

SUPERCONDUCTING FOCUSING SOLENOID FOR X-BAND KLYSTRON

T. Ogitsu, T. Higo and H. Mizuno,

KEK, National Laboratory for High Energy Physics, Tsukuba, Ibaraki, 305 Japan

Y. Imai, T. Inaguchi, T. Minato, T.H. Kim, T. Uemura, and S. Yokoyama,

MELCO, Mitsubishi Electric Corporation, Wadasaki-cho, Hyogo-ku, Kobe, 661 Japan

Z. Wolf, D. Jensen, and P. Radusewicz,

SLAC, Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 USA

A superconducting focusing solenoid for X-band klystron has been developed. The system consists of a conduction cooled NbTi solenoid, high T_c superconductor current leads, and a GM refrigerator. The GM refrigerator can cool down the solenoid from the room temperature to below 4 Kelvin by 4 days. This allow us to operate the system without supplying any cryogen such as liquid helium or nitrogen. The solenoid produces a desired field profile whose maximum value is about 7 kGauss. A normal conducting bucking coil is also implemented in order to tune the field at the cathode. Cool down tests performed at MELCO, KEK, and SLAC confirmed that the system can be cooled down by 4 days. Field measurements performed at those places confirmed that the field profile is very stable between thermal cycles.

I. INTRODUCTION

The X-band klystron, now being developed at KEK [1], requires a focusing solenoid whose warm bore aperture is about 180 mm and maximum axial field is 7 kGauss. The normal conducting solenoid used now consume electric power of about 50 kW. Use of superconducting solenoid, therefore, was considered in order to reduce this electric power consumption. A superconducting magnets, in general however, is needed to be cooled down by liquid helium and special skills are required to cool down the magnet. The superconducting solenoid system developed for the X-band klystron contains a conduction cooled superconducting solenoid, cooled by a Gifford-McMahon type refrigerator, which allows us to operate the system without supplying any cryogen [2,3]. The solenoid is cooled down to an operation temperature of about 4 K just by supplying electric power of 6 kW and cooling water. The system is successfully tested at MELCO, KEK, and SLAC. The cool down performance and field measurement results obtained during these tests will be reported.

II. SYSTEM CONFIGURATION

Figure 1 shows a configuration of the superconducting focusing solenoid system for the X-band klystron. The main components of the system are a conduction cooled

superconducting solenoid, a Gifford-McMahon type refrigerator, and high T_c superconductor current leads.

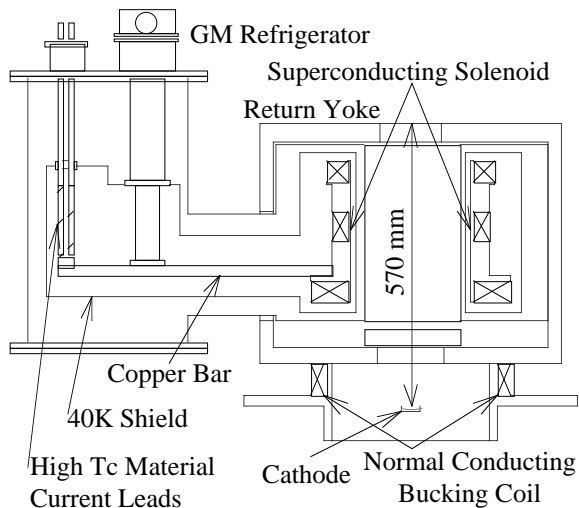


Figure 1 Configuration of the superconducting focusing solenoid system for the X-band klystron

A. Solenoid [2-4]

The solenoid consists of three coils which are wound in series on a stainless steel bobbin which is thermally connected to the cold head of the refrigerator by a copper bar. The coils were cooled by heat conduction through the copper bar and stainless steel bobbin. The solenoid, the inner diameter 250 mm, the outer diameter 400 mm, the overall axial size 280 mm and the overall inductance 36 H, produces a maximum central field of about 0.7 T at the operation current of 17.62 A. The critical temperature at the operation is about 9 K. The solenoid is wound from a wire whose copper to NbTi ratio is 4.5 and diameter is ϕ 0.76 mm. A normal conducting bucking coil is implemented in order to tune the field in the region where a cathode will be placed.

B. GM Refrigerator [2,3]

The system is implemented with a two staged Gifford-McMahon type refrigerator whose refrigeration power is 30 W at 40 K and 1.1 W at 6 K. The fact that the actual heat load to the 6 K head is about 0.2 W allows the system

to cool down the coils to below 4 K which give us a significant amount of operation margin.

C. High T_c Material Current Leads [2,3,5]

High T_c material current leads are used to reduce the heat penetration from the 40 K shield to the 6 K cold head. The leads are constructed from a pair of 200 mm length, 10 mm width, and 1 mm Bi-2223 phase bulk plates reinforced by GFRP. The calculated critical current at 77 K is about 70 A and tested at 25 A under warm and cold head temperatures of about 50 K and 4 K. The heat penetration from the 50 K head from the 4 K head is 46 mW which is significantly smaller than the case using the optimized copper leads which is about 450 mW. Copper leads, 300 mm length and 5 mm² cross section, are used between room temperature and the 40 K shield.

III. CRYOGENIC PERFORMANCE

Temperatures of three coils during a thermal cycle is shown in Figure 2. The data is taken during the first testing cycle at KEK. The figure shows that the solenoid is cooled down from the room temperature to the operation temperature of about 4 K by 4 days. After cold testing, the refrigerator is turned off and the system is warmed up to the room temperature which takes about 10 days. Another thermal cycle has been performed at KEK and three more cycles have been performed at SLAC. In all the cycles the cool down and warm up duration were nearly the same indicating the cryogenic performance is stable over the cycles.

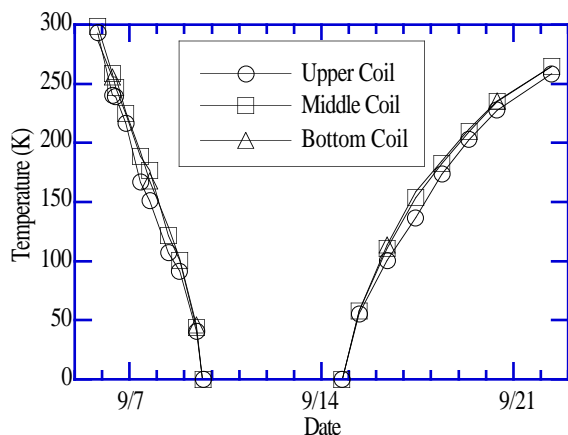


Figure 2 Temperature of the coils during a thermal cycle

A quench test was performed at MELCO [6]. The refrigerator was turned off while the solenoid was excited to 105 percent of the operation current. The solenoid quenched about 1 hour and 20 minutes after the refrigerator was stopped. The solenoid quenched at 9 K and

temperature reached to 20 K after the quench. After the quench, three hours of refrigerator operation was required to recover the system to the operation temperature.

IV. FIELD MEASUREMENTS

Both axial and transverse field measurements were made over several thermal cycles in order to confirm the reproducibility of the field through cycles.

A. Axial Field Measurement

Examples of measured results are shown in Figure 3 in comparison with specification. The measurements shown were taken during the first thermal cycle at KEK and the first thermal cycle at SLAC. The both measurements were made using hall probes which are aligned and moved to measure the axial field along the solenoid center. The measurements are taken under the nominal operation currents for the superconducting solenoid of 17.62 A. No current is fed to the bucking coil. The two measured results overlay each other indicating that field reproducibility over thermal cycles, including the shipping from Japan to USA, is satisfactory. The differences between the specification and the measured results are below 5 percent, the required axial field tolerance, except in the low field region around the cathode position where the field can be tuned by the bucking coil. The current required for bucking coil to tune the field at the cathode position turns out to be about 14 A. The bucking coil is tested and confirmed that it can reach to that current.

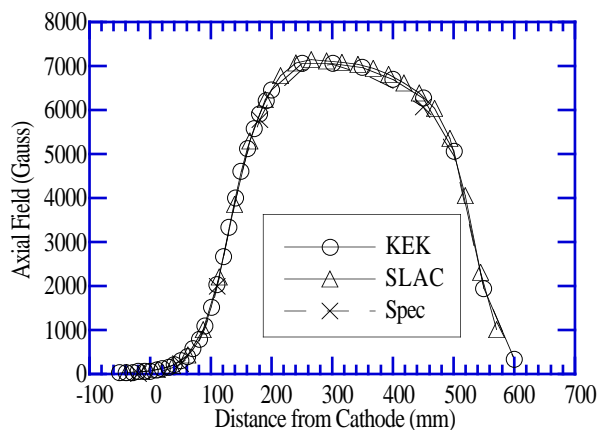


Figure 3 Axial field measurements

B. Transverse Field Measurement

Transverse field measurements are made at SLAC using a rotating coil system. The rotating coil is a radial coil whose radius is about 5 cm and length is about 2.5 cm. The coil was calibrated under an uniform field and it

produces 1 V at 167 Gauss under a rotation speed of 37 Hz. The rotating coil is aligned such that its rotating axis is normal to the top surface of the top pole piece, and it travels along the solenoid center. Measured results taken during the second and third thermal cycle is presented in Figure 4. Figure 4-a shows amplitudes of the transverse fields and Figure 4-b shows phases. The phases are defined counter clockwise looking the solenoid from the top starting from the angle which is rotated 90 degree clockwise from the refrigerator. The measurements were taken under nominal currents of 17.62 A for the solenoid and 0 A for the bucking coil. The measurements were made without changing the alignment of the measuring system from the second thermal cycle to the third one.

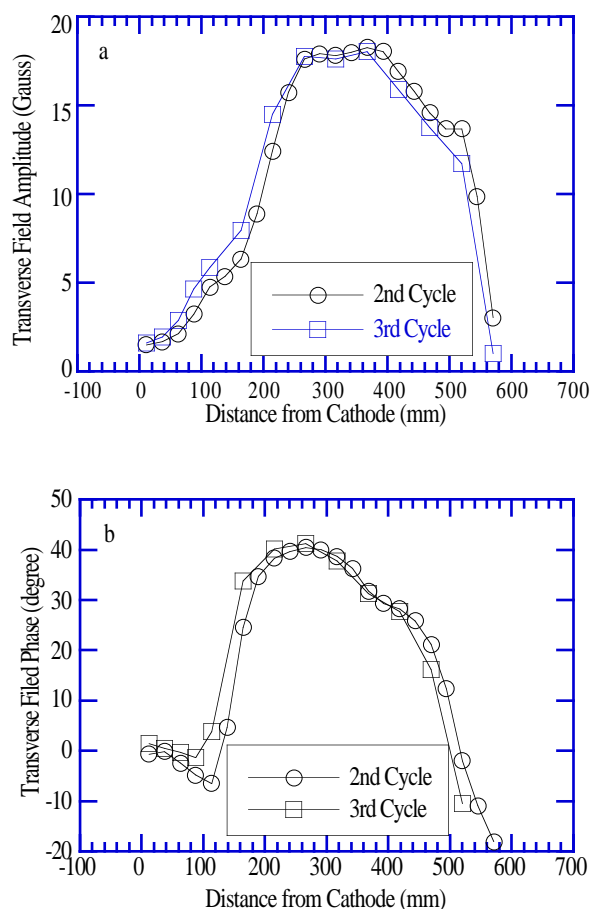


Figure 4 Transverse field measurements a) amplitude b) phase

Two plots overlay each other indicating that the field alignment is not changed from the second to third thermal cycle. The maximum amplitude of the transverse field is about 18 Gauss which is beyond the tolerance required for this solenoid which is 1/500 of the axial field, i.e. about 14 Gauss. Two sources can be considered for this transverse field; 1) misalignment of the solenoid, 2)

misalignment of the rotating coil. In order to examine the source 2, the alignment of the rotating coil is re-checked after measurements. It was confirmed that the rotating coil was aligned correctly with respect to the top surface of the top pole piece. It was found, however, the top surface of the top pole piece is not exactly perpendicular to the solenoid axis, defined by the line connecting the centers of the top and bottom pole pieces. This results in the rotating coil misalignment of about 0.9 mrad towards 56 degree direction with respect to the solenoid axis which can produce about 6 Gauss of transverse field. In fact, the transverse field compensated for this effect reduced its maximum amplitude to 12 Gauss. The value is below the tolerance and that the field quality of the solenoid may sustains actual use of the solenoid on power tests of a klystron.

V. CONCLUSION

A superconducting focusing solenoid system for an X-band klystron has been developed. The system consists of a conduction cooled superconducting solenoid, a GM refrigerator and high T_c material current leads. The system cools down to the operation temperature of about 4 K by 4 days just by turning on the refrigerator. Axial field measurements were performed at KEK and SLAC. It was confirmed that the field is stable over the thermal cycles and the field profile is satisfactory. Transverse field measurements were performed at SLAC. It was also confirmed that the field is unchanged over a thermal cycle. The amplitude of the transverse field appears to be within the tolerance. The system is now shipped backed to KEK and waiting for actual use on power tests of a klystron.

VI. REFERENCES

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