Sheared Radial Electric-Field Effects on Turbulence Suppression due to Doubly Advanced Potential-Height Formation

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Remarkable effects of radially produced shear of electric fields dE_r/dr on both turbulent fluctuations and drift waves are experimentally demonstrated with improvement in plasma confinement for the first time in the tandem mirror GAMMA 10. These electric-shear effects are performed on the basis of a factor of two progress in ion-confining potential (ϕ_c) formation due to advanced electron-cyclotron-heating powers and vacuum conditions; the dependence of ϕ_c is consistent with our proposed physics scaling.

Keywords:

shear effects, turbulence suppression, drift wave suppression, confinement improvement, radially produced electric fields

Experimental verification of the effects of radially sheared electric-field (or potential) formation in plasmas is one of the most critical issues in order to understand the physics basis for plasma confinement improvements [1]. A remarkable characteristic advantage of open-ended mirror devices is the ease of control of a radial potential profile due to locally heated electron axial flow from a plug region [2] into a machine end region along the lines of magnetic force. This potential control ability in mirrors allows for flexible experimental studies of relations between radially produced electric shear profiles and the suppression of fluctuation-driven radial losses (or transverse plasma confinement). The importance of such relations has been noted in several confinement-improvement studies including torus plasmas [1].

In the present manuscript, we focus on experimental findings of shear formation effects on the suppression of not only coherent drift waves but turbulent fluctuations with confinement improvement. Here, electron-cyclotron heatings (ECH) for ion-confining potential (ϕ_c) formation [2,3] are applied in association with a significant rise in the absolute value of the central-cell potential Φ_c and the resulting formation of a strong shear of electric fields of the order of 10 kV/m^2 in the radial direction of the plasma column (dE_r/dr).

In Fig. 1, recent achievement of a factor of two progress in data on ϕ_c, in comparison to those attained 1992-2002, is shown in accordance with the physics scaling law of ϕ_c with thermal-barrier potentials ϕ_b as a function of the density ratio of the plug to central densities n_p/n_c (see the solid theoretical curves) [2]. Here, a 20% increase in plug ECH powers along with a factor of 2 improvement in recycling hydrogen particles is applied to the hot-ion mode plasmas at several keV ion temperatures (T_i) on the GAMMA 10 tandem mirror [2]. This progress provides the basis for the following remarkable effects of a strong dE_r/dr, given that dE_r/dr is proportional to the Φ_c height, which is closely connected with and raised by plug potential rise due to plug ECH Gaussian beams.

Figure 2 shows the results of plasmas heated by ion-cyclotron heatings (ICH; 1–190 ms) along with ECH for 80–110 ms. The central-cell line density nl_c viewed through r_c = 0 is shown in Fig. 2(a). An increase in nl_c associated with a decrease in fluctuations is found during the ECH period.

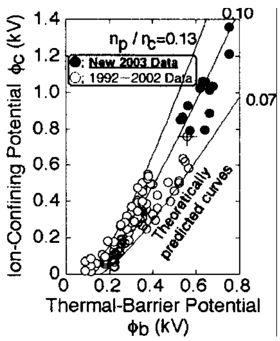

Fig. 1 Recent achievement of a factor of two progress in ϕ_c (filled circles) compared to the ϕ_c attained 1992-2002 (open circles). Physics scaling of ϕ_c with ϕ_b [2,5] is well extended.

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Various fluctuation diagnostics including a movable interferometer, soft x rays, eight Langmuir probes (i.e., every 45° at r_c = 18 cm) for wave phasing diagnostics, two heavy-ion beam probes (HIBP) and four sets of end-loss ion-energy spectrometer arrays (IES), and simultaneous potential diagnostics with HIBP and IES [4] show the following consistent features. Two data sets, one before and one during ECH, are summarized in Figs. 2(b)-2(e) (t = 70–80 ms) and 2(f)-2(i) (t = 100–110 ms), respectively. Frequency analyses of IES signals, for instance, are shown in Fig. 2(b). The existence of electron drift waves with the mode numbers m = 1, 2, etc., giving a peaked structure (see arrows) over a few kHz (for more detail, see Ref. 3), and turbulence-like fluctuations without any coherent azimuthal phasing relation below a few kHz are found. In Figs. 2(c) and 2(d), the integrated intensities of the drift waves and the turbulent fluctuations are plotted at several radii r_c, respectively. The value of dE_r/dr deduced from Φ_c measurements with IES and consistently with HIBP is plotted in Fig. 2(e). Merely a weak shear is formed in the case without ECH.

On the other hand, a similar data set during ECH [Figs. 2(f)-2(i)] shows a significant difference with a stronger shear [Fig. 2(i)]. Some finite levels of turbulent fluctuations near r_c = 6 cm with dE_r/dr = 0 [Fig. 2(h)] and remarkable suppression of turbulence are found for the first time in both positive (r_c < 6 cm) and negative (r_c > 6 cm) electric shear regions.

In Fig. 3, a similar data set before ECH application is obtained, as shown in Figs. 3(b)-3(e), with a shear [Fig. 3(e)] as weak as that in Figs. 2(b)-2(e). However, the data attained during ECH [Figs. 3(f)-3(i)] are remarkably different from those in Figs. 2(f)-2(i). As can be seen in Fig. 3(i), a weaker shear than that in Fig. 2(i) is formed. Further, a low-level saturation of density rise during plug ECH in Fig. 3(a) with stronger density fluctuations is found, as compared to density rise in Fig. 2(a) during ECH.

This behavior of nl_c is interpreted from particle balance analyses [2,3]. In Fig. 2(a), with a strong shear, the rising rate of edN/dt well balances the difference between the particle source currents I_s and the axial loss currents $I_{//}$ [Fig. 2(j)]. Also, good agreement with Pastukhov's theoretical prediction is obtained. These indicate negligible transverse particle losses. In contrast, Fig. 3(a) shows a strong turbulence and a smaller density rise. These are interpreted in terms of additional fluctuation-driven non-ambipolar transverse particle losses [3] under a weak E_r shear condition.

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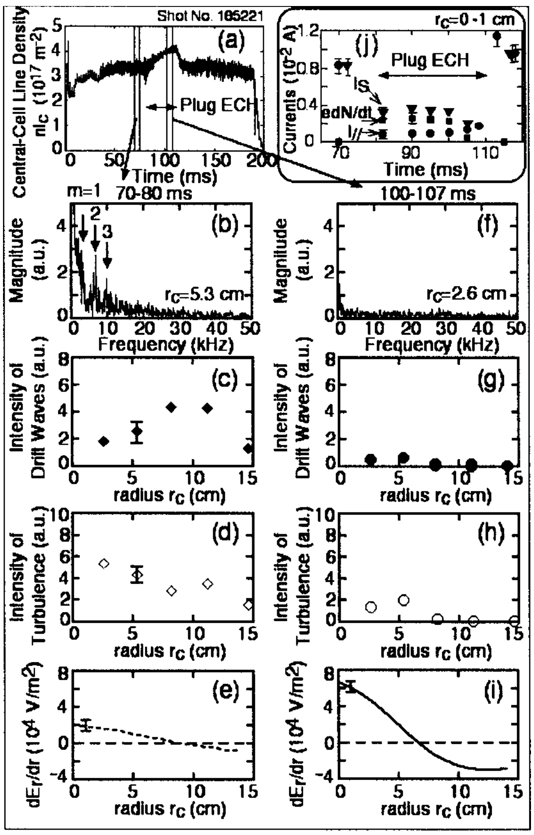

Fig. 2 Improved confinement with a strong shear dE_r/dr formation for fluctuation suppression during the ECH period.

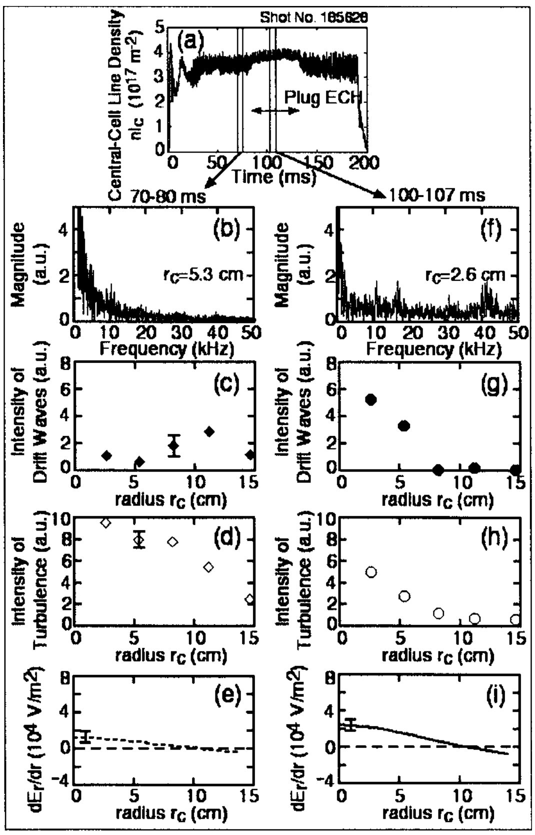

Fig. 3 Poor confinement with a weak shear formation providing strong fluctuations of drift waves and incoherent turbulence.