COMPACT HIGH-TC 2G SUPERCONDUCTING SOLENOID FOR SUPERCONDUCTING RF ELECTRON GUN

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Abstract

A solenoid with second generation (2G) high-temperature superconducting (HTS) coils for use in the superconducting RF (SRF) electron gun of the WiFEL free electron laser at the University of Wisconsin, Madison, has successfully been designed, manufactured, tested and magnetically characterized at Danfysik. The solenoid is designed to operate in the temperature range between 5 K and 70 K. A stack of 16 serially connected pancake coils wound from SuperPower 2G HTS-tape is mounted inside a cylindrical iron yoke with end caps. The solenoid was designed with an excitation current margin of at least 130 % of the nominal operation current in the whole temperature range. At operation, 17.2 kA-turns yield a center field of 0.19 T and a field integral of 3.1 T^2mm, with very small integrated field errors. With a yoke outer diameter of 176 mm and a total length of 136 mm, the solenoid is very compact, and can therefore be placed very close to the RF cavity, improving its emittance compensating efficiency. Careful magnetic design minimizes the leakage field at the SC cavity surface. Heat dissipation is negligible hence conduction cooling through copper braids attached to the iron yoke is sufficient.

INTRODUCTION

Compact solenoids are employed for transverse emittance compensation in low-emittance SRF photoelectron guns. As magnetostatic compensation cannot be inside the SRF cavity, the solenoid is situated as close as possible to the cavity resulting in compactness and a limitation on fringing fields toward the cavity. The application of High Temperature Superconductor (HTS) for the solenoid coils at operation temperatures of up to 70 K relaxes the cooling requirements as compared to Low Temperature Superconductor (LTS), presenting solutions which are both very compact and also more robust towards small disturbances, in cooling for instance.

Danfysik has successfully designed, manufactured and tested a very compact, low-field HTS solenoid for the SRF electron gun for WiFEL, University of Wisconsin, Madison [1],[2]. In Fig. 1 the solenoid can be seen as mounted in the final setup before it is inserted in the cryostat. The technology for insulating HTS-tape and manufacturing coils was developed at Danfysik, as was the test cryostat including current feedthroughs [3],[4].

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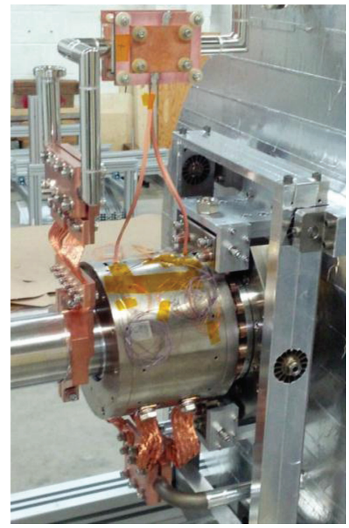

Figure 1: Photograph of the HTS solenoid mounted in the final setup at SRC before insertion into the cryostat.

DESIGN

Magnetic Design

The solenoid coils and yoke layout were designed according to dimensional and magnetic specifications (Table 1) with the aid of Vector Fields Opera 2D software [5] field calculations. A 2D cross sectional view of the design can be seen in Fig. 2. The solenoid yoke is 136 mm long and has an outer diameter of 176 mm, the bore diameter is 91.5 mm. The design has eight equally spaced double pancake (DP) coils, of which the two outermost coils have a larger diameter than the others in order to reduce the magnetic field component orthogonal to the tape.

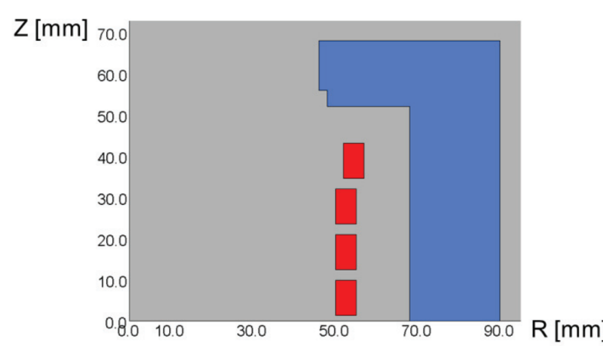

Figure 2: Opera 2D cross sectional view of the axisymmetric solenoid model. The HTS coils are shown in red, and the iron yoke is shown in blue.

Table 1: Solenoid Magnetic Specifications

Parameter	Requirement	Test result
Magnetic field integral [T^2mm]	≥ 3.1	3.1 (target)
Magnetic field in centre [T]	-	0.19
Nominal current [A]	-	38.5
Fringe field at cavity [mT]	< 20	2.5
Residual field at cavity [µT] (solenoid current 0.40 A)	≤ 1	0 ±0.2
Misalignment mech. to magn. axis, offset [mm]/angle [mrad]	≤ ±0.2/≤ ±5	0.15/3.5
Integr. dipole field [µTm]	< 90	45
Integr. quadrupole field [mT]	< 1	0.4

Mechanical and Thermal Design

A 3D view of the solenoid is presented in Fig. 3. The HTS DP coils are mounted on a stainless steel support tube with aluminium spacer rings between the DP coils as can be seen through the cutaway in the yoke in Fig. 3. The yoke is made from XC06 steel and it consists of a centre ring and two end caps. The coil support tube fits tightly into recesses in the yoke end caps, ensuring that the coils and the yoke are concentric. The solenoid is fiducialized by three pinholes, two in the downstream end cap and one in the upstream end cap, referenced to the yoke axis.

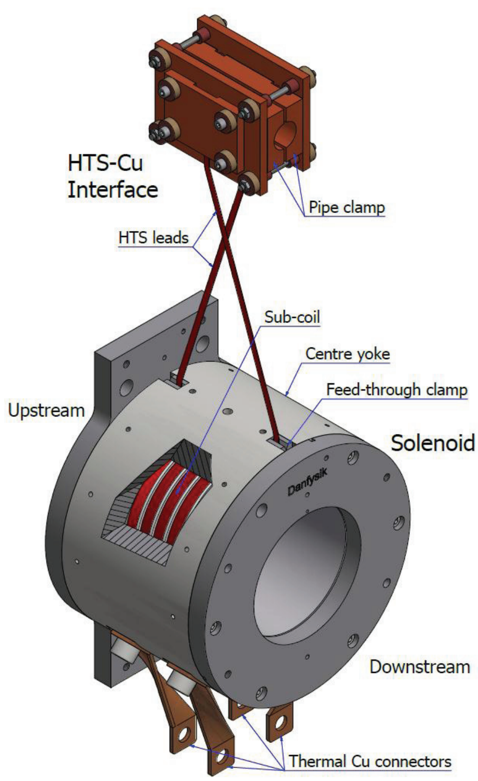

Figure 3: Schematic view of the solenoid.

The thermal conduction between all coils, the spacers and the support is improved by applying thermally conducting paste, and the coils are cooled by the yoke via the support tube. The yoke is cooled via four copper braids seen at the bottom of the solenoid in Fig. 3. Figure 3 further shows the HTS-to-copper interface of the current leads at the top which will be cooled by the gaseous helium return line in the electron gun. Each of the leads from the solenoid consists of three HTS tapes in parallel, the tape pieces being soldered onto the tapes at the solenoid ends.

HTS COILS

For the coils, 4 mm wide HTS YBCO coated conductor from Superpower Inc. was used [6]. The HTS tape was insulated by applying a 20 µm thick layer of alumina powder filled epoxy. The coils were then wound as DP coils with the inner joint made from a 6 mm broad, overlapping HTS piece to which the inner ends of the two pancakes were soldered. After winding, the DP coils were vacuum impregnated with alumina powder filled epoxy; the filler improves the thermal conductivity of the potting.

Individual Coil Test

After epoxy impregnation the DP coils were tested individually at 78 K in an open liquid nitrogen bath. VI-curves were obtained up to 45 A, and the DP coils built into the solenoid all showed voltages of less than 200 µV at 45 A and in self-field, which corresponds to about 0.1 µV/cm.

SOLENOID TEST

The test program for the HTS solenoid involved electrical testing in terms of VI-characterization and ramping speed tests as well as magnetic characterization by Hall probe scanning and stretched wire measurements for determining absolute fields as well as transverse integrated field and angular errors, respectively. A fluxgate magnetometer was used for measuring remanent fields.

Quench Protection

The solenoid is actively quench protected; a detection of an imbalance between the voltage drops across the two halves of the solenoid is followed by switching in an external dump resistance and disconnecting the power supply. Voltage tap wires for detection are soldered on to the soldering joining the two DP coils in the middle and to the HTS pieces at the solenoid ends.

Test Cryostat

An existing test cryostat [3],[4] was slightly modified to accommodate the HTS solenoid. Cooling is provided by two two-stage Gifford McMahon cryo-coolers, the first stages of which remove the heat from the radiation shield and the HTS-to-copper interface, respectively. The solenoid itself is cooled by the second stage of one of the cryo-coolers via a copper bus bar connected to the cooling

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copper braids. The test cryostat facilitates magnetic characterization at room temperature using a warm bore pipe through the solenoid. After cool-down, a final temperature of 26 K is reached.

Magnetic Characterization

Careful alignment of both the Hall probe mapper and the stretched wire fixation points to the solenoid mechanical axis is crucial. The Hall probe mapper was aligned to the solenoid by scanning over a magnetic cone placed in the three alignment pin holes described earlier. The stretched wire bench was aligned by means of a theodolite and optical cross hairs. The results of the magnetic characterization are summarized in Table 1 together with the specified requirements.

The nominal current was determined to be 38.45 A from integration of Hall measurement scans along the solenoid axis with the integrated field target value of 3.1 T^2mm. Figure 4 shows a plot of the axial magnetic field versus position along the solenoid axis at nominal current. The centre field at nominal current is 0.19 T. The fringe field at the cavity position which is 146 mm from the solenoid centre was measured to be 2.5 mT, well below the specification.

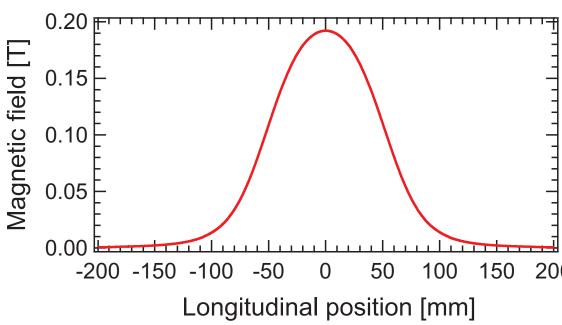

Figure 4: Plot of the axial magnetic field measured along the solenoid axis.

First the stretch wire was set up to be parallel to the solenoid axis, and measurements were made at equidistant points on a horizontal and a vertical line through the solenoid centre. The maximum integrated dipole error was measured to be 45 μTm, and the maximum integrated quadrupole error was 0.4 mT. Then the stretched wire was systematically misaligned angularly to the solenoid axis in order to determine the angle where the integrated dipole field would be minimized. From these measurements, a misalignment angle of known direction of 3.5 mrad between the solenoids magnetic and mechanical axes was deduced, well within the specified requirement.

By proper magnetic cycling, the solenoid yoke was brought onto the +/- nominal current hysteresis curve. The magnetic background field as measured with the fluxgate magnetometer at the position of the cavity was then determined as the average of the measurements at positive and negative nominal currents, respectively. Finally the solenoid current was adjusted to yield a fluxgate measurement equal to the background field, indicating that the remanence field from the yoke was cancelled. It was found, that a current of +0.40 A cancels the residual field from the yoke.

Excitation Tests

As part of the test program, the solenoid was cycled three times between room temperature and 26 K. Voltage-current characteristics of the solenoid were obtained up to 50 A at 26 K and at 70 K, and they were seen to be reproducible for all thermal cycles. The slope of the VI-curves gives a total ohmic resistance due to the soldered joints in the solenoid of < 400 nΩ at 26 K, or < 24 nΩ/solder connection.

No quench was observed when the magnet was ramped to 40 A at increasing ramping rates with a maximum of 110 A/s.

CONCLUSION

A compact, low-field HTS solenoid for application in an SRF electron gun has been designed, manufactured and tested. The factory acceptance test revealed that all specifications were met. The HTS coil technology builds on development work previously performed at Danfysik, and the successful completion and test of this solenoid proves that the technology is mature for use in accelerators.

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