

SUPERCONDUCTING SOLENOID PACKAGE PROTOTYPING FOR FRIB SRF LINAC*

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Abstract

The solenoid package is consisted of a beam focusing superconducting 8 T 25 cm long solenoid coil wound by two graded NbTi SC wires and two racetrack shape X, Y-steering dipole beam corrector coils. All these coils were wound by “dry” winding. The solenoid coil was cold tested in the vertical cryostat and could reach to the design value of 8.9 T (99.5 A) without training. The full solenoid package was cold tested, including simultaneous excitation tests of all three coils, in the vertical cryostat successfully.

INTRODUCTION

KEK has more than 20 years long experience of design, fabrication, and cold test of small size 7T superconducting NbTi solenoid coils. We can utilize the existing coil winding machine and also the cryogenic facility for its cold test in KEK. A superconducting solenoid package prototyping for FRIB SRF Linac was designed, fabricated and cold tested at KEK under KEK/MSU collaboration program. The “dry” winding was used for the solenoid coil and racetrack shape steering coil winding, instead of using “wet” winding which is usually used for this size of solenoid coils. The “dry” winding has been developed and to date used for the fabrication of the small size solenoid coil in KEK.

REQUIREMENT

The required magnetic field of the solenoid package for FRIB are is 8 T with nominal operation current smaller than 100A. The operation temperature is 4.5 K and its temperature margin is +0.5 K. Inner diameter of the cold bore is larger than 4.0 cm and the solenoid coil length is

Table 1: Main Parameters of Coil and SC Wire

	Inner coil	Outer coil
Length [mm]	250	250
Inner diameter [mm]	54.25	86.25
Outer diameter [mm]	86.5	131
Turns per layer	311	355
Layers	22	34
Dia. of bare SC wire [mm]	0.80	0.65
Dia. of insulated SC wire [mm]	0.75	0.70
Copper / SC	1.3	2.4
Filament diameter [μm]	18	35
SC wire vender	Furukawa	Hitachi

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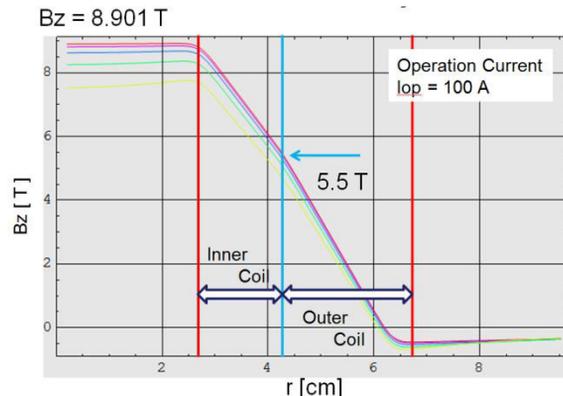


Figure 1: Magnetic Bz profile for the solenoid coil.

25 cm. The integrated magnetic dipole field strength for the steering coil is 0.03 Tm or larger at an operating current of 50 A. The field uniformity must be within 5% for both X and Y steering dipoles.

DESIGN OF 8T 25CM SOLENOID COIL

The main parameters of the solenoid and SC wires for inner and outer coils are summarized in Table 1. Figure 1 shows calculated Bz field profiles along radial direction for at z = 0 cm, 3 cm, 5 cm, 7 cm, 9 cm from the centre. The field uniformity inside the coil bore is very good due to the coil length is large compare to the coil inner diameter, and the field enhancement factor Bmax / B₀ is 1.0032. The self-inductance of this coil is 8.0 H.

Figure 2 shows the load line of the designed solenoid coil and critical curves (I_c) at 4.2 K and 4.5 K of the SC wire for the inner coil. The solenoid magnetic field Bz at the centre of coil reaches almost 9T at 4.2 K and 8.6 T at nominal operation temperature 4.5K over the required specification value 8T for FRIB. The solenoid has a temperature margin of 0.4 – 0.5 K

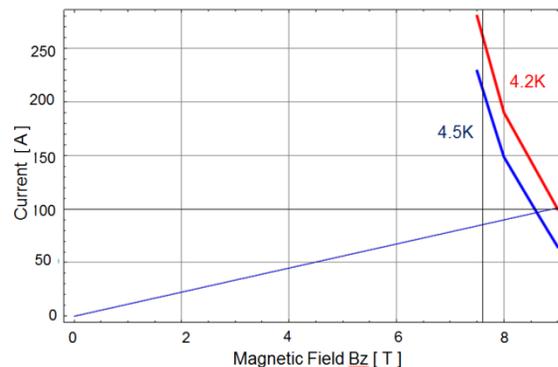


Figure 2: Load line of the solenoid coil with Ic curves.

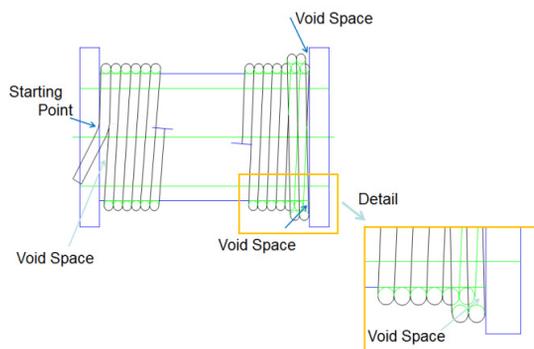


Figure 3: Schematic drawing of coil winding.

STRUCTURE OF THE SOLENOID COIL

The coil bobbin is assembled from a stainless steel body and both end flanges by welding. Before the welding two 2mm tick G-10 insulation disks are installed inside the end flanges. Four OFC copper terminals (two for solenoid coil current leads and two for interconnection of inner and outer coils) are set outside the e end flange.

Winding of the Solenoid Coil

Figure 3 shows the schematic drawing of the solenoid coil winding. A void space appears at the winding start point in the first layer. Other void spaces also form at the winding end of each layer, i.e. at ramping to next layer as shown in the figure. These void spaces are filled by green epoxy putty just to fill the void spaces to prevent falling of next layer winding wire. Usually the green epoxy putty is sticky and glues the G-10 insulation disk (not shown in this schematic drawing) and the SC wire together. The SC wire stuck on the G-10 end plate could be separated suddenly by strong compressing electromagnetic force. We have devised a mechanism to suppress this kind of sudden wire movement, i.e. prevent the SC wire from sticking on G-10 plate with green epoxy putty by painting a release agent on the G-10 surface, and we could successfully eliminate quench.

Inner coil was wound on the coil bobbin which was ground insulated by one layer of 0.125mm thick Kapton. Outer coil was wound directly on the inner coil after wrapped by one layer of 0.125mm thick Kapton. During coil winding process the tension of each SC wire was maintained at 4kgf (inner coil) and 3kgf (outer coil) by tensioner. The outer coil surface was wrapped with 0.125mm thick Kapton film and then two layers of 1mm diameter stainless steel wire was wound for pre-stress to the coil and for protection from mechanical damage during the handling it.

COLD TEST OF SOLENOID COIL

The completed solenoid coil has a weight of about 22kg, which was hanged to the top flange of 200mm inner diameter vertical cryostat. Two dump resistors made from 2mm diameter stainless steel wire with 0.16Ω at 4.2K were connected to the inner and outer coils in parallel and installed inside the cryostat. The solenoid coil was excited

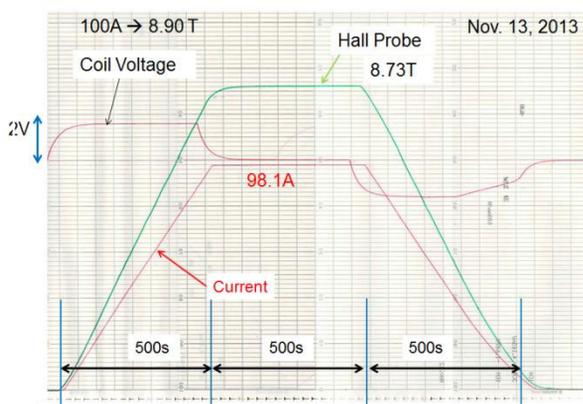


Figure 4: Pattern Excitation of Solenoid Coil.

using DC power supply (inverter regulated 160 A x 6 V, KIKUSUI PAK6-160). The over voltage of the power supply was used for quench detection.

Cool down and Excitation of the Solenoid Coil

The solenoid coil was pre-cooled first by liquid nitrogen then installed in the cryostat and cool down by liquid helium. At the first excitation test the coil current was increased manually up to 80 A, which correspond to 7.2 T, no quench occurred, then increased slowly and the coil quenched at 99.5 A (8.9 T). After liquid helium was refilled, the second excitation test was tried. This excitation is shown in Fig. 4. The current was increased up to 98.7 A (8.7 T) in 500 sec and the current was hold for 500sec and downed to 0 A in 500sec so-called 500 sec interval pattern operation. The pattern operations were repeated two times. No quench occurred in both excitation tests.

Thermal Cycle Test

After the first cold test of the solenoid coil, the thermal cycle tests from room temperature to liquid nitrogen temperature took place to check the resistance of dry winding coil against the thermal cycles. The solenoid coil was cooled down by liquid nitrogen and warmed up in the vertical cryostat. The cool down speed of the solenoid coil from room temperature to liquid nitrogen temperature was very quick about 1hour and hold at least 1hour and warmed up. After the thermal cycle tests of 12 times, the solenoid coil was cold tested at 4.2 K. The solenoid was excited up to 98.7 A without quench under the same excitation condition of the first cold test (500 sec interval pattern operation).

DESIGN OF STEERING DIPOLE COIL

. Two pair of race track shape coils, for X, Y steering dipole correctors are arranged in iron shield pipe as shown in Fig 5. The coil inner width and inner length are 96.25 mm and 250.25 mm respectively and the cross section is 12.1 mm x 13.2 mm. The spacing of two coils is 141mm. When this steering dipole coil is excited without iron magnetic shield, the maximum dipole field on the

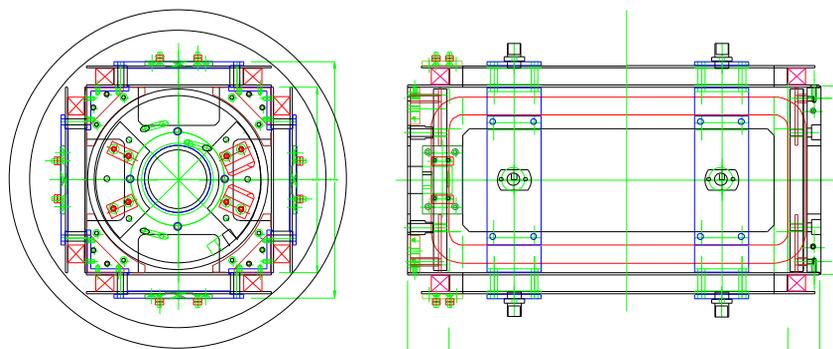


Figure 5: 8 T 25 cm Solenoid package for FRIB Prototyping.

beam axis is 0.127 T and integral dipole magnetic field is 0.031 Tm at 48 A, lower than specification current of 50A and larger than specification value of 0.03Tm.

Winding of Steering Coil

The “dry” winding was also applied for the steering coil, but different from solenoid winding, the “close pack” winding was used. The 0.55mm in diameter SC wire (copper super ration of 2.0) was wound in this coil bobbin under winding tension of 2 kgf. The winding was very smooth and the positioning of the SC wire could be controlled very accurately. The number of layer was 26 and the total wound number was 559 turns. The coil winding procedures including insulation were completely the same to the solenoid winding, except non stainless steel winding wire outside the coil.

Assembling of Steering Dipole Coil

The straight sections of the racetrack coil were pressed into shape by 1.5mm thick stainless steel plates. These compression forces from outside the coil were added by screwed M4 bolts into the support plates which were fixed to both end flanges by pins.

Assembling of Solenoid Package

Two pairs of steering dipole coils (X, Y) were assembled into the square shape steering dipole coil frame outside the solenoid coil (Figure 5). As shown in Fig. 6, the solenoid coil installed inside the steering coil frame and each solenoid coil flange was fixed longitudinally to its end plates and supported radially by 4-divided support plates which were connected to the same end plate. The weight of the solenoid package was 34kg.



Figure 6: Steering coil assembly on the main solenoid.

Cold Test of Solenoid Package

The total of six quench protection resistors were installed inside the cryostat and connected in parallel to each coil, i.e. inner and outer coils of the solenoid and the steering coils. Three Hall probes were installed at the centre of the solenoid coil to measure the three directions of the magnetic field.

Integrate Excitation Test

The cold test of the solenoid package, i.e. cold integration test of the solenoid coil and steering dipole coils, was carried out four times. In these cold tests following excitations were tried; 1) individual two steering coils (X,Y) without the solenoid field, 2) steering coil X and coil Y at same time, without the solenoid field, 3) individual coil X and coil Y with the solenoid field, 4) coil X and coil Y and the solenoid coils, all three at same time.

The measured dipole field for the steering coil X and coil Y were 0.23 T at 80 A which are larger than 3D calculation field of 0.21 T. The self-inductance of the steering coils was also measured to be 0.26 H by using the coil voltage and ramping speed of the excitation current.

The solenoid coil was excited manually up to 95 A (8.45 T) and hold at this current, then the steering coil X was excited up to 80 A by 250 sec interval pattern operation first and then the steering coil Y was also excited up to 80 A by the same pattern, the steering coil Y quenched at 77A (0.22 T) during ramped up. However, this current was high enough for the specification of 48 A.

CONCLUSION

We designed and fabricated an 8 T 25 cm solenoid package prototyping by using “dry winding”. By cold test we could successfully confirm the performance meets requirements of FRIB SRF Linac.

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