Superconducting Fault Current Limiters

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KIT-ENERGY CENTRE

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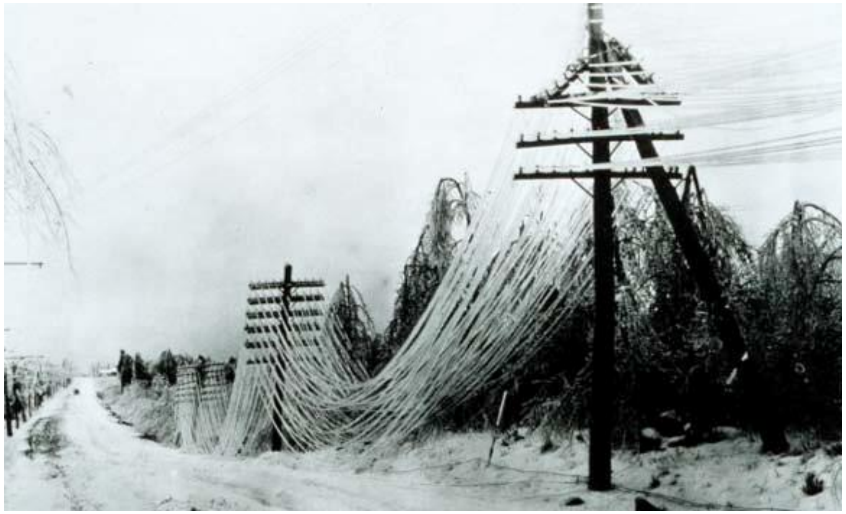
It is impossible to avoid short-cicuit currents



Superconducting Fault Current Limiters
Short-Circuit Limitation

Compromise in power systems

High short-circuit capacity
during normal operation
(low short-circuit impedance)

- Low voltage drops
  - High power quality
- High steady-state and transient stability
- Low system pertub[...]

Low short-circuit capacity
during fault conditions
(high short-circuit impedance)

- Low thermal and mechanical strain
- Reduced breaker capacity

Optimal solution
FCL/SCFCL

- Low impedance during normal operation
- Fast and effective current limitation
- Automatic and fast recovery

Conventional Measures to limit short-circuit currents

		Low Voltage < 1 kV	Medium Voltage	High Voltage > 100 kV
Topological measures	Introduction of a higher voltage level	applied	applied	applied
	Splitting of busbars	no	applied	applied
	Choose or upgrade to higher voltage	no	applied	applied
Apparatus measures	High impedance transformers	no	applied	applied
	Current limiting air coil reactors	applied	applied	applied
	Fuses	applied	applied	no
	I_S-Limiter	no	applied	no
	SCFCL	??	applied	yes

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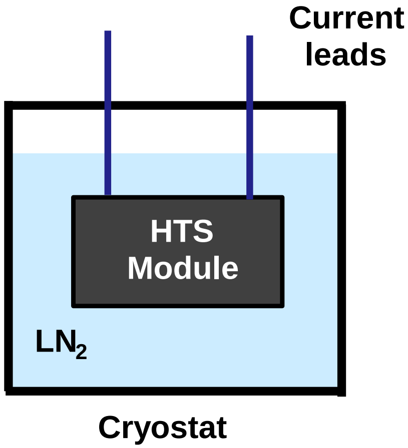
- Motivation
- **Basic Principles**
- Design Example
- State-of-the-Art
- Summary

- Your questions are welcome any time

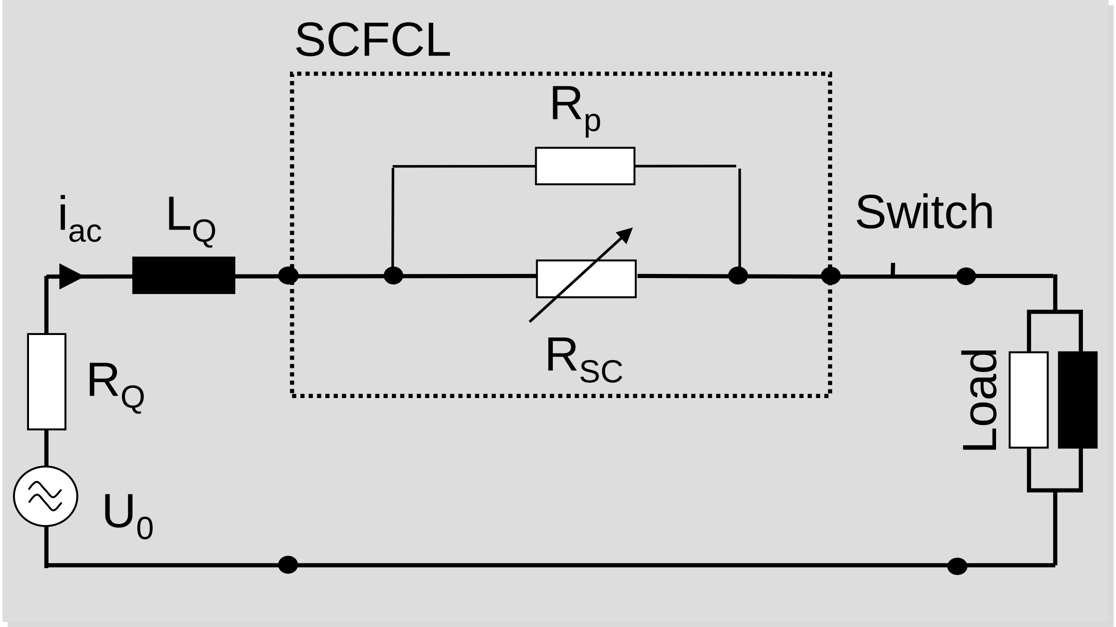
Superconducting Fault Current Limiters
Different types

Resistive type



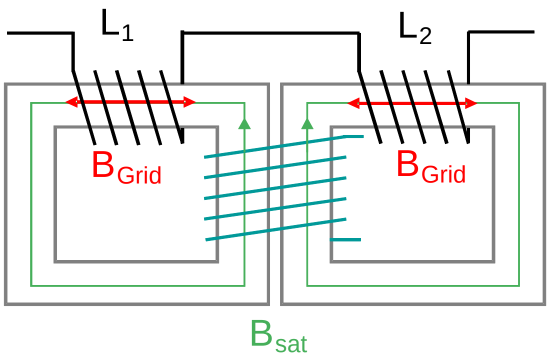
- ☺ Simple concept
- ☺ fail safe
- ☺ compact, low weight
- ☹ Current leads to low temp.

Electric circuit



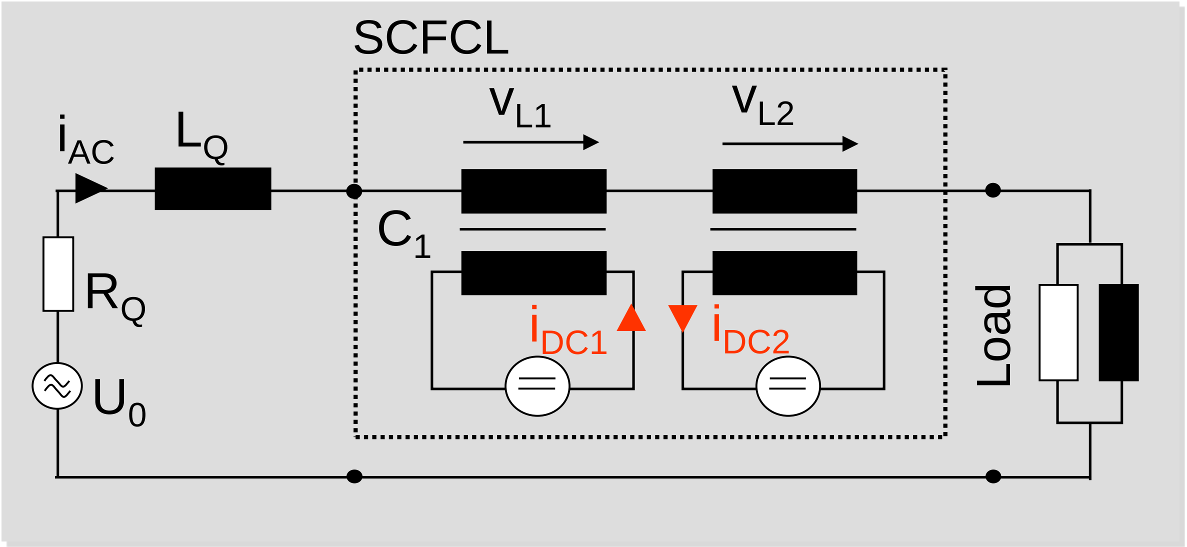
Superconducting Fault Current Limiters
Different types

DC biased iron core „saturated iron core“



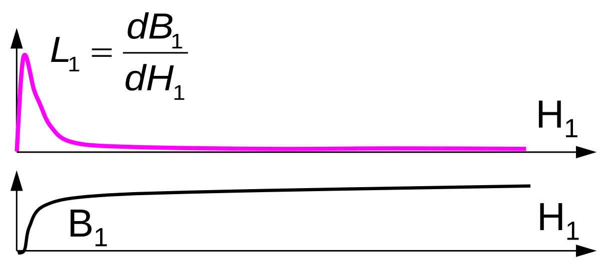
- ☺ no SC quench
- ☺ immediate recovery
- ☺ adjustable trigger current
- ☹ High volume and weight
- ☹ High impedance at normal op.

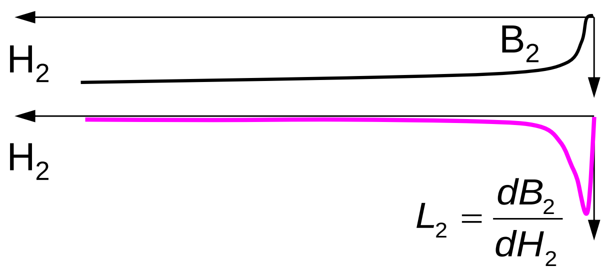
Electric circuit



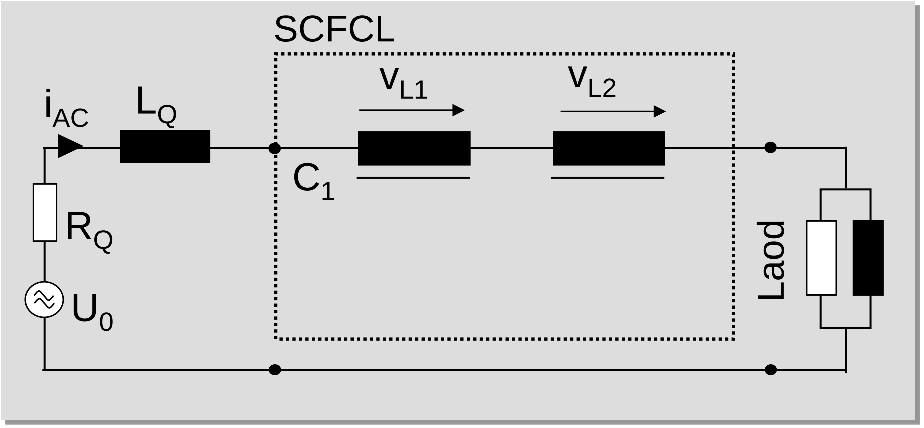
Superconducting Fault Current Limiters
DC biased iron core / Saturated Iron Core

Iron core characteristic



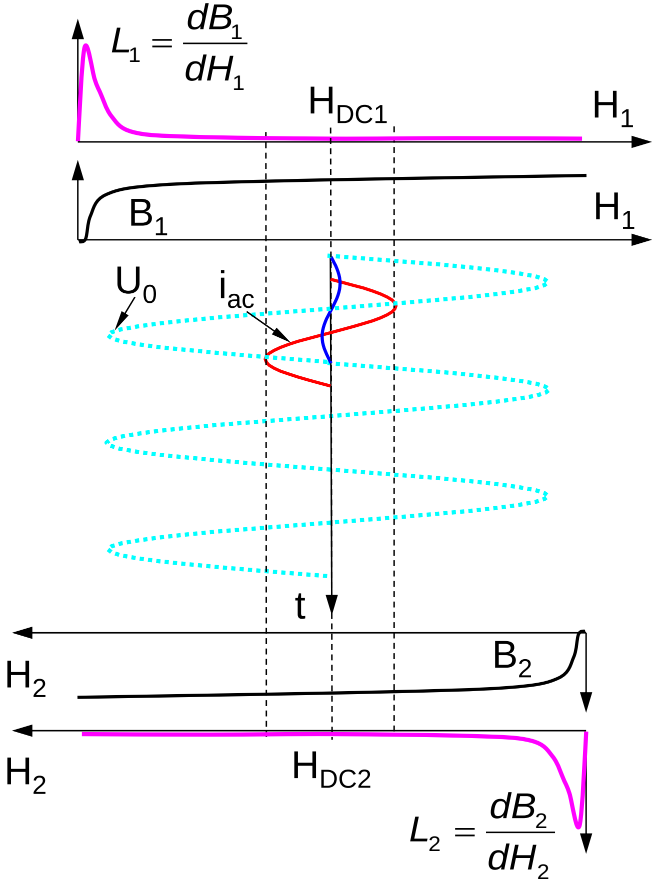


Electric circuit

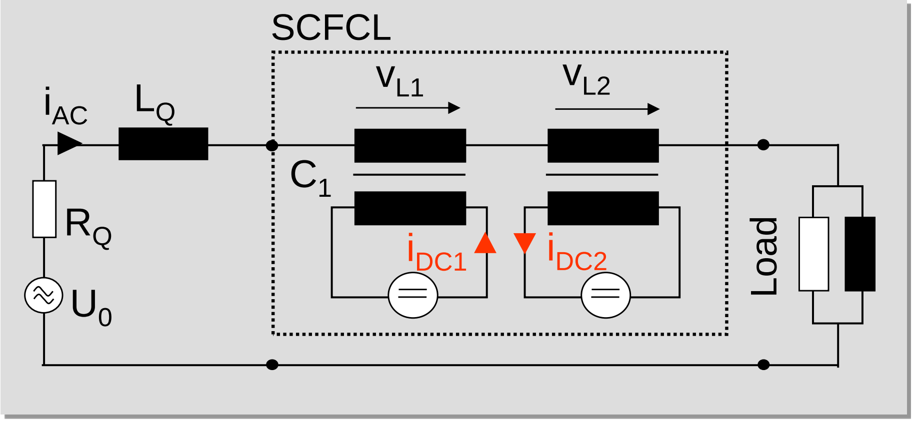


Superconducting Fault Current Limiters
DC biased iron core / Saturated Iron Core

Iron core characteristic

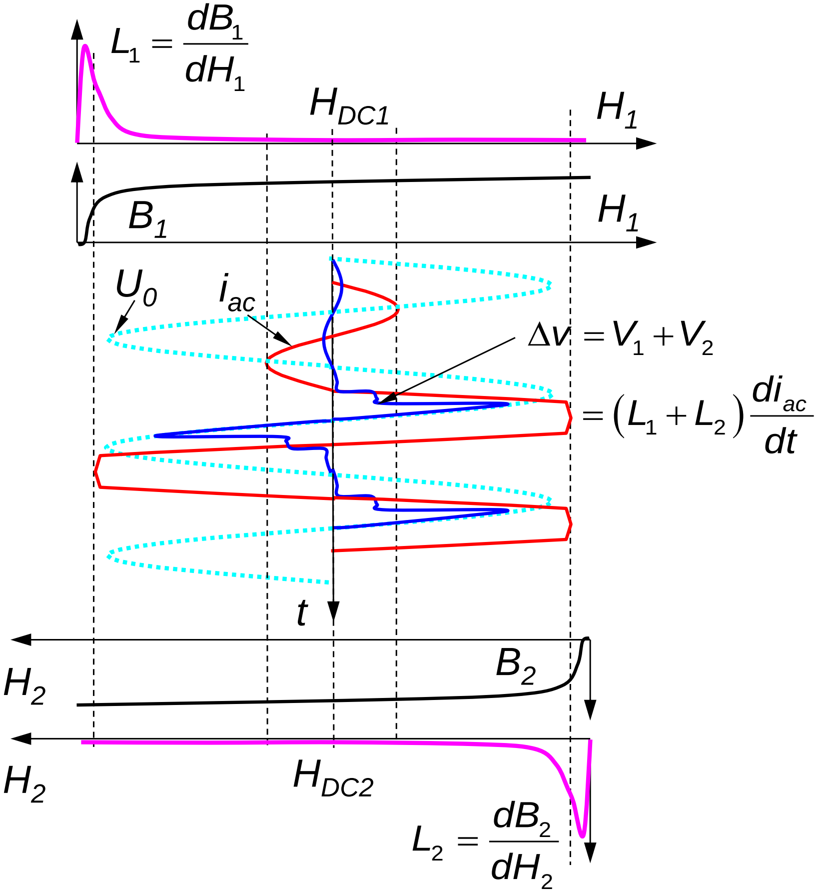


Electric circuit

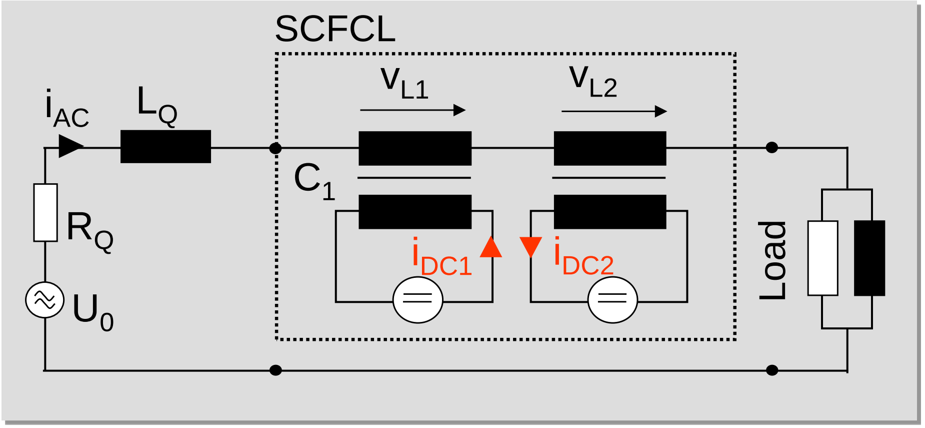


Superconducting Fault Current Limiters
DC biased iron core / Saturated Iron Core

Iron core characteristic

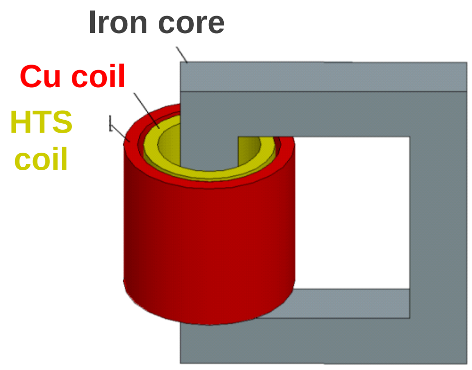


Electric circuit



Superconducting Fault Current Limiters
Different types

Shielded iron core
„Inductive“



☺ No current leads to low temp.

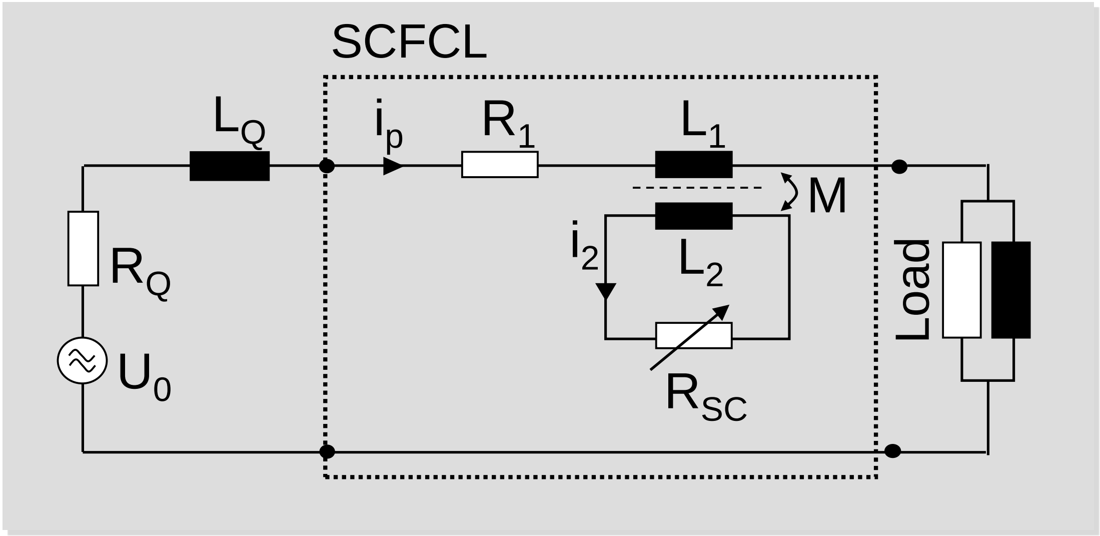
☺ Fail safe

☹ High volume

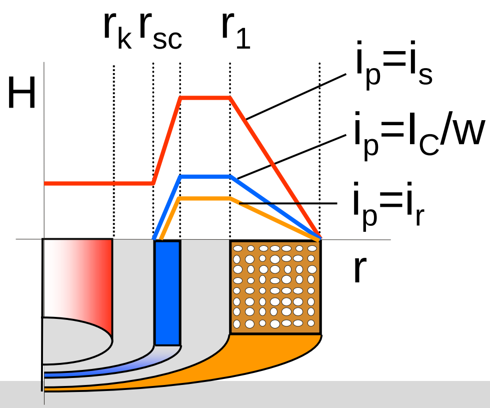
☹ High weight

and many more…

Electric scheme



Magnetic field



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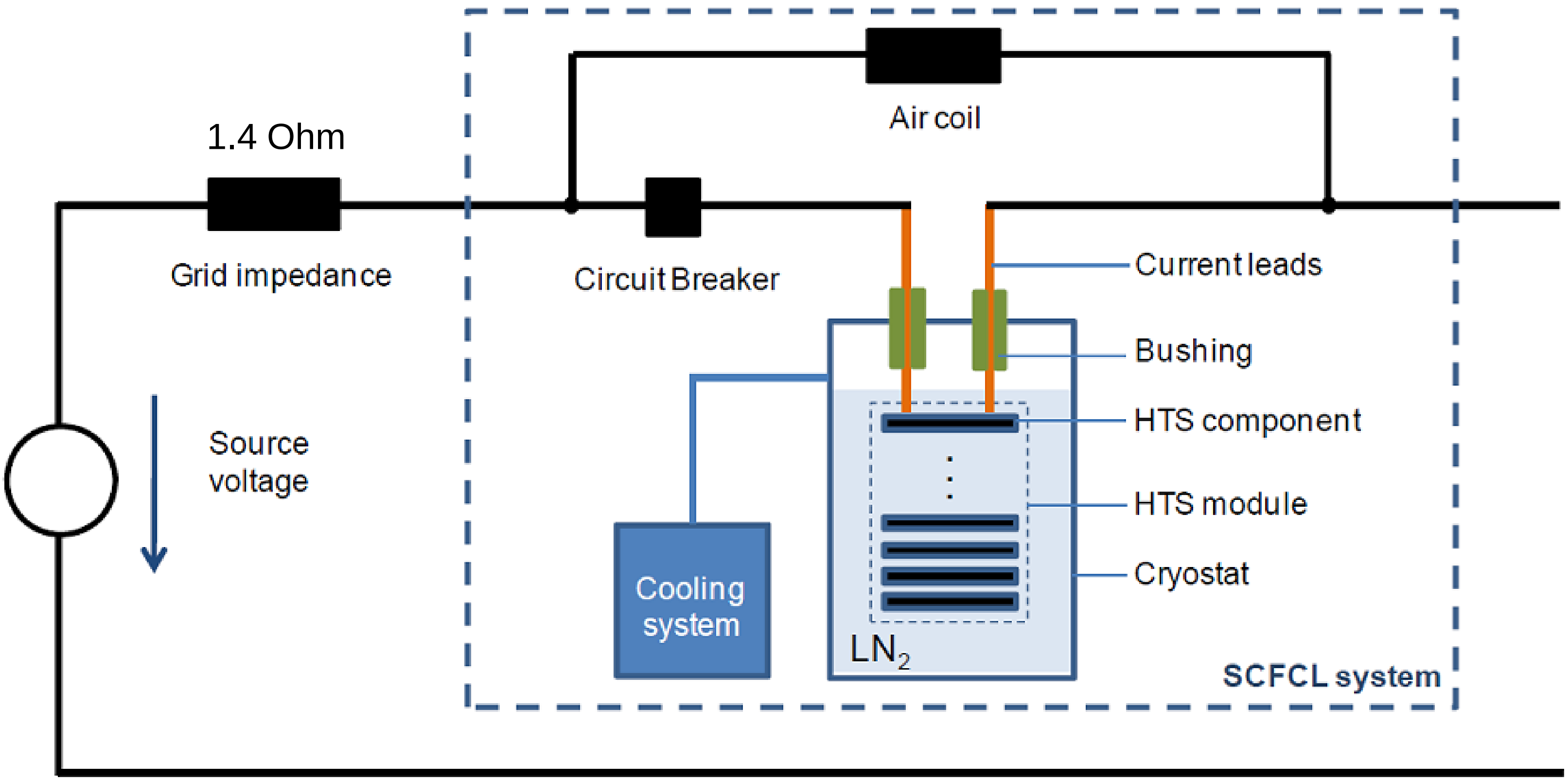
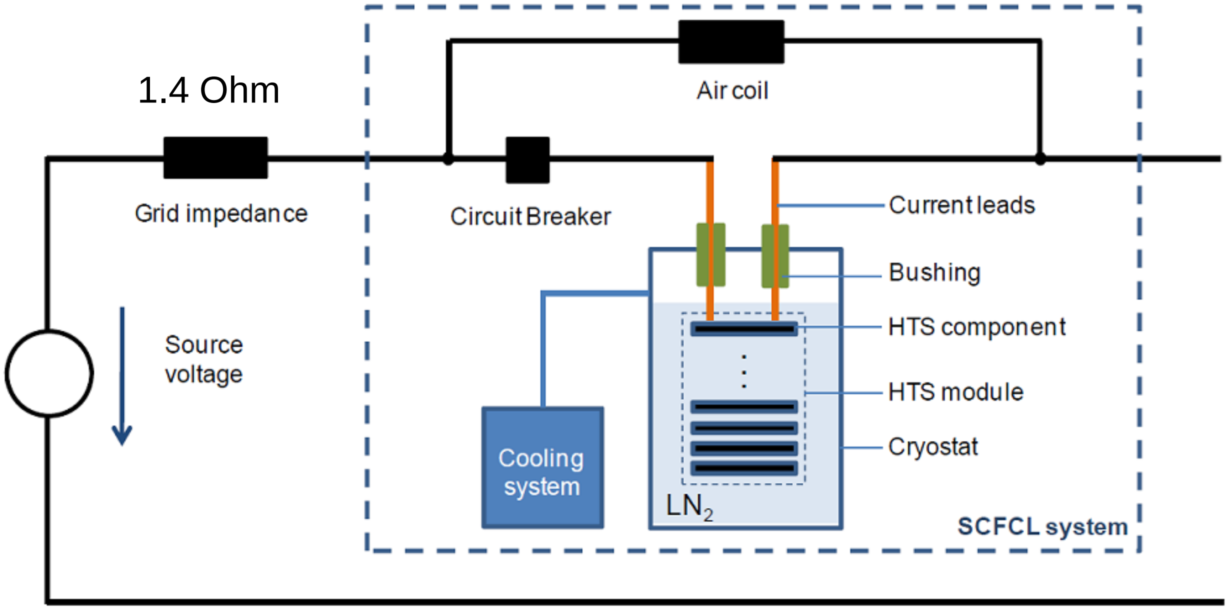
Superconducting Fault Current Limiters
How to design a resistive fault current limiter?

Karlsruher Institut für Technologie



Source: Noe, M, Hobl, A, Tixador, P, Martini, L, Dutoit, B,Conceptual design of a 24 kV, 1 kA resistive superconducting fault current limiter, IEEE Transactions on Applied Superconductivity, 22, 3, 5600304-5600304, 2012

Superconducting Fault Current Limiters
How to design a resistive fault current limiter?



Nominal voltage	24 kV
Nominal current	1005 A
AC withstand voltage	50 kV
Lightning impulse	125 kV
Max. prospective current (peak)	10.8 kA
Limitation time	120 ms
Max. short-circuit current cont. (RMS)	4 kA
Recovery time	< 30 s

Superconducting fault current limiters
How much superconducting wire is needed?

How many tapes in parallel?

$$n_p \geq \frac{\sqrt{2} I_r}{I_c} = \frac{1.414 \cdot 1005A}{275A} = 5.16$$

Assumption 2011 for 10mm wide YBCO tape at 77K, sf

What is the total tape length?

1) What is the total voltage along the tape during limiation?

$$U_{\mathrm{lim},RMS} = \frac{24kV}{\sqrt{3}} - 4kA\ 1.4\Omega = 8.25kV$$

2) Do not overheat the tape during limitation?

For a electrical field of 0,43 V/cm the temperature during limitation time of 120 ms can be kept below 360 K.

$$l_{SC} = 190m \cdot 6 \cdot 3 = 3420m$$

Superconducting fault current limiters
Which configuration for the HTS?

A	B	C	D
Straight line	Bifilar straight	Monofilar coil	Bifilar coil

Superconducting fault current limiters
How to calculate the total loss?

Current lead loss?

45 W/kA for uncooled and optimized copper current lead from 300 K to 77 K

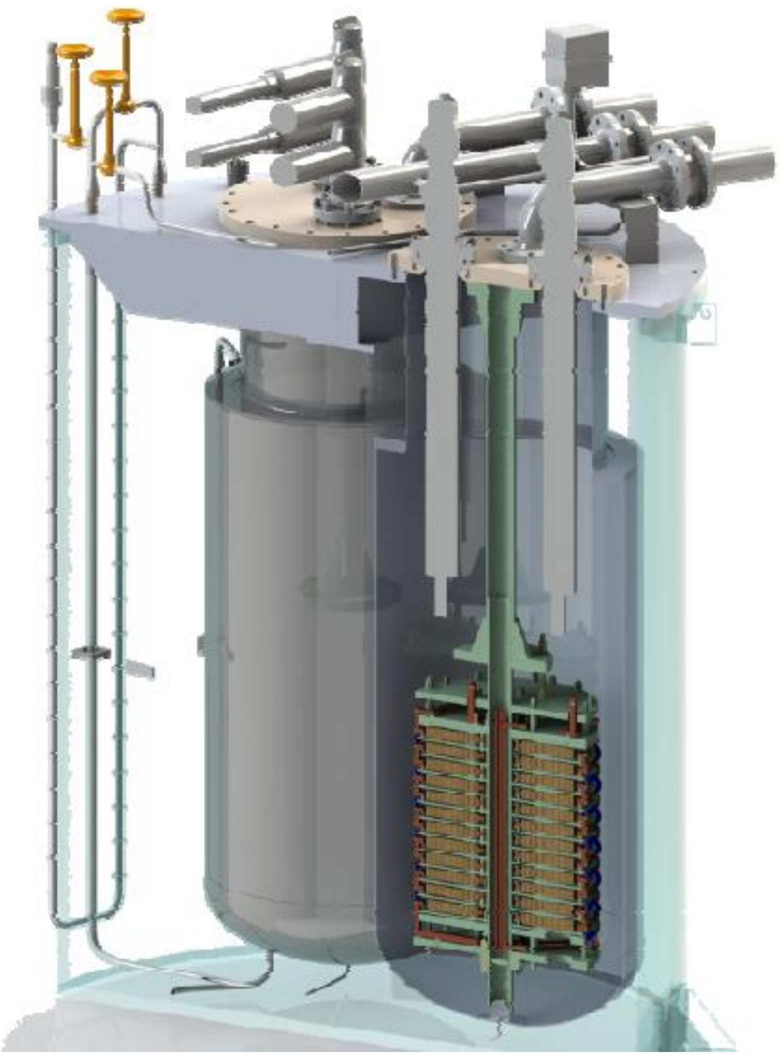
45 W/kA * 1 kA *6=270 W at nominal current

Superconducting fault current limiters
How to calculate the total loss?

Loss of the cyrostat?

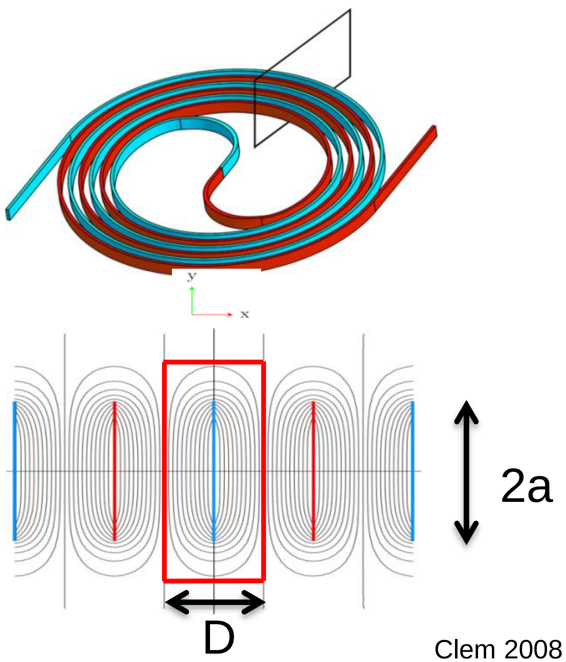
P=120 W

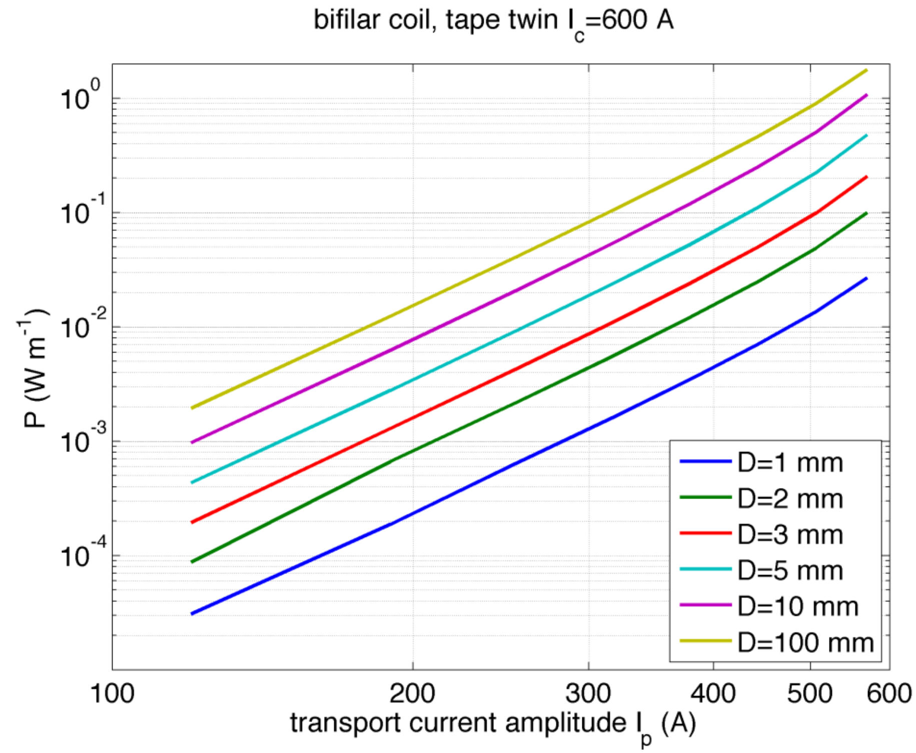
Three LN2 vessels in one vacuum vessel.



Superconducting fault current limiters
How to calculate the total loss?

AC loss of the superconductor?





Clem 2008 PRB **77** 134506

$$P = f \mu_0 I_c^2 \left[\frac{2}{\pi a^2} \int_c^a (a-x) \tanh^{-1} \sqrt{\frac{\sinh^2 \frac{\pi x}{D} - \sinh^2 \frac{\pi c}{D}}{\sinh^2 \frac{\pi a}{D} - \sinh^2 \frac{\pi c}{D}}}\, dx + \frac{d}{12a} \left\{ 1 - \frac{c}{a} + \frac{8}{\pi^3 a} \int_0^c \tan^{-1} \sqrt{\frac{\sinh^2 \frac{\pi a}{D} - \sinh^2 \frac{\pi c}{D}}{\sinh^2 \frac{\pi c}{D} - \sinh^2 \frac{\pi x}{D}}}\, dx \right\} \right]$$

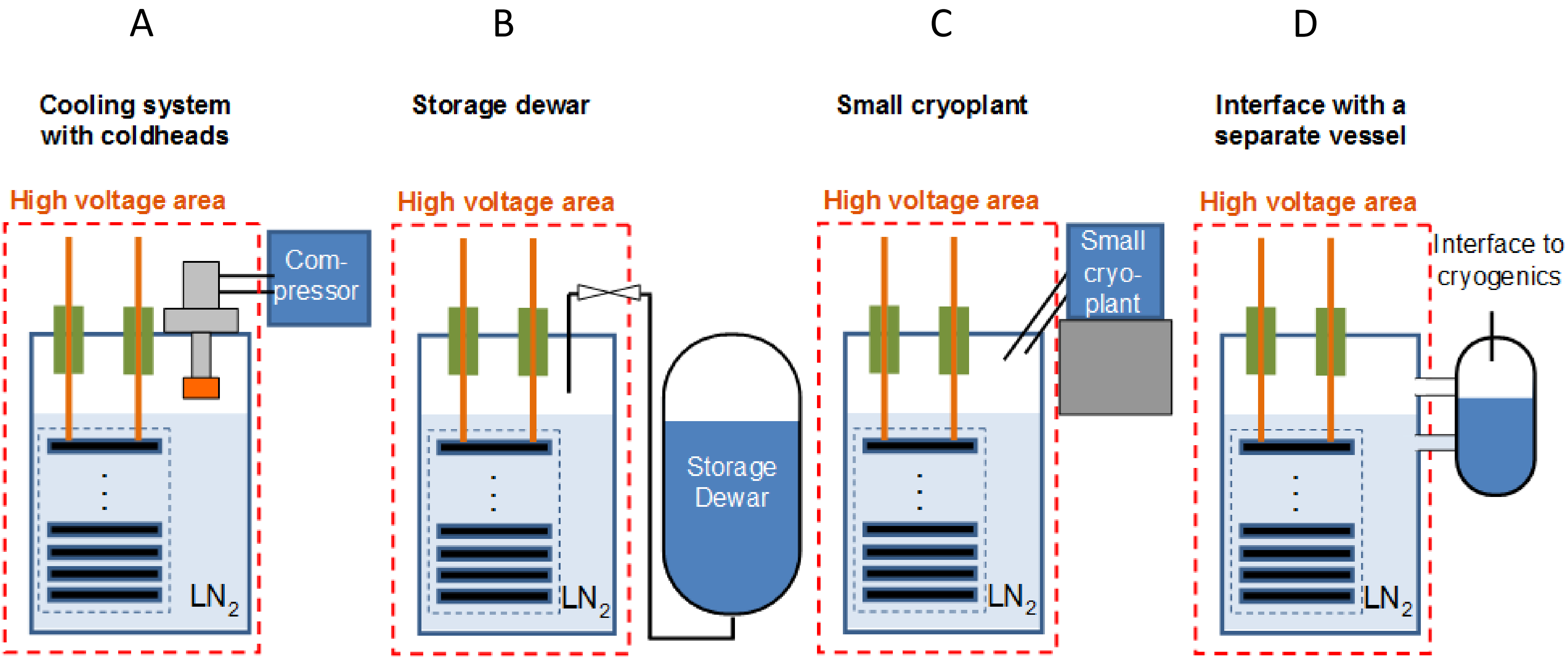
Superconducting fault current limiters
How to calculate the total loss?

Summary of total loss

Loss contribution	Loss at 0.1 I_c	Loss at 0.5 I_c	Loss at 1 I_c
Max. superconductor AC loss [1)]	< 1 W	~ 10 W	150 W
Max. current lead loss [2)]	180 W	~ 220 W	270 W
Cryostat loss [3)]	120 W	120 W	120 W
Max. additional loss [4)]	1 W	15 W	60 W
Max. total loss at 77 K	**~ 300 W**	**~ 365 W**	**600 W**
Max. electric power at RT[5)]	**~ 6990 W**	**8504 W**	**13980 W**

1) According to AC Loss report [2.1.1] Ic=300 A, L=3.4 km
2) Specific current lead loss 45 W/kA [2.6.4]
3) According to Cryostat Design [2.4.1]
4) HTS-Copper-0.5µΩ•12•2/3=4µΩ, Copper connections-2µΩ•12•2/3=16µΩ
5) GM Cryocooler efficiency (GM600) 1/23.3

Superconducting fault current limiters
Which cooling option?



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- Your questions are welcome any time

Superconducting fault current limiters
Major projects on resistive type SFCL

Lead Company	Year/Country [1)]	Data [2)]	Phase	Superconductor
ACCEL/NexansSC	D / ´04	12 kV, 600 A	3-ph.✓	Bi 2212 bulk
CESI RICERCA	Italy / ´05	3.2 kV, 220 A	3-ph.	Bi 2223 tape
Siemens / AMSC	D / USA / ´07	7.5 kV, 300 A	1-ph.	YBCO tape
LSIS	Korea /’07	24 kV, 630A	3-ph.	YBCO tape
Hyundai / AMSC	Korea / ´07	13.2 kV, 630 A	1-ph.	YBCO tape
KEPRI	Korea / ´07	22.9 kV, 630 A	3-ph.	Bi 2212 bulk
Toshiba	J / 2008	6.6 kV, 72 A	3-ph.✓	YBCO tape
Nexans SC	D / 2009	12 kV, 100 A	3-ph.✓	Bi 2212 bulk
Nexans SC	D / 2009	12 kV, 800 A	3-ph.✓	Bi 2212 bulk
RSE	I / 2011	9 kV, 250 A	3-ph.✓	Bi 2223 tape
RSE	I / 2012	9 kV, 1 kA	3-ph.✓	YBCO tape
KEPRI	Korea / 2011	22.9 kV, 3 kA	3-ph.✓	YBCO tape
Nexans SC	D / 2011	12 kV, 800 A	3-ph.✓	YBCO tape
AMSC / Siemens	USA / D / 2012	115 kV, 1.2 kA	3-ph.✓	YBCO tape
Rolls Royce	UK / -	11.5 kV, 400 A	3-ph.	MgB_2 wire
Nexans SC	D/2013	10 kV, 2.4 kA	3-ph. ✓	YBCO tape
Nexans SC	EU 2013	24 kV, 1 kA	3-ph. ✓	YBCO tape
Applied Materiaks	US /2013	15 kV / 1kA	3-ph. ✓	YBCO tape
Nexans SC	UK/2015	12 kV/1.6 kA	3-ph. ✓	YBCO tape
Applied Materials	US / 2016	115 kV	3-ph. ✓	YBCO tape

Plus more Projects in Russia, China, India

Superconducting Fault Current Limiters
State-of-the-Art

Nexans

Resistive type, YBCO
12 kV, 1600 A
Installed 11/2015

Siemens

Resistive type, YBCO
12 kV, 815 A
Installed 3/2016

Applied Materials

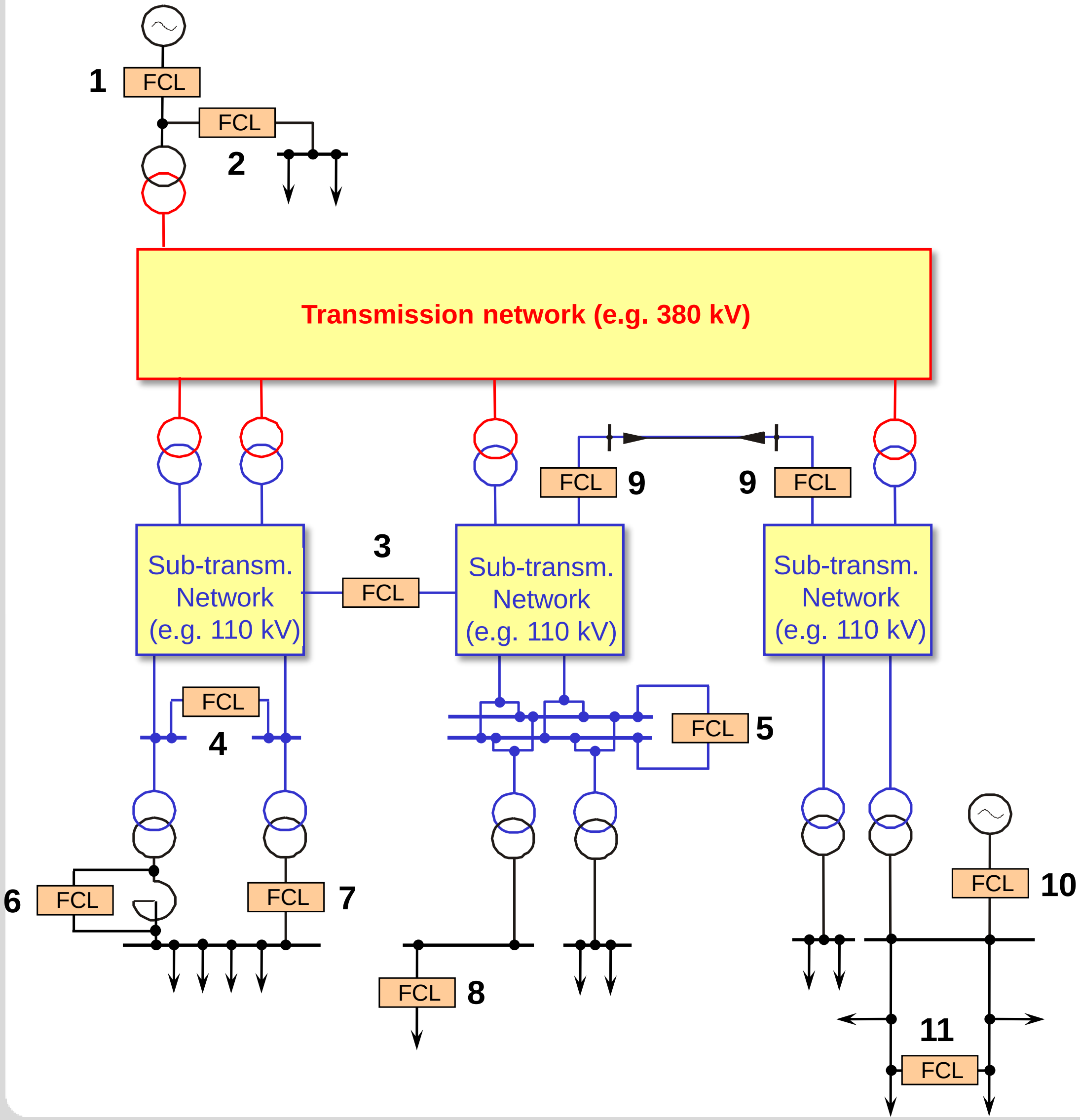
Resistive type, YBCO
115 kV, 550 A
Installed 7/2016

Superconducting fault current limiters
Recent installation

12 kV, 1600 A resistive FCL installed in busbar at Western Power Distribution, Chester Street, Birmingham, since End 2015

Quelle: Nexans

Superconducting fault current limiters
Applications



1 Generator feeder

2 Power station auxiliaries

3 Network coupling

4,5 Bus tie

6 Shunting current limiting reactor

7 Transformer feeder

8 Outgoing feeder

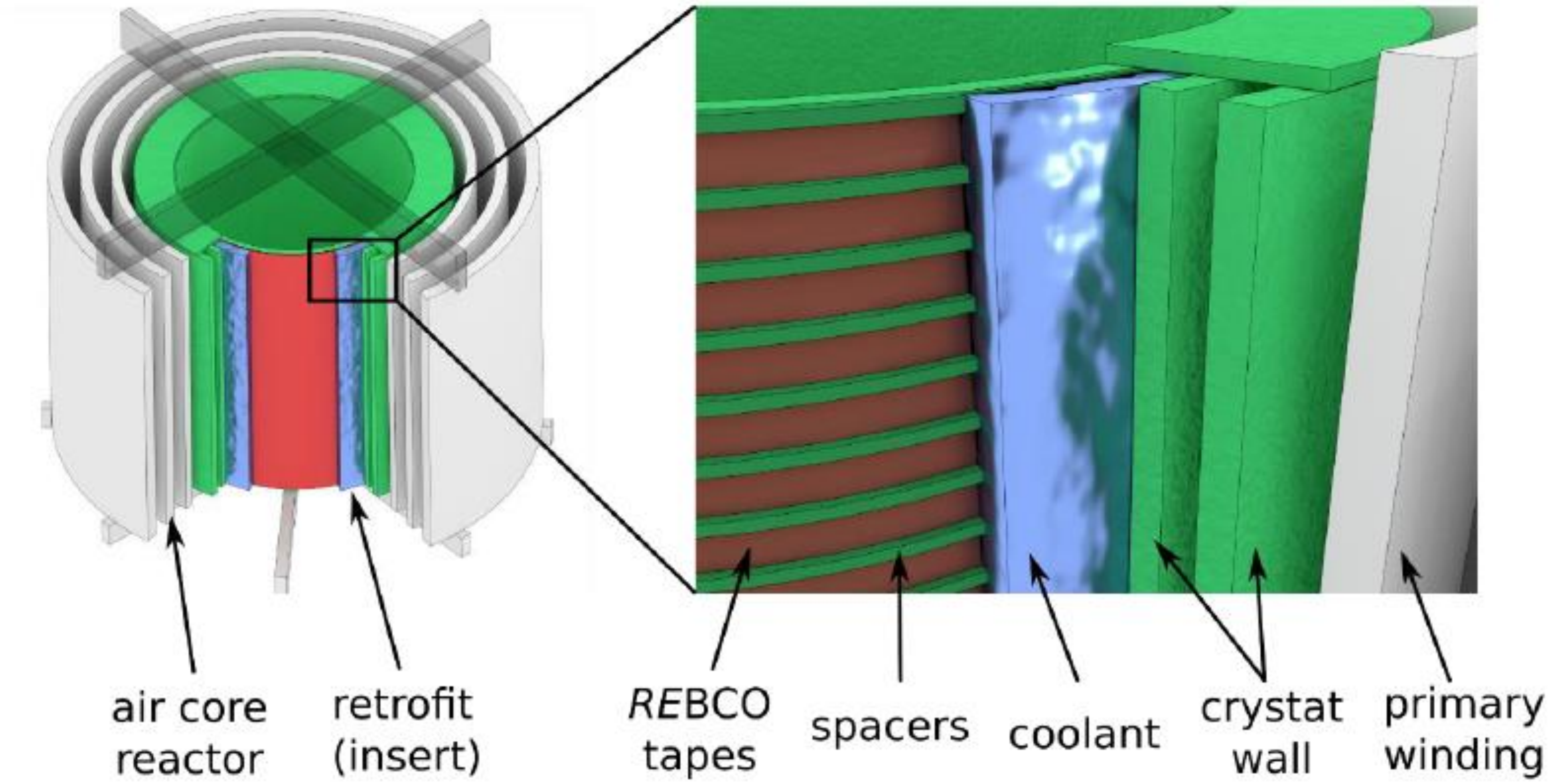
9 Combination with SC cables

10 Coupling local generating units

11 Closing ring circuits

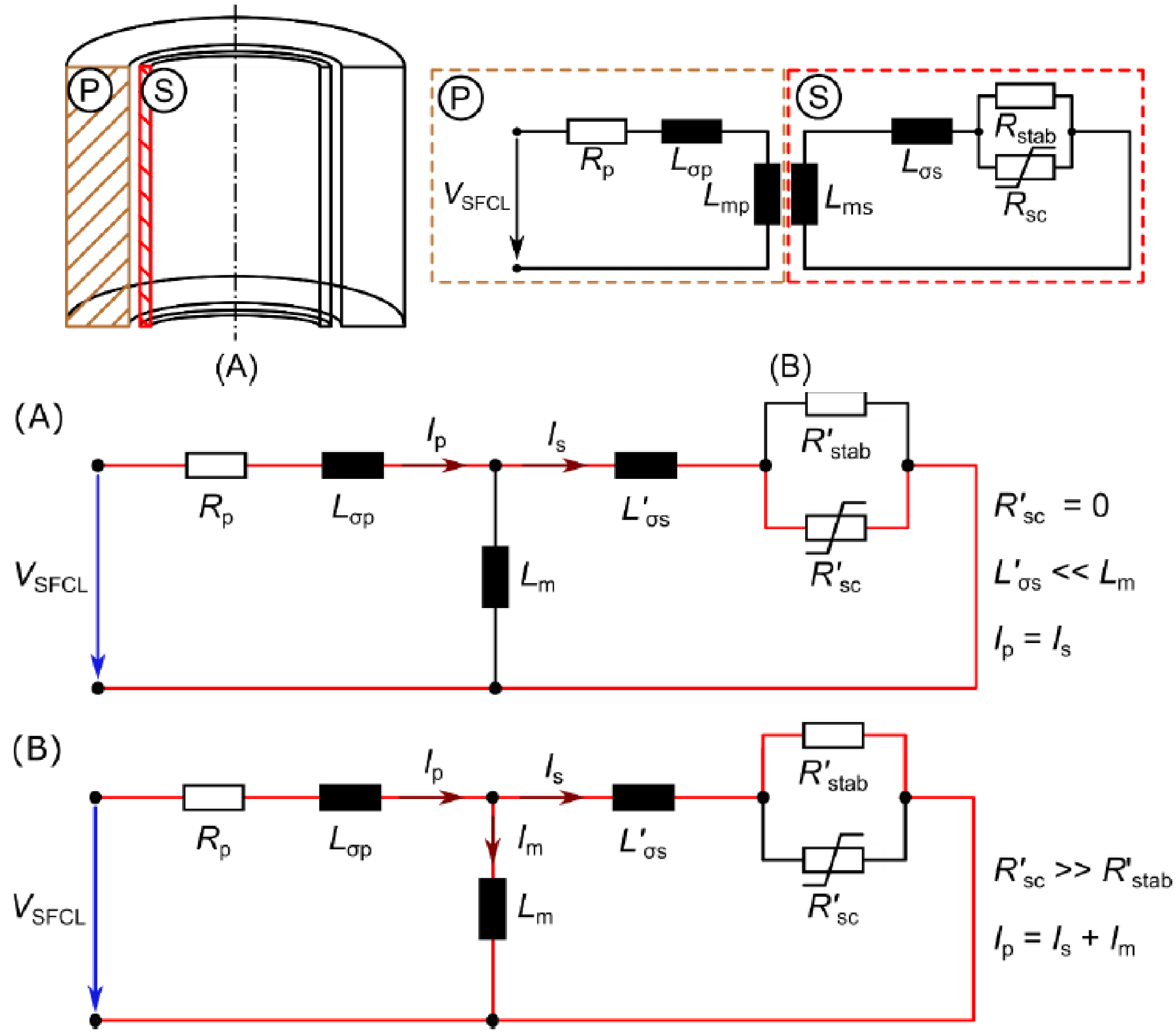
Source:
Noe, M.; Oswald, B.R., "Technical and economical benefits of superconducting fault current limiters in power systems", IEEE Trans. Appl. Supercon. Vol. 9/2, June 1999, pp. 1347 –1350

Superconducting Air Core Fault Current Limiters
R&D Example



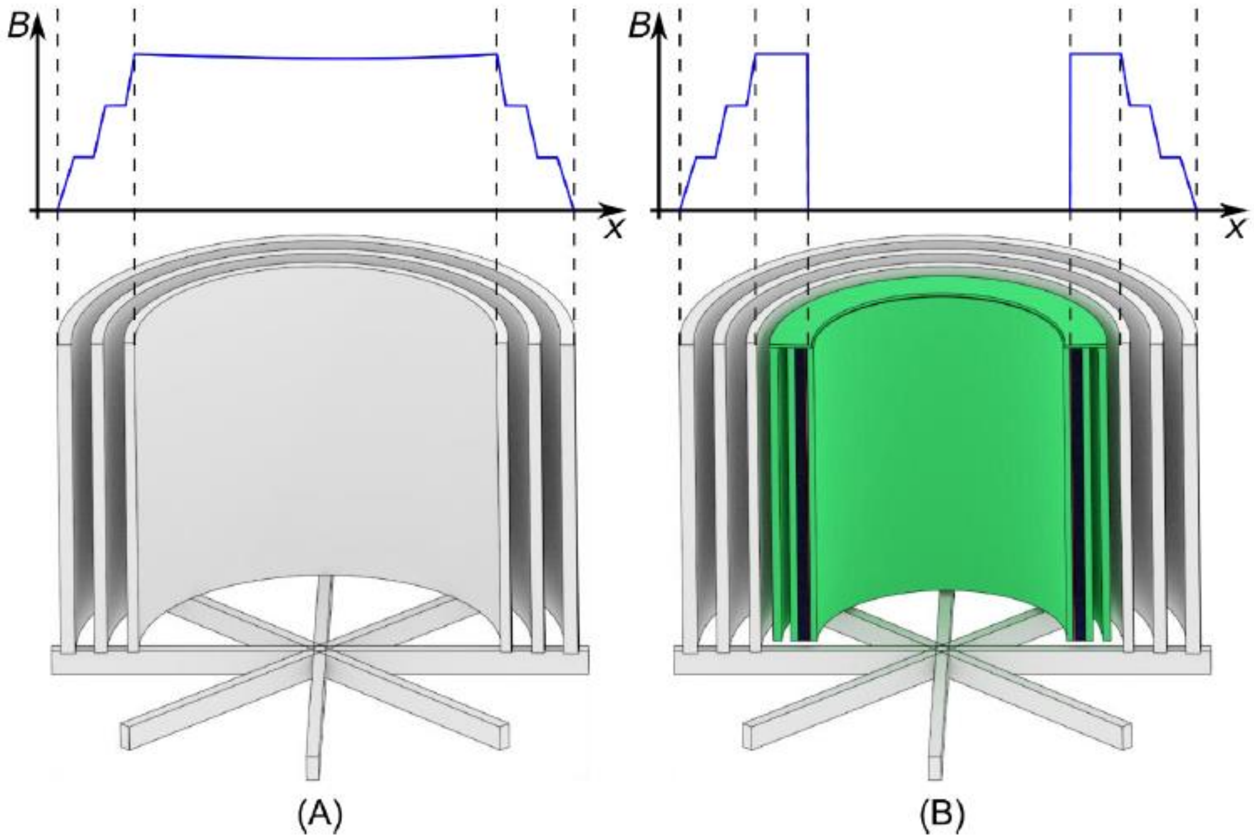
Superconducting Air Core Fault Current Limiters
R&D Example

Electrical Equivalent Circuit



Superconducting Air Core Fault Current Limiters
R&D Example

Magnetic field distribution in case of (A) the air core reactor and (B) the AC-SFCL during normal operation



Superconducting Air Core Fault Current Limiters R&D Example

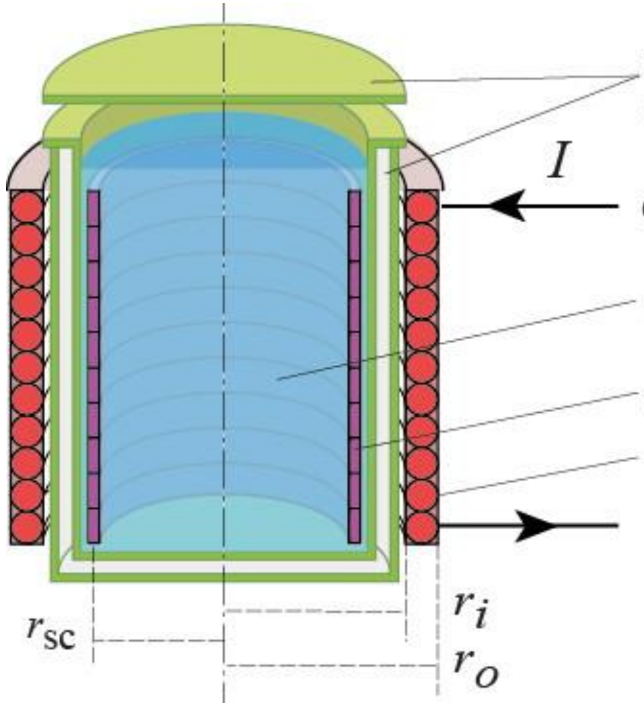
Karlsruher Institut für Technologie

Objectives

Built and test a single phase 10 kV, 600 A air coil SFCL

Project partners

Siemens, KIT



Projektträger Jülich
Forschungszentrum Jülich

Supported by:

Federal Ministry of Economics and Technology

on the basis of a decision by the German Bundestag

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Superconducting Fault Current Limiters
Research Directions

- Develop compact and inexpensive medium voltage SCFCLs
- Develop high voltage SCFCL prototypes and first field installations
- Demonstrate and improve reliability with long term tests
- Develop tests standards
    - IEEE test guide for FCLs available
- Show value proposition and „educate costumer“

Some manufacturers offer commercial applications.

Status of Superconducting Fault Current Limiters

- Successful field installations up to 220 kV for different types.
- A few companies started to offer first products.
- An IEEE test guide has been published.