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Exhaust control in alternative divertors for transient heat load management

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Managing the power exhausted from the core fusion plasma towards the reactor wall remains a major challenge for fusion energy. Since this exhaust power fluctuates due to plasma disturbances, active power exhaust control is essential for reactors: a loss of detachment leads to target destruction while excessive cooling can trigger a highly damaging disruption. However, maintaining acceptable divertor conditions is challenging as the power fluctuations can be too fast for actuators to respond to. Alternative Divertor Configurations (ADCs) offer a potential solution to this problem due to their superior performance compared to conventional divertors \[1,2].

Our work on MAST-U successfully demonstrates power exhaust control in ADCs (Figure 1), representing the first such demonstration beyond conventional divertors \[3,4]. This is achieved through novel sensor techniques, enabling control of the detached plasma in between the target and the X-point in real-time using D_2 Fulcher emission measurements. Detachment control was not possible in conventional divertor scenarios on MAST-U, as their divertor state was too sensitive to perturbations, giving gas actuators insufficient time to actuate.

We demonstrate that ADCs can tackle key risks and uncertainties for fusion energy: 1) their highly reduced sensitivity to perturbations enables active exhaust control in otherwise unfeasible situations and facilitates 2) an increased passive absorption of fast transients which would otherwise damage the divertor; furthermore, we observe 3) a strong isolation of each divertor from other reactor regions through tight baffling which prevents divertor neutrals from spreading into the main chamber and effecting the core plasma.

This divertor isolation is evidenced in Figure 1d, where exhaust control using a divertor fueling valve did not influence core plasma conditions, contrary to midplane valve exhaust control experiments \[5]. This enables near-independent control of the divertors and core plasma which, although highly beneficial to all reactor concepts, is essential to compensate the asymmetric power transients expected in reactors with Double-Null divertor configurations.

The recent introduction of a cryopump in MAST-U further improves control capabilities by allowing the detachment front to be moved downwards, towards more attached conditions. This marks a significant improvement over previous experiments without cryopumping where a buildup of neutral pressure prevented the transition to more attached conditions \[5]. This highlights the importance of adequate pumping for exhaust control.

In summary, our results demonstrate the practical advantages of ADCs for effective heat load management in fusion power reactors.

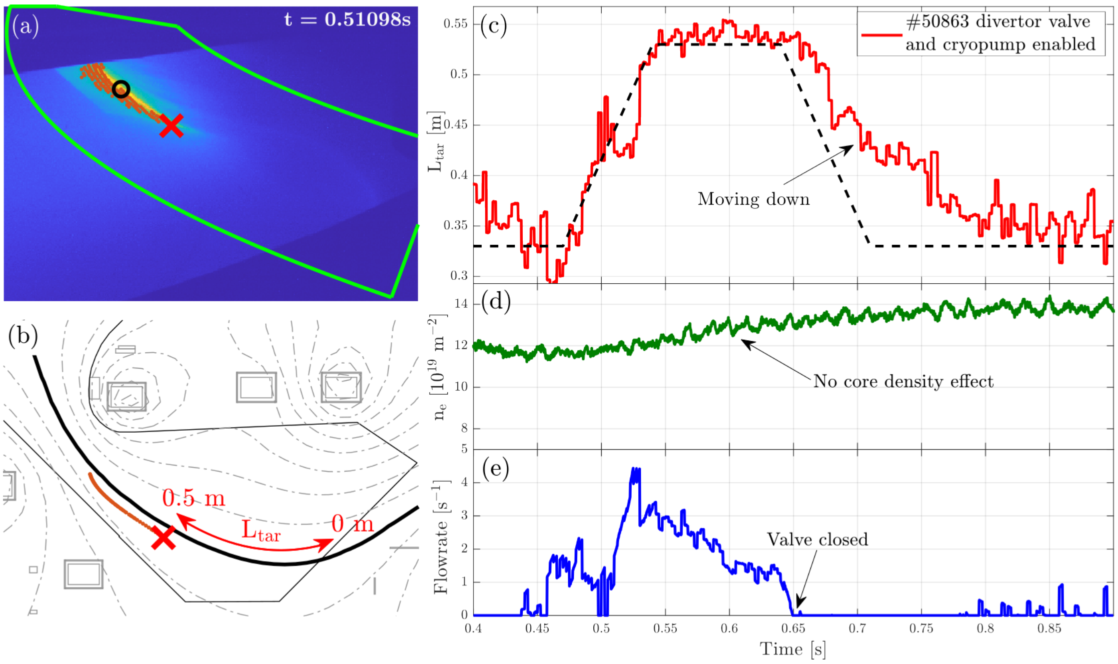

Figure 1:

Figure 1: Exhaust control in the MAST-U Super-X divertor using cryopumping and divertor fueling. **(a)** D_2 Fulcher-band filtered image of the lower divertor, showing the tracking area (green box) \[6], maximum intensity (black circle), detected divertor leg (orange dots), and the detected emission front (red cross). **(b)** Corresponding divertor cross-section with magnetic divertor topology (black), detected divertor leg (orange dots), and the detected emission front (red cross). The red arrow indicates the distance-to-target measurement Ltar. **(c)** Time evolution of the emission front position (Ltar) compared to the reference signal (dashed). Cryopumping also allows the front to be moved down, closer to the target, contrary to non-cryopumped experiments \[5]. **(d)** Line-integrated core density, showing no response to divertor actuation, contrary to midplane fueling experiments \[5]. **(e)** Gas flow request to the lower divertor valve by the exhaust controller.

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