Steady State Turbulent ITER-like Plasmas with RF Drivers

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Abstract. Extended MHD stability analysis performed taking into account the anisotropic pressure tensor in the outer most closed flux surfaces inside the magnetic separatrix where the ions and electrons dynamics strongly differ. The stability results are consistent with the I-mode confinement. Both ECRH and LHCD RF drivers are analysed for controlling the long-pulse ITER-like plasmas. Resonance cyclotron heating is analyzed with PIC simulations for understanding X-O mode conversions. Lower hybrid current drive [LHCD] simulations in single null separatrix fusion plasma with RF waves scattering from drift wave density fluctuations is shown to penetrate into the core plasma producing the broadened x-ray spectral observed in Tore Supra and EAST.

1. Introduction

Long-pulse fusion grade plasmas in ITER requires developing an integrated system of stability beyond that given my isotropic MHD along with external control with high power radio frequency [RF] antennas for driving and externally controlling the 10MA toroidal plasma current $I_p(t)$ that produces the confinement magnetic field. A single null poloidal field separatrix is required to control the escaping fusion plasma and the influx of impurity ions.

2. Stability and Transport in RF driven plasmas in ITER-like geometries

The stability inside and across the single null divertor magnetic separatrix is analyzed using new kinetically modified MHD stability equations analyzed with theory and with advanced simulations. A new extended MHD stability analysis is presented that describes in detail the outer most closed flux surfaces inside the magnetic separatrix where the ions and electrons dynamics differ [1]. The new physics includes the effect of charge separation in the response functions used in the MHD-ballooning modes. Anisotropic contributions to the extended MHD dynamics arising from the pressure tensor from the different ion and electron dynamics in this steep pedestal gradient region. A clear distinction is made in the response of the trapped and passing electron orbits just inside the magnetic separatrix. The cross-field flux function gradients of the toroidal plasma current density and the plasma pressure tensor are included in the new generalized stability analysis. This physics shifts the marginal stability boundaries for MHD-like eigenmodes as shown in new marginal stability boundaries which are compared with the standard MHD marginal stability diagrams. The effect is favorable for the beta limit and has been suggested to be related to the I- mode stability data.

2. LHCD and Electron RF heating

Anisotropy in the ITG and ETG turbulence is analyzed with kinetic theory and used to describe the steady state response of the fusion-grade plasma from the heating and current drive from RF waves. Reduced five-field coupled nonlinear partial differential equations are constructed and analysed to show that the new reduced system has Hamiltonian structure allowing theorems to be applied for the properties of the nonlinear dynamics [2].

Earlier reduced three-field descriptions of electromagnetic electron temperature gradient driven turbulence simulations were used to model the quasi-steady RF driven plasmas in Tore Supra. The extension to the new WEST plasmas is presented showing the change in the heating and confinement across the magnetic separatrix. The turbulence in the electron density scatters the direction and polarization of the current driving lower hybrid waves [3]. The new models are expected to relate to the experiments in Tore Supra and EAST to the upcoming experiments in WEST. The scattering of the launched LHCD waves by the ETG turbulence using quasilinear equation for the electron distribution functions and the RF plasmons is developed. The scattering of the antenna launched wave spectrum of the quasi-electrostatic slow drift waves produces a whistler fast wave component in the core plasma. The RF wave scattering by the turbulence in the electron density is required to explain the broaden, anisotropic fast electron energy spectra measured deduced from the x-ray spectra in Tore Supra and in the EAST tokamak experiments.

The fusion plasma is confined within a single null magnetic separatrix that breaks the vertical and inside-outside symmetry. Mappings of the magnetic field around the torus that include the perturbations form from combinations of wall antennas and ports then induce a chaos and magnetic islands in the surface of section at a fixed poloidal plane [5]. The resulting complex plasma density variations produce a scattering of the RF waves and the ray trajectory representations of the RF waves further spreading the RF power across the magnetic separatrix.

Both ECRH [4] and LHCD [6-8] RF drivers are key to controlling the steady state tokamak fusion systems. The resonance cyclotron heating is analyzed with PIC simulations giving a deeper understanding of the propagation through the density profile and the mode conversion mechanism from vacuum antenna waves to self-consistent plasma waves. The ECH are simulated with PIC codes for frequency 150 – 170 GHz ECH both in radial and oblique propagation across mode conversion surfaces producing the strong electron heating observed in the tokamaks. The targeted feedback control of magnetic island structures is also simulated. Observations and feedback control of available and future electron temperature profile data and the x-ray spectra from the high power ECRH and LHCD drivers are required for controlled steady state tokamaks EAST, WEST and KSTAR and for the future DEMO experiments. PIC simulations of the complex mode conversion processes are reported. Mode conversions using kinetic particle-in-cell (PIC) simulations performed with an open source code EPOCH [4] for simplified radial density profiles. The fully self-consistent PIC simulations allowed us to investigate nonlinearities associated with a higher incident intensity and the effect of a steeper (and more realistic) density gradient. The results are compared with previous simple models of mode conversion and the effective creation of non-Maxwellian electron distribution functions. The simulations are carried out both for the tokamak regime $\omega_{ce} > \omega_{pe}$ and the low field NSTX-U regime where $\omega_{ce} < \omega_{pe}$. In the second higher density regime there is linear mode conversion from fast to slow waves. The distortion of the electron distribution function changes the stability of the ETG as derived extending the earlier from the Nyquist stability analysis formula based on linear stability theory.

2. Conclusions

New LHCD and ECRN simulations with the single null divertor separatrix show the wave scattering and penetration into the core plasma producing the broadened x-ray spectral observed in Tore Supra and EAST. The ETG density fluctuation in space but frozen in time with respect to 2.5 to 5 GigaHertz RF waves scatters the waves between the slow and fast wave polarizations smoothing spatial distribution of deposited RF power in the core plasma. The spatially spread distribution of the RF power plasma is consistent with the broadened x-ray spectra observed in the LHCD experiments in Tore Supra and EAST. The relatively low level of plasma fluctuations in the I-mode confinement regime reported first in ASDEX now confirmed in other tokamaks appears consistent with an extended stability analysis beyond MHD that includes electron pressure anisotropy and charge separation.

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