OVERVIEW OF THE MAST UPGRADE PHYSICS PROGRAMME: TESTING NOVEL CONCEPTS AT LOW ASPECT RATIO TO INFORM FUTURE DEVICES

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Recent physics results from MAST Upgrade make significant and unique advances in understanding key physics issues governing the operation of ITER and future fusion power plants. The operating space has expanded considerably thanks to new capabilities including an active lower divertor cryopump to control the neutral pressure and sophisticated real-time equilibrium shape control to reach higher elongation (κ ~1.8 $\rightarrow$ 2.5) and a larger range of triangularity (δ ~ -0.15 $\rightarrow$ 0.5), reaching negative triangularity for the first time in a spherical tokamak. Operation with Super-X divertor configurations in the attached regime has been achieved with the cryopumped divertor, enabling studies of detachment onset. The plasma conditions in the divertors and main chamber can be effectively decoupled, due to the tightly baffled divertor chambers, which is rarely observed in current devices and enables pioneering studies of core-edge-divertor integration. On- and off-axis Neutral Beam Injectors (NBI) enable studies of the confinement and instability effects of super-Alfvénic fast ions that more closely mimics the products of fusion reactions. Recent results from MAST Upgrade are presented, emphasising results that develop the physics basis for spherical tokamaks (STs) and future high beta devices.

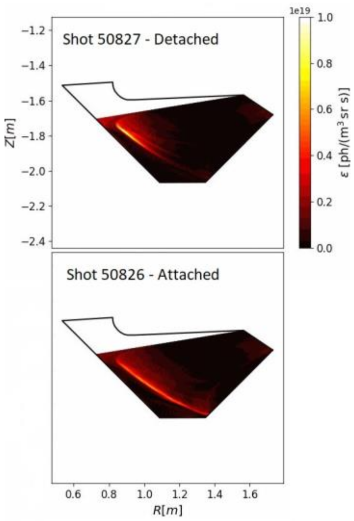

Figure 1: Inverted Multi-Wavelength Imaging of D_2 Fulcher band emission in experiments with a Super-X divertor and lower divertor cryopumping at high (top) and low (bottom) density. The presence of Fulcher band emission extending to the strike point at low density indicates the divertor is attached.

The development of plasma exhaust solutions for future high power density devices is a high priority for fusion research and MAST Upgrade is a unique testbed to study conventional and alternative divertor configurations at low aspect ratio, enabling studies at very high of total flux expansion. The new cryopumped lower divertor in MAST Upgrade has reduced the divertor neutral pressure by ~30-50%, enabling operation with hotter plasma temperatures in long-legged divertor configurations to study access to the detached divertor regime, as indicated in Figure 1. The impact of the cryopump on shorter leg divertor configurations is modest, highlighting the role of plasma-neutral interactions within the closed lower divertor chamber. The pressure in the main chamber and the upper divertor is weakly affected by the cryopump, as tight baffled divertors effectively decouple the pumping of the lower divertor chamber from the rest of the device, in agreement with SOLPS-ITER simulations. The lower divertor cryopump enables the neutral pressure in the lower divertor to be varied over an order of magnitude, revealing a dependence of core line-average density on the lower divertor neutral pressure, $n_e \propto p_{0,div}^{0.3}$ when there is strong fuelling from the divertor chamber. Real-time divertor detachment control has been implemented based on imaging measurements of D_2 Fulcher band emission, showing that the detachment state of the upper and lower divertors is effectively decoupled, even in topologies close to connected double null. Studies of the controllability of detachment in the Super-X divertor configuration indicate a reduced sensitivity to gas puff actuator action, in agreement with analytic models that predict passive stabilisation of the detachment by gradients in the parallel heat flux across the divertor. The buffering of transient heat loads in the Super-X divertor configuration has been studied in detail with unique ultra-fast spectroscopy and imaging diagnostics. Buffering of transients with energy ≤ 1kJ is effective with D_2 fuelling alone, in agreement with simplified models based on the energy required to ionize the gas in the divertor chamber [1]. Increasing poloidal flux expansion in NBI heated L-mode experiments resulted in plasma-molecule interactions occurring over a larger volume. Studies of power exhaust in H-mode have been extended to the X-point target configuration, indicating the presence of detached outer divertors with minimal impact on the plasma core, in common with the Super-X, with evidence of stronger plasma-neutral interactions. Initial studies of NBI heated snowflake divertor configurations in both divertors have been performed, showing the presence of strong radiative losses in the region between the poloidal nulls and reduced losses near the confined plasma. Fine control of the divertor geometry in conventional and alternative divertor configurations has been enabled via the use of shape controllers calculated using a novel technique based on spherical harmonics [2].

Confinement in high-performance MAST Upgrade scenarios is limited by the presence 2/1 tearing modes that can be the dominant source of fast ion losses and have been observed in ITER baseline scenarios on other devices, including DIII-D [3]. The onset of these modes is consistent with the q = 2 flux surface being situated in a local minimum of the current density profile. Operation at κ~2.5 with early divertor formation and NBI injection enable sustainment of $q_0 > 2$ for ~300ms, avoiding low-n mode activity and enabling studies of confinement and stability with q profiles closer to those envisaged in future large spherical tokamaks (e.g. [4], [5]). The onset of the mode has been postponed by optimising plasma scenarios to maximise q_0, and mitigated by maximising elongation, performing vertical oscillations and using gas fuelling from the low-field side to modify the edge bootstrap current, leading to increases in β_N of ~15%. The plasma current ramp-up phase has been optimised to enter H-mode as early as possible in the ramp-up to avoid internal reconnection events and to sustain higher q_0. To date, the highest achieved β_N is ~4.2 transiently, close to the n = 1 ideal MHD no-wall beta limit, where mode locking and minor disruptions occurred. In optimised pulses, β_N = 3.5 has been sustained while avoiding mode locking. At higher beta, $q_0 > 1$ the absence of sawteeth has been observed for several confinement times, indicating the action of flux pumping in spherical tokamaks for the first time [6].

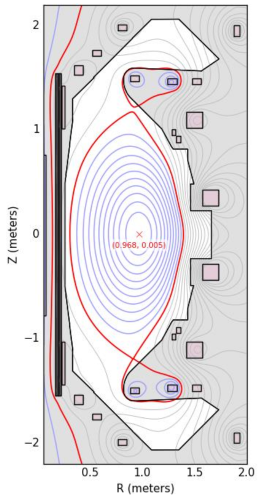

Figure 2: negative triangularity scenario on MAST-U

Understanding the stability of, and transport across the edge pedestal is essential to maximise confinement and to avoid ELMs. The strong shaping capabilities, neutral beam heating and cryopumping available in MAST-U have enabled sustainment of high pedestal top temperatures up to 400 eV. The dependence of the highest achievable pedestal top pressure as a function of plasma shaping is in good agreement with peeling-ballooning stability and pedestal parameter close to the peeling boundary have been observed. Carbon impurities can be a significant contributor to the pedestal top density, as the egress of carbon from the plasma is inhibited by the edge transport barrier. This can be avoided by forming a divertor configuration early in the pulse to reduce the initial carbon source. Initial studies of neutral beam heated negative triangularity plasmas have been performed for the first time in a low aspect ratio device, shown in Figure 2, suggesting a transition from an ELMing to an ELM-free regime at $\delta < -0.06$ [7]. In positive triangularity, a high-density stationary ELM-free pedestal regime has been identified similar to the EDA H-mode.

The confinement of energetic particles due to external heating in current devices and fusion reactions in future is critical to optimise plasma performance and avoid excessive wall loads. The first measurements of fusion protons have been obtained using a diamond detector that is more resilient to the environment of a fusion device than conventional silicon detectors [8]. Measurements of fast ion losses with a Fast Ion Loss Detector have been validated against ASCOT simulations, to enable studies of the interaction of MHD instabilities on fast ion confinement, including type-III ELMs that result in a 25-30% enhancement of fast ion losses from passing orbits [9]. High frequency Global Alfvén Eigenmodes (GAEs) can be excited in current and future devices with anisotropic fast ions, degrading neutral beam current drive. Co- and counter-propagating GAEs have been observed simultaneously [10], with co-propagating GAEs occurring due to the formation of minima in the second shear Alfvén continuum produced by regions of low magnetic shear that extend up to half of the plasma radius.

Following the current campaign of experiments, extensive improvements to the capabilities of MAST Upgrade will be implemented, including a 5 MW neutral beam system, a 1.6 MW electron Bernstein wave heating and current drive system, a high frequency pellet injector, new diagnostics and an operational upper divertor cryopump. This will enable significant expansion of the operational space towards more reactor-relevant conditions (including, but not limited to, higher β and q_0, lower collisionality) and to test the limits of alternative divertor configurations at high heat flux.

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