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全円環トーラス周辺乱流シミュレーションのための数値手法開発
A BOUT++ extension for full annular tokamak edge turbulence simulation

瀬戸春樹[1)], DUDSON Benjamin Daniel [2,3)], XU XueQiao[2)], 矢木雅敏[1)]
SETO Haruki[1)], DUDSON Benjamin Daniel[2,3)], XU XueQiao[2)], YAGI Masatoshi[1)]

1) 量研六ヶ所, 2) LLNL, 3) ヨーク大
1) QST Rokkasho, 2) LLNL, 3) U. York

The intermittent heat flux released by edge localized modes (ELMs) should be avoided or mitigated to low level enough to remain heat load constraints on plasma facing components in future fusion reactors. It is therefore one of critical issues to understand nonlinear dynamics underling ELMs and resultant energy loss process as well as particle loss process. For simulation studies on ELMs triggered by middle-n ~ high-n ballooning modes, nonlinear MHD codes using field-aligned coordinate system are suitable due to the reduction of grid resolution in the direction parallel to the magnetic field.

BOUT++ [1] employs both field-aligned coordinates and flux-surface coordinates for tokamak edge simulations in combination with the radial derivative method and the shifted metric method to simulate ballooning mode instabilities with reasonable computational cost and high accuracy and has provided qualitative understandings on ELMs triggered by middle-n ~ high-n ballooning modes [2]. Taking fluctuation-driven n=0 and very low-n flow and magnetic field however has been an open issue due to the numerical problem in the flute-ordered Poisson solver required for BOUT++ coordinates.

These limitations have been partially removed by the use of the flute-ordering-free Poisson solver designed for n=0 mode [3] which enables BOUT++ to simulate an interplay between fluctuation driven n=0 net flow and MHD turbulence during ELM crash triggered by middle-n ~ high-n ballooning modes. In our previous works [4,5], it is revealed that the zonal net flow generated during the pedestal collapse can trigger subsequent turbulence bursts accompanied with cyclic oscillations between pressure gradient, zonal flow and turbulence and enhance turbulent energy transport after the pedestal collapse. This framework however has a problem in handling very low-n modes and simulation domains are limited to annular wedge torus domain.

A new flute-ordering-free Poisson solver designed for very low-n modes as well as n=0 mode is developed for full annular torus tokamak edge turbulence simulations. Figure 1 shows the time evolution of energy loss level and that of perpendicular kinetic energy spectra showing zonal flow (n=0) and turbulence (n≠0) activities in the resistive ballooning mode (RBM) driven ELM crash simulation in full annular torus domain with shifted circular cross section (no X-points) taking n=0, 1, …, 80 modes. It is found that the initially unstable modes (n~32) set the onset of the pedestal collapse at t~200t_A but the energy loss increases slowly when the very low-n modes (n=1~3) nonlinearly generated are dominant (t=200t_A~300t_A). After the large collapse at t~300t_A, the zonal flow becomes dominant and the energy loss enhancement by interplay between flow and turbulence is observed like the previous ELM crash simulations in 1/5th annular wedge torus domains [4,5].

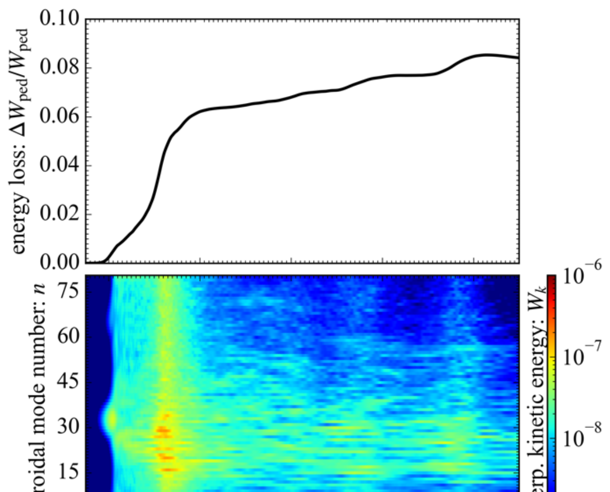

Figure 1: Time evolution of energy loss level (top) and time evolution of perpendicular kinetic energy spectra (bottom) in RBM-driven ELM crash.

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