Building the Grid of Tomorrow:

Superconducting Paths to Efficiency and Reliability

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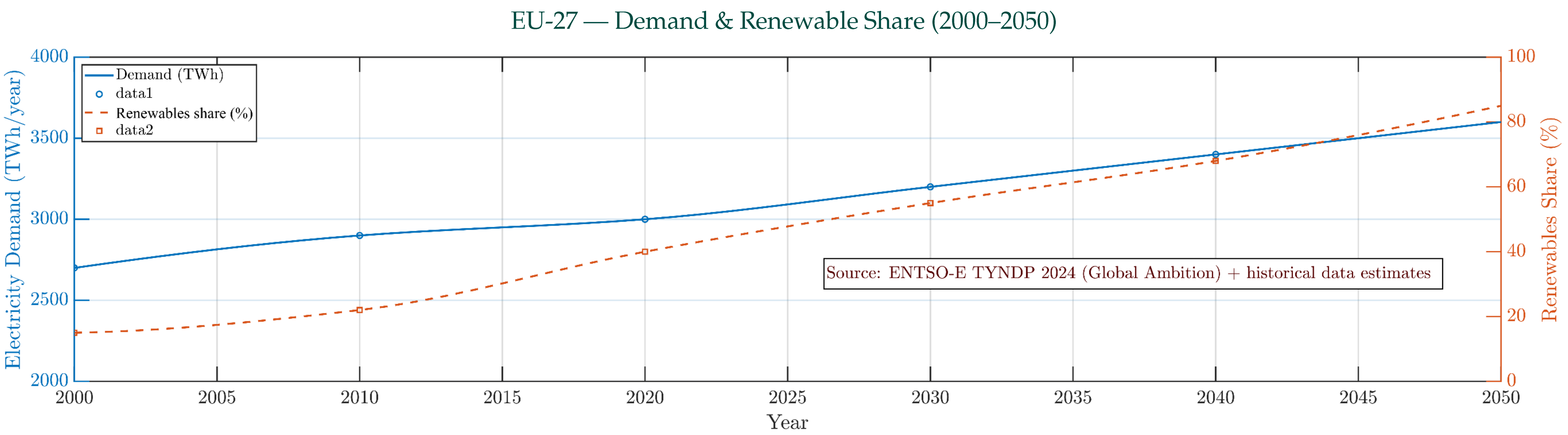
The Future Grid Challenge

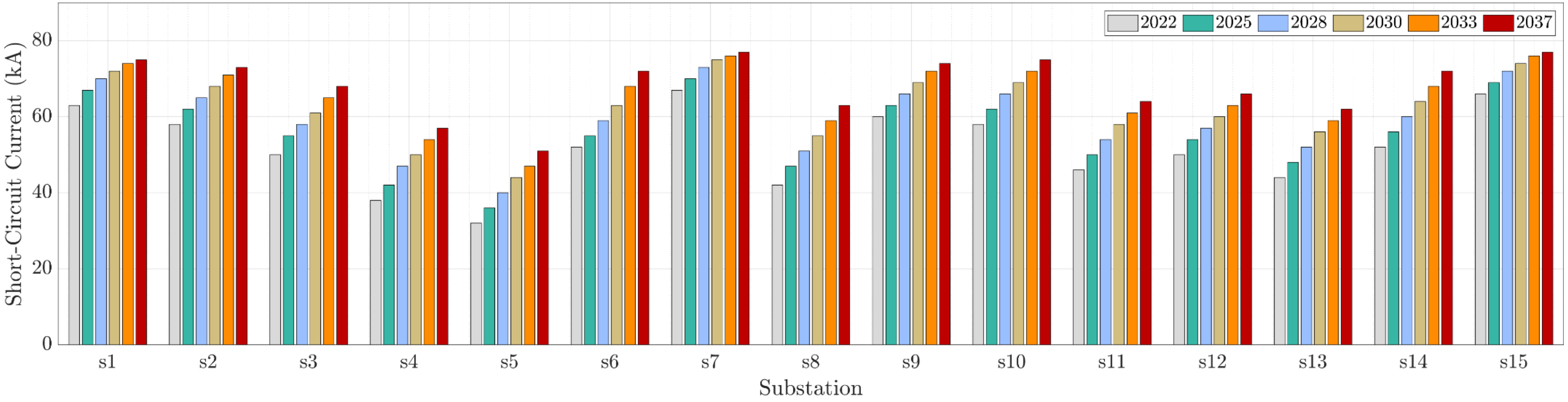
- The growing shift toward renewable energy requires the transmission of significantly larger amounts of electrical power to urban centers.
- Existing power grids, many of which were designed and installed over 50 years ago, are increasingly strained by modern energy demands. The electrification of transport, industry, and heating is accelerating;



The Future Grid Challenge

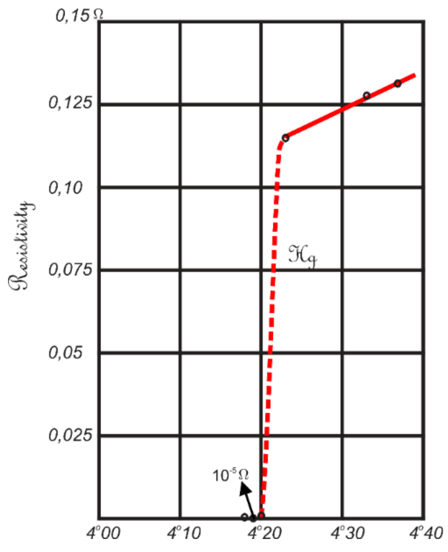
- Upgrading these aging infrastructures to accommodate high power transmission presents substantial technical and economic challenges.
  - Transmission losses ~5–10% → wasted energy and higher costs.
  - Urban space constraints make conventional reinforcements often impractical.
  - Grid upgrades are costly and slow.
  - **Rising fault currents threaten equipment safety.**

Forecasted development of fault current levels in the German high-voltage grid



Superconductivity?

- **Zero electrical resistance below a critical temperature**
  - near-zero losses.
  - High current density
    - Copper → 1.2 to 2 A / mm²
    - High Temperature Superconductor → **> 1000 A** / mm²
      - This enables compact, high-capacity components.



08.04.1911

…Kwik nagenoeg nul…

(Resistance of mercury practicaly zero)

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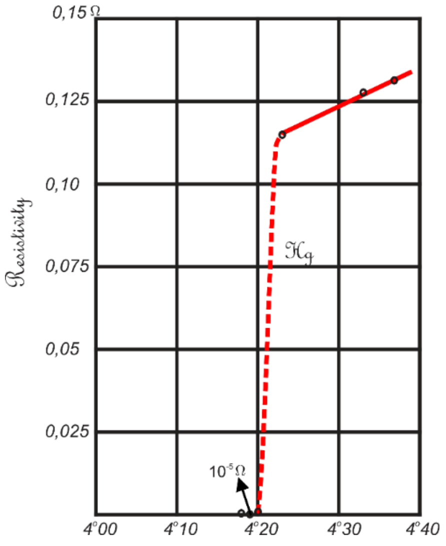
- **Meissner-Ochsenfel Effect**
  - Magnetic Shielding



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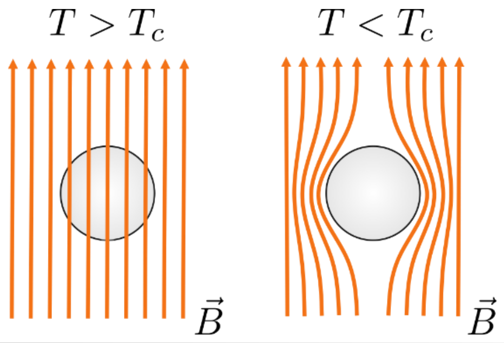

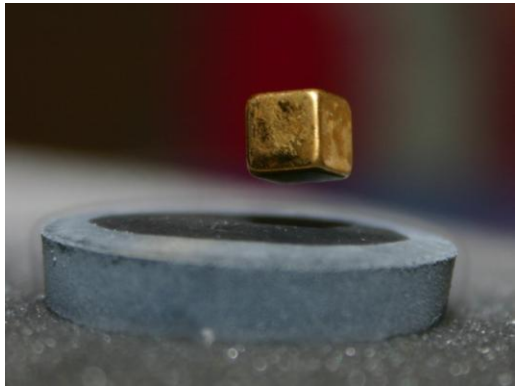

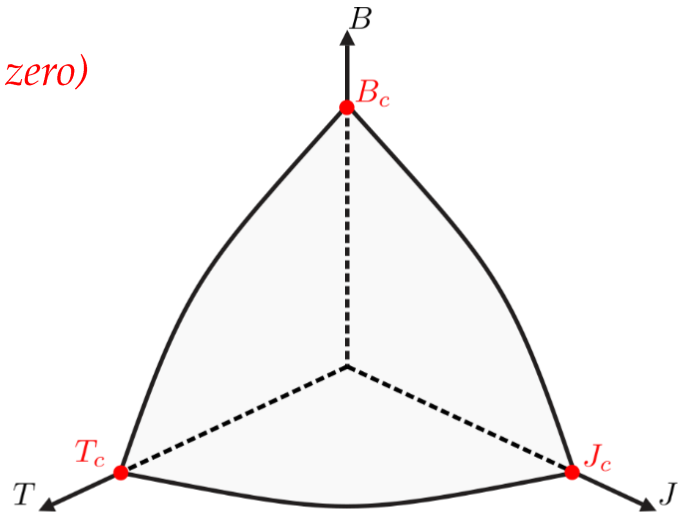

The Future Grid Challenge – Why Superconductors?

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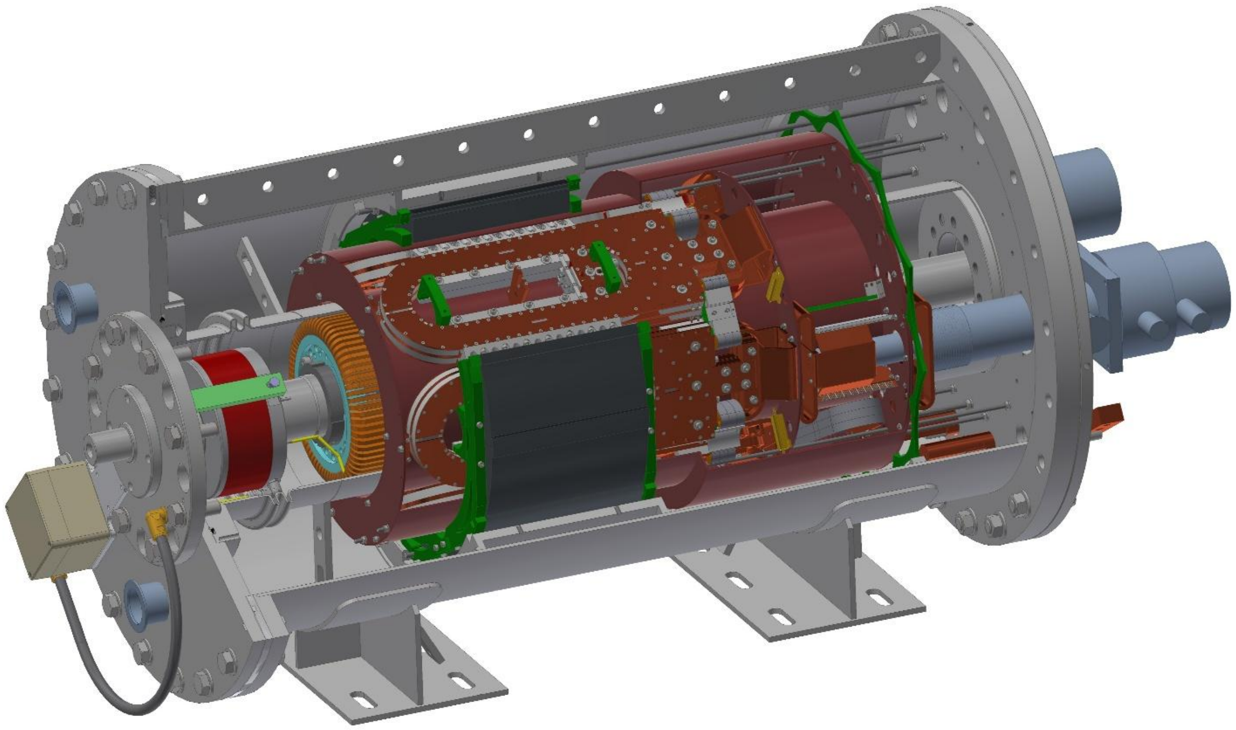
- <u>Impact on Power Applications</u>
  - **Improved energy efficiency**



Application Examples	Loss Reduction
Generators (some MVA)	30-40 %
Generators (> 100 MVA)	40-50 %
Transformers	~ 50 %
Magnetic heating	~ 50 %
Magnetic separation	> 80 %
HTS currents leads	70-80 %
HTS high field magnets	> 90 %

Schreiner, F. "*Development and test of a technology wind generator demonstrator with no insulation field coils applying high temperature superconductors*", KIT, 2022

The Future Grid Challenge – Why Superconductors?

- **Impact on Power Applications**
  - Improved energy efficiency
  - **Higher power density**

Application Examples	Volume and weight Reduction
Generators	30-50 %
Transformers	30-50 %
Cables	> 50 %

Superconducting Railway Transformer

Conventional Railway Transformer

The Future Grid Challenge – Why Superconductors?

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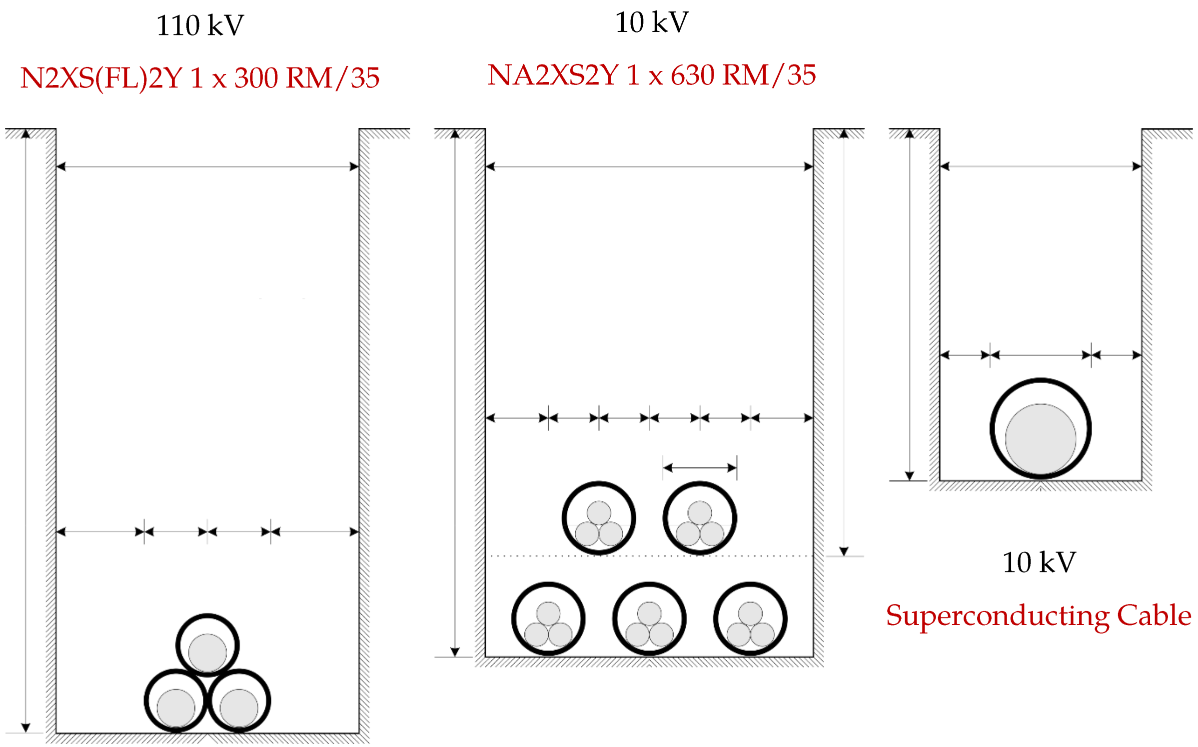
  - **Higher power density**



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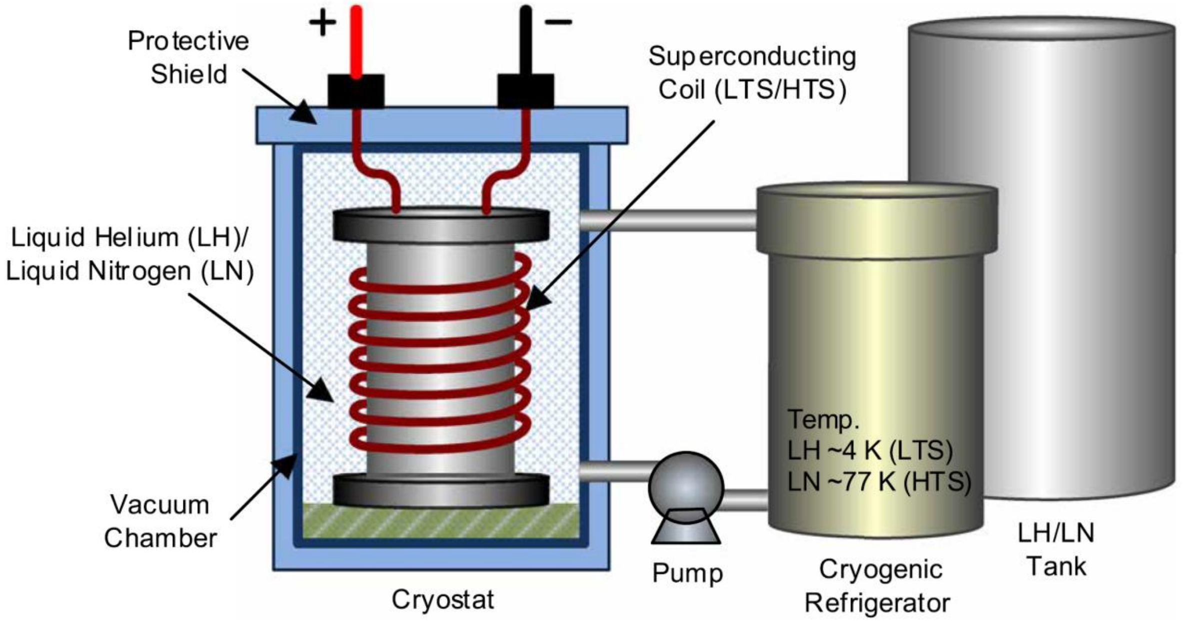
Generators	30-50 %
Transformers	30-50 %
Cables	> 50 %

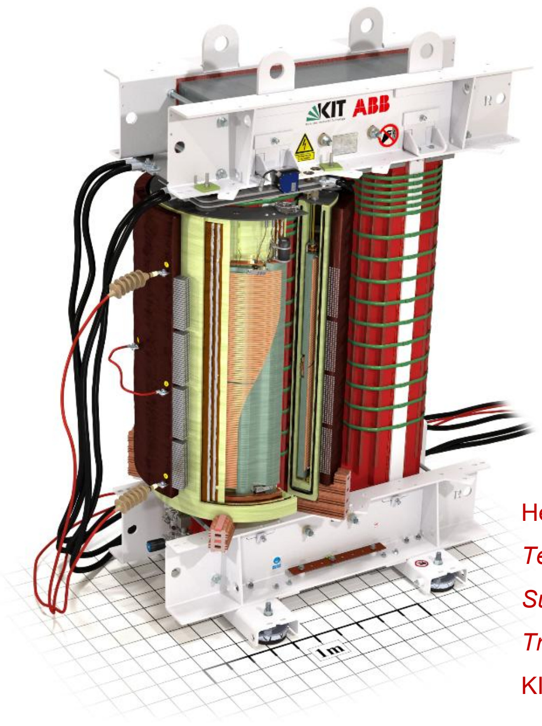
Cable System Comparison (40 MVA)

The Future Grid Challenge – Why Superconductors?

- **Impact on Power Applications**
  - Improved energy efficiency
  - Higher power density
  - **New technologies**

Superconductivity facilitates
Superconducting Fault Current Limiters
Superconducting Power Cables
Superconducting magnetic energy storage (SMES)





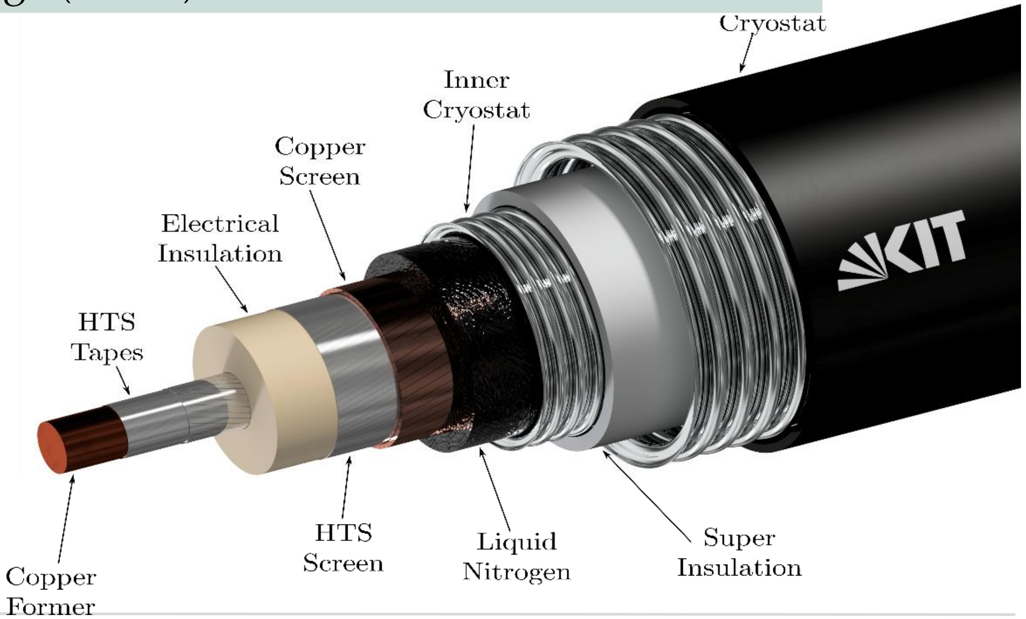
Hellmann, S., "*Research and Technology Development on Superconducting Limiting Transformers*", PhD. Thesis, KIT, 2018

The Future Grid Challenge – Why Superconductors?

- **Impact on Power Applications**
  - Improved energy efficiency
  - Higher power density
  - New technologies
  - **Higher Power Quality**

Higher Power Quality
Low impedance of superconducting power equipment
High short-circuit capacity of grids with fault current limiters
Fast compensation of disturbances with superconducting magnetic energy storage (SMES)

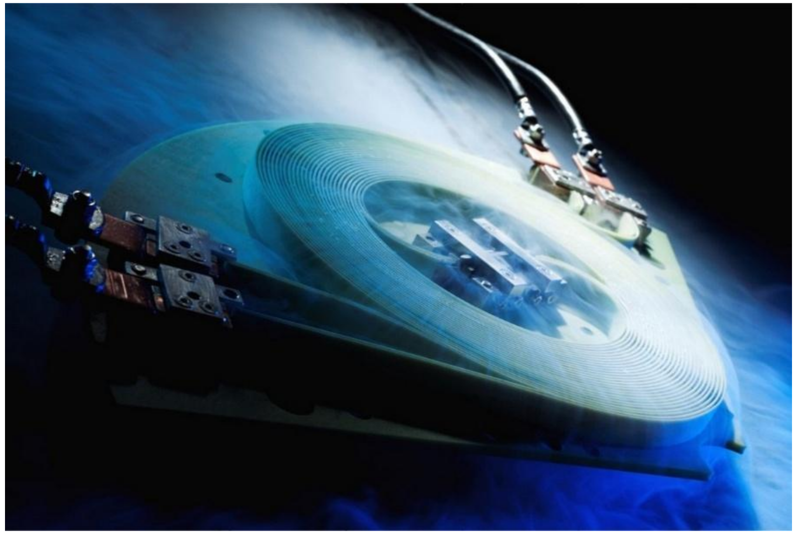
Mikhail Moyzykh, *et. al.*, "*First Russian 220 kV Superconducting Fault Current Limiter (SFCL) For Application in City Grid*", IEEE TASC, 2021



The Future Grid Challenge – Why Superconductors?

- **Impact on Power Applications**
  - Improved energy efficiency
  - Higher power density
  - New technologies
  - Higher Power Quality
  - **Environment friendly**

Liquid Nitrogen LN_2
LN_2 is used as cooling liquid and electrical insulation
• easily available • inflammable



Superconduting Power Cables

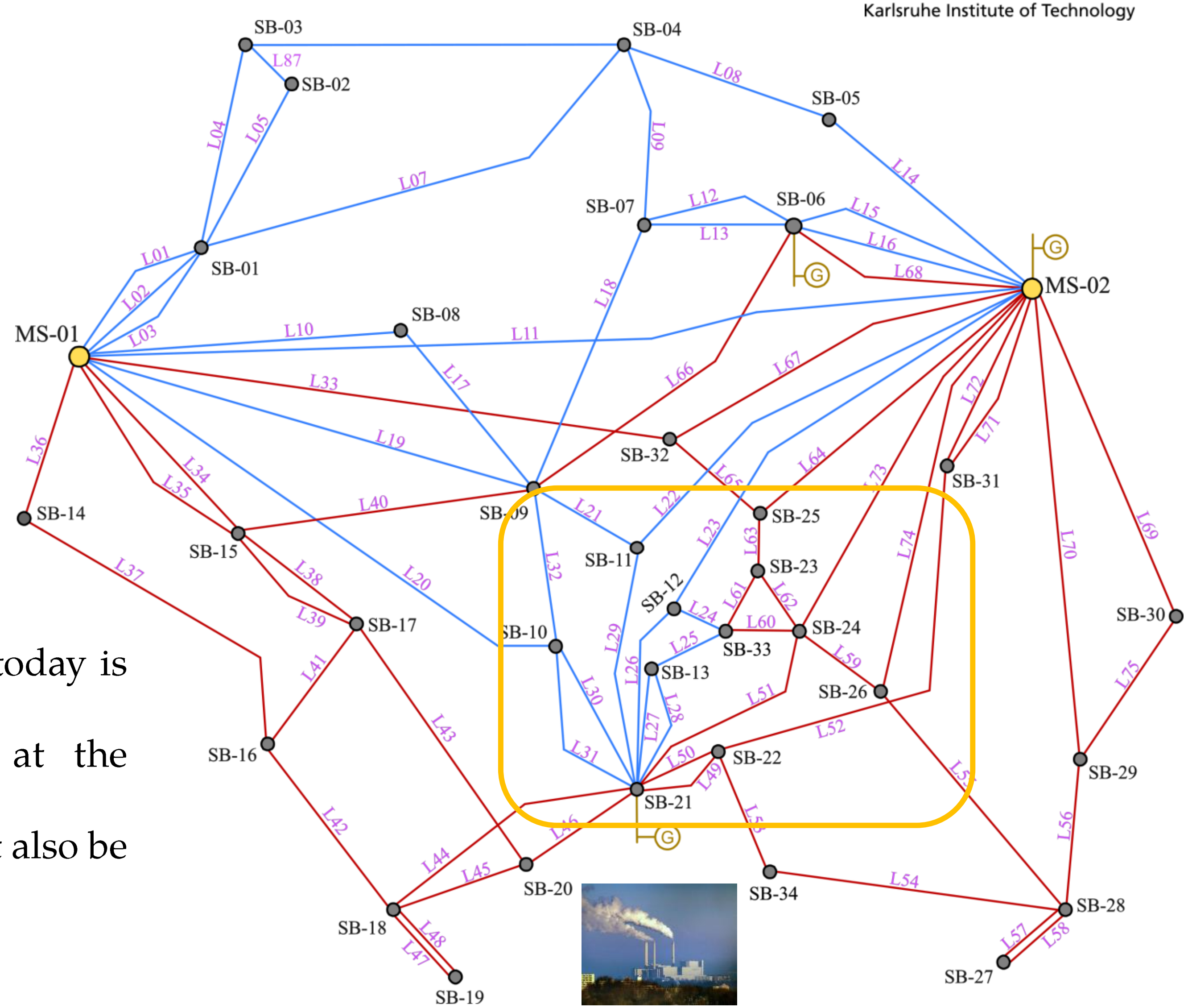
- The research on superconducting power cables has prompted industry and research centers.
  - SuperLink – NKT Cables
    - Germany – 110 kV AC Cable
  - SCARLET – Nexans
    - EU Consortium - MVDC Cables (HTS and MgB_2)
  - SuperRail – Nexans
    - France – 1.5 kV DC Cable for railway network
  - Data Center Cables – VEIR
    - USA – 1.0 kV AC Cable
  - 35 kV AC Cable – Shanghai Superconductors
    - China – 35 kV AC Cable

HTS Cables Special Session at EUCAS 2025

SuperLink Project - Motivation

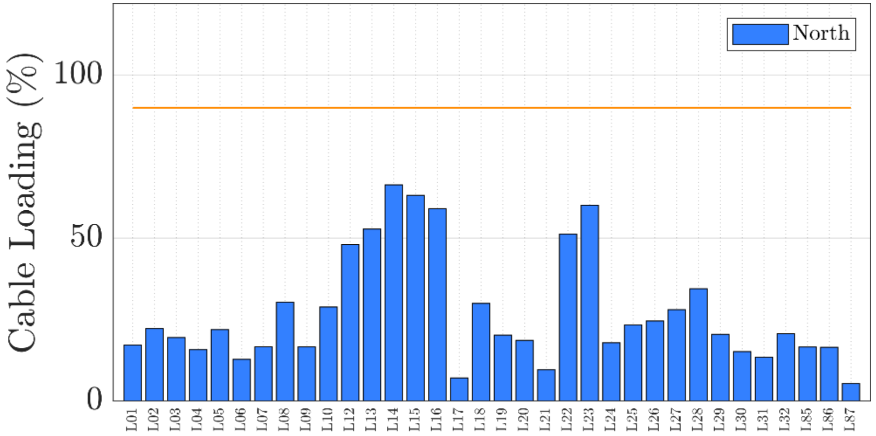
- **Connect HV-Substation**
  - The network operator of Munich needs a high-power line between the main HV-Substation (MS-01) to the highlighted zone.

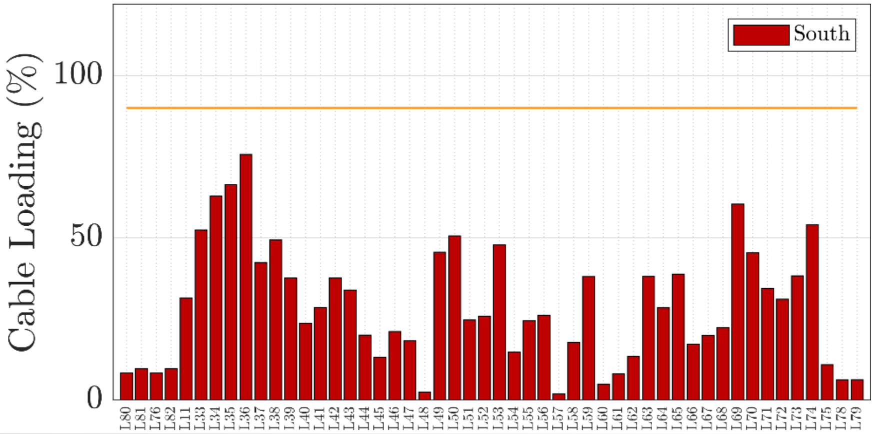
- **Export Power**
  - A major challenge for the 110 kV network in Munich today is managing off-peak times, when power generated at the southern substation should not only supply Munich but also be exported to external networks.



SuperLink Project - Motivation

- 2019 – Peak Load = **1210 MVA**
  - **Network running fine ☺**





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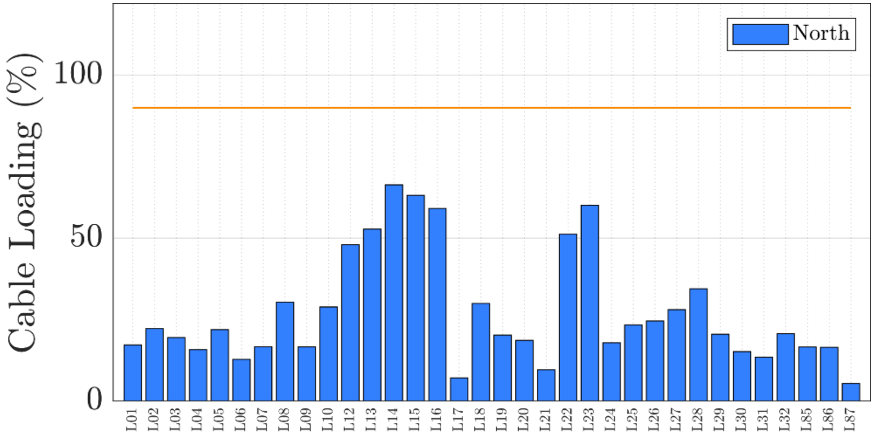
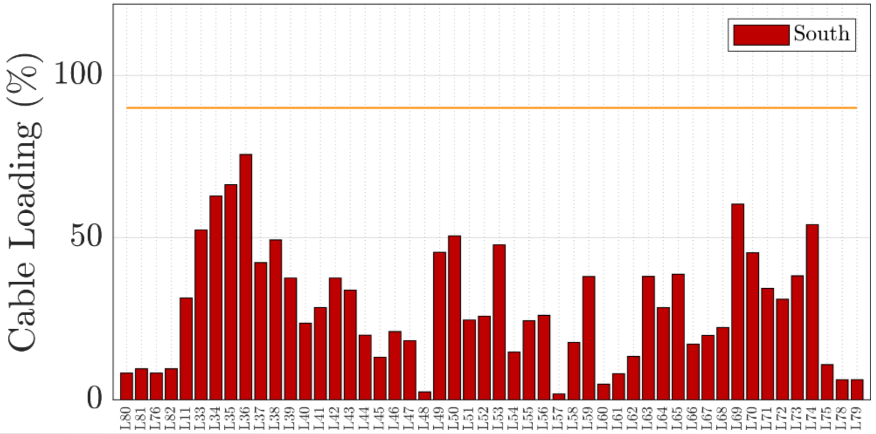
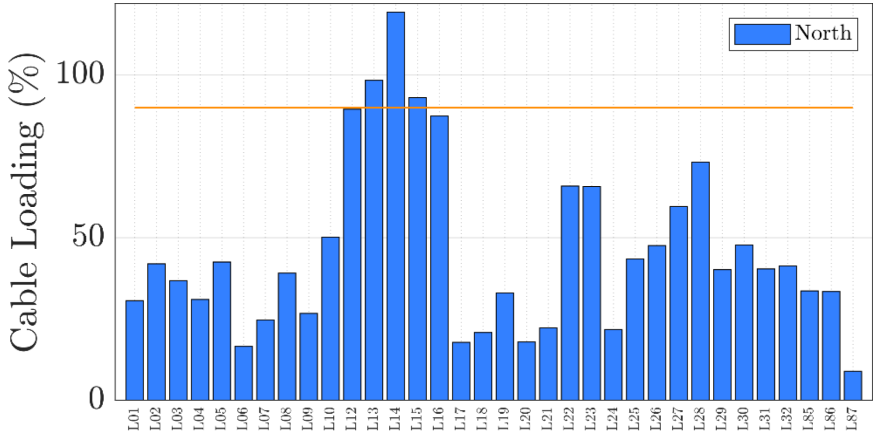
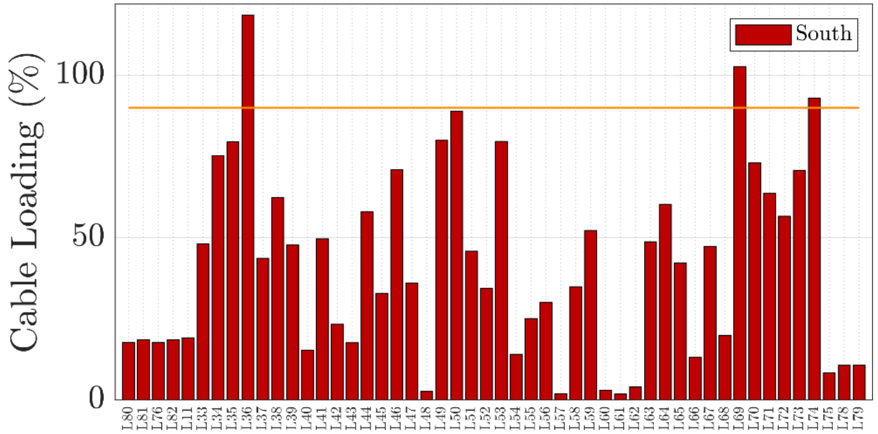




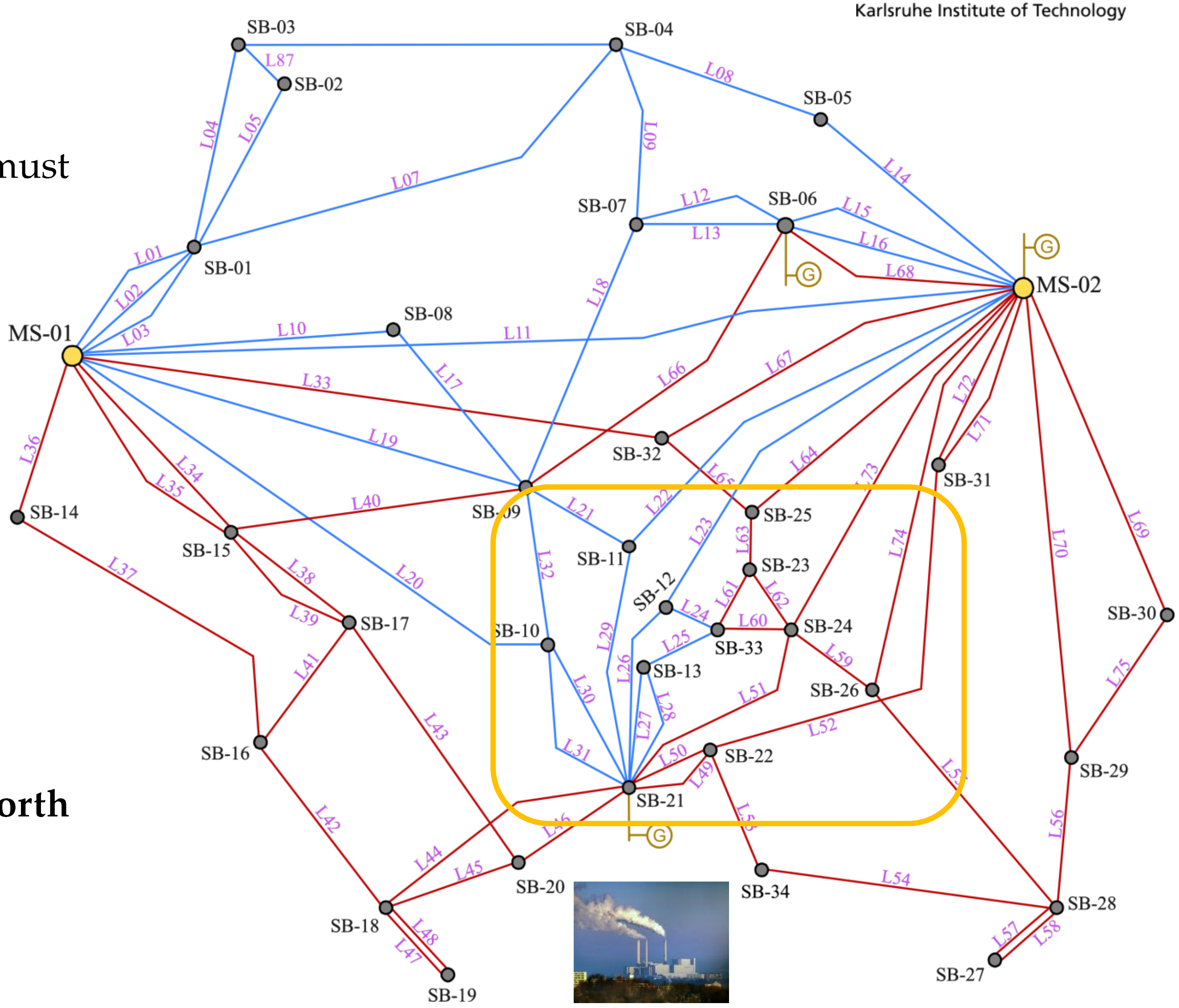
- Projection of the Peak Load for comig years ≈ **2500 MVA**
- Critical situation – not only overloaded cables, but also….. ☹





SuperLink Project - Motivation

- Projection of the Peak Load for the next years ≈ 2500 MVA
- To supply such a high load, all the thermal power stations must be dispached
  - Besides the overloading of cables…
    - Not good from the economical point of view…
      - Operating and maintenance costs will rise sharply
    - Not good from the ecological point of view…
      - Massive increase in gas emissions
- **The network operator needs a high-power line between North and South with 500 MW and appr. 15 km**



SuperLink Project – Possible Solutions

- **400 kV XLPE Cable System**
  - Would require the construction of tunnels

- **400 kV Overhead Lines**
  - Not feasible inside the city
  - Even in the city surroundings is almost unfeasible

- **Multiple 110 kV XLPE Cables**
  - can only be used with limited cross-section (500 or 630 mm^2 Cu) due to bending radii.

- **110 kV HTS Cables**
  - Less Space required
  - HTS-Cable can easily transport more than 500 MVA
  - Low Losses

SuperLink – The longest Superconducting Power Cable in the World

Karlsruhe Institute of Technology

Stromtransport: Das längste Hochspannungs-Supraleiterkabel der Welt

In München soll das längste Supraleiterkabel der Welt realisiert und wirtschaftlich eingesetzt werden. Das KIT ist an dem Projekt beteiligt.

Die Wissenschaftlerinnen und Wissenschaftler am KIT konzipieren mit den Projektpartnern effiziente und leistungsstarke supraleitende Dreileiterkabel (Abbildung: NKT Cables Group)

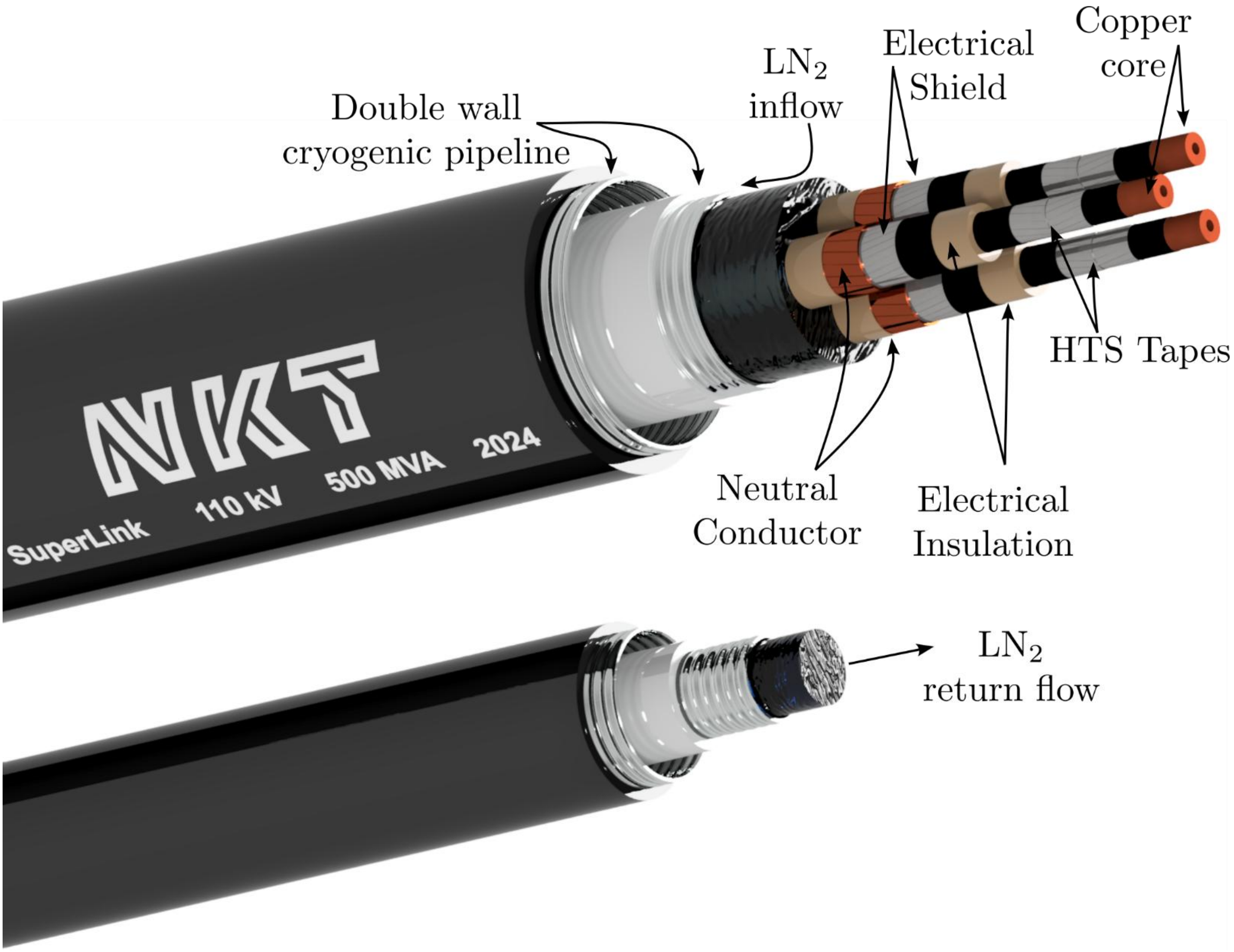
Im Stromnetz der Zukunft müssen große Mengen elektrischer Energie aus erneuerbaren Quellen in dicht bebaute städtische Lastzentren geleitet werden. Mit Supraleitern kann Strom ohne Widerstand und Verlust transportiert werden. „Die Leitung soll perspektivisch insgesamt zwölf Kilometer lang werden und kann eine bestehende 380 Kilovolt Leitung im regulären Betrieb ersetzen", sagt Mathias Noe, Direktor des Instituts für Technische Physik am KIT. „Wir nutzten ein Hochtemperatur-Supraleiterkabel, das sich durch extreme Kompaktheit und hohe Leistung auszeichnet."

Gemeinsam möchte das Konsortium innerhalb von zwei Jahren alle notwendigen technischen Voraussetzungen erfüllen und die wichtigsten Komponenten entwickeln; hierzu gehören ein 200 Meter langes Kabelteilstück, Endverschlüsse und die Kühlung. Nach erfolgreichem Abschluss des Projektes sollen dann die zwölf Kilometer angegangen werden. Die Forschungsarbeiten des KIT umfassen vor allem die komplexe Simulation des elektromagnetischen und thermischen Verhaltens des Kabels.

Die Forschungen sind Teil des vom Bundesministerium für Wirtschaft und Energie geförderten Projekts „SuperLink". Dem Projektkonsortium gehören neben dem KIT und der Fachhochschule Südwestfalen die Stadtwerke München sowie die Unternehmen THEVA, NKT Cables Group und Industriegase-Konzern Linde an.

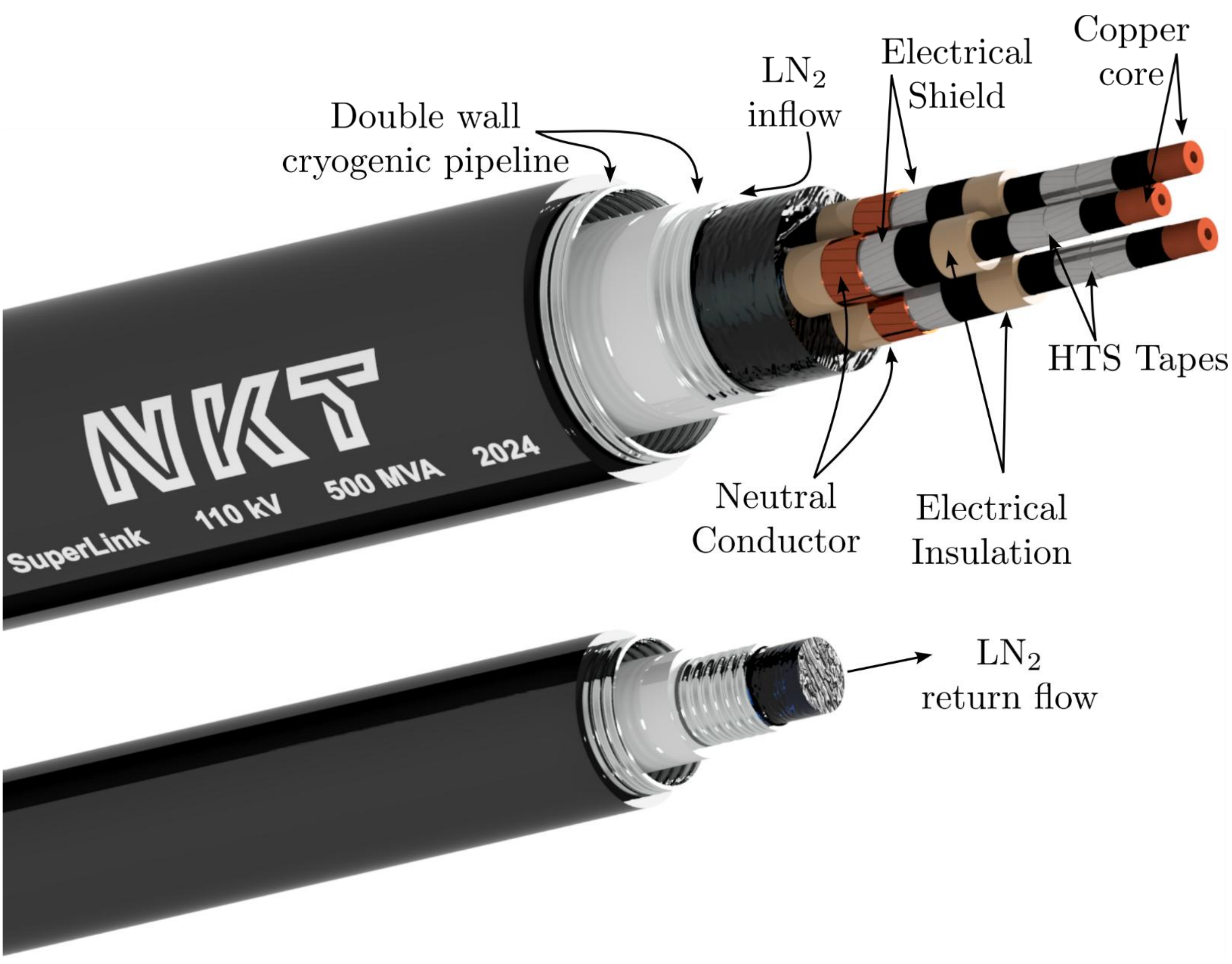
SW//M | NKT | THEVA | Fachhochschule Südwestfalen University of Applied Sciences | Linde | KIT Karlsruhe Institute of Technology | Gefördert durch: Bundesministerium für Wirtschaft und Klimaschutz

SuperLink – Cable Layout

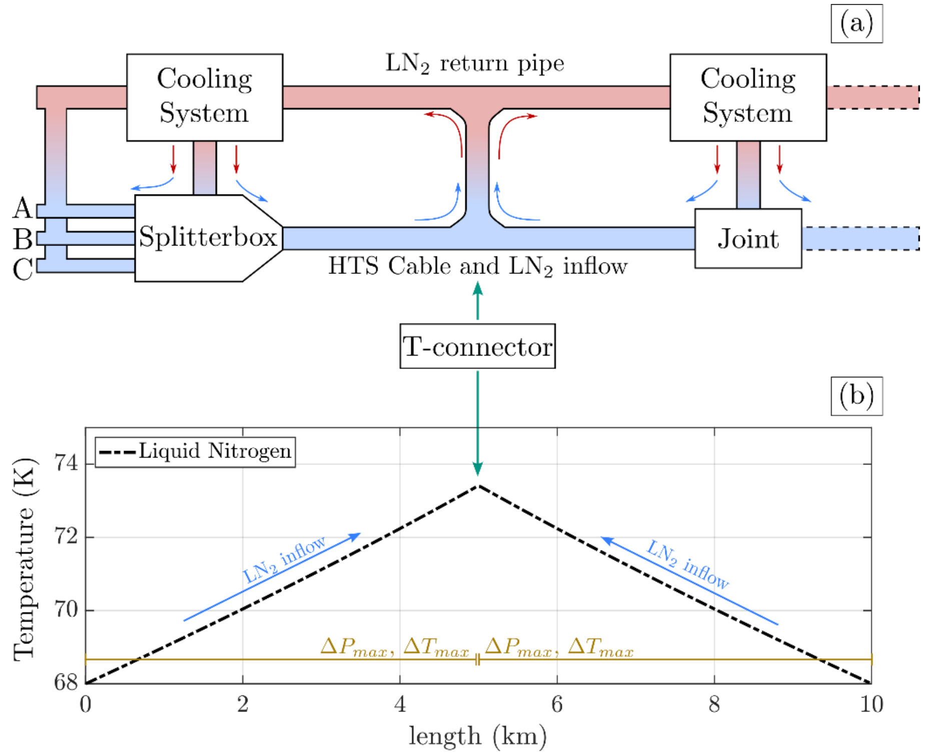


- **Cable Design**
  - 15 km long high-power HTS cable
  - 110 kV, 500 MVA, 2.6 kA
  - Superconducting phases and screens
  - Fault Current Resilient (40 kA, 1 s)
  - Three Phases in one Cryostat
  - Low AC- Losses (lower than 0.5 W/m per phase)

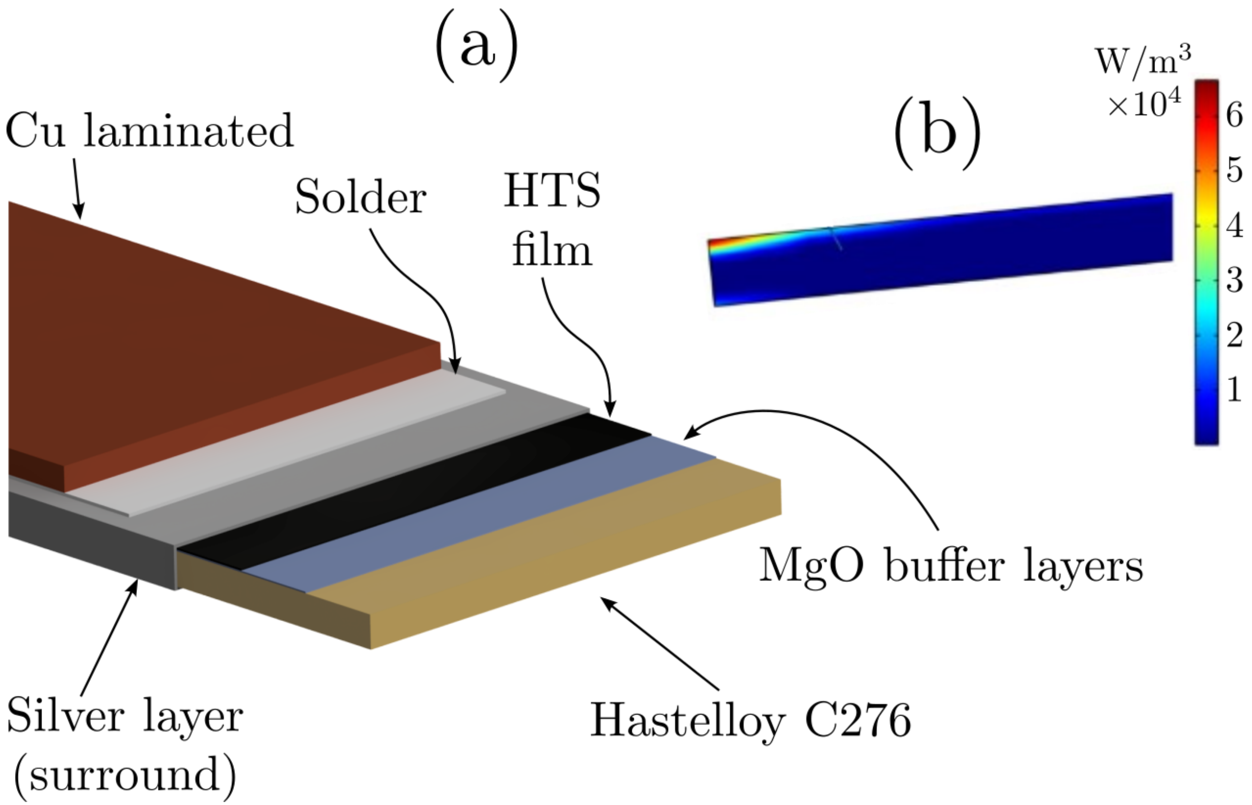
SuperLink – Cable Layout



- **Closed cooling system**
  - Separate LN_2 return pipe (single, one-way cable)
  - Low temperature and high pressure of LN_2 can be maintained in the main cryostat



SuperLink – HTS Tapes



- HTS wire optimized for AC-cable manufacturing
- Robust, single-sided Cu-laminated
- 3 mm laser-slit wire, narrow tolerances
- Trapezoidal shape to fit on round core and minimize gaps
- $I_{c,avg}$ (3mm, @77 K) = 163 A

SuperLink – Network analysis

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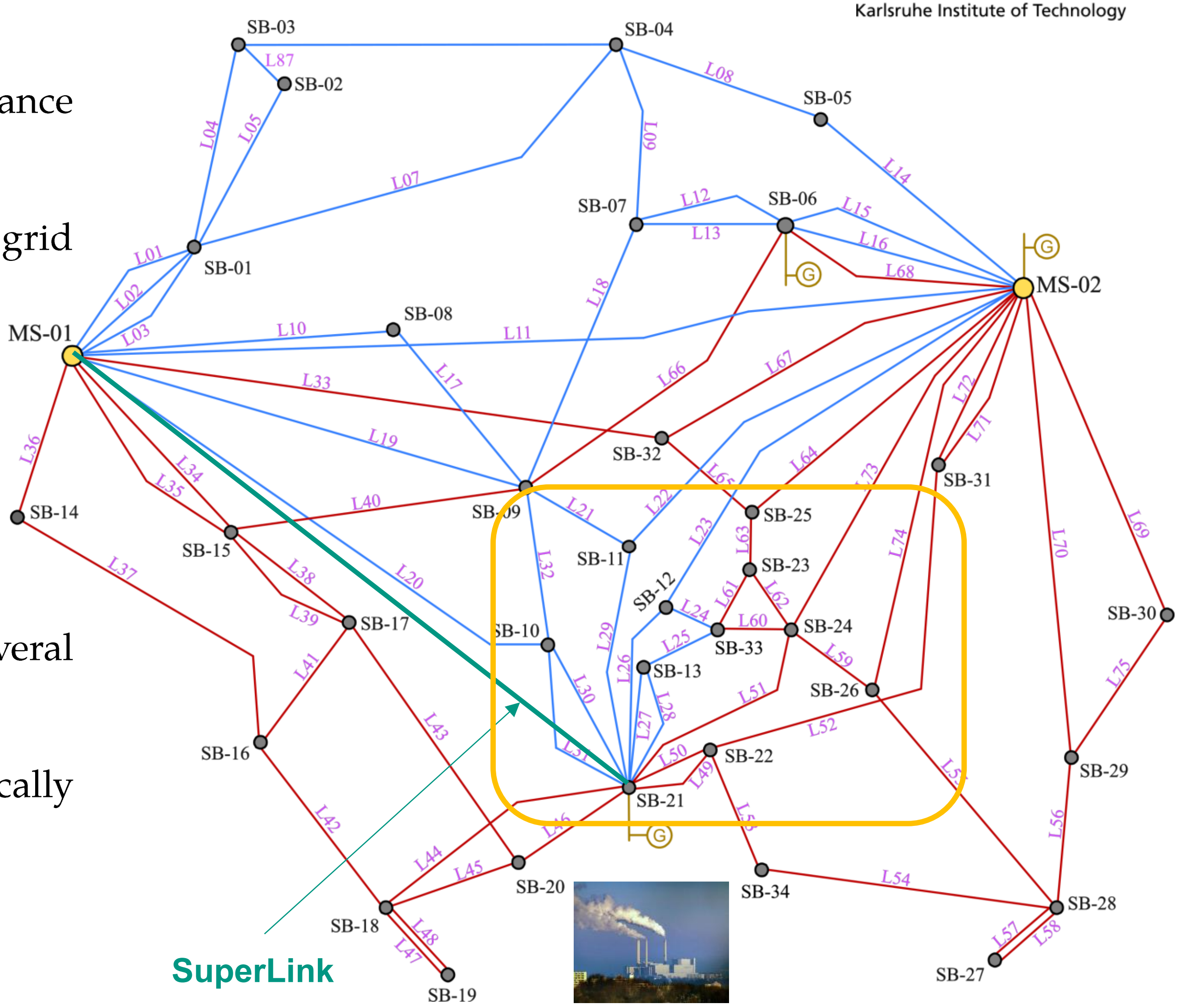
- Due to its high-power transmission capacity and low impedance characteristics, the integration of such a cable into the grid requires careful investigation

- In collaboration with the network operator in Munich, several loading and generation scenarios have been theoretically analyzed (+ 120).



SuperLink – Analysis method

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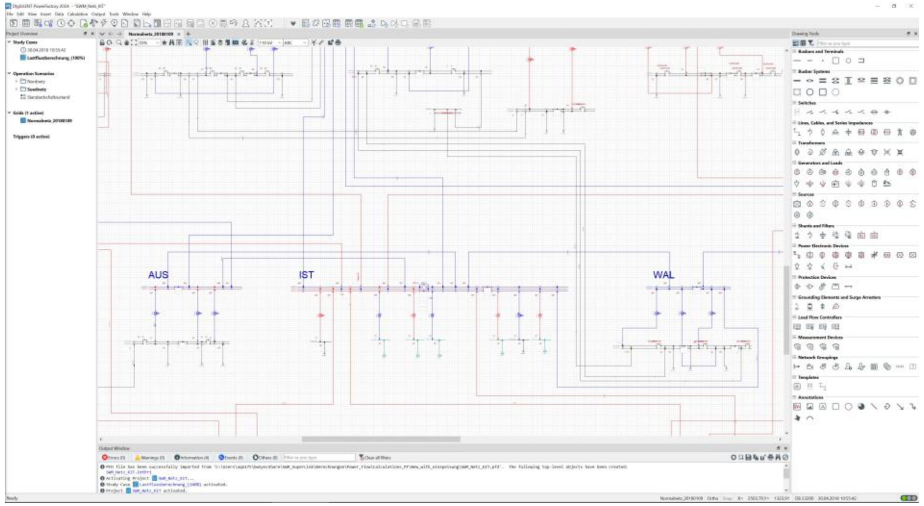
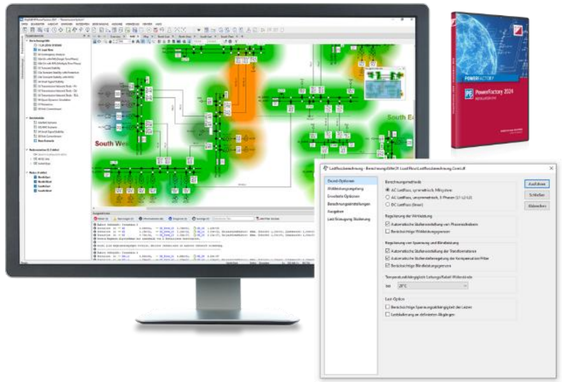
- **Load-Flow Calculations**
  - Cable loading (percentage of current)
    - Cables with 90% of its capacity are considered “overloaded”



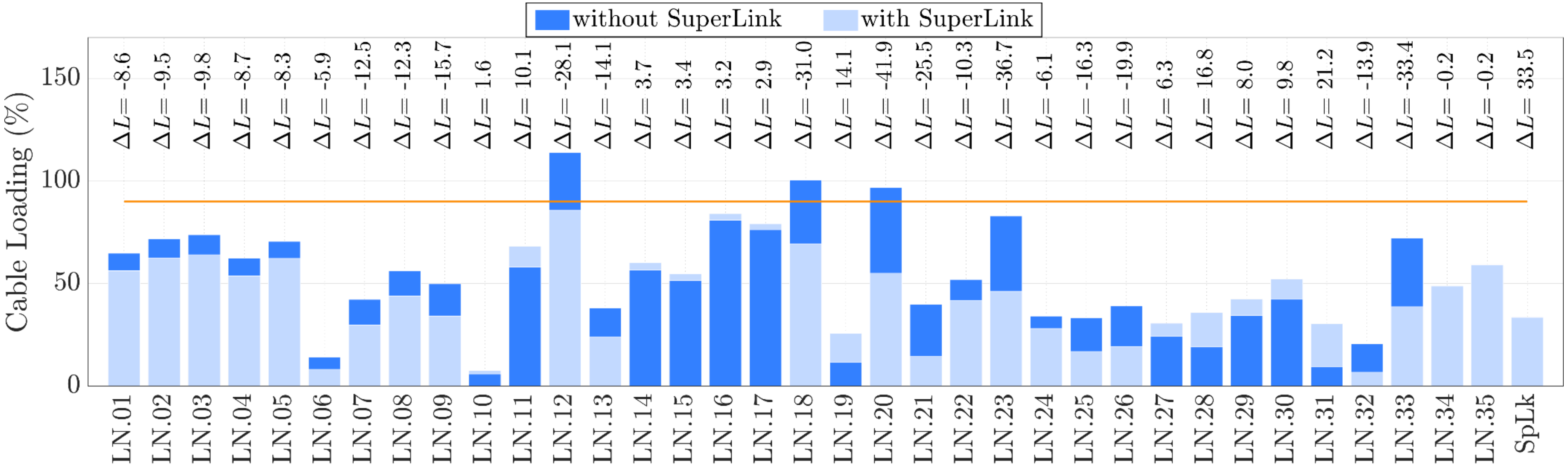
  - Maximum 3-phase short-circuit currents (IK") on each 110 kV busbar of the network
    - Investigation on fault-current levels before and after the installation of SuperLink Cable



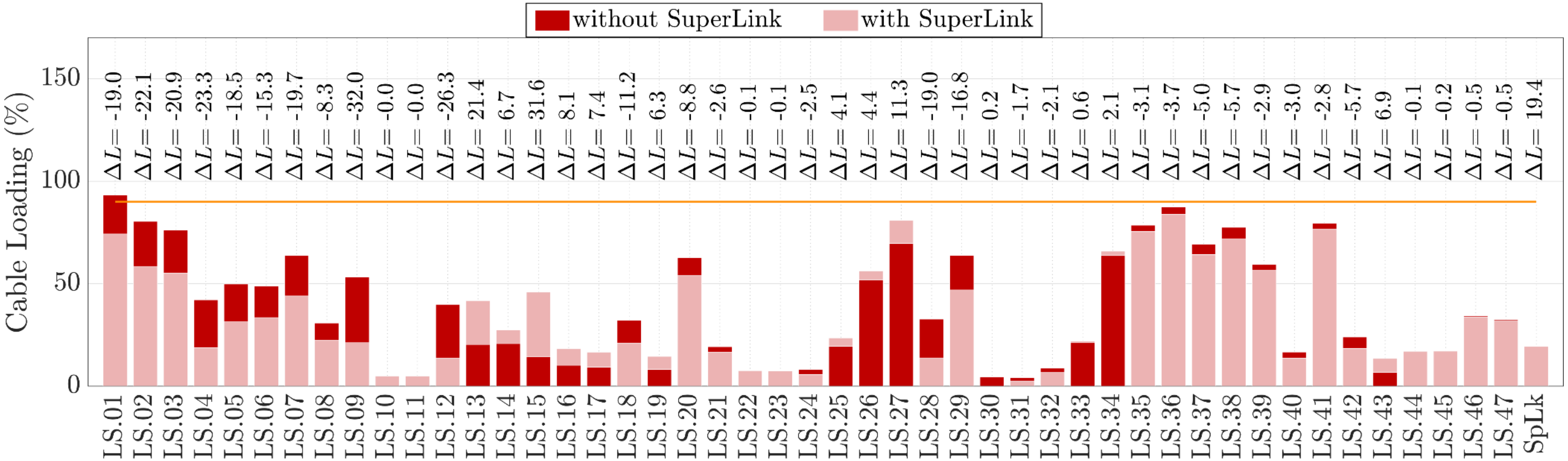
  - Network Ohmic Losses

$$P_\Omega = \sum_{n=1}^{N} R_n \cdot I_n^2$$

SuperLink – Load Flow Analysis – Cable Loading

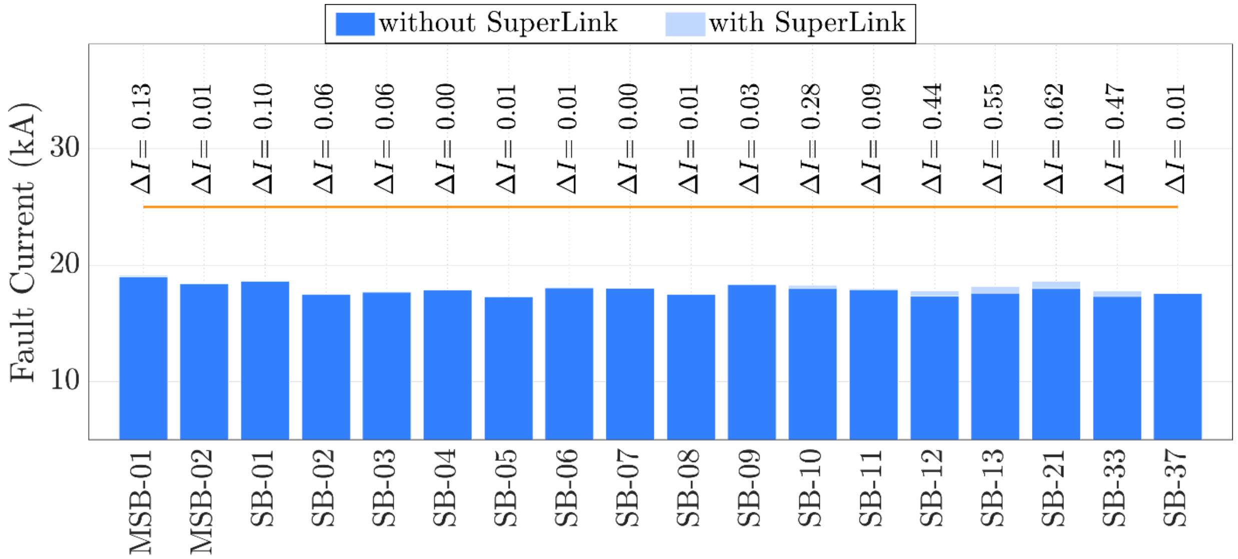


- **Northern Sector**
  - W/o: 3 Cables above threshold
  - W/: 0 Cables above threshold
  - Losses: 1.37 MW to 1.13 MW

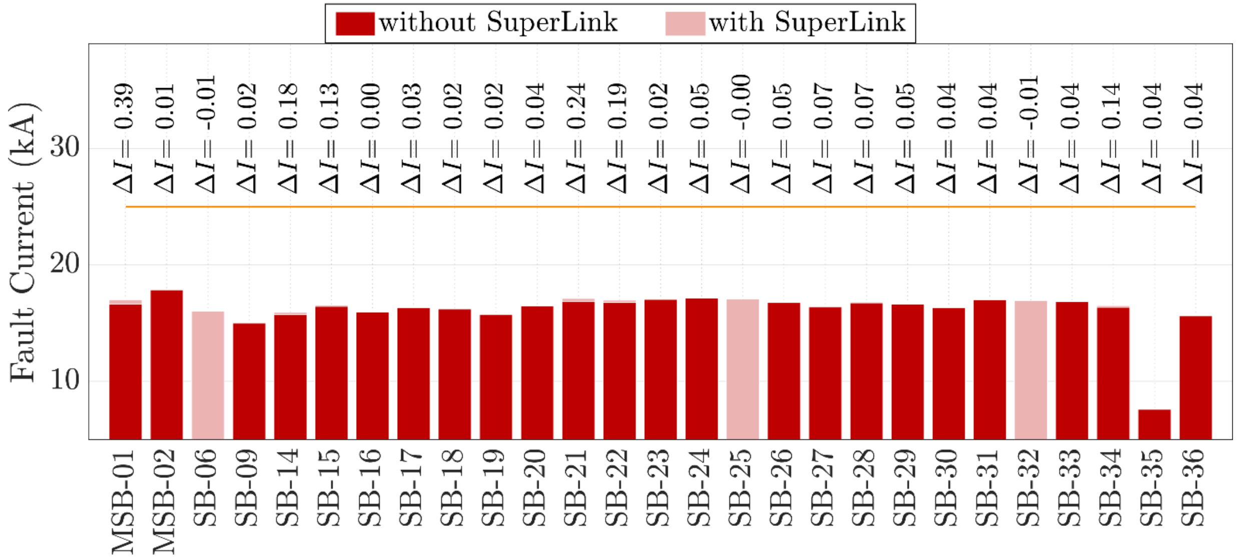


- **Southern Sector**
  - W/o: 1 Cable above threshold
  - W/: 0 Cables above threshold
  - Losses: 2.03 MW to 1.62 MW

SuperLink – Load Flow Analysis – Fault Current Level



- **Northern Sector**
  - No signifcant increase on fault current levels.



- **Southern Sector**
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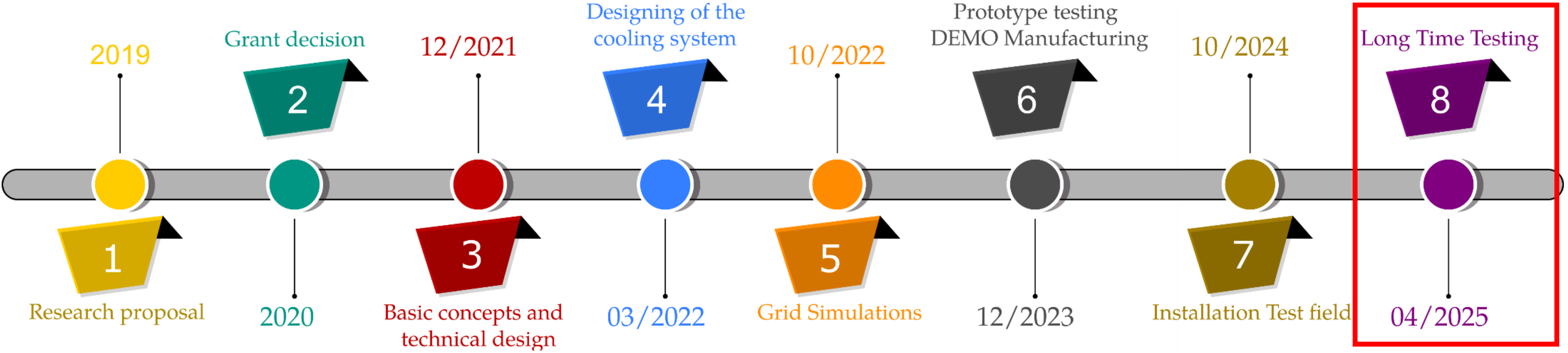
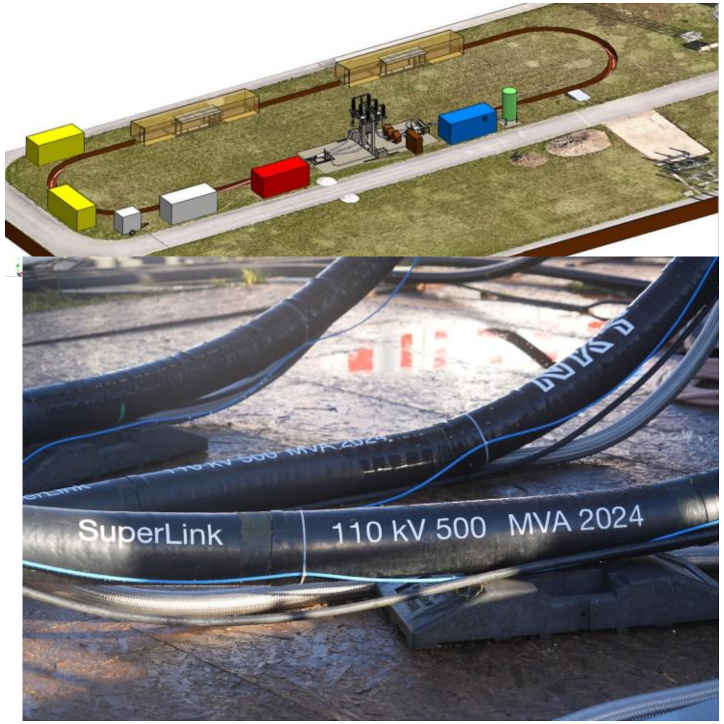
SuperLink – Status



- Field Test finished



SuperLink – Summary

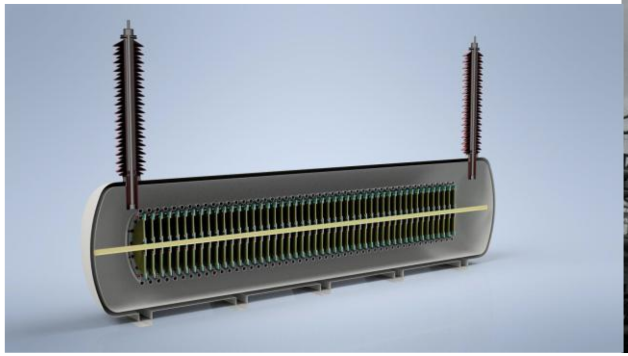
- The cable system successfully completed continuous operation in the 110 kV grid under various load scenarios and weather conditions. It was able to reach its full rated power of 500 MVA, with all three phases reliably carrying the specified current of 2.6 Arms.

- In all investigated scenarios, several cables will benefit from the integration of the Superlink Cable in the 100 kV grid.

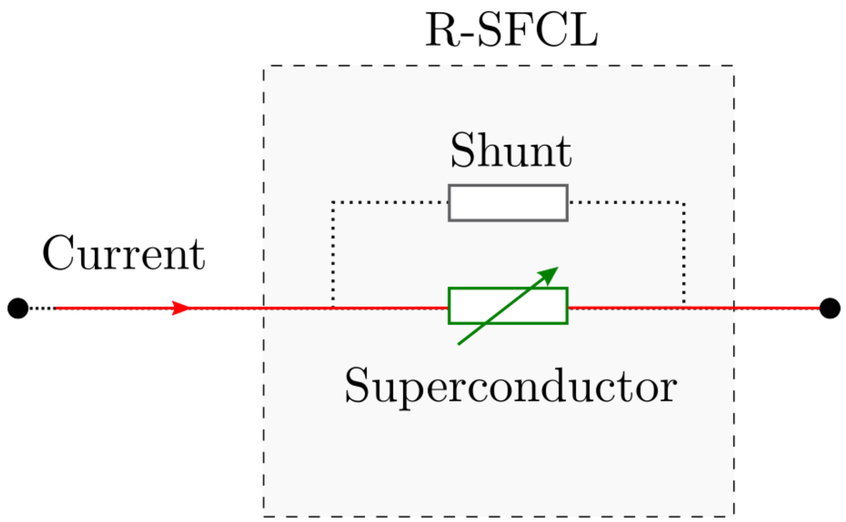
- Connecting MS-01 and SB-2 with a very low impedance cable eases the exportation of power to external networks.

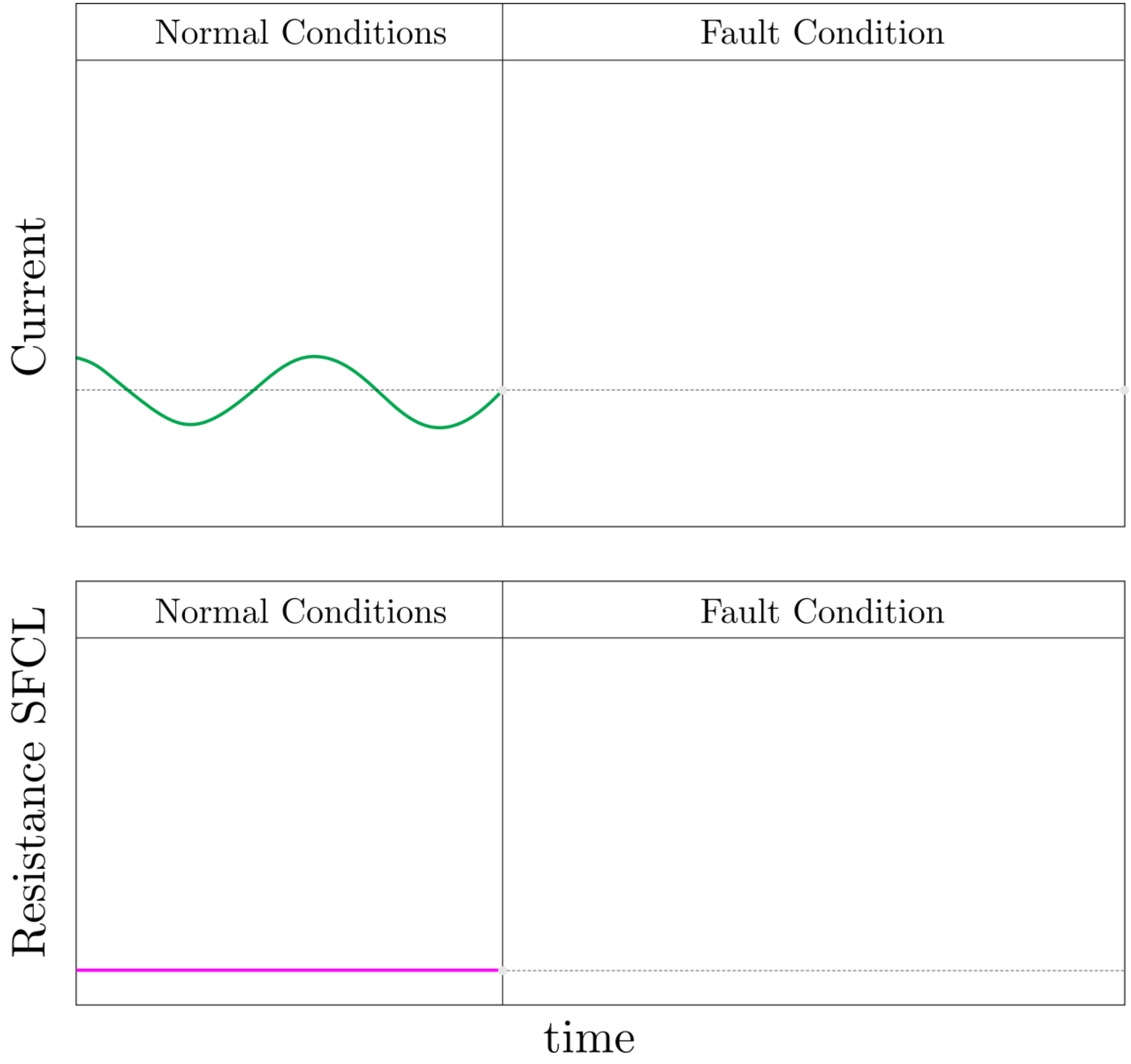
SuperLink – Summary

- Network remains stable.
  - No changes on the busbars voltage levels
  - No increase on fault current levels
  - However, the network must remain divided;
    - Otherwise, the 25 kA threshold will be exceeded.
  - Possible Solution:
    - **Superconducting Fault Current Limiters**



Superconducting Fault Current Limiters (SFCL)





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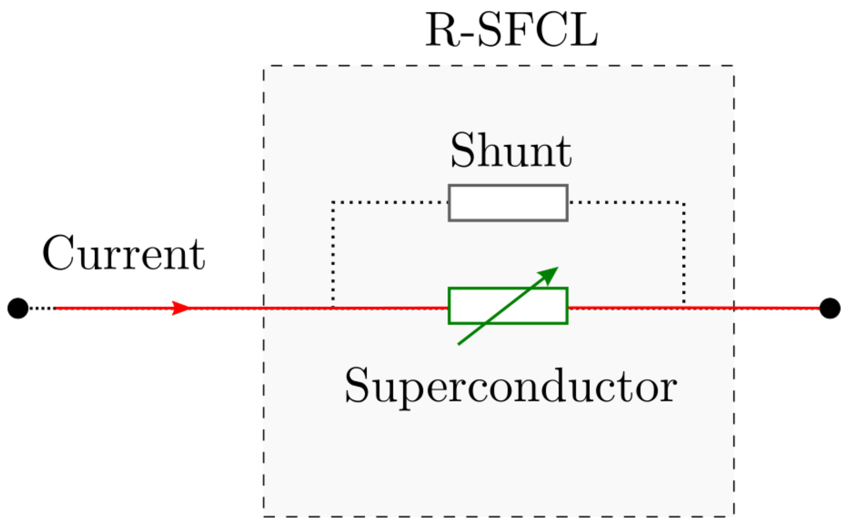

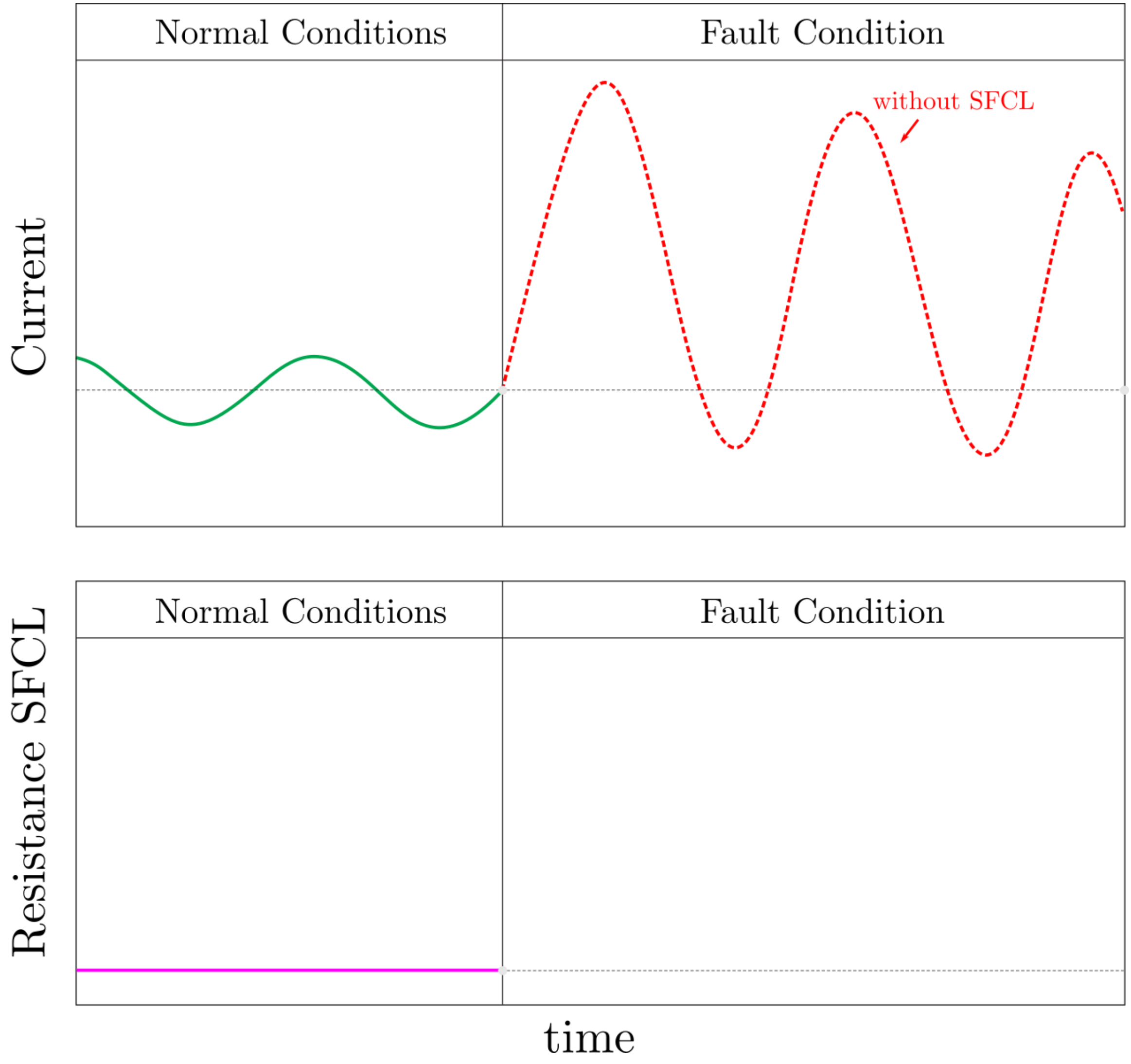

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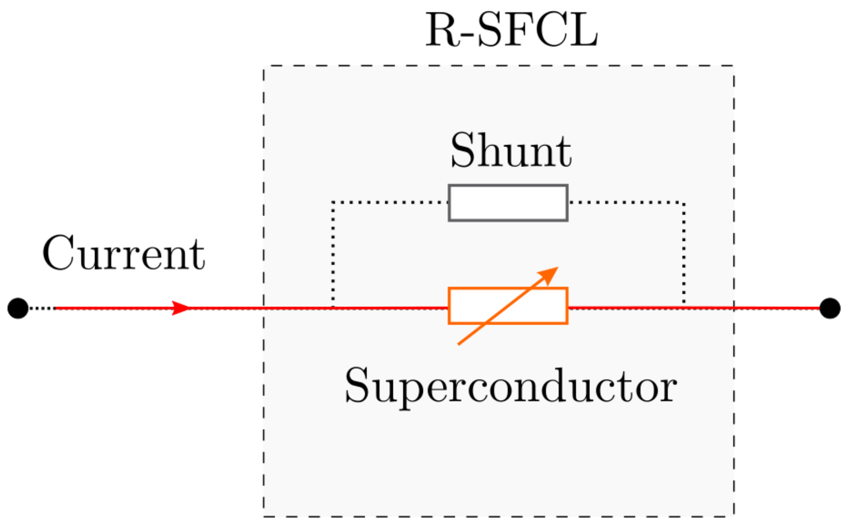
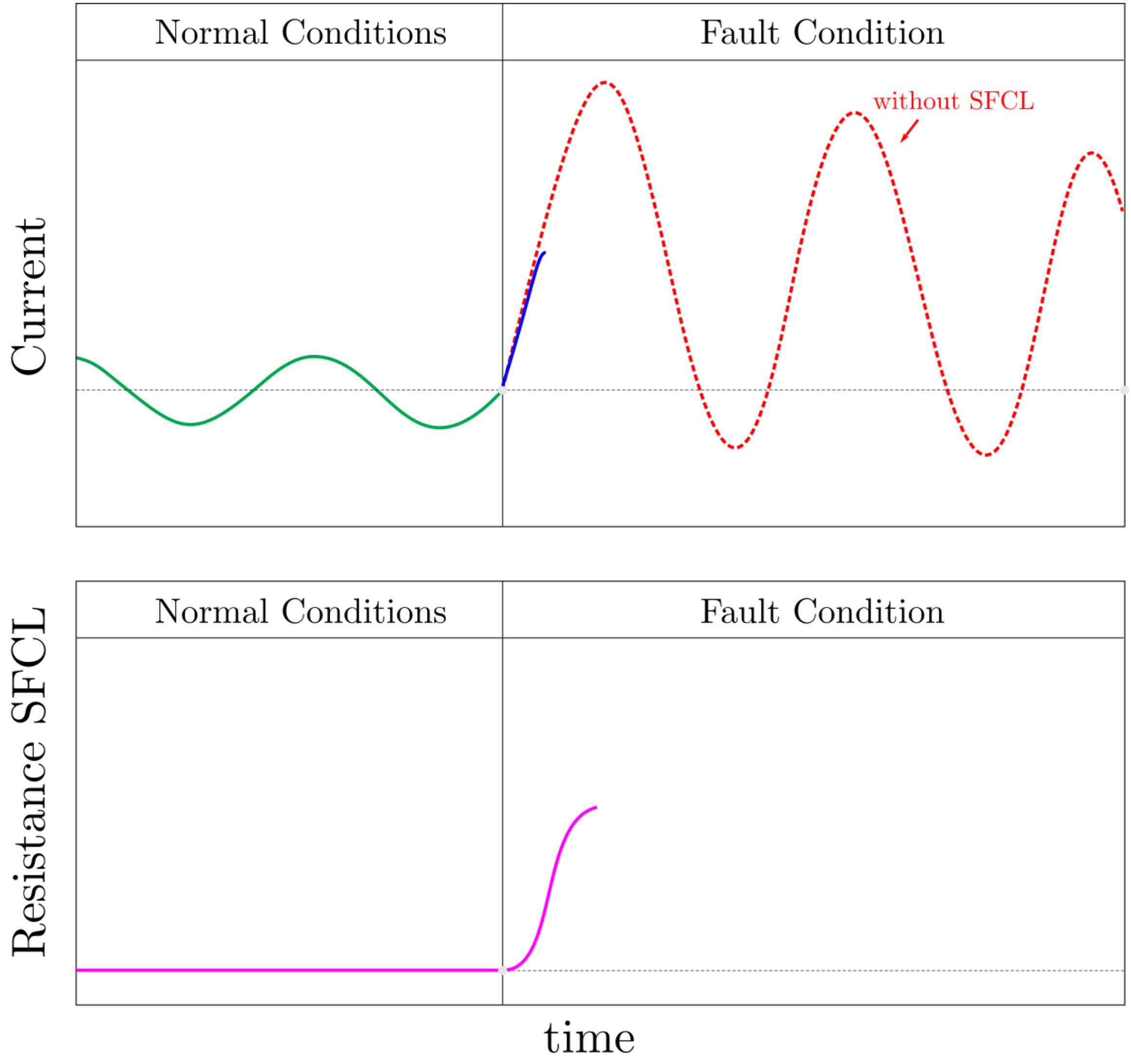
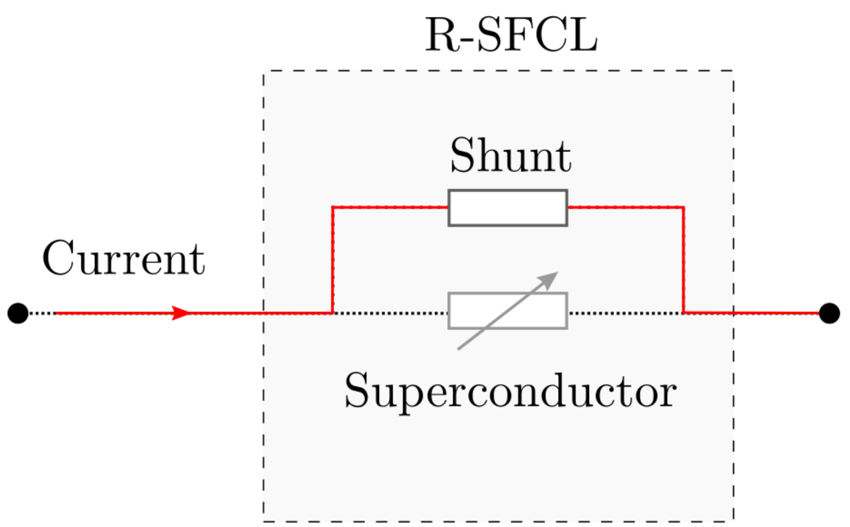
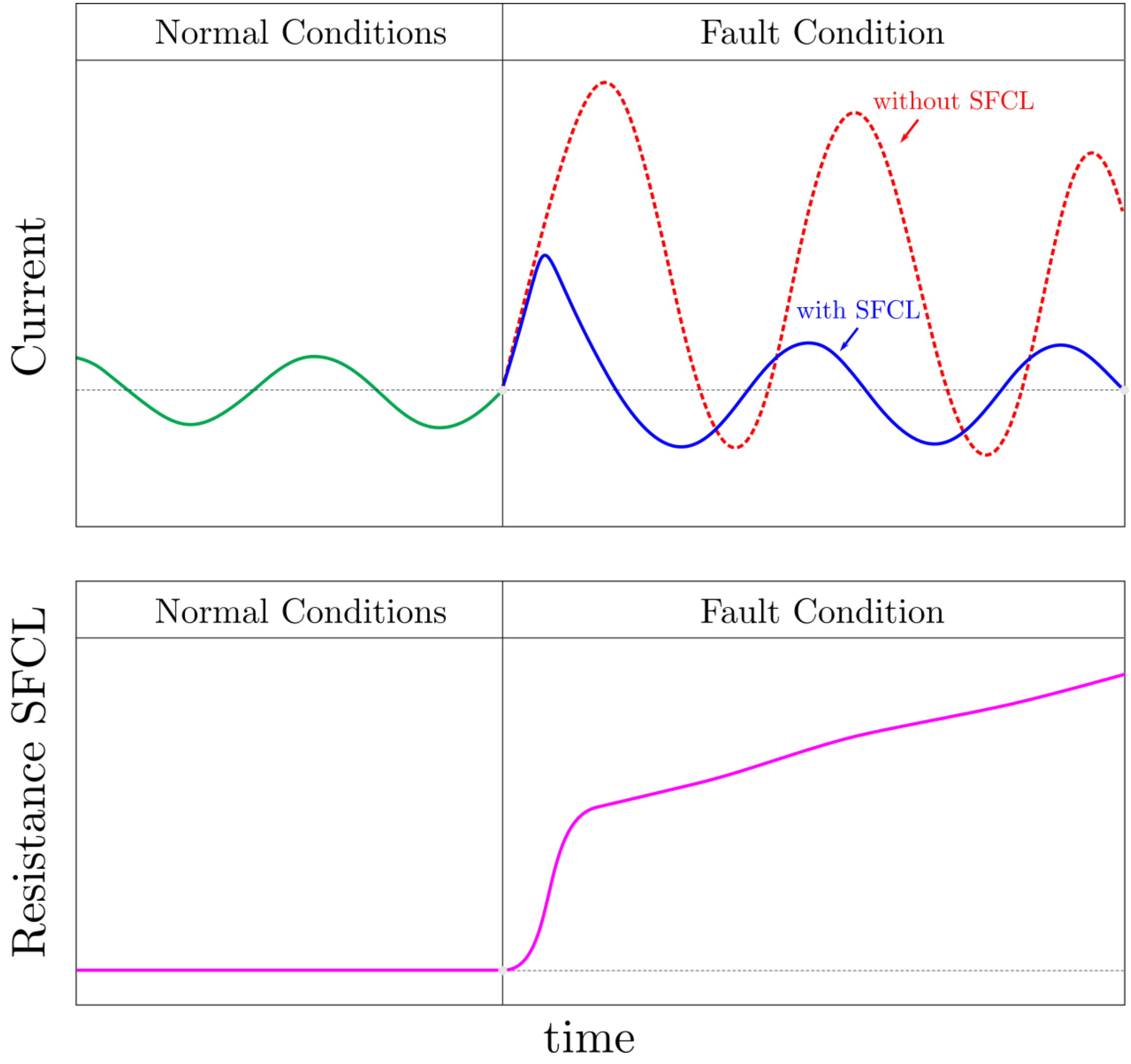




Superconducting Fault Current Limiters (SFCL)

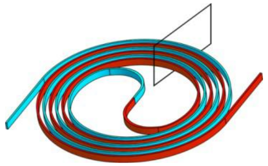
- SFCL is a fail safe device. ☺

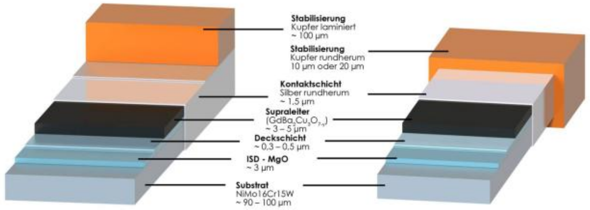


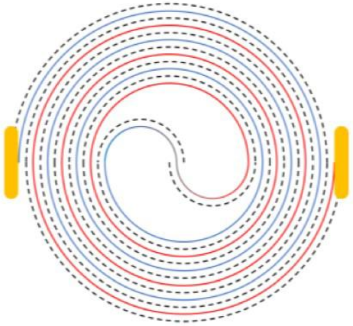


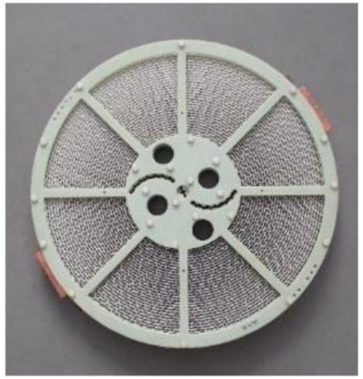
Superconducting Fault Current Limiters (SFCL) – 110 kV Design

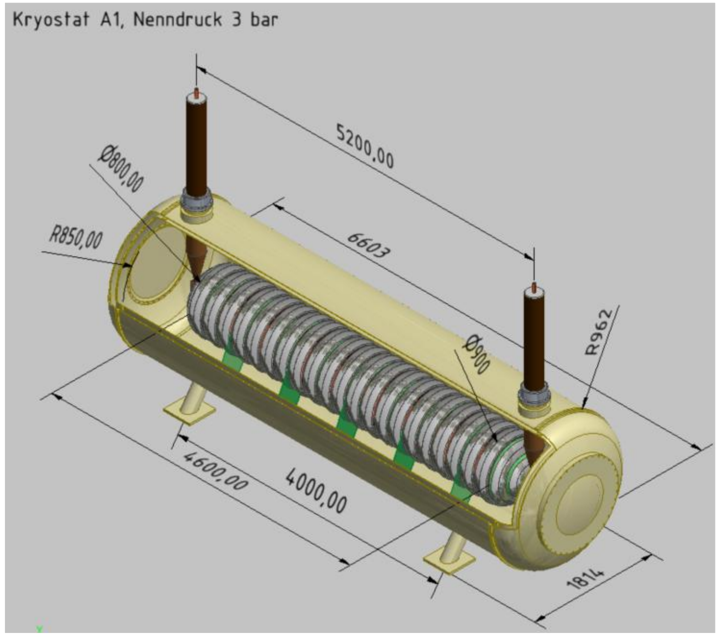
- **110 kV SFCL Study – Conducted by KIT in partnership with German network operators**
  - **Functional principle, design, and operation:** Analysis of basic concept of resistive SFCLs → HTS material in a cryostat with nitrogen cooling, including quench behavior, fault-ride-through capability, and requirements for current/voltage ratings, recovery times, and fault durations





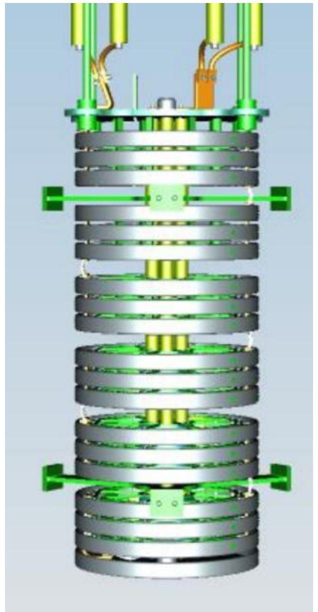


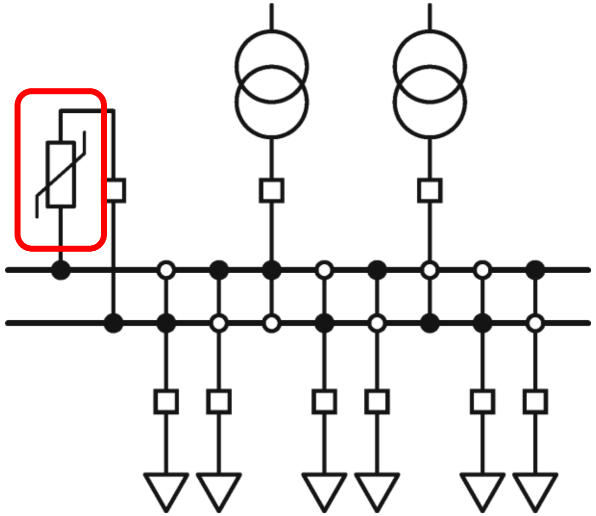


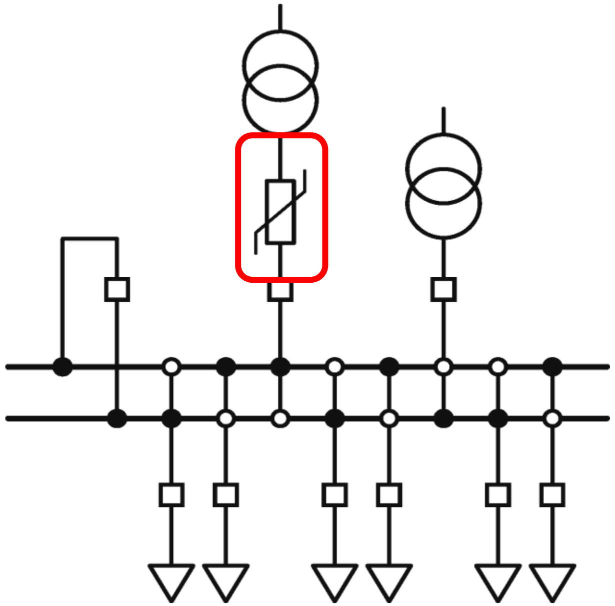


Superconducting Fault Current Limiters (SFCL) - 110 kV Design

- **110 kV SFCL Study – Conducted by KIT in partnership with German network operators**
  - **Technical and application evaluation**: It examined performance at different grid locations (bus coupler vs. transformer feeder), assessing short-circuit current limitation, heat load, cryogenic needs, superconducting material demand, and ability to meet high-voltage insulation and FRT (fault-ride-through) requirements





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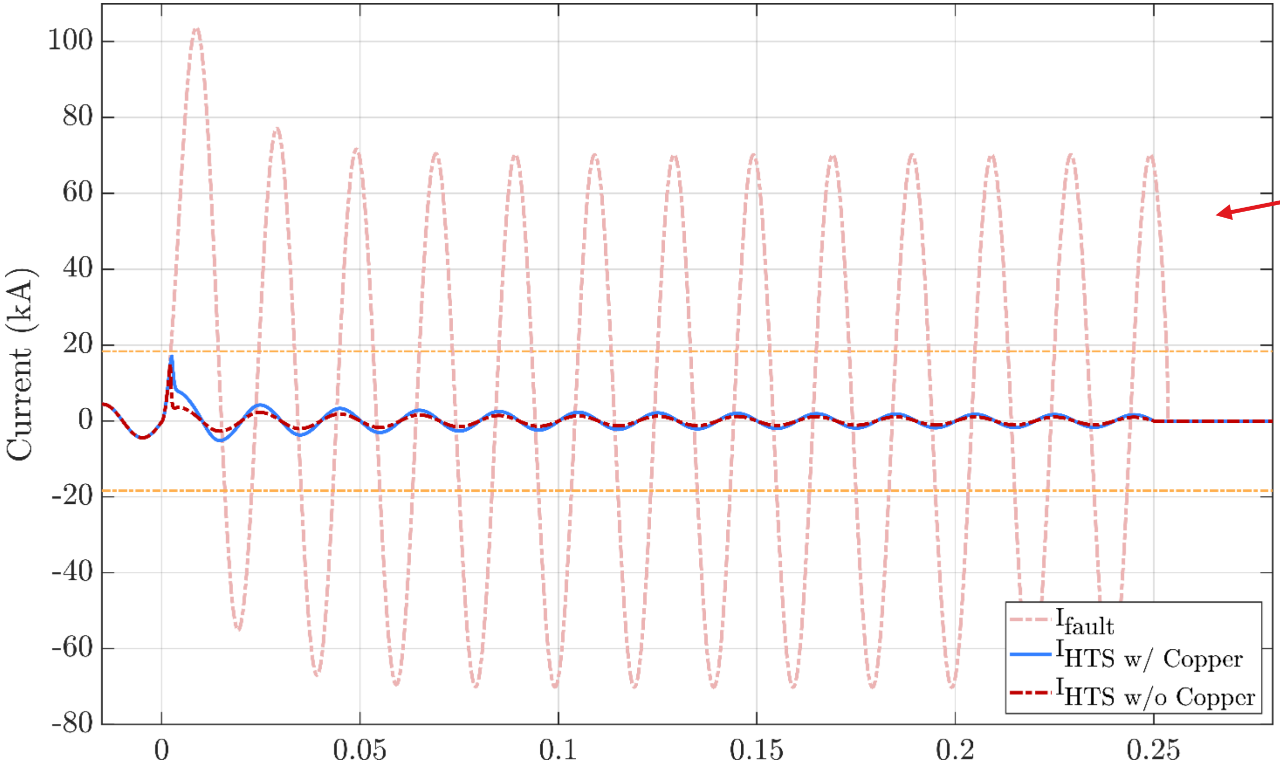
Vergleichende Studie zwischen supraleitendem resistivem Fehlerstrombegrenzer "SSB" und supraleitendem induktivem Fehlerstrombegrenzer "SmartCoil"

– Technische und wirtschaftliche Machbarkeit –

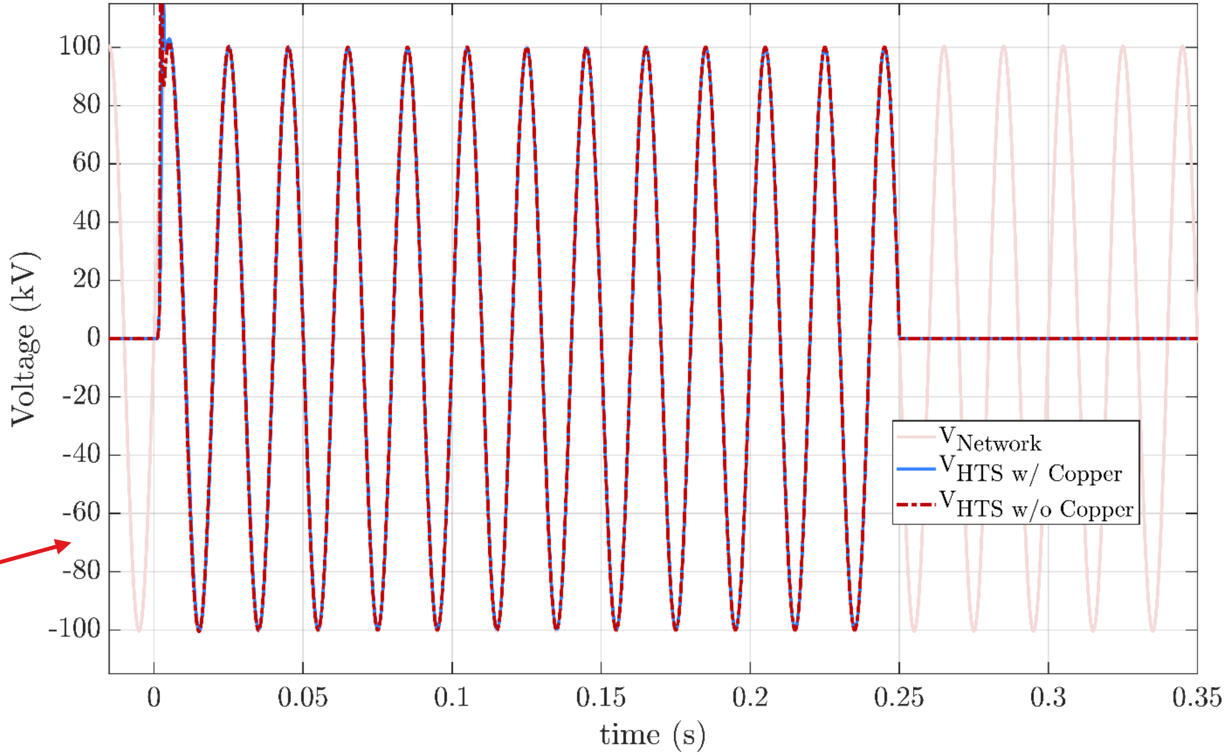
Version: 4.2.2022

VISION ELECTRIC Super Conductors
KIT

Superconducting Fault Current Limiters (SFCL) - 110 kV Design



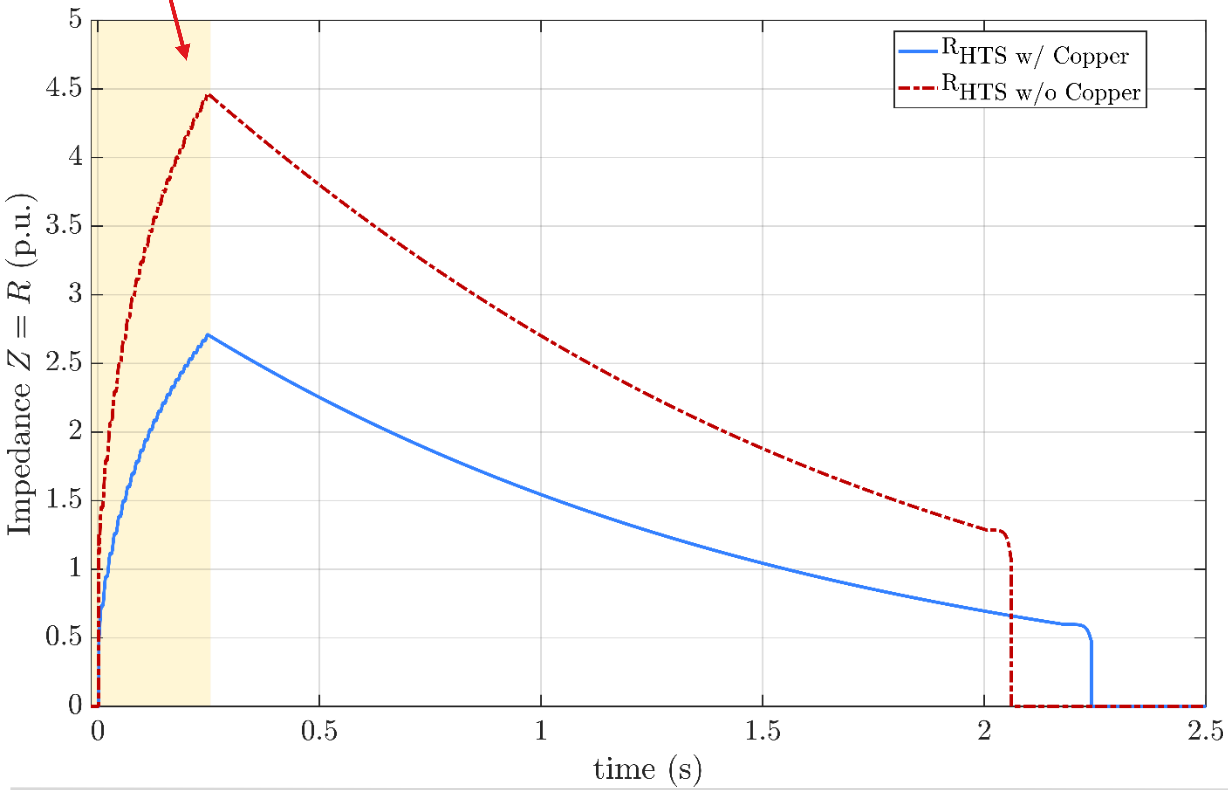
- 50 kA Fault Current limited below 18 kA
  - Fault Duration: 250 ms

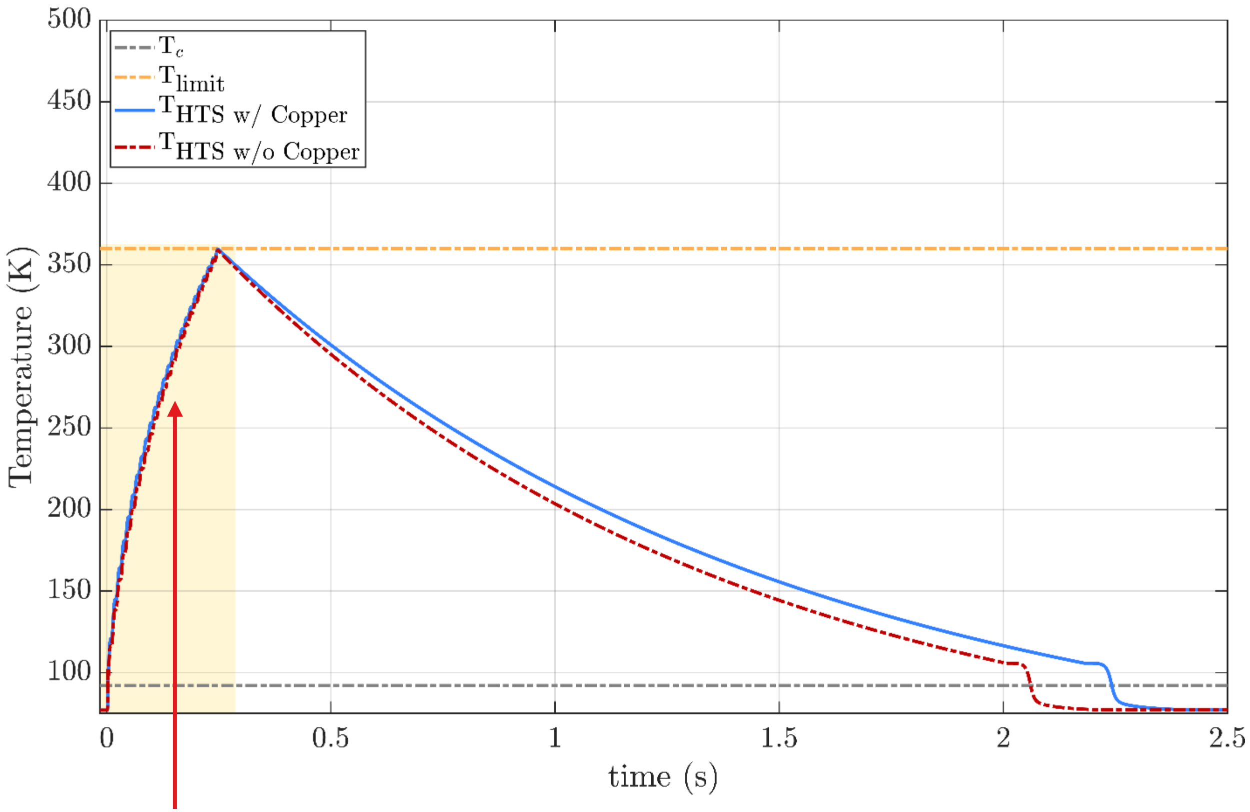


- No voltage drop over SFCL before fault period
  - No losses under normal conditions

Superconducting Fault Current Limiters (SFCL) - 110 kV Design

- Immediate Resistance development after fault ocurrence
  - Overshoot of HTS Critical Current

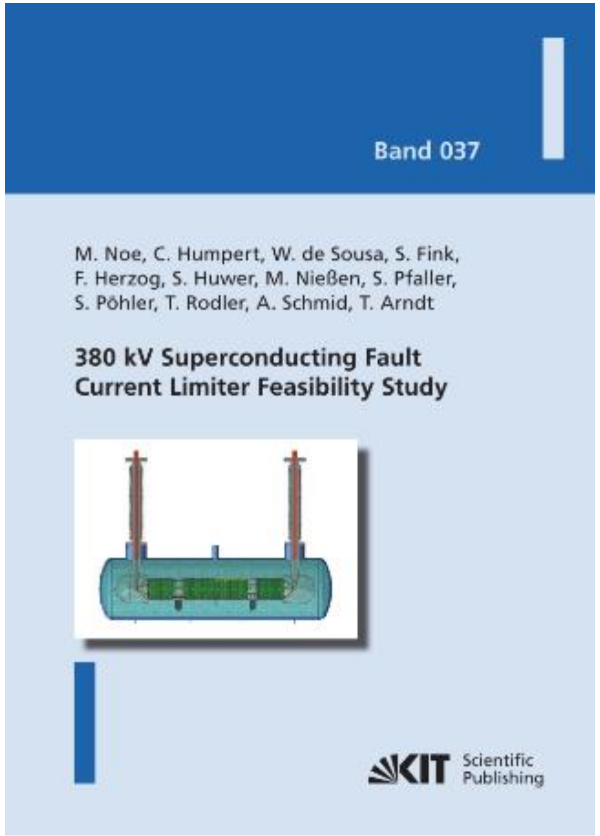




- Designed to prevent temperature higher than 360 K
  - T > 360 K = Permanent damages of the SFCL
- Recovery within 10 s

Superconducting Fault Current Limiters (SFCL)

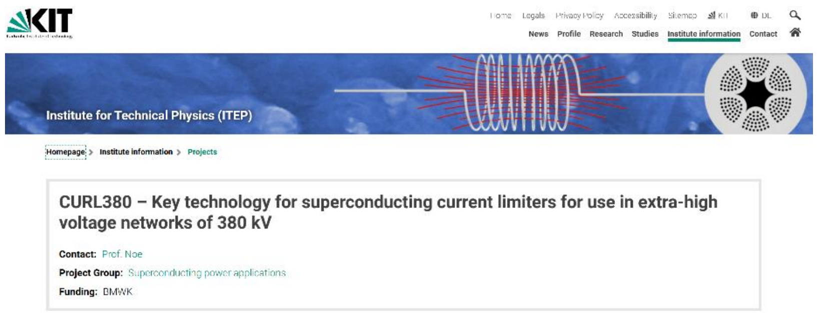
- Actually, the integration of a 110 kV SFCL in the network of Münich is under investigation at KIT
  - Determine the better instalation location → coupling southern and northern
  - Increases systems **reliability**
- **In general, the interest for SFCL in Power systems increases**
  - Nexans + SNCF Réseau – France – SFCL for Rail Electrification (2025)
  - SuperGrid Institute – France – 50 kV SFCL Prototype for AC & DC Grids (2025)
  - Siemens Energy – Germany - SFCL systems for European transmission operator (2014)
  - ASG Superconductors - Italy – 36 kV SFCL Device for Grid Integration (2018)
  - KEPCO – Korea – 22.9 kV Hybrid SFCL (2009 - 2011)
  - KIT – Germany - 380 kV Superconducting Fault Current Limiter Feasibility Study (2023)



380 kV Superconducting Fault Current Limiter – CURL380

Gefördert durch:
Bundesministerium für Wirtschaft und Klimaschutz

- **CURL380 – 04/2025**
  - In cooperation with German HV Operators
  - 380 kV, 5 kA, 3.3 GVA
  - **Funded by the Federal Ministry for Economic Affairs and Climate Action of Germany.**


Institute for Technical Physics (ITEP)

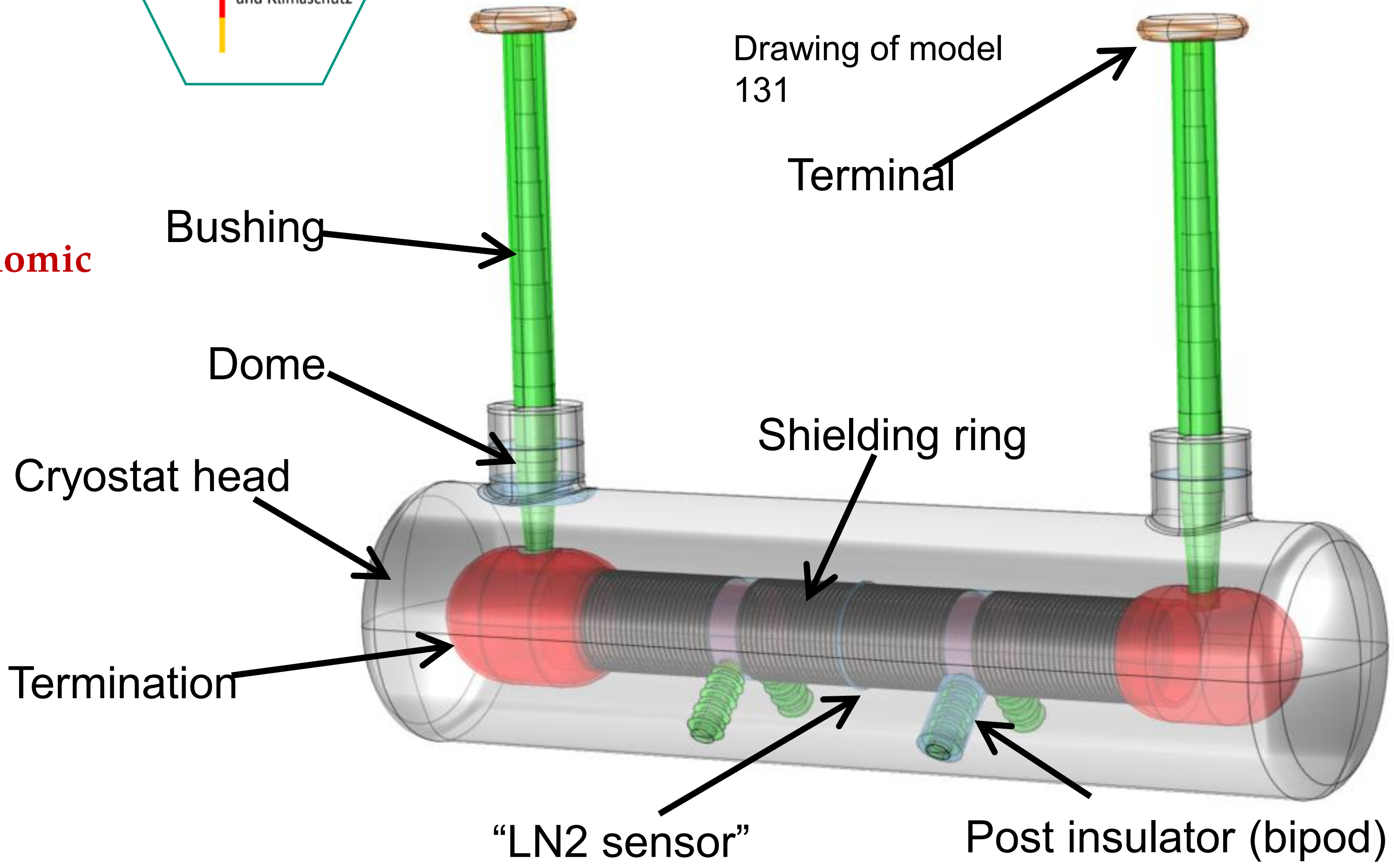
Homepage > Institute information > Projects

CURL380 – Key technology for superconducting current limiters for use in extra-high voltage networks of 380 kV

Contact: Prof. Noe

Project Group: Superconducting power applications

Funding: BMWK

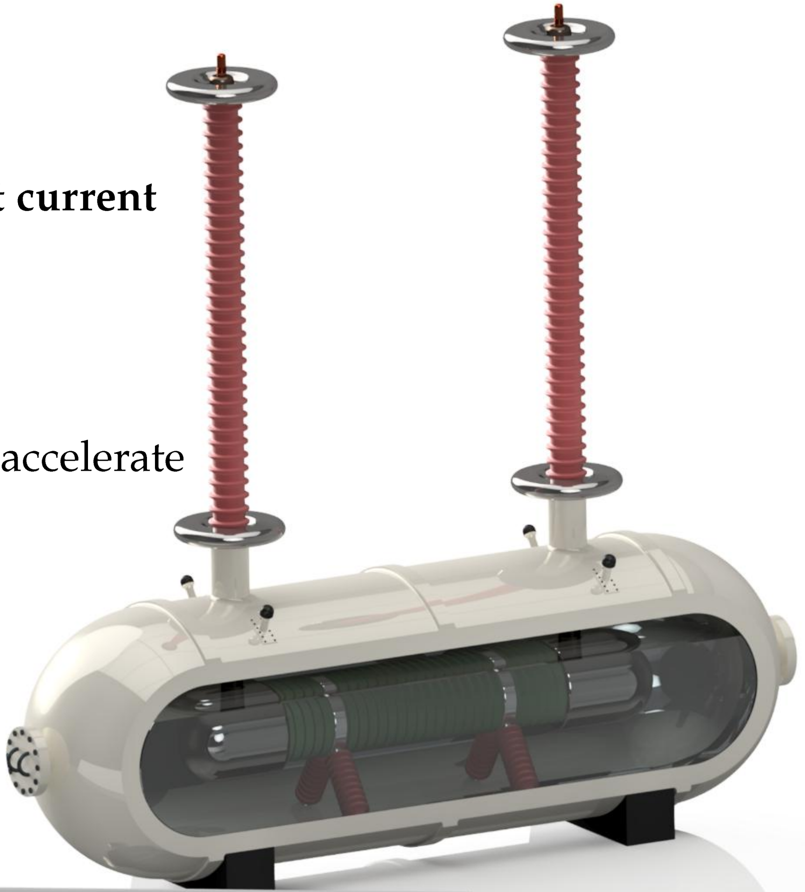


Key Takeaways

- **Superconducting technologies** such as SFCLs and HTS cables offer unparalleled efficiency, compactness, and current-handling capabilities

- They address two of the most critical challenges in modern power networks: **rising fault current levels** and the need for **higher transmission capacity**.

- Collaboration between **grid operators**, **manufacturers**, and **policymakers** is essential to accelerate deployment and standardization.



Outulook and Future Directions

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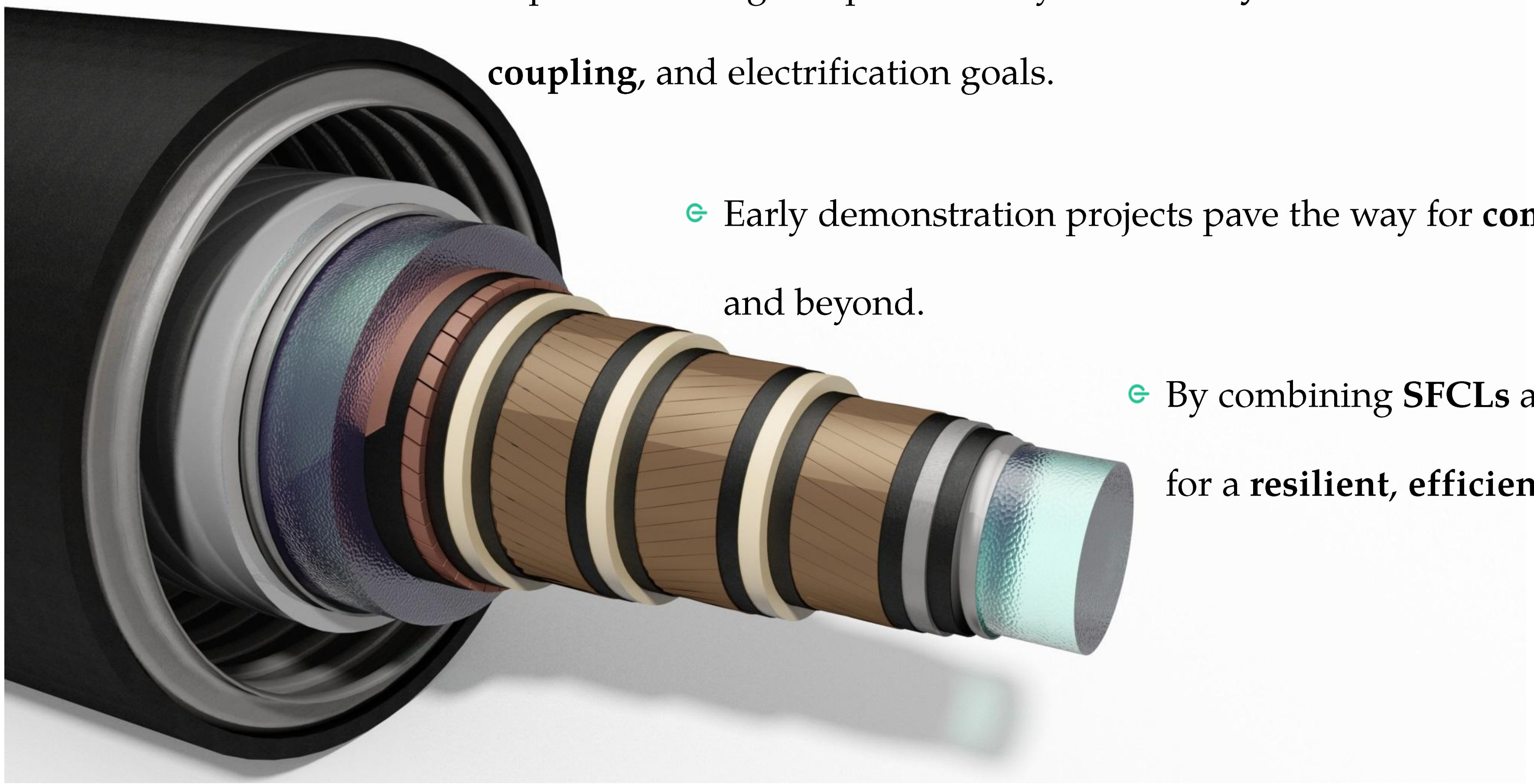
- Continued innovation will further improve **material performance, cooling efficiency**, and **system reliability.**



- Superconducting components may become **key enablers for renewable integration**, **sector coupling**, and electrification goals.
- Early demonstration projects pave the way for **commercial-scale adoption** across Europe and beyond.
- By combining **SFCLs** and **HTS cables**, we unlock the potential for a **resilient**, **efficient**, and **future-proof transmission grid**.

Closing Statement

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Superconductivity is no longer a laboratory curiosity. It is the basis of the resilient, efficient, and decarbonized power grid of tomorrow. The question is not *if* we will build it, but *how fast* we choose to make it a reality.

Thank you! 매우 감사합니다 !

Dr. Wescley Tiago B. de Sousa

Senior Researcher

Karlsruhe Institute of Technology – Institute for Technical Physics

Group Leader - Numerical Simulations of Superconducting Power Components

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