ST Path to Fusion: First Results from ST40

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Spherical Tokamak (ST) path to Fusion has been proposed by R Stambaugh [1] and experiments on STs since then demonstrated feasibility of this approach. Advances in the high temperature superconductor magnet technology [2] allows significant increase in the toroidal field (TF) which was found to improve confinement in STs. The combination of the high β, which has been achieved in STs [3], and the high TF that can be produced by HTS TF magnets, opens a path to lower-volume fusion reactors, in accordance with the fusion power scaling proportional to $\beta^2 B_t^4 V$ (V is the plasma volume). Feasibility of a low-power compact ST reactor and physics and engineering challenges of the ST path to Fusion Power are discussed in [1, 4,5]. Several devices have been built by Tokamak Energy on the development of this path. A small tokamak ST25 (R/a = 0.25/0.125m, I_{pl} < 10kA, B_t < 0.2T, τ_{pulse} up to 30 s, circular and D-shaped vessels) was operational since 2012, testing EBW pre-ionisation and current drive. 29h discharge has been demonstrated in a similar small tokamak, but with all-HTS magnets [6].

A new high field spherical tokamak ST40, Fig.1, (R=0.4-0.6m, R/a=1.6-1.8, I_{pl}=2MA, B_t=3T, k=2.5, τ_{pulse}~1-10sec, 2MW NBI, DD and DT operations) has been constructed and the first experimental campaign has been completed. Plasma current of 300kA was achieved at B_t=0.72T during first weeks of operations that started in January 2018. By the end of the first experimental campaign (June 2018), plasma current was increased to 350 kA, pulse durations increased to 50 ms with flat-tops up to 15 ms, Fig.2. Here traces of the plasma current, toroidal field at the plasma geometrical axis, H_α, CIII, R_{geo}, loop voltage at the central post and the stored energy W_{MHD} are shown. The toroidal field at the geometric axis of the plasma was then increased above 1.5T (1.25 T at the designed final major radius of 0.4m).

Achieved toroidal field is the highest in spherical tokamaks, well above previously achieved, or planned for MAST-U, NSTX-U and Globus-MU. Operations at a high toroidal field have a goal to confirm the positive effect of increasing the TF on the plasma confinement that was demonstrated on STs and to show feasibility of a high-field ST.

The plasma was formed using merging-compression method as used on START and MAST tokamaks [7] and the flat-top was achieved without the use of a central solenoid. Magnetic reconstruction code PFIT [8] has been used to reconstruct magnetic flux structure and main plasma parameters during both merging-compression and flat-top phases. Fig.3, left, shows magnetic reconstruction (right) and visible light image of the plasma after compression.

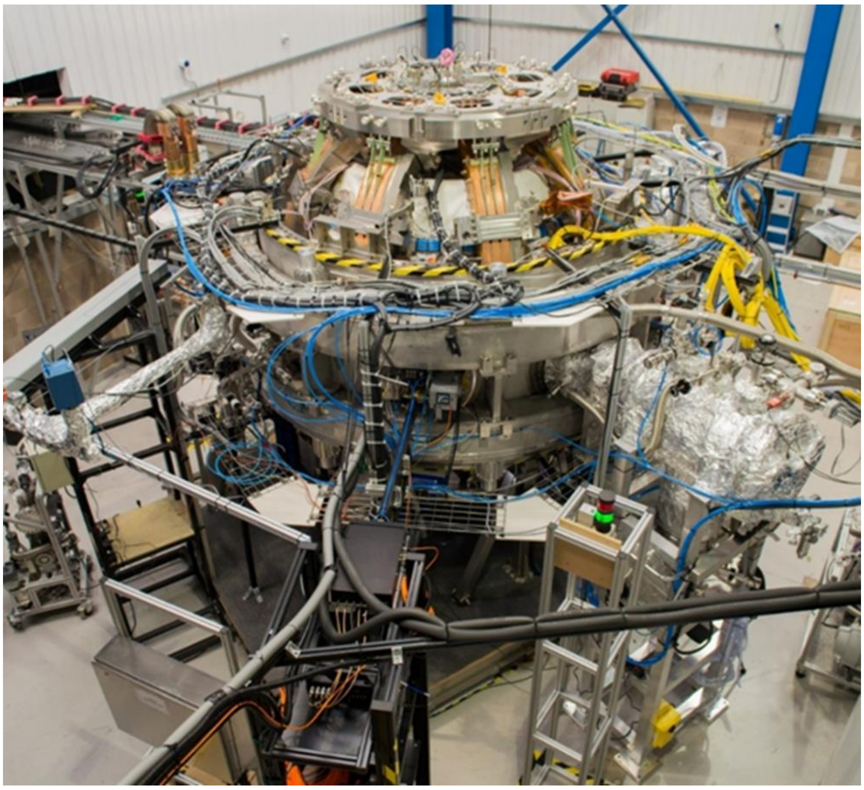

Figure 1. ST40 during the first experimental campaign.

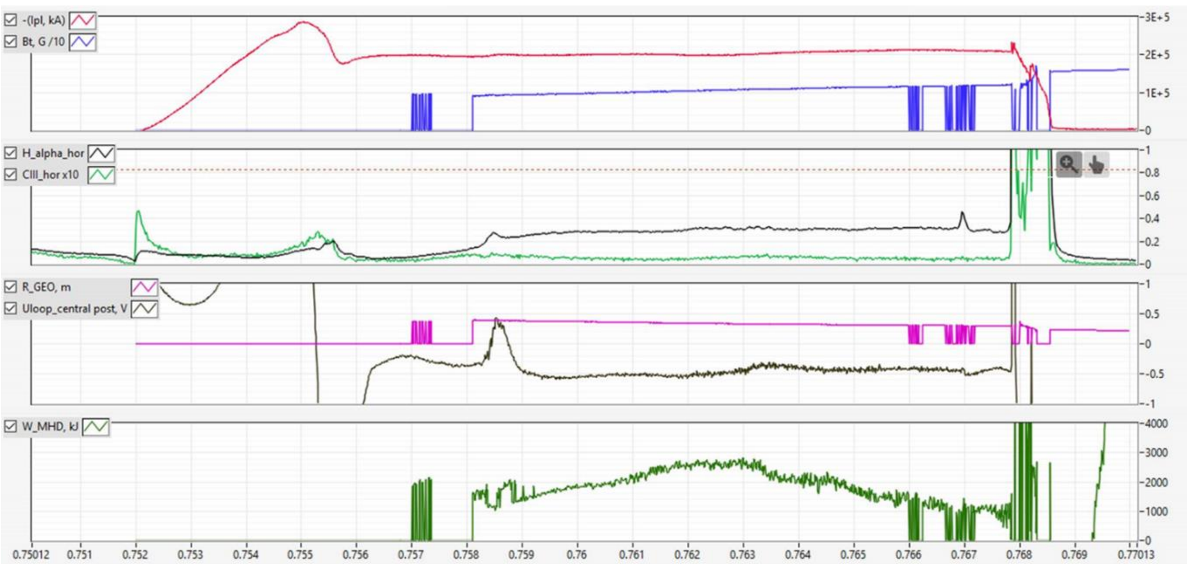

Figure 2. Traces for a typical pulse #5157: plasma current, toroidal field at the plasma geometrical axis, H_α, CIII, R_{geo}, loop voltage at the central post and the stored energy W_{MHD}.

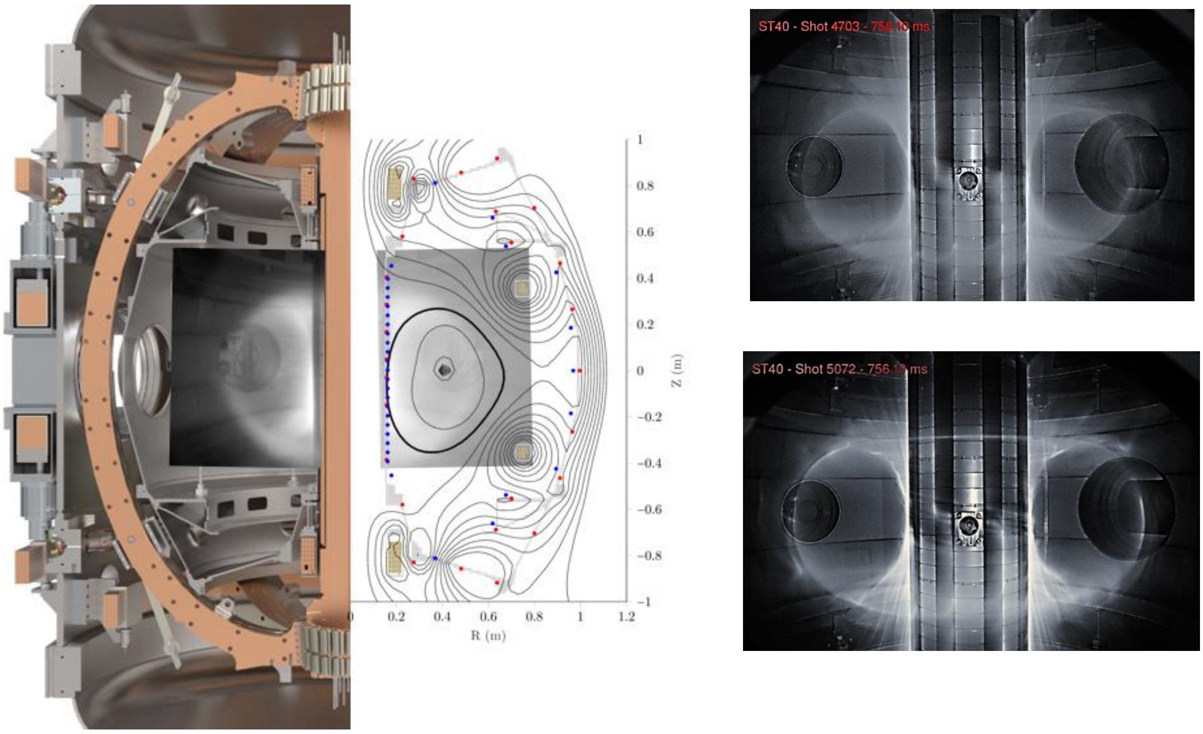

Figure 3. Magnetic reconstruction and visible light images of the plasma made by high speed CCD camera. Right pictures: sharp-edged plasmas spontaneously appearing during the flat-top.

During merging of two plasma rings, magnetic field line breaking and reconnection converts some poloidal magnetic flux into thermal energy with very high efficiency. Experiments on TS-3 and MAST show that the magnetic reconnection transforms 90% of the dissipated magnetic energy into the ion thermal energy [9]. So, this formation method not only provides non-solenoid start-up, which is essential for spherical tokamaks, but according to empirical scaling [9], (Fig.4), may provide a direct path to the burning plasma conditions [10]. So, this method may be useful for the fast start-up of a burning plasma STs without or without or using less additional heating [10]. Early results from ST40 show positive trend, Fig.4, as ion temperatures in 1 – 2 keV range have been measured using Doppler spectroscopy.

Fig.3, right, shows an example of plasma images after a spontaneous transition to a sharp-edge plasma periphery. Reduction in H_α and increase in W_{MHD} up to factor of 2 after transition suggests a possibility of achievement of an ohmic H-mode.

Results of numerical simulations on the energy, fast ions and alpha particle confinement, stability and equilibrium are being published and/or presented at this conference [11-14]. According to simulations, due to low collisionality, high TF and low ion neoclassical transport, a hot ion mode with T_i ~ 10-15keV may be achieved in ST40 even with a moderate confinement and heating.

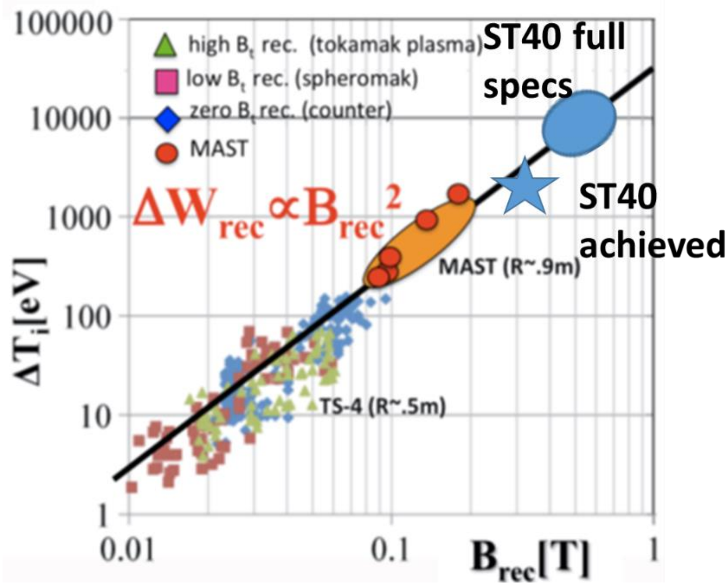

Figure 4. Comparison of ST40 results with those from MAST and other devices.

We will undertake experiments on ST40 to demonstrate how high field STs can approach burning plasma conditions and to support designs of next step devices on the ST accelerated path to Fusion.

Upgrades in 2018-2019 include installation of the central solenoid, divertor, LN2 cooled passive plates for vertical position control; LN2 cooling of the TF magnet to increase TF up to 3T; 2 NBIs and significant upgrade of diagnostics (NPA, TS, SXT imaging etc).

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