The ST25 Tokamak for Rapid Technological Development

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Abstract— **The ST25 tokamak is a new table-top tokamak, of major radius 25cm and aspect ratio 2, and hence (marginally) a 'spherical' tokamak (ST). It was designed specifically to test out the feasibility of a fully superconducting device made entirely from High Temperature Superconductor (HTS) and hence be the first tokamak to demonstrate the practicality of this new medium. As a prerequisite a version with simple copper coils wound from cable has been assembled to establish operating conditions such as good vacuum, gas handling, wall conditioning, control and data acquisition etc. This has proved a valuable facility in its own right and rather than stripping off the copper coils to replace with cryostats, it will be retained and indeed upgraded, and a new vessel (denoted ST25HTS) is under construction, and will be equipped with HTS coils. Details are given of the existing copper-coil ST25, its upgrade, and the new superconducting tokamak ST25HTS.**

Keywords — spherical tokamak ;superconductor

I. Introduction

The potential importance of High Temperature Superconducting magnets (especially the toroidal field) is described in Section II, together with a summary of the properties of this new material, and recent advances in production and performance. The advantages of operating at temperatures in the region of ~20K (whereas superconductivity is achieved at ~77K) are discussed.

The first HTS magnets – a pair of poloidal field coils – have already been installed by the present authors on the GOLEM tokamak in Prague [1] with good results. However the toroidal field coil provides a significant challenge as it is both much more complex, and cannot easily be added to an existing device; so the decision was made to construct an in-house tokamak.

To establish tokamak operations, an initial version with copper coils and powered by capacitor banks using IGBT switchgear has been implemented, and this device is described in Section III. This ST25 tokamak has proved very successful; the decision has been made to upgrade it to further increase its potential as a conventional small Spherical Tokamak; this upgrade is described in Section IV.

The new superconducting poloidal field cryostats have now been completed and are under test, and details are given in Section V, together with an account of design of the TF coil and progress with manufacture. The final assembly, which will be the world's first HTS-superconducting tokamak, should be operational towards the end of 2013.

Plans for further development, and future experimental devices, are outlined in Section VI.

II. High Temperature Superconductor (HTS)

Discovered in 1986, the development of 'High Temperature' superconductors could have far-reaching application. Historically, the discovery of YBCO preceded Bi2212, but was initially difficult to process into the very strong textures required for optimum performance, and Bi2212 became the first generation of HTS, available in wire form. A key advance was the introduction of textured metallic substrates and a variety of thin film deposition methods which enabled YBCO to be used in very thin, but highly textured HTS layers. In this 2nd generation form it appears to possess very good properties. It is presently manufactured as a ceramic superconducting layer one micron thick backed by copper and hastelloy in a tape of 0.1mm thickness, available in widths of up to 12mm (Fig 1).

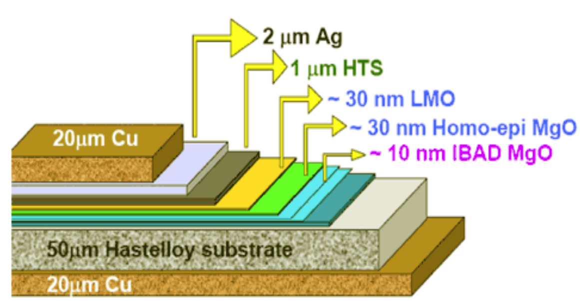

Fig 1 YBCO HTS tape (Superpower)

At first, HTS were considered a more convenient form of low temperature superconductors (LTS) in that they give similar performance but at temperatures around 77K (liquid nitrogen) rather than 4K (liquid helium) temperatures. However a great improvement in critical current density is available by operating at lower than 77K; 20K appears ideal, as current is high (as shown in Fig 2 for a similar tape) and removing heat at 20K is much more efficient than at 4K.

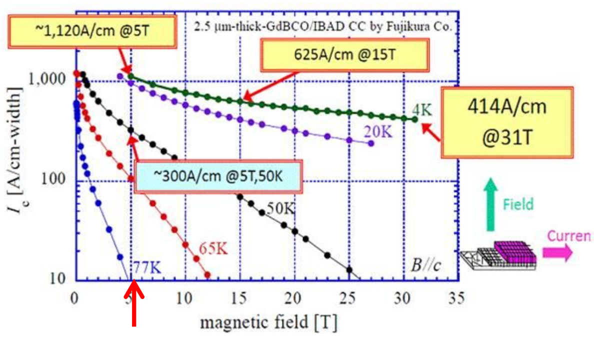

Fig 2 critical current per cm width of 2nd-generation HTS tape, as a function of perpendicular magnetic field, for a range of temperatures. Note that in a field of 5T (arrowed) the critical current increases from 10A/cm-width at 77K to 1000A/cm-width at 20K.

Progress in manufacturing of this novel tape has been rapid, both in availability (initially only short lengths of a few metres could be produced), and in current-carrying capability. The rate of improvement predicted is shown in Fig 3; there are also possibilities of optimisation of the tape structure for use in steady-state magnets (such as the toroidal field in a fusion device) which may bring quantum jumps in performance.

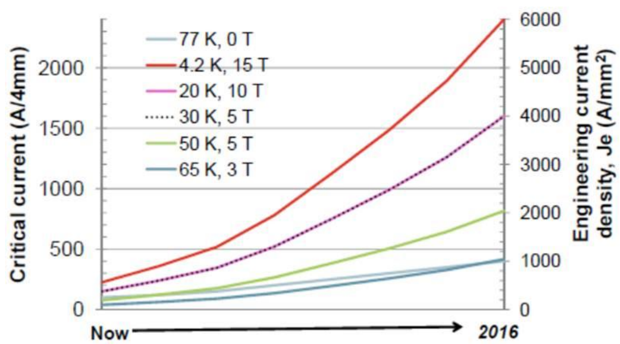

Fig 3 prediction in 2011 for increase in HTS tape performance – a factor x10 at 20K over 5 years [2]

III. Application of HTS to Tokamaks

It is important to gain experience in the behaviour of this material in a tokamak environment – and to encourage development of optimal tape by manufacturers. The authors have performed the first test of an HTS magnet on a fusion device, by fitting PF coils on the GOLEM tokamak at Prague. These were installed in Sept 2011 (Fig 4), and several papers have been published/accepted e.g. [1].

A more severe test of the HTS material is provided by the toroidal field coil, where tape lengths are long, the geometry is complicated, and stresses are high. The authors are building a fully HTS tokamak; a preliminary version with all-copper coils is presently operating at Culham Innovation Centre; this is now being transferred to larger premises at Milton Park where there is adequate space for the helium and nitrogen dewars required for the HTS version. The present copper coil version, ST25, is described in the next section; its upgrade (still in copper form) in section IV; and an HTS version, now under construction, in Section V.

IV. The ST25 Tokamak

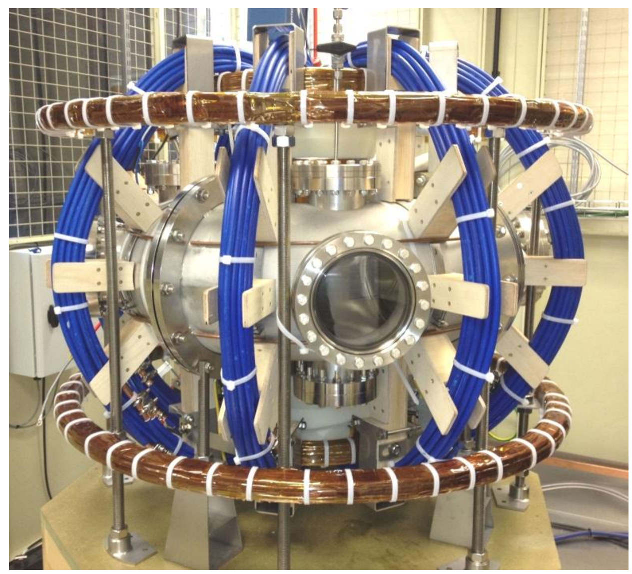

Fig 5 ST25 tokamak – copper coil version – now operational at Culham Innovation Centre.

Fig 4 Commissioning the HTS poloidal field coils on the GOLEM tokamak in Prague

The Tokamak Solutions team have built the small table-top tokamak, ST25 (denoting “Spherical Tokamak radius 25cm”) with copper coils. This obtained first plasma in October 2012. ST25 has major radius 25cm, minor radius 12.5cm, assembled from 4 stainless steel quadrants with insulating breaks. All coils are wound from copper cable. Power is supplied from capacitor banks: high voltage low capacity capacitors are used to provide the initial fast swing required from the solenoid and vertical field coils, linked to low voltage high capacity supercapacitors which provide pulse control after the initial formation of the plasma current. The toroidal field magnet comprises 8 limbs each of 14 turns, powered by eight 1-Farad 325V supercapacitors (Fig 6). These have proved very robust; they have significant internal resistance which limits the performance of each capacitor, but enables them to be joined without fault-limiting resistors.

The combination of the high inductance of the 112-turn winding and the high capacity of the bank enables relatively long plasma pulses, an order of magnitude longer than the pioneering START experiment.

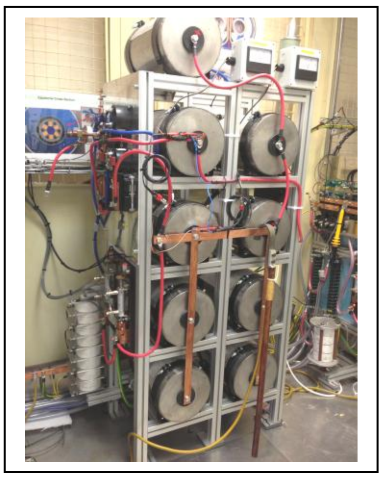

Fig 6 bank of Tavrima Supercapacitors
8 Farad in total (the top capacitor is used as a buffer for waveform control, typically to obtain flat-top).

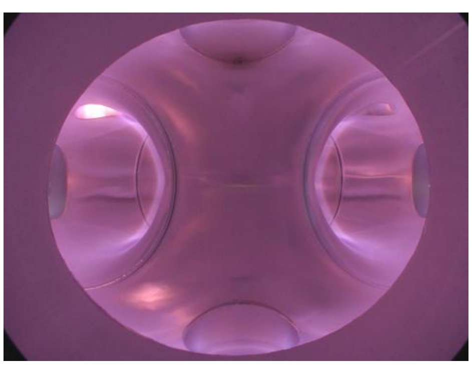

Fig 7 GDC in Argon; Helium (giving turquoise glow) is more commonly used as argon is slow to remove

The existing installation has a maximum toroidal field of 0.2Tesla, and plasma current of ~10kA (both field and current could be increased by adding extra capacitors). Switching is by means of modern IGBT devices, giving options of detailed waveform control. Plasmas are induced by a central solenoid which is a two-layer coil wound from 16mm cable, in total 128 turns, assisted by a extension coils shown in Fig 8.

A useful feature is that when the plasma discharge ceases to be of interest – for example in inductively driven plasmas, which only last 10’s of ms – the TF current can be readily terminated, preventing unnecessary heating of the TF coil, and leaving the TF bank only slightly discharged.

In this initial installation, there is no limiter or divertor, the plasma being contained within polished stainless steel walls. A small cryo-pump is positioned in series with the turbo pump, greatly reducing water impurity.

The ST25 tokamak is equipped with a 3kW magnetron (steady-state operation) of 2.45GHz. First results with high-field side injection using the angled top launch window shown in Fig 8 appear promising: long discharges of approx 2s show evidence of current drive (Fig 9).

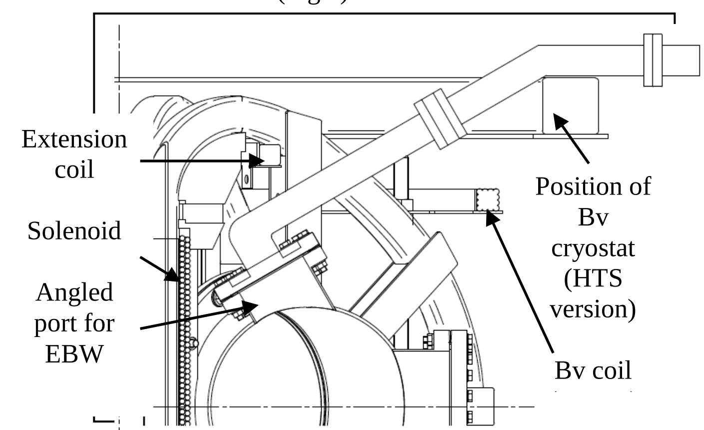

Fig 8 angled high field port for RF current drive studies

Current drive has more recently been observed using low field side RF injection via a skewed and tilted waveguide; a report is in preparation.

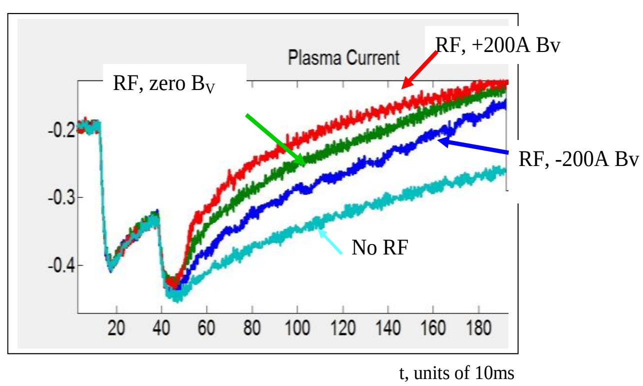

Fig 9 Plasma Rogowski trace indicating plasma current of ~100A produced by ~800W of RF, with addition (subtraction) of a further 25A due to Electron Bernstein Wave current drive component (whose direction reverses with applied vertical field).

A feature of the facility is that the tokamak and all its ancillaries and power supplies are contained in a Faraday cage of approx. 6m x 4m, and require only 32A of 3-phase 415V power supplies.

V. UPGRADE FOR THE COPPER ST25

Although originally intended just as a means of commissioning the tokamak (developing plasma conditioning, GDC, pre-ionisation, gas handling etc techniques) before dismantling the vessel and re-assembling inside the HTS TF cryostat, the ST25 tokamak has proved to a be a valuable tool for testing equipment, training, and novel studies such as the EBW current drive discussed in the previous Section. For these reasons a new vessel is being constructed to install in the HTS cryostats to form the superconducting tokamak ST25HTS, and the existing copper ST25 is being upgraded. The main features of the Upgrade will be a 4-layer potted solenoid, longer and wound from copper strip on a rigid former, providing an order of magnitude increase in available volt-seconds (when used with an upgraded power supply circuit); TF cables wound in precisely positioned steel guides; increased height allowing inclusion of divertor coils. A cylindrical vessel with torispherical ends is in design, as an option to replace the present 4-quadrant cylindrical section vessel; this new vessel will not have toroidal breaks, but will use a thin Inconel inboard cylinder to reduce induced toroidal currents.

VI. SUPERCONDUCTING TOKAMAK: ST25HTS

This is now in manufacture. The completed assembly should appear as shown in Fig 10.

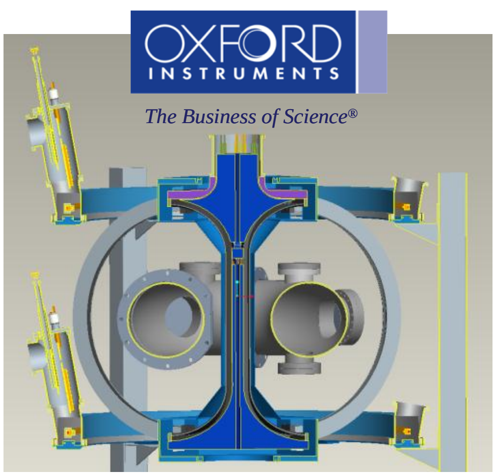

Fig 10 design of superconducting tokamak ST25HTS. The ST25 vacuum vessel will be assembled (4 quadrants) inside the 6-limb TF cryostat. (Some of the TF thermal insulation is removed in this illustration)

Capacitor banks will not be required for the superconducting TF and PF coils, these being powered by low voltage high current supplies. However high voltage, low capacity banks will be required to induce plasmas via solenoid operation, and to provide a rapidly changing vertical field to support the rapid current rise. The solenoid will be wound from 16mm^2 cable around the steel centre column. Plasma currents produced by RF current drive should however be sustainable steady state.

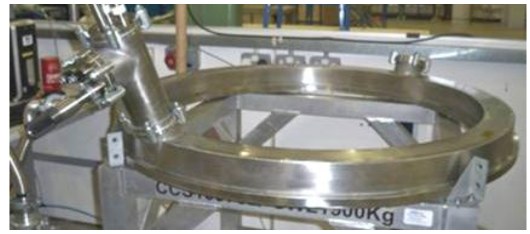

Fig 11 Upper PF coil, wound using HTS tape, undergoing cooling tests (20K using helium gas)

Fig 12 Half of 6-limb TF cryostat case…in manufacture

VII. FUTURE PLANS

The pair of PF coils, presently being commissioned at Oxford Instruments, will be installed on the copper ST25 for testing in conjunction with the existing copper coils (locations shown in Fig 8).

A new 4-quadrant vessel will be installed inside the 6-limb HTS TF cryostat, and the HTS PF coils added. 'Steady state' operation on ST25(HTS) will then be commissioned, the plasma being maintained by RF. This device may then be transferred to Imperial College.

The original copper ST25 will be upgraded with a high-performance solenoid (4-layer, copper strip, bonded in resin), with various other improvements (divertor coils, auto-tuner on RF), and retained as a demonstration tokamak. It is planned to rebuild with a D-shaped vacuum vessel to more fully exploit the advantages of the spherical Tokamak.

ACKNOWLEDGEMENTS

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