Karlsruher Institut für Technologie

Superconducting Cables

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Institute for Technical Physics

EASITrain Summer School, September 3rd-7th 2018, Vienna

KIT-ZENTRUM ENERGIE

Table of Content

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

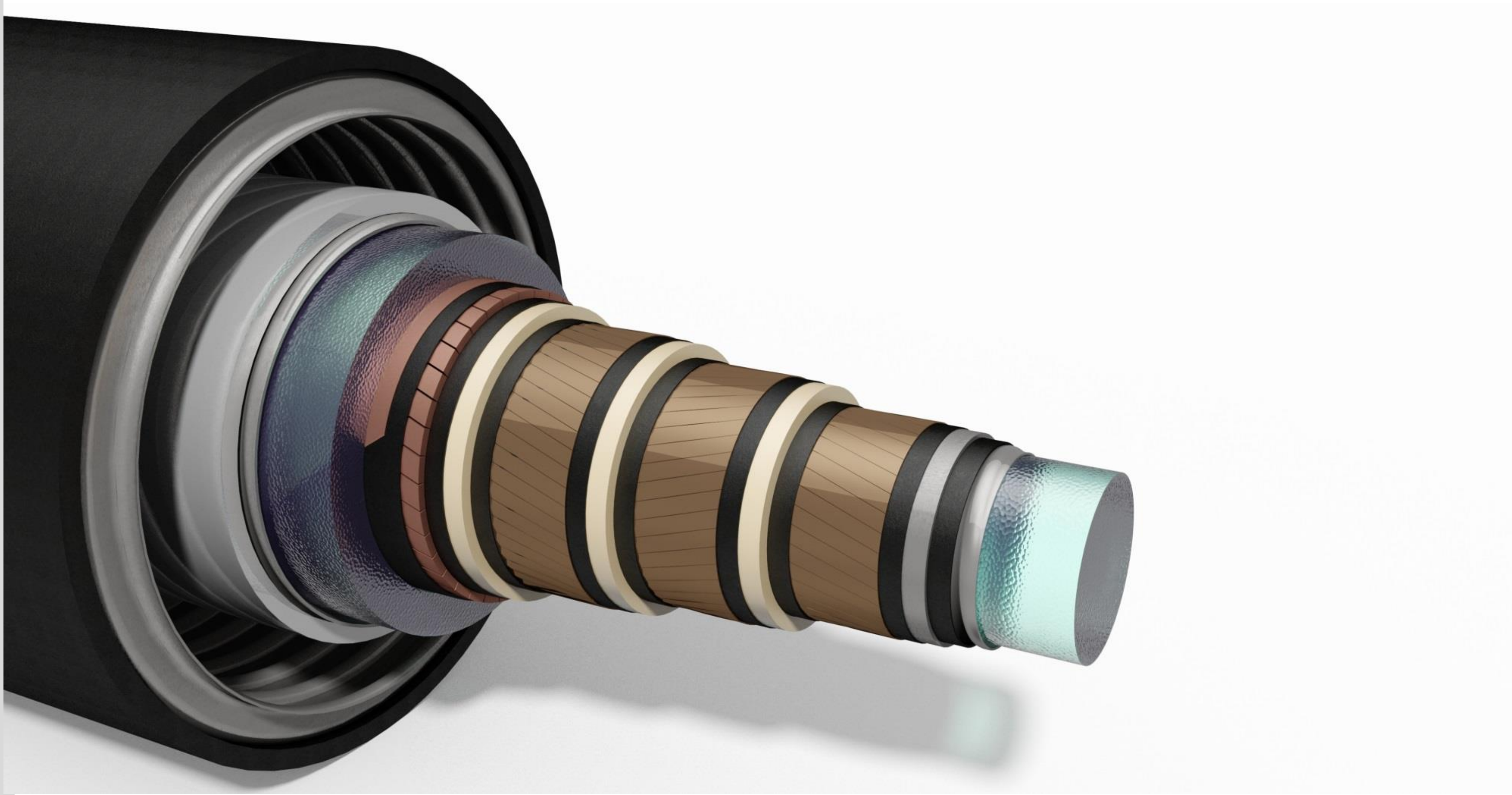
Operation

- Low impedance
- Operation at natural load

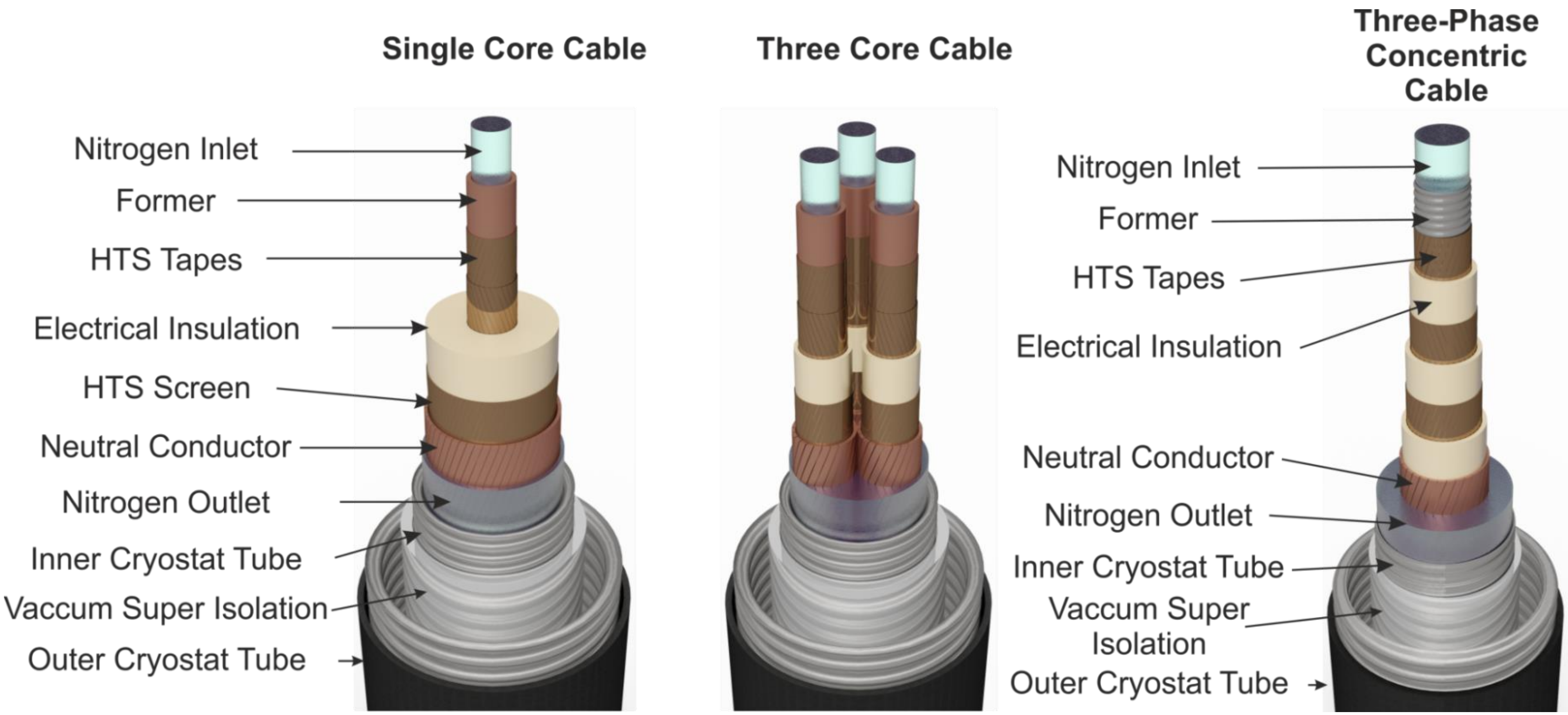
Enables unique cable systems and new power system structures

Table of Content

General Setup – Outer Protection, extruded PE



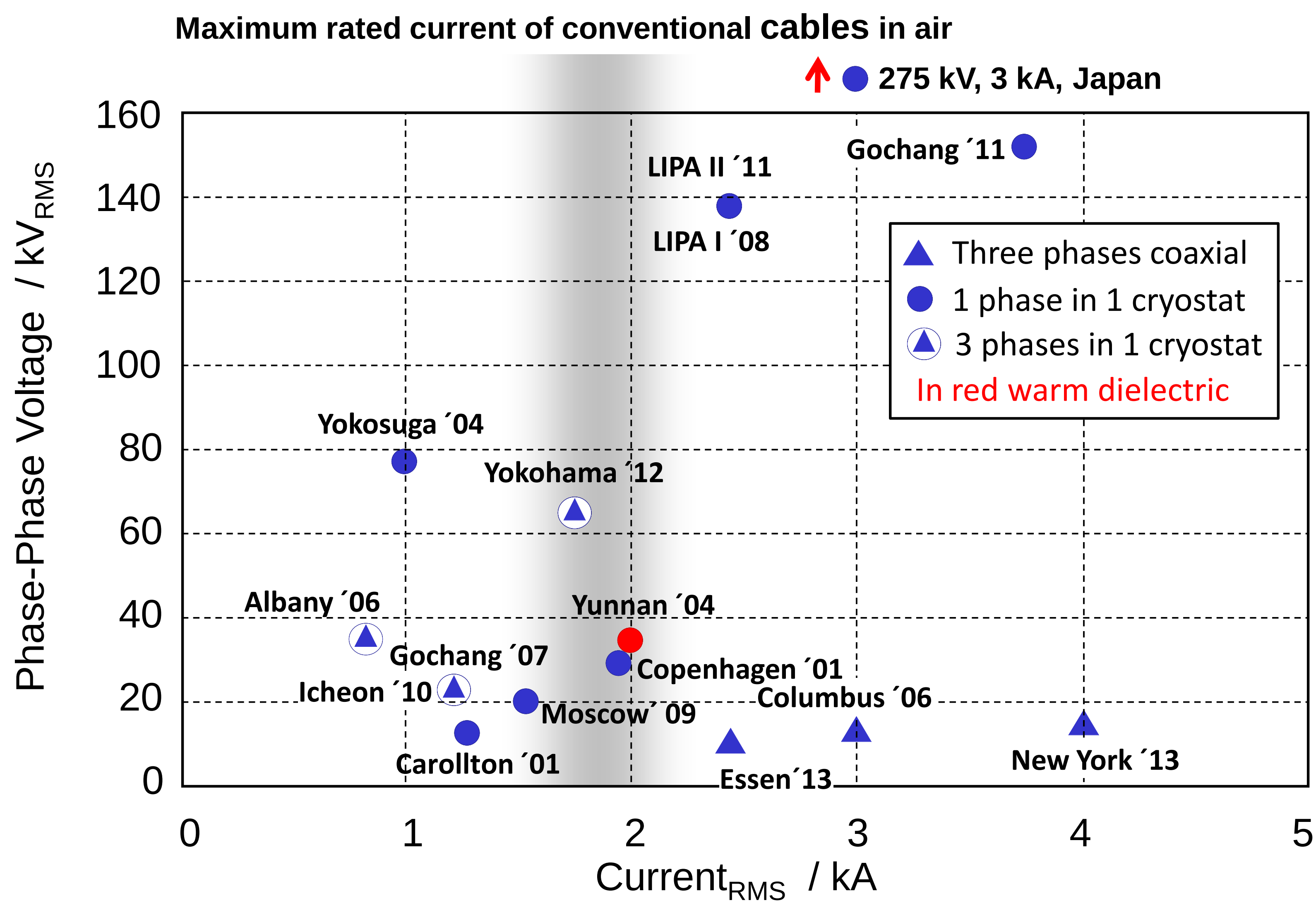
Cable Types – Cold Dielectric



	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

Table of Content

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



Superconducting AC Cables
State-of-the-Art

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Columbus

Figure: Ultera

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

LIPA

Figure: Nexans

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

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

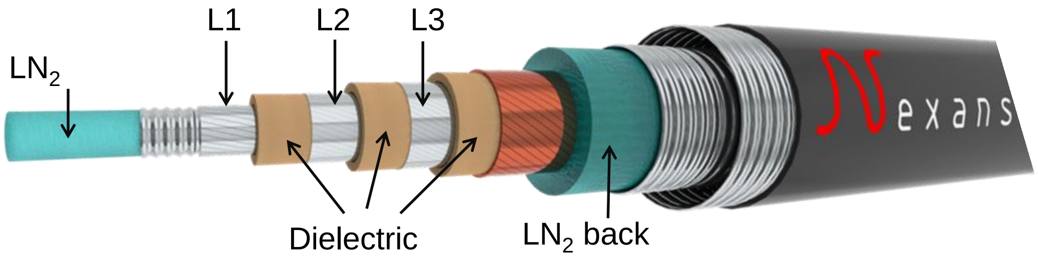
Manufacturer	Place ,Country, Year	Data	HTS
??	Chicago, US	12 kV, a few miles	??
LS Cable	Seoul, Korea, 2017	22.9 kV, 1000 m	YBCO
Nexans	Essen, Deutschland, 2014	10 kV, 2.4 kA, 1000 m	BSCCO
Sumitomo	Yokohama, Japan, 2013	66 kV, 1.8 kA, 240 m	BSCCO
LS Cable	Icheon, Korea, 2011	22.9 kV, 3.0 kA, 100 m	BSCCO
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.

Table of Content

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:

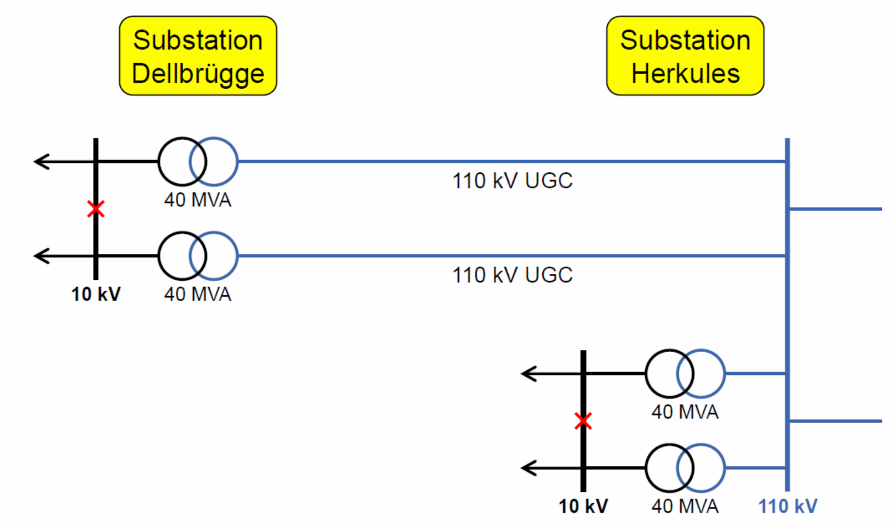
Supported by: Federal Ministry of Economics and Technology on the basis of a decision by the German Bundestag

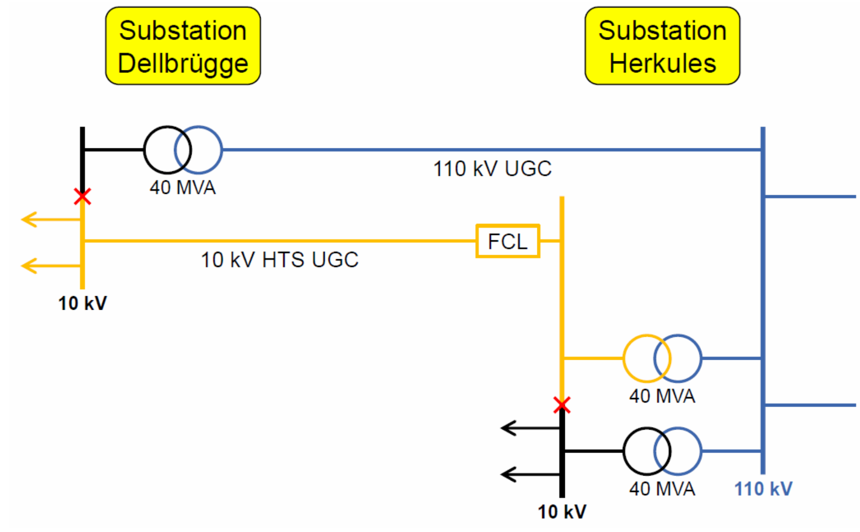
Projektträger Jülich Forschungszentrum Jülich

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

AMPACITY
Smart grids for the city

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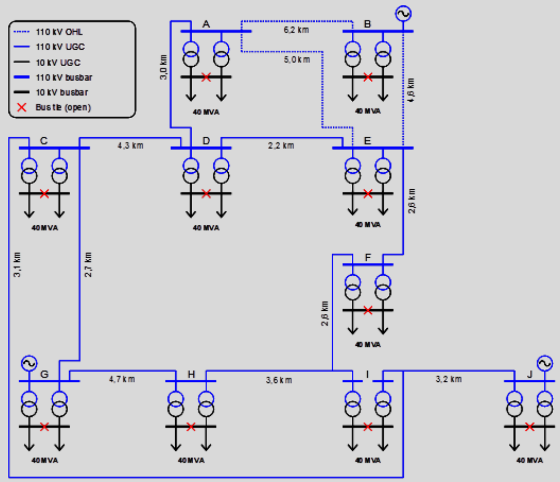
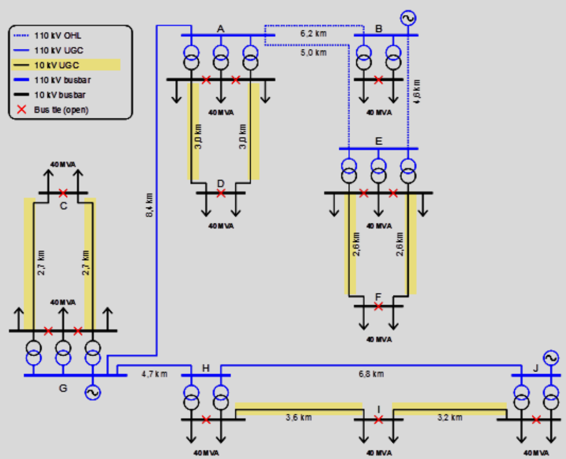
Variant target grid A:

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

AampaCity Cooling Unit

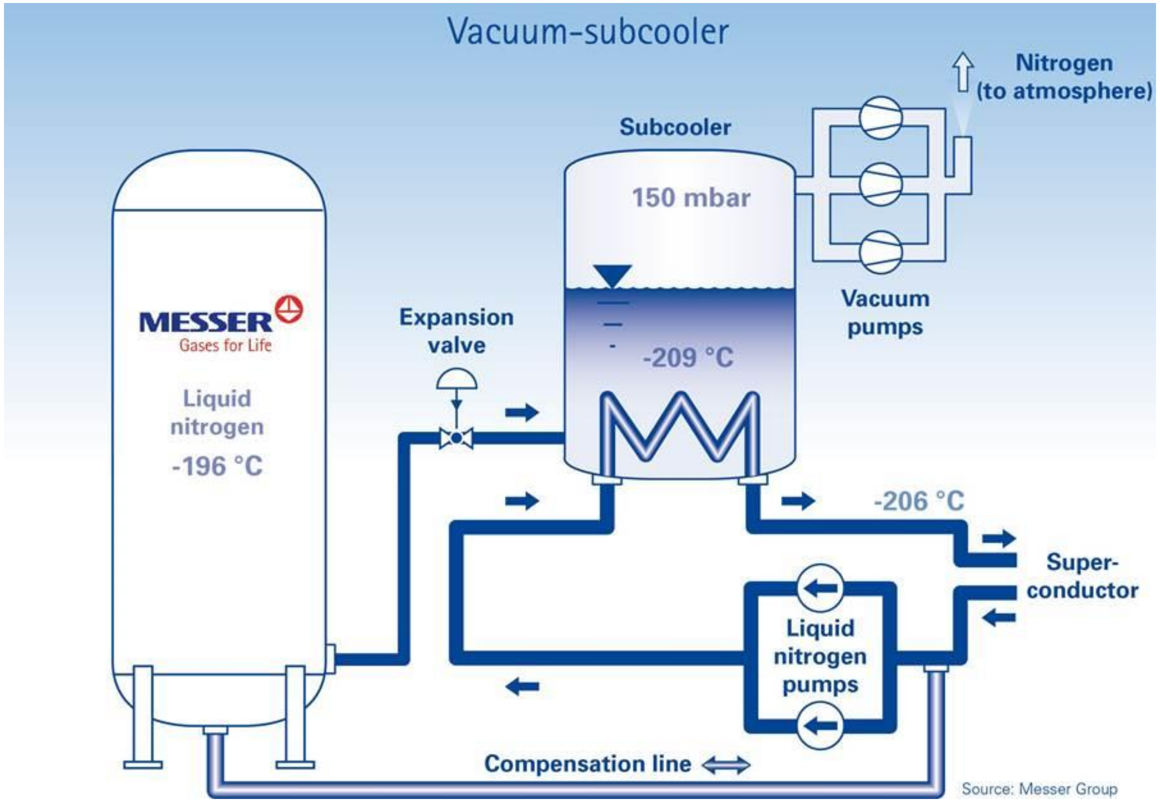
Liquid nitrogen is used
- as heat transfer medium
- as cooling agent

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

MESSER Gases for Life

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<u>HTS-Cable</u>

Voltage	10,000 V	
Capacity	40,000 kW	
Ccooling demand (actual):	1.8 kW (@ 67 K)	
<u>Cooling unit</u>	**actual**	➔ design
Cooling capacity – delivered:	**1.8 kW (@ 67 K)**	➔ 4.0 kW
Cooling capacity - total:	**3.4 kW (@ 64 K)**	➔ 5.6 kW
Liquid nitrogen consumption:	**68 kg/h**	➔ 110 kg/h
Pel.	**9 kW**	➔ 13 kW

<u>Redundancy</u>

2 circulation pumps (instead of 1)

3 vacuum pumps (instead of 2)

almost 100% redundany 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.

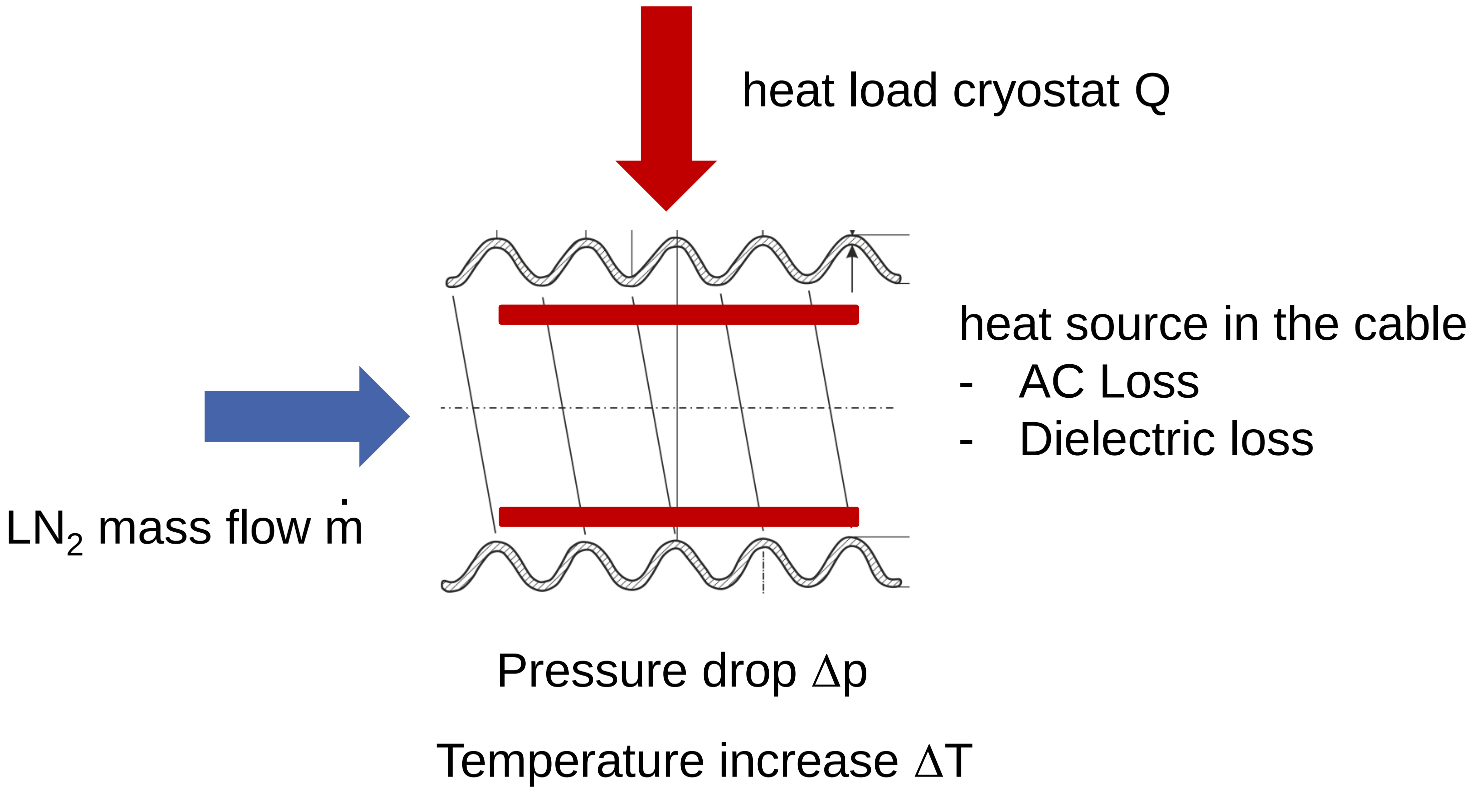
Status

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

Table of Content

Introduction

- Pressure drop and temperature increase in a cable

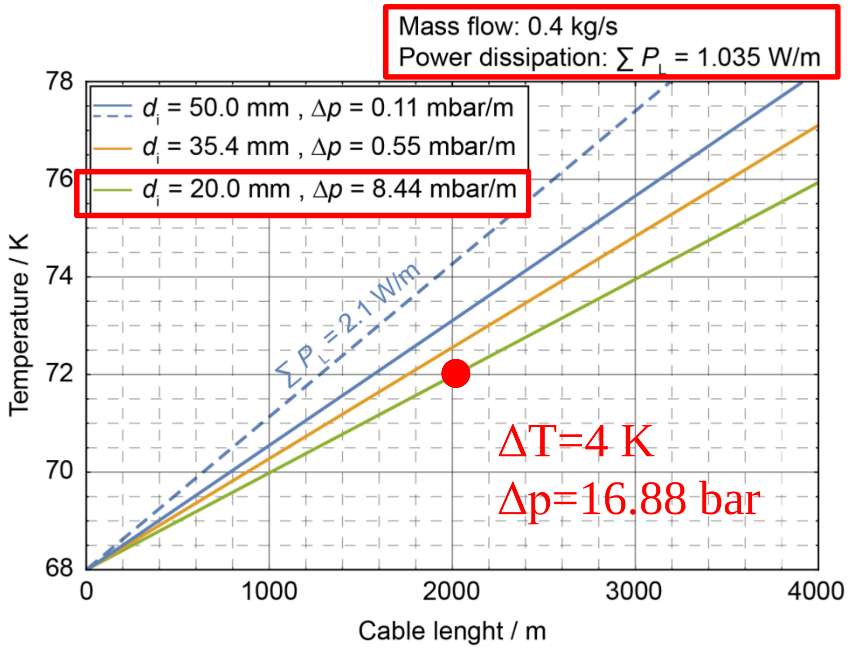


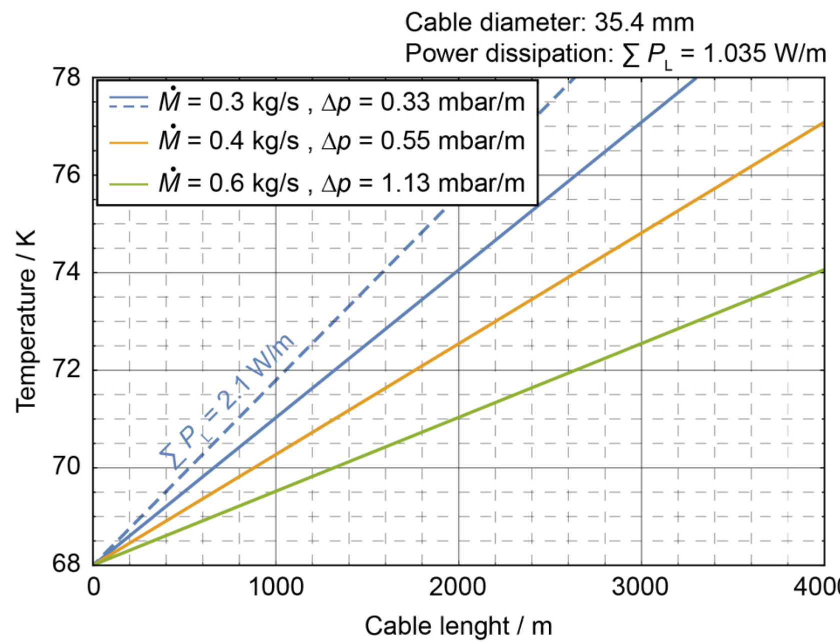
In comparison to conventional cables the cable length has a major influence on the cable design.

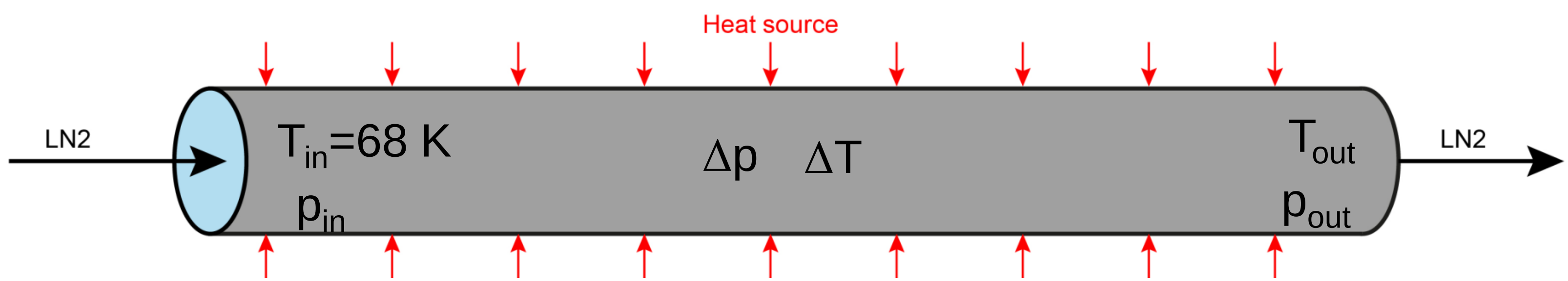
Introduction

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

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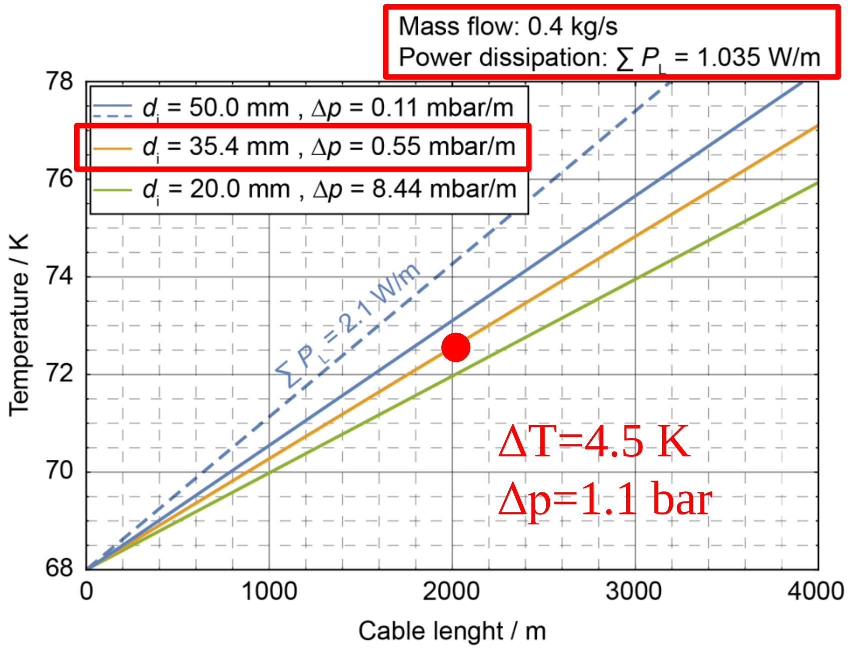
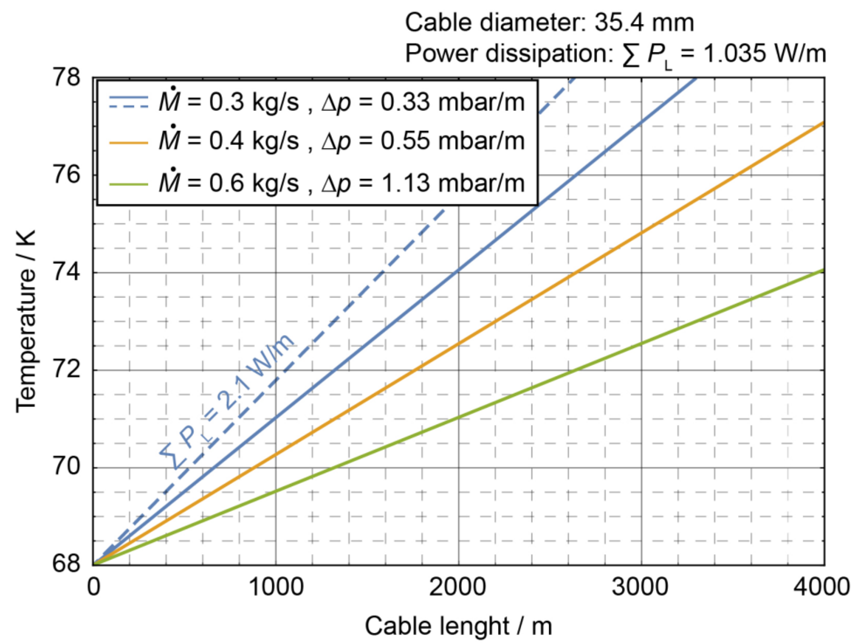
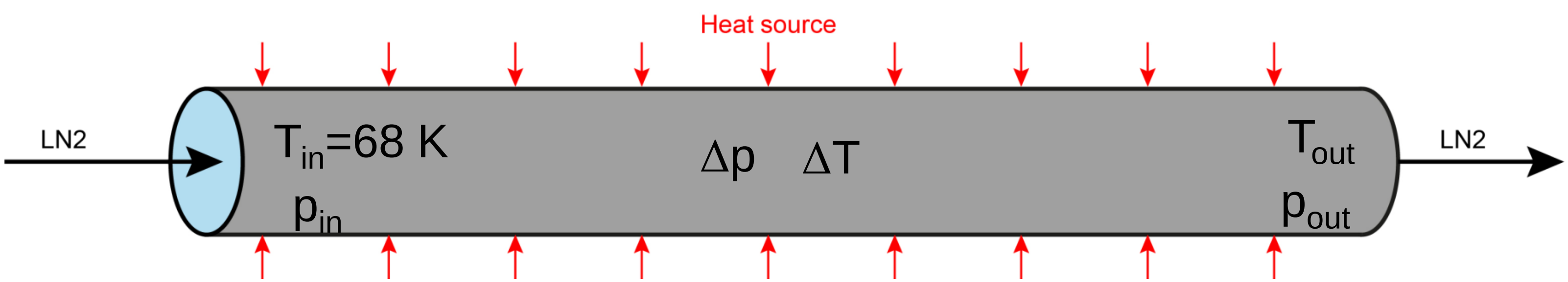
- Pressure drop and temperature increase in a cable







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 contineous 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

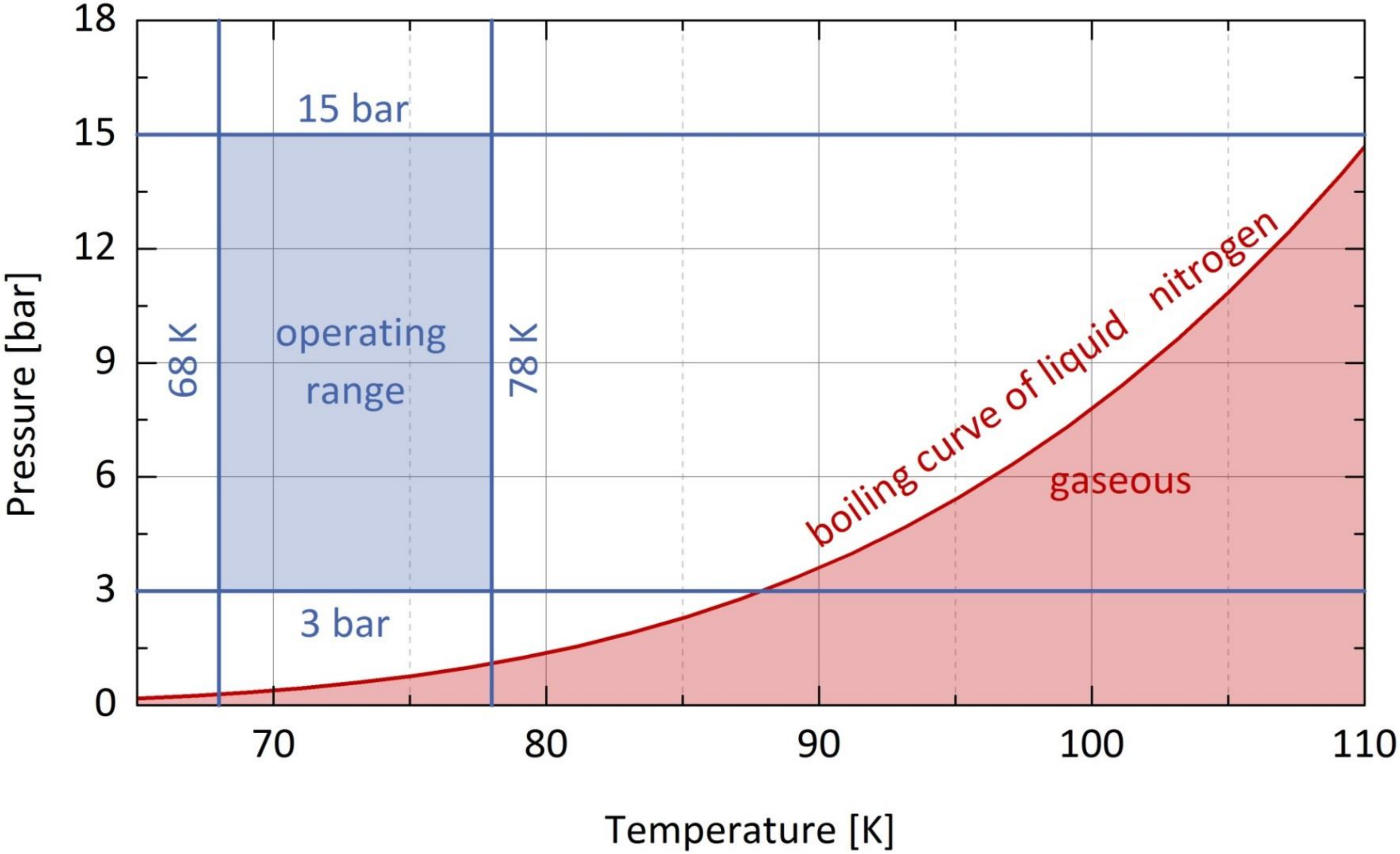
The load factor is defined as the average load divided by the peak load in a specified time period. It can be derived from the load profile.

Maximum outer diameter of the cable – self explaining

Length of the cable – self explaining

This data is provided by the utility

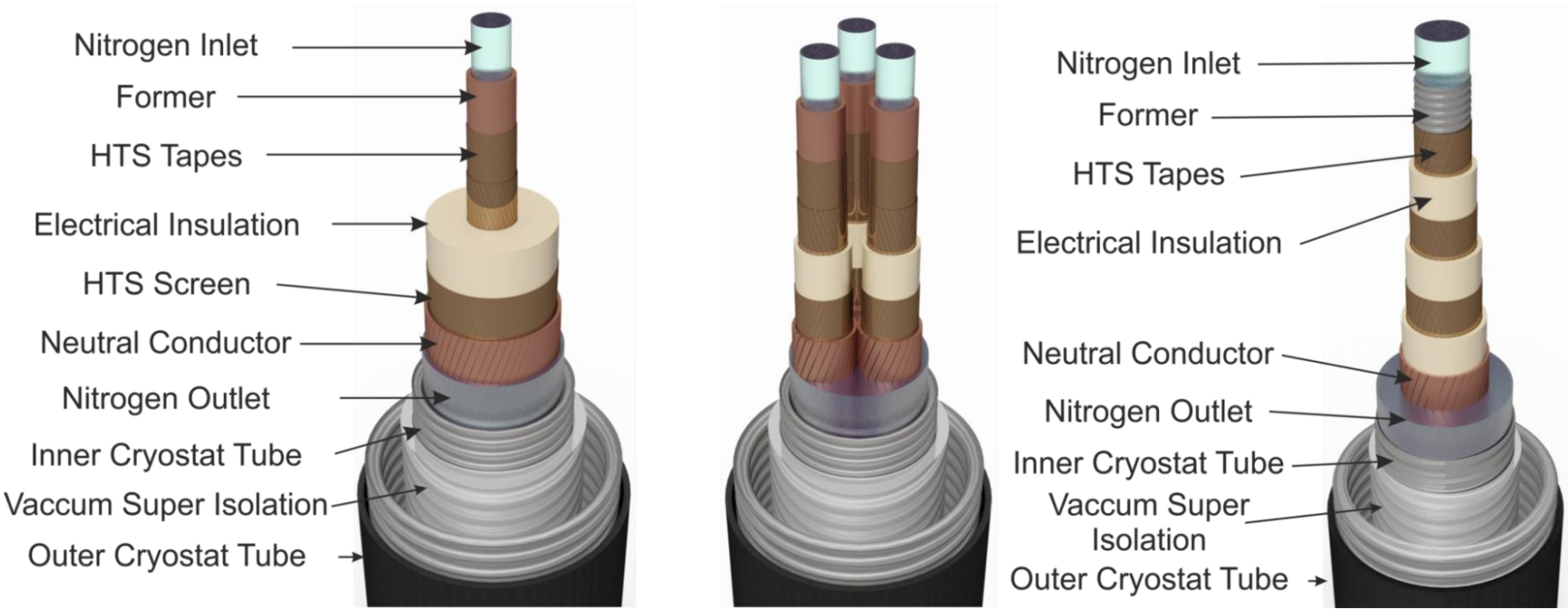
Temperature and Pressure Requirements



Define operating range for pressure and temperature.

Cable Types

Single Core Cable | **Three Core Cable** | **Three-Phase Concentric Cable**

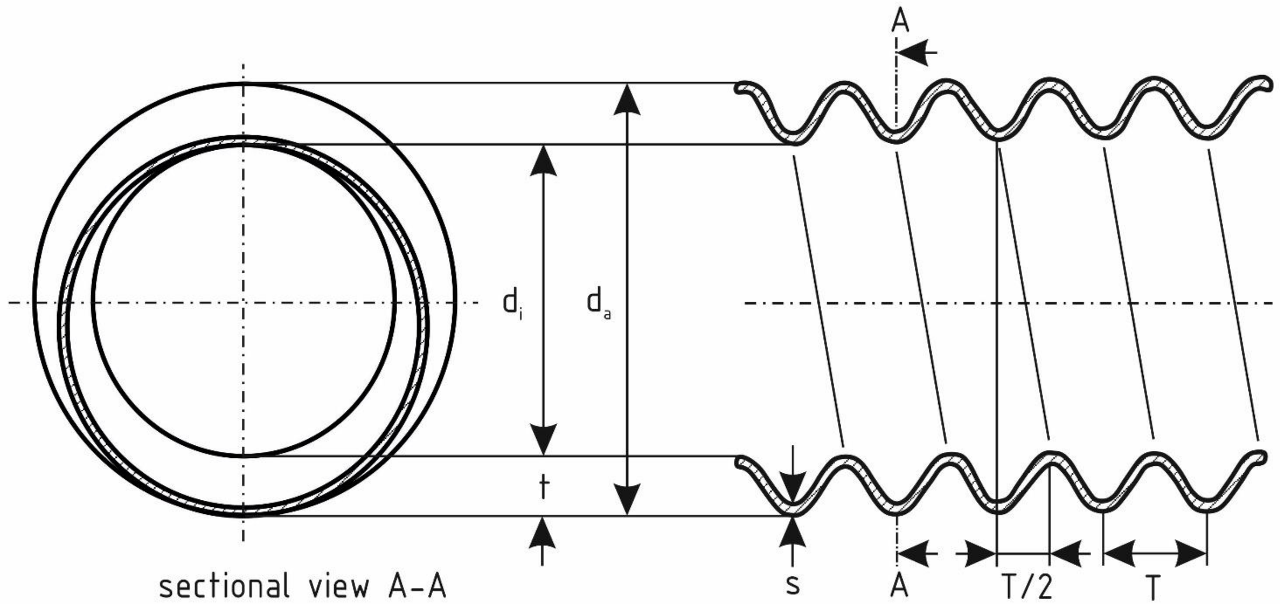


	Three single phases	Three phase in one cryostat	Three phase concentric
Voltage level	High voltage > 110 kV	30-110 kV	10-50 kV
Amount of superconductor	higher	higher	smaller
Cryostat loss	higher	smaller	smaller

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 continous load
Max. Outer Diameter	105 mm
Length	2.6 km

Typical data for urban area power system in Germany.

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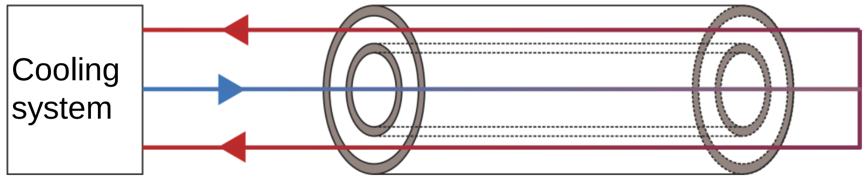
Next steps

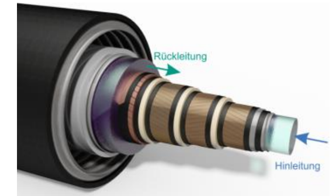
- Start with diameter of LN_2 inner tube.
- Put enough HTS tapes to carry the current.
- Calculate max. electrical field.
- Calculate the AC losses and cryogenic losses.

Cooling Options

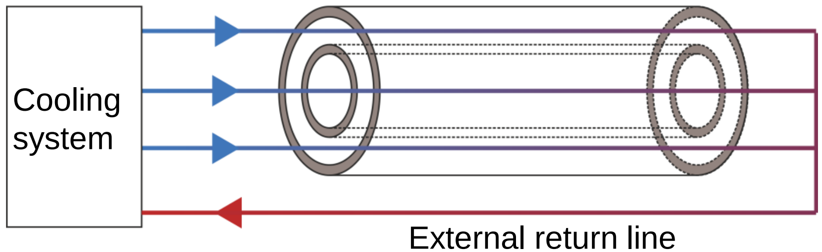
Blue	Cold 68 K	▶	LN_2 in (<15 bar)
Red	Warm < 78 K	◀	LN_2 return (>3 bar)

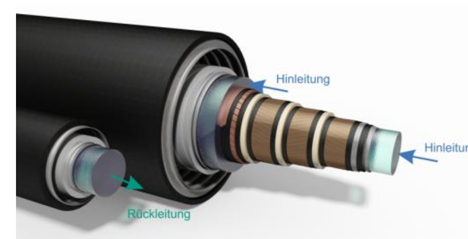
Option 1:
+ no external feedback line



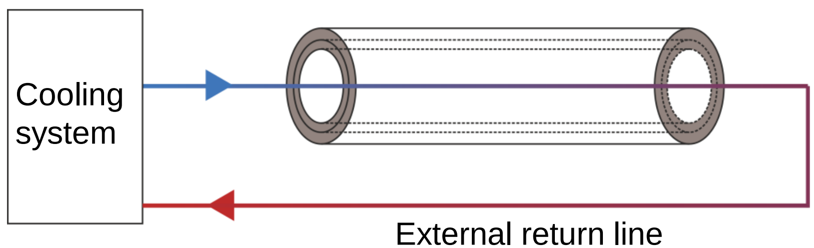


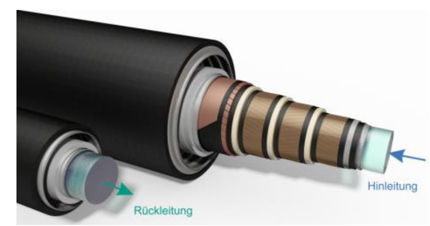
Option 2:
+ longer cable length





Option 3:
+ smallest cable diameter





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

Cable Loss Option 3 (inner LN_2 diameter 25 mm)

Loss component	Loss $0,1 \cdot I_N$	Loss $0,5 \cdot I_N$	Loss $1 \cdot I_N$
Cooling Power	**9037 W**	**9061 W**	**9379 W**
AC Loss	0,0 W	12 W	290 W
Cryostat[1)]	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.

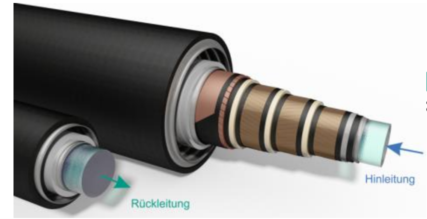
Loss Energy per Year* Option 3 (inner LN_2 diameter 25mm)

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



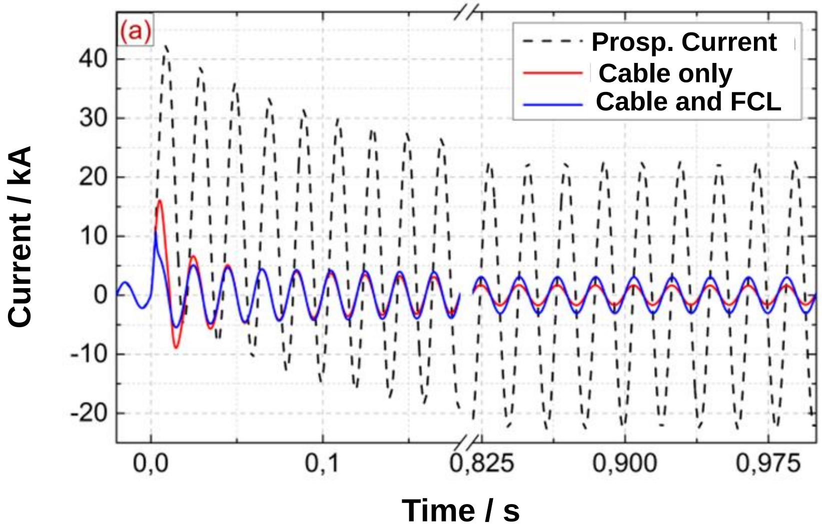
		Radius inner LN_2 tube			
Radius inner cryostat	Mass flow	20 mm	25 mm	32 mm	40 mm
65 mm	$\dot{M} = 0{,}25\ \mathrm{kg/s}$	X	X	X	X
	$\dot{M} = 0{,}5\ \mathrm{kg/s}$	X	3420 m	X	X
	$\dot{M} = 0{,}75\ \mathrm{kg/s}$	X	X	X	X
	$\dot{M} = 1\ \mathrm{kg/s}$	X	X	X	X
80 mm	$\dot{M} = 0{,}25\ \mathrm{kg/s}$	X	X	X	X
	$\dot{M} = 0{,}5\ \mathrm{kg/s}$	X	3920 m	4210 m	X
	$\dot{M} = 0{,}75\ \mathrm{kg/s}$	X	X	6210 m	X
	$\dot{M} = 1\ \mathrm{kg/s}$	X	X	X	X

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

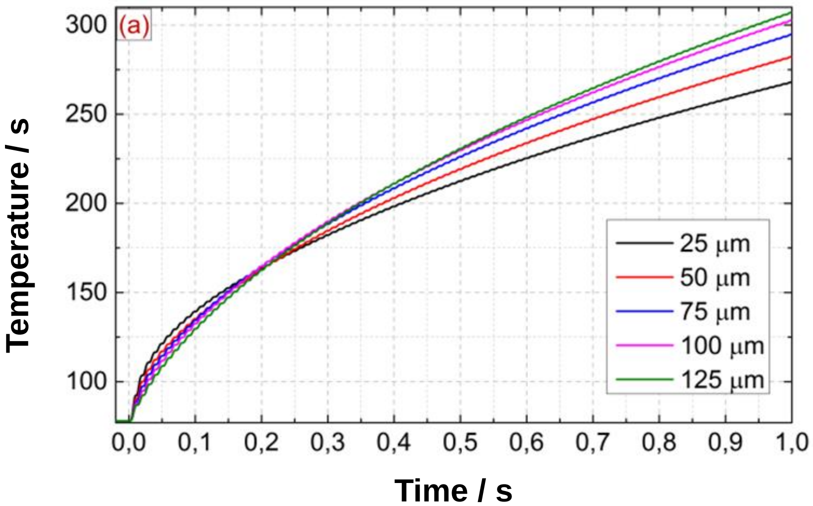
With an inner LN_2 tube of 25 mm and an inner cryostat tube of 65 mm all requirements are fullfilled.

Short-Circuit Behaviour (20 kA, 1 s)

Short-circuit Current (Cu=25 µm)



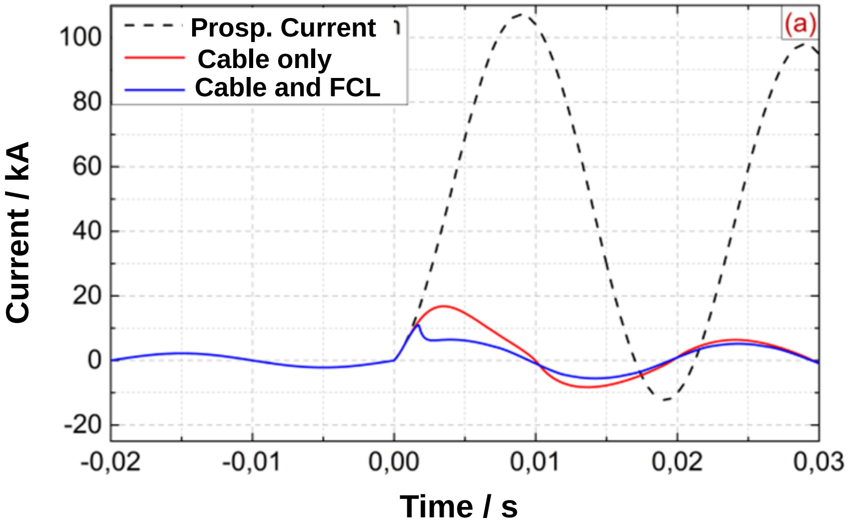
HTS Temperature Increase



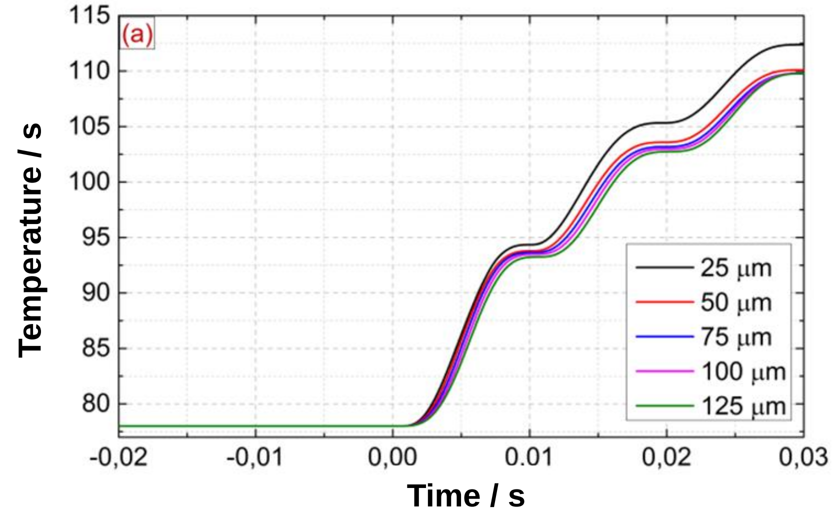
In case the temperature would be to high an SFCL can be considered.

Short-Circuit Behaviour (50 kA, 30 ms)

Short-circuit Current (Cu=25 µm)

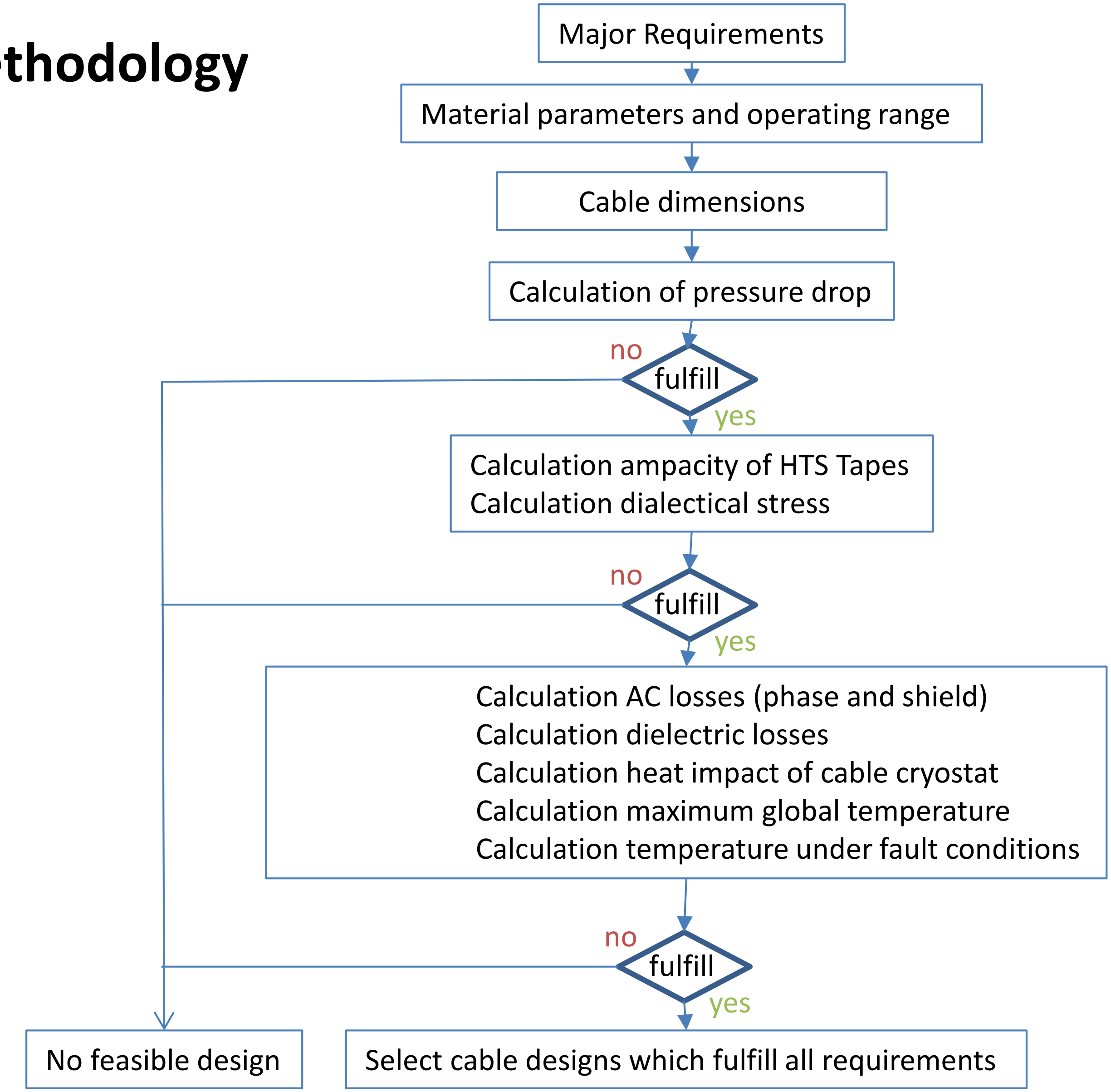


HTS Temperature Increase



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 continous load
Max. Outer Diameter	105 mm
Length	2.6 km

Main data	
Capacitance	1.47 µF/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

Table of Content

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.