Flow Shear and Turbulence Suppression in the Helimak

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In an experimental realization of the sheared cylindrical slab, the level of plasma turbulence may be strongly reduced by application of a sufficient bias potential in the radial direction. Density fluctuation levels $\Delta n_{rms}/n$ decrease by as much as a factor of five. The ion flow velocity profile is measured spectroscopically from the Doppler shift of an argon ion line. Although the bias changes the flow velocity and shear profile, there is no correlation between the shearing rate and the turbulence level or reduction, contrary to expectations. Similar results are seen in a two-fluid nonlinear simulation of the experiment [1].

The Helimak [2] has the basic magnetic configuration of a cylindrical (R,f,z) slab with a dominant toroidal (azimuthal) field, but with a weak vertical (z) component so that the field lines are helices on a surface of constant radius – a Simple Magnetized Torus [3]. The plasma is produced by microwave power at the electron cyclotron frequency and is thus similar in some respects to that of Torpex [4], although many dimensionless parameters are quite different. A cross-section is shown in Fig. 1. The radii of the inner and outer walls are 0.6 m and 1.6 m. The height is 2 m. The central magnetic field is typically 0.1 T. With a filling pressure of 2 mPa of argon, the maximum density approaches $10^{17} m^{-3}$ at an electron temperature of 10 eV. Because of symmetry and long mean free paths along the field lines, plasma parameters depend primarily on radius – a cylindrical slab. For all values of the control parameters – fill pressure, toroidal field, and pitch, the plasma exhibits a high level, $\Delta n/n \geq 30\%$, of broadband turbulence with complex structure. The radial correlation length is less than 0.1 m, comparable with the density scale length, short compared with the system size, but long compared with ρ_s~0.02 m for the argon ions. Therefore observations at different radii can be considered local and independent of behavior more than 0.1 m away. The correlation length in the z direction is somewhat longer, ~ 0.1 m. In the region of uniform negative density gradient well beyond

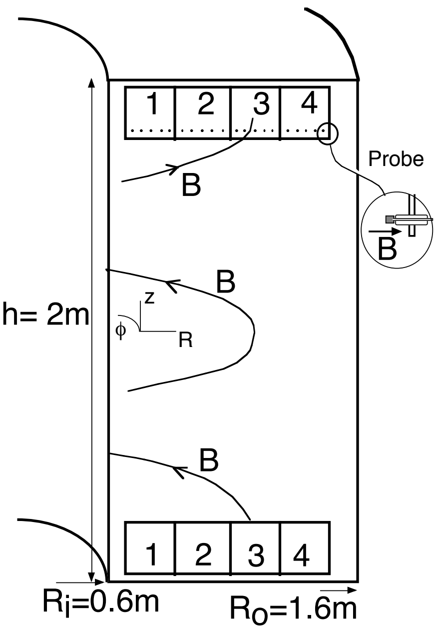

Figure 1. Helimak Schematic

the radius of maximum density, the turbulence propagates in the z direction (analogous to the poloidal direction in a tokamak) at the diamagnetic velocity, ~ 1000 m/s for typical parameters in argon. The wavenumbers fall in the range $0.1 < k_z\rho_s < 1$ and are most likely interchange modes for these parameters [3]. The parallel wavenumbers are much smaller, between drift-wave values and the zero of interchange modes.

A unique feature of this device is the ability to apply bias and alter the radial electric fields. Bias is applied using a set of metal plates, numbered 1-4 in Fig. 1, at the top and bottom. The plates lie in the R,z plane; the magnetic field is nearly perpendicular to the plates. Each plate is electrically isolated and has surface-mounted Langmuir probes. For these experiments, the connection length from top to bottom was 50 m (similar to the parallel correlation length) and the pitch was 22 cm/turn at R=1.1m. Two sets of plates as shown in Fig. 1 are installed 180° apart toroidally to intercept all the field lines for this pitch. Since the purpose is to control the potential of the plasma on a magnetic surface (fixed R), all plates spanning the same range of R – the same number in Fig. 1 -- are connected together. For normal operation, all plates are connected to the vacuum vessel ground. For biased operation, the four plates labeled 2 are connected to a controlled bias voltage. Although this bears some resemblance to edge biasing experiments in tokamaks [5], this experiment is simpler and more direct, with its uniform open field line configuration. The strong flux constraint for a confined plasma of having to conduct the entire input power across each flux surface is absent. This experiment is unique in directly measuring the ion flow velocity of the predominant plasma ion with no ion diamagnetic correction.

Biasing drives a simple, strong transition in the turbulence level, as shown in Fig. 2. The ion saturation current for a number of probes at different radii is shown as a function of time as the bias voltage on plate set 2 is swept from 0 to -50 V and back to zero over the course of a twenty-second discharge. The turbulence level decreases, the average density may increase, and Δn/n decreases at the transition. It is a switch between two states

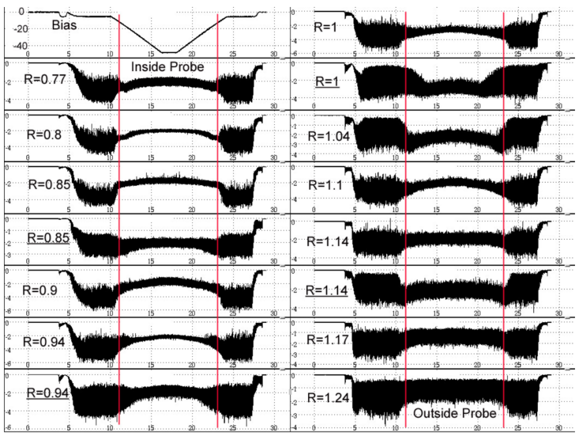

Fig. 2 Ion saturation current at various radii as a function of bias voltage; change at ≈ -15 V.

with little hysteresis as the threshold is approached from either direction. The transition time, a few hundred milliseconds, is independent of the sweep rate of the bias voltage and is characterized by increasing quiet intervals between bursts of turbulence.

Common H-mode and internal transport barrier transitions are typically faster and sharper than those in the Helimak, but this case is simpler because the drive is continuously and more directly controlled. The lack of hysteresis is an indication of this simplicity. There is no feedback in which the change in turbulence changes the equilibrium by steepening the profiles. In the Helimak, parallel flows to the top and bottom constitute a strong loss channel (~80% of net particle loss) that is independent of radial turbulent transport. Quenching the turbulence makes only a modest change to the equilibrium state and does not alter the threshold condition.

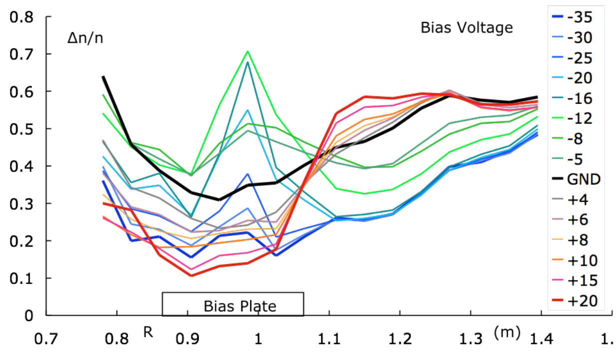

Fig. 3 Turbulence profiles for each bias voltage

Turbulence reductions are obtained for both negative and positive bias voltages. The radial profiles of density fluctuations (Δn_{rms}/<n>) for various values of bias are shown in Fig. 3. For positive bias, the reductions are localized to the region of the biased plate, whereas the reductions are more extensive in radius for negative bias. The details are complex.

A very general mechanism for turbulence reduction in a magnetized plasms is shear in the flow velocity [6], to which nearly all turbulence reductions in tokamaks are ascribed. To assess the role of velocity shear in producing these turbulence reductions, the plasma flow transverse to the toroidal magnetic field was measured spectroscopically from the Doppler shift of an argon ion line (Ar II 488.0 nm) along vertical chords through the plasma. The spatial resolution for the measurement was 1 cm. The measurement was integrated over a few seconds during which plasma parameters and turbulence were stationary. Fits to the velocity profiles are shown in Fig. 4, as are data points for zero bias. Since the stabilization depends only on the magnitude of the shear, that quantity is plotted in

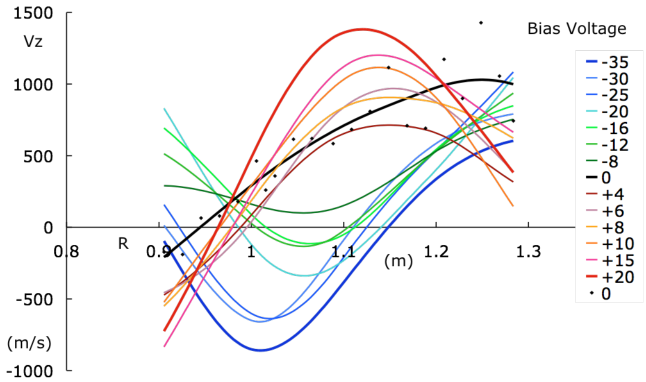

Fig. 4 Measured flow V_z (E_r x B_T)

Fig. 5., calculated from Fig. 4. The requirements for shear stabilization [6] are all met, provided only that the shearing rate is larger than the turbulence decorrelation rate (inverse auto-correlation time). Decorrelation rates are generally comparable with shearing rates, but both vary greatly with radius and bias. (The inequality can go either way but is unrelated to turbulence level or reduction, consistent with Fig. 6.)

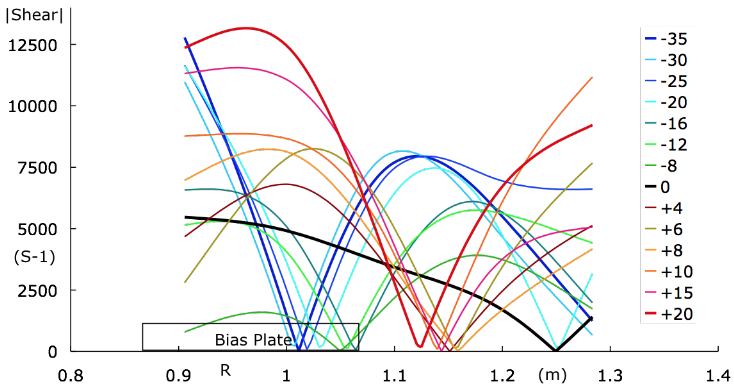

Fig. 5 Shearing rate

The observed relation between turbulence level and shearing rate may be represented in several ways; Fig. 6 is representative, but all lead to the same conclusion. Figure 6 plots turbulence level as a function of shear, collecting data from all radii and all bias values. The triangles denote points with bias for which the turbulence level is substantially reduced from the unbiased case at that radius. The lack of correlation is clear, with many instances of high turbulence levels at high shear and low, reduced turbulence at low shear. Similar results are seen in the simulation [1], which finds a strong reduction in turbulence above a threshold bias level, but with no general increase in shearing rate. In this experiment, high rates of flow shear do not (necessarily) reduce turbulence levels, and reduction of turbulence by biasing is not (necessarily) accompanied by high flow shear.

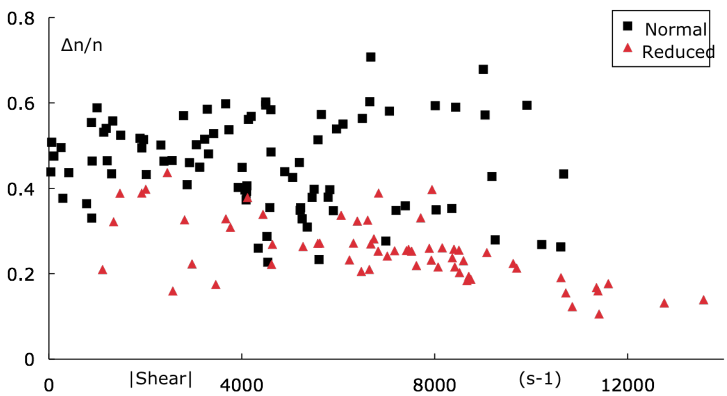

Fig. 6 Turbulence level vs. flow shearing rate

Work supported by the Department of Energy Office of Fusion Energy Sciences DE-FG02-04ER54766.

[1] B. Li, et al., Phys. Rev. E **83**,056406 (2011).

[2] K.W. Gentle and H. Huang, Plasma Science and Technology **10**, 1 (2008).

[3] P. Ricci, B.N. Rogers, S. Brunner, Phys. Rev. Lett. **100,** 225002 (2008).

[4] S.H. Müller, et al., Phys.Rev.Lett. **93**, 165003(2004).

[5] G. Van Oost, et al., Plasma Phys. Control. Fusion **45**, 621 (2003).

[6] P.W. Terry, Rev. Mod. Phy. **72**, 109 (2000).