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Joint testing of the 3 Tesla ST40 spherical tokamak toroidal field coil test assembly

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HIGHLIGHTS

- 250 kA toroidal field coil joints.
- Electrical joint testing using a variety of interfaces and contact pressures.
- Comparison with NSTX contact resistances.

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ABSTRACT

Spherical Tokamaks used in magnetic fusion have a small centre-stack by design which causes a higher field on the conductor. ST40 [1] is a 3 Tesla spherical tokamak with a major radius of $R = 40$ cm and minor radius of $a = 26$ cm being built by Tokamak Energy Ltd. The high toroidal field (TF) requirement requires a wire current of 250 kA flowing in each of the 24 limbs totalling 6 MA in the centre-stack. Joint testing was used to investigate the interface resistance between the centre-stack and return limbs under a variety of contact pressures, using different shims, different coatings on the conductor and soldering. Initially a DC 400 A current source was used and later an air-core pulsed transformer delivering up to 16 kA of current was specifically designed and built for these measurements. Results from this paper can be used to predict the behaviour of critical joints in the region at the ends of the centre-stack where current is passed to the TF return limbs. A comparison with TF joint data from the National Spherical Torus Experiment (NSTX) is also given. This will aid in deciding which jointing method to use for ST40 and the required pressure to pre-load the interface.

1. Introduction

Tokamaks generate large magnetic fields and generally need large currents in order to do this. Many tokamaks are designed to operate in a pulsed mode because they have a resistive magnet system. The operation of the tokamak plasma is limited by the resistive heating caused by the high current densities. It is therefore important to understand and improve upon the constraints caused by resistive heating as this can affect tokamak performance.

The weakest part of a many electrical systems is at the joints [2]. In order to prevent deterioration and eventual failure the joints need to be carefully designed. A tokamak centre-stack joint failure is likely unrecoverable [3,4] and results in the dismantling of most, if not the entire tokamak. This paper is concerned with the Toroidal Field (TF) joints for the ST40 tokamak, which has a constant tension [5] TF coil composed of 24 limbs each carrying 250 kA. This creates a total rod current of 6 MA. The field at the major radius of 40 cm is $B = 0.2 * 6/0.4 = 3$ T. A unique feature of the ST40 TF system is the twisted centre-stack which helps reduce the number of joints since the current will feed from one limb to the adjacent limb through the twist. This paper presents experimental data on the different contact interfaces under varying contact pressures.

2. The Toroidal Field coil assembly

The TF assembly (Fig. 1) constists of a return limb made from hardened copper (proof stress 180 MPa 0.2% min). This is then soft soldered (Sn60Pb40, solder temperature approx. 190 degrees Celsius) onto a “flexible block” (Fig. 2). The flexible block is designed to flex in the out-of-plane direction to accomodate out of plane movement and forces. It does not have flexibility in the axial (i.e. vertical plane) direction due to the restraining

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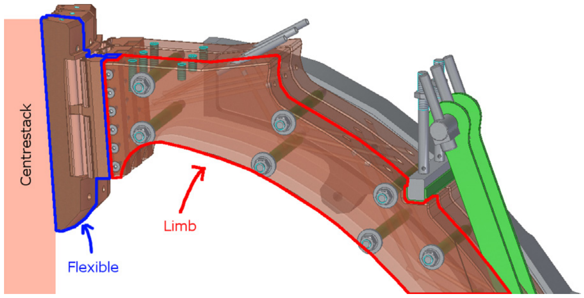

Fig. 1. The final assembly of a triplet of return limbs. In total there are 8 sets of triplets amounting to 24 limbs in total.

support structure with prevents movement in this direction. The flexible block has flexible links that were soldered (PbSn5Ag2,5, solder temperature approx. 300 °C) after electron beam welding did not work as expected. Finally the flexible block which contains a "shoe" (i.e. large block of copper) which can then be held by compression (and could also be soldered) onto the centre-stack wedges. Initially it is thought that this joint may be a compression joint and would make this joint the weakest link in the TF system. This joint has therefore been the primary focus of this paper, but the results can be applicable to many joints, not just the shoe to centre-stack joint. From this point in "joint" by default means the flexible copper shoe to centre-stack joint.

3. Reducing heating in the joint

In the Toroidal Field (TF) coil system the largest current densities are experienced in the centre-stack, and are expected to peak at approximately 250 kA/1500 mm^2 = 167 A/mm^2. The heating in copper, for temperature rises in the range 0 to 100 °C can reasonably be estimated by $dT/dt = 0.005 * J^2$ where the temperature rise rate is measured in K/s and the current density is measured in A/mm^2. Initially ST40 will operate at room temperature which can give significant temperature rise rates of $dT/dt = 0.005 * 167^2 \sim 140$ K/s. In the joints the current carrying contact area (a-spots) is significant lower than the bulk contact area [6,7] and heating in these areas leads to much faster deterioration. ST40 is designed to have a large contact area at the joint in order to reduce the current density and help mitigate potential problems. The joint (Fig. 2) contact area

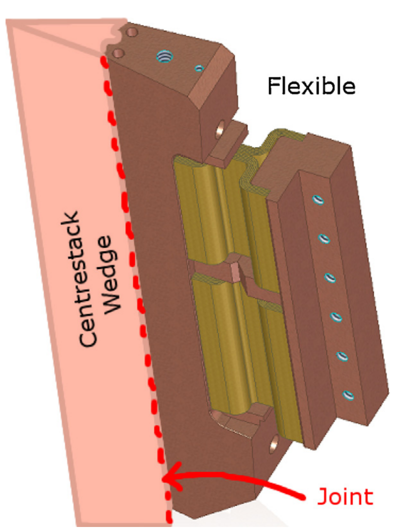

Fig. 2. Flexible block expanded view from Fig. 1. The compression joint is between the flexible and the centre-stack wedge. The flexible part is made of copper sheets 0.2 mm thick press welded.

is approximately $27 * 343 = 9261$ mm^2 which results in a current density $J = 250000/9261 \sim 27$ A/mm^2. The copper around this joint is subjected to a heating rate of $dT/dt = 0.005 * 27^2 \sim 3.6$ K/s. This shows that the heating rate around the joint is $140/3.6 \sim 39$ times lower than the bulk current density in the centre-stack wedge. It is debatable exactly what factor to aim for but as a rule of thumb it would seem reasonable to ensure the heating rate factor at the joint is better than 1/10 of the heating rate of the bulk conductor.

4. Experimental setup

4.1. Pulsed transformer

A simple pulsed transformer was commissioned specifically for this test. The pulse transformer was an air-core transformer which consisted of a drum of 50 mm^2 cable forming the primary (inductance 2.8 mH, resistance ~70 uOhm) and copper sheets layered in parallel (inductance ~1 uH, resistance ~30 uOhm) as the secondary. The transformer was powered by a 14 mF capacitor bank charged to 1 kV. Current was switched by a 3.3 kV 1500 A (CM1500HC-66R) IGBT. The advantage of an air-core was to ensure no distortion of the waveform and ensure a pure sine wave output. The disadvantage of this transformer is the inability to do a full $I^2 \cdot t$ test which would heat the copper and joint interface. All tests involved resistance measurements made over short timescales (up to 150 ms).

4.2. Contact pressure rig

Contact pressure tests used with a Strong Arm press with a load cell that enabled measurement of the load (Fig. 3). The press is manually hydraulically actuated and care was taken to ensure the measurement was made quickly after the pressure was applied otherwise the pressure could "sag" by ~5% if left for more than a 5 min. The peak load was 2 tonnes, and most measurements were made at the following contact pressures (2 N/mm^2, 4 N/mm^2, 10 N/mm^2).

4.3. Full scale rig

The full-scale test consisted of a partial return limb, centre-stack, full-sized shoe and flexible placeholder. The purpose of the full-scale test being to see if it was possible to solder the joint and measure the contact resistance (Fig. 4). This is a fallback option from a compression joint. The soldering was done under "real" conditions with the wedge assembled vertically using indium solder

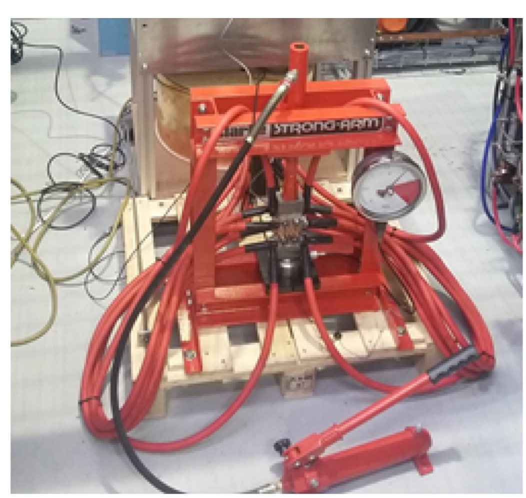

Fig. 3. Jig used for applying contact pressures to different contact interfaces. The peak load that could be applied was 2 tonnes onto a scaled contact area.

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