Alpha-Channeling Simulation Experiment in the DIII-D Tokamak

K. L. Wong, R. Budny, and R. Nazikian
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA

C. C. Petty and C. M. Greenfield
General Atomics, P.O. Box 85608, San Diego, California 92186, USA

W.W. Heidbrink and E. Ruskov
Department of Physics, University of California, Irvine, California 92697, USA

(Received 18 September 2003; published 17 August 2004)

Alfvén instabilities can reduce the central magnetic shear via redistribution of energetic ions. They can sustain a steady state internal transport barrier as demonstrated in this DIII-D tokamak experiment. Improvement in burning plasma performance based on this mechanism is discussed.

DOI: 10.1103/PhysRevLett.93.085002 PACS numbers: 52.55.Pi, 52.35.Bj, 52.35.Py, 52.35.Qz

After ignition, a DT fusion reactor is sustained by α particle heating which transfers the α particle energy to the thermal electrons and ions via Coulomb collisions. Because of their high birth energy (3.5 MeV), most of the α particle energy goes to the electrons which is undesirable since the electrons do not fuse. The "α channeling" concept was proposed more than a decade ago to channel the α power to accomplish more useful functions, e.g., current drive or ion heating, instead of electron heating. A poloidally and toroidally propagating lower hybrid wave was first proposed to extract the α particle energy [1], and a two-wave scheme, ion Bernstein wave combined with toroidal Alfvén eigenmode (TAE) [2], was proposed later. The fusion power density can double if 75% of the α particle energy is channeled to the D/T ions [2]. Since the wave characteristics are quite demanding, they have not yet been realized in laboratory experiments. In this Letter, we show that the two-wave scheme [2] may not be necessary and that Alfvén modes alone selectively move some α particles to form a transport barrier, in addition to electron heating. Experimental data from DIII-D are presented here, for the first time, to demonstrate this mechanism where energetic beam ions are substituted for α particles.

Internal transport barriers (ITB) are usually produced in negative central magnetic shear (NCS) plasmas to avoid ballooning modes and ion channel transport can be reduced to the neoclassical level [3]. This is attributed to the stabilization of ion temperature gradient turbulence [4] by the gradient of the radial electric field (E_r) as well as the magnetic well effect. These experiments also work in plasmas with flat or slightly positive magnetic shear because of the magnetic well stabilization effect [5]. NCS plasmas in tokamaks are usually transient [3] in nature. A steady state ITB requires some off-axis current drive scheme to arrest the evolution of the q profile. Data from DIII-D show that redistribution of energetic ions from Alfvén instabilities can be such a scheme.

Energetic ions from neutral beam injection can excite Alfvén instabilities which eject the energetic ions from the plasma core to the periphery [6,7]. When the beam deposition profile is centrally peaked, the unstable Alfvén modes always propagate toroidally parallel to the plasma current [6]. This is because the geometry dictates the direction of k_ϕ as explained in Ref. [8]. Therefore, only comoving (toroidal velocity parallel to the plasma current) fast ions can resonate with the excited Alfvén modes and get ejected from the core to the outer region. The ejected fast ions drive a cocurrent that lowers the q value in the outer region of the plasma. These fast ions come from the core; losing them results in a reduced current in the core that would raise the q value there. Therefore, redistribution of these energetic ions due to the Alfvén modes provides a mechanism for the reduction or reversal of the magnetic shear in the plasma core which happens in the current diffusion time scale (~ 1 s in existing tokamaks). This process is schematically illustrated in Fig. 1.

Experimental evidence of this process was found in the DIII-D tokamak. When one cobeam source was injected into a 700 kA plasma at $B = 1.8$ T, $n_e < 10^{19}\,\mathrm{m}^{-3}$, the excited Alfvén eigenmodes (AE) at 60 kHz ($n = 1$) and 85 kHz ($n = 2$) appear in the Mirnov coil signal as depicted in Fig. 2. Both modes propagate parallel to the plasma current. The instabilities appear in bursts with the frequency sweeps down. The mode frequency of about 60 kHz is much higher than the central toroidal rotation frequency of about 20 kHz. The frequency in the plasma frame is significantly lower than the nominal TAE frequency of 200 kHz; the energetic particle mode (EPM) [9] is the most likely candidate. These "chirping modes" are rare in DIII-D, but they were reported previously [10]. Empirically in DIII-D, low plasma density and weak

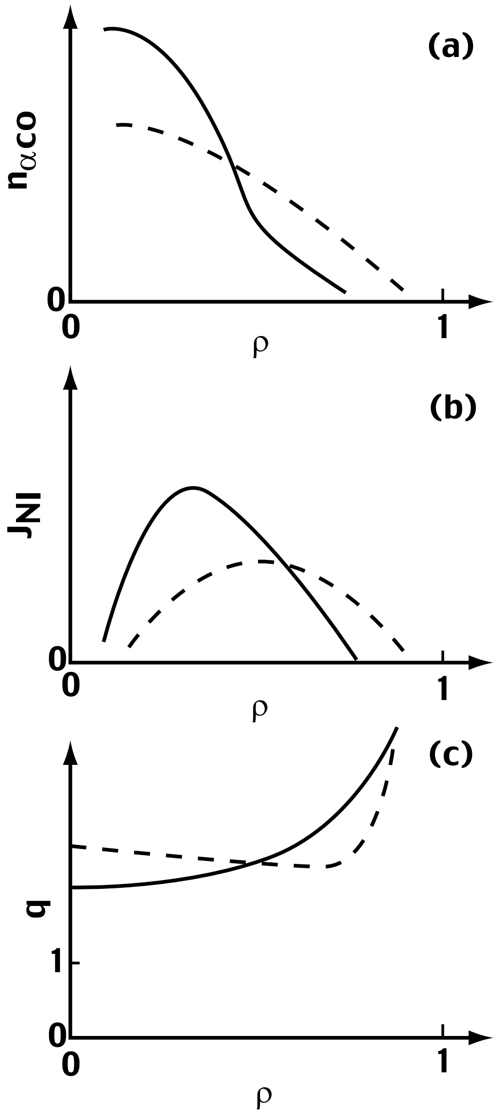

FIG. 1. Schematic diagrams to illustrate formation of NCS configuration due to the redistribution of comoving fast ions. The solid (dotted) line denotes the profile before (after) redistribution. (a) Density profile of comoving fast ions. (b) Noninductive current density profile. (c) q profile.

magnetic shear are conducive to beam-driven instabilities [11].

An ITB is formed in shot 92 755 at $\rho \sim 0.4$ with $T_i(0) > 10$ keV, $T_e(0) > 4$ keV. The q profile hardly changes during the beam pulse; q remains flat in the core with $q(0) > 1.8$ until the neutral beam is turned off at 2.8 s [Fig. 3(a)]. This is very different from those shots without AEs where $q(0)$ drops to 1 very quickly. The calculated beam deposition profile is centrally peaked. The "experimental" beam ion density profile in Fig. 3(b) is obtained from the difference between the thermal plasma pressure profile from plasma kinetic measurements and the total pressure profile from EFIT modeling [12] with motional Stark effect data. It is significantly broader than the results from TRANSP [13] modeling because the redistribution of beam ions by the AEs is not included in TRANSP. In the absence of AEs, the experimental and modeled beam ion density profiles are in good agreement.

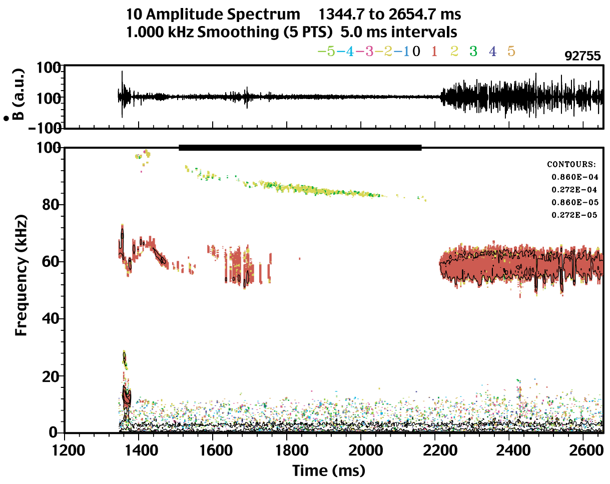

FIG. 2 (color online). Mirnov coil signal from the $n = 1$ (~ 60 kHz) and the $n = 2$ (~ 85 kHz) modes.

High performance plasma with a quasisteady state ITB was produced in DIII-D (shot 94 777) by two cobeam sources injected into a 600 kA plasma with $n_e \sim 1.5 \times 10^{19}$ m^{-3}, $B = 1.9$ T, $q(0) > 1.6$. Similar to the previous shot, the central magnetic shear stays flat until the beam is turned off. The ITB at $\rho \sim 0.4$ lasts until the end of the

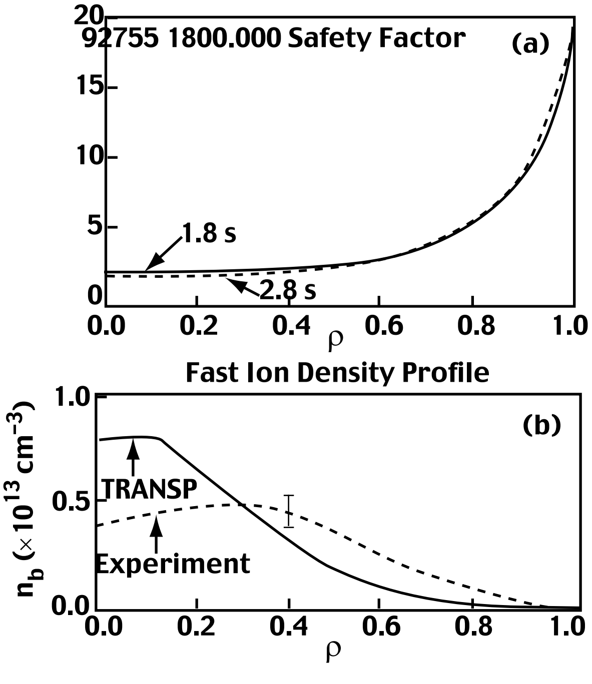

FIG. 3. (a) q profile for shot 92 755 at 1.8 and 2.8 s. (b) Calculated beam ion density profile compared to that obtained from the experimental data.

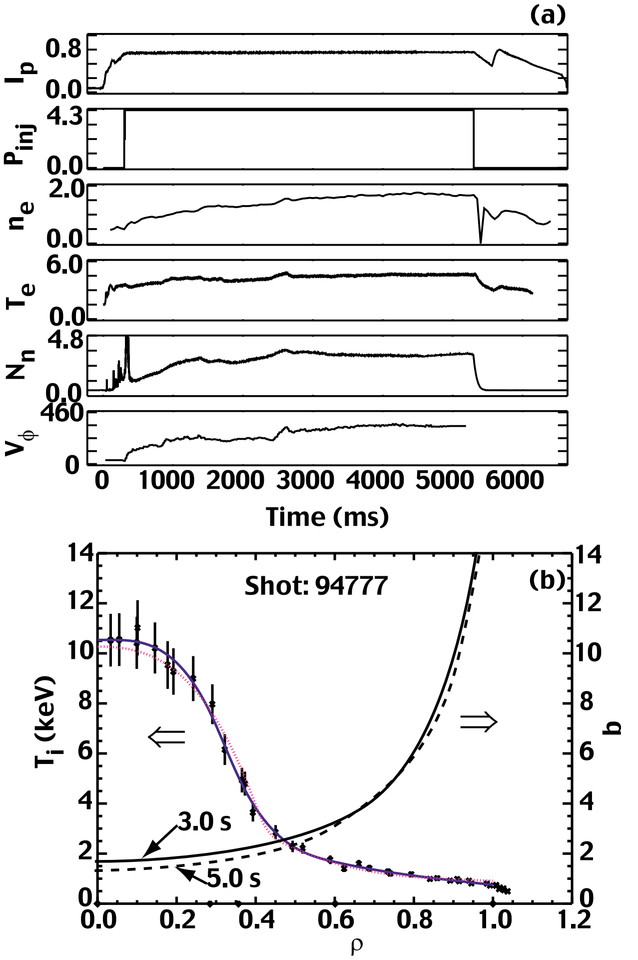

FIG. 4 (color online). Plasma characteristics for shot 94 777: (a) Plasma current I_p (MA), injected neutral beam power P_{inj} (MW), line-averaged electron density n_e (10^{19} m^{-3}), core electron temperature T_e (keV), total neutron emission rate N_n (10^{14} neutrons/s), and core toroidal rotation velocity v_ϕ (km/s). (b) Ion temperature profile and q profile at $t = 3.0$ and 5.0 s.

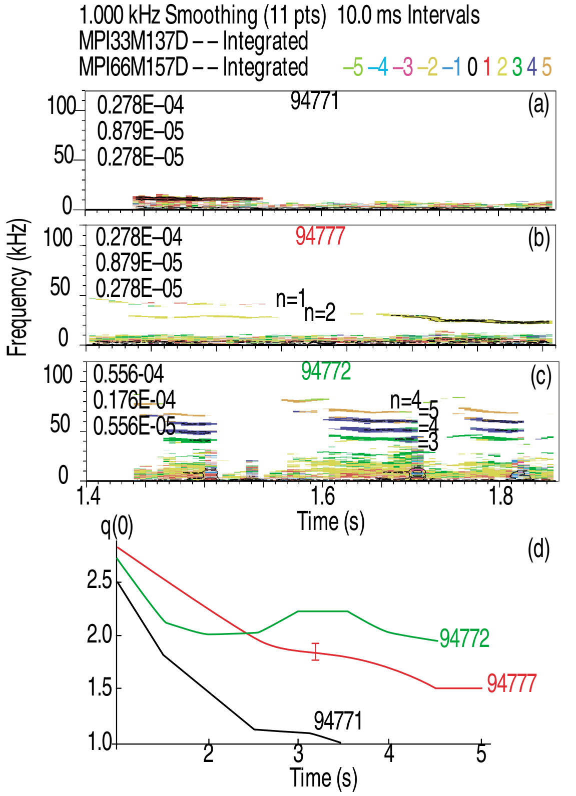

FIG. 5 (color online). Correlation between AE activities in three pulses (a)–(c), with (d) the evolution of $q(0)$ in these pulses.

5 s long beam pulse. Figure 4 shows that the electron and ion temperatures are almost independent of time from 3 to 5 s. However, this is not exactly a steady state plasma; $q(0)$ drops very slowly in time, and n_e rises monotonically inside the ITB which is typical for plasmas with beam fueling. A very large anomalous diffusion coefficient for the fast ions in the core yields the best TRANSP modeling fit for the low neutron rate. This is consistent with the ejection of fast ions from the core to the edge.

AEs eject some comoving energetic ions from the plasma core and reduce the current density there. Since $q(0) = (2B_\phi/\mu_0 R)/J(0)$, the best way to detect the proposed mechanism depicted in Fig. 1 is to correlate the value of q in the vicinity of the magnetic axis with the AE activities excited by the fast ions. Figure 5 compares three similar plasma pulses with different levels of AE activities in the Mirnov coil signal. AEs are marginally stable at $P_b = 3.1$ MW in shot #94 771, and $q(0)$ reaches 1.0 at $t = 3.4$ s. The beam power is 25% higher ($P_b = 4.3$ MW) in shot #94 777, AEs are unstable, and $q(0)$ stays above 1.6 until the end of the 5 s beam pulse. At the same beam power but slightly higher startup density, AE activities are even stronger in shot #94 772 and $q(0)$ stays above 2 throughout the 5 s beam pulse. The AE frequencies are near the resonant kinetic ballooning mode frequency [11]; these are probably EPM modes where the energetic particles play an important role. There are no data on the mode structure and the fast ion distribution function; both are needed for definitive mode identification. A detailed classification of these modes is not necessary here because the proposed mechanism does not depend on any specific mode. All AEs tend to flatten the energetic ion pressure gradient. The behavior of $q(0)$ depicted in Fig. 5 is a strong indication that the mechanism shown in Fig. 1 is at work. The toroidal mode numbers of the AEs in all these pulses are measured by a toroidal array of magnetic probes. All modes propagate parallel to the plasma current as expected.

Two pulses (#94 771 and #94 777) are analyzed with the TRANSP code for quantitative comparison. Because of the 25% difference in heating power and the ITB, it is inevitable that there are differences in plasma density. Profiles of $q(\rho)$, the fast ion pressure, and various com-

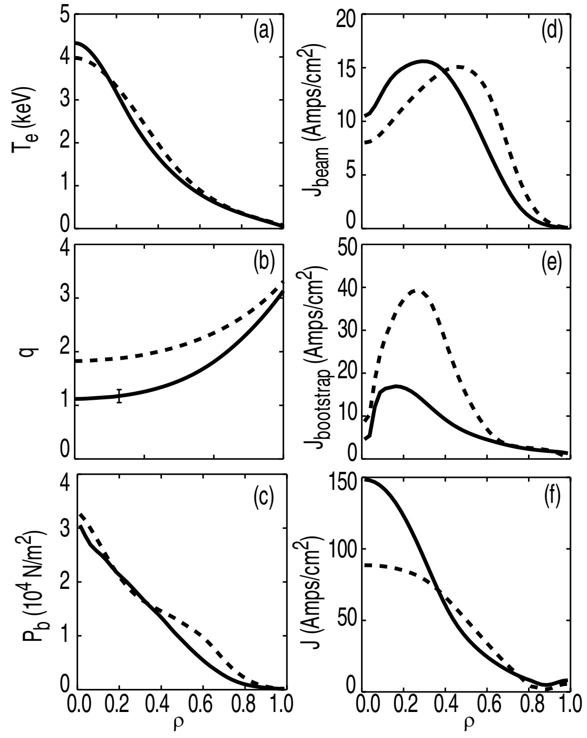

FIG. 6. Comparison of two pulses with (#94 777—solid line) and without (#94 771—dashed line) Alfvén modes: measured (a) electron temperature profile and (b) q profile. Modeling results from TRANSP: (c) beam ion pressure profile, (d) beam-driven current density profile, (e) bootstrap current density profile, and (f) total current density profile.

ponents of the plasma current density are also different as shown in Fig. 6. Just as in the Tokamak Fusion Test Reactor, fast ion ejection happens in short bursts [6], and the time-averaged energetic ion pressure gradient is held at the critical value corresponding to the instability threshold. Figure 6(c) shows that the additional beam power in pulse 94 777 is redistributed to the outer region of the plasma ($\rho = 0.4$–0.8) by the AEs. It gives rise to a higher beam-driven current in the same region in Fig. 6(d). Figure 6(e) shows that the bootstrap current is significantly higher in pulse #94 777 just inside $\rho = 0.4$ which is the ITB location. The bootstrap current is a significant part of the noninductive current, but it is the total current density profile that determines the q profile. The total core current density in pulse #94 777 (with AEs) is significantly lower [Fig. 6(f)] which corresponds to a significantly higher $q(0)$. The beam deposition profile from the charge exchange process peaks at $\rho = 0$ in this low density plasma, but the AEs provide an off-axis current drive mechanism that tends to balance the inward diffusion of inductive current and maintains $q(0)$ significantly above 1 until the end of the 5 s beam pulse. TRANSP modeling provides a quantitative, self-consistent result in agreement with the intuitive picture shown in Fig. 1.

These encouraging results prompted us to assess the possibility of forming a steady state ITB in a burning plasma based on this mechanism. Unlike DT experiments in the past [14], orbits of energetic α particles are small in a fusion reactor, with almost isotropic velocity distribution. Contrary to a common misconception, only the comoving energetic α particles are ejected by the AEs because only the copropagating Alfvén modes can be unstable. This reduces the central magnetic shear and raises the plasma flow shear and the gradient in E_r. Estimates with ITER parameters [15] indicate that it may be possible to improve plasma confinement based on this mechanism; i.e., it may be possible to design a fusion reactor with an ITB as a natural steady state of the burning plasma. Details of these calculations will be presented in a separate paper.

This work is supported by U.S. DoE under Contracts No. DE-AC02-76CH03073 and No. DE-AC03-99ER54463.

[1] N. J. Fisch and J. M. Rax, Phys. Rev. Lett. **69**, 612 (1992).
[2] N. J. Fisch and M. C. Herrmann, Nucl. Fusion **35**, 1753 (1995); Nucl. Fusion **34**, 1541 (1994).
[3] F. M. Leviton *et al.*, Phys. Rev. Lett. **75**, 4417 (1995).
[4] T. S. Hahm and K. H. Burrell, Phys. Plasmas **2**, 1648 (1995).
[5] J. M. Greene and M. S. Chance, Nucl. Fusion **21**, 453 (1981).
[6] K. L. Wong *et al.*, Phys. Rev. Lett. **66**, 1874 (1991); also Phys. Fluids B **4**, 2122 (1992).
[7] W.W. Heidbrink *et al.*, Nucl. Fusion **31**, 1635 (1991).
[8] K. L. Wong, Plasma Phys. Controlled Fusion **41**, R1 (1999).
[9] Liu Chen, Phys. Plasmas **1**, 1519 (1994).
[10] W.W. Heidbrink, Plasma Phys. Controlled Fusion **37**, 937 (1995).
[11] W.W. Heidbrink *et al.*, Phys. Plasmas **6**, 1147 (1999); also N. N. Gorelenkov and W.W. Heidbrink, Nucl. Fusion **42**, 150 (2002).
[12] L. L. Lao *et al.*, Nucl. Fusion **30**, 1035 (1990).
[13] R. J. Hawryluk, in *Physics of Plasmas Close to Thermonuclear Conditions*, edited by B. Coppi (ECE, Brussels, 1980), Vol. 1, p. 19.
[14] K. L. Wong *et al.*, Phys. Rev. Lett. **76**, 2286 (1996); also R. Nazikian *et al.*, Phys. Rev. Lett. **78**, 2976 (1997).
[15] D. J. Campbell, Phys. Plasmas **8** 2041 (2001).