EXPERIMENTAL OBSERVATION OF ZONAL FLOW AND ITS SCALINGS IN AXISYMMETRIC MAGNETIC FIELD

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The anomalous radial transport generated by drift wave turbulence is a fundamental open physics question in magnetic confinement systems, both in modern tokamaks and current and next generation mirror machines. The role of self-generated zonal flows (ZF) in transport regulation via its shear is a potent concept and a physics issue[1]*. ZF are believed to be spontaneously excited by drift wave turbulence via Reynolds stress from small-scale fluctuations to large-scale flow.*

A basic physics experimental study of zonal flows associated with ITG (ion temperature gradient) drift modes has been performed in the Columbia Linear Machine (CLM). The difficult problem of detection of ZF has been solved via a novel diagnostic using the paradigm of FM (frequency modulation) in radio transmission[2]*. We find a power spectrum peak at ITG ('carrier') frequency of* $\sim 120kHz$ *and FM sidebands at frequency of* $\sim 2kHz$*. We have definitively identified ZF with azimuthal and axial symmetry* $(k_\theta \approx 0, k_{//} \approx 0)$ *and radially inhomogeneous* $(k_r \neq 0)$ *flow structures in cylindrical plasmas in uniform axisymmetric magnetic field . However, quantitatively, the stabilizing effect of ZF shear appears to be small and no significant isotopic effects are observed. The unique complementary roles of ion acoustic damping and ZF shearing in the saturation of ITG has been experimentally demonstrated using stabilizing and destabilizing feedback techniques. Theoretically ZF is supposed to be saturated via* ν_{ii} *(Ref.1). As this is very small both in tokamaks and CLM, we investigate the scaling ZF with* ν_{in} *which can be significant in CLM.*

I. INTRODUCTION

A fundamental open physics question in plasma physics is transport scaling. The role of zonal flows (ZF) in transport regulation and transport barriers is an important critical concept. ZF are believed to be spontaneously excited by drift wave turbulence via Reynolds stress from small scale fluctuations to large scale flow[1, 3-6]. ZF are azimuthally and axially symmetric $(k_\theta \approx 0, k_{//} \approx 0)$ and radially inhomogeneous $(k_r \neq 0)$ flow structures in axisymmetric plasmas. The theories also predict low frequency (nearly zero) for ZF. The experiments in tokamaks to detect ZF are very difficult and fairly inconclusive[7], with the possible exception of Fujisawa et al[8]. The difficulty of direct measurements and the lack of definitive experimental results in tokamaks motivated our basic physics study of ZF in the Columbia Linear Machine (CLM)[9,10]. In CLM experiments we use slab ITG (ion temperature gradient) drift waves to study this phenomenon.

II. REVIEW OF ELECTROSTATIC MODES IN COLUMBIA LINEAR MACHINE

The layout of CLM has been described in Ref. 9 and 10. A steady-state collisionless cylindrical plasma column in a uniform axial magnetic field is created in CLM. The core of the plasma is effectively heated by RF in the parallel direction so that an ITG mode is excited[9]. Figure 1 shows the typical average power spectra of density fluctuations.

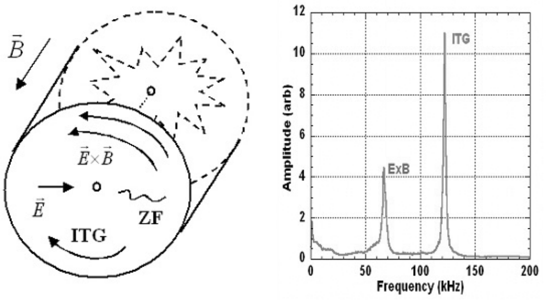

Fig. 1. Modes in CLM and typical power spectra of density fluctuations.

The mode with frequency $f \sim 65kHz$ has been identified as ***E*x*B*** mode with azimuthal mode number *m =1, k*$_{//}$*=0.* This mode is believed to be a rotationally driven Rayleigh-Taylor type instability, driven by ***E*x*B*** rotation of the plasma column[11] . The mode with frequency *f~120 kHz* has been identified as an ITG mode with azimuthal mode number $m = 2$, $k_{//} \sim 2\pi /400cm^{-1}$ and propagates in the ion diamagnetic direction and has been definitively identified[12].

III. A NOVEL DIAGNOSTIC FOR ZONAL FLOWS DETECTION

The difficulties of direct measurement of the ZF are due to its existence the presence of a large equilibrium radial electric field causing a Doppler shift which is much larger than ZF. This has been resolved via a novel diagnostic based on the paradigm of FM modulation of the ITG mode by ZF[2]. Here a small ZF at same low frequency is considered to modulate larger "carrier" frequency of ExB equilibrium frequency. In the CLM's laboratory frame the frequency of the ITG mode (*m=2*) is

$$\omega(t) = 2\Omega_{ExB} + 2\Omega_{ZF}(t) - \omega_{ITG} ,$$

where Ω_{ExB} is the Doppler shift due to the equilibrium ***E*x*B*** rotation, Ω_{ZF} is the additional Doppler shift due to the ZF, ω_{ITG} is the ITG mode frequency in plasma frame. It is noted that ZF itself does not suffer a Doppler shift as its *m=0*, however ITG with *m=2* does suffer an additional Doppler shift due to $\boldsymbol{E_{ZF}} \times \boldsymbol{B}$. We can consider the ZF time dependence as $\Omega_{ZF}(t) = \Omega \cdot \cos(\omega_{ZF} t)$, where $\Omega = |E_{ZF}| / rB$ is the zonal flow amplitude (i.e. rotational frequency) and ω_{ZF} is the very low intrinsic zonal flow frequency. Then a typical signal from probes corresponding to the ITG mode is given by the following Fourier series:

$$U(t) = U_0 \cos(2\Omega_{E\times B} t + \varepsilon \sin(\omega_{ZF} t) - \omega_{ITG} t) = U_0 \sum_{n=-\infty}^{\infty} J_n(\varepsilon) \cos(2\Omega_{E\times B} t + n\omega_{ZF} t - \omega_{ITG} t) \qquad (1)$$

where $\varepsilon = 2\Omega/\omega_{ZF}$. A schematic power spectrum of the ideal signal with FM modulation is shown in Fig.4. in Ref. 13.

Our typical data records of fluctuation of density or floating potential of plasma contained *256K* points with digitization frequency of *1MS/s* (Ref. 13). In the following data collection scenario we utilize discrete short time Fourier transform with *2048* μs FFT window size and *256* μs shift between the window frames resulting in frequency resolution of about ~ *0.49kHz* and about *1000* samples of spectra are used for sample averaging. The resulting power spectra of ITG mode were tested for the presence of sidebands according to the criterion below. We selected the spectra with a clear ITG mode and two sideband peaks located symmetrically at both sides and for the amplitudes of sidebands higher than the threshold noise level. We found that up to *25%* of total number of FFT frames satisfy this criterion.

IV. EXPERIMENTAL OBSERVATION OF ZONAL FLOWS

The typical result of the sample averaged ITG spectra which satisfied above mentioned criterion is shown in Fig.3.

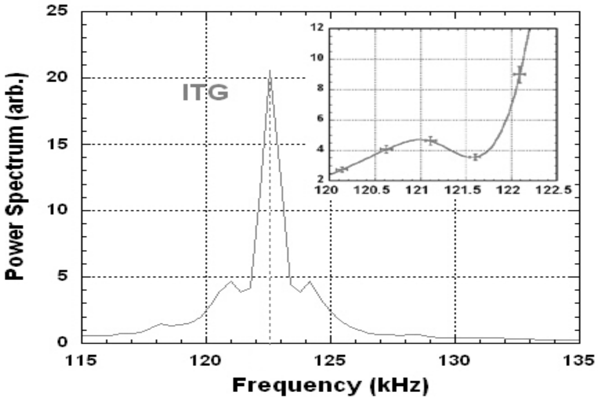

Fig. 3. Fine structure of power spectrum of ITG density fluctuations.

The frequency of the ITG mode in the laboratory frame is about *122kHz* and the sideband frequency is $\omega_{ZF} /2\pi = 1.9kHz \pm 0.6kHz$ The power spectrum of potential fluctuations has very similar sideband picture[2,13]. Now the value of $\varepsilon \approx 1$ is determined from $[J_1(\varepsilon)/J_0(\varepsilon)]^2 \approx 1/3$, which is equal to the ratio of the power in the sideband and that in the ITG mode measured in our experiment. Lastly, the ZF amplitude $\Omega \approx 1kHz$ is determined from the definition of the parameter $\varepsilon = 2\Omega/\omega_{ZF}$ and the measurement of $\omega_{ZF} \approx 2kHz$ mentioned above. We can also estimate value of electric potential $\tilde{\varphi}_{ZF}$ which created this ExB frequency of about *1kHz* , as $e\tilde{\varphi}_{ZF} / kT_e \approx 0.6\%$. This is a factor of 3 higher than the prediction of Reductive Perturbation method[13].

We now discuss the data for wave numbers of ZF. First it is noted that for both ion acoustic modes with frequency *f < 20kHz* (Ref. 14) and *2kHz* ZF in our present experiments the azimuthal number *m=0* have been found. Next another signature of ZF $k_{//}=0$ is confirmed by the measurement of $k_{//}$ in region around ω_{ZF} frequency. The parallel wave number is determined from the axial phase shift measured via cross-correlation of two Langmuir probes, displaced axially by *33cm* (Ref.14). The resulting phase shift for the low frequency part of measured spectra, which satisfies the above mentioned ZF criteria indicates that $k_{//} \approx 0$ at the frequency $\omega_{ZF} / 2\pi$ ~ *2kHz* (Ref. 2), which is perfectly consistent with ω_{ZF} obtained from the sideband analysis above.

We now present the data for the radial structure of ZF and the resulting flow shear. We determine both the intrinsic ZF frequency ω_{ZF} and the amplitude of ZF $\Omega \sim |E_{ZF}|$ at several radial points and obtain radial profiles of the latter. Then we calculate the radial shear of the corresponding azimuthal flow (~ $\partial(r\Omega)/\partial r$). Figure 4 shows the radial profiles of density fluctuation of ITG mode, the radially resolved amplitude of the electric field $|E_{ZF}| \sim \Omega$ caused by ZF and the corresponding flow shear. When the ITG fluctuation level is low (< *1.5%*), the error bar in our analysis is too large. ZF shear is about *1.5 kHz* (~ *1/10* γ_{ITG}) and this is roughly consistent with the nonlinear mode coupling theory[13,14] which predicts $(\Delta f)_{shear} \sim 0.7kHz$.

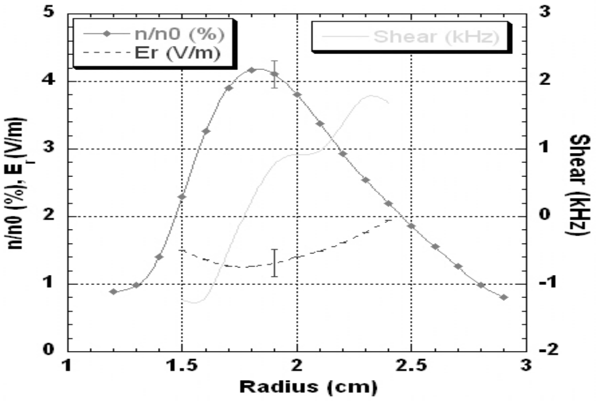

Fig. 4.Radial profiles of density fluctuations, ZF field and shear $\partial(r\Omega)/\partial r$.

V. ZONAL FLOWS SCALINGS

Most theories rely[1] on ν_{ii} to damp the ZF, therefore we want to test this concept. We changed neutral pressure and discharge current fore variation of ν_{ii} and ν_{in}. For our experimental condition ν_{in} is about 10 ν_{ii} then we obtain scaling with ν_{in}. In figure 5 we cam see amplitude of ZF vs ν_{in} for two different level of ITG mode. No ν_{in} scaling is observed in contrast to theory.

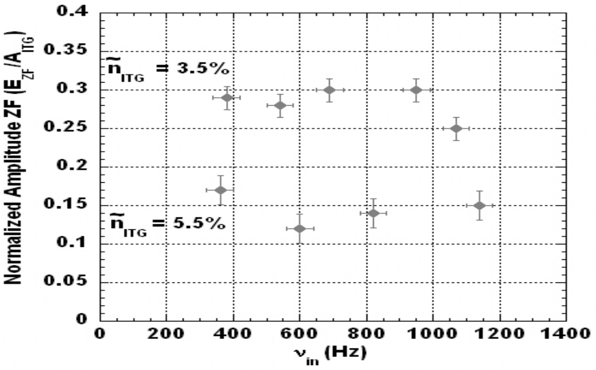

Fig. 5. Scaling of ZF amplitude vs collision rate

The isotopic effects on ZF generation is an important question, as some theories suggest that the isotopic effects on ZF and its shear can translate into isotopic effects on transport leading to the breaking of gyro-Bohm scaling. We use hydrogen and deuterium plasmas and focus on maintaining the most important parameters rigorously constant for both gases. We obtained very similar radial profiles of fluctuation level of ITG modes and identical ZF shears for different gases[2] . Therefore, our experiments do not confirm the theoretical premise of breaking of gyro-Bohm scaling via isotopic effects on ZF shear.

We now present data of ZF amplitude scaling. Figure 6 shows the experimental scaling of ZF amplitude with ITG amplitude under different plasma parameters via RF heating which determines the ITG drive η_i.

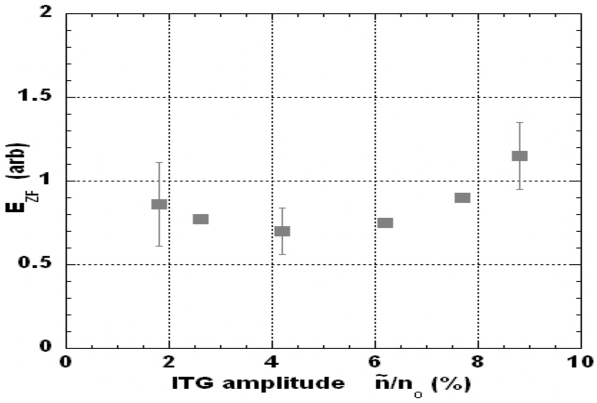

Fig. 6. Scaling of ZF amplitude vs ITG amplitude.

It is noted that with the above method of increasing the ITG mode amplitude via variable RF (as well as discharge current), that many plasma parameters will simultaneously change. Therefore, this scenario will affect ITG amplitude via multiple causal paths (besides the obvious ITG drive parameter η_i), e.g. FLR, T_e/T_i, Landau parameter $\omega / k_{//} v_{thi}$ etc. It may also affect (stabilize, de-stabilize) the various potential mode coupling partners: ITG radial harmonic, IA (ion acoustic mode) and ZF. This will obscure the direct exploration of the basic physics of interaction between ITG and ZF. For example, an ideal process for this could involve only the variation of linear growth rate of ITG, while keeping all other plasma parameters invariant. This can be easily achieved via linear feedback used as a diagnostic tool. In general, linear feedback does not change the equilibrium parameters of a system, almost by definition.

Therefore, we now discuss a novel feedback (stabilizing/destabilizing) technique which allows probing of selective coupling between ITG, ZF and IA modes. In principle, one can feedback stabilize (de-stabilize) any one of the mode coupling partners: ITG, IA and ZF.

First we discuss the high frequency feedback of the ITG mode at 120KHz. Two standard Langmuir probes displaced azimuthally by 180^0 at same radius, whose signals are summed to act as a sensor with spatial filtering: canceling out odd modes (m=1, m=3) as shown in Fig.2. in ref 10. Another probe displaced axially 33 cm is used as feedback suppressor. The frequency band of the feedback loop was limited by a band pass filter at 100kHz -150kHz. We obtain the scaling relationship between ZF and ITG amplitudes shown in Fig.7. The origin of the differences between Figs 6 & 7 is discussed above.

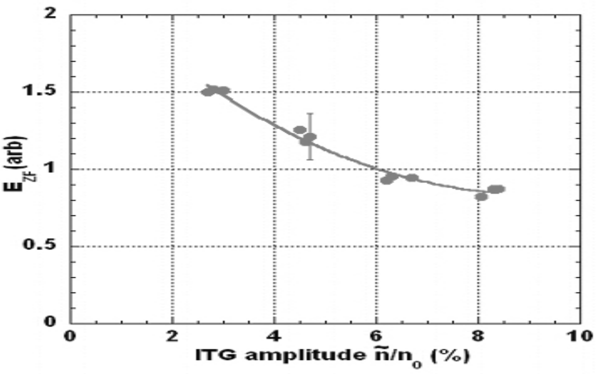

Fig. 7. Zonal flow scaling with ITG under feedback (band pass filter 100kHz-150kHz)

We now consider the selective diagnostic involving feedback control of low frequency IA and ZF modes. For this we use especially designed ring Langmuir probes, which are placed coaxial with the plasma column, to spatially filter out the ITG mode (m=2), the ExB mode (m=1) and leave both the ZF (m=0) and the IA (m=0) modes unaltered. Two identical ring probes with diameters 3.2 cm displaced axially by *13 cm*, are used as a sensor and suppressor. The frequency band of the feedback loop was limited by a low pass electronic filter at 5 kHz. The results are shown in Fig.8, where the amplitude of ITG mode is again varied by feedback.

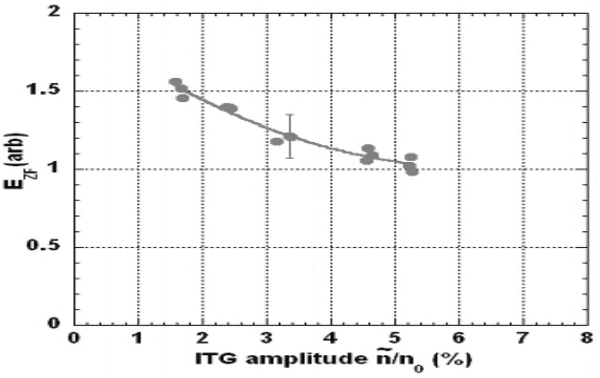

Fig. 8. Zonal flow scaling with ITG under feedback (low pass filter < 5kHz)

In terms of the complimentary roles of ion acoustic mode and ZF, there is a partial similarity to the result of a gyrokinetic simulation that GAM (geodesic acoustic mode) instead of ZF, dominates in the tokamak edge[15]. Here we make the reasonable assumption that GAM is the toroidal cousin of the IA mode propagating along the uniform axial magnetic field of CLM. However, the similarity does not extend to the scaling behavior discussed above, probably because the very low amplitude ITG regime has not been explained.

VI. CONCLUSIONS

A basic physics experimental study of ZF associated with ITG drift modes has been performed in the Columbia Linear Machine. Using a novel diagnostic we have definitively identified ZF with azimuthal and axial symmetry and very low frequency. However, the stabilizing effect of ZF on the parent ITG modes appears to be small and no significant isotopic effects are seen. No ν_{in} scaling is observed in contrast to theory.

The unique complementary roles of IA damping and ZF shearing in the saturation of ITG modes has been experimentally demonstrated using stabilizing and destabilizing feedback techniques. Furthermore, the scaling of ZF amplitude with that of ITG via increasing ITG drive through increasing ion temperature gradient via rf heating, reveals an expected monotonic behavior.

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