Nonlinear Viscosity in the Interchangeable Module Stellarator

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The experimental observation of nonlinear parallel viscosity in the Interchangeable Module Stellarator is reported. The damping of plasma flows, by poloidal viscosity and ion-neutral collisions, is determined from the dependence of the radial current on the radial electric field in the plasma. At low neutral density, the radial current drops and a jump in the radial electric field occurs at a poloidal Mach number in the range -10 to -15, in reasonable agreement with a model based on nonlinear viscosity. The nonlinearity of viscosity diminishes as the neutral density is increased. [S0031-9007(98)05995-X]

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Improving the confinement in toroidal magnetic devices has been a central focus of the fusion program since the discovery of the *L-H* transition in ASDEX [1] in the early 1980s to the more recent dramatic reduction in core turbulent transport with reverse magnetic shear in the TFTR [2] and DIII-D [3] tokamaks. In the past few years, spontaneous *L-H* transitions have also been reported in the Wendelstein VII-AS [4] and CHS [5] stellarators, and recently in the H-1 heliac [6]. Pioneering efforts to improve confinement in toroidal machines using biased electrodes dates back to 1966 and the B-3 stellarator [7]. Biased electrode experiments in tokamaks [8–10], meanwhile, have shown that there is a sudden jump in the radial electric field during the *L-H* transition about a poloidal Mach number ($M_p = -E_r/B_p \nu_t$ where E_r is the radial electric field, B_p is poloidal magnetic field, and ν_t is the thermal velocity of ions) of unity. It has been suggested that the jump in the radial electric field is a result of the nonlinearity of viscosity at high $\mathbf{E} \times \mathbf{B}$ flow speeds [11].

In this Letter, we show the first results of a sudden jump in the radial electric field at a poloidal Mach number much greater than one, in reasonable agreement with an expression by Shaing for the parallel viscosity in stellarators [12]. The unity poloidal Mach number in tokamaks occurs because of the purely toroidal modulation of the magnetic field; the higher poloidal Mach number in stellarators occurs because of the additional helical modulation of the magnetic field. Furthermore, we show that the bifurcation of the radial electric field due to the nonlinear viscosity can be suppressed by an increase in the neutral density. The competition between neoclassical parallel viscosity and ion-neutral collisions in a stellarator has been described theoretically for low speed [13] when the viscosity is linear with the flow, and for high rotation speed [12] when the viscosity becomes nonlinear. Previous experiments [14] in the Interchangeable Module Stellarator (IMS) [15] measuring the radial conductivity, flow speed, and damping rate confirmed the neoclassical model at low rotation speeds. The work described here confirms the model at high rotation speed. A higher power plasma source, higher plasma densities, and larger bias voltages contributed to the higher rotation speeds observed in this paper compared to previous experimental results.

IMS is a seven field period, $l = 3$ modular stellarator (where l is the poloidal mode number), with 40 cm major radius and ~4 cm average plasma radius. Hydrogen plasmas are produced with an electron cyclotron heating source (0.5–5.5 kW) operating at 9.31 GHz and a magnetic field strength $B_0 = 0.31$ T. The neutral density can be varied in the range $N_n = 18-260$ μTorr. Calculations indicate that the neutral density profile is fairly uniform since the mean free path for ionization (due to electron impact ionization and dissociation) is much greater than the minor radius. Typical plasma parameters are electron temperatures in the range of 6–20 eV, ion temperatures in the 2–8 eV range, and line average densities of $1-3 \times 10^{11}$ cm^{-3}. Plasma and floating potentials as well as electron density and temperatures are measured with a Langmuir probe. Ion temperatures are measured with an Electrostatic Gridded Energy Analyzer. For the data presented here, the bias probe is positioned at minor radius $r = 3.2$ cm.

Plasma flows are induced in two ways: (a) By application of a triangular signal to the bias electrode. The dynamics of changes in the radial electric field profile and the bias current can be observed as the bias voltage varies using this technique. Measurements have indicated that the electron temperature profiles are flat in the IMS. Therefore, the difference in the floating potential (3 mm increments) is used to determine the radial electric field in this case. (b) By application of a dc voltage during a shot and varying the bias voltage from shot to shot. In this case, radial electric fields are determined by measuring plasma potentials using the swept Langmuir probes. Up to ten discharges have been performed to verify the reproducibility of the results.

Figure 1 shows the temporal evolution of the triangular bias voltage, plasma radial current, and the radial electric field at $r = 3.3$, 3.6, and 3.9 cm for the neutral pressure $N_n = 18$ μTorr and input power $P_{\text{rf}} = 2.0$ kW. There is

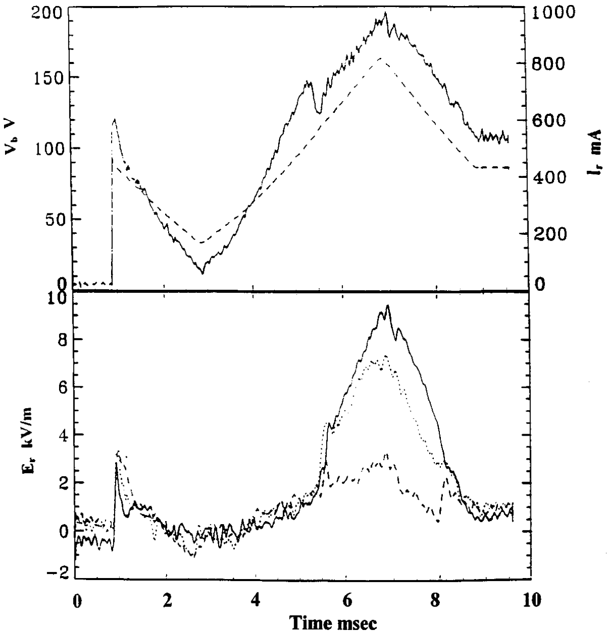

FIG. 1. Top: The bias voltage (dashed line) and the plasma radial current (solid line). Bottom: The radial electric field at $r = 3.3$ (solid line), 3.6 (dotted line), and 3.9 (dashed line) cm for 2.0 kW input power and 18 μTorr neutral pressure.

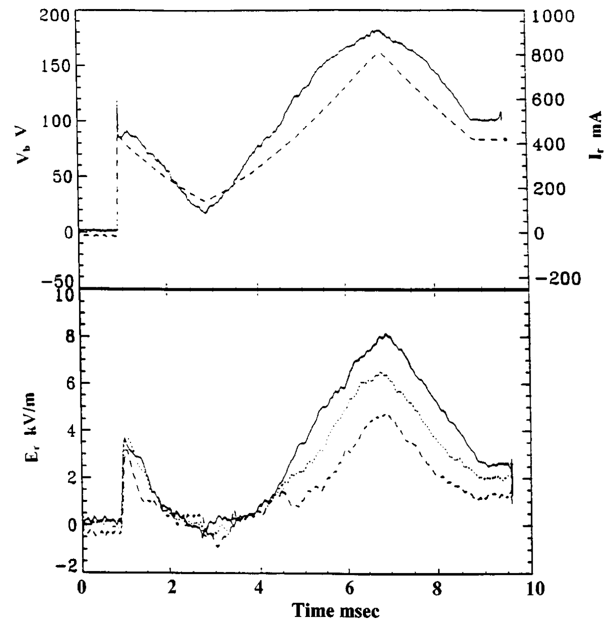

FIG. 2. Top: The bias voltage (dashed line) and the plasma radial current (solid line). Bottom: The radial electric field at $r = 3.3$ (solid line), 3.6 (dotted line), and 3.9 (dashed line) cm for 2.0 kW input power and 80 μTorr neutral pressure.

a drop in the radial current, I_r, from ~800 to 620 mA at $t \sim 5.4$ msec. The drop occurs only during the increasing slope of the bias voltage. Concurrently with or a few hundred microseconds after the drop in the radial current, sudden changes in the radial electric profiles occur: The radial electric field, E_r, at $r = 3.3$ cm jumps from ~2.2 to 4.2 kV/m, and the radial electric field at $r = 3.6$ cm shows a similar jump from ~2 to 4 kV/m [16]. The gradient of the radial electric field at $r = 3.6$ cm is small in the $t = 2.5$–5.3 msec interval and increases after the drop in the radial current.

Figure 2 shows the same set of data as indicated in Fig. 1 for $N_n = 80$ μTorr. There is no noticeable sudden change in the radial current during the entire biasing period. There are no signs of a jump in the radial electric fields after $t \sim 4$ msec. The gradient of the radial electric field at $r = 3.6$ cm is small in the $t \sim 3.5$–4.4 msec period, and it increases at $t \sim 4.6$ msec. The transition to a high gradient regime ($t \sim 4.5$–9 msec) is gradual (no drop in the radial current or jump in the radial electric field), rather than sudden, as was the case in Fig. 1.

Figure 3 shows the plasma radial current versus the poloidal Mach number at $r = 3.3$ cm (with rotational transform $\iota \approx 0.27$, inverse aspect ratio $\varepsilon \approx 0.066$, and ion temperature $T_i \approx 3.5$ eV) for $N_n = 18$ (solid line), 40 (dotted line), and 80 (dashed line) μTorr, respectively. There is a distinct local maximum in the radial current at $M_p \sim -15$ for $N_n = 18$ μTorr. The slope of this curve is negative in the range $M_p = -20$ to -30. The local maximum and the negative slope of the curve diminish as the neutral pressure is increased.

Similar behavior in the radial currents and radial electric fields are observed when dc bias voltages are applied and the plasma potentials are measured. Figure 4 shows the plasma radial current vs the normalized electric field at $r = 3.3$ cm for $N_n = 18$, 40, and 80 μTorr. No drop in the radial current is observed for $N_n = 40$ and 80 μTorr. For $N_n = 18$ μTorr a drop in the radial current from ~1350 to 1150 mA is observed at $M_p \sim -12 \pm 2$. An increase in the gradient of the radial electric field and the electron density at $r = 3.3$ cm is observed ~100 μsec after the radial current drops.

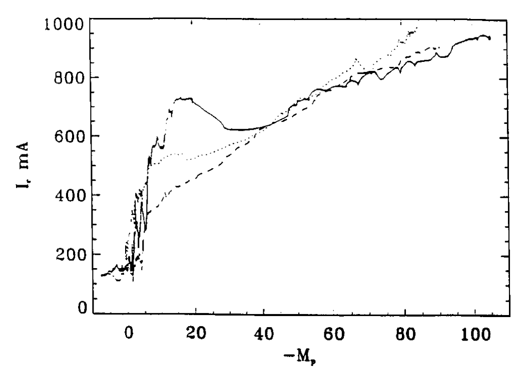

FIG. 3. Plasma radial current versus (minus) poloidal Mach number for 2.0 kW input power and 18 (solid line), 40 (dotted line), and 80 μTorr neutral pressure.

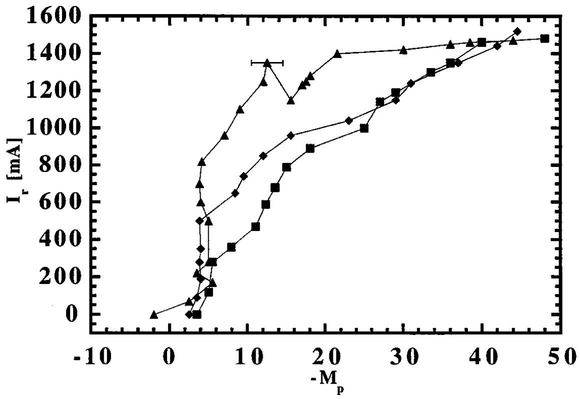

FIG. 4. Plasma radial current vs (minus) poloidal Mach number at $r = 3.3$ cm for 5.5 kW input power and $N_n = 18$ (triangle), 40 (diamond), and 80 (square) μTorr.

In steady state, the poloidal momentum balance equation in the Hamada coordinate system [17] can be written as

$$\frac{B^\theta B^\zeta}{c} \langle \mathbf{J} \cdot \nabla V \rangle = -\langle \mathbf{B}_p \cdot \nabla \cdot \overleftrightarrow{\pi} \rangle - v_{i\text{-}n} NM \langle \mathbf{B}_p \cdot \mathbf{V} \rangle, \tag{1}$$

where B^θ and B^ζ are poloidal and toroidal contravariant components of the magnetic field, c is the speed of light, $\mathbf{J}$ is plasma current density, V is the volume, $\overleftrightarrow{\pi}$ is viscous stress tensor, $v_{i\text{-}n}$ is the ion-neutral collision frequency, N and M are ion density and mass, respectively, and $\mathbf{V}$ is the fluid velocity. The left side of Eq. (1) is the drive term which causes the $\mathbf{J} \times \mathbf{B}$ torque. In biased electrode experiments, the radial plasma current is drawn by the bias probe ($J_r \approx -J_{\text{bias}}$). The terms on the right side of Eq. (1) are the damping terms due to the viscosity and ion-neutral collisions. Damping due to ion-neutral collisions depends linearly on M_p and, hence, is dominant at higher flow speeds. Damping due to the viscosity, however, is nonlinear in M_p and has local peaks at $M_p \sim |m - nq|/m$, where m and n are the poloidal and toroidal mode numbers of the magnetic field spectrum and q is the safety factor on a magnetic flux surface [12]. Accordingly, the dependence of the plasma radial current on the radial electric field characterizes the total damping (the sum of the damping due to viscosity and ion-neutral collisions).

A calculation of the viscous and ion-neutral damping in IMS was done based on a Fourier decomposition of the magnetic field strength in Hamada coordinates. Figure 5 shows the total damping versus poloidal Mach number at $r = 3.3$ cm in IMS for zero (solid line), low (dotted line), and high (dashed line) neutral densities, respectively. The poloidal component of the parallel viscosity has two local peaks, one at $M_p \sim 2$ due to toroidal curvature and another at $M_p \sim 10$ due to the helical components of the magnetic field spectrum. There are also peaks in viscosity at the corresponding negative poloidal Mach numbers, not shown

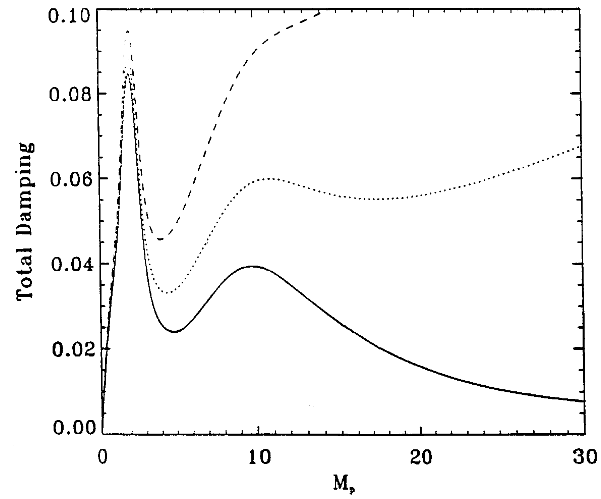

FIG. 5. Total damping versus poloidal Mach number for zero (solid line), low (dotted line), and high (dashed line) neutral pressure.

in this figure. An increase in neutral density diminishes the local peaks.

The drop in the radial current is observed only when the bias probe is located in a narrow range at the plasma edge ($r = 3.1$–3.5 cm). One explanation of this observation is the following: Since the size of the magnetic ripples decreases at smaller minor radii, damping due to the viscosity diminishes as the bias probe is moved toward the plasma center. On the other hand, the plasma density decreases for $r > 3.1$ cm. For $r > 3.5$ cm, the radial current saturates at higher bias voltages and the higher poloidal Mach numbers are not achievable.

In conclusion, we have observed experimental evidence of the nonlinearity of viscosity in IMS. The characteristics of this nonlinearity are similar to those observed in other biasing experiments in tokamaks. These include a drop in the plasma radial current, a jump in the radial electric field, and an increase in the gradient of the radial electric field. The nonlinearity of viscosity in tokamaks occurs at a poloidal Mach number on the order of unity, whereas in IMS it occurs at $M_p \sim -10$ to -15, which is close to the value predicted by Shaing's model. With an increase in the neutral density, the nonlinearity of the viscosity is no longer observed.

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