Developing understanding of spherical tokamaks with MAST Upgrade

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MAST Upgrade (MAST-U) is a new low aspect ratio device (R/a = 0.85/0.65 ~ 1.3) based on the MAST tokamak. It has substantial new capabilities compared with the original MAST device, with 19 new poloidal field coils (14 of which are within the vacuum vessel) and new, closed, up-down symmetric divertors with Super-X capability. MAST-U is designed to operate at higher toroidal field (0.585 T to 0.85 T at full current). The new solenoid nearly doubles the inductive flux from 0.9Vs to 1.7Vs, allowing for the maximum plasma current and pulse length to be up to 2MA and 5s respectively with a combination of on and off-axis neutral beam heating and current drive. This paper summarises some of the main achievements from the first MAST-U physics campaign that ran from October 2020 until October 2021.

High Performance Scenarios

The first physics campaign had pulses that ran for up to 750kA for 1 second duration and 0.65 T toroidal field at R=0.8 m. It had both on and off axis beam power at ~1.7 MW per beam line, for a total of 3.5 MW of injected power for 1 second. These values are somewhat below the maximum design parameters, as the machine operating limits are to be increased gradually between campaigns. A representative high performance pulse is shown in figure 1. This pulse has a 1s plasma current flat-top, neutral beams duration exceeding 1s and long type I ELMy H-mode period. This is a significant advance on MAST where the H-mode duration for comparable pulses at this plasma current were typically <0.4s duration. Pulse 45272 also had a high and relatively stable stored energy as shown in figure 1d. This stored energy, and correspondingly confinement time, reduces as the plasma density increases above the optimal Greenwald fraction of ~0.6 as shown in figure 1a.

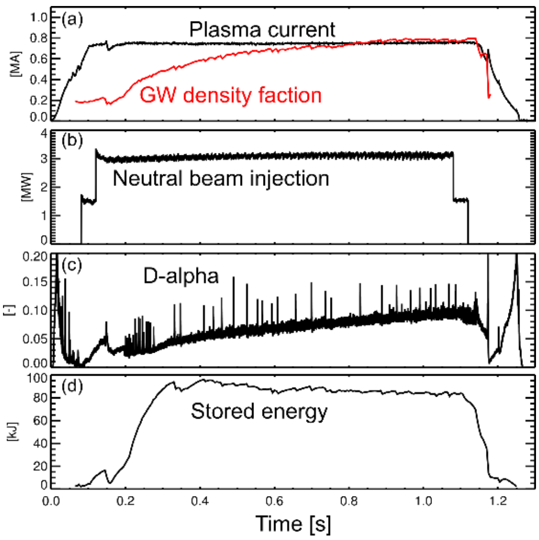

Figure 1 – MAST-U pulse # 45272. This pulse demonstrates >1s beam power injection, plasma current flat-top and H-mode with high stored energy.

Substantial progress has been made towards developing robust, high performance plasma scenarios with on- and off-axis neutral beam (NBI) heating. In 750 kA discharges with NBI heating exceeding 3.0

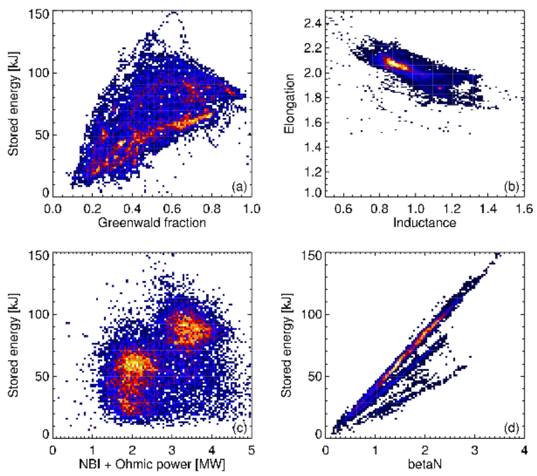

Figure 2 – Existence space of plasma parameters in first MAST-U physics campaign.

MW, pedestal top temperatures approaching 300 eV and stored energies of 100 kJ have been obtained, with the pedestal reaching the peeling stability limit (compared with the ballooning limit previously observed on MAST). Good performance has been obtained in strongly shaped plasmas with relatively high elongation, κ, of ~2.2 with good vertical stability. The existence space of plasma parameters for the first campaign, as obtained from intershot EFIT runs, is summarised in figure 2. The dataset shows a peak in stored energy at moderate Greenwald fraction. Figure 2c shows the stored energy versus power and figure 2d shows stored energy versus β_N, the three continuous lines indicating the different plasma currents in the core scenarios. There was no difficulty with H-mode access on MAST Upgrade, with even ohmic H-modes observed during early plasmas. The transition to and from H-mode was in particular straight forward to initiate once the Z controller was enabled. Access was also found to be sensitive to the gas injection location, with H-mode easier with increased high field side gas puff.

Optimisation of the plasma breakdown and early I_p ramp was performed using a semi-empirical model [1] to ensure robust, repeatable breakdown and minimal solenoid flux consumption. Careful manipulation of the plasma current ramp up is required to tailor the q-profile to avoid MHD stabilities later in the discharge. The on- and off-axis neutral beams determine gradients in the fast ion pressure that drive fast particle modes that degrade fast ion confinement. Results from initial studies show the off-axis neutral beam produces fewer neutrons than the on axis beam. There are several different physics reasons for this, in particular the shorter slowing down time of fast ions in the colder off axis portion of the plasma, but also lower off-axis fast ion confinement due to prompt losses. Scenario development in the second campaign will aim to increase elongation and broaden the temperature profile. This, as well as operating at higher plasma current should improve the plasma performance with the off axis beam. It has been observed that there is substantially reduced core MHD when using the off axis beam compared with the on axis beam which is a clear benefit. Progress during the first campaign went in step with the introduction of feedback control on various parameters. Vertical, plasma current and radial position feedback control were all brought online. Plasma density control is expected to be brought online at the start of the next campaign as well as improved shape controllers.

Plasma Exhaust and the Super-X divertor

Power exhaust is a key challenge facing for future, high power fusion reactors. A key physics mission for MAST-U is to explore the benefits of alternative divertor configurations, especially the Super-X [2], that offer substantially reduced power loads in steady-state [3, 4]. Some of the various achievable magnetic configurations are shown in figure 3 below. Figure 3a shows a standard connected double null with conventional divertor configuration. This pulse is similar to those performed on the MAST device in terms of divertor configuration. Figure 3c shows the Super-X divertor configuration where the divertor leg has been brought all the way out to the outer target (or T5 tile) and expanded at that point to further reduce the heat load. The configurations shown in figure 3b and d are conventional target with additional poloidal flux expansion and an extended leg without additional poloidal flux expansion respectively. Figure 3e shows a *disconnected* double null where the flux surfaces going through the upper and lower X-points are separated, resulting in this case in significantly increased flux to the lower divertor. Snowflake divertor configurations have also been achieved in the first campaign and there are plans to optimise configurations shown and explore other configurations in future campaigns.

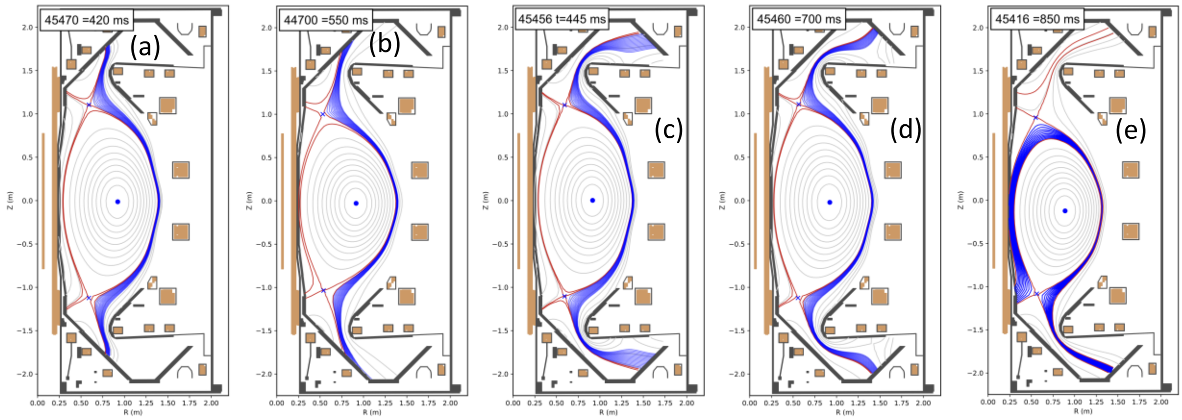

Figure 3 – A selection of some of the magnetic topologies obtained during the first MAST-U campaign. (a) Double null conventional divertor (b) Double null X-divertor (c) Double null Super-X divertor (d) Double null extended leg divertor (e) Disconnected double null extended leg divertor

The Super-X is designed to reduce target heat flux to the divertor compared with conventional divertor configurations. This is due to a longer field line length from the outer mid-plane to divertor target, allowing expelled plasma more time to radiate and cool. The larger strike point major radius in the Super-X also increases the plasma wetted area further reducing heat flux. Improved control of the detachment front position is expected due to the magnetic field being significantly higher at the x-point compared with the divertor strike point in low aspect ratio devices, leading to commensurate gradients in the parallel heat flux [5]. Divertor heat flux mitigation of factor ~x10 has been observed in the Super-X configuration in ohmic and strongly NBI heated L-mode discharges from infrared thermography measurements.

Initial results from MAST Upgrade indicate the detachment threshold based on the core line-average density is up to 50% lower in the Super-X configuration compared to the conventional divertor, which is in reasonable agreement with predictive modelling predictions [6]. The n_e and T_e evolution in the super-X can be directly measured by a dedicated divertor Thomson scattering system [7] whose chord follows the field lines toward the target. Measurements are shown in figure 4 for three pulses at different gas rates. In this figure, the main chamber density increases with increasing gas rate. As the main chamber density increases, the divertor T_e falls. The divertor n_e however varies non-linearly, initially increasing with main chamber density, but then decreasing at the highest density. This can be understood as the lowest gas rate pulse (45463) is during attached divertor conditions and following this an increase in main chamber density increases target density (45461) but the final reduction in target density at highest gas rate occurs because the divertor is in the deeply detached regime, so a reduction in ionised plasma near the target is observed with increased particle flux from the core (45463). Detailed characterisation of the mechanisms governing the onset and evolution of detachment suggest a complex interplay between plasma-molecule interactions, volumetric ionization and recombination processes.

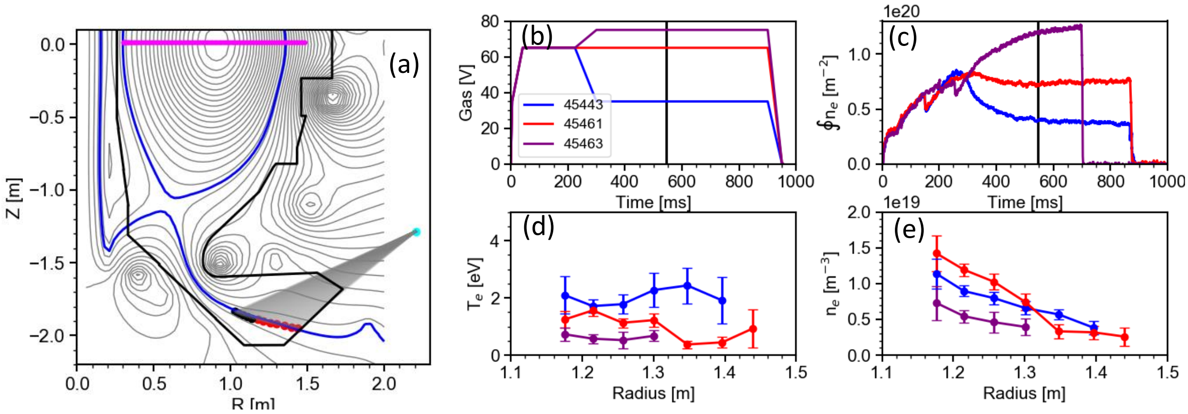

Figure 4 – Measurements in the super-X strike leg from divertor Thomson scattering. (a) shows the flux surfaces with TS measurement points overlaid in red (b) (c) Time traces of gas and line integral density, vertical line at 550ms shows measurement timings (d) & (e) radial profiles of T_e and n_e in divertor. The 45443 profile corresponds to measurements in an attached plasma, 45461 show measurements during detachment onset and finally measurements in 45463 show measurements in the deeply detached regime.

Conclusions and Outlook

The first MAST-U campaign has been very successful in advancing spherical tokamak plasma scenarios demonstrating high performance and long pulse operation. Divertor power mitigation has been demonstrated in a range of scenarios and in particular with very large reduction in target heat flux during Super-X operation. The coming campaign will see further advances with improved scenarios through increases in toroidal field, plasma current and beam power to further expand the operational space as well as improved diagnostic capabilities to fully understand the plasma behaviour.

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