Zonal flows, GAM, and radial electric field in the H-1 heliac *)

M.G. Shats **), H. Xia, H. Punzmann

Plasma Research Laboratory, Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200, Australia

Received 2 October 2006

Experimental results on the role of zonal flows and geodesic acoustic modes in formation of transport barriers in the H-1 heliac are reviewed.

PACS: 52.25.Fi, 52.35.Ra
Key words: zonal flow, transport barrier, H mode, pedestal

1 Introduction

The ubiquity of zonal flows in toroidal plasma is now well recognized (see [1] for review on zonal flow theory and a special March issue of *Plasma Physics and Controlled Nuclear Fusion* **87** (2006) for the latest experimental papers).

Two main branches of zonal flows have been identified. Both have zero poloidal and toroidal mode numbers, $m = n = 0$. One of them is a zero-frequency, finite-bandwidth zonal flow, often referred to as *stationary zonal flow* while the other is the finite-frequency mode often referred to as a *geodesic acoustic mode*, or GAM. The latter originates from the geodesic curvature in toroidal geometry and develops as a result of coupling between mean zonal flow and the $m = 1, n = 0$ pressure (density) perturbation [2].

Zonal flows are found in both low and high confinement modes. There is growing evidence that zonal flows play important roles in generation of transport barriers in the plasma. Since structures of transport barriers are closely related to the global stability, confinement and hence the plasma performance, understanding zonal flows formation and their spatial localization becomes crucial for the physics of transport barriers.

Zonal flows have been studied in the H-1 heliac in the context of confinement improvement and pedestal formation. These results are reviewed in this paper. Emphasis is made on the interplay between turbulence, electric field, zonal flows and geodesic acoustic modes.

Relevance of the H-1 results to other experiments is justified by dimensional similarity of the low-temperature plasma in the H-1 and plasma in larger tokamaks and stellarators. A concept of the dimensionally similar plasmas proposed by Kadomtsev [3] and developed by Connor and Taylor [4] has been extensively used with regard to both tokamaks and stellarators to develop and justify the trans-

*) Presented at the Workshop "Electric Fields, Structures and Relaxation in Edge Plasmas", Roma, Italy, June 26–27, 2006.

**) E-mail: `Michael.Shats@anu.edu.au`

port scaling laws capable of predicting plasma confinement in larger fusion-relevant experiments. Plasmas are referred to as dimensionally similar if several essential non-dimensional parameters are the same.

For example, several non-dimensional parameters are similar in the pedestal regions of the DIII-D tokamak and H-1: the ion gyroradius normalized by the density scale length ($L_n = n_e/\nabla n_e$), is $\rho^* = 0.4$–1 in both machines; the relative collisionality, ν^*, defined as the ratio of the effective collision rate ν_{ei} to the bounce frequency ω_{be} of the magnetically trapped particles, is in the range of $\nu^* = 0.5$–5 in H-1 and $\nu^* = 1$–12 in DIII-D; the ratio of the plasma pressure to the magnetic pressure, is $\beta \approx 0.01$ at the pedestal in both experiments. Ranges for all three of the above non-dimensional parameters coincide or substantially overlap in both the H-1 confinement region and in the tokamak edge plasmas.

The paper is organized as follows. Section 2 describes experimental conditions and diagnostics. In Section 3 we review results on the generation of GAMs in L-mode discharges and on the role of GAM in spontaneous L-H transitions and in sustaining the density pedestal in H-mode.

2 Experimental conditions and diagnostics

All results discussed in this paper were obtained in the H-1 heliac [5], a helical axis stellarator having a major radius of $R_0 = 1.0$ m and a minor plasma radius of less than 0.2 m. The magnetic field structure of H-1 is characterized by a relatively high rotational transform ($\iota \approx 1.4$ in the described experiments) and very low global magnetic shear. In the experiments discussed here H-1 was operated at low magnetic fields (< 0.15 T) with current-free plasma produced by the pulsed radio-frequency (rf) power of less than 100 kW at 7 MHz. The rf power pulse length is about 80 ms. The electron temperature in the discharge is low enough ($T_e = 5$–40 eV) so that a number of electric probes can be inserted as far as magnetic axis. The experiments are performed in argon, which gives typically more reproducible discharges, and are less affected by the insertion of the probes. The ion temperature, as measured using the electrostatic ion energy analyzer (which has also been confirmed by spectroscopic Doppler broadening measurements) is in the range between 20 and 50 eV.

Fluctuations in the plasma electrostatic potential and electron density are studied using various combinations of the triple probes. Each triple probe [6] is capable of measuring the ion saturation current I_s, the plasma potential ϕ_p, and the electron temperature T_e with good time resolution (2 microseconds). Pairs of triple probes have been employed to measure fluctuations in the poloidal and the radial electric fields. To avoid the cross-coupling of the poloidal and radial components of the electric field probes have been aligned with respect to the flux surface using the electron beam mapping technique.

The probe geometry used for the determination of the poloidal and toroidal wave numbers of the potential fluctuations are illustrated in Fig. 1. Poloidal and toroidal mode numbers are estimated from poloidally (1 and 2) and toroidally separated (2

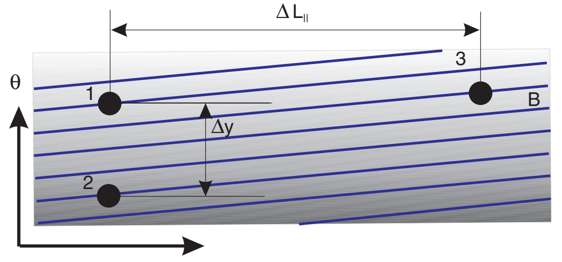

Fig. 1. Schematic of the probe arrangement for the determination of the fluctuation wave numbers.

and 3) probes. It is usually difficult to align toroidally separated probes to exactly the same poloidal position. As a result, a phase shift between probes 1 and 3 will occur due to the uncertainty in the poloidal separation between the probes, Δy_{13}:

$$\Delta\varphi_{13}(f) = k_{\|}(f)\Delta L_{\|} + k_{\theta}(f)\Delta y_{13}\,, \tag{1}$$

where $\Delta L_{\|}$ and y_{13} are toroidal and poloidal separation between probes 1 and 3 respectively, and $k_{\theta}(f)$ is known from the phase difference between probes 1 and 2. In case of zonal flow, $m = 0$, the second term on the right-hand side becomes zero (since $k_{\theta} = 0$), such that the poloidal uncertainty Δy_{13} becomes unimportant and the toroidal wave number can be reliably estimated by measuring $\Delta\varphi_{13}$.

3 Geodesic acoustic modes and their role in L-H transitions

Radial electric field causes $E \times B$ flow in poloidal direction. Since in toroidal systems B is not constant in poloidal direction, this flow leads to the density accumulation proportional to $\mathbf{E} \times \mathbf{B} \cdot \nabla B^2/B^4$. Poloidal variation of B in toroidal devices is associated with the geodesic curvature, that is, the surface component of the magnetic field line curvature. Since GAMs have a distinct frequency, they should be considerably easier to identify in experiments. A linear theory of GAM predicts oscillations at a frequency, which in a tokamak geometry is determined as [1]

$$\omega_{\mathrm{GAM}} \approx \frac{c_{\mathrm{s}}}{R}\sqrt{2 + q^{-2}}\,, \tag{2}$$

where c_{s} is the ion acoustic velocity, R is a major radius of a tokamak and $q = 1/\iota$ is the safety factor.

Magnetic field line has a finite geodesic curvature, the $E \times B$ motion induces compression and turns into a density perturbation if the frequency is in the range of $c/(qR)$ or higher. Here $L_{||} = qR$ is the parallel connection length in a tokamak. In stellarators $L_{||}$ should be significantly shorter due to the inherent B-ripple, such that the GAM frequency should be higher.

It is shown in [7] that in the H-1 heliac GAM frequency is a factor of 2 to 3 higher than in equivalent tokamak due to shorter parallel connection length $L_{||}$

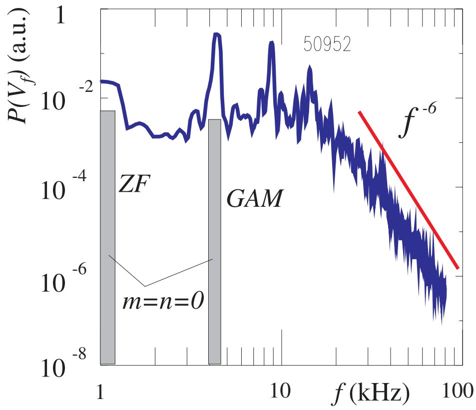

Fig. 2. Spectrum of the floating potential fluctuations in L-mode.

in H-1. An estimate of the geodesic acoustic frequency in the H-1 plasma gives $f_{\rm GAM} = c_{\rm s}/L_{||} \approx (4\text{–}5)\,$kHz. The first identification of GAMs in toroidal plasma has been reported in [8]. Along with GAM having finite frequency, stationary zonal flows seen as spectrally broadened $f \approx 0$ potential features have also been identified in H-1 [7]. Figure 2 shows power spectrum of the floating potential fluctuations measured in H-1. Two poloidally symmetric spectral features are observed: the first one at $f \approx 0$ has been identified as a stationary zonal flow, while the second coherent mode having $f \approx 4.2\,$kHz is GAM. Additionally, several other coherent modes develop in L-mode in H-1. Usually, their development precedes the onset of GAM.

The onset of the $m = 0, n = 0$ GAM is observed close to the threshold for the L-H transition in H-1. When the magnetic field is increased above some critical value, the fluctuation level is greatly reduced, while the mean E_r is further increased securing the confinement transition to H-mode.

It has been shown in numerical simulations that the energy of the mean zonal flow can be transferred to coherent modes via the geodesic transfer mechanism which acts as a sink and may prevent the growth of zonal flow [9]. Simulations of the tokamak edge turbulence have shown that the zonal flow energy is depleted by toroidal coupling to the pressure and leads to the generation of a relatively large number of the sideband modes [10]. This finding has been supported by observations of GAM in the ASDEX Upgrade tokamak [11]. It has been noted that the GAM itself, or the $m = 0, n = 0$ mode, may not be even clearly observable in the developed sideband mode regime [9]. These results are of great importance for the physics of zonal flows since they offer a mechanism of the zonal flow dissipation in addition to collisional damping.

Somewhat similar conclusions have been made based on the analysis of the H-1 results [7]. It was suggested that the development of coherent sideband modes in H-1 slows down the growth of the stationary zonal flow before the L-H transition. As

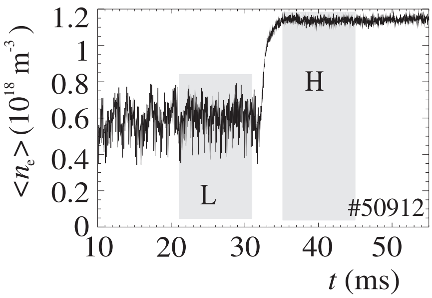

Fig. 3. Temporal evolution of mean electron density during spontaneous L-H transition.

stationary zonal flow develops in the plasma, coherent oscillation having $m = 1$ at the GAM frequency also develops. If spectral energy, delivered from the broadband turbulence into stationary zonal flow, is further increased, the energy of coherent low-m modes also increases. Thus GAM and sideband modes act as the energy sink for zonal flow. In fact, GAM stores some of the zonal flows energy, while sideband modes dissipate it via Landau damping [7].

When E_r and its shear reach the E_r-shear decorrelation threshold, the $m = 1$ mode can no longer exist, closing thus the energy escape route for stationary zonal flow. This leads to a further jump in local E_r and to the suppression of other low-m modes. It is possible that the shear decorrelation criterion needs to be satisfied only for the $m = 1$ mode and this will lead to the suppression of all other coherent modes.

GAM seem to play an active role in the plasma spatio-temporal dynamics during spontaneous L-H transitions. Density evolution during such a transition in the H-1 heliac is illustrated in Fig. 3. As shown in [12], transition to H-mode coincides with the formation of the density pedestal. This pedestal, observed as a characteristic kink in the radial profile of electron density is shown in Fig. 4a. Prior to L-H transition, strong GAM is observed, whose maximum is localized close to the top of the pedestal. This GAM leads to rather strong oscillations in the radial electric field. This oscillations $\widetilde{E}_r$ are shown in Fig. 4b as a grey-shaded envelope. The $\widetilde{E}_r$ oscillations produce substantial oscillating E_r shear, seen in Fig. 4c. The maximum of the $\widetilde{E}'_r$ in L-mode is localized in the pedestal region, near its top.

Thus radial localization of GAM in L-mode may be predetermining the localization of the pedestal in H-mode. It has been suggested [12] that the development of GAM before the L-H transition and its spatial correlation with the localization of the density pedestal in H-mode, is an indication on the active role played by the zonal flow-GAM dynamics in the formation of transport barrier.

Recent results from H-1 [13] confirm the role of zonal flows in sustaining the transport barrier in H-mode. Strong stationary zonal flows have been found in the density pedestal region in H-mode. This is illustrated in Fig. 5. Radial profile of E_r shows spatial corrugation. This corrugation spatially correlates with the localization of the $f \approx 0$ zonal flows shown in Fig. 5b. Zonal flows seems to be responsible for

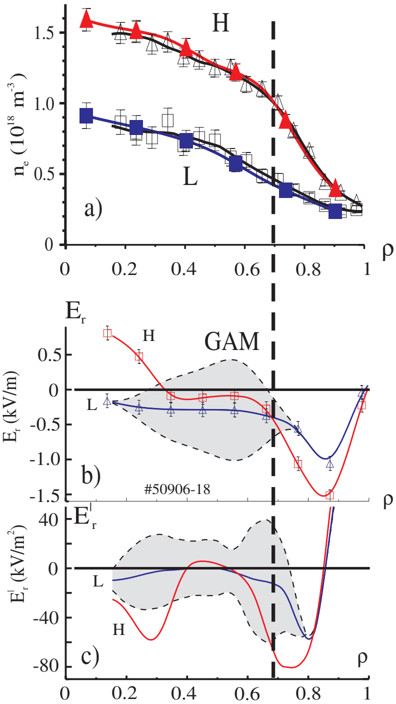

Fig. 4. Radial profiles of (a) electron density, (b) radial electric field E_r and (c) radial electric field shear E_r' during spontaneous transition from L (black line) to H (grey line) confinement modes. Shaded envelopes show time-varying contributions to E_r and E_r' from GAM ($f \approx 5\,$kHz).

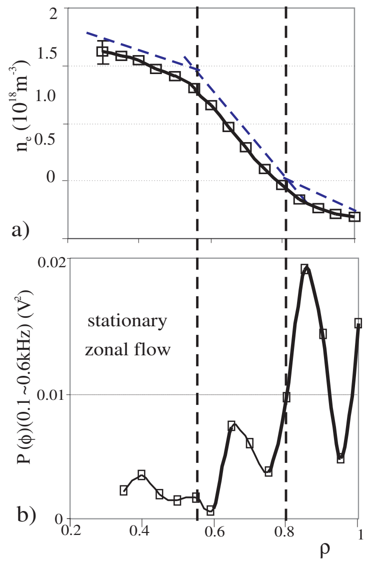

Fig. 5. Radial profles of a) electron density and b) of the zonal flow spectral power (0.1–0.6 kHz) in H-mode.

generating strong E_r shear in the radial regions which determine the top and the foot of the density pedestal in H-mode.

Summarizing, zonal flows seem to play important roles in the transport barrier physics. There is growing evidence that the development of stationary zonal flows in L-mode might be slowed down via mechanism of the geodesic transfer [10]. Geodesic acoustic mode at about (4–5) kHz developing along with several coherent 'sideband' modes are observed near the threshold for L-H transition. The nature of interaction between stationary zonal flow, GAM and sideband modes is rather complex, as discussed in [7]. It has been suggested in [7, 12] that it is the combined effect of mean E_r and GAM that may be responsible for triggering formation of the transport barrier related to the density pedestal in H-mode. Observation of strong stationary zonal flow in H-mode in the pedestal region confirms the hypothesis that generation of GAM and of the stationary zonal flow are related physics processes.

References

[1] P.H. Diamond *et al.*: Plasma Phys. Control. Fusion **47** (2005) R35.

[2] N. Winsor, J.L. Johnson, and J. Dawson: Phys. Fluids **11** (1968) 2448.

[3] B.B. Kadomtsev: Fizika Plazmy **1** (1975) 531.

[4] J.W. Connor and J.B. Taylor: Nucl. Fusion **17** (1977) 1047.

[5] S.M. Hamberger *et al.*: Fusion Technol. **17** (1990) 123.

[6] S. Chen and T. Sekiguchi: J. Appl. Phys. **36** (1965) 2363.

[7] M.G. Shats, H. Xia, and M. Yokoyama: Plasma Phys. Control. Fusion **48** (2006) S17.

[8] M.G. Shats and W.M. Solomon: Phys. Rev. Lett. **88** (2002) 045001.

[9] B. Scott: Phys. Lett. A **320** (2003) 53.

[10] B.D. Scott: New J. Phys. **7** (2005) 92.

[11] G.D. Conway: Plasma Phys. Control. Fusion **47** (2005) 1165.

[12] H. Punzmann and M.G. Shats: Phys. Rev. Lett. **93** (2004) 125003.

[13] H. Xia, M.G. Shats, and H. Punzmann: submitted for publication to Phys. Rev. Lett. (2006).