First Results from Tests of High Temperature Superconductor Magnets on Tokamak

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Introduction

Coils of steady-state tokamak magnets will have to be superconductive to reduce otherwise high running costs [1, 2]. Although present low temperature superconductors are widely used (e.g. Tore-Supra, KSTAR, EAST), they have to be cooled using liquid helium which is both expensive and technologically challenging and requires bulky cryostats. This contribution presents results of the first tests of high temperature superconductor (HTS) coils on the GOLEM tokamak. The HTS used in the experiments are a 2^{nd} generation of (Re)BCO tape SCS12050-AP supplied by SuperPower Inc., US at a low price of 100 $/m. The tape becomes superconductive already at the relatively high temperature of $\sim$ 91 K with a critical current $\sim$ 350 A according to its specifications. As the critical temperature is above the boiling point of nitrogen, liquid nitrogen (LN) can be used for cooling. The tape has dimensions of 0.1 $\times$ 12 mm. The HTS itself is only a 1 μm thick layer between two 20 μm Cu stabilizing layers on a 50 μm Hastelloy substrate.

Experimental setup

GOLEM (R = 0.4 m, a = 0.085 m) is a small iron-core transformer tokamak operating at modest parameters $I_p < 4$ kA, $B_t < 0.5$ T [3]. It is assumed that such low magnetic fields do not affect the performance of the HTS. A set of 4 six-turn Cu poloidal coils in a dipole (or quadrupole regarding the currents) configuration as seen in Figure 1 are used for plasma position stabilization using a radial or vertical magnetic field. For the purpose of the HTS tests the two outer coils were replaced with HTS tape coils with an equal number of turns. All poloidal coils were connected in series (with orientation appropriate to the target orientation of the generated magnetic field) to a capacitor bank.

The maximum achievable current was limited by the resistance of the non-superconductive inner poloidal coils, inductance of the coils and the resistance of the cables connecting the coils to the capacitor bank. As in some experiments only the superconductive coils were used, the characteristic time constant of the circuit had to be prolonged by connecting a choke coil in series and/or a resistor was connected in series to limit the maximum achievable current.

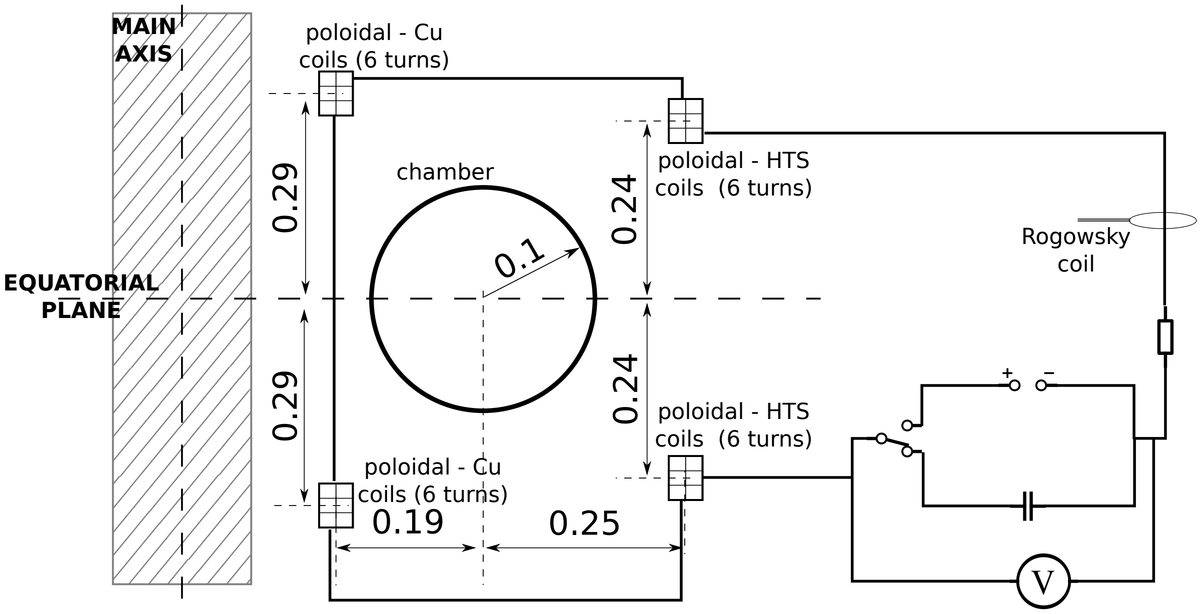

Figure 1: Poloidal coils configuration at the GOLEM tokamak during HTS tests

Cooling system

Each HTS tape coil submerged in LN is contained in a circular-basin cryostat made of 4 quadrants for easy assembly on the machine. To endure the regular changes of hundreds of K the first cryostats were made of plywood. Later, the cryostat quadrants were cut out from extruded polystyrene (JACKODUR KF 300 Gefiniert GL) using a hot resistive wire and then glued together using standard polystyrene glue. The resulting cryostats offer exceptional heat insulation (half of LN remains after $\sim$ 45 min) and can be easily repaired in comparison with the frequently leaking plywood cryostats. The six turns of HTS tape are insulated from each other using Kapton tape. The two cryostats are filled independently from two Dewar flasks to maintain a given level of LN using a system of valves controlling the flow of pressurized air into each flask.

Conducted measurements

The HTS tape was subject to a wide range of experiments in which its performance under higher current loads and various current ramp-up speeds was observed. With sufficient LN cooling no rise in resistance of the tape up to a maximum current of $\sim$ 250 A supplied by a DC power source was observed. Each poloidal coil consisting of six turn of the HTS tape has a resistance $\sim 1\Omega$ in a non-superconductive state. With sufficient LN cooling the coil becomes superconductive within several minutes even under a low current load $\sim$ 10 A.

For pulse regime operation the performance of the HTS under various current ramp-up speeds has been investigated. Most importantly, the appearance of quenches during current ramp-up was examined. Under slow DC current ramp-up <= 10 kA/s no quenches have been observed. By discharging a capacitor bank into the HTS coils in a superconductive state current ramp-up speeds of hundreds of kA/s were achieved without any apparent quenches. However, during other experiments the bottom HTS coil was irrecoverably damaged in one segment on all 6 turns due to insufficient LN cooling. The damaged segments had to be removed and the remaining tape was soldered together and re-installed. The voltage drop on these joins was measured throughout the fast current ramp-up operation. Only one join exhibited quenches, all the other 5 joins only posed as a negligible resistance.

A simple method of ensuring there are no short-circuits between the turns of the HTS coils has been developed: A low loop voltage was induced through the tokamak transformer and the voltage induced on the coils was measured. If the measured voltage was six times the loop voltage, no short-circuits were assumed to be present.

Plasma position stabilization

As can be seen in Figure 2, an appropriate radial magnetic field can prolong the plasma pulse by compensating the tendency of the plasma column to go upwards. With HTS coils in a superconductive state the coils target current can be reached with a much lower capacitor bank charging voltage than with the coils in a non-superconductive state. However, due to the low resistance the characteristic time constant of the circuit changed and the stabilization pulse was much shorter, making it ideal for fast feedback systems.

Current driven only by poloidal coils

Outer poloidal coils can generate a change of the vertical magnetic flux which induces a loop voltage in the tokamak vessel as a transformer would. With this principle plasma breakdown was achieved and current driven without using the primary windings of the transformer. The breakdown voltage was 20V with a maximum poloidal coils current 280 A for coils in a non-superconductive state, 15V and 480 A in a superconductive state.

Conclusion

The HTS coils have been routinely and successfully used at the GOLEM tokamak both for plasma generation and stabilization. Provided the LN cooling is sufficient and sustained, the HTS coils are reliable and can greatly reduce the necessary capacitor bank charging voltage,

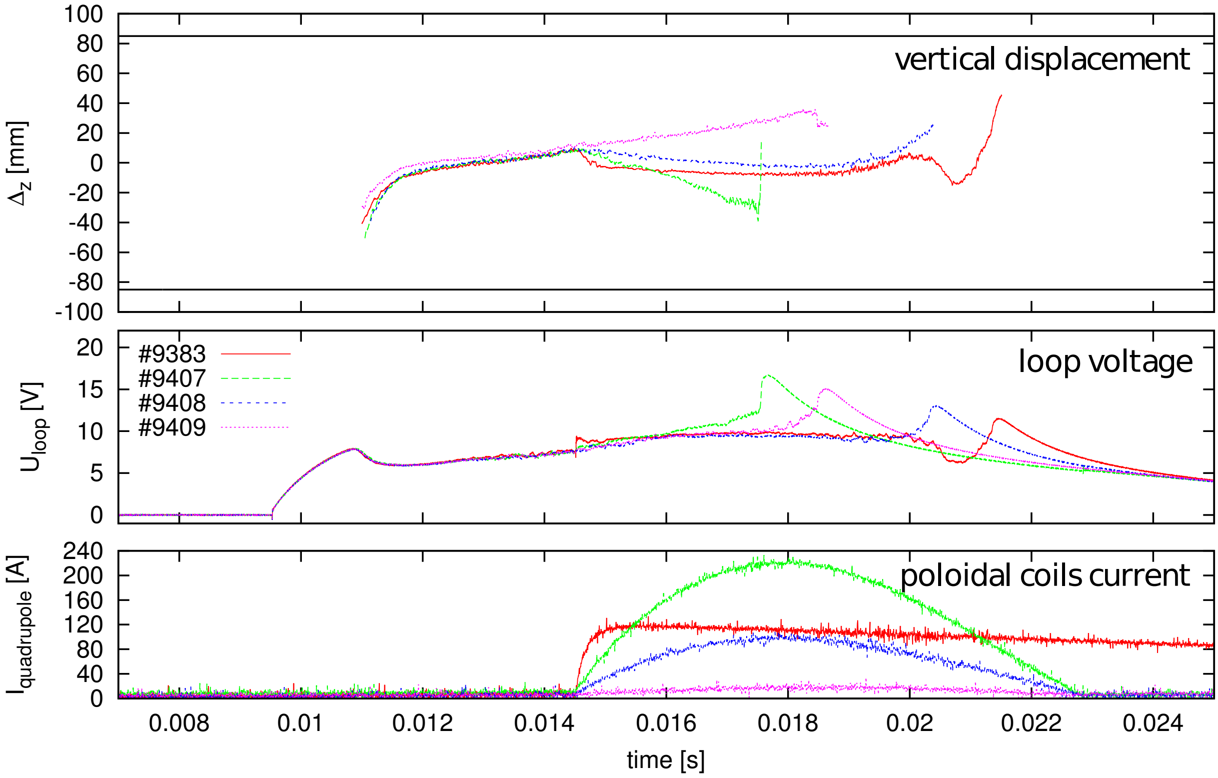

Figure 2: Plasma displacement using the HTS coils. In discharges #9407 and #9408 the HTS coils were in a superconductive state and the capacitor bank charging voltage was only 70 V and 20 V whereas it was 400 V in discharge #9383 where the coils were in a non-superconductive state and the coil current was similar. Discharge #9409 is a reference discharge with no radial stabilizing field.

thus lowering the energy demands for plasma position control. The coil currents in fast ramp-up pulse operation exceeded those in the tape specification by almost 50 %.

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