EXAMINING BOUNDARIES FOR OPERATION ON ALCATOR C-MOD FROM THE SEPARATRIX PERSPECTIVE AND PROJECTION TO SPARC

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The separatrix operational space (SepOS) model [1] is validated against measurements from the Alcator C-Mod tokamak at high plasma density, n, and high magnetic field, B, supporting application of the model to the SPARC tokamak. Data from C-Mod have enabled novel findings, namely that particle transport grows with proximity to the model boundaries and that SepOS may inform access to high confinement regimes free of large edge localized modes (ELMs). Few large ELMs will be tolerable on SPARC, and understanding access to these regimes is crucial. Developed on AUG, the SepOS model provides a theoretical basis with which to understand three key tokamak operational boundaries: the transition between the L-mode and H-mode (L-H), the L-mode density limit (LDL), and the ideal ballooning MHD limit (IBML). The model is found to well describe the operational space of Alcator C-Mod across a wide range in operational parameters. Values of n and B on C-Mod reach up to three times higher than on AUG, more closely approaching the parameters expected on SPARC than any other diverted tokamak currently or previously operating. Measurements of cross-field particle flux, $\Gamma_\perp$, across the separatrix are evaluated for a subset of data and are found to well correlate with proximity to high density operational limits, in both H-mode and L-mode. The increase of $\Gamma_\perp$ near these limits provide compelling evidence for commonalities in changes to particle transport and their effect on the resulting density profile in both regimes. Changes to edge particle transport are linked to saturation of the density pedestal [2], a possible feature of high-density H-modes near operational limits. Finally, the physics of transport at the separatrix is leveraged to evaluate access to regimes free of ELMs – the Enhanced D_α (EDA) H-mode and the I-mode. Insights from the core SepOS model and new findings on C-Mod connect the separatrix condition with pedestal transport to make predictions for SPARC operation.

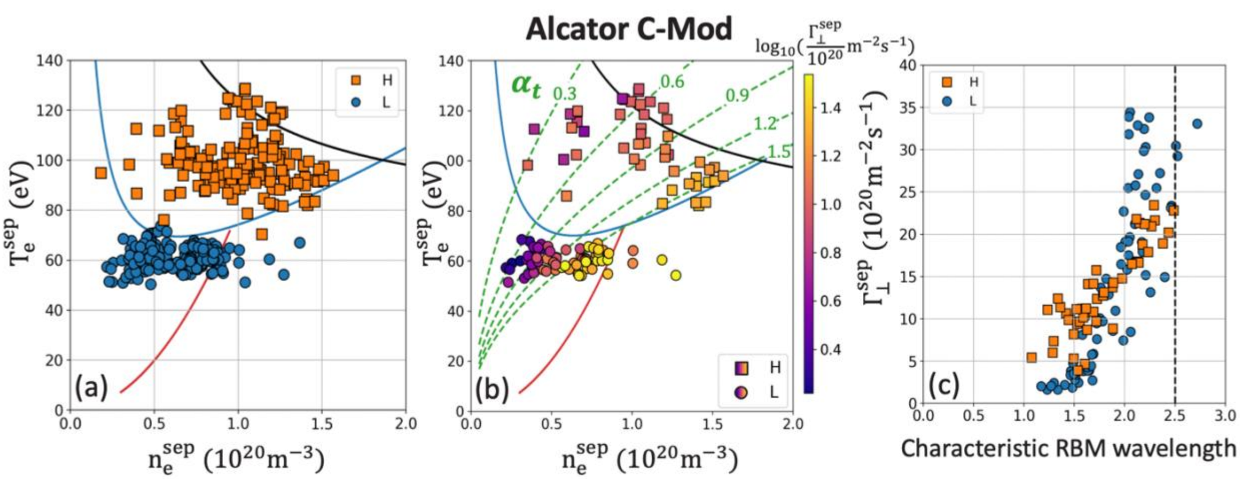

Figure 1: (a) Separatrix operational space showing electron temperature and electron density of H- and L-modes, as well as boundaries from SepOS model. (b) A subset of the dataset contains shown in color includes measurement of cross-field particle flux. (c) Particle flux against the characteristic wavelength for RBM turbulence, which depends on α_t and λ_{p_e}.

SepOS is a reduced model for operational boundaries and is built from interchange-drift-Alvén turbulence theory [1]. In this work, the model is validated on Alcator C-Mod using a dataset ranging widely in toroidal magnetic field, B_t, between 3.0 – 8.0 T and plasma current, I_P, between 0.4 – 1.8 MA. The dataset contains L-modes, different types of H-modes, and I-modes, in both the favorable and the unfavorable ion ∇B-drift direction. For the subset of data in the favorable drift direction, the three SepOS boundaries, namely the L-H, the LDL, and the IBML boundary well describe the possible operational regimes on C-Mod. The large dataset is sub-selected for fixed $B_t = 5.4$ T and $I_P = 0.8$ MA. For this smaller subset, the normalized boundaries are translated into (n_e, T_e)-space at the separatrix and are found to fall in the regions of operational space predicted by the SepOS (Figure 1). This dataset also contains neutral emission measurements, made with a midplane Lyman-α camera, enabling inferences of $\Gamma_\perp$. H-modes and L-modes with large $\Gamma_\perp$ are observed to approach the L-H and LDL boundaries, respectively, at high values of α_t, a collisionality-like turbulence control parameter related to adiabaticity [1]. Both are found to exhibit large growth of $\Gamma_\perp$ as $1/k_{RBM}$, the characteristic wavelength of the resistive ballooning mode (RBM), approaches a critical value.

This exercise also provides evidence that the SepOS may inform the physics of the pedestal in high density H-modes and of access to regimes free of Type-I ELMs, specifically, the EDA H-mode and the I-mode. Density pedestal saturation on Alcator C-Mod at large ionization rates was recently studied [2]. The phenomenon was linked to increased RBM turbulence, ultimately thought responsible for increasing edge $\Gamma_\perp$ and for limiting the pedestal gradient at high α_t. Analysis using the SepOS framework links this gradient saturation to approach to the L-H (or H-L) boundary, implying a limit to the achievable pedestal density at high α_t and near the H-L back-transition. Furthermore, based on new analysis of C-Mod data, additional boundaries mediating access to the EDA H-mode and the I-mode at the separatrix are proposed. As with the quasi-continuous exhaust regime (QCE) on AUG [3], C-Mod EDAs are generally found at $\alpha_t > 0.55$. For C-Mod, it is found that EDAs typically exhibit $k_{EM} > k_{RBM}$, implying that when the RBM turbulence becomes electromagnetic, suppression of large ELMs ensues. I-modes are also analyzed for the first time using the SepOS framework. These are accessed in the unfavorable ∇B-drift direction, and they are found at low n_e^{sep} (and high T_e^{sep}), typically when $\alpha_t < 0.3$. Work to connect this observation to theories for dissipation of T_e fluctuations [4] and to express these in terms of the SepOS framework for dataset comparison are ongoing. The success of the model on both Alcator C-Mod and AUG motivates application to next-step devices, like SPARC. For the engineering parameters of SPARC's primary reference discharge, the main SepOS boundaries and newly proposed boundaries for avoidance of large ELMs are computed in terms of n_e^{sep} and T_e^{sep} (Figure 2). These boundaries provide an easily interpretable control room map that SPARC's operators may use to navigate a plasma through operational space. Application of the SepOS to SPARC critically develops prediction of avoidance of disruptive limits and access to regimes free of ELMs needed to ensure divertor survivability.

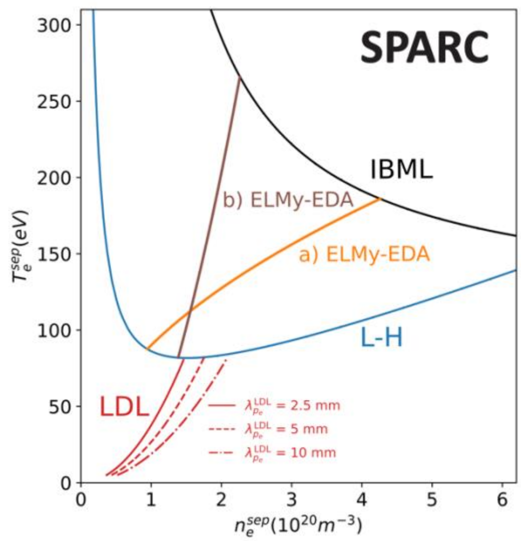

Figure 2: The operational space of SPARC in the favorable drift direction based on the core SepOS model boundaries as well as two tentative boundaries for the transition to operation in the EDA H-mode, a regime closely related to the QCE.

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