J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 69–73

Energetic Ion Transport due to Alfvén Eigenmode Bursts

TODO Yasushi, BERK Herbert L.[1] and BREIZMAN Boris[1]
National Institute for Fusion Science, Toki 509-5292, Japan
[1]Institute for Fusion Studies, University of Texas at Austin, Austin, Texas 78712, USA
(Received: 10 December 2003 / Accepted: 6 July 2004)

Abstract

Recurrent bursts of toroidicity-induced Alfvén eigenmodes (TAE) are studied using a self-consistent simulation model. Bursts of beam ion losses observed in the neutral beam injection experiment at the Tokamak Fusion Test Reactor are reproduced using experimental parameters. Only co-injected beam ions build up to a significant stored energy even though their distribution is flattened in the plasma center. They are not directly lost as their orbits extend beyond the outer plasma edge when the core plasma leans on a high field side limiter. The time evolution of the beam ion density during a burst and the particle loss mechanism are presented. In the simulation, the distance to the limiter is decreased after the stored beam energy saturates. We show that the co-passing beam particles may not readily reach the limiter even if the orbit width of edge-located particles is larger than outer edge spacing between the limiter and plasma. For the parameters of this run the stored energy of the co-injected beam density only drops rapidly, after the gap width from the plasma edge to the limiter becomes less than 0.3 of the minor radius. The existence of KAM (Kolmogorov-Arnold-Moser) surfaces of the edge mode even at large field amplitudes apparently inhibits energetic co-passing particles from being lost to the limiter at larger gap widths.

Keywords:

Alfvén eigenmode burst, energetic particles, transport, limiter, computer simulation

1. Introduction

The toroidicity-induced Alfvén eigenmode (TAE) [1] can be destabilized by fast ions which have velocities comparable to the Alfvén velocity. A decade ago recurrent bursts of TAEs were observed with neutral beam injection (NBI) in the Tokamak Fusion Test Reactor (TFTR) [2] and DIII-D [3] experiments. Nearly synchronous with these TAE excitations, there were observed drops in neutron emission. Hence it was inferred that the TAE excitations caused a direct loss of the injected beam ions. In the experiments cited multiple TAE mode bursting at regular time intervals were observed. The modulation depth of the drop in neutron emission in the TFTR plasma was typically ~10 % (Fig. 4 of ref. [2]) and the beam confinement time is about one-half to one-third of the collisional slowing-down time [4]. This means that the TAE activity in these experiments substantially reduced the beam ion energy confinement time because TAE activity expels a substantial fraction of the energetic beam ions before this energy is absorbed by the core plasma through drag that is caused by classical collisions.

Recently, simulations, based on a reduced magneto-hydrodynamic (MHD) method for a configuration typical of the TFTR experiment which had balanced beam injection [2], were carried out and the results were reported in ref. [5]. The results of the simulation reproduced quite closely the following aspects of the experimental parameters; a) synchronized bursts of multiple TAEs taking place at regular time intervals close to the experimental value; b) a modulation depth in the stored beam energy that is close to the one inferred in experiment; c) stored beam energy that is about one-third of the classical slowing-down distribution. Only co-injected beam ions build up to a significant stored energy even though their distribution is flattened in the plasma center. They are not directly lost as their orbits extend beyond the outer plasma edge when the core plasma leans on a high field side limiter.

The effects of the distance from the plasma edge to the limiter are important for energetic ion confinement. To demonstrate it, we carried a run where the distance to the limiter in the low field side is decreased after the stored beam energy reaches roughly a constant level. In this paper, we report on the simulation results and also present the time evolution of the beam ion density during a burst and the particle loss mechanism.

2. Simulation model

The simulation uses a perturbative approach where the TAE spatial profile is assumed fixed, while amplitudes and

Corresponding author's e-mail: todo@nifs.ac.jp

phases of the eigenmodes and the fast-ion nonlinear dynamics is followed self-consistently. The algorithm to advance the amplitude and phase of TAE modes is similar to the one developed in refs. [6] and [7], and is described in detail in ref. [5]. For the TAE burst simulation the safety factor (q) profile is taken to vary quadratically with minor radius from a central value of 1.2 to an edge value of 3.0, $q(r) = 1.2 + 1.8(r/a)^2$, where a is the minor radius and r is the minor radius coordinate. For simplicity we consider concentric circular magnetic surfaces to describe the equilibrium magnetic field. In the "vacuum" region the q-profile is modeled with a simplified form of $q(r) = 3(r/a)^2$. The major and minor radii are R_0 = 2.4 m and a = 0.75 m. The magnetic field is 1.0 T on axis. The spatial structure and the real frequency of the eigenmodes are obtained from a Fokker-Planck-MHD simulation [8]. The plasma density in the simulation is chosen for simplicity to be uniform 2.2×10^{19} m^{-3}. Both the core plasma ions and the beam ions are deuterium. Five eigenmodes are taken into account. Their toroidal mode number and real frequency are, respectively, a) $n = 1$, $\omega = 0.283\omega_A$ (mode 1), b) $n = 2$, $\omega = 0.404\omega_A$ (mode 2), c) $n = 2$, $\omega = 0.278\omega_A$ (mode 3), d) $n = 2$, $\omega = 0.257\omega_A$ (mode 4), and e) $n = 3$, $\omega = 0.330\omega_A$ (mode 5), where $\omega_A \equiv V_A/R_0 = 1.35 \times 10^6$ s^{-1} and is the Alfvén velocity. The spatial profile of the eigenmodes is shown in Fig. 1. The linear damping rate of each mode is assumed to be constant at 4×10^3 s^{-1}. The Fokker-Planck-MHD simulation does not give the part of the mode damping rate which depends on the kinetic properties of the bulk plasma. This leads to an arbitrariness in the choice of the damping rate and the eigenmodes in the present simulation. We have chosen the aforementioned set of eigenmodes and damping rates that roughly reproduces the experimental results.

Beam ions have balanced injection with a constant heating power of 10 MW and with a spatial Gaussian profile whose radial scale length is 0.3 m. The injection energy is 110 keV which roughly corresponds to the Alfvén velocity parallel to the magnetic field. The injected particle speed is $V = V_0$. The injected beam ion has a uniform pitch angle distribution in the range of $0.7 \le |\lambda| \le 1$, where $\lambda \equiv V_{\|}/V$ and $V_{\|}$ is the velocity parallel to the magnetic field. In the TFTR experiment two types of limiters, toroidal belt limiter and three poloidal limiters, were used. In the poloidal cross section the limiters roughly defined a circle of radius 1 m. We model these limiters by removing particles if they reach a torus with axis at $R/a = 3.53$ (R = 2.65 m) on the midplane and minor radius $1.33a$ (1 m). Figure 2 shows the configuration of the plasma and the limiter where particles are removed. Thus the plasma is leaning on the limiter at the high field side, while at the low field side there is a space from the plasma edge to the limiter whose width is $\Delta = 0.67a$ (0.5 m). In addition to the plasma and the limiter, examples of counter-injected beam ion orbit and co-injected beam ion orbit are shown in Fig. 2. By convention the velocity of a co-injected ion is parallel to the plasma current and in our case the velocity is parallel to the toroidal magnetic field as well.

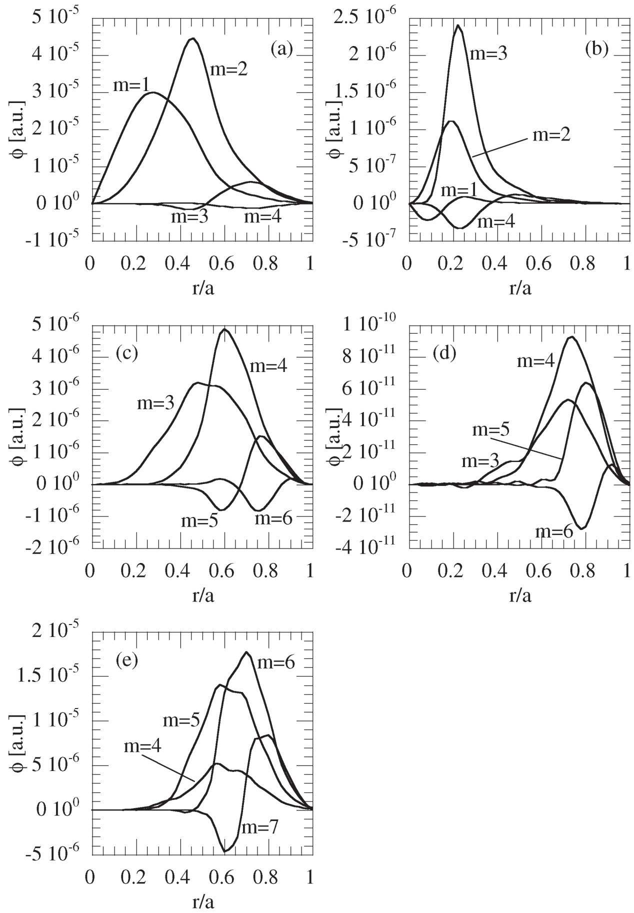

Fig. 1 Major four harmonics of the electric potential of Alfvén eigenmodes with the toroidal mode number of a) $n = 1$, $\omega = 0.283\omega_A$ (mode 1), b) $n = 2$, $\omega = 0.404\omega_A$ (mode 2), c) $n = 2$, $\omega = 0.278\omega_A$ (mode 3), d) $n = 2$, $\omega = 0.257\omega_A$ (mode 4), and e) $n = 3$, $\omega = 0.330\omega_A$ (mode 5), where $\omega_A \equiv V_A/R_0 = 1.35 \times 10^6$ s^{-1} [5].

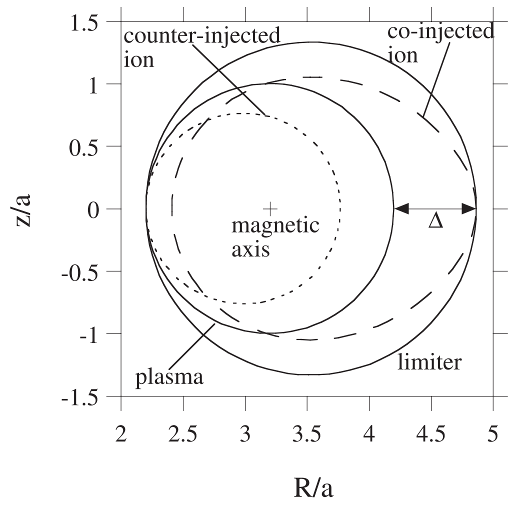

Fig. 2 Configuration of the plasma and the limiter, and examples of counter-injected beam ion orbit and co-injected beam ion orbit. The velocity of the co-injected ion is parallel to the plasma current. The orbits of co-injected (counter-injected) beam ions are displaced from magnetic surfaces towards the low (high) field side. The distance from the plasma edge to the limiter in the low field side is denoted as Δ.

Thus negative values of λ correspond to the counter-injected beam ions and positive values of λ correspond to co-injected beam ions. The orbits of co-injected (counter-injected) beam ions first encounter the plasma edge on the low (high) field side. Note that the co-injected particles can stick out of the plasma on the low field side, whereas the counter-injected particles are immediately removed by the limiter when they reach the edge of the high field side.

Particle collisions, slowing down and pitch angle scattering, are taken into account in the simulation. The slowing-down time is assumed to be 100 ms. For an experimental electron temperature of 2 keV the critical energy, above which the collisions with electrons dominate the slowing down process, is 37 keV. The pitch angle scattering rate is given by $\nu_d = \nu V_c^3/2V^3$, where ν is the rate of the slowing down and V_c is the critical velocity corresponding to 37 keV. Because the pitch angle scattering rate diverges as the particle speed reaches zero, we remove particles when they reach $V = 0.1V_0$. The number of particles used in the simulation runs is 2×10^6. Convergence with particle number was investigated in ref. [5]. It was concluded that we have a good numerical convergence so that the number of particles used is sufficient.

3. TAE bursts with variable distance to the limiter

3.1 Simulation results

We start the simulation at an initial time taken as t = 0 when the beam ions are first injected. As time passes, energetic ions gradually accumulate. After t = 66.8 ms when the stored beam energy have reached roughly a constant level, the distance from the plasma edge to the limiter Δ is decreased linearly in time with a time scale 30 ms. The time evolution of the amplitude of each mode is shown in Fig. 3. We see that before t = 66.8 ms synchronized bursts take place recurrently at a burst interval that is roughly 2.9 ms which is reasonably close to that of the experimental value 2.2 ms in the TFTR experiment that we are comparing with. Figure 4 shows the time evolution of the distance from the plasma edge to the limiter in the low field side (denoted as Δ) and of the stored energy of co and counter injected beams. Before we discuss the effects of the change in Δ, we summarize the results with the steady limiter configuration before t = 66.8 ms. The modulation depth of the drop in the stored beam energy is 10 % which is close to the inferred experimental value of 7 %. In the relative units of Fig. 4, the sum of the stored beam energy of the co and counter injected beams with TAE bursts saturates at a relative level of 0.31 which is 40 % of that of the classical distribution which is established with only a particle source and particle collisions. We thereby find good agreement between the simulation and the experiment where the stored beam energy is about one-half to one-third of the classical distribution [4]. A basic feature of the simulation that is apparent in Fig. 4 is the dramatic difference between the stored beam energy of co- and counter-injected beams whose velocity is parallel and anti-parallel to the plasma current, respectively. The loss in counter-injected beam energy induced by the TAEs' activity is 88 %, while that in co-injected beam energy is 37 %. Figure 5 shows the time evolution of the dominant two modes 2 and 5 and the density of the co-injected beam ions [5]. We can see that the mode 2, which is located at the plasma center, has precursory growth before the modes grow together during each burst. Because the beam injection profile peaks at the plasma center, mode 2 is destabilized before mode 5. We can see a complete flattening of the density at the plasma core (r/a < 0.72) while small increase in the density at the plasma edge (r/a > 0.72). The beam ions stored at the plasma core during the quiescent phases are transported to the plasma edge and lost primarily during the bursts.

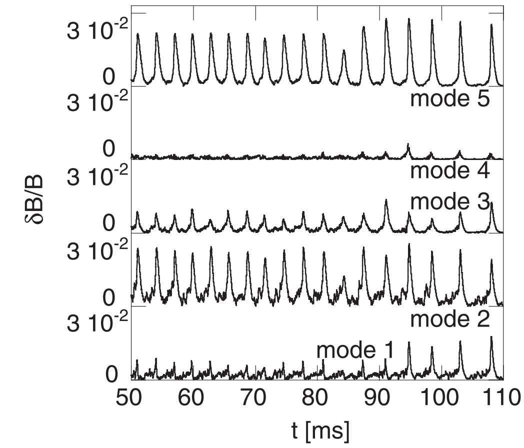

Fig. 3 Amplitude evolution of all the eigenmodes.

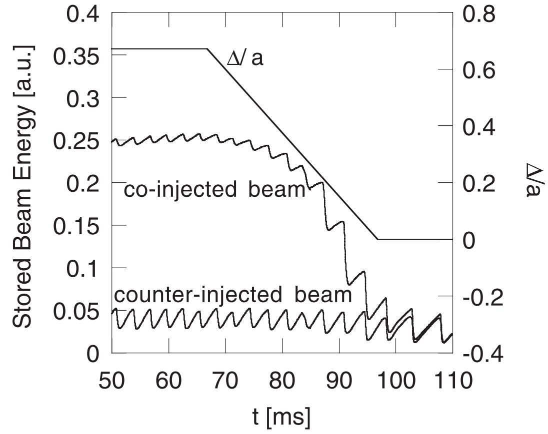

Fig. 4 Time evolution of the distance from the plasma edge to the limiter in the low field side (denoted as Δ) and of the stored energy of co and counter injected beams.

3.2 Particle loss mechanism

We now consider how the energetic particle loss mechanism is to be understood. To study this, we studied surface of section plots where only one eigenmode is taken into account and the amplitude of the eigenmode is at a constant value [5]. In the surface of section plot we print out the major radius of a counter-passing (co-passing) particle

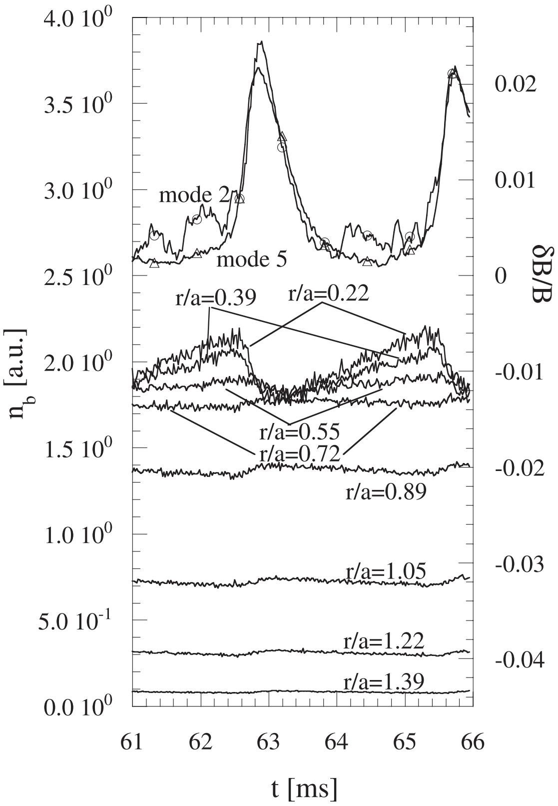

Fig. 5 The time evolution of the dominant two modes 2 and 5 and the density of the co-injected beam ions at various minor radius [5].

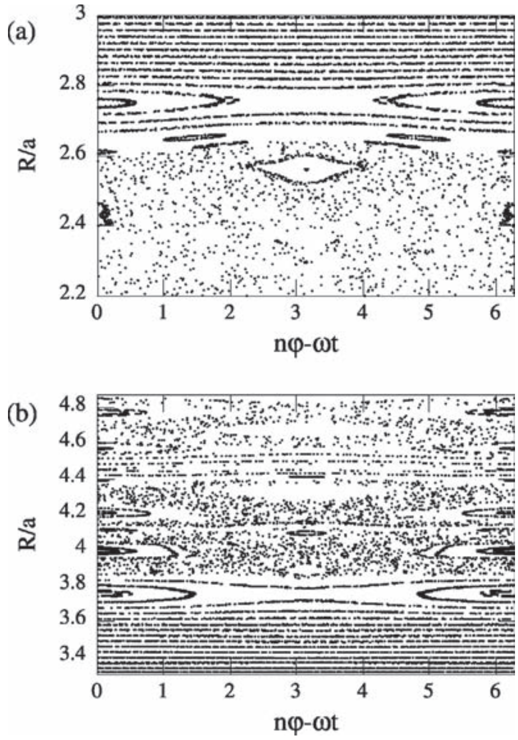

Fig. 6 Surface of section plots for a) counter-injected and b) co-injected beam ions where the amplitude of mode 5 is fixed in time at $\delta B/B = 6 \times 10^{-3}$ and φ denotes the toroidal angle.

each time the poloidal angle of the particle reaches $\vartheta = 180°$ (0°). We show in Fig. 6 surface of section plots for the (a) counter-passing and (b) co-passing particles, respectively, where the field amplitude of mode 5 is fixed in time at $\delta B/B = 6 \times 10^{-3}$. At this amplitude the stored beam energy takes on relative maximum values during the simulation run. This amplitude is higher than the ambient amplitudes between bursts, but considerably lower than the peak amplitudes the bursts reach. We see in Fig. 6(a) and (b) that the KAM surfaces (see *e.g.* [9]) are destroyed for mode 5 near the plasma edge $R/a < 2.6$ and $R/a > 4.6$, respectively, which then leads particle loss even before the modes reach their peak amplitude. The destruction of KAM surfaces takes place due to overlap of higher-order islands [5,10]. We should notice that in Fig. 6(b) the KAM surfaces exist at $4.4 < R/a < 4.6$ for co-injected beam ions, which do not allow the particle diffusion from the plasma center to the edge at that field amplitude and lead to substantial delay in particle loss compared with the counter-injected beam ions. We have studied surface of section plots for all the eigenmodes both for counter-passing and co-passing particles at the field amplitude that induces enough loss to prevent the increase in the stored beam energy. We have found that no eigenmode has a global stochastic region which extends from the plasma center to the limiter not only for co-passing particles, but also for counter-passing particles which are lost at this amplitude. This and the synchronization of all the eigenmodes suggests that the resonance overlap of different eigenmodes [11] is also important as the particle loss mechanism.

3.3 Effects of the distance to the limiter

Next, we turn to the results after t = 66.8 ms. The distance from the plasma edge to the limiter in the low field side Δ is decreased in 30 ms. We can see in Fig. 4 that the stored energy of co-injected beam drops rapidly after Δ/a is reduced to about 0.3. In Fig. 6(b) the KAM surfaces exist at $4.4 < R/a < 4.6$ for co-injected beam ions, which do not allow the particle diffusion from the plasma center to the edge and lead to substantial delay in particle loss compared with the counter-injected beam ions. After Δ/a becomes less than about 0.3, the limiter comes inside the KAM surfaces leading to disappearance of this effective barrier. After Δ/a reaches 0, the time evolution of the stored energy of the co-injected beam is roughly the same as that of the counter-injected beam. Thus, it is clear that the difference in the stored energy of the co and counter beams before t = 66.8 ms was created due to the limiter configuration which allows only the co-injected beam ions to stick out of the plasma. We see in Fig. 3 that as Δ decreases in time after t = 66.8 ms, the burst interval becomes longer. After Δ reaches 0 at t = 96.8 ms, the burst intervals are about 5 ms.

4. Summary

Recurrent bursts of toroidicity-induced Alfvén eigenmodes (TAE) have been studied using a self-consistent simulation model. Bursts of beam ion losses observed in the neutral beam injection experiment at the TFTR were reproduced using experimental parameters. Only co-injected beam ions build up to a significant stored energy even though their distribution is flattened in the plasma center. They are not directly lost as their orbits extend beyond the outer plasma edge when the core plasma leans on a high field side limiter. To demonstrate the effects of the distance from the plasma edge to the limiter in thí low field side, the distance to the limiter is decreased after the stored beam energy saturates in the simulation. The stored energy of co-injected beam drops rapidly, after the distance from the plasma edge to the limiter becomes roughly less than 0.3 of the minor radius. Surface of section plots have demonstrated that both the resonance overlap of different eigenmodes and the disappearance of KAM surfaces in phase space due to overlap of higher-order islands created by a single eigenmode lead to particle loss.

References

[1] C.Z. Cheng and M.S. Chance, Phys.Fluids **29**, 3659 (1986).

[2] K.L. Wong, R.J. Fonck, S.F. Paul *et al.*, Phys. Rev. Lett. **66**, 1874 (1991).

[3] W.W. Heidbrink, E.J. Strait, E. Doyle *et al.*, Nucl. Fusion **31**, 1635 (1991).

[4] K.L. Wong, R. Durst, R.J. Fonck *et al.*, Phys. Fluids B **4**, 2122 (1992).

[5] Y. Todo, H.L. Berk and B.N. Breizman, Phys. Plasmas **10**, 2888 (2003).

[6] H.L. Berk, B.N. Breizman and M.S. Pekker, Nucl. Fusion **35**, 1713 (1995).

[7] Y. Chen, R.B. White, G.Y. Fu and R. Nazikian, Phys. Plasmas **6**, 226 (1999).

[8] Y. Todo, T.H. Watanabe, H.B. Park and T. Sato, Nucl. Fusion **41**, 1153 (2001).

[9] W. Horton and Y.H. Ichikawa, *Chaos and Structures in Nonlinear Plasmas* (World Scientific, Singapore, 1996).

[10] J. Candy, H.L. Berk, B.N. Breizman and F. Porcelli, Phys. Plasmas **6**, 1822 (1999).

[11] H.L. Berk, B.N. Breizman and M.S. Pekker, Nucl. Fusion **35**, 1713 (1995).