OVERVIEW OF ST40 RESULTS AND FUTURE: EXPANDING THE PHYSICS BASIS OF HIGH-FIELD SPHERICAL TOKAMAKS

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The goal of the ST40 programme is to explore the physics of high-field spherical tokamaks (STs), to validate, empirical and theoretical models and, hence, to build confidence in predictions required to support the design of future generations of STs. The main research areas include: (i) transport and confinement, (ii) power exhaust, (iii) solenoid-free plasma start-up schemes, and (iv) high-performance scenarios. ST40 is designed, built, and operated by Tokamak Energy Ltd. It has copper magnets, and its defining feature is the high toroidal magnetic field: ST40 has been operated at up to B_t=2.1T at major radius of R_0=0.4m – more than two times higher than any other ST. Parameters achieved by ST40 are $R_0 \approx 0.4{-}0.5$m, $I_p \approx 0.25{-}0.8$MA, $B_t(R$=0.4m) $\approx 0.7{-}2.1$T $\kappa < 1.9$, and $A \approx 1.6{-}1.9$. ST40 has two co-current deuterium neutral beam injectors (NBIs) that deliver up to 1.0MW and 0.8MW of power at beam energies of 55kV and 24kV. For plasma start-up, ST40 uses the merging-compression process [2] that can produce up to ~0.5MA of plasma current. ST40 central solenoid provides ~200mVs of flux for additional current drive, extending the plasma current flattop up to 200ms at I_p =450kA.

Divertor heat load is one of the key parameters driving the design of future ST pilot plants. Understanding it in existing devices, and predicting it in future devices, is of significant interest. To analyse the scrape-off-layer (SOL) power fall-off width (λ_q) in ST40, an infrared thermography analysis toolchain [3,4] has been implemented. It combines (i) the measurement of surface heat flux on a section of the low-field-side region of the ST40 upper divertor (top panel of Fig. 1), (ii) the 3D surface geometry of the divertor, and (iii) the magnetic geometry from the equilibrium reconstruction code EFIT and calculates the heat flux parallel to magnetic field lines in the SOL (bottom panel of Fig. 1). Fitting these heat flux profiles with single and double exponential profiles has allowed extracting measurements of λ_q and revealed a bifurcation into a 'wide' branch that follows existing H-mode scalings and a 'narrow' branch that falls up to 10 times below the predictions of established scalings [5].

Thermal energy confinement in STs at B_t <1T has been found to be characteristically different from that observed in large aspect ratio tokamaks [6]: a linear scaling of energy confinement time with B_t has been demonstrated in NSTX, MAST and GLOBUS-M(2) H-mode plasmas [7-9]. ST40 H-mode plasmas, while demonstrating many of the usual features of the standard H-mode plasmas, such as a sudden drop in D-alpha emission combined with increased particle and energy confinement and formation of density pedestal, typically only have a small temperature pedestal, modest increase in stored energy, and no ELMs. Transport analysis of ST40 plasmas with B_t=1.0–1.5T suggests a weaker dependence of energy confinement time on B_t in ELM-free regimes compared to

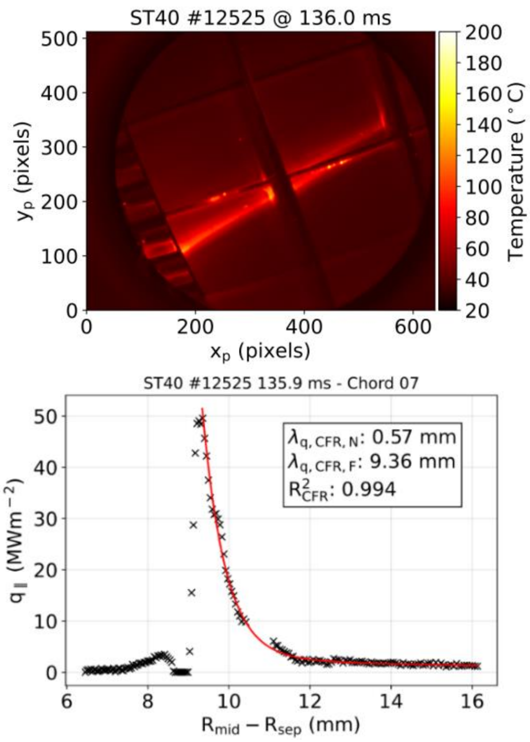

Figure 2 (top) Surface temperature measurements of the divertor by the infrared camera. (bottom) Parallel heat flux along a radial chord on the low-field-side upper divertor, mapped upstream to the outer midplane. Data is fit with a double exponential decay, characterised by the near and far-SOL widths, $\lambda_{q,CFR,N}$ and $\lambda_{q,CFR,F}$.

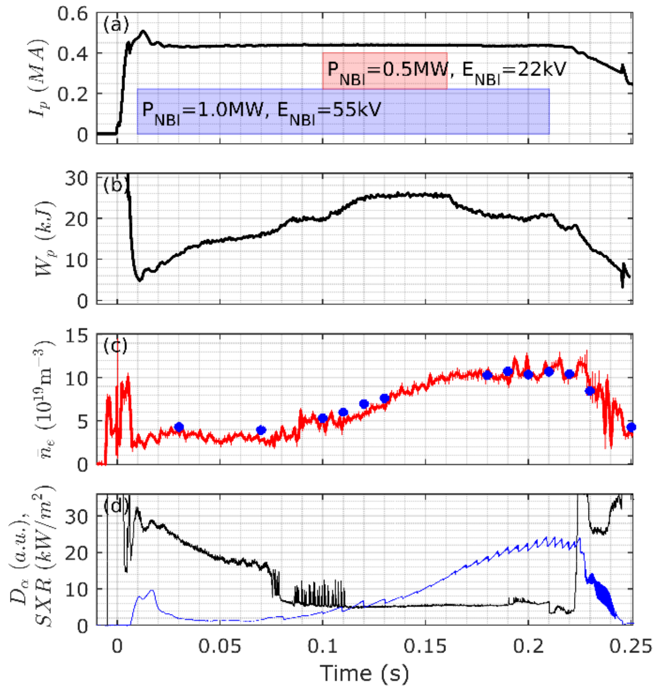

Figure 1 (a) Plasma current, and NBI times and powers; (b) stored energy from EFIT; (c) line-integrated density measured by a sub-millimeter interferometer (red line) and Thomson scattering (blue dots); and (d) D_α and soft X-ray (SXR) measurements from ST40 pulse #12839 that exhibits the transition from L-mode through an I-phase to an ELM-free H-mode. This is manifested by the oscillations, at around t=0.1s, and subsequent flattening of D_α signal, together with increasing density, SXR, and stored energy.

the scalings obtained on other STs. In many pulses, the L- to H-mode transition happens via an intermediate state that has been identified as I-phase [10,11]. The presence of I-phase indicates proximity to the L-H power threshold and is characterised by oscillations in the kHz range in various plasma signals; electron density, D-alpha radiation, poloidal magnetic field. The I-phase state has also been observed without a transition to H-mode. An example of a pulse with L-H transition through and I-phase is depicted in Fig. 2. Further experiments on the scaling of confinement with engineering and dimensionless parameters in L- and H-mode diverted plasmas will be performed in spring 2025.

ST40 real-time control capabilities have recently been enhanced by (i) upgrading the power supply configuration of the in-vessel merging-compression (MC) coils so that, in addition to plasma start-up, they can be used for plasma vertical stabilisation, and (ii) developing a real-time capable version of the in-house open-source equilibrium reconstruction code GSFit for gap control. Bayesian inference analysis workflows are routinely used thanks to the order of magnitude increase in speed obtained by moving from Markov Chain Monte Carlo to Bayesian Optimisation. Surrogate diagnostic models are being trained on the forward model outputs, enabling a robust analysis of the surrogate capabilities and an understanding of the boundary conditions for their application.

In summer 2025, ST40 will embark on a major upgrade. This upgrade is funded primarily by a cross-governmental public-private partnership between Tokamak Energy, the U.S. Department of Energy, and UK Department of Energy Security and Net Zero, and supported by continued collaborations with Princeton Plasma Physics Laboratory and Oak Ridge National Laboratory. Its main objectives are (i) to replace ST40 graphite limiters with metal plasma-facing components (PFCs), (ii) to furnish ST40 with hardware required for studying the effect of lithium-coated PFCs and, in particular, low wall recycling; (iii) to install a 1MW dual-frequency (104/137 GHz) gyrotron for radio-frequency start-up, heating, and current drive; (iv) to install a deuterium pellet injector for core fuelling; and (v) to replace the centre column to improve robustness of the toroidal field coil joints and the central solenoid. Notable additions and improvements to ST40 diagnostics will include Lyman-alpha arrays for edge neutral studies, infrared camera on (also) the bottom divertor for divertor heat load and SOL width studies, a new charge-exchange spectrometer view of the 1MW NBI to resolve ion profiles up to the plasma edge, and new filters for the Thomson scattering system to allow more robust measurements of the plasma edge.

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