IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This presentation was given at EFATS 2022, August 30-31, 2022.

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Electric Aircraft Superconducting DC Network Fault Protection

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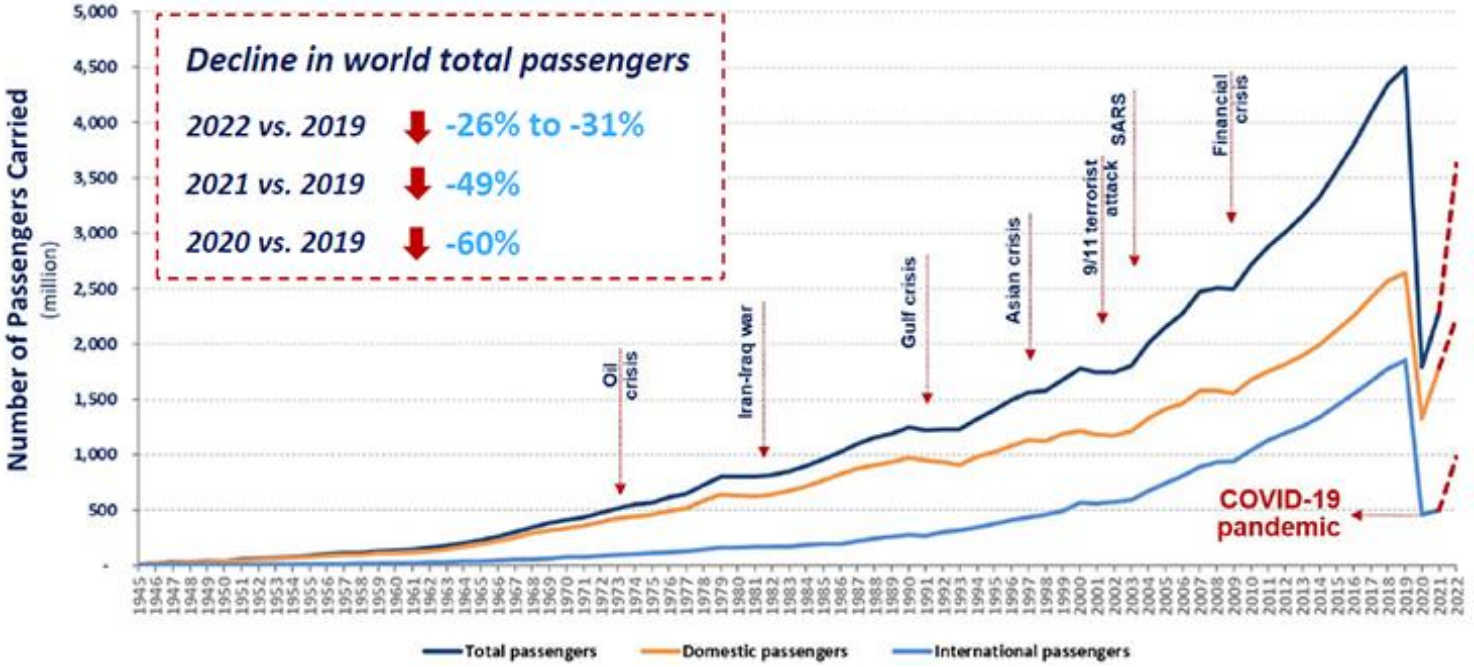
Centre for Sustainable Power Distribution

EFATS
ELECTRIC AIRCRAFT PROPULSION

Content

- **Sustainable aviation**
- **DC network fault current interruption challenges**
- **Integration of SFCL with DC circuit breaker**
- **Conclusions**

Sustainable aviation

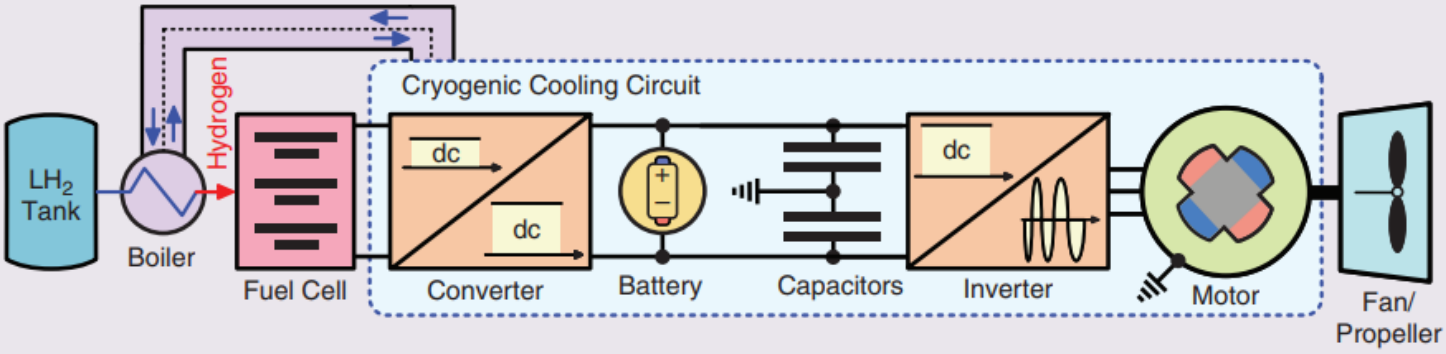


- European Union Flightpath 2050
- Aviation 2050 - The future of UK aviation
- UK's Ten Point Plan Point 6 (Jet Zero and Green Ships)
- …

Hydrogen-powered aircraft

Zero emission aircraft powered by hydrogen address the environment impact and also opens new opportunities for superconductivity technology.

Hydrogen fuel cell powered aircraft



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.

Hydrogen-powered aircraft

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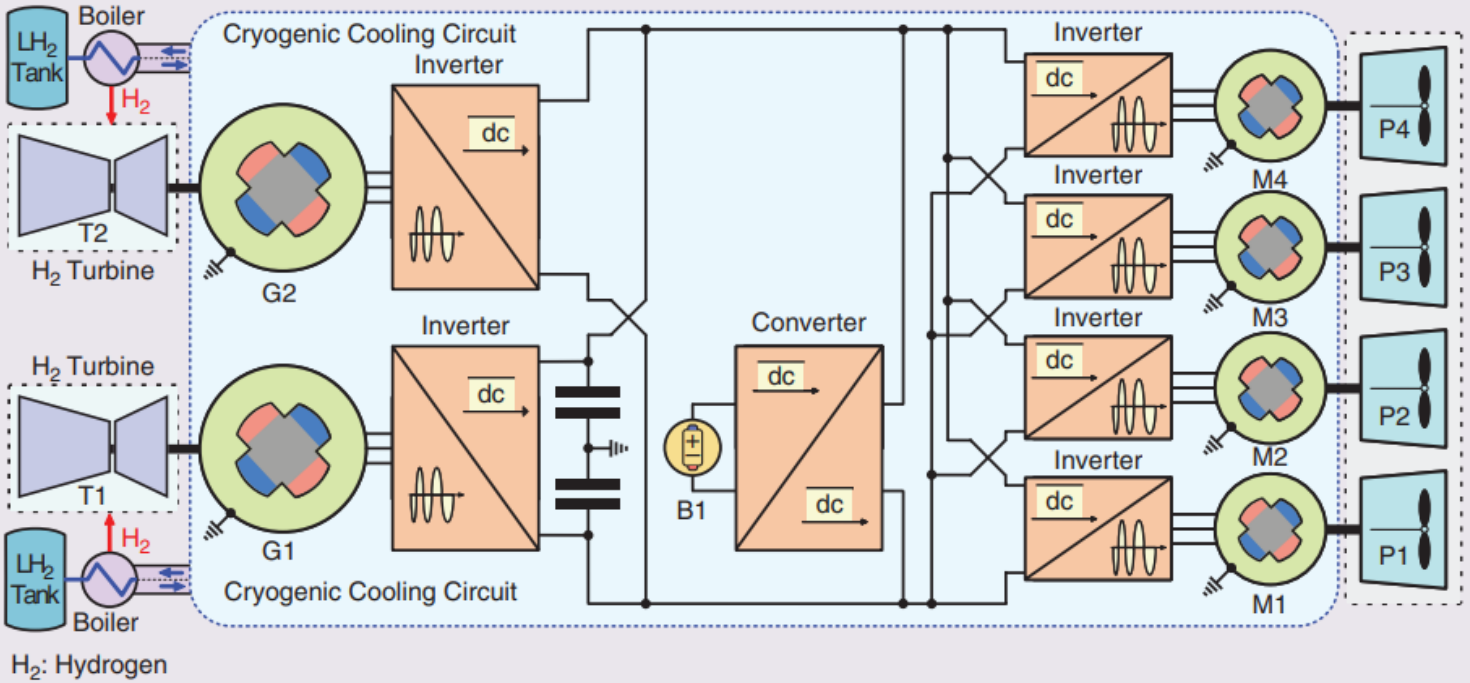
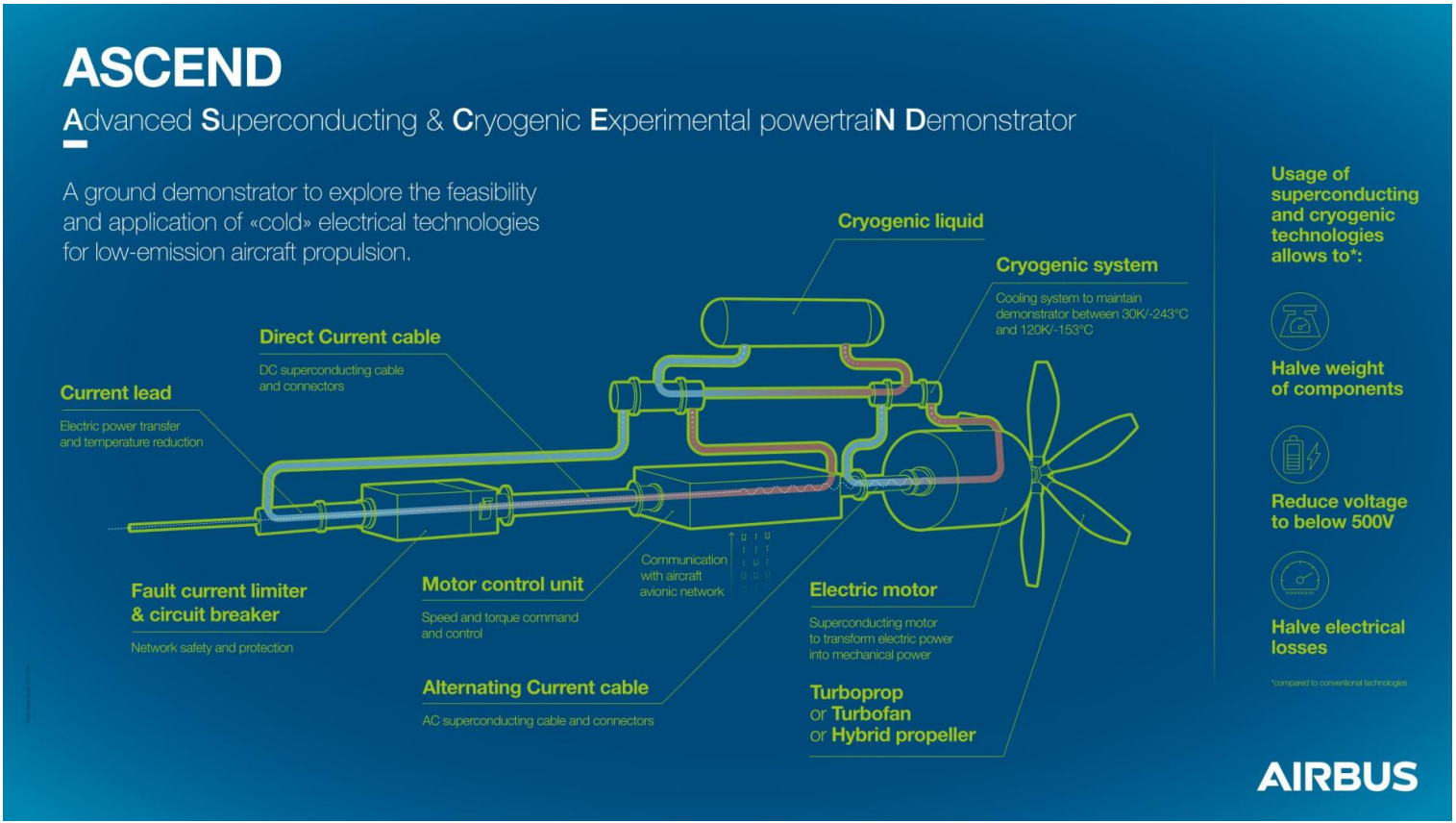
Hydrogen turbine powered aircraft



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.

ASCEND



Source: Airbus

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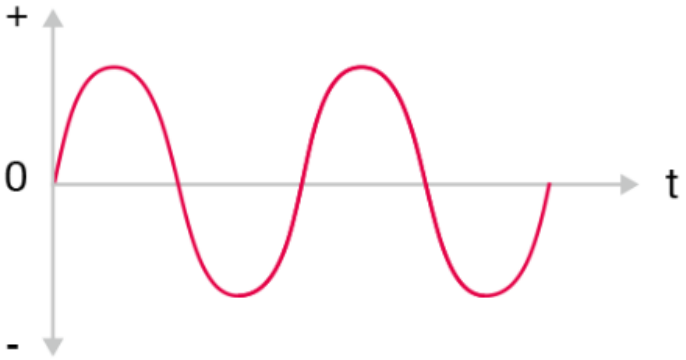
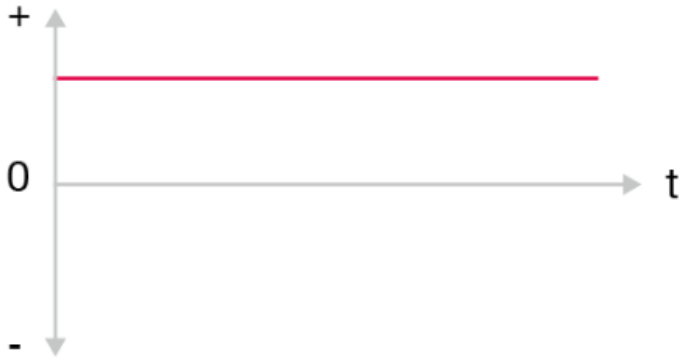
DC Network Protection Challenges

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



AC

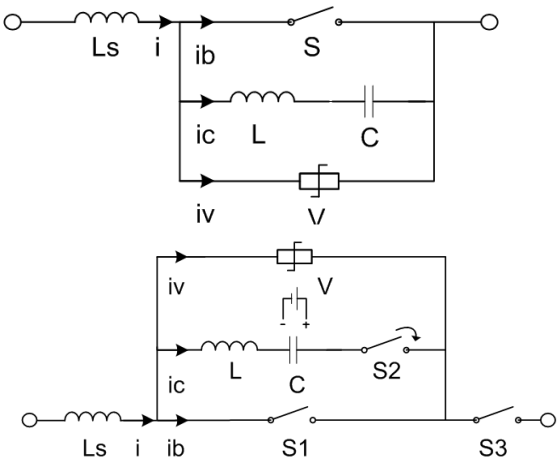
- Current crosses zero twice in each cycle.



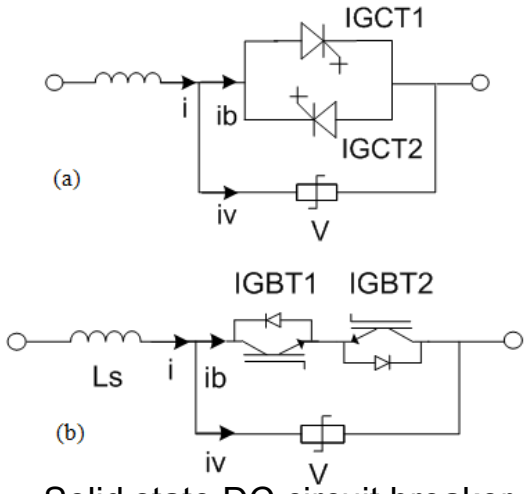
DC

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

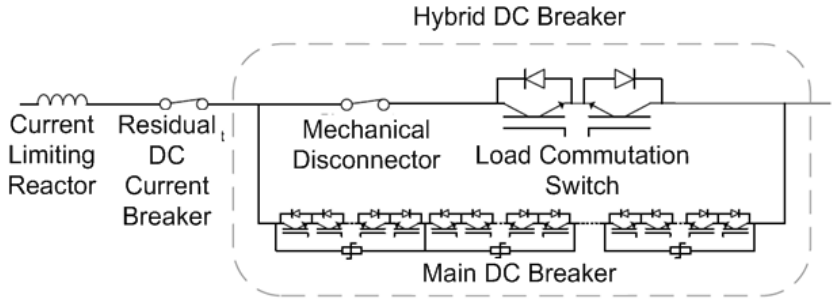
DC Circuit Breaker Review



Mechanical DC circuit breaker



Solid state DC circuit breaker



Proactive hybrid DC circuit breaker

Pei, X, Cwikowski, O, Vilchis-Rodriguez, DS, Barnes, M, Smith, AC & Shuttleworth, R 2016, A review of technologies for MVDC circuit breakers. in Proceedings of the IECON 2016 - 42nd Annual Conference of the Industrial Electronics Society., 7793492,.

SFCL+HCB

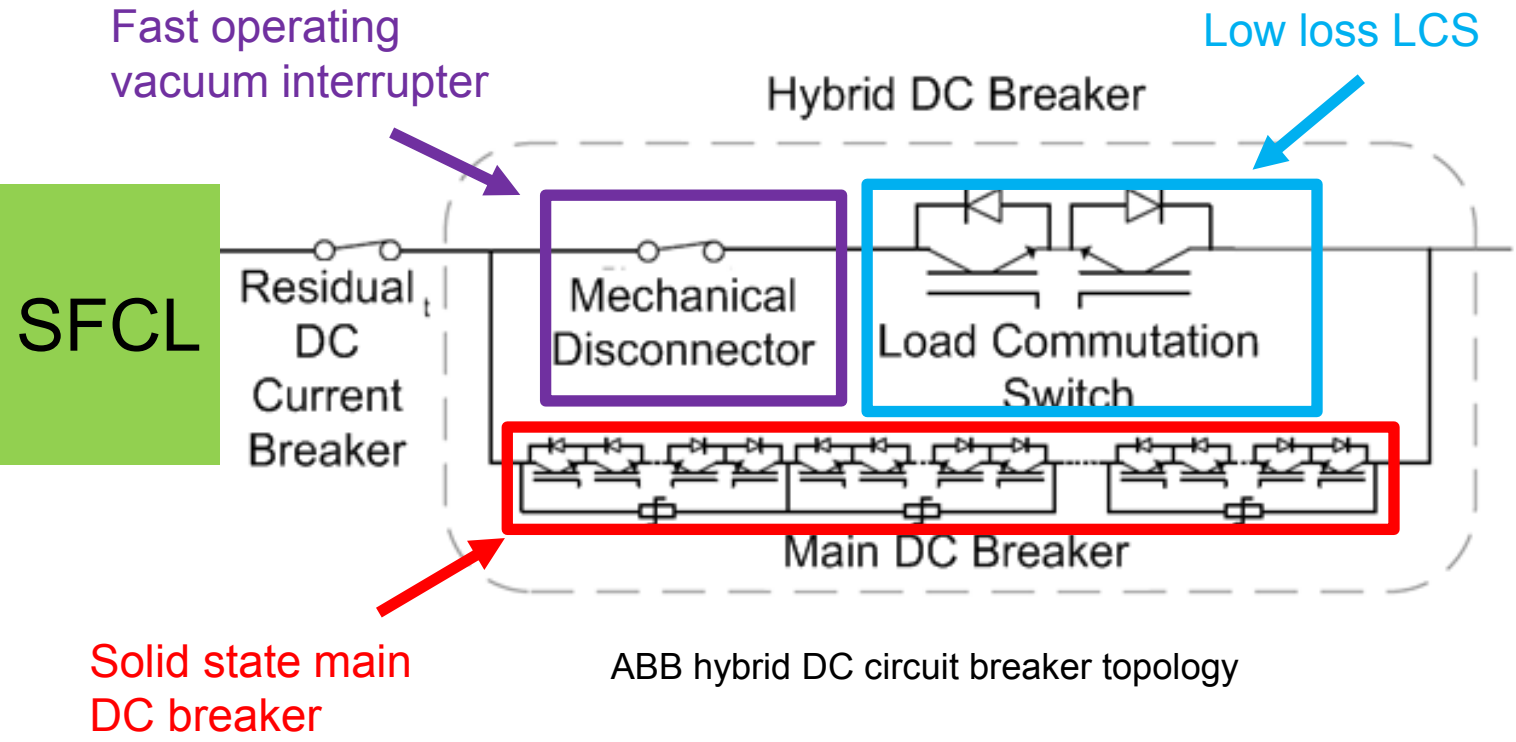


ABB hybrid DC circuit breaker topology

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SFCL+HCB

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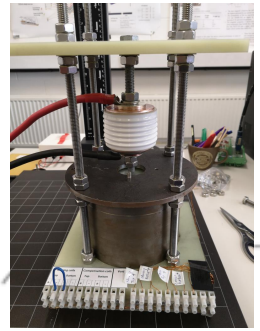
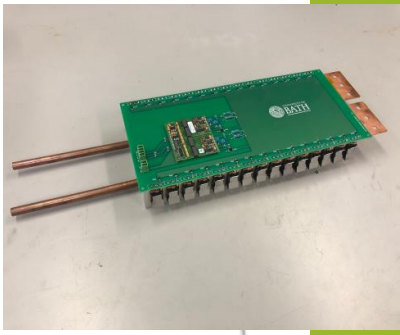
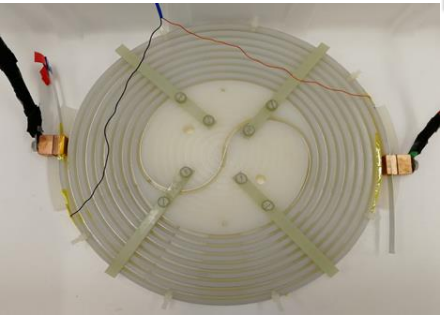
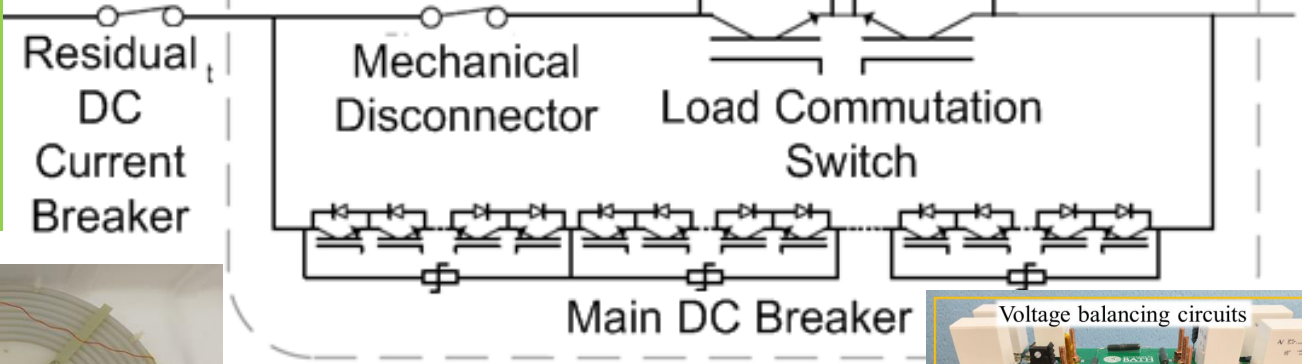
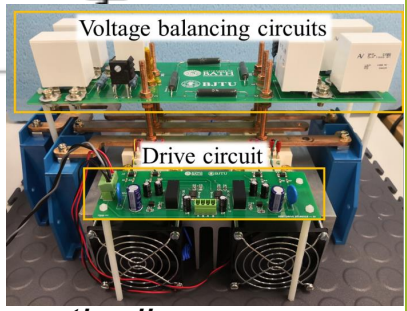
SFCL





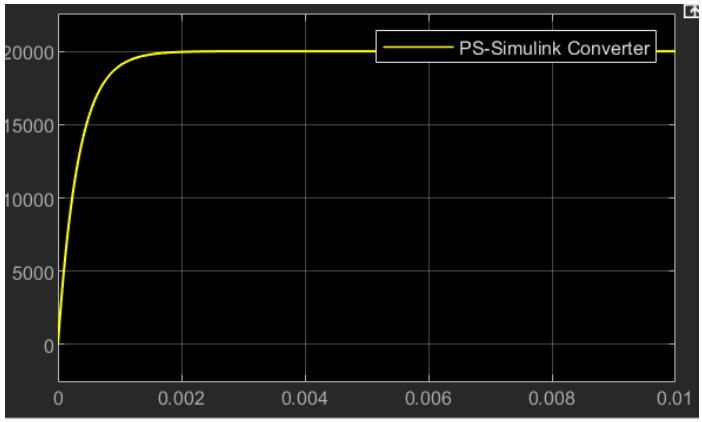




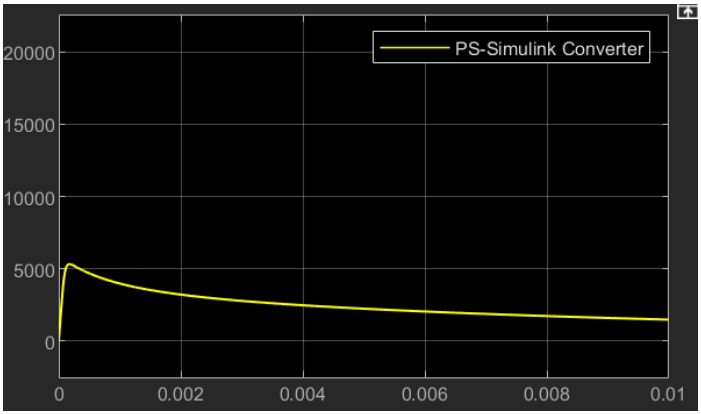


SFCL and cryogenic hybrid DC circuit breaker schematic diagram

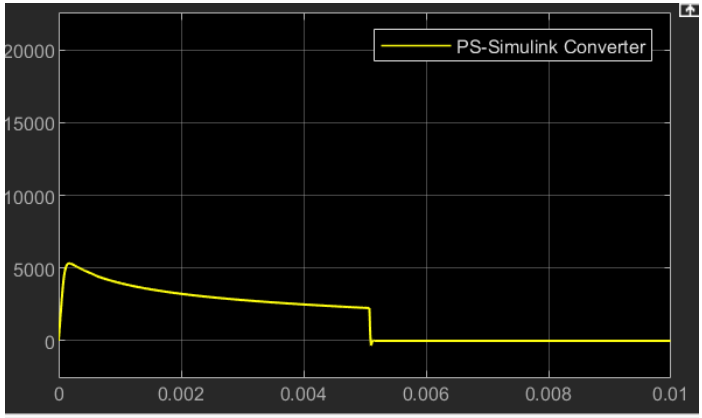
SFCL+HCB Simulation



Prospective fault current



SFCL current limitation

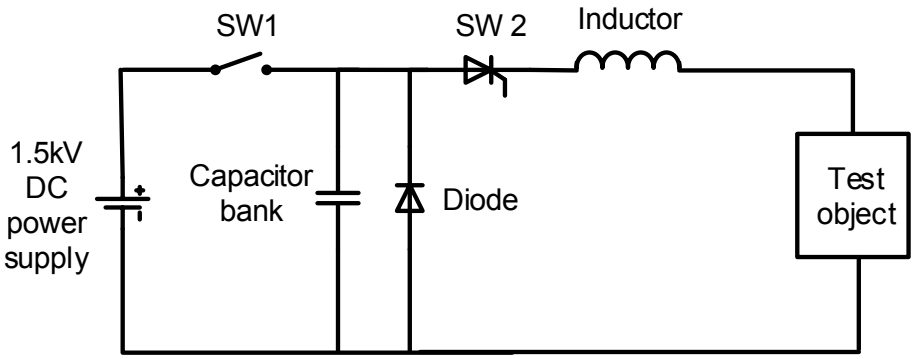


Current interruption

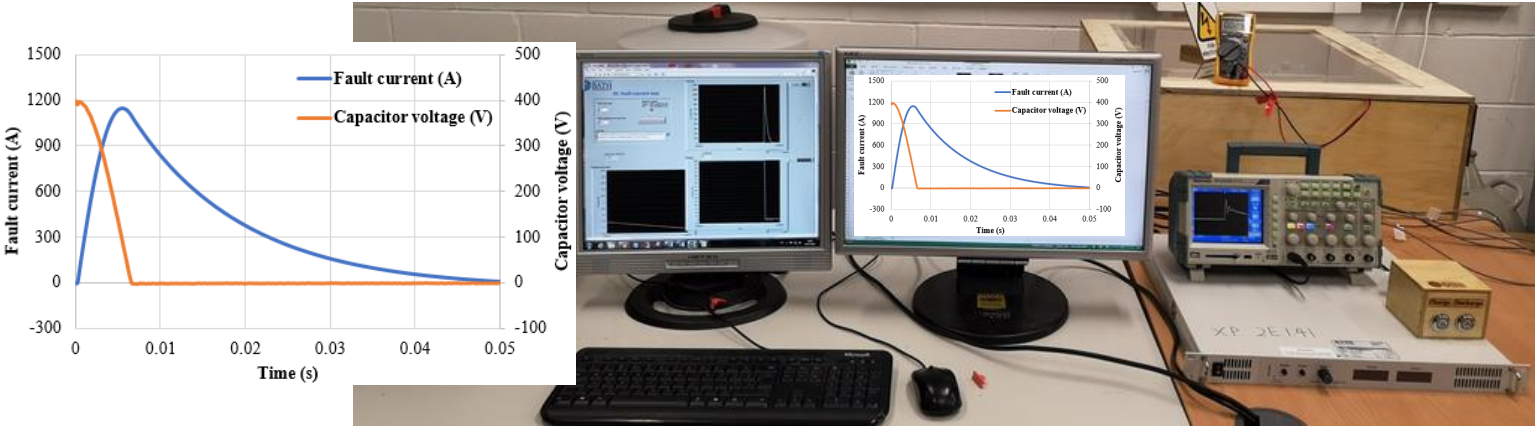
- Fault current is limited from 20 kA to 5.5 kA.
- Hybrid DC circuit breaker interrupts fault at 5 ms.

3 kA DC Fault Current Test Circuit

Capacitor



Inductor



- Automatic control with data acquisition to simulate DC fault current up to 3 kA.

SFCL Different Types

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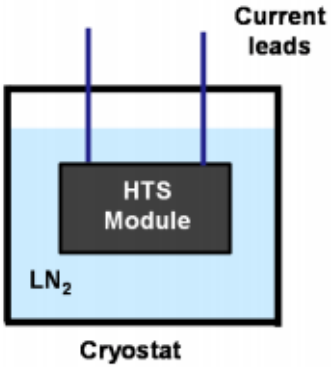
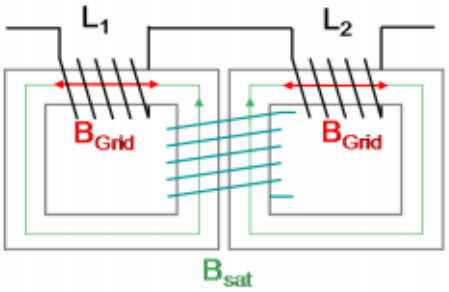
Resistive type



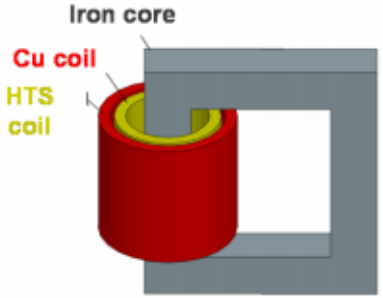
- ☺ Simple concept
- ☺ fail safe
- ☺ compact, low weight
- ☹ Current leads to low temp.

DC biased iron core „saturated iron core“



- ☺ no SC quench
- ☺ immediate recovery
- ☺ adjustable trigger current
- ☹ High volume and weight
- ☹ High impedance at normal op.

Shielded iron core „Inductive“

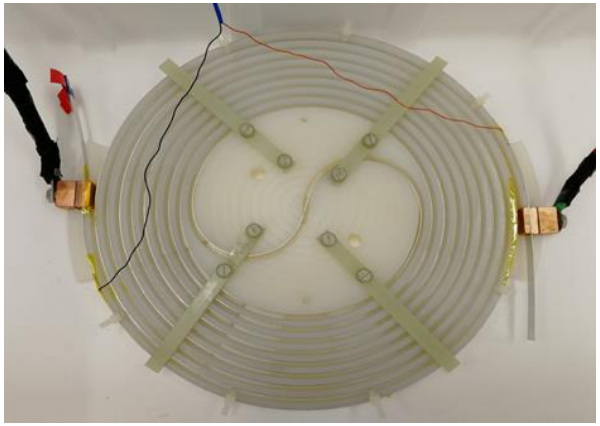


- ☺ No current leads to low temp.
- ☺ Fail safe
- ☹ High volume
- ☹ High weight

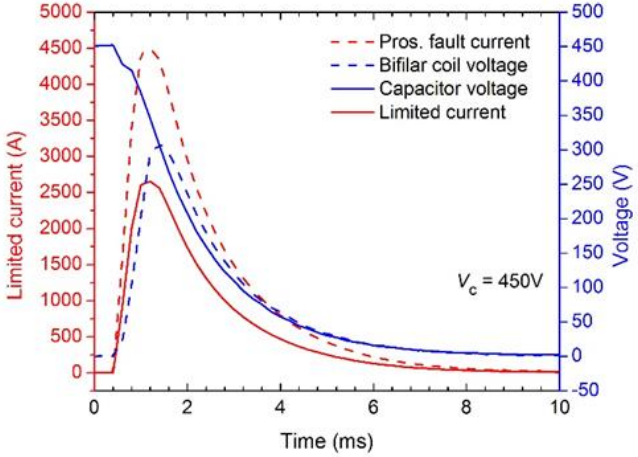
Source: M. Noe tutorial

SFCL

Helical bifilar SFCL coil



Pancake bifilar SFCL coil



Hybrid DC Circuit Breaker

SFCL

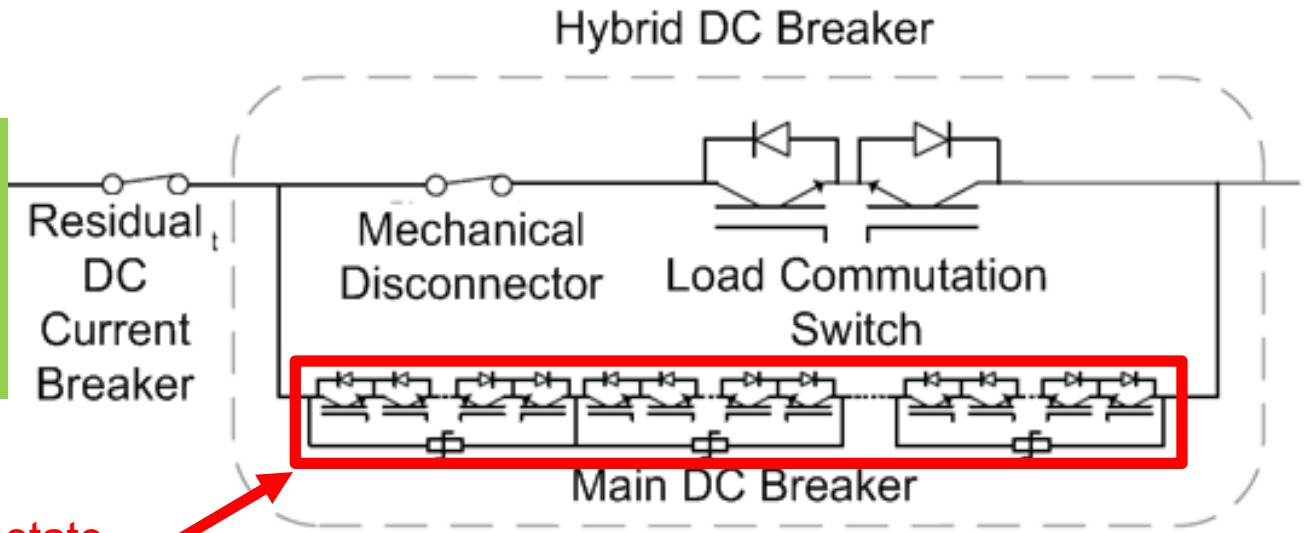
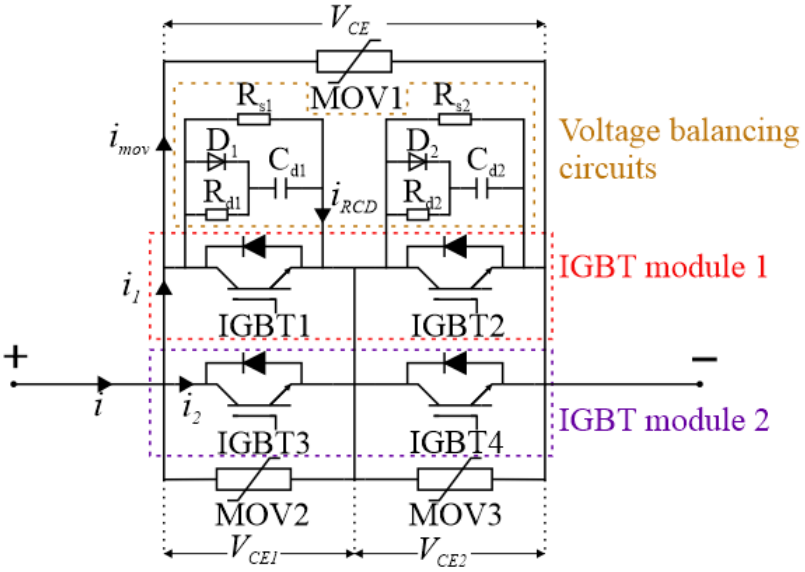
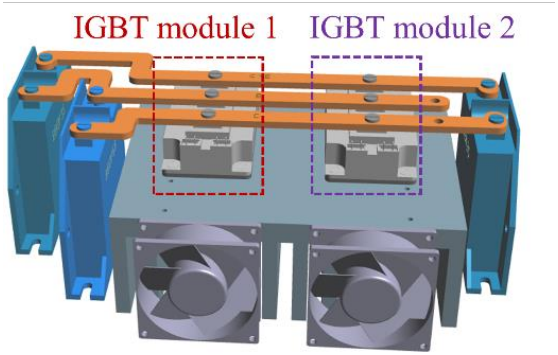


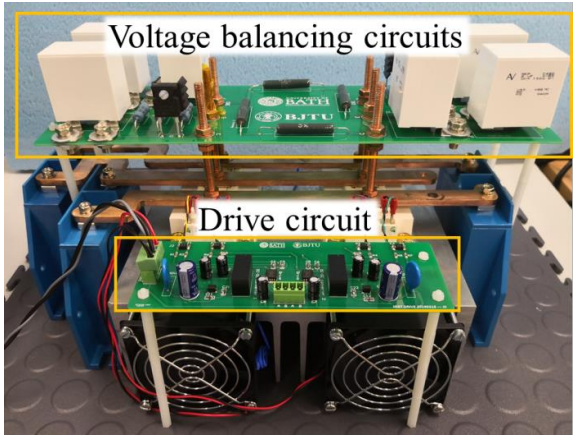
ABB hybrid DC circuit breaker topology

Source: M. Callavik, A. Blomberg, J. Hafner, and B. Jacobson, “The hybrid HVDC breaker: an innovation breakthrough enabling reliable HVDC grids,” ABB grid systems, Tech. Report. Nov. 2012.

Solid-State Circuit Breaker (SSCB)

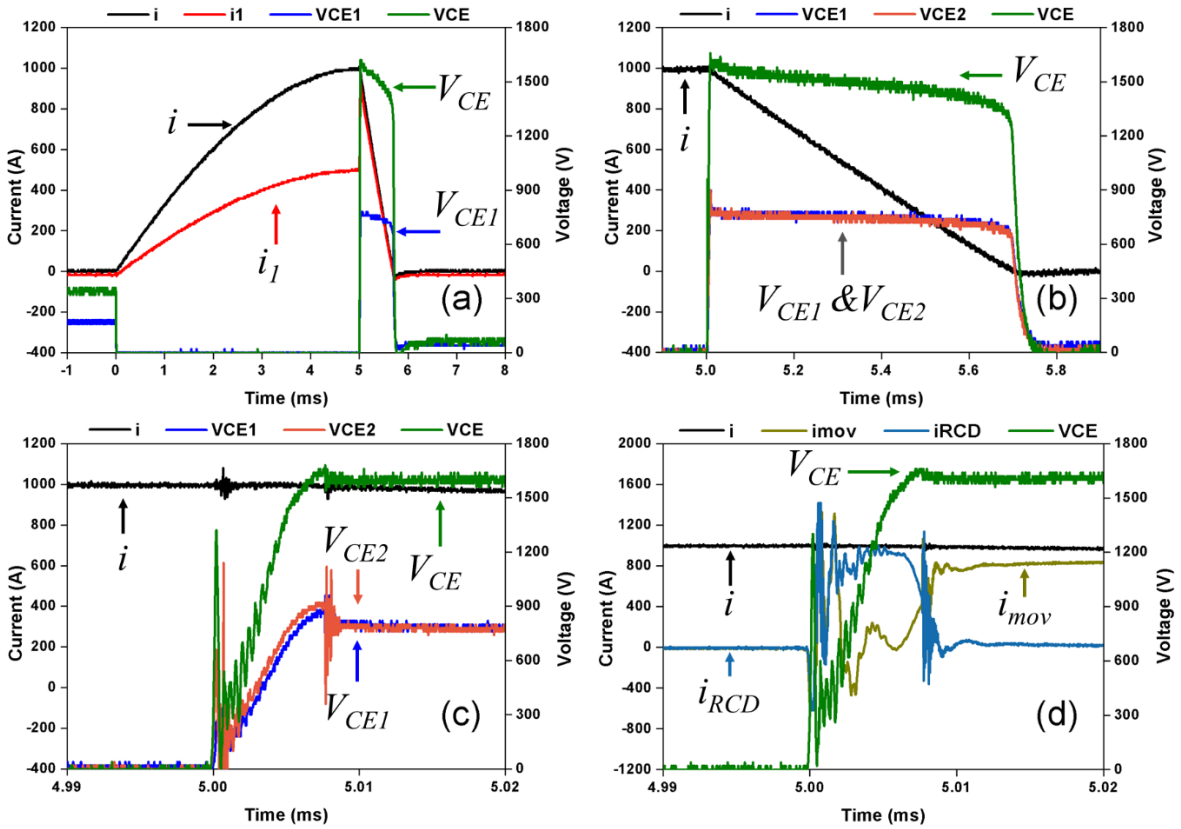






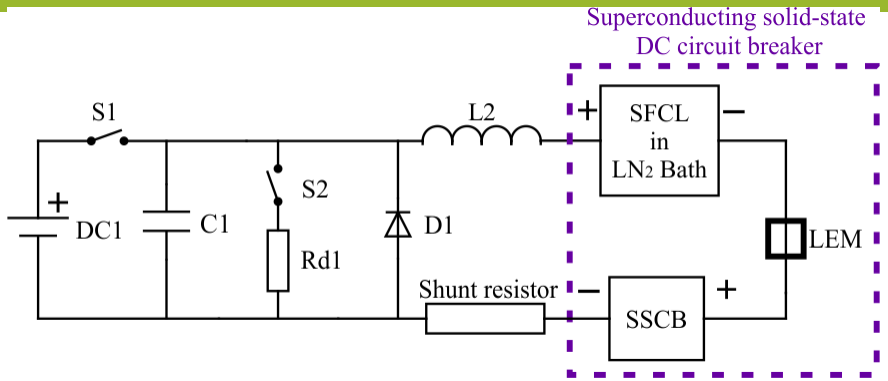
J. Xi, X. Pei, X. Zeng and L. Niu, "Design, modelling, and test of a solid-state main breaker for hybrid DC circuit breaker," 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe), 2020.

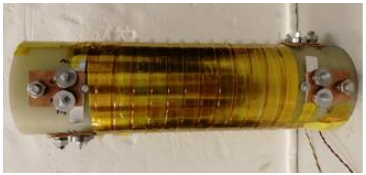
Dynamic Tests

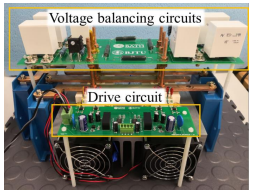


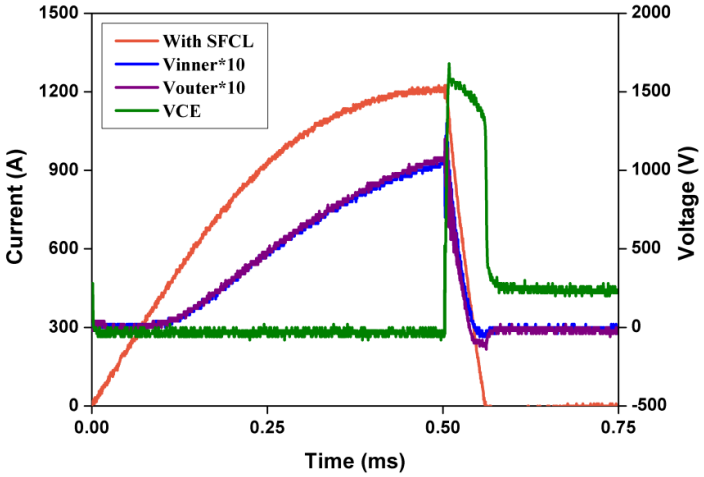
Current and voltage waveforms under current interruption test of 1000 A: (a) entire test duration; (b) current interruption period; (c) voltage increase period; (d) current commutation from IGBT to RCD and MOV

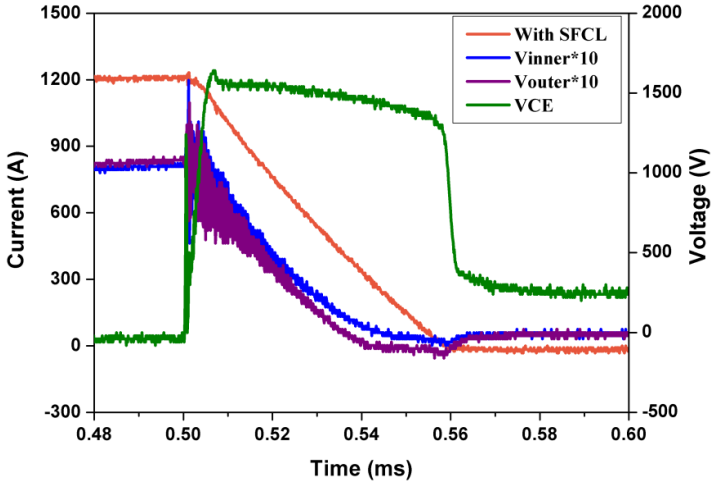
SFCL with DC Circuit Breaker Results











- SFCL limits the fault current from 3000 A to 1200 A.
- Solid state circuit breaker interrupts the fault current of 1200 A.

Hybrid DC Circuit Breaker

SFCL

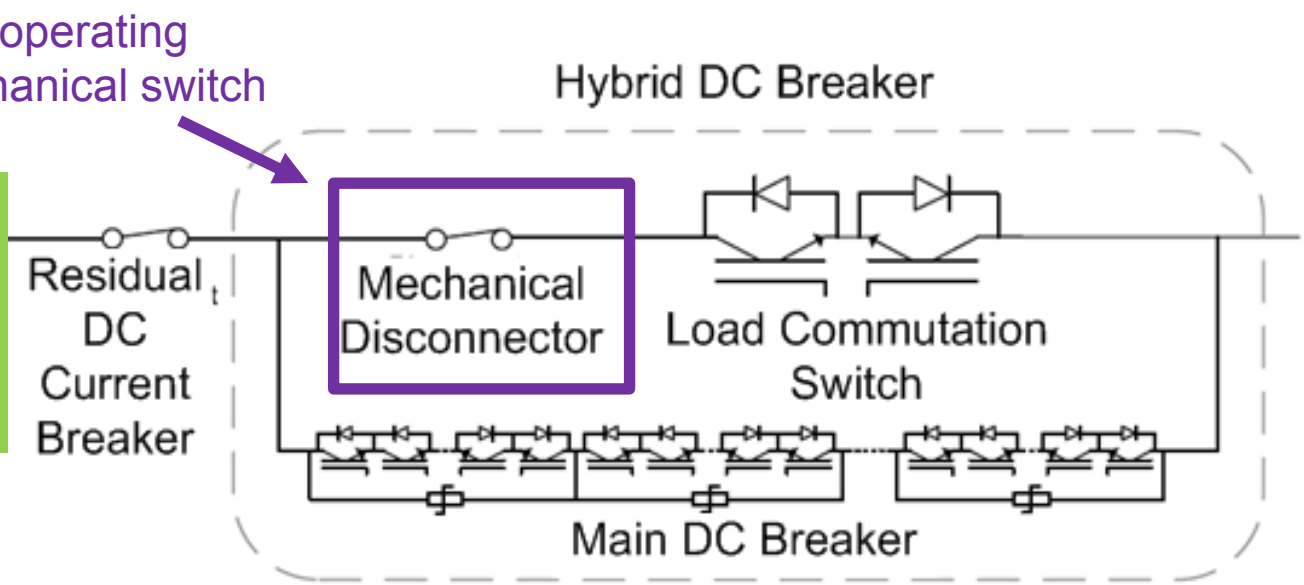
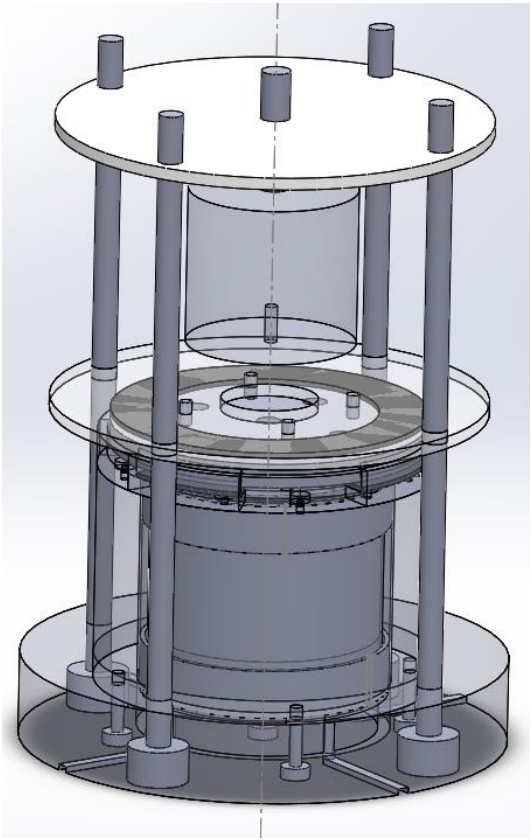
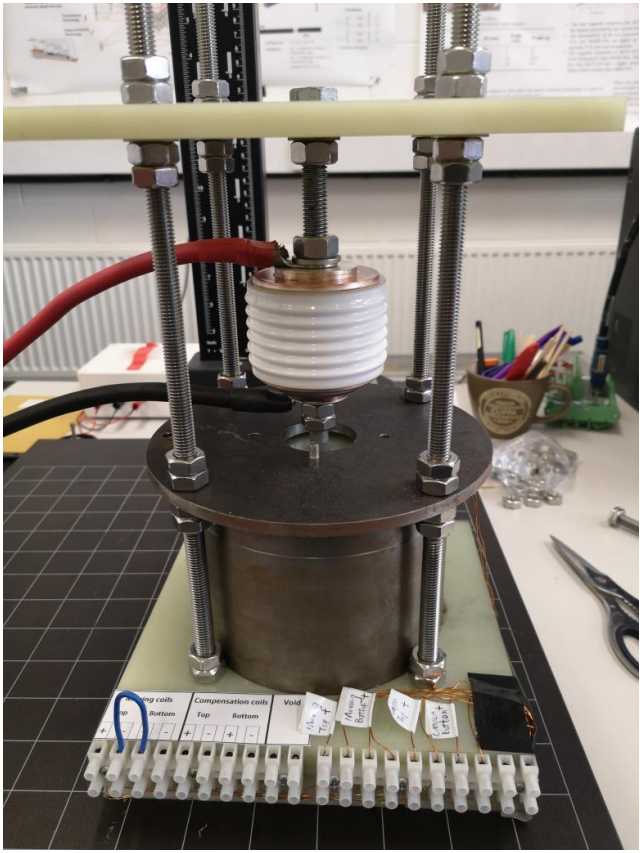


ABB hybrid DC circuit breaker topology

Source: M. Callavik, A. Blomberg, J. Hafner, and B. Jacobson, “The hybrid HVDC breaker: an innovation breakthrough enabling reliable HVDC grids,” ABB grid systems, Tech. Report. Nov. 2012.

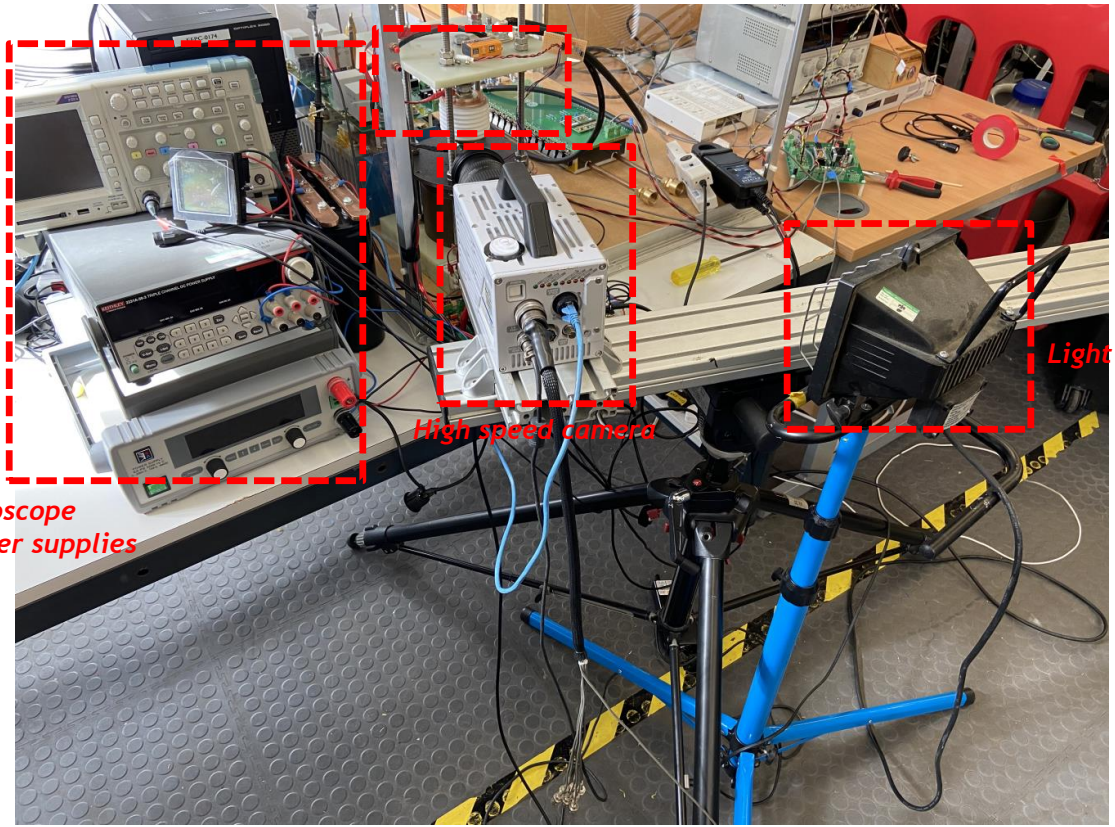
Mechanical Switch Moving Coil Actuator





B. Yin, X. Zeng, J. F. Eastham, D. S. Vilchis-Rodriguez and X. Pei, "Novel Fast Operating Moving Coil Actuator with Compensation Coil for HVDC Circuit Breakers" CSEE Journal of Power and Energy Systems.

Mechanical Switch Moving Coil Actuator



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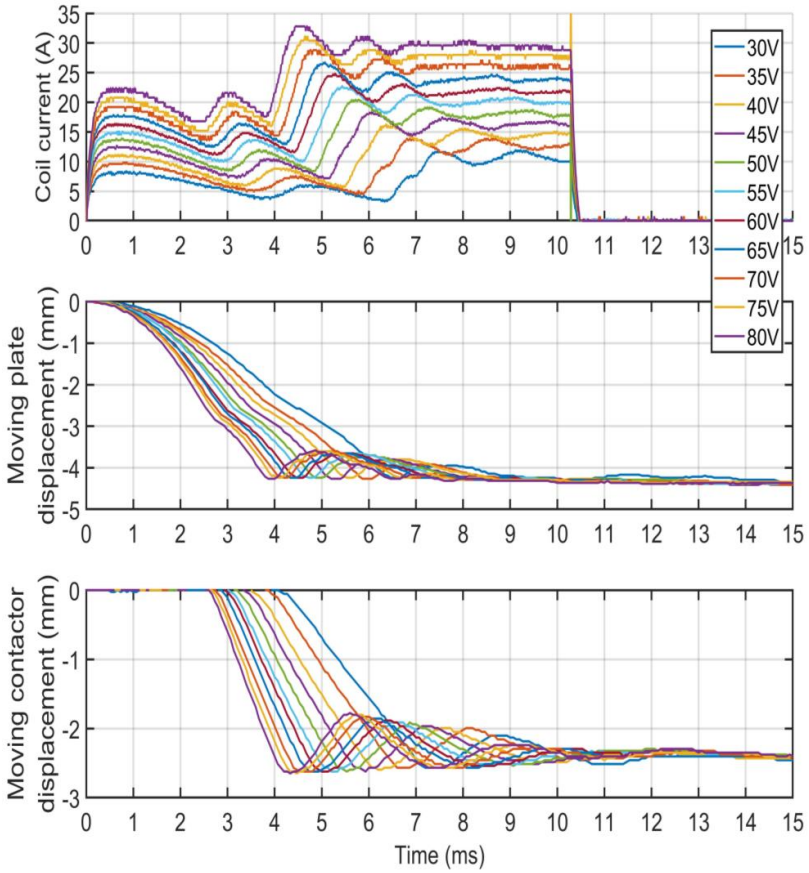
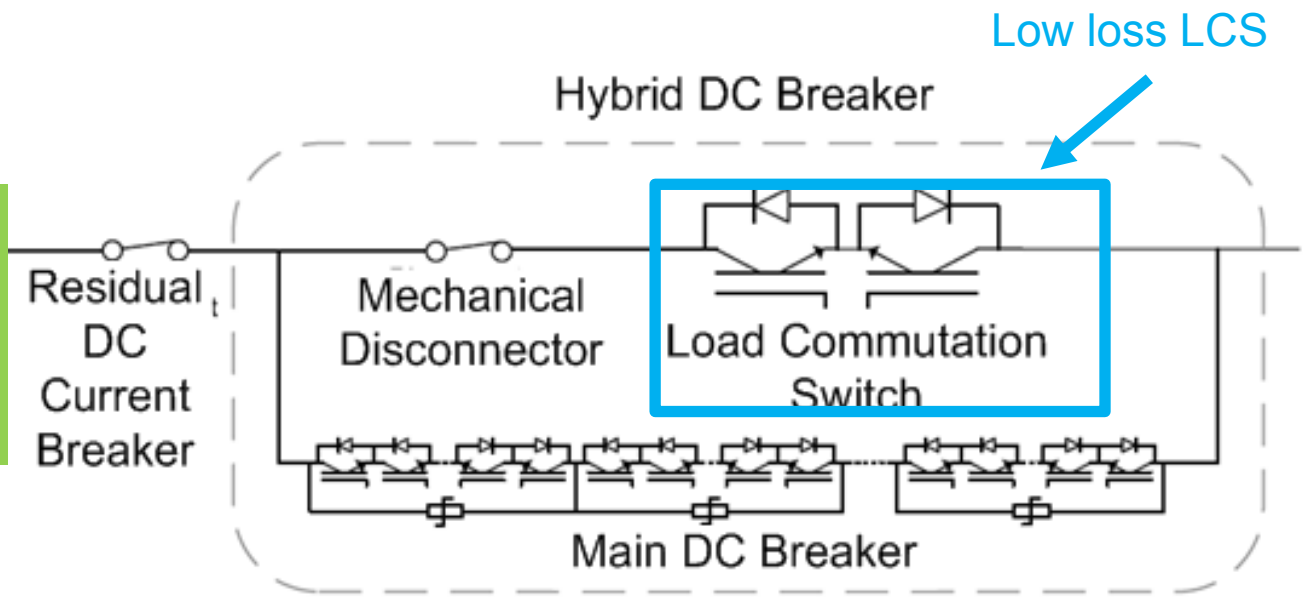


- Moving coil actuator opens the vacuum interrupt within 4 ms.

SFCL+HCB

SFCL



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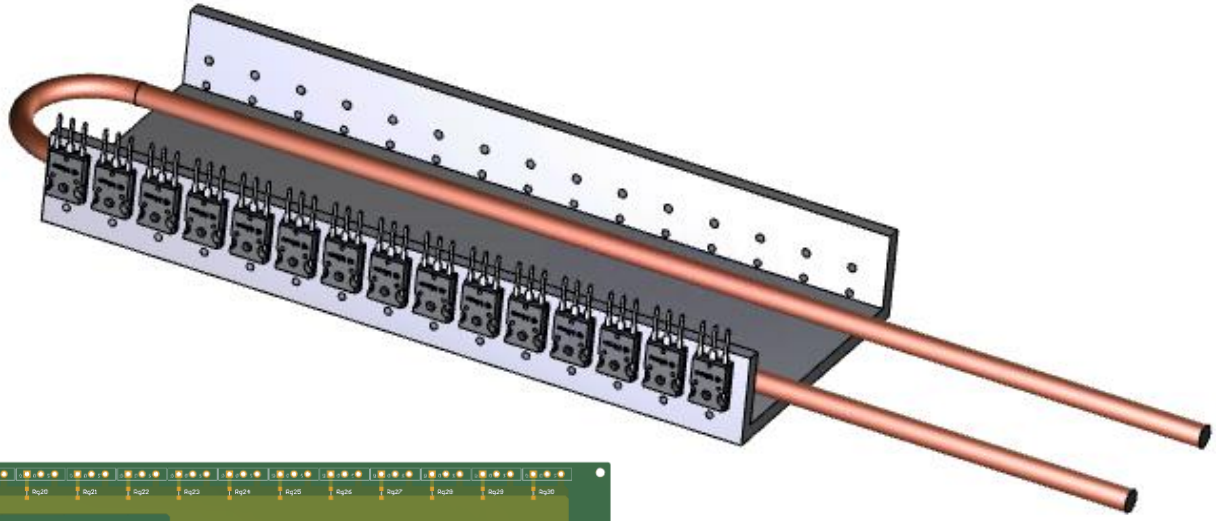
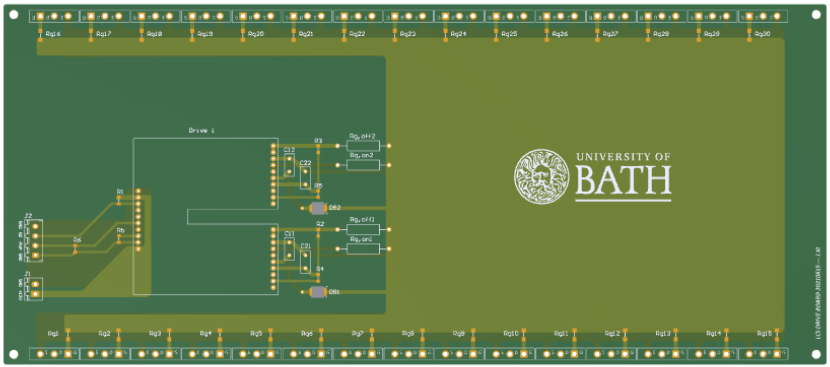
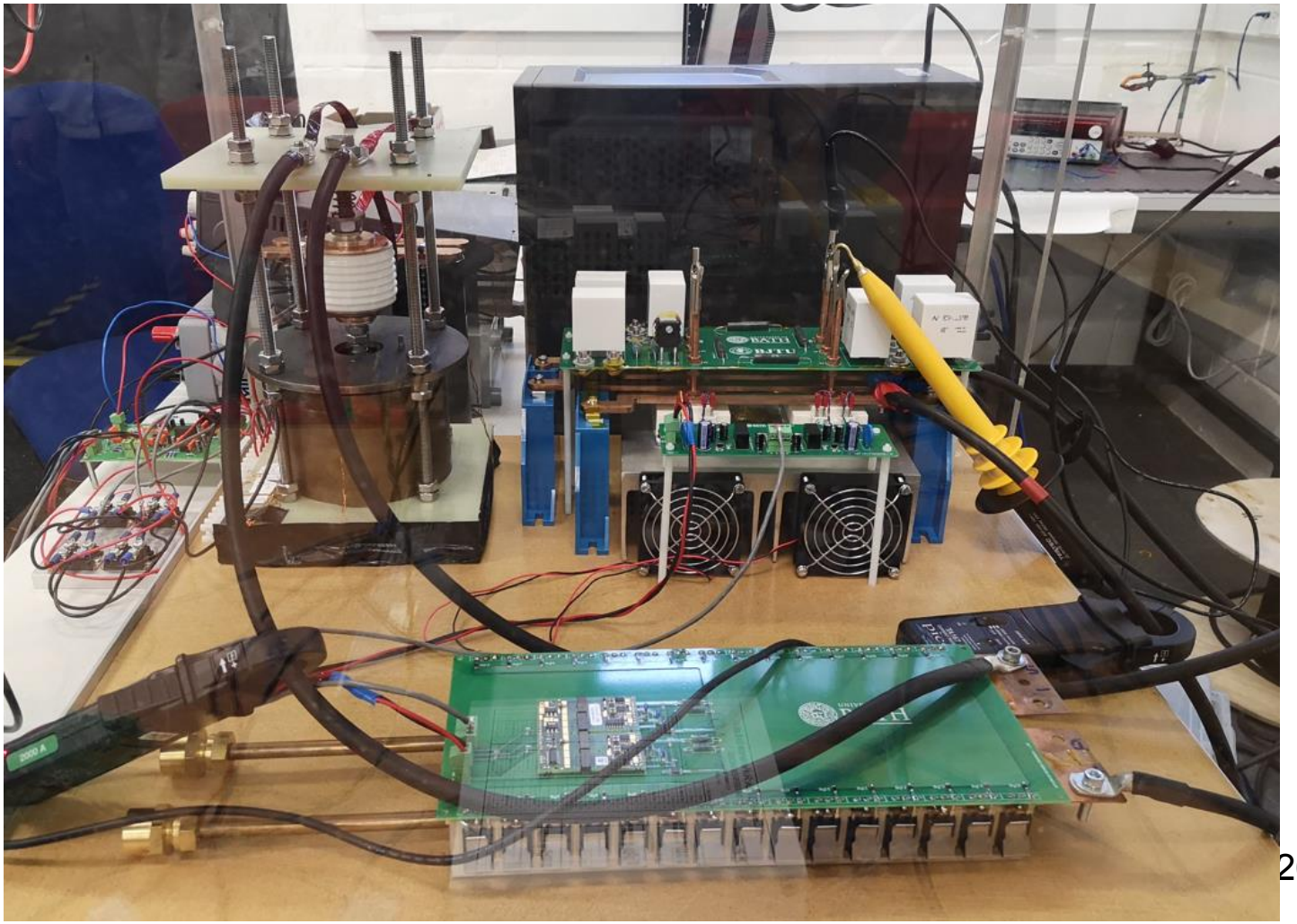
Load Commutation Switch

MosFETs on Coldplate

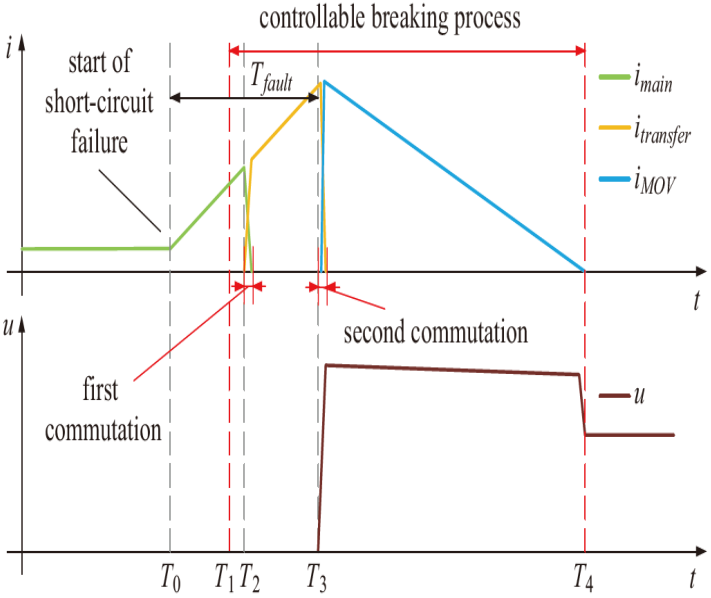




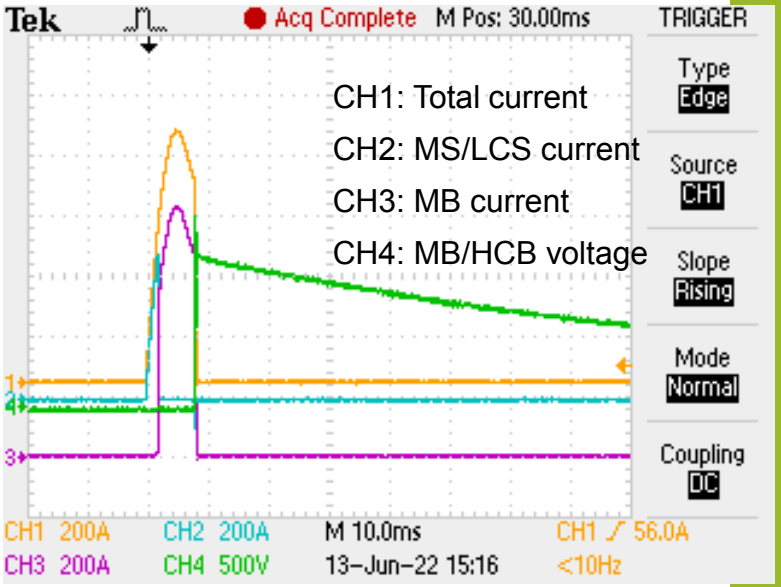
Hybrid DC circuit breaker



Hybrid DC circuit breaker



Hybrid DC circuit breaker interruption process



Experimental result

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

Summary

- Zero emission aircraft powered by hydrogen address the environment impact and also opens new opportunities for superconductivity technology.
- Superconductors offer high current density and high efficiency but also have many design challenges.
- 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.

Thank you!

Questions?

Dr Xiaoze PEI

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Centre for Sustainable Power Distribution