COOLING CONSIDERATIONS FOR THE LONG LENGTH HVDC CABLES CRYOSTAT WITHIN BEST PATHS PROJECT

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**Best Paths project**

**BEyond State-of-the-art Technologies for Power AC corridors and multi-Terminal HVDC Systems**

RD&D project founded by the European commission under FP7


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<td>Interoperability of HVDC-VSC multiterminal multivendor solutions</td>
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Demo 5 consortium

- Optimization of MgB$_2$ wires and conductors
- Cable system
- Cryogenic machines
- Testing in GHe
- Integration into the Grid
- Reliability
- Integration into Transmission grid
- Cable system
- Cable system
- Cable system

BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems". It is co-funded by the European Commission under the Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612745.
Principle cable cryostat design

MgB$_2$ cable:

\[
d_c = 9 \text{ mm} \\
I = 10 \text{ kA} \\
U = 320 \text{ kV} \\
P_{cl} = 3.2 \text{ GW}
\]
Simple model

Analytical formulation shows dependencies and possible improvements
→ Fast assessment of viable options, influence of parameters on cooled length

\[ \Delta p = \frac{\rho}{2} u^2 f \frac{L}{D_i} \]

\[ \dot{Q} = \dot{q} A_h = \Delta h \dot{m} \]

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

- \( L \propto D_i \)
- \( L \propto \Delta h^{2/3} \)
- \( L \propto \Delta p^{1/3} \)
- \( L \propto \dot{q}^{-2/3} \)
- \( L \propto f^{-1/3} \)
- \( L \propto C^{1/3} \)

Parameter space?
**Diameter**

\[ L \propto D_i \]

Limitations outer diameter:
- duct size
- bending radius
- cable drum

\[ \dot{Q} \propto D_i \rightarrow \dot{Q} \propto L \]
Pressure span

\[ L \propto \Delta p^{1/3} \]

Limitations:
- Pumping machinery and power
- Mechanical integrity cryostat: 20 bar
- Single phase fluid only
Pressure loss

\[ L \propto f^{-1/3} \]

Literature correlations show large spread (0.02..0.08)

Straight tubes optimal
Enthalpy span

\[ L \propto \Delta h^{2/3} \]

Limitations:
- operational range MgB\(_2\)
- single-phase fluid
- lowest starting temperature

\[ T_{out} \leq 25 \, K \]
## Enthalpy span

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

### Alternative coolants:

<table>
<thead>
<tr>
<th></th>
<th>LH₂</th>
<th>GHe</th>
<th>LHe→GHe</th>
<th>SH₂+LH₂</th>
<th>SNe+LNe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{in}}$</td>
<td>15 K</td>
<td>15 K</td>
<td>5.00 K</td>
<td>14.4 K</td>
<td>25 K</td>
</tr>
<tr>
<td>$p_{\text{in}}$</td>
<td>2 MPa</td>
<td>2 MPa</td>
<td>2 MPa</td>
<td>2 MPa</td>
<td>0.975 MPa</td>
</tr>
<tr>
<td>$h_{\text{in}}$</td>
<td>-23.32 kJ/kg</td>
<td>69.10 kJ/kg</td>
<td>11.30 kJ/kg</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$T_{\text{out}}$</td>
<td>25 K</td>
<td>25 K</td>
<td>25 K</td>
<td>25 K</td>
<td>25 K</td>
</tr>
<tr>
<td>$p_{\text{out}}$</td>
<td>0.35 MPa</td>
<td>0.5 MPa</td>
<td>0.5 MPa</td>
<td>0.35 MPa</td>
<td>0.1 MPa</td>
</tr>
<tr>
<td>$h_{\text{out}}$</td>
<td>55.86 kJ/kg</td>
<td>133.21 kJ/kg</td>
<td>133.21 kJ/kg</td>
<td>55.86 kJ/kg</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta h$</td>
<td>79.19 kJ/kg</td>
<td>64.11 kJ/kg</td>
<td>121.91 kJ/kg</td>
<td>112.06 kJ/kg</td>
<td>8.3 kJ/kg</td>
</tr>
<tr>
<td>$L/L_{\text{LH₂}}$</td>
<td>100%</td>
<td>68.8%</td>
<td>106%</td>
<td>125%</td>
<td>36%</td>
</tr>
</tbody>
</table>

### Slush hydrogen is the only viable alternative

Continuous, unmanned operation of an auger plant? Agglomeration of SH₂ in corrugations?
Heat inleak

\[ L \propto q^{-2/3} \]

Load bearing MLI

Margins for:
- Long time vacuum stability
- Bending
- Additional AC-losses

Calculation based on literature data

\[ q_{300 \text{K} \rightarrow 77 \text{K}} = 4.3 \text{ W m}^{-2} \]

\[ q_{77 \text{K} \rightarrow 20 \text{K}} = 0.9 \text{ W m}^{-2} \]

→ Neumann: -36% heat inleak
**Cable diameter**

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

$C = 1 - \left( \frac{D_c}{D_i} \right)^2 + 2 \left( \frac{D_c}{D_i} \right)^3 + \left( \frac{D_c}{D_i} \right)^4 - \left( \frac{D_c}{D_i} \right)^5$

Small cable $\rightarrow$ minor influence on length

Larger effect for el. insulation

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Exemplary geometry

Distance between reactive power compensation stations in France: ca. 50 km
→ Cable design for 50 km

Mass flow LH$_2$: 0.175 kg/s → 15 t/d
Mass flow LN$_2$: 4.4 kg/s → 380 t/d = circulation rate

→ 53 t/d for re-cooling of LN2 from 80 K to 65 K
900 m$^3$ storage for two weeks
Summary

Cooling of kilometric long cables is possible with flexible cryostat
Down scaling of cable cryostat not possible
→Minimal el. power to justify investment (GW range)
   integration into grid
   redundancy etc.? 

Outlook

Replacement of el. insulation with spacer
Design with straight tubing

Design of pump/recooling station
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