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Hybrid Energy Transfer Line with Liquid Hydrogen and Superconducting MgB_2 Cable – First Experimental Proof of Concept

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***Abstract*— The transfer of high power flows over long distances will be the one of the principal tasks for the energetics in this century. The attraction of liquid hydrogen is apparent because it has the highest energy content of any known fuel and when it burned water is the "waste". It could be transferred via cryogenic tubes like other cryogen liquids. Moreover the usage of "gratis" cold to cool a superconducting cable permits to deliver extra electrical power can be delivered with the same line. One of solutions is to use a DC power cable based on MgB_2 superconductor with single phase liquid hydrogen as a coolant and energy carrier. The team of Russian researchers developed and tested the first prototype of the future hydrogen and superconducting energy transmission system. In the paper the analysis of superconducting materials working at temperatures ~20K are considered and choice of MgB_2 is substantiated. The experimental MgB_2 cable design and the test facility are described. Test results of the first of the concept of hybrid energy systems are presented. The future prospective of hybrid transmission systems is discussed.**

***Index Terms*—liquid hydrogen, superconducting cables, MgB_2, energy transmission.**

I. Introduction

THE energy transmission from a production site to the place of its consuming is as much important task as just energy production itself. Very often the energy production facilities are located far away from densely populated areas. It can apply to both nuclear and future thermonuclear energy production. It may be applied on hydropower stations as well. Speaking on green energy, the world-wide deployment of new forms of the electricity generation such as wind, geothermal or solar cannot occur without a renewed investment in the energy transmission infrastructures. New connections should be built to link areas with vast potential to deliver the energy to the areas that have demands for power. Different energy carriers could be used: oil, gas, and certainly electricity.

The problem of the energy transfer in the volume of some GWs and more is discussed for many years. One of the initial discussions returns us back far to 1967 and consider low-T_c superconductors [1]. A few low-T_c high power superconducting cables based on Nb3Sn has been developed [2]-[4] and tested in the end of 70-ties - 80-ties. Anyway the AC cables put into effect a delivery only for distance up to 35-40 km from over rising of the reactive power.

Superconductivity is the choice for the electricity transmission by DC cables. Absence of any losses except only for cooling makes DC superconductivity very effective. It was also discussed for a long time starting from [1] and later, for example in [5]. One of the most extensive reviews of the previous projects of the AC and DC cable may be found in [6].

The discovery of high temperature superconducting (HTS) materials has inspired onto a new development for energy transmission by means of superconducting cables. It is generally acknowledged that superconducting power cables are the most advanced HTS materials applications and they are the most close to the commercialization. Up to now the biggest HTS AC power cable is 600 m in length and has rated power about ~570 MWA [7].

Nevertheless, the future power transmission demands should be more than tenths of GW. The discussions about such power grids renewed again with HTS discovery, see for example [6]. The similar issues were discussed during symposium [8]. And one of ideas that were in the wind for a long time is to use the liquid hydrogen both as a cryogen and as an extra fuel to provide a very high flow of the energy. This led to the idea of a super-grid [9] that is more attractive as the necessity to use of hydrogen in the power energetics and other purposes becomes more and more popular a point of view.

We have to acknowledge that the concept of the dual delivery of chemical and electrical power employing just MgB_2 wire cooled by liquid hydrogen through a single "cable corridor" was first mentioned by P.M. Grant as early as 2001-2002 [10], [11], very shortly after MgB_2 has been discovered in January 2001. This concept has been termed as "hydricity" under "hydrogen + electricity". Later in a lot of papers, both popular and peer-reviewed, the problems of the hybrid energy

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delivery were discussed using a “hydricity” concept [12]-[19].

Combusting hydrogen as a fuel would be the optimal choice. It has highest fuel efficiency among others – 120 MJ/kg. It could be transferred as a liquid fuel through a long cryogenic transferring line to place of consuming. On the other hand, the liquid hydrogen is the best cryogen having the cooling capacity 446 kJ/kg against 20.3 kJ/kg for LHe and 199 kJ/kg for LN_2. Thus, the idea to place into a transfer line of liquid hydrogen a superconducting cable to transmit the electricity in parallel is quite natural. Besides references mentioned, this idea has been discussed in [20]-[22] as well.

The question is what kind of superconductor should be used for the cable in an energy transfer line. It was shown that an optimal choice has to be recently discovered MgB_2 with a critical temperature of ~ 39 K [20].

So, there are a lot of theoretical and simulation works concerning a possible hybrid energy transfer line using liquid hydrogen both as fuel and cryogen, and a superconducting power cable to deliver extra electrical energy [8] - [23]. Nevertheless no any experimental works have been performed to proof this concept. We accepted the task to complete the experimental study of hybrid energy transmission.

The major goals of our work were:

- To learn how to work with LH_2;

- To get the first experimental data about hybrid energy transport systems with LH_2 and superconductivity.

To succeed these goals we should do:

- choose the proper superconductor: that is surely MgB_2;
- check characteristics of MgB2, its manufacturability and how to work with it;
- design and make a superconducting cable with it;
- develop and manufacture a liquid hydrogen cryogenic line;
- insert a cable inside a cryogenic line and connect to cryogenic system and electric main;
- deliver it to a test facility fitted out with liquid hydrogen;
- make tests.

Here we are presenting the data on the superconducting wire and cable which were used, and the test results of the prototype of a hybrid energy transfer system. The details of the cryogenic system were presented earlier in [24].

II. Choice of Superconductor

The most common superconductors that are used in applications and are available at the market are listed in the Table I. The liquid hydrogen has temperature ~20 K at atmospheric pressure. Thus it is out of the question to use customary LTS superconductors. The choice should be done between superconductors that can work at LH_2. There are either HTS or MgB_2. HTS of both generations (1G and 2G) are freely available at the market. But considering the price (see the Table I) and the good superconducting properties including the high stability at 20 K [25], the MgB_2 is the preferable choice for a system with liquid hydrogen.

Only two companies are offering MgB_2 wires right now: Hyper Tech Research Inc. in Columbus, Ohio, USA [26] and Columbus Superconductor SpA in Genoa, Italy [27].

The first company offers MgB_2 wires that should be heat treated after the twisting. Assuredly they are good for any winding and magnets, but definitely are not suitable for the long cables. It is difficult to imagine heat treatment of long cable with ~100-200 m length that could be bending and unbending after heat treatment. On the other hand, the Columbus Superconductor offers long length wires that can be used without heat treatment. The shape of the wires is varying from round and quadratic wires to different flat tapes [26].

Previously we developed the technology of HTS power cables made of flat HTS tapes [27]. For this project we also decided to use flat tape to use the same cabling and insulation technology as for HTS power cables.

The selected tape and its critical current dependence on field and temperature obtained from [26] are shown in Fig.1. The cross section of the wire is: 3.64 mm x 0.65 mm; MgB_2 cross section - 12% of total area; cross section of copper - 15% of total area. The minimum diameter of bending with no degradation of critical current is 110 mm.

As there were no specific data about critical currents at ~20 K in self field for the wire selected we used extrapolation data shown in Fig.1, that provided expected I_c(20 K) ~ 520 - 540 A. This value was used for the preliminary design of the cable. Later we performed measuring of $Ic(T)$ for this wire and found that there is some scattering of Ic along a sample and evaluated the influence of scattering on the current of a cable [30]. Anyway the preliminary estimation returned fair result for the cable current evaluation.

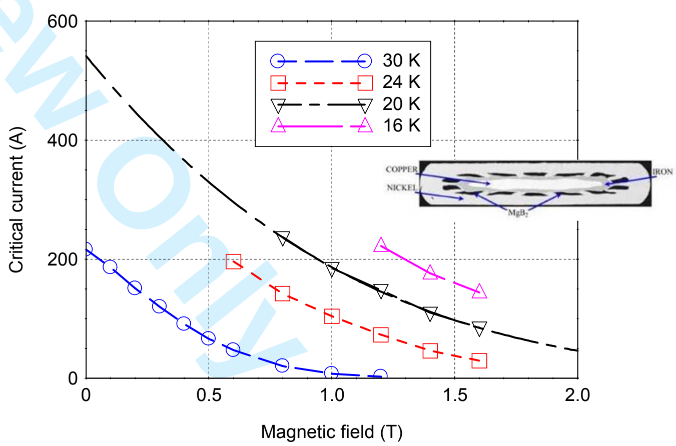

Fig. 1. Dependence of the critical current on the magnetic field and the temperature for the flat MgB_2 wire used in our experiment [16]. The cross-section of the wire used is shown.

III. Cable Design and Production

The design of a prototype of a superconducting MgB_2 cable consists of three elements: a former, current carrying layers and an insulation (Fig.2, a). The former is a central element that performed the supporting function. It consists of:

- the main supporting stainless steel spiral that formed a ~12 mm diameter internal channel for the flow of liquid hydrogen;

TABLE I.
PROPERTIES OF MOST COMMON SUPERCONDUCTORS

Type - Superconducting technology	Basic material, T_c	Cryogen and its temperature	Approximate prices US$ per 1кA·м (as of mid-2012)
LTS – metallurgy	NbTi - alloy ~ 10 K	Liquid helium at 4.2 K and below	Up to 3-5$ @ 4.2 K
LTS – metallurgy	Nb_3Sn – compound ~ 18 K	Helium up to 8-10 K and below	Up to 15$ @ 4.2K
HTS 1 Generation (Powder in tube – metallurgy)	Ceramic $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ (Bi-2223,Bi-2212) ~90-110 K	Liquid nitrogen at 77 K and below (with other cryogens)	About 120-150$ @ 77 K About 40-50$ @ 20 K
HTS 2 Generation (Long coated conductors - electronics)	Ceramic $YBa_2Cu_3O_{7-d}$ ~90 K	Liquid nitrogen at 77 K and below (with other cryogens)	About 300-500$ @ 77 K About 80-150$ @ 20 K
Magnesium diboride - (Powder in tube – metallurgy)	MgB_2 – compound ~39 K	Liquid hydrogen and below (with other cryogens)	About 5$ @ 20 K

- a twisted winding of copper wires with a total cross section sufficient to ensure reliable protection of the main current carrying layer in case of short circuit;
- copper tapes winding providing a smooth outer surface of the former for assembling the superconducting MgB_2 tapes which are the main current carrying layer.

The main current carrying layer consists of two serially connected layers; each of them consists of five MgB_2 tapes helically wound on the former. The number of tapes has been selected to ensure the maximum current not more than 3 kA in inasmuch as DC power supplies limited us at the current. The insulation consists of 20 layers of a polyimide (Kapton™) film with the thickness of 50 µm. The total insulation thickness of ~1 mm allowed the cable to operate in principle at voltages more than 20 kV. In Figure 2a is shown the design of a cable with all sizes, an artistic view of a cable (Fig.2 b); cross-section (Fig.2 c) and a general view (Fig.2 d) of the MgB_2 cable. The cable had a length of about 10 m. At one end both current layers were connected by jumpers to provide the returning current. Thus, the total length of the current carrying element considering the two layers assembly was ~20 m. We expected that the critical current of the cable could be ~2.5–3 kA at a temperature of ~20 K.

The cable has been manufactured on the standard cable equipment in JSC "VNIIKP" and under the technology developed for HTS power cable production [29]. The process of the cable manufacturing is shown in Fig.3.

After production the cable has been delivered to the Moscow Aviation Institute to be installed into a cryostat.

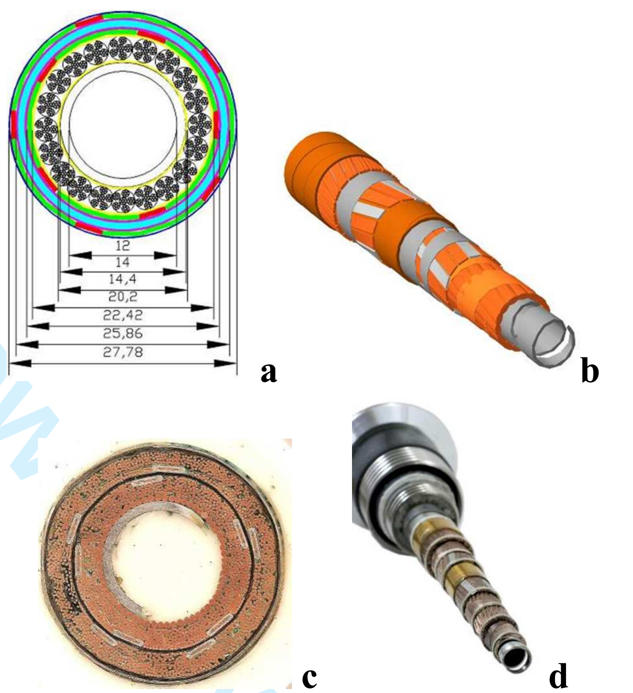

Fig.2 MgB_2 cable design: a – cables sizes; b – artistic view of a cable design; c – cable's cross-section; d – photo of the cable's maket

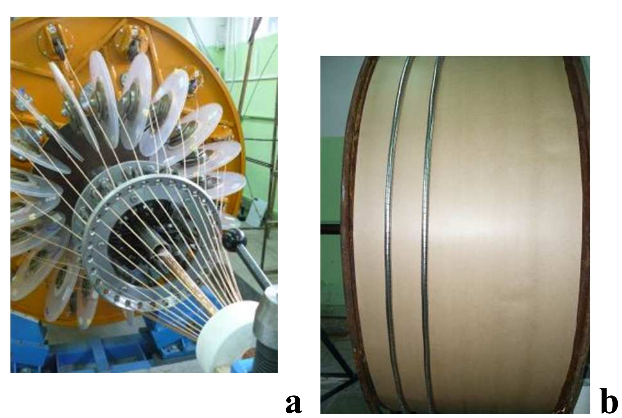

Fig.3 Cable's production: a – wires output from a a cabling machine; cable on a take in drum.

IV. HYBRID ENERGY TRANSMISSION LINE

The Hybrid Energy Transmission Line (HETL) has been described in details in [14], [15]. It consists of a long hydrogen cryostat with ~12 m length, a system for liquid hydrogen supplying and an experiment control system (Fig. 4). These systems provide the liquid hydrogen supply with controlled parameters of pressure, flow and temperature.

The cryostat for the liquid hydrogen transfer at 20–30 K

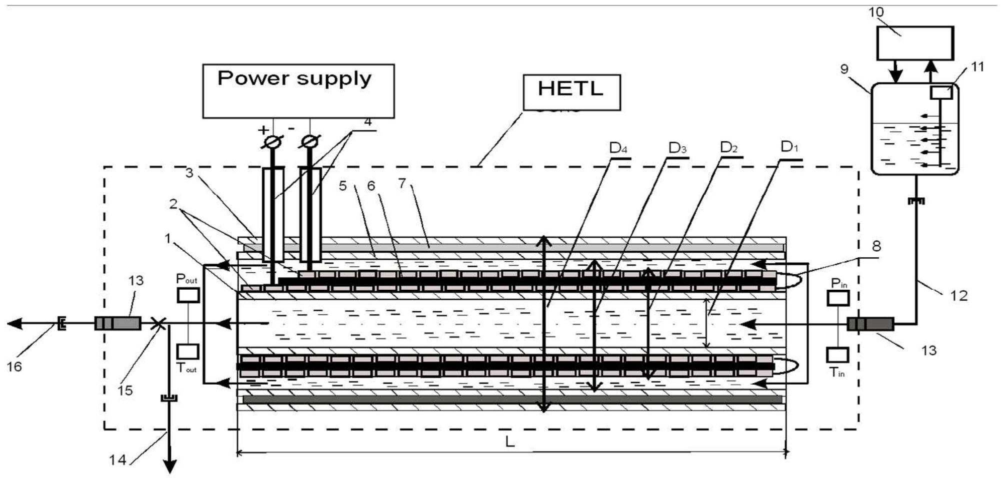

Fig. 4. The scheme of the experimental test facility HETL: 1- former; 2 – current carrying superconductors; 3 – outer tube of cryostat; 4 – current leads; 5 – inner tube of the cryostat; 6 – polyimide; 7 – layered super-insulation; 8 – current jumpers; 9 – liquid hydrogen storage tank; 10 – filling, pressure busting and drainage systems; 11 – level meter and temperature sensors; 12 – flexible liquid hydrogen 12 m transfer line; 13 – bayonet connectors ∅ = 32 mm; 14 – drainage 4 m flexible line ∅ =32 mm; 15 – jet nozzle ∅= 4 mm; 16 – drainage flexible line ∅ =32 mm; L~12 m, is the total length of the cryostat, the length of the cable is 10 m.

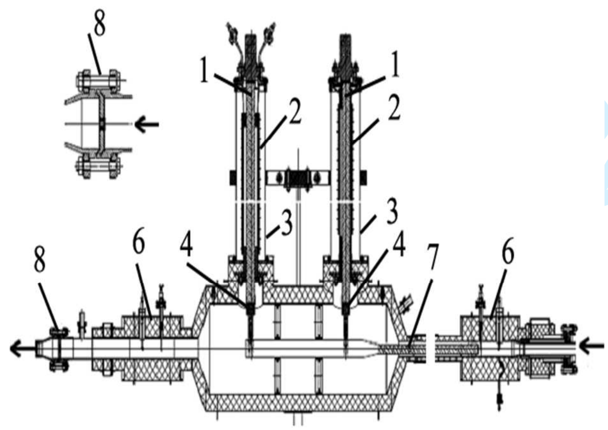

Fig. 5. Current leads for the superconducting cable of the HETL: 1 – current pathway; 2 – insulating polyimide tube with outer bandages; 3 – load bearing support; 4 – connection of the joint with a cable; 5 – getter; 6 – measuring probes; 7 – connections of flexible copper bunches and superconductors; 8 – mounting part.

simultaneously ensures cryostating of the MgB_2 cable for the transfer of the electricity and the flow of LH2 delivering it as a fuel. The other parts are: power sources, measuring systems and test control systems.

The cryostat (Fig.4) consist of an outer shell (3) with diameter D4 = 80 mm, a vacuum thermal insulation (7) and an inner cryostat shell (5) with diameter D3 = 40 mm. There were 4 sections of the cryostat to provide the safe work in case of vacuum loss in one of sections.

The current leads (terminations) are shown in Fig.5. A current lead consists of:

- a vessel formed by inner and outer shells with diameters 270 mm and 370 mm correspondingly;
- flexible copper current pathways with 600 mm^2 cross-section (1);
- polyimide insulating tubes with an outer banding and welded edges made from stainless steel flanges (2);
- a load bearing support to provide the rigidity of the insulating tube (3);
- joints of current pathways (4) with flexible copper bunches and superconductors (7);
- joints for power cables from power supplies.

At the inlet and outlet of the HETL two measuring have been installed to measure pressure and temperature of the liquid hydrogen flow.

The HETL was mounted on the rigid frame with 10.2 m length and 0.8 m width. The cantilevers of the frame provided vertical stability of current leads that have 1.26 m height. The total height of the HETL was 2.48 m. General view of HETL installed at the test facility is shown in Fig.6

V. Test Results

The experiments with the prototype of the hybrid power transmission line with forced flow of liquid hydrogen were carried out in November 2011 on a special facility intended for testing oxygen–hydrogen liquid propellant rocket engines and employed a hydrogen production produced on a plant of the KB “Khimavtomatika” (Voronezh City). The detailed results of the cryogenic tests are presented in [24].

The total cooling time was ~380 s. To cool the system ~ 2.3 kg of LH_2 was used. The evaluated heat losses were below 10±2 W/m, the current lead losses at 2600 A were ~300 W. The variations of temperature during measurements were from 20 K to 26 K, pressure was from 0.12 MPa to 0.5 MPa.

For electrical measurements the three parallel power supplies Agilent 6680A were used. Current has been measured by a standard 7500A - 75 mV shunt. The output signal from the shunt and the values of voltages from the voltage taps of the cable were measured by a multichannel digital analyzing oscilloscope Yokogawa DL 850. The operation of current sources and oscilloscope was remotely controlled via special communication lines.

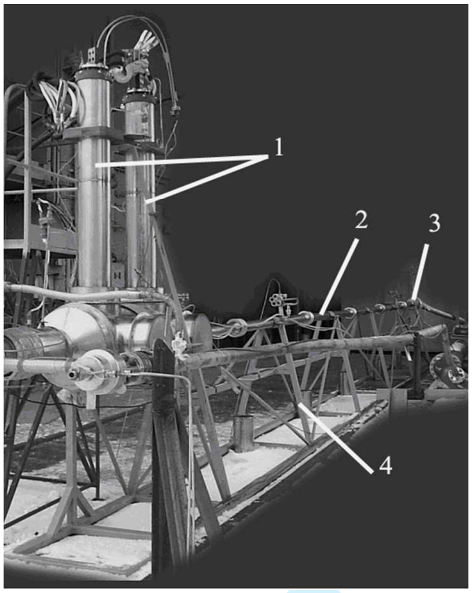

Fig. 6. General view of the HETL installed at the test facility 1 – current leads; 2 - cryostat; 3 – inlet part; 4 – mounting frame

The current carrying characteristics of the MgB_2 cable were recorded at the liquid hydrogen temperatures within 20–26 K, with the pressure (as mentioned above) in the interval from 0.12 to 0.5 MPa, and the mass flow rates in the range from 18 g/s to 250 g/s. The pressure drop at 250 g/s did not exceed 28 kPa. The view of the main control monitor during experiments is shown in Fig.7.

Fig. 7. The general view of the control monitor during tests

The variation of a temperature along a cable was from 0.2 to 0.8 K depending on the hydrogen flow rate. These conditions of cooling mean that the liquid phase of subcooled LH_2 under pressure was without bubbles.

The critical current $I_c(T)$ at a given temperature T was defined as the current for which the electric field between the voltage taps amounted to 1 μV/cm. The temperature, the pressure, and the flow rate of liquid hydrogen in the line were monitored simultaneously with the measurement of voltage on the internal and external current layers of the cable.

In Fig. 8 is shown a typical experimental plot of voltage V on the current carrying layers against current I (voltage – current characteristic). The measurements of current were performed at low voltages up to ~3 V. The values of critical currents determined from these plots amounted to ~2640 A at T = 20.4 K and ~2020 A at T = 25.7 K. Fig. 9 shows the corresponding temperature dependence against the critical current.

In Fig.9 is shown the sum of currents of five wires from extrapolation to zero field data in Fig.1. The evaluation of critical current by averaging its non-uniformity along a wire from [30] for five wires is presented also. One can see the good coincidence of all data that confirm good state of a cable after an industrial manufacturing process.

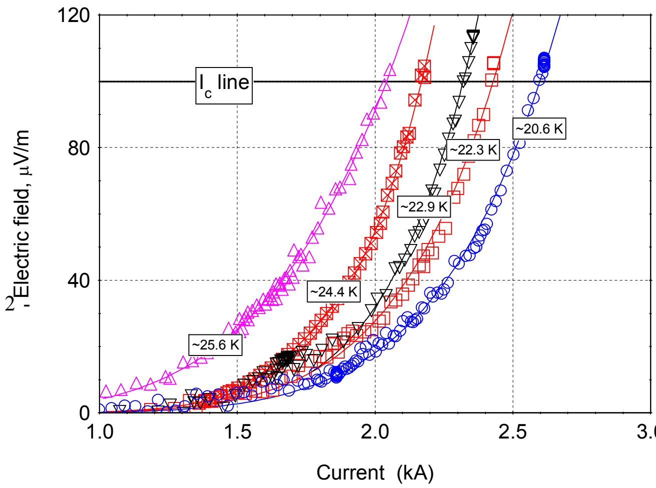

Fig.8 Typical V-I characteristics of MgB2 cable at different temperatures

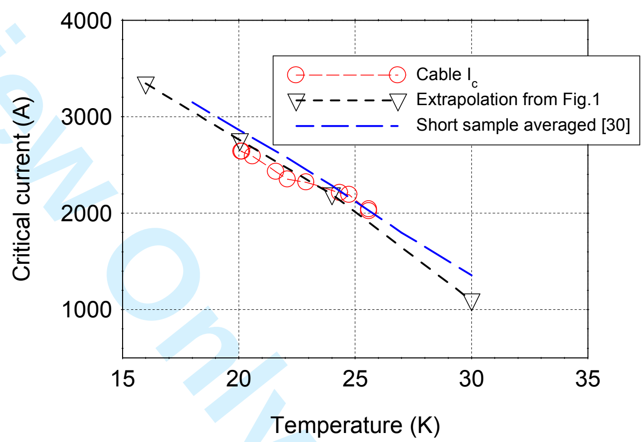

Fig.9. Measured dependence of critical current on temperature of MgB_2 cable

VI. Discussion and Future Plans

With LH_2 flow 250 g/s achieved in our cryostat, the energy transfer line would deliver ~31 MW of thermal power. Superconducting cable at 2.5 kA and 20 kV prospective voltages would be able to deliver extra 50 MW, so ~80 MW in total with only 5 MgB_2 tapes.

As it is seen in Fig.2 it is easy to add at least ten tapes more that will increase the electrical power to 150 MW and the total power to ~180 MW. The cross section of an energy line is about 50 cm^2. Therefore the prototype of the tested hybrid energy transfer line is able to deliver a power more than 100-150 MW with power flow density more than p~$3{\cdot}10^6$ W/cm^2.

The first thread of the "North Stream" (gas pipeline from Russia to Europe) has to deliver $27.5{\cdot}10^9$ m^3/year of natural gas. This means ~870 m^3/s and deeming of the fuel efficiency

~ 40 MJ/m^3 [31] this amounts to ~$3.5\cdot10^{10}$ W of power. The ordinal diameters of gas pipeline tubes are ~150 cm that means that the cross section is s~18000 cm^2 and power density flow p~$2\cdot10^6$ W/cm^2. Thus our hybrid line being rather modest in size has potential to provide power flow similar to the biggest gas pipelines.

Acknowledging the result of executed tests the concept of a hybrid energy transmission system with high energy flows, first mentioned in [10], [11] should be considered experimentally proved.

During these experiments we had no opportunity to perform high voltage tests, so we only have estimated the high voltage prospective. Therefore the high voltage test is our first priority in future. Right now we are developing a longer and flexible cryogenic line (~ 30 m). The cable will be longer also. The test plan is considering and including the separate high voltage test and the current test with LH_2 cooling. Cryostat and new cable should be ready by the end of this year. The hydrogen test of a new system is planning for the 2013.

VII. Conclusion

The first in the world prototype of hybrid energy transfer line consisting of liquid hydrogen cryogenic line and MgB_2 based superconducting cable has been developed and successfully tested.

The flat MgB_2 wire from Columbus Superconductor has a good manufacturability and could be used for an industrial cable production. Its superconducting parameters are good with more than ~220 A/mm^2 of overall critical current density at 20 K.

The liquid hydrogen cryogenic line with special current leads has been developed and tested. The maximum of a liquid hydrogen flow achieved 250 g/s. The first hydrodynamic and superconducting data of the hybrid energy transport system has been obtained [24], [25].

The MgB_2 based superconducting power cable prototype with 10 m length has been developed produced and tested. Currents achieved were ~ 2000-2600 A.

These developments and experiments demonstrated high potential and perspectives of hybrid energy transfer lines which are able to deliver a high power with modest sizes of a line. The concept of hybrid energy transfer lines [10]-[11] has been proved experimentally.

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