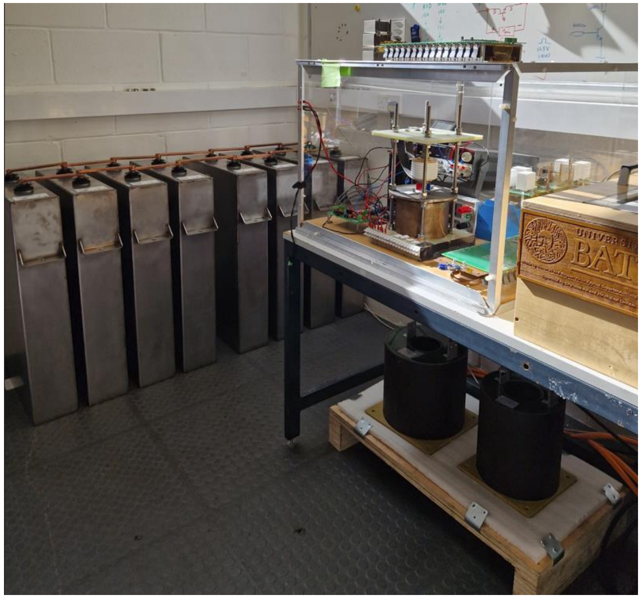
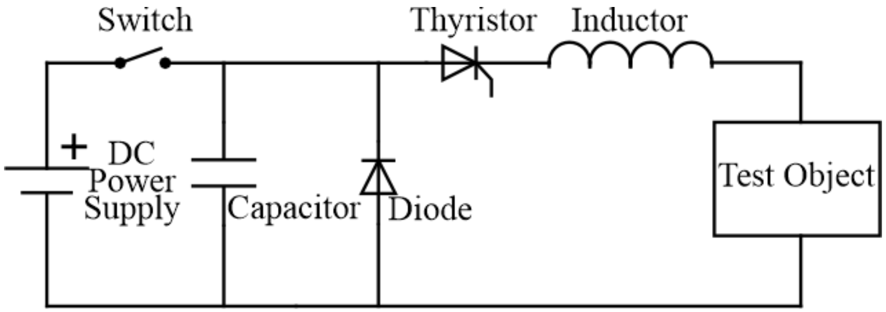
- Closed loop cryostat controllable from RT to 35 K
- Cryomech AL600 cold head
- Four current leads of 1000A, 2000V

DC Fault Current Test Rig

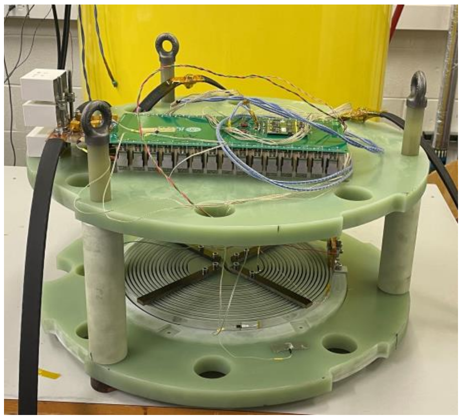




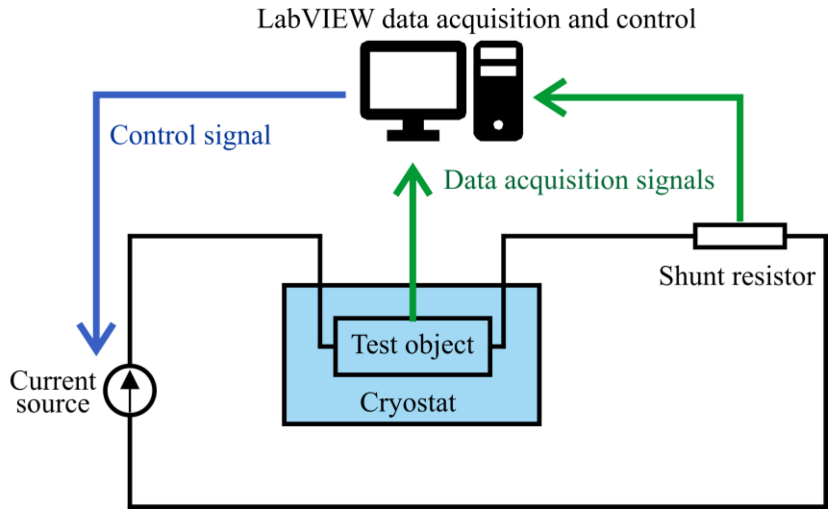


- Automatic control with data acquisition to simulate DC fault current up to 20 kA.

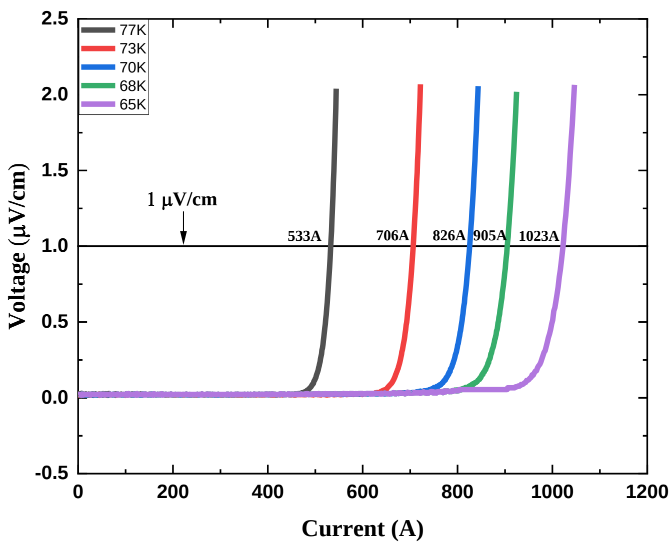
SFCL Experimental Test Results

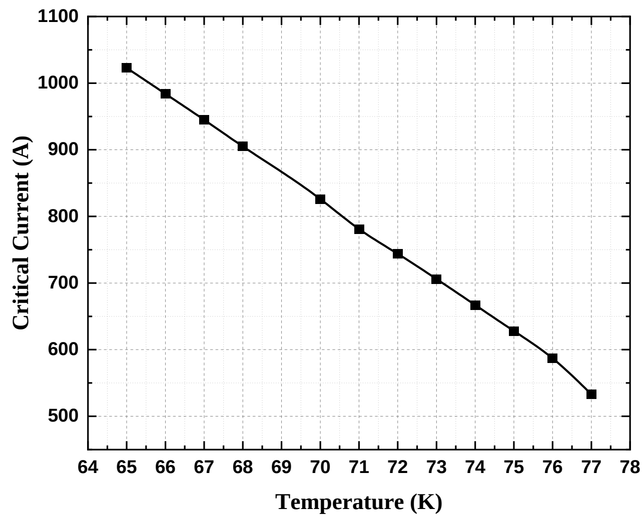


SFCL on the sample holder



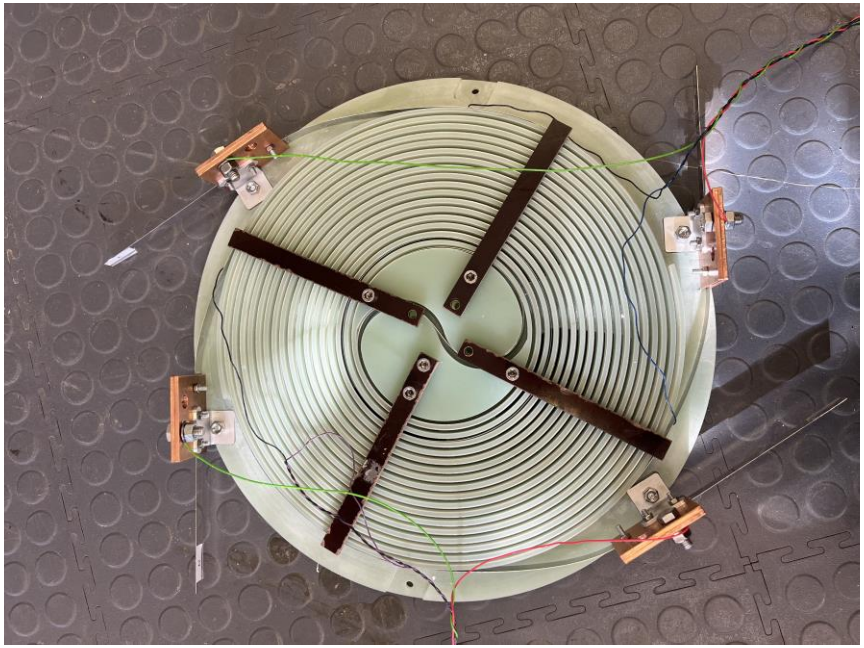
SFCL coil critical current test circuit



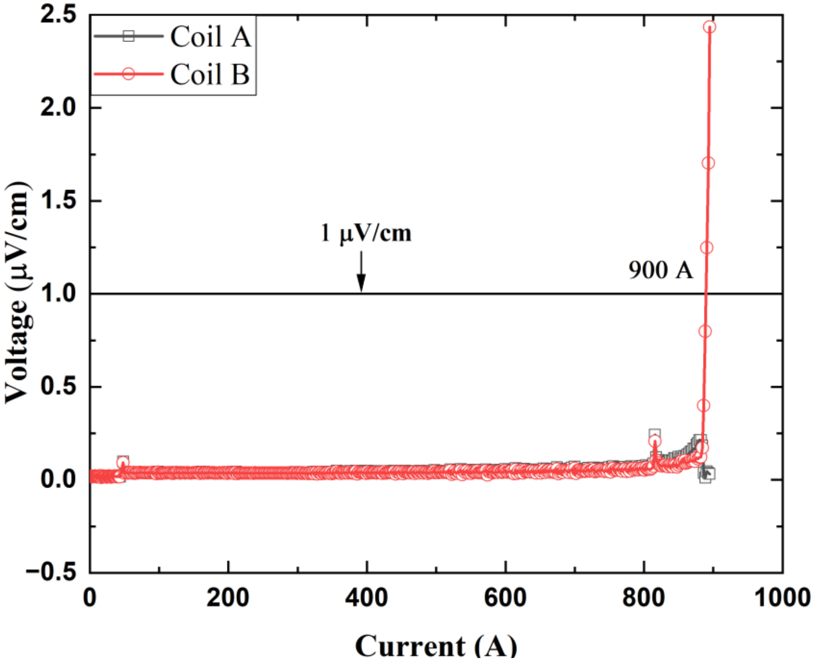


SFCL coil critical current

Double Tape SFCL

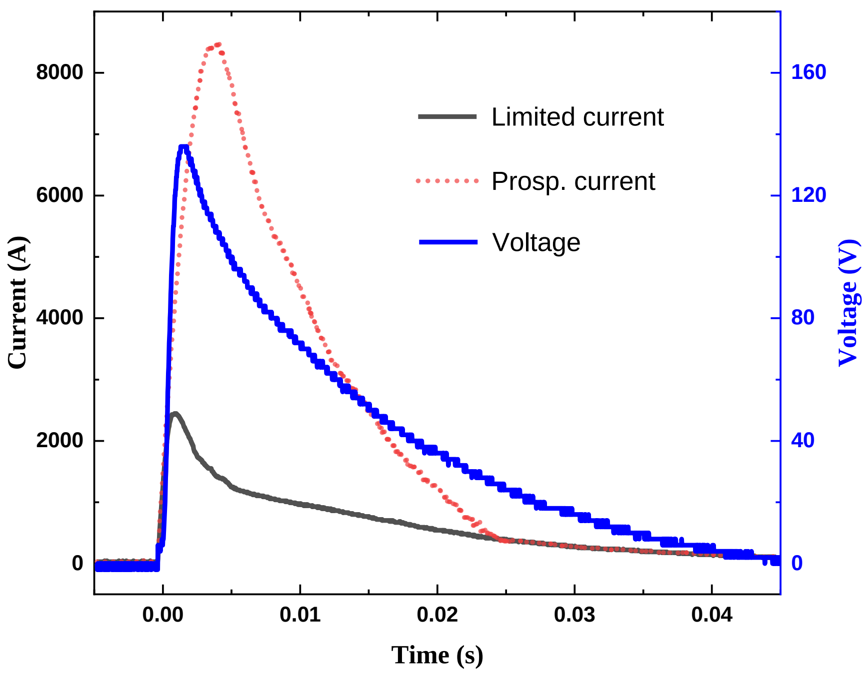


SFCL made by two tapes in parallel

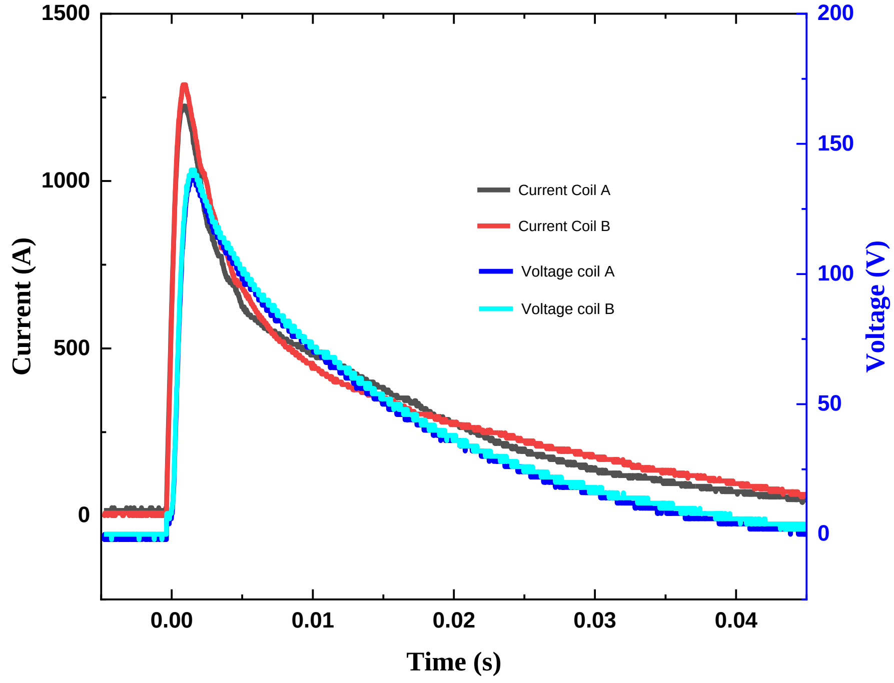


Critical current test at 77 K

Double Tape SFCL Experimental Test Results



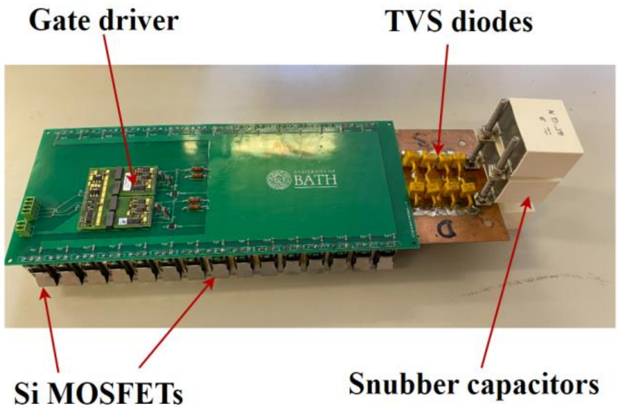
Double tape SFCL current limitation

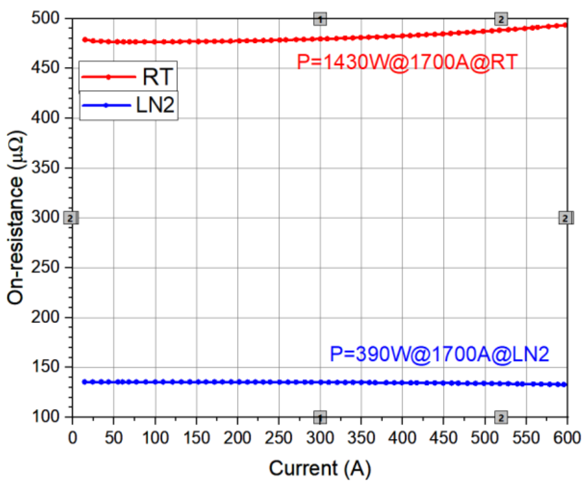


Current sharing in two HTS tapes

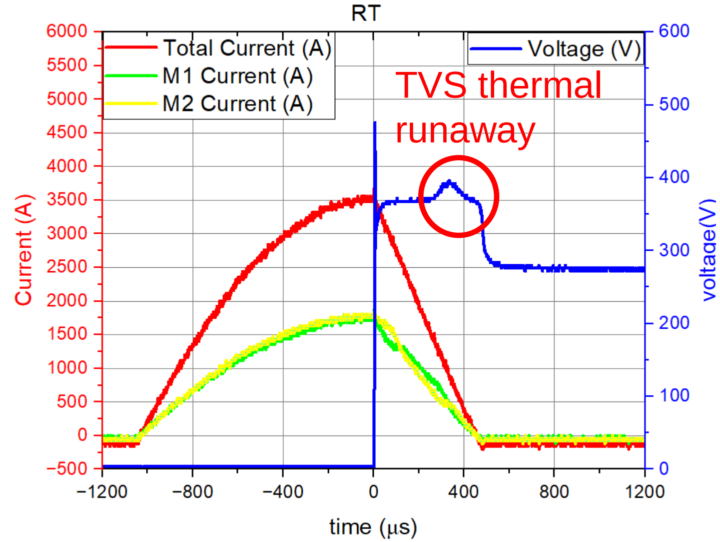
- Even current sharing and fault current limitation in two parallel HTS tapes.
- SFCL limits the fault current to 2-3 times critical current.

Solid State Circuit Breaker

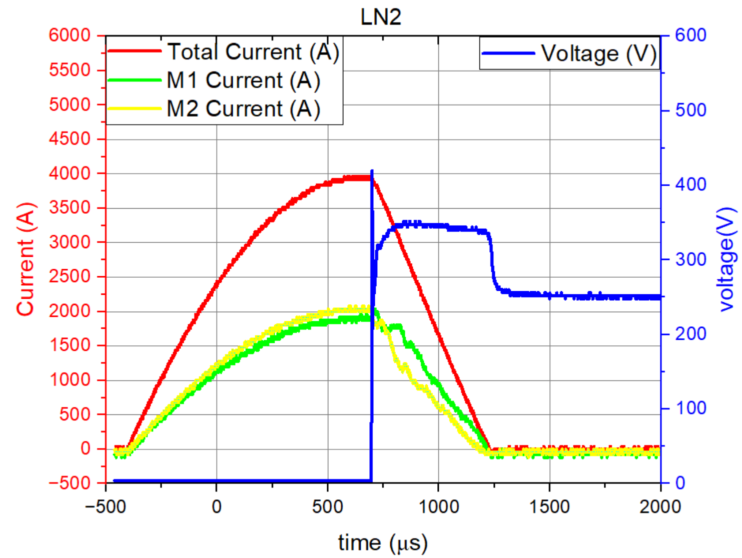




- SSCB on-state losses is reduced to 25% in liquid nitrogen than room temperature.
- TVS diodes are used absorb residual energy and liquid nitrogen provides better thermal condition than air.

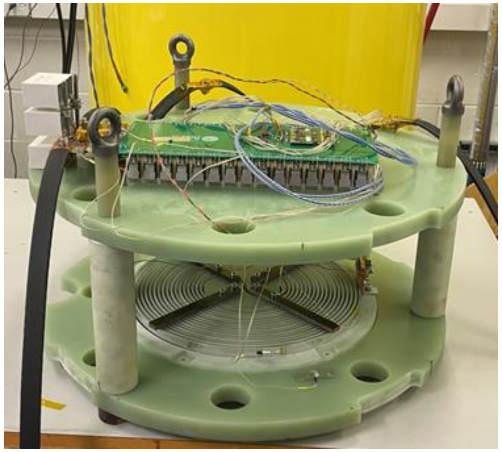


Current interruption at RT

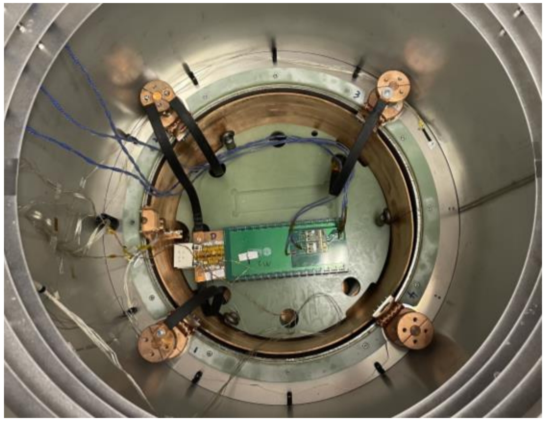


Current interruption in liquid nitrogen

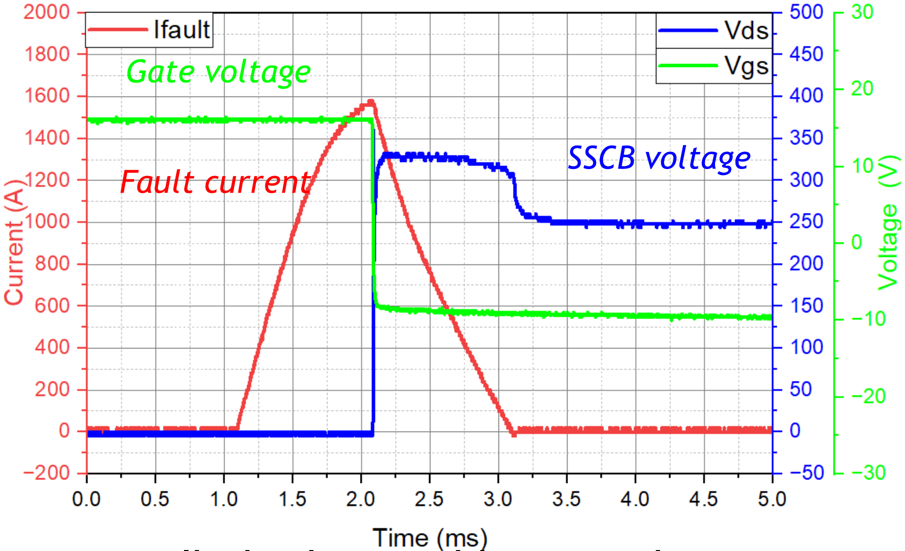
Integration of SFCL with SSCB



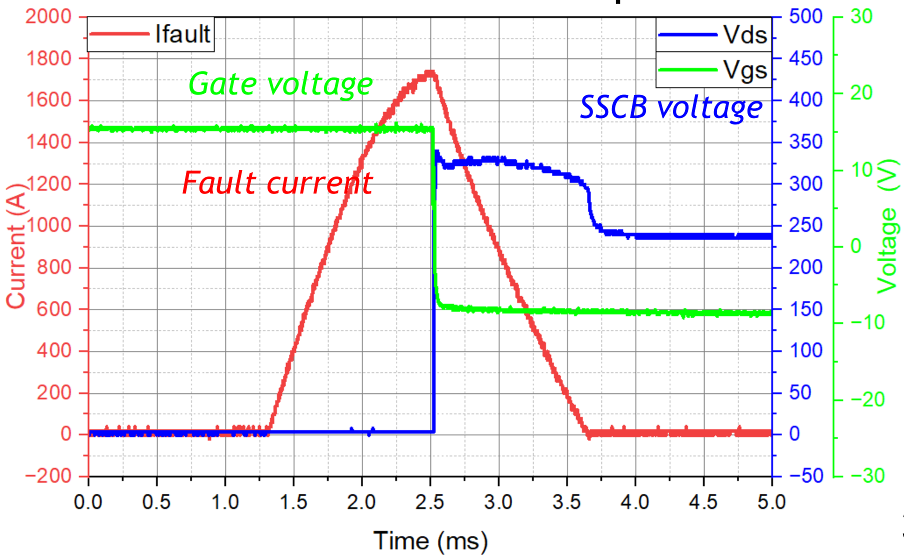
Integrated into cryostat



- SFCL and SSCB successfully operate in both LN2 and subcooled LN2.
- SFCL coil limits fault current from 2.5 kA to 1.6 kA at 77 K, and SSCB successfully interrupts the fault current at 1.6 kA.



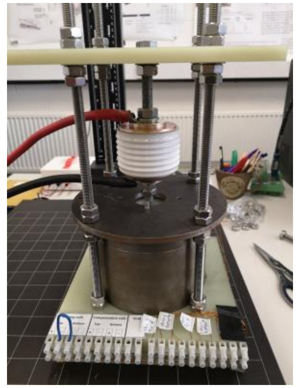
Current limitation and interruption at 77 K

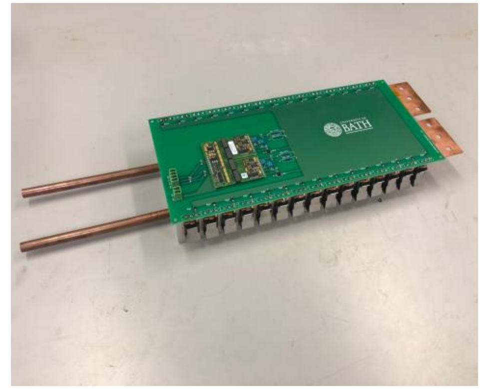


Current limitation and interruption at 73 K

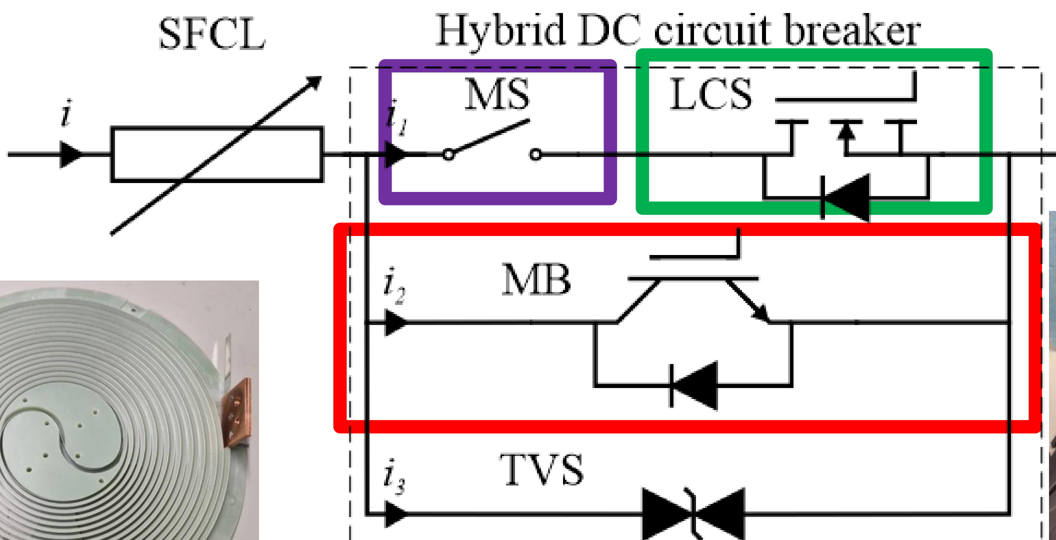
Integration of SFCL with HCB

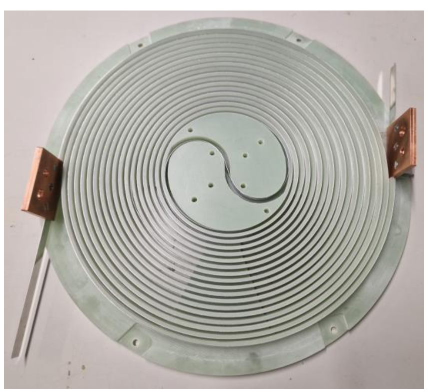
Fast operating mechanical switch

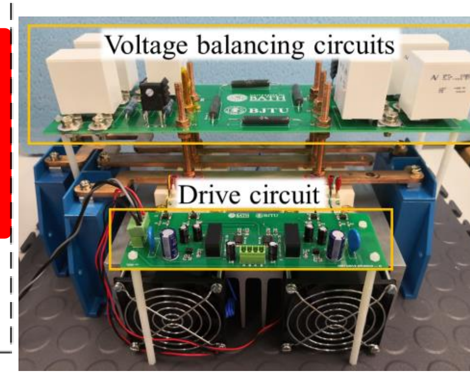




Low loss load commutation switch



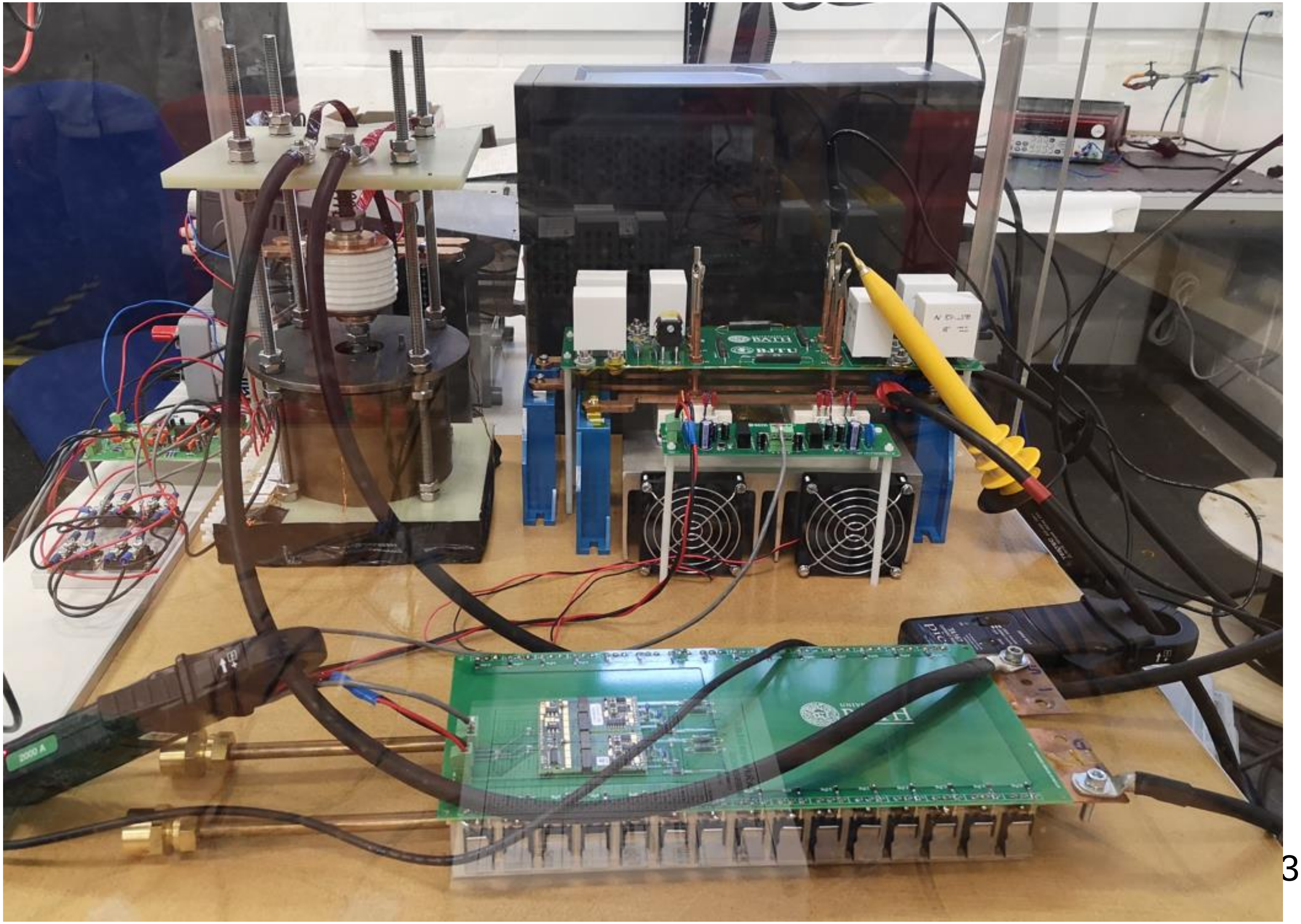




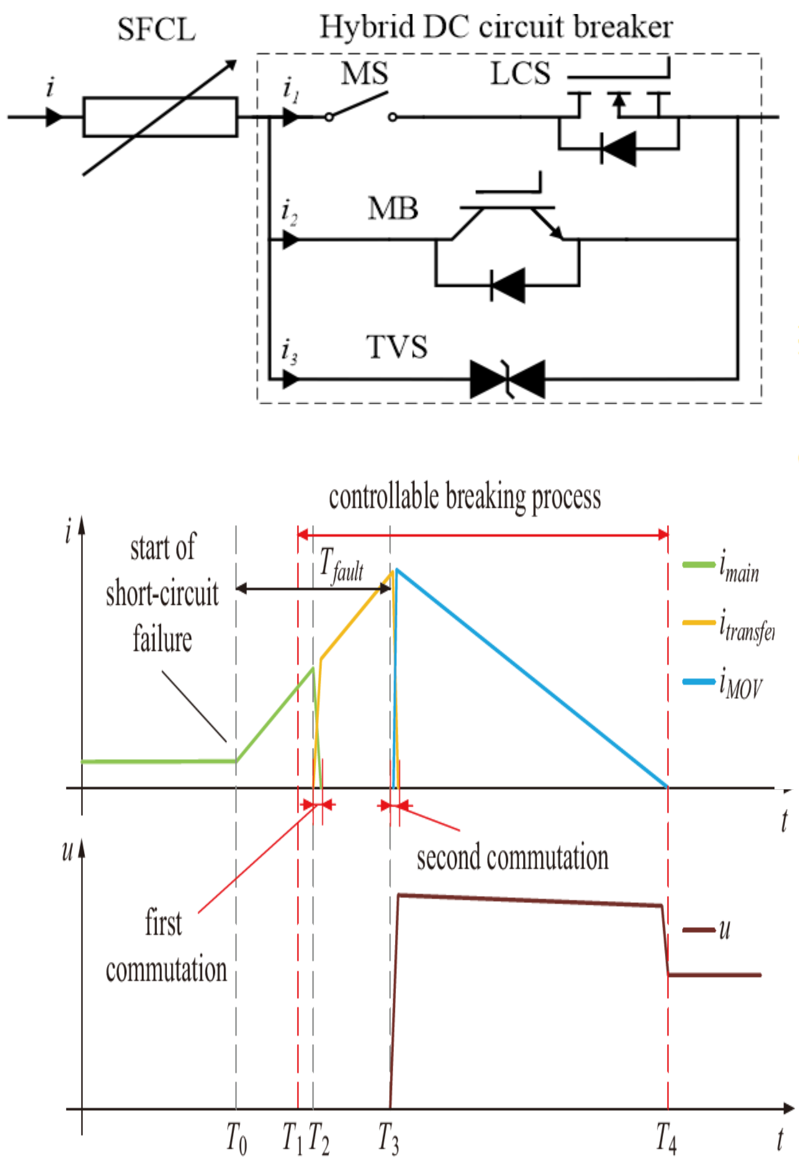
Solid state main breaker

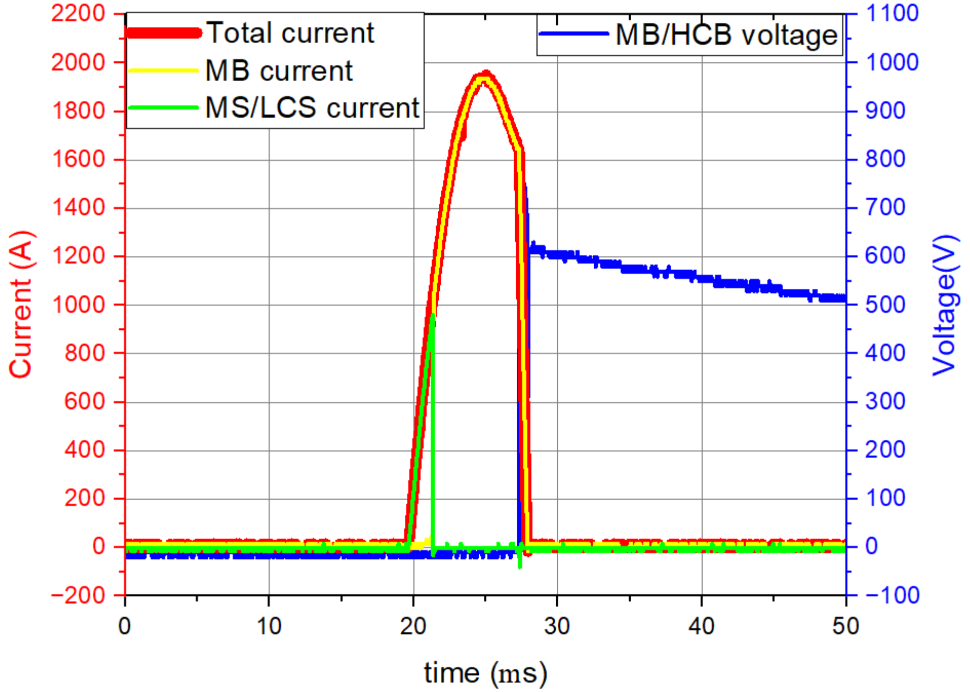
SFCL and hybrid DC circuit breaker schematic diagram

Hybrid Circuit Breaker Testing



Hybrid Circuit Breaker Testing



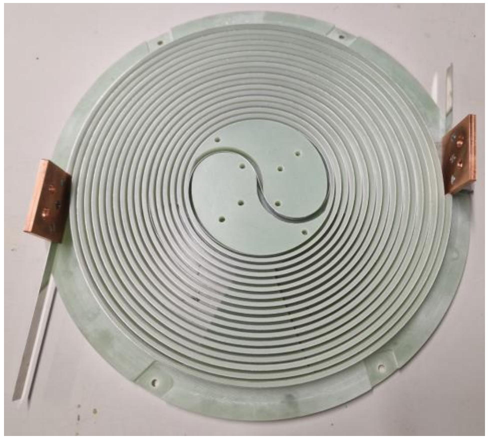


Experimental result

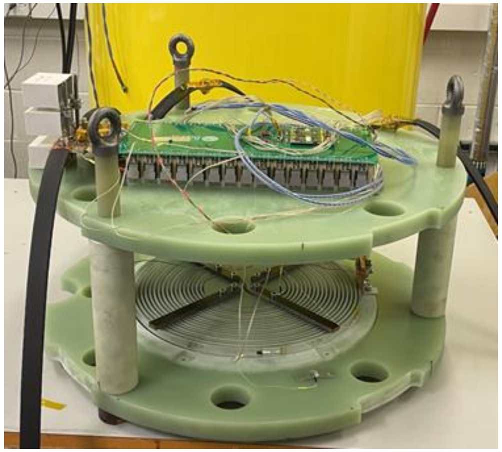
- Hybrid DC circuit breaker interrupts fault current of 1 kA within 5 ms.

SSCB vs HCB

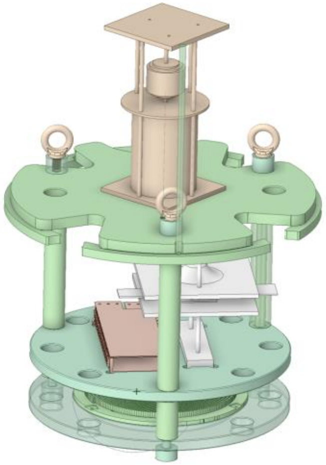
Technical solution	SFCL+SSCB	SFCL + Hybrid CB
Active mass	10 kg	50 kg
Power density	50 kW/kg	10 kW/kg
Loss	500 W	225 W
Efficiency	99.9%	99.95%
Fault clearance time	< 1 ms	5 ms



SFCL



SFCL+SSCB



SFCL+HCB

Summary

- Hydrogen electric propulsion address the environment impact and also opens new opportunities for superconductivity technology.
- Superconducting and cryogenic propulsion systems must be considered from an integrated electrical and thermal system perspective.
- Electric aircraft has very high fault current as the on-board power system is closely coupled.
- Superconducting fault current limiter offers effective current limitation allowing DC circuit breakers to operate quickly and reliably, which is a promising solution for on-board DC network protection.
- Integration of SFCL with DC circuit breaker in one cryostat can reduce the thermal leak and on-state losses.

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