Microtearing Instabilities and Electron Transport in the NSTX Spherical Tokamak

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We report a successful quantitative account of the experimentally determined electron thermal conductivity χ_e in a beam-heated H mode plasma by the magnetic fluctuations from microtearing instabilities. The calculated χ_e based on existing nonlinear theory agrees with the result from transport analysis of the experimental data. Without using any adjustable parameter, the good agreement spans the entire region where there is a steep electron temperature gradient to drive the instability.

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The source of electron transport in magnetized plasmas is still an unsolved problem in magnetic fusion research. The observed electron energy transport is much larger than one would expect from diffusive process due to Coulomb collisions, which can be a major obstacle in the way toward practical nuclear fusion power. Because of the success of ion temperature gradient mode (ITG) turbulence in explaining anomalous ion transport, it is natural to think that electron temperature gradient mode (ETG) turbulence may be responsible for electron transport [1]. While active theoretical and experimental research is being carried out along this path, and the correlation between short wavelength fluctuations and local electron heat diffusivity has been observed in the Tokamak Fusion Test Reactor (TFTR) tokamak [2], a mechanism based on broken magnetic surfaces proposed three decades ago [3] is a viable explanation in some situations. Imperfect magnetic surfaces can be produced by error fields due to poor magnetic coil alignment or from electromagnetic instabilities. One well-known instability is the microtearing mode driven by electron temperature gradient [4]. A nonlinear theory for the saturation level of the instability was developed [5], but it was found later that these modes should be stable in conventional tokamaks [6] except near the plasma edge where electron temperature is low [7,8]. Plasma parameters in current spherical tokamak (ST) experiments are quite different from conventional tokamaks, and microtearing modes can be the most unstable mode in National Spherical Torus Experiment (NSTX) [9] and Mega-Ampere Spherical Tokamak (MAST) [10] over a certain range of parameters. Since the magnetic field in a spherical tokamak is substantially lower than that in a conventional tokamak, the microtearing instability is predicted to saturate at a significantly higher amplitude [5], making it the dominant mechanism that governs electron transport in some spherical tokamak plasmas; this is consistent with the high electron thermal conductivity χ_e in the plasma core and its strong magnetic field dependence observed recently [11]. This result prompted us to examine carefully the role of this mechanism in NSTX. In a well-behaved H mode plasma, it is found that microtearing modes can produce global stochastic magnetic fields, resulting in a χ_e that is in good agreement with the values from transport analysis of the experimental data over the entire region where the electron temperature gradient is strong enough to make the microtearing mode the most unstable mode in the wavelength range of $k_\theta \rho_s \sim 1$. There is no adjustable parameter in this comparison. To the best of our knowledge, this is the first successful quantitative account of electron thermal conductivity in a tokamak experiment using this mechanism.

NSTX is a spherical tokamak operating with major radius $R = 0.85$ m and minor radius $a = 0.67$ m ($R/a = 1.27$). An H mode discharge with 6 MW deuterium neutral beam heating at $I_p = 0.75$ MA, $B_t = 0.5$ T was chosen for detailed analysis. At $t = 0.9$ s, Motional Stark Effect measurements of the magnetic field pitch indicate that the plasma has monotonically increasing q with $q(0) > 1$ so that there are no sawteeth or other significant MHD activities in the plasma core observable by the soft x-ray array or Mirnov coils. The smoothed electron temperature, density, and q profiles for this case are shown in Fig. 1 where the radial location is represented by the square root of the normalized flux, $(\phi/\phi_a)^{1/2} \cong r/a$. There is a steep temperature gradient at $(\phi/\phi_a)^{1/2} \geq 0.4$ where electron confinement is good. The GS2 gyrokinetic stability code [12] is used to calculate the linear growth rate and the eigenmode structure for the most unstable mode in a preset range of wave numbers. The input parameters, including the equilibrium, are imported directly from the TRANSP [13] output file. The linear growth rates were calculated for wave numbers in the range $k\rho_s = 0.1$ to 1. Two kinds of unstable modes were found: the ITG mode and the microtearing mode. They have distinctly different mode structures: the perturbed electric (magnetic) field has even (odd) parity for ITG, and the parities for the perturbed fields are opposite for microtearing modes, which also have an extended mode structure along the magnetic field. ITG modes propagate in the ion diamagnetic drift direction; the microtearing modes propagate in the electron diamagnetic drift direction, and this is reflected in the negative sign of the real frequency. Microtearing modes are found to be the most unstable mode in the region $(\phi/\phi_a)^{1/2} = 0.4$ to 0.75 of this plasma. Figure 2 depicts the linear growth rate of these

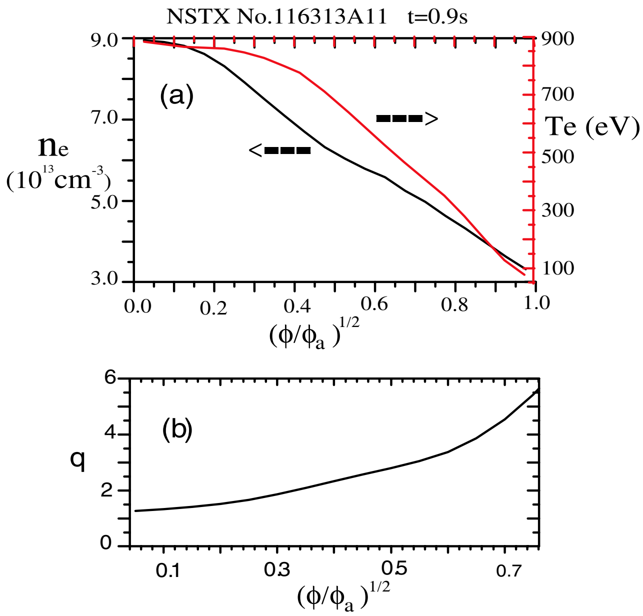

FIG. 1 (color online). Profiles of electron temperature, electron density, and safety factor for shot 116313.

unstable modes for various wave numbers at $(\phi/\phi_a)^{1/2} =$ 0.4, 0.5 , 0.65, and 0.75.

While nonlinear gyrokinetic simulation of electromagnetic fluctuations is still in the development stage at the moment, we rely on Drake's theory [5] for the nonlinear saturation level of the instability; i.e., the unstable modes should saturate at the amplitude $\delta B/B \approx \rho_e/L_T$, the ratio of electron gyroradius to the electron temperature scale length. This theory assumes negligible magnetic shear and other simplifications argued to be applicable to conventional tokamaks. The theory has not been checked for spherical tokamak nor with nonlinear numerical simulation. Since microtearing modes have $k_\parallel = 0$ and δB has even parity, they are very effective in producing magnetic

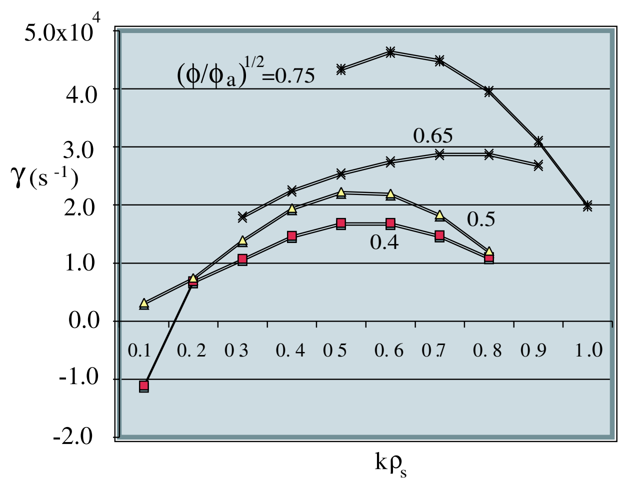

FIG. 2 (color online). Linear growth rate of unstable microtearing modes at various radial locations.

islands [14] near rational magnetic surfaces where $q = m/n$. When the islands are small, stochastic field lines are localized in the vicinity of the separatrix. Island chains of different helicity are separated by good magnetic surfaces (KAM surfaces), which serve as electron transport barriers. Substantial heat transport should ensue when either adjacent island chains or resistive layers overlap [15]. The latter requires [15] the poloidal mode number $m > m_o = q(2q'\rho_s)^{-1/2}$ where $\rho_s = (2T_e/m_i)^{1/2}/\omega_{ci}$ and q' denotes the derivative of q with respect to the minor radius r. The values of m_o and $k_o = m_o/r$ at various radial locations are listed in Table I. Most of the unstable modes shown in Fig. 2 have $k > k_o$; i.e., the resistive layer overlap criterion is well satisfied. One can also estimate the saturated island width based on the mode amplitude $\delta B/B \approx \rho_e/L_T$ and find that adjacent island chains also overlap. Therefore, the region $0.4 \leq (\phi/\phi_a)^{1/2} \leq 0.75$ should be occupied by stochastic magnetic field lines.

A rigorous plasma transport theory in a stochastic magnetic field is extremely complicated [16]. However, the electron thermal conductivity χ_e in a stochastic magnetic field can be derived based on a simple test particle transport model [3]; χ_e is proportional to the magnetic field diffusivity $D_M = R|\delta B/B|^2$. Following Kadomtsev [17], the connection length qR is chosen to be the magnetic field correlation length L_c. Then, the thermal electrons with thermal velocity v_e in this NSTX discharge are in the collisional regime; i.e., the electron mean free path λ_{mfp} is shorter than L_c and χ_e due to saturated microtearing modes becomes

$$\chi_e = (\rho_e/L_T)^2 R v_e(\lambda_{\mathrm{mfp}}/L_c) = (\rho_e/L_T)^2 v_e^2/(\nu_{ei}q), \quad (1)$$

where ν_{ei} is the electron-ion Coulomb collision rate. All the values of the plasma parameters on the right hand side of Eq. (1) can be obtained from the plasma equilibrium. These theoretical values are compared to the χ_e obtained from transport analysis with the TRANSP code [13]. The theoretical values are roughly a factor of 2 lower as depicted in Fig. 3. Drake's nonlinear theory [5] was derived with the assumption that the plasma electron density is uniform, and the instability is entirely driven by the electron temperature gradient. In the experiment, we have $2 > L_n/L_T > 1$. If we assume that the density gradient drives the instability the same way as the temperature gradient and replace L_T in Eq. (1) with L, where

$$L^{-1} = L_T^{-1} + L_n^{-1}, \quad (2)$$

TABLE I. Threshold mode number m_o for resistive layer overlap.

$(\phi/\phi_a)^{1/2} \cong r/a$	ρ_s (cm)	m_o	$k_o = m_o/r$ (cm^{-1})
0.4	1.1	6.3	0.24
0.5	1.1	7.2	0.22
0.6	1.0	6.3	0.16
0.7	0.8	6.5	0.14

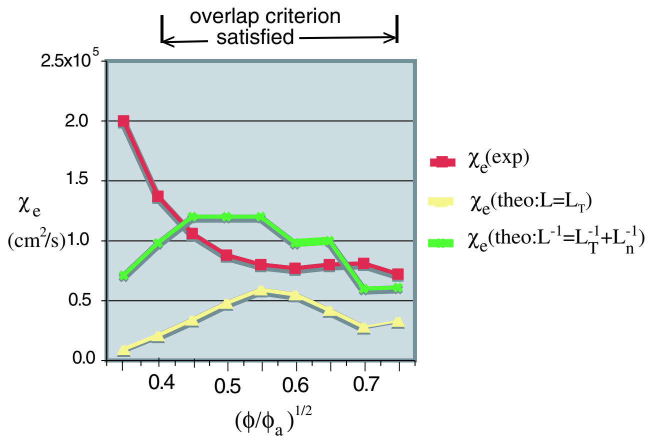

FIG. 3 (color online). Comparison between values of electron thermal conductivity from TRANSP analysis of experimental data and those calculated from Eq. (1).

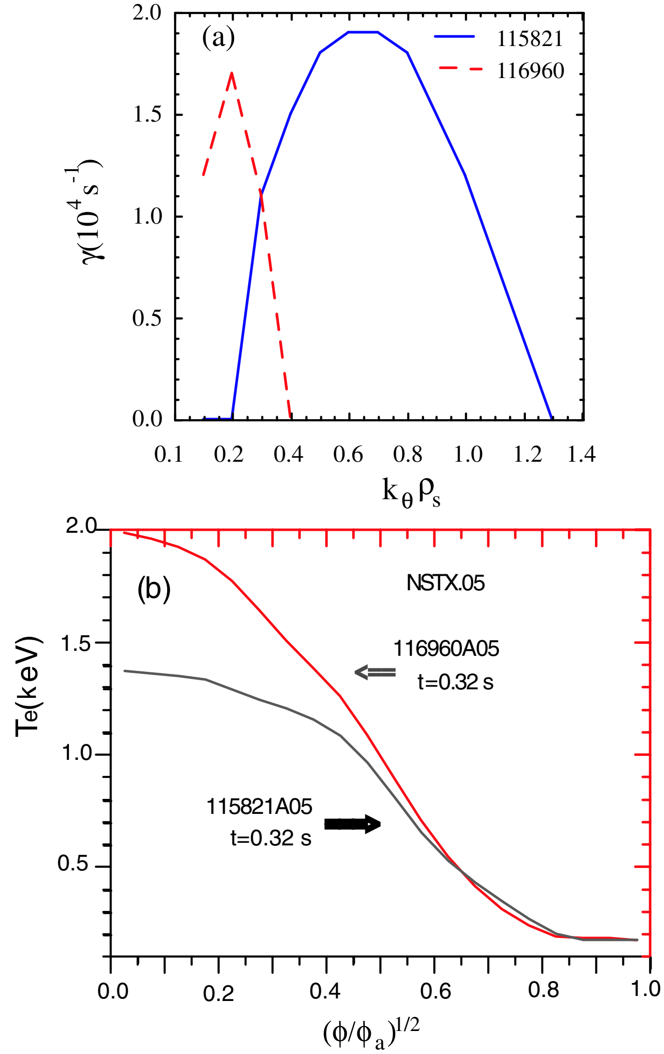

FIG. 4 (color online). (a) GS2 calculation shows that microtearing modes with high k_θ are unstable at $(\phi/\phi_a)^{1/2} = 0.3$ in shot 115821 but are stable in shot 116960 where the magnetic shear is reversed. (b) The central electron temperature is substantially higher in shot 116960 when microtearing modes with high k_θ are stable.

the theoretical χ_e would be closer to the experimental value as indicated by the green curve in Fig. 3. However, microtearing modes are mainly driven by electron temperature gradient, and the theoretical value should be represented by the yellow curve. A factor two agreement with experiment is satisfactory considering the uncertainty of the nonlinear theory and the transport analysis of the experimental data. $T_e(r)$ is very flat near the magnetic axis $[(\phi/\phi_a)^{1/2} \leq 0.3]$ where microtearing modes are stable; χ_e there is very large due to other mechanisms not yet identified.

Should microtearing modes be the dominant electron transport mechanism, χ_e will be significantly reduced when these modes are stable, which is the case in a plasma with reversed central magnetic shear [18]. Figure 4(a) shows the growth rate at $(\phi/\phi_a)^{1/2} = 0.3$ for such a shot (no. 116960) and its comparison shot (no. 115821). Microtearing modes are unstable in no. 115821 over a wide range of $k_\theta \rho_s$, but are unstable over a much narrower range in no. 116960 where the magnetic shear is reversed. The unstable modes in no. 116960 have low mode number and do not satisfy the overlap criterion [15]. Both shots have the same plasma current, density, magnetic field, plasma shape, position, and neutral beam heating power. As depicted on Fig. 4(b), the central electron temperature is substantially higher (2 keV vs 1.4 keV) in no. 116960 where high-k_θ microtearing modes are stable. This is a strong indication that microtearing modes may be the dominant mechanism responsible for the electron transport at this location in this type of plasma. At present, however, there is no diagnostic on NSTX capable of measuring the internal magnetic field fluctuations to confirm the existence of microtearing modes.

In summary, we have shown that the observed electron thermal conductivity in one type of NSTX discharge can be explained by the magnetic fluctuations from microtearing instabilities. These modes saturate at large amplitude due to the low magnetic field; they produce global stochastic magnetic fields, and therefore Eq. (1) is applicable. This explains the good agreement between the theoretical and the observed electron thermal conductivity over the entire region where the microtearing mode is the fastest growing instability with $k_\theta \rho_s \sim 1$. This instability is an important limit [19] on electron temperature in STs where the intrinsic high $E \times B$ shears can stabilize the usual long-wavelength instabilities. NSTX has the flexibility to operate in many regimes. This instability could be suppressed by reversed magnetic shear, by raising the electron temperature such that $\nu_{ei} < \omega_{*e}$, or by operating at higher magnetic field to reduce the saturation amplitude. This result does not rule out ETG turbulence in controlling electron transport in NSTX. ETG modes are calculated to be important in other discharges and/or at other locations.

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