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APPLYING SUPERCONDUCTING MAGNET TECHNOLOGY FOR HIGH-EFFICIENCY KLYSTRONS IN PARTICLE ACCELERATOR RF SYSTEMS

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Abstract

An MgB_2 superconducting solenoid magnet has been developed for electron beam focusing in X-band (12 GHz) klystrons for particle accelerator RF systems, to provide a central field of 0.8 T at 57 A and at $\geq$ 20 K. It has successfully realized significant AC-plug power saving in one order of magnitude compared with that for a conventional Cu solenoid magnet. The large-scale application may be expected for the Compact Linear Collider (CLIC) project proposed as a future accelerator candidate at CERN. It requires ~ 5,000 klystrons, and the MgB_2 magnet application will realize significant AC-plug power saving. This paper describes progress in a prototype MgB_2 superconducting solenoid magnet development and discusses the future prospect.

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***Abstract*— An MgB_2 superconducting solenoid magnet has been developed for electron beam focusing in X-band (12 GHz) klystrons for particle accelerator RF systems, to provide a central field of 0.8 T at 57 A and at ≥ 20 K. It has successfully realized significant AC-plug power saving in one order of magnitude compared with that for a conventional Cu solenoid magnet. The large-scale application may be expected for the Compact Linear Collider (CLIC) project proposed as a future accelerator candidate at CERN. It requires ~ 5,000 klystrons, and the MgB_2 magnet application will realize significant AC-plug power saving. This paper describes progress in a prototype MgB_2 superconducting solenoid magnet development and discusses the future prospect.**

***Index Terms*— MgB_2 superconducting solenoid magnet, Klystron, Particle accelerators, RF power system, and CLIC.**

I. INTRODUCTION

THE Compact Linear Collider, CLIC, has been proposed as a future electron-positron collider accelerator candidate at CERN [1]. It is planned to be built in staging at a center-of-mass collision energy of 380 GeV, CLIC-380, as the general layout shown in Fig. 1, and to be extend up to 3 TeV. A klystron-based RF power system in the CLIC-380 staging has been investigated as illustrated in Fig. 2. It requires X-band (12 GHz, 50 MW) klystrons and the high efficiency in the AC-plug power consumption is a critically issue. The klystron consisting of an electron-beam accelerator for RF power amplification requires the beam focusing with solenoidal magnetic field. A conventional Cu solenoid magnet consumes an AC plug-power of ~ 20 kW, to be resulted in ~100 MW consumption with ~ 5,000 klystrons. The Application of MgB_2 superconducting solenoid magnets at an operational temperature of ~ 20 K may contribute to the significant power saving with one order of magnitude, even including the cryogenics operation power [2]. A prototype MgB_2 superconducting solenoid magnet with a solenoidal field of 0.8 T has been developed, and it has successfully demonstrated stable and safe operation at ≥ 20 K, with achieving significant AC plug-power saving down to < 3 kW, corresponding down to ~15 % of that for the Cu solenoid. The progress is described in this paper.

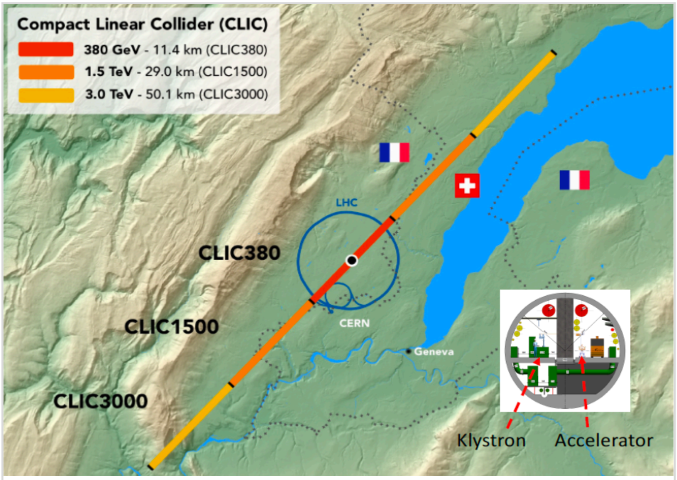

Fig. 1. A schematic layout of the Compact Linear Collider (CLIC) with Klystron RF system, proposed as a future electron-positron linear collider.

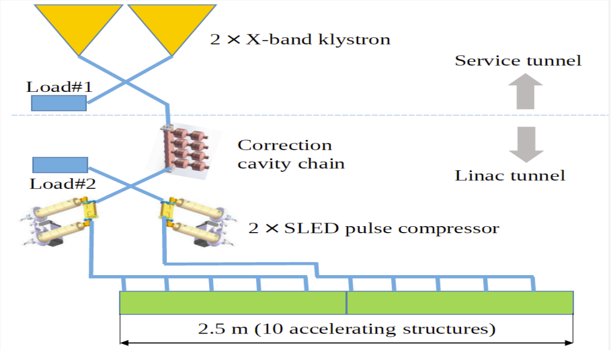

Fig. 2. A concept of pairing klystrons for supplying RF power to CLIC380.

II. MGB_2 MAGNET DEVELOPMENT

A. General Design

The prototype MgB_2 solenoid magnet was designed to demonstrate significant power saving in electron-beam focusing for the 12 GHz, 50 MW klystron expected in the CLIC-380 staging option [2]. Fig. 3 shows (a) the 12 GHz, 50 MW klystron and the electron beam accelerating structure, (b) the

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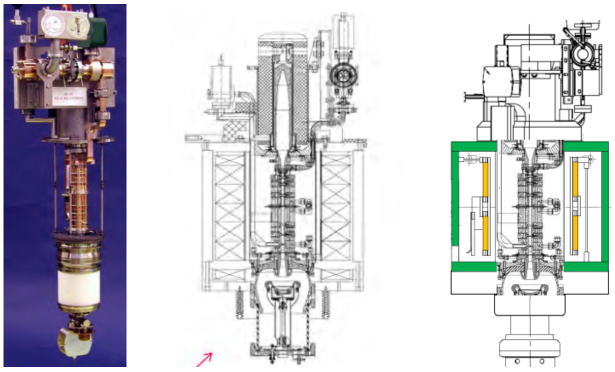


(a) (b) (c)

Fig. 3. (a) 12 GHz Klystron (main RF part), (b) Klystron assembled with conventional Cu solenoid, and (c) Klystrons assembled with a superconducting solenoid magnet.

klystron assembled with traditional, conventional Cu solenoid coils, and (c) the klystron assembled with a pair of superconducting solenoid coils developed [3, 4]. Table I summarizes main parameters of the superconducting solenoid magnet including the cryostat and cryo-cooler. A central field of 0.8 T is provided in a warm bore diameter of 0.25 m, at an operation current of 57.1 A, and an operation temperature of ≥ 20 K, by using MgB_2 superconductor, with an AC plug-power of ≤ 3 kW mainly required for a cryocooler to cool a pair of current leads [5]. The magnet power supply consumption is relatively small (~ ≤100 W mainly for power-supply cable consumption). The magnet structure including magnetic flux return yoke is compatibly designed to the existing conventional Cu solenoid magnet structure, enabling to be replaced.

TABLE I
MAIN PARAMETERS OF THE MgB_2 SUPERCONDUCTING SOLENOID.

Elements	Parameters
Superconductor	
Material	MgB_2/Cu /Fe/Monel ®
Strand bare diameter	0.67 mm
Insulation on strand (thickness)	Glass-braid (80 μm)
SC solenoid coil	
Inner diameter and Length	0.34 and 0.30 m
Central field, and max. field in coil	0.8 T and 1.06 T
Current	57.1 A
Inductance	7.23 H
Stored energy	11.8 kJ
Cold mass (coil, Cu-insert, Bobbin)	71 (14 + 25 + 32) kg
Heat-treatment	600 C x 6 hours
Insulation after heat-treatment	Epoxy-resin impregnated
Cryostat	
Warm ID, Iron-yoke OD, and Hight	0.25, 0.63, and 0.52 m
Cryo-cooler	
Cooling capacity	4 W at 20 K, 13.5 W at 80K
AC plug-power	≤ 3 kW

B. *Superconductor*

The superconducting coil operation at higher temperature is an important requirement to improve thermal efficiency, and therefore MgB_2 is an optimum material to be operated at ≥ 20 K [6]. Fig. 4 shows superconductor performance of the MgB_2 conductor [7]. A continuous length of 8 km of the MgB_2 conductor was successfully fabricated and a part of 5.6 km has been used to this solenoid coil. The superconductor is insulated with glass-braid prior to the coil winding, for enabling the wind-and-react process during the coil fabrication.

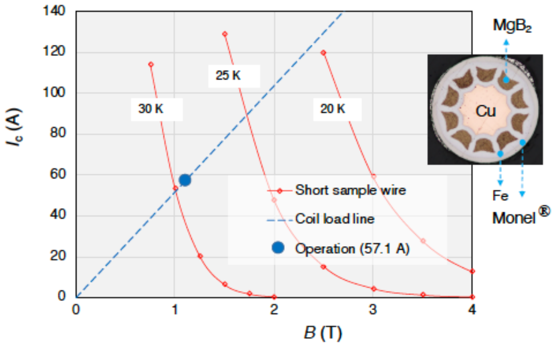


Fig. 4. MgB_2 superconductor characteristics and operational point expected.

C. *Superconducting Coil*

The superconducting solenoid coil design consists of a pair-solenoids with axial gaps at the middle and both ends facing to the iron return-yoke, providing solenoidal focusing field for electron beam acceleration in the klystron. The coil design parameters are optimized to realize a self-protected coil without requiring an active quench protection system for realizing the simple magnet operation, based on simulation study in the design phase and on experimental study by using a small test coil prior to the prototype coil fabrication [8].

Each half coil using the MgB_2 conductor on the coil bobbin made of stainless steel. It consists of 152 turns and 16 layers per coil. Thin, 0.2 mm thick Cu sheets (half cylinder shells) are embedded between coil layers to enhance conducting cooling power and quench propagation velocity along the coil axial direction. The coil is heat-treated at 600 C for 6 hours in argon gas after the coil winding and is impregnated with epoxy-resin in vacuum to complete the electrical insulation.

D. *Assembly into Cryostat and Cooling with Cryocooler*

The superconducting coil is installed into a cryostat consisting of an inner warm bore tube made of stainless steel, an outer cylinder, and axial end-plate structure made of iron for magnetic flux return-yoke function. A cryocooler is applied for conduction cooling of the coil via Cu thermal link. A set of current leads are thermally anchored at the 1st stage of the cryocooler. No thermal, radiation shield plate is placed between the coil and the cryostat except for multilayer superinsulation. A cross section of the magnet assembly is shown in Fig. 5.

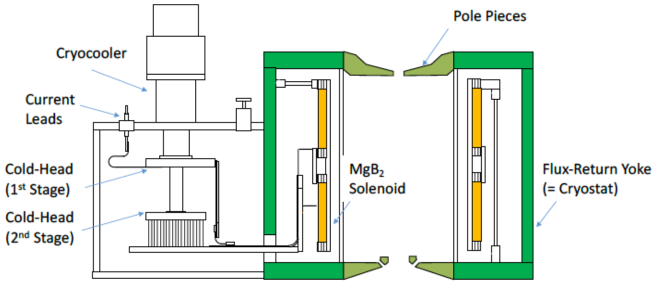


Fig. 5. A cross section of the MgB_2 superconducting solenoid magnet conductively cooled by using a cryocooler. Axial end plates and outer cylinder of the cryostat are functioning as magnetic flux return yoke. A set of pole tips are attached at both end plates for magnetic field shaping.

III. PERFORMANCE

A. Cooldown

The MgB_2 superconducting coil was conductively cooled down by using the cryo-cooler, in one week, as the cooldown trend shown in Fig. 6. The temperature distribution in the coil was kept within 50K, contributed by axial thermal conduction enhancement with Cu sheets placed along the coil axis as described in the previous section.

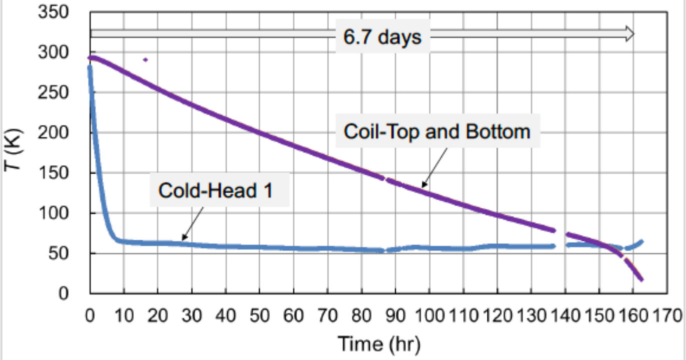


Fig. 6. The initial cooldown characteristics of the MgB_2 solenoid magnet.

B. Magnet Excitation

The magnet was charged by using a compact solid-state power supply with a bypass diode at the output terminal to provide the current loop secured for the superconducting coil during discharge, as shown in Fig. 7. In the nominal operation, the magnet was charged with a ramp rate of 0.2 A/s, reaching the design current of 57.1 A in 4 min., and passively discharged according to voltage drop through power supplying cable resistance (~ 30 mΩ) and a by-pass diode at the power-supply output, within 5 min. No active quench protection system was required because of the self-protected coil design and fabrication, as details described in a separate report [8]. The very simple operation has been realized, as similar as the conventional Cu-based coil operation.

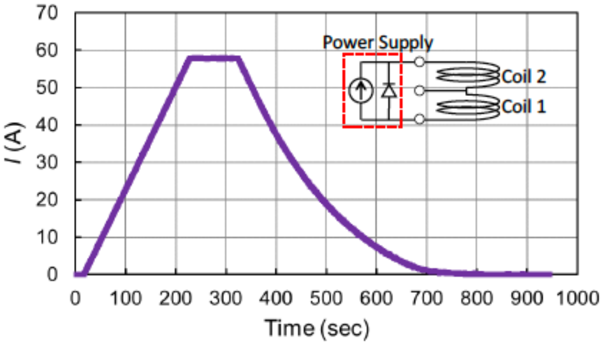


Fig. 7. A typical solenoid magnet excitation characteristics.

C. Magnetic Field Profile confirmed

The magnetic field profile along the solenoid axis was measured by using a hall-probe and the result well reproduced the design profile required for the electron beam focusing along the Klystron, as shown in Fig. 8. It is consistent with the original Cu solenoid design given by SLAC [3, 4, 8].

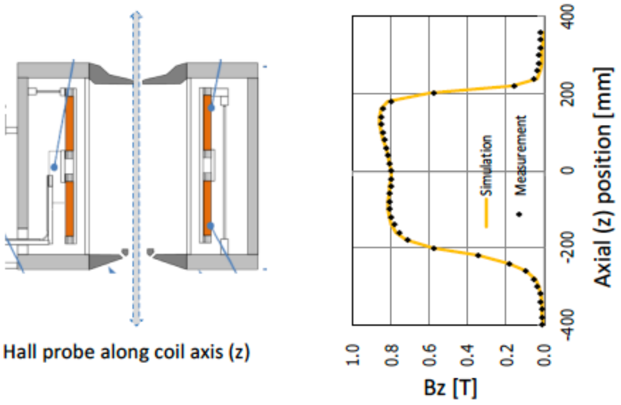
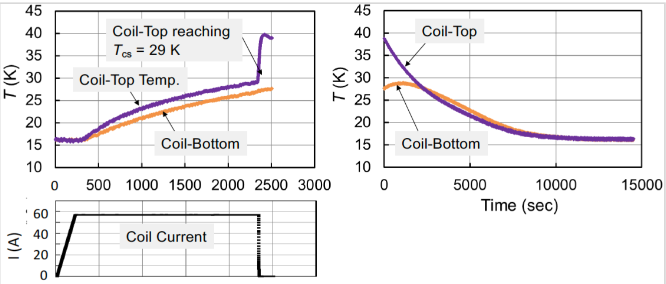


Fig. 8. A typical solenoid magnet excitation characteristics.

D. Safe Operation confirmed at ≤ T_{cs}

The safe and stable operation of the MgB_2 superconducting coil up to the current sharing temperature (T_{cs}) at 29 K was demonstrated, by gradually raising the coil temperature by using a heater attached at the 2nd-stage cold-head of the cryocooler. Fig. 9 shows the trend of the coil temperature increase at a coil current of 57.1 A. The critical temperature for current sharing (T_{cs}) because of the super-to-normal transition was confirmed at 29 K consistently with the conductor performance test result shown in Fig. 4 [7, 8]. After a passive power supply trip-off due to the power supply voltage limit, the maximum coil temperature of 40 K was observed on the insulated inner surface of the coil with epoxy-resin impregnation. It was a result to indicate the peak coil-temperature safely kept sufficiently lower than a safety guideline of 140 K, as discussed in the next section, even in case of an emergency such as stop of the cryocooler due to AC power outage. The test demonstrated the MgB_2 superconducting solenoid magnet with the self-protected coil design to be safely operated by using a simple circuit system as similar as that for the conventional magnet.

The re-cooldown time of the superconducting coil by using the cryocooler after the quench was also observed, as shown in Fig. 9 (b). It took ~1.5 hours for enabling the re-excitation at the coil temperature below 25 K. It sounded practical.



(a) (b)

Fig. 9. Trends of (a) the coil temperature increase and the normal transition at T_{cs}, and (b) re-cooldown in 1.5 hours for enabling the coil excitation.

E. Quench Safety

The quench safety was evaluated through a combined effort of simulation study with two stages of local heater quench tests using a dedicated, small test coil and the prototype coil, prior to the assembly into the cryostat, with numbers of voltage taps and temperature sensors to monitor the quench behavior and to confirm the safety. The results are discussed in another report and a major result was summarized that the peak temperature in the coil after the localized quench be kept below 140 K in the prototype magnet [8]. Then, the prototype coil was assembled with the cryostat with limited numbers of diagnostics for safety and reliability reasons in long-term prototype magnet operation combined with the klystron.

IV. DISCUSSION

A. General Performance and Energy Saving

The MgB_2 superconducting magnet for Klystron electron beam focusing has been successfully demonstrated with the general performance of 0.8 T at 57.1 A, at T_{cs} = 29K, at an AC plug-power consumption of < 3 kW, realizing to save the AC plug power down to one seventh (nearly one order of magnitude). Comparisons of Cu, NbTi, MgB_2, and HTS (GdBCO/EuBCO) are summarized in Table II from a viewpoint of AC-plug power saving [8-10]. The simplified operation with no requirement for an active quench protection system is also an important feature and advantage. We have demonstrated that the MgB_2 superconducting magnet is a very stable and cost-effective approach in good balance of the operational AC power efficiency and the cost-effective conductor availability.

V. SUMMARY

The MgB_2 superconducting solenoid magnet for the klystron beam focusing has been successfully developed. The general performance of the central field of 0.8 T, below the T_{cs} of 29 K is demonstrated. The stable operation at a temperature range of 20 ~ 25 K has been ensured at the AC-plug power of < 3 kW with the power saving nearly in one order of magnitude, compared with the conventional Cu solenoid. It may extend to a large-scale application such as CLIC-380, enabling an overall power saving of ~100 MW for 5,000 klystron operation. Based on this development experience, the application of the HTS conductor will be an expected direction for further power saving, in future, assuming the higher operational temperature in a range of 65 – 70 K, if cost-effective HTS conductor may be realized.

TABLE II
COMPARISONS OF CU/MgB_2/HTS COILS AND POWER CONSUMPTIONS

Coil material	unit	Cu	NbTi	MgB_2	HTS (GdBCO)
Coil					
Central field	T	0.6	0.8	0.8	0.8
Current	A	2 x 300	57	57	57
Voltage	V	35	0	0	0
Power	KW	20	0	0	0
Cooling					
Cooling method		WC	CC	CC	CC
Temp	K	300	4.5	~ 25	~ 65
Capacity	W	n/a	1	4	3
AC-power @ RT	kW	n/a	6	< 3	< 2
Total Power	kW	>20	6	< 3	< 2
Reference		[3]	[9]	[8]	[10]

WC: Water cooling, CC: Cryo-cooler cooling:

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