First Results from Tests of High Temperature Superconductor Magnets on Tokamak.

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It has long been known that high temperature superconductors (HTS) could have an important role to play in the future of the tokamak fusion research [1,2]. In this paper we present first results of the use of HTS in a tokamak magnet. In the experiment, the two copper poloidal field coils of the small tokamak GOLEM in Prague [3] were replaced by two coils with 6 turns of the 2nd generation HTS (Re)BCO tape SCS12050-AP supplied by "SuperPower Inc.", US. The coils were wound *in-situ* by hand to avoid the need to disassemble the tokamak. The dimensions of the tape are approximately 0.1x12mm, HTS thickness ~1μm, with two 20μm Cu stabilising layers on the 50μm Hastelloy substrate and the maximum claimed current capacity at liquid nitrogen (77K) temperature of ~ 320 Amps. Two simple liquid nitrogen (LN) cryostats made by "Forma Machinery Ltd" in Latvia, were assembled and filled with LN to cool the HTS tape to below the critical temperature at which it becomes superconducting. Plasma pulses were then fired in a normal way with HTS coils providing the vertical field and the tokamak operated exactly as expected. There had been concerns that the plasma pulses might cause a "quench", i.e. cause a sudden and potentially damaging transition from superconductor to normal conductor. However, many plasma pulses were achieved without any quenches. In addition, experiments without plasma have been performed to study properties of the HTS in a tokamak environment, i.e. critical current and its dependence on magnetic and electrical fields generated in a tokamak both in DC and AC operations, maximum current ramp-up speed, performance of the HTS tape after number of artificially induced quenches etc. Considerable experience has been gained during design and fabrication of the cryostat, coils, isolation and insulation, feeds and cryosystems. The tokamak GOLEM is now routinely operated with HTS coils and design and construction of next step HTS tokamaks have started and are on-going.

Fig.1. Plasma pulse in the GOLEM tokamak with HTS poloidal field coils.

Fig.1 shows the GOLEM tokamak with two HTS vertical field coils. The plasma is seen through the midplane port. GOLEM is a small tokamak of circular cross-section, and is the oldest operating tokamak in the world. It began operation at the Kurchatov in the early 1960's, becoming CASTOR at the Institute of Plasma Physics, Czech Academy of Sciences, before undergoing further modifications and a move to FNSPE, the Czech Technical University in Prague, and being renamed GOLEM. It has operated routinely for nearly two years at a modest range of parameters B_t<0.5T, I_p<8kA, pulse length <25ms. Its present mission is as an educational device for training domestic as well as for foreign students, the latter via remote participation. Thus the oldest operating tokamak in the world is now equipped with the most modern and advanced HTS technology.

The cryostat, feeds and coil designs have evolved and the final version of the cryostat has improved insulation, so the ice seen in Fig.1 on the coils has been avoided. The typical time of cooling to superconducting conditions has decreased from the initial value of 90min to 15min. The final design of feeds avoids the local overheating observed in earlier designs. It was also found that circulation of LN in the cryostat resulted in ~15% increase in the critical current.

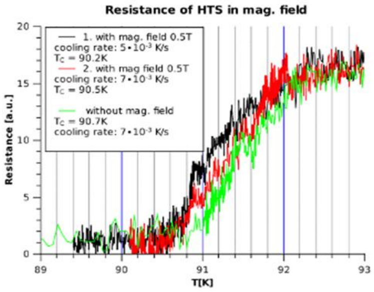

Fig.2. *Dependence of the critical temperature for achievement of superconductivity in the HTS coil without and with 0.5T on GOLEM.*

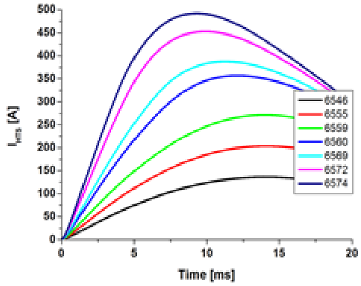

Fig.3. *Evolution of the inductively induced current in the HTS coil in different pulses.*

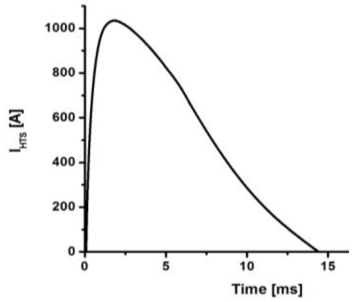

Fig.4. *Evolution of the inductively induced current in record pulse 6975.*

Although it is known that the critical current in HTS strongly depends on magnetic field, for the GOLEM conditions, where magnetic fields at the coil position do not exceed 0.5T, little effect has been observed for perpendicular field up to 0.5T and superconductivity has been achieved at ~90.5^{0}K, Fig.2. No quench has been observed at DC currents up to 250A (the limit of the available power supply) during bench tests of the tape. The HTS was kept on the full current for tens of minutes with no observed changes in resistivity. In the AC tests, current up to 1kA through the tape (6kA-turns through the coil) has been achieved with no degradation of the HTS performance afterwards, although in such short pulse the current was probably distributed between the HTS and other components of the tape. Fig.3 shows time evolution of the inductively induced current in the HTS coil demonstrating the current ramp-up speed of up to 90kA/s, however, the highest rate of ~0.6MA/s has been achieved in pulse #6975, Fig.4, where current through the tape has reached 1kA.

In typical plasma pulses such a high level of current in equilibrium field coils is not needed and plasma operations have been performed with moderate I_{HTS} ~ 50-100A current in the tape. This probably explains the absence of quenches during plasma pulses as the current was much below the critical value. However in some cases plasma disruptions occurred with corresponding induced electrical fields, and they also did not cause quenches. In future experiments, increases in both the plasma current and pulse duration are planned. To study quenches in DC operations, the current was increased and quenches have been observed at I_{HTS} ~ 150A when operating together with other tokamak magnets but without plasma. When “up-to-destruction” tests have been performed, a quench caused an arc in the inter-turn isolation in one coil. There was no surprise that the location of the quench was under the limb of the iron transformer, where the highest leakage magnetic field has been measured. The damaged pieces of the tape have been cut out, the ends re-soldered and the coil has shown the same performance as before the accident, i.e. the local quench has not affected the performance of the rest of the coil. Over 25 quenches have been performed and a whole series of further experiments is now planned. The internal structure of the damage caused by the quench that caused arcing is under investigation.

The next step in the application of HTS magnets in tokamaks is construction of a fully-HTS tokamak that has started at the Tokamak Solutions UK premises in the Culham Science Centre, UK. It is planned to operate a small tokamak with A=2 and circular cross section in steady state with plasma currents of 10-20kA driven by Electron Bernstein Wave current drive at densities above $10^{19}m^{-3}$. In parallel, the design and manufacture of a high-field (3-5T) HTS TF coil for a spherical tokamak will be carried out.

1. L Bromberg et al, Fusion Eng. and Design, 54 (2001) 167

2. G Janeschitz et al.; “*High Temperture Superconductors for Future Fusion Magnet Systems - Status, Prospects and Challenges*” Proceedings of the 21st IAEA Conference, Chengdu, 16–21 October 2006, IT/2-2, http://www.swip.ac.cn/xsyd/p1292/papers/it 2-2.pdf

3. V. Svoboda et al., *Multi-mode remote participation on the GOLEM tokamak*, Fusion Eng. and Design 86 (2011) 1310