Nonlinear MHD simulations of QH-mode plasmas in DIII-D

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1 Introduction

The good energy confinement performance in the H-mode makes it the preferred operation in tokamak devices and ITER. However, edge localized modes (ELMs) driven by large pressure gradients in the H-mode edge pedestal produce high transient power and particle loads to the plasma facing components (PFCs), which can lead to increased erosion of the divertor in ITER. In recent years the quiescent H-mode (QH-mode) regime, originally developed at the DIII-D tokamak [1] and investigated in other current devices, has been found to provide high confinement without transient energy fluxes to PFCs associated with ELMs. In DIII-D, this operational regime has been extended to conditions suitable for ITER operation such as low torque input [2] and high normalized density operation [3]. In the QH-mode, the edge harmonic oscillation (EHO) is found to provide a continuous edge particle transport which replaces the periodic expulsion of particles and energy by ELMs. The EHO is thought to be a saturated kink-peeling mode driven unstable by edge current and rotation, which maintains the edge pressure gradient near but below the ELM instability boundary [4]. Understanding the nonlinear MHD physics mechanisms that lead to the growth of the kink-peeling mode and its saturation including the role of plasma rotation in these processes is essential to project the QH-mode as an alternative ELM-free regime for ITER high Q operation. For this purpose, the JOREK code [5] is applied to study the physics of the nonlinear MHD instabilities of QH-mode plasma in DIII-D.

The JOREK code is a non-linear MHD code, developed with the aim of studying the non-linear evolution of the MHD instabilities such as ELMs, tearing modes, kink-peeling and ballooning modes, in full toroidal X-point geometry including the separatrix, open and closed field lines. In this work, nonlinear MHD simulations of DIII-D QH-mode plasmas have been carried out for the first time, both for ideal wall and resistive wall boundary conditions for low toroidal number modes. The influence of toroidal rotation as well as the effect of the vacuum vessel wall on the destabilization and saturation of edge modes for DIII-D QH-mode plasma has been studied.

Two representative DIII-D QH-mode discharges #145117, I_p =1.1MA, B_t =1.9T, counter beam neutral injection at first and switched to co-injection later, with 3-D non-axisymmetric (NA) fields perturbation, and #153440 I_p =1.4MA, B_t =1.9T, with strong counter neutral beam injection throughout and without NA fields have been used as an initial state for the MHD simulations.

2 Nonlinear simulation with JOREK for DIII-D QH plasmas

Nonlinear MHD simulations of DIII-D shot #145117 performed with the JOREK code assuming ideal wall boundary conditions have been carried out. The influence of 3-D NA fields applied in this discharge is not modelled in this first study. The initial 2-D static equilibrium is obtained from a kinetic EFIT fit. Figure 1a shows the time evolution of the magnetic energy perturbation for the toroidal harmonics n=1-5 included in the simulation. The initial state, characterised by a large edge current density, is unstable to n=1-5 kink-peeling modes with the largest linear growth rate for n=5. In the non-linear phase, the amplitude of the perturbation saturates into a 3-D stationary state. The dominant mode number changes from n=5 in the linear phase down to an n=1 perturbation in the stationary state. The fast growth of the n=1 harmonic is due to the non-linear coupling between the n=3-5 harmonics. This leads to a non-linear growth rate about 10x the linear n=1 growth rate.

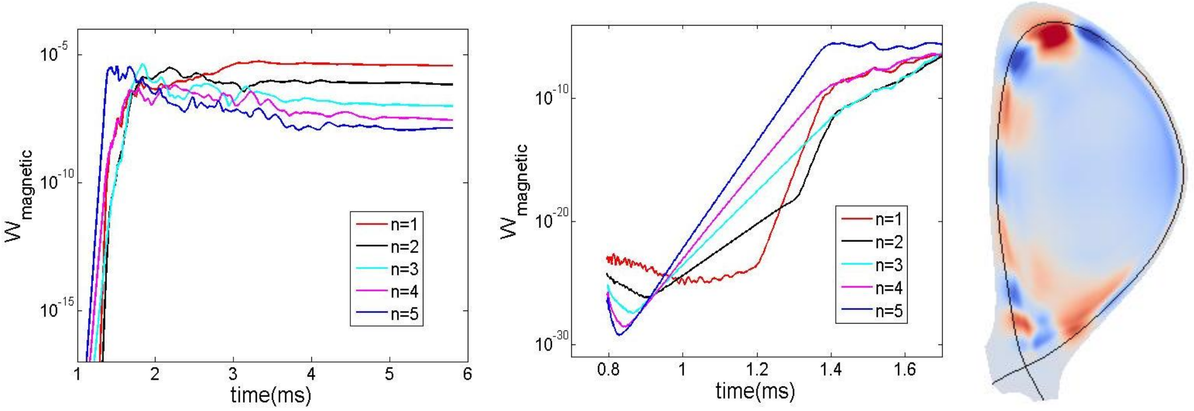

Figure 1 (a) *Evolution of the perturbed magnetic energy (n=1-5) as a function of time* ***(b)*** *Contour plot of poloidal flux perturbation of the saturated n=1-5 kink/peeling modes from MHD simulations.*

A contour plot (Figure 1b) of the perturbation of the poloidal flux of the saturated state (including toroidal mode numbers n=1-5) shows the typical mode structure of a non-linearly saturated kink-peeling mode localised around the separatrix. In this case, without diamagnetic, neoclassical nor toroidal rotation, the dominant n=1 perturbation with a frequency of ~1.6 kHz rotating in the counter clockwise poloidal direction due to the ExB velocity, causes a 1.3 cm oscillation of the density profile in the outer mid-plane, just inside the separatrix. Figure 2a compares the density profiles at two toroidal phases (φ = 0, π).

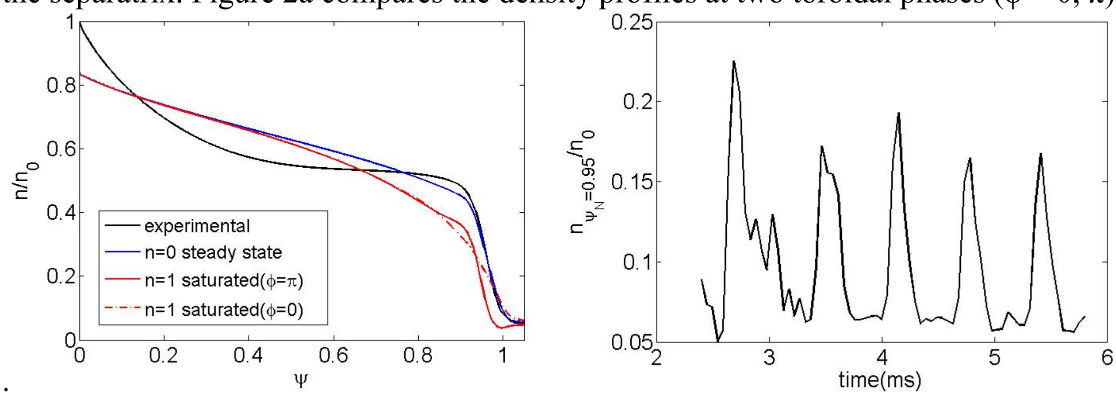

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Figure 2 (a) *density profiles for initial time (black curve), saturated n=0 mode (blue curve) and saturated mode n=1(red curve).* ***(b)*** *the time evolution of the density in the outer mid-plane at* ψ_N*=0.95 (normalized to the central density).*

The diffusive transport coefficients in the density and energy equations in the MHD simulations are chosen such as to keep the original pedestal profiles constant over time, see Fig 2a (in absence of any MHD perturbation, see n=0 curve in Fig.2a). The saturated kink-peeling mode causes an additional density loss due to the ExB convection pattern of the mode. The density at the top of the pedestal drops by about 25% while the pedestal gradient maintains the same steepness. The temperature profile does not change significantly.

The time evolution of the density in the outer mid-plane (see Figure 2b) shows a non-sinusoidal behavior. This indicates that the 3-D stationary state is composed of multiple toroidal harmonics leading to some degree of toroidal localization, consistent with typical observations of multi-harmonic spectra in QH mode plasmas [2,6,7]. The density losses due to the ExB flows of the saturated kink-peeling mode may explain the clamping of the density rise in QH modes as compared to Type-I ELMy H-modes.

The simulation of discharge #153440, starting from a static equilibrium shows a different non-linear behavior. Instead of a 3-D stationary state, the system develops regular bursts of kink-peeling mode activity. Figure 3 compares the time evolution of the magnetic energy of the two cases. One clear difference is the mode rotation. In the 3-D stationary state the MHD instability is continuously rotating with a frequency of 1.6 kHz whereas in the bursting case the mode has zero rotation. Further analyses will be carried out in order to clarify the reasons for this different behavior.

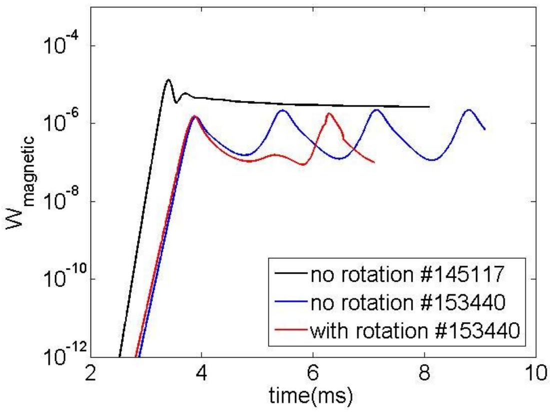

Figure 3 *Comparison of the evolution of the magnetic energy perturbation (n=1) of a 3-D stationary state and a case with a bursting behavior of the kink-peeling mode with/without parallel rotation for the latter.*

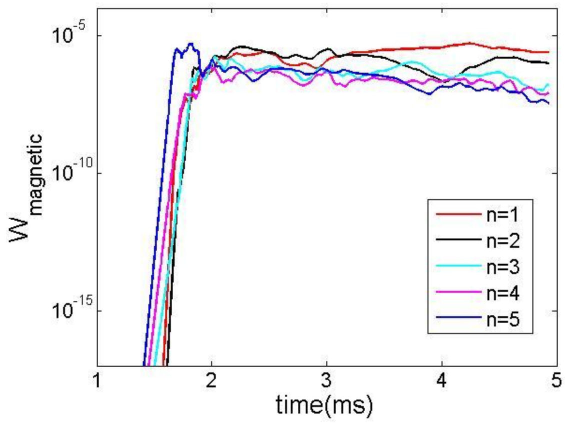

Figure 4 *Magnetic energy time evolution (n=1-5) for #145117 with parallel equilibrium rotation.*

3 Parallel equilibrium rotation

Recent investigations [2,6] indicate that the EHO is possibly driven by edge rotation and rotation shear destabilizing kink-peeling modes. In order to understand the effect of edge rotation in QH mode, we include toroidal rotation (here approximated as parallel rotation) in the nonlinear simulations by utilizing a profile for the toroidal rotation similar to the one measured experimentally. The toroidal rotation at the top of the pedestal in the simulations is 20 km/s for #145117. The time evolution of the magnetic energy for the modes n=1-5 with parallel rotation is shown in Figure 4 for #145117. The parallel rotation profile (with a strong rotation shear at the pedestal) at this amplitude does not significantly change the linear growth rates or the non-linear evolution (compare with Fig.1a). The saturation levels are comparable with and without toroidal rotation, although the case with rotation exhibits a more irregular time behaviour. The density (and pressure) at the top of the pedestal is reduced by 25% in both cases and the EHO frequency obtained is also similar for both cases.

4 Resistive wall

The influence of a realistic resistive DIII-D wall has been studied with the coupled codes JOREK and STARWALL [8]. The STARWALL code calculates the response from the vacuum and the evolution of the induced currents in the resistive wall. This response is used as a boundary condition on the poloidal flux evolution in JOREK.

Figure 5 shows the flux perturbation and the current potential in the resistive wall during the saturated state for #153440 with a parallel rotation at the pedestal top of 80km/s as measured experimentally. Initially the mode is rotating but in the saturated phase the mode is locked to the wall. A scan of the pedestal parallel rotation speed shows a small increase in the linear growth rate by 20% between 0 km/s and 80km/s. The saturation amplitude does not change significantly with the parallel rotation speed (except the 0 km/s case which, surprisingly, has a much smaller saturation level), indicating that rotation influences the non-linear mode evolution when a resistive wall is included. The saturation of the peeling-kink mode does not require a finite rotation but is likely due to the formation of islands and an ergodic layer in the pedestal.

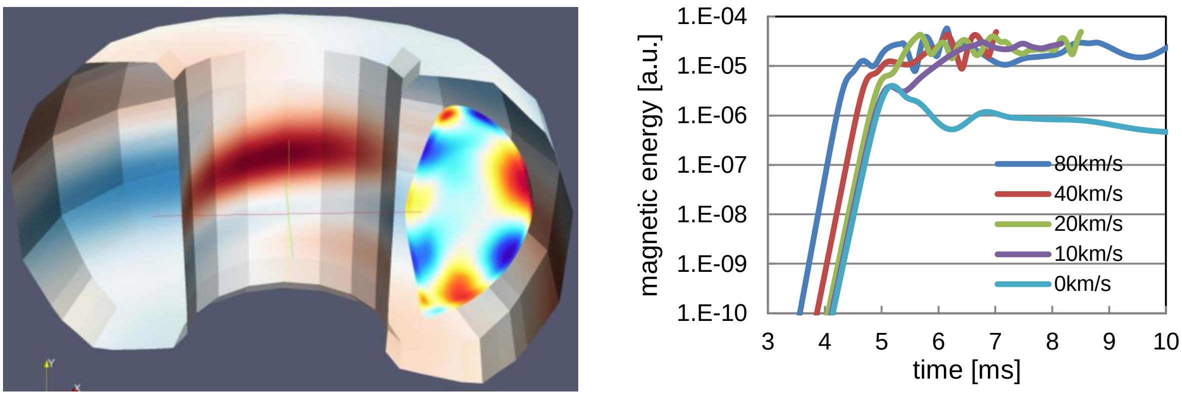

***Figure 5a** The perturbed flux and wall potential on the resistive wall of a saturated kink peeling mode (#153440, $v_{||}$=80km/s) **(b)** The (n=1) magnetic energy for a scan of the assumed parallel rotation speed at the top of the pedestal.*

5 Conclusions

MHD nonlinear simulations using two DIII-D QH-mode discharges as the initial state have been performed with the JOREK code. The linearly unstable kink-peeling modes non-linearly saturate into a new 3-D stationary state. The oscillations show the typical multi-harmonic content associated with the EHO in QH-mode plasmas. The effect of parallel rotation and of its shear at the plasma edge for both QH-mode discharges appears to be small, however self-consistent simulations including neoclassical poloidal velocities and diamagnetic effects should be included in order to properly calculate the radial electric field and fully clarify this point. Further analyses will be done in this direction including resistive wall conditions as well. The possibility of QH-mode operation for ITER will be also analysed on the basis of the validation of the QH-mode physics picture with JOREK for DIII-D in the future.

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