HTS power transmission (and distribution): status and prospects

Antonio Morandi

DEI – Guglielmo Marconi
Dep. of Electrical, Electronic and Information Engineering
University of Bologna, Italy

antonio.morandi@unibo.it

CCA (Coated Conductor for Applications) 2025 workshop

Tuesday, March 11, 2024, CERN - Geneve, Switzerland

International Workshop on Coated Conductors for Applications

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Outline

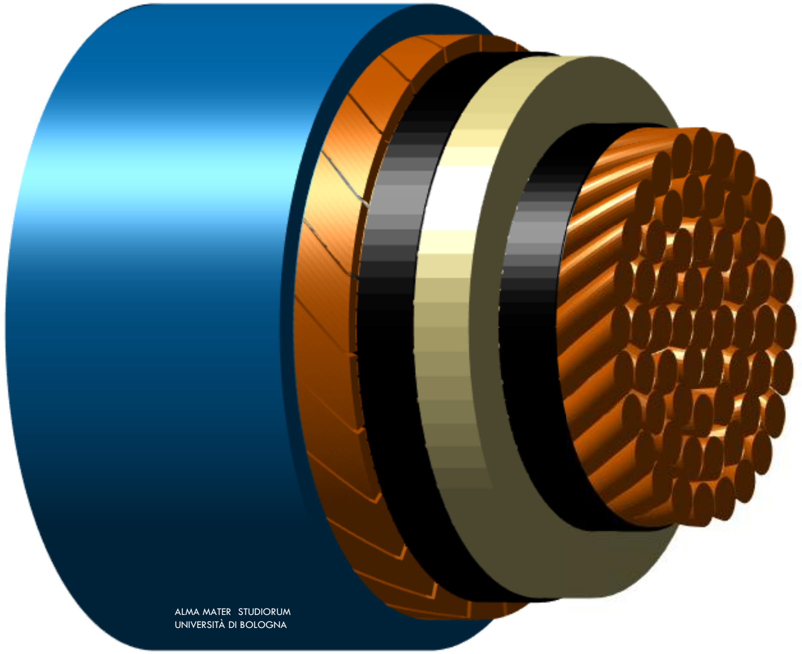
HTS power cables:

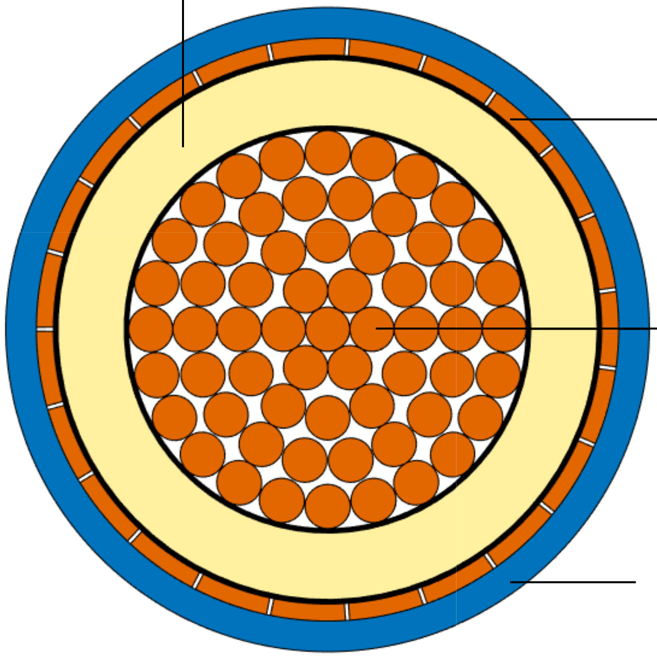
- **What they are**
  - **General characteristics**
  - **State of the art**

- **What they can do for you - power cable need today and tomorrow**
  - **How much**
  - **Which type**

The role of HTS power cables

Layout of a conventional HV power cable





A metallic shied (copper) is added to HV voltage cables in order to

- Equalize electric field stress in the cable insulation
- Provide shielding of electromagnetic field + return path for cable neutral and fault current

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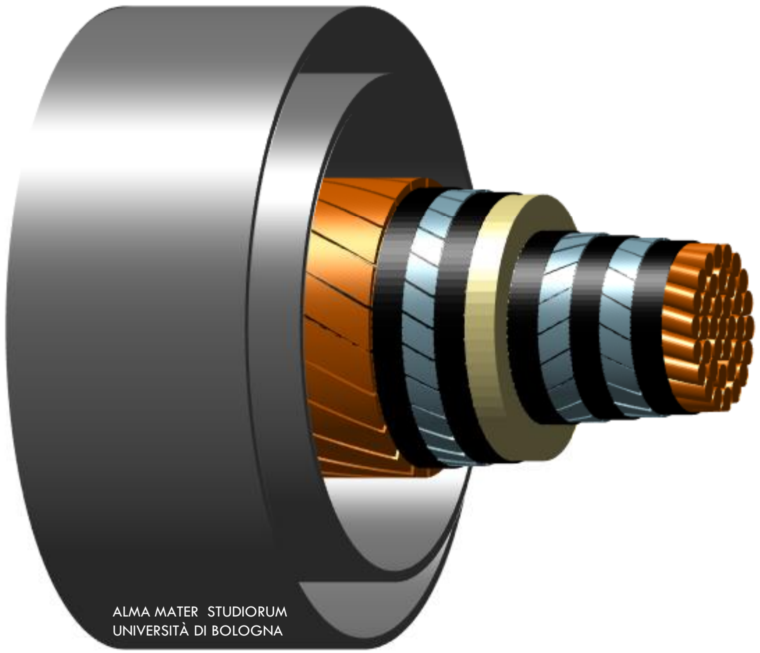
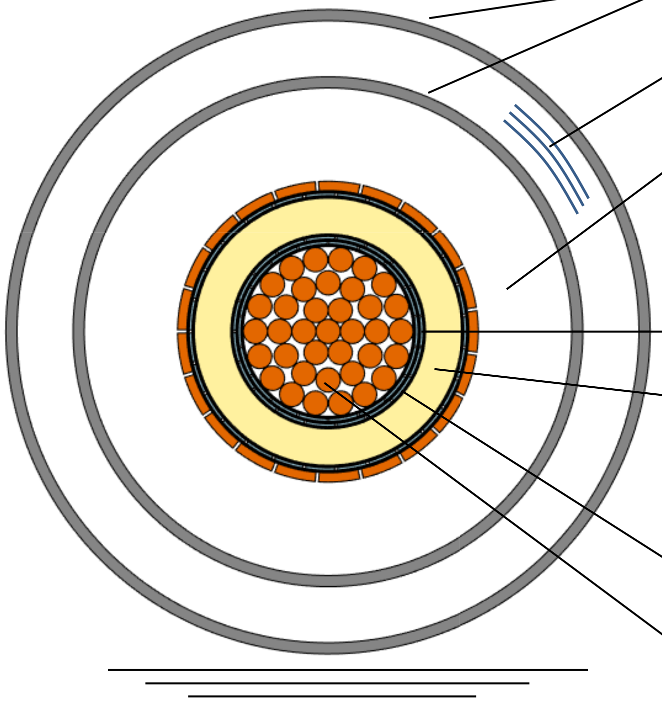
Layout of a cold dielectric superconducting power cable

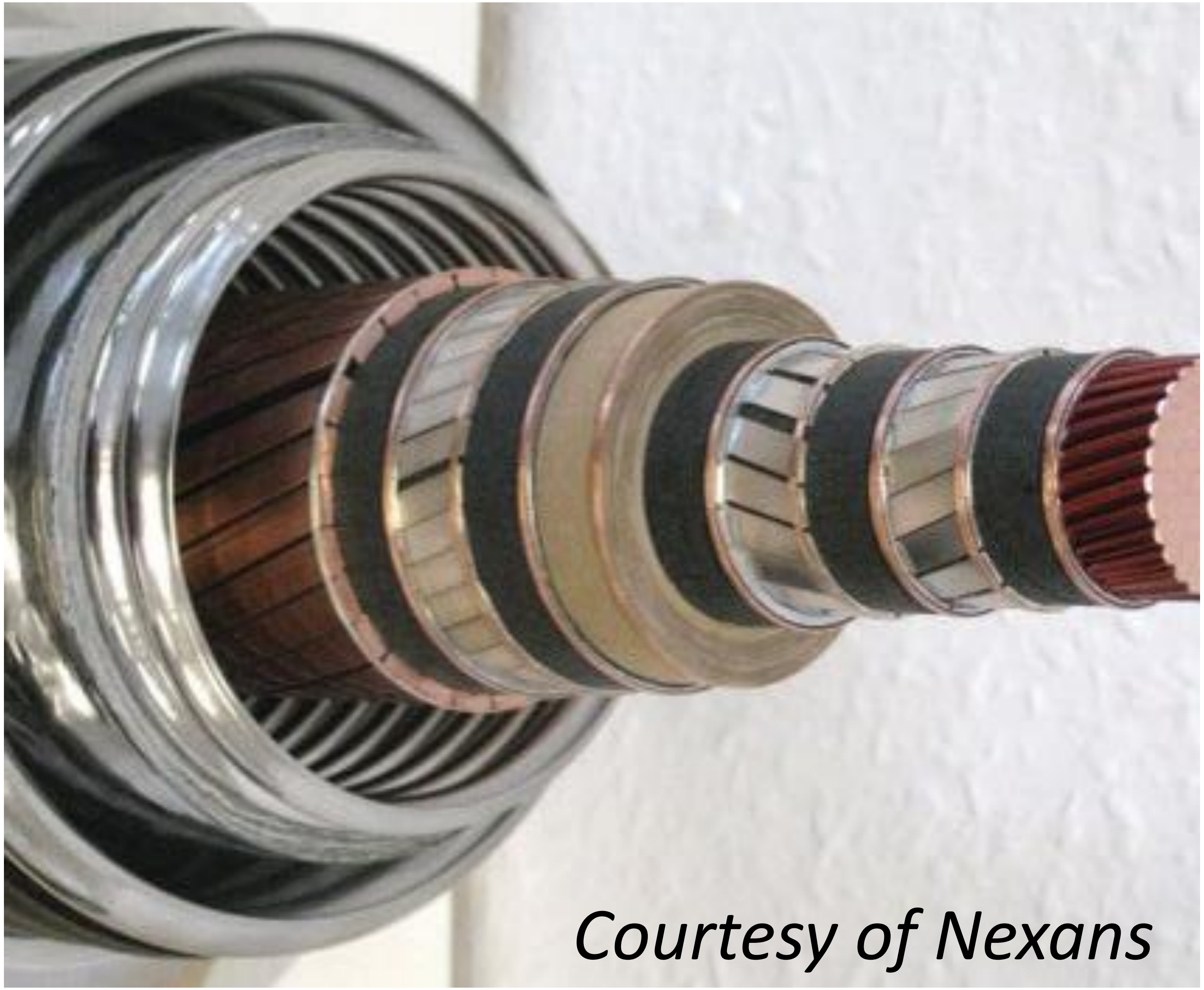




A shield is required to

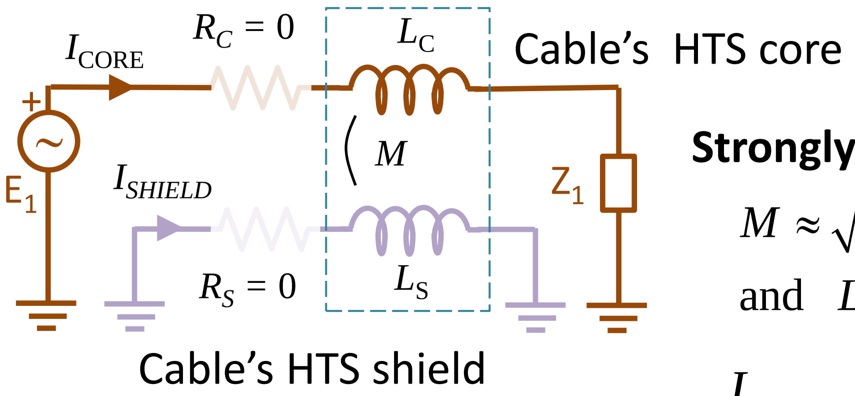
- Equalize electric field stress in the cable insulation
- Shield EM field + provide return path for neutral and fault current
- **Prevent induced currents and loss in metallic pipes** →

A shield requiring as much SC as the core is needed in AC applications


Courtesy of Nexans

Shield design of DC superconductor cables

DC cable system (pipes not drawn)

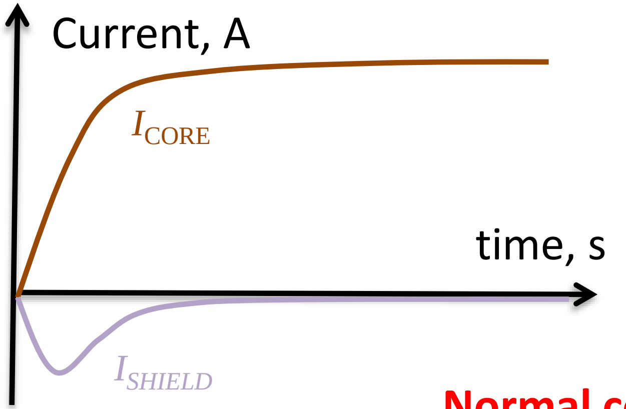


Strongly coupled

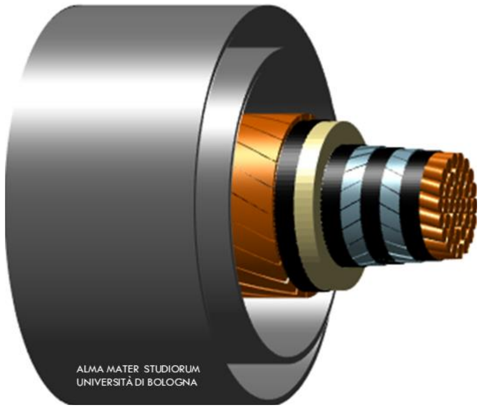
$$M \approx \sqrt{L_C\, L_S}$$

and $L_C \approx L_S$

$$I_{SHIELD} \approx I_{CORE}$$



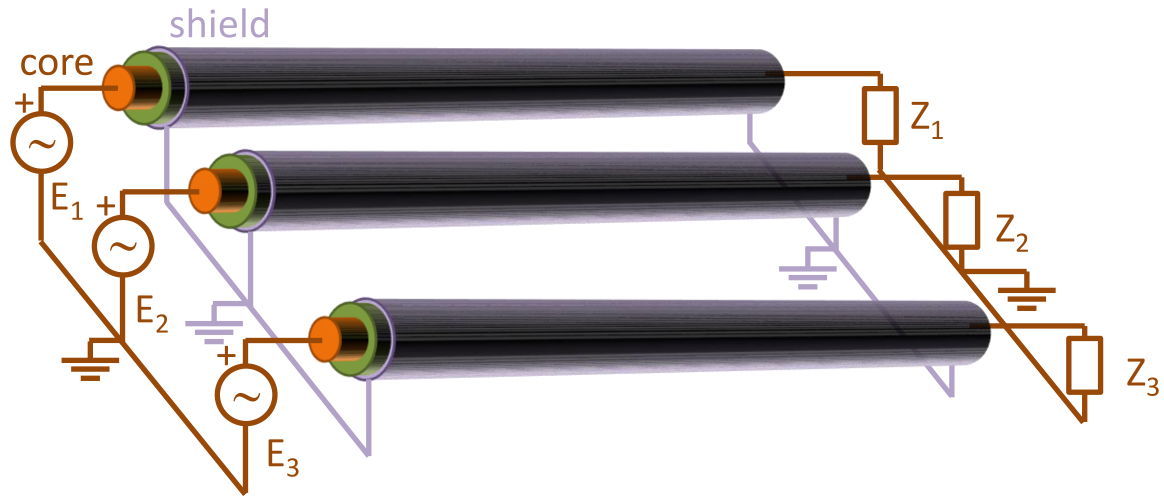
- Current is induced in the shield only during transients (energization and fault)
- No significant heating is added to the cable also in case of copper shield

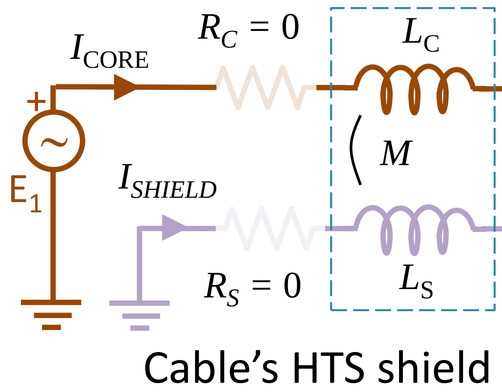


Normal conducting shield for DC superconducting cables is viable

Shield design of AC superconductor cables

AC cable system (pipes not drawn)





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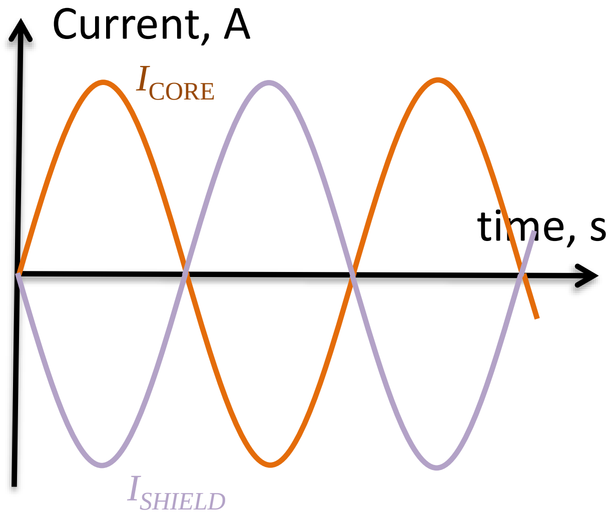
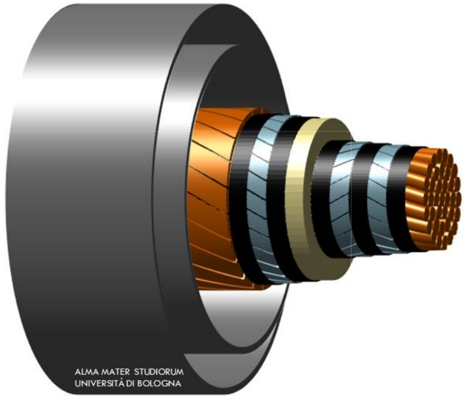
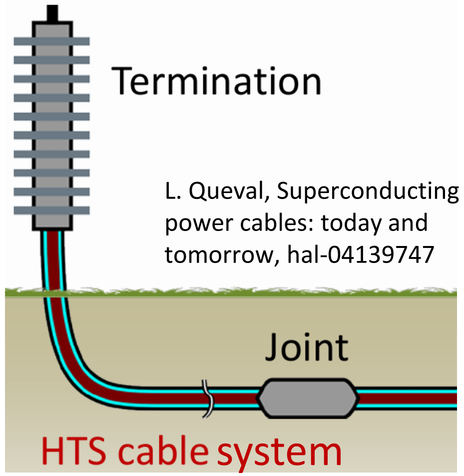


- Induced currents in inner metallic pipe and additional heat load are prevented with the HTS shield
- Practically the same AC current (with 180° phase shift) of the core circulates in the shielding steady AC regime. **The same amount of SC as for the core is needed for the shield**



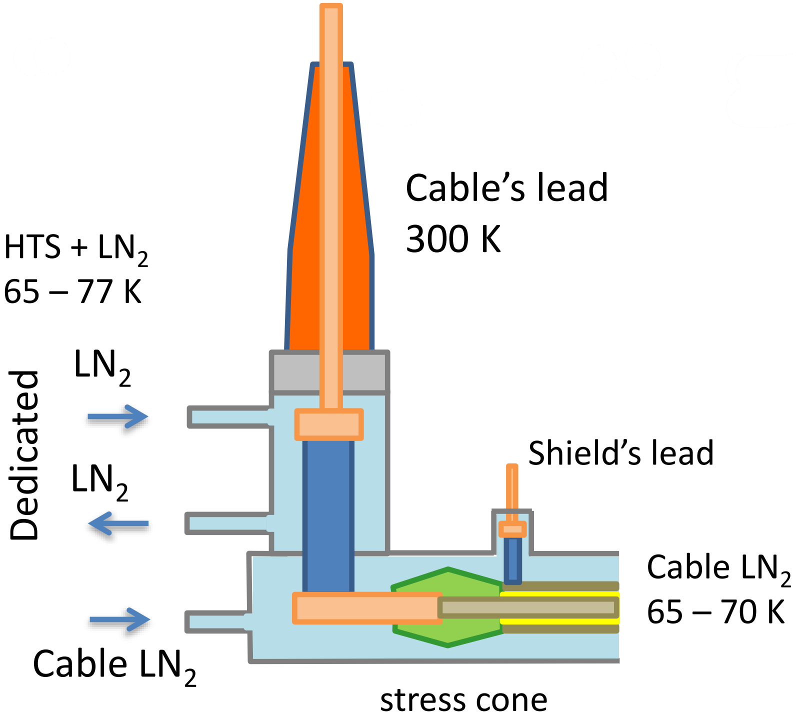
Essential “accessories” of HTS (and conventional) power cables: terminations and joints



L. Queval, Superconducting power cables: today and tomorrow, hal-04139747

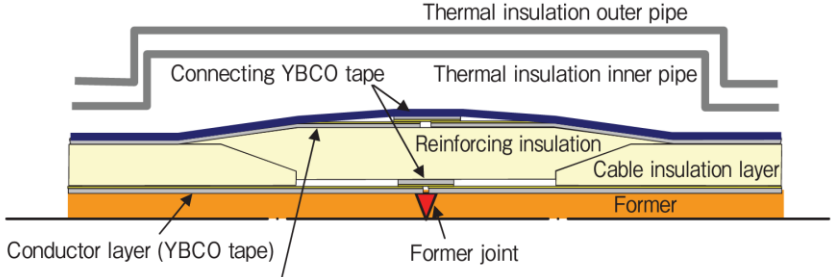
Termination of the LIPA1 HTS cable

Schematic of the termination



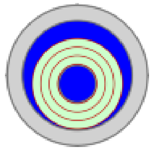
- **Connection to the grid**
- **Management of electric stress**
- **Management of thermal gradient**
- **Management of mechanical contraction during cool down**

Schematic of the joint

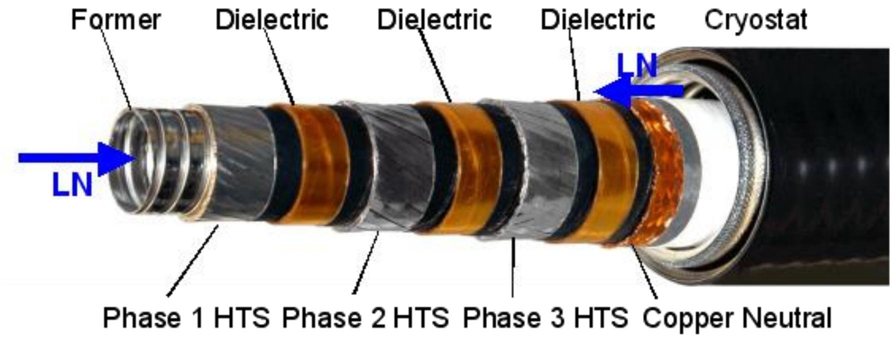


S. Mukoyama et al., Development of YBCO High-Tc Superconducting Power Cables, Furukawa Review, No. 35 2009

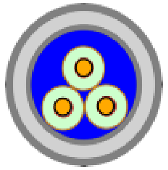
AC three phase (or DC bipolar) arrangements



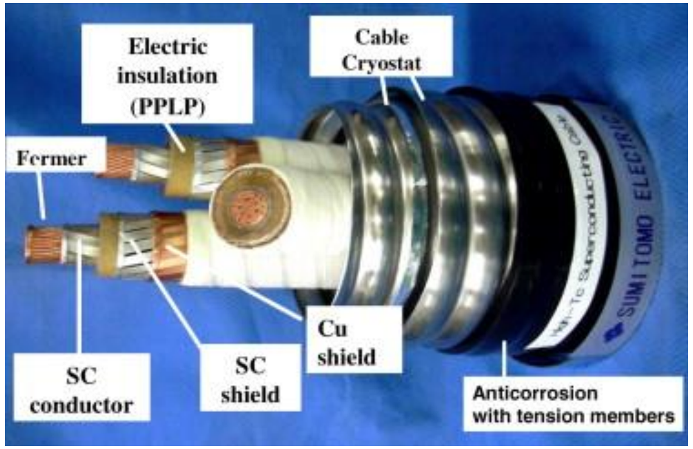
10 – 20 kV



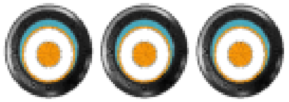
Concentric phases



30 – 100 kV



Separate phases with shared cryostat



> 100 kV

voltage

Separate phases and cryostat

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The HTS cable system

Thermohydraulic design:

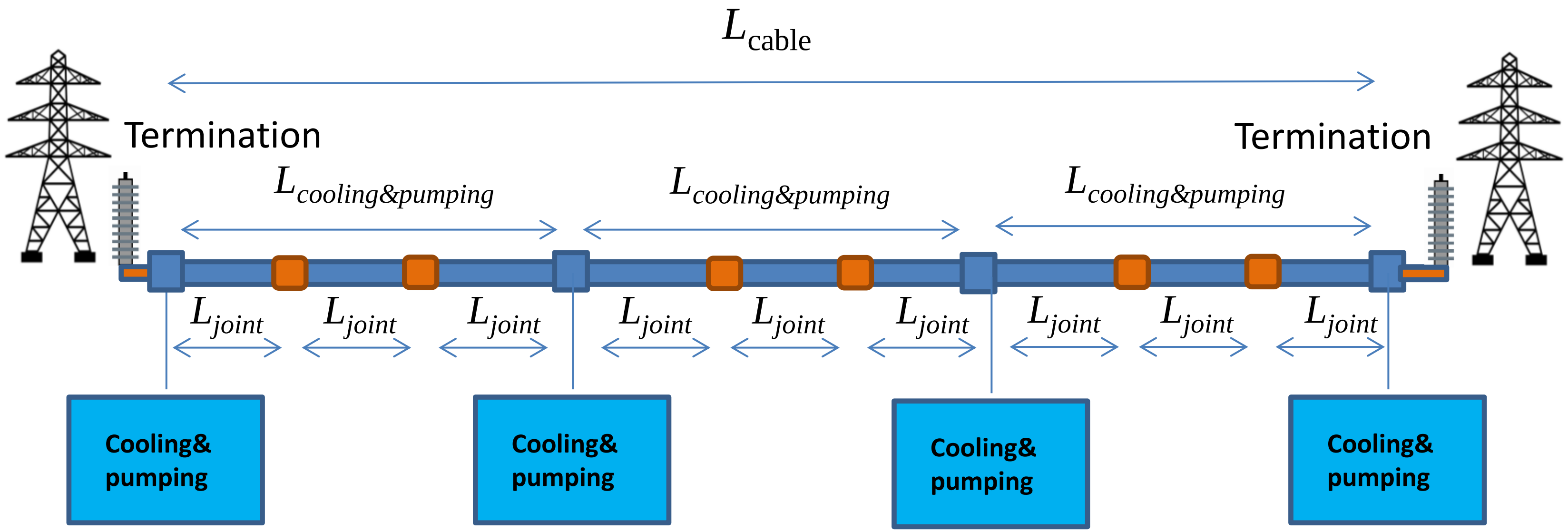
Distance $L_{cooling\&pumping}$ between cooling&pumping stations must be compatible with acceptable temperature and pressure, and may differ from overall length L_{cable} of the cable system

$$\frac{\Delta P}{\Delta x}(D_{\text{o}},\dot{m}) \le \frac{P^{\text{in}} - P^{\text{out}}_{\text{min}}}{L_{cooling\,\&\,pumping}}$$

$$\frac{\Delta T}{\Delta x}(D_{\text{o}},\dot{m}) \le \frac{T^{\text{in}} - T^{\text{out}}_{\text{max}}}{L_{cooling\,\&\,pumping}}$$

Outer diameter D_{o}

Mass flow $\dot{m}$



$L_{cooling\&pumping}$ may reach up to 20-30 km, depending on the thermohydraulic design $(D_{\text{o}}\,,\,\dot{m})$

Distance L_{joint} between joints in the range 100-500 m due to manufacturing and transportation limits

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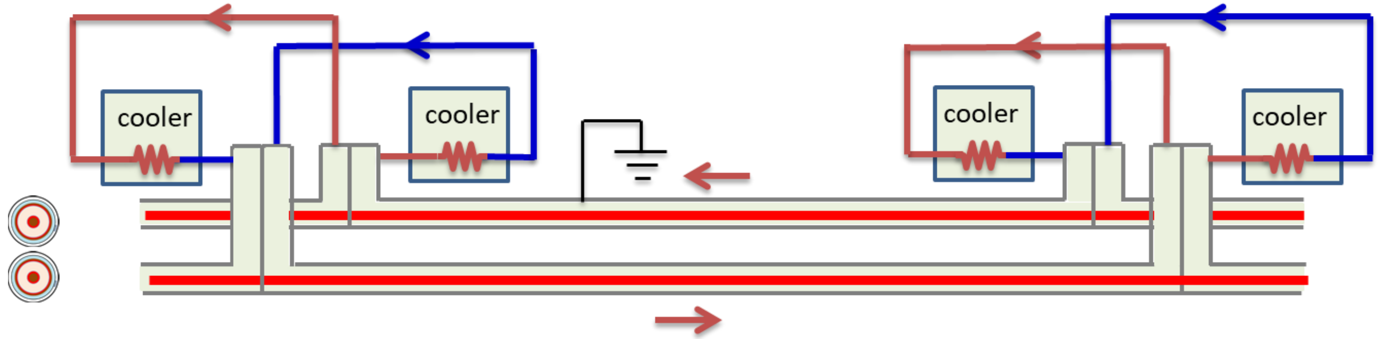
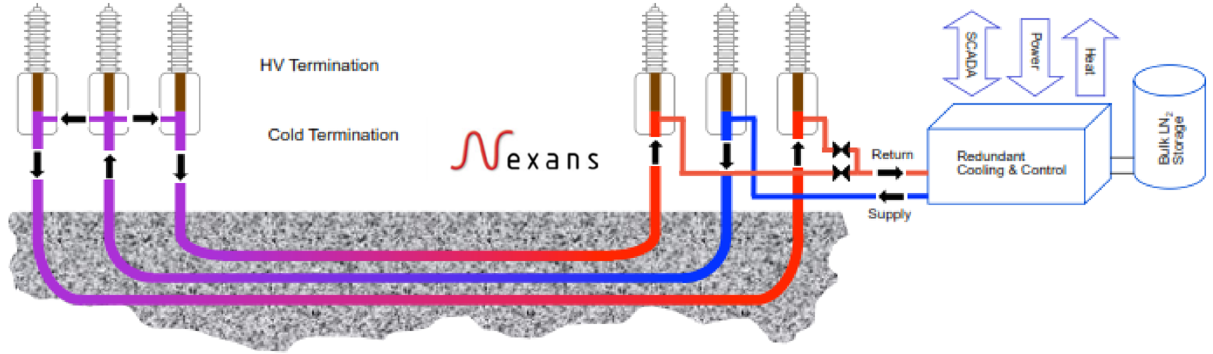
Different circulation schemes of coolant between cooling and pumping stations can be adopted depending on the layout of the cable sytem and in particular:

- **Number of phases or poles per cryostat**
- **Internal or external return path of coolant**

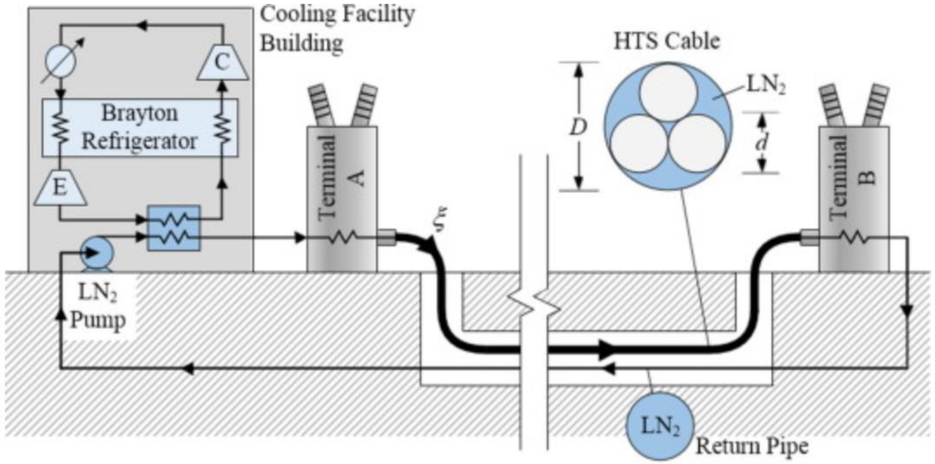
Example 1 - closed-loop circulation of coolant for a long DC cable system made of two monopoles with distinct cryostats



Example 2 - closed-loop circulation of coolant for the LIPA1 three phase HV cable



Example 3 - closed-loop circulation of coolant for the Shingal three phase MV concentric cable



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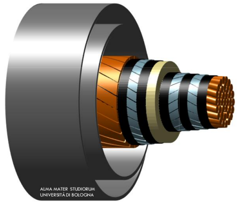
Ho-Myung Chang et al., Cryogenics, 83, 2017, Cryogenic design of liquid-nitrogen circulation system for long-length HTS cables with altitude variation

Motivations for SC power cables - 1. more power and/or less voltage



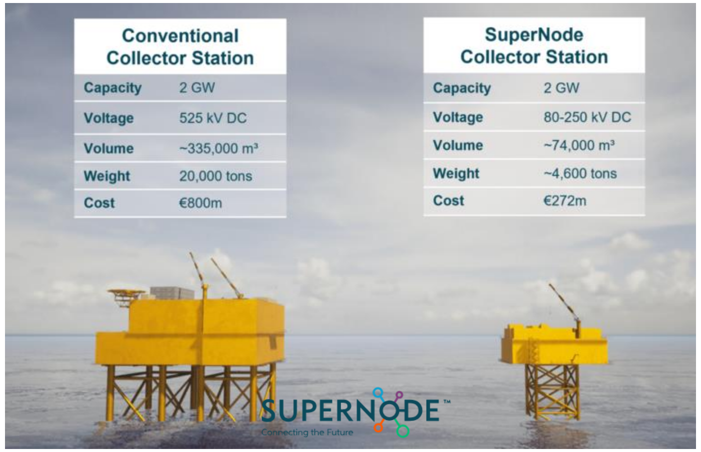
higher transport current I, up to 5-10 more than conventional cable through same section

$$P = V\,I$$

More power at the same voltage

Less voltage at the same power

(+ *operation at constant T*)



- Reducing right of way & soil occupation
- Much faster installation

- Use of existing utility civil infrastructures
- Use of other existing civil infrastructures and possibility of new integrated energy infrastructures concepts

- Simplify electric equipment: conversion stages, converters' layout, platform ….

Motivations for SC power cables - 2. Less losses (cooling included)

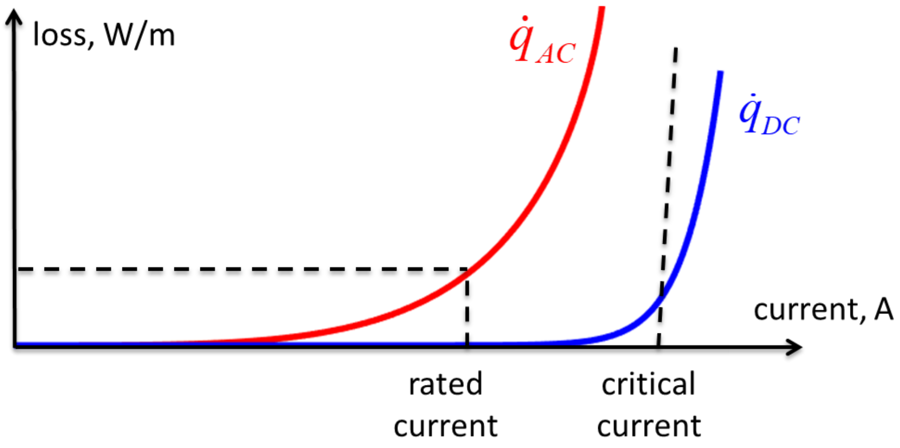
Electromagnetic losses per unit length (W/m) of current carrying superconductors:

AC transport current losses - Hysteretic diffusion of B and J

$$\dot{q}_{AC} = f\,\frac{\mu_0 I_c}{\pi}\left[(1-i)\ln(1-i)+(1+i)\ln(1+i)-i^2\right] \qquad i=\frac{I_{peak}}{I_c}$$

DC transport current losses - Flux creep

$$\dot{q}_{DC} = k\, i^n \quad (W/m) \qquad i=\frac{I_{peak}}{I_c}$$



Typical losses at 65-80 K in cold dielectric power cables

C. E. Bruzek, "Introduction to superconducting power cable systems", ESAS Summer School, Bologna 2016

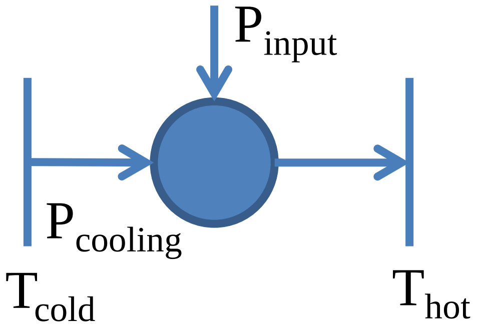
	Dependence	Parameters	Losses at 65-77 K	Losses at RT
Radiation	Room temperature	Super-insulation spacer and diameter	0,5 to 2 W/m	12,5 à 50 W/m
HTS AC losses	Transported current Magnetic field distribution	Cable design (pitches, diameter,..)	0,05 to 1 W/kA.m	1,25 to 15 W/kA.m
Dielectric AC losses	Voltage level	Capacity of the cable and material (tg δ)	Up to 1 W/m	Up to 12,5 W/m for 220 kV
Eddy current AC on the cryostat	Magnetic field distribution	Cable design (pitches, diameter,..)	0,05 to 0,1 W/kA.m	1,25 to 2,5 W/kA.m

Electromagnetic

Absent for DC cables

For a Cu cable typycal 20 W/kAm

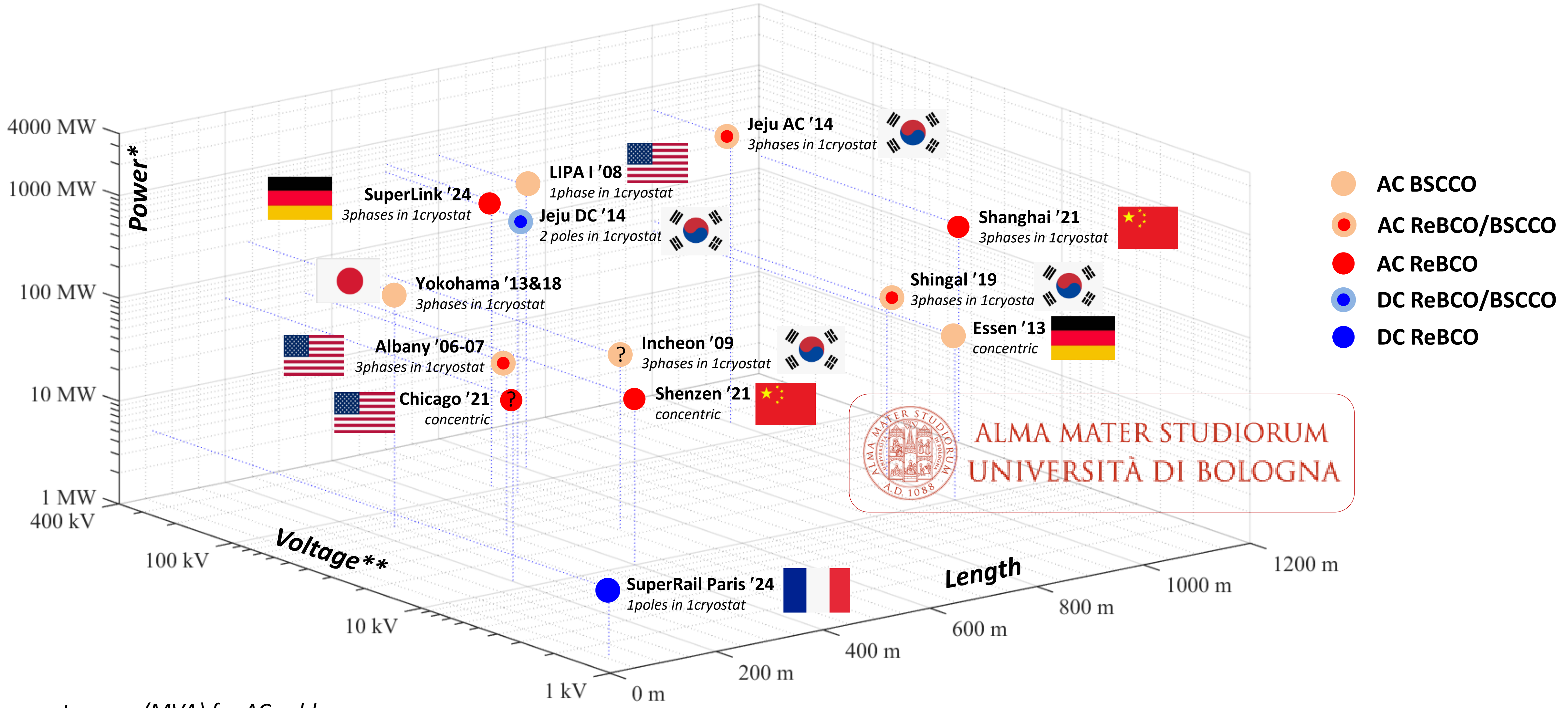
In DC cables no practical loss occurs in the superconductor



$$COP = \frac{\text{Watt of input power}}{\text{Watt of heat removed}}$$

- Cooling power a SC cable can be estimated to be approximately 25% of the losses of conventional cable system at full load
- Cooling energy over discontinuous operation (e.g. wind power transm.) may increase up to approx. 60%

State-of-the-Art of SC cable technology – main operational or demonstration projects (AC and DC)



* *Apparent power (MVA) for AC cables*

** *Line-to-line RMS value for AC cables / Pole-to-ground value for DC cables*

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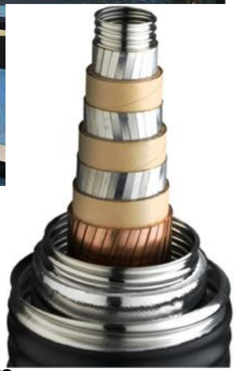
Chicago



AMSc
12 kV, 3 kA,
200 m
Single coaxial design
HTS material?
Energized 2021

Figure:
AMSC

LIPA

Nexans
138 kV, 2.4 kA,
600 m
Single coaxial design
BSCCO 2223
Energized 2008

Figure:
Nexans

Shanghai

LS Cable
35 kV, 133 MVA, 1200 m
2G HTS
Energized 2022

Outline

HTS power cables:

- What they are
  - General characteristics
  - State of the art

- What they can do for you - power cable need today and tomorrow
  - How much
  - Which type

The role of HTS power cables

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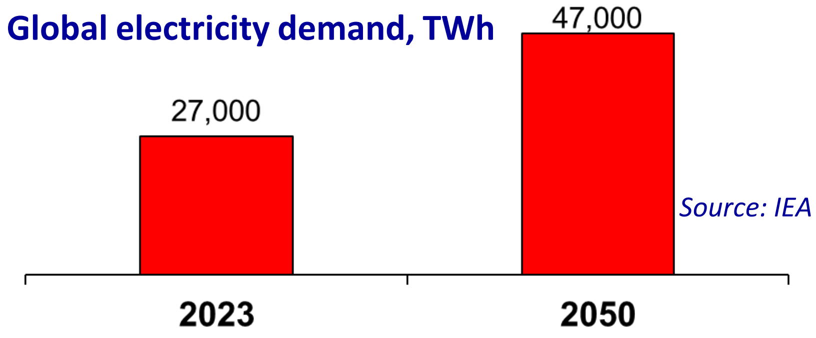
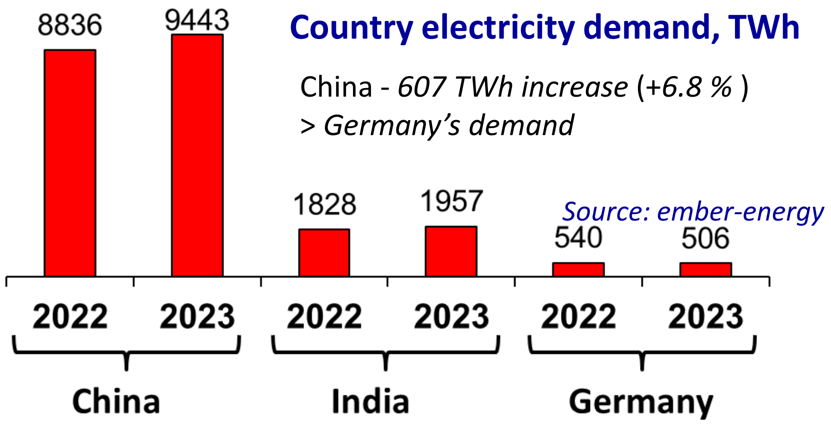
Global electricity demand – today and tomorrow

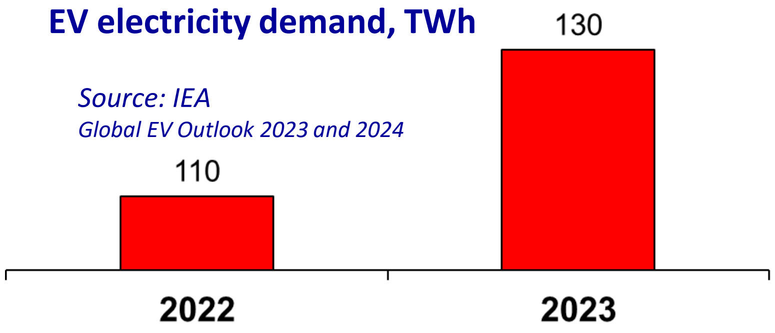
Growth in global electricity demand is set to accelerate at an average rate of 4% in the coming years due to:

1. **Growth of emerging economies**
2. **“Electrification of everything” to meet decarbonization (i.e. electrification of terrestrial, marine and air transportation, more electric buildings, more electric heating in industry**
3. **Exponential growth of new electricity needs: data centers**

Over the next years, we will need to add as much power capacity as it took us a century to build

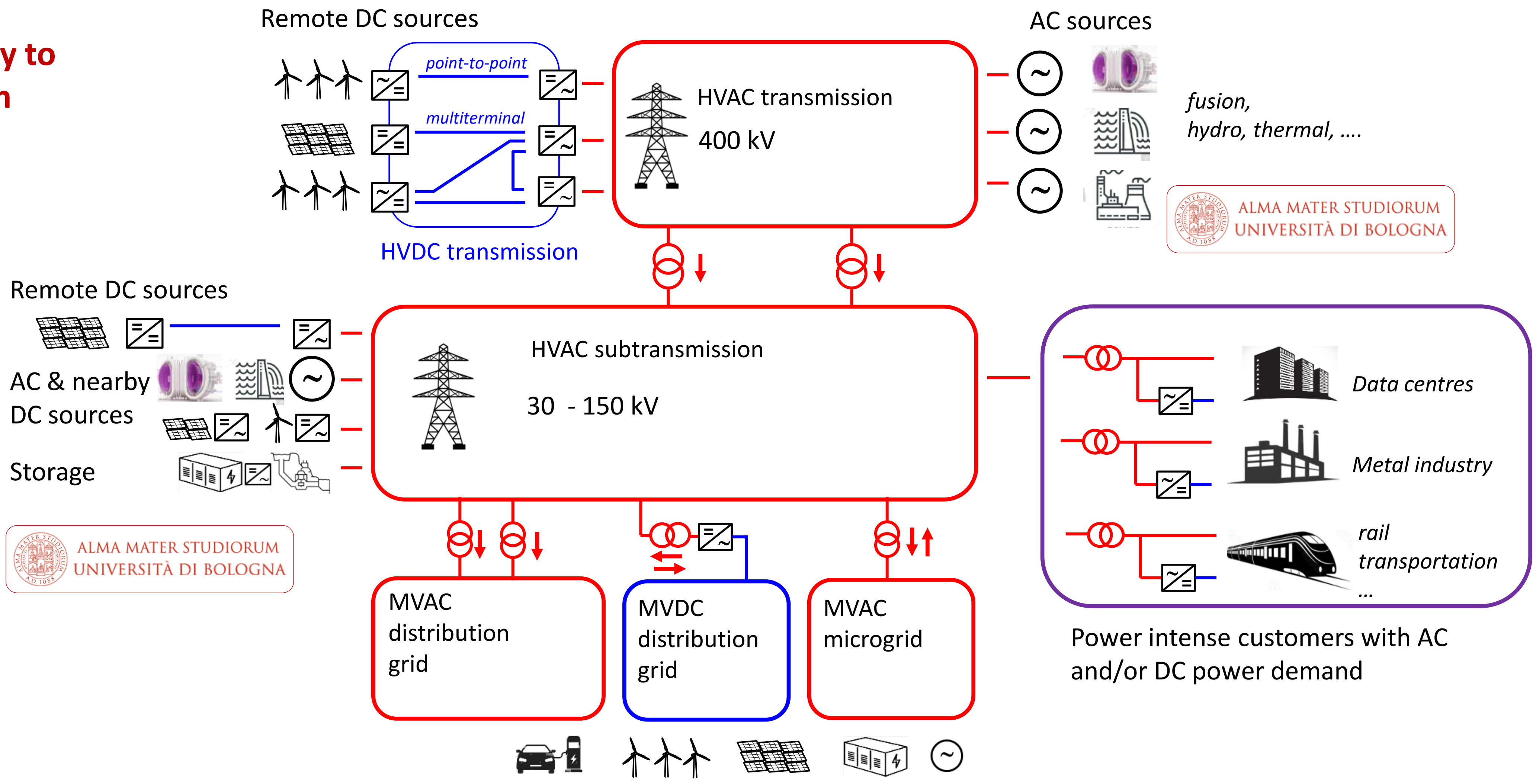


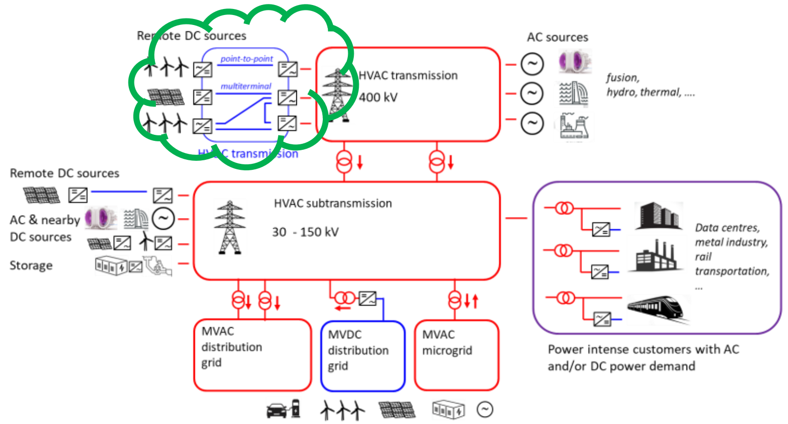




Addressing the challenge of **growing and transforming** electricity demand

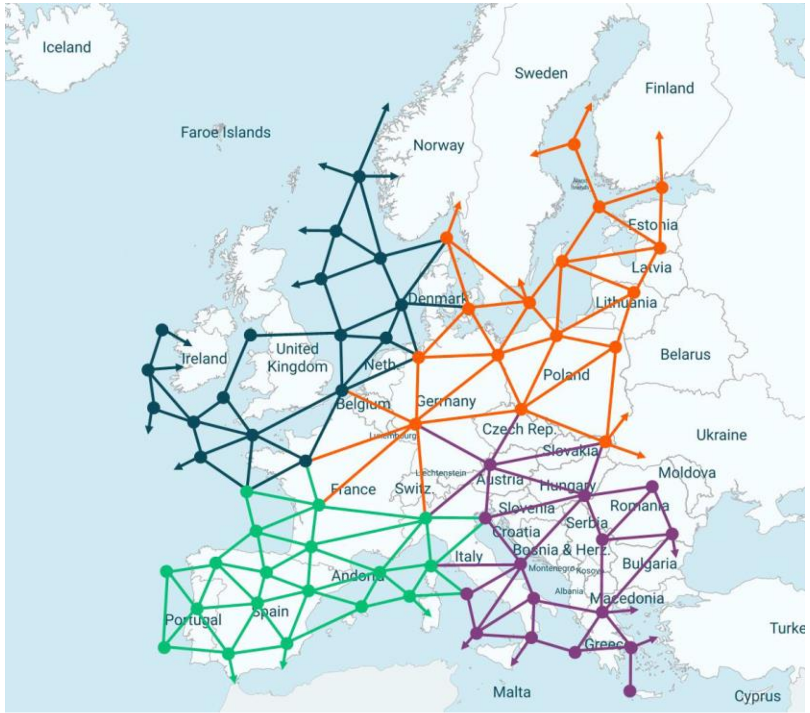
Schematic pathway to grid modernization and expansion





- **EU strategy on offshore renewable energy:** 60 GW of offshore wind and at least 1 GW of ocean energy by 2030, with a view to reach by 2050 300 GW and 40 GW
- **EU Solar Energy Strategy:** over 320 GW of solar photovoltaic by 2025 (more than doubling compared to 2020) and almost 600 GW by 2030
- **India's wind power potential** is estimated to be 695.50 GW at 120 meters and 1163.9 GW at 150 meters above ground level.

continental transmission grid



- **Extremely high-power density DC corridors are needed for implementing this vision which can only be achieved trough HTS technology**

Superconductors will do for electricity what fiber optic cables did for telecoms by replacing the twisted pair. They will revolutionise power transfer, enabling ultra high capacity unobtrusive transmission.”

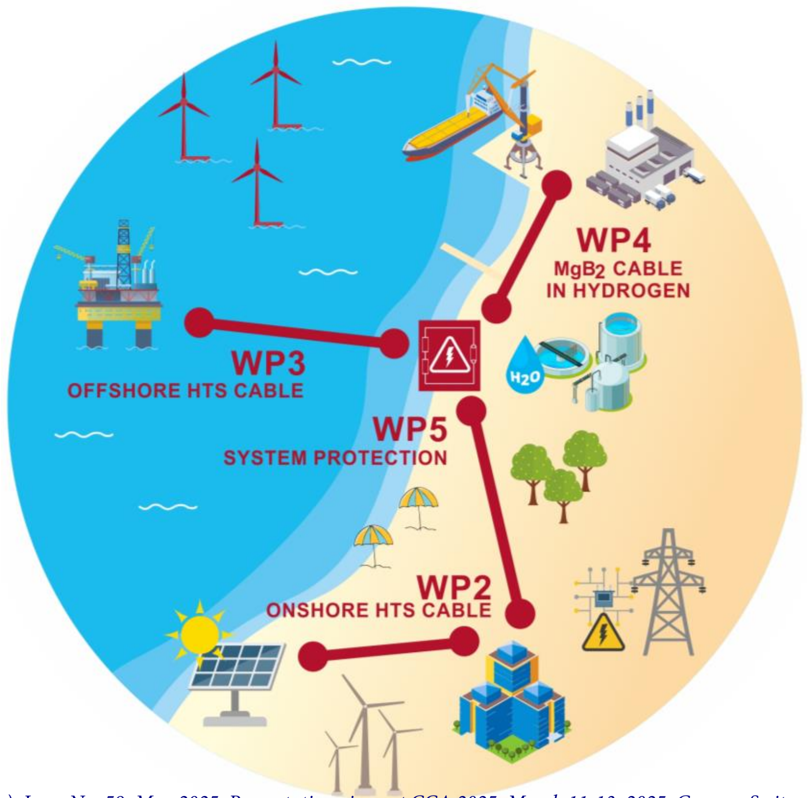
Pat Cox, SuperNode Chairman and Former President of the European Parliament

European Project SCARLET (2022-2027)

SCARLET
Superconducting CAbles foR sustainable Energy Transition

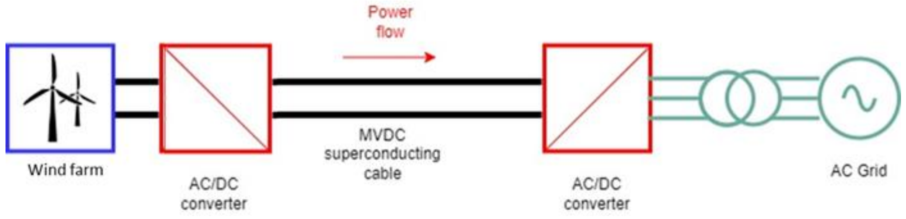
- Goal: develop and industrially manufacture superconducting cable systems at the gigawatt level, bringing them to the last qualification step before commercialization
- Expertise from 15 industry and research organisations in the fields of material sciences, cryogenics, energy systems and electrical engineering

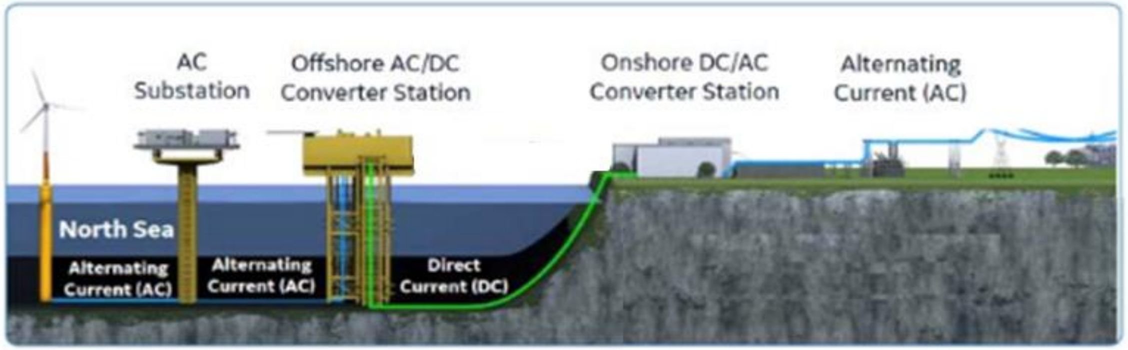
- 3 demonstration work packages
  - long-length onshore superconducting cable systems (WP2)
  - MgB_2 cables in liquid hydrogen (WP4)
  - system protection (WP5)
- 1 work package on architectures of offshore superconducting cable systems (WP3)
- 1 work package for integration studies and economic evaluation (WP1)
- lastly, work packages for communication and coordination (WP6)



The selected case: unidiretional MVDC grid connection 1 GW offshore wind park

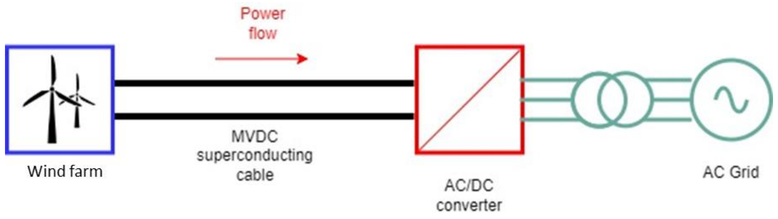
HVDC conventional links

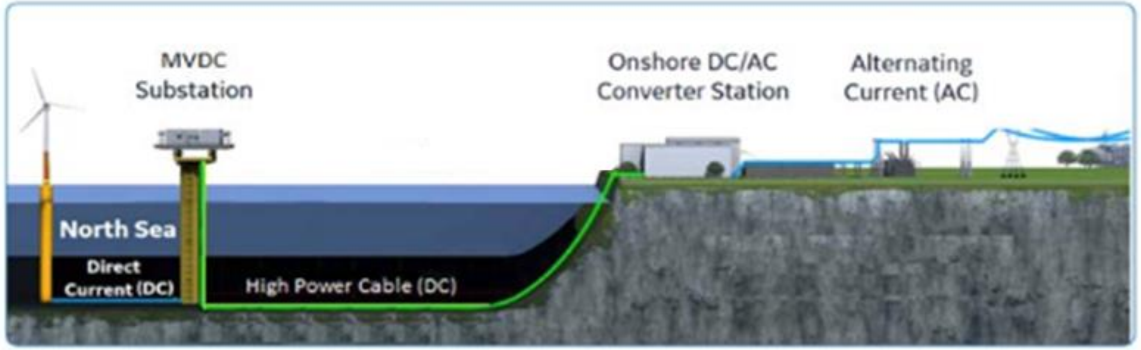




	Cu/XLPE
Voltage, kVdc	±525
Current, kAdc	0.93
Temperature	70-90 C°
Cooling, kW/km	40
Cooling of terminations, kW	---

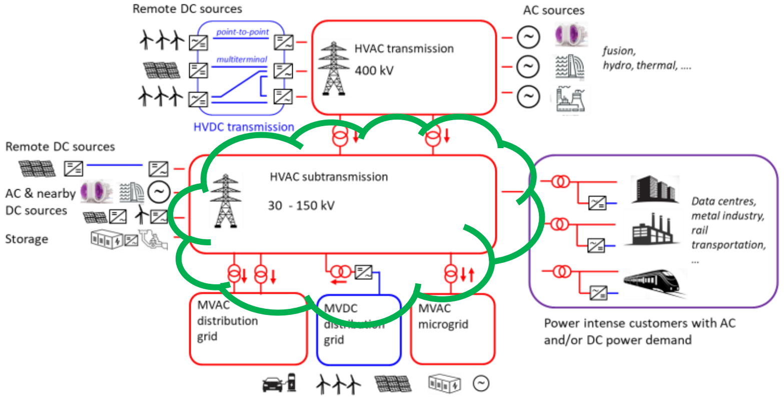
MVDC Superconducting links





No offshore substation

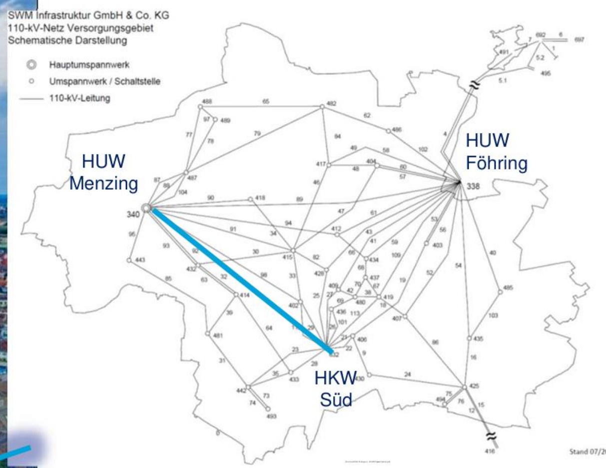
	HTS/LN2	MgB2/LH2
Voltage, kVdc	±50	±25
Current, kAdc	10	20
Temperature	65-75 K	20 K
Cooling, kW/km	23	36
Cooling of terminations, kW	30	30



- **Delivering abundant renewable power to users will require increasing the capacity existing subtransmission grid with minimum infrastructural impact**

SWM: How do you transfer 500 MW across...?!?

NKT



München

Partners

SW//M NKT THEVA SuperLink Fachhochschule Südwestfalen University of Applied Sciences Linde KIT Karlsruher Institut für Technologie

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

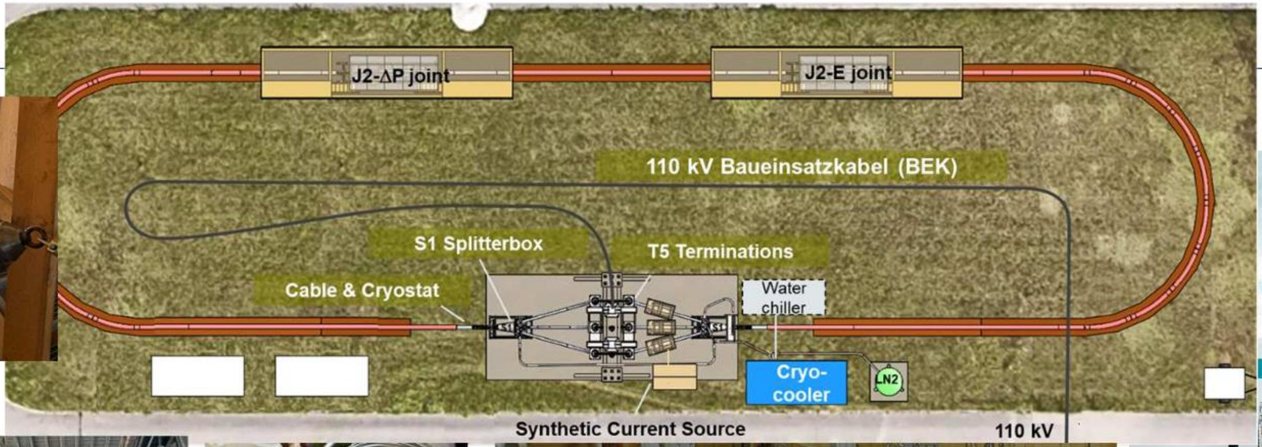
aufgrund eines Beschlusses des Deutschen Bundestages

Courtesy of Dag Willen, NKT

D. Willen et al. "Development SuperLink" ASC2024 1LOr1C-05 | 02.09.2024 | 3

150 m Demo field test

NKT

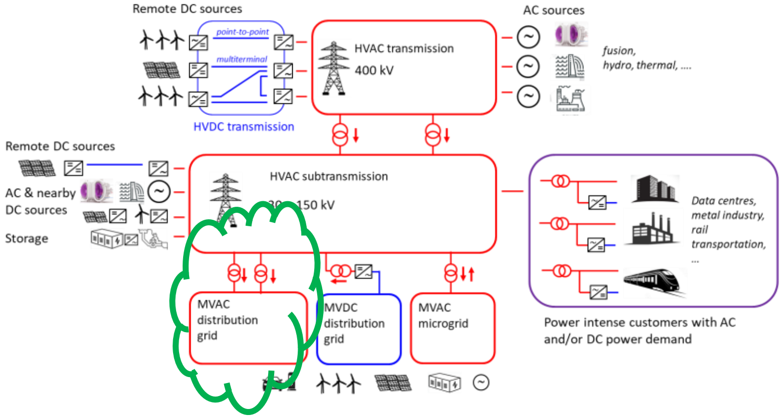


Courtesy of Dag Willen, NKT

Successful installation of cryostat, manufacturing of 600 m cable, installation of 3 x 150 m cable, joints, splitterboxes and terminations under realistic conditions

Feasibility of 110 kV, 500 MW **2G** HTS cables in the grid demonstrated

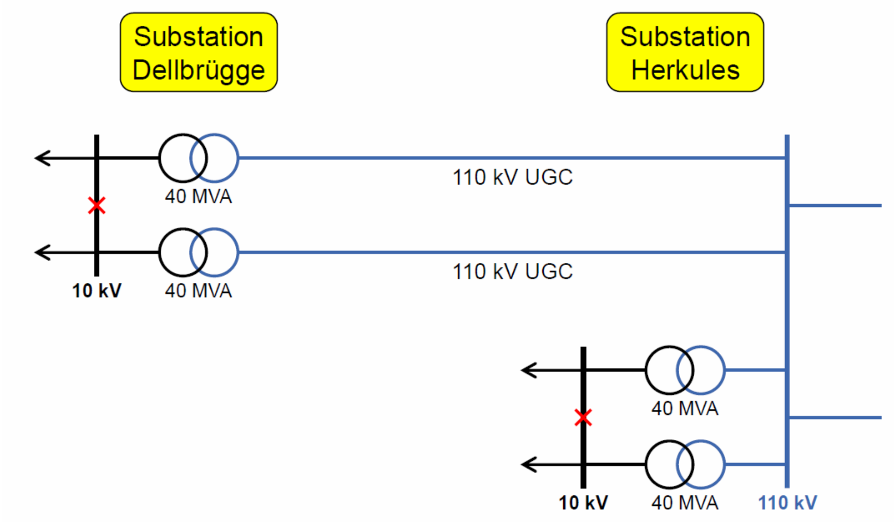
- **Similar projects based on 1G HTS were demonstrated in US (LIPA 2008), Japan (Yokohama 2013) and Korea (Jeju 2014) tthrough infield operation**



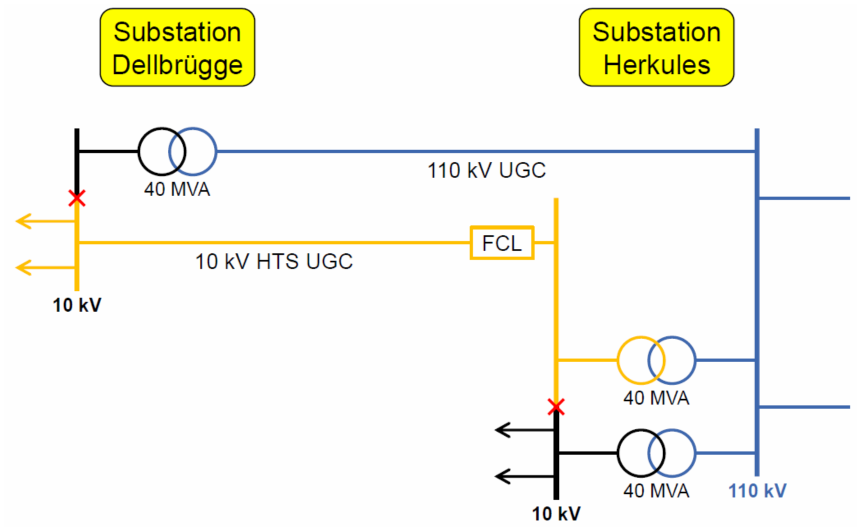
- **Meeting the increasing load demand of congested areas will require the upgrade and/or the reconception of distribution grids**

The Ampacity Project in Essen-Germany

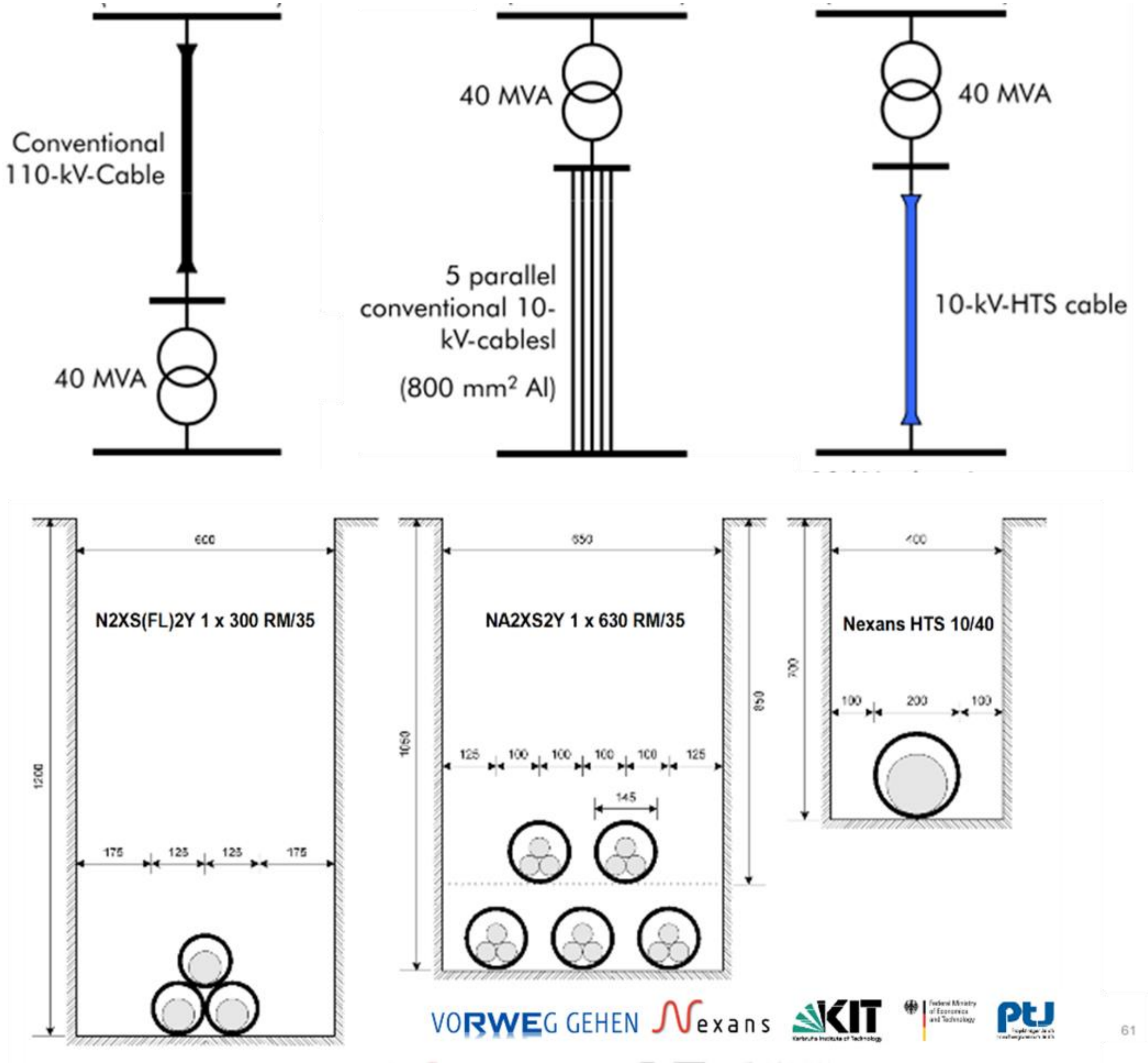
Conventional Situation in Essen



HTS Cable plus FCL Situation in Essen



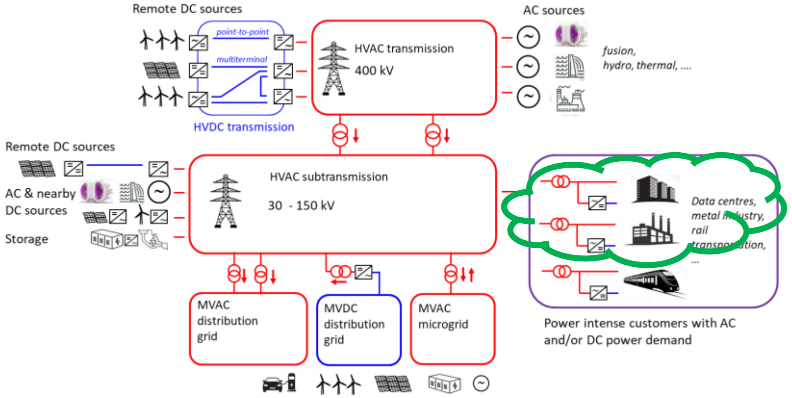
M. Noe, EUCAS2017, Short Course on Power Applications



Delivery of 40 MVA at the city center achieved with exploiting existing infrastructure and with no need ofHV transformer

- **First of its kind solution successfully demonstrated in 2013 by means of 1G HTS**
- **Followed by Shingal cable project put in operation in Korea in 2019**
- **Similar projects based on 2G HTS demonstrated in Chicacgo, Shanghai and Shenzen in 2021 through infield operation**

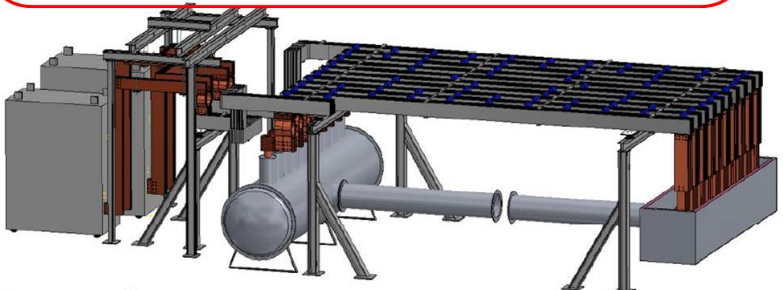
M. Noe, EUCAS2017, Short Course on Power Applications



- **Supplying established (metal industry) and emerging (data centers) power-intense and current-intense DC customers**

From DEMO200 to SuprAl

- DEMO200
  - R&D-Demonstrator 200 kA, world record
  - Aluminium smelter applications
  - Test successfully performed 2024-09,

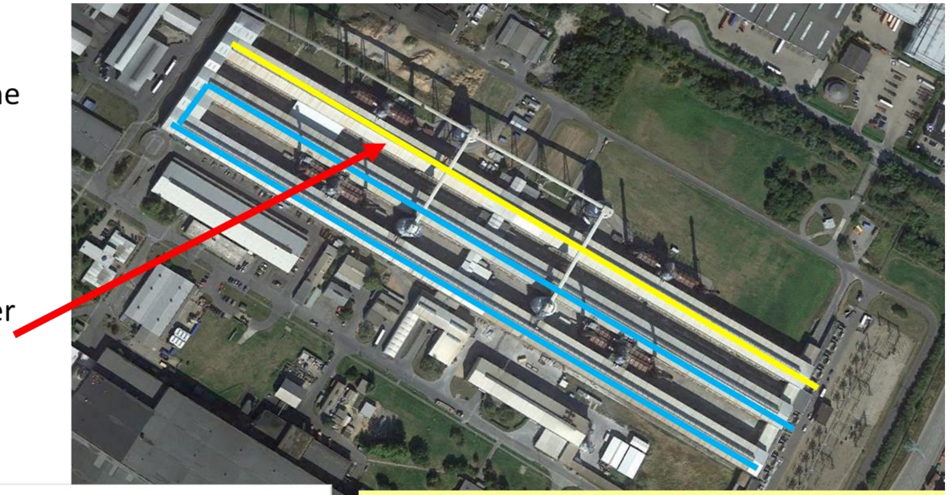


Gesamtaufbau

- **Step 1**: DEMO200, partially funded by the German Government → www.demo200.de

  → Goal reached in 2024-IV
- **Step 2**: Installation of 200 kA superconductor busbar at Trimet smelter in Hamburg in parallel to existing aluminium busbars (yellow line)

  → Cut down of electrical losses by **approx. 90%**



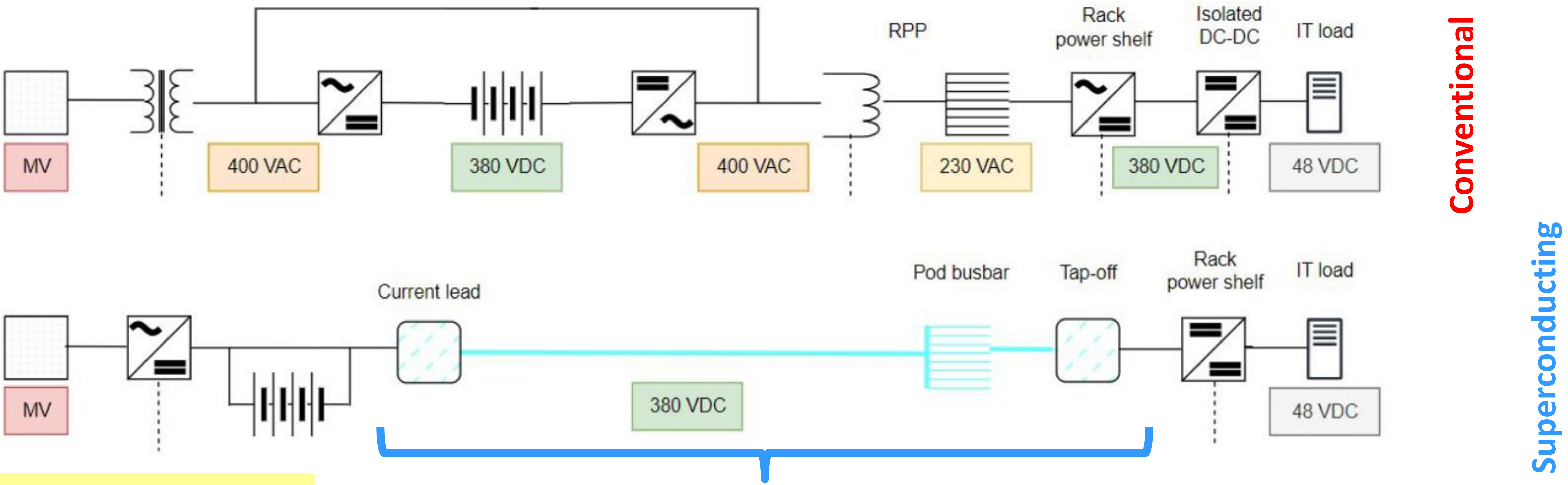
Supported by:
Federal Ministry for Economic Affairs and Energy
PtJ
on the basis of a decision by the German Bundestag

- Practical field test at Trimet as a step for grid approval
  - Low-loss transport
  - 2 GW: ±50kV/20kA or ±20kV/50kA instead of conventional ±500kV/2kA

VESC 2024 Dr. Wolfgang Reiser

Courtesy of Wolfgang Reiser VESC

Conventional vs. Superconducting Hyper Scale DataCenters



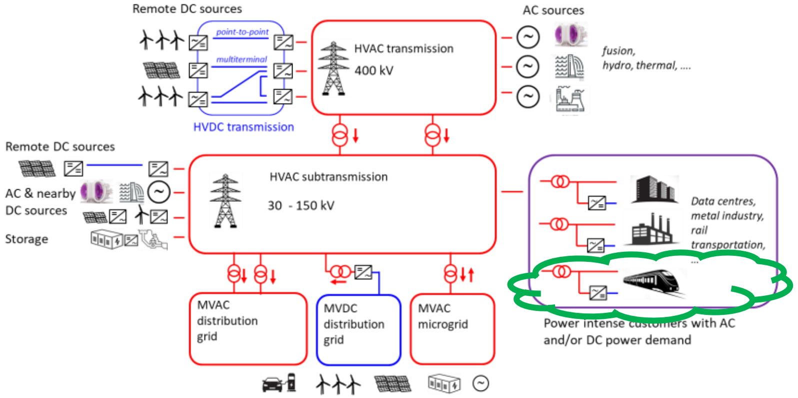
Superconducting Busbar with multiple Tap-offs
Reduction of Power Conversion Steps
DC Distribution: Up to 100 MW on Low Voltage

Motivation

- Increased demand for Hyperscale DataCenters
- Increased Power per Rack
  - Up to 200 kW per Rack for AI-Applications
- Increased Efficiency Demand

Courtesy of Wolfgang Reiser VESC

www.vesc-superbar.de

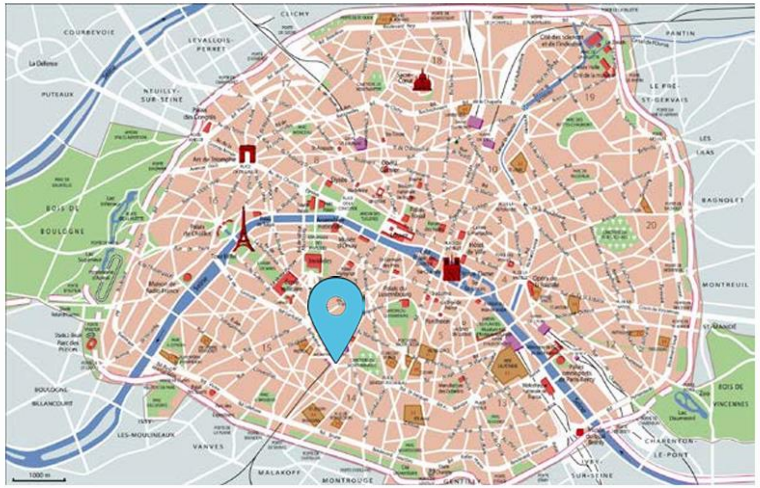


- **Upgrade of the railway power supply infrastructure**

Existing rights of way saturated
only 2× Φ100 mm conduit left
= 2× 400 mm² copper cable
= 2× 500 A reinforcement

Instead of the required 3000 A

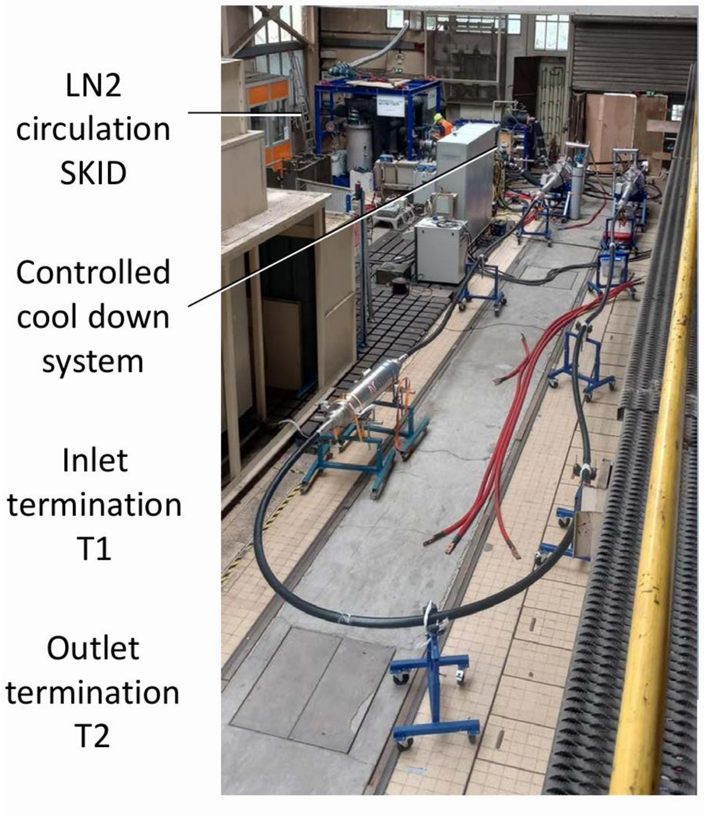
Reinforcement of Paris Montparnasse train station
28 tracks, 200 000 passengers/day on 750 trains
50 Millions of passengers in 2020, 90 Millions in 2030



4.5 MW of nominal power (3000 A @1500 VDC)
10.5 MW of inrush power (7000 A)
Fault current of 67 kA during 100 ms

Courtesy of Loïc Quéval, GeePs, CentraleSupélec,

loic.queval@centralesupelec.fr ASC 2024 2024-09-03



Summary of type test at SNCF AEF

Test	Results
Thermal cycles	✓
Pressure	✓
Dielectric	✓
Lightning impulse	✓
Nominal current	✓
System losses & pressure drop	✓
Fault current & recovery time	✓
V-I characteristic	✓

4.5 MW of nominal power (3000 A @1500 VDC) sucessufully devoped and qualified

Commisisoning for final installation started in 2025

Conclusion

HTS power cables system have been widely established through many demonstration projects worldwide

Cheap and abundant coated conductors are needed to improve penetration and to finally enable mass adoption of HTS power cable technology in the energy sector, providing a vital asset for decarbonization.

Wire should be optimized for low field operation in the range 65-77 K

Thanks for your attention

antonio.morandi@unibo.it

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.