Introduction to superconducting power cable systems

CE BRUZEK

Nexans France

ESAS Summer school –8-14 June 2016

Content

Introduction to superconducting power cable systems

1. The 5 main components
   - A. Superconducting tapes and wires
   - B. Cryogenic envelopes
   - C. Cryogenic machines
   - D. Cable designs
     - Warm dielectric
     - Cold dielectric
   - E. Terminations & Joints
2. Tests & Reliability
3. Some applications
4. HTS power cable system benefits

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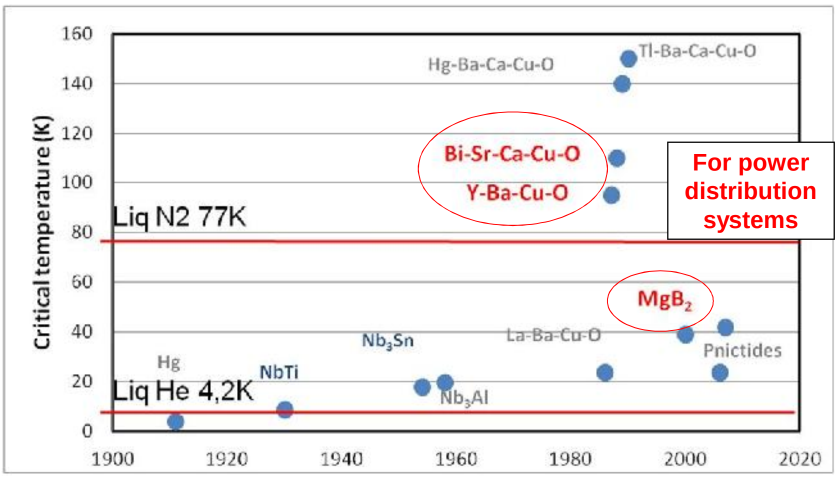
Superconducting tapes & wires (1)



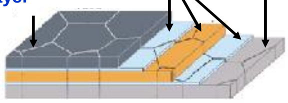
Superconducting tapes & wires (2)

HTS tapes or MgB_2 wires for current transportation

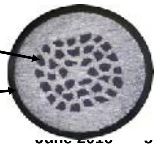
2 kinds of tapes and 1 wire are available in long lengths

- 1st generation: Multifilamentary Bi 2223 tapes

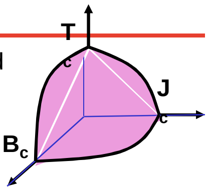
- 2nd generation: YBCO Coated conductor



- Multi-filamentary wire (T_{op} =20-25K)



Superconducting tapes & wires (3)



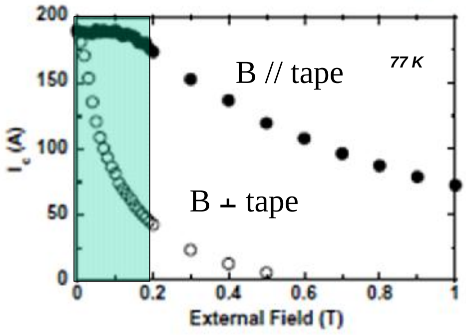
Superconducting materials lose their properties when the transported current exceeds the critical current density dependant on

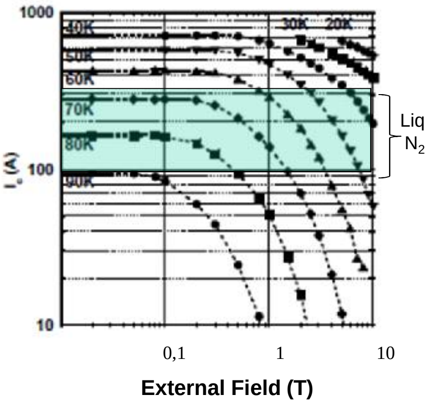
1. Magnetic field
2. Temperature

	Shape	Dimensions		Commercial performances	
		Width (mm)	Thickness (mm)	Je (Amm^{-2}) @77K; self field *($A.cm^{-1}$)*	Length (m)
Bi2223	Laminated tapes	4,5	0.32-0.36	140-150 A/mm² *(475 – 500 A/cm)*	< 2000 m
YBCO	Laminated NiW Tapes	4 to 12	0.3-0.45	100- 120 A/mm²	< 500 m
	IBAD tapes		0.1	500- 700 A/mm²	
				(500-650 A/cm)	
		Diameter (mm)		*Je (Amm^{-2}) @20 K ; 1T*	*Length (m)*
MgB_2	Cylindrical wires	0.8 -1.5 mm		350	< 5000 m

Superconducting tapes & wires (4)

Bi2223 tapes at 65-77K





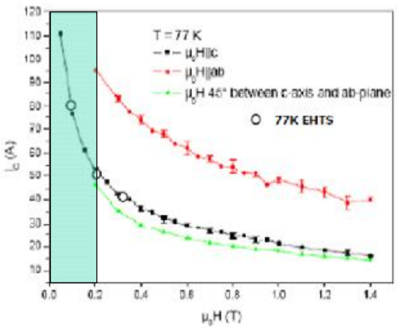
1. Keep the magnetic field parallel to the tape
2. Keep the magnetic as low as possible with a cable conductor relatively large d >25 mm and moderate current of few kA

3. Operate in Liq N_2 the closest to 65K to benefit of a 2 factor on Ic

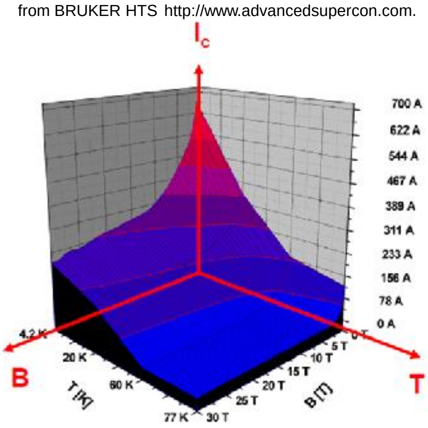
From Resarch, Fabrication and Applications of Bi-2223 HTS Wires edited by Ken Sato ;World Scientific collection

Superconducting tapes & wires (5)

YBCO tapes at 65K-77K



from BRUKER HTS http://www.advancedsupercon.com.



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Superconducting tapes & wires (6)

In superconducting tapes, AC Losses are mostly hysteresis losses that can be evaluted by:

$H_a >> H_p$

$$P_{vol} = \frac{8}{3\pi} J_c \; d \; f \; B_a \quad [W/m^3]$$

$$P_\ell = \frac{8}{3\pi} I_c \; d \; f \; B_a \quad [W/m]$$

d is the distance **perpendicular** to the applied field

High **transverse** field ac losses

PIT tapes : l/e = 20 (l = 4 mm ; e = 0.23 mm)

Coated Conductors : l/e = 2000 (l = 4 mm ; e = 0.002 mm)

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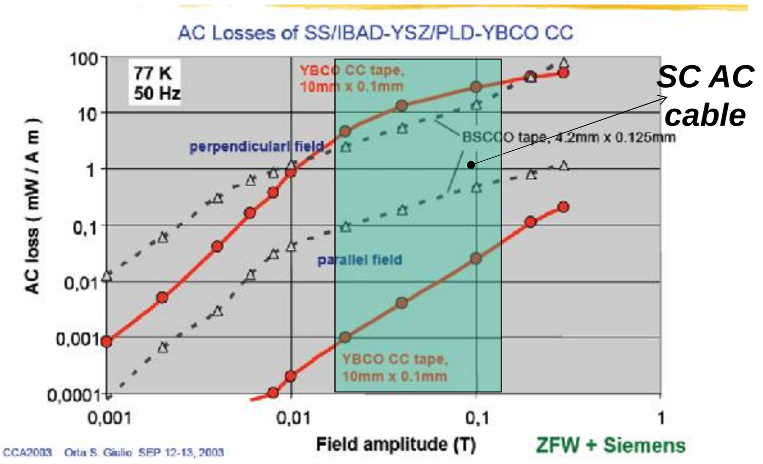
Superconducting tapes & wires (7)



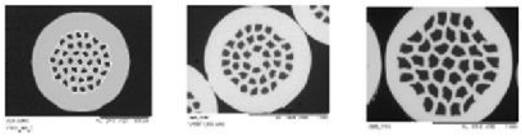
From P Tixador

Keep the magnetic field as low as possible and parallel to the tape

Superconducting tapes & wires (8)

MgB_2 wires at 20-25K

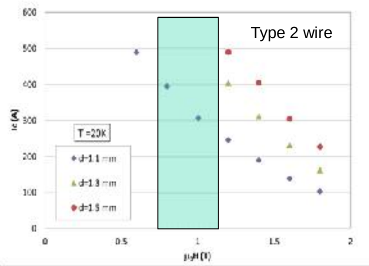
A large variety of possible designs

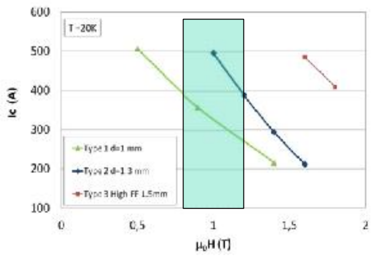


Type 1	Type 2	Type 3
Diameter: 1 mm •37 MgB_2 filaments •Filling factor: 11.5% •Nickel matrix, Monel sheath; Niobium barriers; Copper and Tin electroplated layer	Diameter: 1.33 mm •36 MgB_2 filaments •Filling factor: 17% •Nickel matrix, Monel sheath	Diameter: 1.5 mm •37 MgB_2 filaments •Filling factor: 30% •Nickel matrix, Monel sheath

1. For high ampacity DC cable > 10kA
2. Keep the magnetic field around 1T
3. Small cable conductor diameter <15 mm to use the smallest cryogenic envelope

From Columbus SPA http://www.columbussuperconductors.com





Superconducting tapes & wires (9)

Typical cabling machine

Superconducting tapes & wires (10)

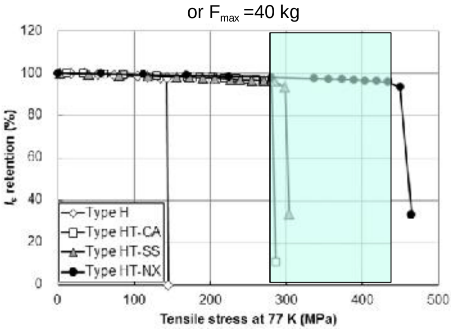
Handling laminated 1G tape at room temperature for cabling operations
Different possible reinforcements

1. CA: copper alloys
2. SS: stainless steel
3. NX: nickel alloys

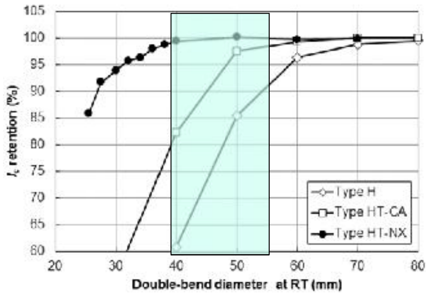
HT-CA tape

•width: approx. 4,3 mm
•thickness: approx. 0.3 mm

σ=300 to 400 MPa
or F_{max} =40 kg



D ~40 mm



Superconducting tapes & wires (11)

Handling 2G tapes at room temperature for cabling operations

- Mechanical properties:
  - ✓ Average thickness: 0.36 - 0.44 mm
  - ✓ Minimum width: 4.24 mm
  - ✓ Maximum width: 4.55 mm
  - ✓ Minimum double bend diameter (RT): 35 mm
  - ✓ Maximum rated tensile stress (RT): 200 MPa
  - ✓ Maximum rated wire tension (RT): 20 kg
  - ✓ Maximum rated tensile strain(77K): 0.3%

- Cabling reliability:
  - ✓ Designed for cabling on a wide range of formers with tight pitch and large back tension.
  - ✓ Durable in pressure cycled liquid nitrogen, including splices and joints

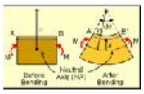
From American superconductors http://www.amsc.com

Superconducting tapes & wires (12)

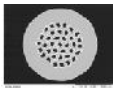
Handling MgB_2 wires at room temperature for cabling operations

Mechanical properties:

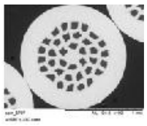
- Maximum rated tensile stress (RT): 150 MPa Fmax= 15-20 kg
- Maximum rated tensile strain(77K): 0.3%
- Minimum bending radius (see below)



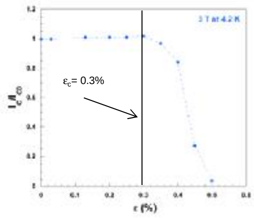
$$\varepsilon = \frac{A'B' - AB}{AB} = \frac{y}{\rho}$$

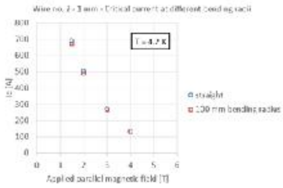


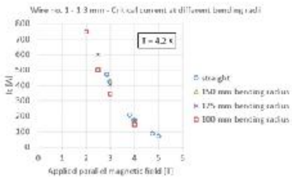
Type 1: Rc=100mm
r=0.3mm strain 0.3%



Type 2: Rc=125mm
r=0.4mm strain 0.32%







Courtesy to Cern

Content

Introduction to superconducting power cable systems

Cryogenic envelopes (1)

To maintain the low temperature and to transport the cryogenic fluids

Simple envelope

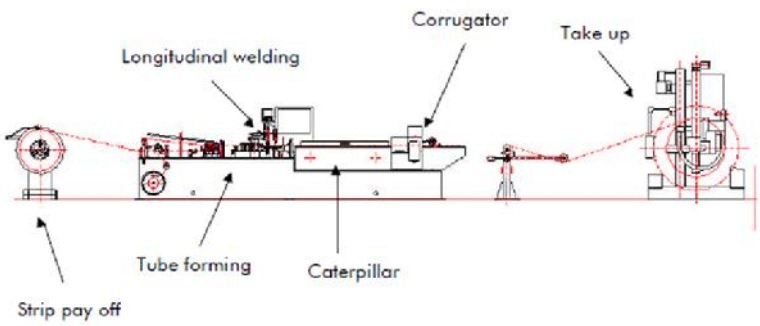
1. Corrugated inner tube
2. Low-loss spacer
3. Vacuum space
4. Multilayer superinsulation
5. Corrugated outer tube
6. PE jacket (optional)

Double envelope with thermal shield for MgB_2

Cryogenic envelops (2)

Tube with shape & longitudinal welding process

- Tube length are kilometric depending on
  - The strip length
  - The tube diameter



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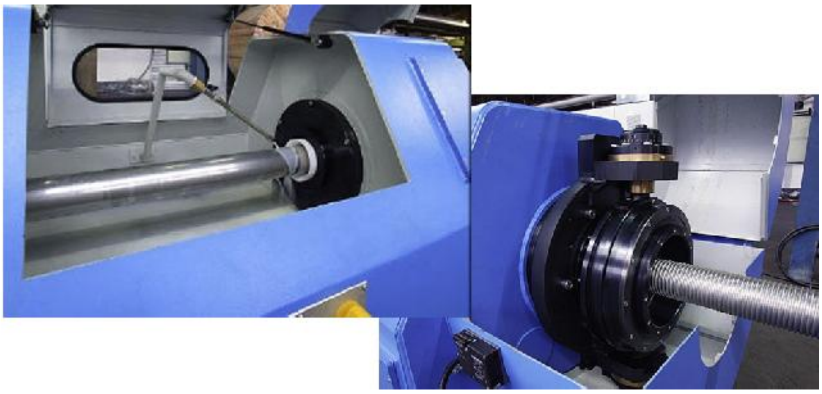
Cryogenic envelops (3)

Corrugation of tubes (Flexibility)



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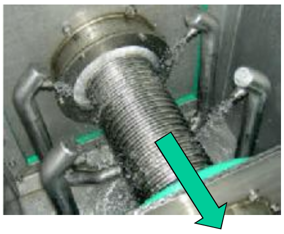
Cryogenic envelops (4)

Thermal insulation *(super-insulation and spacer)*



Ultra-sonic cleaning

Super insolation laying

Spacer

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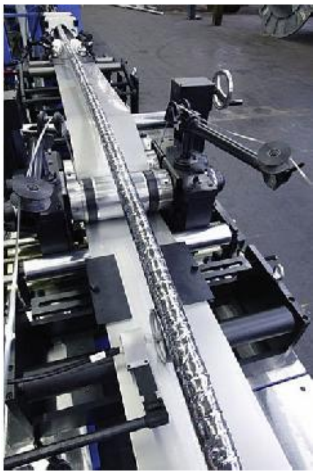
Cryogenic envelops (5)

Outer tube shaping & welding



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Cryogenic envelops (6)

1. Envelops are flexible (corrugation)
2. Life time
   - Experience of more than 20 years in progress…
3. Maintenance
   - Monitoring of vacuum level in operation
   - Crack location by non destructive controls (ultrasonic or Acoustic emission..)
4. Piece lengths from 250 m up to 1000 m depending on the diameter
   - Limitation: Ground transportation of the spools…
   - but low losses cryogenic couplings (bayonet) already exist

L H2 Coupling

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Cryogenic envelops (7)

Thermal heat load depending on:

1. Envelop diameter
2. The number of super insolating layers
3. The gap between the inner and the outer tubes
4. The quality of vacuum

Heat inlet can be significantly **locally** increased when the cryo-envelope is **bent** or **perpendicularly pressed**

	2 walls					4 walls*		
Models	Small		Medium		Large	Small	Medium	Large
Int /Ext Dia Meter (mm) (Shield) *	14/34	21/44	39/66	60/110	75/125	21/44 + (60/110)*	39/66 + (90/147)*	75/125 + (147/220)*
Bending radius *(Several bends)* (m)	0.6	0.7	1.1	1.8	2	2	2.5	3
Heat inleak at T_{op} /Shield* ($W.m^{-1}$)	0.4	0.6	1	1.2	1.4	0.07/1.2*	0.12/1.5*	0.3/2*
Weight ($kg.m^{-1}$)	0.5	0.8	1.7	4	6.7	5	7.5	10

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Content

Introduction to superconducting power cable systems

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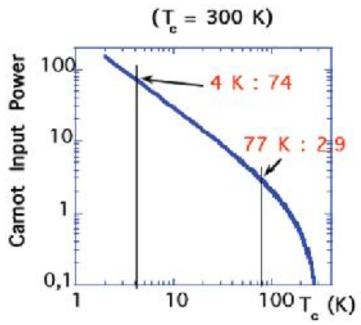
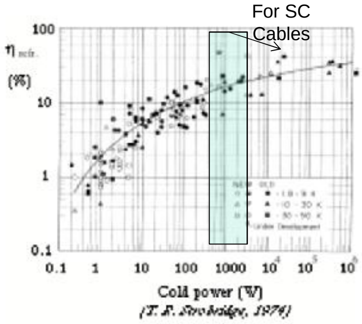
- Energetic cost

$$\frac{W_{min}}{Q} = \frac{1}{\eta_f} \frac{T_o - T_c}{T_c}$$



From P Tixador



1W at 77K needs 10 to 25 W at RT
1 W at 20 K needs 100 to 140 W at RT

1. To recover the cold power and the cryogenic fluid pressure
2. To circulate the cryogenic fluids

Large number of machines are commercially available from small to large cold power production to work in **close loop**

Ex Gifford Mc-Mahon machines

Cold power: up to *500W at 70K and 60W à 20K*

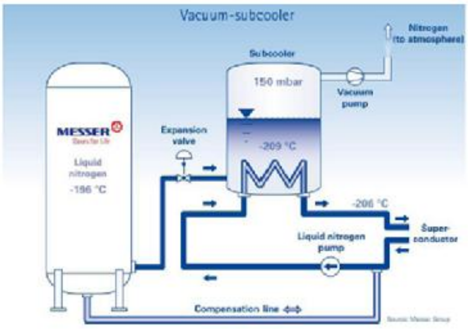
Ex: Turbo Brayton machines

Cold power: *from 5kW to 30 kW at 70K and up to 5 kW at 20K*

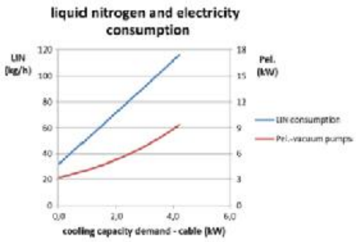
Also possible to use **open loop system** when LN_2 delivery on site is possible

Benefit: Use liquefied N2 as primary cooling source

Example: Messer system at Ampacity Essen site



Principle



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Cable designs (1)

- Cable: Transport the power from one termination to an other
  - High Currents and voltages management with the lower losses
  - 2 solutions for high voltage management:

1. Dielectric applied to the external envelope ⇒Warm dielectric design

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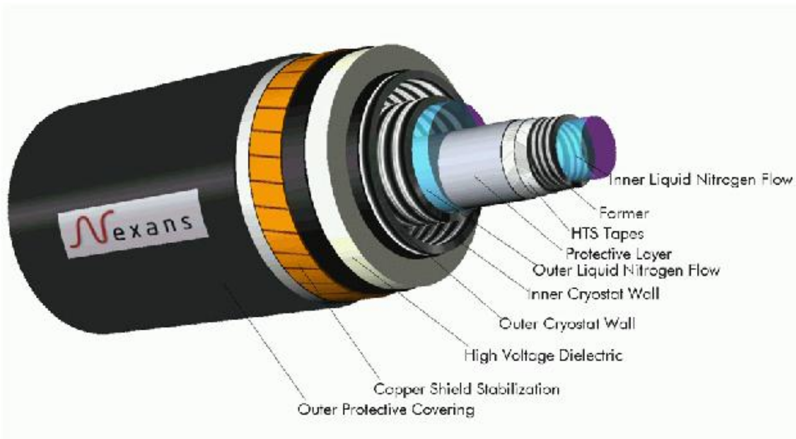
Cable designs (2)

Dielectric material applied on the external Envelope

extruded PE



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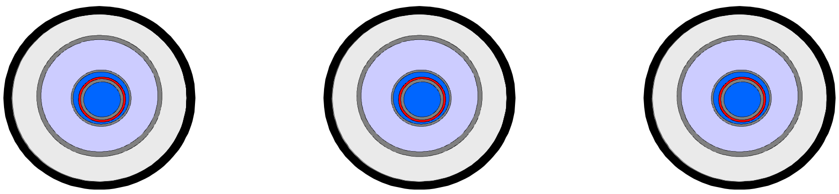
Cable designs (5)

3 separated phases



- Magnetic field from one phase affect the others
- Needs to separate the 3 phases
- Difficult to manufacture joints

Not realistic for long length power link

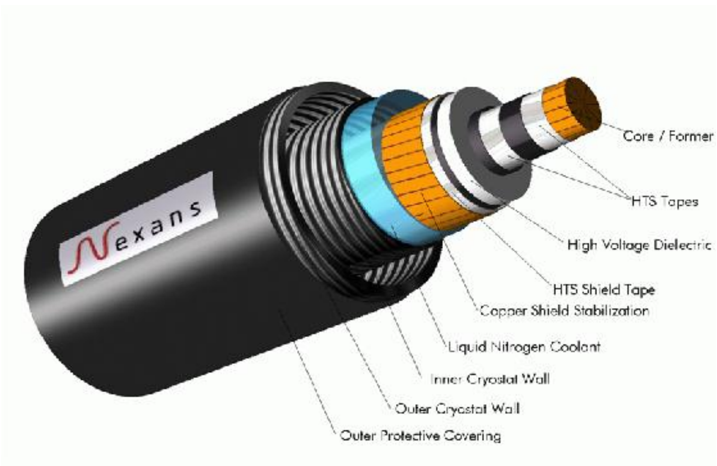
Cable designs (6)

- Cable: Transport the power from one termination to an other
  - High Currents and voltages management with the lower losses
  - 2 solutions for high voltage management:

1. Dielectric applied to the external envelope ⇒Warm dielectric design
2. Dielectric inside the inner envelope ⇒Cold dielectric design

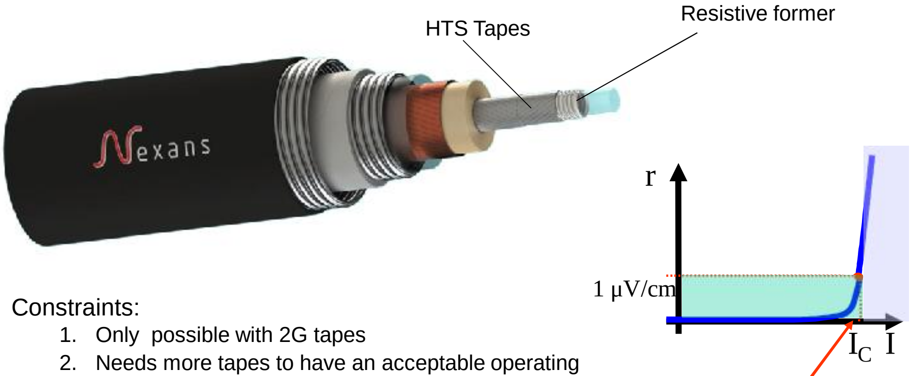
Cable designs (7)

1. Fault tolerant design



Cable designs (8)

2. Fault limiting design



Constraints:

1. Only possible with 2G tapes
2. Needs more tapes to have an acceptable operating current/critical current ratio
3. Amount of fault current limitation depends on cable length and voltage level (about 10 V/m are needed)
4. Parallel paths of the grid need to be present

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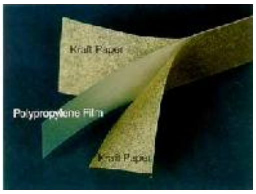
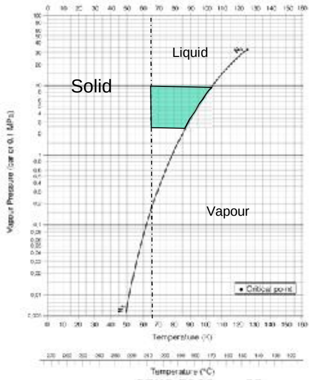
Cable designs (9)

Cold dielectric material

1. Kraft paper for DC
   - Dielectric strength 25-50 kV/mm & εr = 2-5
2. Poly Propylene Laminated Paper (PPLP) for AC
   - Low dielectric losses and can stand low cryogenic temperature
   - Dielectric strength ~ 40 to 45 kV/mm (LN2 pressure dependent) & εr = 2,2
3. But also Liq N_2 under 5 to 10 bar
   - Dielectric strength ~ 40 to 80 kV/mm (pressure dependant) & εr =1.4
   - **But in N_2 gas dielectric strength only 2-3 kV/mm Ĝ Gaz bubbles are forbidden ..**





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Cable designs (10)

PPLP AC Losses in HV insulation

$$Wins = 2\pi\ f \tan\delta\ C\, U^2$$

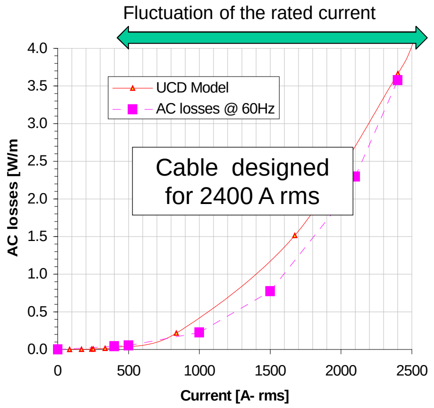
f	Frequency in [Hz]	typically 50-60 Hz
C	Capacity of the cable per meter in [F/m] $C/m = 2\pi\varepsilon_r\varepsilon_0 \ln(\frac{r_{ext}}{r_{int}})$ C ~ to 1,2 10^{-10} F/m for high voltage cable	
U	V_{rms} voltage in [V] between ground and phase	
δ	Loss angle from the insulation material in [°]	~0,001 to 0,002

Voltage rms	Losses W/m at 77K
63 kV	0,05-1
110 kV	0,15-0,3
220 kV	0,5-1
400 kV	2-4

Typical losses from Cryogenic envelopes ~1 to 1,5 W/m

Cable design (11)

Many models exists to estimate the AC losses in assembled power cable

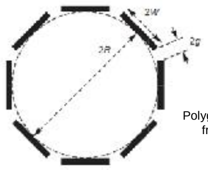


Example: UCD model & measurements
Cable core with 2 layers of Bi2223 + 1 screen

The AC losses are dependant on the **instantaneous** current and not the design current

Rem : If **only parralel field** is considered losses at 2400 A rms ~2,6 W/m

A limited contribution of the **perpendicular field** at the edges of tapes due to polygonal shape has to be considered !!!



Polygonal shape of the cable from Mawatari, Y. &All

Cable designs (12)

Losses at 65-80 K in cold dielectric power cables

	Dependence	Parameters	Losses at 65-77 K	Losses at RT
Cryogenic envelop losses	None	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 à 1 W/m	Up to 12,5 W/m for 220 kV
Eddy current AC losses	Magnetic field distribution	Cable design (pitches, diameter,..)	0,05 to 0,1 W/kA.m	1,25 to 2,5 W/kA.m

For a Cu cable typycal. 20 W/kA.m

Nb: For DC current, the losses are only from the cryogenic envelop

Cable designs (13) for AC mode

Systems	2 or 3 coaxial poles or phases	2 or 3 poles or phases in one envelop	1 pole or phase per envelop
Conception			 X3
Voltage	For low voltage < 30 kV	Up to medium Voltage < 90 kV	For high voltage
Interests	- Reduced costs minimized the quantity of tapes - One termination for the 2 poles or 3 phases	Possibility for one termination for the 2 poles or 3 phases	-For very high power(500 MW or more) - Possibility for the longest lengths
	No environmental impact		

Cables designs (14) but also for DC mode

Systems	2 coaxial poles	2 twisted poles in one envelope	1 pole per envelope
Conception			 x2
Voltage	Low voltage < 30 kV	Medium voltage≤ 90 kV	Medium to high voltage > 90 kV
Benefits	Very compact cables		Very bulk power transferred up to 5 GW
	- No magnetic impact -Common terminations and joints for both poles	Common terminations and joints for both pole	Maximize unit length
	No thermal impact		

Cable designs (15)

Other important parameters to consider

1. Cabling process (Multi-steps process)
   - Cabling machines ⇒Tension & torsion on tapes & assembled semi-finish conductors
   - Insulation lapping machines ⇒ Radial pressure generated by the lapped insulation
   - Caterpillars & capstans
   - Bending on drums
2. Installation on site
   - Push & pull
   - Drum size and access
   - Turns of the cable path way
3. Thermal shrinkage
   - Shrinkage ~0.3% contraction between 300K to 77 K ⇒ 3 m per km or a stress of few tons ⇒ Stress/strain management into the system is required
   - Compatibility of the different materials

Cable designs (16)

Exceptional events : The superconducting power distribution system shall survive

1. Fault currents
   - Very high current pulses = 10 to 50 time nominal current during the switching time of few 100 ms

     Solution: **Use copper or aluminum core to transfer the energy of the fault combined with high pressure LN2 (3 to 10 bars) to avoid bubbles**
2. Impulse voltage
   - Lightning voltage pulses = few hundreds to million of kV during a few ms
     - Tested with a HV pulse (HT increase 1,2 ms / HT decrease 50 ms)
   - Switching voltage pulses = few hundreds of kV during a few ms
     - Tested with a HV pulse (HT increase 250ms / HT decrease 2500 ms)

     Solution : **Use high pressure LN_2 (3 to 10 bars) to avoid bubbles in HV insulation**
3. Over-voltage
   - High voltage pulses (few % more than rated voltage)

     Solution: **Design of the cable with a sufficient insulation thickness to meet safety requirements**

Content

Introduction to superconducting power cable systems

1. The 5 main components
   - A. Superconducting tapes and wires
   - B. Cryogenic envelopes
   - C. Cryogenic machines
   - D. Cable designs
     - Warm dielectric
     - Cold dielectric
   - E. Terminations & Joints
2. Tests & Reliability
3. Some applications
4. HTS power cable system benefits

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Terminations & Joints (1)

- Termination: a key componant to connect the power cable to the grid
  - Multifunction piece with complex stresses:

Current & voltage transmission to the Network

Thermal gradien management

Warm electrical insulation between ground & voltage

Inject the LN2 flow

Cold electrical insulation between ground & voltage (Cable)

Thermal insulation (Cable)

Current and voltage transmission to the cable (Low resistivity)

Complete or partial management of the shrinkage of the cable

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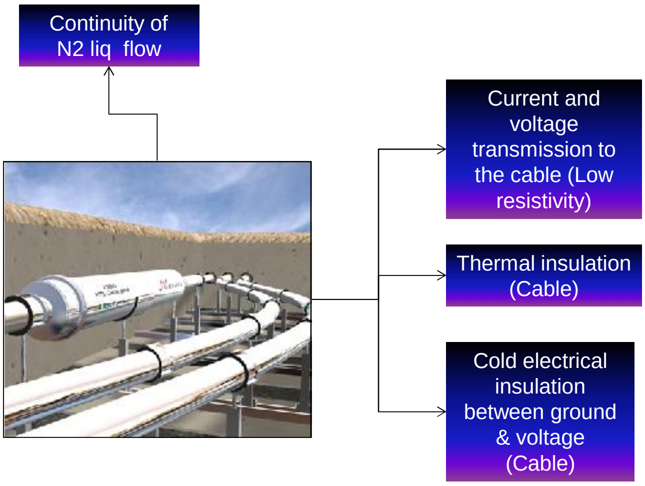
Terminaisons & Joints (2)

- Joint: Cold electrical connection for long cables on field



Terminations & Joints (3)

- Cryostat losses
  - Depending on the size from 1 to 5 W at 77K)
- For current leads a balance between
  1. Thermal conduction of the current leads for termination
  2. Electrical resistance of the current leads
- Electrical & resistive connections of the cable
  - Core & screen

W/kA	77K	RT
Termination when energized	40 à 50 W/kA	0,8 to 1 kW/kA
Termination When I tr=0	20 to 25 W/kA	0,4 to 0,5 kW/kA
Joint ~1 µ Ω	1	20 W

1. Terminations: can be tested in lab before field installation
2. Field Joint: tests only on prototypes

Nexans

Terminations & Joints (4)

- Failures generally come from:
  - Thermal stresses and fatigue
    - ✓ Thermo-mechanical modeling
      - ➔ Differential shrinkage
      - ➔ Cooling rates
    - ✓ Materials properties to be measured on prototypes (thermal expansion coefficient, thermal conduction,…)
  - Aging of dielectric materials
    - ✓ Only few data on the materials used
      - ➔ but low temperature (77K) will help to limit aging phenomena

⇒ To be qualified by cooling down several times on the final terminations & joints

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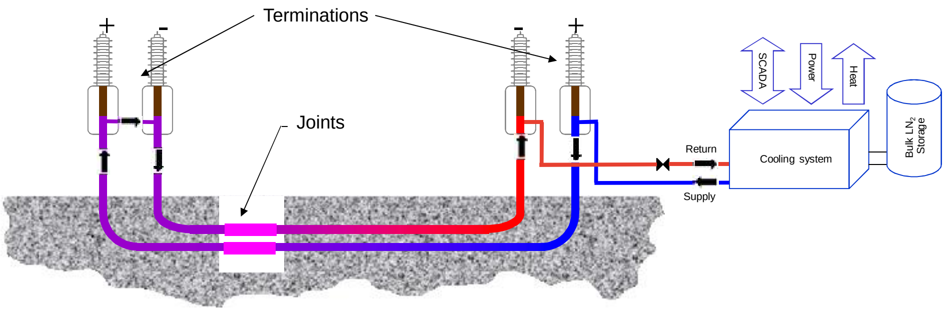
System integration (1)



1. The coolant can be gaseous or liquid
2. Temperature difference and pressure drop between inlet and outlet depend on:
   - Length of the cable
   - Thermal and electrical losses

⇒For optimized system this temperature difference <2 K and pressure drop less than 3-5 bars

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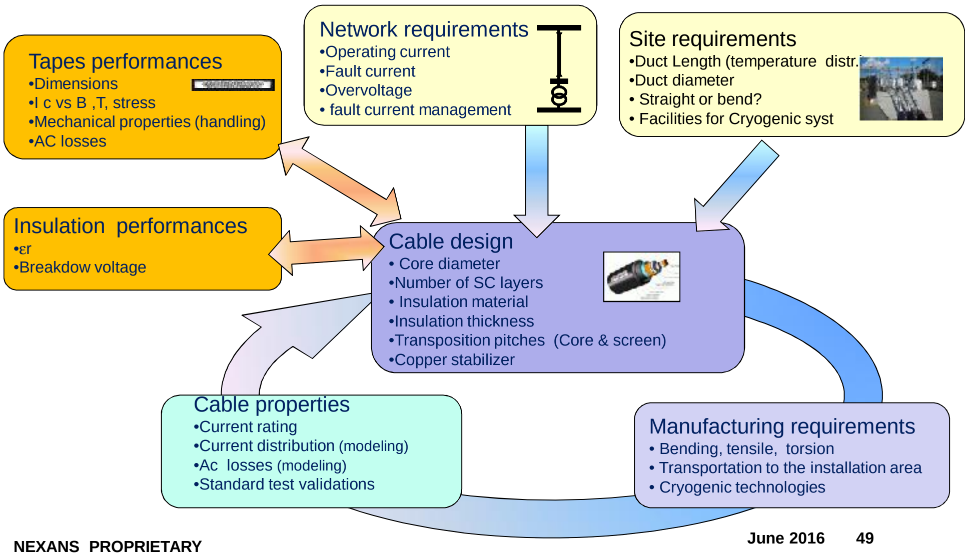
System integration (2)

- Electro-magnetic optimization for : the highest current *(optimum magnetic field on tapes)* with the highest efficiency *(reduction of costs of cryogenic systems)*



Content

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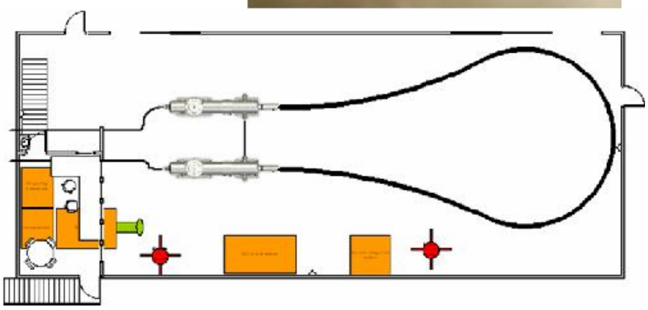
Tests & Reliability (1)

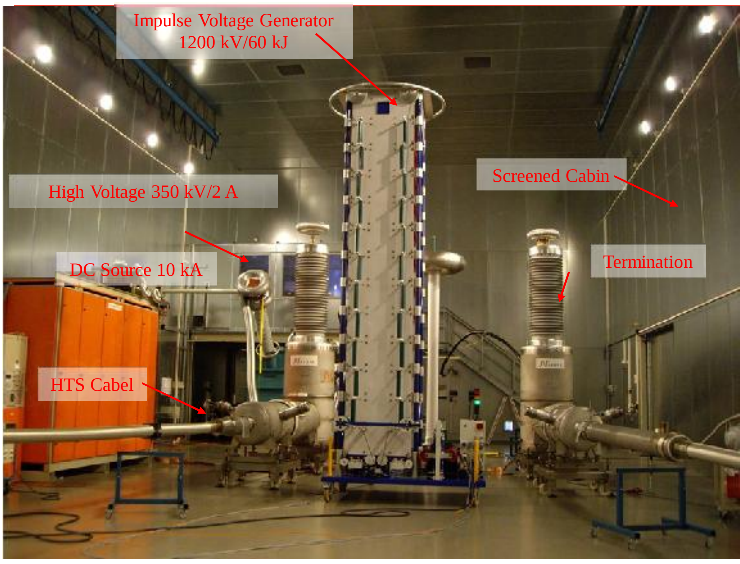
1. Reliability & long time test programs are running
   - LIPA cable is in the Long Island network since april 2008
   - Southwire cable energized in august 2006
   - Fujikura cable is running long time tests with CREPRI
   - Ampacity cable runs since 2014
2. Standard tests similar as for « resistive » HV cables
   - Over-voltage tests
   - Accelerate “aging” experiments
     - ✓ Over voltages & currents
   - Long time validations on plateforms
   - New standard under preparation for AC cables based on CIGRE works

Tests & Reliability (2)

- Faraday cage de 30 m x 12 m x 9 m supply with presurized Liq N2



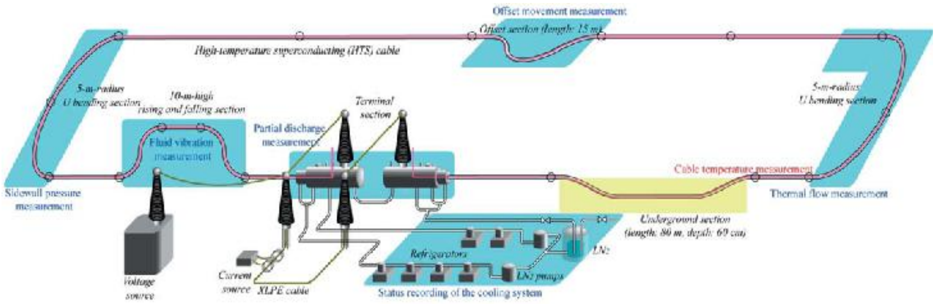
Tests & Reliability (3)



138 kV, 2400 A, 30 m Prototype in the test field in Hanover

Tests & Reliability (4)

CRIEPI Test field



Test field for the different cases of installation

1. Tension: 77 kV
2. Current: 1kA

Content

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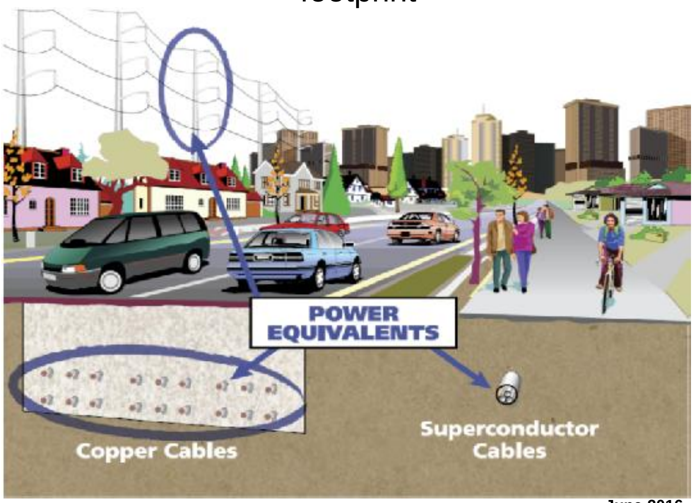
some applications
1- Urban grids

In urban girds, superconducting cables only need a reduced footprint



Some applications
1. Urban grids: Ampacity project at Essen (1)

AMPACITY
Smart grids for the city

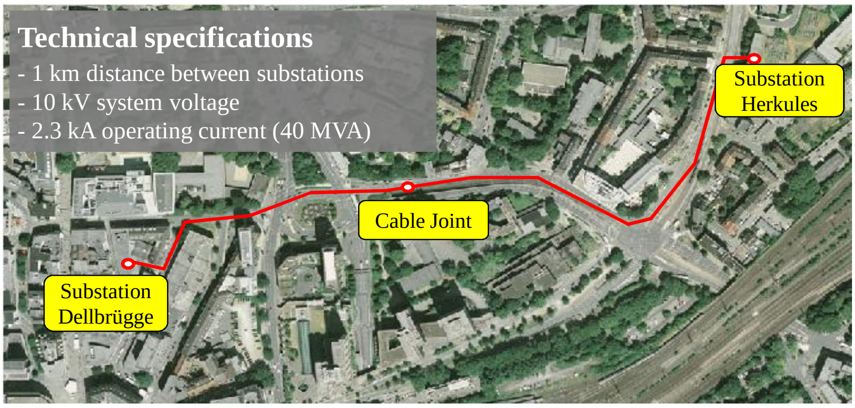
- **Application:**
  Feeding the center of Essen at medium voltage (10 kV) level with a superconducting cable

- **Economic viability:**
  The higher cost of the superconducting cable is compensated by savings in substation equipment

- **Additional benefit**:
  Real estate becomes available in the city center

VORWEG GEHEN

Some applications
1. Urban grids: Ampacity project at Essen (2)

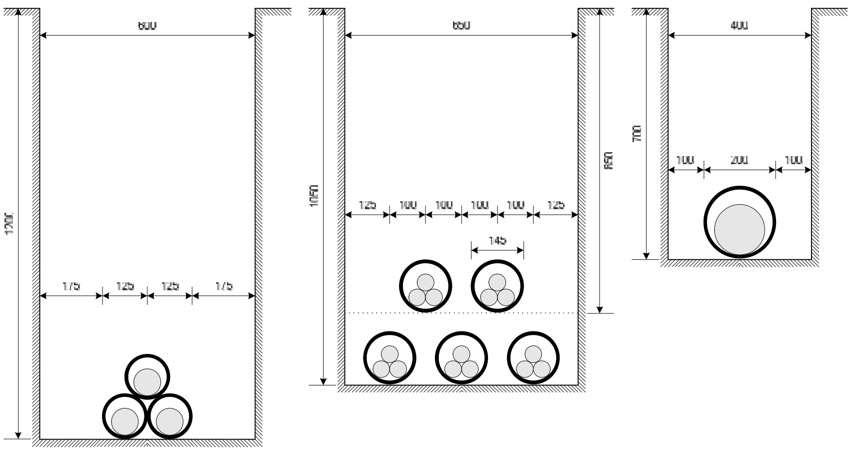


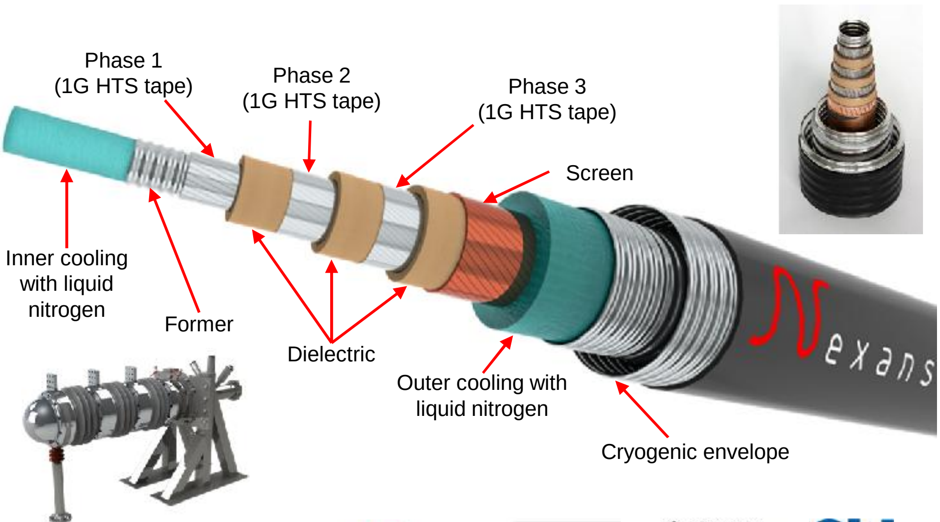
Longest high temperature superconducting (HTS) cable in the world !

VORWEG GEHEN

3 solutions considered

Conventional 110 kV cable | **Conventional 10 kV cables** | **10 kV HTS cable**





VORWEG GEHEN

Some applications
1. Urban grids: Ampacity project at Essen

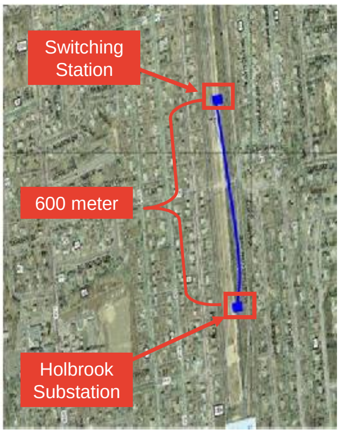
Official celebration on April 30, 2014

From left to right: Dr. Joachim Schneider, CTO RWE Deutschland AG, Dr. Arndt Neuhaus, CEO RWE Deutschland AG, Peter Terium, CEO RWE AG, Reinhard Paß, Lord Mayor of the City of Essen, Dr. Johannes Georg Bednorz, Nobel laureate 1987, Dr. Hans-Christoph Wirth, German Federal Ministry for Economic Affairs and Energy, Hannelore Kraft, Prime Minister of the German federal state North Rhine-Westphalia, Christof Barklage, CEO Nexans Deutschland GmbH, Prof. h.c. Dr. Joachim Knebel, area manager Karlsruhe Institute for Technology

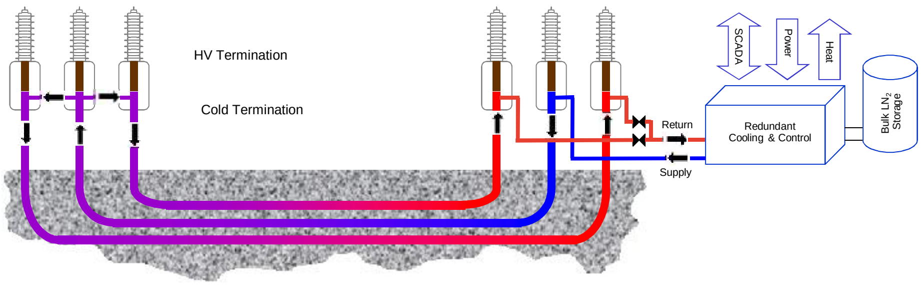
Some applications
2. Urban HV grids: LIPA project at Long Island

Demonstrated the feasibility of HV superconducting cables

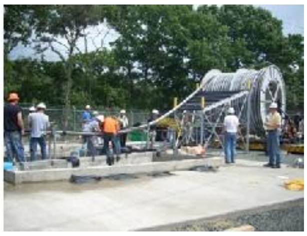
- Partners: American Superconductor (leader), Long Island Power Utility (LIPA), Air Liquide
- Funding: U. S. Department of Energy
- 600 m long cable system
  138kV/2400A ~ 574MVA
- Design fault current:
  51 kA @ 12 line cycles (200ms)
- Cable phases pulled in
  underground polyethylene conduits



Some applications
2. Urban HV grids: LIPA project at Long Island



Some applications
2.Urban HV grids: LIPA project at Long Island



Cable successfully energized on April 22, 2008

Some applications
2.Urban HV grids: LIPA project at Long Island

World's longest HTS cable (at that time) successfully energized on April 22, 2008

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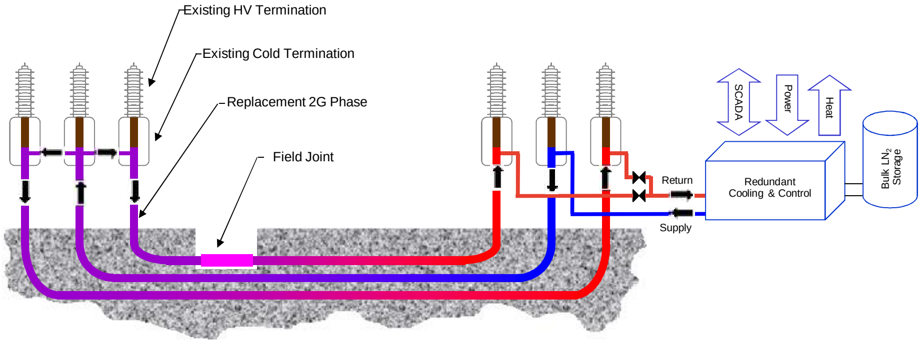
Some applications
2.Urban HV grids: LIPA 2 project at Long Island



- Project objectives
  - Thermal contraction inside the cable
  - Cable joint development
  - Repairable cryostat
  - Use of 2G wire
  - Development of modular refrigeration unit

- in March 2012
  - Single phase of stabilized 2G cable to survive short circuit currents
  - New cryostat (2 pieces)
  - Cable joint

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Some applications

2. Urban HV grids: LIPA 2 project at Long Island

HVAC cable joint developed and installed in field

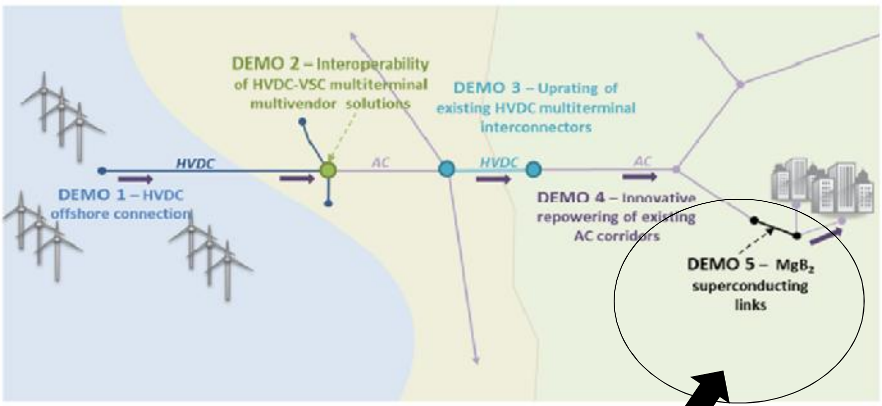
- 138 kV HTS cable joint has been developed and qualified in a type test sequence on such small loop

Some applications

3. HVDC grids: Bestpaths FP7 Project

Best Paths PROJECT

5 high level demonstration projects



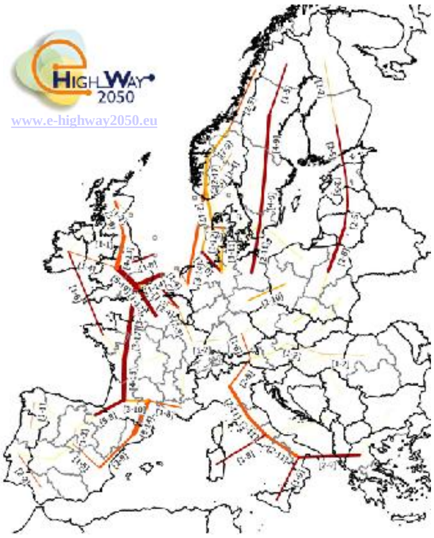
October 2014 September 2018	Total budget (EC contribution: 57 %) 62.8 M€ = M$ 70.8 = 460 M¥

Some applications
3. HVDC grids: Bestpaths FP7 Project

Future prospects of transmission grid development

- European **eHighWay2050** Project brings very useful input data
  - New methodology to support grid planning
  - Focusing on 2020 to 2050
  - To ensure the reliable delivery of renewable electricity and pan-European market integration
  - Five extreme energy mix scenarios considered
- Whatever the scenario, 5 to 20 GW corridors are identified
  - Major North-South corridors are necessary
  - Connections of peninsulas and islands to continental Europe are critical
- How to transmit more than 4 GW on long distance?

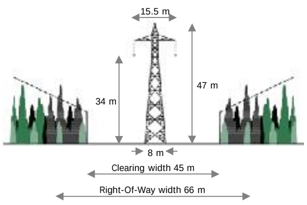
www.e-highway2050.eu



Some applications
3. HVDC grids: Bestpaths FP7 Project

How transmit bulk power 3-5 GW? (examples of corridors)

Nelson River DC line (Canada)
1600+1800 MVA (+2000 under construction)



Raesfeld (380 kV AC, Germany)
2x 1800 MW

Some applications
3. HVDC grids: Bestpaths FP7 Project

10 partners for Demo 5

Nexans
- Optimization of MgB2 wires and conductors
- Cable system
- Cryogenic machines
- Testing in GHe
- Integration into the Grid

CERN
- Optimization of MgB_2 wires and conductors
- Cable system

Columbus Superconductors
- MgB_2 wire
- Optimization of MgB2 wires and conductors

Technische Universität Dresden
- Cryogenic machines

Politécnica "Engineering the future"
- Reliability
- Integration into Transmission grid

RTE – Réseau de transport d'électricité
- Cable system
- Integration into Transmission grid
- Testing in GHe
- Reliability

IASS Potsdam
- Scientific coordination
- Dissemination & exploitation

ESPCI ParisTech
- Cable system

KIT – Karlsruhe Institute of Technology
- Cable system

RSE
- Cable system

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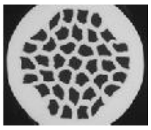
Some applications
3. HVDC grids: Bestpaths FP7 Project

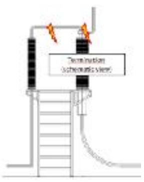
Main objectives of the superconducting demonstrator

- 10 partners to demonstrate the following objectives
- Demonstrate full-scale **3 GW** class HVDC superconducting cable system operating at 320 kV and 10 kA
- Validate the novel **MgB_2** superconductor for high-power electricity transfer
- Provide guidance on technical aspects, economic viability, and environmental impact of this innovative technology

Process development to manufacture a large quantity of high performance MgB_2 wires at low cost

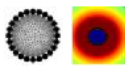


Cable and termination development + manufacturing processes



Validation of cable operations with laboratory experiments performed in He gas at variable temperature

Operating demonstration of a full scale cable system transferring up to 3.2 GW



System integration pathways for HDVC applications

Investigation in the availability of the cable system

Preparation of the possible use of H_2 liquid for long length power links

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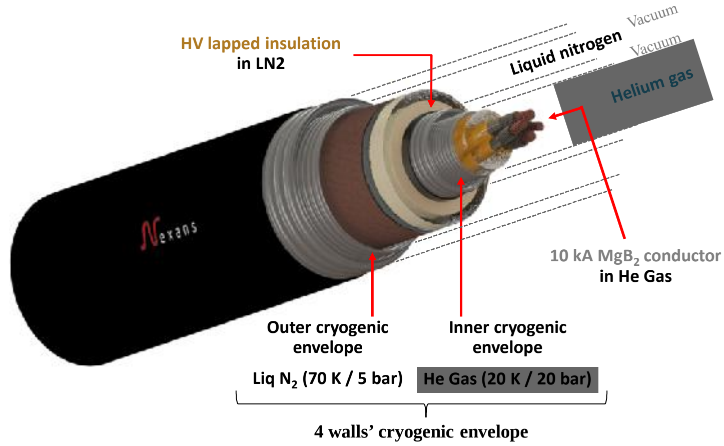
Some applications
3. HVDC grids: Best Paths FP7 project

Superconducting HVDC cable concept

Conceptual design

- Two fluids to guaranty the safety of the operation



Demonstrator characteristics
Monopole
3.2 GW
320 kV
10 kA
20 - 30 m

Project on going….

Some applications
3. HVDC grids: Best Paths FP7 project

Reduced space for cable installation and substations

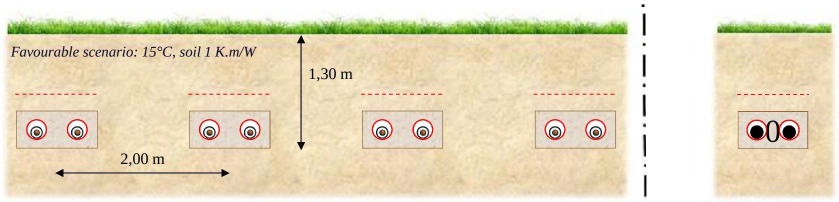
Significant reduction of right-of-way and excavated soil

No thermal dependence to the environment

Example: 6.4 GW DC power link with XLPE cables

Foot print = 7 m

Foot print = 0.8 m

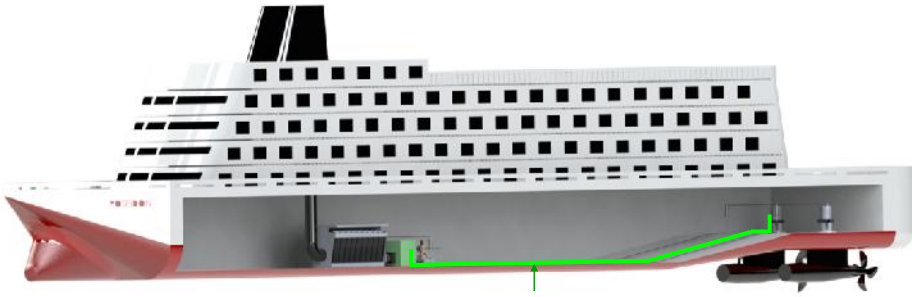


Resistive cables (8 x 400 kV - 2 kA)

Best Paths Demo 5
(2 x 320 kV - 10 kA)

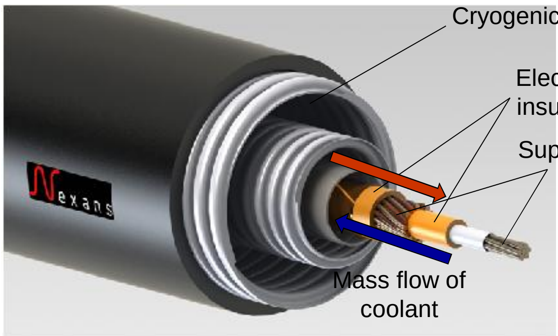
Project on-going….To be tested in 2017

Some applications
4. HTS cables onboard a ship



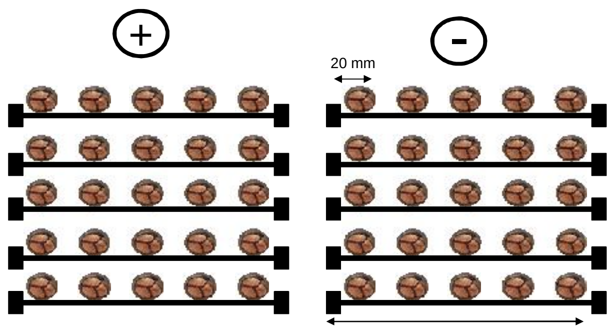
Some applications
4. HTS cables onboard a ship

1. Distribution of high power possible at low voltage (<4 kV)
2. Reduction of the losses for distributed power P> 5MW



3. No environmental impact *(thermal or electromagnetic)*
4. Very compact and light cable
   - D ext = 60 mm for bifilar SC cable 66 MW 10 kA/3,3 kV
   - Cryogenics system footprint between 1 to 5 m²

Conventional system (2 x 25 x 400 A)



1. Large commercial electrical ships *(several electrical motors P> 5 MW)*
   - Cruise ships
   - Container cargos
   - LNG tankers
     - Large cooling power available on board
     - Habilitation for operation in cold environment
   - FPSO (Floating production storage and offloading)

2. Navy ships
   - Degaussing cables (ex USS Higgins)
   - Submarines

Some applications
5. HTS cable on board a plane

The electrical or hybrid plane will allow to reach the objective of 50% CO_2 reduction per passenger in 2020

- From 5 to 100 MW are necessary to power the plane according to the number of passagers

Voltair project from Airbus ind.

Up to 95 % of weight reduction with superconducting cables !!!

Ex: Cable 1,2 MW
Uop= 200 V, Iop = 2 x 3000 A
Weight < 6 kg/m (<1kg/km.A)
(140 kg/m for equivalent copper cables)

Some applications
6. Others

All activities requiring large electrical power at low voltage such as:

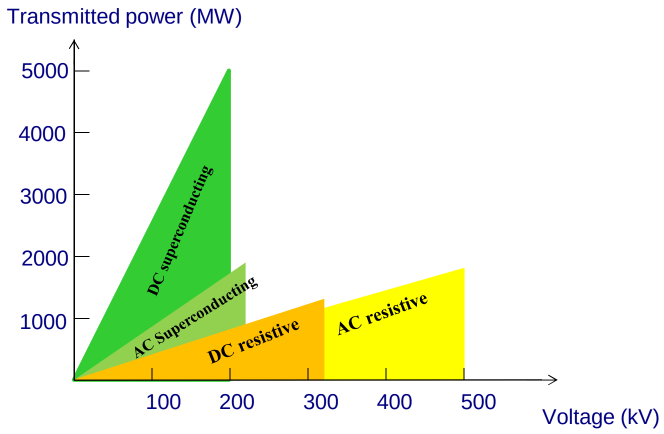
- Data centers
- Metallurgy plants
- Harbor and off shore platforms
- Railways
- Large reviewable energy farms
- …..

can potentially benefit from superconducting cable technologies…

Content

Introduction to superconducting power cable systems

HTS power cable system benefits (1)



HTS cables provide a much higher power transfer capability at the same voltage

HTS power cable system benefits (2)

1. Increased power transferred at a reduced voltage level
2. Negligible thermal impact on the environment
3. No outer magnetic field during normal operation
4. Reduce volume of raw materials required
5. Reduced space for cable installation and substations
   - Easier cable installation
   - Increase the possibilities of electrification

Conclusion

1. Superconducting cables are a new tool to adapt the electrical network and improve the efficiency in a world becoming increasingly urban with a production of electricity less centralized.
2. All the elements are ready to build superconducting links adapted to many applications for the environmental challenges of tomorrow
3. Superconducting cables are vectors of the energy transition required for our future
4. But still a lot of technical and commercial works is needed for an optimized use and general acceptance…..

Thank you for your attention !

Cartoon by
Thomas Kodenkandath
(*The Week, 1988*)