Multi
disciplinary Approach to the Design of Superconducting
Electrical Machines

K Kovalev1, V Penkin1, N Ivanov1, A, N Kosheleva2, G Serovaev2
1 Moscow aviation institute (National research university)
2 Institute of Continuous Media Mechanics UB RAS, Perm, Russia

Abstract. Compared to traditional machines, superconducting electrical machines have
significant advantages, i.e.: improved weight and dimensions, higher efficiency, lower values of
inductive parameters, reduced noise level, greater stability when operating in electrical networks.
Development of such machines requires the solution of a whole series of scientific and
engineering problems related to many fields of science and technology. Along with the solution
of traditional problems of the usual "warm" electrical engineering, one has to solve the problems
associated with cooling of superconducting windings and the stability of their superconducting
state under the action of external heat leakage, centrifugal and ponderomotive forces, as well as
vibrations. The design of cryogenic machines should provide for the compensation of thermal
compression of structural elements and windings during cooling process. This paper presents
some interdisciplinary tasks, the solution of which will allow to reach a new level in the field of
superconducting electrical machines and to create samples of electric motors and generators,
surpassing all existing analogues in specific parameters.

1. Introduction

Compared to traditional machines, superconducting electrical machines have significant
advantages, i.e: improved weight and dimensions, higher efficiency, lower values of inductive parameters, reduced noise level, greater stability when operating in electrical networks [1]. The development of superconducting electromechanical transducers in the Russian Federation and abroad has been underway since the early 1960s. For the first time for the needs of the navy in 1966, the British company International Research & Development manufactured a superconducting unipolar motor with a capacity of 37.5 kW and a rotational speed of about 2000 rpm [2, 3]. In the United States, Westinghouse and General Electric have developed a number of general industrial and aviation generators [2,4,5]. In Russia in aggregate design office Yakor together with MAI, an onboard aviation synchronous generator based on low-temperature superconductors (LTS) with a capacity of 780 kVA [1] was designed and manufactured. In the USA, a 36.5 MW marine superconducting synchronous electric motor has been created. In Germany, a 4 MW shipboard HTS electric motor and a 4 MVA HTS generator were developed [6]. The design schemes have a number of drawbacks, such as a bulky cryogenic supply system, the presence of rotating cryostats with HTS windings, and, as a rule, low rotational speed (for HTS devices).

Until now, superconducting machines have predominantly experimental status. There are single cases of their use in industry [1,7,8]. This is due, firstly, the high cost of their production and operation. And secondly, it is not yet possible to achieve the required level of specific (kW/kg) and volumetric (kW/m³) power. Superconducting electrical machines are complex technical devices, the creation of which requires the solution of a whole series of scientific and engineering problems related to many fields of science and technology. Along with the solution of traditional problems of the usual "warm" electrical engineering, one has to solve the problems associated with cooling of superconducting windings and the stability of their superconducting state under the action of external heat leakage, centrifugal and ponderomotive forces, as well as vibrations. The design of cryogenic machines should provide for the compensation of thermal compression of structural elements and windings during cooling process.

This paper presents some interdisciplinary tasks, the solution of which will allow to reach a new level
in the field of superconducting electrical machines and to create samples of electric motors and generators, surpassing all existing analogues in specific parameters.

2. Features of modern superconducting materials

There are two types of wires used in the manufacturing of electrical machine windings: composite wires based on low-temperature superconducting (LTS) alloys and intermetallic compounds and tapes based on high-temperature superconducting (HTS) ceramics. The latter, in turn, are divided into tapes of the first (1G) and second generation (2G). The tapes of the first generation are made of Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ bismuth ceramics and represent a multilayer structure in a silver matrix, which leads to their high cost compared to LTS wires. The tapes of the second generation are also a multi-layer structure, but the current-carrying layer with a thickness of 1 μm is unique and made of ReBa$_2$Cu$_3$O$_x$ ceramics. Here Re is one of the rare earth metals, usually yttrium or gadolinium.

Currently, a large number of works on the creation of SC machines involve the use of HTS tapes and wires from the MgB$_2$ binary compound [9–11]. Despite the similar dimensions of the first and second generations of HTS tapes, the minimum bending radius of the second-generation tapes is several times smaller. This means that a pole winding made of this tape will provide a large fill factor. It is also seen that the current density of second-generation HTS tapes in the presence of an external magnetic field is several times higher [12,13].

Currently, HTS tapes from different manufacturers have similar properties. For example, at temperatures above 65 K, all tapes have a rather low critical current, but at a temperature of 20 K, the difference becomes noticeable (see Figure 1a) [13]. In addition, the critical current depends not only on temperature, but also on an external magnetic field. Figure 1b shows the dependences for the temperature of 77 K [13]. It is seen that as the field increases, the current decreases 10 times. In an electric machine, the characteristic value of magnetic induction in the region of HTS windings without a ferromagnetic core can be 1 T at liquid nitrogen temperatures (Figure 2) or more with decreasing temperature. Therefore, to create electric machines with high values of specific and volumetric power it is necessary to choose the right HTS tape.

![Figure 1. Critical current of HTS vs: a) - temperature; b) - external field at 77K.](image-url)

The mechanical stresses arising in the HTS tape during its operation in the composition of the windings of electrical machines also reduce its critical current. In addition, the disadvantage of tapes compared with round wires is associated with a critical magnetic field for a superconductor depending on the orientation of the field relative to the tape surface (Figure 3).

One of the main problems in the production and use of HTS tapes is related to the fact that any thermomechanical and mechanical stresses lead to the destruction of the superconducting layer [14] and,
consequently, to a decrease in the critical current in HTS tapes [15,16]. In [17] experimental studies of the destruction process of HTS tapes under tension of the tape in the transverse direction are given. Samples were tested in the form of strips with various widths, which were cut from an YBCO tape. In the tension in the transverse direction, the stress of the sample was measured. It should be noted that the voltage was constant until the beginning of the critical current drop. In [18] the necessity in the research of mechanical properties of HTS tapes in order to reduce the possibility of destruction of the superconducting layer under different operating loads was shown. In [19], it is demonstrated how the superconducting layer is destroyed after bending the HTS tapes. Photos from a microscope are presented, where you can see the destroyed superconducting layer in the HTS tape. In subsequent papers [20] solutions are presented, as well as the results of numerical modeling of this problem. The problem of reducing the critical current in a HTS tape during bending is devoted to work that offers various options for tapes laying in a cable. For example, in [21] the results of a finite-element parametric study of a cable with HTS tapes under the torsion are presented. HTS tapes were stacked in a multi-level way while modeling. These results were verified experimentally. However, in order to achieve a reliable quantitative level of prediction using FEM, it is necessary to optimize the cable model, as well as to provide additional extensive experiments to simplify the cable configuration. In [22] the effect of the influence of the configuration of torsional chirality on the electromechanical behavior of multilayer superconducting tapes is studied. Also, the authors give recommendations on the methods of laying and selection of HTS for the optimal configuration of the cable.

Thus, constructions containing HTS require the development of numerical models that could take into account the following features: the specific heterogeneous geometry of this material, the ultralow thickness of some layers, the nonlinear behavior of the constituent material under different operating loads. Since the development of an analytical solution seems to be time consuming, optimal numerical
models should be created and used.

3. Determination of the stress-strain state of HTS coils

In contrast to the usual magnetic systems, in superconducting ones the permissible deformations and stresses are determined not only by the corresponding strength and by stiffness limits, but also depend on a number of factors related to the stability of the superconducting state. When working in the windings of electric machines, the coils from HTS absorb centrifugal forces during rotation of the rotor, as well as electromagnetic forces arising due to the presence of strong magnetic fields. In addition, low operating temperatures invoke thermal stresses in the structural elements of the machine, especially when it is thermally cycled. It is experimentally established, that the effect of degradation arise, which means that the critical current in the superconducting winding turns out to be lower than the current of the short sample. It may be due to mechanical stresses in the SC and friction on the contact surfaces adjacent to the bandage and the frame, and between the layers [23]. The considered features of the mechanical behavior of SC systems indicate the need for a comprehensive analysis of the stress-strain state of the system. The following requirements can be formulated for the main elements of HTS electrical machines. The design of the rotor must meet the requirements of mechanical strength in the temperature range of 300-20 K and vibratory requirements and also provide access to the elements of the HTS windings for their diagnosis, repair, or replacement. The design of HTS windings must meet the requirements of mechanical strength under the action of centrifugal and electrodynamic forces, allow for element-by-element testing of coils, contain the minimum possible number of junctions and ensure their placement in the zone of the minimum magnetic field during intensive cooling. It also mandatory to eliminate degradation of the SC by organizing effective cooling of each conductor, and the reliable mechanical fixation. The system of diagnostics of winding parameters should have a minimum error, have working temperatures in the range of 300-20 K and provide an indication of the thermal and electrical state of the machine's structural elements and their stress-strain state.

As mentioned above, modern HTS tapes have a composite structure. In some cases, the coils are compounded to provide mechanical strength and increase thermal conductivity. However, the properties of such compounded modules at low temperatures are not fully understood. If non-vacuum compounding is used, unfilled zones may be present (region II in Figure 4). In addition, it is necessary to take into account the presence of an insulation layer, which can be up to 20% of the thickness of an HTS tape. At the same time, the properties of the materials forming the coil differ significantly. It should also be noted that the coil is wound on a frame (area I in Figure 4), which can have a rather complex shape. In this regard, and to reduce weight, these structural elements can be made of plastics using 3D printing technology. Thus, the HTS coil is a composite structure of 3-4 different materials. It is obvious that such a structure is inhomogeneous, and its properties are anisotropic.

![Figure 4. Example of HTS coil: I is the frame area; II is the coil separation region (not filled with compound tape), III is the uniform winding region of the HTS tape, IV is deformation of the tape layers.](image-url)
In addition to the homogeneous zone there is an area, where the deformation of the tape layers occurs, the connection between the layers and the frame is broken (region IV in Figure 4). The presence of such defects can lead to a decrease in the operating current. This will especially affect the operation of the coil on alternating current, when under the action of electromagnetic forces uncoupled coils start to move. As a result, there is an increase in losses, and it can lead to a coil failure.

A non-uniform temperature field, internal stresses and thermoelastic deformations will occur in the operational process under the temperature influence and mechanical loads in the HTS coil. To estimate these parameters, it is necessary to solve the associated dynamic problem of thermoelasticity, the main relations of which are given below:

\[ \sigma_{ij} + F_i = \rho \ddot{u}_i \]  
\[ \sigma_{ij} = C_{ijkl} \varepsilon_{kl} - \beta_{ij} \Delta T \]  
\[ \varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}) \]  
\[ \frac{\partial T}{\partial t} - \frac{k_{ij}}{c_p \rho} \frac{\partial^2 T}{\partial x_i \partial x_j} = w \]

where \( \sigma_{ij} \) - the stress tensor components; \( \varepsilon_{ij} \) - the strain tensor components; \( C_{ijkl} \) - the stiffness tensor components; \( F_i \) - the volume force vector components; \( \rho \) - material density; \( u_i \) - the displacement vector components; \( \beta_{ij} \) - the thermoelastic coefficients tensor components; \( k_{ij} \) - the heat conductivity tensor components; \( c_p \) - the specific heat capacity; \( w \) - the power density of heat sources.

Thus, it is necessary under certain initial and boundary conditions to find the 6 components of the stress tensor \( \sigma_{ij} \), 6 strain tensor components \( \varepsilon_{ij} \), the displacement vector components \( u_i \) and temperature \( T \), which should satisfy the equations of motion (1), the relations between stresses and strains (2), the relations between strains and displacements (3) and the heat equation (4).

The calculation of stresses arising in composite structures is a complex scientific task requiring the use of numerical calculation methods. In particular, various software packages of the finite element analysis can be used, such as ANSYS, ABAQUS, COMSOL Multiphysics, etc., which allow to carry out calculations of coupled problems of thermoelasticity, thermoelectroelasticity. Finite element modeling allows to study objects with a complex geometric configuration, to take into account materials with anisotropic properties and demonstrating both linear and non-linear behavior. In addition, modern numerical approaches allow to model various processes of destruction, including delamination between the components of the composite structure.

The determination of the stress-strain state of HTS tapes in the coil is an important task. Its solution is one of the necessary steps on the way to solving problems of increasing the reliability of machines, reducing the overall dimensions of the windings, increasing the filling factor of the cross section of the HTS winding with a tape and also increasing the operating current. All this will lead to an increase in the electromagnetic loads of the machine and an increase in its specific (kW/kg) and volumetric power (kW/m³).

4. Determination of the state of HTS coils

The second problem to be solved is the determination of the state of the HTS coils. First of all, it refers to the temperature of the individual layers. When designing HTS electric machines, thermal calculation is important. It is known that traditional electric machines can operate with a certain excess of a given initial temperature. In this case, the working temperature lies in the range in which the working capacity of the machine is maintained. When it comes to SC machines, the problem of thermal calculation is complicated by the need to maintain the temperature of the SC windings. A temperature jump of 1 degree can lead to a decrease in the current-carrying capacity of HTS, and in the case when the working temperature is close to critical (77 K), exceeding it can lead to an avalanche-like transition of the SC.
Determining the temperature of HTS windings can be carried out in several ways. The greatest accuracy is ensured by the installation of temperature sensors on various structural elements of the HTS machine, including the windings. When using composite multilayer coils of HTS, the temperature of the various layers may differ. In this case, the most dangerous can be both internal turns and medium ones, which is determined by the design of the coils. Accurate determination of the temperature of the various turns in the coil will make it possible to develop recommendations for intensifying cooling and, accordingly, increasing the operating current of the windings.

The greatest effect is achieved by controlling both the temperature of the windings and the stresses arising in them. Fiber optic sensors can be used for this purpose. Fiber optic sensors (FOS) based on the Bragg grating have several advantages over other sensors. In addition to the fact that FOS can measure various physical and mechanical quantities, they are small and can be embedded in almost any part / structure without any special consequences or glued to the surface of the part. It is easy and accessible to produce FOS. A single fiber can contain several sensors, which makes it possible to obtain data along the entire length of the part. Under harsh conditions FOS have advantages in sensitivity compared to other sensors. FOS are not affected by electromagnetic noise. They are safe when using flammable liquids and pressure. They can be used to monitor the parts in real time, including at operational loads. Also FOS can be easily integrated with other equipment for remote control of parts or objects.

In addition, FOS have a large range of operating temperatures depending on the outer coating. A lot of scientific literature is devoted to the study of the FOS behavior at cryogenic temperatures. For example, the experimental characteristics of FBG sensors with three different wavelengths in the range from 123 K to 273 K were checked in [24] The FBG sensors demonstrated a non-linear temperature response, which can be approximated by a third-order polynomial. Under isothermal conditions, FOS showed a linear relationship with changes in the strains. In the study was shown a stable sensitivity of FBG to strains and the dependence of its sensitivity on temperature. The strains arising in the FBG increased with decreasing temperature in a cryogenic medium. In [25] was provided a very useful tool for determining the minimum thickness of a metal coating (FOS coating) required to achieve maximum sensitivity of FOS based on the Bragg grating. Materials studies with different properties allow to choose the best coating depending on the purpose of measurement (for example, the temperature range), which makes it possible to optimize different sensors for each measured temperature range. In [26] sensors in a zinc and glass coating were investigated. The conducted studies show the stability of the readings and the sensitivity of the sensors in different temperature ranges. Also the comparison with the sensors in a standard polyimide coating is shown. Recommendations on the use of FOS and their calibration are given. In [27] the strain characteristics of a FOS with silicon dioxide coating in a dynamic experiment from 30 to 273 K was investigated. Also the tests on static tension in a medium with liquid nitrogen were performed. Based on the analysis of experimental data, a formula for the strain calibration coefficient of FBG with silicon dioxide coating in the temperature range of 30–273 K was obtained and proposed.

However, despite the abundance of scientific research, the main disadvantage of fiber-optic sensors based on the Bragg grating is a significant decrease in sensitivity with decreasing temperature, mainly due to the critical decrease in the thermo-optical fiber coefficient and very low thermal expansion coefficient (CTE) of fused silica at cryogenic temperatures. Thus, it is important to increase the sensitivity to temperature, as well as to choose the right coating in order to possess a higher CTE, but in the same time does not detract from the sensitivity of fiber-optic sensors based on the Bragg grating. Therefore, it is important to develop models that would take into account the particularities of this challenging issue: temperature, optimum location of sensors, issues of gluing, input and output of sensors, etc.

5. Rational solutions for the design of modern HTS machines

Currently, various papers contain design schemes of HTS electrical machines without a steel ferromagnetic core [4,11]. The ability to abandon iron elements and replace them with non-magnetic ones, such as titanium, aluminum, or various non-metals, turns out to be very attractive for reducing the mass of the machine. In this case, the increased magnetic resistance is compensated by the growth of the EMF of the excitation winding due to the high current in the HTS winding. In this case, the use of
constructions made of a combination of different materials may be relevant.

Figure 5 shows an example of the field of winding pole of a synchronous electric machine. Traditionally, the pole core and the tip are performed in one piece. In the framework of a weight reduction task, an alternative design may be proposed (Figure 5b). In this case, the metal plate plays a role of a supporting structure that provides rigidity and strength of the coil and the pole, and the non-metallic pole tip is designed to ensure the streamlining of the rotor during its rotation in a gas or liquid medium.

![Figure 5. The design of the field winding pole: a) - traditional, b) – composite.](image)

Another example is the use of a polyimide composite material for constructive machine parts, for example, a housing and bearing shields. In this case, not only the mass can be reduced, but also the heat influx from the environment into the cryogenic volume. These composites were developed at Salyut Design Bureau and are polyimide films with one or two sided fluoroplastic coating [28]. They have low gas permeability, increased strength, high chemical resistance, which ensures their performance at cryogenic temperatures. Another important advantage is the ability to weld these composite products and steel parts [28]. These materials are used as current-insulating and heat-insulating parts of current leads intended for the electrical connection of the current-carrying elements of the HTS power electrical cable with the cable network elements [29]. The use of such solutions in the design of electrical machines can reduce the mass of structural elements by 15-20%, as well as reduce heat gain from the external environment.

6. Conclusions
This paper presents some interdisciplinary tasks, the solution of which will allow us to reach a new level in the field of superconducting electrical machines and to create models of motors and generators, surpassing all analogs existing today in specific parameters. The following is a brief list of these tasks:

1. Development of analytical and numerical models of structures containing HTS, that take into account the following features: the specific heterogeneous geometry of this material, the ultralow thickness of some layers, and the nonlinear behavior of the constituent material under various operational loads.
2. Determination of the stress-strain state of HTS tapes in the composition of the coil, which is a composite structure with anisotropic properties.
3. Determination of state of superconducting coils, especially temperature and mechanical stress.
4. Determination of the possibility of strain registration as well as the appearance and development of damage in the HTS coil using FOSS under various operating loads.
5. Development of new design solutions based on composite materials and additive technologies.

The experience accumulated at the MAI and the Institute of Continuous Media Mechanics of the Ural Branch of the Russian Academy of Sciences allows us to develop solutions to the problems posed and search for new SC technologies.

7. Acknowledgments
This work was supported by Russian Science Foundation (project No. 17-19-01269)

References
[1] Penkin V and Kovalev K 2018 *Synchronous electrical machines with composite and bulk superconductors for transport systems* (Moscow: MAI publisher)
[2] Bertinov A 1982 *Special electric machines* (Moscow: Energoizdat)
temperatures to room temper
grating sensors
the electromechanical behavior of multilayer superconducting tapes
experimental validation
Nijhuis A 2018 Bending of CORC® cables and wires: finite element parametric study and
Haugan T J, Weiss
Simplified Numerical Model for the Design of 2G High
Wires
Sarigiannidou E, Porcar L, Soubeyroux J, Odier P and Waeckerle T 2012 New HTS 2G Round
Characteristics of Coated Conductor for Conduction Cooled HTS Coil
Park, Kideok Sim, Hong
APPLICATION
Usability of HTS Electrical Machines in Future
10
E, Bjerkli J and King P 2018 Fabrication of a Fully Superconducting Synchronous Generator
Electric Aircraft
IEEE Trans. Appl. Supercond. 28 2–6
Magnusson N, Eliasson J C, Abrahamsen A B, Hellesø S M, Runde M, Nysveen A, Moslatt L
E, Bjerkløv J and King P 2018 Fabrication of a Scaled MgB2 Racetrack Demonstrator Pole for a
10-MW Direct-Drive Wind Turbine Generator IEEE Trans. Appl. Supercond. 28
Dezhin D, Ivanov N, Kovalev K, Kozbaeva I and Semenihin V 2018 System Approach of
Usability of HTS Electrical Machines in Future Electric Aircraft IEEE Trans. Appl. Supercond.
Holzapfel B 2017 Status of Industrial Coated Conductor Production and Properties Conductor
Application EUCAS 2017, Geneva
Anon High-temperature superconducting wire critical database
http://htsdb.wimbush.eu/
Laan D C van der, Ekin J W, Clickner C C and Stauffer T C 2007 Delamination strength of
YBCO coated conductors under transverse tensile stress Supercond. Sci. Technol. 20 765–70
van der Laan D C and Ekin J W 2008 Dependence of the critical current of YBa2Cu3O7–δ
coated conductors on in-plane bending Supercond. Sci. Technol. 21 115002
van der Laan D C, Ekin J W, Douglas J F, Clickner C C, Stauffer T C and Goodrich L F 2010
Effect of strain, magnetic field and field angle on the critical current density of Y Ba 2 Cu 3 O
7–δ coated conductors Supercond. Sci. Technol. 23 072001
Gorospe A, Nisay A and Shin H-S 2014 Delamination behaviour in differently copper
laminated REBCO coated conductor tapes under transverse loading Phys. C Supercond. its
Appl. 504 47–52
Hwanjun Jeong, Heecheol Park, Seokho Kim, Minwon Park, In-Keun Yu, Sangjin Lee, Taejun
Park, Kideok Sim, Hong-Soo Ha, Sang-Su Oh and Seung-Hyun Moon 2012 De-Lamination
Characteristics of Coated Conductor for Conduction Cooled HTS Coil IEEE Trans. Appl.
Supercond. 22 7700804–7700804
Bruzek C E, Allais A, Morice S, Theune C-F, Petit S, Mikolajczyk M, Dechoux N, Jimenez C,
Sarigiannidou E, Porcar L, Soubeyroux J, Odier P and Waeckerle T 2012 New HTS 2G Round
Wires IEEE Trans. Appl. Supercond. 22 5800204–5800204
Kosheleva N, Shahroir I, Bruzek C E, Vega G and Kolmogorov G 2016 Development of a
Simplified Numerical Model for the Design of 2G High-Temperature Superconductors IEEE
Trans. Appl. Supercond. 26 1–5
Anvar V A, Ilin K, Yagotintsev K A, Monachan B, Ashok K B, Kortman B A, Pellen B,
Haugan T J, Weiss J D, van der Laan D C, Thomas R J, Prakash M J, Hossain M S A and
Nijhuis A 2018 Bending of CORC® cables and wires: finite element parametric study and
experimental validation Supercond. Sci. Technol. 31 115006
Ta W, Liu Y, Wang K, Liu L and Gao Y 2019 Effect of the twisting chirality configuration on the
electromechanical behavior of multilayer superconducting tapes Phys. Lett. A 383 949–56
Aliyevskiy B 1993 Superconducting electrical machines an magnetic systems (Moscow: MAI
publisher)
Guo Z-S, Feng J and Wang H 2012 Cryogenic temperature characteristics of the fiber Bragg
grating sensors Cryogenics (Guild). 52 457–60
Vendittozzi C, Felli F and Lupi C 2018 Modeling FBG sensors sensitivity from cryogenic
temperatures to room temperature as a function of metal coating thickness Opt. Fiber Technol.
[26] Swinehart P R, Maklad M, Courts S S, Weisend J G, Barclay J, Breon S, Demko J, DiPirro M, Kelley J P, Kittel P, Klebaner A, Zeller A, Zagarola M, Van Sciver S, Rowe A, Pfotenauer J, Peterson T and Lock J 2008 CRYOGENIC FIBER OPTIC SENSORS BASED ON FIBER BRAGG GRATINGS AIP Conference Proceedings vol 985 (AIP) pp 940–6

[27] Li L, Lv D, Yang M, Xiong L, Luo J and Tan L 2018 Strain characteristics of the silica-based fiber Bragg gratings for 30–273 K Cryogenics (Guildf). 92 93–7

[28] Anon 2006 Technical developments of OKB-23 - KB “Salut” (Moscow)

[29] Kostyuk V V., Blagov E V., Antyukhov I V., Firsov V P, Vysotsky V S, Nosov A A, Fetisov S S, Zanegin S Y, Svalov G G, Rachuk V S and Katargin B I 2015 Cryogenic design and test results of 30-m flexible hybrid energy transfer line with liquid hydrogen and superconducting MgB2 cable Cryogenics (Guildf).