ISSN 0915-633X

INTERNATIONAL ATOMIC ENERGY AGENCY

19 th IAEA Fusion Energy Conference
Lyon, France, 14-19 October 2002

IAEA-CN-94/ TH/P3-18

NATIONAL INSTITUTE FOR FUSION SCIENCE

Simulation Study of Beam Ion Loss due to Alfvén Eigenmode Bursts

Y. Todo, H.L. Berk and B.N. Breizman

(Received - Sep. 24, 2002)

NIFS-749 Oct. 2002

This report was prepared as a preprint of work performed as a collaboration research of the National Institute for Fusion Science (NIFS) of Japan. The views presented here are solely those of the authors. This document is intended for information only and for future publication in a journal after some rearrangements of its contents.

Inquiries about copyright and reproduction should be addressed to the Research Information Center, National Institute for Fusion Science, Oroshi-cho, Toki-shi, Gifu-ken 509-5292 Japan.

RESEARCH REPORT
NIFS Series

This is a preprint of a paper intended for presentation at a scientific meeting. Because of the provisional nature of its content and since changes of substance or detail may have to be made before publication, the preprint is made available on the understanding that it will not be cited in the literature or in any way be reproduced in its present form. The views expressed and the statements made remain the responsibility of the named author(s); the views do not necessarily reflect those of the government of the designating Member State(s) or of the designating organization(s). In particular, neither the IAEA nor any other organization or body sponsoring this meeting can be held responsible for any material reproduced in this preprint.

TOKI, JAPAN

Simulation Study of Beam Ion Loss due to Alfvén Eigenmode Bursts

Y. Todo 1), H. L. Berk 2), B. N. Breizman 2)
1) Theory and Computer Simulation Center, National Institute for Fusion Science, Toki, Japan
2) Institute for Fusion Studies,University of Texas at Austin, Austin, United States

e-mail contact of main author: todo@nifs.ac.jp

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. It is found that synchronized TAE bursts take place at regular time intervals of 2.9 ms, which is close to the experimental value of 2.2 ms. The stored beam energy saturates at 40% of that of the classical slowing down distribution. The stored beam energy drop associated with each burst has a modulation depth of 10% which is also close to the inferred experimental value of 7%. Surface of section plots demonstrate 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. The saturation amplitude is $\delta B/B \sim 2\times10^{-2}$, is larger than would appear to be compatible with experiment, but reasons are given why our other results may be robust. The stored beam is primarily from co-injected particles when there is a limiter leaning on the inner edge.

1. Introduction

The toroidicity-induced Alfvén eigenmode (TAE) [1] can be destabilized by fast ions that have velocities comparable to the Alfvén velocity. A decade ago recurrent bursts of TAEs were observed with drops in neutron emission during neutral beam injection (NBI) in the Tokamak Fusion Test Reactor (TFTR) [2] and DIII-D [3]. The drops in neutron emission have been recognized as a manifestation of TAE-induced beam ion loss. In the experiments cited multiple TAEs were destabilized during TAE bursts that took place at regular time intervals. The modulation depth of the drop in neutron emission in the TFTR plasma was typically ~10% (Fig. 4 of Ref. [2]). The most important result is that the beam confinement time is about one-half to one-third of the collisional slowing-down time [4]. This means that TAE activity expels beam ions before their energy is absorbed by the core plasma. In this paper we report on an investigation, based on a reduced MHD method, for a configuration typical of the TFTR experiment with balanced beam injection [2].

2. Simulation Model

The simulation uses a perturbative approach where the TAE spatial profile is assumed fixed, while amplitudes and phases of the eigenmodes and the fast-ion nonlinear dynamics is followed self-consistently. For simplicity we consider concentric circular magnetic surfaces to describe the equilibrium magnetic field. The magnetic field is given by $\mathbf{B}=B_\varphi\hat{\varphi}+B_\vartheta\hat{\vartheta}$ with $B_\varphi=B_0R_0/R$, $B_\vartheta=-rB_0/q(r)R$, where R is the local major radius, R_0 is the major radius on the magnetic axis, r is the minor radius, $q(r)$ is the safety factor, and ϑ is the poloidal angle with $\nabla\vartheta=\hat{\vartheta}/r$. The electromagnetic field is a superposition of this equilibrium field and the perturbed fields due to the TAE modes. The fast-ion dynamics is followed using the guiding-center approximation with the particle velocity the sum of $\mathbf{E}\times\mathbf{B}/B^2$, grad-B, curvature drifts, and the velocity parallel to the magnetic field lines. A fourth-order Runge-Kutta method is employed to integrate the particle orbit equations. The pitch angle scattering is taken into account at the end of each time step using a Monte Carlo approach [5]. The algorithm to advance the amplitudes and phases of TAE modes are similar to the ones developed in Ref. [6,7].

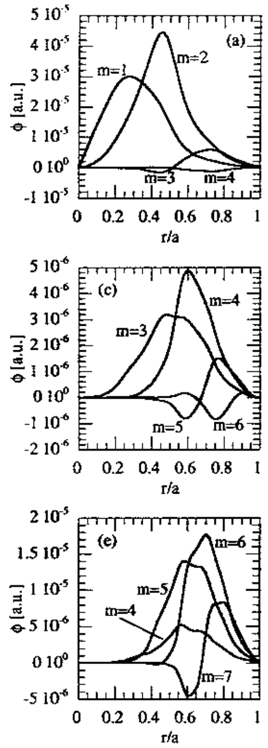

Fig.1 Major four harmonics of the electrostatic potential of Alfvén eigenmodes.

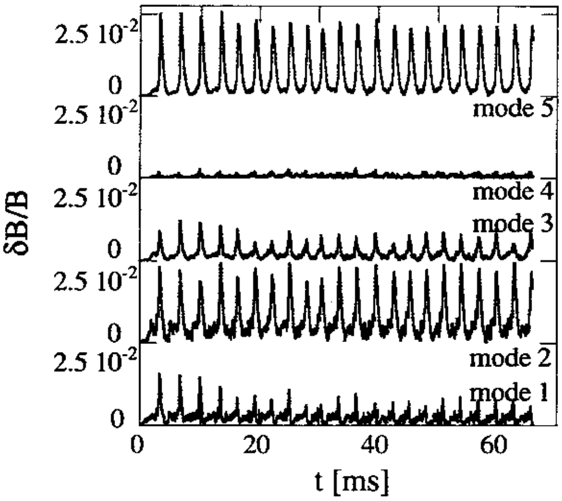

Fig.2 Amplitude evolutions of all the eigenmodes.

3. TAE Bursts

3.1 Simulation Results

For the TAE burst simulation the q-profile is taken to vary quadratically with minor radius from a central value of 1.2 to an edge value of 3.0, $q(r)=1.2+1.8(r/a)^2$. 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 $2.2\times10^{19}\mathrm{m}^{-3}$. 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 $\omega_A\equiv V_A/R_0=1.35\times10^6\mathrm{s}^{-1}$. The spatial profile of the eigenmodes is shown in Fig. 1. The linear damping rate of each mode is assumed to be constant at $4\times10^3\mathrm{s}^{-1}$. Beam ions have balanced injection with a constant heating power of 10 MW and with a spatial Gaussian profile whose radial scale length is 0.3m. The injection energy is 110 keV which corresponds roughly to the Alfvén velocity parallel to the magnetic field. The injected beam ion has a uniform pitch angle distribution in the range of $0.7\le|V_\parallel/V|\le1$ with V the speed of the injected particle. 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 1m. We model these limiters by removing particles if they reach a torus with axis at R=2.65m on the midplane and minor radius 1m. Thus the plasma is leaning on the limiter on the strong field side, while on the weak field side at the midplane there is a 0.5m space between the plasma edge and the limiter. The slowing-down time is assumed to be 100 ms. For the experimental electron temperature of 2 keV the critical energy, above which the collisions with electrons dominate the slowing

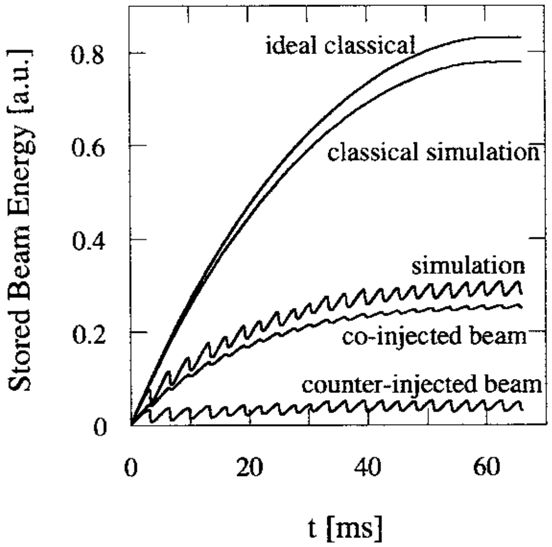

Fig.3 Time evolution of stored beam energy with that of the classical distribution and the classical simulation results.

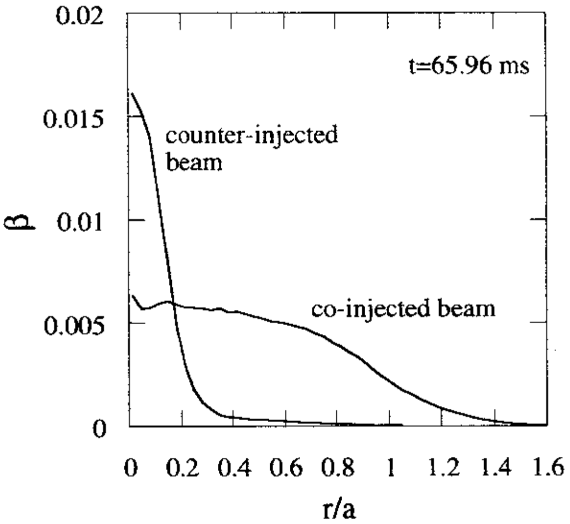

Fig.4 Beta profiles of both co- and counter-injected beams at the end of the simulation.

down process, is 37 keV. In the simulation runs for the TAE bursts described below the number of particles used is 2.1×10^{6}.

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. The time evolution of the amplitude of each mode is shown in Fig. 2. We see that synchronized bursts take place recurrently at a burst interval that is roughly 2.9 ms which closely matches that of experimental value 2.2 ms in the TFTR experiment that we are comparing with. In Fig. 3 we show the time evolution of the stored beam energy and compare it with that of the "ideal classical" slowing down distribution (without pitch angle scattering) and the "classical simulation" where pitch angle scattering is included but the interaction with the TAEs is switched off. 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 this figure, the classical simulation saturates at relative level of 0.78, whereas that of the simulation saturates at a relative level of 0.31, namely, 40 % of that of the classical simulation The volume average beam ion beta value, which here is 2/3 of stored kinetic energy divided by the magnetic field energy averaged over the volume, is 0.6%. We find a good agreement in simulation and experiment where the beam ion confinement time is about one-half to one-third of their slowing down time and the estimated beam ion beta value is 0.5 % [2,4]. In Fig. 3 we can also see a 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 4 shows the spatial beta profiles of both co- and counter-injected beams at the end of the simulation. The beta profile of the co-injected beam ions is broadened and extended beyond the plasma edge (r/a=1), while that of the counter-injected ones sharply peaks at the plasma center. Figure 5 shows the time evolution of the dominant two modes 2 and 5 and the density of the co-injected beam ions. We can see that the mode 2, which is located at the plasma center, has precursory growth before both 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 during the bursts.

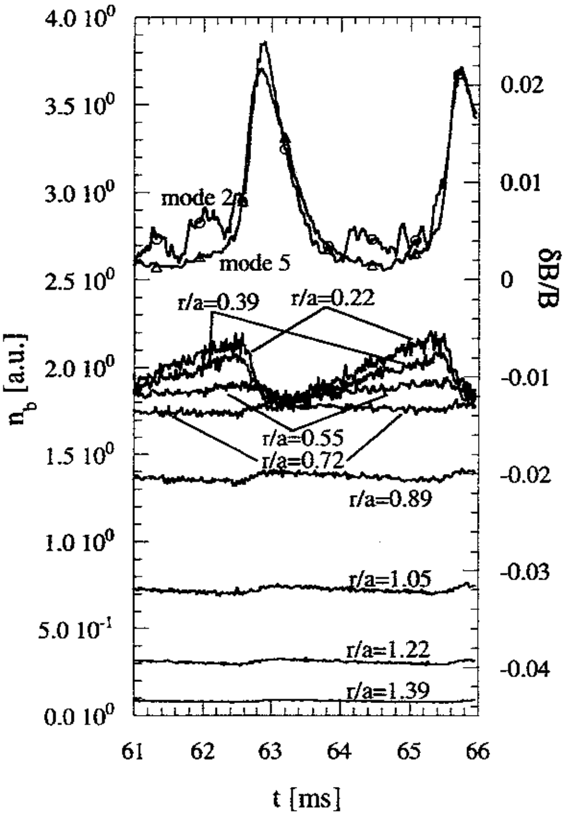

Fig.5 The time evolution of the dominant two modes 2 and 5 and the density of the co-injected beam ions at various minor radius.

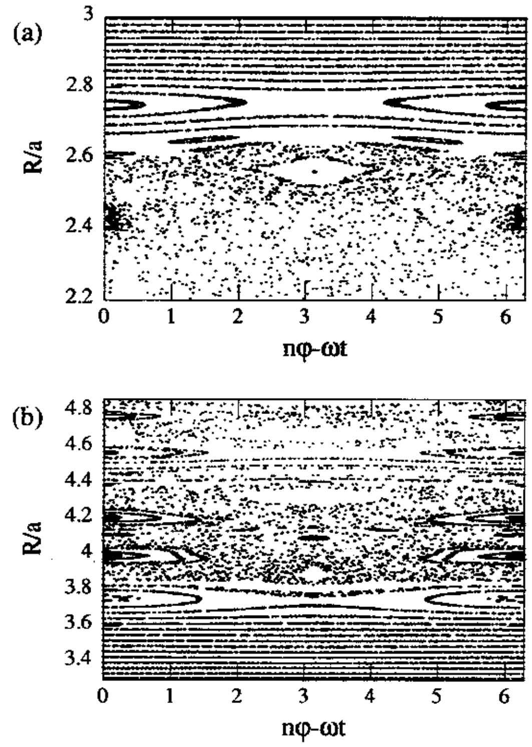

Fig.6 Surface of section plots for a) counter-injected and b) co-injected beam ions where the amplitude of mode 5 is fixed in time at $\delta B/B = 6\times10^{-3}$.

3.2 Particle Loss Mechanism

We now consider how the energetic particle loss mechanism is to be understood. To study this, we study surface of section plots where only one eigenmode is taken into account and the amplitude of the eigenmode is at a constant value. In the surface of section plot we print out the major radius of a counter-passing (co-passing) particle each time the poliodal angle of the particle reaches $\vartheta = 180^\circ$ (0°). We examine the field amplitude when the loss stops the increase in the stored beam energy. 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 $\delta B/B = 6\times10^{-3}$. 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 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 [9]. 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.

4. Discussion and Summary

In this paper we have made the first numerical demonstration with parameters that are quite similar to that of experiment and closely reproduce many experimental characteristics. These include: a) the synchronization of multiple TAEs takes place at time intervals fairly close to the experimental value, b) the modulation depth of the drop in the stored beam energy that closely matches the experimental value, c) the stored beam energy saturates at about one-half to one-third of the classical slowing down distribution. We have analyzed the particle loss mechanism and found 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. We have found that counter-injected beam ions are more easily lost than co-injected passing particles when the limiter is such as to preferably scrape-off particles whose equilibrium orbits are shifted to the inside of the toroidal boundary. The co-injected beam ion in plasma that lean on an inner limiter have difficulty being lost, because they can stick out on the outside of the plasma where they interact weakly with the internally generated Alfvén waves. This allows for the support of a relatively high energy density storage of co-injected particles, while there is a low level of counter injected particles supported.

Our simulation of the energetic particle interaction with a selected set of TAE modes predicts saturation levels of $\delta B/B \sim 2\times 10^{-2}$. On the other hand, the experimental plasma displacement has been estimated $\xi \sim 5-10$ mm from the density fluctuation [10]. This enables us to estimate the amplitude $\delta B/B \sim V/V_A \sim \omega\xi/\omega_A R \sim 0.6-1.3\times 10^{-3}$. What our simulation seems to lack is a mechanism to produce fast diffusion at perturbed field levels that are closer to what experiment would estimate. One possibility is that MHD mode coupling to shorter wavelengths would reduce the saturation level while still allowing the global diffusion of the rate observed in our simulation. Except for the saturation of the field level, our simulations appear to match the TFTR experiment [2,4]. Clearly further experimental studies with TAE experiments with strong particle loss are needed to check our assertion that the stored beam is primarily from co-injected particles (when there is a limiter leaning on the inner edge). In addition more sophisticated MHD calculations are needed to examine how lower level saturation can be achieved.

Acknowledgments

We wish to express our gratitude to Dr. E. D. Fredrickson for helpful suggestions for determining the experimental eigenmode amplitude and for the configuration of limiters. Numerical computations were performed at the Man-Machine Interactive System for Simulation (MISSION) of National Institute for Fusion Science.

References

[1] C. Z. Cheng and M. S. Chance, Phys.Fluids **29**, 3659 (1986).
[2] K. L. Wong *et al.*, Phys. Rev. Lett. **66**, 1874 (1991).
[3] W. W. Heidbrink *et al.*, Nucl. Fusion **31**, 1635 (1991).
[4] K. L. Wong *et al.*, Phys. Fluids B **4**, 2122 (1992).
[5] A. H. Boozer and G. Kuo-Petravic, Phys. Fluids **24**, 851 (1981).
[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, Hyoung-Bin Park, T. Sato, Nucl. Fusion **41**, 1153 (2001).
[9] J. Candy, H. L. Berk, B. N. Breizman, and F. Porcelli, Phys. Plasmas **6**, 1822 (1999).
[10] R. D. Durst *et al.*, Phys. Fluids B **4**, 3707 (1992).