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Progress in application of high temperature superconductor in tokamak magnets

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HIGHLIGHTS

- We report on first results of the use of HTS in tokamak Golem poloidal field coils.
- We show that superconductivity has been achieved at 91 K with liquid Nitrogen cooling.
- We show that current in 12 mm SuperPower YBCO tape used can exceed 1 kA in pulses and current ramp speed can exceed 100 kA/s.
- We show that quenches do not cause degradation in the coil performance if controlled.
- We report on plans and progress in design and constructions of the first full-HTS tokamak ST25.

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ABSTRACT

It has long been known that high temperature superconductors (HTS) could have an important role to play in the future of tokamak fusion research. Here we report on first results of the use of HTS in a tokamak magnet and on the progress in design and construction of the first fully-HTS tokamak.

1. Introduction

The key advantage for fusion devices of the use of new generation superconducting materials (HTS) is that they not only, like traditional low temperature superconductors (LTS), conduct current with zero electrical resistance so that coils can be run without any resistive heating, but also that HTS are much better in all the main characteristics of importance for application in tokamak magnets: higher fields, higher critical current at high magnetic fields, better irradiation resilience [1–3]. Very high magnetic fields (above 30 T) have been already achieved using HTS in magnets [7] and technology is progressing rapidly to increase of the critical current, currently above 500 A at 77 K at self-field in a commercially available 0.1 mm × 12 mm (RE)BCO tape from SuperPower. In [4], it has been claimed that the superconductivity of YBCO vanishes only above a fluence between 0.5×10^{23} n/m^{-2} at low fields and 2×10^{23} n/m^{-2} at higher fields and that the intragrain critical current density increases with increasing fluence, so irradiation performance overtakes that for the LTS.

These predictions have stimulated both the testing of HTS coils on an operating tokamak and the design of a fully-HTS tokamak. Results of these studies are presented in this paper.

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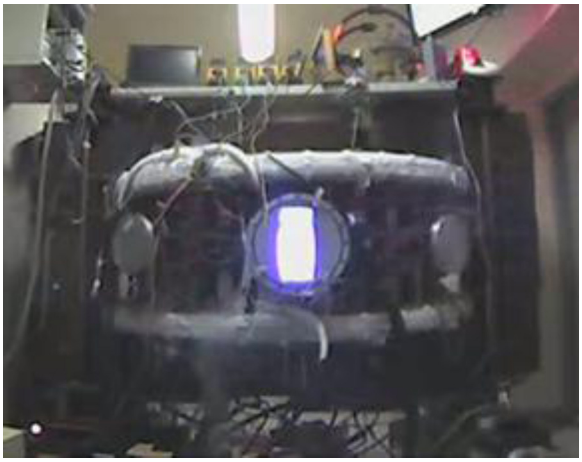

Fig. 1. Plasma discharge in the GOLEM tokamak (plasma seen through the midplane port). Two icy cryostats have 6 turns of (RE)BCO tape in each, cooled by liquid nitrogen.

2. Experiments on GOLEM tokamak

In August–September 2011, Tokamak Solutions and Oxford Instruments, in collaboration with the Czech Technical University in Prague and IPP AS CR Prague, carried out the first successful tests of an HTS coil on a tokamak. In the experiments, two of the copper poloidal field (PF) coils on the Golem tokamak in Prague were replaced with a pair of liquid nitrogen cooled coils made of the 2nd generation HTS (RE)BCO tape material manufactured by SuperPower (US) [5]. Fig. 1 shows the GOLEM tokamak with a plasma seen through the midplane port and two icy cryostats that contain coils each with 6 turns of HTS (Re)BCO tape. Liquid nitrogen was used to cool the coils to below the critical temperature at which HTS becomes superconducting. Several modifications have been made to the cryostat to provide better thermo-insulation and the icing has been completely avoided in the final version with the cooling time from room temperature reduced to just 5 min.

Little effect on the HTS critical current has been observed for perpendicular field up to 0.5 T (the maximum possible field at HTS coils position expected on GOLEM) and superconductivity has been achieved at ~90.5 K during bench tests (Fig. 2). Here the resistance of a sample piece of the HTS tape is shown vs. the temperature measured by a thermocouple at the surface of the tape, with and without external field and at different cooling rates.

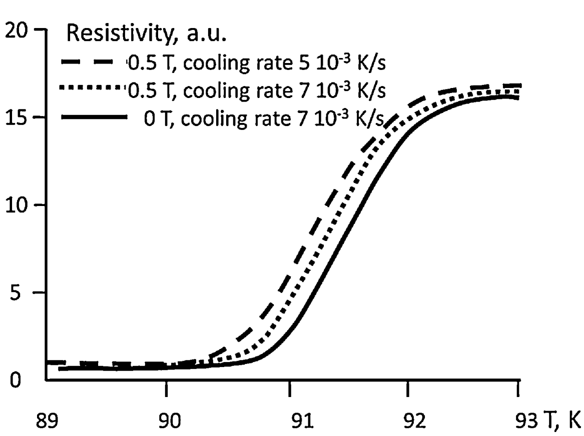

Fig. 2. Superconductivity achieved at 90.7 K with zero external field at cooling ratio 7×10^{-3} K/s, at 90.5 K with 0.5 T external field and cooling ratio 7×10^{-3} K/s and at 90.2 K with 0.5 T external field and cooling ratio 5×10^{-3} K/s; here resistance of a HTS sample is shown vs. temperature.

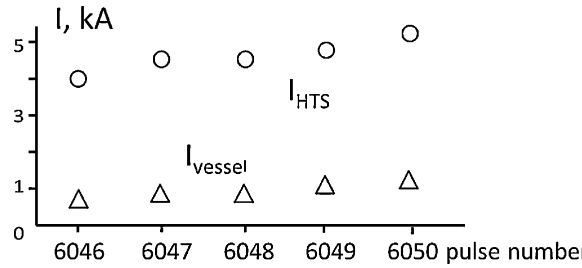

Fig. 3. Maximum current in the HTS coil in different pulses. 5 kA (840 A through the tape, which is ~2.5 times higher than I_{crit} specification) has been achieved in the pulse #6050. I_{vessel} is the current in the vacuum vessel induced by the change of PF coils current.

There had been concerns that the plasma pulses and pulsed magnetic fields might cause a "quench" in the HTS, i.e. a sudden and potentially damaging transition from superconductor to normal conductor. However, many pulses with and without plasma were fired and no quench occurred. Several experiments have been performed to measure the practical critical current in the coil and to optimise cooling for the best performance. No quench has been observed at DC currents up to 200 A (1.2 kA × turns through the coil). In short pulses, when the coil was connected to a capacitor bank, current up to 0.84 kA through the tape (5 kA × turns) has been achieved (Fig. 3) with no subsequent degradation of the HTS performance with a current ramp rate up to 0.1 MA/s (Fig. 4). The manufacturer's specification for this tape was 330 A, so the current exceeded the specification value by 2.5 times with no visible degradation in performance.

In the next set of experiments, a DC power supply was connected to HTS coils and tokamak pulses, with and without plasma, have been performed while the DC current in the coil has been increased in steps up to 180 A. Fig. 5 shows coil current evolution in time with dots indicating times when tokamak pulses were fired, with and without plasma. Spikes in the current trace represent increases in the coil current induced by the applied loop voltage in tokamak plasma pulses, however the slow digitisation does not provide the real current value on this plot (which was also measured using fast digitising channels). In some cases, the current was deliberately reduced, but some current drops represented quenches, i.e. at time 14,400 s and 14,700 s. It was found that although without a tokamak pulse quenches appeared at about 180 A, they appeared at about 140 A during a tokamak pulse. In these experiments, no quench protection was used, so the current was ramped down manually when the resistance of the coil started to increase. So, for several seconds the superconductivity has been lost in each quench case, which sometimes created damage to the tape, visible as hot spots.

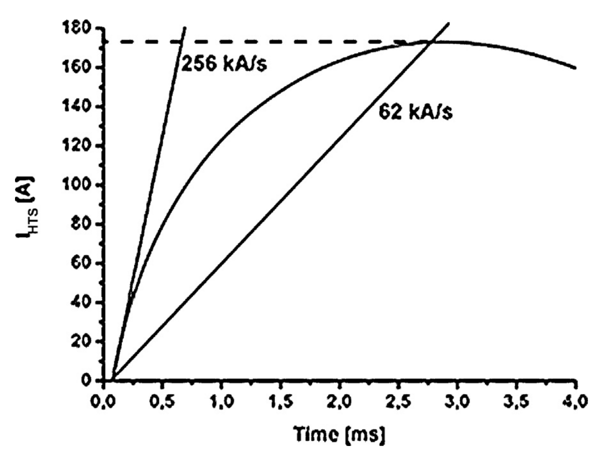

Fig. 4. Current in the HTS coil. Current ramp-up speed ~100 kA/s.

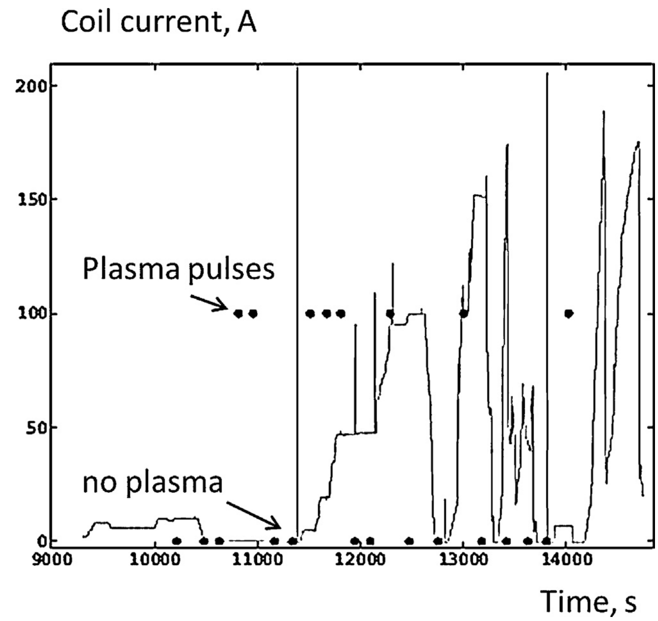

Fig. 5. Current in the HTS coil. Dots indicate moments when tokamak pulses were fired, top set – with plasma, bottom set – without plasma.

Table 1
Main parameters of ST25.

Parameter	Cu coils	HTS coils
R/a, cm	25/12.5	
B_t, T	0.1–1	
I_{pl}, kA	5–20 kA	
t_{pulse}, s	1–5	s/state
P_{RF}, kW	3	20
Freq, GHz	2.45	28

However, even a number of such damaging events surprisingly did not significantly affect the overall performance, e.g. the maximum achievable current.

Fig. 6 shows the voltage over the HTS coil and the current in it during two consequent quenches. After the increase in the voltage has been observed by a tokamak operator, the current in the coil was reduced to about 50 A and then slowly increased close to the

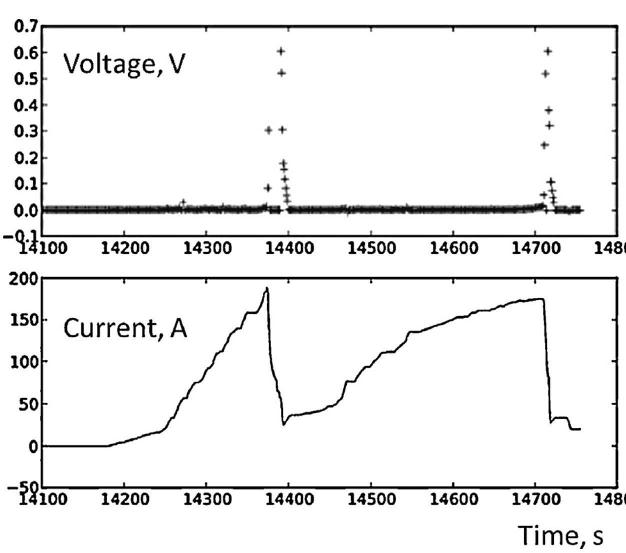

Fig. 6. Top – voltage drop on HTS coil, bottom – current in HTS tape during series of quenches.

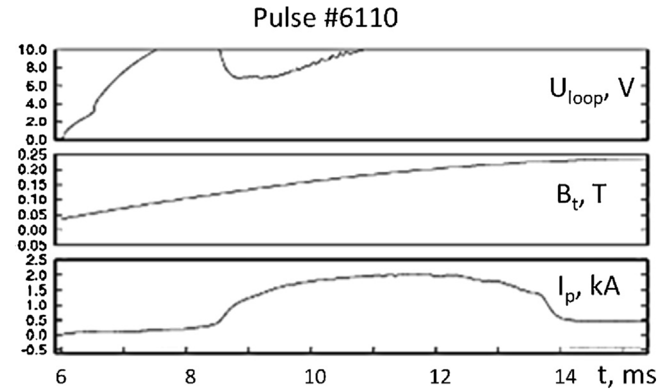

Fig. 7. Traces of a typical 2 kA plasma pulse on Golem with two HTS PF coils with 50 A in HTS coils.

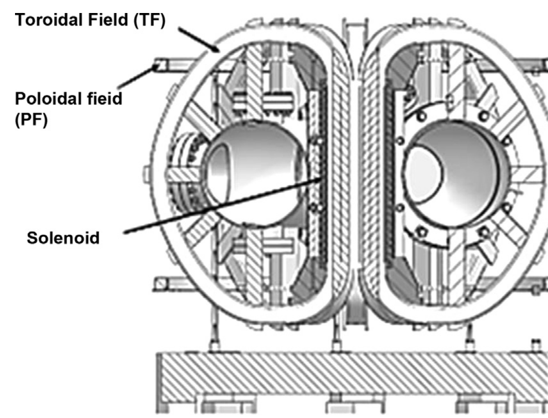

Fig. 8. Cross-section view of ST25, Cu coils.

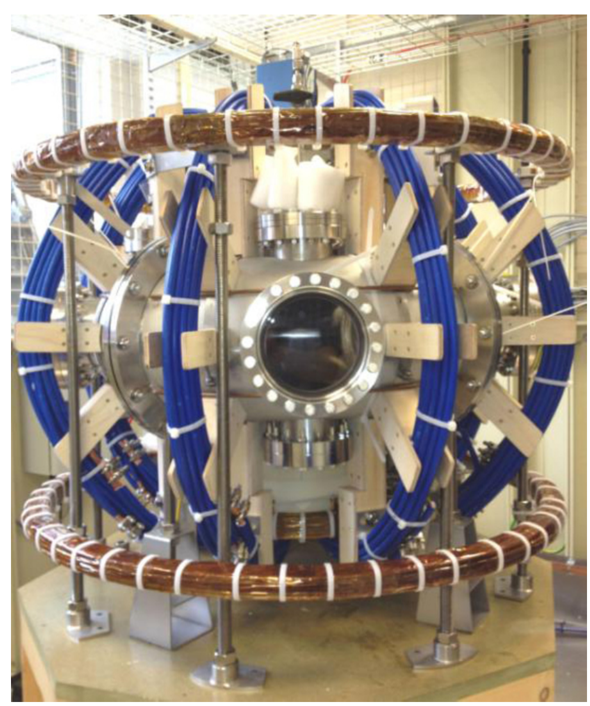

Fig. 9. ST25 with Cu magnets, August 2012.

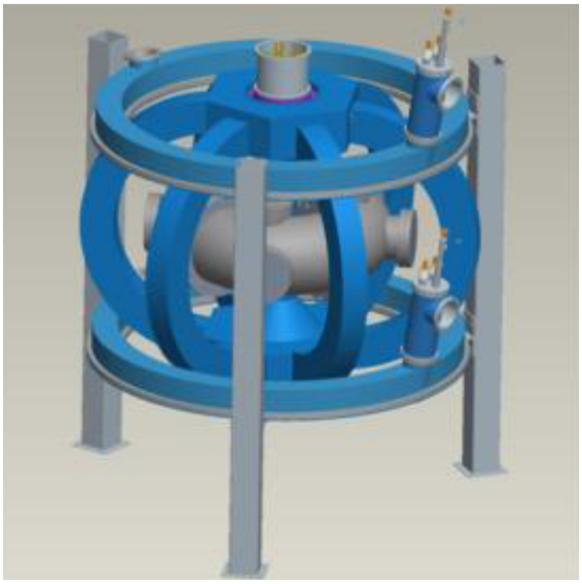

Fig. 10. 3D view of ST25 with full-HTS magnets.

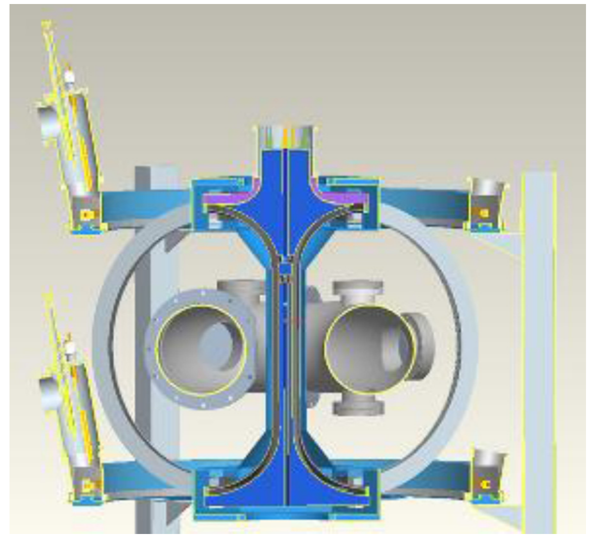

Fig. 11. Cut-off view of ST25 with full-HTS magnets.

maximum value achieved before, and another quench happened at about the same current, so the previous quench has little effect on the HTS performance.

Fig. 7 presents traces of a typical 2 kA plasma pulse on Golem with two HTS PF coils, from top to bottom: loop voltage, toroidal field, plasma current. For the GOLEM plasma current of 2 kA, the current in PF coils should be not more than 300 A × turns, i.e. 50 A in the HTS tape. This value is much below the critical current, so plasma operations require the HTS performance well below critical conditions and quenches in normal tokamak plasma pulses should be very unlikely.

3. ST25, status and future plans

Successful tests of HTS coils on GOLEM provided enough confidence to design and start construction of the first full-HTS tokamak, ST25. It was constructed in March–July 2012, at first stage with Cu coils to be replaced by HTS coils early in 2013, and the first plasma has been achieved in September 2012. Main parameters are presented in Table 1.

Fig. 8 shows cross-section of ST25 with Cu magnets. Fig. 9 shows a photo of the device. 8 TF coils of 14 turns each are made from the welding cable. Two outer PF coils provide equilibrium and shaping. A small solenoid is wound between the vessel and TF coils (Fig. 8). Two solenoid compensation PF coils are wound inside TF coils (shown in Fig. 8, and also in Fig. 9 – a coil just above the low outer PF coil).

After a period of short pulse operations, ST25 Cu magnets will be replaced with full-HTS magnets (Figs. 10 and 11). Details of the design can be found in [6]. After the commissioning of the HTS magnets, experiments will be performed to study several aspects of steady-state operations: EBW current drive efficiency, plasma-wall interaction in long (steady-state) discharges, dust formation, impact of Li coating on all these issues. At first, a 3 kW, 2.45 GHz magnetron will be used for pre-ionisation and current drive. To operate at the fundamental harmonics, toroidal field will need to be reduced to 0.1 T. At the next stage, a 28 GHz, 20 kW gyrotron is considered, with the toroidal field increased up to 1 T. Both low field side midplane and high field side top launch will be possible.

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