Overview and status of construction of ST40

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Abstract. Overview and status of construction of a new compact high field spherical tokamak ST40 are presented.

Recent advances in the development of high temperature superconductors (HTS) [1], and encouraging results on a strong favourable dependence of electron transport on higher toroidal field (TF) in Spherical Tokamaks (ST) [2], open new prospects for a high field ST as a compact fusion reactor or a powerful neutron source [3]. The combination of the high β (ratio of the plasma pressure to magnetic pressure), which has been achieved in STs, and the high TF that can be produced by HTS TF magnets, opens a path to lower-volume fusion devices, in accordance with the fusion power scaling proportional to $\beta^2 B_t^4 V$.

Tokamak Energy (TE) Ltd's path to development of Fusion Power is based on the use of compact high field spherical tokamaks. The feasibility of a low-power compact ST reactor and the physics and engineering challenges of the ST path to Fusion Power and details of the development programme are given in [4, 5]. Several recent advances addressing the main issues on the path to a compact Fusion Reactor include: development of superconducting magnets using 2nd generation HTS; optimisation of the current drive for steady-state operations and heating; and revision of the requirements for α-particle confinement in a compact ST based on full-orbit simulations. Recent results of experiments on the small tokamak ST25 and the fully superconducting ST25-HTS support the programme; and the high field spherical tokamak ST40, which aims to demonstrate the possibility of achieving burning plasma conditions in a compact ST, is presently under construction.

To date STs have operated at 1T or below. For high fusion performance, ST devices operating at 3 - 5 T or above will be needed. In order to construct an ST that can operate at fields at this level innovative engineering solutions will be needed especially for the central column. To develop and demonstrate solutions to the key engineering aspects, TE Ltd, as the first step, has designed a device with copper magnets that is intended to operate at fields up to 3 T. Beyond this device TE is planning higher field STs using HTS.

This new generation high field spherical tokamak, ST40, FIG.1, is under construction with the first plasma operations expected in early 2017. The main parameters are: R_0=0.4-0.6m, A=1.7-2.0, I_{pl}=2MA, B_t=3T, k=2.5, τ_{pulse} ~1-10sec, 2MW of auxiliary heating power, Cu liquid nitrogen (LN2) cooled magnets and power supplies based on supercapacitors. The main physics and engineering challenges are connected with the high toroidal field, high plasma current and high wall and divertor power loads. The device is aimed at demonstrating burning plasma condition parameters ($nT\tau_E$) and may also be suitable for DT operations in future.

ST40 has a design field of B_{T0} = 3 T at major radius of R_0 = 40 cm. Use of copper for the TF coil has the advantages of combining structural strength with good conductivity (especially when cooled to liquid nitrogen temperature). Whereas existing STs have operated typically at 0.3 - 0.5T, with the recent MAST, Globus-M and NSTX upgrades striving for 1T, special design features are employed to enable ST40 to operate at up to 3T. Principal amongst these is the use of constant tension curve TF limbs, specially designed so that over the permitted temperature rise (whether starting from ambient or from liquid nitrogen temperature) the expansions of the centre post and the return limbs are matched, so that minimal movement occurs at the critical top and bottom joints, a simple robust flexi-joint being provided to accommodate the movement. At fields of 3T, stresses are high; and an external support structure based on two steel rings accommodates in-plane and out of plane forces, such as those arising from tolerance errors in the radial position, and the JxB twists arising from TF-PF and TF-solenoid interactions.

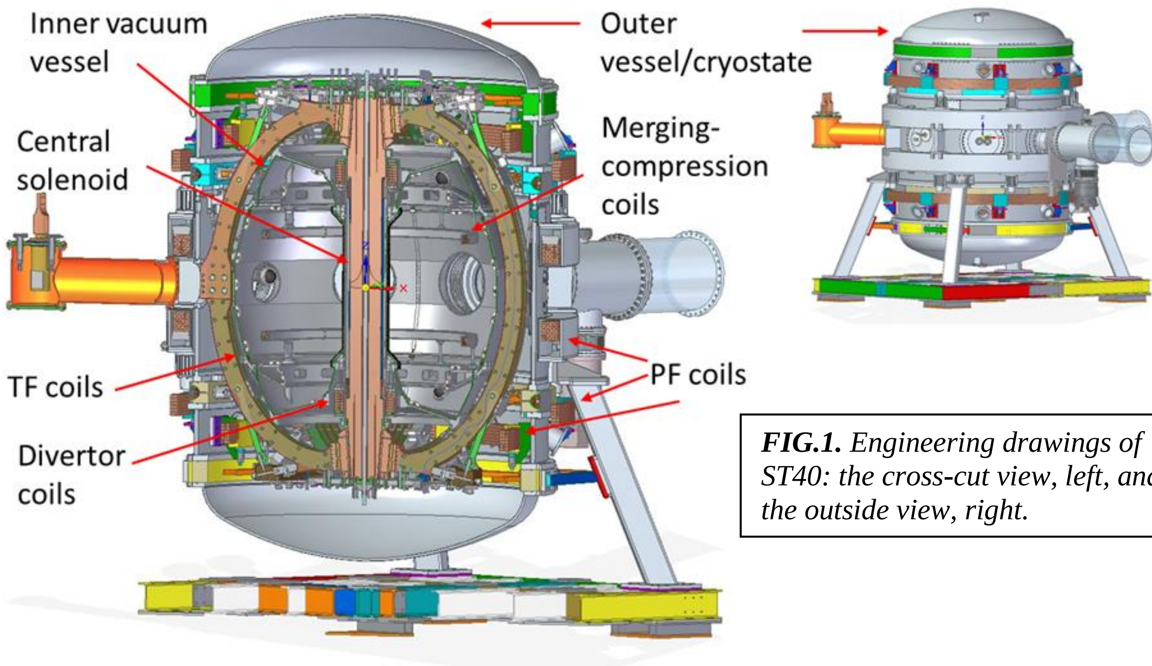

FIG.1. *Engineering drawings of ST40: the cross-cut view, left, and the outside view, right.*

An important aid to obtaining such a high field is the use of a minimal central solenoid. The merging compression formation, when the plasma is first formed as two rings around in-vessel (MC) coils (indicated in FIG.1), which then merge at midplane utilizing heating due to transformation of the magnetic energy to the plasma heating via reconnection and then compression of the formed plasma ring along the major radius forming the final ST configuration operated successfully in START and MAST, and in ST40 are capable of generating a hot (10-keV range) dense (1-5x$10^{20}$$m^{-3}$) ST plasma of up to 2 MA with only minimal support from the small central solenoid, which is thus mainly needed to maintain the flat-top current – assisted by the high bootstrap fractions expected, and current drive from the up to 2MW NBI. Also, current will be increased due to utilization of the energy from the ramp-up of the current in external poloidal field coils during NBI heating (so-called BV ramp-up), the mechanism that is very efficient in STs. Hence, the solenoid is considerably smaller than in MAST and NSTX and their upgrades. This reduces JxB twisting stresses, takes less copper from the TF column thus reducing TF resistance and TF heating, and provides a stronger TF post.

The center post is constructed from 24 wedges, each twisted by 15 degrees over their length thus obviating the need for a TF compensating coil and also helps to reduce twisting forces due to interaction between TF and poloidal fields from the solenoid and other PF coils. Except for the MC coils (which require a fast HV bank), the TF, solenoid and PF coils are powered by 'supercapacitors' such as the Maxwell 125V, 63F, 0.5 MJ transport module, providing a very economic power supply from laboratory power supplies. Each unit has a limiting fault current ~ 7 kA even under dead short conditions providing safety; an important consideration in a 100 MJ capacitor bank.

As mentioned above, ST40, like START and MAST, will use the merging-compression plasma formation method. Empirical scaling, based on experimental data from TS3, TS4, UTST, START and MAST [6, 9], predicts square dependence of the plasma temperature on the magnetic field and shows no dependence on the dimensions of the device. In ST40, this field will be at least three times higher than in MAST, which demonstrated electron and ion temperatures up to 1.2keV; so expectation of 10keV range temperatures can be justified. Moderate extrapolation of the achievable plasma current from MAST and START data predicts achievement of 2MA in ST40. As the ST40 operating regime assumes densities in 1-5x10^{20}m^{-3} range, conditions close to burning plasma requirements ($nT\tau_E > 3x10^{21}$) are expected, providing that the plasma confinement will be sufficient and follow optimistic predictions based on MAST and NSTX data.

As the toroidal field will be increased at least by factor of 5 compared to MAST, stability is also expected to improve. ST40 will have elongation k<2.5, moderate for an ST, so vertical position control, supported by optimized inboard and outboard passive plates, is expected to be good. These passive plates will be LN2 cooled. That should not only reduce the growth rate of the vertical instability to a level <10sec^{-1}, but should also improve the edge stability allowing high pressure pedestals. Lithium wall conditioning is expected to produce a low recycling regime with broad temperature profiles. This should significantly reduce temperature gradient micro-instabilities resulting in enhanced plasma confinement. The increase in TF should also lead to good confinement, according to evidence from MAST/NSTX [2], so overall high values of $nT\tau_E$ are expected to be sustained after the plasma formation. ASTRA/NUBEAM simulations have been performed to support these predictions, they also show that plasma transport in ST40 may be fully determined by neoclassical effects, which helps to create a plasma transport model for the prediction of performance.

Auxiliary heating will be 1-2MW NBI, however RF or EC/EBW heating are also considered. A new approach to optimization of the current drive in a compact ST is based on the possibility to produce high toroidal rotation using optimized NBI (e.g. with reduced E_b, ~40-60keV). Results of the optimization of the NBI conditions for the direct current drive and for the torque, using several full-orbit codes NFREYA, ASCOT; NUBEAM, NFIFPC, ASTRA and 1.5D-transport code TORUS II [8] show that these conditions are quite different in the optimized beam energy and the launch geometry. Using the perpendicular viscosity and heat diffusivity from MAST data [7] and the torque and power deposition of the neutral beam, for optimised density profiles and tangency radius we get maximum possible toroidal plasma velocity of ≈ 200 km/sec. Such high rotation may result in suppression of the ITG and other modes and so in improved plasma confinement. Optimization also includes the aim to reduce fast ion losses in a compact ST40. Full-orbit analysis of α-particle losses show that they may be not as high as expected at such low plasma current (2MA) as those in conventional aspect ratio tokamaks [8] and should not exceed ~50%. The wall heating due to such losses is tolerable, but not negligible. Despite expected high plasma parameters, the optimised geometry of the double-null divertor results is predicted by SOLPS4.3 simulations to produce comparatively low divertor loads, ~5MW/m^2, which for the relatively short-pulse ST40 should not create an issue.

The position of ST40 relative to other tokamaks in dimensionless parameters is shown on a (ν_i^*, ρ^*) plot in FIG.2. As for all projected devices, shown by open symbols, the clear trend to a low collisionality plasma in comparison with currently operated machines is seen.

ST40 is designed to be compatible with Tritium operations. The neutron yield S_N(DT), calculated with the ASTRA code [10] is shown in FIG.3 for different confinement models. The maximal fusion power reaches the level of 1MW if the high field ST scaling laws based on NSTX and MAST experiments [2] are used together with 1MW of additional power. Recalculation of the MAST neutron output for a 50%/50% D/T mixture is performed for the MAST points with the NUBEAM code [10] and the results are also presented in FIG.3. Note that the neutrons measured in MAST shots [7] have their main contribution from the beam-plasma reactions.

It is clearly seen from FIG.3 that for all confinement models ST40 has an optimal value of electron density, which is close to 1-5x10^{20}m^{-3}, for S_N(DT) to be maximized. This density is chosen to be a reference electron density in ST40. As the fast ion contribution also reduces with the density increase, it would not significantly change the position of the maximal S_N(DT).

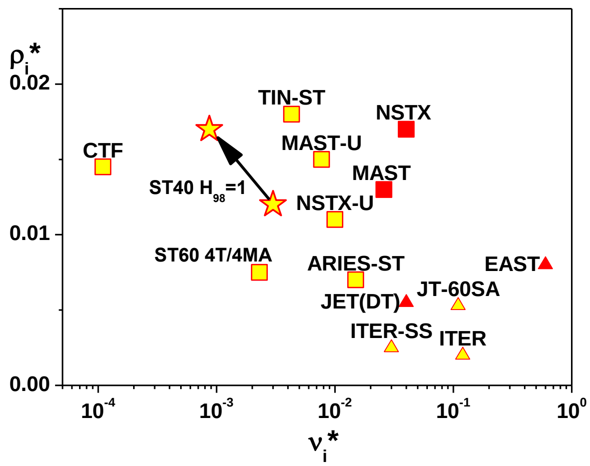

FIG.2. Operational space in the dimensionless plane for different tokamaks: ST40 (stars), in operation (bold), projects (open), conventional geometry (triangles) and low aspect ratio (squares). Arrow shows the possible transition to a low density hot ion mode in ST40 [10].

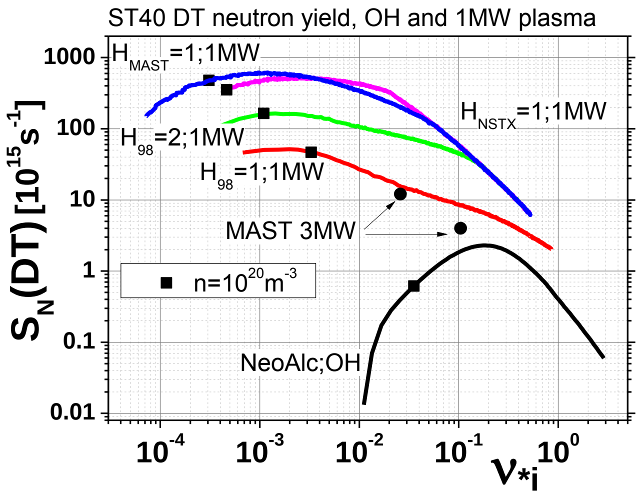

FIG.3. *Neutron yield from DT fusion for D-T mixture $n_D=n_T=\bar{n}_e/2$ with no fast ion contribution for ST40.*

The demonstration of reliable operations of a compact high field ST, with the toroidal field up to 3 times higher than in presently operating STs, will significantly advance ST research. Many engineering challenges have been dealt with during one year of design activities. Most of them are connected with the goal to achieve high field, high pressure and high current in a compact ST. Full ANSYS analysis of thermal and mechanical stresses have been performed, as well as of stresses connected with halo currents produced during disruptions.

The present status of the construction (as in September 2016) supports expectations of the first plasma in late 2016 or early 2017. The vacuum vessel, FIG.4, has been manufactured and is currently under baking and GDC conditioning. Internal diagnostics and graphite tiles have been manufactured. FIG.5 shows samples of graphite tiles that will partially cover the central post. All in-vessel magnetic diagnostics are either under these tiles, or under BN2 protection caps. Divertors, passive plates and cryopanels will be added during later stages of the project.

FIG.4. *ST40 vacuum vessel. General view, left and view from inside, right. Divertor, internal diagnostics and graphite tiles are not installed.*

FIG.5. *Samples of the central post graphite tiles.*

Boronisation and use of Li are the main tools to reduce recycling during all stages of ST40 operations. Boron and Li evaporators are combined with RF antennas that will be used for pre-ionisation both during GDC and main operations. There is some uncertainty in terms of the optimal antenna design for RF pre-ionization in ST40. From the literature it seems that capacitive coupling is more efficient for the RF breakdown especially at the lower pressure end. For this reason, some RF pre-ionization experiments were conducted at Tokamak Energy using a glass tube and a 13.56 MHz 1kW RF generator with an impedance matching unit. Such an assemble represents a capacitive coupling of RF power to the plasma.

FIG.6*. Left: RF glow discharge in He gas with the BN dish filled with crystalline boron at the bottom; right: Li evaporation experiments with RF discharge in He.*

FIG.6, left, shows RF glow discharge (using only ~60W RF power) in He gas at 0.27 mbar with the BN2 dish filled with crystalline boron at the bottom. FIG.6 right shows Li evaporation with RF discharge in He after 1-hour glow. The green colour of the discharge is a clear evidence of predominant presence of Li ions in the plasma.

Merging-compression coils are the only in-vessel coils in ST40, see FIG.1. They have been manufacured at the similar way to the in-vessel coils used on START and MAST. One of the coils is shown in FIG.7. They will be installed inside the vessel after preliminary baking and conditioning are performed.

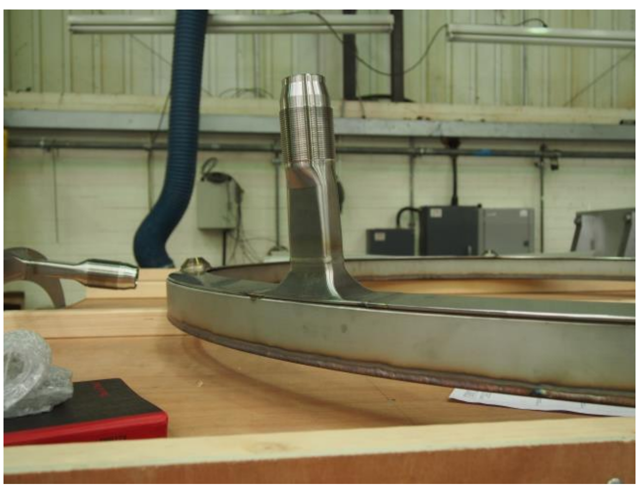

FIG. 7. *One of two merging-compression coils*.

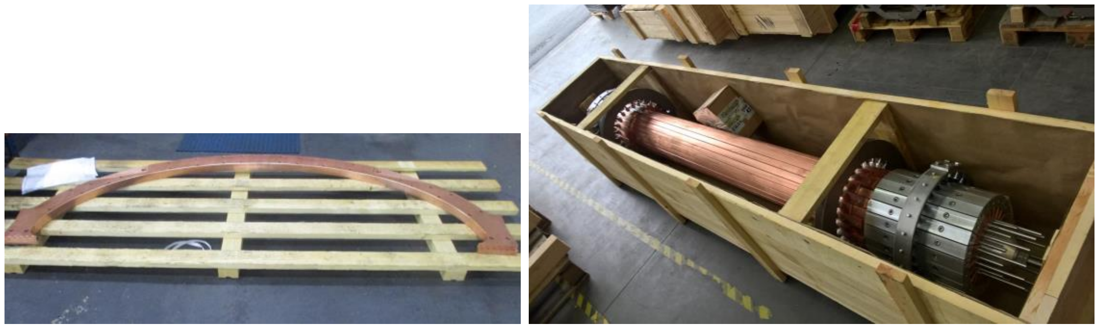

FIG.8. *Toroidal field magnet: one of 24 return limbs, left, and the central post, right.*

The toroidal field magnet consists of 24 turns arranged in 8 limbs of 3 turns each, all connected in series. Each outer segment, FIG.8, left, and the central wedges, shown right, are connected with flexible demountable joints. The central solenoid is wound on the central post (not shown in the picture).

The power supplies are under constraction and some of them are shown in FIG.9. They will be connected to ST40 by Cu busbars and cables. FIG.10 shows the general layout of the ST40 assembly.

FIG.9. *Power supply units.*

Construction of ST40 is on-going. After the assembly, integrated commissioning will be done followed by the plasma commissioning. The first phase of the experimental campaign, planned for the first half of 2017, will be mainly aimed at optimization of the merging-compression formation. This will be followed by the ‘double-null merging’ experiments, when the plasma is formed not around the merging-compression coils, but at nulls between these coils, and the divertor coils (the innermost coils in FIG. 1). The next phase will be installation of the double-null divertor assembly designed to sustain up to 5MW/m^2 of the thermal load, cryopanels in the closed divertor volume, LN2 cooled passive plates and NBI. The experimental campaign aimed to demonstrate all advantages of a high-field ST will be performed in 2018. ST40 will also be an important step in the commercial development of Fusion Energy as the project is funded mainly by private investments.

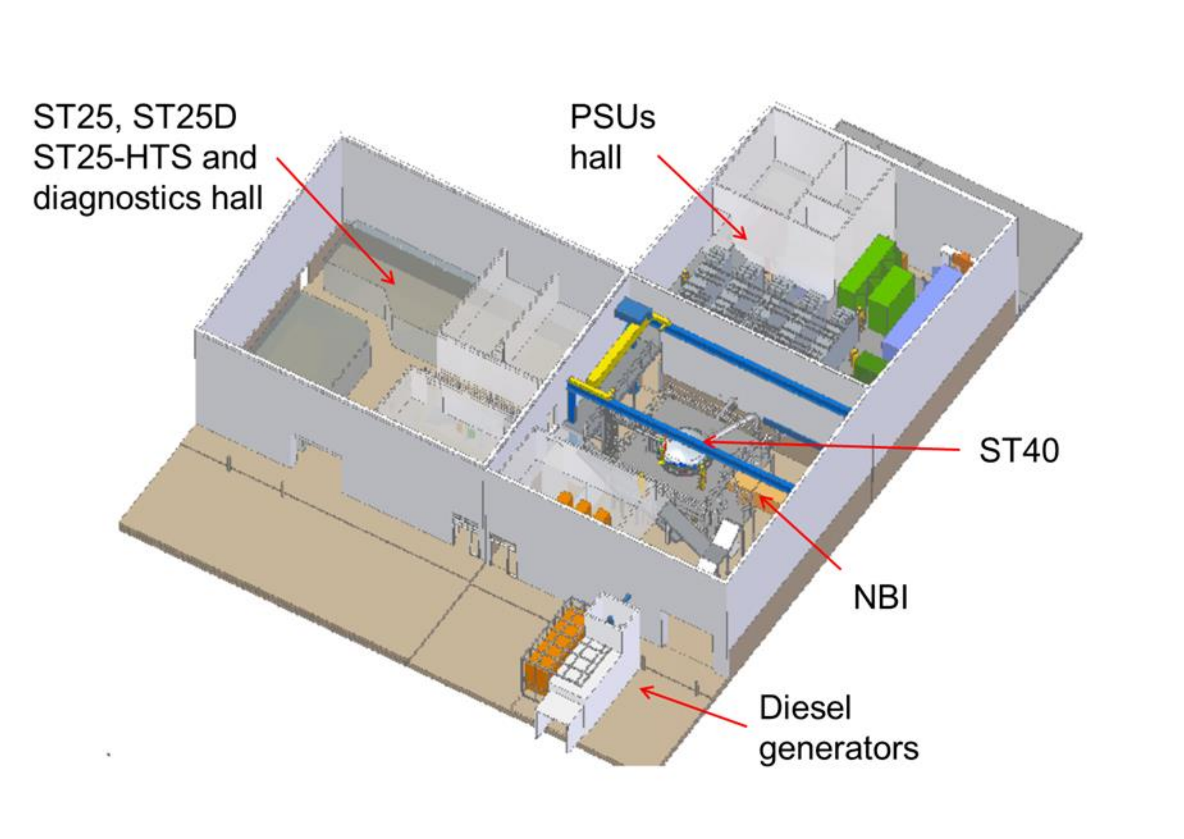

FIG.10. *The general layout of the ST40 assembly.*

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