Superconducting cables

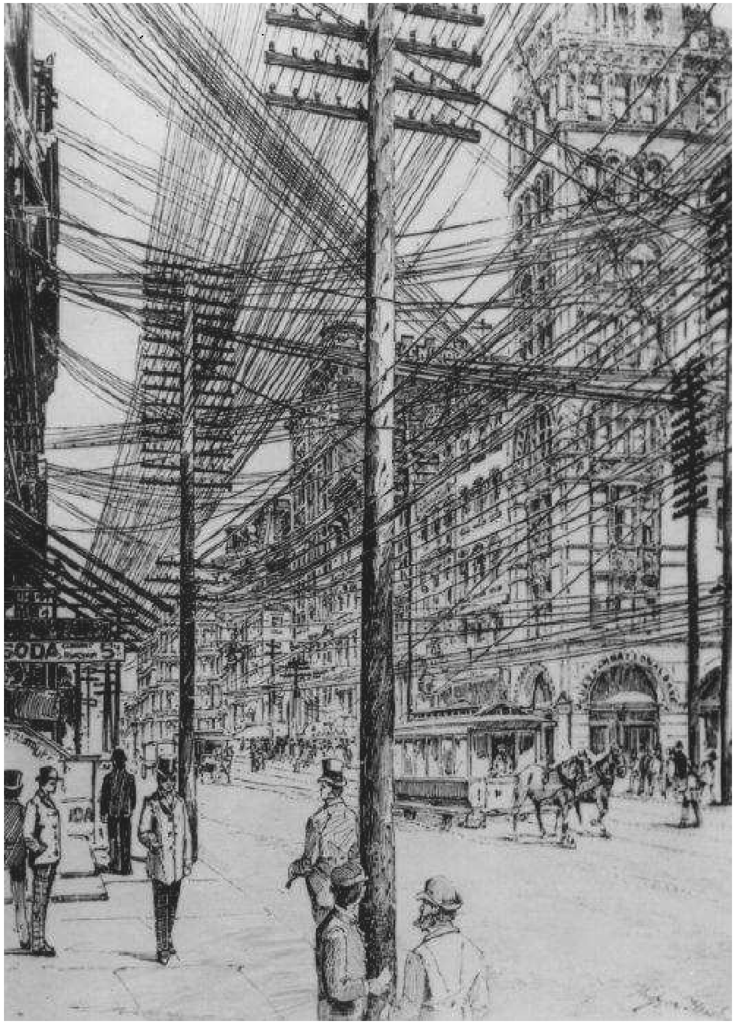
1 Motivation

2 Structure of superconducting cables
2.1 Cable types

3 Transmission characteristics
3.1 Operating parameters and four-terminal equivalent circuit
3.2 Transmission characteristics
3.3 AC losses

4 State of the Art
4.1 Overview
4.2 Application examples
4.3 Latest developments

Why cables?



Manhattan „overhead“ around 1880

Why superconducting cables?

Manhattan „underground“ 2003

Superconducting cables enable significantly higher transmission capacity with the same cable diameter.

Motivation

- **Cable laying**
  - Smaller space and rout requirements (inner cities, partial underground cabling)
  - Less efford in laying cables, easier approval
- **Environment and marketing**
  - No electromagnetic leakage fields and no soil heating
  - High energy and resource efficiency
- **Operation**
  - Higher transmission performance
  - Lower voltage level (substitution of high voltage)
  - At the same outer diameter (Right of way for retrofit)
  - Lower impedance
  - Lower voltage rise at no load
  - Lower voltage drop
  - Operation with natural loading possible

Possible uses

- Increasing the transmission capacity of existing conventional point-to-point cable routes (retrofit)
- Relocation of high-voltage overhead lines underground (as with conventional cable systems)
- Generator feeders and powerplant feeders
- Relocation of industrial customer connections to high-voltage substations
- High-power HVDC power transmission over long distances (in the future)
- Power transmission and distribution in metropolitan areas (retrofit)
- Grid connection of substations at distribution voltage level

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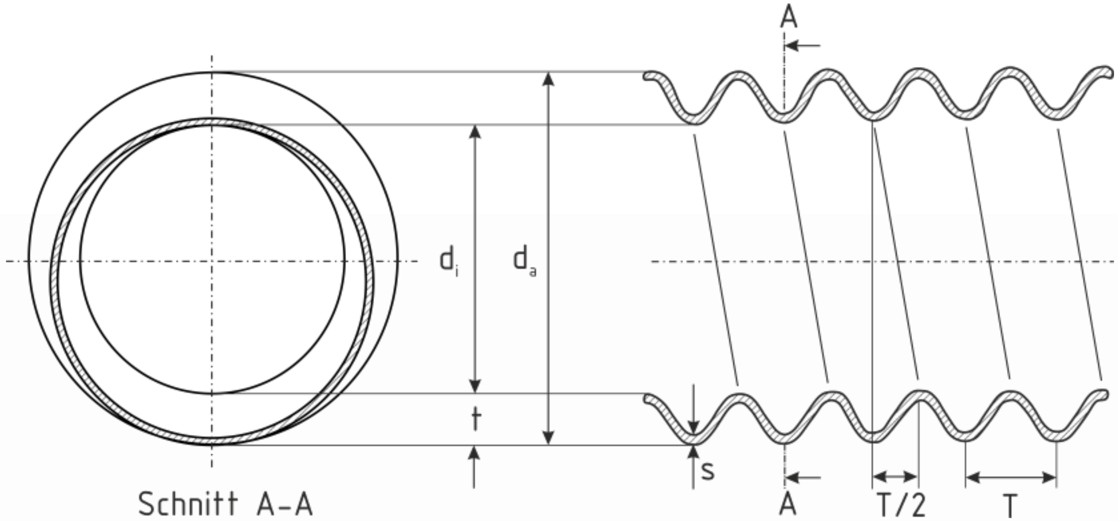
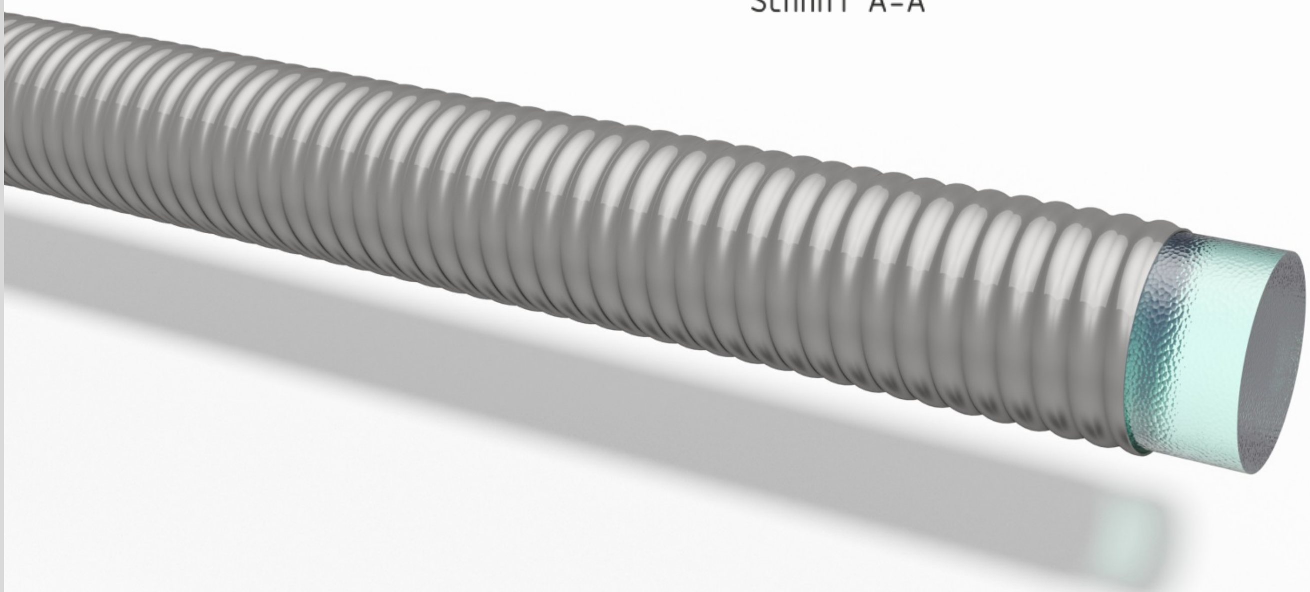
Corrugated pipe

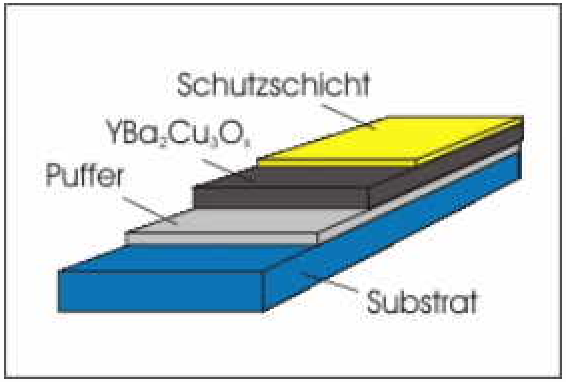
Edelstahlwellrohre nach DIN EN 13480-2 – Metallische industrielle Rohrleitungen“



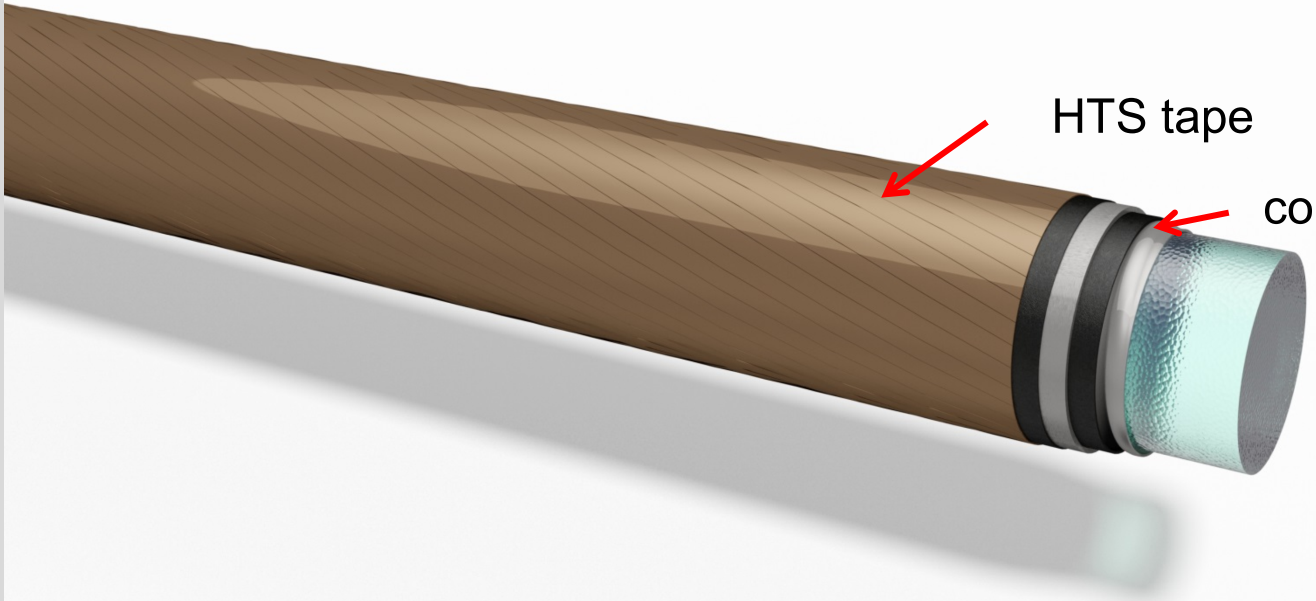


HTS layer

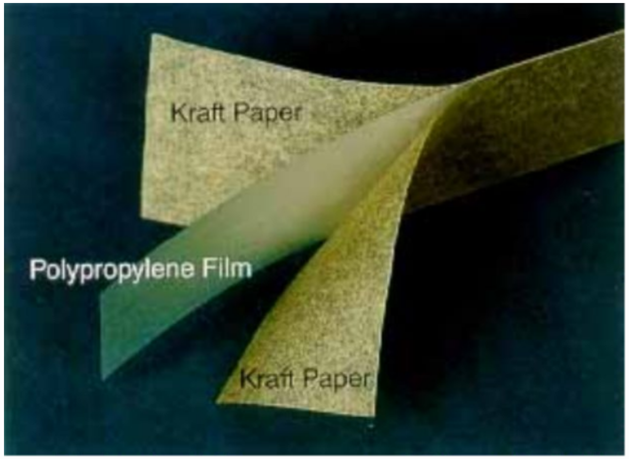
HTS tape



4 mm width
50-100 µm thickness
400-600 A at 77 K, self-field
More than 10 manufacturers worldwide



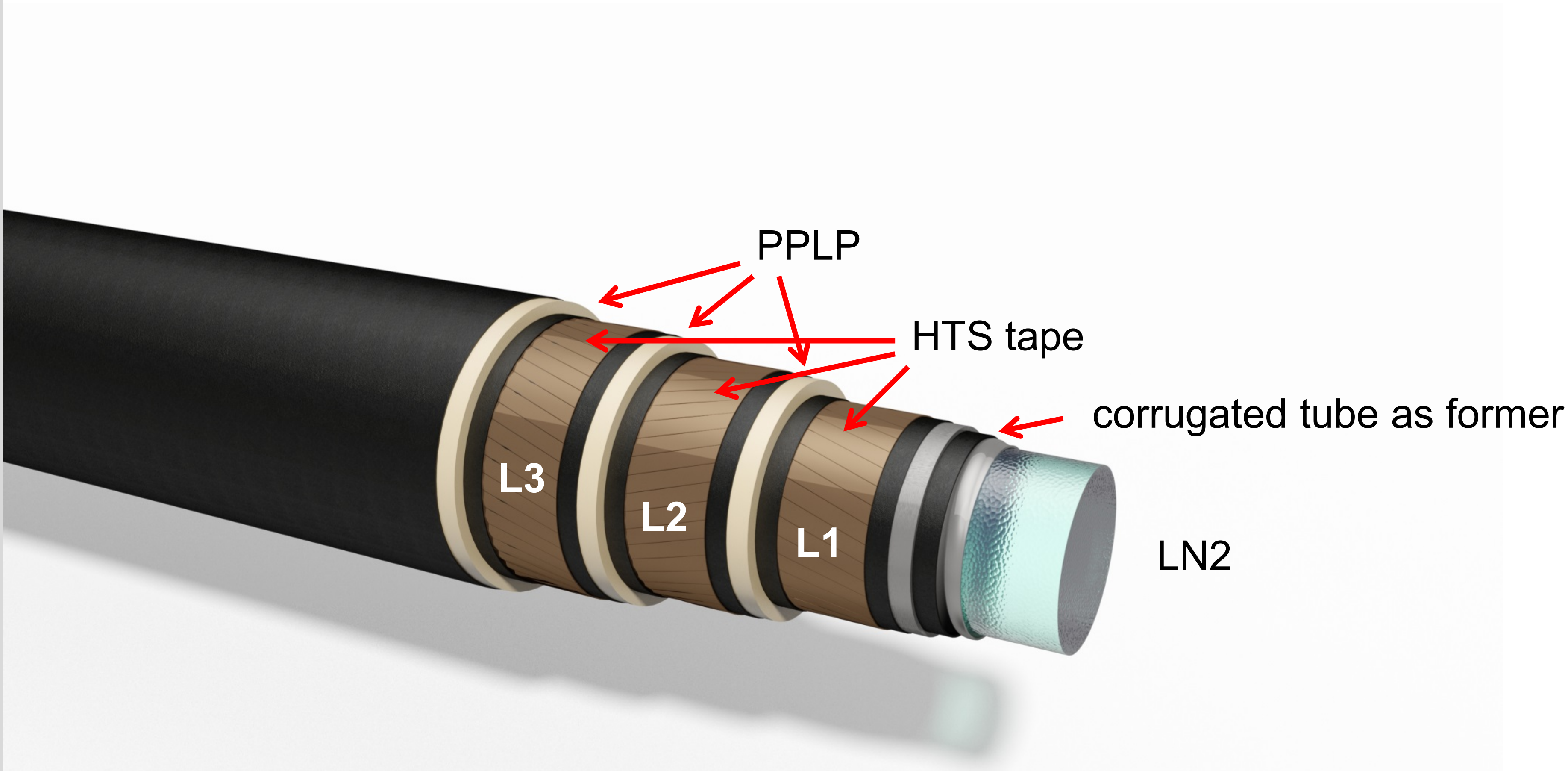
Dielectric insulation



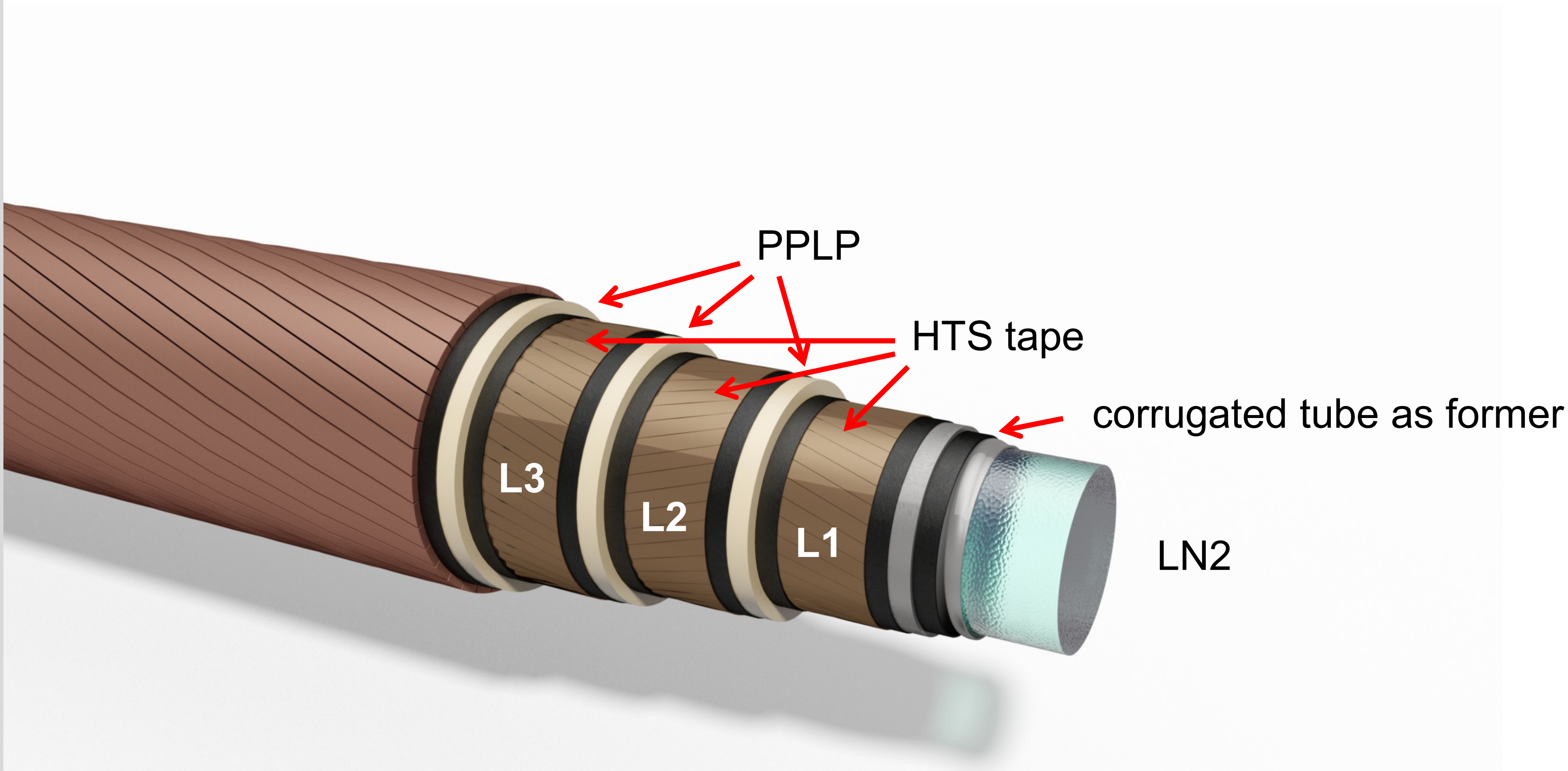
Polypropylene Laminated Paper (PPLP)

Paper – liquid nitrogen insulation

3-phase coaxial arrangement



Cu neutral conductor



Thermal shell - cryostat

1 Helically corrugated inner tube

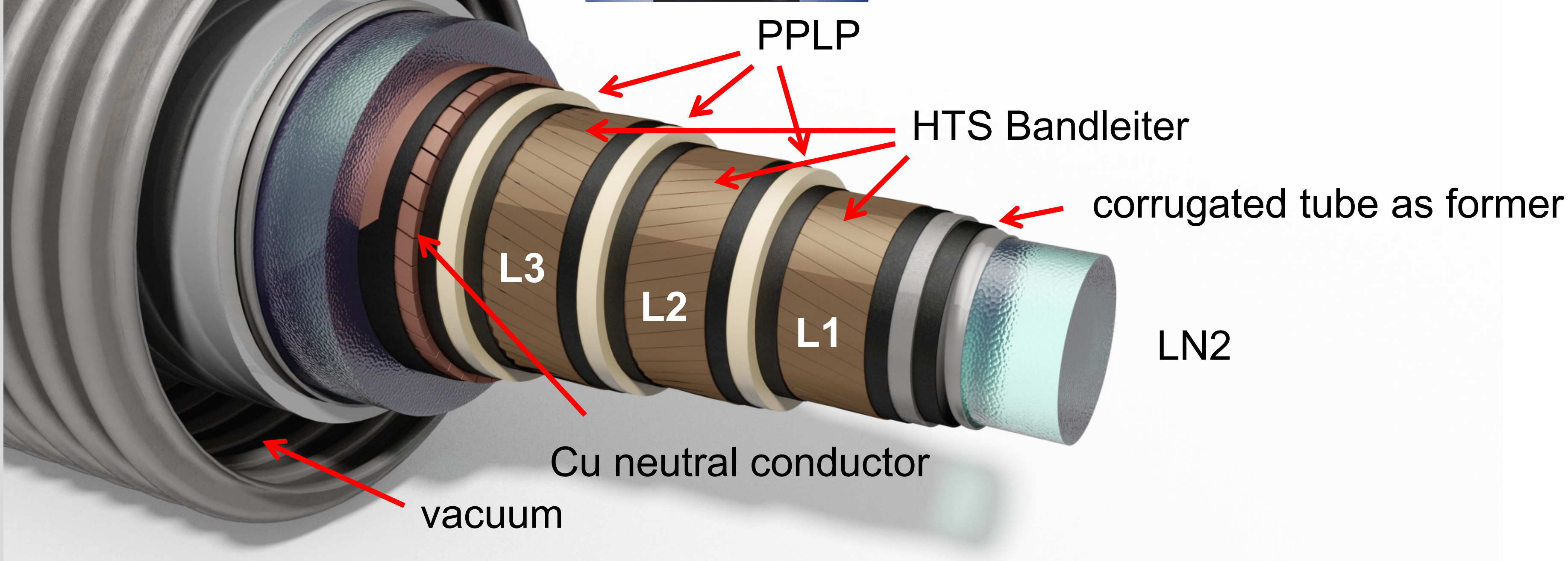
2 Low loss spacer

3 N-layers Super insulation

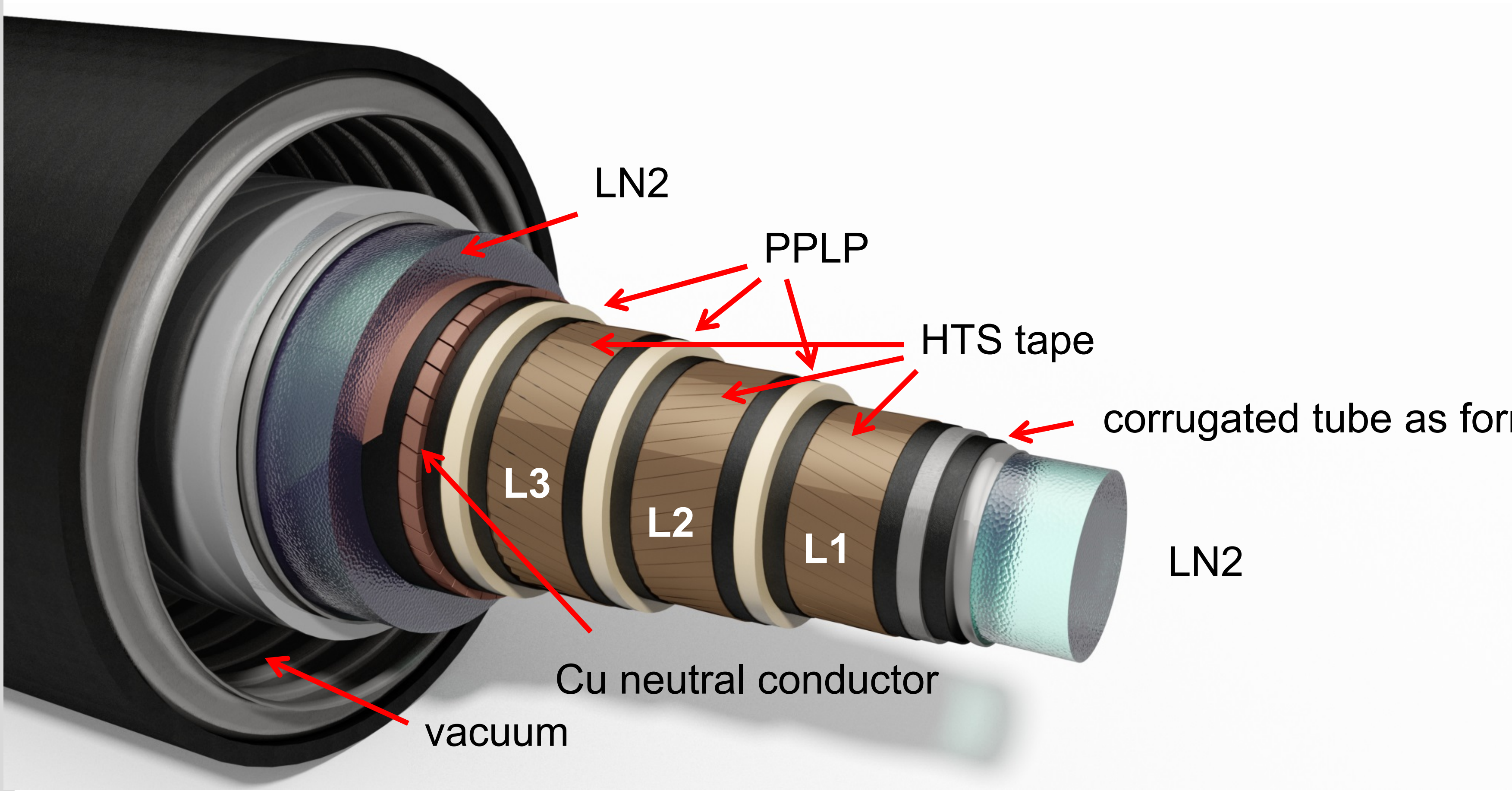
4 Vacuum

5 Helically corrugated outer tube

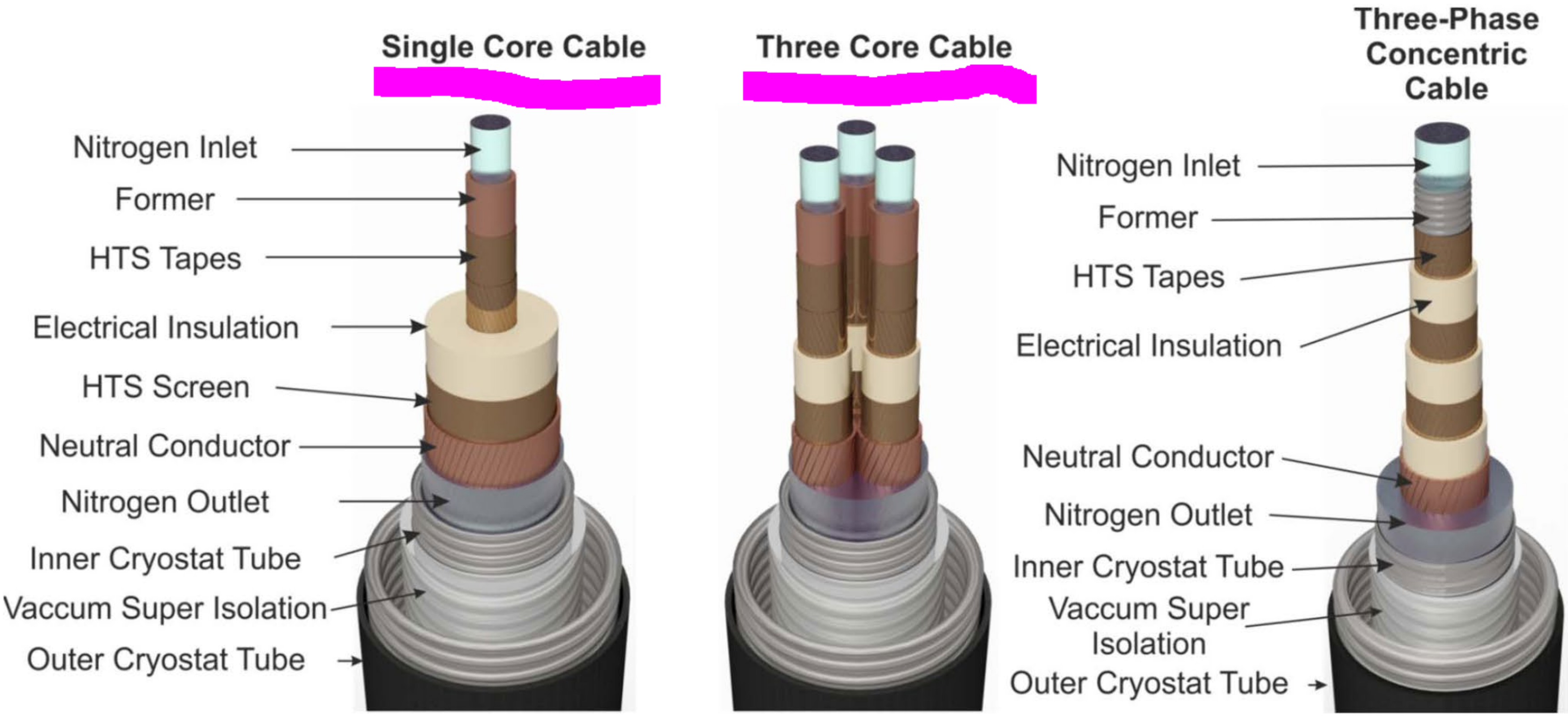
6 PE protection



Outer PE sheath



Cable types



	Three single phases	Three phases in one cryostat	Three phase concentric
Voltage level	High-voltage > 110 kV	30-110 kV	10-50 kV
Amount of superconductor	Higher	higher	smaller
Cryostat loss	Higher	smaller	smaller

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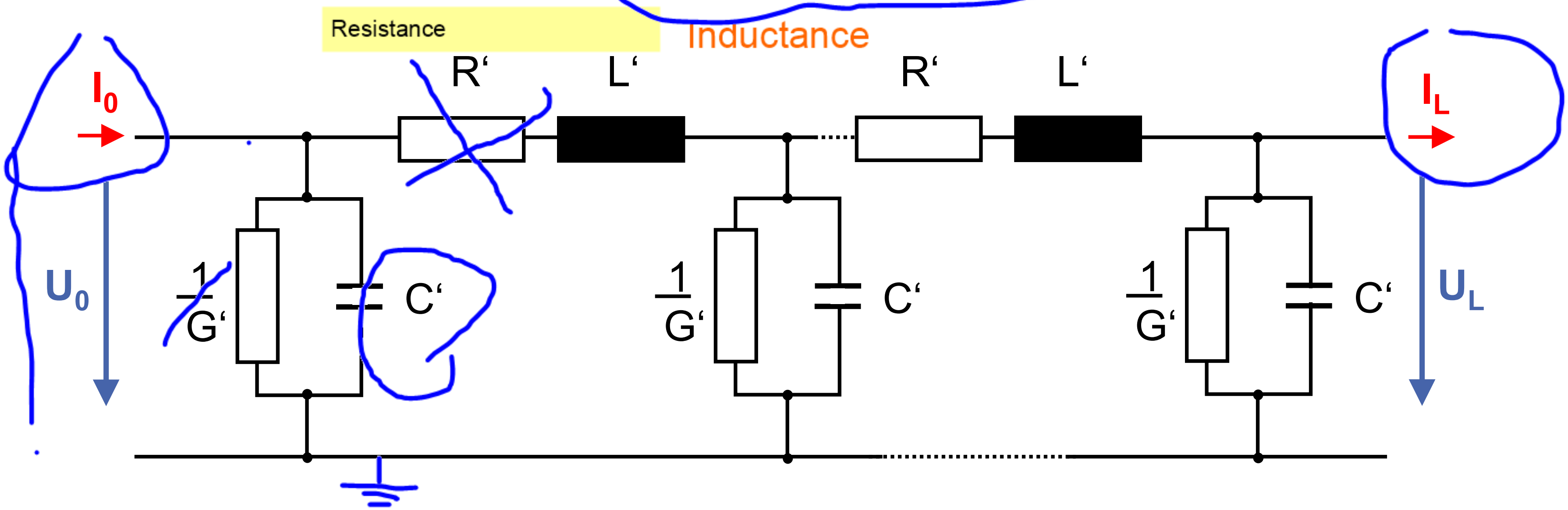
Four-terminal equivalent circuit of a transmission line

$$I_0 = I_L \cosh(\gamma l) + \frac{U_L}{Z_w} \sinh(\gamma l)$$

$$U_0 = U_L \cosh(\gamma l) + I_L Z_w \sinh(\gamma l)$$



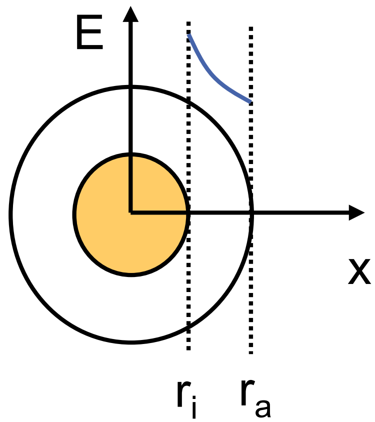
Complex propagation constant

$$\gamma = \alpha + j\beta = \sqrt{(R' + j\omega L')(G' + j\omega C')}$$

Operating parameters of a transmission cable

Curve of the electric field in the electrical insulation

$$E(x) = \frac{U_{LE}}{x} \frac{1}{\ln\left(\frac{r_a}{r_i}\right)} \quad \text{for } r_i < x < r_a$$



Insulator capacitance of a coaxial cable

$$\frac{C_b}{l} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(\frac{r_a}{r_i}\right)}$$

ε_r of VPE = 2,4
ε_r of LN_2 = 1,4
ε_r of PPLP = 2,2

Capacitive charging current

$$I_C = U_{LE}\omega C_b$$

Loop inductance of a coaxial cable

$$\frac{L}{l} = \frac{\mu_0}{2\pi}\ln\left(\frac{r_a}{r_i}\right)$$

Operating parameters

	110 kV cable N2XS(FL)2Y RM/35 1 x 300 mm²	110 kV overhead Al/St 265/35	10 kV cable NA2XS2Y RM/35 1x630 mm²	10 kV HTS cable
Power	113 MVA	130 MVA	8 MVA	40 MVA
Continuos current	591 A	680 A	462 A	2310 A
Loop resistance	95,5 mΩ/km (40° C)	118,3 mΩ/km	60,1 mΩ/km (40 ° C)	0 Ω/km
Loop inductance	188,7 mΩ/km $1{,}75\ 10^{-3}$pu/km	296,3 mΩ/k $3{,}17\ 10^{-3}$pu/km	85,6 mΩ/km $6{,}84\ 10^{-3}$pu/km	11,4 mΩ/km $4{,}56\ 10^{-3}$pu/km
Insulator capacitance	149,1 nF/km	8,0 nF/km	727,0 nF/km	2880,6 nF/km
Charging current	2,97 A/km	0,159 A/km	1,31 A/km	5,2 A/km
tan δ	0,001	-	0,004	0,0012
Reference impedance	107,4 Ω	93,3 Ω	12,5 Ω	2,5 Ω
characteristic impedance	63,7 Ω	343,1 Ω	19,35 Ω	3,54 Ω
Natural loading	190 MW	35,2 MW	5,16 MW	28,1 MW

Operating parameters

Elementary components of 380 kV transmission lines with a current of 3600 A

		overhead	cable	supercondcuting cable	Gas insulated
Loop inductance L'	(mH/km)	0,80	0,48	0,13	0,2
Insulator capacitance C'	(nF/km)	13	230	158	55-70
Loop resistance R'	$(m\Omega/km)$	36	7,2	>1	
characteristic impedance		248 Ω	45, 6 Ω	28,6 Ω	60,3-53,4
Natural loading		582 MW	3,16 GW	5,0 GW	2,39-2,7 GW

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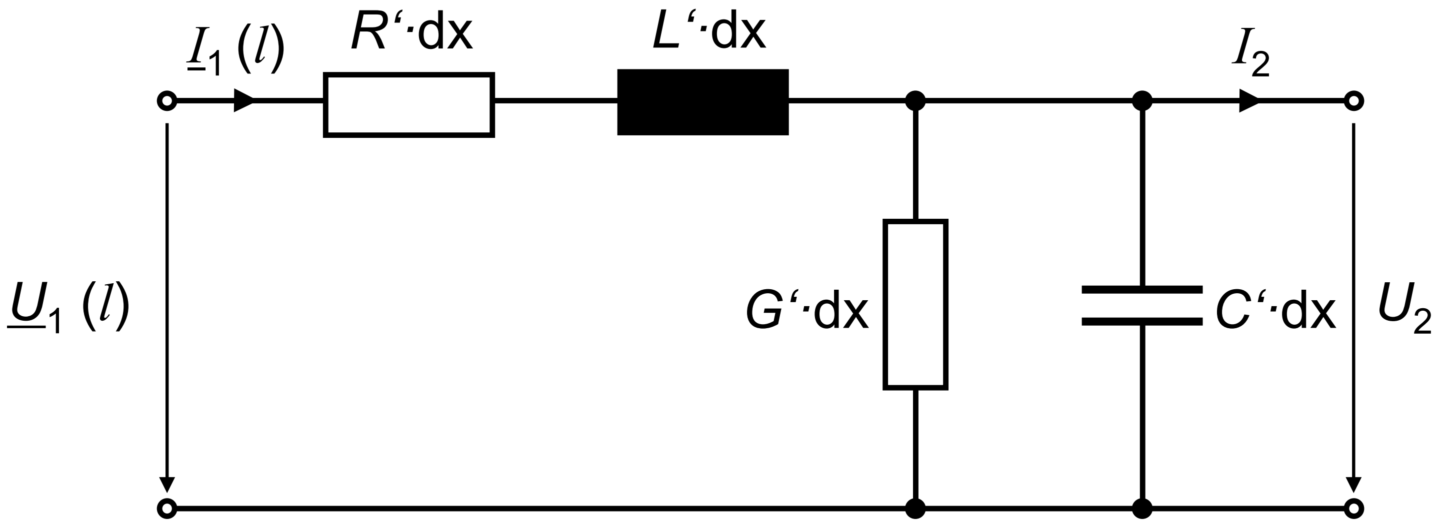
Transmission characteristics

Schematic representation of the elementary component of a transmission line



$$\underline{U}_1(l) = \underline{U}_2 \cosh(\gamma \cdot l) + \underline{I}_2 \cdot \underline{Z}_\mathrm{W} \sinh(\gamma \cdot l)$$

$$\underline{I}_1(l) = \underline{I}_2 \cosh(\gamma \cdot l) + \frac{\underline{U}_2}{\underline{Z}_\mathrm{W}} \sinh(\gamma \cdot l)$$

Transmission characteristics

Characteristic impedance and surge impedance loading (SIL) or natural loading

$$\underline{Z}_W = \sqrt{\frac{R' + j\,\omega\,L'}{G' + j\,\omega\,C'}}$$

⇨ Lossless line
$R' = 0$
$G' = 0$
⇨ $\underline{Z}_W = \sqrt{\frac{L'}{C'}}$

- propagation constant γ

$$\gamma = \sqrt{(R' + j\,\omega\,L')(G' + j\,\omega\,C')}$$

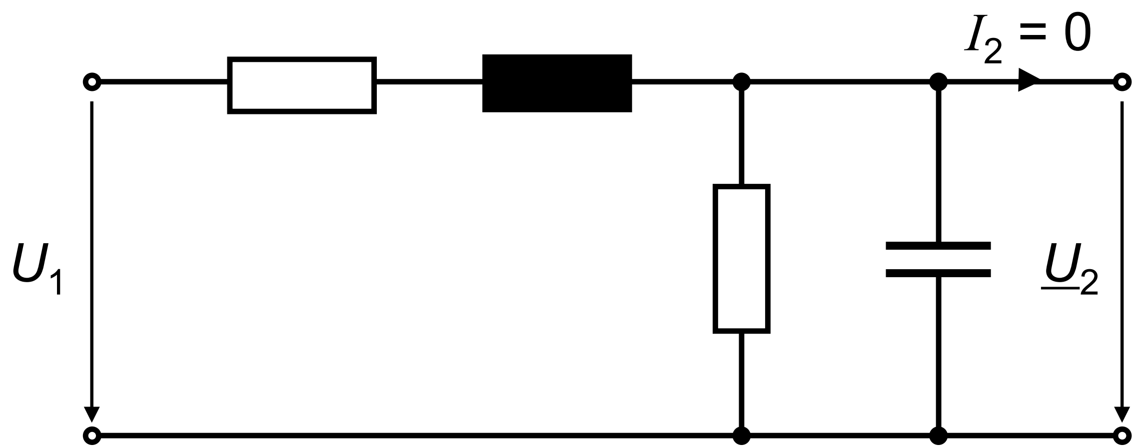
⇨ Lossless line
$R' = 0$
$G' = 0$
⇨ $\gamma = j \cdot \sqrt{\omega^2 L' C'}$

- Natural loading P_{nat}

$$P_{nat} = \frac{U_N^2}{|\underline{Z}_W|}$$

Transmission characteristics

No load



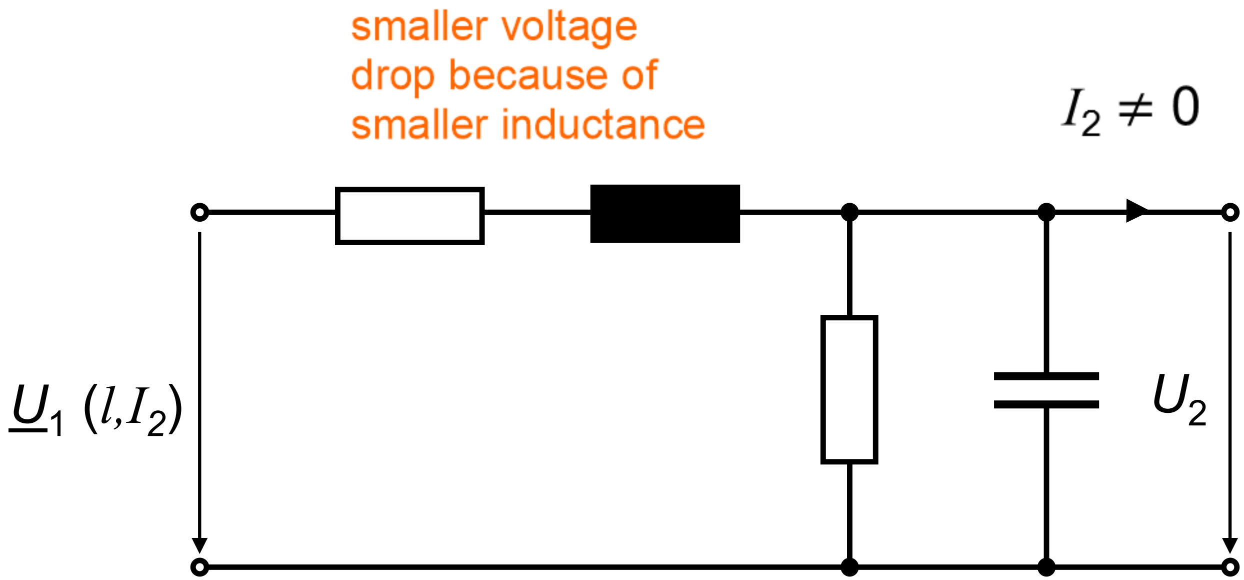
Smaller Voltage change Delta U2 for HTS cables

$$\underline{U}_2(l) = \frac{U_1}{\cosh(\gamma \cdot l)}$$

$$\Delta U_2(l) = \left(\frac{|\underline{U}_2(l)|}{U_1} - 1 \right) \cdot 100\ \%$$

Transmission characteristics

Voltage drop



Preset:
I_2 and U_2 real
$U_2 = U_0$

$$\Delta U_1(l, I_2) = \left(\frac{|\underline{U}_1(l, I_2)|}{U_2} - 1 \right) \cdot 100\ \%$$

Transmission characteristics

Results

Smaller inductance, higher capacitance

Characteristic impedance of HTS cables smaller than that of conventional cables at the same voltage

This results in higher natural load of HTS cables

HTS cables can be operated with natural loads

HTS cables have less charging currents than conventional cables with reference to same load

HTS cables have a smaller voltage drop

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AC losses in superconducting cables

Loss types in conventional cables

- Conduction losses
  - DC resistance
  - Skin effect
  - Proximity effect
- Dielectric losses
- Sheath losses and
  reinforcement losses

Loss types in superconducting cables

ZDF Mission X: Der Stromkrieg broadcasted on 4. Oktober 2006

„ Mit Supraleitern kann man elektrischen Strom vollkommen ohne Verluste über größte Längen transportieren"

„ With superconductors, electric current can be transported over great lengths with absolutely no losses."

AC losses in superconducting cables

Loss types in conventional cables

- Conduction losses
  - DC resistance
  - Skin effect
  - Proximity effect
- Dielectric losses
- Sheath losses and reinforcement losses

Loss types in superconducting cables

- ~~AC losses~~
- ~~Dielectric losses~~

} Zero for DC cable

- Thermal losses
  - Cryostat
  - Termination
- Liquid nitrogen pumps and auxiliary

AC losses in superconducting cables

Karlsruhe Institute of Technology

AC losses

The AC losses in a cable can be estimated by assuming a superconducting hollow cylinder in self-field.

$$P_{ac} = \frac{I_c^2 \mu_0 \omega l}{\pi} \left\{ (1-i)\ln(1-i) + i - \frac{1}{2} i^2 \right\} \qquad i = \frac{I_0}{I_c}$$

Dielectric losses

The superconducting cable represents a cylindrical capacitor with capacitance C.

$$P_d = \omega C \hat{U}_r^2 \tan\delta \qquad \text{mit} \qquad \frac{C}{l} = \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln(\frac{r_{el,a}}{r_{el,i}})}$$

Thermal losses

The following applies to the heat input per conductor length for cylindrical symmetry :

$$P_{th} = \frac{2\pi \lambda_{iso} (T_a - T_{Kühl})}{\ln(\frac{r_{th,a}}{r_{th,i}})}$$

AC losses in superconducting cables in comparison

110 kV, 3 kA, 1000 m
2-VPE cable parallel

- Conduction losses

(1600 mm², 1500 A, 90° C)

- DC losses 30,8 W/m/phase
- Skin effect
- Proximity effect

- Dielectric losses
- sheath losses and

reinforcement losses

(Skin effect, proximity effect, dielectric losses: +5 %)

Total losses 194 kW (I_{max})

110 kV, 3 kA, 1000 m
1-HTS cable

- AC losses ≤ 1 W/m/phase (target)
- Dielectric losses 0,4 W/m/phase
- Thermal losses
  - Cryostat 1-1,5 W/m/phase
  - Termination 20-40 W/kA
- Efficiency cooling unit 1/15-1/20

Total losses 112 kW (I_{max})

AC losses in superconducting cables in comparison

Overview of losses for two **superconducting** 380 kV systems with a rated current of 3.6 kA and a route length of 3200 m

Loss type	Power loss	Power loss	Power loss
	$0{,}1 \cdot I_N$	$0{,}5 \cdot I_N$	$1 \cdot I_N$
Cooling load	45329 W	46303 W	59806 W
AC losses	1,0 W	662 W	13188 W
Dielectric losses	5956 W	5956 W	5956 W
Cryostat losses	38400 W	38400 W	38400 W
Current lead losses	732 W	1045 W	2022 W
Termination losses	240 W	240 W	240 W
Losses at RT	719,5 kW	735,0 kW	949,3 kW

Overview of losses for four **conventional** systems at a rated current of 1.8 kA per system and a route length of 3200 m for 2500 mm² cross-section

Loss type	Power loss	Power loss	Power loss
	$0{,}1 \cdot I_N$	$0{,}5 \cdot I_N$	$1 \cdot I_N$
Resistance losses	14 kW	339 kW	1356 kW
Dielectric losses	136 kW	136 kW	136 kW
Total losses	149 kW	475 kW	1492 kW

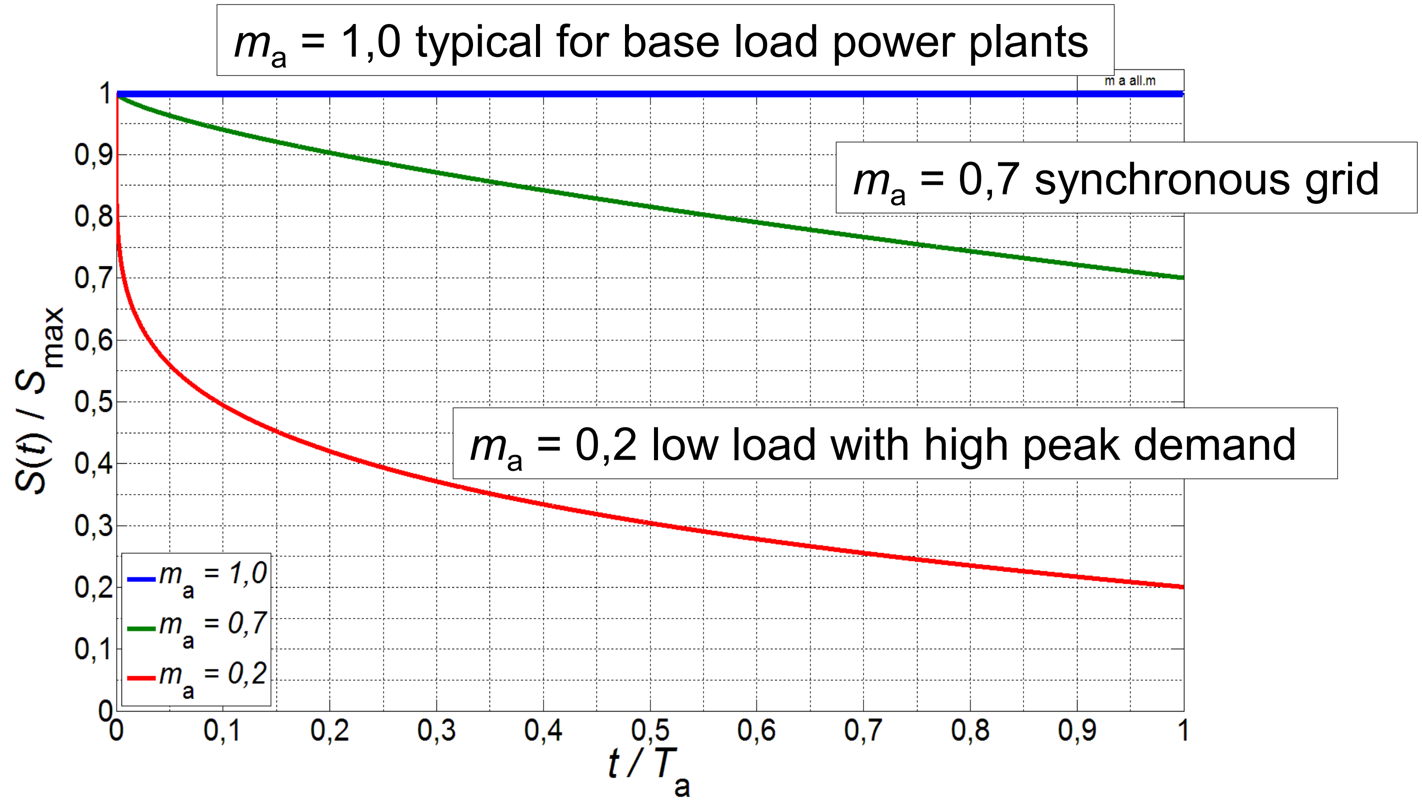
Calculation of the annual energy loss
Load factor

- The load factor m_a specifies the power curve $S(t)$ in relation to the maximum power of a transmission system. It is a measure of the utilization rate.

$$\frac{S(t)}{S_{max}} = 1 - (1 - m_a) \cdot \left(\frac{t}{T_a}\right)^{m_a}$$

- All loss components that are dependent on the load (current) must be weighted with the distibution of $\frac{S(t)}{S_{max}}$.

Calculation of the annual energy loss
Load factor



Comparison of annual energy loss for superconducting cable (380 kV, 3.6 kA, 3.2 km)

Cable type/ annual energy loss	annual energy loss $m_a = 0.3$ MWh	annual energy loss $m_a = 0.5$ MWh	annual energy loss $m_a = 0.7$ MWh
conventional underground cable			
- Resistance losses	1894	4455	7320
- Dielectric losses	1189	1189	1189
Total annual energy loss	**3082**	**5643**	**8509**
Superconducting cable			
- AC losses	103	321	701
- Current lead thermal	100	100	100
- Current lead electric	29	68	112
- Cryostat	2670	2670	2670
- Termination	33	33	33
- Dielectric losses	828	828	828
Total annual energy loss	**3763**	**4020**	**4444**

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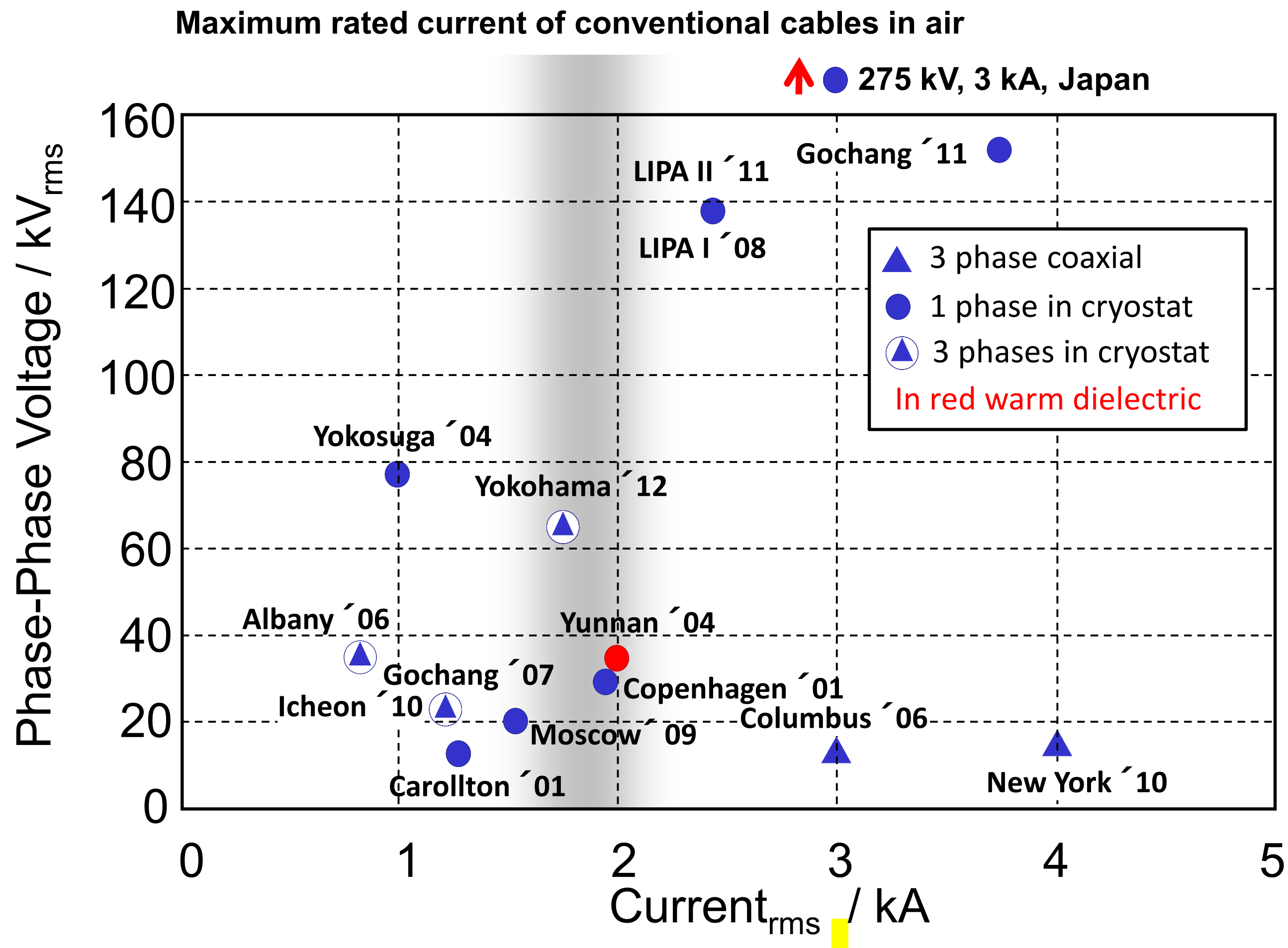
Superconducting AC Cables
State-of-the-Art

Manufacturer	Place ,Country, Year	Data	HTS
SECRI	Shanghai, China, 2021	35 kV, 2.2 kA, 1200 m	YBCO
Nexans	Chicago, US, 2020	12 kV, 200 m	YBCO
LS Cable	Singal, Korea, 2019	22.9 kV, 50 MVA, 1000 m	YBCO
LS Cable	Jeju, Korea, 2016	154 kV, 600 MVA, 1000 m	YBCO
Nexans	Essen, Deutschland, 2014	10 kV, 2.4 kA, 1000 m	BSCCO
Sumitomo	Yokohama, Japan, 2013	66 kV, 1.8 kA, 240 m	BSCCO
LS Cable	Icheon, Korea, 2011	22.9 kV, 3.0 kA, 100 m	BSCCO
LS Cable	Icheon, Korea, 2009	22.9 kV, 1.3 kA, 500 m	BSCCO
Nexans	Long Island, US, 2008	138 kV, 2.4 kA, 600 m	BSCCO/YBCO
LS Cable	Gochang, Korea, 2007	22.9 kV, 1.26 kA, 100 m	BSCCO
Sumitomo	Albany, US, 2006	34.5 kV, 800 A, 350 m	BSCCO
Ultera	Columbus, US, 2006	13.2 kV, 3 kA, 200 m	BSCCO
Sumitomo	Gochang, Korea, 2006	22.9 kV, 1.25 kA, 100 m	BSCCO
Furukawa	Yokosuka, Japan, 2004	77 kV, 1 kA, 500 m	BSCCO

More than 10 years of operational experience and no HTS degradation reported.

State of the Art



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State-of-the-Art

Karlsruhe Institute of Technology

- Technology Readiness Level (EU H2020)

9	Actual system proven in operational environment	High TRL
8	System complete and qualified	High TRL
7	System prototype demonstration in operational environment	High TRL
6	Technology demonstrated in relevant environment	Med. TRL
5	Technology validated in relevant environment	Med. TRL
4	Technology validated in lab	Med. TRL
3	Experimental proof of concept	Low TRL
2	Technology concept formulated	Low TRL
1	Basic principles observed	Low TRL

HTS AC MV Cables – State-of-the-Art

2000 – First HTS cable in public grid operation by Southwire

Three separate phases

Voltage 12.5 kV

Current 1250 A

Length 30 m

HTS BSCCO

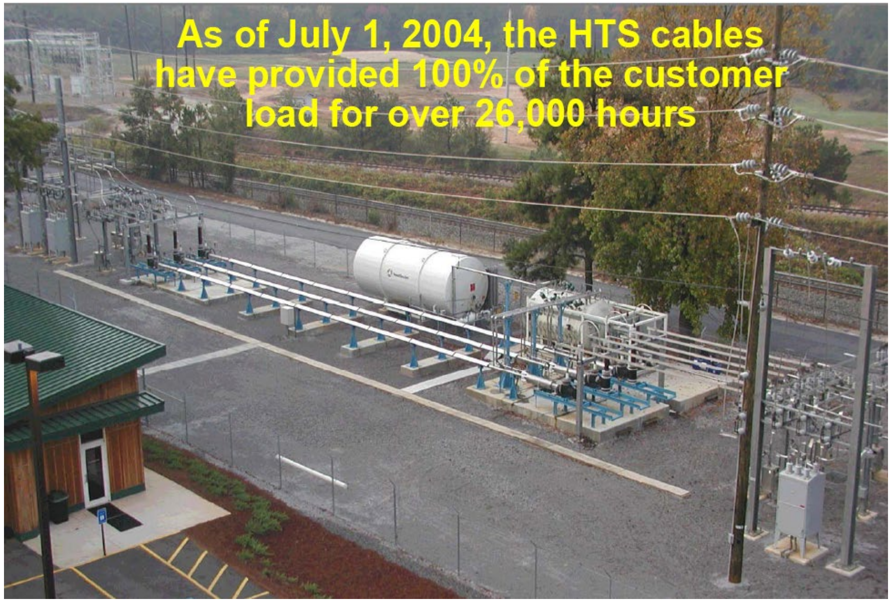
Total loss 1490 W @ 77 K, 600 A

230 W per terminal

1 W/m/Phase Cryostat

0.2 W/m/Phase @ 600 A

Experimental proof of concept



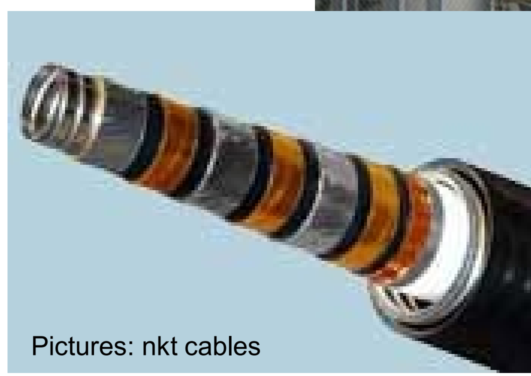
Stovall et.al. IEEE TASC Vol. 11, No.1, March 2001

HTS AC MV Cables – State-of-the-Art

2006 – First three phase concentric design in long term (~ 1 year) field test by Ultera (Southwire, nkt cables)

- Three phase co-axial design
- Voltage 13.2 kV
- Current 3000 A
- Length 200 m
- HTS BSCCO
- Ic > 7000 A at 78.5 K
- 2 W/m Cryostat

Demko et.al. IEEE TASC doi 10.1109/TASC.2007.897842



Pictures: nkt cables

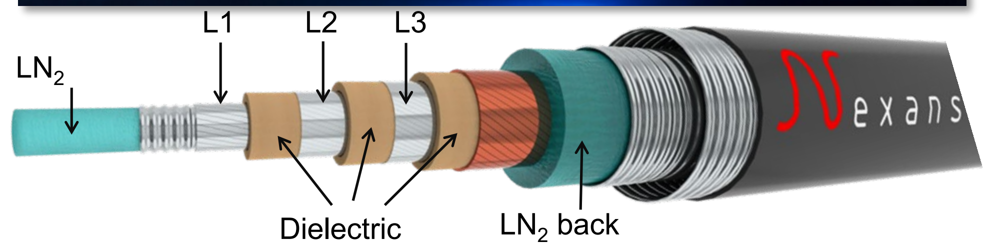
Technology validated in relevant environment

HTS AC MV Cables – State-of-the-Art

2014 – First long term (> 5 years) and continous operation in the grid of Essen by Nexans and Westnetz

- Three phase co-axial design
- Voltage 10 kV
- Power 40 MVA
- Length 1000 m
- HTS BSCCO
- Loss 1.8 kW at 68 K, $I < 0.5\ I_n$

AMPACITY
Smart grids for the city



Stemmle et. al. IEEE PES T&D Conference and Exposition, 14-17 April 2014, Chicago, IL, USU
DOI: 10.1109/TDC.2014.6863566

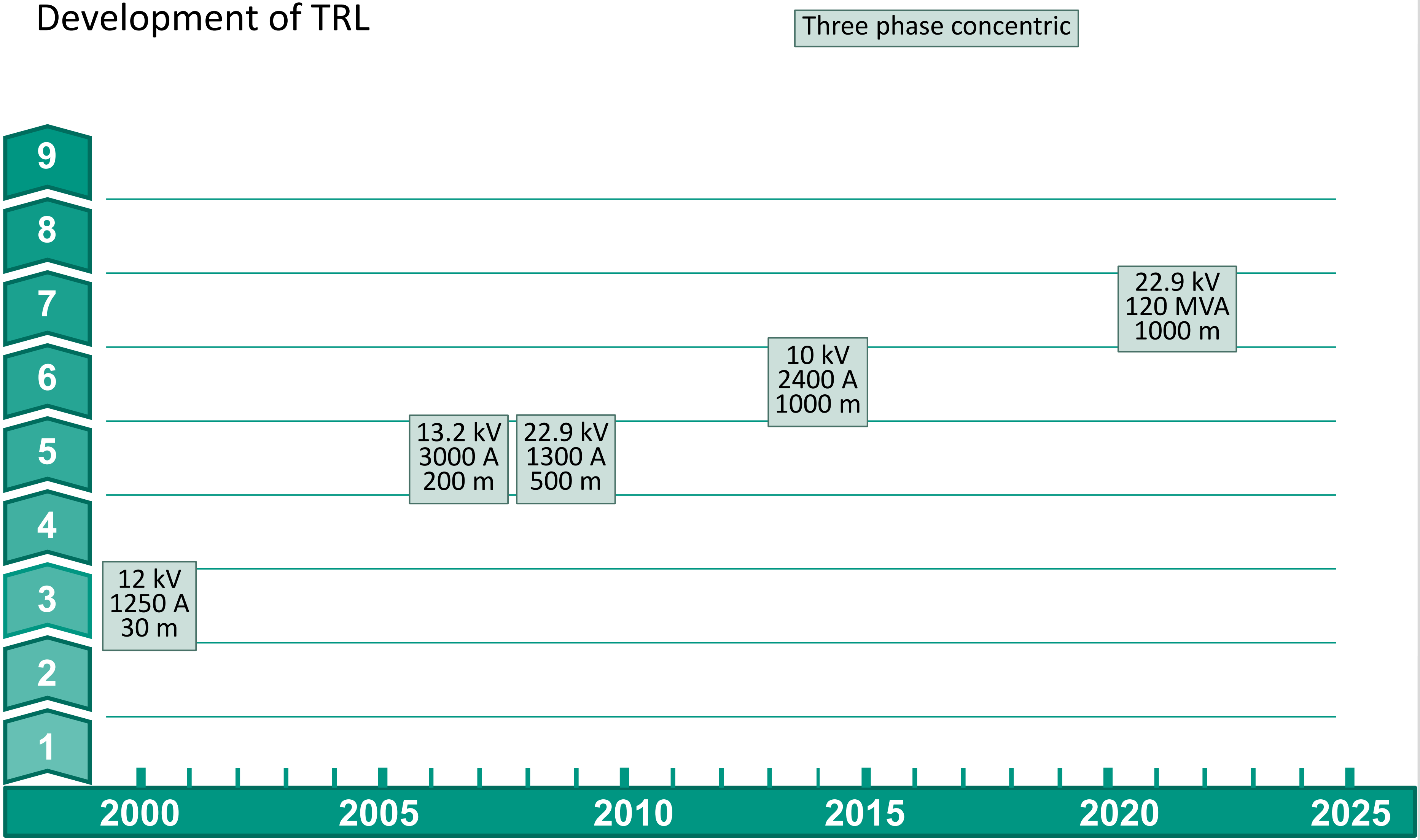
9 8 7 6 5 4 3 2 1

Technology demonstrated in relevant environment

2000 2005 2010 2015 2020 2025

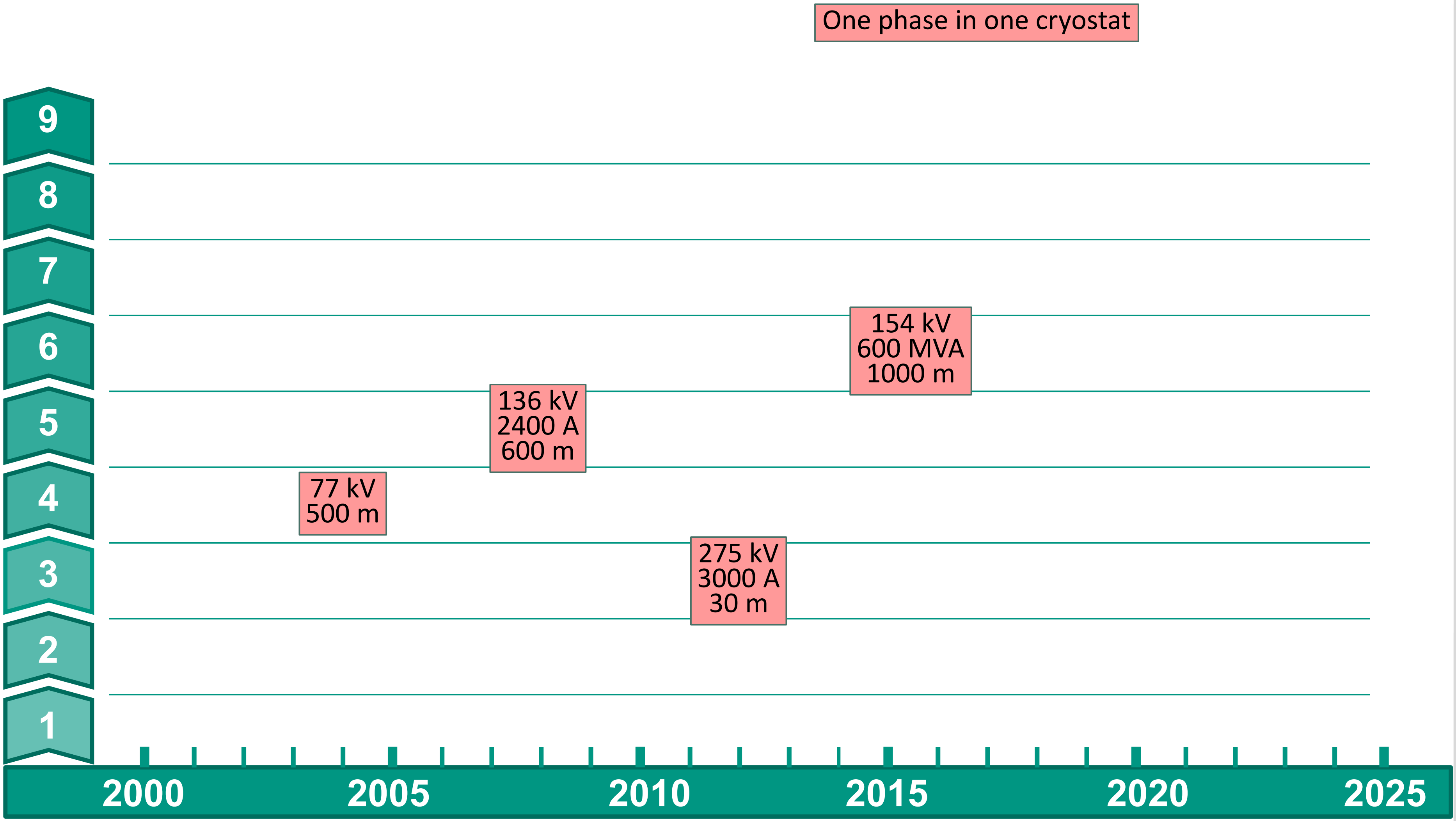
HTS AC MV Cables – State-of-the-Art

Development of TRL



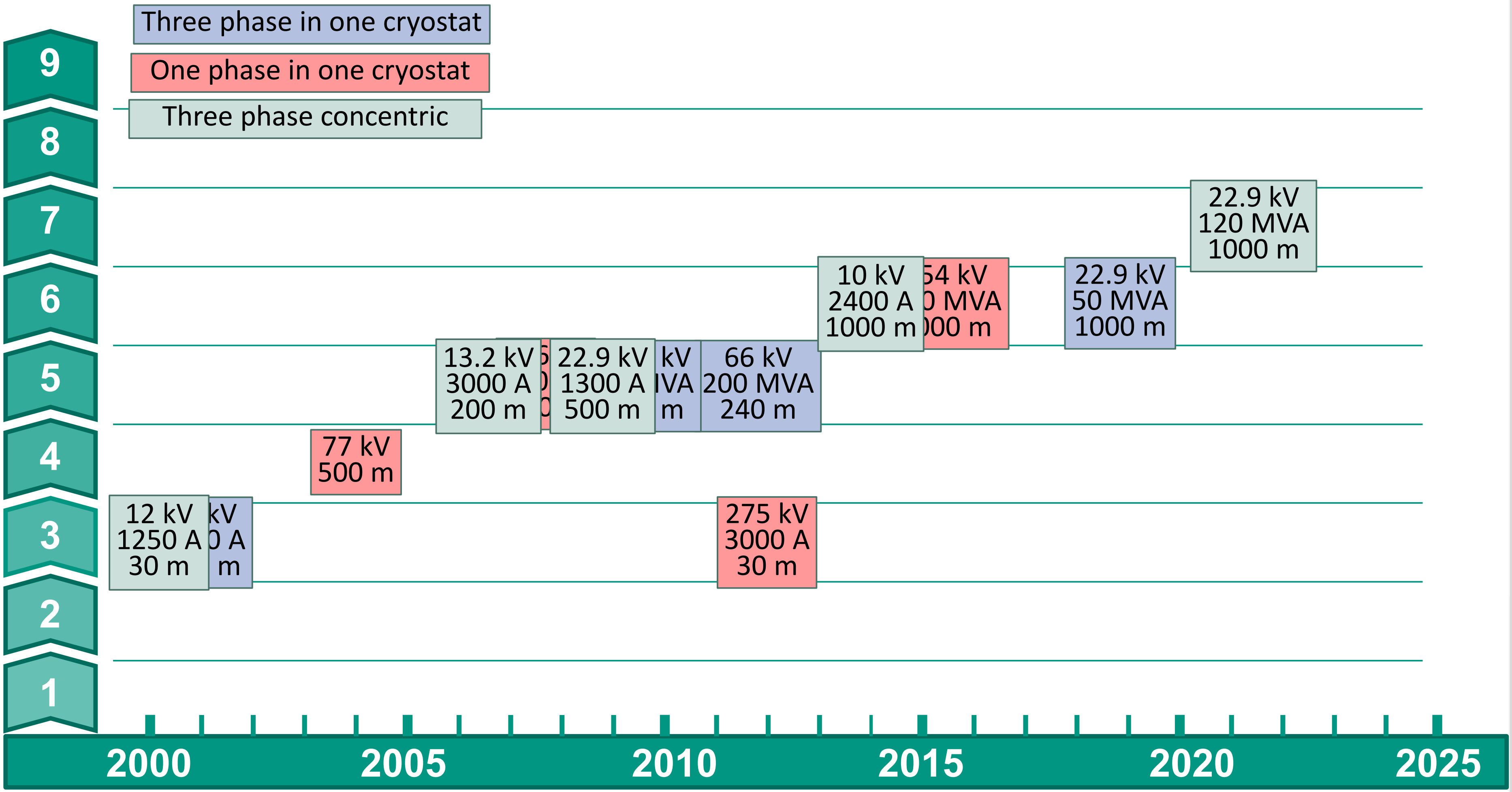
HTS AC HV Cables – State-of-the-Art

Development of TRL



HTS AC MV Cables – State-of-the-Art

Development of TRL



Application examples

138 kV, 2,4 kA, 610 m LIPA cable

Commisioning

November 2007

Locationb

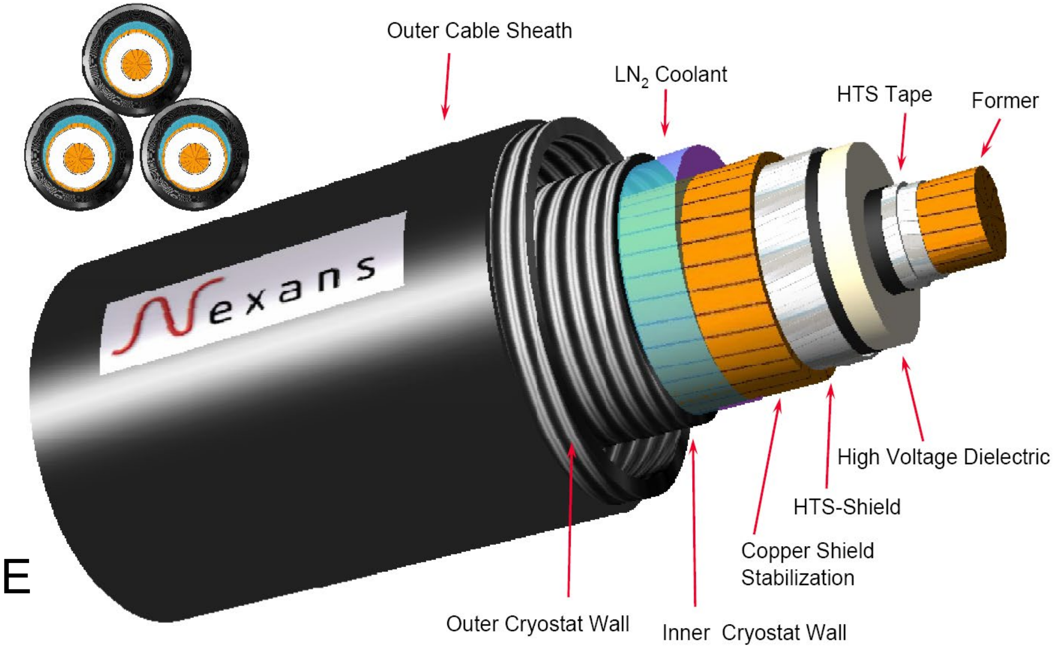
Holbrook Substation
Long Island, New York

Partners

Long Island Power Authority, Nexans, American SuperConductor, Air Liquide, DoE

Superconductor

155 km BSCCO 2223 wire

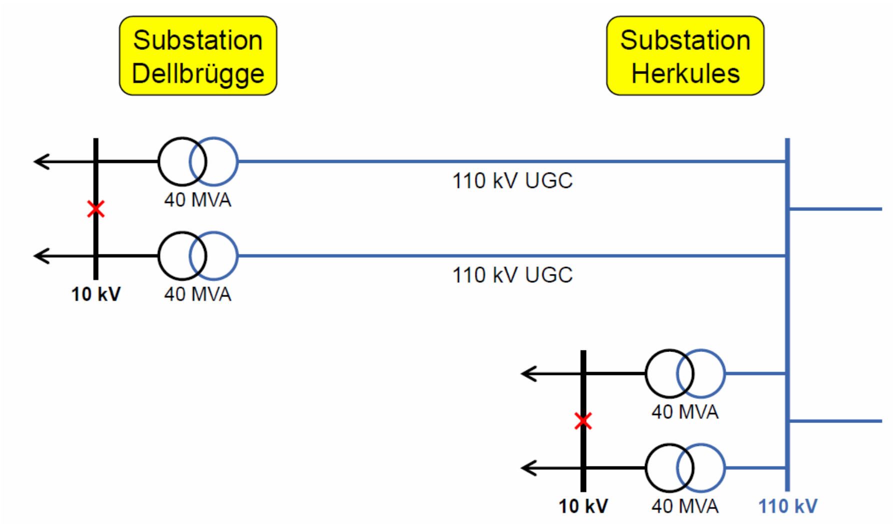


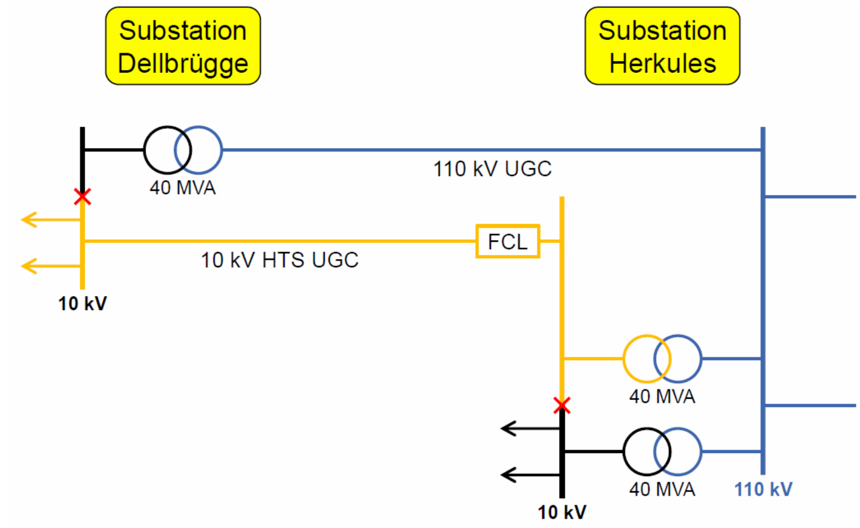
World's first installation of an HTS cable in the transmission voltage level

AmpaCity Project

Conventional Situation in Essen

HTS Cable plus FCL Situation in Essen

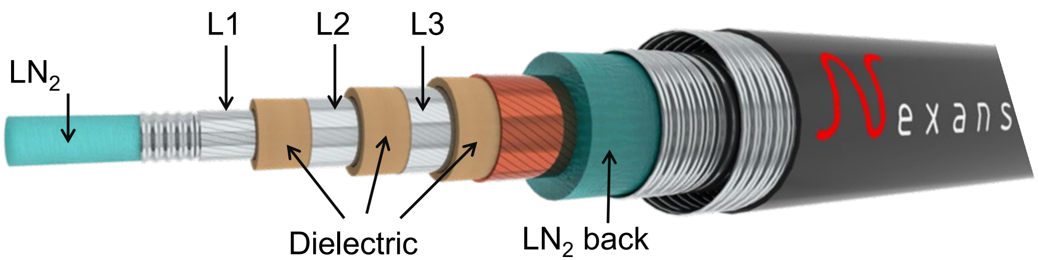




A transformer and a high voltage cable can be replaced by a medium voltage HTS cable in combination with a fault current limiter.

AmpaCity Project

- Objectives
  - Build and test a 40 MVA, 10 kV, 1 km superconducting cable in combination with a fault current limiter
- Project partners
  - Innogy, Nexans, KIT
- Budget
  - 13.5 Mio. €
- Duration
  - Sept. 2011- Feb. 2016



Funded by:

Supported by:
Federal Ministry of Economics and Technology
on the basis of a decision by the German Bundestag

Projektträger Jülich
Forschungszentrum Jülich

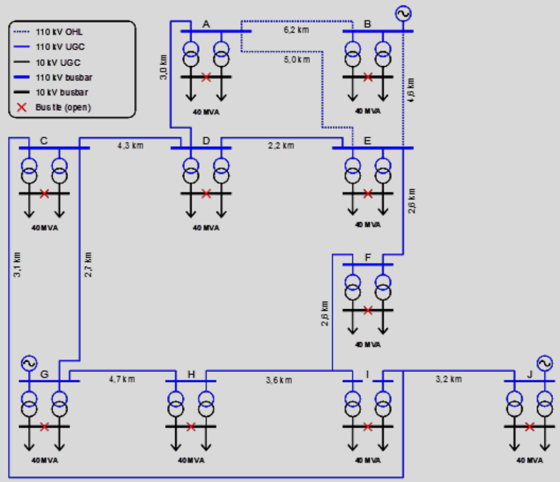
Pre-study AmpaCity Project

AMPACITY
Smart grids for the city

KIT
Karlsruhe Institute of Technology

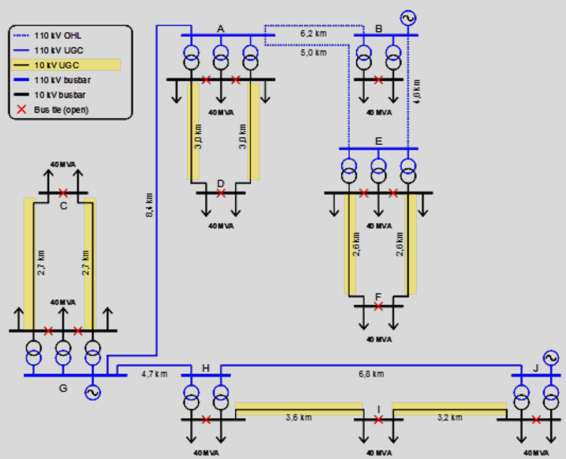
Variant target grid A:

Expansion with „classical“ high voltage technology



Variant target grid B:

Erection of an HTS medium voltage cable ring



Dispensable devices for a new grid concept

- 12.1 km of 110 kV cable systems
- 12 x 110 kV cable switchgear
- 5 x 110/10 kV, 40 MVA transformers
- 5 x 110 kV transformer switchgear
- 5 x 10 kV transformer switchgear

Additionally required devices

+ 23.4 km of 10 kV HTS cable system
+ 16 x 10kV cable switchgear
+ 3 x 10 kV bus ties

AmpaCity Cooling Unit

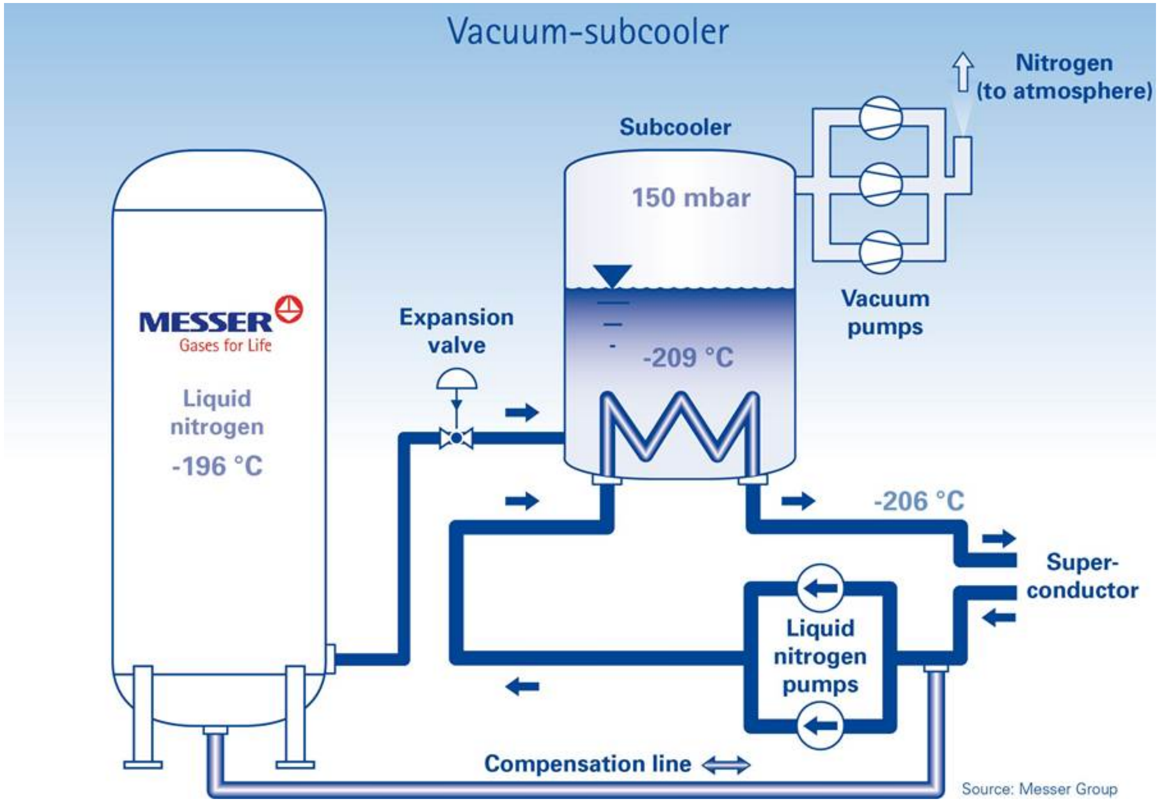
Liquid nitrogen is used
- as heat transfer medium
- as cooling agent

LIN is pumped through the superconducting cable

LIN is recooled in the subcooler (to -206°C)

LIN vaporizes at 150 mbar(a) (forced by vacuum pumps)

LIN temperature decreases to -209°C (expansion through the regulation valve)



Source: F. Herzog, et.al. , „Cooling unit for the AmpaCity project – One year successful operation", Cryogenics Volume 80, Part 2, December 2016, Pages 204-20, DOI: 10.1016/j.cryogenics.2016.04.001

AmpaCity Cooling Unit

Energy-data comparison (regular operation point)

Cable-cooling demand: 1.8 kW (@ 67 K)
Total required cooling capacity: 3.4 kW (@ 64 K)
Liquid nitrogen consumption: 68 kg/h

Required electricity for N2-liquefying: 33 kW
Exergetic effect LN2 transport (130 km): 1 kW
Pel. (vacuum pumps): 5 kW
Pel. (other equipment): 4 kW

total: 43 kW at RT

For comparison:
Pel. for mechanical cooling: 75 to 100 kW*
*(dependant on the availability of cooling water)

Source: F. Herzog, et.al. , „Cooling unit for the AmpaCity project – One year successful operation", Cryogenics Volume 80, Part 2, December 2016, Pages 204-20, DOI: 10.1016/j.cryogenics.2016.04.001

AmpaCity Cooling Unit

MESSER Gases for Life

Karlsruhe Institute of Technology

HTS-cable		
Voltage	10,000 V	
Capacity	40,000 kW	
Cooling demand (actual):	1.8 kW (@ 67 K)	
Cooling unit	**currently**	➔ design
Cooling capacity – required:	**1.8 kW (@ 67 K)**	➔ 4.0 kW
Cooling capacity – total:	**3.4 kW (@ 64 K)**	➔ 5.6 kW
LN2 consumption:	**68 kg/h**	➔ 110 kg/h
Pel.	**9 kW**	➔ 13 kW

Redundancy

- 2 circulation pumps (instead of 1)
- 3 vacuum pumps (instead of 2)
- almost 100% redundancy with 5% additional investment

Source: F. Herzog, et.al. , „Cooling unit for the AmpaCity project – One year successful operation”, Cryogenics Volume 80, Part 2, December 2016, Pages 204-20, DOI: 10.1016/j.cryogenics.2016.04.001

AmpaCity Project

Lessons learned

- The unsymmetrical capacitances need compensation.
- A few leaks in the area of the terminations could be eliminated during commissioning.
- The cable can remain in operation during automatic restart after a short circuit.

Result

- The cable and FCL installation fulfills all technical and operational requirements.

Status

- The operation has been extended.
- Business cases are under development.

Superconducting cables

1 Motivation

2 Structure of superconducting cables

2.1 Cable types

3 Transmission characteristics

3.1 Operating parameters and four-terminal equivalent circuit

3.2 Transmission characteristics

3.3 AC losses

4 State of the Art

4.1 Overview

4.2 Application examples

4.3 Latest developments

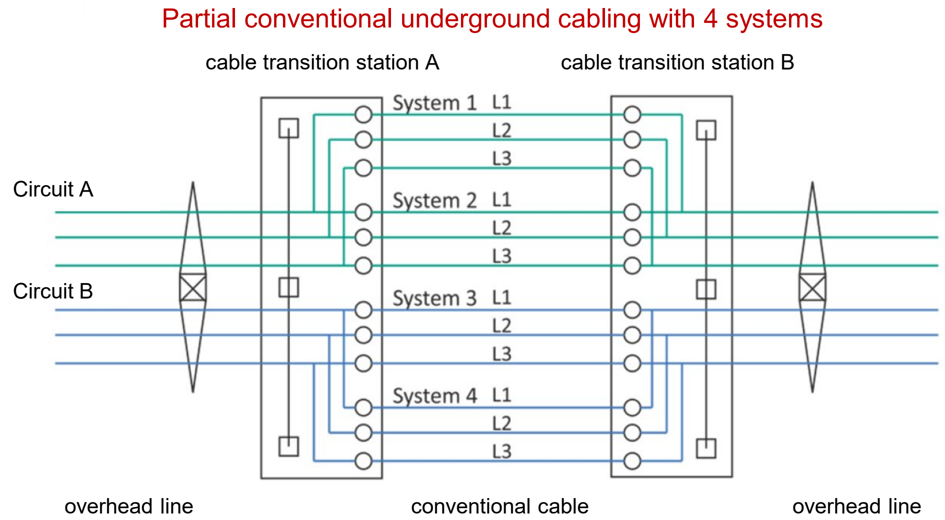
Cable projects in implementation and planning

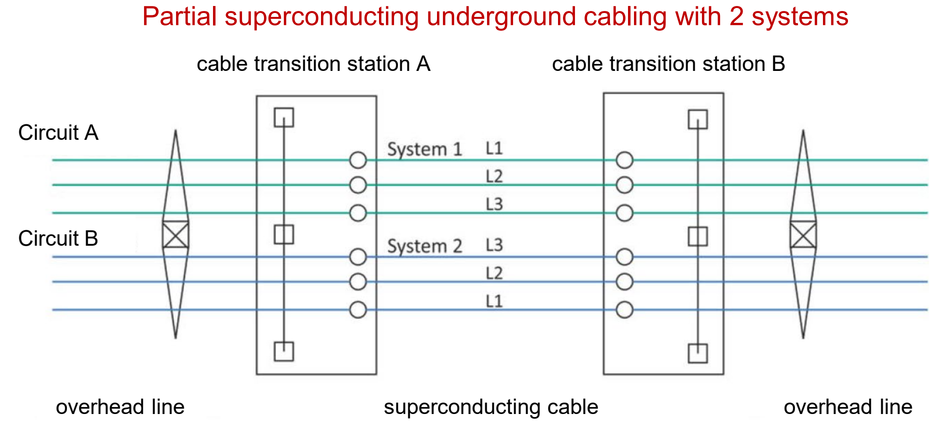
Project (AC 380 kV underground cable)	Commis-sioning (GDP) *Year*	Route length *km*	Cable cores *No.*	Cable sections (plan) *km*
A120 Wahle - Mecklar	Q3 2021	153,3	12	21,7
A210 Emden/Ost – Conneforde	Q4 2021	63	24	16
A220 Wilhelmshaven – Conneforde	Q4 2020	34,2	12	9,2
A240 Conneforde-Cloppenburg-Merzen	Q4 2023	90	12	27
A250 Stade – Landesbergen Section 2-4	Q4 2023	160	12	23
A250 Bereich Stade Section 1			24	0
A260 Dörpen/West – Niederrhein	Q2 2019	31,3	12	3,1
A280 Ganderkesee - Wehrendorf	Q2 2021	60,7	12	12,5
A310 Ostküstenleitung	Q2 2022	120	12	12
Sum (km) of AC 380 kV cable required	**2019 - 2023**			**1.686**

380 kV partial underground cabling

Structure

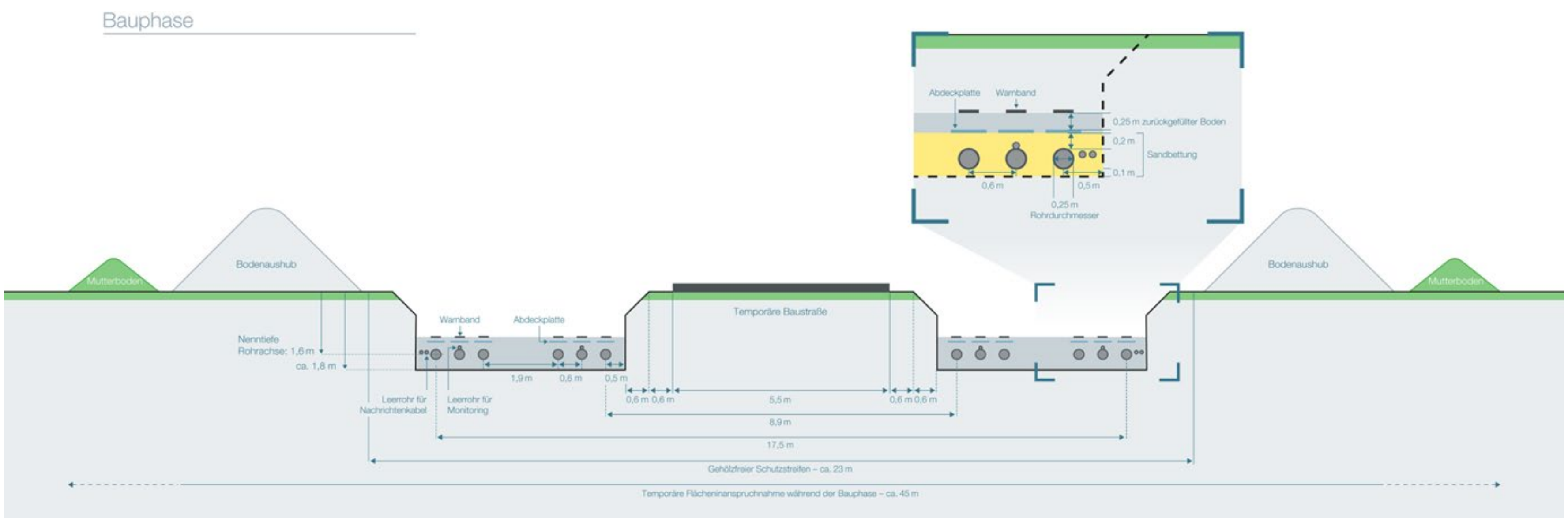
- Conventional cable
  - Two parallel cables per phase required
  - 12 cables in total
- HTS cable
  - One cable per phase
  - 6 cables in total





380 kV partial underground cabling

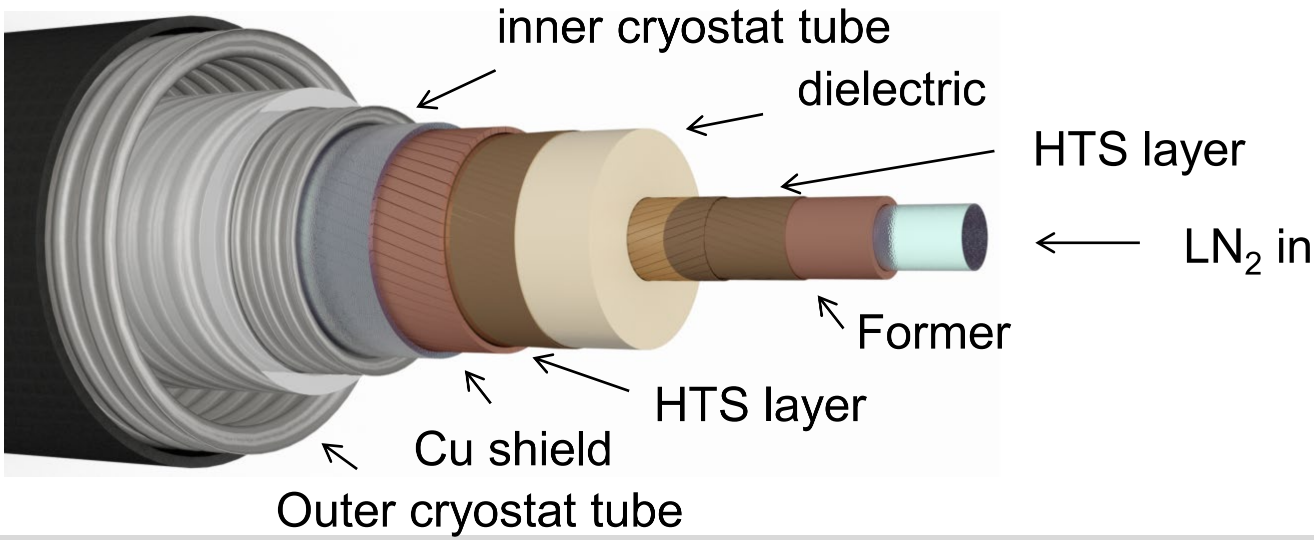
- Minimum specification according to thermal design
- Two cables per phase are required for each phase => 12 cables
- Single cable spacing 0.6 m with depth 1.6 m
- Total width of protective strip 23 m
- Sand bedding in the direct vicinity of the cable
- Temporary double width for storing excavation



380 kV partial underground cabling

- To design a superconducting cable, only the following parameters are required

Rated voltage	380 kV
Rated current	3600 A
Overcurrent I''_K	63 kA, 300 ms
Load factor	0.7
Length	3,2 km



SWM SuperLink Munich

- SWM SuperLink cable in Munich
- Project for development of a 110 kV, 500 MVA cable

SWM	**Stadtwerke München**	Netzbetreiber 400 V – 400 kV Städtische Infrastruktur
NKT	**NKT Cables Group**	HTS - Kabelhersteller Hoch- und Höchstspannungskabel
THE LINDE GROUP	**Linde Group**	Technische Gase Kryotechnik & Kryoanlagenbau
THEVA	**THEVA**	HTS – Bandleiterhersteller
Fachhochschule Südwestfalen University of Applied Sciences	**FH SWF, Soest**	Hochspannungstechnik Kabelprüftechnik, Simulation
KIT Karlsruhe Institute of Technology	**Karlsruhe Institut of Technology**	Expertise für HTS - Netztechnik

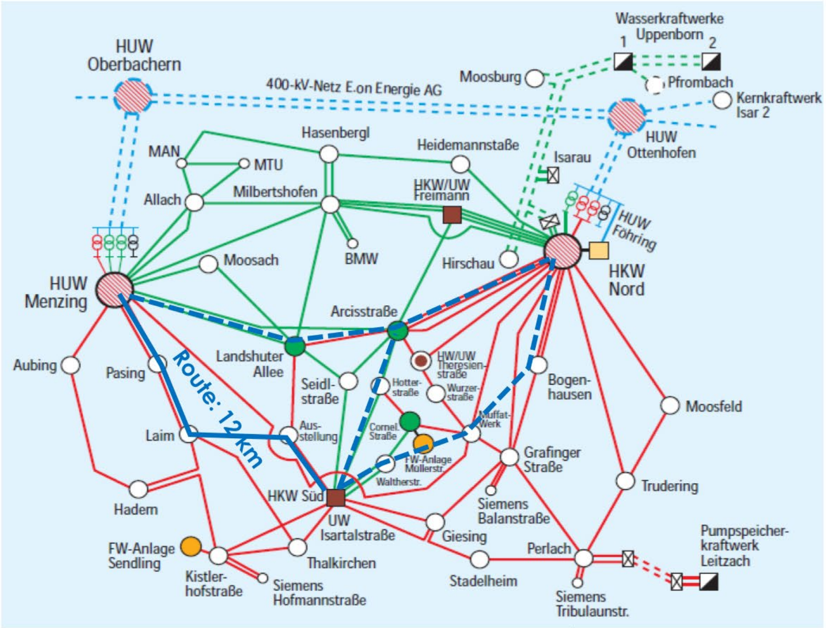
- This is considered the first economic application, as a 10 km tunnel structure for a 380 kV cable could be avoided.

SWM SuperLink Munich

URGING PROBLEM OF THE CITY ULITLITY

Rebuilding the distribution grid and establish a 500 MVA connection across the city

- **Necessary change** in cable technology
  Non-availability of gas-pressure cables
- **Strong renewal pressure**:
  80+ % cables installed before 1980
  Enormous volume >90 HV cable sections
- **Connection of gas power station** in the south to transmission grid (NW) **across the city**
- **Avoidance of new 400/110 kV main substation** (space, cost)



SWM SuperLink Munich

Alternative Solutions

Transport of 500 MVA over 12 km

400 kV XLPE cable system

E.g. tunnel solution, as in Berlin, London etc.

Same for GIL

400 kV overhead line

Not feasible in the city

Multiple 110 kV XLPE cable systems

5 systems & routes

Limited bending radii

Soil warming (spacing)

110 kV HTS cable

Novel technology

SWM SuperLink Munich

Karlsruhe Institute of Technology

ALTERNATIVE SOLUTIONS - ASSESSMENT

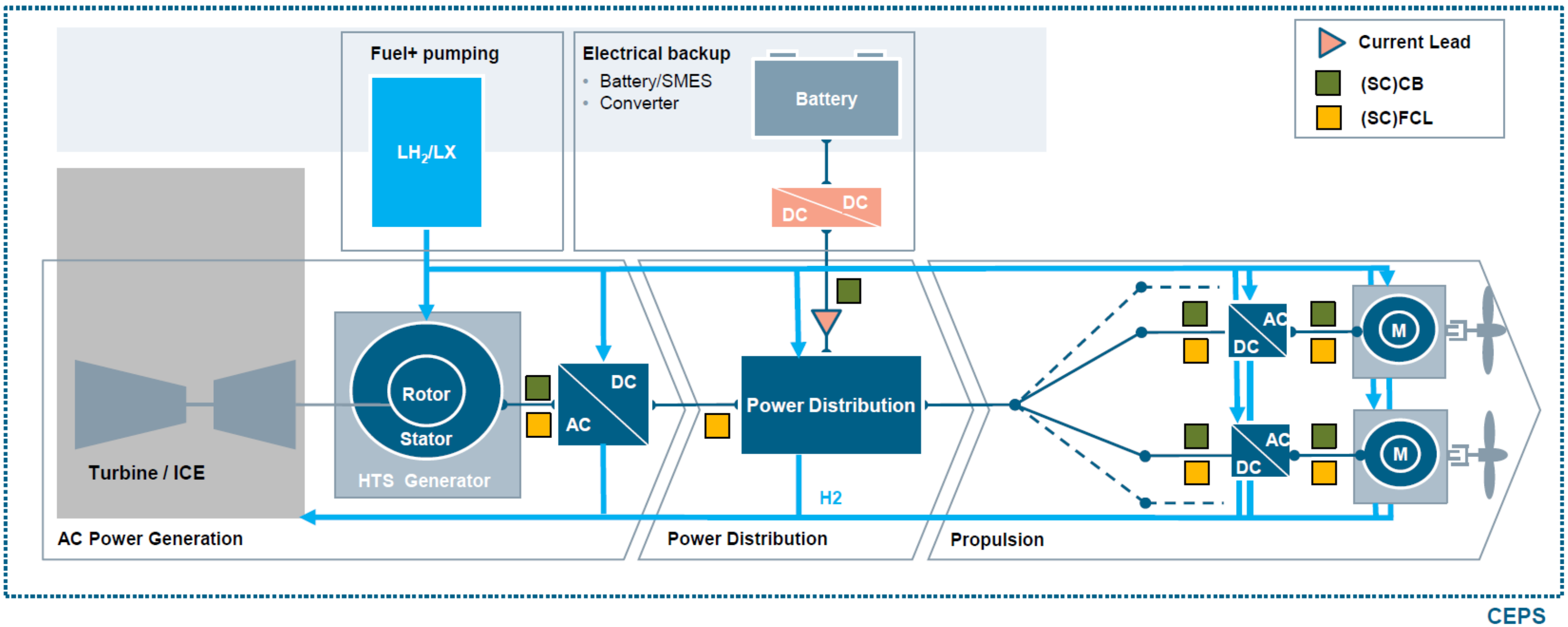
Transport of 500 MVA across 12 km in densely populated area

Criteria	400 kV XLPE	400 kV OHL	Multiple 110 kV	110 KV HTS
Minimum space	🙁	🙁	🙁	🙂
Public acceptance	🙁	🙁	😐	🙂
Economic feasibility	🙁	🙂	🙁	😐
Technical maturity	🙂	🙂	🙂	😐
City grid integration	🙁	🙁	🙂	🙂
Power density	🙂	🙂	🙁	🙂
Low loss	🙁	😐	🙁	🙂

The HTS option is very attractive – but needs development

Electric Aircraft

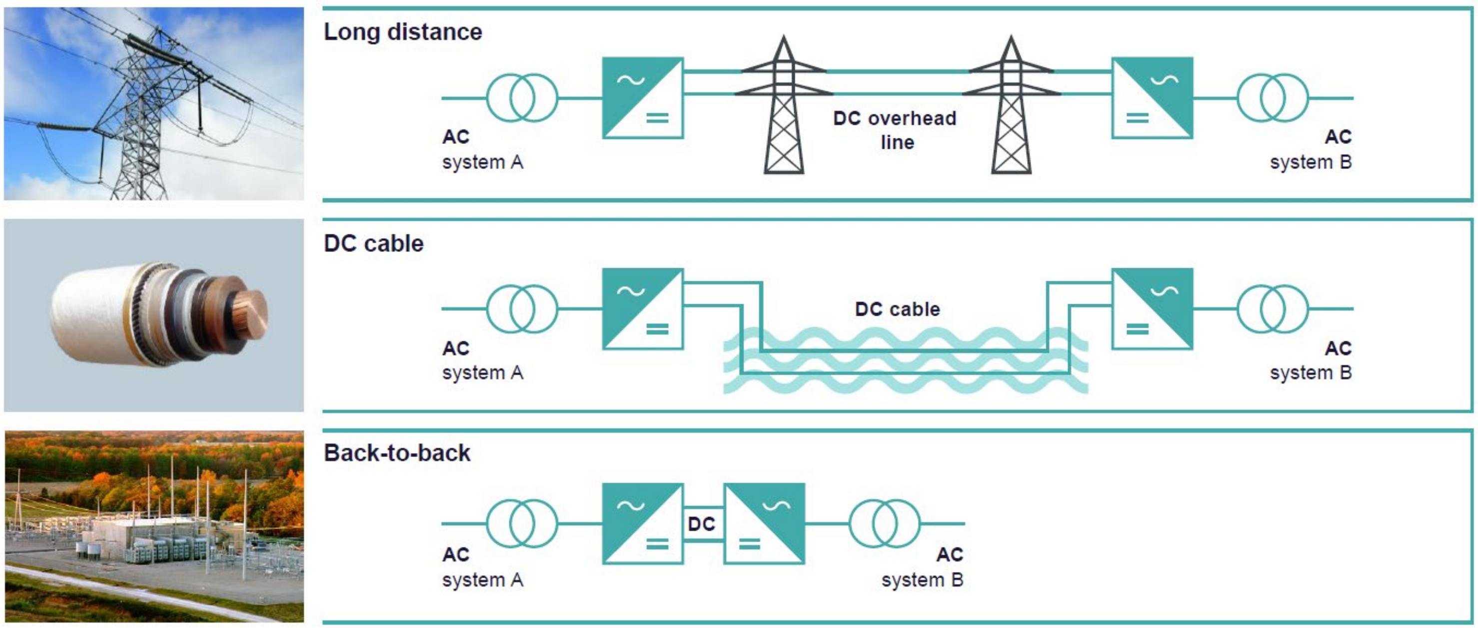
- Example of a power supply scheme of an aircraft with electric propulsion system



Source: Martin Boll, Rolls Royce

Opportunities for DC cables

High voltage high power DC connection



German Kuhn | SE T SO PLM-FACTS 3

2020-11-12

Siemens Energy, 2020

In Germany several 525 kV DC cable connections are planned from north to south

Opportunities for DC cables

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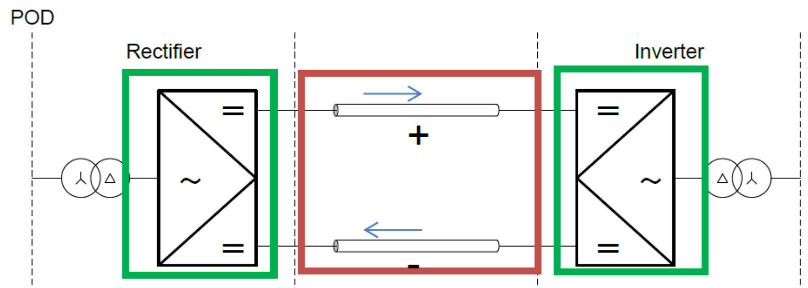
Medium voltage high power DC solutions

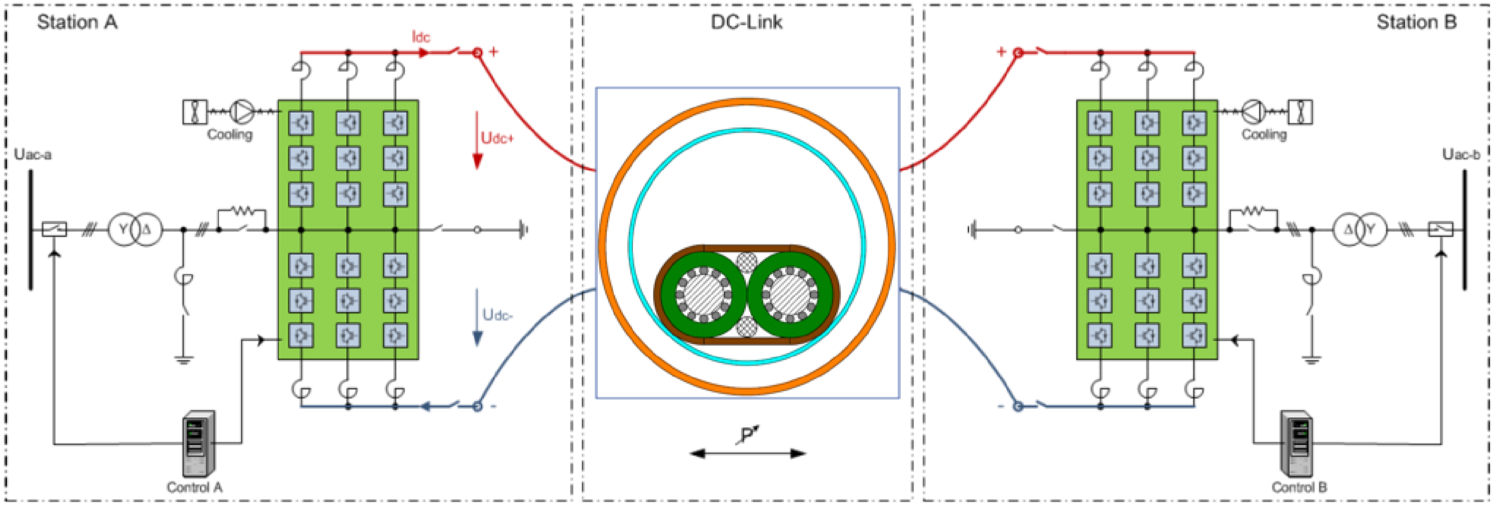


Types from Siemens Energy	Var. 1	Var. 2	Var. 3
DC voltage converter	± 24 kV	± 30 kV	± 50 kV
Real power converter cos φ 0.9	30-70 MW	up to 90 MW	up to 150 MVA
Max. spec. DC Phase resistance	0.01 Ω /km		

Transmission power and length of MVDC is limited by the parameters of conventional cables.
Is it possible to achieve a GW transmission power with MVDC technology and HTS cables?

Opportunities for DC cables

Medium voltage high power DC solutions with HTS DC cable



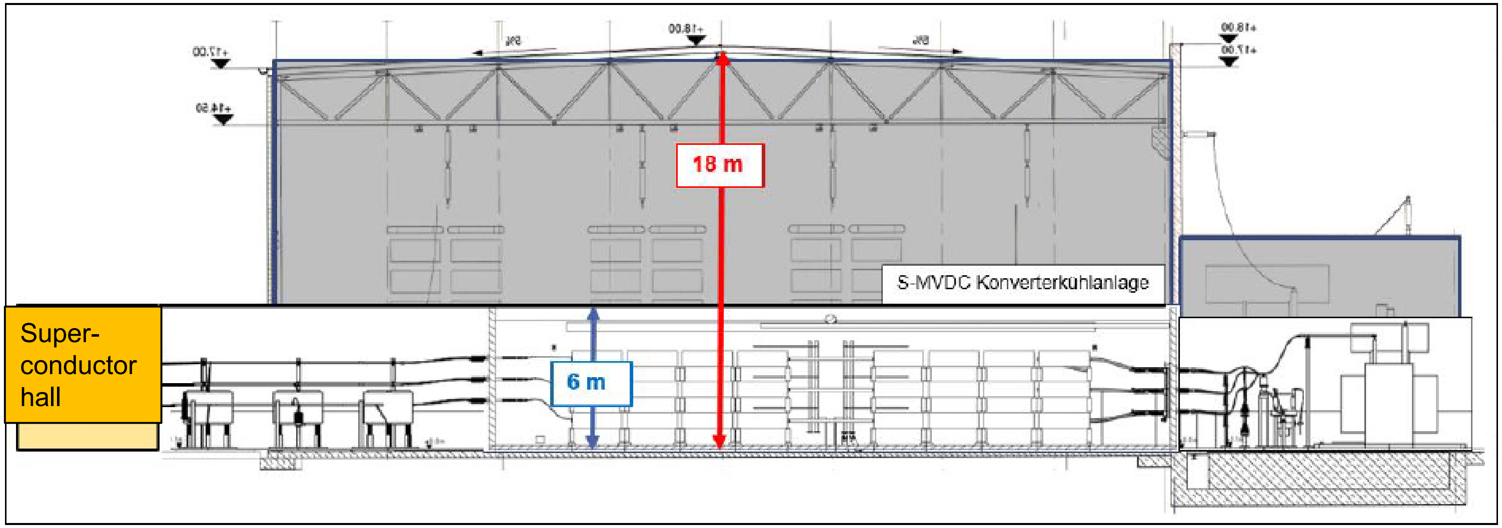
Main advantages
- GW transmission power with several MVDC stations in parallel
- Smaller line width and higher transmission power
- Lower permission effort

Opportunities for DC cables

HTS MVDC high power transmission

Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

Comparison of size of converter buildings



Opportunities for DC cables

HTS MVDC high power transmission

Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

Comparison of size of converter buildings

	HVDC – 1 GW – S-MVDC	
DC voltage	± 320 kV	± 50 kV
Hall space	4800 m²	3300 m²
Outdoor space	1000 m²	1000 m²
Total space	**5800 m²**	**4300 m²**
	100 %	**75 %**
Building height (converter)	18 m	6 m
Building volume	**90.000 m³**	**22.500 m³**
	100 %	**25 %**

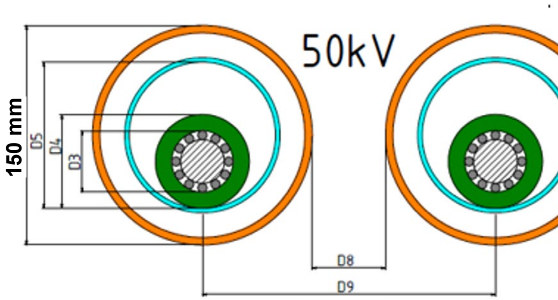
Opportunities for DC cables

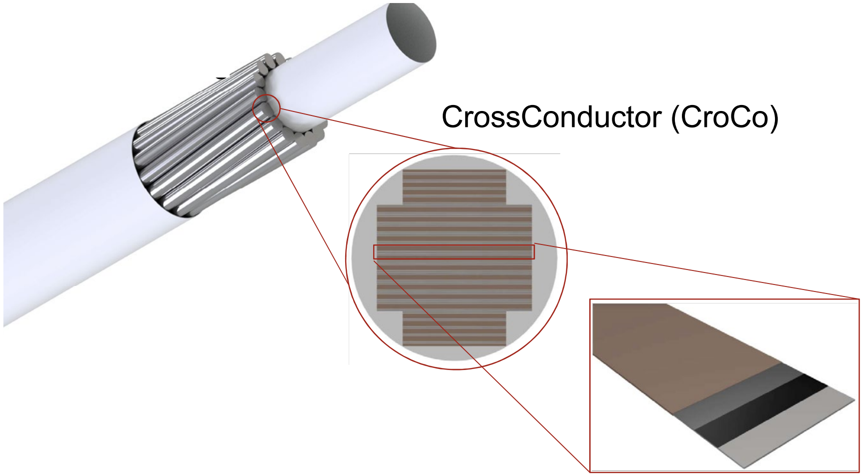
HTS MVDC high power transmission

Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

S-MVDC Cables for 1 GW

One pole in one cryostat





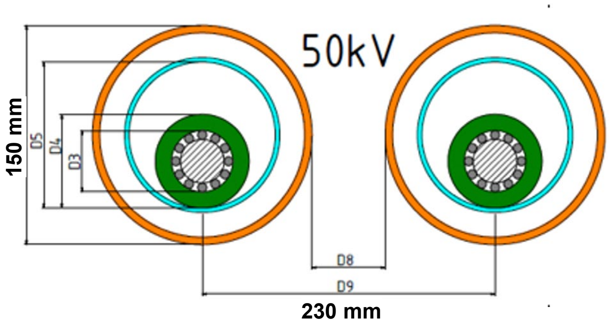
Opportunities for DC cables

HTS MVDC high power transmission

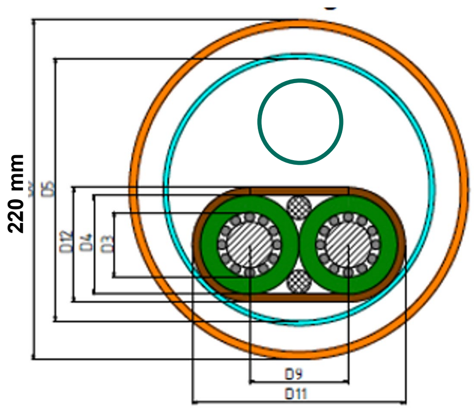
Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

S-MVDC Cables for 1 GW

One pole in one cryostat



Two poles in one cryostat



a) With integrated LN2 return
b) Separate LN2 return

Cryostat

- Laying similar to pipeline
- Corrugated tube up to 500 m
- Plain tube length up to 16 m
- on-site welding L = appr. 1 km

HTS Phase conductor

- Transport length L = 1 - 5 km
- Incl. electr. insulation, and mech. protection
- Optional with HTS-shield

Electromagnetic design that fulfills short-circuit specification with maximum temperature and forces

Opportunities for DC cables

HTS MVDC high power transmission

Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

Summary of main characteristic

Cable routing

☺ Highest acceptance
☺ Lowest impact on environment
☺ Lowest realisation time
☺ Less effort with cable laying

Investment cost

☺ 10 % savings at converter
☹ HTS cable more expensive
☹ Additional cooling
☺ Less effort for laying

Converter stations

☺ Full HVDC functionality
☺ Smaller footprint 75 %
☺ Smaller converter buildings 25 %

Operation cost

☹ Little higher maintenance
☺ Lower losses

Superconducting DC cables enable a 1 GW MVDC power transmission.

Opportunities for superconducting cables

Karlsruhe Institute of Technology

Overview on Superconducting Cable Applications

	Typical Length	TRL 1	TRL2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
AC										
Inner city medium voltage (6-30 kV)	few km							X		
Inner city high voltage (110-220 kV)	few km						X			
High voltage transmission (380 kV)	few 100 km		X							
High voltage partial in ground cables (380 kV)	few km		X							
Generator feeder (6-30 kV)			X							
DC										
Elektrolysis industry (einige 10 kA)	few 10 m					X				
Aluminium industry (> 100 kA)	few 100 m		X			X				
Data Center	few 10 m				X					
Connection of renewable energies	few km					X				
Railway feeder	few km						X			
Medium voltage DC transmission	~ 100 km		X							
High voltage DC transmission	~ 100-1000 km		X							
Elektric aircraft power supply	~ 10-100 m			X						
Degaussing of ships									X	

Low TRL (TRL 1–3) | Medium TRL (TRL 4–6) | High TRL (TRL 7–9)

Many applications for HTS cables exist ranging from a few kA to several 100 kA and from kV to more than 100 kV.

Learning goals

- Being able to describe the essential properties of superconducting cables in comparison with conventional cables
- Be able to point out the advantages and disadvantages of superconducting cables
- Being familiar with the design and construction of superconducting cables and being able to select applications for the different designs and voltage levels
- Understand and be able to explain differences in transmission characteristics compared to conventional transmission lines
- Understand and be able to demonstrate the current state of development
- Be able to point out further developments