

Superconducting Cables

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KIT-ZENTRUM ENERGIE



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 - 3S Project
- Summary

Benefits of Superconducting AC Cables

User

- Higher transmission capacity at lower voltage
 - Avoid high voltage equipment in urban areas
- Higher transmission capacity at lower diameter
 - Flexible laying, less underground work
- Three phases in one cable up to high capacities
 - Less right of way, fast cable laying, less underground work

Environment

- Electromagnetic compatible
- Potential of lower losses
- No ground heating

Operation

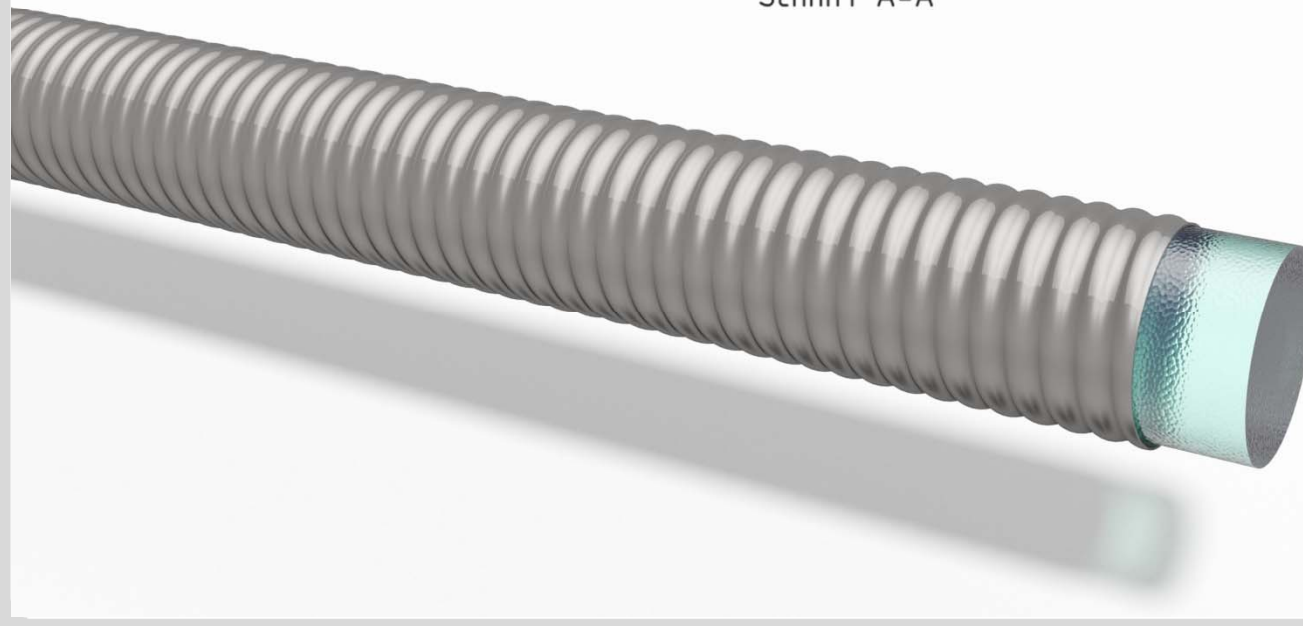
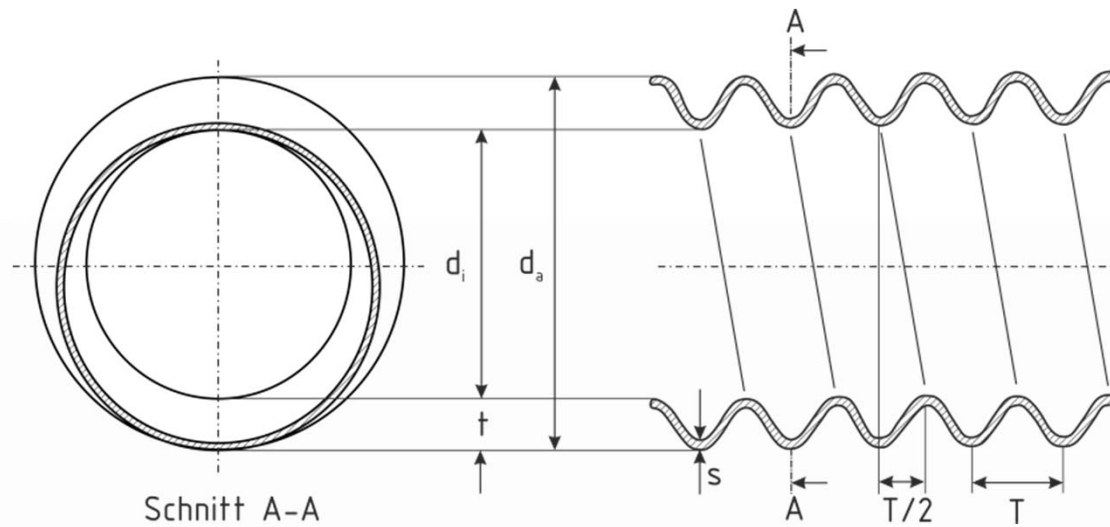
- Low impedance
- Operation at natural load

Enables unique cable systems and new power system structures

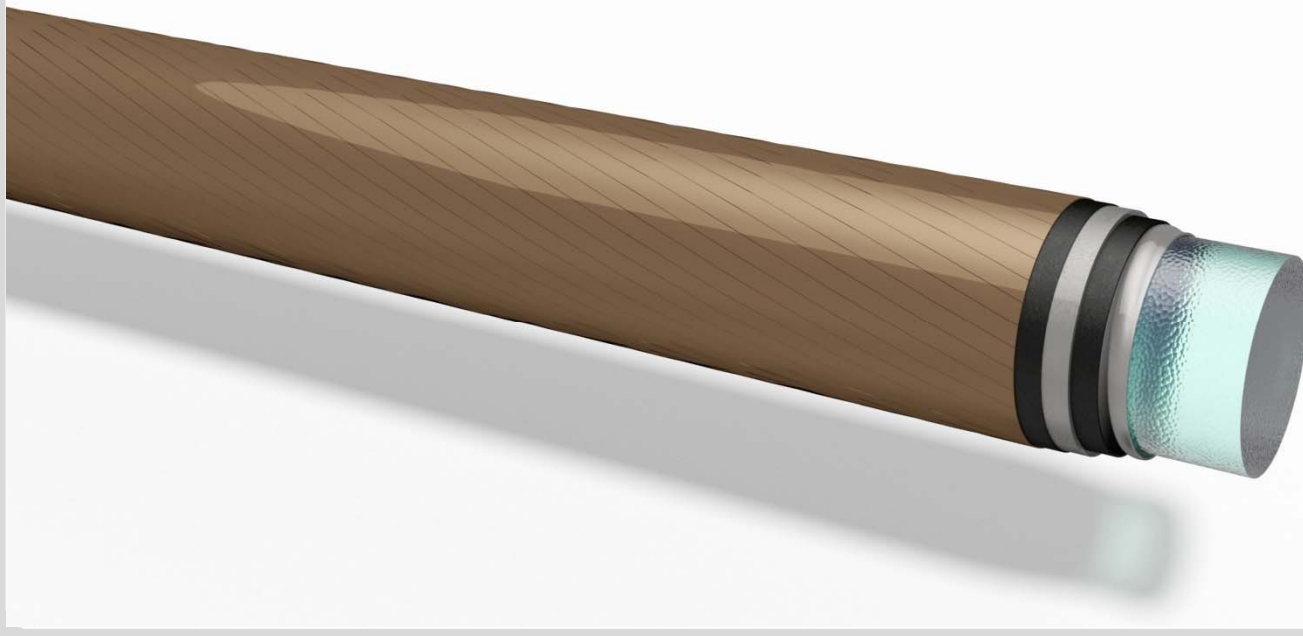
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General Setup - Former

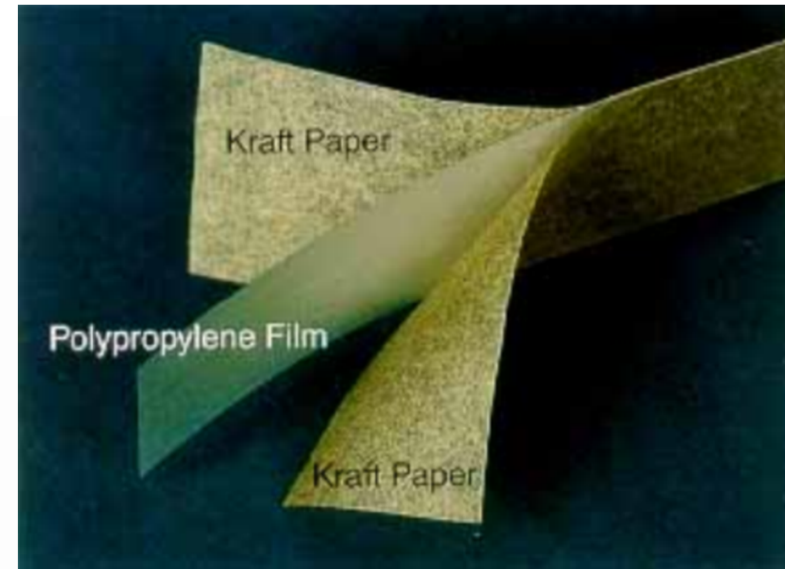


General Setup – HTS Conductor



General Setup – Dielectric Insulation

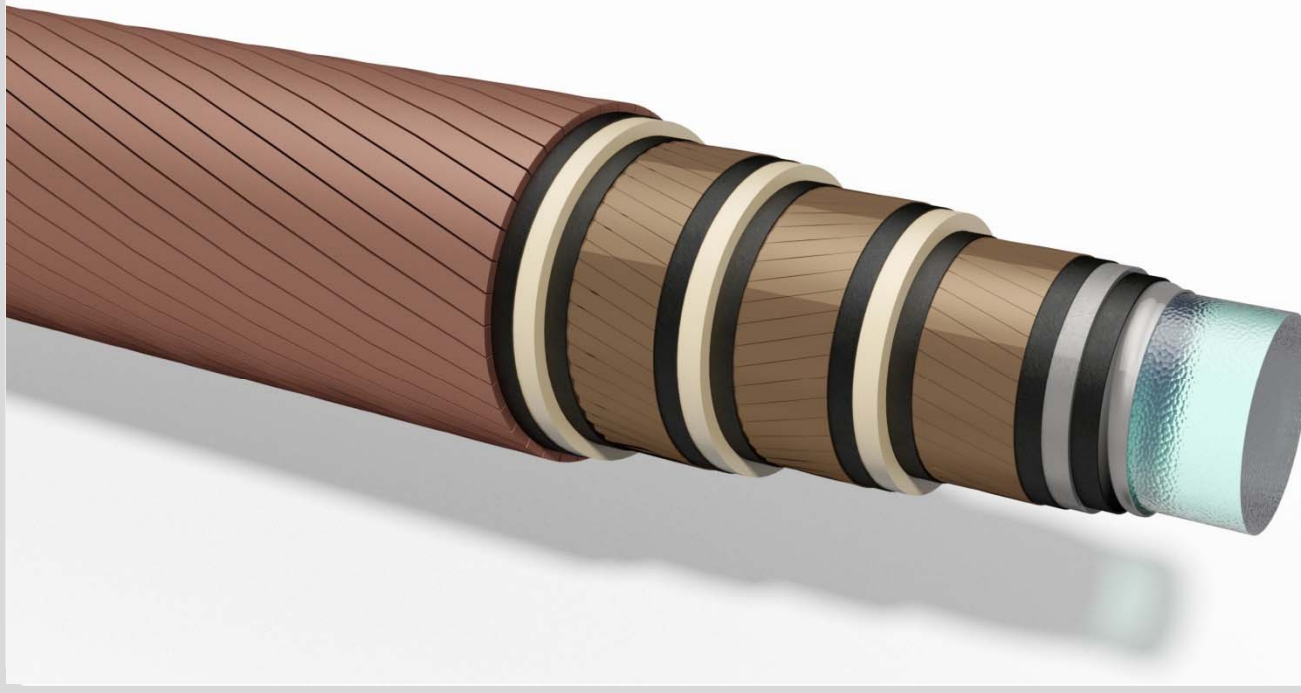
Polypropylene Laminated Paper (PPLP)



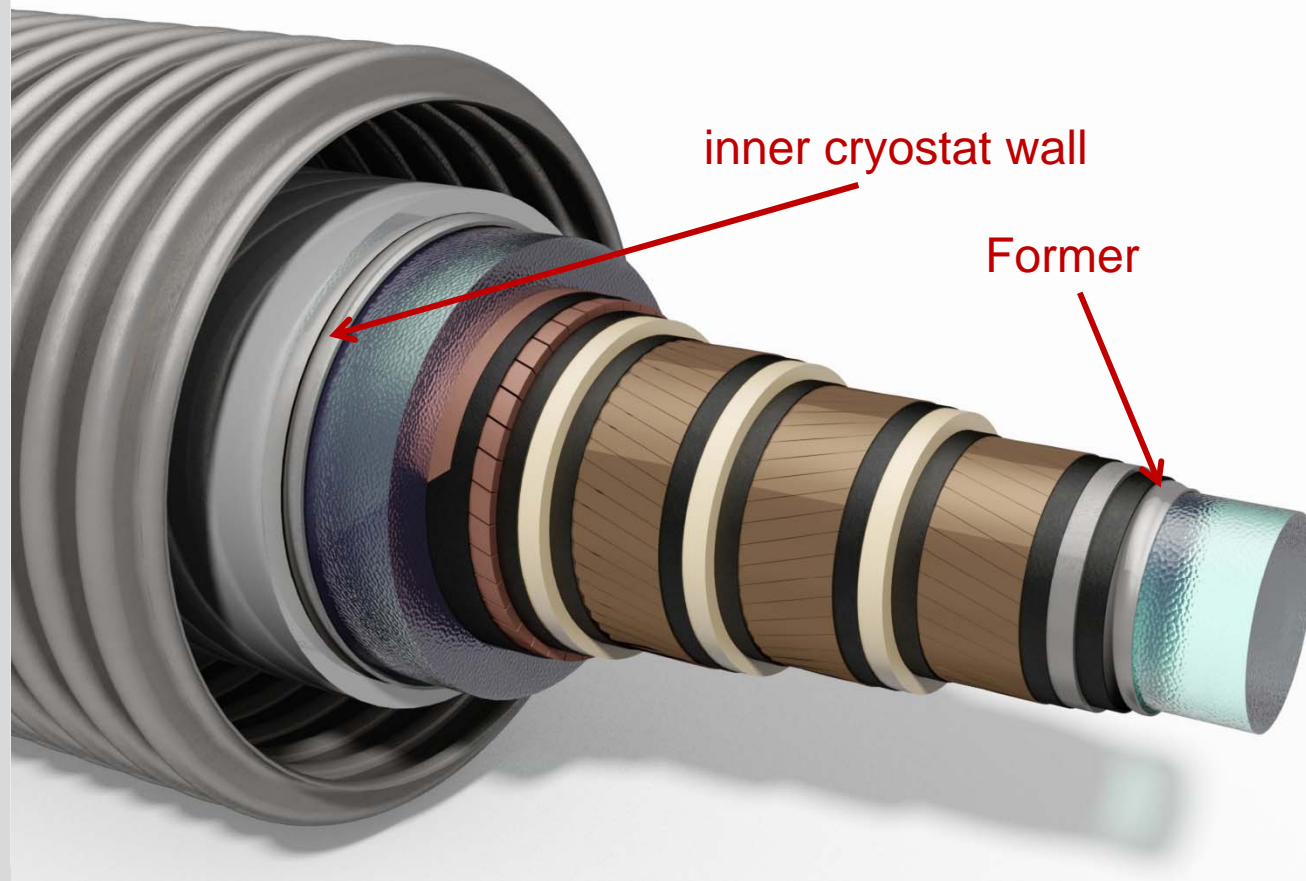
General Setup – Three coaxial phases



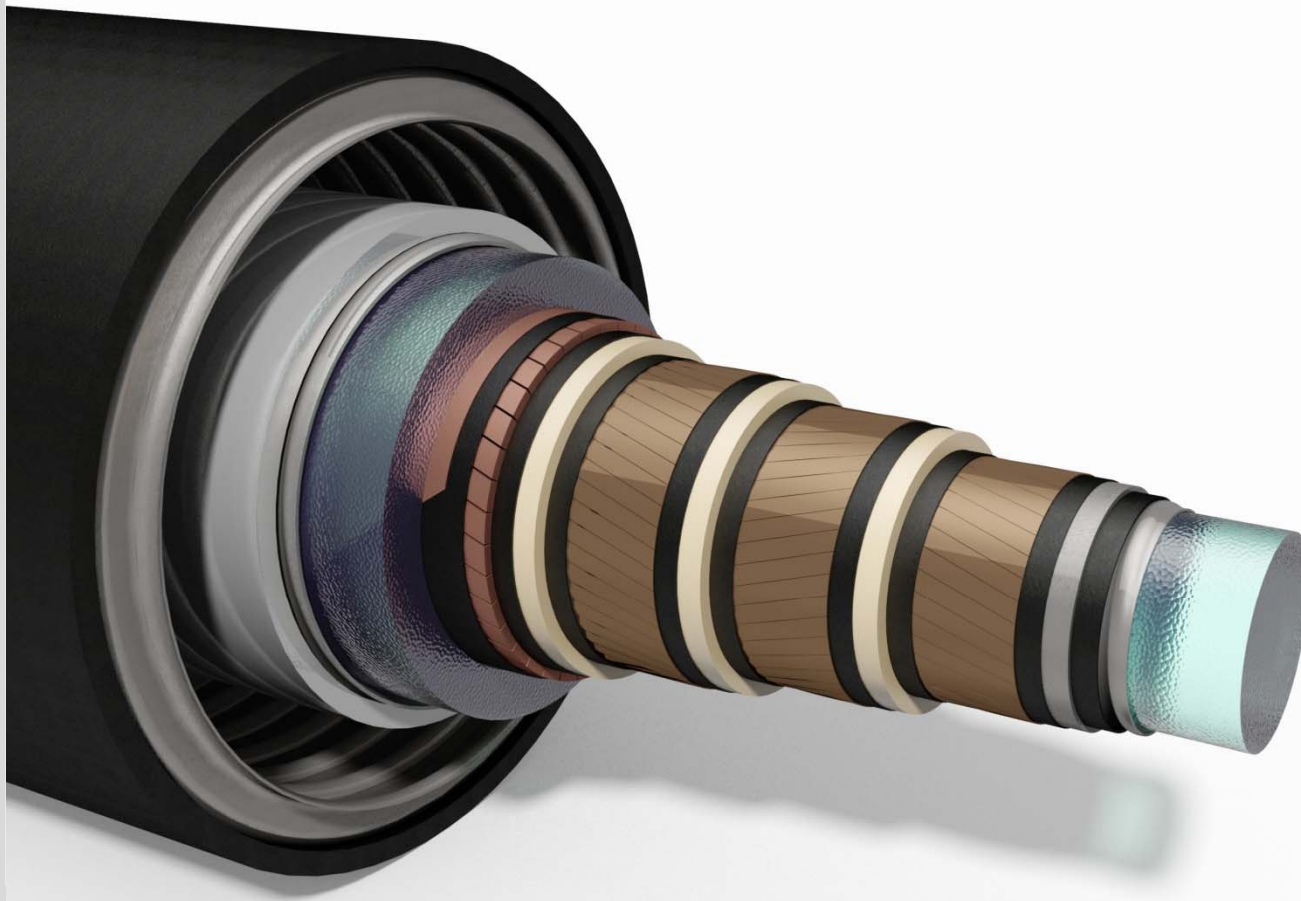
General Setup – Copper Neutral Conductor



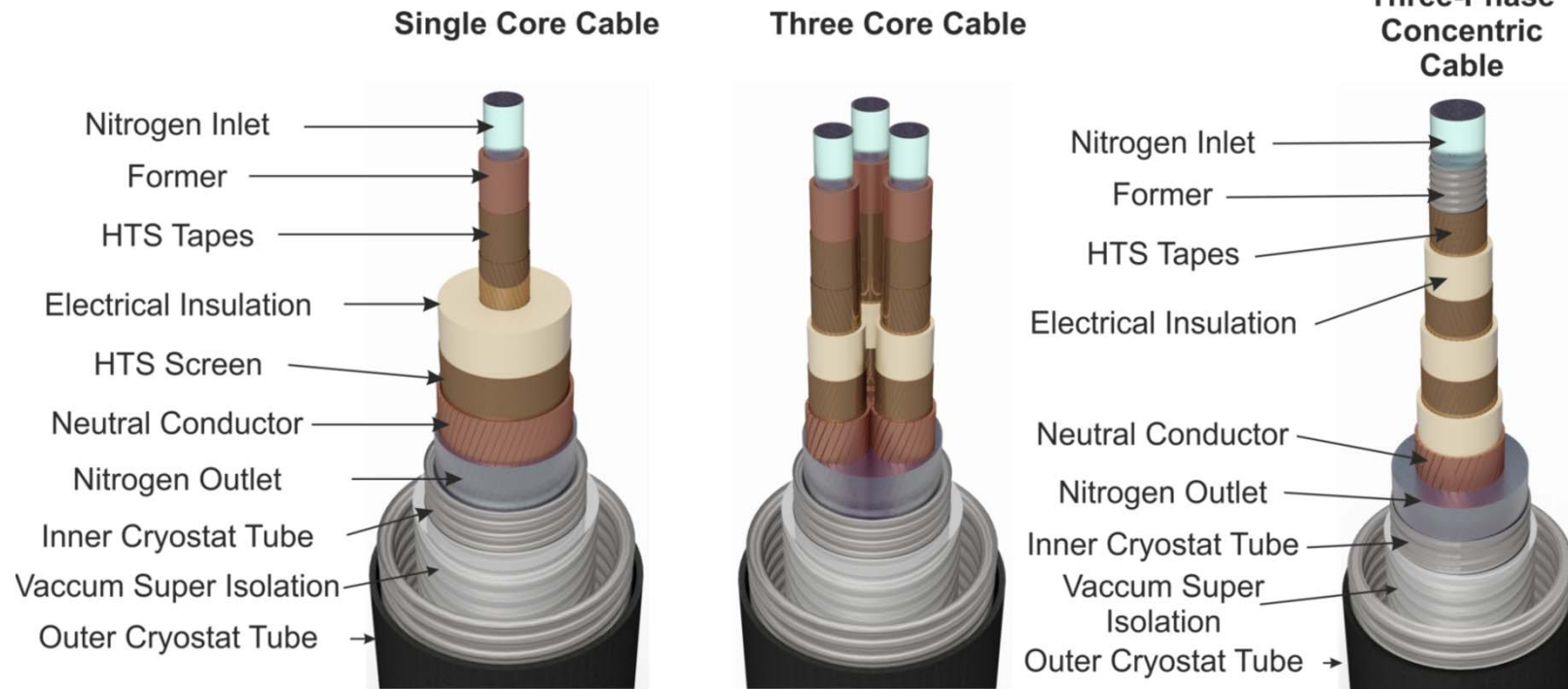
General Setup – Cryostat



General Setup – Outer Protection, extruded PE



Cable Types – Cold Dielectric



	Three single phases	Three phase 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

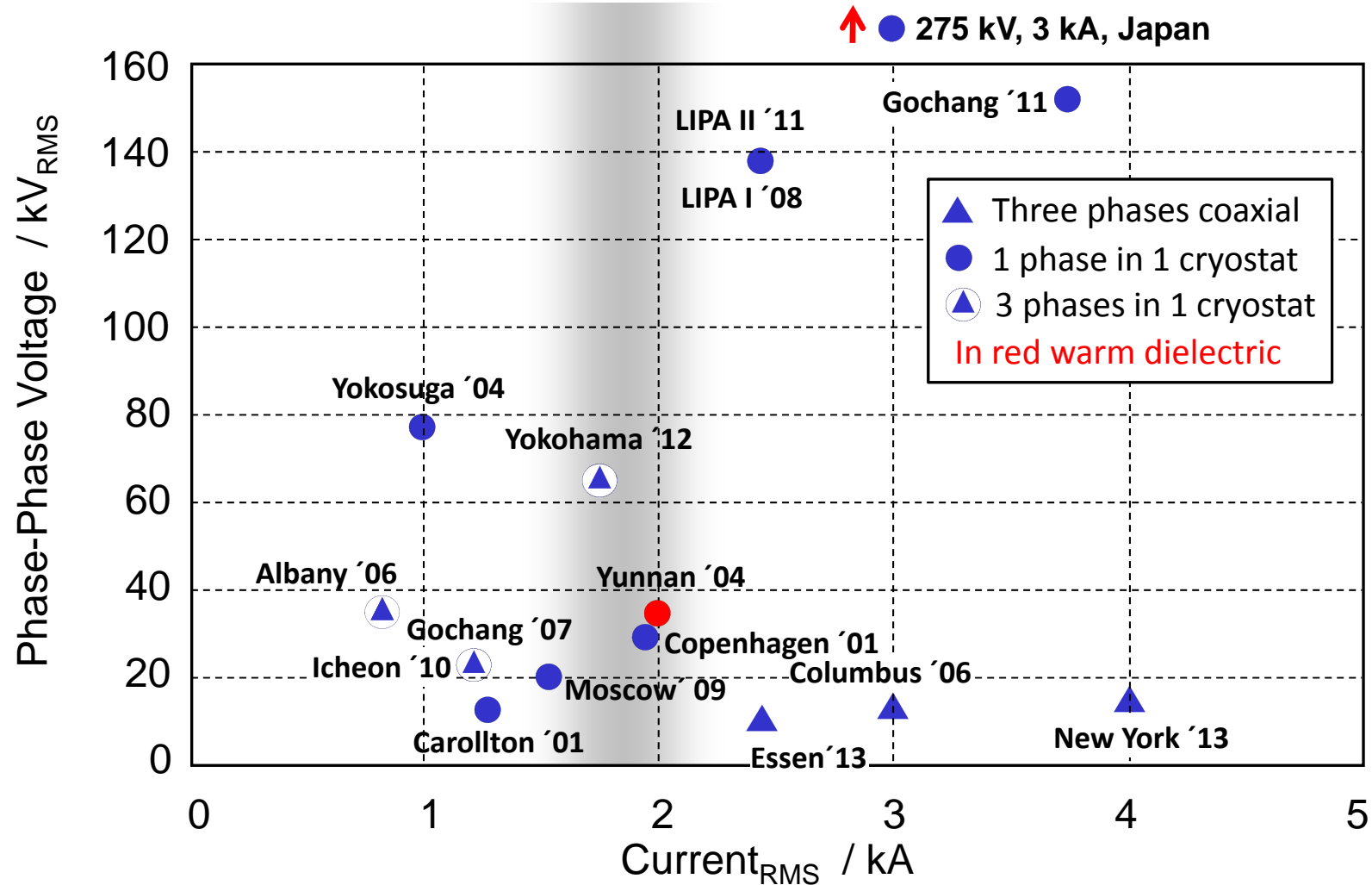
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Superconducting AC Cables

State-of-the-Art of HTS AC Cable Field Tests

Maximum rated current of conventional cables in air



Superconducting AC Cables

State-of-the-Art

Columbus



Ultera
 13.2 kV, 3 kA, 200 m
 Triaxial™ Design
 BSCCO 2223
 Energized 2006
 High reliability

Figure:
Ultera



LIPA



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

Figure:
Nexans



Gochang



Figure: LS Cable

LS Cable
 22.9 kV, 50 MVA, 100 m
 BSCCO 2223
 Energized 2007
 500 m field test with YBCO
 in 2011

Superconducting AC Cables

State-of-the-Art

Status Supernet NL Project

■ Objectives

- Feasibility and demonstration of a superconductive HV cable in the transmission grid (110 kV, 3.4 km, ~ 200 MVA)

■ Project partners

- TenneT, TU Delft, U Twente, HAN U, IWO Project, RH Marine

■ Duration

- Project start August 2015
- Tender procedure finished in 2017
- Demonstration test before commissioning June 2019

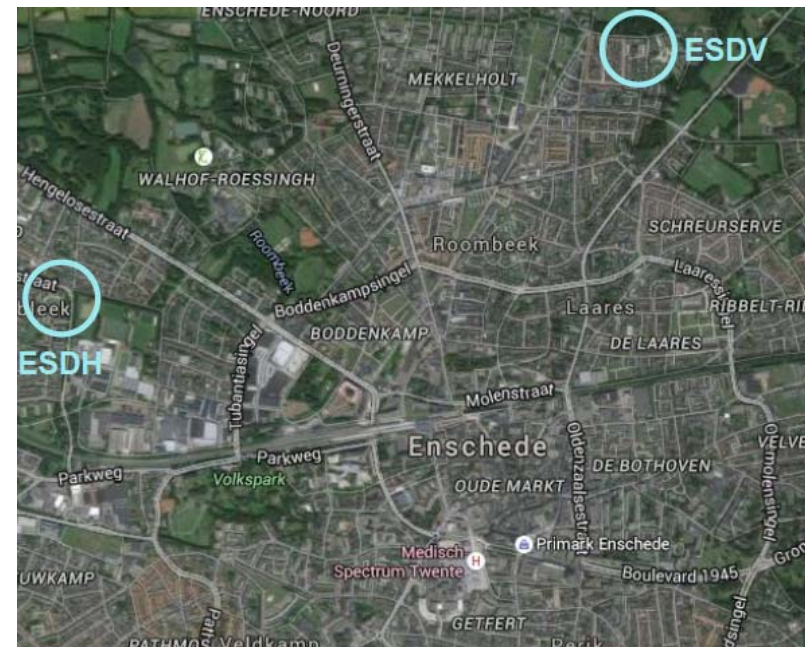


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Status Ampacity Project



Objectives

- Built and test a 40 MVA, 10 kV, 1 km superconducting cable in combination with a fault current limiter

Project partners

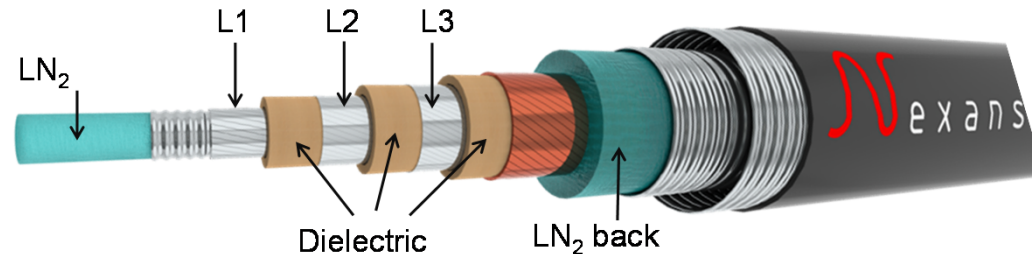
- Innogy, Nexans, KIT

Budget

- 13.5 Mio. €

Duration

- Sept. 2011- Feb. 2016

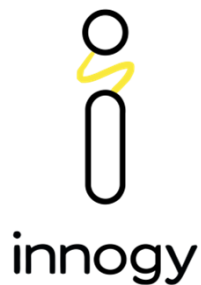


Funded by:

Supported by:



on the basis of a decision by the German Bundestag

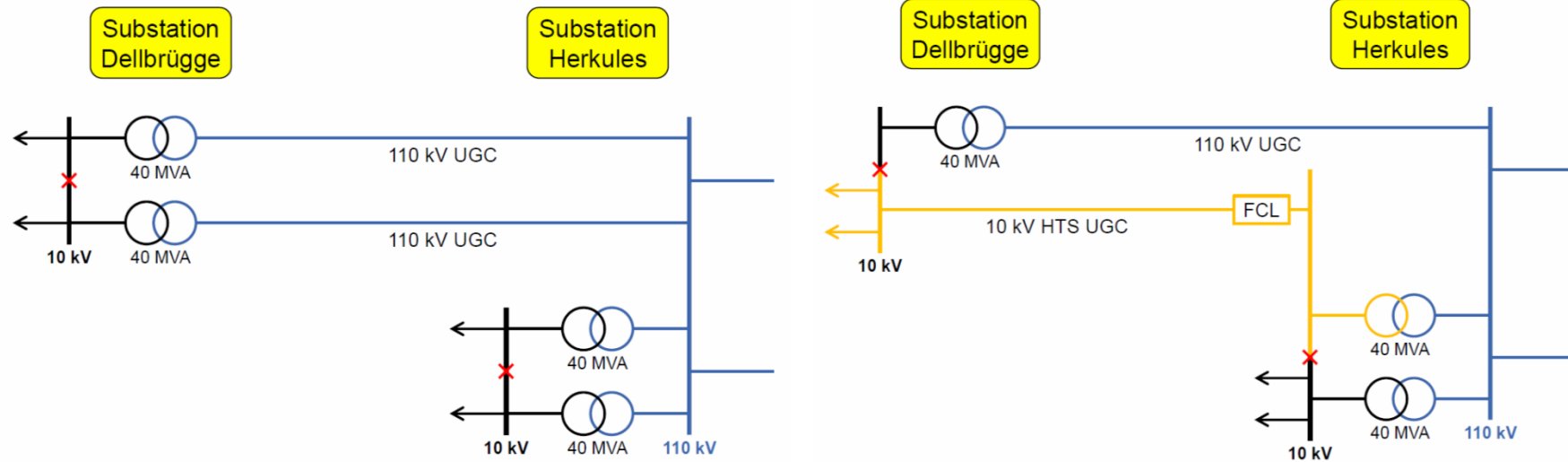


Status Ampacity Project



Conventional Situation in Essen

HTS Cable plus FCL Situation in Essen

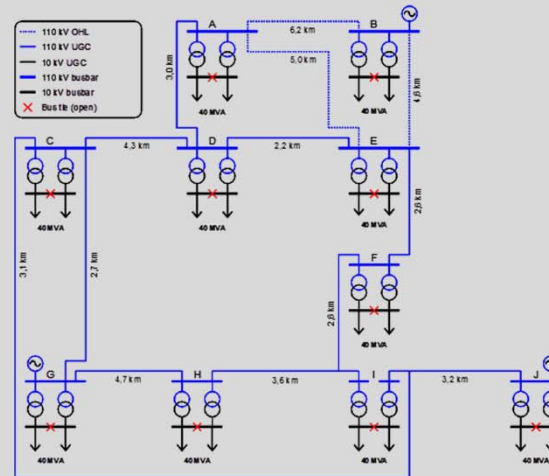


A transformer and a high voltage cable can be replaced by a medium voltage HTS cable in combination with a fault current limiter.

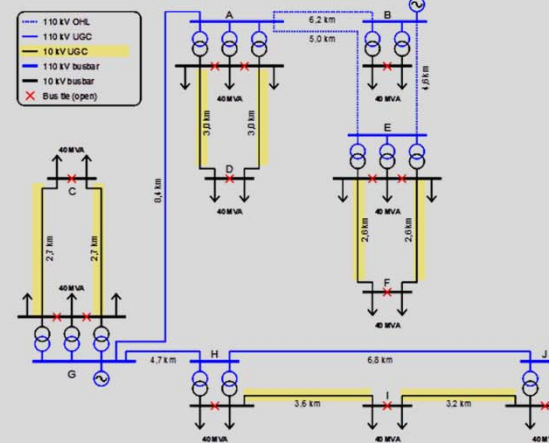
Pre-study Ampacity Project



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

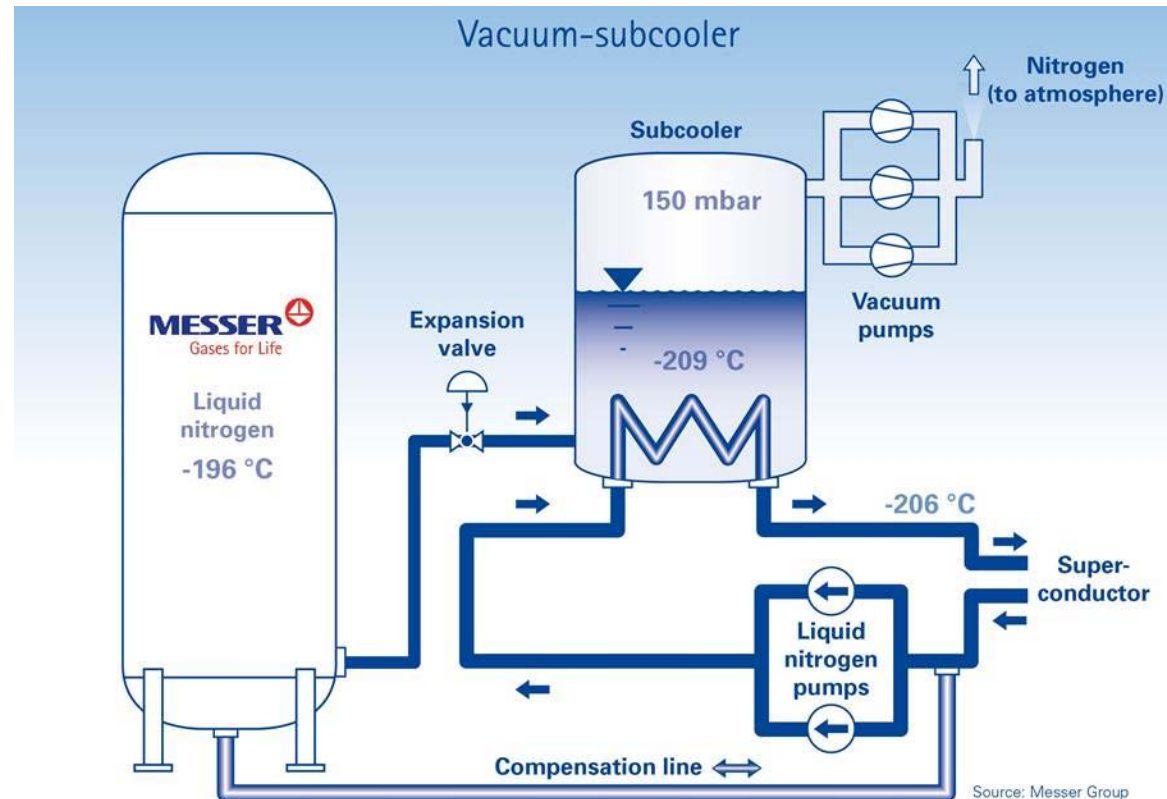
Liquid nitrogen is used
- as heat transfer medium
- as cooling agent

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 LIN 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



HTS-Cable

Voltage	10,000 V
Capacity	40,000 kW
Cooling demand (actual):	1.8 kW (@ 67 K)

Cooling unit

Cooling capacity – delivered:	1.8 kW (@ 67 K)	→ design
Cooling capacity - total:	3.4 kW (@ 64 K)	→ 4.0 kW
Liquid nitrogen consumption:	68 kg/h	→ 5.6 kW
Pel.	9 kW	→ 110 kg/h
		→ 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

Status Ampacity Project



Lessons learned

- The unsymmetrical capacitances need compensation.
- A few leaks have been fixed right after commissioning but during operation.
- The disconnection scheme after a short-circuit with an open-close cycle was changed.

Major result

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

Status

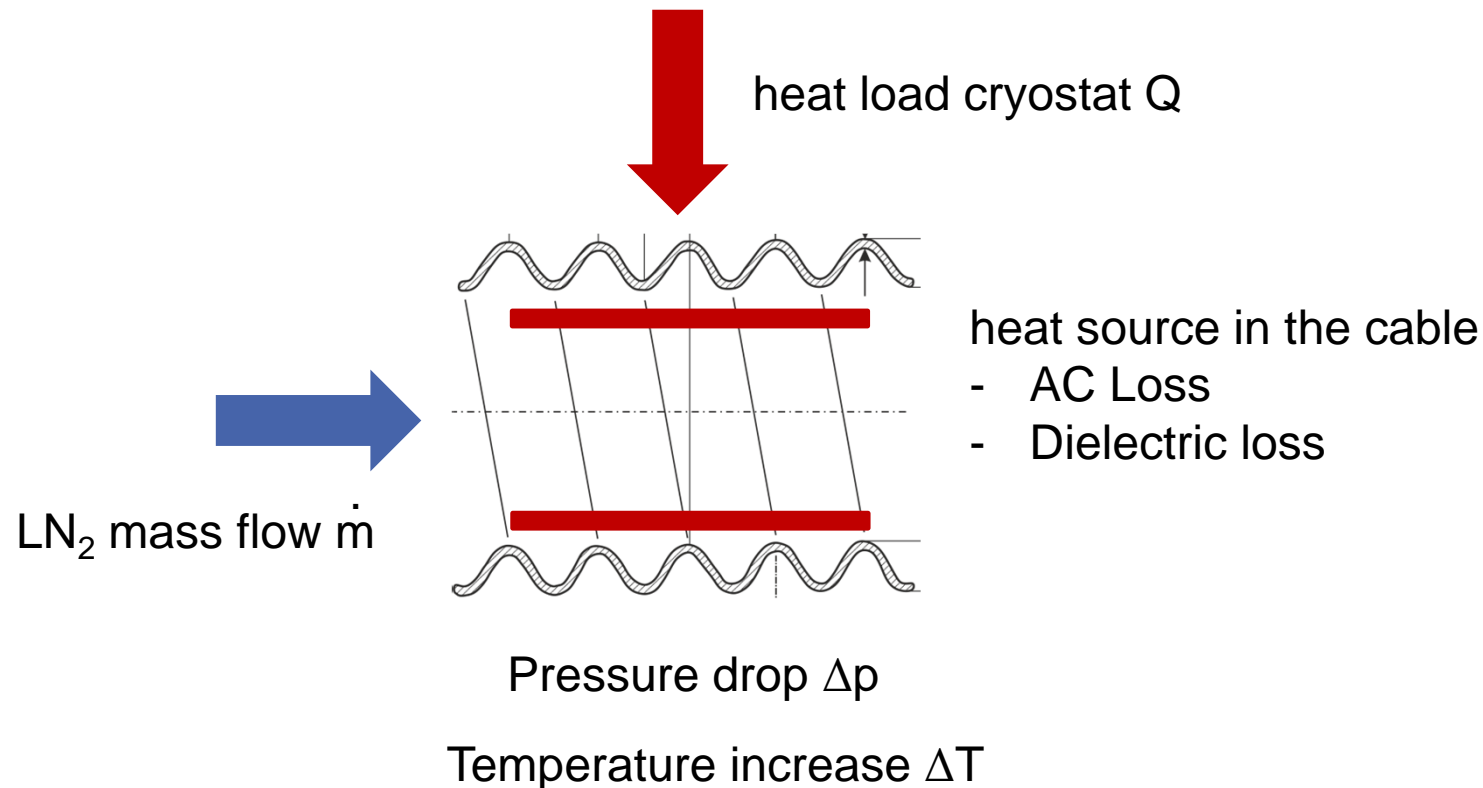
- The operation has been extended.
- Business cases are under development.

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Introduction

- Pressure drop and temperature increase in a cable

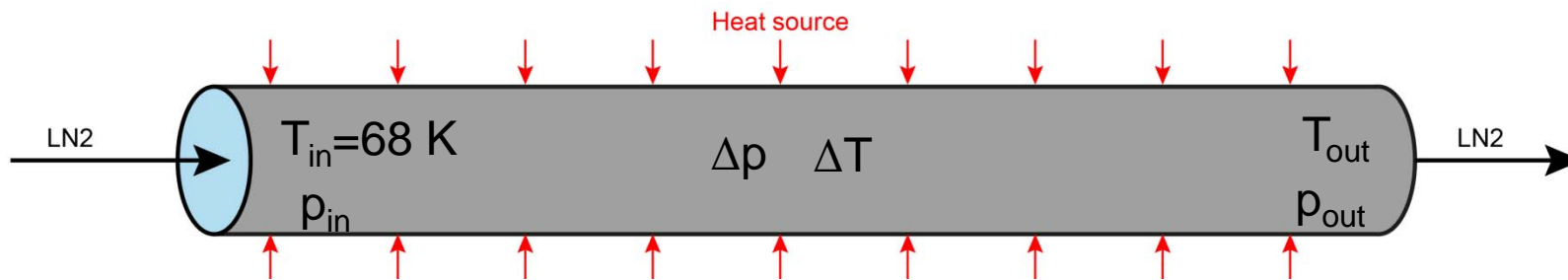
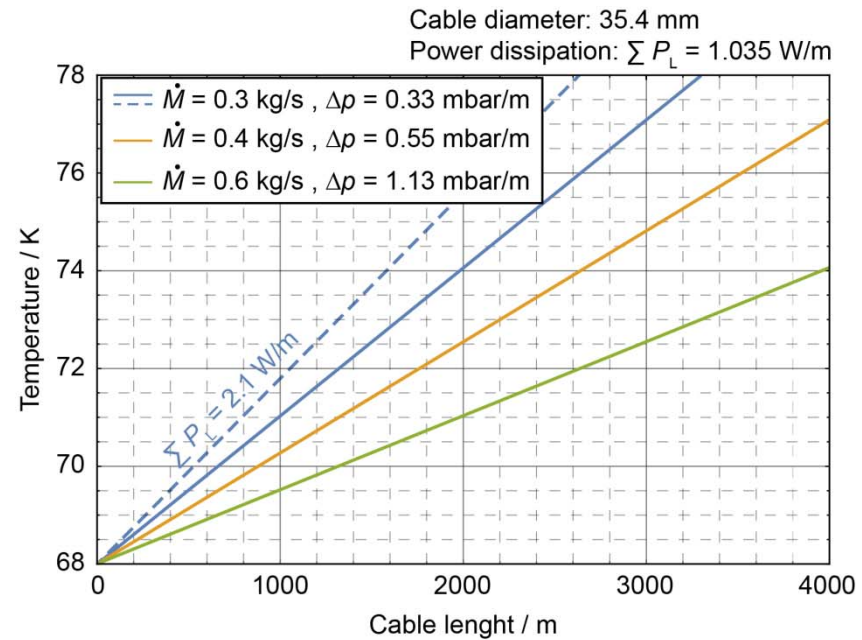
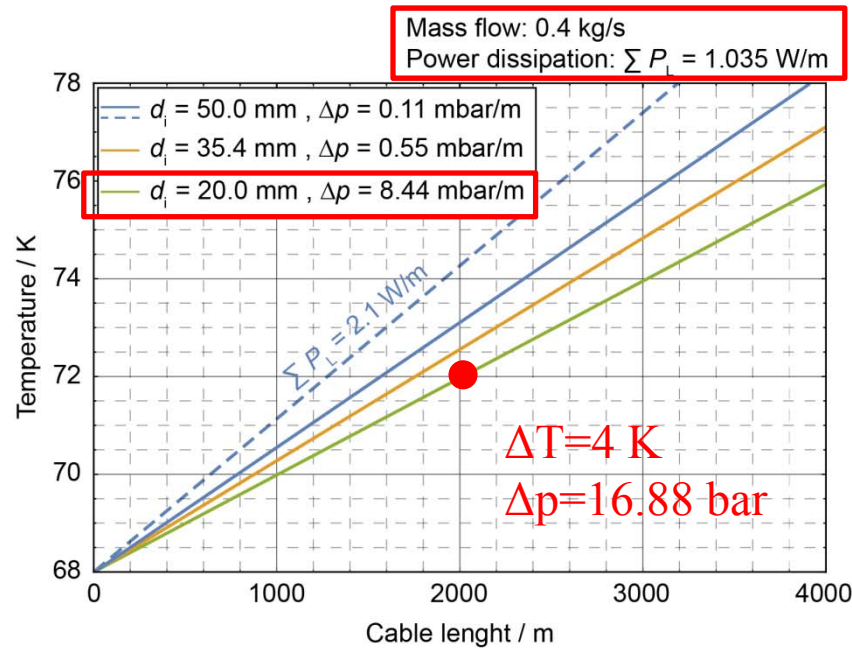


In comparison to conventional cables the cable length has a major influence on the cable design.

Introduction

Source: E. Shabagin, C. Heidt, S. Strauß, S. Grohmann, Modelling of 3D temperature profiles and pressure drop in concentric three-phase HTS power cables, Cryogenics 81, 2017, 24-32

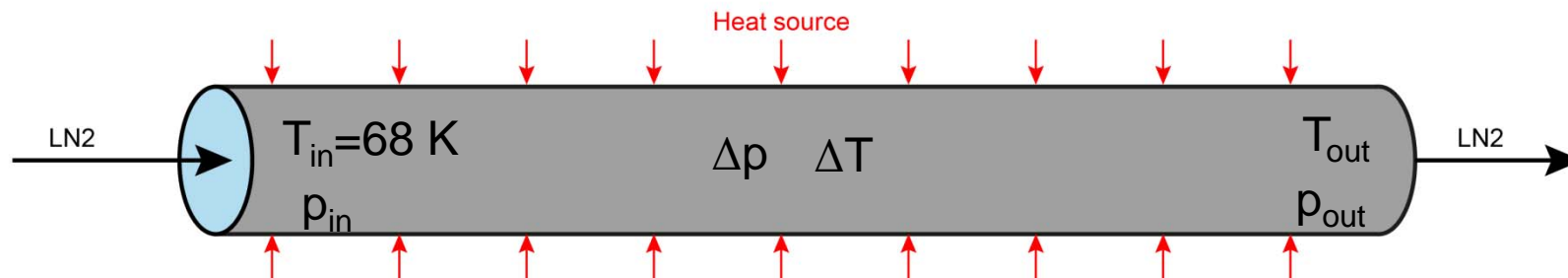
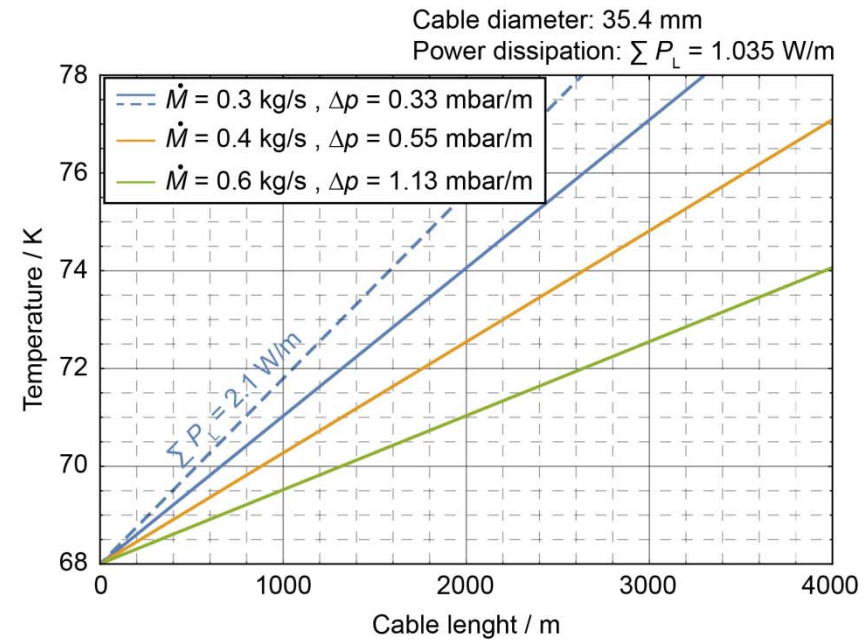
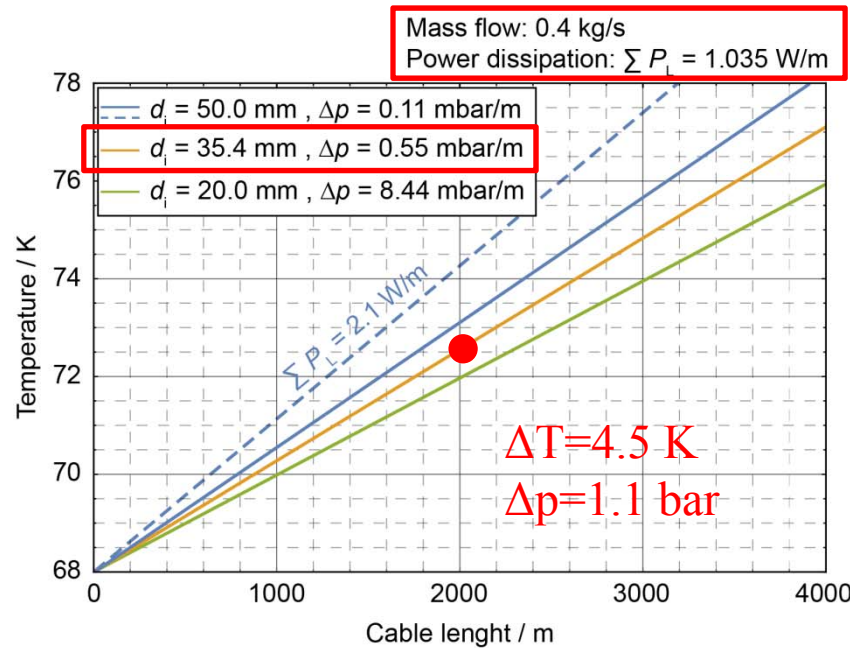
■ Pressure drop and temperature increase in a cable



Introduction

Source: E. Shabagin, C. Heidt, S. Strauß, S. Grohmann, Modelling of 3D temperature profiles and pressure drop in concentric three-phase HTS power cables, Cryogenics 81, 2017, 24-32

■ Pressure drop and temperature increase in a cable



Major Requirements

Rated Voltage

It is the maximum rms value of voltage that the equipment can withstand permanently. IEC 60071-1, e.g. 12, 24 kV in medium voltage level in Germany.

Rated Power

The power rating of equipment is the highest continuous power input allowed to flow through the equipment.

Overcurrents

In an electric power system, overcurrent is a situation where a larger than rated electric current exists for a certain time. For example short-circuit.

Utility Load Factor

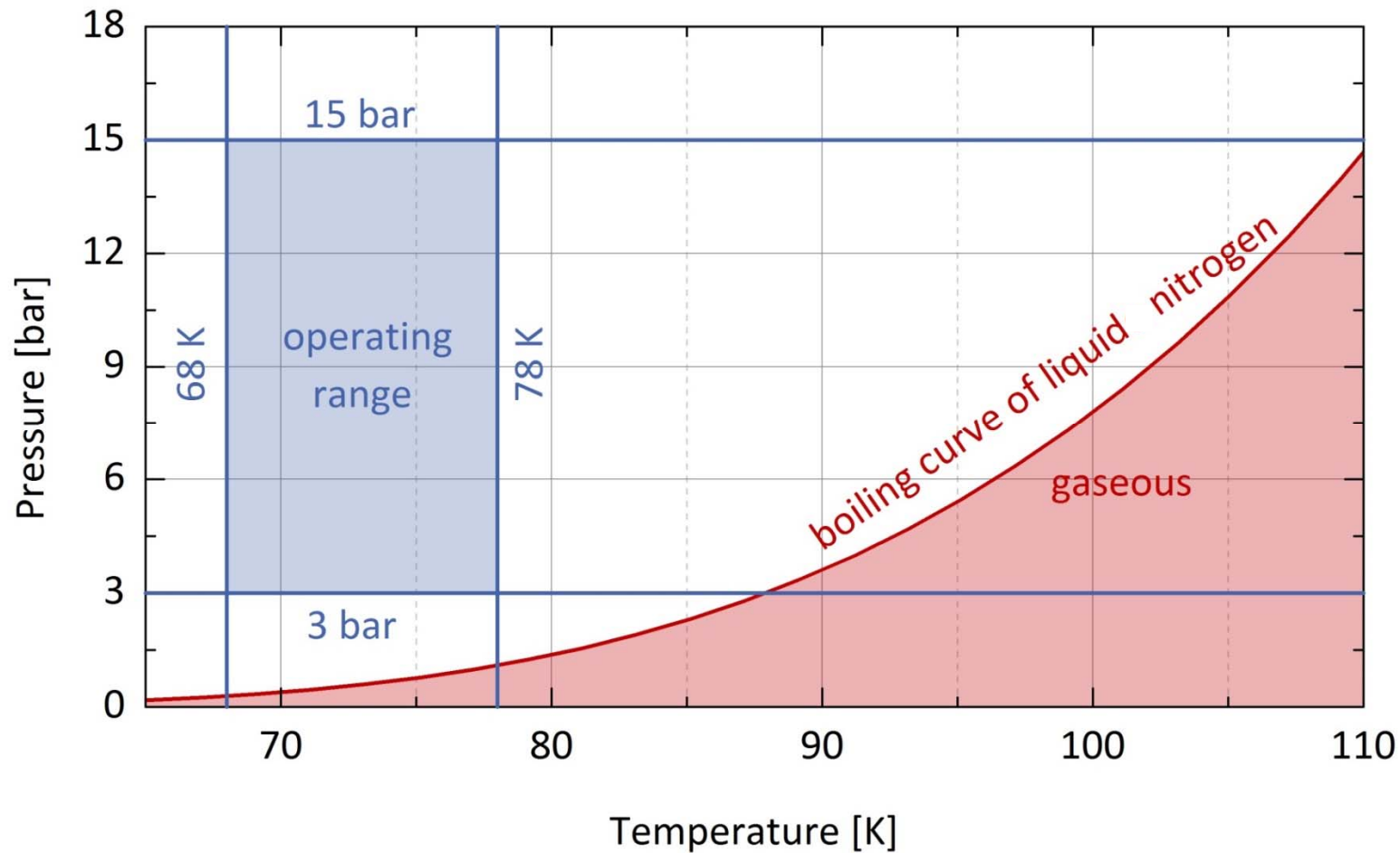
The load factor is defined as the average load divided by the peak load in a specified time period. It can be derived from the load profile.

Maximum outer diameter of the cable – self explaining

Length of the cable – self explaining

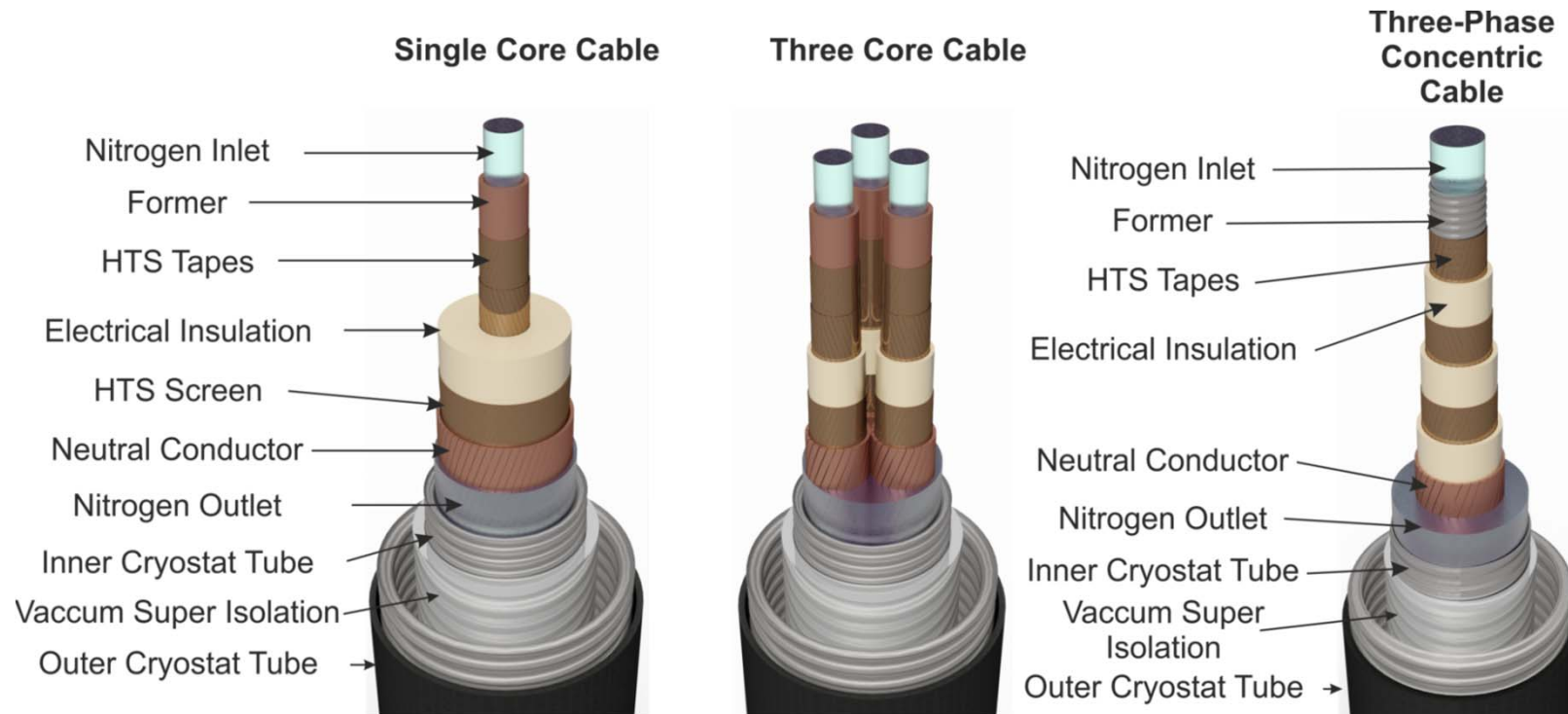
This data is provided by the utility

Temperature and Pressure Requirements



Define operating range for pressure and temperature.

Cable Types

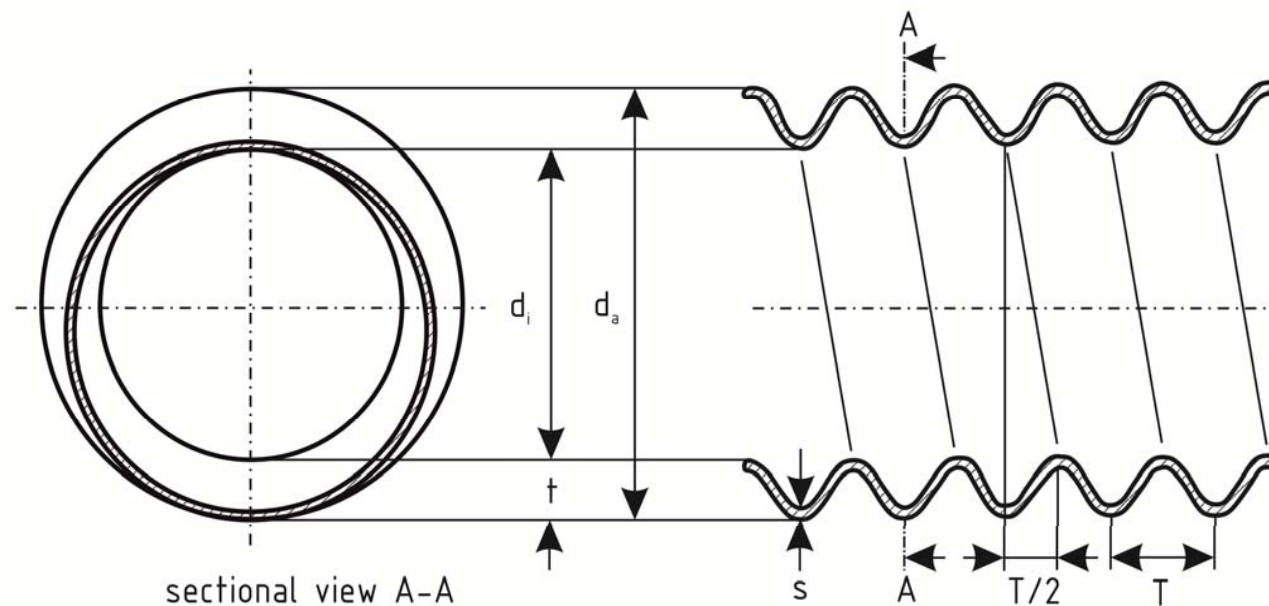


	Three single phases	Three phase in one cryostat	Three phase concentric
Voltage level	High voltage > 110 kV	30-110 kV	10-50 kV
Amount of superconductor	higher	higher	smaller
Cryostat loss	higher	smaller	smaller

Select cable type.

Standard Dimensions for Flexible Tubes

	d_i	d_a
	mm	mm
20	20,2	22,2
25	25,2	27,4
32	33,7	35,9
40	40,0	42,8
50	50,0	52,8
65	65,0	68,4
80	79,8	83,8
100	99,8	104,4
125	125,6	130,8
150	151,9	157,9



Standard dimensions in Germany according to DIN EN 10380.

Design Example – Medium Voltage Cable

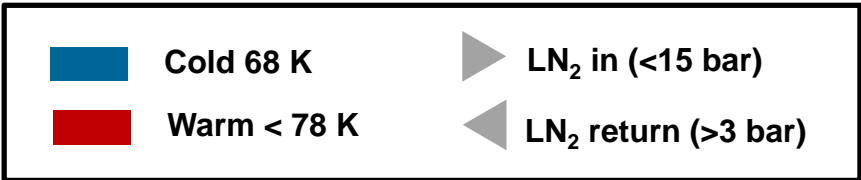
Rated Voltage	12 kV
Rated Power	30 MVA
Overcurrents	20 kA for 1 s 50 kA for 30 ms
Utility Load Factor	0.7 continuous load
Max. Outer Diameter	105 mm
Length	2.6 km

Typical data for urban area power system in Germany.

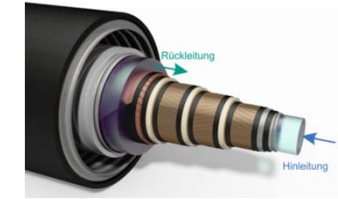
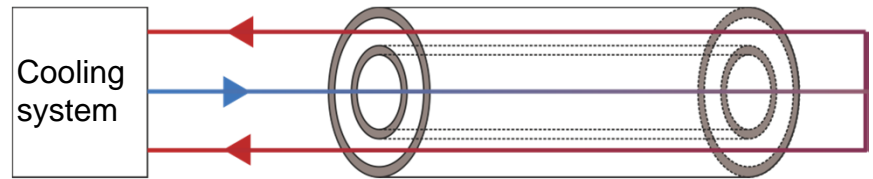
Next steps

- Start with diameter of LN₂ inner tube.
- Put enough HTS tapes to carry the current.
- Calculate max. electrical field.
- Calculate the AC losses and cryogenic losses.

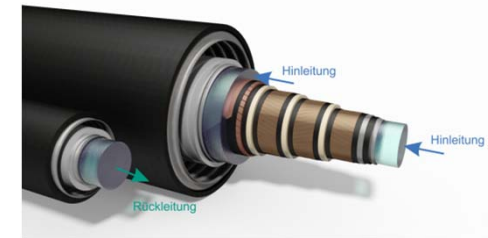
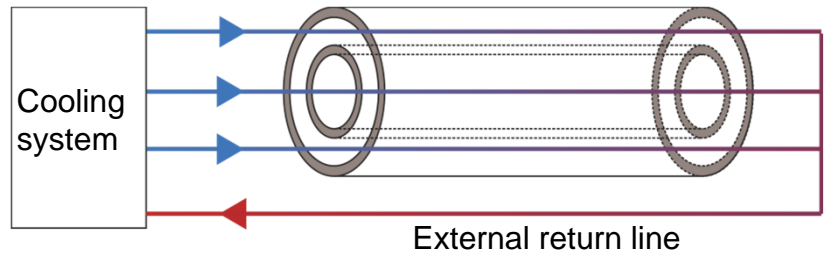
Cooling Options



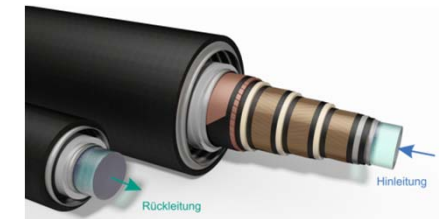
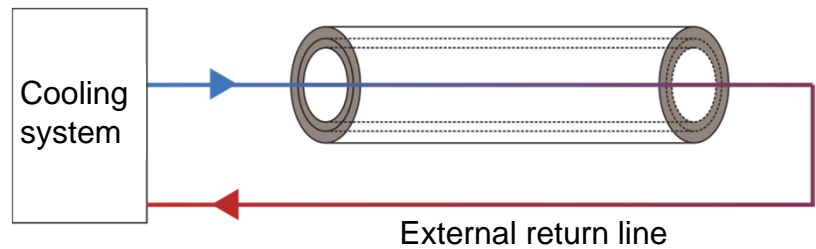
Option 1:
+ no external feedback line



Option 2:
+ longer cable length



Option 3:
+ smallest cable diameter



Option 4:
+ longer cable length
+ no external feedback line



Cable Loss Option 3 (inner LN₂ diameter 25 mm)

Loss component	Loss	Loss	Loss
	$0,1 \cdot I_N$	$0,5 \cdot I_N$	$1 \cdot I_N$
Cooling Power	9037 W	9061 W	9379 W
AC Loss	0,0 W	12 W	290 W
Cryostat¹⁾	8840 W	8840 W	8840 W
Current leads	117 W	130 W	169 W
Terminal cryostat	80 W	80 W	80 W
Loss at RT	143,4 kW	143,8 kW	148,9 kW

1) For option 3 with 1,6 W/m for return line 1,9 W/m for cable cryostat.

Loss Energy per Year* Option 3 (inner LN₂ diameter 25mm)

Loss component	Load factor 0.7	Load factor 1
AC loss	15 MWh	40 MWh
Current lead thermal	16 MWh	16 MWh
Current lead electrical	5 MWh	7 MWh
Cable cryostat	1229 MWh	1229 MWh
Terminal cryostat	11 MWh	11 MWh
Total loss energy per year	1276 MWh	1304 MWh

*without pumps and auxiliary systems

For calculation of loss energy per year see: Kottonau et. al, IEEE Transactions on Applied Superconductivity, Vol. 27., Issue 4, 2017, DOI: 10.1109/TASC.2017.2652856

Maximum Cable Length for Option 3



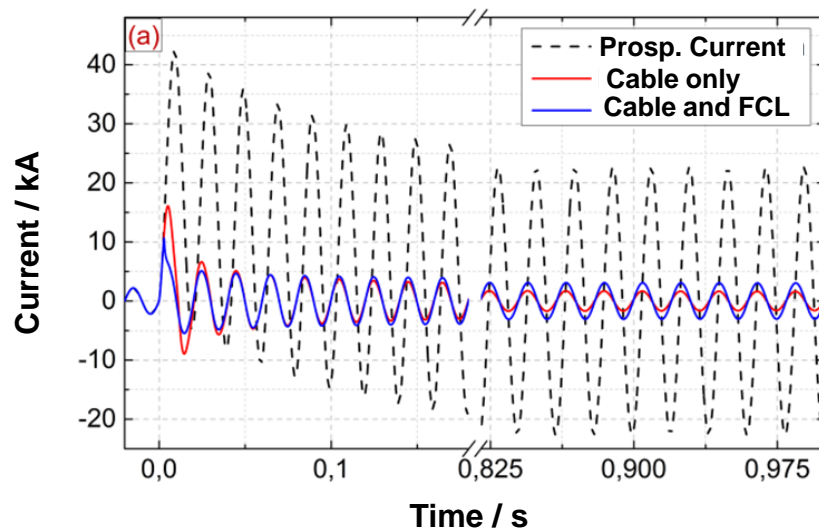
		Radius inner LN ₂ tube			
Radius inner cryostat	Mass flow	20 mm	25 mm	32 mm	40 mm
65 mm	$\dot{M} = 0,25 \text{ kg/s}$	X	X	X	X
	$\dot{M} = 0,5 \text{ kg/s}$	X	3420 m	X	X
	$\dot{M} = 0,75 \text{ kg/s}$	X	X	X	X
	$\dot{M} = 1 \text{ kg/s}$	X	X	X	X
80 mm	$\dot{M} = 0,25 \text{ kg/s}$	X	X	X	X
	$\dot{M} = 0,5 \text{ kg/s}$	X	3920 m	4210 m	X
	$\dot{M} = 0,75 \text{ kg/s}$	X	X	6210 m	X
	$\dot{M} = 1 \text{ kg/s}$	X	X	X	X

X Temperature increase higher than 78 K or pressure drop larger than 12 bar

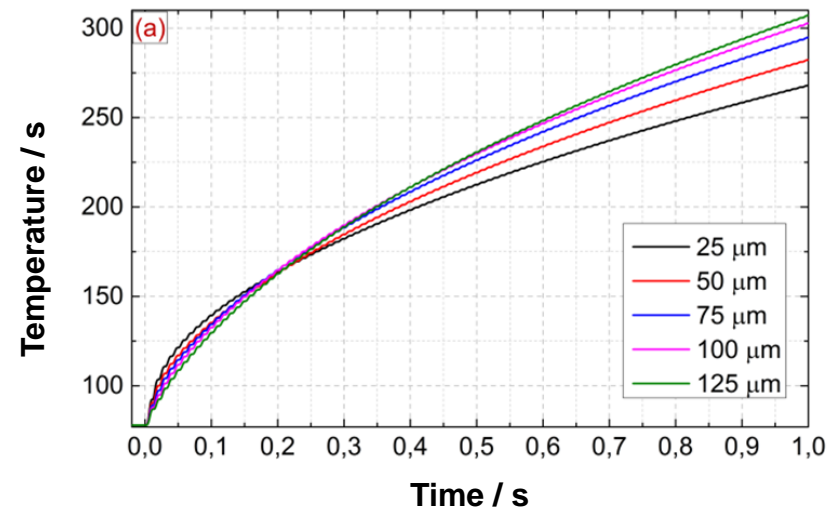
With an inner LN₂ tube of 25 mm and an inner cryostat tube of 65 mm all requirements are fulfilled.

Short-Circuit Behaviour (20 kA, 1 s)

Short-circuit Current ($Cu=25 \mu\text{m}$)



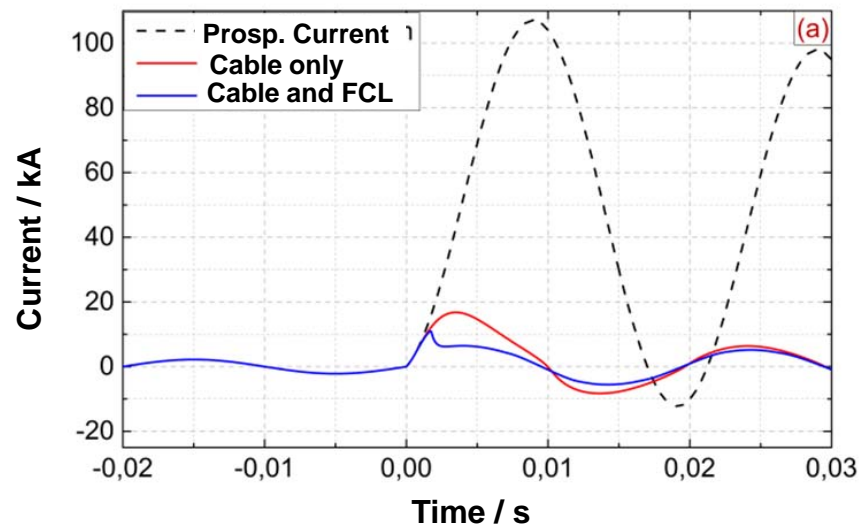
HTS Temperature Increase



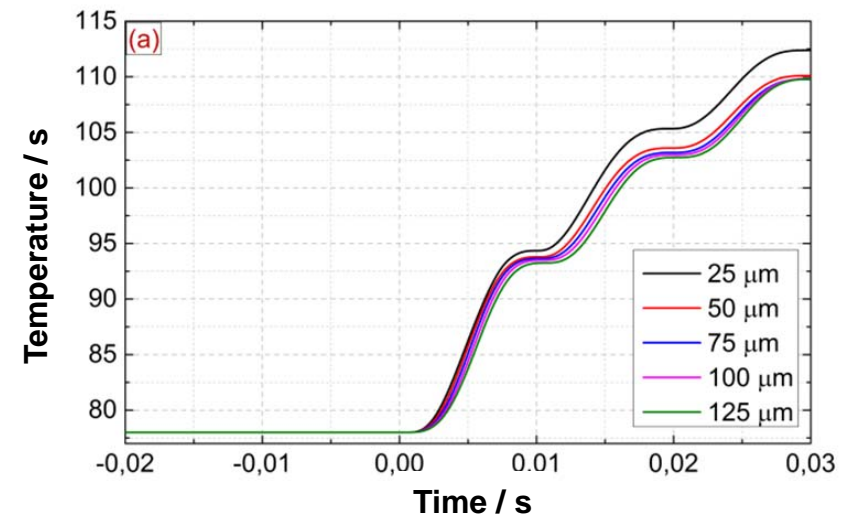
In case the temperature would be too high an SFCL can be considered.

Short-Circuit Behaviour (50 kA, 30 ms)

Short-circuit Current (Cu=25 μm)

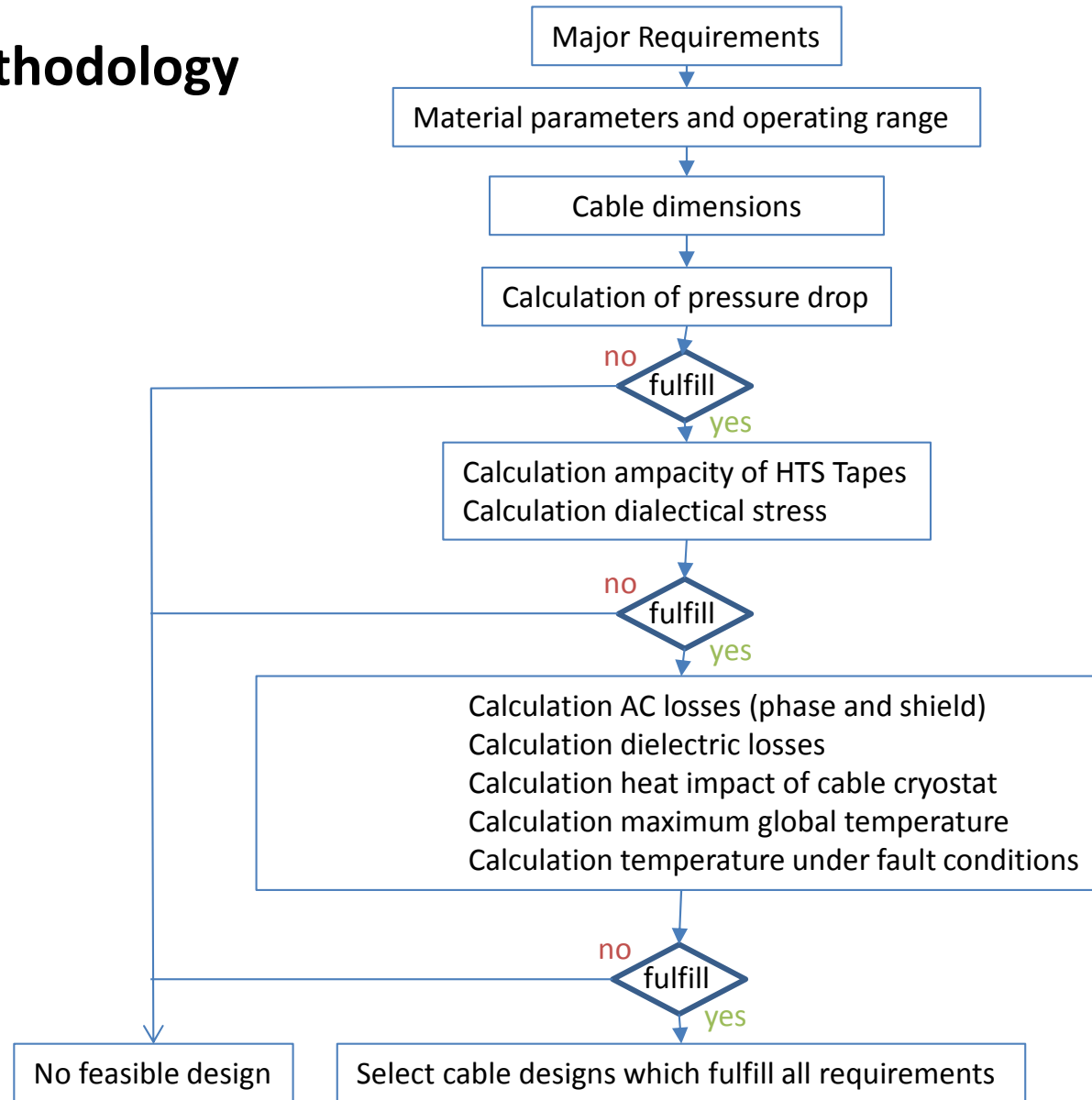


HTS Temperature Increase



Short-circuit with 20 kA, 1 s leads to higher temperature increase.

Design Methodology



Design Summary

Rated Voltage	12 kV
Rated Power	30 MVA
Overcurrents	20 kA for 1 s 50 kA for 30 ms
Utility Load Factor	0.7 continuous load
Max. Outer Diameter	105 mm
Length	2.6 km

Main data

Capacitance	1.47 $\mu\text{F}/\text{km}$
Inductance	0.029 mH/km
Inner LN ₂ tube diameter	25 mm
Inner Cryostat diameter	65 mm
Smallest cable diameter	104.6 mm

Option 3



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Superconducting DC Cables

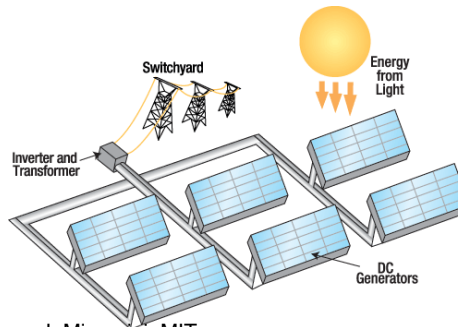
Applications

Industry high current lines



Picture: Vision Electric

Connect renewables



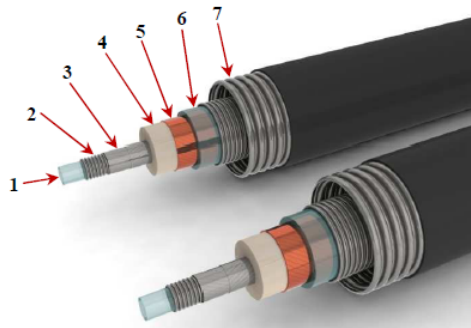
Picture: J. Minervini, MIT

Supply data centers



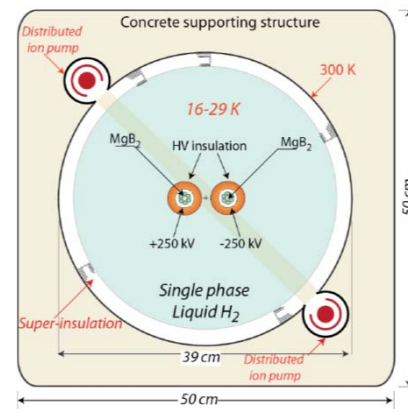
Picture: J. Minervini, MIT

Grounding of HVDC Lines



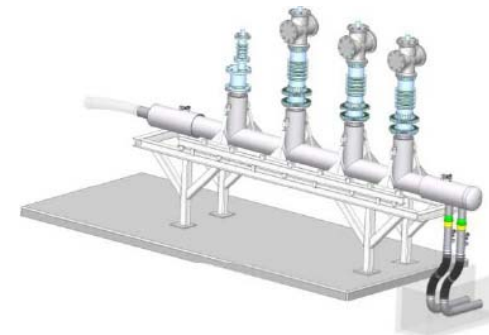
Picture: Nexans

Larger power, long distance transmission



Picture: C. Rubbia, IASS

Degaussing of ships



Picture: B. Fitzpatrick, HTS Peerreview2010

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DC Cables – State-of-the-Art

Place, Country, Year	Application	Data	HTS
Ludwigshafen, D, 2017	Chlor electrolysis	20 kA, 1 kV, 25 m	YBCO
St. Petersburg, Ru, 2016	Substation connection	2.5 kA, 20 kV, 2.5 km	BSCCO
Ishikari, Japan, 2016	Test application	2.5 kA, 20 kV, 1 km	BSCCO
Ishikari, Japan, 2015	Connection PV Datacentre	5 kA, 20 kV, 500 m	BSCCO
Jeju Island, Korea, 2015	Substation connection	3.25 kA, 80 kV, 500 m	YBCO
CERN, CH, 2014	Test application	20 kA, 20 m	MgB ₂
Kunitachi, Japan, 2013	Connection train converter	6 kA, 1,5 kV, 30 m	BSCCO
Gongyi, China, 2012	Aluminium plant	10 kA, 1,3 kV, 360 m	BSCCO
Chubu, Japan, 2010	Test application	2 kA, 10 kV, 200 m	BSCCO
Chubu, Japan, 2006	Test application	2.2 kA, 20 kV, 20 m	BSCCO

Superconducting DC Cables

State-of-the-Art

DC Cable in Japan



Chubu University
10 kV, 1.2 kA, 200 m
Energized 2010

DC Cable in Russia



Customer: General Grid Company

20 kV, 2.5 kA, 2500 m

First full scale sample in 2013

Cable laying in 2016

Experimental operation in 2017

V.E Sytnikov, et. al. "HTS DC cable line project: on-going activities in Russia", IEEE/CSC & ESAS European Superconductivity News Forum (ESNF) No. 23 January 2013

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Status 3S Project

■ Objectives

- Develop and test a 25 m, 20 kA superconducting DC busbar for industry applications, **First rigid modular design**

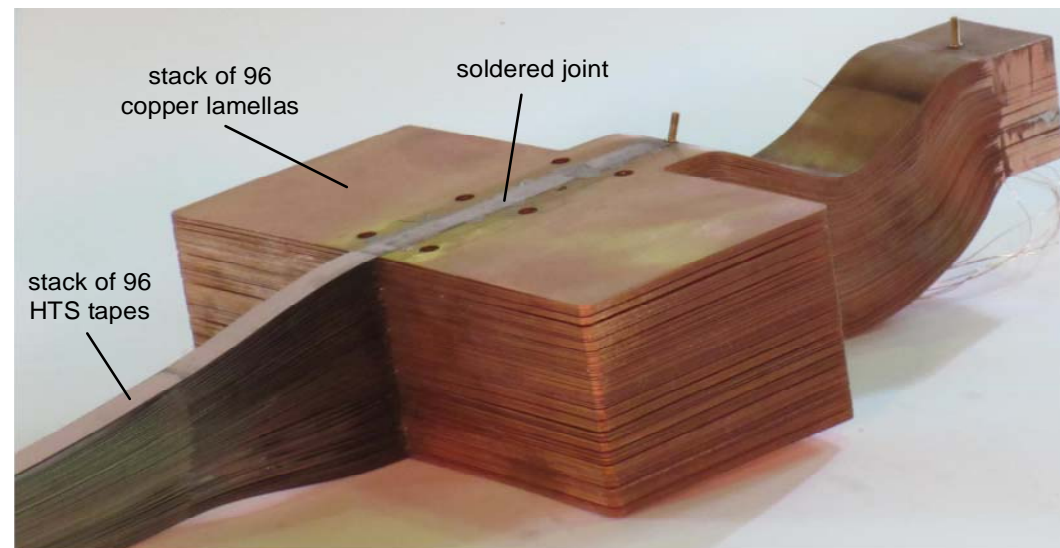
■ Project partners

- Vision Electric Superconductors, KIT, ILK

■ Duration

- May 2015-April 2018

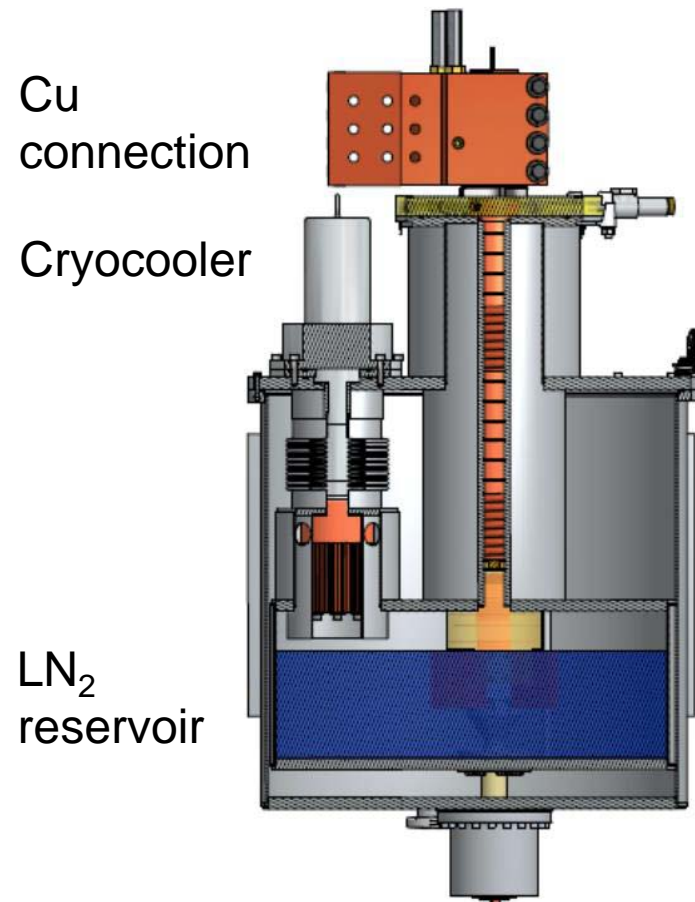
Flexible Copper to HTS contact with low resistance and high number of stacks.



First 20 kA short sample tested and current lead developed outside the project.

Compact, low loss current lead for DC busbars

ICE[®] Link 20 kA current lead



Courtesy: Vision Electric Superconductors

Setup is finished, commissioning tests done.

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Superconducting Cables

Research Direction

- Lower cost and higher performance of HTS material
- Improved thermal insulation at reduced cost
- Work on standards (e.g. How to perform a routine or factory test of HTS cables?)
- Demonstrate reliability and availability in long-term field installations

- More superconducting cable installations.

Superconducting cables are close to commercialization.