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Recent Progress in our Understanding of Electromagnetic Turbulence in a Conceptual Spherical Tokamak FPP (STEP)

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Electromagnetic microinstabilities are expected to dominate anomalous transport in high β next generation spherical tokamak (ST) reactor concepts like STEP [1,2,3], and may limit the achievable plasma performance in other future tokamaks that target steady-state operation. Gyrokinetic (GK) simulations have been remarkably successful in the modelling of anomalous transport in electrostatic turbulence regimes at low β and in conventional aspect ratio devices, but nonlinear simulations of electromagnetic turbulence regimes in higher β ST plasmas (where Alfvénic modes like kinetic ballooning modes, KBMs, and/or microtearing modes, MTMs, may be unstable) are computationally more challenging and have made more limited progress [4].

Local GK simulations of a candidate flat-top operating point for STEP [5], find that the linearly dominant modes are electromagnetic; MTMs and complex hybrid KBM-like modes with significant linear drive from the ion temperature gradient and trapped electrons (h-KBM), where the latter extends to long binormal wavelengths and is only unstable in STEP on inclusion of the perturbed compressional magnetic field, $\delta B_\parallel$ [6,7]. Nonlinear simulations that neglect $\delta B_\parallel$ (to exclude h-KBMs), retain MTMs as the only unstable modes and find that the transport, predominantly of electron heat, saturates cleanly at extremely modest fluxes. Including $\delta B_\parallel$ in nonlinear simulations, however, unleashes the h-KBM and in the absence of equilibrium sheared flow this drives large heat fluxes that are orders of magnitude greater than the available heating power in these conceptual plasmas [6-8]. Mitigation of h-KBM turbulence will be essential for the development of flat-top operating scenarios for STEP and may be important for other future reactor-relevant high performance magnetically confined fusion devices.

The understanding of turbulent transport from ST experiments will be briefly reviewed, and it will be highlighted how the plasma parameters in STEP burning flat-top plasmas must extend beyond the ST operating space that has been explored experimentally. The goal of delivering steady state plasmas with high fusion energy gain, requires the plasma current in STEP to be fully non-inductively driven. This pushes STEP plasma parameters beyond “well charted waters” in the following directions: higher β; lower collisionality; lower rotation; elevated safety factor; and significant fast ion content from fusion reactions. These factors can each have important implications for core turbulent transport.

Advances in our understanding of electromagnetic (EM) turbulence have emerged from recent studies of STEP reference plasmas (neglecting interactions between the turbulence and fast alpha fusion products). These studies include: (i) linear and nonlinear local GK simulations of EM turbulence in STEP [6-8]; (ii) assessing the sensitivity of turbulence to local equilibrium parameters to expose key actuators that mitigate the level of turbulent transport and/or influence the observed threshold for the onset of large fluxes [6-8]; (iii) development of a new physics-based quasi-linear (QL) reduced model to describe core transport from h-KBM turbulence in STEP [9]; (iv) first flux-driven simulation using this model, demonstrating the possible existence (but not accessibility) of a high fusion performance state with more tolerable transport that is qualitatively supported by local GK simulations [9]; and (v) first-of-their-kind global nonlinear EM simulations of STEP to include $\delta B_\parallel$. The latter global results, importantly, support conclusions from local GK, suggesting that the high-transport state is a robust GK prediction and not simply an artefact of the local approximation; at least for the equilibrium modelled. The core transport will be demonstrated to be complex and sensitive to many parameters beyond the kinetic profile gradients: e.g. safety factor, β, its radial gradient β', magnetic shear, flow shear, and collisionality. The most pressing priorities for future work will be discussed.

References

[1] M. Kotschenreuther *et al.,* NF **40** 677 (2000) doi:10.1088/0029-5515/40/3Y/331

[2] H.R. Wilson *et al.,* NF **44** 917 (2004) doi:10.1088/0029-5515/44/8/010

[3] STEP - Spherical Tokamak for Energy Production https://step.ukaea.uk/

[4] S. M. Kaye *et al.*, PPCF **63**, 123001 (2021) doi:10.1088/1361-6587/ac2b38

[5] E. Tholerus *et al.,* NF **64**, 106030 (2024) doi:10.1088/1741-4326/ad6ea2

[6] D. Kennedy *et al.*, NF **63**, 126061 (2023) doi:10.1088/1741-4326/ad08e7

[7] D. Kennedy *et al.*, NF **64**, 086049 (2024) doi: 10.1088/1741-4326/ad58f3

[8] M. Giacomin *et al.*, PPCF **66**, 055010 (2024) doi:10.1088/1361-6587/ad366f

[9] M. Giacomin, et. al. JPP 91, E16 (2025) doi:10.1017/S0022377824001107