ST40: Plans and status of construction

O. Asunta[1,2], M. Gryaznevich[1], P.F. Buxton[1], and the Tokamak Energy Ltd. Team
[1] *Tokamak Energy Ltd, 120A Olympic Avenue, Milton Park, Abingdon, OX14 4SA, UK*
[2] *Department of Applied Physics, Aalto University, FI-00076 AALTO, Finland*

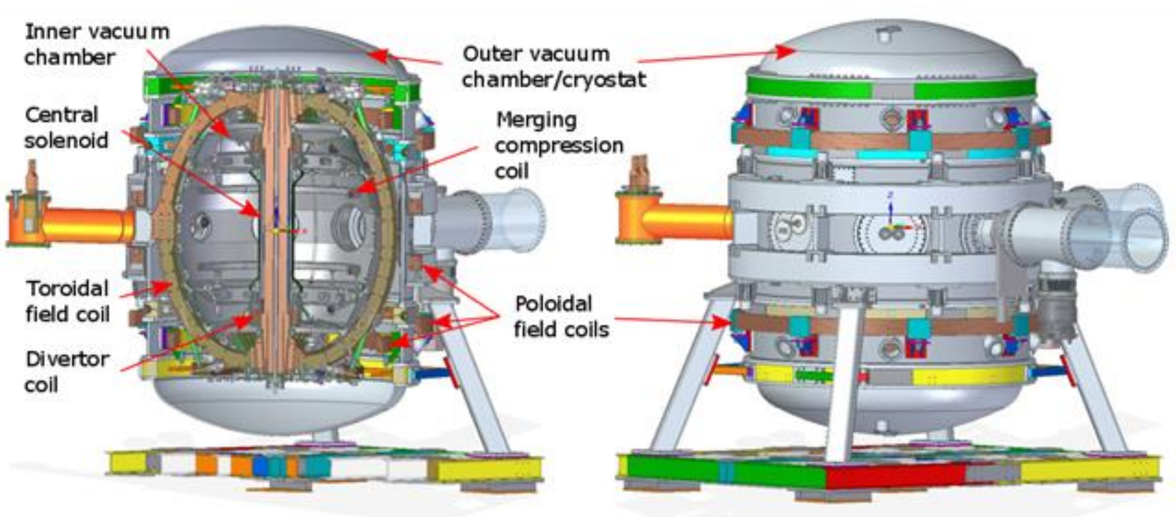
Introduction

In magnetic confinement fusion devices, fusion power is proportional to $\beta_t^2 B_{t0}^4$, where β_t is the ratio of the plasma pressure to magnetic pressure $p_{pl}/p_{mag}=nk_BT/(B_{t0}^2/2\mu_0)$ [1]. Spherical tokamaks (STs) have operated at high β_t but, thus far, only at relatively low toroidal field (TF) of B_{t0}=1T or below.

A new high field spherical tokamak, ST40, is currently under construction at Tokamak Energy Ltd (TE). Its main design parameters are: R_0~0.4m, R/a~1.8, I_p=2MA, B_{t0}=3T, and κ=2.5. Pulse length will be ~1s at full power. ST40 will demonstrate (i) the feasibility of constructing and operating a high field ST, (ii) the benefits of a high field in a ST, (iii) conditions close to burning plasma requirements ($n\sim1\text{–}5\cdot10^{20}m^{-3}$, T~5–10keV, τ_E~100–500ms). In the future, ST40 may also be suitable for DT operations.

ST40 design

The structure of ST40 is illustrated in Figure 1. While the long-term vision of TE is to utilize magnets made of high-temperature superconducting materials, to enable rapid development, ST40 magnets are made of copper. The magnets are powered by capacitor-based power supply units (PSUs) and, at full performance, they will be liquid nitrogen cooled. The outer vacuum chamber (OVC) will act as the cryostat for the toroidal and poloidal field (PF) coils located between the inner vacuum chamber (IVC) and the OVC. The IVC is supported by the



OVC, and the entire assembly sits on top of the assembly platform.

ST40 will only have a small central solenoid, which maximises the size of the TF magnet while maintaining the small aspect ratio. For plasma start-up, ST40 will use a process called merging compression (MC) [2], utilized in START [3] and MAST [4]. In MC start-up, plasma rings are formed around two in-vessel MC coils by rapidly ramping down the current in them. When the rings merge, part of their magnetic energy is converted into plasma thermal energy. The resulting hot plasma is compressed along the major radius using the poloidal field (PF) coils, which further increases the plasma current due to decreasing inductance of the plasma. The central solenoid and up to two 1MW neutral beam injectors are planned to be used to heat the plasma and to extend the pulse. The ST40 PF coil set includes three pairs of coils on the low-field-side, and a pair of divertor coils on the high-field-side (recall Figure 1).

Figure 1: *Glow discharge in ST40 (top), the current state of construction (middle), and the central tube assembly (bottom) with magnetic diagnostics.*

Status of construction

The IVC of ST40 has been assembled and its vacuum capabilities tested down to 10^{-8}mbar. Glow discharge electrodes, as well as pre-ionization filaments have been installed and tested. The first glow discharge plasmas, depicted in Figure 2, were generated in helium at 0.5—5.0mbar.

Two PSUs, namely MC and TF PSU were installed and commissioned, and have already been used for the first integrated tests (discussed in detail in the next section). The TF central rod assembly, which consists of 24 copper wedges, each with a 15-degree twist, was recently installed (see middle of Figure 2), and the installation of the TF return limb assemblies, three turns each, is on-going.

For testing, a temporary plain central tube has been used. The assembly of the magnetic diagnostics, namely B_p-probes and flux loops, on the final central tube was recently finished (see the bottom of Figure 2), while the carbon limiter tiles are yet to be installed.

First integrated tests

The assembly of ST40 is not yet complete, but various systems that make up the device were already used together for the first time for testing the in-vessel MC coils. In addition to testing the MC coils and their power supply, the orchestration of ST40 before, during and after a pulse was successfully demonstrated. Several diagnostics were tested and, as a result, the set of available diagnostics varied throughout the experimental campaign. The diagnostics tested included: 5 B_P-probes, 3 Rogowski coils, (one around each MC coil, one around the IVC), 1 flux loop, a photodiode, near infrared interferometer, slow camera (25fps), fast monochrome camera (400fps), and an infrared camera. The magnetic diagnostics in particular provided high quality measurements with very little noise in them (see Figure 3).

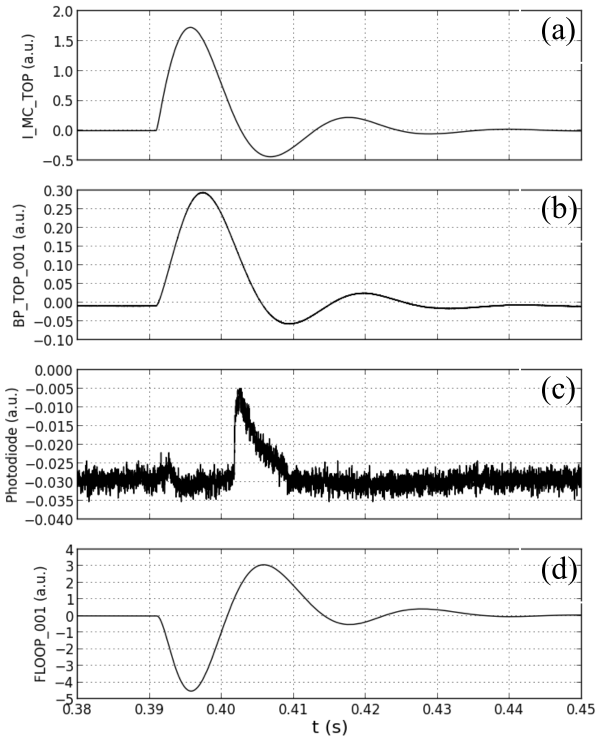


Figure 2: *Uncalibrated time traces of (a) Rogowski coil measurement of current in the top MC coil and its case, (b) poloidal field measured by P001_TOP probe, (c) visible light detected by the photodiode, and (d) the loop volts from FLOOP_001 located outside the IVC, for pulse #2445.*

Figure 3: *Top MC coil fired into a glow discharge during pulse #2502. The peak current in the coil was 420kAt, resulting in ~40 loop volts at the coil, and visible breakdown filaments on the coil.*

Time traces from a typical pulse, #2445, where the top MC coil was fired into a glow discharge plasma, are presented in Figure 2. The MC coil current, measured by a Rogowski coil in panel (a), created a magnetic field detected by a magnetic probe (panel (b)). When the current was ramping down, the induced loop voltage (~40 loop volts close to the coil, based on modelling [5]) momentarily knocked off the glow discharge. The electrons

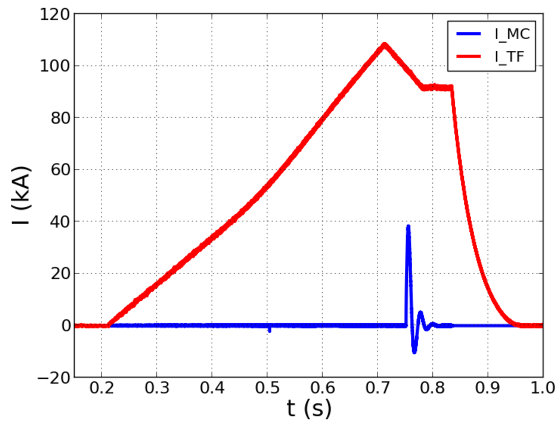


Figure 4: *MC and TF currents, measured by the internal diagnostics of the respective power supplies during pulse #2497.*

remaining from the glow discharge possibly assisted the breakdown, a flash of visible light was seen in the photodiode (see Figure 3(c)), and breakdown filaments appeared in the camera images around the MC coil. An example of a good colour photo of the filaments is presented in Figure 3, taken during pulse #2502 with the maximum MC coil current of 420kAt.

In pulse #2497, TF and MC PSUs were operated synchronously. Up to 38kA wire current (=420kAt) was passed through the top MC coil, while TF PSU output up to ~110kA into a dummy load. The calibrated current time traces provided by the PSUs internal diagnostics are presented in Figure 5.

Future plans

The first MC start-up tests will be carried out later this year. Before that, the installation of the TF magnet system will be finished. Because the TF system support structures will not be in place for the first MC start-up tests, mechanical constraints will limit the allowable B_t to well below 1T. Still, with the help of moderate TF, the first pair of poloidal field coils, and a vastly expanded set of diagnostics available, the goal of those tests is to achieve and diagnose the first hot plasmas in ST40. After the MC start-up tests, the remaining PF coils and the outer vacuum chamber will be installed, which will allow the use of higher toroidal magnetic fields. Once the assembly is complete, the early stages of the ST40 program will focus on optimising the MC start-up. By the end of 2018, the plan is to have the first neutral beam injector, 1MW with E_{max}=25keV, operational.

References

[1] J.E. Menard *et al.*, Nucl. Fusion **56** (2016) 106023
[2] P.F. Buxton *et al.*, Accepted in Fusion Eng Des (2017)
[3] A. Sykes *et al.*, Nucl. Fusion **32** (1992) 694
[4] A. Sykes *et al.*, Nucl. Fusion **41** (2001) 1423
[5] P.F. Buxton *et al.*, P4.156, Proceedings of 44th EPS Conference on Plasma Physics 26.-30. June 2017, Belfast