Superconducting Power Cables
Concepts, design, applications

Antonio Morandi

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

University of Bologna, Italy

Saturday, November 13, 2021

5a Escuela de SUPERCONDUCTIVIDAD
Desde la Ciudad de México

Outline

- Concepts and layouts
- State of the art
- Design criteria

  Electromagnetic

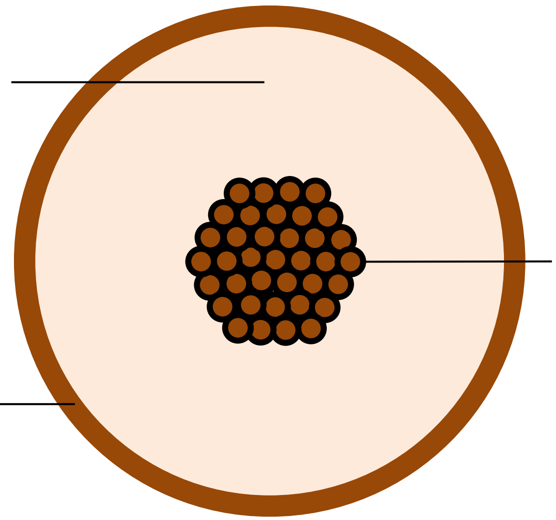
  Thermohydraulic

  Heat load and cooling
- Applications

  The ampacity project

  Customer / Industry

Layout of a conventional HV cable



A metallic shied (copper) is added to HV voltage cables in order to

- **Equalize electric field stress in the cable insulation**
- **Provide Shielding of electromagnetic field**
- **Provide return path for Cable neutral and fault current**

Transport current losses of Superconductors

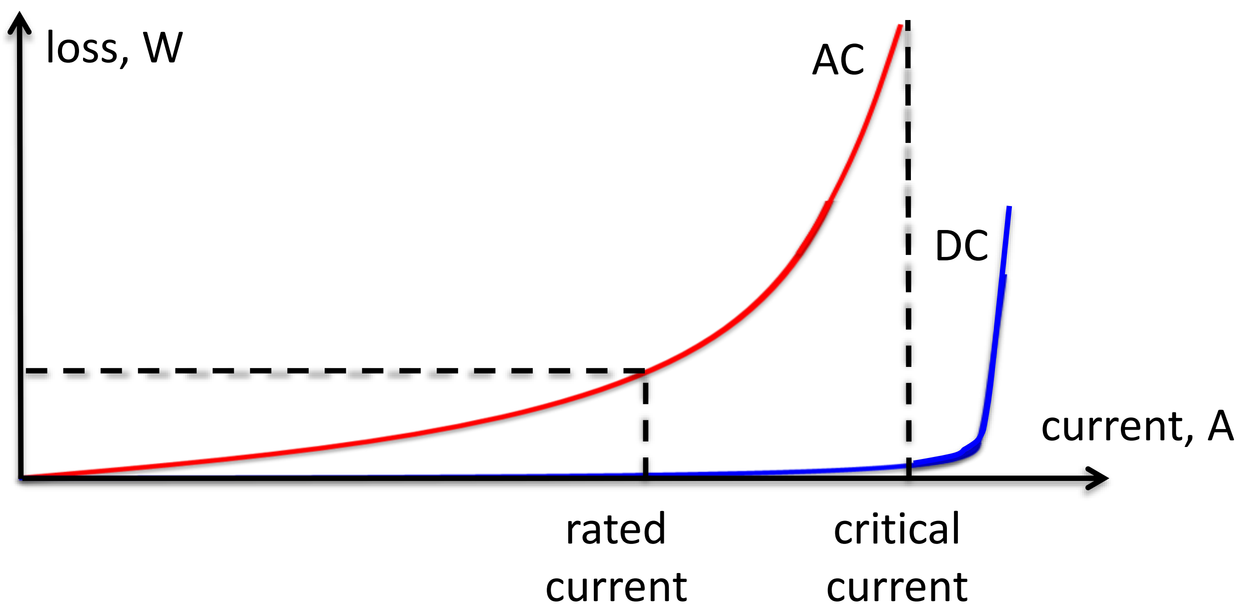
AC Transport current losses (Norris)

$$Q = \frac{{I_c}^2 \mu_0}{\pi} \times \begin{cases} (1-i)\ln(1-i) + (2-i)\frac{i}{2} & \text{ellipse} \\ (1-i)\ln(1-i) + (1+i)\ln(1+i) - i^2 & \text{strip} \end{cases}$$

$i = I_p/I_c, I_p = \text{current amplitude (peak)}$

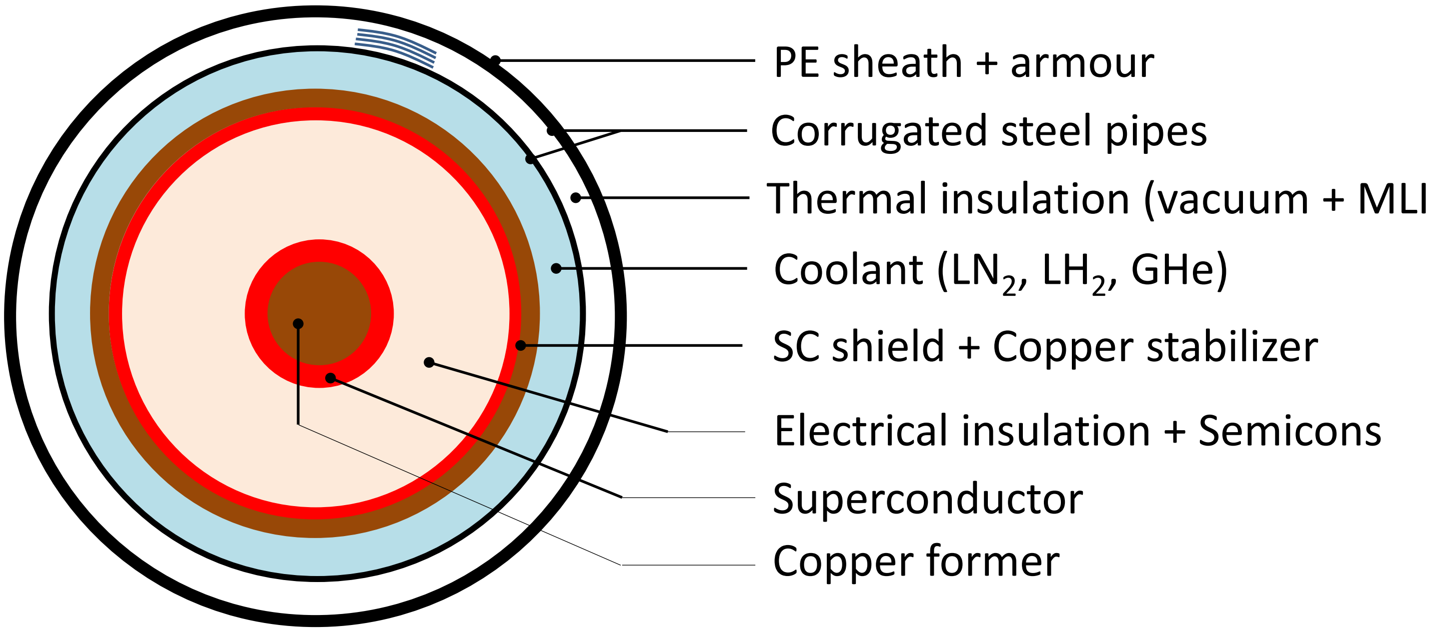
DC Transport current losses (power law)

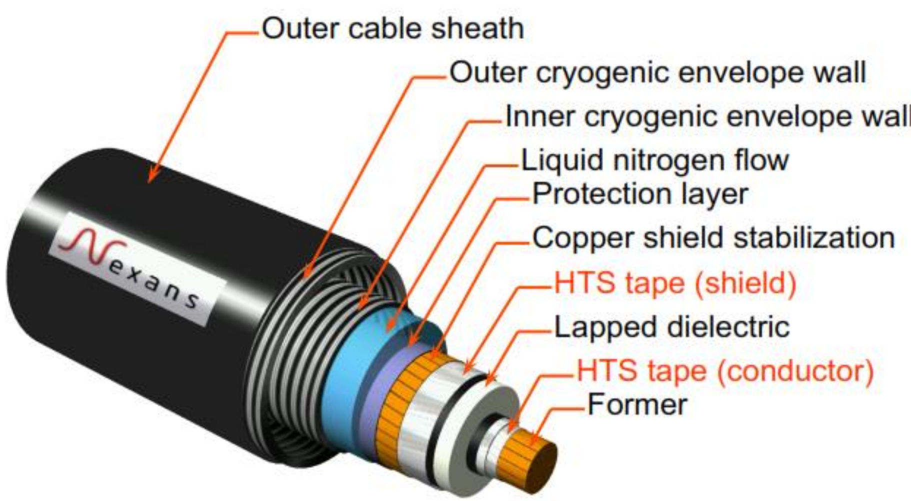
$$Q = k\left(\frac{I}{I_c}\right)^n$$



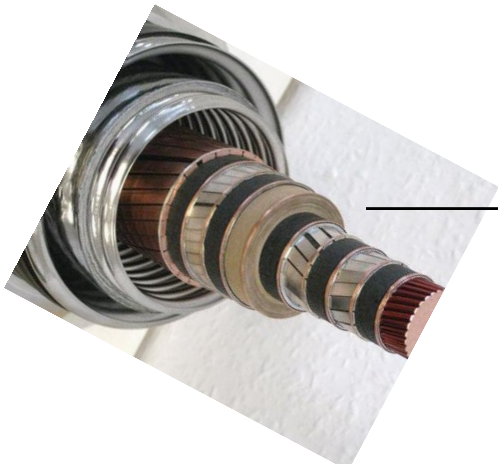
DC superconducting cables have practically no losses for operation below Ic

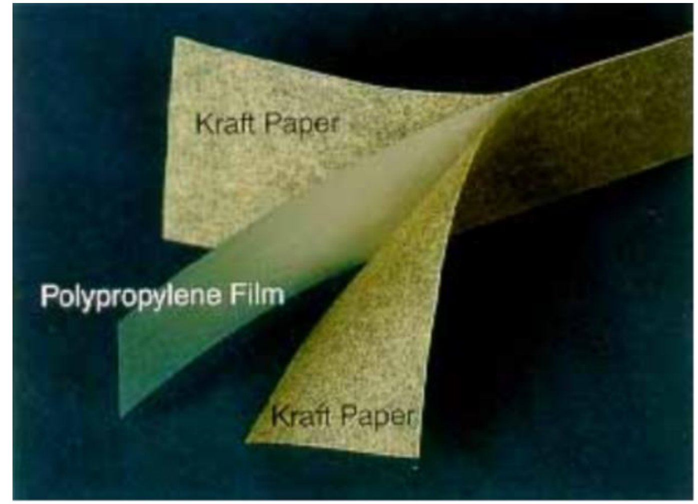
Layout of a cold dielectric SC cable





Cryogenic electrical insulation



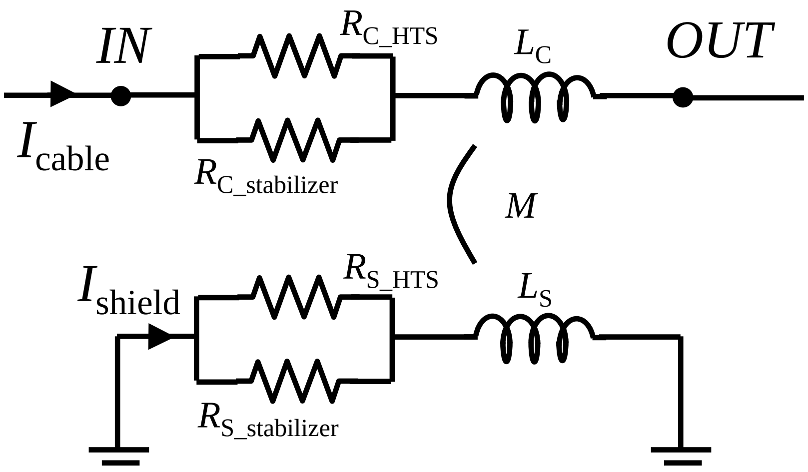


A very reliable hybrid insulation systems based on pressurized liquid nitrogen and polypropylene laminate paper (PPLP) has been successfully developed (up to 275 kV AC)

- Similar to oil impregnated paper insulation system used for conventional high voltage power cable
- Air/moisture bubbles creates breakdown of insulation. High pressure operation of LN2 is required for avoiding bubbles.

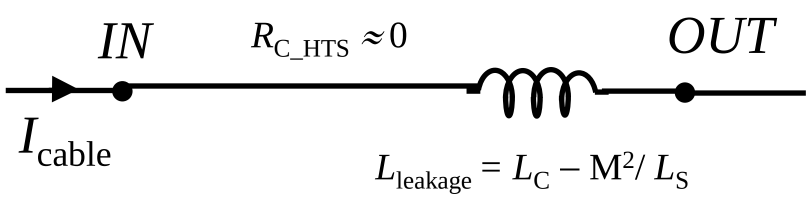
Function of the shield of a cold dielectric HTS cable

The SC shield is periodically grounded along the cable. The two circuits are magnetically coupled.



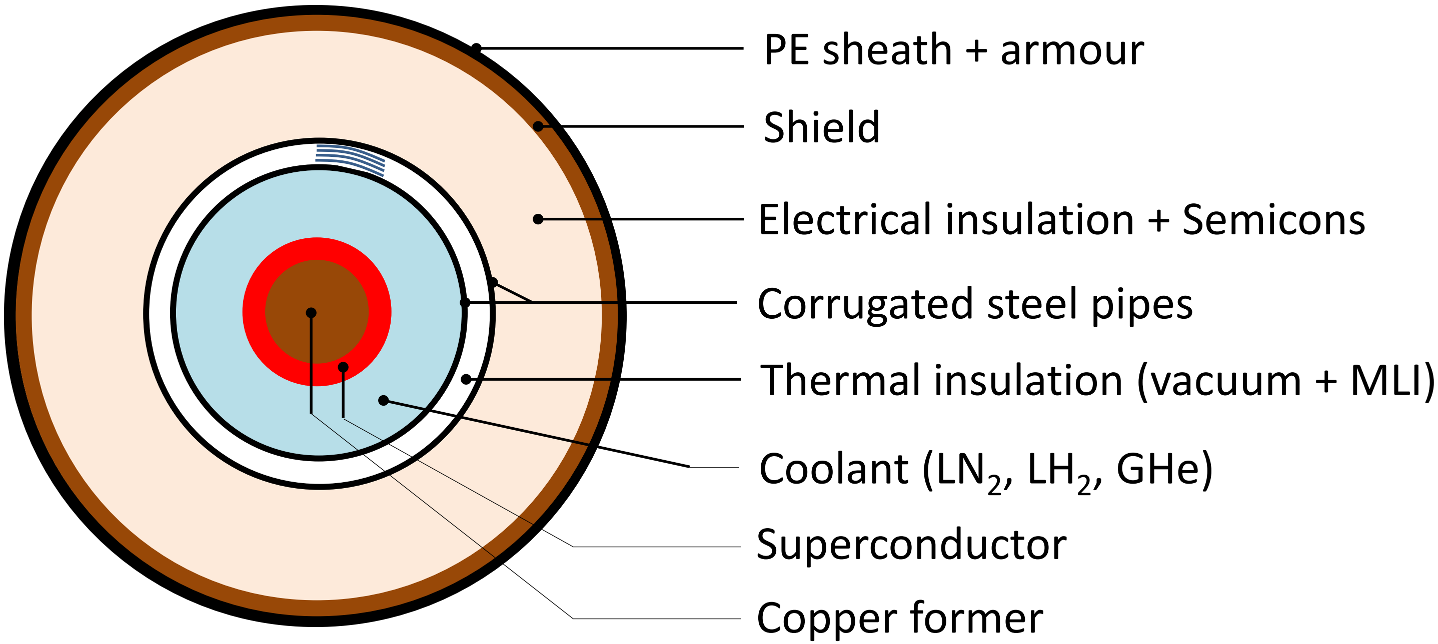
- **Currents are induced in the lossless SC shield preventing induced currents on the pipes in AC operation, thus reducing the total heat load of the cable**
- **A current in the same order of the transport current of the cable circulates in the shield**

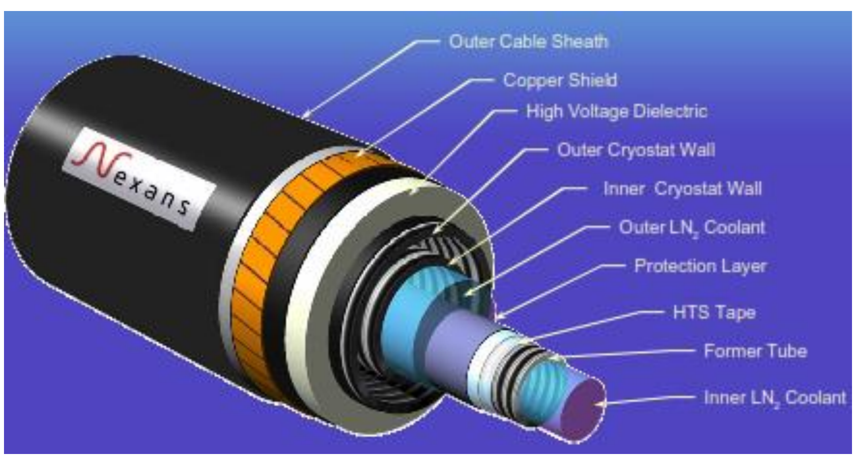
Equivalent circuit at the cable's terminals



- **A very low service inductance is obtained thanks to the shield**

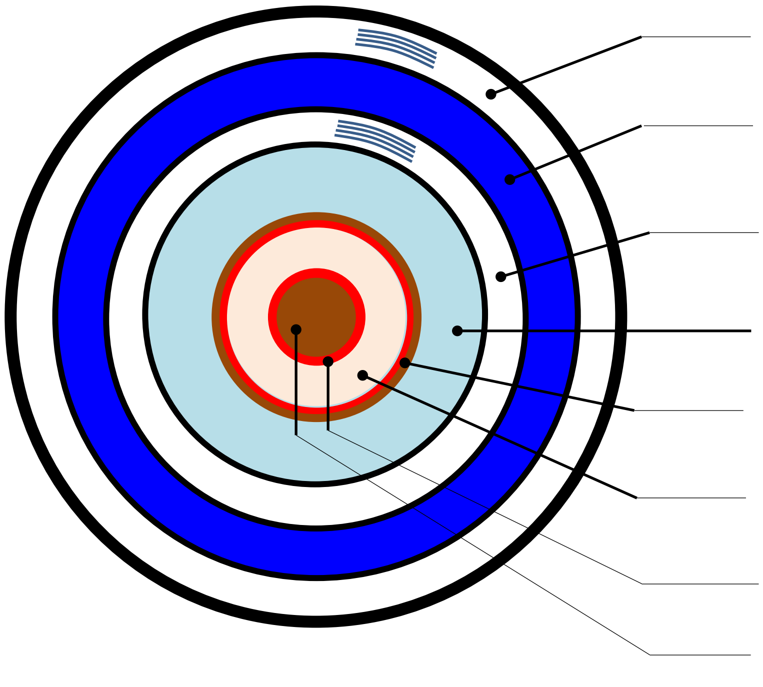
Layout of a warm dielectric SC cable



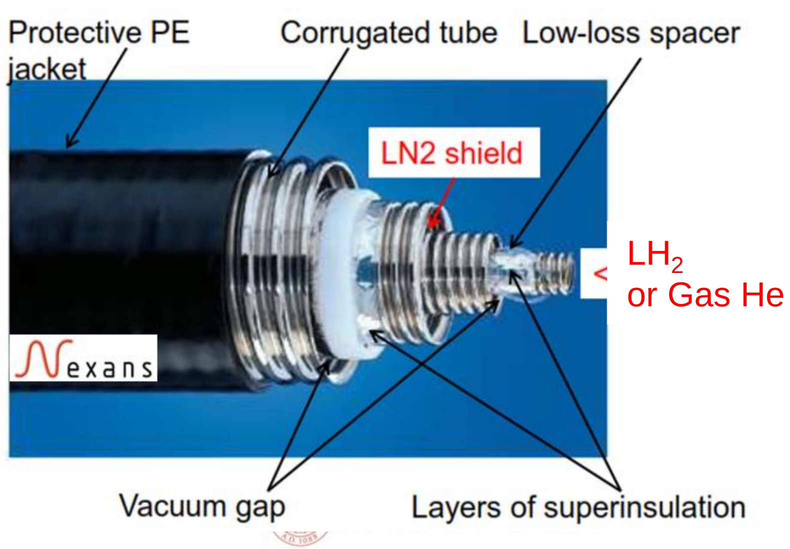


- **The shield operates at warm temperature**
- **Currents are induced on the pipes in AC operation, thus increasing the total heat load of the cable**

Layout of a cold dielectric SC cable with two stage cooling

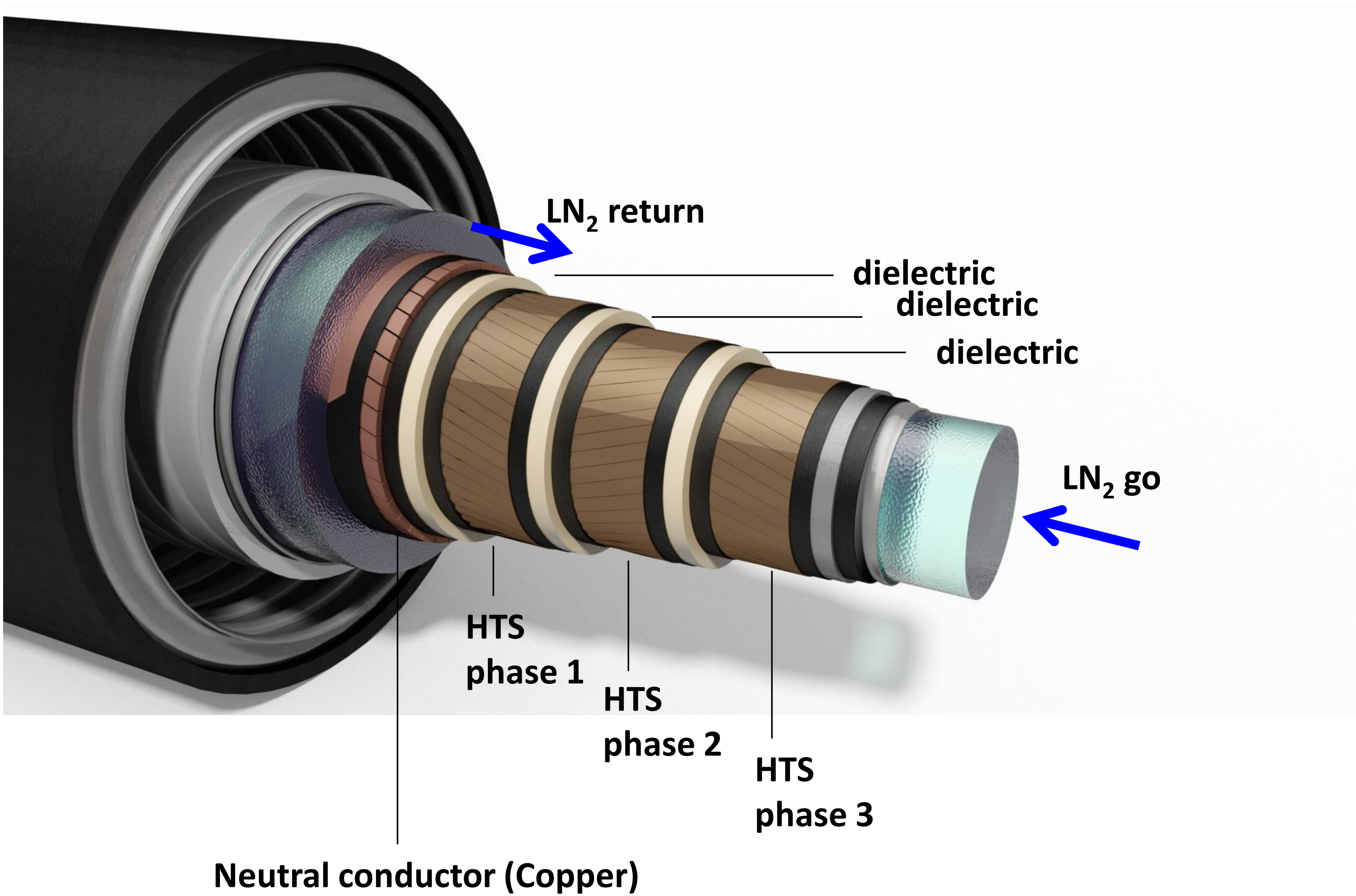


A more complex cable is obtained

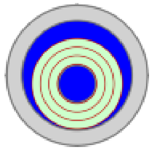


- **LN_2 acts as a thermal shield for the LH_2 pipe**
- **Heat load of LH_2 due to radiation is greatly reduced**
- **Additional heat must be removed form the LN_2 pipe which can be done with lower power due to the higher temperature**

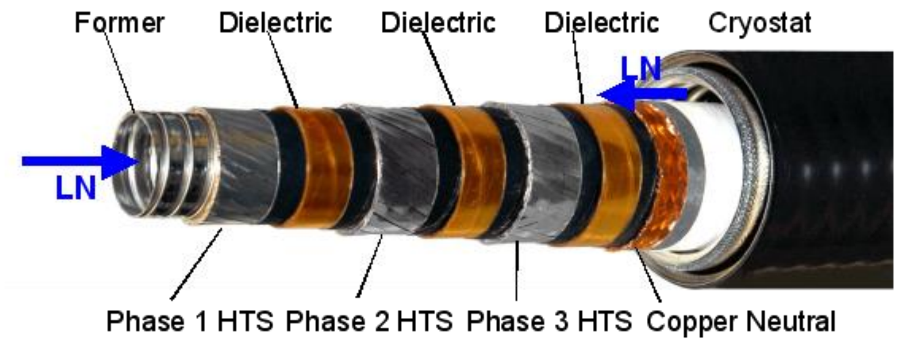
The cold dielectric Three-Phase concentric cable



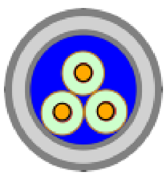
Three phases arrangements



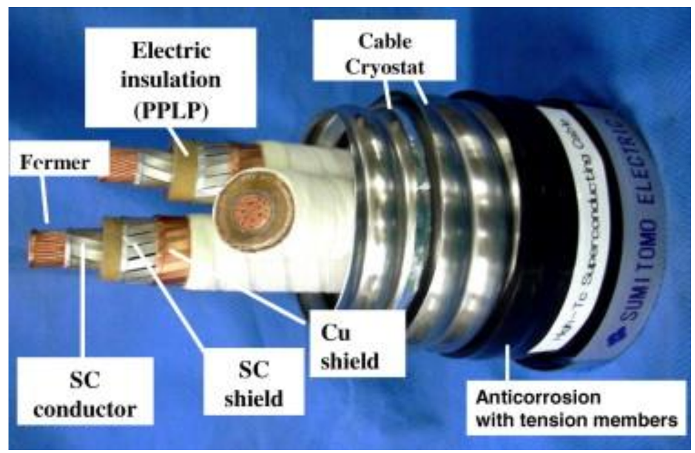
10 – 20 kV



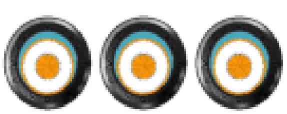
Concentric phases



30 – 100 kV

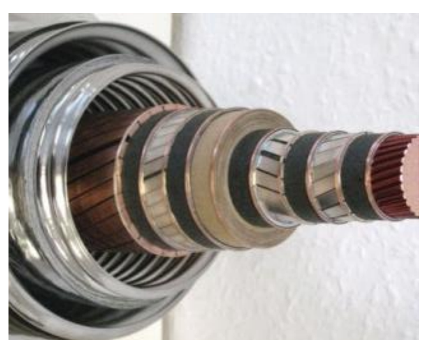


Separate phases with shared cryostat



> 100 kV

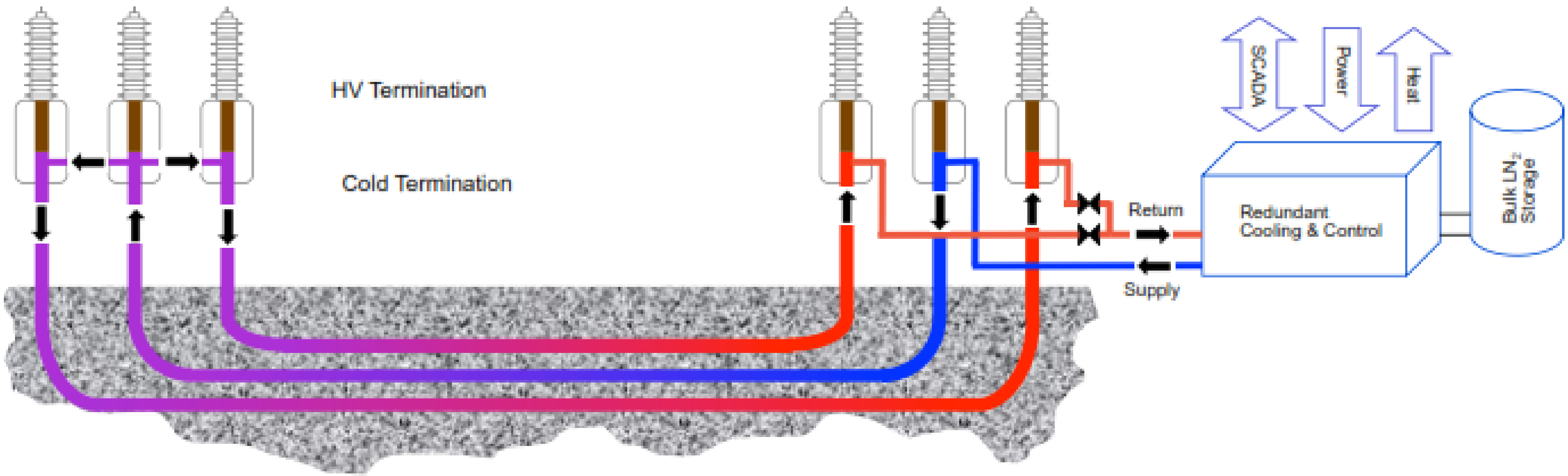
voltage



Separate phases and cryostat

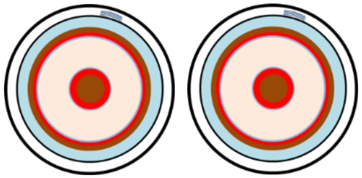
Cold dielectric cable system with one terminal cooling station

LIPA1 project
Cable cooling flow

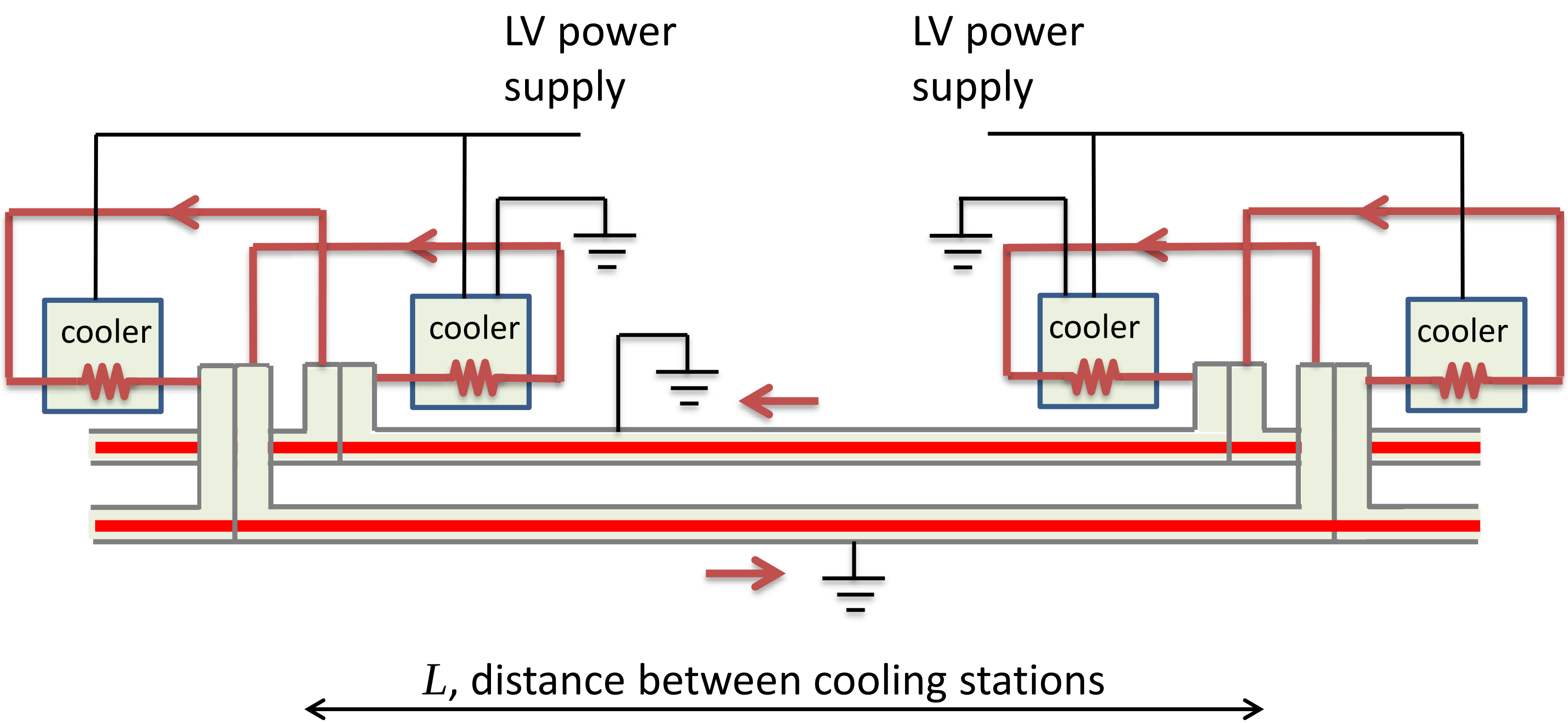


Cooling flow of liquid nitrogen
65 K < T < 77 K
3 bars < P < 20 bars

Cold dielectric cable system with Multiple Cooling points

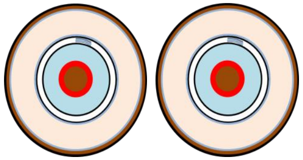


An example: A DC HTS cable system made of two monopoles with distinct cryostats for closed-loop circulation of the coolant

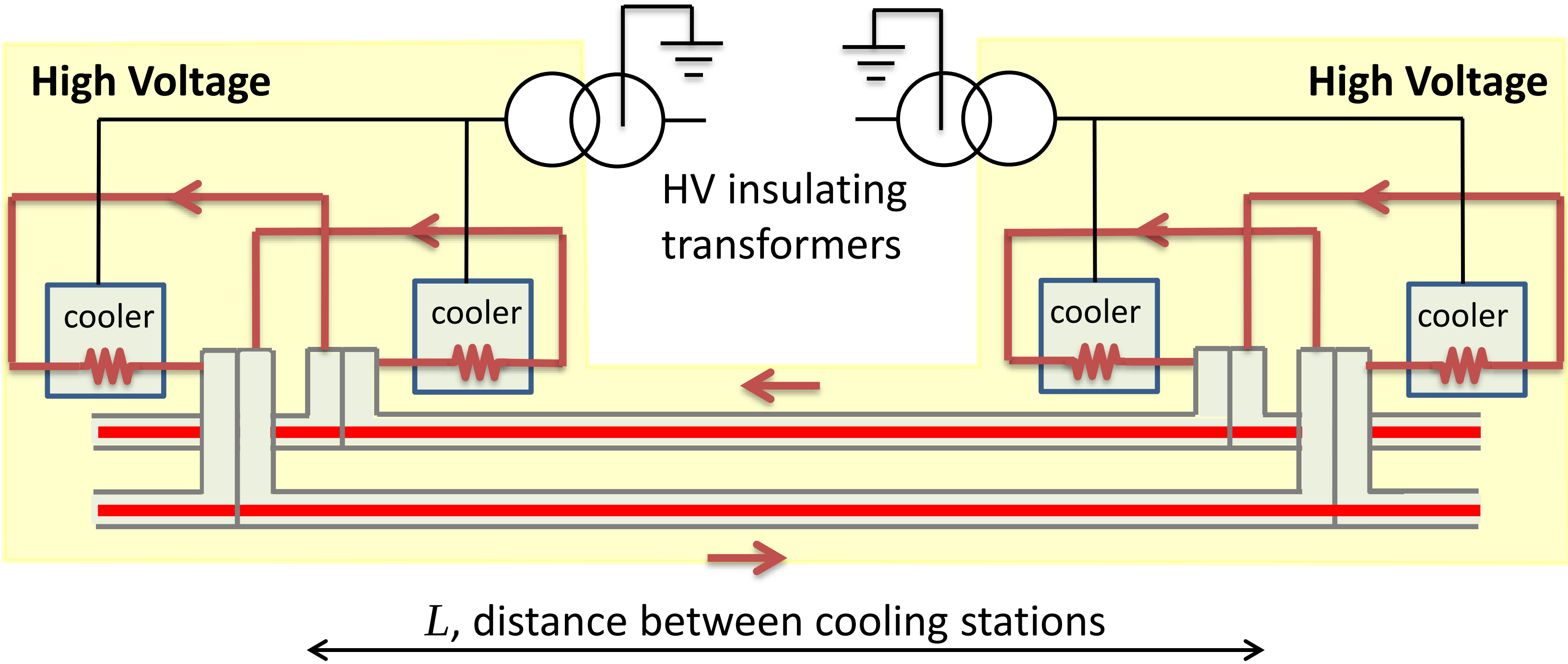


Cryogenic apparatuses are grounded and accessible

Warm dielectric cable system with Multiple Cooling Stations



An example: A DC HTS cable system made of two monopoles with distinct cryostats for closed-loop circulation of the coolant



L, distance between cooling stations

Cryogenic apparatuses operate at high voltage

- **High voltage insulating transformers are needed for their supply**
- **High voltage maintenance must be planned**

Practical cooling system

…. but superconductors rely on cooling. Is cooling technology well established, available and reliable enough?

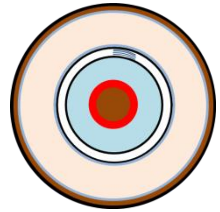
NeoKelvin®-Turbo 10kW

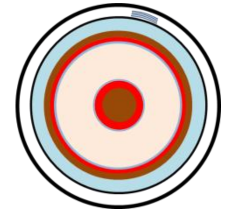
10 kW cooling power at 77 K
12 W input / W cold
30000 hours maintenance

Up to 50 kW cooling power at 77 K
12 W input / W cold
30000 hours maintenance

Highly efficient and capable enough for the cooling of km long cables

Warm dielectric vs Cold dielectric SC cable



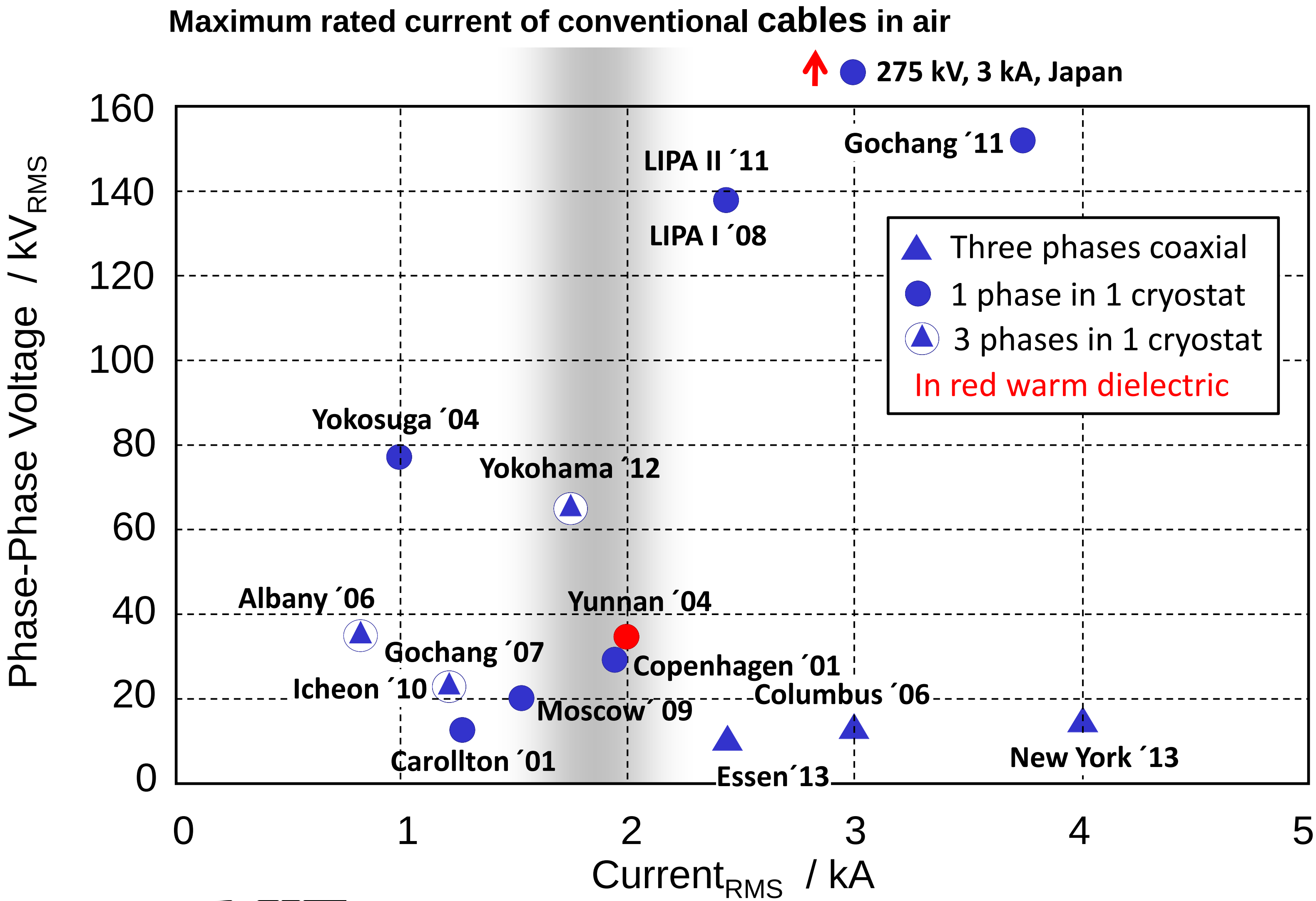


	Warm dielectric	Cold dielectric
Outer wet perimeter (heat load due to radiation)	Low	High
Dielectric	Conventional	Special
During fault reliability of insulation	Normal	Critical (bubbling)
Amount of superconductor	Low	High (shield)
Cryostat and cooling system	High voltage	Conventional
Service inductance	High	Low
Losses due to eddy currents induced in the cryostat	High	Low

Disadvantage of warm dielectric cable are not relevant in DC

Superconducting AC Cables

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



Karlsruhe Institute of Technology

Superconducting AC Cables
State-of-the-Art

Columbus

Figure: Ultera

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

LIPA

Figure: Nexans

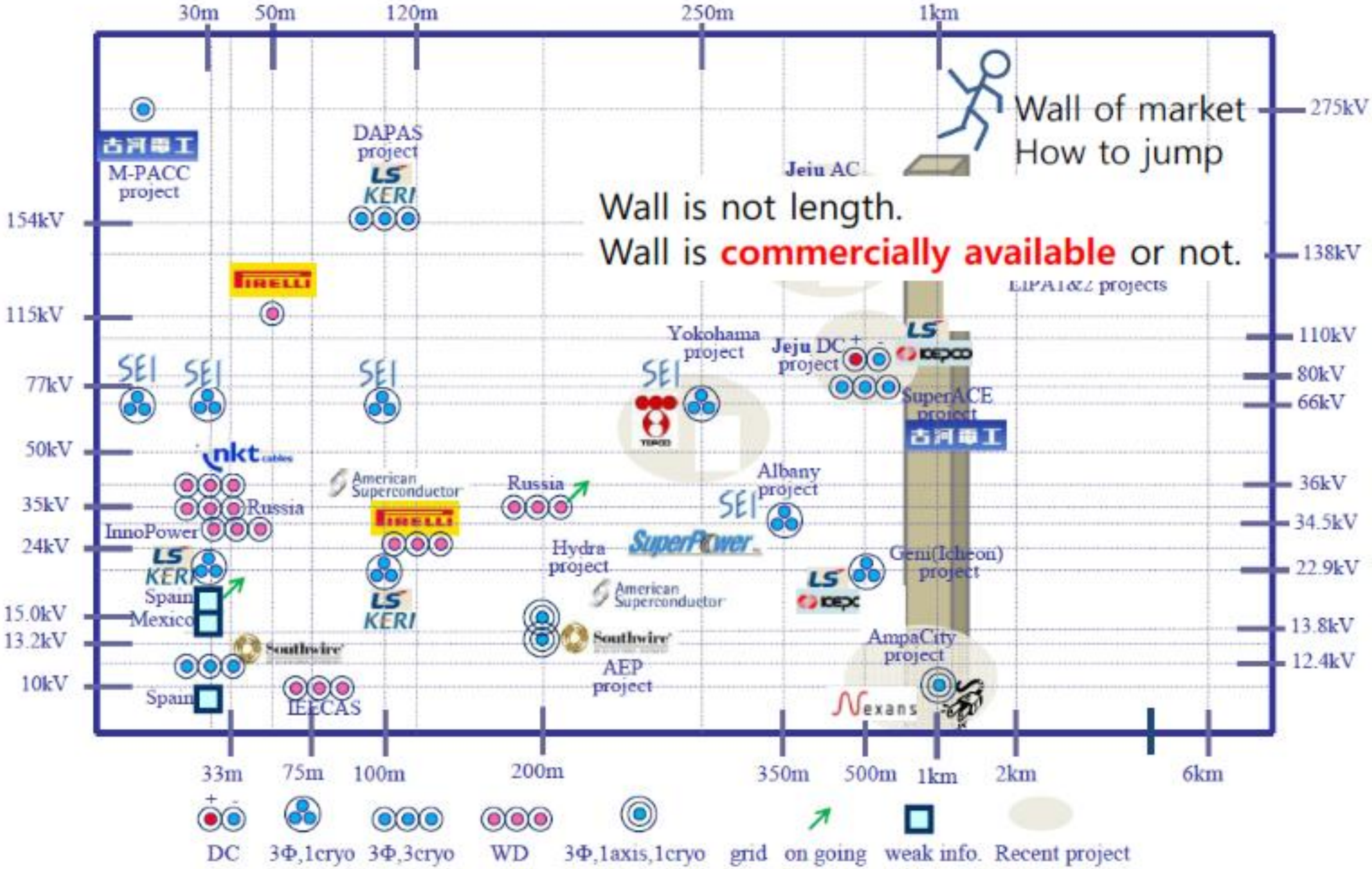
Nexans
138 kV, 2.4 kA,
600 m
Single coaxial design
BSCCO 2223
Energized 2008

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

More on HTS (AC & DC) cables



Minwon Park, Changwon National University, Recent status and progress on the HTS application of AC and DC power transmission in Korea, Sep. 20 2017 EUCAS, GENEVA

Outline

- Concepts and layouts
- State of the art
- **Design criteria**
    - **Electromagnetic**
    - **Thermohydraulic**
    - **Heat load and cooling**
- Applications
    - The ampacity project
    - Customer / Industry

Electromagnetic Design of the cable (cold dielectric)

- **Diameter of the former**

✓ During the fault the current flows through the former producing heating

✓ No bubbles must occur in the coolant in order to avoid breakdown of the dielectric and irreversible damage the cable

$$A_f \int_{T_n}^{T_{final}} c\,dT = \int_{t_f}^{t_f+\Delta t_f} \frac{1}{\sigma}\frac{i^2}{A_f}\,dt$$

A_f, area of the former

T_{final} , temperature at the end of the fault

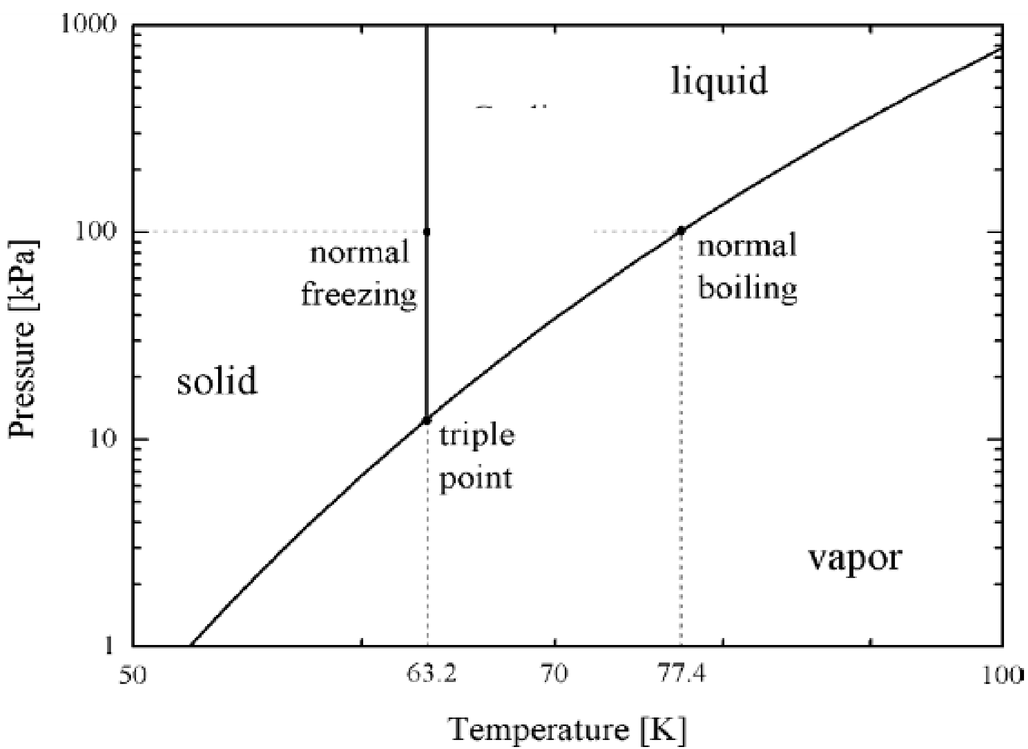
t_f, instant of fault

Δt_f , duration of fault

I, current of the cable during the fault (rms equi

σ, electric conductivity of copper

c, specific heat of copper



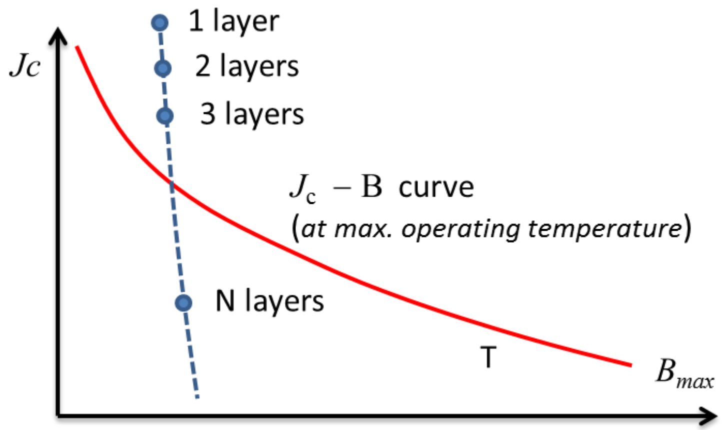
- Temperature rise during the fault must remain within the bubbling limit

- High pressure operation allows higher temperature margin before bubbling

- **Thickness of superconductor**

✓ The operating point ($J - B_{max}$) must be well below the Jc vs B curve

✓ As a first approximation it is assumed that the field is parallel to the tape



$$\delta_{SC} = N_{layers}\,\delta_{tape}$$

$$J = \frac{I_{dc}}{\pi\left((R_f + \delta_{SC})^2 - R_f^2\right)\cos\alpha}$$

$$B_{max} = \mu_0 \frac{I_{dc}}{2\pi(R_f + \delta_{SC})}$$

δ_{SC}, thickness of the tape

N_{layers}, numer of layers

δ_{SC}, thickness of the tape

α , average winding angle s of the layer

I_{dc} , nominal current of the DC cable

- **Thickness of insulation**

✓ The maximum electric field must be well below the breakdown value

$$\delta_{ins} = R_{i,ins}\left(e^{\frac{V_{dc}}{\beta E_{max} R_{i,ins}}} - 1\right)$$

δ_{ins}, thickness of insulation

$R_{i,ins}$, inner radius of insulation

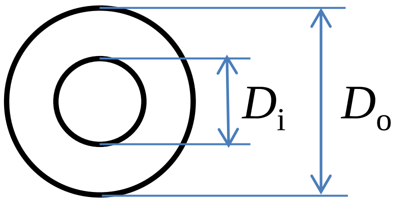
E_{max}, is the breakdown strength of the insulation

β, safety margin (usually 0.33)

Thermo-hydraullic Design of the cable

A cryopipe made of two concentric cylinder is to be designed

D_i, inner diameter of the pipe
D_o, outer diameter of the pipe



The inner diameter D_i is fixed by the electromagnetic design of the cable

$$D_i = 2(R_f + \delta_{SC} + \delta_{ins})$$

- ✓ Pressure at the outlet section cannot be below a proper minimum in order to avoid bubble formation
- ✓ Temperature at the outlet section must not overcome a proper limit in order to assure appropriate performance of the superconductor

Pressure and Temperature constraints assumed for the design of the cable systems

	Tin	Tout	Pin	Pout
LH_2 / MgB_2	**20 K**	**≤25 K**	**20 bar**	**≥5 bar**
LN_2 / HTS	**65 K**	**≤70 K**	**20 bar**	**≥5 bar**

Average pressure and temperature gradients in the pipe (incompressible fluid is assumed)

$$\frac{\Delta P}{\Delta x} = -\frac{f}{D_h}\frac{\rho v^2}{2}$$

$$\frac{\Delta T}{\Delta x} = \frac{f}{D_h}\frac{v^2}{2c_p} + \frac{q}{\dot{m} c_p}$$

f, friction factor
D_h, equivalent hydraulic diameter
v, velocity of the coolant
$\dot{m}$, mass flow rate of the coolant
ρ, mass density
c_p, specific heat at constant pressure
q, total heat load for unit length of cable (W/m)

✓ The friction factor can be estimated by means of the Colebrook-White implicit equation

$$\frac{1}{\sqrt{f}} = -\log_{10}\left(\frac{5.02}{N_{Re}\sqrt{f}}\right)$$

with $N_{Re} = \frac{\rho v D_h}{\mu}$

μ, dynamic viscosity of the coolant

Average physical properties of LH_2 and LN_2 over the considered intervals of Pressure and Temperature

	LH_2	LN_2
Mass density, kg/m^3	72.23	839
Specific heat, J/m^{3}K	9169	2662
Dynamic viscosity, µPa*s	15.70	25.08

Total heat load *q* for unit length of the cable (W/m)

$$q = q_{radiation} + q_{em}$$

q_{rad}, heat load per unit lenght due to radiation from the outer environment

q_{em}, electromagnetic loss per unit length

$$q_{radiation} = \lambda \pi D_o$$

D_o, diameter of the outer pipe

λ, is the heat load per unit surface (W/m^2) due to radiation from the outer enviroment

- Heat load due to radiation is nearly independent on the operating temperature of the cable. Today's technology allows a heat load from 300 K to 20 K of about 1.2 W / m^2

	T_1, K	T_2, K	λ, W/m^2
from room temperature to LN_2	**300**	**77**	**1.195**
from room temperature to LH_2	**300**	**21**	**1.235**
from LN_2 to LH_2	**77**	**21**	**0.040**

Antoni *C. Rubbia, "The future of large power electric transmission " SC Workshop, 2011*

Typical losses at 65-80 K in cold dielectric power cables

	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)

For a Cu cable typycal 20 W/kA.m

Nb: For DC current, the losses are only from radiation

C. E. Bruzek, "Introduction to superconducting power cable systems" , ESAS Summer School, Bologna 2016

✓ Final expression of average pressure drop and temperature increment of the pipe

$$D_h = D_o - D_i$$

$$v = \frac{\dot{m}}{\rho \pi (D_o^2 - D_i^2)}$$

$\longrightarrow$

$$\frac{\Delta P}{\Delta x} = -\frac{f \ \dot{m}^2}{2\pi^2 \rho (D_o - D_i)(D_o^2 - D_i^2)^2}$$

$$\frac{\Delta T}{\Delta x} = \frac{f \ \dot{m}^2}{2 \pi^2 c_p \rho^2 (D_o - D_i)(D_o^2 - D_i^2)^2} + \frac{\lambda \pi D_o + q_{core}}{\dot{m} c_p}$$

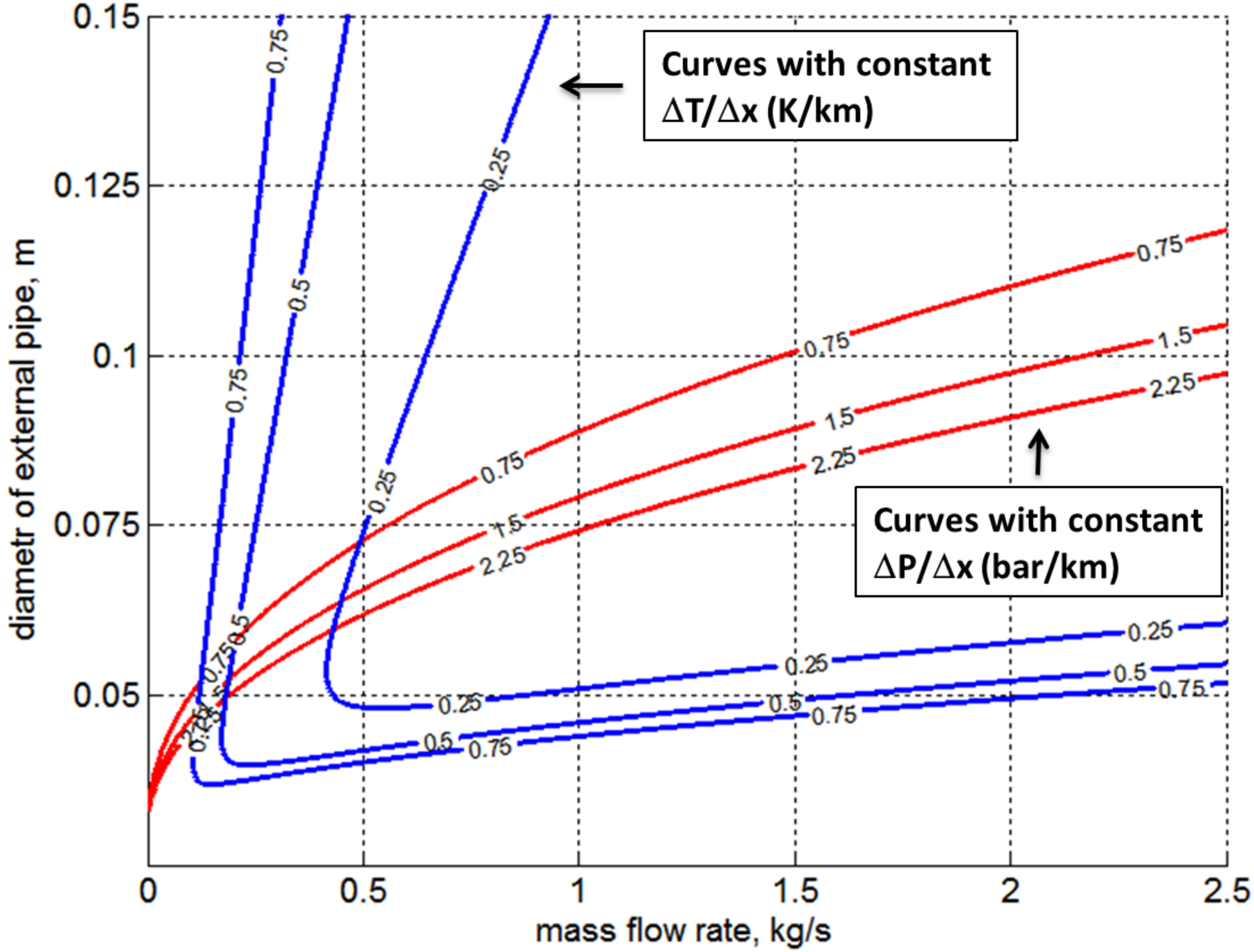
$$\frac{1}{\sqrt{f}} = -\log_{10}\left(\frac{5.04 \mu \pi (D_o + D_i)}{\dot{m} \sqrt{f}} \right)$$

Two degrees of freedom exists for regulating the pressure drop and temperature increment of the pipe:

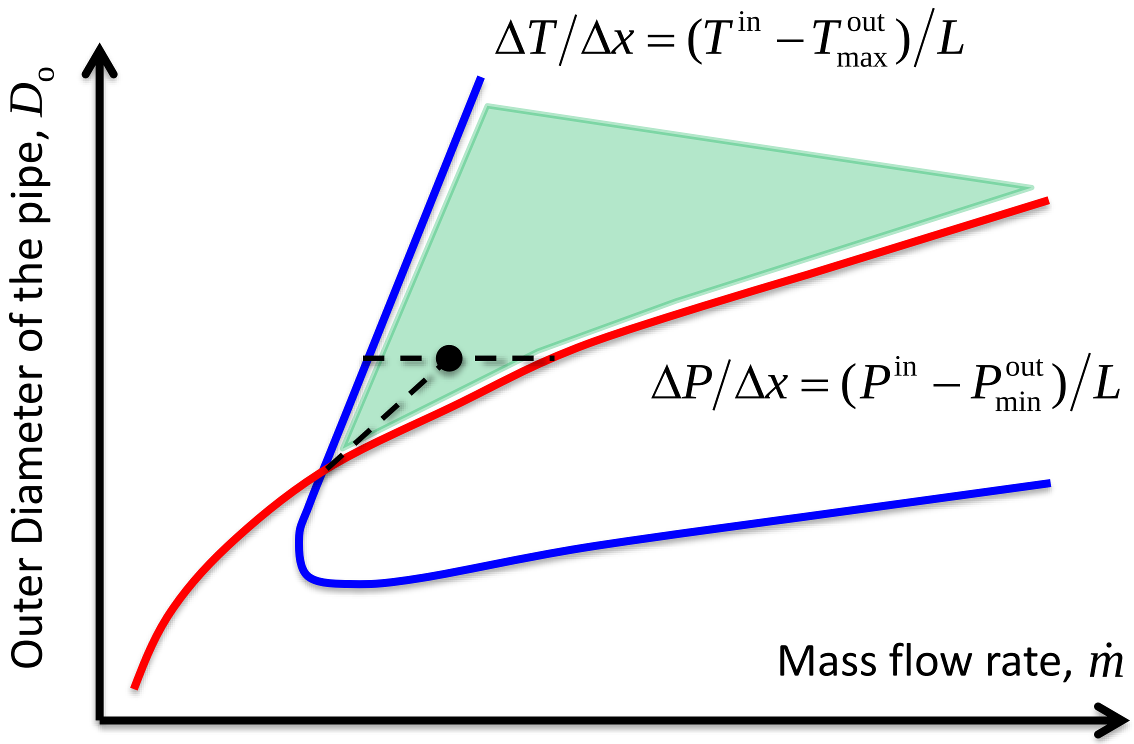
- **the outer diameter of the pipe, D_o**
- **the mass flow rate of the coolant, $\dot{m}$**

Examples of Temperature and Pressure gradients in the $\dot{m} - D_o$ plane

- *Inner diameter of the pipe, D_o = 30 mm*
- *Electromagnetic loss, q_{em} = 0 – DC cable*



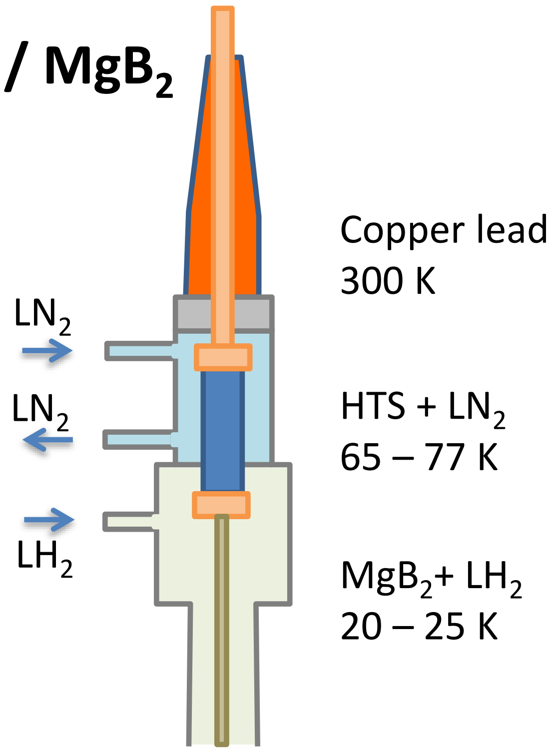
Assignment of D_o and $\dot{m}$ for a given distance L between cooling stations



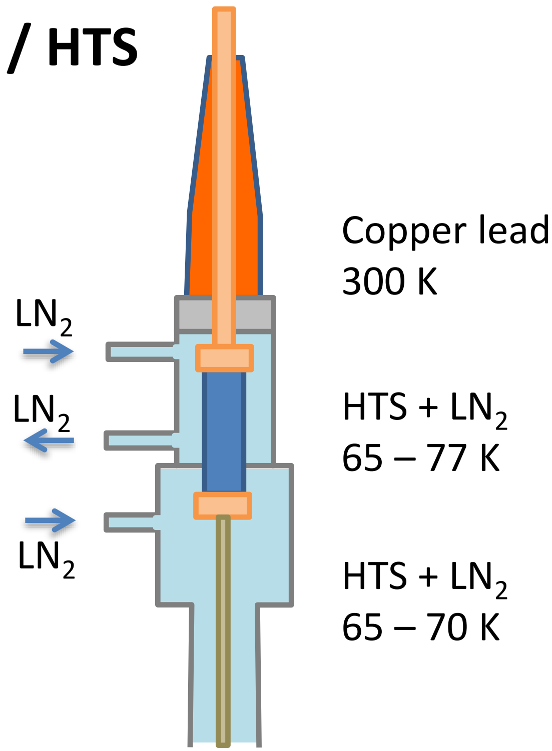
- The iso-curves of maximum allowable temperature and pressure gradient are plotted in the D_o and $\dot{m}$ plane
- Minimum D_o and $\dot{m}$ are found at the intersection of the two curves
- D_o is assigned with an appropriate safety margin (e.g. 1.25); $\dot{m}$ is chosen at the middle of the available interval

Termination – a crucial component

LH_2 / MgB_2



LN_2 / HTS



Thermal income from terminations	
Copper stage from 300 to 77 K	50 W / kA / lead
HTS stage from 77 to 20 K	0.5 W / kA / lead

Typical data widely reported in the literature

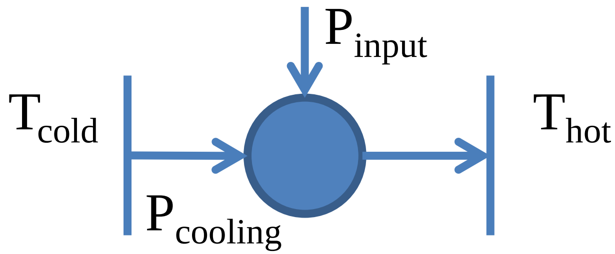
- **The very main part of heat load comes from the copper stage of the termination to LN_2**
- **A dedicated cooling system for the termination is appropriate also in case of LN_2 / HTS system**

LIPA1 project
Termination concept

- **Vertical part:**
  - Thermal gradient management (from 77 to 300 K)
  - Connection to grid

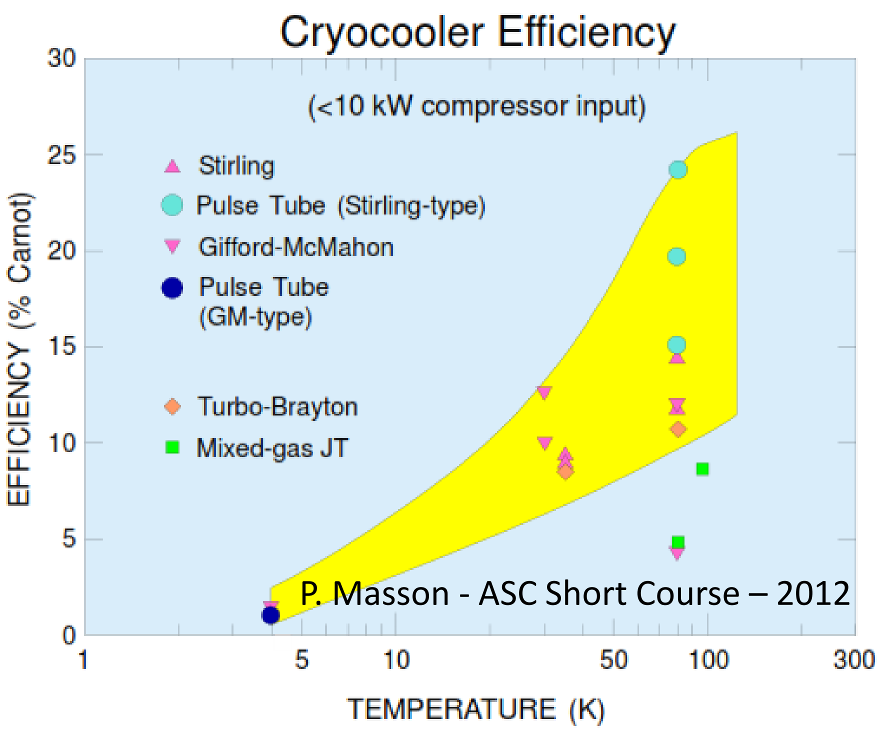
- **Horizontal part:**
  - Connection to HTS cable
  - Management of cable thermal shrinkage

Coefficient of performance of the cooling system



$$COP = \frac{\text{Watt of input power}}{\text{Watt of heat removed}}$$

- Ideal $$COP_{\text{Carnot}} = \frac{1}{\eta_{\text{Carnot}}} = \frac{T_{hot} - T_{cold}}{T_{cold}}$$
- Real $$COP_{\text{Real}} = \frac{COP_{\text{Carnot}}}{0.1 - 0.3}$$



Realistic assumptions are

COP = 22 at 70 K (LN_2) - 15% of Carnot

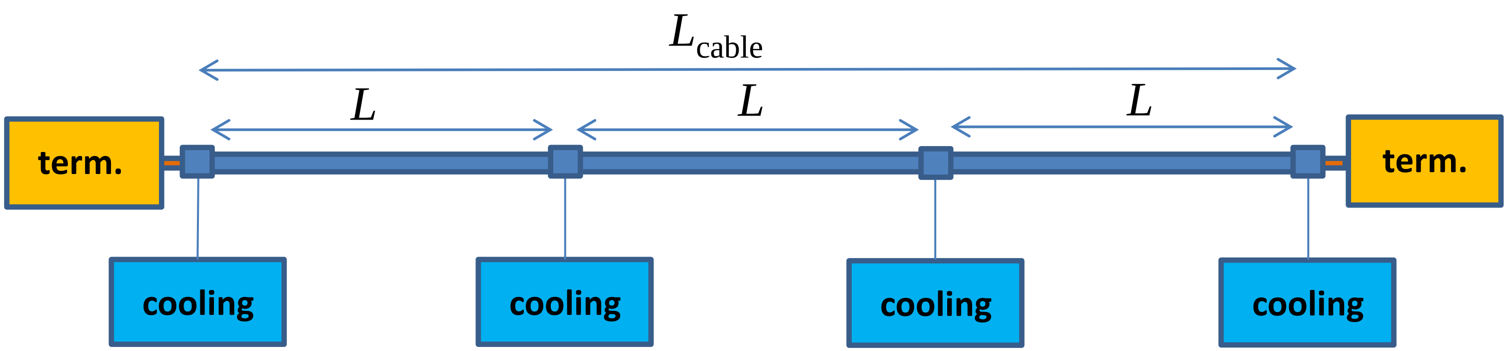
COP = 140 at 20 K (LH_2) - 10% of Carnot

Total cooling losses and efficiency of the DC cable

- Total cooling power

$$P_{\text{cooling}} = COP\left(q_{radiation} + q_{em} + q_{friction}\right)L_{\text{cable}} + COP_{\text{terminations}}\, P_{\text{terminations}}$$

(Pumping losses are negligible)



L_{cable} total length of the cable

L distance between cooling stations

$$L_{\text{cable}} = N * L$$

Given the length the total cooling power of the cable increases with the distance between cooling stations due to the increase of D_o with L

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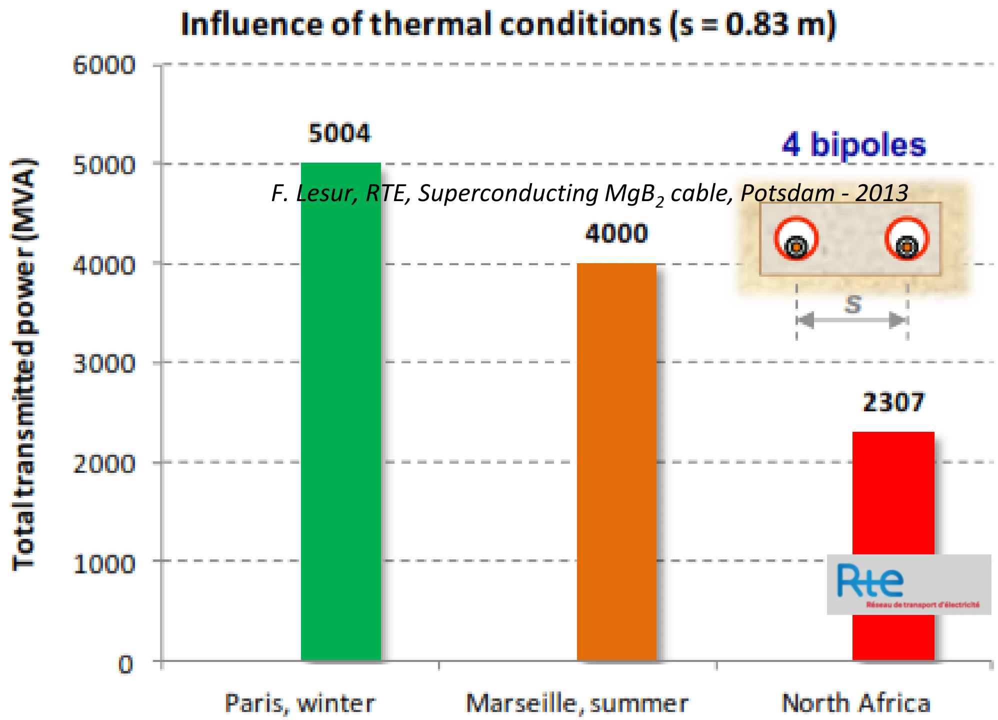
  - Thermohydraulic
  - Heat load and cooling
- **Applications**
  - **The Ampacity project**
  - **Customer / Industry**

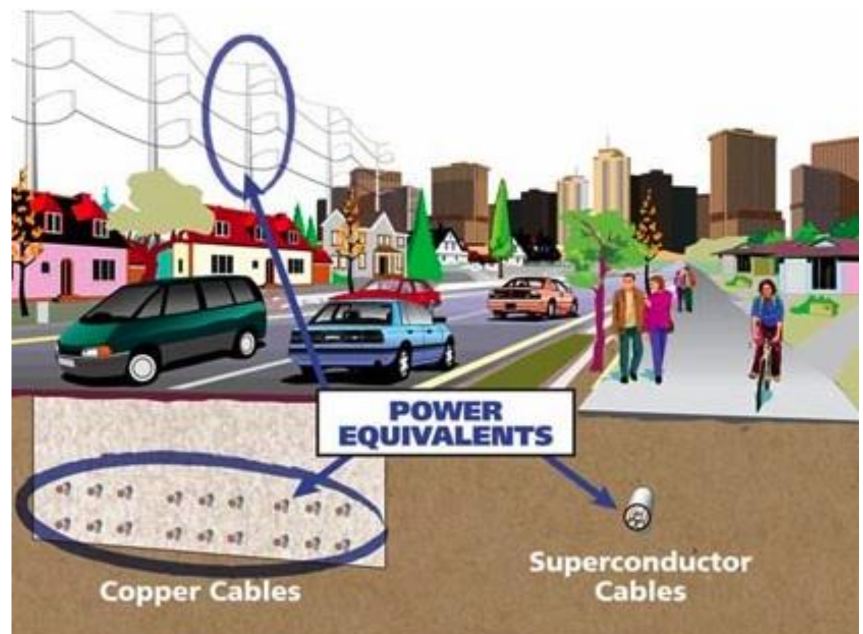
Advantages of HTS cables

- High current capacity & High power density
  - Increased power at the same voltage
  - Reduced voltage at the same power
  - Reduced size

Flexible planning

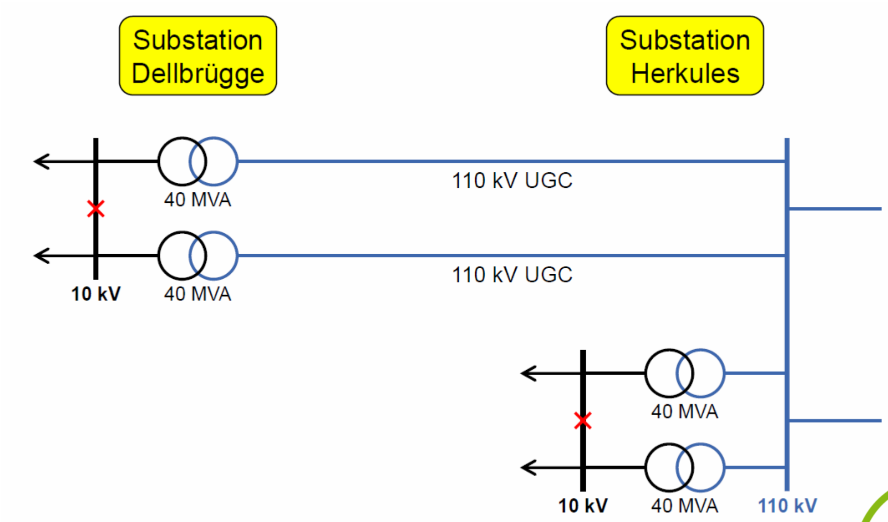
- Constant temperature operation
  - No derating at hot ambient temperature
  - possibility of overload
- Fault current limiting capacity (if properly designed)
- Lower losses (cooling included)
- Lower inductance
- No environmental impact



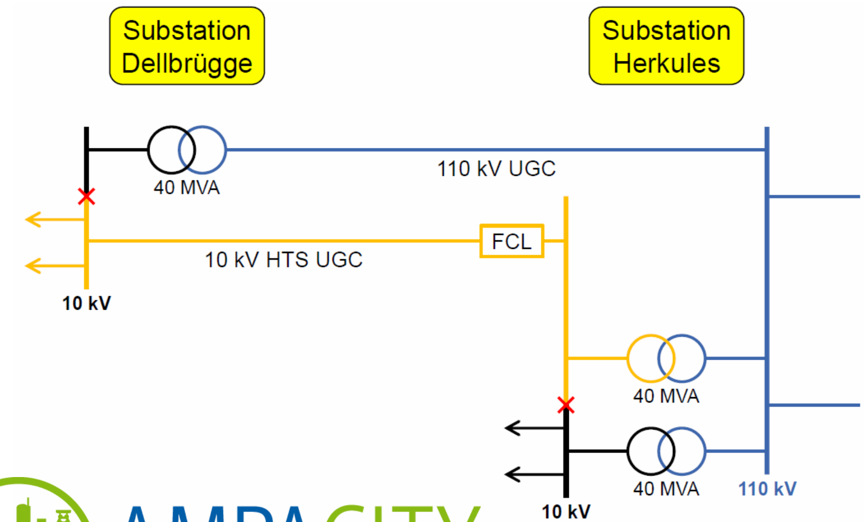


Ampacity Project

Conventional Situation in Essen



HTS Cable plus FCL Situation in Essen



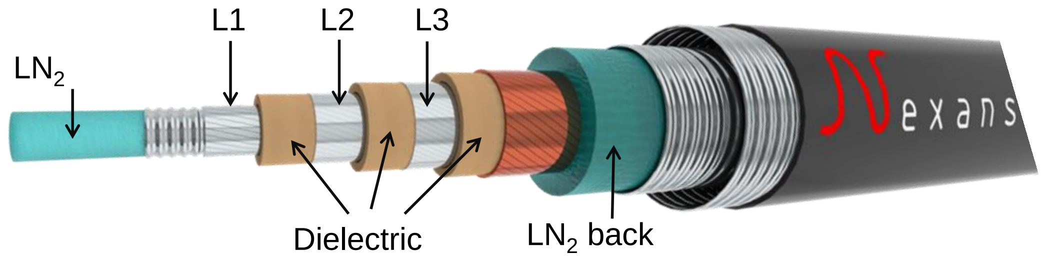
AMPACITY
Smart grids for the city

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

Status Ampacity Project

AMPACITY
Smart grids for the city

- 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



innogy

nexans

KIT Karlsruhe Institute of Technology

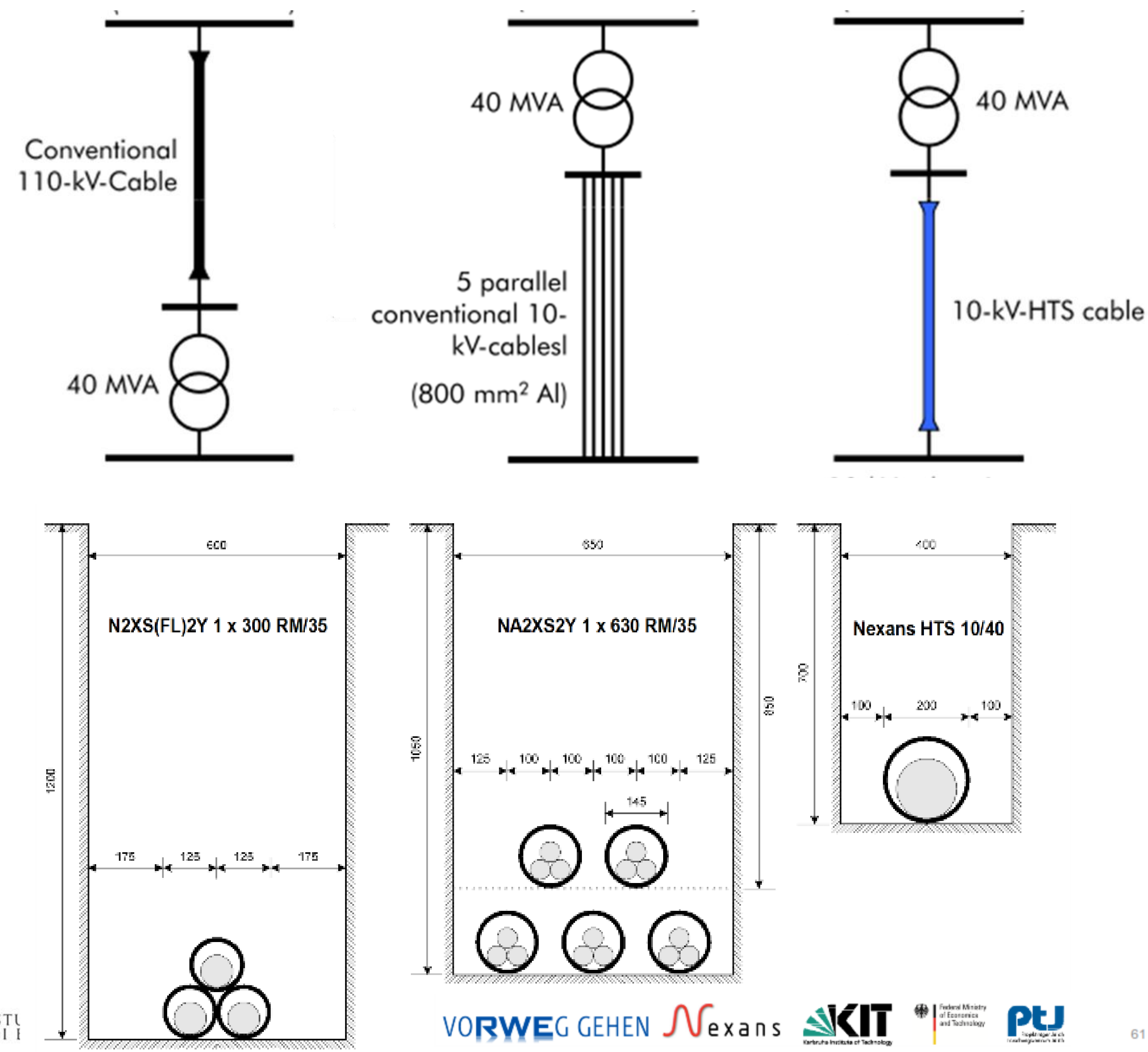
Supported by:
Federal Ministry of Economics and Technology
on the basis of a decision by the German Bundestag

PtJ Projektträger Jülich Forschungszentrum Jülich

110-kV-substation
(suburban area)

40 MVA
2 km

10-kV-substation
(city centre)



AmpaCity Cooling Unit

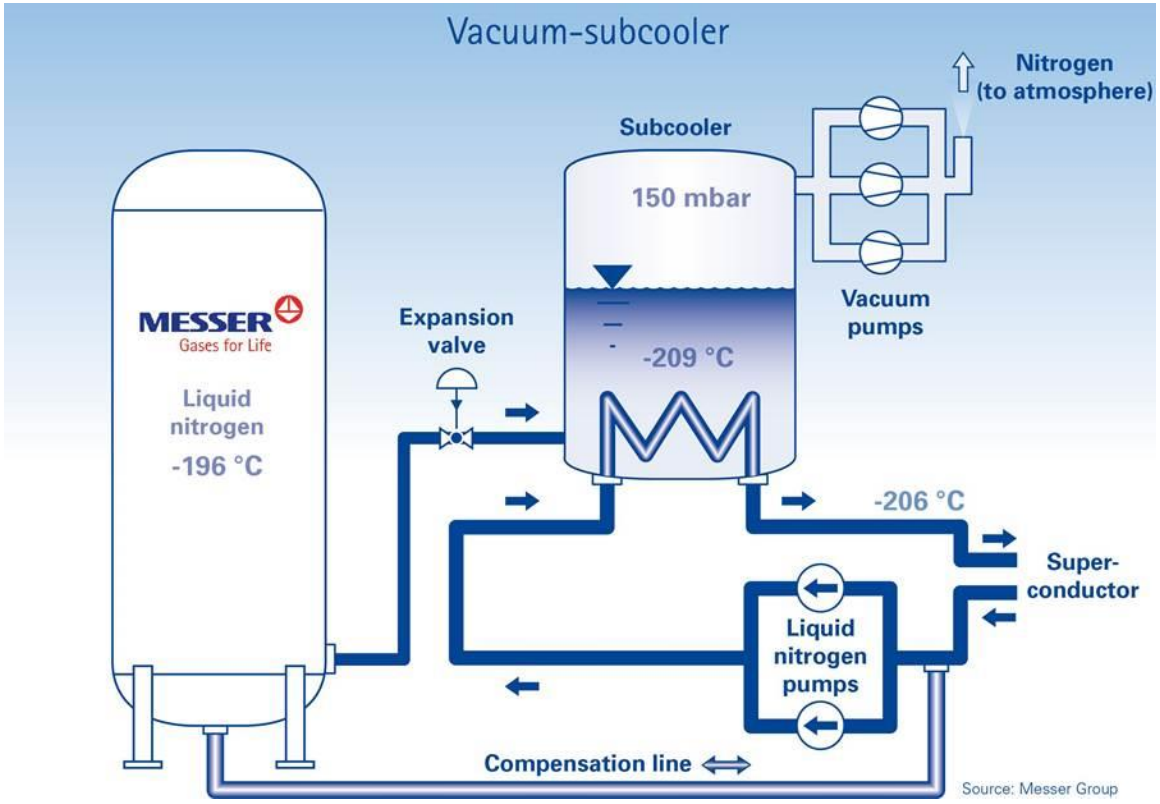
Liquid nitrogen is used
- as heat transfer medium
- as cooling agent

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

MESSER
Gases for Life

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	
Ccooling demand (actual):	1.8 kW (@ 67 K)	
Cooling unit	**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

Redundancy

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

The war of currents – a brief history

1880s DC (Edison) and AC (Westinghouse) power systems were introduced

Low voltage operation – Long distance transmission unpractical

1886 Transformer – Efficient long distance AC transmission possible

Mercury-arc power electronics

1954 First static HVDC system installed in Russia

Power semiconductors devices

1972 First modern HVDC system installed in Canada based on thyristors valves

AC Century

now

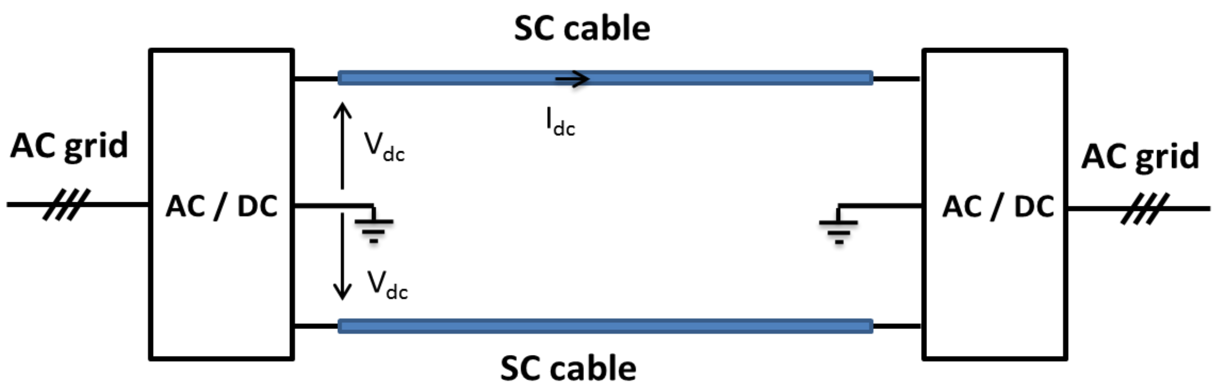
- **Hundreds of high power HVDC systems installed worldwide**
- **Increased penetration of DC technology for management of renewable sources**
- **Increased DC power demand due to customers (ICT, smart grids, control, …)**

DC Centrury is started

A case study in HTS DC transmission

The case study:

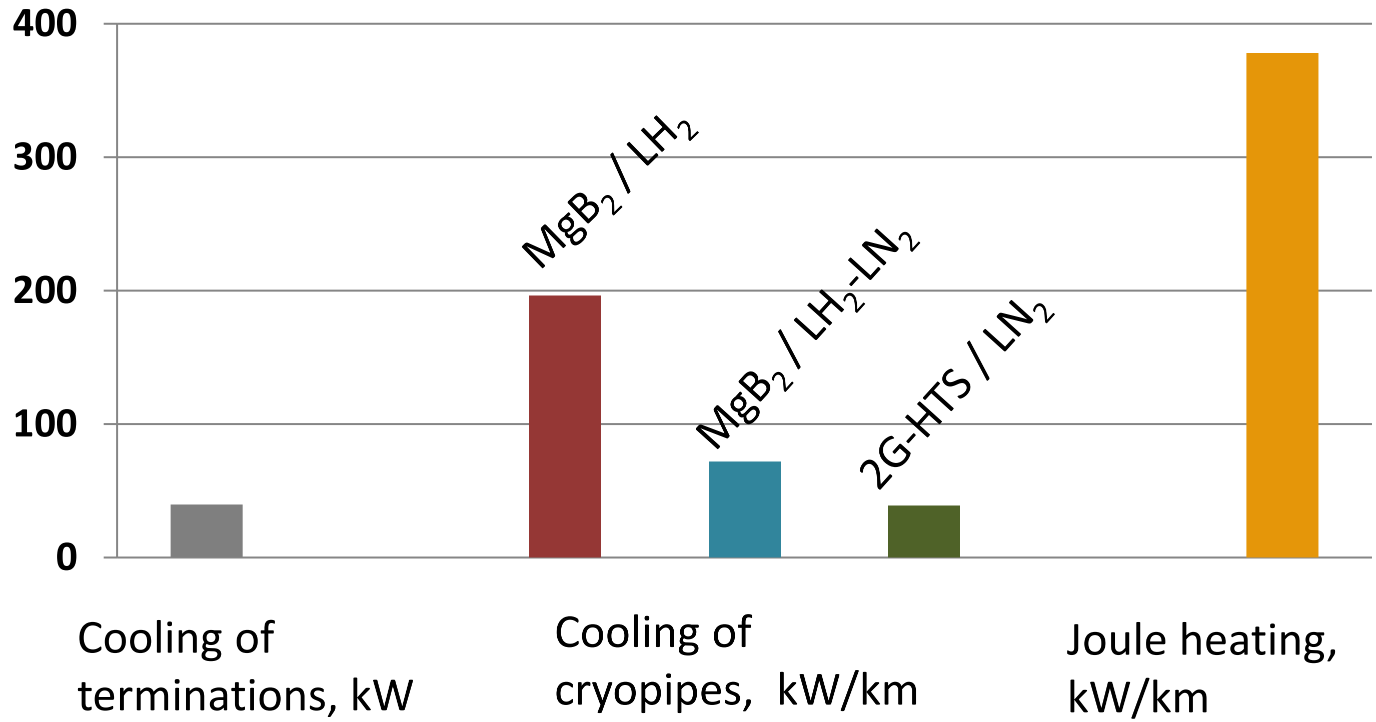
Configuration	Bipolar (two monopoles)
Rated power	Pn = 3600 MW
Rated voltage	$V_{dc} = \pm 200$ kV



As a figure of merit the cooling loss per unit length of the SC cable will be compared with the loss of a copper cable system of the same rating calculate under the assumption

Current density	$J_{Cu} = 1$ A/mm^2
Resistivity,	$\rho_{Cu} = 2.1$ μΩcm

Loss of a transmissionlevel cable system



P_n = 3600 MW
V_{dc} = ± 200 kV

Distance between cooling stations L = 10 km

Termination loss are negligible since they correspond to less than 1 km of cable

Loss reduction (per km) with respect to copper amount to

50 % for MgB_2 / LH_2
81 % for MgB_2 / LH_2-LN_2
87 % for 2G HTS/ LH_2

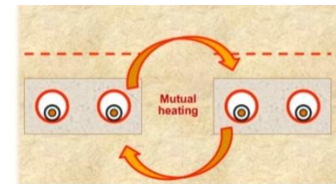
Both 2G HTS/ LH_2 and MgB_2 / LH_2-LN_2 are very competitive for the considered transport power

The right of way

The right of way

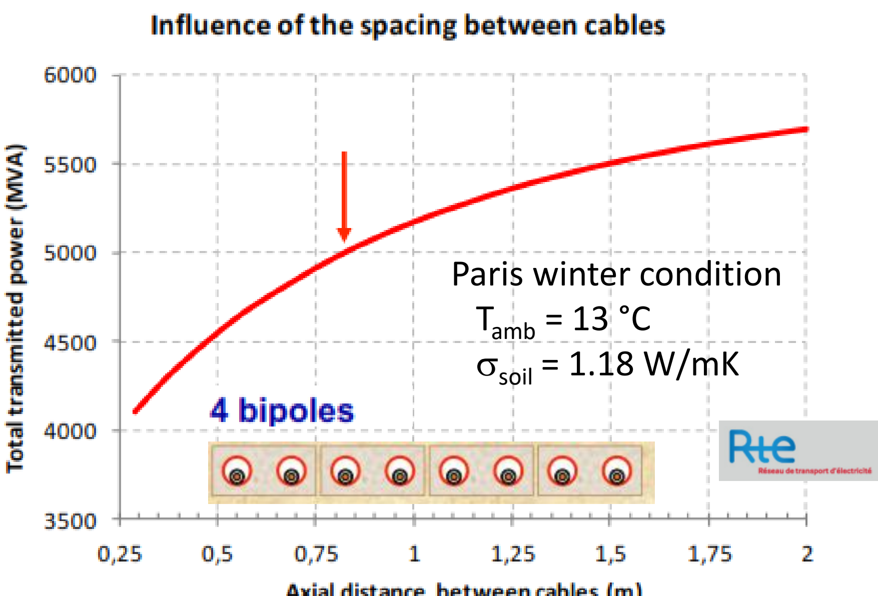
- **Industry limit of the Copper section of conventional HVDC cable:**
  2500 mm² - corresponding to a current capacity of 2.0 - 2.5 kA
- **More cable must be used in parallel if greater current is to be transported**

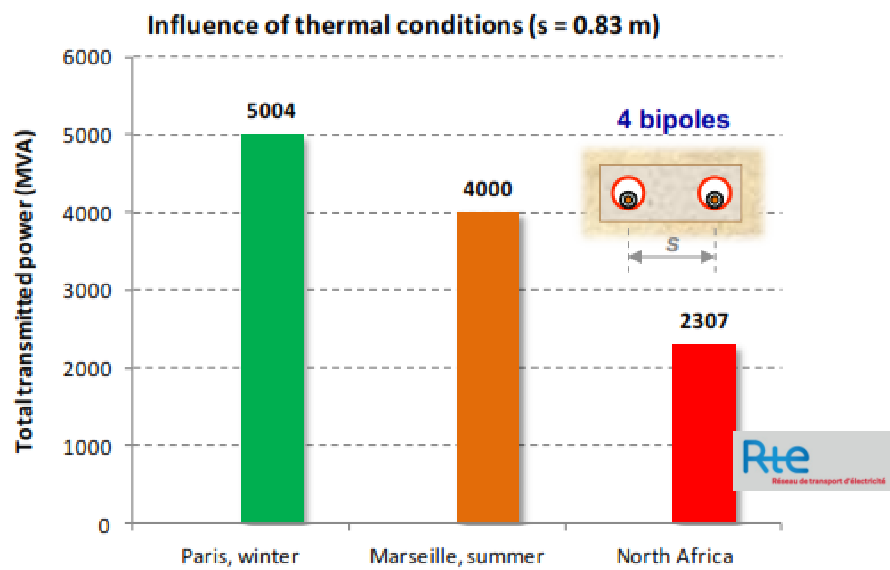
- **Mutual heating occurs between adjacent cables**
- **Appropriate spacing must be provided for avoiding thermal runaway**



The transport capacity of a cable system strongly depends on

- ✓ **spacing between cables**
- ✓ **soil condition**





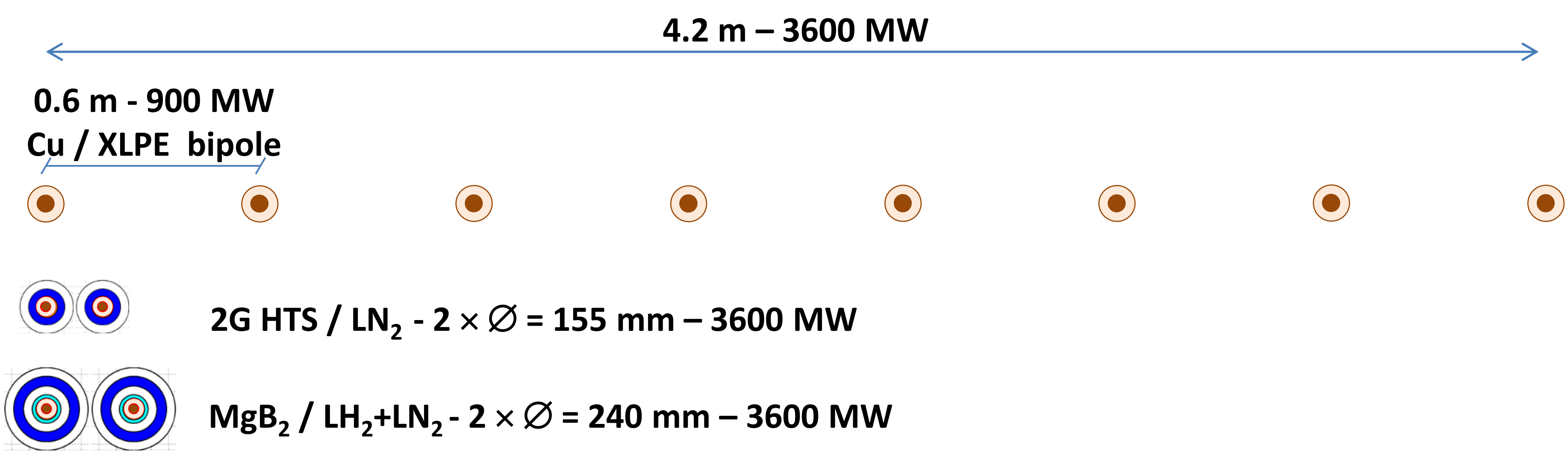
F. Lesur, RTE, Superconducting MgB_2 cable, Potsdam - 2013

1. No spacing concerns exits with SC cables which operates at constant temperature independently on ambient and soil conditions

2. One single cable meets all the required transport capacity

Right of way of high power links is drastically reduced with SC Cables

An example: the right of way of a 3600 MW link – draw is to scale



Thank you for your attention

antonio.morandi@unibo.it