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The Role of Alpha Particles in Turbulence Suppression and Confinement Enhancement in ITER and SPARC

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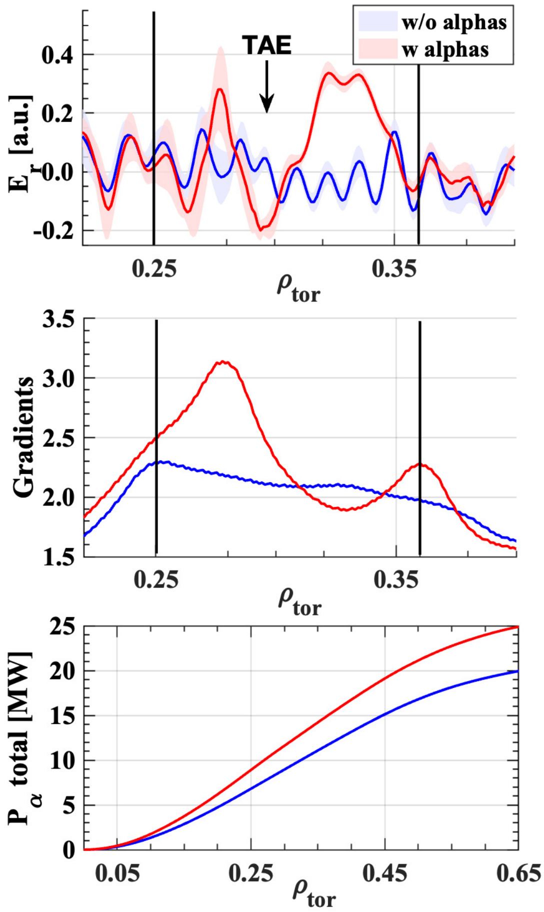
Accurate predictions of plasma performance are essential to optimize confinement and enable reliable operation in next-generation fusion reactors. This contribution presents the first high-fidelity ITER and SPARC [1] plasma performance predictions, leveraging nonlinear, global gyrokinetic simulations with the GENE-Tango framework [2, 3] analyzing the impact of fusion-born alpha particles on plasma confinement. By modeling the full turbulent spectrum—including Alfvén eigenmodes and micro-instabilities—we capture the crucial interplay between alpha-particle-driven Alfvén modes, micro-turbulence, and zonal flows [4]. This interaction is found to play a key role in turbulent transport regulation in the presence of alpha particles.

Our results demonstrate that retaining alpha particles into the GENE-Tango modeling significantly enhances plasma confinement. This improvement is attributed to turbulence suppression caused by alpha-particles driven modes, which enhance zonal flows and, in turn, mitigate plasma micro-instabilities. As a result, fusion alpha heating is found to increase by more than 20%, leading to a substantial improvement in the overall fusion gain Q. We provide a comprehensive analysis of fully nonlinear multiscale processes in burning plasmas, accounting for nonlinear interactions between plasma turbulence, profile evolution, and heating, while also retaining their effects on the self-consistent evolution of plasma geometry for the ITER modelling. This study represents the highest-fidelity simulation of burning plasma to date.

Moreover, we highlight key similarities and differences between SPARC and ITER in these nonlinear processes and propose strategies to further enhance the beneficial effects of alpha particles on plasma confinement, offering potential pathways for optimizing performance in future burning plasma experiments.

Figure 1. Radial profiles of (top) flux-surface-averaged electric field, (middle) normalized logarithmic ion pressure gradient, and (bottom) total alpha particle power for the SPARC reference discharge. Red and blue lines correspond to cases *with* and *without* alpha particles, respectively. Vertical black lines indicate the position of the TAE mode.



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