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Texas Helimak

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Abstract Helimak is an experimental approximation to the ideal cylindrical slab, a one-dimensional magnetized plasma with magnetic curvature and shear. The Texas Helimak realizes this approximation to a large degree; the finite size of the device can be neglected for many phenomena. Specifically, the drift-wave turbulence characteristic of a slab is observed with scale lengths small compared with the device size. The device and the general features of its behavior are described here. The device is capable of studying drift-wave turbulence, scrape-off layer (SOL) turbulence, and the stabilization of turbulence by imposing velocity shear.

Keywords: plasma turbulence, drift waves, particle transport, turbulence suppression

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1 Introduction

Helimak concept arose from the observation that electron cyclotron resonance (ECR) breakdown in a tokamak not only ionized the gas but also produced a stable low-density plasma [1~3]. Although a toroidally symmetric magneto-hydrodynamic (MHD) equilibrium with closed magnetic surfaces requires a plasma current [4], the combination of a toroidal field with a small vertical field in a finite vacuum vessel − as is present at the breakdown in a tokamak − also admits a stable MHD equilibrium [5]. The small currents in the plasma required for equilibrium can flow in a loop closed through the vessel.

This Helimak magnetic configuration, a combination of toroidal and vertical magnetic fields in a finite toroidal vacuum chamber, approximates the infinite sheared cylindrical slab. The Helimak field has both curvature and shear. Although the field lines are open, if the Helical pitch is small and the connection length along the field from top to bottom is long, the end effects can be neglected and the equilibrium will depend on only the single radial coordinate.

The sheared cylindrical slab has considerable theoretical importance. Slab models are the simplest and the most tractable models of a confined plasma. Analytic calculations are the most extensive and computer simulations the most accurate for this case. Adding magnetic curvature and shear to the rudimentary slab are the minimal additions necessary to produce physically significant instabilities in the slab. Helimak is thus ideal for fundamental tests of the physics of plasma micro-turbulence.

This introduction to the behavior of the Texas Helimak is organized as follows: section 2 describes the Texas Helimak, section 3 surveys the plasma equilibria observed in the device, and section 4 briefly reviews the turbulence found. Section 5 adds the mechanisms for turbulence stabilization, and section 6 offers conclusions.

2 Texas Helimak device

The Helimak resembles a tokamak in having toroidal symmetry. It consists of a toroidal vacuum vessel, a set of sixteen toroidal field coils with 28 turns for each, and a set of three vertical field coils − 126 turns in the top and the bottom coils and 75 turns in the center coil. The minor cross-section of Texas Helimak is shown in Fig. 1. The magnetic field lines are helices, whence the Helimak draws its name, and the puncture plots of typical field lines at three radii are shown in Fig. 1. In standard cylindrical coordinates R, ϕ, z as shown in Fig. 1, the field lines on a surface of fixed R may be described as

$$z(\phi;\phi_0,R)=2\pi\alpha R^2(\phi-\phi_0)/R_0, \qquad (1)$$

where $\alpha=B_{\mathrm{v}}/B_{\mathrm{T}}$, the ratio of vertical (VF) to toroidal (TF) magnetic field at R_{o}, a fixed reference radius conveniently chosen in the middle of the vessel, and ϕ_o is the angle at which the field line crosses the $z=0$ midplane. The deviations from Eq. (1) are quite small for the Texas Helimak field coil set. The radial excursions of the field lines from toroidal ripple are a few millimeters at worst. The radial excursions caused by the radial components of the vertical field are less than a centimeter. Both TF and VF coils are driven by one 12-pulse SCR-controlled power supply capable of delivering 500 V at 1500 A. This suffices to place the cyclotron resonance at any radius within the vacuum vessel. The ratio α can be reduced from its maximum by adding an adjustable resistance in series with the VF coils. The value of α is most usefully described in terms of its physical consequence, the connection length, defined here as the length along the field line from top to bottom. The connection lengths at the center of the vacuum vessel ($R_o = 1.1$ m) can be varied from 10 m to several kilometers.

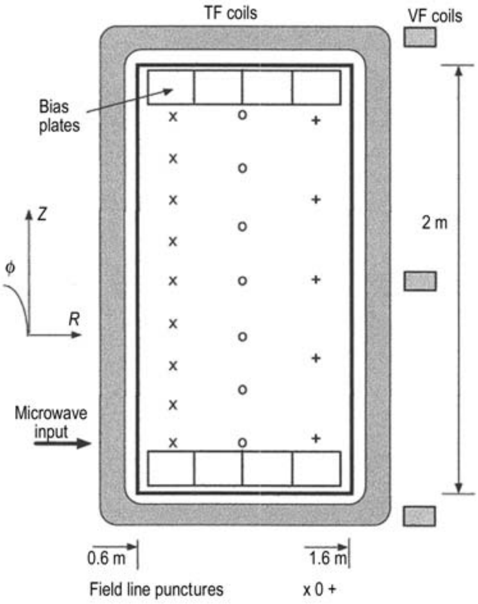

Fig.1 Cross-section of the Texas Helimak showing the major components and the standard coordinate system. Cylindrical symmetry axis to left. Magnetic field punctures of representative field lines at three major radii are shown

The plasma is produced by electron cyclotron resonance heating(ECRH) at the fundamental 2.45 GHz, the industrial standard microwave heating frequency. The power supply is a commercial 6 kW magnetron with additional LC filtering added to the three-phase full wave rectifier. A four-stub tuner matches the waveguide to the vacuum vessel cavity through a simple quartz waveguide window on the high field side as indicated in Fig. 1. With plasma, reflected power can generally be maintained below 4%. The window is sealed with low-loss silicone O-rings and cooled by forced air. Provided the ECRH resonance radius is at least 0.1 m greater than the radius of the inside wall, no failures will occur.

Although all systems are capable of continuous operation, the lack of water cooling of the TF coils imposes certain limitations. In practice, it is convenient to segment operation into distinct pulses, each at a fixed value of α, toroidal field, gas pressure, etc. This has the important consequence of permitting the use of MDS+ for data acquisition, archiving, and display. Individual pulses of 30 s provide excellent data sets. Given that several minutes are needed between shots to review the data and change settings, sequences of a hundred shots are possible before reaching the thermal limits for one day.

The vacuum vessel is of stainless steel with metal-sealed flanges developed for the TEXT tokamak [6]. Although the volume of almost 20 m^3 is pumped with only a 1000 L/s turbomolecular pump, base pressures on the 10^{-7} Torr scale are reached. Plasmas are produced in the noble gases: helium, neon, argon, and xenon. Satisfactory ECRH discharges are obtained for filling pressures from below 10^{-5} Torr to below 1 mTorr. (The upper pressure limit is determined by the pressure at which breakdown occurs at the microwave window, independent of magnetic field.) The gas is fed continuously through a controlled leak. The equilibration time for pressure changes is several minutes. A change in gas species requires an hour.

After a vacuum ventilation, several hours of pulses are required to clean the system. Thereafter, the discharge has the color characteristic of the filling gas, and the pressure does not change during the plasma discharge.

Although the magnetic field lines necessarily terminate on the top and the bottom plates of the vacuum vessel, it is advantageous to intercept them on the bias plates shown in Fig. 1. There are four sets of these plates, two on the top and two on the bottom, located 180° apart toroidally. The normal to the plate is in the ϕ direction, nearly in the direction of the magnetic field. Unless the pitch of the field lines is quite large (large α, short connection length), all field lines from the interior will be intercepted by a plate before reaching the top or the bottom vessel walls. The plates serve two purposes. First, they are a valuable surface for mounting Langmuir probes. The probes may be arrayed to cover all R and a range of z ($\sim$0.2 m). At present, the Texas Helimak has over 500 such surface probes. Second, the plates may be easily insulated and electrically isolated from the vacuum vessel. At each location, the plates are divided into four separate pieces, spanning a radial range of 0.2 m, as indicated in Fig. 1. In most cases, they are all connected to the vacuum vessel, but other connections are described in section 5.

The extensive array of Langmuir probes is the primary diagnostic for plasma measurement. In addition, a movable probe set at $R = 1.3$ m may be lowered from the top as much as 0.5 m below the top plate to measure the variations with z. A set of magnetic probes may be inserted radially from the outside 0.2 m into the plasma near the bottom plates. Spectroscopic instrumentation is being added to measure the bulk flow velocities from the Doppler shift of ion lines.

Data from the probes is acquired by two digitizers, one with 64 channels at a 7 kHz sampling rate and the other with 16 channels at a 100 kHz sampling rate. Both are equipped with isolation amplifiers for measuring probe current or potential. The slow digitizer is used for monitoring the profiles and measuring the probe characteristics to determine density, temperature, and floating potential. The fast digitizer is used for the fluctuation measurements. The Nyquist frequency of 50 kHz is much higher than typical fluctuation frequencies, which are below 5 kHz.

Table 1. Parameters of Texas Helimak

Gas	Helium	Argon
T_e (eV)	15	10
n (m^{-3})	$\leq 5\times10^{16}$	$\leq 1\times10^{17}$
B_ϕ (T)	0.05 to 0.13	0.05 to 0.13
$< R >$ (m)	1.1	1.1
$L_n = n/(dn/dr)$ (m)	0.1	0.1
c_s (m/s)	2×10^4	5×10^3
ρ_s (mm)	8	20
v_{de} (m/s)	10^3	10^3
β	3×10^{-5}	4×10^{-5}
ν_{ee} (s^{-1})	$\leq 10^5$	$\leq 2\times10^5$
Connection length $L_{\|\|}$ (m)	$500 \geq L_{\|\|} \geq 12$	$500 \geq L_{\|\|} \geq 12$
Neutral pressure (Torr)	$\geq 10^{-5}$	$\geq 10^{-5}$
ν_{en} (s^{-1})	$\geq 4\times10^5$	$\geq 4\times10^5$

3 Equilibrium plasmas

Typical plasma parameters obtained in the Texas Helimak are listed in Table 1. Here v_{de} is the electron diamagnetic drift velocity, the expected phase velocity of drift waves. Representative profiles of plasma density, temperature, and floating potential are shown in Figs. 2 and 3. The electron temperatures are of the order of 10 eV with broad profiles and values of one half to one third the ionization potential of the filling gas. The peak electron density corresponds to a plasma frequency somewhat below the ECRH frequency and occurs on the low field side of the resonance radius. The density falls off quickly on the high field side of resonance. On the low field side, the density profile may be broad, depending upon the conditions, especially the microwave power. There is one simple energy constraint on the plasma density. The total number of particles in the volume N is roughly fixed by the input power P_{in}, the particle loss time τ, and the total energy required per ionization E_o (~100 eV) as

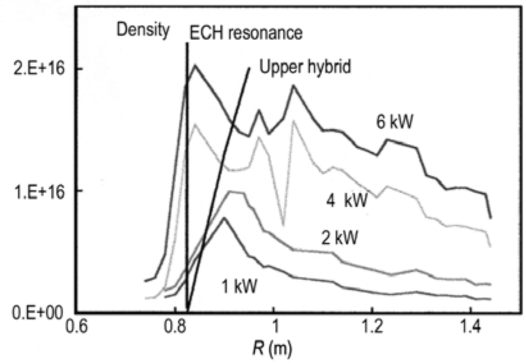

Fig.2 Representative density profiles for several levels of microwave power in helium

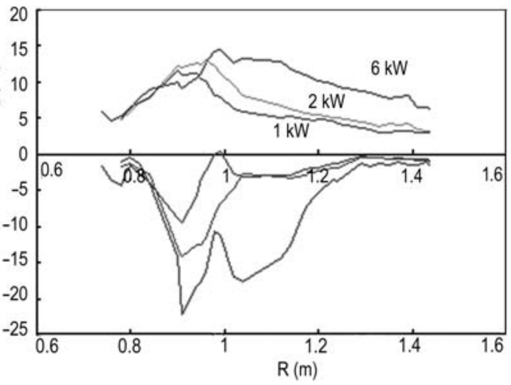

Fig.3 Representative temperature and floating potential profiles for several levels of microwave power in helium

$$N = \frac{P_{in}\tau}{E_o} = \frac{P_{in}L_c}{E_o c_s}, \tag{2}$$

where the second form assumes the losses are by parallel flow with L_c the connection length and c_s the sound speed, which is correct if L_c is not too long. This loss rate is the usual result for the SOL[7,8], to which the Helimak closely resembles. The breadth of the density and the temperature profiles involves some complex physics including the upper hybrid resonance. For a simple density profile, the upper hybrid resonance would occur at a specific radius, just like the cyclotron resonance. However, as will be described in section 4, these plasmas are highly turbulent with large density fluctuations. There is a broad range of radii for which the upper hybrid resonance condition will be met sometimes during the density variation. This produces a sort of "turbulent broadening" of the absorption region for the microwave power.

The movable probe shows no variation with z. For connection lengths below 100 m, the top and the bottom probes show identical profiles. The equilibrium is indeed one-dimensional, depending only on R, not on z or ϕ. At longer connection lengths, asymmetries develop between top and bottom as the cross-field drifts compete with the smaller component of c_s in the z direction.

Neutral gas pressure (density) has little effect on the equilibrium plasma. Gas species likewise has little effect except that the lower ionization potential correlates with the higher density, other things being equal. The profile shapes are nearly invariant for changes in toroidal field, remaining fixed with respect to the cyclotron resonance radius. A corresponding invariance for fluctuations is illustrated in Fig. 4.

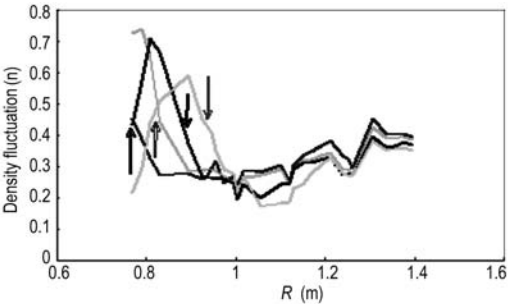

Fig.4 Profiles of fractional density fluctuation level for several toroidal fields. The arrows indicate positions of the ECRH resonance, the position where the toroidal field located is 0.087 T

4 Characteristics of turbulence

Theoretically, the Helimak configuration is MHD stable provided the vertical field is sufficient to meet the Sudam[5] criterion, not very restrictive for these low-density, low-temperature plasmas. In practice, only if the vertical field coils are open is there occasional indication of MHD instability. However, the plasma is always in a nonlinearly saturated state of microturbulence, fluctuations with correlation lengths perpendicular to the magnetic field of the order of 0.1 m. Representative levels of fractional density fluctuations, $\Delta n/n$, are shown in Fig. 4, although the standard deviation is often an inadequate description of fluctuations that are generally not Gaussian.

Although the plasma is always turbulent everywhere, the causes are diverse. The highest fractional levels at the left of Fig. 4 are simply turbulent spreading from the density maximum into the steep density gradient on the high field side the ECRH resonance as shown in Fig. 2. The turbulence near the density maximum is difficult to describe analytically. Fluid codes[9] indicate a mixture of Rayleigh-Taylor and Kelvin-Helmholz instabilities depending upon conditions. These codes are applicable to a tokamak SOL. Work is continuing to use the Texas Helimak as a simple and well-diagnosed test case for the codes. In the region of density gradient on the right side of Fig. 2, the unfavorable magnetic curvature drives drift waves unstable. This region has been analyzed by PEREZ, et al[10]. Some typical signatures of drift waves are shown in Fig. 5. The density fluctuations at two probes displaced by $\Delta z = 0.04$ m in the bias plates are highly coherent and have a phase difference increasing linearly with the frequency, a linear dispersion relation. The phase velocity − in the direction perpendicular to **B**, and the density gradient − matches the diamagnetic drift velocity at the location of the probes, as expected for drift waves, and the wavelengths likewise span the range of $k\perp\rho_s$ expected for unstable drift waves.

The statistical analysis used to extract characteristics of the turbulence[11] as in Fig. 5, is part of an extensive suite of data analysis tools coupled to the MDS+ database on the Texas Helimak. The tools also includes auto and cross correlation, FFT, PDF, $S(k,\omega)$, bispectra, R/S statistic (the rescaled, adjusted-range statistic for estimation of the Hurst exponent), conditional averages, and turbulence-driven particle fluxes, as well as the programs to analyze Langmuir probe characteristics. The various statistical measures are obtained with high accuracy and low noise. The stationary phase of a shot produces data sets with over 10^6 points for analysis.

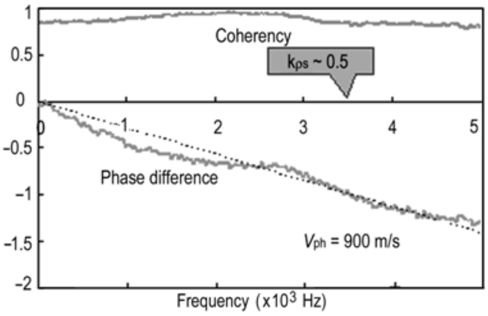

Fig.5 Cross-spectrum between two probes separated in z by 0.04 m at $R = 1.2$ m, in a region of density gradient. The Fourier spectrum is broad, decreasing to higher frequency, and there is significant power over the full range of frequencies shown. The coherency is high, and there is a well-defined phase difference between the probes that increases almost linearly with the frequency. A line corresponding to a phase velocity of 900 m/s is shown. This line is a reasonable fit to the data and is also consistent with the diamagnetic drift velocity for this case. The range of frequencies shown corresponds to $k\rho_s < 1$

5 Turbulence stabilization

A unique feature of open field lines is the ability to affect the plasma potential on the field line by biasing the conductor on which the line terminates. In a strongly magnetized plasma with weak cross-field conductivity, the plasma would simply "float" up or down with the potential of the end plates. For the Texas Helimak as shown in Fig. 1, if all four bias plates at a particular range of R were connected together, the entire annular region would be affected by an applied bias. (This analysis applies only for $L_c > 50$ m; for shorter connection lengths and steeper pitches, some field lines miss the plates and terminate directly on the vessel.) The bias thus induces a radial electric field between the biased annulus and the adjacent plasma. The radial electric field causes an $\mathbf{E}\times\mathbf{B}$ drift velocity in the z-direction, analogous to the poloidal direction in a tokamak. The velocity will be localized and produce a velocity shear. For sufficiently high shear, the turbulence should be stabilized[12]. This offers the possibility of a direct, controlled test of shear stabilization of turbulence.

The possibility has been realized. For the experiments described here, the four plates second from the inside were connected together and biased. The turbulence reduction is illustrated directly in Fig. 6, which shows time traces of the ion saturation current from eleven probes distributed radially across the profile.

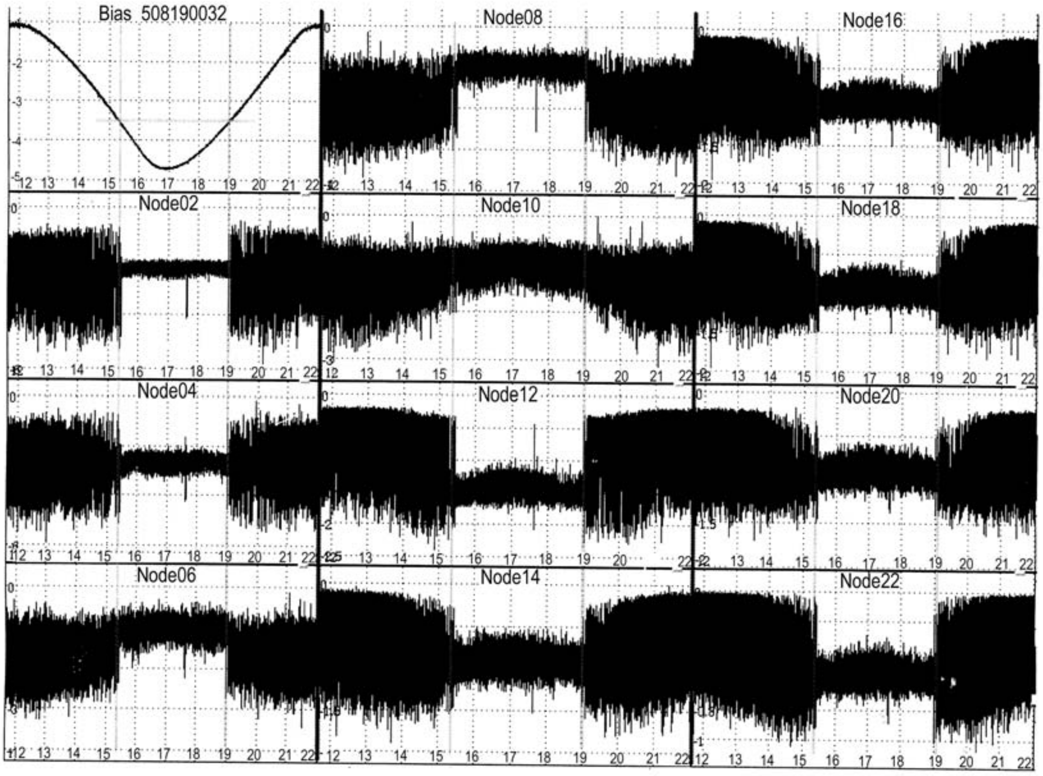

Fig.6 Time traces of negative bias voltage and ion saturation current from eleven probes during a shot of 22 sec duration as displayed on an MDS scope. The vertical lines indicate the times of transition between high and low turbulence states. The horizontal line on the voltage trace indicates that the transition occurs at the same voltage in both directions.

(Ion saturation current is negative; zero is near the top of each panel.) The time history of the (negative) bias voltage is shown in the panel at the upper left. At a critical threshold voltage, the fluctuation level at most positions abruptly decreases to a much lower level and remains there until the bias voltage returns across the threshold, where upon the turbulence immediately returns to its former level. The stabilization is a bifurcation with no indication of intermediate states or a gradual transition. There is no hysteresis, as occurs for a conventional H-mode.

The lack of hysteresis is plausible because the stabilization of turbulence has little effect on the underlying equilibrium, breaking the usual self-consistent feedback loop in which the equilibrium determines the turbulence transport level, which in turn determines the equilibrium. The Helimak equilibrium is determined largely by parallel flows to the ends, not radial turbulent diffusion. More surprising is the bifurcation since most theories predict a gradual weakening of the instability as the velocity shear approaches the value needed for complete stabilization.

The stabilization is a robust phenomenon that occurs for a wide variety of conditions in all gases. It occurs for both negative and positive bias, although at very different bias voltages. The process is more complex than the simple picture described above. Specifically, the cross-field conductivity is significant; the biased plates draw a substantial current. The threshold current is several amperes for both positive and negative bias, and a current distribution among all the plates is necessary for stabilization. Circumstantial evidence suggests that the $\mathbf{j} \times \mathbf{B}$ force from the radial current is driving the flows and flow shear. Further experiments and direct measurement of the flow velocity will be required to resolve these questions.

The complexity is also illustrated by the variety of responses shown at different radii in Fig. 6. The reduction in turbulence level is much stronger at some radii than at others, and the mean density increases at some radii (node 12), but decreases at others (node 8). At small radii, inside the peak of the density profile, the stabilization effect becomes weak (node 10).

6 Conclusion

The Texas Helimak is a useful device for basic studies of plasma turbulence and transport. It produces a simple one-dimensional equilibrium with magnetic curvature and shear that is subject to the same instabilities found in confined plasmas and SOL. The analysis is easier and the measurements more complete in the Helimak. The Texas Helimak is also capable of producing states of greatly reduced turbulence by biasing, which should be useful for exploring the mechanisms of flow-driven turbulence stabilization.

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