Correlation between Electron Transport and Shear Alfvén Activity in the National Spherical Torus Experiment

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(Received 17 November 2008; published 18 March 2009)

We report the observation of a correlation between shear Alfvén eigenmode activity and electron transport in plasma regimes where the electron temperature gradient is flat, and thus the drive for temperature gradient microinstabilities is absent. Plasmas having rapid central electron transport show intense, broadband global Alfvén eigenmode (GAE) activity in the 0.5–1.1 MHz range, while plasmas with low transport are essentially GAE-free. The first theoretical assessment of a GAE-electron transport connection indicates that overlapping modes can resonantly couple to the bulk thermal electrons and induce their stochastic diffusion.

DOI: 10.1103/PhysRevLett.102.115002 PACS numbers: 52.55.Fa, 52.25.Fi, 52.35.Qz, 52.35.Ra

In order to generate a net energy the fusion plasma has to be maintained at a ''burning'' temperature by the alpha particle heating. This requires first good energy confinement. Magnetic fusion research has demonstrated high confinement levels, thus paving the way toward future devices such as ITER.

This good confinement was however obtained in devices without the large population of alphas that will occur in burning plasma. An implicit assumption is that the energetic ions will not interact with the burning plasma in ways that can substantially degrade the energy confinement. With the advent of the ITER project, the investigation of this assumption has become a priority, especially as concerns the effects of the magnetohydrodynamic (MHD) activity driven by the energetic ions, on their own redistribution or loss. For instance, shear Alfvén eigenmodes (AEs) have been shown to be able to affect the fast ion loss and density profile in tokamaks [1,2].

There could also be effects of the fast ion driven AE activity on the working particle transport [2]. The National Spherical Torus Experiment (NSTX) [3] provides a good environment to explore such effects. NSTX is a low toroidal field ($B_t \leq 0.5$ T), high plasma current ($I_p \leq 1.3$ MA) spherical torus, having working particle temperature around 1 keV and density of several 10^{19} m^{-3}. In these conditions, the injection of up to 7 MW of $E \leq 100$ keV neutral D beams produces a large fraction of ions with velocity in excess of the Alfvén speed, which in turn can destabilize a broad spectrum of AE activity [4,5]. NSTX, therefore, offers an ideal test bed for the study of a possible connection between AE activity and working particle transport.

This Letter reports the first experimental observation of such a correlation, between the beam driven global Alfvén eigenmode activity (GAE) [4,5] and enhanced electron thermal transport. The initial observation which motivated this investigation is an unusual effect in some beam heated high confinement (H mode) discharges, exhibited by the flattening of the electron temperature profile T_e, as the beam power P_b is increased. This effect is illustrated in Fig. 1(a) with a plot of the T_e profiles in H modes heated by 2, 4, and 6 MW of 90 kV beams and having $I_p = 1$ MA and $B_t = 0.45$ T. The electron density n_e is flat for all cases, with a central value of $\sim(5–6) \times 10^{19}$ m^{-3}. The ion temperature profiles T_i roughly follow the T_e profiles, with T_i/T_e in the range ~0.95–1.1. The safety factor $q(r)$ is at all times above unity, thus avoiding the central sawtooth instability. The peripheral MHD activity at the time of interest consists of benign type-V edge localized modes [6]. The T_e flattening effect persists throughout the discharge, as well as at higher toroidal fields and plasma currents.

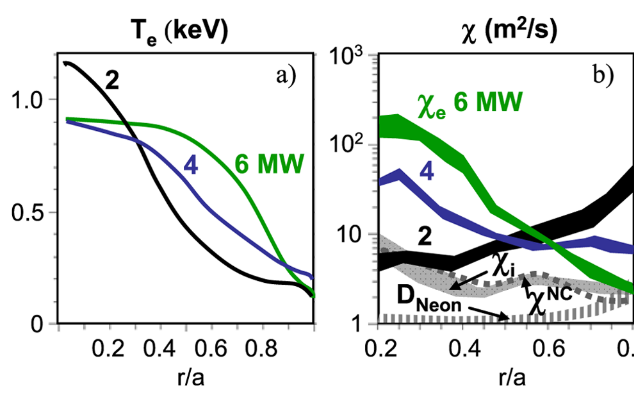

FIG. 1 (color online). (a) T_e profiles in 2, 4, and 6 MW NSTX H modes at $t \sim 0.4$ s. The measurement uncertainty is around 25 eV. (b) TRANSP computed χ_e in the same plasmas. Also shown are the χ_i and NCLASS ion thermal diffusivity for the 6 MW case and the measured neon diffusivity. The bands of values represent the 20 ms variability.

The power balance analysis with the TRANSP code [7] indicates that the T_e flattening is associated with a high central ($r/a \leq 0.4$–0.5) electron heat diffusivity χ_e, in the range of several tens of m^2/s [Fig. 1(b)]. Since χ_e is computed by dividing the electron heat flux to the T_e gradient, its uncertainty is larger in the region of flattened T_e. Nevertheless, a strong relative change in central electron transport with beam power is clearly evident, even considering all uncertainties. For instance, to reduce the electron heat flux at $r/a = 0.3$ in the 6 MW case down to the level of the 2 MW case, while holding everything else fixed, would require reducing the beam heating of the electrons by about 50%. This is well beyond the confidence level in the classical beam slowing down calculation, as further discussed.

Additionally, the central ion heat diffusivity χ_i in these plasmas is near the neoclassical (collisional) level, as illustrated also in Fig. 1(b) for the 6 MW case. The neoclassical value χ^{NC} is computed using the NCLASS code [8]. Although the uncertainty in both quantities is around a factor of 2 [see Ref. [9] for a discussion], more than an order of magnitude difference between the central χ_e and χ_i is evident at high P_b. The measured impurity diffusivity in these plasmas also demonstrates nearly 2 orders of magnitude difference between the central electron thermal and ion particle transport [Fig. 1(b) and Ref. [10]). Lastly, we observe that the χ_e profile in the high P_b NSTX H mode differs significantly from that in a conventional tokamak, where χ_e is typically of the order of a few m^2/s in the center and increases with plasma radius [11].

The first question to ask is whether the T_e flattening is a genuine electron transport effect. That it is a transport and not a heating source effect is supported by a number of observations. First, the magnetic and soft x-ray measurements rule out low frequency MHD activity, such as tearing modes, as a contributing factor. One could invoke nevertheless more subtle mechanisms that could result in a reduction in the central electron heating, such as a flattening of the fast beam ion density (the main electron heating source in NSTX) by high frequency MHD activity [1,2], or a nonclassical mechanism of beam slowing down on the thermal ions [12]. However, as detailed in Ref. [13], a significant flattening of the fast beam ion profile is not consistent with the good agreement between the measured and computed neutron rates in these discharges. In addition, calculations have indicated low sensitivity of the electron power balance to changes in the fast ion density profile in this region of the plasma. Furthermore, measurements of the fast ion density in these plasmas with a fast-ion D-alpha diagnostic [14] indicate strongly peaked profiles, while neutral particle analyzer measurements indicate that the fast ion spectral distribution is not affected by anomalous losses [15]. Lastly, the possibility of dominant nonclassical beam slowing down on thermal ions can also be ruled out in the high n_e, $T_i \sim T_e$ discharges here under discussion. Indeed, due to strong ion-electron collisional coupling at high n_e, a substantial anomaly in the ion heating would result in a very small or negative χ_i [12]. In the present discharges, however, χ_i stays within the neoclassical range of $\geq$ few m^2/s, even when n_e reaches $\sim 10^{20}$ m^{-3}.

An independent support of the increase in central electron transport with increasing P_b comes from perturbative electron transport experiments, which show more rapid propagation of T_e perturbations in high power H modes than in low power ones. The perturbed χ_e in the center of high P_b H modes is in the range of tens of m^2/s, i.e., comparable to that from the power balance [13,16].

We must infer therefore that the T_e flattening is caused by an increase in central electron transport with beam power. The ensuing questions are thus, what is the nature of this transport, electrostatic or magnetic, and what drives it in the absence of a significant T_e gradient? In fact, as shown in Fig. 2(a), *all* working particle gradients inside $r/a < 0.5$ are small in these plasmas.

With regard to the first question, the fact that the ion thermal and particle transport is in the neoclassical range suggests the absence of anomalous transport associated with ion-scale electrostatic fluctuations in these plasmas (see also discussion in Ref. [17]). In addition, the first measurements with the NSTX high-k microwave scattering diagnostic [18] indicate also a very low level of electron-scale density fluctuations in the central plasma of the high P_b H modes.

This picture of a microstable central plasma is also supported by stability analysis using the linear GS2 code [19], which indicates that the central gradients in Fig. 2(a) are too weak to drive any known microinstability. This is illustrated in Fig. 2(b) by a plot of the instability growth rates γ, as a function of $k_\theta \rho_s$ (k_θ poloidal wave number, ρ_s ion gyroradius at sound speed), at $r/a = 0.2$ and $r/a = 0.4$ in a 4 MW NSTX H mode [10]. The calculation shows that all the growth rates in the inner plasma half are almost 2 orders of magnitude lower than the $\mathbf{E} \times \mathbf{B}$ shearing rate

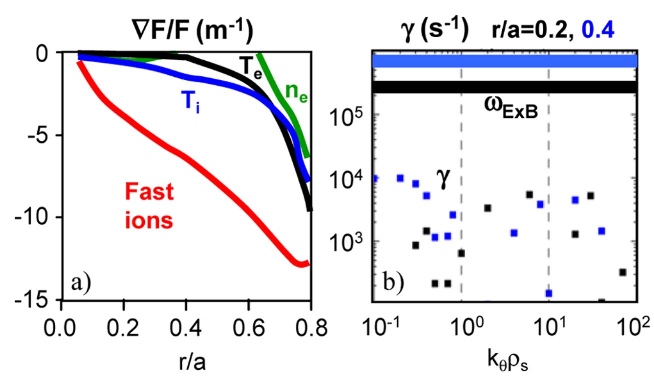

FIG. 2 (color online). (a) Thermal and density gradients in the 6 MW NSTX H mode. Also shown is the gradient in the fast ion density computed by TRANSP. (b) Linear microstability assessment of 4 MW 1 MA, 0.45 T NSTX H mode, at $r/a = 0.2$ and 0.4 ($t = 0.5$ s). The most unstable growth rates are shown as a function of $k_\theta \rho_s$. Also shown as bands is the range of $\mathbf{E} \times \mathbf{B}$ shearing rates computed by TRANSP [10].

$\omega_{E\times B}$, which is known to suppress turbulent fluctuations when $\omega_{E\times B}$ is of the order of γ [20].

As temperature gradient driven microinstabilities appear to be suppressed, this suggests that a form of magnetic transport must be operative in the flat T_e region of the NSTX H mode. This inference is also supported by the nearly 2 orders of magnitude gap between the electron thermal and impurity particle diffusivity in this region. Indeed, as discussed in Ref. [21], if electrons are transported along stochastic magnetic field lines, one can expect a ratio between χ_e and the impurity diffusivity of the order of $(M_{\mathrm{imp}}/m_e)^{1/2} \sim 10^2$, i.e., consistent with the data in Fig. 1(b). The presence of stochastic electron transport would also explain why some of the 6 MW NSTX T_e and χ_e profiles resemble those of a reversed field pinch, where tearing activity is driving stochastic electron transport in the central plasma [22].

The main question is what drives this type of transport in NSTX in the absence of both thermal gradients and of tearing modes. As shown in Fig. 2(a), the only constituents having a substantial gradient inside $r/a \leq 0.5$ are the nonthermal beam ions. They also have strong gradients in the velocity space. As such, we hypothesize that it is the fast ion gradient that drives electron transport through the high frequency AE activity they induce. Indeed, while in the 6 MW H modes the lower frequency MHD activity, including toroidal Alfvén eigenmodes, is faint or absent, there is intense, broadband AE activity in the 0.5–1.1 MHz range. Signal peaks crossing in time is a definite signature of GAEs [4,5], the feature clearly seen in Fig. 3. As shown in Ref. [4], the most unstable GAE modes in NSTX have frequency between 0.2–0.5ω_{ci}, with ω_{ci} the ion cyclotron frequency of ~3 MHz. These modes are mainly driven by the anisotropy in the beam ion velocity space, have toroidal numbers $n \sim 2$–7, are localized near the plasma axis, and have a large shear (B_{radial}) component. Additionally, since the GAE mode frequencies overlap with important characteristic electron frequencies in NSTX, such as the trapped electron bounce frequency ω_{be}, these modes can potentially affect electron transport.

To verify this hypothesis, experiments were designed in which the beam power was varied while the q, n_e and rotation profiles were held fixed. Keeping a constant q profile is critical in NSTX, due to the strong dependence of the electron transport on magnetic shear [23]. The experimental technique is detailed in Ref. [13]. In essence, the current profile is "frozen in" by preheating the plasma at fixed power for 0.4 s followed by stepping the beam power up or down by 2 MW. Thermal transport is then assessed after a few beam slowing down times, when the fast ion population has nearly reached equilibrium, but the q, $\omega_{E\times B}$ and n_e profiles did not yet have time to significantly change. The results are illustrated in Fig. 3, and indicate a correlation between the level of central electron transport and the level of beam driven GAE activity, apparent as broadband magnetic fluctuations in the 0.5–1.1 MHz frequency range. Plasmas having flattened T_e profile and rapid central transport have intense, broadband GAE activity, while plasmas with low transport are essentially GAE-free.

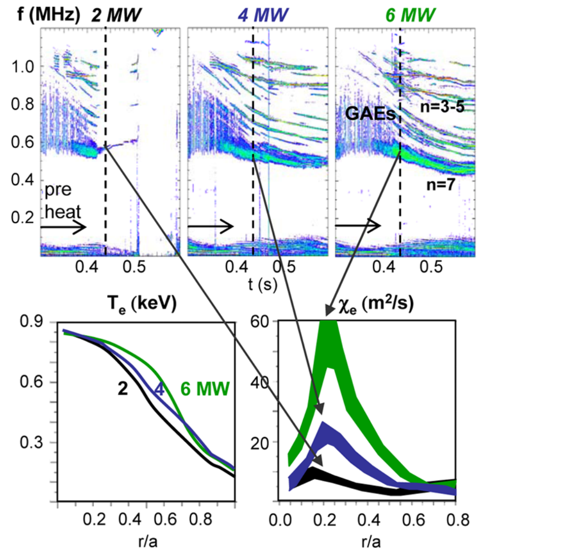

FIG. 3 (color online). Correlation between GAE activity, T_e flattening, and central χ_e increase in NSTX H modes heated by 2, 4, and 6 MW neutral beam, at $t \sim 0.44$ s. Within the uncertainties, the q, n_e, and $\omega_{E\times B}$ profiles are the same in all discharges at the time of the transport correlation [13].

The above correlation was also confirmed in experiments in which the beam energy was scanned between ~60 and 90 keV, in order to more finely vary the level of GAE activity. In addition, other observations support such a correlation: the level of GAE activity and that of T_e peaking are related also in L modes, the application of rf power to beam heated plasmas appears to increase central T_e only when the GAE activity is low, and the central T_e is seen to spontaneously peak when the GAE activity occasionally ceases. An example is illustrated in Fig. 4, which shows the correlation between the level of GAE activity and the evolution of the central T_e in 2 MW beam driven NSTX H modes, to which 1.5 MW of rf power is transiently applied. The degree of peaking in the central T_e profile is also shown as the ratio between T_e on axis and at midradius. The n_e and T_i profiles evolve similarly in the two discharges. The mechanism for different levels of GAE activity is not yet clear, but seems related to small MHD perturbations of the early q profile. As seen, in discharges with strong GAEs the central T_e responds weakly to the rf pulse and the profile stays nearly flat, whereas in discharges with faint GAEs the central T_e has a stronger increase with the rf application and the profile becomes peaked.

The amplitude of the density fluctuations associated with the band of 0.5–1.1 MHz GAE activity was measured in a 6 MW H mode using the NSTX high-k microwave scattering system [18] in interferometric mode. The spectrum of high frequency density and magnetic fluctuations

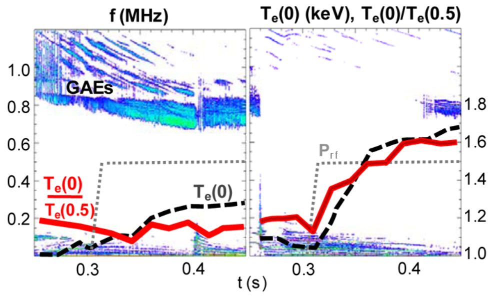

FIG. 4 (color online). Correlation between level of GAE activity and the evolution of the central T_e in rf heated NSTX H modes sustained by continuous 2 MW beam injection. The level of peaking in the central profile is characterized by the ratio $T_e(r/a = 0)/T_e(r/a = 0.5)$.

in a 6 MW H mode obtained with a line of sight of the diagnostic tangent at $r/a \sim 0.25$ is shown in Fig. 5. Assuming an integration path through the mode corresponding to the predicted toroidal extent [4], the line averaged fluctuation amplitude of the perturbed electron density for the strongest GAE band (identified as $n = 2$–3) is $\langle \tilde{n} \rangle / \langle n \rangle \sim 1.5 \times 10^{-4}$, where the brackets indicate line averaged values. Given the GAE mode localization, the peak density perturbation amplitude is expected to be significantly higher. In addition, the broadband, overlapping character of the GAE modes in a high beam power discharge is also evident in the high time resolution magnetic data.

An initial theoretical assessment of the proposed GAE-electron transport connection was performed using the ORBIT code [24]. The results support the experimental observations, indicating that the GAEs may resonantly couple to the bulk (~1 keV energy), primarily trapped electron population. This can be seen by evaluating characteristic electron drift motion frequencies, which are 0.6 MHz for trapped electron bounce frequency and 1.5–2 MHz for passing electron transit frequency. Hence, the bulk plasma primarily trapped electrons can be in resonances with the broadband GAE activity. At sufficiently large amplitudes, the overlap of such phase space resonant structures due to multiple GAE instabilities may induce stochastic diffusion of these electrons. Preliminary simulations indicate that thermal electron heat conductivity scaling versus GAE amplitude is consistent with such transport mechanism, which is further enhanced by collisions. In addition, our calculations suggest that the GAE amplitude experimentally estimated from microwave interferometry may lead to electron heat diffusivity levels >10 m^2/s, which is comparable to those inferred from the power balance analysis.

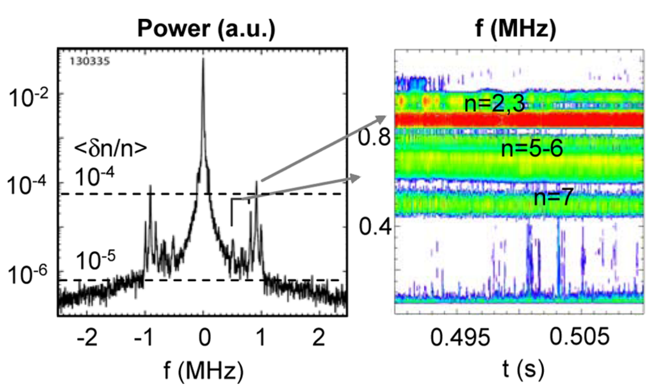

FIG. 5 (color online). Power spectrum of line integrated density fluctuations due to GAE activity in 6 MW, 1 MA, 0.45 T NSTX H mode, measured with the high-k microwave scattering diagnostic in interferometric mode at $t \sim 0.5$ s [18]. Also shown on the right is the magnetic fluctuations spectrum using a 0.05 ms time window for analysis.

The above mechanism could potentially have significant implications for fusion. First, it could be a source for electron transport in all devices in regions where the temperature profiles are too flat to drive conventional micro-instabilities [25]. Second, it might prove relevant for burning plasma conditions, where the GAEs driven by the energetic alpha population are expected.

This work was supported by U.S. Department of Energy Grant No. DE-FG02-99ER5452 at JHU.

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