Numerical study of a strongly pressure redistributing mode in LHD plasmas driven by energetic particles

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The presence of energetic particles in magnetic confinement fusion plasmas is necessary for maintaining it at the high temperature required for fusion reactions to occur. Energetic particles refer to particles whose energy is much higher than the averaged thermal energy of the plasma. They usually only amount to a small portion of the total density, but due to their energy, can have a pressure contribution comparable to that of the thermal plasma. For that reason, they can have a strong influence on the plasma dynamics, destabilizing modes, and can be ejected from the plasma core, rendering them unable to heat the thermal plasma.

A recent observation of energetic particle driven interchange mode (EIC) in the Large Helical Device [1, 2] shows an instability with mode numbers $m/n = 1/1$ (m and n being the poloidal and toroidal mode numbers respectively) that is present when perpendicular Neutral Beam Injection (NBI) is active. During the bursts of instability, a significant portion of energetic ions are ejected from the plasma core, as can be concluded from a reduction of neutron yield in deuterium experiments [3]. The observation of this mode motivates the study of energetic particle driven instabilities in the LHD, with energetic ions consistent with perpendicular NBI.

Model and initial conditions

The study conducted here is accomplished using the hybrid code MEGA [4, 5], allowing us to separate the dynamics of the bulk plasma, treated as a fluid using the MHD equations, from the energetic particles, which are treated using a kinetic description. The use of a hybrid model enables us to study wave particle interaction for the energetic particles, as well as non-maxwellian distribution functions.

The equilibrium for the bulk plasma is based on a reconstruction of the high performance deuterium LHD shot #135730 done with the HINT code [6, 7]. The whole device is simulated in a cylindrical geometry (R,φ,Z), with a resolution of (128,640,128).

The energetic particle population, consisting of deuterium ions, has a slowing down distribution in velocity, and a Gaussian distribution in pitch-angle as:

$$f(v,\Lambda) = \frac{F_0}{v^3 + v_{crit}^3} \times 0.5 \times \mathrm{erfc}\left(\frac{v - v_{birth}}{\Delta_v}\right) \times \exp\left(\frac{(\Lambda - \Lambda_0)^2}{\Delta_\Lambda^2}\right) \qquad (1)$$

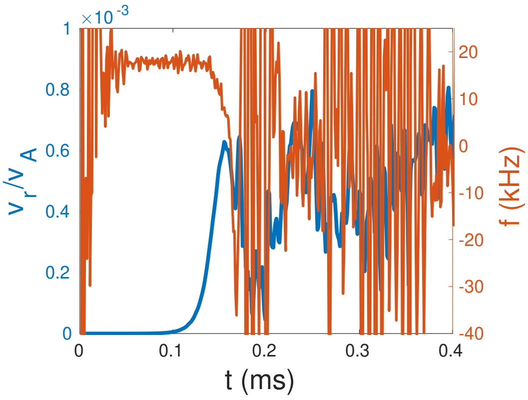

Figure 1: *Time evolution of the mode amplitude in blue and mode frequency in orange.*

where F_0 is a normalizing parameter, v is the particle velocity, v_{birth} is the injection velocity, $\Lambda = \mu B_0/E_{kin}$ is the pitch-angle, and Λ_0 is the center of the distribution in pitch-angle direction. In the case shown here, the birth velocity is $v_{birth} = 0.23 v_A$ (corresponding to a 60keV injection energy), and $\Lambda_0 = 1$, corresponding to a perpendicular NBI, and leading to a majority of helically trapped energetic particles.

The energetic particle spatial pressure profile is peaked on the plasma center, and decreases to zero at the edge. The position of maximum radial pressure gradient is located at the $\iota = 0.5$ (where ι is the rotational transform).

Energetic particle driven mode destabilization

When the energetic particle pressure is high enough ($\beta \approx 0.01$), an $m/n = 2/1$ fast growing mode is destabilized. With the conditions described above, this mode has a frequency of 17kHz, and a growth rate of $4.4 \times 10^4 s^{-1}$. The mode profile is wide, and is centered on the $\iota = 0.5$ surface. The mode grows and saturates for a value of $v/v_A \approx 10^{-3}$, and during the saturation and beginning of the nonlinear phase, the frequency chirps rapidly and changes sign in a short time (less than a full mode period). Figure 1 shows the time evolution of the mode amplitude and frequency, and shows the frequency time change at saturation. Figure 2 shows the energetic particle pressure profile during the linear phase (in blue), shortly after the saturation (in red), and later during the nonlinear phase. It can be seen that, right after the frequency sign inversion, the radial pressure gradient becomes positive around the $\iota = 0.5$ position, indicating a very quick pressure redistribution. Later in the nonlinear phase, the radial gradient flattens and becomes negative again, and the central pressure has significantly decreased.

Energetic particle behavior

In the equilibrium, the precession average velocity is positive in the θ-direction, and negative in the φ-direction, with a ratio of $f_\theta / f_\varphi \approx -5$ due to the particles following the helical shape of

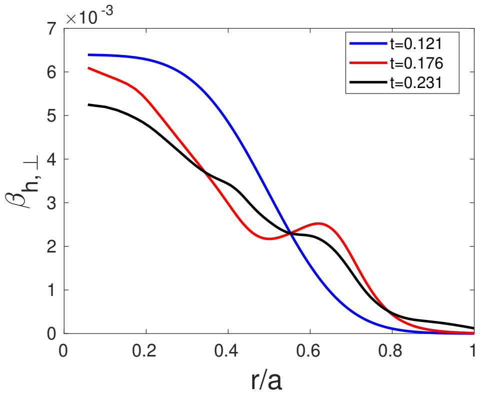

Figure 2: *Energetic particle perpendicular pressure profile at 3 times in the evolution. Blue:* $t = 0.121ms$ *is the end of the linear phase, red:* $t = 0.176ms$ *early nonlinear phase, black:* $t = 0.231ms$ *late nonlinear phase.*

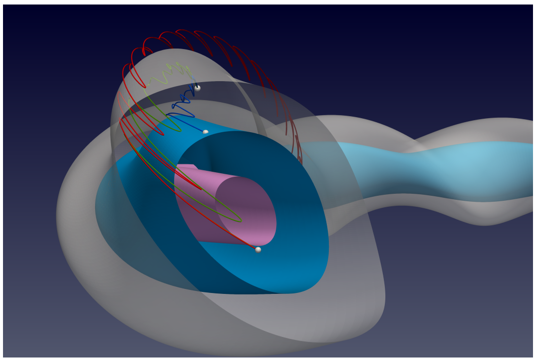

Figure 3: *Trajectory of a typical particle. Blue: from* $t = 0.11ms$ *to* $0.153ms$*, green:* $t = 0.153ms$ *to* $0.216ms$*, red:* $t = 0.216ms$ *to* $0.44ms$*. Three magnetic flux surfaces are shown for context.*

the LHD. The mode propagates in the same direction during the linear phase. However, during the nonlinear phase, starting at the same time as the mode frequency starts chirping, a significant portion of helically trapped ions that interact strongly with the mode have their precession direction change. It becomes negative in the θ-direction and positive φ-direction, and keeps the same ratio of -5, meaning that the particles remain helically trapped, and their precession direction is reversed. During this reversal, the particles affected also experience an outward motion, before returning to their original direction at a higher radius. This behavior is very important to explain the quick perpendicular pressure redistribution, as indeed it is observed for almost all the trapped particles that interact strongly with the mode during the nonlinear phase, and for up to approximately 40% of them simultaneously. Figure 3 shows the evolution of a typical particle that interacts strongly with the mode. In blue, we show the trajectory at the end of the linear phase. Then in green, we show the precession direction reversal, and can see that it goes in the opposite direction, and that it moves outward. Finally, in red is shown the trajectory

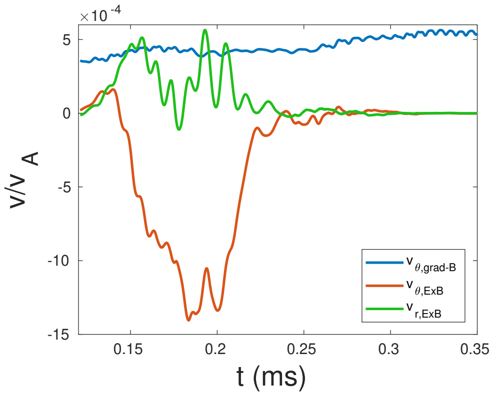

Figure 4: *Blue: grad-B drift contribution in the θ-direction. Orange: $E\times B$ drift contribution in the θ-direction. Green: radial $E\times B$ drift contribution.*

after the particles returns to its original direction at a higher radius. During this phase, it follows an equilibrium trajectory, and stays at the same radius.

An analysis of the interaction of the particles with the mode shows that the reversal is due to the continued interaction with the mode's radial electric field. We have analyzed the contributions of the $E\times B$ drift caused by the electric field on the particle, as well as the grad-B and curvature drifts averaged over the bounce motion. For trapped particles, the curvature drift is much smaller than the grad-B drift. The grad-B drift is the main contributor to the precession motion in the equilibrium. In figure 4, we show in blue the grad-B drift velocity in the θ-direction, and in orange the $E\times B$ drift velocity in the θ-direction. It should be noted that the grad-B drift remains positive and only varies a little during the whole evolution. It can be seen that, at the end of the linear phase, the $E\times B$ drift is nearly zero, which then becomes negative at the time of the saturation (around $t = 0.15$ms), and stronger than the grad-B drift, before coming back close to zero for the rest of the nonlinear phase. At the same time, the radial contribution of the $E\times B$ drift becomes positive, and goes back to zero later in the nonlinear phase. This clearly indicates that the $E\times B$ drift generated by the interaction with the mode causes the precession drift reversal, and the energetic particle ejection from the plasma core.

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