Cooling Requirements of Superconducting Power Cables

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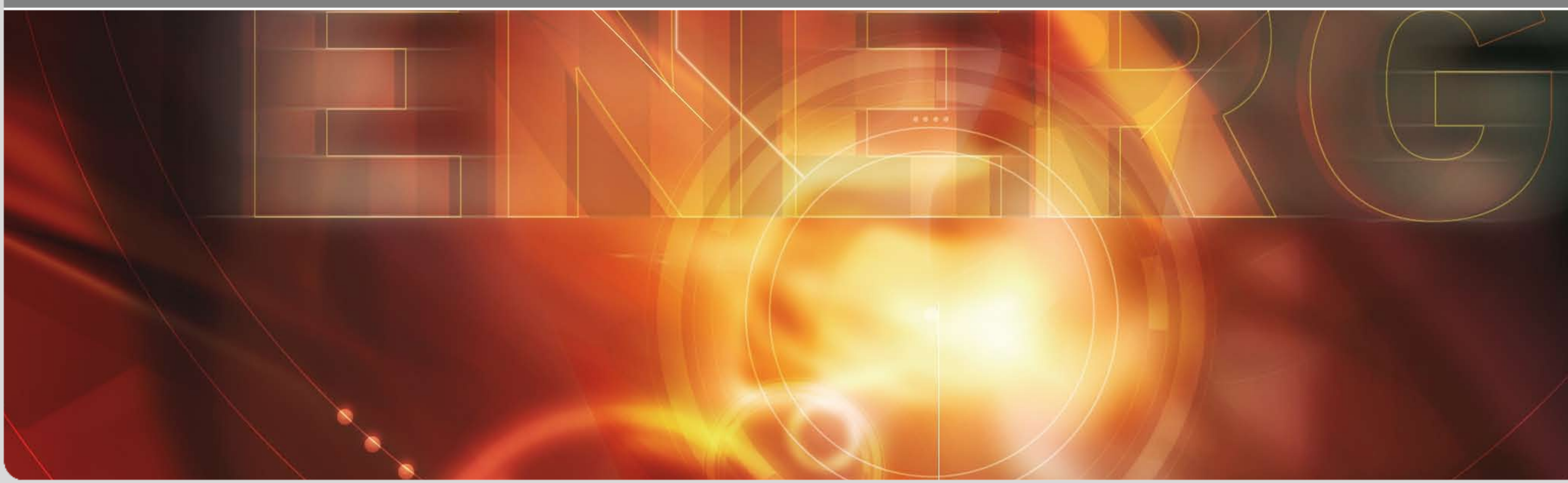

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  - Medium Voltage Cable
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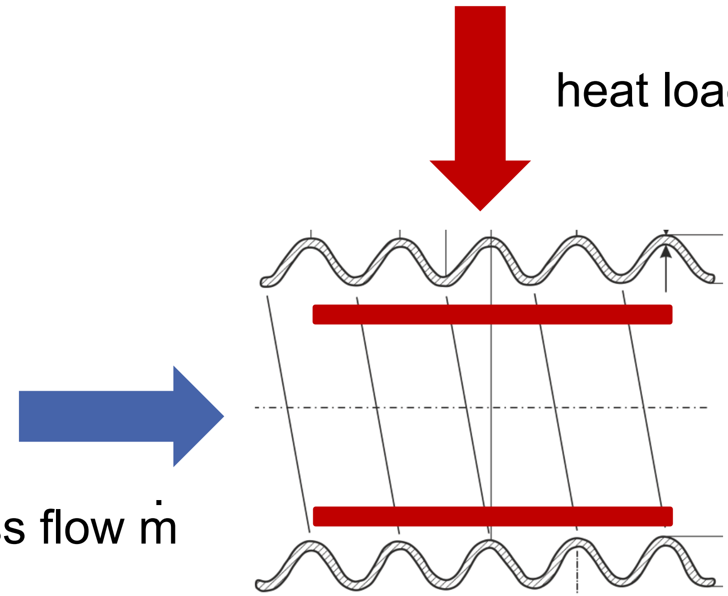
- Summary

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

See Friday: E. Shabagin et.al. Calculation of temperature profiles and pressure drop in concentric three-phase HTS power cables

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

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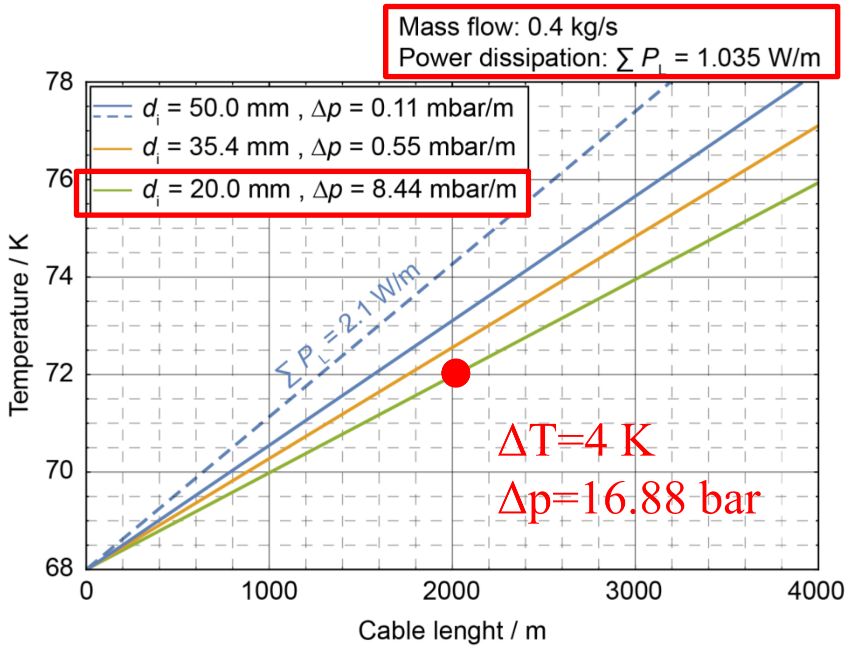

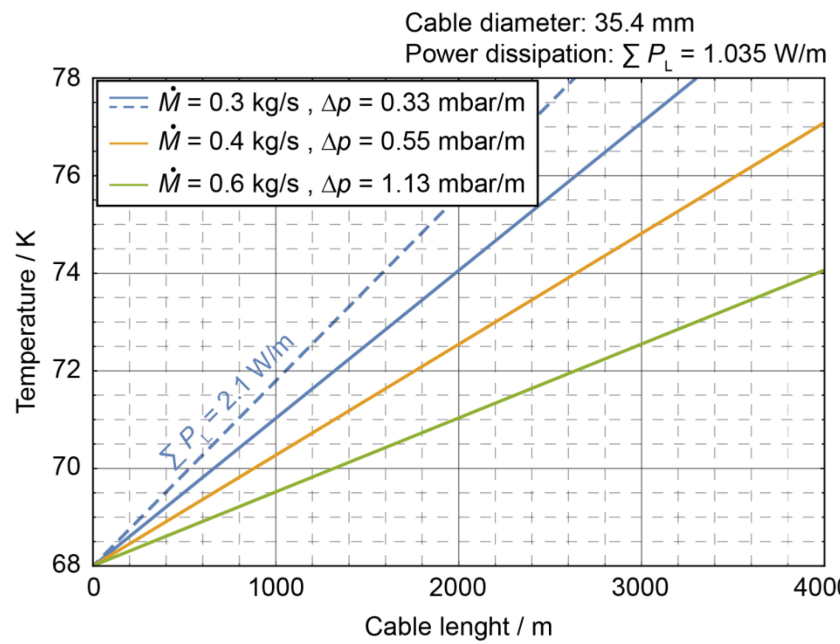

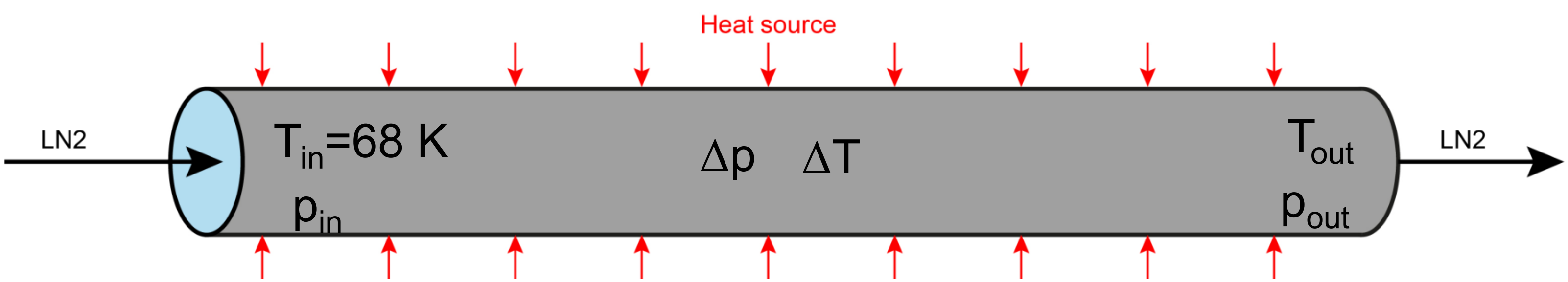

Introduction

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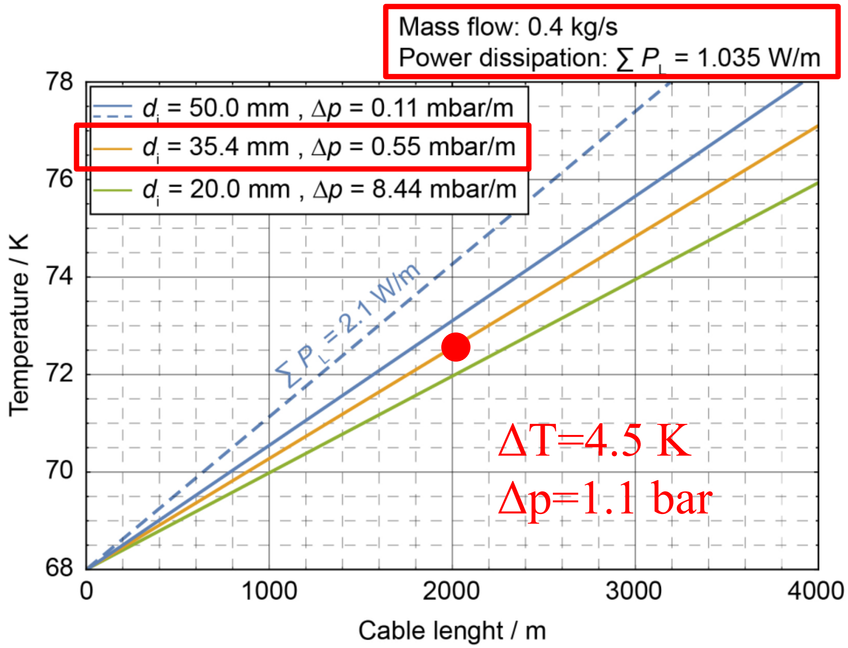

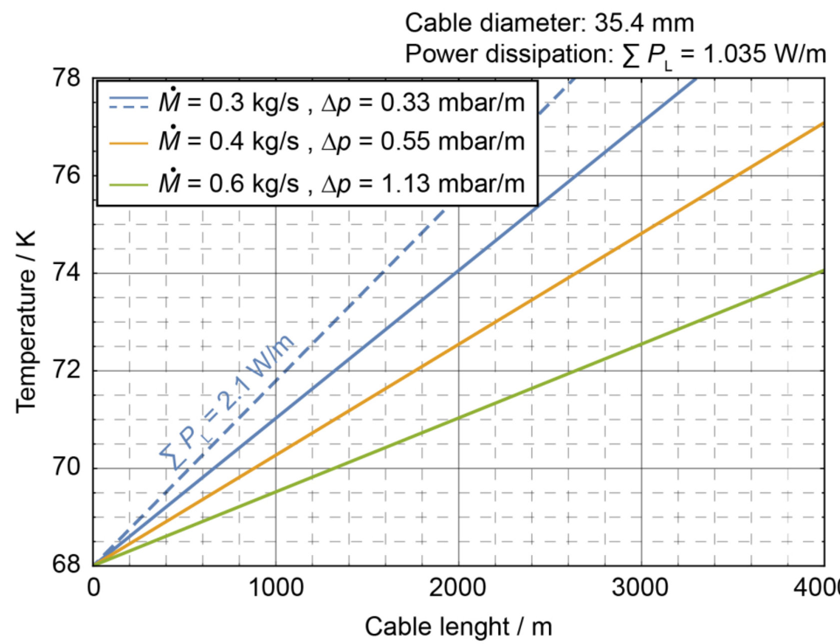

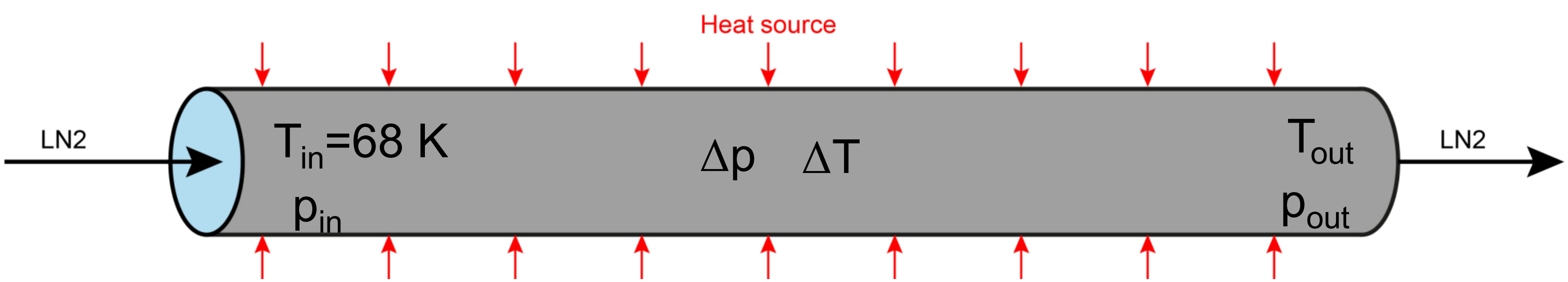

Major Requirements

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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

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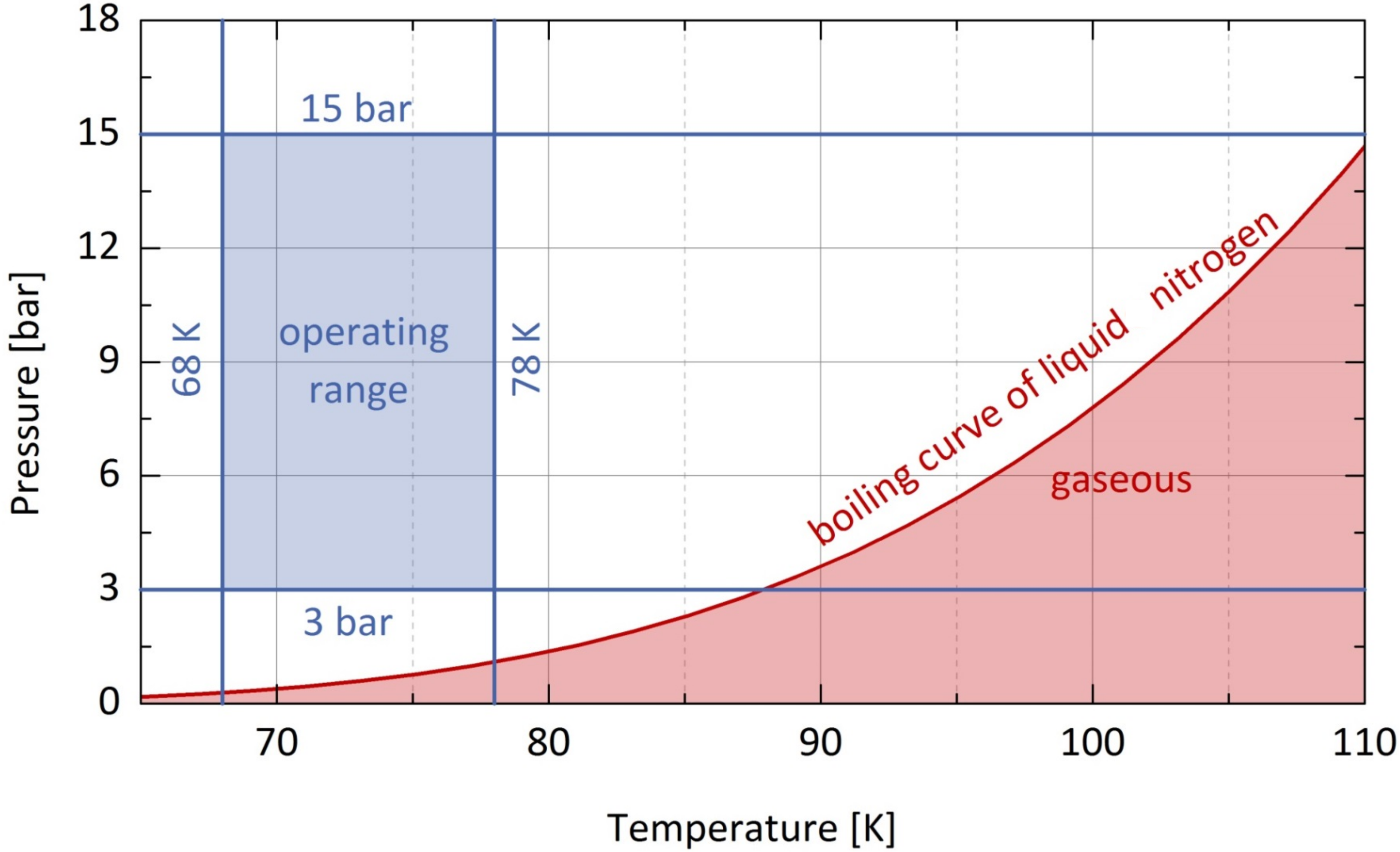
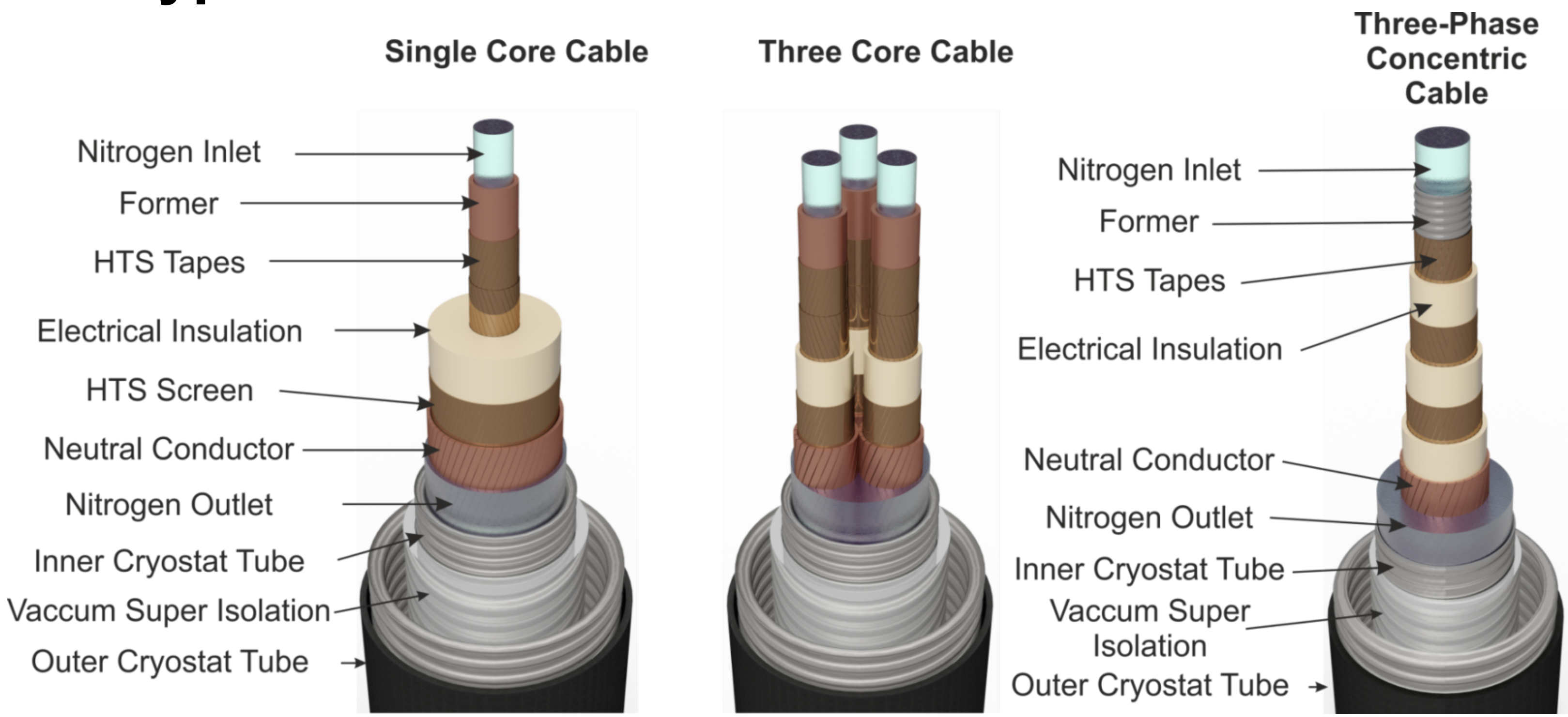


Define operating range for pressure and temperature.

Cable Types

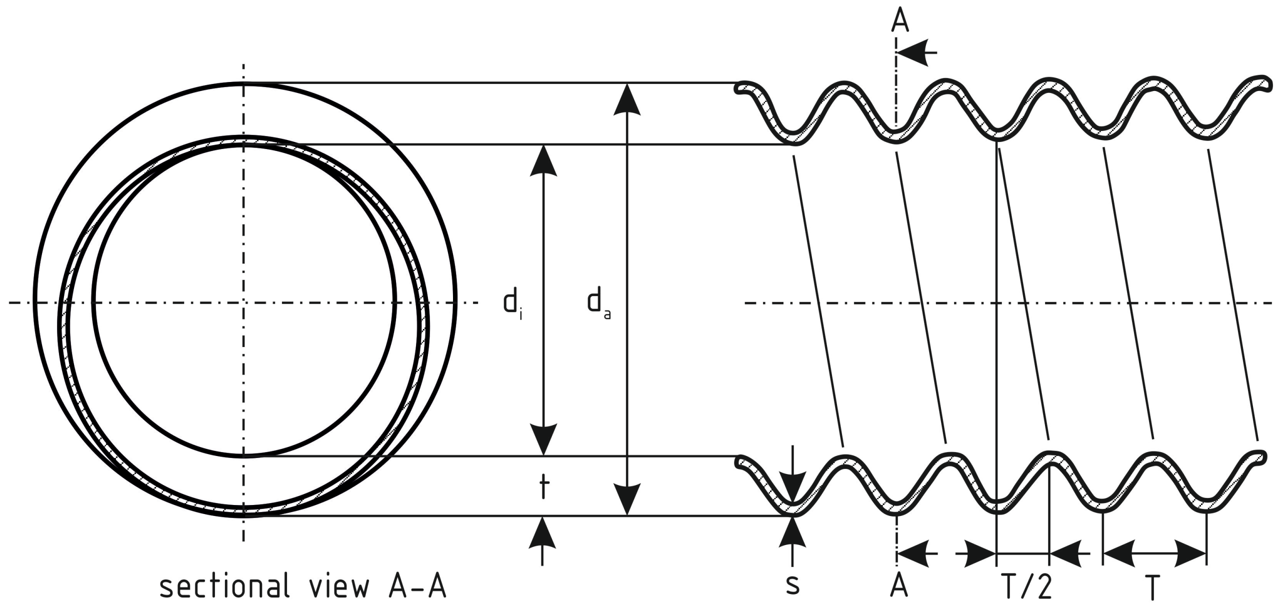


	Three single phases	Three phase in one cryostat	Three phase concentric
Voltage level	High voltage > 110 kV	30-110 kV	10-50 kV
Amount of superconductor	higher	higher	smaller
Cryostat loss	higher	smaller	smaller

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.

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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.

Next steps

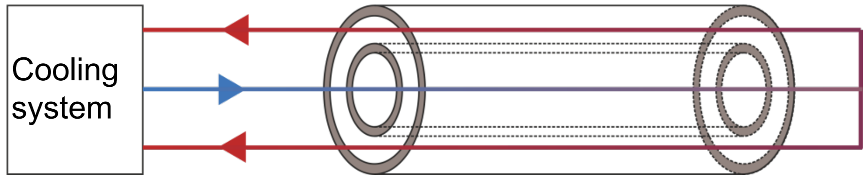
- Start with diameter of LN_2 inner tube.
- Put enough HTS tapes to carry the current.
- Calculate max. electrical field.
- Calculate the AC losses and cryogenic losses.

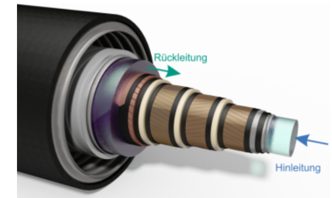
Cooling Options

Cold 68 K | ▶ LN_2 in (<15 bar)

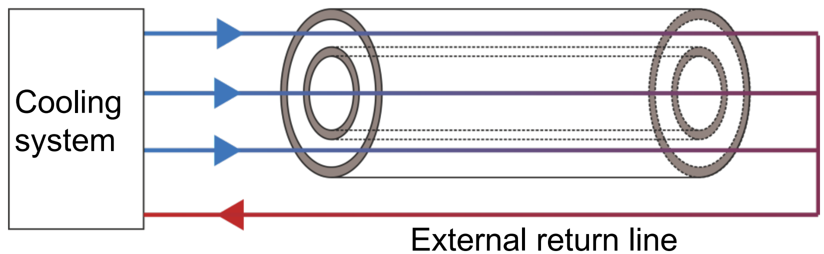
Warm < 78 K | ◀ LN_2 return (>3 bar)

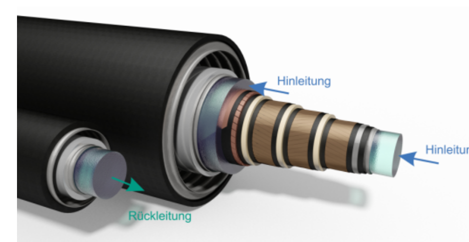
Option 1:
+ no external feedback line



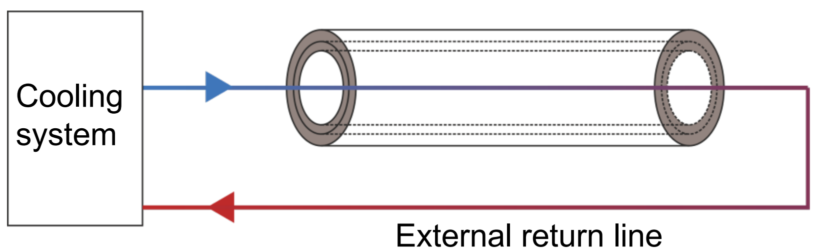


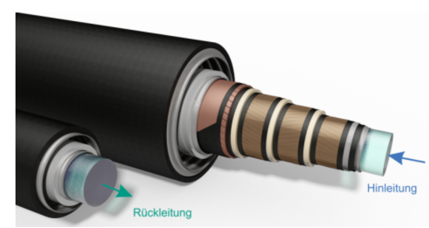
Option 2:
+ longer cable length



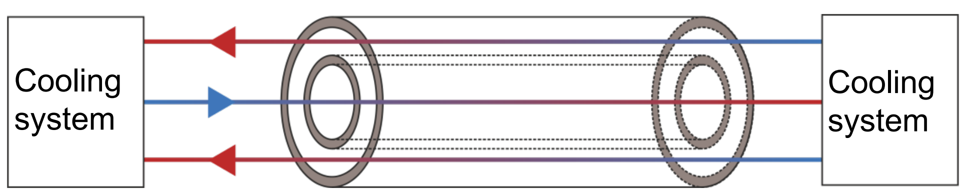


Option 3:
+ smallest cable diameter





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.

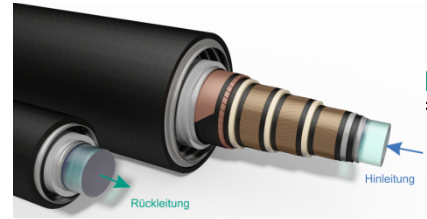
Loss Energy per Year* Option 3 (inner LN_2 diameter 25mm)

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



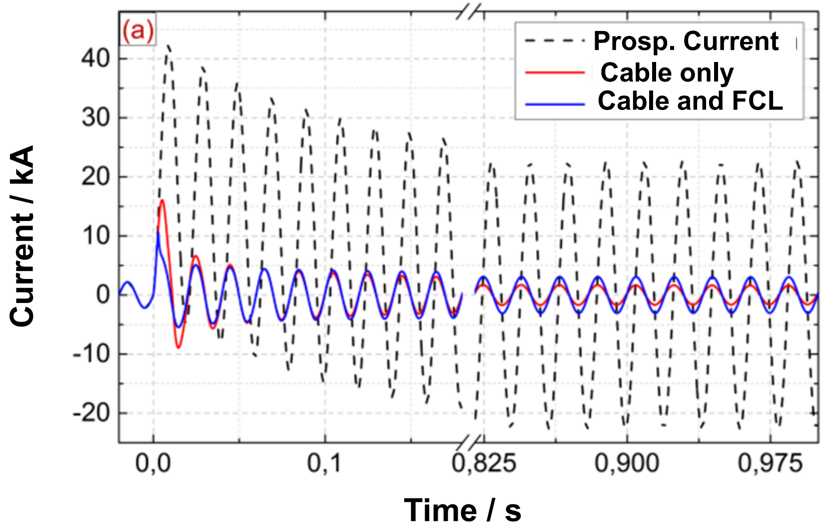
		Radius inner LN_2 tube			
Radius inner cryostat	Mass flow	20 mm	25 mm	32 mm	40 mm
65 mm	$\dot{M} = 0{,}25$ kg/s	X	X	X	X
	$\dot{M} = 0{,}5$ kg/s	X	3420 m	X	X
	$\dot{M} = 0{,}75$ kg/s	X	X	X	X
	$\dot{M} = 1$ kg/s	X	X	X	X
80 mm	$\dot{M} = 0{,}25$ kg/s	X	X	X	X
	$\dot{M} = 0{,}5$ kg/s	X	3920 m	4210 m	X
	$\dot{M}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

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

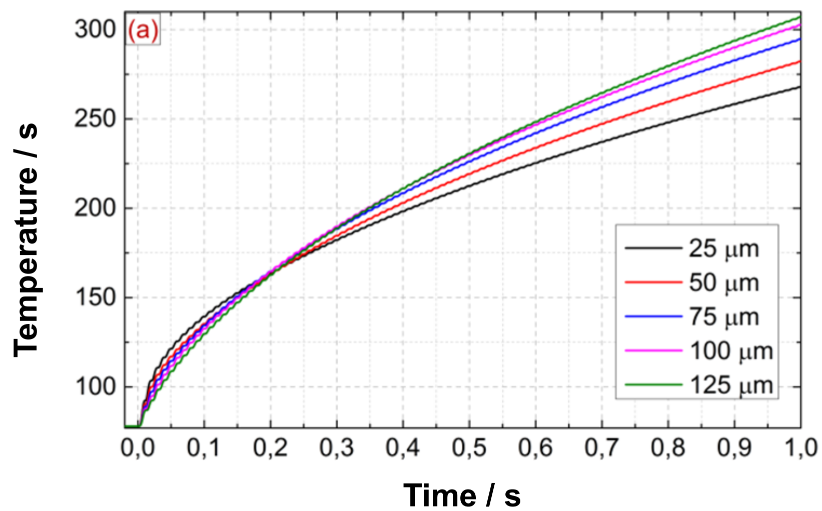
With an inner LN_2 tube of 25 mm and an inner cryostat tube of 65 mm all requirements are fullfilled.

Short-Circuit Behaviour (20 kA, 1 s)

Short-circuit Current (Cu=25 μm)



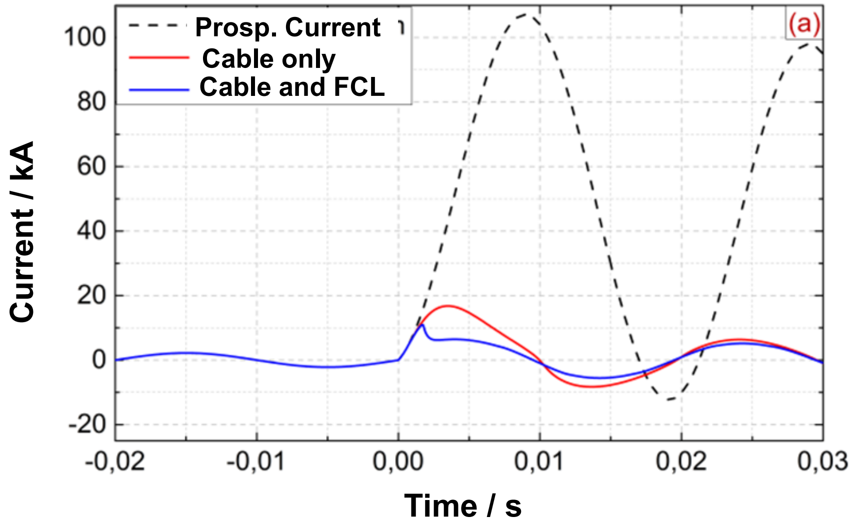
HTS Temperature Increase



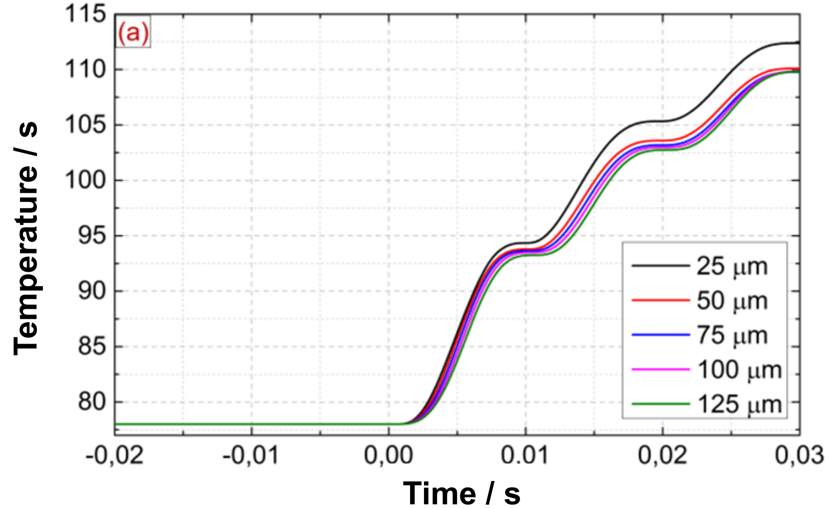
In case the temperature would be to high an SFCL can be considered.

Short-Circuit Behaviour (50 kA, 30 ms)

Short-circuit Current (Cu=25 μm)

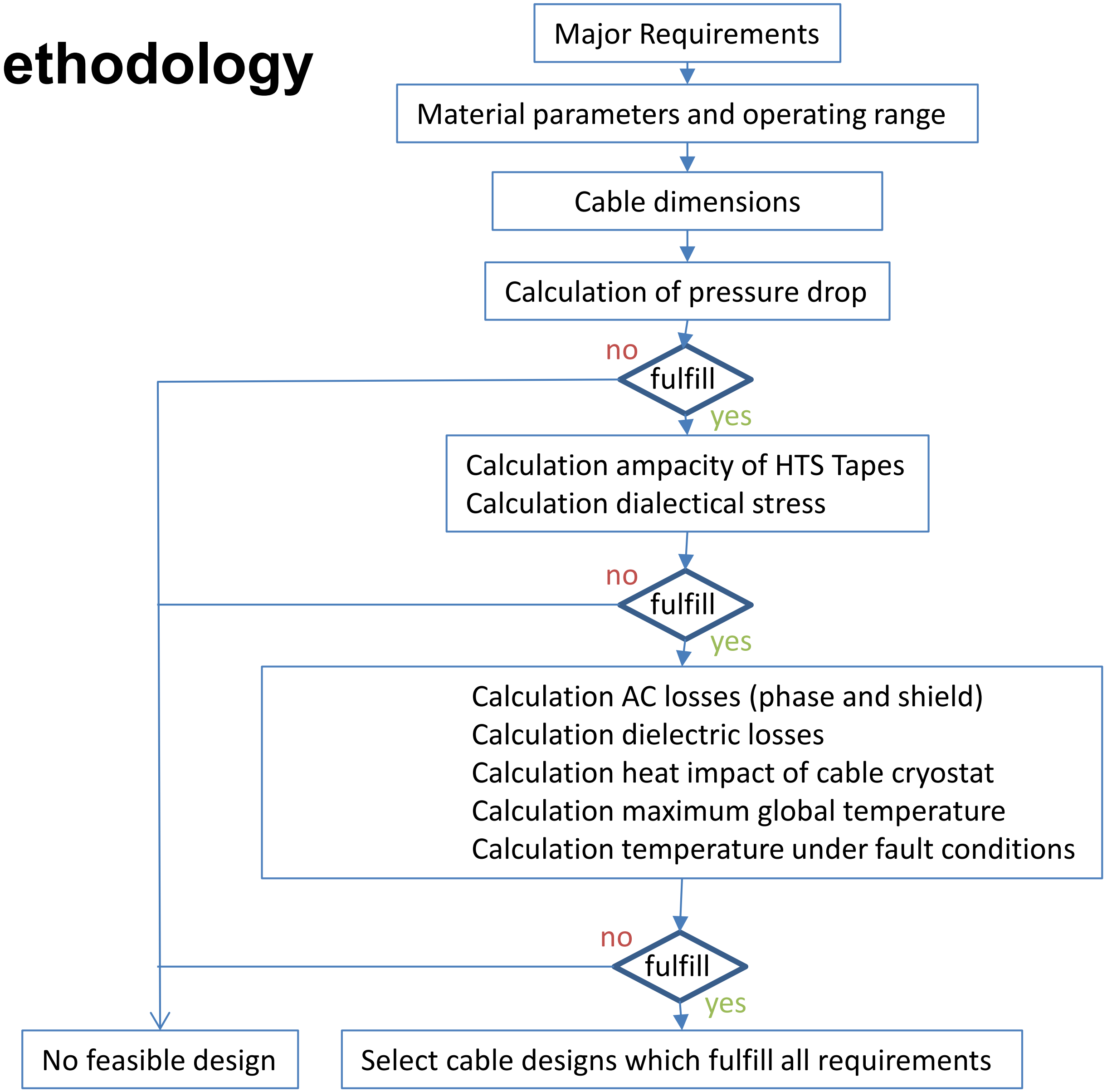


HTS Temperature Increase



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

Design Methodology



Design Summary

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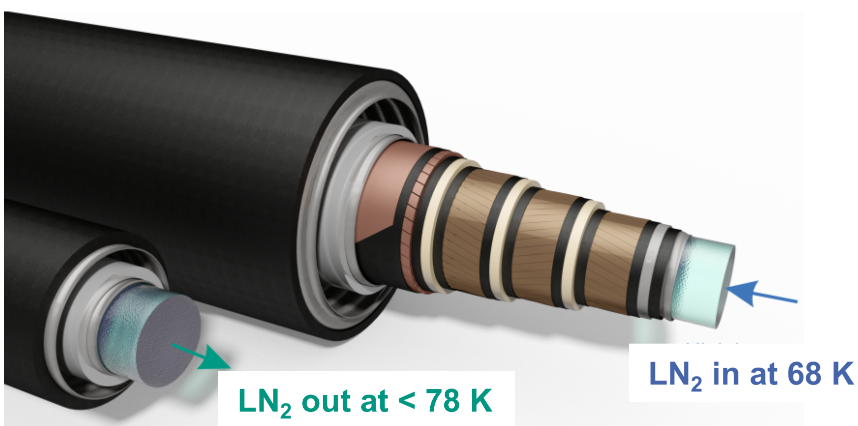
Utility Load Factor	0.7 continous load
Max. Outer Diameter	105 mm
Length	2.6 km

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



Motivation of Superconducting High Voltage Cables

We have to built several 1000 km of new high voltage transmission lines in Germany due to the Energy Transition and some parts need an underground cable.

Design Example – High Voltage Cable

Rated Voltage	380 kV
Rated Power	3600 A
Overcurrents	Not yet defined
Utility Load Factor	0.7
Max. Outer Diameter	< 200 mm
Length	5 km

Typical data for German High Voltage System

380 kV 2 three phase cable systems in Raesfeld
Picture: Amprion

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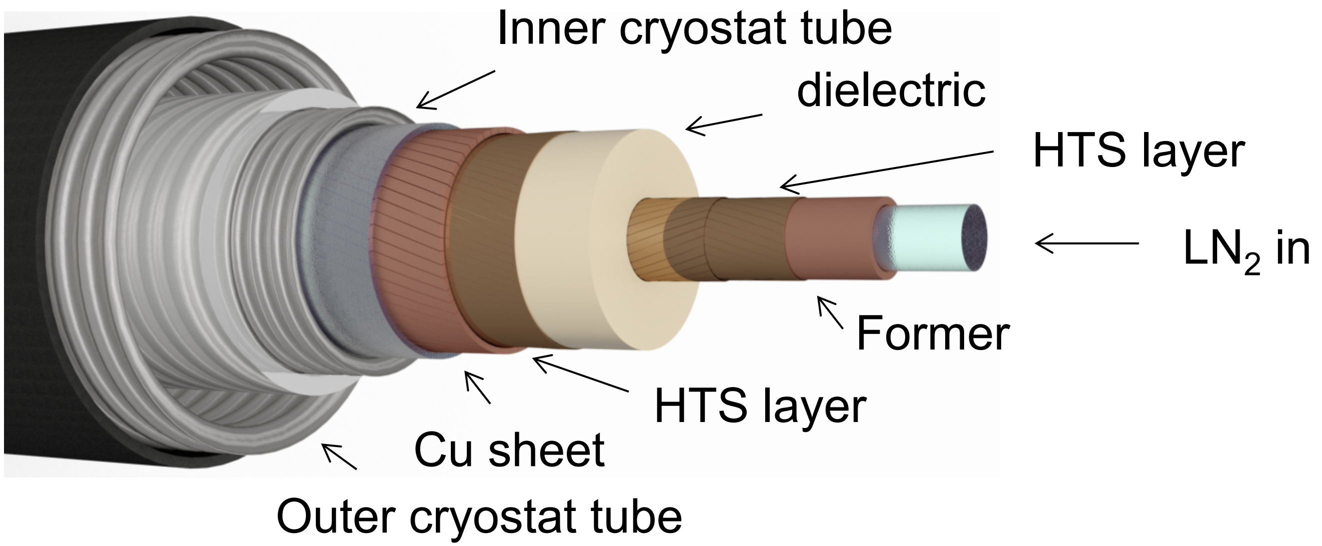
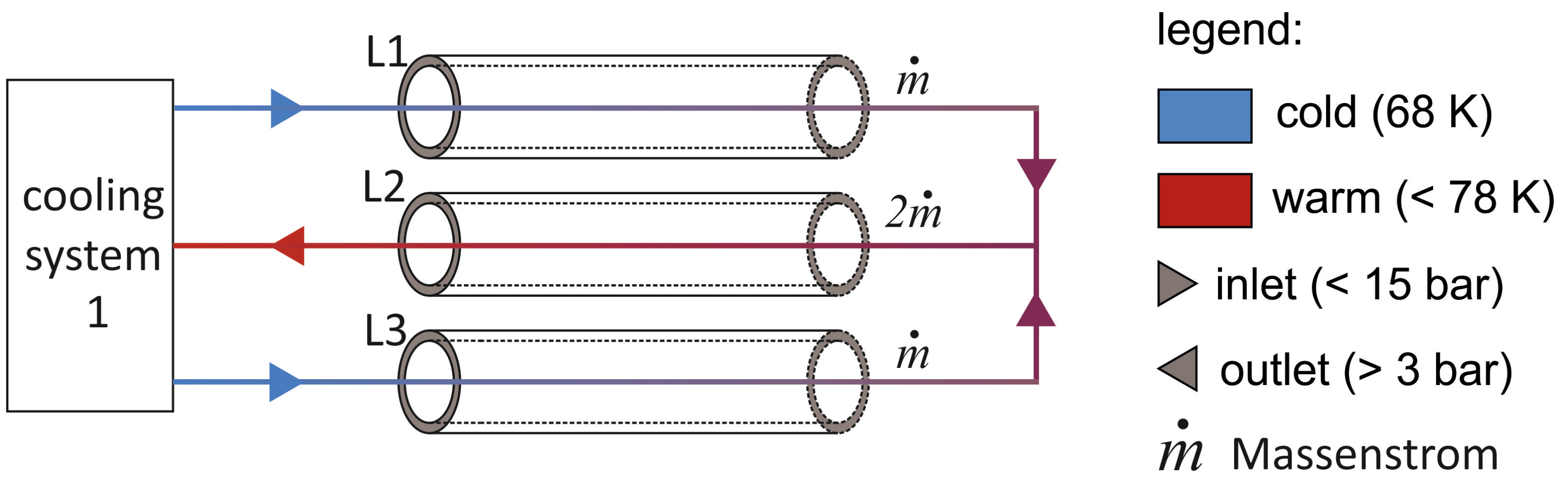
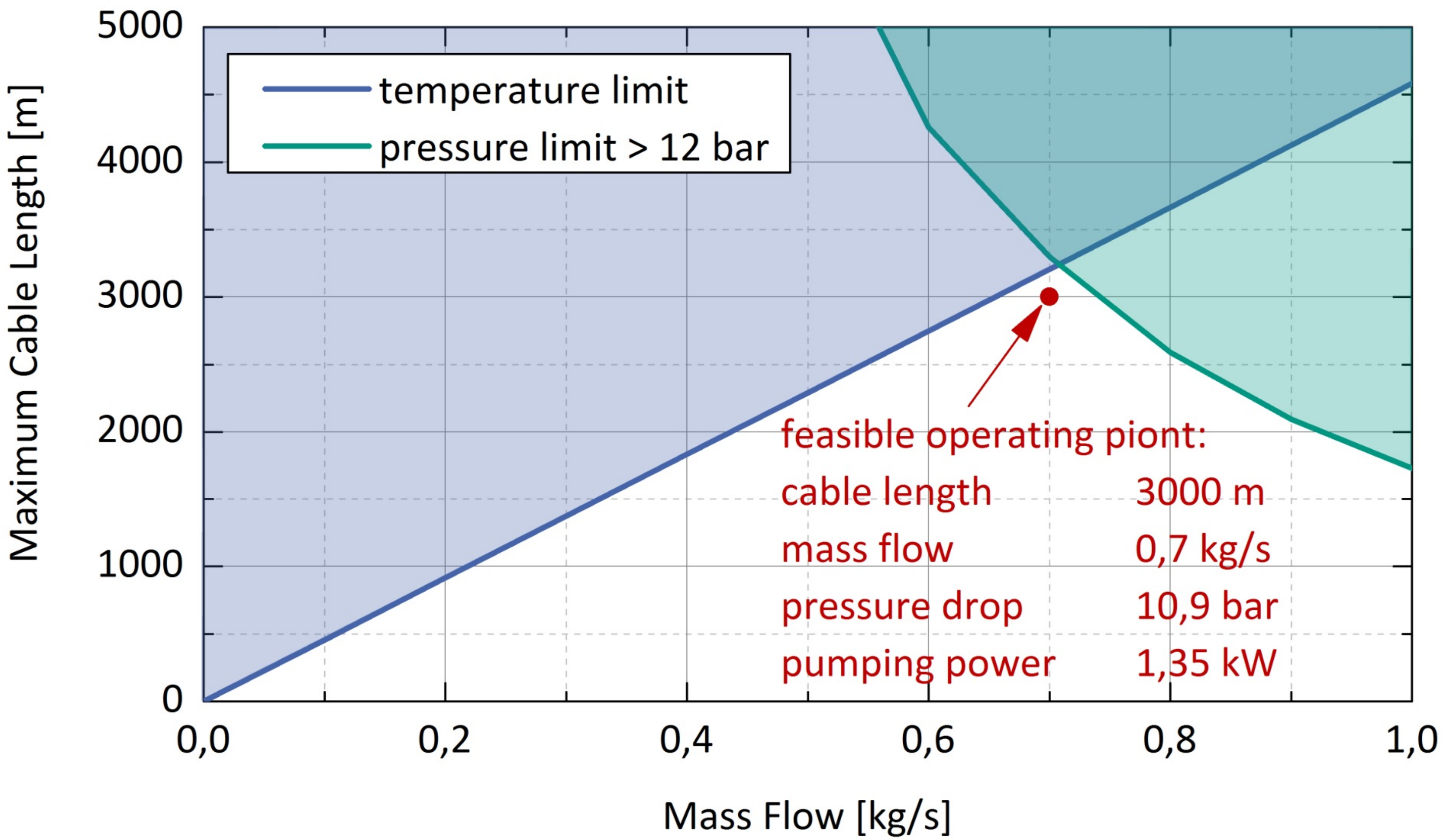


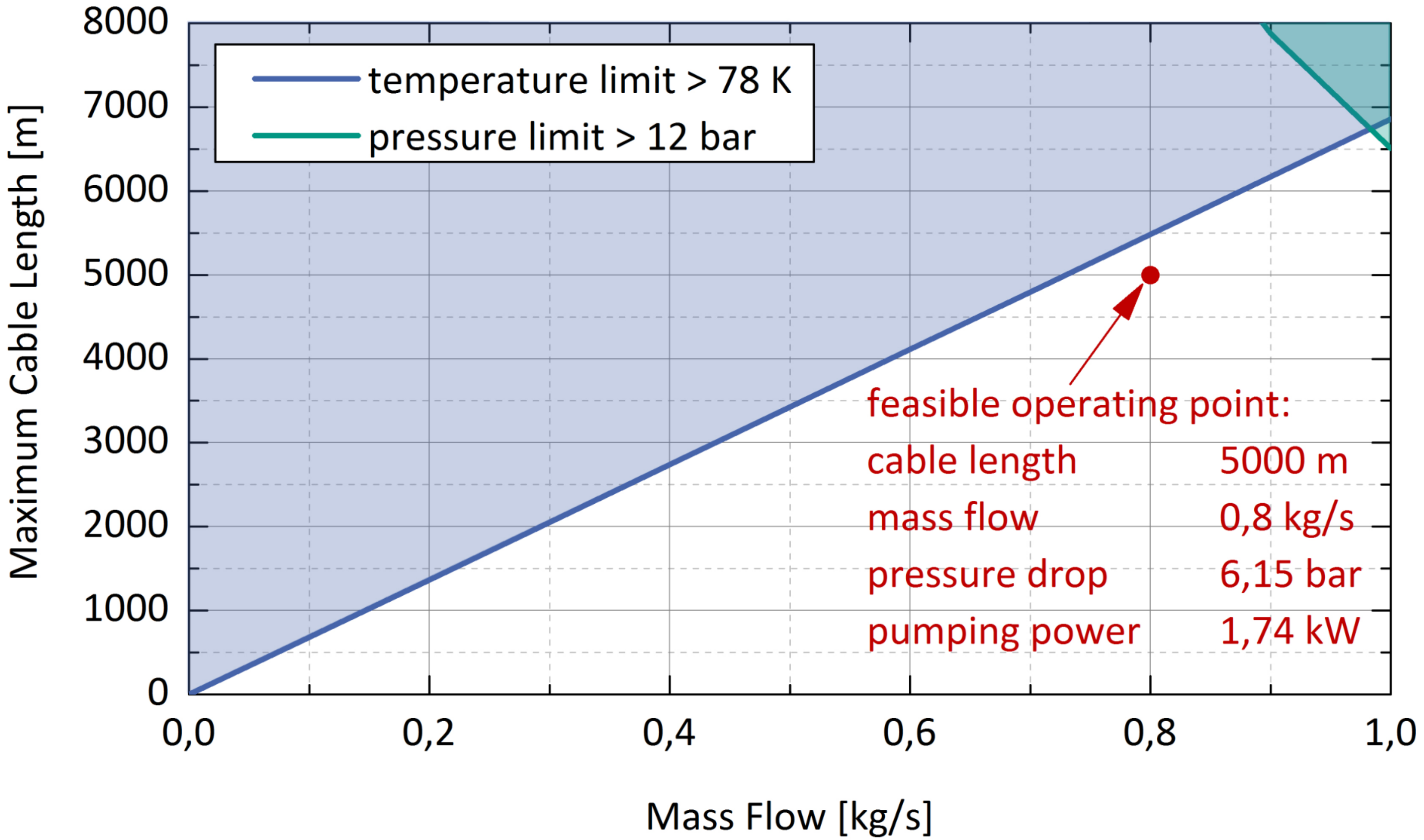
Cooling System



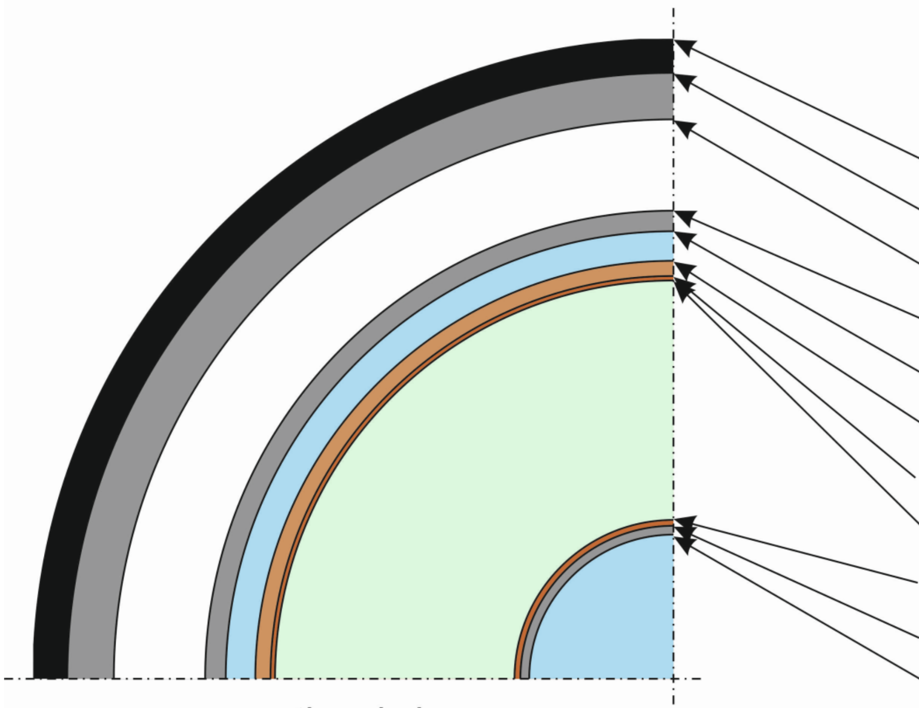
Temperature and Pressure Limits (I.D. 40 mm)



Temperature and Pressure Limits (I.D. 50 mm)



Cable Design 380 kV, 3600 A



sectional view

layer	symbol	diameter in mm former nominal diameter - DN 50
sheath (OD)	$d_{M,a}$	172,0
sheath (ID)	$d_{M,i}$	162,0
outer cryostat tube (ID)	$d_{AK,i}$	150,0
inner cryostat tube (OD)	$d_{IK,a}$	130,2
inner cryostat tube (ID)	$d_{IK,i}$	125,0
neutral conductor (OD)	$d_{NL,a}$	106,0
shield (OD)	$d_{SS,a}$	102,0
electrical insulation (OD)	$d_{ISO,a}$	101,6
HTS conductor (OD)	$d_{BLS,a}$	53,6
former (OD)	$d_{IR,a}$	52,8
former (ID)	$d_{IR,i}$	50,0

Conventional 380 kV cable in ground has similar diameter and current of 1.1-1.5 kA.

Summary

- We have developed and validated a tool to calculate pressure drop and temperature increase in single phase and three phase coaxial superconducting cables.
- As a pre-requisite only a few input parameters from the utility are needed.
- This allows calculation of losses and maximum cable length without intermediate cooling.
- You are welcome to ask us for design studies.

Thank you very much for your attention!

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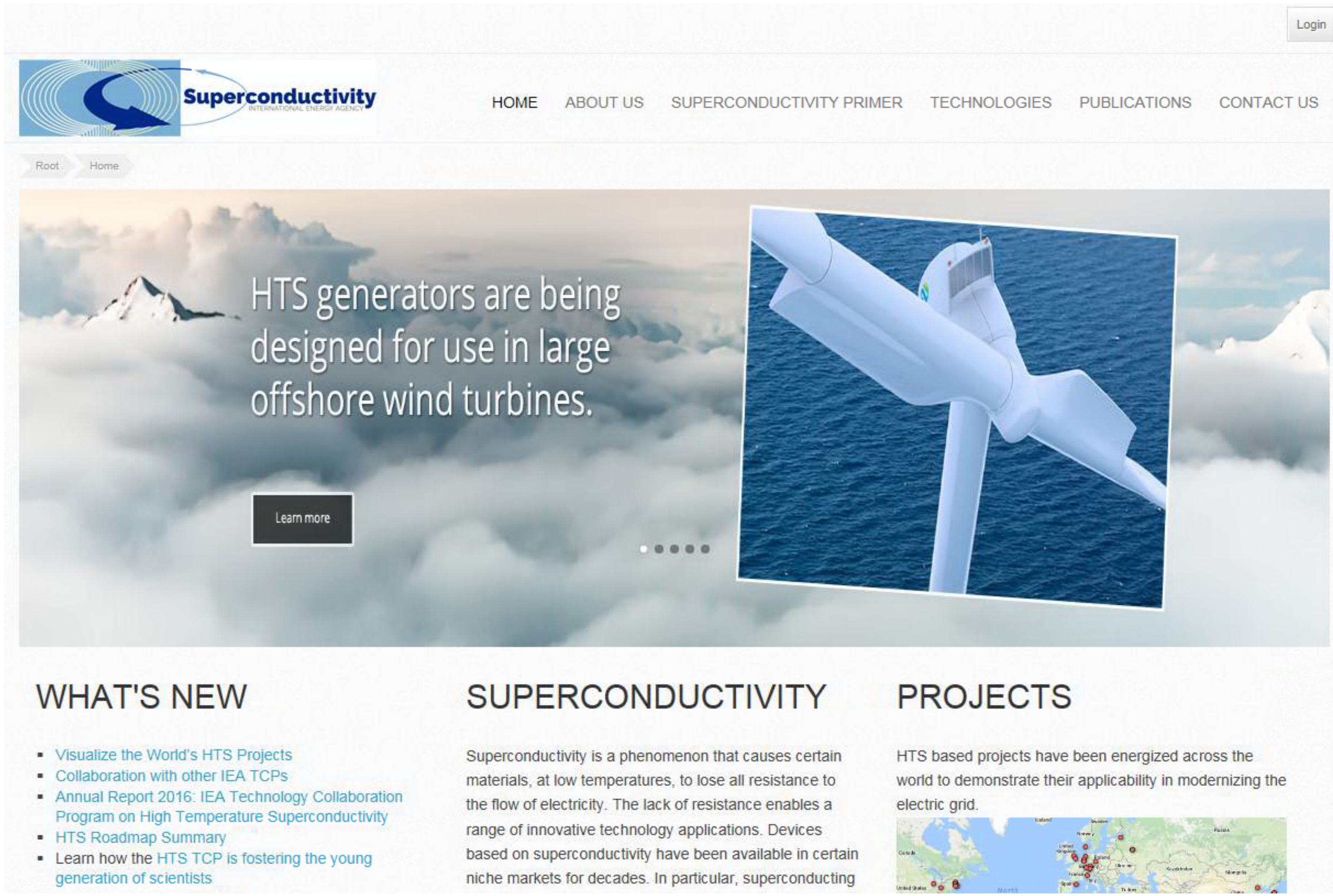

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