Hybrid Energy Transfer Line with Liquid Hydrogen and Superconducting MgB2 Cable – First Experimental Proof of Concept

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Background of the work

* Energy should be not only produced but delivered to the place of consuming
* It is being produced sometimes very far from the consuming area
* Distance could be hundreds and thousands kilometers
* It is transferred by an energy carrier

**Energy carriers could be:**

Gas, sometime LPG  \hspace{1cm} Oil \hspace{1cm} Electricity
Background of the work

Examples of the energy transferring routes

Solar energy in Sahara

East Siberia for South-East Asia

From N. Nakićenović
IASS Workshop, May, 2011, Potsdam
Background of the work -

**electricity is the most common method for energy transfer**

- **HVDC overhead lines 750-800 kV** Huge sizes

- **Power density:**
  - $800 \text{ kV} \times \sim 1 \text{ kA} \sim 0.8-1 \text{ GW}$
  - $s \sim 50 \text{ m} \times 100 \text{ m} \sim 10^4 \text{ m}^2$
  - $p \sim 20 \text{ W/cm}^2$

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From C. Rubbia
IASS Workshop, May, 2011, Potsdam
Background of the work -

Superconductivity is the matter of choice to transfer electricity

From the Garwin-Matisoo ideas

- LHe cooled
- Nb$_3$Sn ($T_C = 18$ K)
  - $J_C = 200$ kA/cm$^2$
  - $H^* = 10$ T
- Capacity = 100 GW
  - +/- 100 kV dc
  - 500 kA
- Length = 1000 km

And early VNIIKP (and BNL) works with LTS

From P. Grant
IASS Workshop, May, 2011, Potsdam

We are moving to HTS!!
Background of the work -
Superconducting HTS cables

Sumitomo

~ 100-500 MVA; s~1000 cm²
p~ 1 ÷ 5 \cdot 10^5 W/cm²

Usual cables – about the same sizes, but 20% of losses and less power density

Russia - VNIIKP

20 kV – 1.5/2 kA -50/70 MVA

Ultera-ORNL

~500 MVA

Nexans-AMSC

IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM, No. 22, October/November 2012.
Oil and gas – traditional and it is clear about them

LNG, T~150-160 K – we have no such superconductors 😐, yet…

“North Stream” gas pipeline: 27.5 \( \cdot 10^9 \) m\(^3\)/year; ~870 m\(^3\)/s; ~40 MJ/m\(^3\) - 3.5\( \cdot 10^{10} \) W; with s~18000 cm\(^2\) (Ø~150 cm) \( p\approx 2 \cdot 10^6 \) W/cm\(^2\)

What about hydrogen?

120 MJ/kg – best fuel!

Being liquid – best cryogen! 446kJ/kg against 20.3 kJ/kg for LH2 and 199 kJ/kg for LN2

When burned – water is remained – best ecology!

And could be transferred at liquid state at T~ 20-27 K!

We DO HAVE superconductors for such temperatures!

Why not use it after all?
Energy SuperGrid: hydrogen + superconducting cable = hydricity

MgB$_2$ with single phase liquid hydrogen with or even without additional single phase N$_2$ coolant offers major simplifications with respect to classic Nb-alloys and boiling He + N$_2$, with practical distances of up to several hundred km.


Old and long time discussed idea. Of course it is may be a bit exotic and may be for the day far after tomorrow. But in any case sometimes it should be started and we somebody should go to practical realization of this.

And we got some practical results!!
Our project is to prove EXPERIMENTALLY the concept of: Energy transfer with liquid hydrogen and superconducting cable - hybrid energy transfer system

Experimental tasks

- To choose the proper superconductor
- To develop and make superconducting cable with it
- To develop and produce liquid hydrogen cryogenic line with test facility
- To insert a cable inside cryogenic line and connect to cryogenics and electricity
- Bring to a site with liquid hydrogen
- Make tests...

Major goals were to understand:

- What is MgB2, its manufacturability and how to work with it
- How to make LH2 cryostat and current leads and to learn how to work with LH2
  (see: “First in the world prototype of the hydrogen - superconducting energy transport system”, Proceedings of ICEC 24-ICMC 2012, Fukuoka, Japan, May 2012, in press)
- To get the first experimental data about hybrid energy transport systems (HETL)
### Superconductor's choice

<table>
<thead>
<tr>
<th>Type - Superconducting technology</th>
<th>Basic material, $T_c$</th>
<th>Cryogen and its temperature</th>
<th>Prices US$ per 1kA·m</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTS – metallurgy</td>
<td>NbTi - alloy ~ 10K</td>
<td>Liquid helium at 4.2 K and below</td>
<td>Up to 3-5$ @ 4.2 K</td>
</tr>
<tr>
<td>LTS – metallurgy</td>
<td>Nb$_3$Sn – compound  ~ 18 K</td>
<td>Helium up to 8-10 K and below</td>
<td>Up to 15$ @ 4.2 K</td>
</tr>
<tr>
<td>HTS 1 generation (Powder in tube – metallurgy)</td>
<td>Ceramic Bi$_2$Sr$<em>2$Ca$</em>{n-1}$Cu$<em>n$O$</em>{2n+4}$ (Bi-2223,Bi-2212) ~90-110 K</td>
<td>Liquid nitrogen at 77 K and below (with other cryogens)</td>
<td>About 120-150$ @ 77 K About 40-50$ @ 20 K</td>
</tr>
<tr>
<td>HTS 2 generation (Long coated conductors - electronics)</td>
<td>Ceramic YBa$_2$Cu$<em>3$O$</em>{7-d}$ ~90 K</td>
<td>Liquid nitrogen at 77 K and below (with other cryogens)</td>
<td>About 300-500$ @ 77K About 80-150$ @ 20K</td>
</tr>
<tr>
<td>Magnesium diboride - (Powder in tube – metallurgy)</td>
<td>MgB$_2$ – compound ~39 K</td>
<td>Liquid hydrogen and below (with other cryogens)</td>
<td>About 5$ @ 20 K</td>
</tr>
</tbody>
</table>

Magnesium diboride: now available, has high parameters (overall current density about $2-7 \cdot 10^4$ A/cm$^2$ at LH$_2$ temperatures) and most important: pretty cheap!
Superconductor’s choice

Flat wire has been selected to use technology developed for HTS power cable made of BSCCO tapes

![Graph showing critical current vs. magnetic field](image)

Basic tape: 3.65 mm x 0.65 mm MgB$_2$, Fe barrier, Ni matrix, Cu stabilizer

Produced by Columbus superconductor, Genoa, Italy

Estimated: $I_c$ (20 K, s.f.) ~520-540 A

Good stability at 20 K

Data from: [http://www.columbussuperconductors.com](http://www.columbussuperconductors.com)

Later we studied $I_c(T)$ for short wires – you could see our poster 2MPC-11 this morning
Cable: five tapes, two layers, total length 10 м, copper stabilization ~90 мм² for each layer

Insulation – 10 layers of Kapton, δ~1 мм, estimated as enough for 20-40 кV
The cable has been made with standard cable equipment with technologies similar to those used for HTS cables.
Details in: “First in the world prototype of the hydrogen - superconducting energy transport system”, Proceedings of ICEC 24-ICMC 2012, Fukuoka, Japan, May 2012,

Test facility and cryostat
Developed by MAI (schematic view)

1- former; 2 – current carrying superconductors; 3 – outer tube of cryostat; 4 – current leads; 5 – inner tube of the cryostat; 6 – polyimide; 7 – layered super-insulation; 8 – current jumpers; 9 – liquid hydrogen storage tank; 10 – filling, pressure busting and drainage systems; 11 – level meter and temperature sensors; 12 – flexible liquid hydrogen 12 m transfer line; 13 – bayonet connectors Ø = 32 мм; 14 – drainage 4 m flexible line Ø =32 мм; 15 – jet nozzle Ø= 4 mm; 16 – drainage flexible line Ø =32 мм

Inner diameter 40 mm, outer 80 mm; Vacuum Super-Insulation;
Four sections with safety diaphragms; Nozzles to regulate LH2 flow
1 – current pathway; 2 – insulating polyimide tube with outer bandages; 3 – load bearing support; 4 – connection of the joint with a cable; 5 – getter; 6 – measuring probes; 7 – connections of flexible copper bunches and superconductors; 8 – mounting part.

Ratings: ~3-4 κA and voltage ~20kV.
General view of the hybrid energy transport system
Tests at the DBCA, November 2011
Tests process

General view of the system

DAS monitor

Liquid hydrogen input

Control computer

Hydrogen afterburner
Cryogenics test results were presented before at ICEC-24

Total cooling time ~380 s.
To cool the system it was used ~ 2.3 kg of LH₂.
Estimated heat losses were below 10±2 W/m (good for LH₂), current lead losses at 2600 A~300 W.
Temperature at measurements were form 20 K to 26 K, pressures from 0.12 to 0.5 MPa
Temperatures variations along a cable from 0.2 K to 0.8 K depending on flow rate

LH₂ flow from 10 g/s to 250 g/s.
Test results - superconductivity

V-I characteristics at different temperatures have been measured. Data about critical current were obtained.

Ic(T) dependence

Data from wire supplier and from measurements of short samples coincides well with cable’s data.
CONCLUSIONS - I

- Liquid hydrogen cryogenic line with special current leads has been developed – **works well**
- MgB2 from Columbus Superconductor has a good manufacturability and could be used for industrial cable production.
- **Superconducting parameters are good as well**
- Developed, produced and tested **MgB2 superconducting cable** with 10 m length with currents ~ **2000-2600 A**.
- **First hydrodynamic and superconducting data** of the hybrid energy transport system **has been obtained**
• With LH₂ flow 250 g/s – the delivering power is ~31 MW.
• Superconducting cable at 2.5 kA and 20 kV – is able to deliver extra 50 MW, so 80 MW in total with only 5 tapes.
• It is easy to add five or ten tapes more and we can increase electrical power to 100 – 150 MW and total power to 130 - 180 MW.
• Therefore, the energy transfer line tested is able to deliver energy flow more than 100 MW.
CONCLUSIONS - III

We tested first in the world experimental prototype hydrogen + superconducting energy transporting system

The conception of hybrid energy transport system has been proved

From this real experiment we can get data that permit to make evaluations and to plan the next developments. Our nearest plans: longer flexible line, high voltage test, more hydrodynamic and superconducting data
Thank you for your attention!