IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 63, Mar. 2026. Presentation given at ISS 2025, Nagasaki, Japan, Dec. 2025.

# DC Superconducting Cables for present and future power needs

**Antonio Morandi, Massimo Fabbri, Mattia Simonazzi, Emiliano Guerra**

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

*antonio.morandi@unibo.it*

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# Outline

## HTS power cables:

- Technology and state of the art
  - General characteristics and main components of SC cables systems
  - State of the art
- DC superconducting cable for today and tomorrow’s power needs
  - How much
  - Which type

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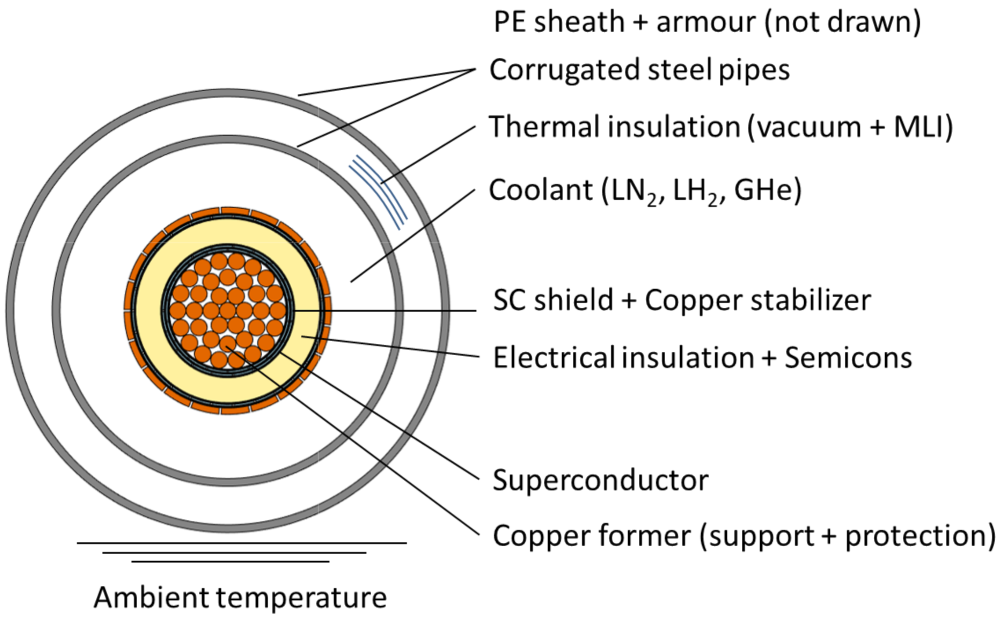
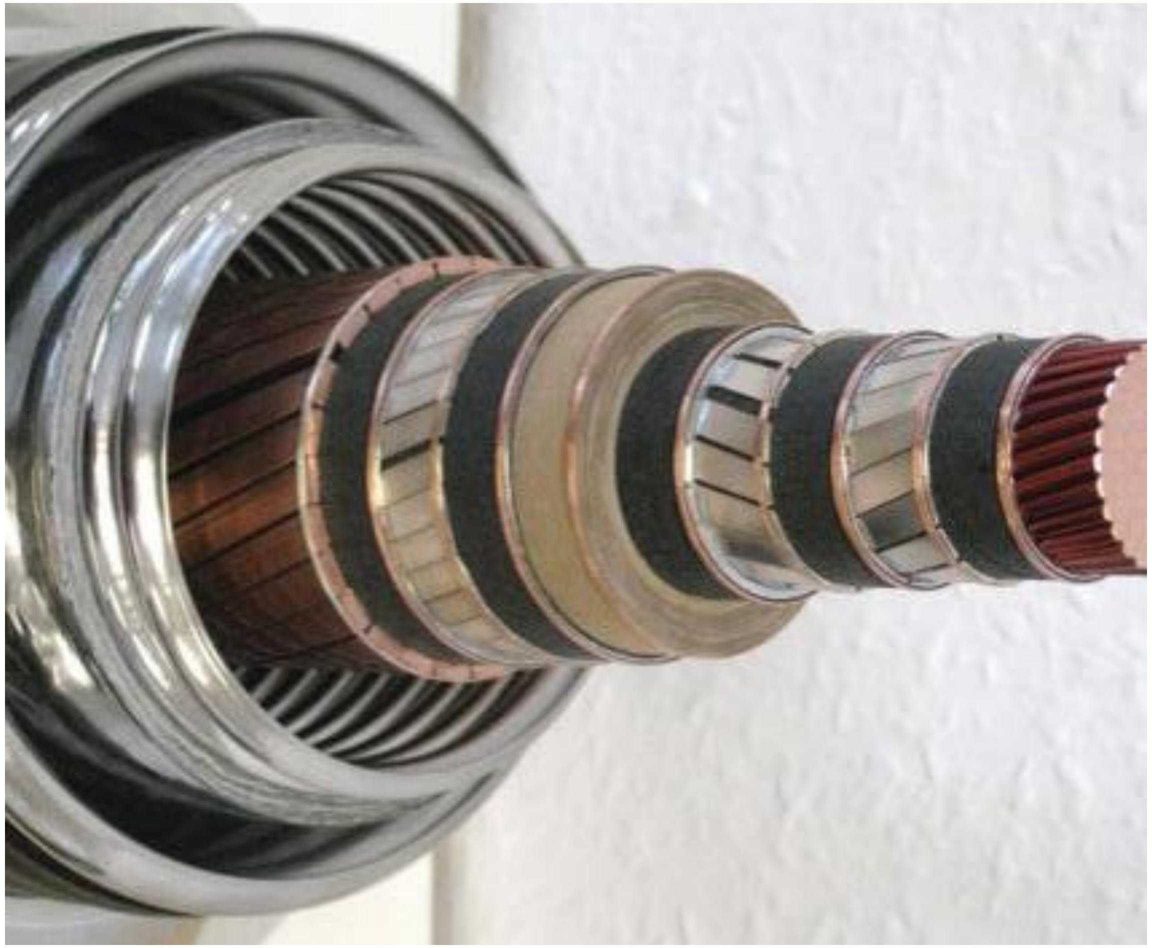
# Layout of a cold dielectric superconducting power cable



*Courtesy of Nexans*

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**

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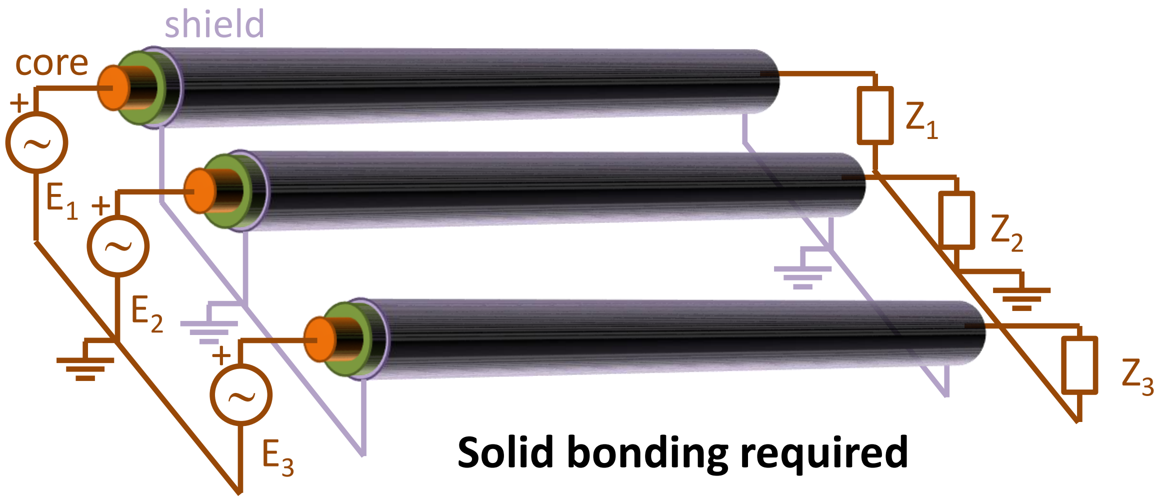
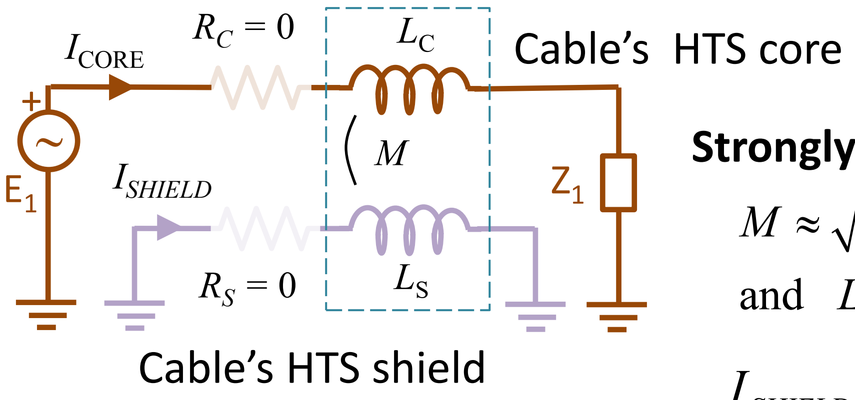
# Shield design of AC superconductor cables

**AC cable system (pipes not drawn)**




**Solid bonding required**

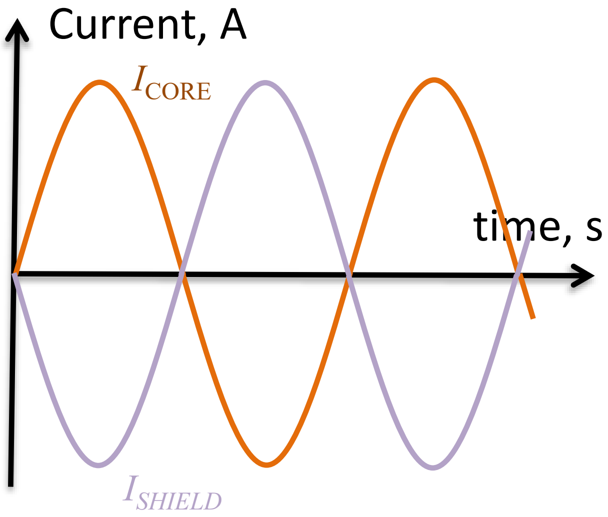



**Strongly coupled**

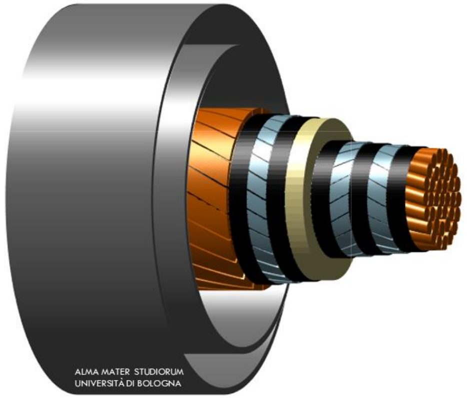
$M \approx \sqrt{L_C L_S}$

and $L_C \approx L_S$

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

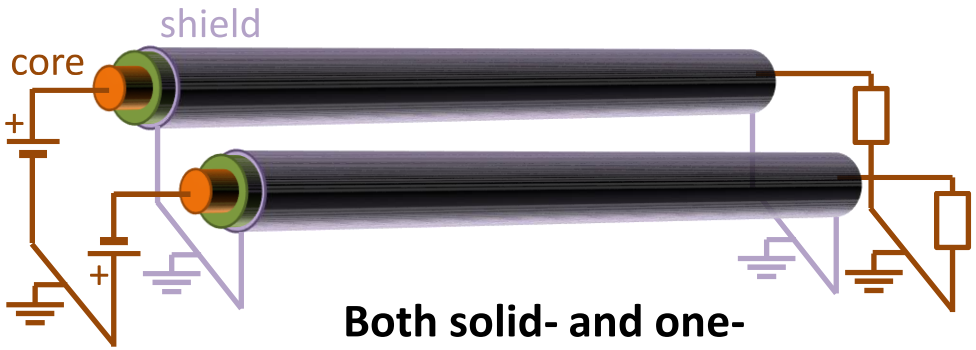



- Induced currents in inner metallic pipe and additional heat load are prevented with the HTS shield
- Practically the same AC current (with 180° phase shift) of the core circulates in the shielding steady AC regime. **The same amount of SC as for the core is needed for the shield**

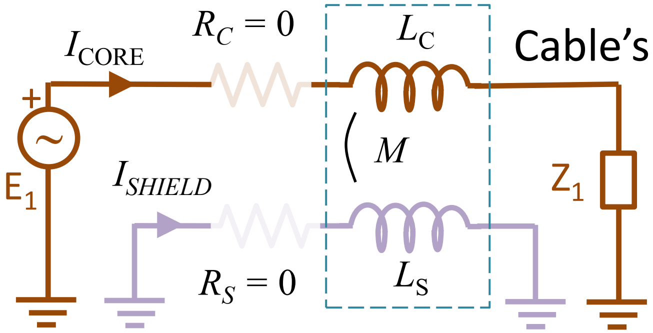


# Shield design of DC superconductor cables

**DC cable system (pipes not drawn)**




**Both solid- and one-point bonding possible**




Cable's HTS core

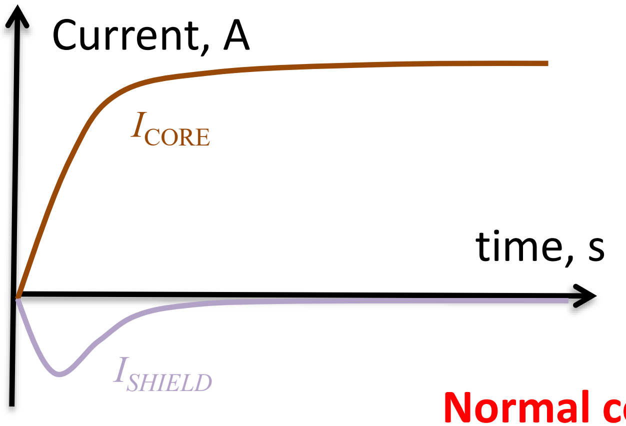
Cable's HTS shield

**Strongly coupled**

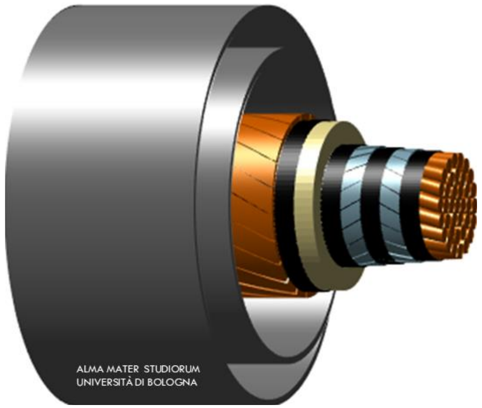
$M \approx \sqrt{L_C L_S}$

and $L_C \approx L_S$

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

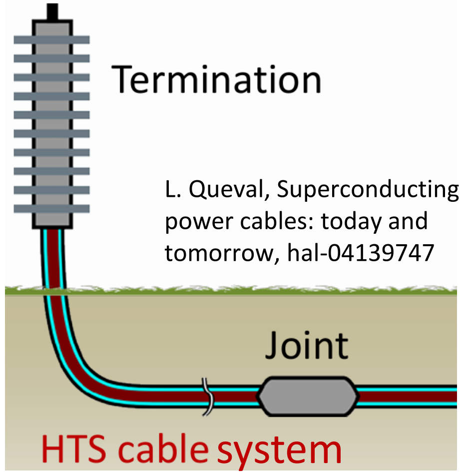



- **Current is induced in the shield only during transients (energization and fault)**
- **No significant heating is added to the cable also in case of copper shield**




**Normal conducting shield for DC superconducting cables is viable**

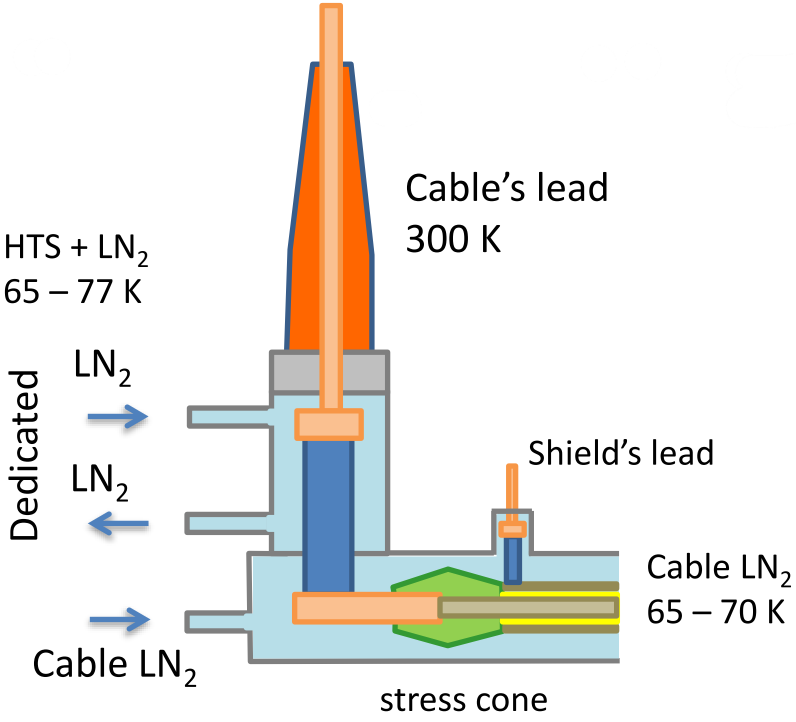
# Essential "accessories" of HTS (and conventional) power cables: terminations and joints




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

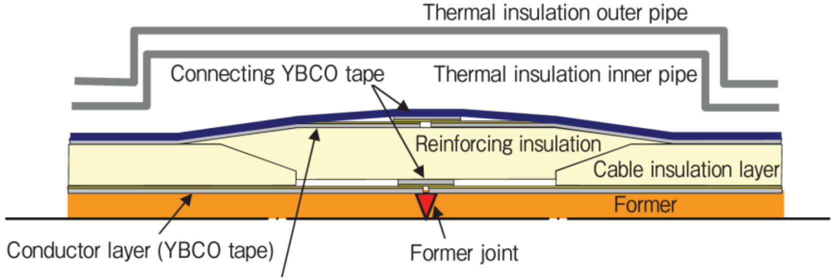
## Termination of the LIPA1 HTS cable


## 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

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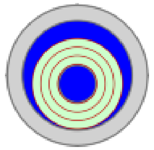
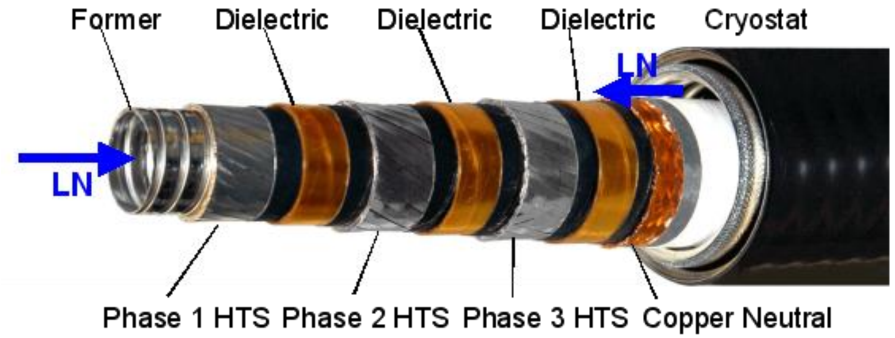
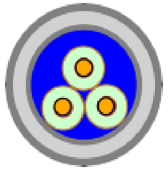
# AC three phase or DC bipolar arrangements



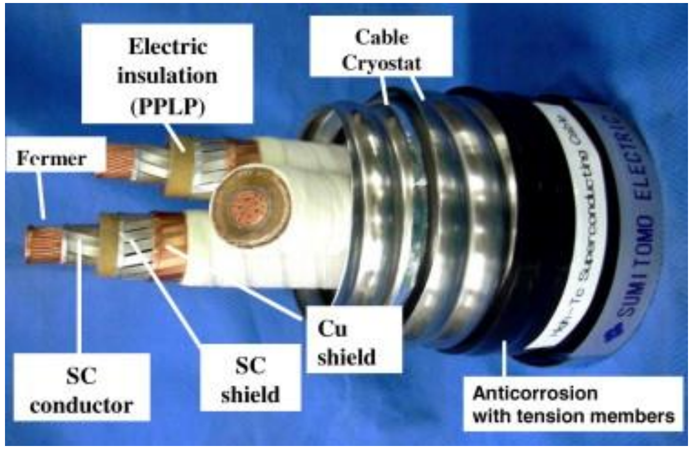
**10 – 20 kV**



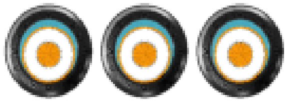

**Concentric phases/poles**



**30 – 100 kV**




**Separate phases/poles with shared cryostat**



**> 100 kV**

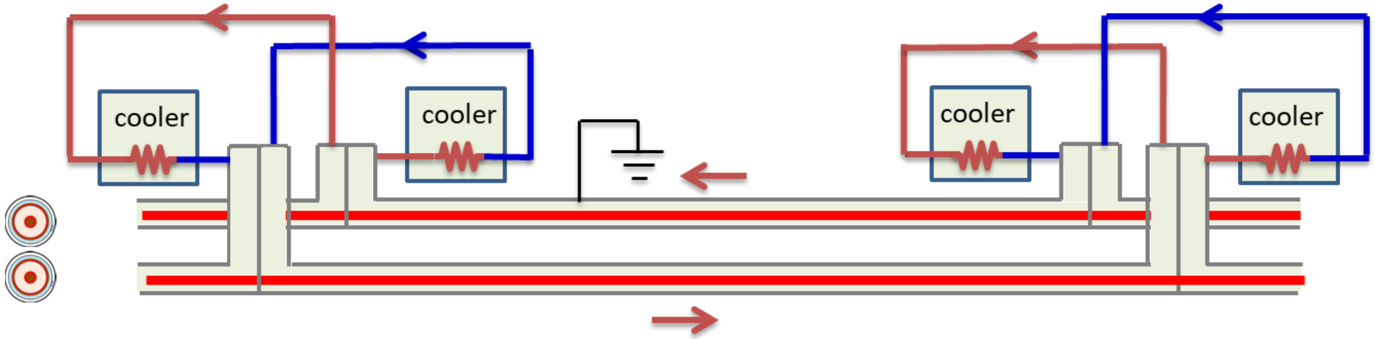
voltage

**Separate phases/poles and cryostat**

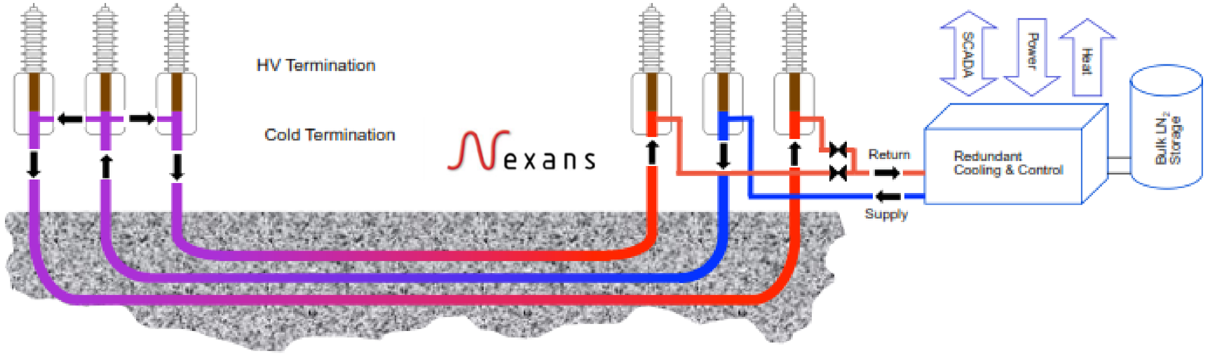
**Different circulation schemes of coolant between cooling and pumping stations can be adopted depending on the layout of the cable sytem and in particular:**

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

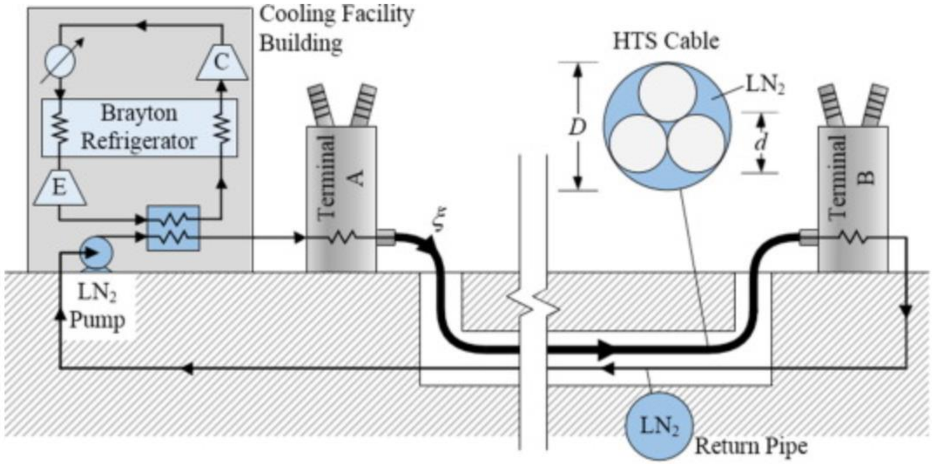
***Example 1 - closed-loop circulation of coolant for a long DC cable system made of two monopoles with distinct cryostats***




***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***




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

# The HTS cable system

## Thermohydraulic design:

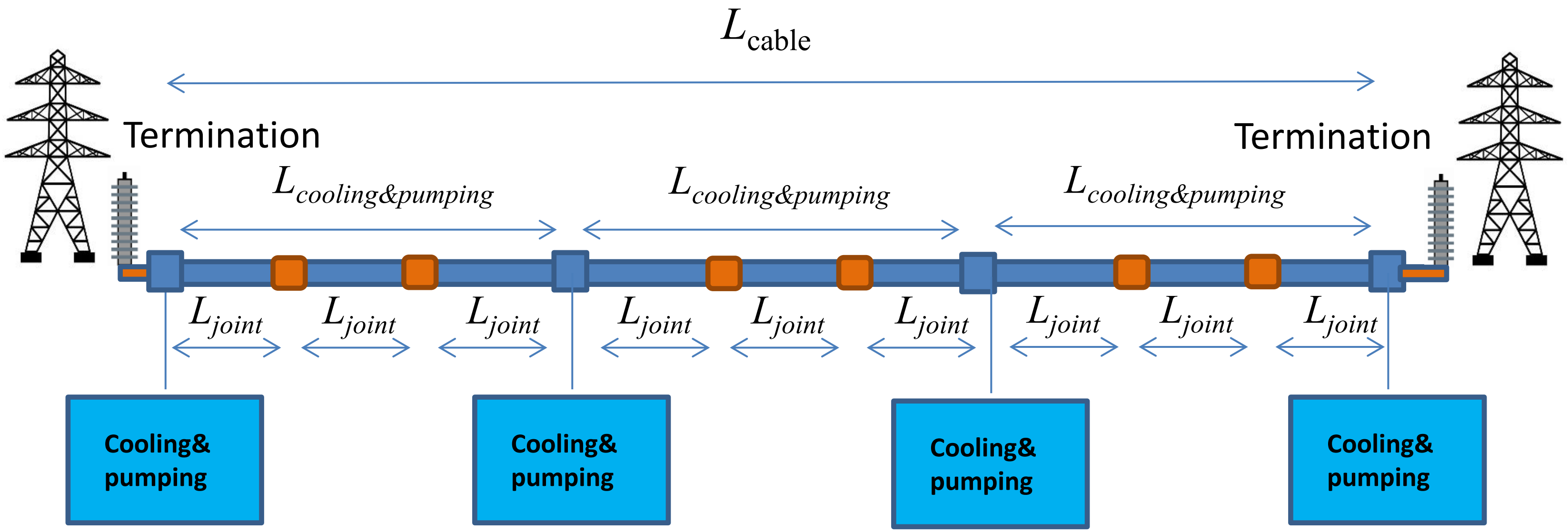
**Distance $L_{cooling\&pumping}$ between cooling&pumping stations must be compatible with acceptable temperature and pressure, and may differ from overall length $L_{\mathrm{cable}}$ of the cable system**

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

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

Outer diameter $D_{\mathrm{o}}$

Mass flow $\dot{m}$




$L_{cooling\&pumping}$ may reach up to 20-40 km, depending on thermohydraulic design ($D_{\mathrm{o}}$, $\dot{m}$) and cosntraits (see depth)

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

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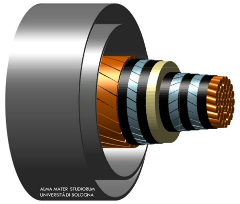
# Motivations for SC power cables - 1. more power and/or less voltage



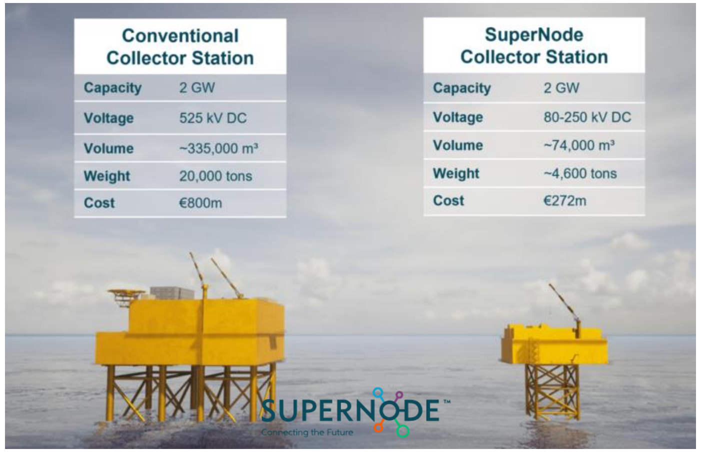
**higher transport current $I$, up to 5-10 more than conventional cable through same section**

$$P = V\,I$$

More power at the same voltage

Less voltage at the same power

(+ *operation at constant T*)



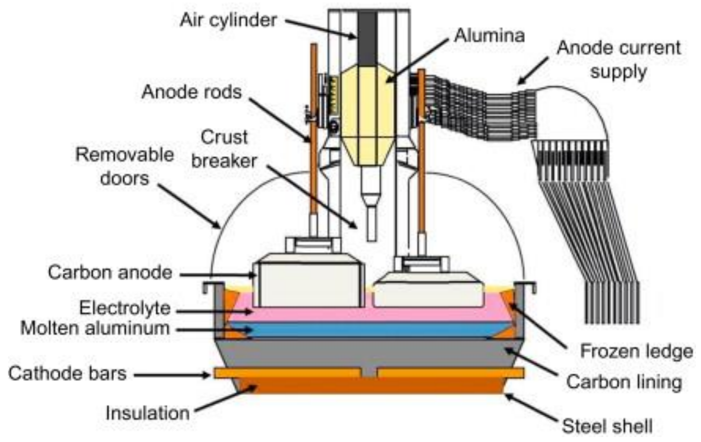

- Reducing right of way & soil occupation
- Much faster installation

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

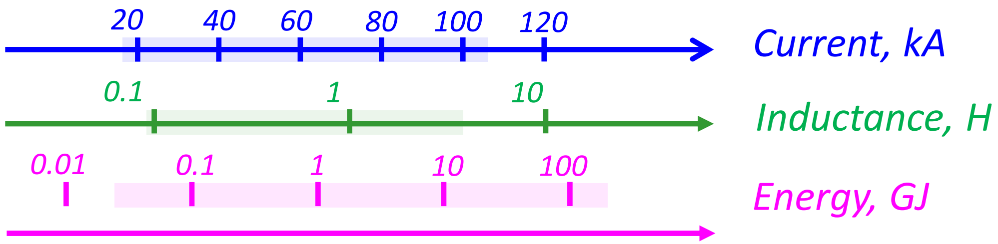
- Simplify electric equipment: conversion stages, converters' layout, platform ….

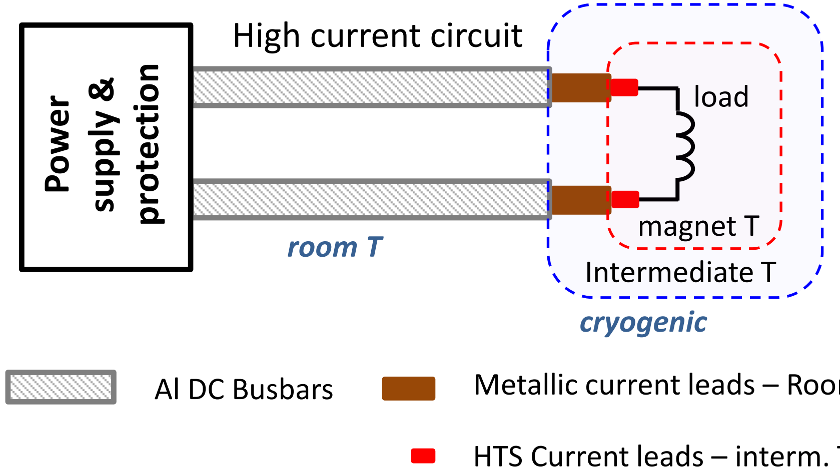
# Motivations for SC power cables - 2. high current loads (regardless of the power)

1. **Applications like chlorine, copper or zinc electrolysis as well as aluminum smelters need INTRINISC (process) direct current ranging from 10 kA up to 600 kA.**




2. **DC SC magnets for fusion reactors (Tokamak or Stellarator) operate with large DC currents in the range 20-105 kAs.**




# Motivations for SC power cables - 3. Less losses (cooling included)

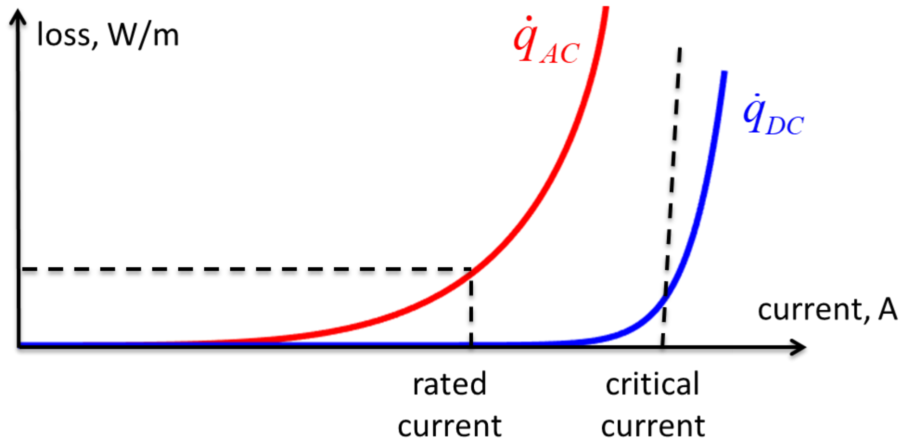
Electromagnetic losses per unit length (W/m) of current carrying superconductors:

**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*

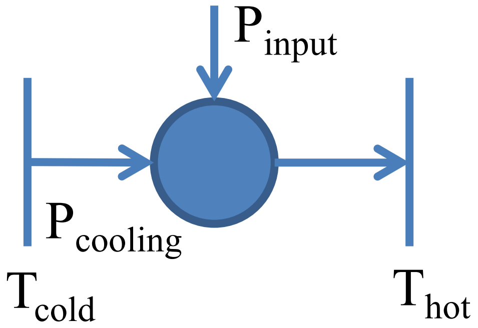
| | Dependence | Parameters | Losses at 65-77 K | Losses at RT |
|---|---|---|---|---|
| **Radiation** | Room temperature | Super-insulation spacer and diameter | 0,5 to 2 W/m | 12,5 à 50 W/m |
| **HTS AC losses** | Transported current Magnetic field distribution | Cable design (pitches, diameter,..) | 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 (HTS AC losses, Dielectric AC losses, Eddy current AC on the cryostat)

**Absent for DC cables** (HTS AC losses, Dielectric AC losses, Eddy current AC on the cryostat)

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%

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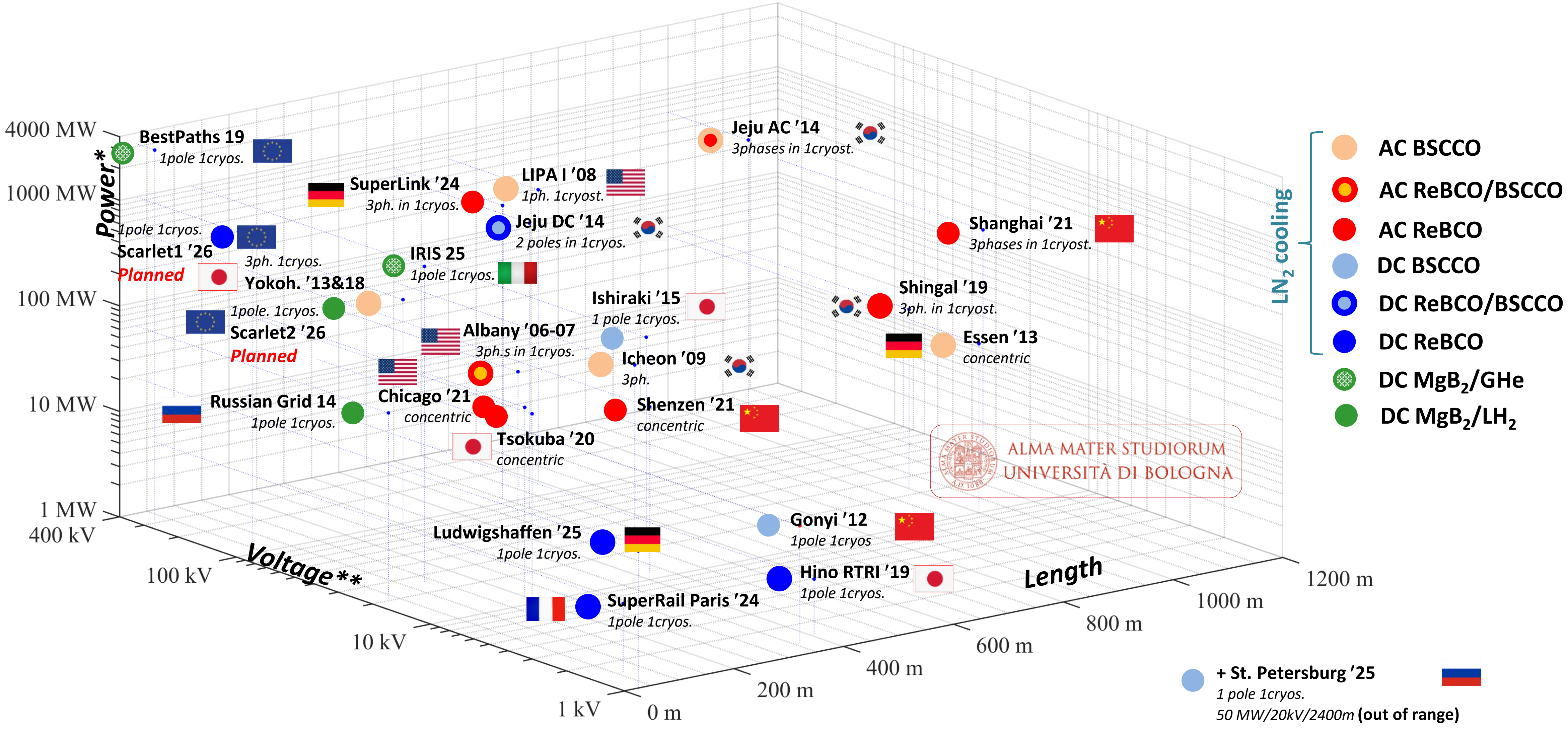
# State-of-the-Art of SC cable technology – main operational or demonstration projects (AC and DC)




* *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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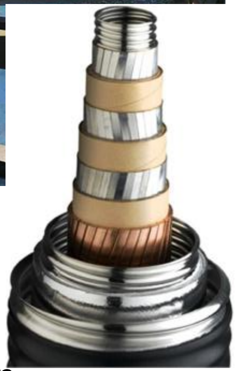
## Chicago

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

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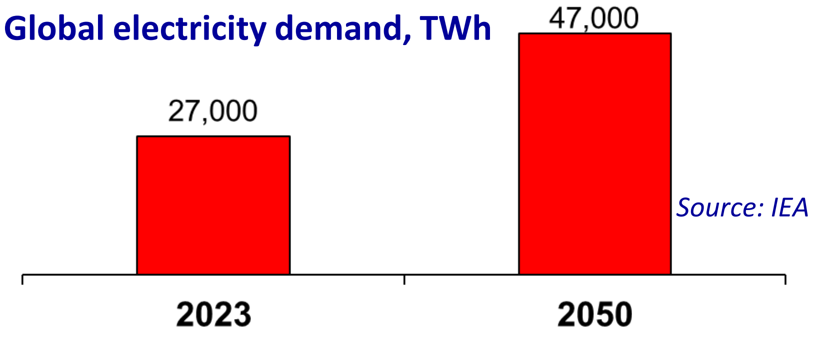
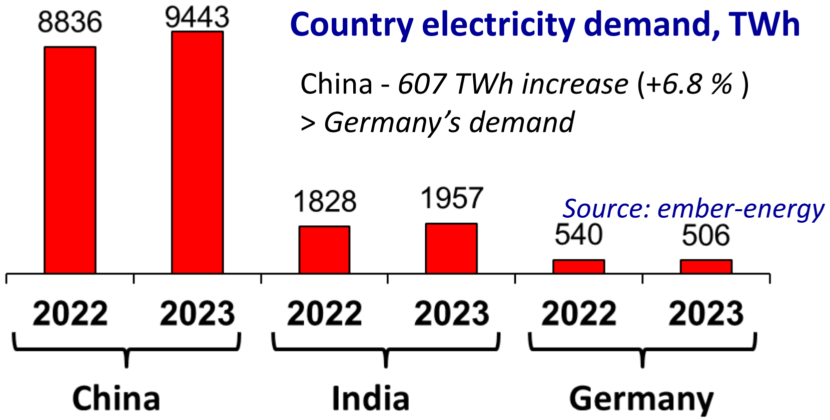
# Global electricity demand – today and tomorrow

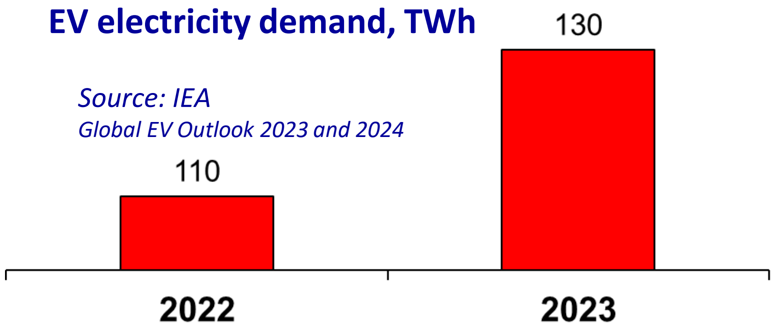
**Growth in global electricity demand is set to accelerate at an average rate of 4% in the coming years due to:**

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**

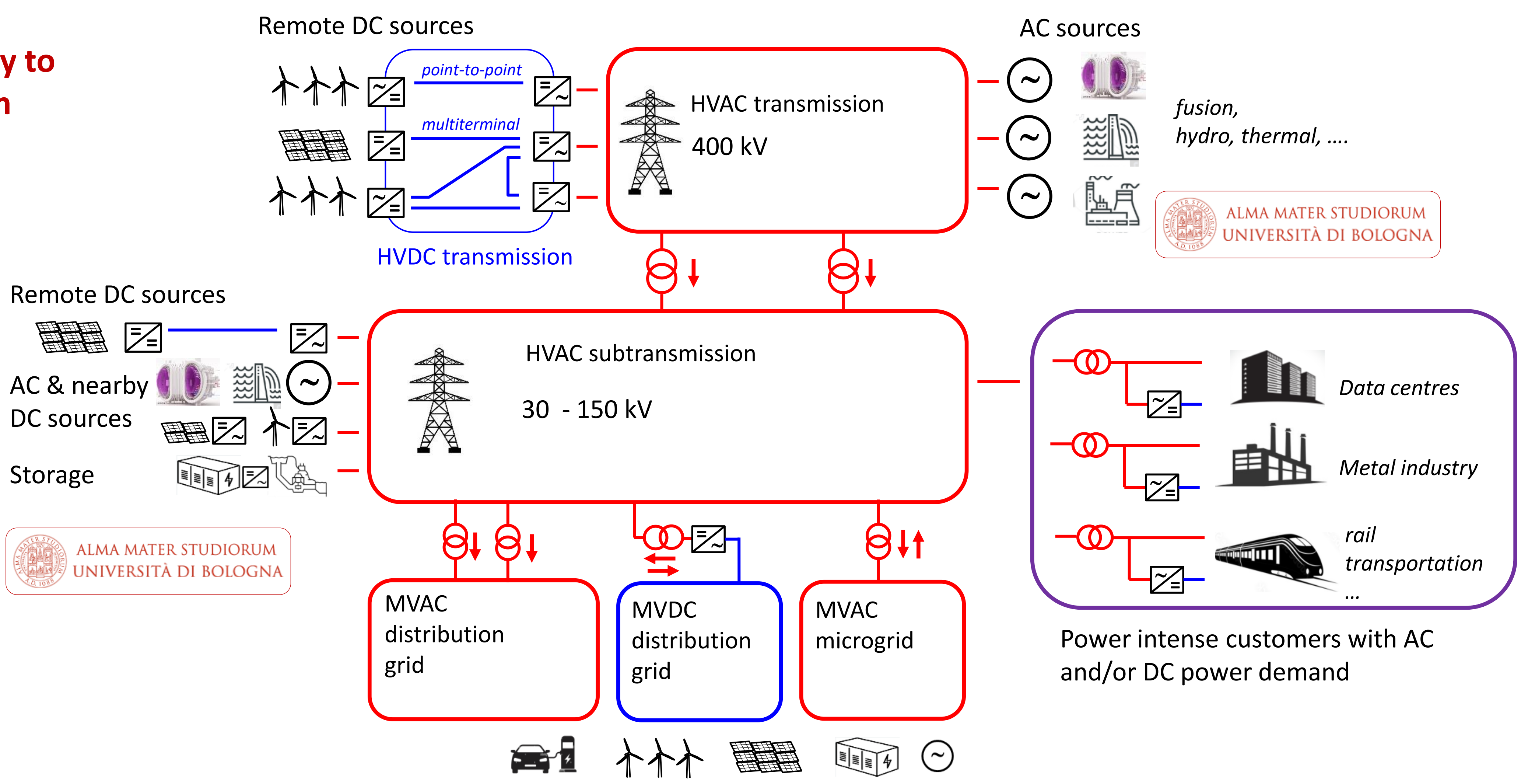


# Addressing the challenge of **growing and transforming** electricity demand

**Schematic pathway to grid modernization and expansion**



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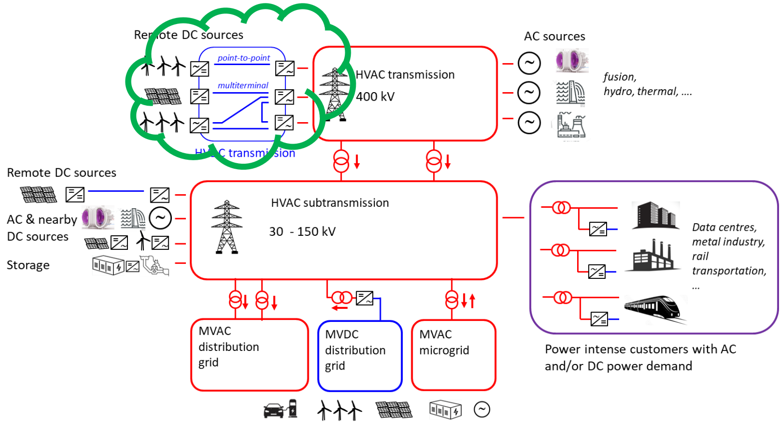
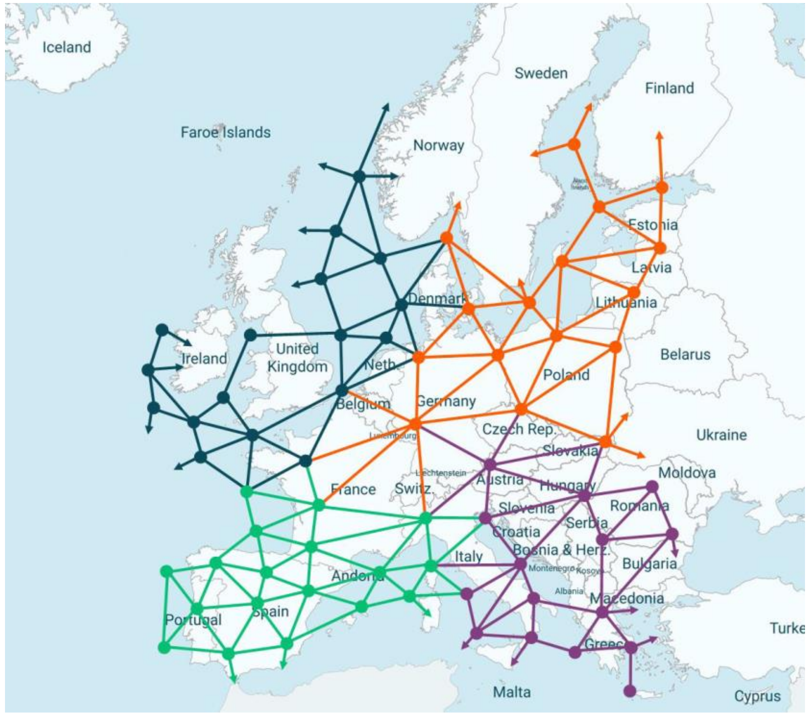



- **EU strategy on offshore renewable energy:** 60 GW of offshore wind and at least 1 GW of ocean energy by 2030, with a view to reach by 2050 300 GW
- **EU Solar Energy Strategy:** over 320 GW of solar photovoltaic by 2025 (more than doubling compared to 2020) and almost 600 GW by 2030
- **India's wind 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**

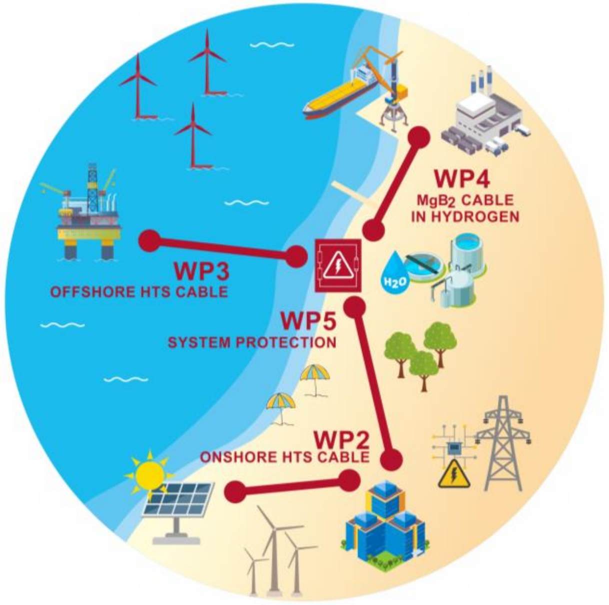
*Superconductors will do for electricity what fiber optic cables did for telecoms by replacing the twisted pair. They will revolutionise power transfer, enabling ultra high capacity unobtrusive transmission.”*

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)




SINTEF, IASS POTSDAM, WavEC Offshore Renewables, ELÚ, Alma Mater Studiorum Università di Bologna, ASG Superconductors, Nexans, SUPERNODE, RINA, ESPCI PARIS PSL, SuperGrid Institute – Shaping power transmission, ABSOLUT SYSTEM – Innovative Cryogenic Solutions, VISION ELECTRIC Super Conductors, RSE Ricerca Sistema Energetico

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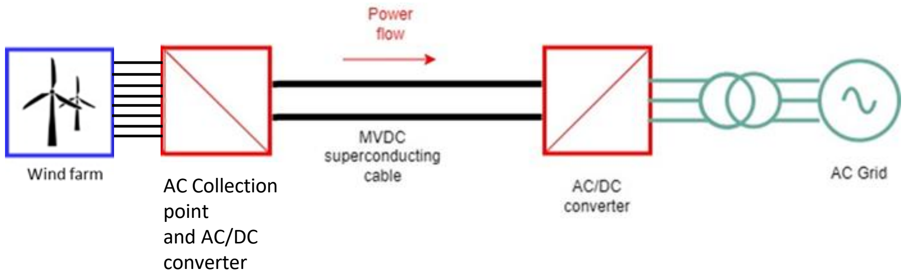
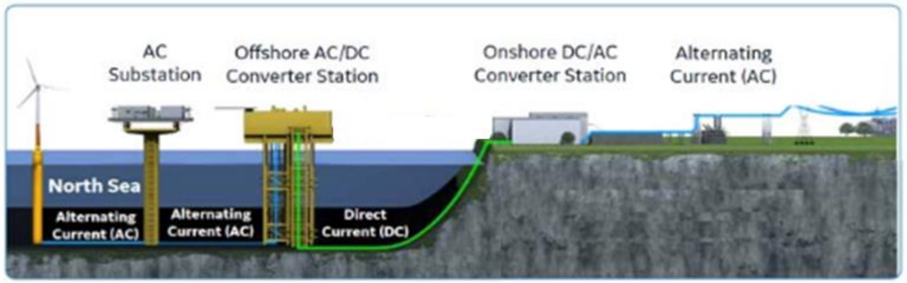
# The selected case: unidiretional MVDC grid connection 1 GW offshore wind park

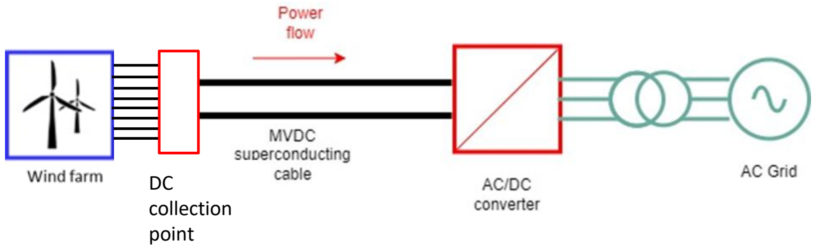
## HVDC conventional links




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

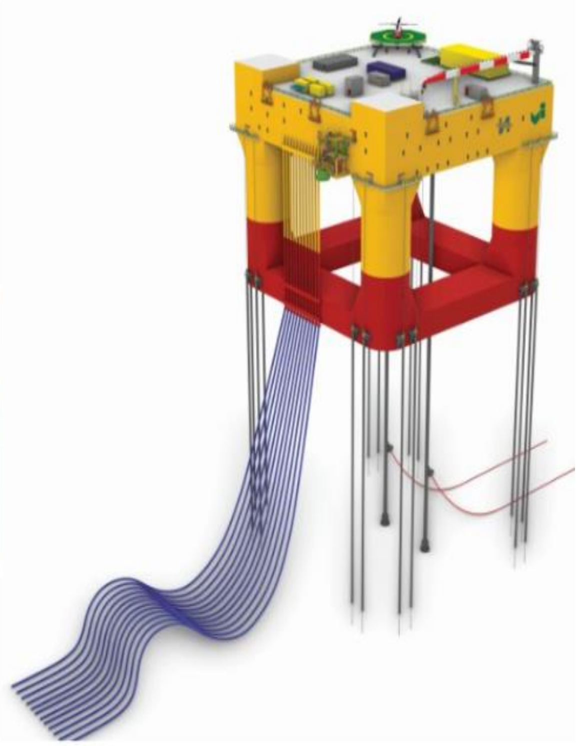
## MVDC Superconducting links





***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 |



***A much simplified platform hosting DC collection point is required***

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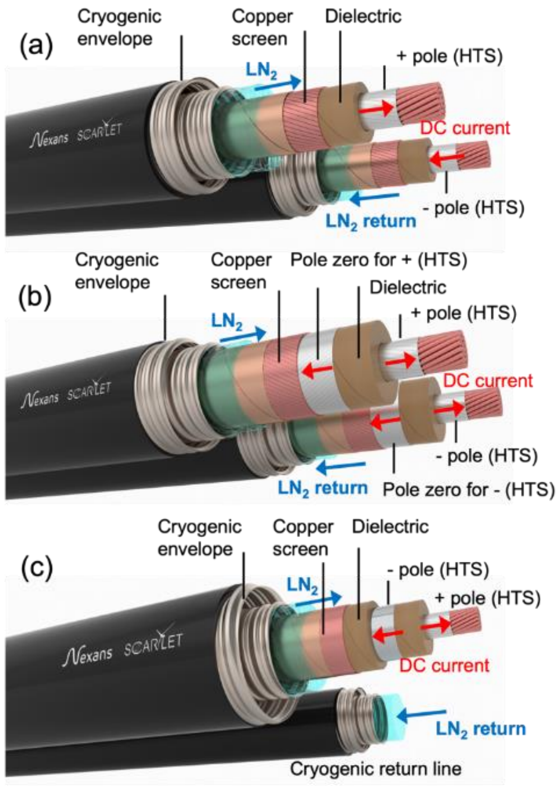
# SCARLET - WP2&3 progress on 1 GW HTS/LN2 cable system for off-shore wind 1/1

SCARLET
Superconducting CAbles foR sustainabLe Energy Transition

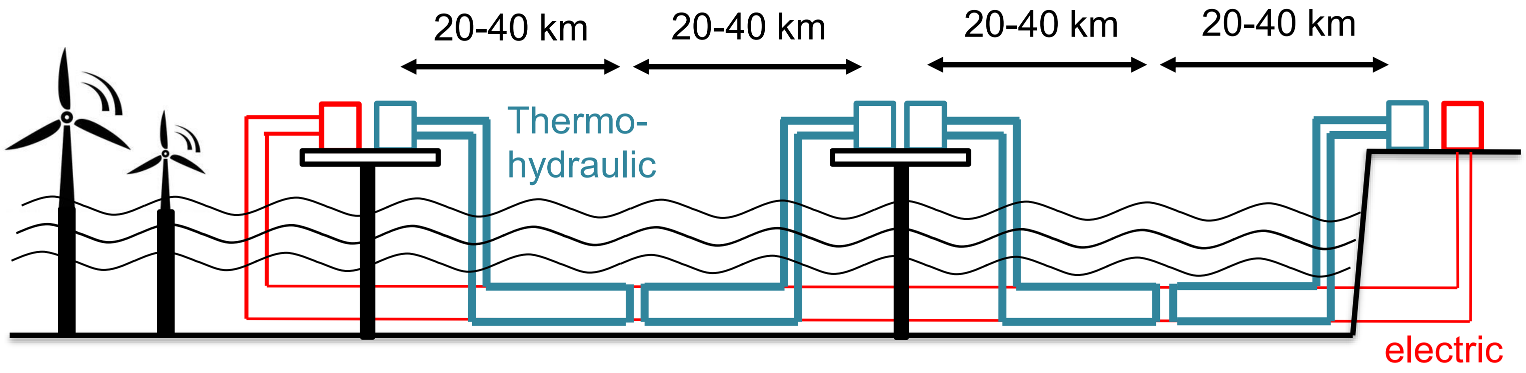



Three system layouts analyses based on

- Two ±50 kV/10 kA monopoles with or without HTS shield
- Single ±50 kV/10 kA HTS cable with concentric design and separate $LN_2$ return

**Final design to be chosen by March 2026**

- $LN_2$-immersed cable cores, terminations&joints and cooling units developed for land based HTS cable directly applicable to submarine environments
- adapting the cryogenic envelope to withstand water pressure and dynamic mechanical stresses poses a significant challenge.




*$LN_2$-immersed HTS cbales can be cooled from a single station for lengths between 20 and nearly 40 km depending on sea depth*

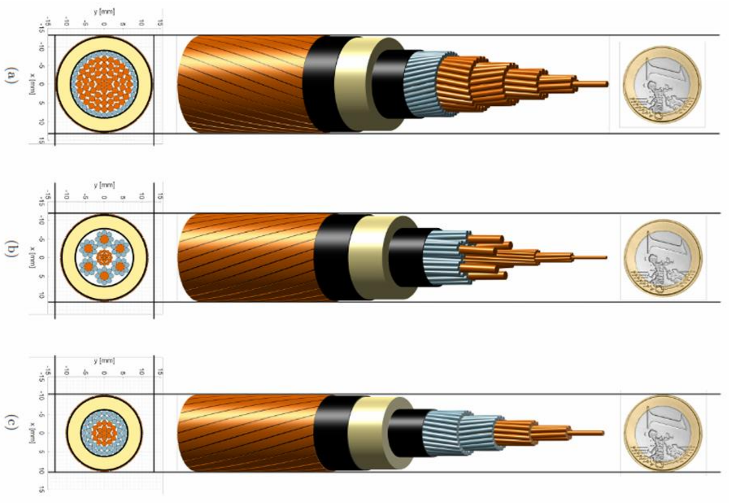
**Max distance of a HTS DC cable link with no intermediate stations can reach up to 80 km**

Nexans

Source: Grid integration of high-power MVDC superconducting cables based on HTS and $MgB_2$, JICABLE2025

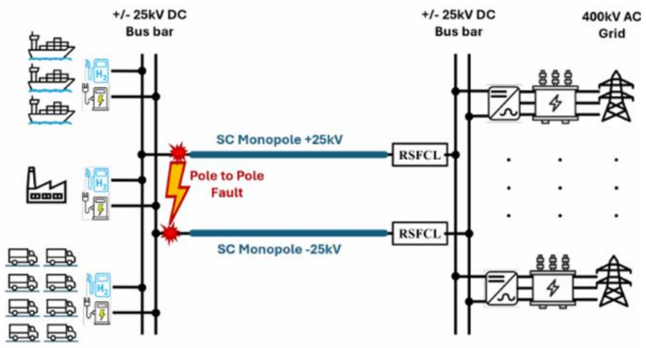
# SCARLET – WP4 progress on 1 GW $MgB_2/LH_2$ cable system 1/2

SCARLET
Superconducting CAbles foR sustainabLe Energy Transition



**Electromagnetic design of the ±50 kV/10 kA cable completed**

- Various geometrical configurations were analyzed and compared based on electrothermal transients.
- A single-layer $MgB_2$ cable was selected for its superior transient performance and manufacturing simplicity.




ASG SUPERCONDUCTORS

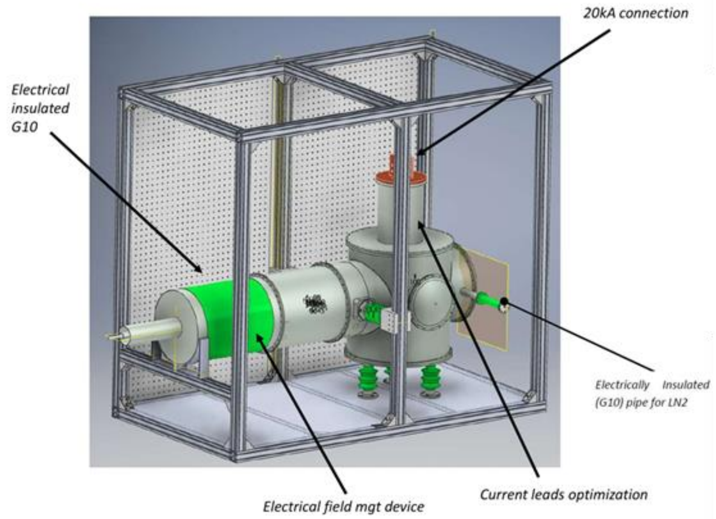
SuperGrid Institute
Shaping power transmission

**Desing of PPLP/LH2 electric insulation completed**

Novel setup developed to measure electrical properties of lapped insulation in $LH_2$

ESPCI PARIS
EDUCATION SCIENCE INNOVATION

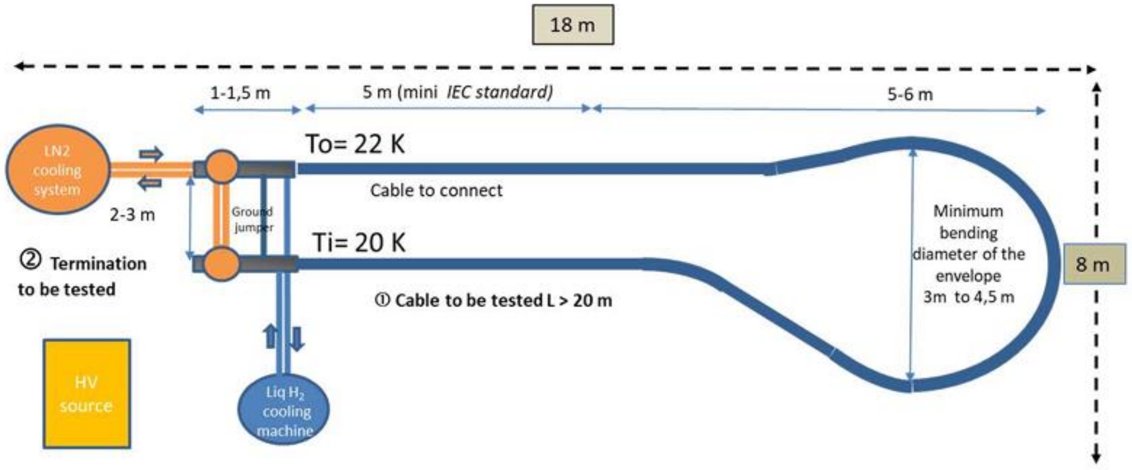
**Desing of terminations and joints completed**



# SCARLET – WP4 progress on 1 GW $MgB_2$/$LH_2$ cable system 2/2

SCARLET Superconducting CAbles foR sustainabLe Energy Transition

- **The manufacturing of the cable is planned for the first quarter of 2026**
- **Final test of the cable system at SINTEF premises scheduled by 2026**


Not easy to purchase LH2 for the test (below 200kg).

The cooling system will be probably based on closed cooling loop, to recycle Hydrogen during the test with a RHCL (Rempote Helium Cooling loop) subcooling the LH2.

The decision will be taken by the end of the year based on LH consumption evaluation and delivery possibility.

Type test at Sintef followed by long duration test at Abslout System

# The IRIS ±25 kV/40 kA 1 GW $MgB_2$/GHe cable system 1/3

ASG SUPERCONDUCTORS

## IRIS Project:
## Innovative Research Infrastructure on Applied Superconductivity)

Innovative Research Infrastructure on applied Superconductivity IRIS

in the frame of a large recovery effort called *PNRR,*
the Italian branch of the Next Generation EU framework.

IRIS (Innovative Research Infrastructure on applied Superconductivity) is led by INFN (through its LASA lab in Milan) and includes also CNR-SPIN and 5 Universities).

**Goal:** developing applied superconductivity for HEP future collider (FCC-hh) and **exploiting potential applications to society in green energy** (higher sustainability) and in medical field.

| IRIS | |
|---|---|
| Power rating | 1 GW |
| Voltage | 25 kV |
| DC current | 40 kA |
| Operating temperature | 20 K |
| Cooling medium | He gas |
| Superconductor | $MgB_2$ |
| Line length | 130 m |
| Inner pressure | 10 bar |

INFN
Istituto Nazionale di Fisica Nucleare

Istituto Nazionale di Fisica Nucleare PARTNERS

SPIN — Università degli Studi di Genova — Università degli Studi di Milano — Università degli Studi di Napoli Federico II — CIRMIS — Università del Salento — Università degli Studi di Salerno


- 60 M € including taxes (39 M € scientific instrumentation)
- Geographical distribution 45% North 55% South
- 36 Fixed-term positions (50% academic) 5 PhD
- Project duration: started on 1 Nov 2022, ending by 30 Apr 2026 (42 months)

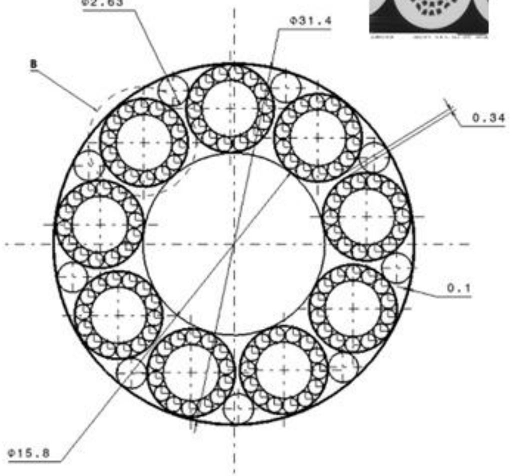
Finanziato dall'Unione europea NextGenerationEU — Ministero dell'Università e della Ricerca — Italiadomani Piano Nazionale di Ripresa e Resilienza

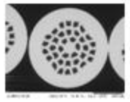
# The IRIS ±25 kV/40 kA 2 GW $MgB_2$ cable system 2/3

ASG SUPERCONDUCTORS

## CABLE DESIGN AND TEST VALIDATION

IRIS – Innovative Research Infrastructure on applied Superconductivity



1.3mm wire

The cable has been designed in the multi-petals configuration
Able to carry 40kA with an operative margin higher than
25% at 25K and 50% at 23K

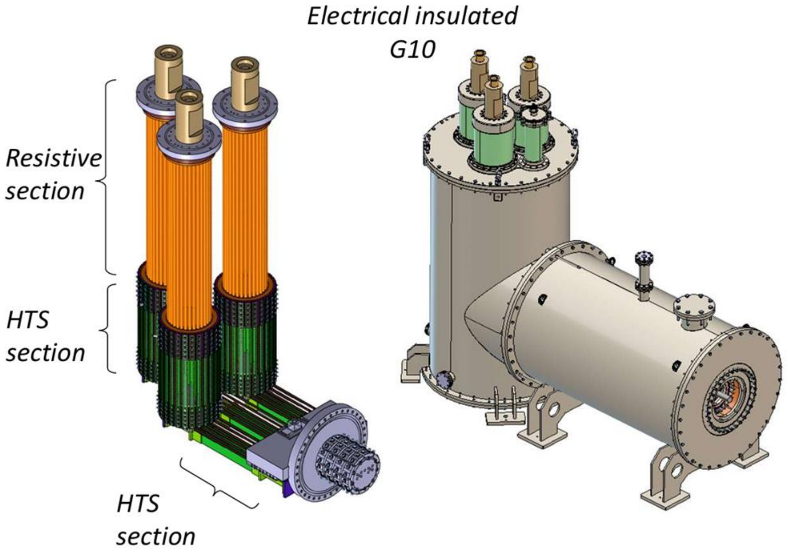
More than 100km of MgB2 wires has been produced
to validate the cabling process and to manufacture the cable
Cabling and insulation activities has been completed

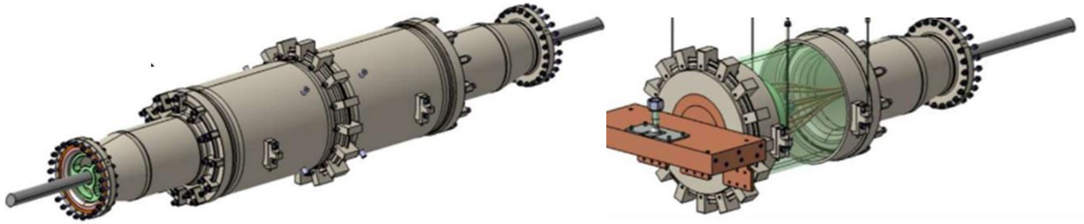
In the next weeks 20m long full cable will be
tested at ASG plant

ICAS TRATOS

# The IRIS ±25 kV/40 kA 2 GW $MgB_2$ cable system 3/3

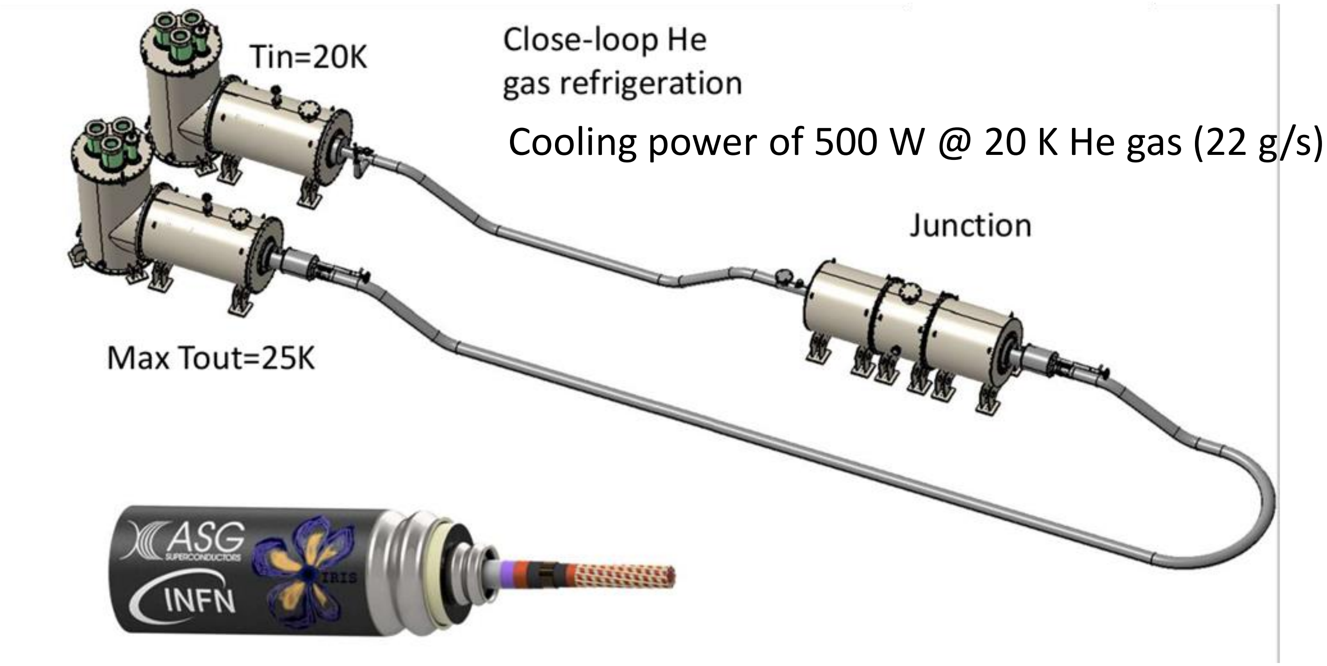
## Terminations and joints



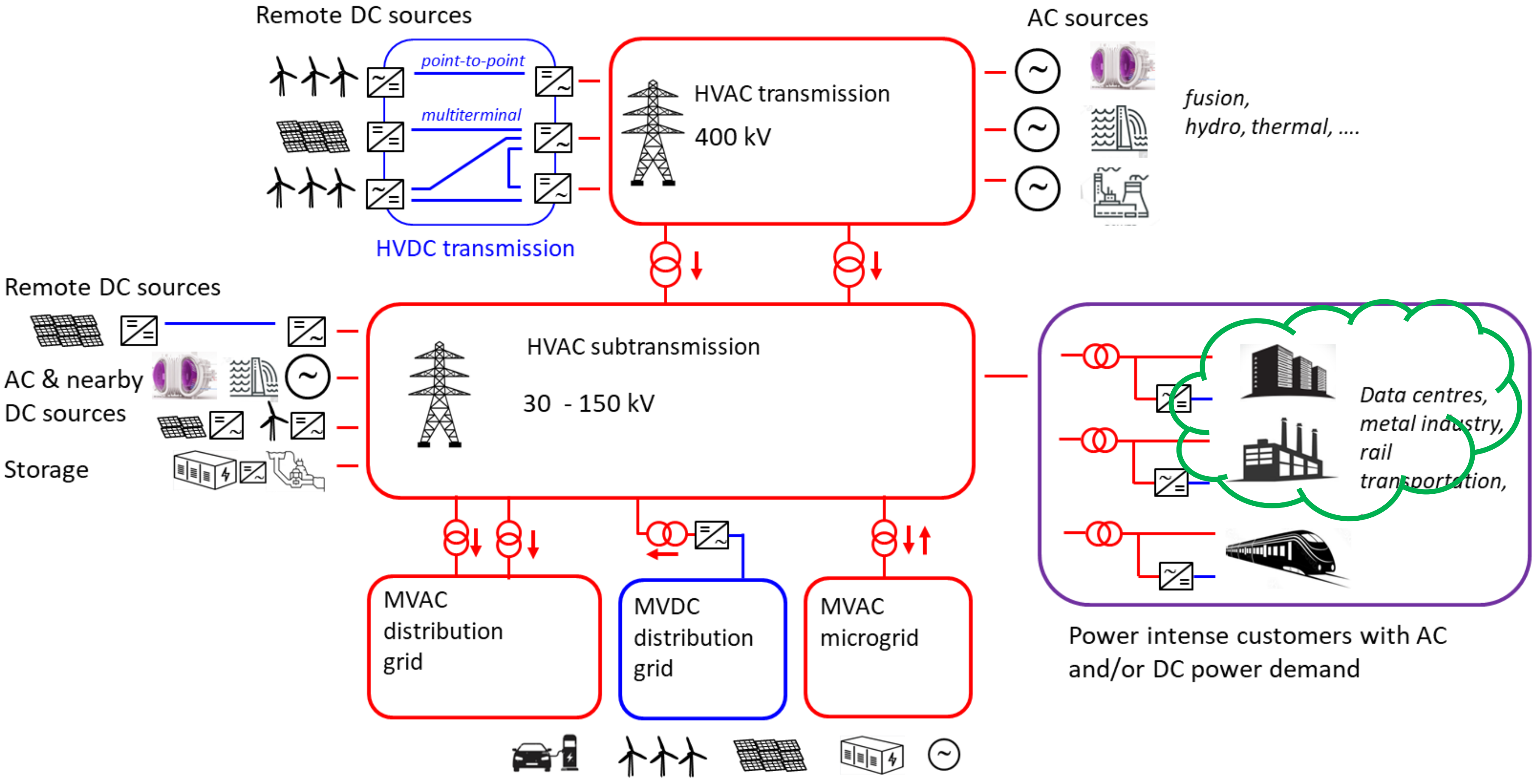
**Design completed, now in construction with most of the materials already supplied**

## Test Line




**Test to start by the end of 2025**

# DC SC busbars for low-voltage power-intensive customers




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

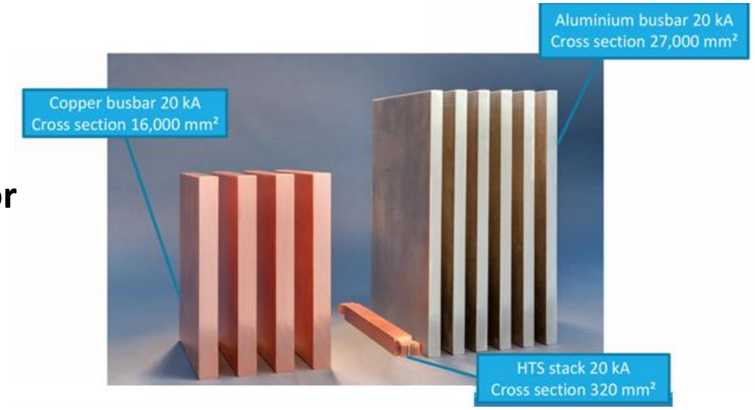
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 63, Mar. 2026. Presentation given at ISS 2025, Nagasaki, Japan, Dec. 2025.

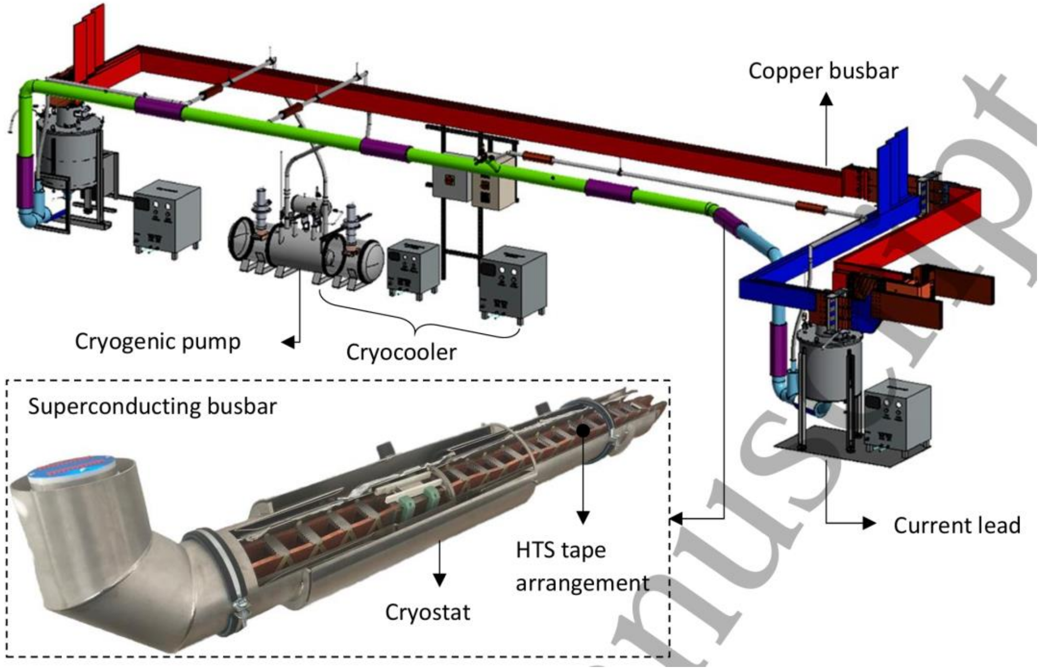
# DC high-current low-voltage busbar - the VESC R&D projects 1/2

VISION® ELECTRIC Super Conductors

**1 kV / 20 kA busbars for chlorine electrolysis successfully developed**

***Ludwigshaffen ’25***

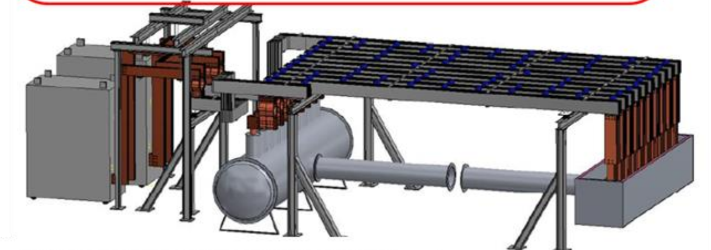



**Next:**
**Scale up to 200 kA for aluminum electrolysis applications**


**Demonstration of the short-length 200 kA HTS busbars successfully completed in 2024**

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

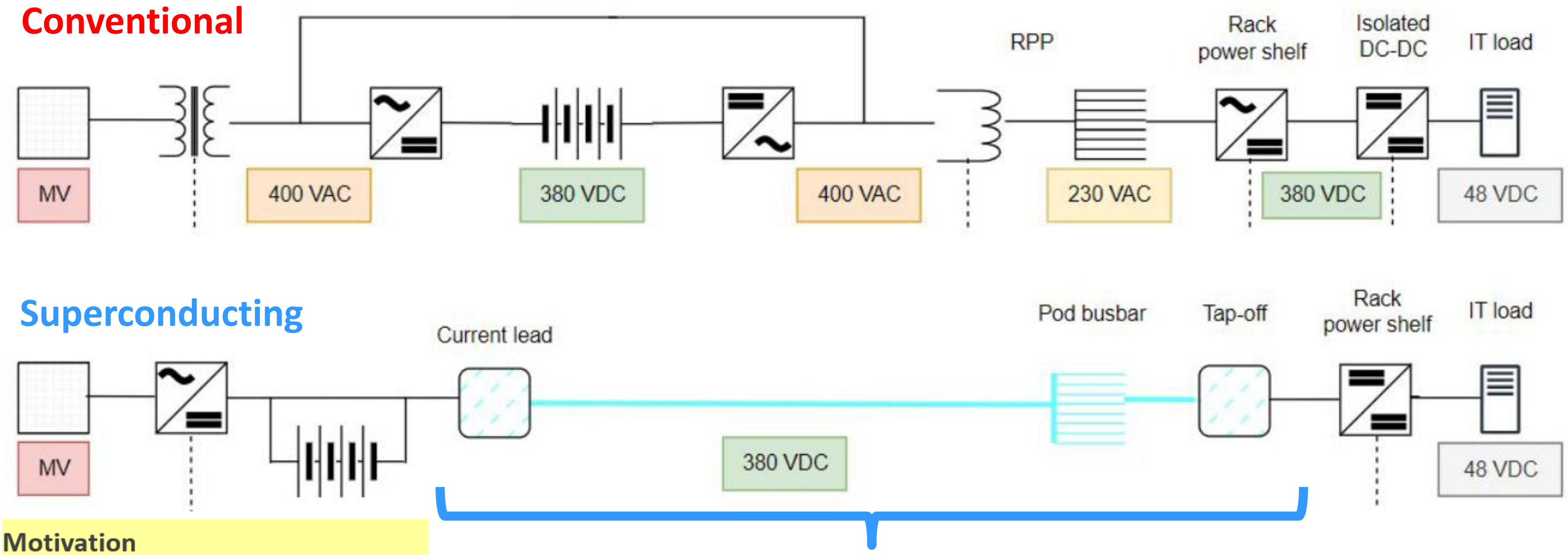


*Courtesy of Wolfgang Reiser VESC*

**In progress: development of a 200 kA HTS busbar, operating in parallel with existing aluminum busbars, for installation at the TRIMET industrial site**

# DC high-current low-voltage busbar - the VESC experience 2/2

## Conventional vs. Superconducting Hyper Scale DataCenters




**Motivation**

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

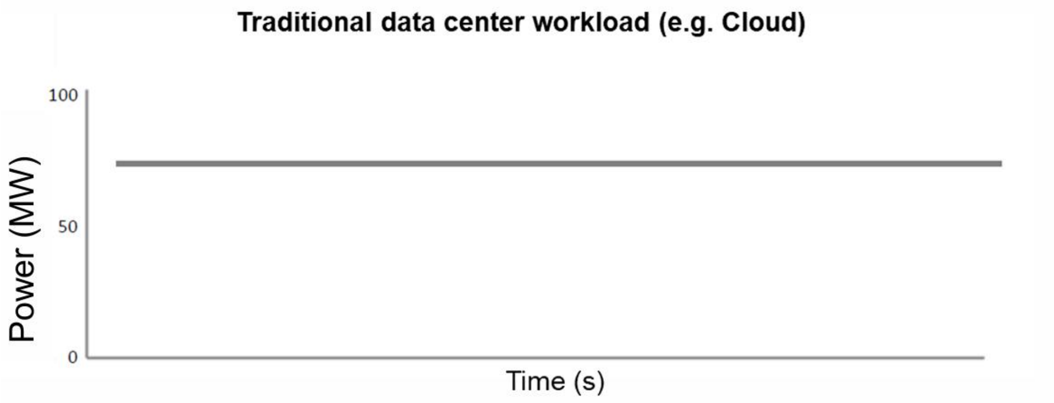
**Superconducting Busbar with multiple Tap-offs**
**Reduction of Power Conversion Steps**
**DC Distribution: Up to 100 MW on Low Voltage**

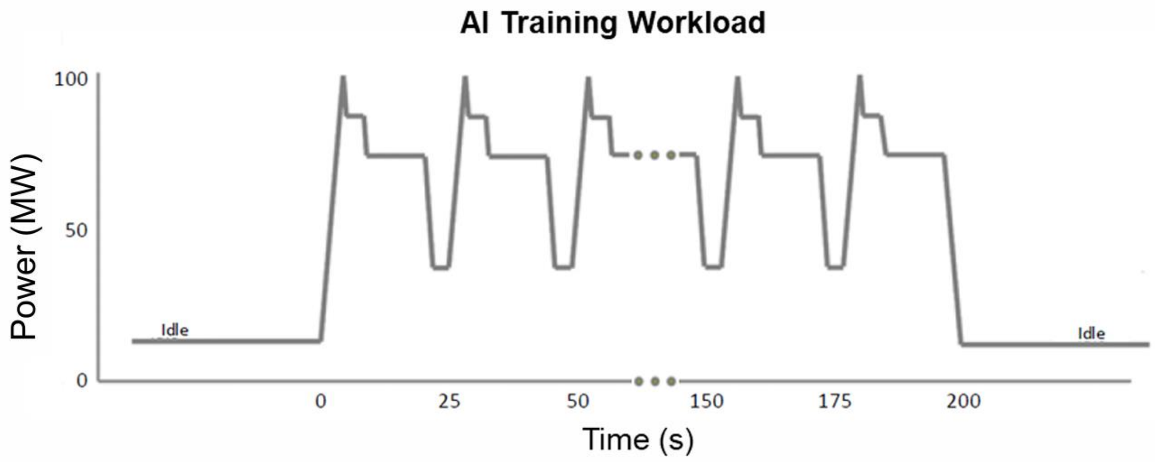
*Courtesy of Wolfgang Reiser VESC*

# A warning – is rack power required by data centers ultimately DC?

## Traditional data center vs AI training Data Center

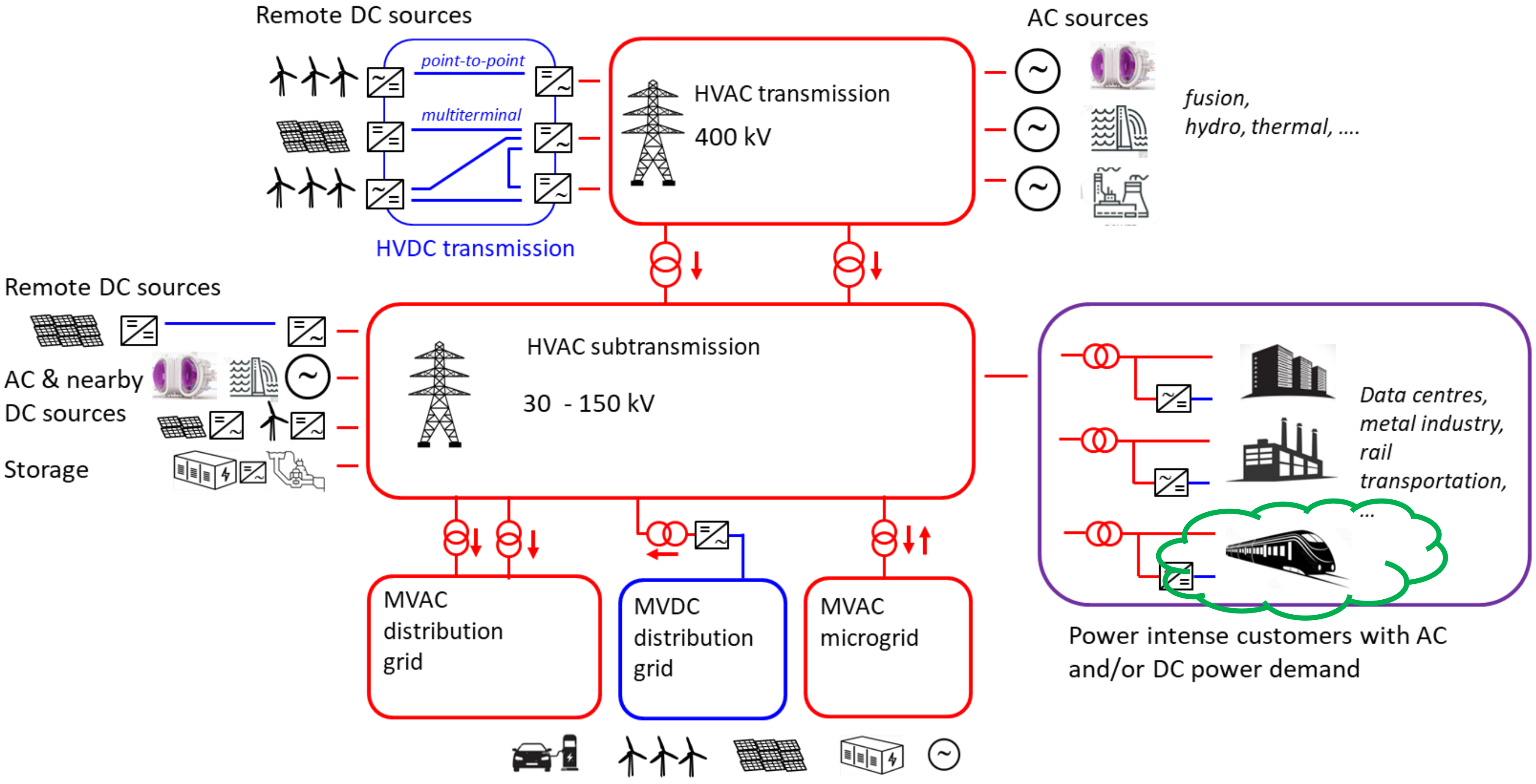
| Aspect | Traditional Data Center | AI Training Data Center |
|---|---|---|
| **Purpose and Operation** | Designed for **steady, continuous workloads** — web hosting, storage, and cloud applications.<br>Load profile is **flat and predictable**. | Runs **intense, batch-based workloads** — AI model training and inference.<br>Load profile is **highly variable**, with **spikes during training** and idle periods between jobs. |




**Large power/current fluctuations occur in DC data center supply systems, which impact the design of the proposed SC solution**

# DC SC busbars for low-voltage power-intensive customers




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

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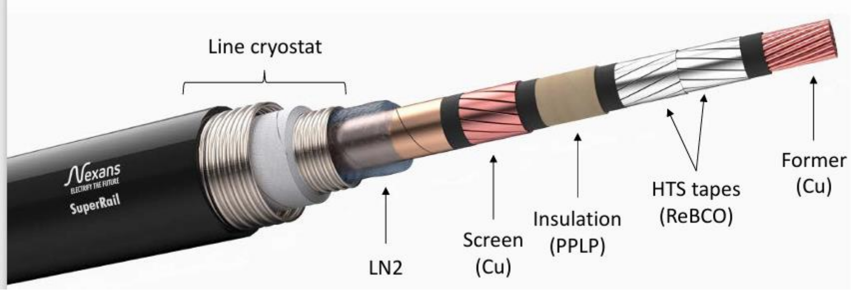
# DC HTS cables for railway power supply – The SuperRail Project 1/2

- **Motivation: the need to increase rail traffic in densely populated areas translates into the the need for upgrade of the railway power supply infrastructure**

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

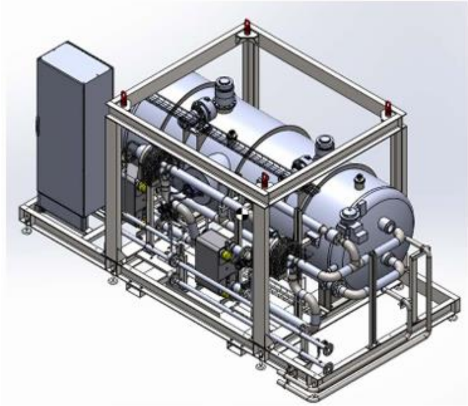
Existing rights of way saturated
only 2× Φ100 mm conduit left
= 2× 400 mm² copper cable
= 2× 500 A reinforcement
Instead of the required 3000 A

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




| Electric parameters | |
|---|---|
| Nominal voltage | 1500 V |
| Nominal current | 1500 A |
| Inrush current | 3500 A |
| Critical current | >4000 A |
| Fault current | 67 kA - 100 ms |

| Geometric parameters | |
|---|---|
| Cryostat outer diameter | 74 mm |
| Minimum bending radius | 1.5 m |
| Length | 2x 60 m |



Reverse Turbo Brayton (RTB) for the final installation, with high efficiency and low maintenance
1.7 kW @67 K

*Courtesy of Loïc Quéval, GeePs, CentraleSupélec,*

# DC HTS cables for railway power supply – The SuperRail Project 2/2

LN2 circulation SKID

Controlled cool down system

Inlet termination T1

Outlet termination T2

## 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) successfully developed and qualified**

**Commissioning for final installation started in 2025**

# Conclusion

- HTS and $MgB_2$ DC power cable technology has been widely established through many demonstration projects worldwide.
- DC cable systems with current ratings up to 200 kA and voltage ratings in the hundreds of kV, providing a breakthrough asset for a wide spectrum of applications, are now feasible based on HTS and $MgB_2$ technologies.

- Long-running in-field demonstrators need to be deployed in order to cover the final steps toward mass market penetration
- Cheap and abundant superconductors are required, along with reliable and high-capacity cooling machines and accessories, and industry production capacity of the entire cable system

Thanks for your attention

antonio.morandi@unibo.it