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New Aspects in the Design of Non-Metallic Cryostats for Liquid Helium and Nitrogen

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ABSTRACT

The ILK Dresden designs, develops and manufactures customized non-metallic cryostats for very different applications. For the needs of a wide variety of applications both, geometrical constraints and material selection, can be realized. These cryostats are characterized by long holding time of vacuum and hence they exhibit a very long storage time of the cryogenic fluid. Not only the cryostat itself is of crucial importance to the functionality, but also the fixtures needed as a carrier for measurements inside a cryostat. Minimized thermal expansion, low vibration, maximum variability and low magnetic noise are possible features of the cryostats.

Various material-testing and experimental results are presented as well as special solutions for applications and details of construction. The following points are also discussed:

- Properties of a cryostat for elevated ambient temperatures of the cryostat
- Geometrical limitations
- Important aspects in the design of low-noise magnetic-field cryostats

Cryostats for LN_2 and LHe can also be designed, manufactured, and approved for pressure applications according to the European Pressure Vessel Regulation (Pressure Equipment Directive (PED) 2014/68/EU).

Keywords: cryostats, low-magnetic noise, GFRP, liquid nitrogen, liquid helium

1. INTRODUCTION

The requirements for cryostats have become more and more challenging in recent years. On the one hand, this results from requirements for high-temperature superconductor applications, and, on the other hand, from the need to minimize heat input or to design systems with low-noise magnetic properties.

A large number of recent results in the field of cryostat development has been gained from a R&D project on non-metallic cryostats for extreme requirements (EuroNorm MF 140104). The aim of this project was to evaluate new materials and manufacturing processes for fiber composites based on epoxy resins with regard to their suitability for cryostat construction in order to realize cryostats for extreme requirements, such as high temperatures and increased stability and, further, to develop joining technologies between them in order to enable novel combinations of materials. Important results of this research project have been implemented into the development of the three cryostats shown here as examples.

2. MATERIAL SELECTION

In previous years, there were already successful developments of sophisticated glass fiber reinforced plastics (GFRP) cryostats at ILK Dresden, which were used at ambient temperature near standard conditions.

However, scientific projects on special inductive current limiters manifest that temperatures of 150 °C can occur e.g. at the primary coil of a current limiter, depending on the special configuration and on operating parameters. This is a challenging task for cryogenics since superconducting inductive current limiters (cooled with liquid nitrogen, LN_2) only work with non-metallic cryostats.

Special material-engineering studies were required to compile AD2000 to capture all the parameters needed to calculate the mechanical strength of the composite.

In order to be able to use this material for the cryostat construction (in accordance with the pressure equipment directive (PED) and AD 2000-Regelwerk, defined test specimens with a special resin suitable for the high temperature were produced and material properties at 155 °C were determined. Using classical laminate theory, these values were converted into mechanical properties of specific tubes regarding the winding of the fibres, which can be used for the design of cryostats.

The following values have been obtained:

- Compressive strength axial: 50.9 N/mm²
- Compressive strength tangential: 177 N/mm²
- Bending modulus axial: 11.2 N/mm²
- Bending modulus tangential: 35.8 N/mm²

The glass transition temperature (T_g) of this specific GFRP material is about 170 °C.

The strength calculations for determining the wall thickness of pressure-bearing GFRP components was carried out according to AD-2000 Merkblatt N1 and Merkblatt B5, issue 06.2014. For the further qualification of the material for cryostat construction according to AD-2000, the company Llyod's Register was incorporated as so-called "notified body".

The acquired know-how has been used to develop a special cryostat for the SmartCoil project, see Figure 1. The aim of this project was to demonstrate the technical functionality of a novel passive impedance short-circuit limiting inductor with variable impedance. ILK´s GFRP cryostat for cooling the superconducting coil has a height of more than 2 m and a LN_2 volume of 1.800 litre, max. 2 bar absolute pressure.

Figure 1: Cryostat for HTS cooling (left: schema including mounted safety valve, right: finished cryostat)

3. GEOMETRICAL LIMITATIONS

Depending on the application, various requirements for cryostats are notable: the pressure load, temperatures, heat load, feed through and temperature gradients during cool-down.

As a general aspect, the wall thickness necessary for stable construction must be calculated. As a result, this parameter is limited to a minimum value for each given application. Manufacturing cryostats, special requirements with regard to manufacturing tolerances and gap dimensions must be fulfilled. Particularly in the construction of very large cryostat systems, the production of GFRP semi-finished products (tubes) is extremely demanding, since the diameters are usually subject to strong fluctuations. The larger the dimension of cryostats, the larger the deviation in diameter, respectively the wall thickness.

The geometry of a respective, complete cryogenic system is strictly connected with the heat losses. Especially in the case of helium applications, a sufficient length of the cryostat´s neck is required. If this demand is hampered by e.g. limited space due to the application, heat losses and, consequently, evaporation rate will increase. Thus, very small cryostats are limited in their operation time.

An interesting option for cooling of small applications is to employ a cryocooler instead a cryogenic fluids. In the case of a non-continuous operation however, one has to consider the remarkable heat load due to the cooler in the off-state. For such applications, a heat switch can be a good solution. Such devices are available for a wide field of needs and parameters.

4. LOW NOISE MAGNETIC FIELD CRYOSTATS AND APPLICATIONS

High-quality signal-to-noise ratio (SNR) measurements for magnetic resonance imaging (MRI) require cooled coils. For the Technical University of Denmark, Kgs. Lyngby, Denmark (Department of Electrical Engineering) a special MRI transparent cryostat for small-animal imaging has been developed which allows a coil-to-sample distance below 3 mm. With the outer surface at room temperature the coil temperature works at a temperature of 88 K. The warm opening diameter for animals is 73 mm. This cryostat for magnetic resonance examinations does not contain any metallic structures in its inner structure (see Figures 2 and 3). Further details are given by Sánchez (2018).

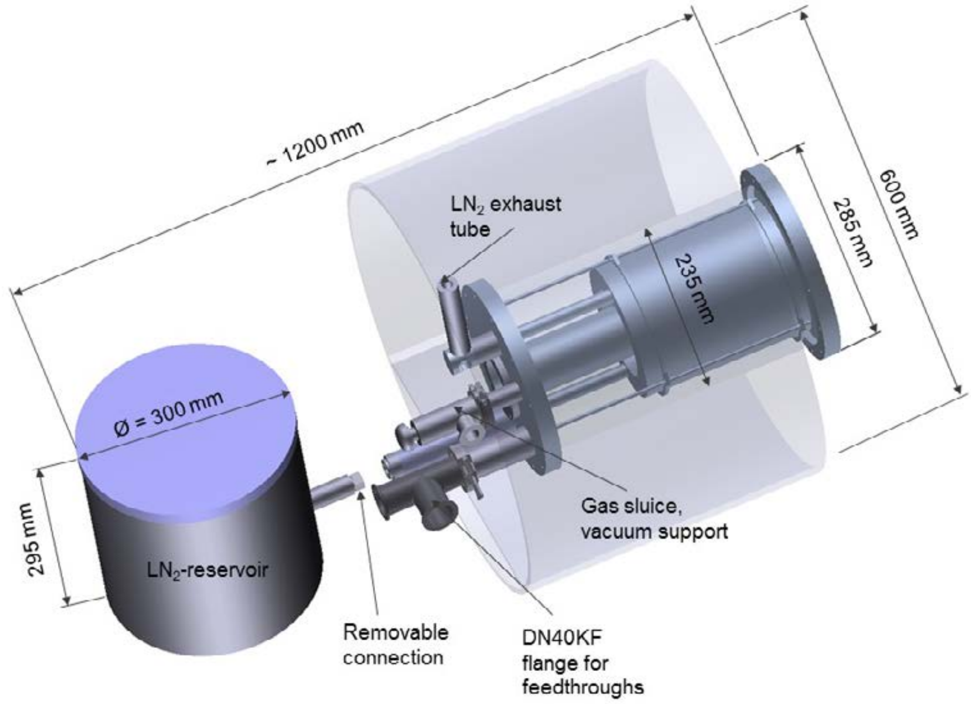

Figure 2: Non-metallic cryostat for small-animal MRI (scheme)

Figure 3: Non-metallic cryostat for small-animal MRI

One more actual application is a non-metallic variable temperature insert (VTI) for a helium cryostat for matter-antimatter experiments. The research of the scientific working group "Atomic Tests of Fundamental Symmetries" at the Institute of Physics at Mainz University (Budker Lab) is focused on testing fundamental symmetries of nature in experiments that utilize the methods of atomic, molecular, and optical physics. Especially for investigations of the nuclear spin resonance of liquid Xenon as a fundamental physics experiment a non-metallic VTI (variable temperature insert) is needed. This VTI should be suited for immersion into a liquid-helium vessel (cryostat). The sample holder is to work at a temperature level of 165 K ± 1 K by a gaseous flow of temperature-stabilized nitrogen. Furthermore, a magnetic field up to 2.000 Gauss will be applied.

The cryostat (see Figure 4) consists of a vertical LHe-cooled glass fibre reinforced plastics (GFRP) structure with an inner bore where the sample holder with the temperature control by gaseous nitrogen can be inserted. The main part of the VTI is vacuum insulated.

Special features of this VTI are:

- height adjustment by the use of two gas springs and two adjusting screws
- rough adjustment: 10 mm ± 1 mm
- fine adjustment: 1 mm ± 0.1 mm
- low value of mechanical vibrations
- combination of GFRP and stainless steel with very low magnetic noise (head of the VTI)
- no metallic components in the tail

Figure 4: Non-metallic variable temperature insert (VTI) for a helium cryostat

5. SUMMARY

For sophisticated applications of GFRP in the field of the design of cryostats, a material based on a special resin has been developed and tested for the use at an environmental temperature of 155 °C. For a novel passive impedance short-circuit limiting inductor with variable impedance, such a cryostat featuring a LN2 volume of 1.800 liter has been designed, manufactured and tested. Beyond the environmental conditions of a cryostat, constraints are given by the required wall thickness and by unavoidable heat losses. Consequently, a careful design of each cryogenic solution is essential. Two recent examples are a special MRI transparent cryostat for small-animal imaging which features a coil-to-sample distance below 3 mm and which does not contain any metallic structures in its inner structure and, further, a non-metallic variable temperature insert for a helium cryostat for matter-antimatter experiments whose sample holder is to work at a temperature of 165 K ± 1 K by a gaseous flow of temperature-stabilized nitrogen and which has no metallic components in its tail.

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