Overview of ST40 results and planned upgrades

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In 2018 Tokamak Energy Ltd. completed the first campaign of operations in the low aspect ratio ST40 tokamak, and recently have begun the next campaign of operations. In this paper we present results from Merging/Compression start-up and first confinement results from ST40, along with planned upgrades - taking ST40 to it's design parameters of $R/a = 0.4/0.22 = 1.8$, 2 MA plasma current, 3 T toroidal field and up to 4 MW auxiliary heating.

Merging/Compression start-up

Start-up in ST40 is achieved using the Merging/Compression technique [1, 2, 3], which involves inductively forming two toroidal plasma rings around two high voltage poloidal field coils located inside the primary vacuum vessel. When the current in each plasma ring is sufficiently high, the two plasma rings are attracted towards each other and merge to form a single axis tokamak plasma. The primary objective of ST40's first campaign has been to develop the Merging/Compression start-up scenario and to test reconnection heating theory. Figure 1 shows how the ion temperature and stored thermal energy, measured using ion Doppler broadening and a diamagnetic loop, depends on the plasma current just before merging - which is a good proxy for the reconnecting flux. The reconnecting plasma current was scanned from $\sim$ 200kA to 350kA. From this scan we find that $T_i \propto I_p^2$ and $W_{\mathrm{dia}} \propto I_p^2$, and at $\sim$ 350kA the ions are heated up to $\sim$ 900eV. This result is in agreement with reconnection theory [4] and experimental results from other devices [1, 4]. In the future the Merging/Compression start-up coils will be upgraded to a higher current from 572 kA · Turns to 800 kA · Turns which will allow us to achieve higher reconnecting ion temperatures and to test the reconnection heating theory at higher reconnecting fields.

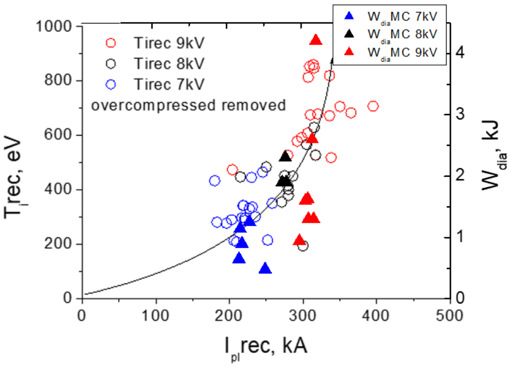


Figure 1: *Measured ion temperature and stored energy just after merging compared to the reconnecting plasma current.*

First confinement results

In the first campaign ST40 was operated without the use of a central solenoid or active feedback control. Despite this, there were many pulses where the plasma was maintained with an approximately constant plasma current for between 5 and 15 ms after merging. After merging no external heating was applied, however the Merging/Compression start-up induces large eddy currents to flow within the toroidally conducting vessel and supporting structures (up to 1 MA at full M/C coil voltage). These eddy currents decay on the L/R timescale of the complete toroidal circuit ($\sim$ 30 ms) and whilst decaying produce a toroidal electric field which ohmically heats the plasma. The exact amount of ohmic heating power during this phase after merging is difficult to calculate and is further complicated by the plasma shrinking during the pulse (as the eddy currents decay, so the vertical field increases).

In the first programme we performed a scan where we kept the M/C charge voltage constant (9 kV) while scanning the toroidal field (factor of 1.5 change in rod current). Figure 3 shows a plot of the plasma current waveforms in this scan. We note that all have a flat top current between 150 and 180 kA and there is little difference between the high and low toroidal fields. During a pulse the majority of heating was from the Merging/Compression start-up, which primary heated the ions. Figure 2 shows how the ion temperature measured just after merging depends on toroidal field - from which we also see little dependence on toroidal field. We calculate the flat top time to be slightly longer than the confinement time, therefore, we postulate that the temperature at the end of a pulse is primarily set by the plasma's energy confinement time.

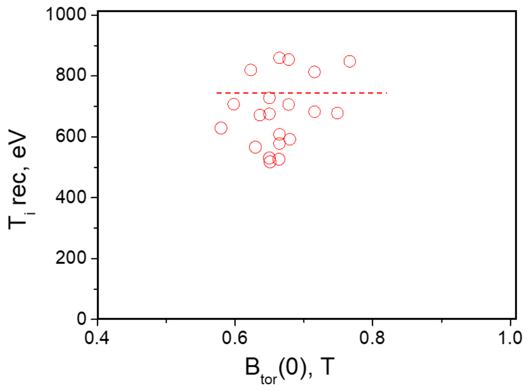


Figure 2: *Dependence of ion temperature immediately after merging on the toroidal field, at a fixed M/C charge voltage.*

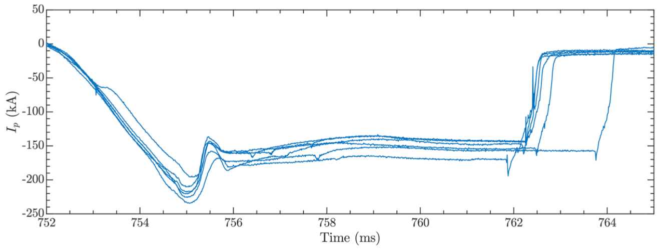
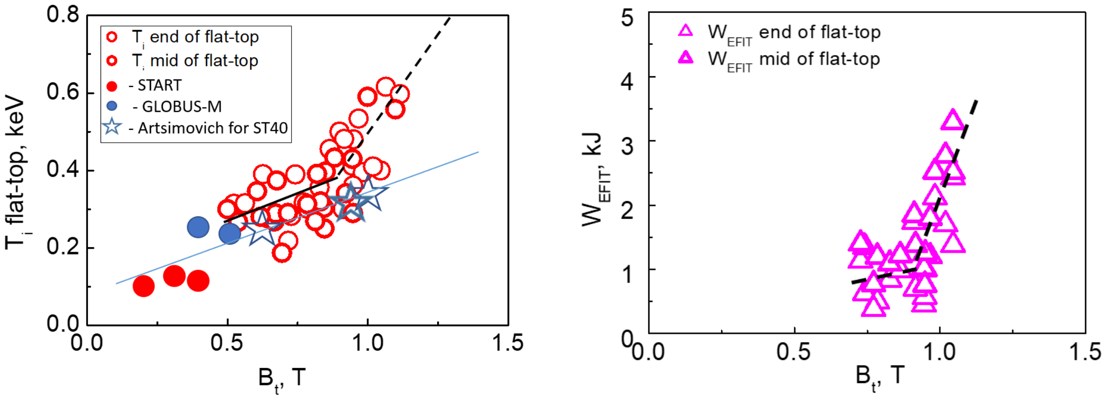


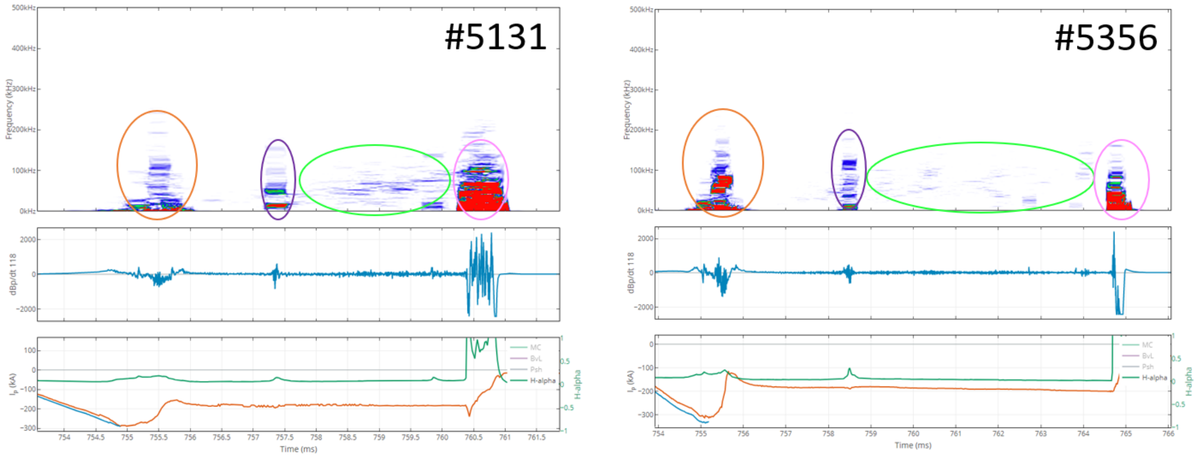
Figure 3: *Plasma current waveform for several pulses keeping the M/C charge voltage constant at* 9 kV*) while scanning the toroidal field from* $I_{\text{rod}} = 50$ *to* 70 kA

Figure 4b shows how the ion temperature depends on the toroidal magnetic field. Data from START, Globus-M and ASTRA simulations assuming Artsimovich ion scaling [5] for ST40 are shown. At low toroidal field the we find the ion temperature increases linearly with toroidal field, while at higher toroidal fields (above 1 T) this dependence becomes stronger. Figure 5 compares the MHD activity during the flat top for two representative pulses: one at low toroidal field and the other at high field. From this we observe that the MHD activity in the $\sim 20-150$kHz frequency range is reduced at higher field.



(a) (b)

Figure 4: *(a) Ion temperature during and at the end of the flat top plotted against the toroidal field. (b) Stored thermal energy calculated from an EFIT plasma reconstruction plotted against toroidal field. Note, the toroidal field was calculated at the plasma's geometric centre at the time when the ion temperature measurement was made.*



(a) (b)

Figure 5: *MHD activity at (a)* 0.65 T *and (b)* 1.1 T. *Taken from a centre post Mirnov coil with a* 0.32 ms *window. From left to right the highlighted times are: plasma merging, Internal Reconnection Event (IRE), MHD activity during flat top period, and plasma disruption. We note less MHD activity during the flat top period at the higher toroidal field.*

ST40 upgrades to design parameters

ST40 will have a series of rolling upgrades until it reaches it's design parameters of 2 MA plasma current, 3 T toroidal field and up to 4 MW auxiliary heating.

Diagnostics A Diagnostic Neutral Beam Injection (DNBI) has been installed and in the next campaign Charge eXchange Recombination Spectroscopy (CXRS) will be used to measure the ion temperature at a spatial location. A Neutral Particle Analyser (NPA) has been installed to measure peak ion temperature. Electron density will be measured using a submillimetre interferometer (SMM) and a Near-InfraRed interferometer (NIR). A Thomson Scattering (TS) system is being designed to measure electron temperature and density profiles.

Heating A 1MW, 25-100ms, 25keV heating Neutral Beam Injection (NBI) system is being commissioned and another 1MW, 2s, 55keV NBI system has been ordered. 1MW, 2s, 84/126GHz Electron Bernstein Wave (EBW) and 1MW, 2s, 140/170GHz Electron Cyclotron Resonance Heating (ECRH) systems are both under design.

PF and TF power supplies The TF magnet has been tested (without plasma) up to 3 MA rod current (125 kA wire current) which produced 1.5 T at $R = 0.4\,\mathrm{m}$. The power supplies are made from modular supercapacitor banks and will undergo several upgrades as we increase plasma current and toroidal field. In order to achieve $B_T > 2\,\mathrm{T}$ and $I_p > 1\,\mathrm{MA}$ with a 1 second flat top it will be necessary to cool the coils with liquid nitrogen.

Load assembly A new all-metal vacuum vessel with a molybdenum divertor and passive plates has been designed and ordered.

Bio-shield Neutronics calculations have been performed and a composite bio-shield is under designed.

References

[1] M Gryaznevich, *et al.*, Merging-compression formation of high temperature tokamak plasma, Nuc. Fusion, (2017)

[2] P.F. Buxton, *et al.*, Merging compression start-up predictions for ST40, Fusion Eng. Des., (2017)

[3] PF Buxton, *et al.*, Merging/Compression start-up in ST40: Analysis of first experimental results, EPS conference, (2018)

[4] Y. Ono, *et al.*, High power heating of magnetic reconnection in merging tokamak experiments, Phys. Plasma, (2015)

[5] LA Artsimovich, Nucl. Fus. 12 (1972) 215