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Best Paths
Transmission for sustainability

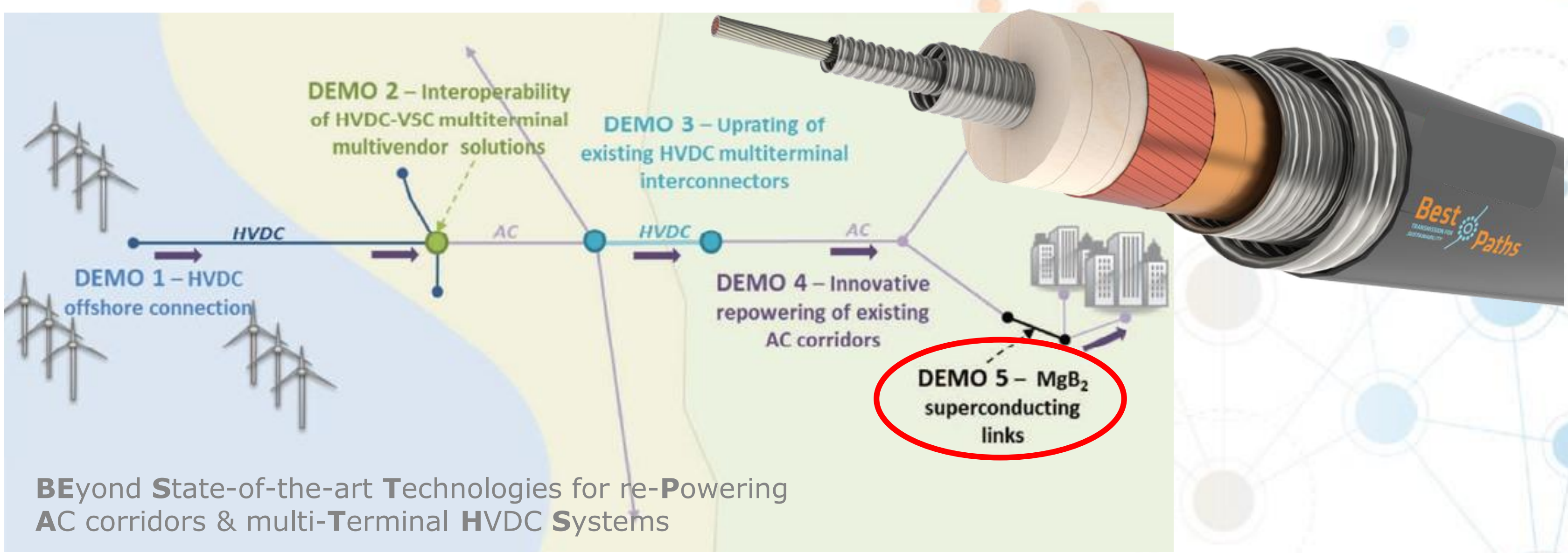
MGB2 SUPERCONDUCTOR: A 3.2 GW DEMONSTRATOR FOR BULK HVDC UNDERGROUND TRANSMISSION

Frédéric LESUR (Nexans, France)

(on behalf of the Best Paths Demo 5 project team)

A project to overcome the challenges of integrating renewable energies into Europe's energy mix

Best Paths Project: the largest project ever supported by the European Commission R&D Framework Programs within the field of power grids



October 2014
September 2018

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

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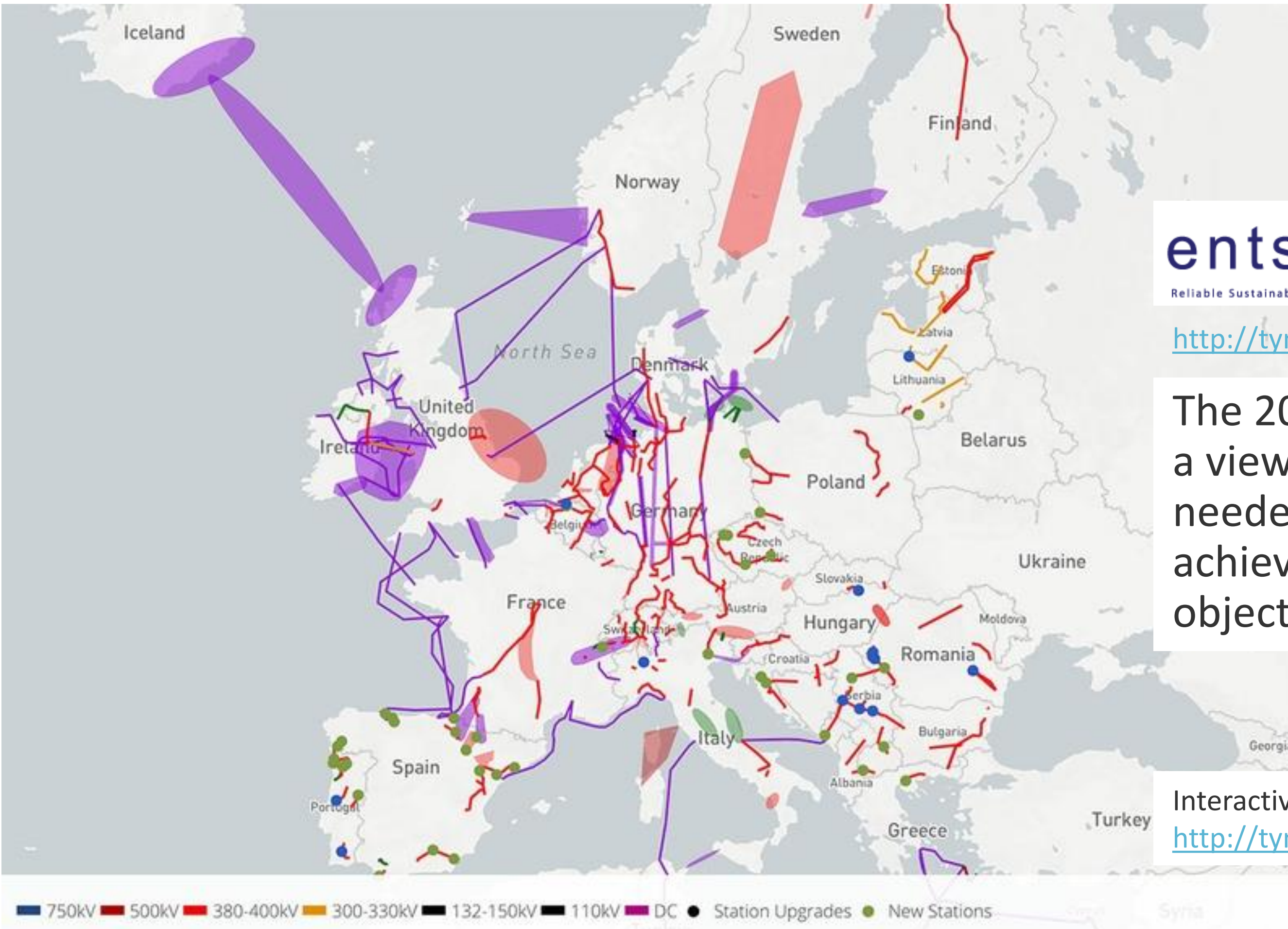
TYNDP = Ten-year network development plan (ENTSO-E)



entsoe
european network of transmission system operators for electricity
Reliable Sustainable Connected

http://tyndp.entsoe.eu

The 2016 edition offers a view on what grid is needed where to achieve Europe's climate objectives by 2030

Interactive map:
http://tyndp.entsoe.eu/reference/#map

Future prospects of transmission grid development

European **eHighWay2050** Project brings very useful input data

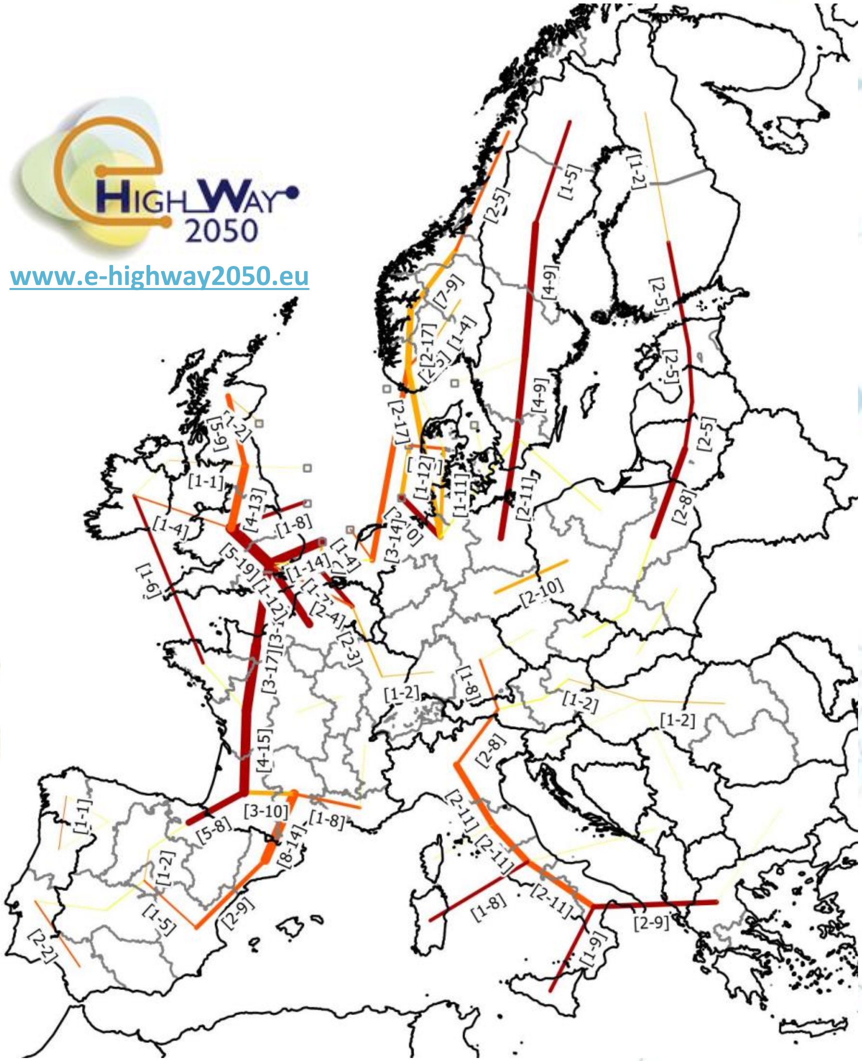
- New methodology to support grid planning
- Focusing on 2020 to 2050
- To ensure the reliable delivery of renewable electricity and pan-European market integration
- Five extreme energy mix scenarios considered

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 over long distances?

www.e-highway2050.eu



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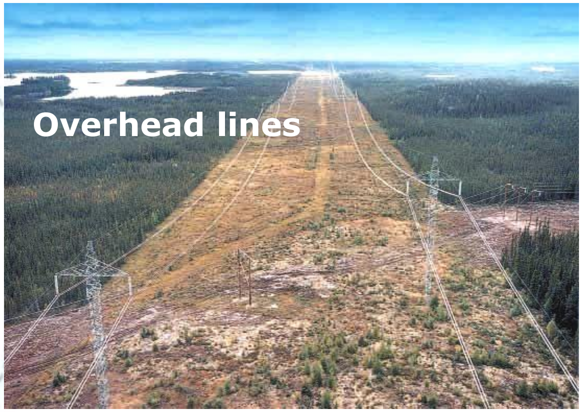
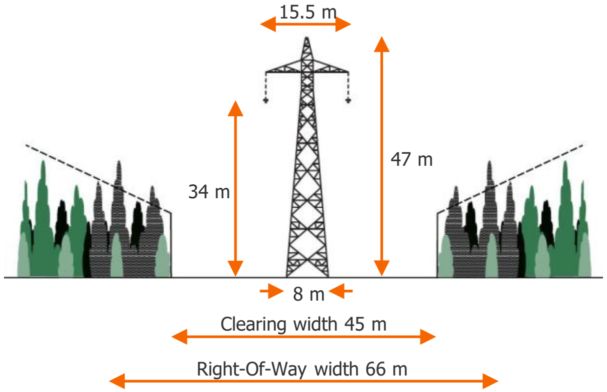
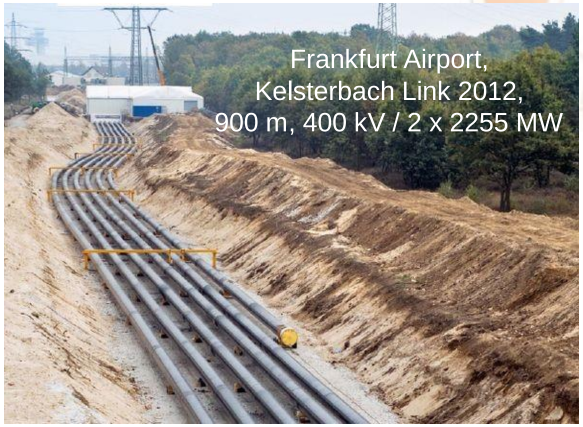
How to transmit bulk power 3-5 GW? (examples of corridors)



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





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

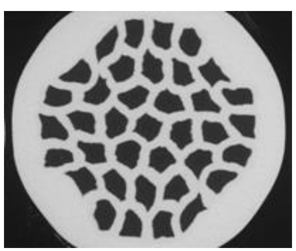
Bulk power: is there an alternative solution to UHVDC?

Main objectives of the superconducting demonstrator

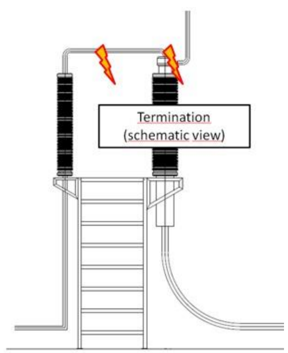
10 partners to demonstrate the following objectives

- 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

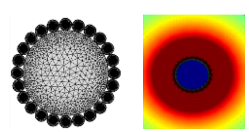


Cable and termination development + manufacturing processes



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



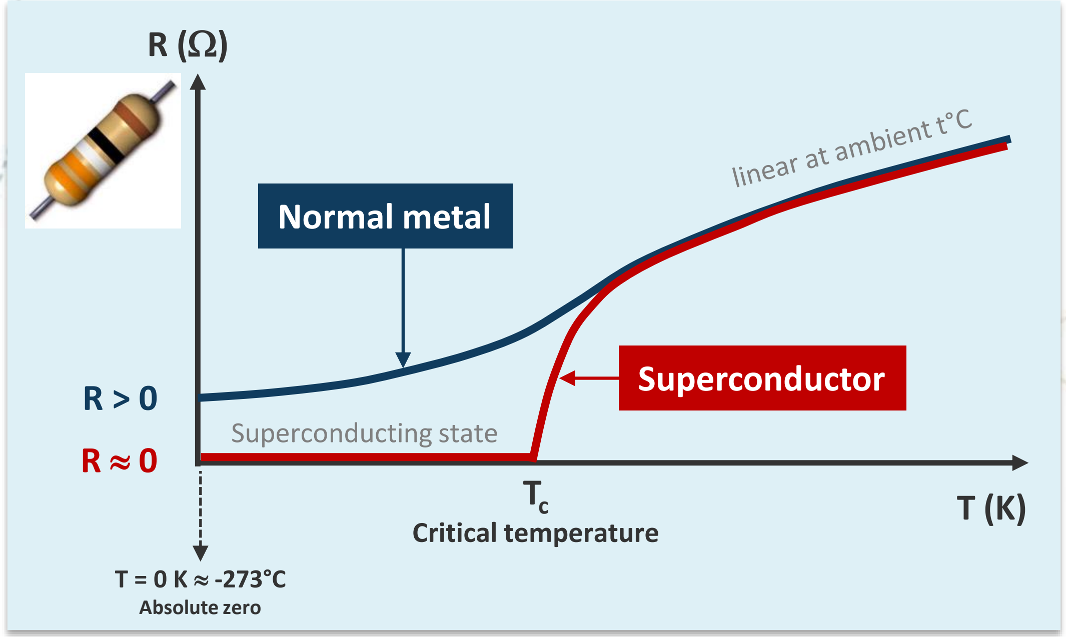
System integration pathways for HDVC applications

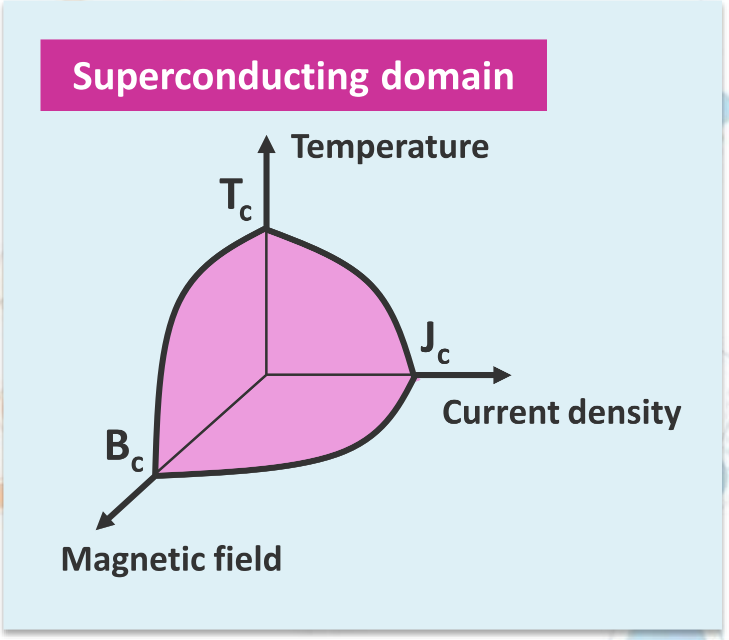
Investigation in the availability of the cable system

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

What is superconductivity?

Superconductors = almost perfect conductors of electricity:
no electrical resistance!





Requirement of cooling at very low temperatures

T = 0°C ≈ 273 K
(water becomes ice)

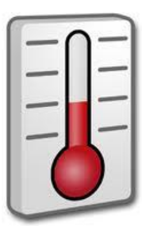
Ambient temperature

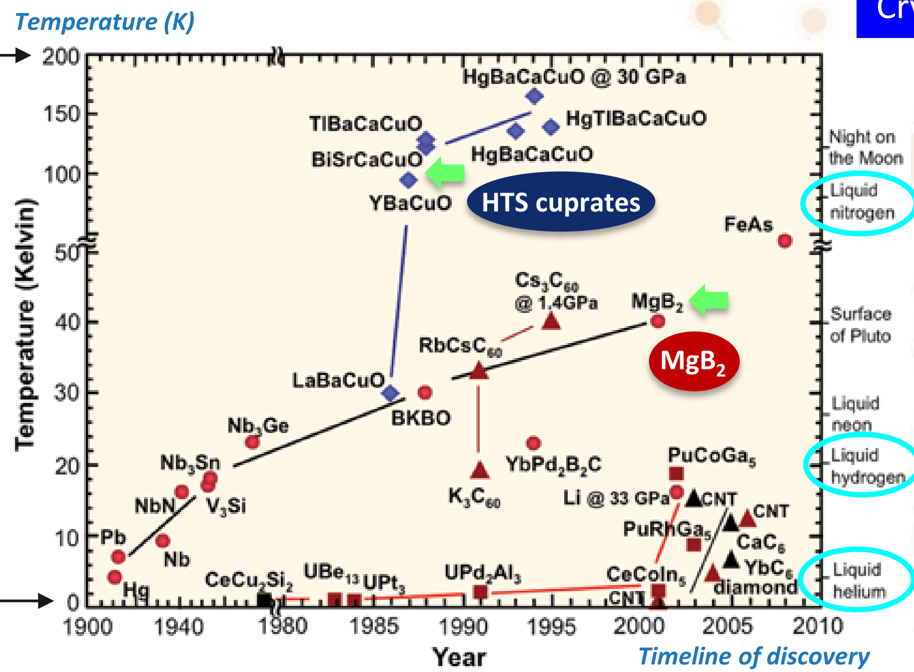
Superconducting materials

Cryogenic fluids

T = 200 K ≈ -73°C

Industrial cooling





Liquid nitrogen

Liquid hydrogen

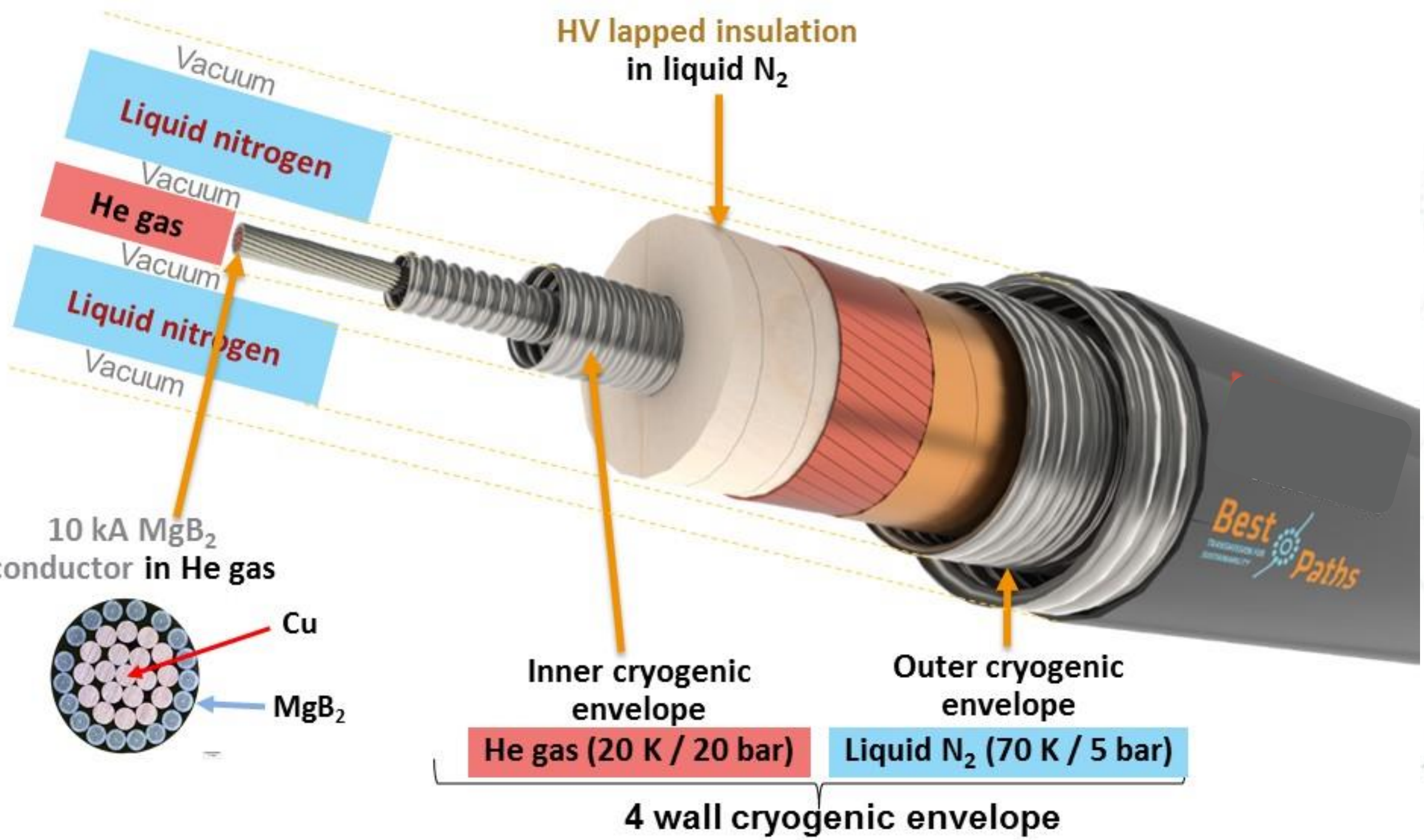
Liquid helium

Extreme cold

T = 0 K ≈ -273°C
Absolute Zero
(lowest temperature that can be reached in the universe)

Conceptual design

Two fluids to guarantee reliable operation



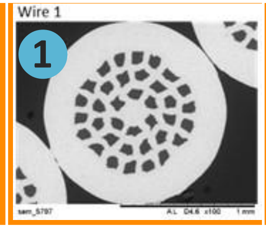
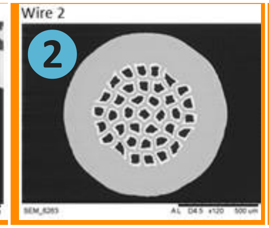
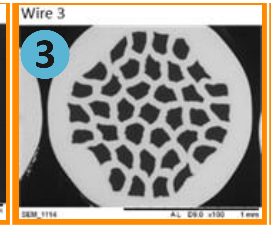
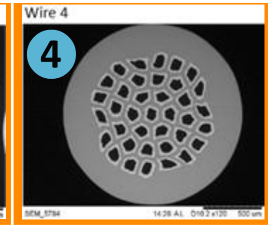
Demonstrator technical specification and testing strategy

Characteristics	
Structure	Monopole
Power	3.2 GW
Voltage	320 kV
Current	10 kA
Length	~ 20 m
Cooling media	Liq N_2 for the electrical insulation He gas for MgB_2 conductor
Losses of the demonstrator	< 50 W He gas (~20 K)
Fault current	35 kA during 100 ms
AC Ripples on 10 kA DC current	< 1% amplitude 50 Hz
Change of power flow direction	100 MW/s up to 10 GW/s

- Test of operating conditions on the demonstrator
- But use only modeling to check the cable behavior during faults and polarity changes

Completed R&D work on the MgB_2 round wires

RESULTS

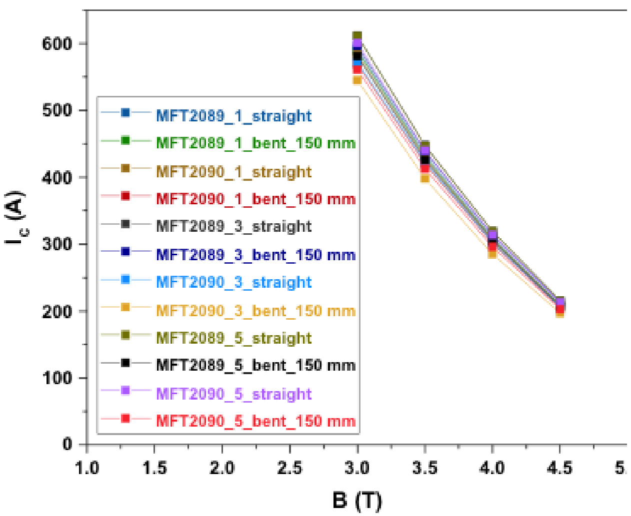
MgB_2 wires				
Diameter (mm)	1.3	1.0	1.5	1.5
Materials	Monel, Ni	Monel, Ni, Nb	Monel, Ni	Monel, Ni, Nb
MgB_2 volume fraction	17 %	12 %	30 %	12 %
I_c (A) @ 20 K & 1 T	500	300	> 650	> 650
I_c (A) @ 4.2 K & 3 T	280	400	> 700	600
r_c (mm)	125	100	200	150

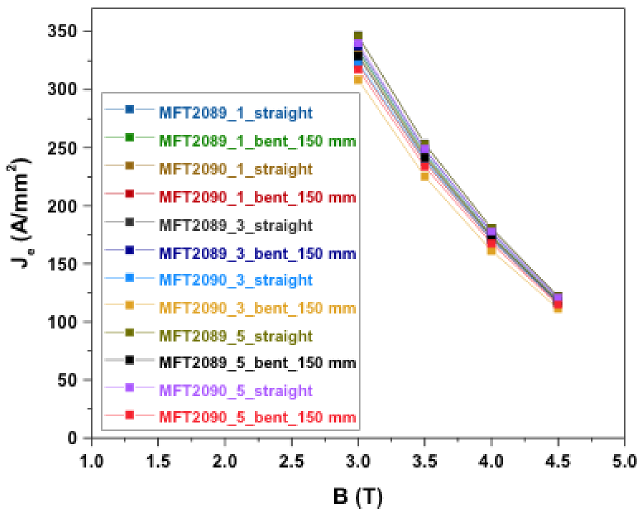
- Wire diameter homogeneity achieved along the entire batch length of about **2 km**
- Confirmation of the wire process capability to stay within the **specification limits**

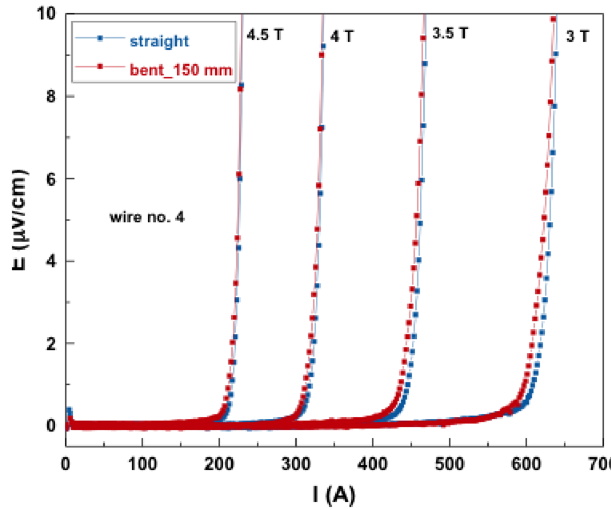
Measurements performed on the high-power MgB_2 wires

RESULTS

No I_c degradation measured







- Measurements at 4.2 K performed on straight and bent samples from last **long-length production run**
- The magnetic field was applied **parallel** to the longitudinal axis of the wire

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MgB_2 cable conductor designs with a fault tolerant configuration

Base design with wire #1

- Cable manufactured on industrial cabling machines
- Measurements of extracted wires performed after cabling after bending on 0,8 m diameter drum by Columbus SPA show no degradation
- Validation by electrical characterization of cable prototypes at CERN: Measurements of the critical current of 2 meter long prototype cable tested in liquid (at 4.3 K)

18 MgB_2 wires
I_c = 14000 A
I_{op}/I_c = 0.72
D= 9.6 mm

Modeling: transient phenomena

- **Power inversion from 100 MW/s up to 10 GW/s**
  - Risk of quench identified at 10 GW/s ramp
  - But possible at 5 GW/s
- **Fault current: 35 kA during 100 ms**
  - Fault tolerant cable conductor design validated:
    - For the controlled quench cable design, the temperature after a fault has been estimated (≈ 90 K)
    - Time to recover ≈ several seconds
- **Ripple losses due to current source into the MgB_2 wire**
  - Ripples are acceptable:
    - 1 % 50 Hz ripples generate coupling losses in the same order of magnitude as the cryo-envelop (0.1 W/m) manageable with the cooling system

MgB_2 cable conductor designs with a fault tolerant configuration

RESULTS

Upgraded design with the new wire #4 developed

- 90 m of cable manufactured on industrial cabling machines

Next steps

Measurements of extracted wires performed after cabling after bending on 0,8 m diameter drum by Columbus SPA show no degradation

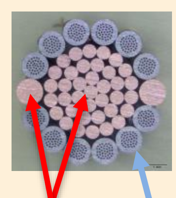
Validation by electrical characterization of cable prototypes at CERN: Measurements of the critical current of 2 meter long prototype cable tested in liquid (at 4.3 K)

12 MgB_2 +2 Cu wires

I_c = 13700 A

I_{op}/I_c = 0.73

D= 8,6 mm



Modeling: transient phenomena

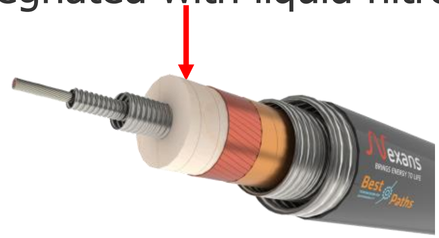
- **Power inversion from 100 MW/s up to 10 GW/s**
  - No quench expected at 10 GW/by implementation of long twist pitch (1000 mm)
- **Fault current: 35 kA during 100 ms**
  - Fault tolerant cable conductor design validated:
    - For the controlled quench cable design, the temperature after a fault has been estimated (≈ 100 K)
    - Time to recover ≈ several seconds
- **Ripple losses due to current source into the MgB_2 wire**
  - Ripples are negligible by implementation of long twist pitch (1000 mm)
    - coupling losses from ripples losses as the are 10 times lower than the cryogenic envelop

Cable system

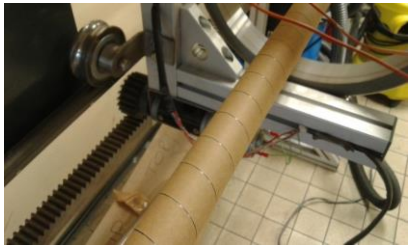
1. Find the best the high voltage insulation of the cable and the termination to pass the type test testing sequence defined in the Cigré recommendation TB-496 – ”Testing DC extruded cable systems for power transmission up to 500 kV” when relevant
2. Verify that no charge carrier is trapped into the cable insulation that can generate disastrous voltage breakdown in operation
3. Design accessories (Termination)
4. Specify a cooling system for the demonstrator

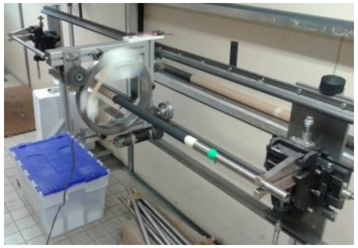
Cable system: HV cable insulation

HV cable insulation= lapped tapes impregnated with liquid nitrogen



A versatile and quick lapping line has been designed for preparation of short model 1 samples
- Different tapes' material (paper, PP, PPLP, etc…)
- Different dimensions (thickness, width,…)
- Different pitches and gaps between the tapes

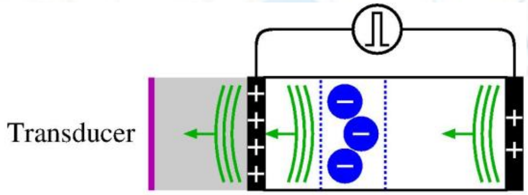




Select the best material to limit the space charges in DC with the highest voltage breakdown

A unique cryogenic HV testing equipment for space charge measurements close to operating conditions of the cable HV insulation was designed and is operational

It is based on electro acoustic method



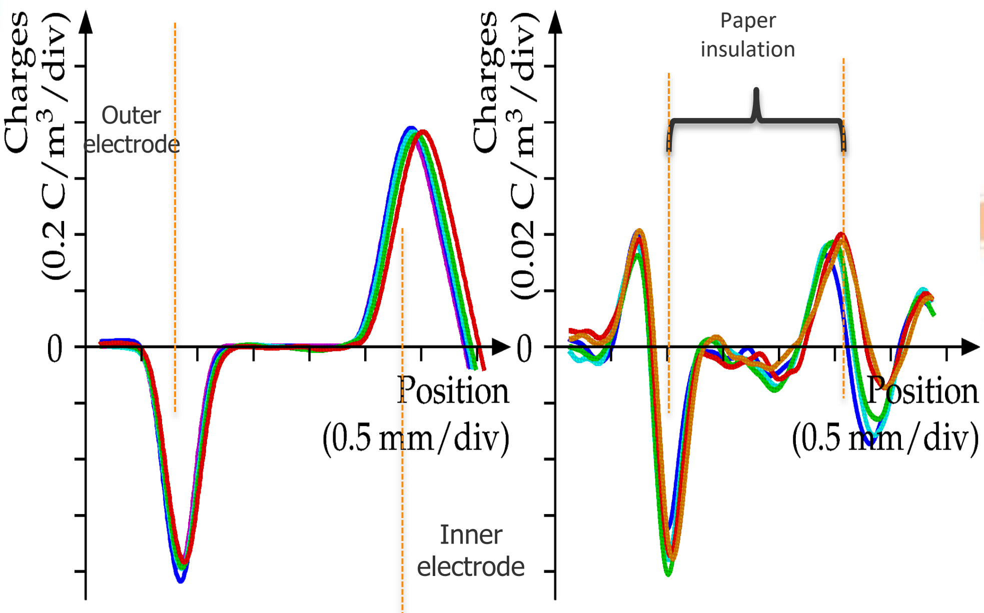
Cable system: HV cable insulation

Details to be published in IEEE mag and conférences

RESULTS

- 20 tests are applying 40 kV and 60 kV across a 2 mm thick Kraft paper and PPLP impregnated with Liq N_2 at 1 bar and 5 bar have been carried out

40 kV (20kV/mm) Short circuit



- No trapped charge carrier is found in the insulation
- Limited trapped charges due to the carbon black paper electrodes are found at the interfaces
- **HV insulation made using paper impregnated with Liq N2 looks like a good candidate for HVDC superconducting cable**

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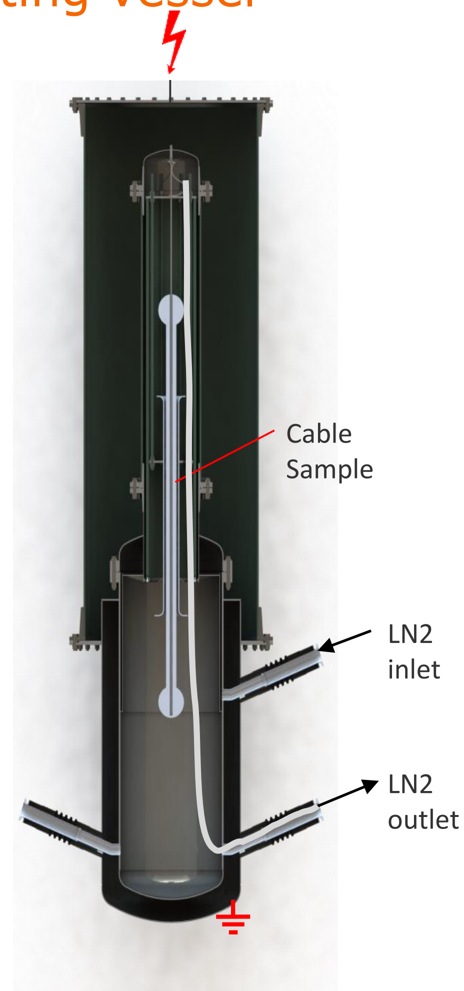
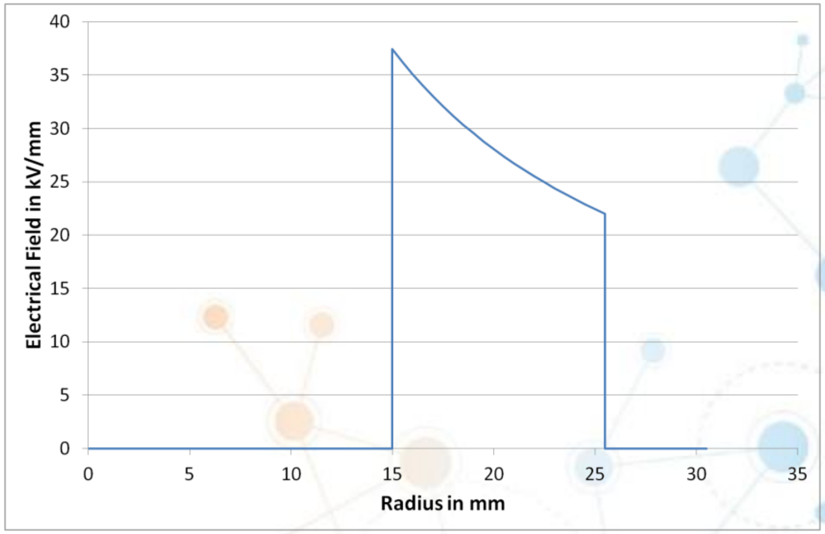
Cable system: Full scale HV cable

Testing vessel



Cable system: Full scale HV cable

DC Test Voltage: 298 kV



Measurements of performances

- Alternating tests AC/DC
- Increase of the test voltages in steps
- Impulse Voltage Test at the End

	Maximum test voltage*	Maximum electrical field
AC	140 kV	17.59 kV/mm
DC	298 kV **	**37.44 kV/mm**
Impulse voltage	325 kV	40.83 kV/mm

* without breakdown
** based on160 kV nominal voltage level

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Cable system: Demonstrator design

For 320 kV DC class cable testing up to **592 kV DC**

Cable design

Electrical field breakdown : 37 kV/mm

Cable conductor
OD 9 mm

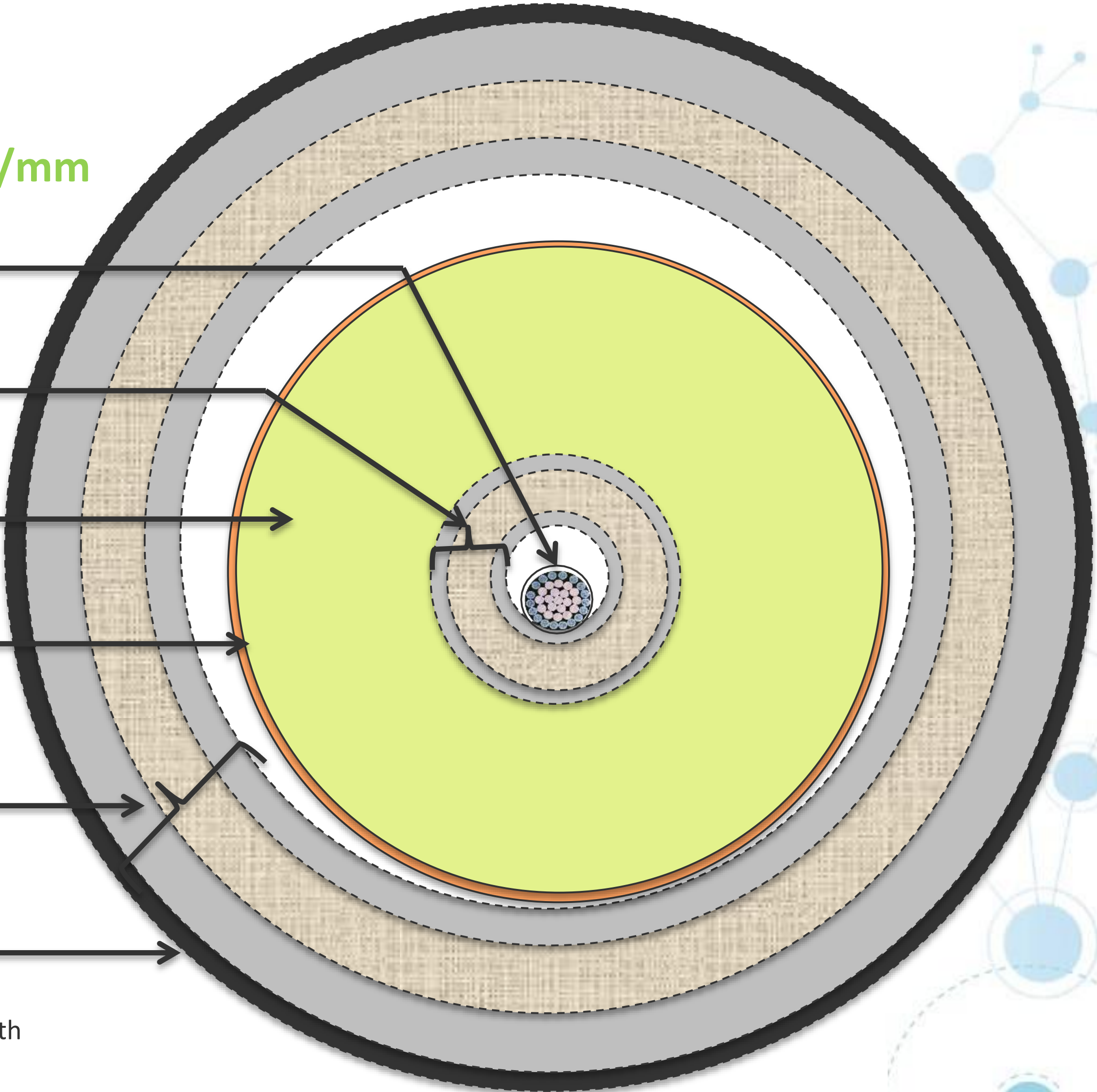
Inner cryogenic envelope
*ID * 14/18 mm*
*OD * 30/34 mm*

HV insulation
OD 88 mm t=27 mm

Ground electrical shield
OD 92 mm

Outer cryogenic Envelope
*ID * 100/110 mm*
OD 127/143 mm*

Outer PE sheet
OD 148 mm



* The two diameters indicate the casrrugation depth

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Cable system: Demonstrator design

HVDC termination concept design

Cooling system for the demonstration

RESULTS

Pressurized subcooled Liq N2

Available on the cable manufacturer Test HV platform

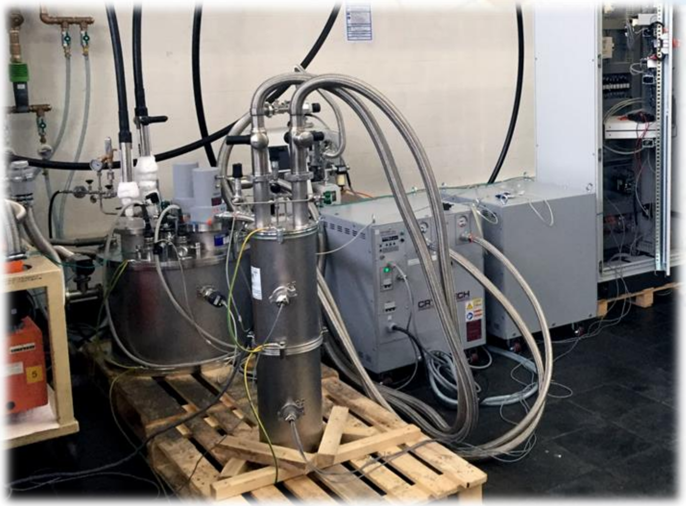
Cooling system for Gas He 15K-25K

Specification:

110 W @ 20 K (20 bara) net cooling power with 1 m³/h He flow rate

2 Gifford-Mac Mahon cooling heads

Possibility to add one



✔ Commissioning of the 20 K cooling machine is done

Grid integration / Social & economic profitability

eHighWay2050 results

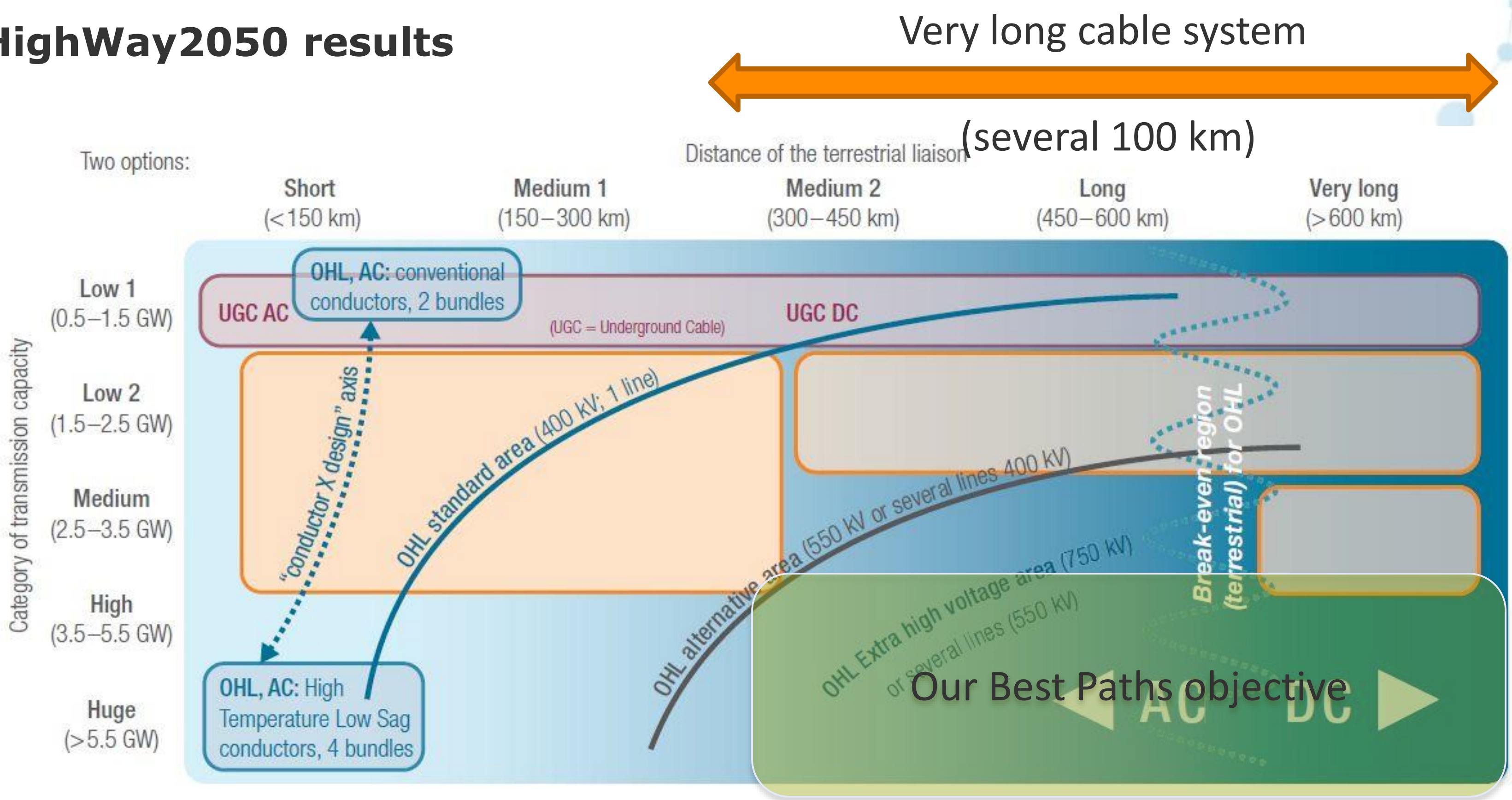


Figure 19: RD&D gap analysis: terrestrial needs (orange cells) compared to available technology options (OHL options: various grades of blue, from the more conventional to the less conventional; terrestrial cables options: in purple color)

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Grid integration / Social & economic profitability

What are the critical parameters for TSO to manage long-length systems?

1. Intrinsic features and design

- Management of a non-resistive component inserted into the transmission grid
- No dependence on scarce resources (e.g. no rare earths, limited volume of **gaseous He**)
- Simplicity of design and execution for the joints (electrical and cryogenic continuity), in order to replicate elementary sections of cable
- Distance between pumping and cooling stations **ideally fitting with existing power substations (in average every 50 km)**
- Ability to face ascending elevation (e.g. **liquid N_2**)

2. Installation

- Delivery of long lengths of cable on drums
- Ability to use existing techniques for civil works and installation

3. Reliability

- Robustness of the system, especially the joints (wire continuity, absence of insulation stress)
- Maintainability, availability and reliability, as key performances for industrial equipment (no outage longer than 2 minutes/year)

4. Public acceptance

- Installation of the underground system along a reasonable and efficient cable route

Details presented at IWC-HTS (Karlsruhe).

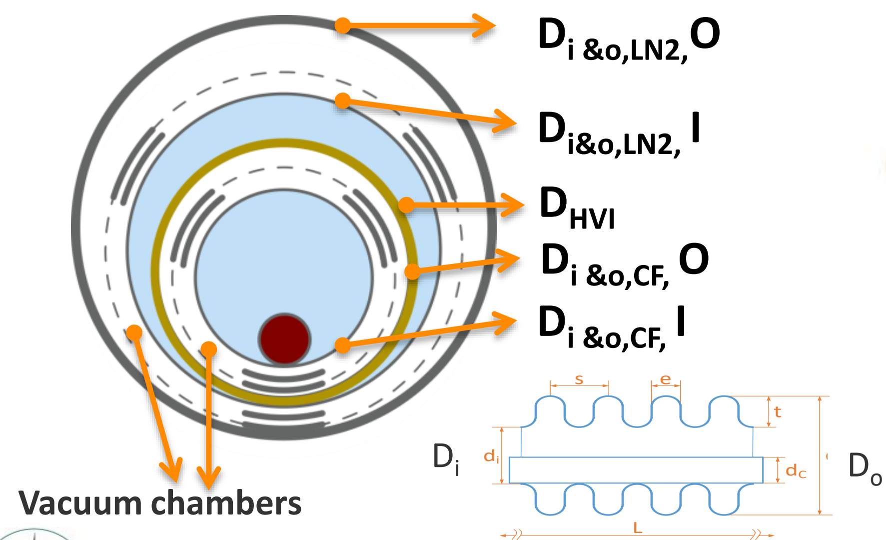
Long length cable concept

First results of the cryostat modeling

2 Cooling Fluids (CF) considered (Gas He and Liq H_2)

Integration of a Liq N_2 thermal shield

T_{in} CF[K]	15	$T_{in,LN2}$ [K]	65
T_{out}CF [K]	25	$T_{out,LN2}$ [K]	80
P_{in}CF[MPa]	2	$p_{in,LN2}$ [MPa]	2
P_{out}LH2/GHe [MPa]	0.35/0.5	$p_{out,LN2}$ [MPa]	0.2



Based on analytical approach

$$L = \frac{D_i}{2}\sqrt[3]{\frac{\Delta p \Delta h^2 \rho}{f \dot{q}^2 \delta^2}C}$$

$L \propto D_i$

$L \propto \Delta h^{2/3}$

$L \propto \Delta p^{1/3}$

$L \propto \dot{q}^{-2/3}$

$L \propto f^{-1/3}$

$L \propto C^{1/3}$

Options	G He *Demo based design*	G He Long Length	Liq H2 Long Length
$D_{i\&O,CF,}$ I [mm]	21/23	93/99	76/81
$D_{i\&O,CF,}$ O [mm]	33/37	108/114	91/96
D_{HVI} [mm]	90	154	136
$D_{i\&O,LN2}$ I [mm]	98/110	228/251	228/251
$D_{i\&O,LN2,}$ I [mm]	129/143	272/300	272/300
L_{tot}[km]	**7** ⚠	**62** ✔	**74** ✔

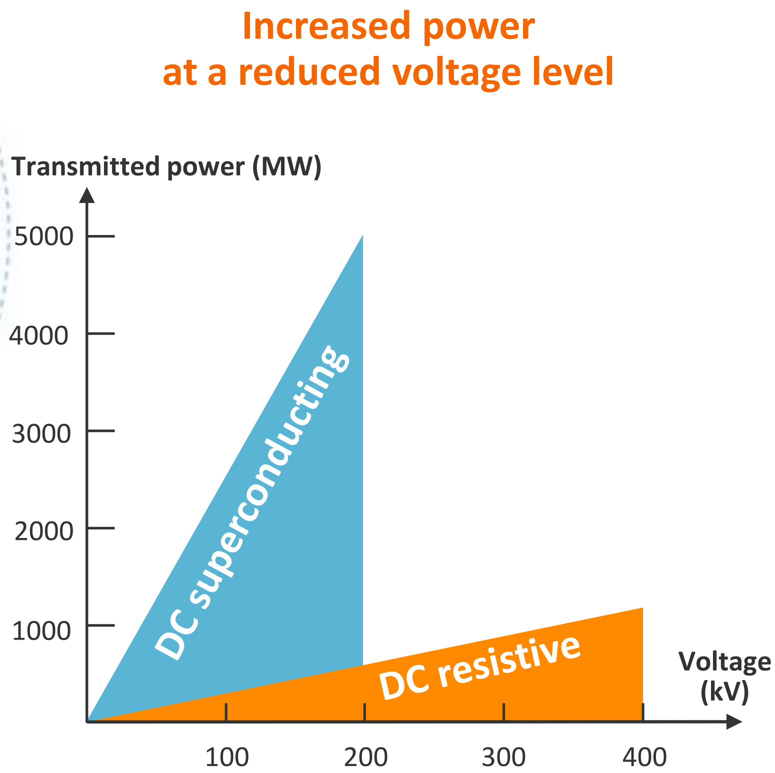
1- Optimized friction factor f [-] = 0,04 (adapted corrugation)

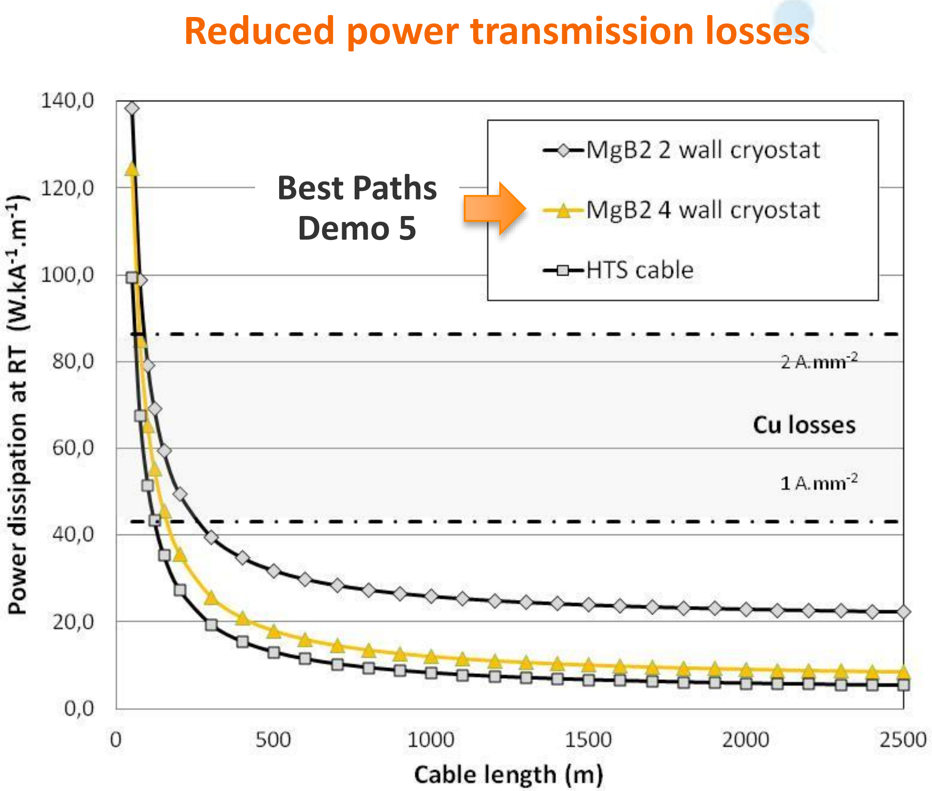
2-Flat installation - no ascending elevation

2- Viscosity of Gas He is higher than Liq H_2

3- Density and Cp of Gas He is lower than Liq H_2

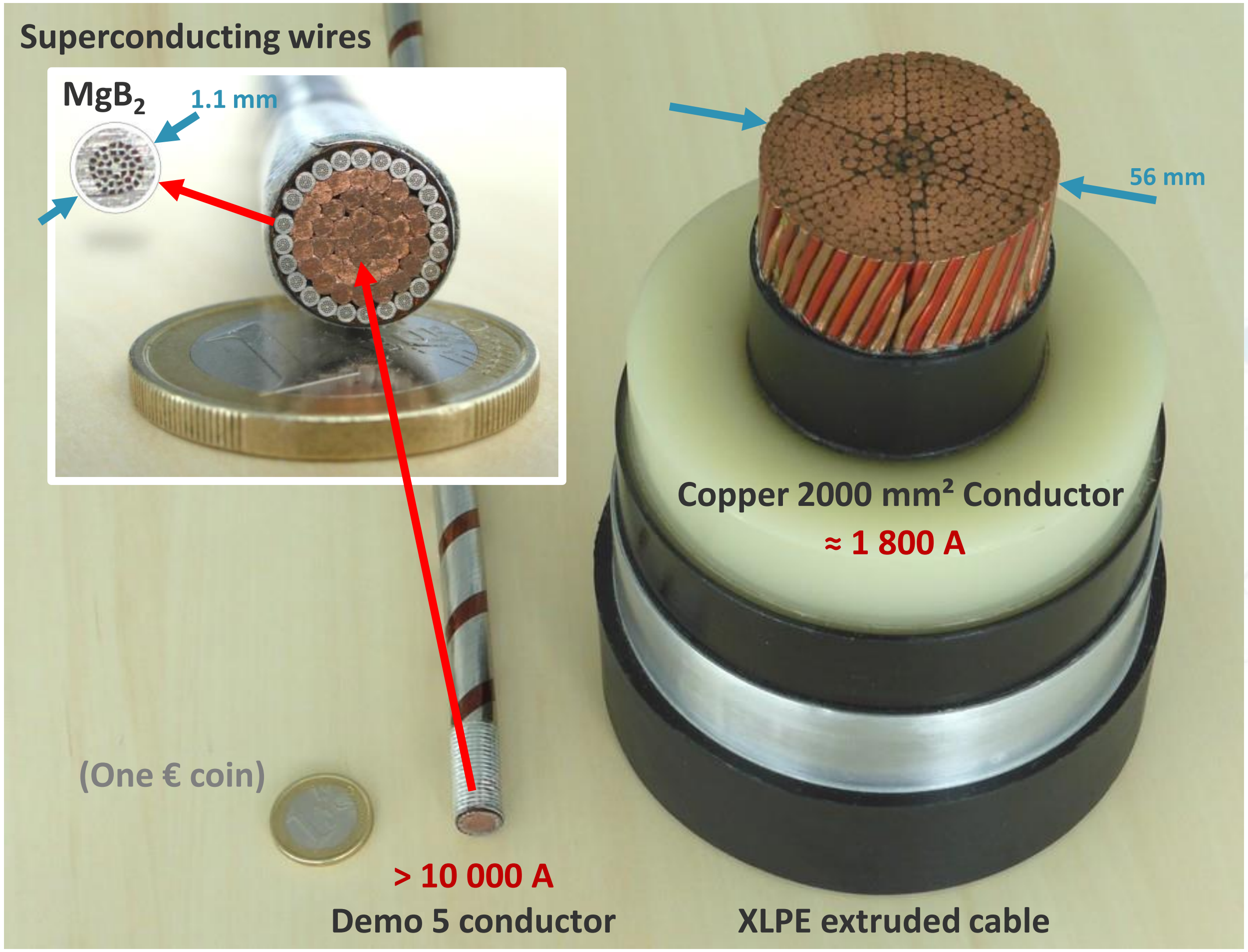
Expected results and impact





Eco-friendly Innovations in Electricity Transmission and Distribution Networks,
Woodhead Publishing Series in Energy: Number 72;
2015 Edited by Jean-Luc Bessede P158

Consequent reduction of raw materials



Reduced space for cable installation and substations

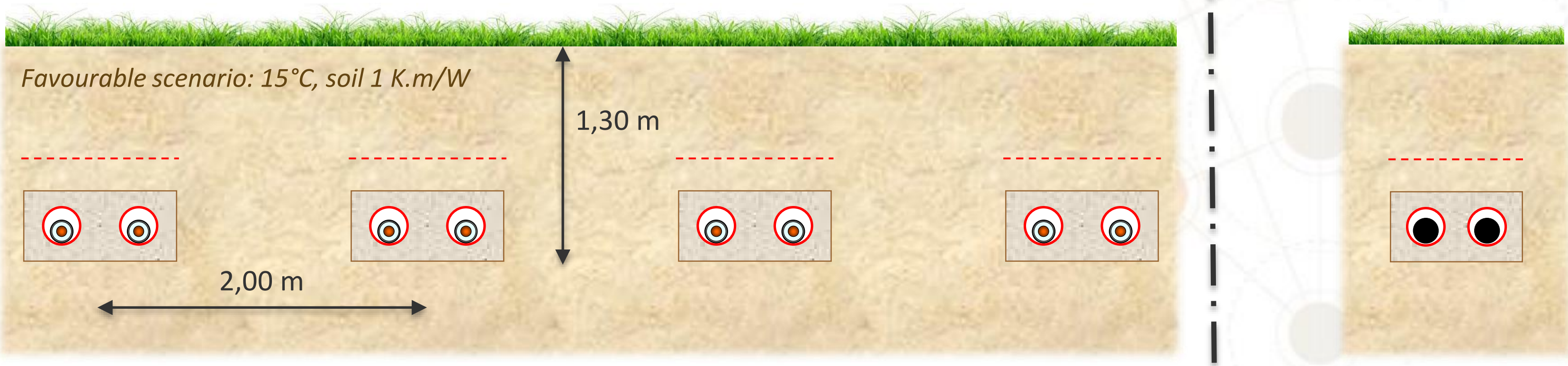
Significant reduction of right-of-way corridors and of excavation work

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)

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

Conclusions

1. MgB_2 wire has been specially adapted to the project specifications (reduced losses, higher critical current density)
2. With them, two possible cable conductors have been manufactured and their characterization is ongoing.
3. Accessories *(terminations and cooling systems)* have been designed and specified and partially commissioned
4. So far, No technical blocking point is identified, the project is now ready for the demonstrator phase on testing platform
5. First design of cable systems have been proposed for 100 km long links
6. Based on the results and expected solutions on grid integration and social and economical profitability is now started.

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www.bestpaths-project.eu

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10 project partners

Nexans
- Demo coordination
- Optimisation of MgB_2 wires and conductors
- Cable system
- Cryogenic machines
- Testing in He gas
- Integration into the grid

CERN
- Optimisation of MgB_2 wires and conductors
- Cable system
- Testing in He gas

Columbus Superconductors
- Manufacturing and optimisation of wires

IASS Potsdam
- Scientific coordination
- Dissemination

KIT Karlsruhe Institute of Technology
- Cable system
- Liquid hydrogen management

Technische Universität Dresden
- Cooling systems

ESPCI ParisTech
- Cable system
- Dielectric behaviour

Universidad Politécnica de Madrid
- Integration to the grid
- Reliability and maintenance

RSE Ricerca Sistema Energetico
- Cable system

RTE
- Integration into the grid
- Socio-economical impact