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14 kA HTS current leads with one 4.8 K helium stream for the prototype test facility at GSI

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Abstract

The key part of the international FAIR project in Darmstadt, Germany, is the synchrotron SIS100, for which superconducting magnets are employed. For the First of Series Dipole a pair of HTS current leads with a nominal current of 14 kA DC were specified, manufactured and successfully tested. The motivation for these current leads was a high operation current and the liquefaction limit of 1 g/s of the cooling plant. In the design it has to be taken into account that per lead only one helium stream is available for the entirely inner cooling. For I=0 (8 kA DC) only 0.25 g/s/lead (0.38) were necessary to be compared to 0.365 (0.51) specified. Slow ramping with 50 A/s up to 17 kA was accomplished. Triangular cycles with 27 kA/s up to 14 kA were achieved. The current leads withstood the test voltage of 3 kV between two leads and between lead and ground. The one stream helium flow is regulated by the temperature at the warm end of the HTS to be 50 K. The reliability of the first pair, especially of the cold terminal, is a clear go for the series of HTS current leads needed for the Series Test Facility, the String Test and the SIS100 ring. There is a separate 50 K helium gas supply which allows a significant reduction of cooling requirements. These 19 pairs in total shall have a common design which will be slightly different to that of the first pair for the Prototype Test Facility.

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Keywords: HTS current leads; one cooling stream; inner cooling; FAIR; SIS100

1. Introduction

In the coming years the new international accelerator facility FAIR (Facility for Antiproton and Ion Research), one of the largest research projects worldwide, will be built at GSI Helmholtzzentrum in Darmstadt/Germany. At FAIR an unprecedented variety of experiments will be possible. Scientists from all over the world will be able to gain new insights into the structure of matter and the evolution of the universe from the Big Bang to the present. The heart of FAIR will be the heavy ion sychrontron SIS100 with a circumference of 1100 m. In the SIS100 superconducting magnets are employed. The low temperature superconductor (LTS) Niobium Titanium needs helium at about 5 K

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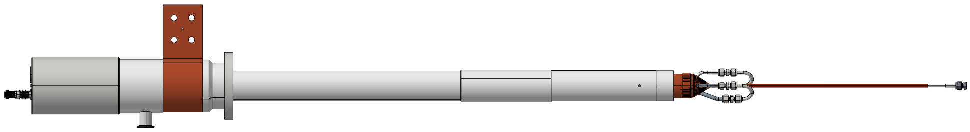

Fig. 1. A CAD picture of the current lead. The warm terminal is on the left.

whereas the ambient temperature of the cryostat is about 300 K. The device that bridges the electrical circuit between 300 K and 5 K is a pair of current leads. The cooling has to compensate for two heat sources. First, the heat leak coming from the warm end, and second, the Joule heating of the electrical current during operation.

For the testing of the First of Series (FoS) Dipole a pair of current leads is needed. The nominal current is 14 kA_{DC}. Only helium at 4.8 K and 1.3 bar(a) with a maximal mass flow rate of 0.5 g/s/lead is available in steady-state operation at the Prototype Test Facility (PTF). Therefore it was decided to built the current leads with high temperature superconductor (HTS) in the colder section.

2. Design

2.1. Requirements

The design of the current leads had to take into account the following requirements:

- Entirely inner cooling with only one helium stream.
- Optimised for a nominal current of 14 kA_{DC}.
- For 8 kA_{DC} the helium consumption shall not exceed 0.51 g/s/lead. This relates to a triangular cycle with 14 kA peak.
- A maximal current of 17 kA shall be reached during a slow ramping with 50 A/s. This operation mode is needed for magnet training.
- The fastest triangular cycles would be with 27 kA/s and a peak of 14 kA.
- Each lead has to fit through the hole of a DN 100 CF flange. The holes in the feedboxes are even a bit narrower, 98 mm in diameter.
- The maximal length between the tip of the cold terminal and the top of the warm terminal shall not exceed 2.2 m.
- The maximal pressure is 5 bar(a). The operating pressures are 1.3 bar(a) at the inlet and 1.1 bar(a) at the return.
- The current leads have to withstand a test voltage of 3000 V. This voltage is to be applied between life circuit and ground and between life circuit and helium circuit for 2 minutes. The leakage current shall not exceed 3 μA.
- The electrical insulation shall hold for a vacuum better than 10^{-4} mbar.
- The leakage rate shall be below 10^{-8} mbar $\cdot$ l/s.

2.2. The solution: from bottom to top

The solution is a current lead that measures 2152 mm from the bottom to the top, see Fig. 1. At the cold end it starts with a piece of Nuclotron cable which consists of a nickle tube for the helium and 23 strands made of niobium titanium and copper. The Nuclotron cable has a length of approximately 600 mm and is foreseen to be soldered to the busbar which is also a Nuclotron cable. The helium with a temperature of 4.8 K is guided through a heat exchanger in the cold terminal that keeps the cold terminal below 5.8 K. The possibility of a seperate cooling of the cold terminal with a cold helium return makes it necessary to guide the helium outside and inside the current lead again. From there it flows to the warm end of the HTS into the main heat exchanger. The temperature of the warm end of the HTS shall be below 50 K. The main heat exchanger is made of copper with a Risidual Resistance Ratio (RRR) of 6.5. It consists of a hexagon with tubes inside. The helium gas flows inside the hexagon and outside the tubes. This allows for a large area where helium and copper are in thermal contact. The main heat exchanger reaches until the warm terminal. An auxiliary heat exchanger in the warm terminal brings the helium gas to approximately room temperature. At the side of the warm terminal there is a warm helium return.

The electrical current is provided to the warm terminal by a water-cooled cable. From there the current flows through the copper of the main heat exchanger into the HTS. The 23 HTS stacks are soldered in the grooves of a stainless steel tube. Stainless steel is used here on account of the low thermal conductivity, the good electrical conductivity (needed in case of a quench inside the HTS) and the similar thermal expansion as copper. An HTS stack has a length of about 300 mm. It consists of 4 BSCCO tapes. At its cold end each stack is soldered to one low temperature superconductor (LTS) strand of the Nuclotron cable, cf. Fig. 2.

The current lead is equipped with voltage taps, temperature sensors, and heaters. There are two voltage taps at the cold terminal, two at the interface between HTS and main heat exchanger, and two at the warm terminal. One CERNOX temperature sensor is placed at the cold terminal, two calibrated PT100 at the warm end of the HTS, two PT100 at 90% of the main heat exchanger, and one PT100 at the warm terminal. In order to prevent condensation or icing at the warm terminal, there are heating elements with a total power of 800 W.

The helium gas flow is regulated by one valve for the whole pair. It depends on the temperature at the interface of HTS and main heat exchanger which is supposed to be 50 K.

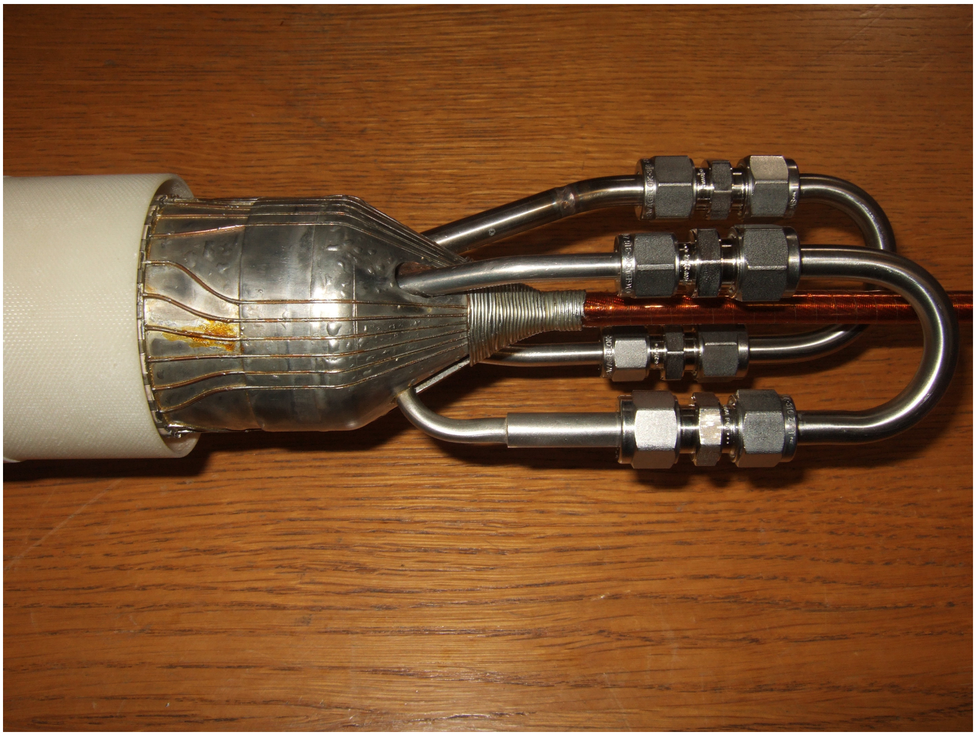

Fig. 2. A photograph of the cold terminal with LTS wires.

3. Factory Acceptance Test

The Factory Acceptance Test (FAT) took place at Kvistgaard, Denmark, on 8th October 2013. All tests were performed at room temperature.

First, the leak tightness was tested. Each current lead had been mounted in a vacuum vessel with a pressure of 10^{-2} mbar. Then the leads were filled with helium at a pressure of 1 bar(a). After 10 minutes the leakage rate was measured not to be higher than $0.8 \cdot 10^{-9}$ mbar $\cdot$ l/s.

Then a voltage of 600 V was applied between life circuit and ground and the leakage current measured after 2 minutes. Then the test was repeated for 1200, 1800, 2400, and 3000 V. The leakage currents were far below 3 μA, in the order of 1 nA.

Afterwards the high voltage was applied between life circuit and helium circuit for 2 minutes. The helium pressures were 2 bar(a), 1.5 bar(a), and 1 bar(a). The voltages 600, 1200, 1800, 2400, and 3000 V. Again the leakage current was in the order of 1 nA.

Dimensional controls were performed e.g. to make sure that the current leads fit through a hole with a diameter of 98 mm.

The resistances between voltage tap connector and life circuit were measured to see that the voltage taps are well attached and in the right order.

The FAT was successful and the current leads delivered to GSI.

4. Site Acceptance Test

The Site Acceptance Test (SAT) was performed at GSI Prototype Test Facility in October and November 2013. First all tests of the FAT were repeated at room temperature with unmounted current leads. Then busbars were soldered to the cold terminals and the leads mounted in the CN 100 flanges of a feedbox. For the SAT the busbars were shortcut. An isolation vacuum was established in the order of 10^{-4} to 10^{-5} mbar. The current leads were cooled down to temperatures of about 6 K at the cold terminal. No cold leaks occurred.

The first test in the cold with current was in the DC mode. Currents up to 14 kA were applied and the mass flow rate measured to keep the warm end of the HTS at 50 K. It was observed that the actual flow rates were well below the specified ones, cf. Table 1.

Table 1. Helium mass flow rates for different DC currents.

I_{DC} / kA	actual mass flow rates per lead / g/s	specified mass flow rates per lead / g/s
0	0.25	0.365
8	0.38	0.51
13.5	0.625	0.67

The slow ramping up to 17 kA was successful. For this purpose, first 14 kA were reached with 500 A/s. After 0.5 s the ramping continued with 50 A/s and 17 kA were kept for 5 s. The ramping down to 0 was with 500 A/s.

Fast ramping was performed with triangular cycles. The highest peak was 14 kA with 27 kA/s in the fastest cycles. If a quench occurred it was due to the superconducting joints connecting current lead and busbar, not to the current leads themselves. The quenches did not occur if a) the delay time was short enough or b) it was long enough. In case of an intermediate delay time the joints were not cooled well since the helium valve was partly closed and did not open fast enough when the fast ramping started again. The difficulty can be circumvented in the future by increasing the helium flow a short time before the ramping is started.

The contact resistance between the HTS and LTS sections at the cold terminal was below 4 nΩ.

5. Conclusion

A second pair for the Prototype Test Facility has been manufactured identical to the first pair. The FAT was successful, the SAT is in progress. The successful tests are a clear go for the series that consists of 19 pairs in total for the Series Test Facility, the String Test, and the SIS100 ring itself. The design shall be similar to that of the first pair for the Prototype Test Facility. However, for the series current leads there will be a supply with 50 K helium which allows for a much more economic cooling. Furthermore the main heat exchanger has to withstand a test pressure of 22 bar(a). The consequence is a thicker hexagone and a larger length.

The first pair for the Prototype Test Facility supplies the First of Series Dipole with current since December 2013.