fluctuations and stability of plasmas in the H-1NF heliac


Abstract

The H-1NF heliac is a medium-sized helical axis stellarator experiment with major radius $R = 1$ m, and average plasma minor radius $a = 0.15–0.2$m. Its ‘flexible-heliac’ [2] coil set permits considerable variation in the low-shear rotational transform profile in the range $0.6 < \iota < 2.0$ and variable average magnetic well. Variation of the rotational transform is effected by changing the relative currents in the axisymmetric circular coil and the helical trim coil that is wrapped around it (figure 1). For the experiments described in this paper, the rotational transform was in the range $1.1 < \iota < 1.5$.

H-1NF is currently operated in two modes. At low toroidal fields (≤0.2T), up to 100kW of 7MHz helicon heating is applied [3] using helical picture frame antennas to produce argon and helium plasmas with $T_i = (20–40)$ eV, $T_e = (6–30)$ eV, $n_i(0) \sim 1 \times 10^{18}$ m$^{-3}$. At a higher toroidal field (0.5 T), the same heating system produces similar plasmas using 7 MHz ICRF in 50%/50% H–He mixtures. The argon plasmas are cool enough to be extensively diagnosed using electric and magnetic probes, and visible spectroscopy.

The ultimate design ratings of the H-1NF facility are: toroidal magnetic field $B = 1$ T and heating power $P \approx 500$ kWe. Plasmas have been successfully produced at 0.5 T with 200 kW of 2nd harmonic ECH at 28 GHz and 160 kW of ICRF, but these plasmas have not been diagnosed in detail as yet.

1. Introduction

The H-1NF [1] is a medium-sized helical axis stellarator experiment with major radius $R = 1$ m, average plasma minor radius $a = 0.15–0.2$m. Its ‘flexible-heliac’ [2] coil set permits considerable variation in the low-shear rotational transform profile in the range $0.6 < \iota < 2.0$ and variable average magnetic well. Variation of the rotational transform is effected by changing the relative currents in the axisymmetric circular coil and the helical trim coil that is wrapped around it (figure 1). For the experiments described in this paper, the rotational transform was in the range $1.1 < \iota < 1.5$.

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2. Turbulent transport and zonal flows

In helicon-wave heated argon plasmas at toroidal field $B_t \sim 0.1–0.2$ T, the ion-Larmor radius is large compared with the system size ($\rho_i/a \sim 0.2$). The entire H-1NF plasma thus resembles that in the edge of a large, high power toroidal device.

Plasmas in this operational regime exhibit spontaneous confinement transitions at very low powers ~60 kW [4] from a low-density mode showing a spectrum of coherent drift-type oscillations to a quiescent mode where the fluctuations drop dramatically (figure 2). These transitions have been found [4, 5] to exhibit many of the features seen in L–H transitions in large toroidal devices at much higher temperatures and powers. The features observed include a sharp rise in density accompanied by a strong reduction in fluctuation levels and local fluctuation-induced transport. The density profile peaks, and the electric field becomes more negative, as shown in figure 3.

Recent confinement transition experiments have examined the relative particle fluxes for the ions and electrons separately using a five probe array [6]. This array is comprised of two radially-separated ($\Delta r = 15$ mm) triple-Langmuir probes for measuring radial electric fields, two poloidally-separated (by 30 mm) triple-Langmuir probes for measuring temperature, density, and poloidal electric fields and their fluctuations, and a radially-oriented Mach (or paddle) probe for measuring
radial ion velocities and their fluctuations [7]. All the probes were carefully aligned to the heliac flux surfaces with electron beams.

The fluctuation-induced electron flux is assumed to come solely from $\tilde{E}_p \times B_t$, where $\tilde{E}_p$ is the fluctuating poloidal electric field and $B_t$ is the toroidal magnetic field, and is determined from

$$\Gamma_{\text{e}} = \langle \tilde{n} \tilde{V}_e \rangle = \langle \tilde{n} \tilde{E}_p \rangle / B_t$$

The fluctuation-induced ion flux is estimated independently from the Mach probe measurements of fluctuating radial ion velocities as

$$\Gamma_{\text{i}} = \langle \tilde{n} \tilde{V}_i \rangle$$

In the regions of maximum fluctuation, the $\tilde{E}_p / B_t$ velocity $\sim 2\,\text{km}\,\text{s}^{-1}$, while $\tilde{V}_i$ is found to be $10\times$ smaller [6, 7]. Thus, the electron and ion fluxes can differ, and the transport can be non-ambipolar. In retrospect, this is not surprising in a plasma in which the ion Larmor radii are large.

Figure 4 shows how the fluctuation-induced fluxes measured with the probe arrays combine with the other losses (neoclassical fluxes and direct ion-orbit losses) to determine the radial electric field which keeps the plasma charge neutral in the heliac. At the L–H confinement transition, the fluctuations and their associated electron particle flux suddenly decrease. The resulting change of the radial electric field can be estimated from Poisson’s equation to be $\Delta E_r = -(e\Gamma_{\text{AN}} \Delta t) / (\epsilon_0 \varepsilon_\perp)$, where $\Gamma_{\text{AN}}$ is the non-ambipolar fluctuation-induced flux before the transition, $\Delta t \approx 1\,\text{ms}$ is the transition time, and $\epsilon_0 \varepsilon_\perp$ is the dielectric constant. Figure 3 shows that this estimate agrees with the overall change in the electric field profile at the L–H transition.

The probe studies have also been used to identify zonal flows in low-field H-1NF discharges [8]. Zonal flows are generated by inverse turbulent cascades, and are an important candidate mechanism for self-regulation of plasma turbulence and transport [9].

The H-1NF measurements reveal strong electric field fluctuation components at low frequency that are poloidally symmetric, radially localized, and do not produce any fluctuation-induced particle transport. Bi-spectral analysis of the probe signals shows that the summed bi-coherence is large at low frequencies, indicating that the phase coupling is strong.
Fluctuations and stability of plasmas

Figure 2. (a) Visible light picture showing the rf-produced plasma filling the heliac inside the helical winding structure. (b) Plasma waveforms for low-to-high confinement transition in a low-field discharge.

Figure 3. Electron density and electric field profiles (both measured with Langmuir probes) in low and high confinement helicon-wave heated argon plasmas in the H-1NF heliac.

Figure 4. Measured electron and ion fluxes and electric field profiles before and after the L–H transition, $\Delta E_r$ is the change in electric field due to the sudden suppression of the non-ambipolar turbulent particle flux at the transition.

Figure 5. Radial profiles of fluctuation-induced particle flux (---) and low-frequency electric-field zonal flow (——) in the L-mode heliac discharge.

Figure 6 shows another example of radial electric field generation, this time in a high-mode discharge. After an early transition to the high mode, the radial field shear continues to increase, reaching $>50 \text{kV m}^{-2}$. The density rises further, and additional fluctuations arise; we, thus, classify these discharges as ‘fluctuating high-confinement modes [10]’. In the example shown in figure 4, at $t = 50–52 \text{ ms}$, low-frequency (1 kHz) fluctuations in the electric field develop, and at $t = 56 \text{ ms}$, these increase in amplitude. These low-frequency structures also have the characteristics of zonal flows with $k_r > k_{pol}$. The poloidally-symmetric flows do not

and that spectral energy is being transferred from high to low wave numbers, as would be expected for zonal flows.
themselves carry particle flux, but do modulate the measured fluctuation-induced particle flux, as is also shown in figure 6.

3. Configuration resonances and magnetic fluctuations

The variation of the rotational transform has long been seen to have a strong effect on confinement in low-shear stellarators [11]: as the transform passes through rational values $\tau = n/m$, the plasma confinement decreases. It can be shown theoretically [12] that the pressure gradient at a rational magnetic surface tends to zero. Experimentally, the best confinement in low-shear stellarators is generally obtained when the rotational transform falls close to, but not on, major resonances [13]. Evidence of similar fine structure near rational surfaces has also been seen in tokamak experiments, most clearly in the RTP device [14].

In the H-1NF heliac, the rotational transform can be varied by changing the relative currents in the circular and helical core windings. The installation of a new, high precision power supply with very low ripple (1 part in $10^{6}$) allows this to be done precisely in very small steps of $\Delta \tau = 0.0025$.

For the present experiments, ICRF plasmas in fully magnetized H–He plasmas, at $B = 0.5$ T, with heating powers of 60–100 kW, at a frequency of 7 MHz were used. The temperature and density ranges are similar to those for the low-field argon plasmas described in section 2 ($((1–2) \times 10^{10})$ cm$^{-3}$ and 10–40 eV), but the ion-Larmor radius is much smaller at the higher field, $\rho_i / a \sim 0.01$. These plasmas do not show the large amplitude, coherent drift-type oscillations seen in the low-field argon plasmas, but have low level ($\delta E_p / E_{\text{th}} \leq 5 \times 10^{-3}$), coherent oscillations in the poloidal field measured outside the plasma.

For these experiments, variation in the relative currents in the helical and circular core windings was used to vary the rotational transform profile over the range $1.1 < \tau < 1.5$, as shown in figure 7. As the ratio of the helical winding current to the ring coil current ($\kappa_0$) is increased, the transform on the magnetic axis increases. This introduces a central region of positive shear (in the tokamak sense, with $dq/dr > 0$, where the safety factor $q$ is $1/\tau$), which changes to negative shear ($dq/dr < 0$) in the outer portion of the plasma. This situation is the inverse of that seen in a reversed-shear tokamak, where $dq/dr < 0$ in the plasma core, and $dq/dr > 0$ in the outer region. The value of $\tau$ at the inflection point of the profile where $\tau = 0$ is important in characterizing our experiments, as is the value of $q(q' = 0)$ in reversed-shear tokamaks [15]. The plasma–antenna spacing (and coupling) remain approximately constant over this scan.

All the configurations in the scan illustrated in figure 7 have average magnetic wells, ranging in depth from 0.5%, for zero helical winding current ($\kappa_0 = 0$), to $\sim 5\%$ ($\kappa_0 = 1.2$). Vacuum field studies of H-1NF [16] have shown that islands at major rational surfaces ($\tau = 3/4, 5/4, \text{etc}$) are small ($\leq 2$ cm), and are typically observed when the resonance is located at the plasma edge [9]. The plasma pressure is negligible, so the actual field structure with the plasma present should be very close indeed to that of the vacuum field.

Extensive transform scans with constant gas feed and heating power show a complex structure in confinement as a function of rotational transform. Figure 8 shows the plasma line-averaged density (measured by microwave interferometry) at a fixed reference time in the discharge (the results are qualitatively similar with other choices of reference time), plotted as a function of the rotational transform at the inflection point in the transform profile, $\tau(\tau' = 0)$. The transform varied in sequences of discharges with very small steps in transform $= 0.0025$, which is within the control and ripple accuracy of the precisely controlled power supplies built for this purpose. Also shown as a function of $\tau(\tau' = 0)$ are the radial locations of major rational transform values and the magnitudes of the coherent fluctuations in the poloidal magnetic field measured using Mirnov coils separated poloidally by 5 cm (for coherence determination) outside the plasma, divided into frequency bins 2 kHz wide [17].

We first consider the density variation with rotational transform. The density shows sharp drops exactly at the points where $\tau(\tau' = 0) = 6/5$ and $5/4$, and just above $\tau(\tau' = 0) = 4/3$. These are the lowest order resonances present in the H-1NF field structure. This strong correlation at three critical points is not obtained if other values of transform on the profile are used as the independent coordinate, for example, the rotational transform on-axis or at the plasma edge (the latter value has been found to correlate well with resonant confinement effects in the W7A [11] and W7AS [13] devices). If we take the density maxima and minima as proxies for confinement, this finding suggests that the inflection point in the transform plays an important role in confinement in H-1NF, as does the inflection point in $q(r)$ in reversed-shear tokamaks [15].

We now examine the correlation of magnetic fluctuations with resonances in figure 8. On the three principal resonances, $\tau(\tau' = 0) = 6/5, 5/4, \text{and } 4/3$, the fluctuations actually show...
**Figure 7.** Rotational transform profiles and flux surfaces for a helical winding current scan in the H-1NF heliac. Average minor radii (determined computationally from the cross-sectional area) are used because of the strongly non-circular shape of the flux surfaces.

minima. However, as \( t(t' = 0) \) approaches the resonances from below, strong fluctuations are seen. The details of the behaviour of the density in these regions differ somewhat for the three resonances.

1. Below the 6/5 resonance, the fluctuations and density decrease together as \( t(t' = 0) \) approaches 6/5, for which the inflection point \( \rho(t' = 0) \), is near the magnetic axis. Note that the \( t = 6/5 \) resonance is moving inwards in minor radius as the fluctuations decrease. Both the density and fluctuations increase to the right of the resonance.

2. Below the 5/4 resonance, the fluctuations and density decrease together gradually as \( t(t' = 0) \) approaches 5/4 and then drop sharply as the inflection point hits the resonance at a normalized radius \( \rho \approx 0.25 \). Again, the fluctuations decrease as the \( t = 5/4 \) resonance moves inwards in minor radius. A further increase in \( t(t' = 0) \) above the 5/4 resonance causes the density to recover, and the fluctuations to increase again. There is a narrow peak in density just above 5/4 that falls as fluctuations rise.

3. Below the 4/3 resonance, in the region \( 1.3 < t(t' = 0) < 1.33 \), the fluctuations increase strongly, while the density drops proportionally. However, as \( t(t' = 0) \) increases so that the transform profile becomes double-valued, crossing 4/3 both near the centre and the edge (at normalized minor radius \( \rho \approx 0.6 \)), the fluctuations begin to decrease, while the density increases. When the two resonant points \( t = 4/3 \) merge just outside the half radius, the density is at a local maximum and the fluctuations are small. A small further increase in \( t(t' = 0) \) causes the plasma density to collapse, with a large gap of poor confinement.

Other features on the graphs suggest similar behaviour near other resonances. There is a density peak just below the \( 11/9 \) resonance that drops on the resonance itself. As \( t(t' = 0) \) approaches 7/5, the fluctuations rise and then fall at the resonance, and the density rises and then falls as \( t(t' = 0) \) passes 7/5. The region near the 9/7 resonance shows decreased fluctuations, but confinement is maintained on this higher order resonance.

The maxima in magnetic fluctuations generally occur when resonances fall in the gradient region \( 0.6 < \rho < 0.8 \), which suggest that the fluctuations are pressure-driven. This would also explain why the fluctuations vanish when major resonances (such as \( t = 5/4 \) and \( 4/3 \)) are in regions of zero shear: the confinement and heating of the plasma are strongly suppressed, and there is simply no pressure to drive fluctuations.
Figure 8. Density (middle plot), magnetic fluctuation amplitudes (top plot) at reference time (on density flat-top at \( t = 40 \) ms) in a sequence of discharges in rotational transform scan. The rotational transform at the inflection point of the profile (see figure 6) is the independent variable. The bottom plots show how the radial locations of the principal resonances change during the scan. The resonances \( \ell = n/m \) are ordered by \( 1/m \), where \( m \) is the poloidal mode number.

Phase measurements of the coherent magnetic fluctuations from the two available probes have been used to show that the fluctuations have a poloidal spectrum with effective mode numbers \( \sim 4-8 \). The poloidal mode spectra (measured by cross-coherence signal processing techniques [17]) are broad, as would be expected for the strongly shaped heliac magnetic surfaces. The individual spectrograms typically show multiple coherent bands whose detailed structure varies with the rotational transform. Additional measurements (now in progress) with a more widely spaced array of coils are needed to make better mode number determinations, especially in view of the non-circular shape of the flux surfaces.

Limited measurements of coherent radial magnetic field fluctuations inside the plasma have been made using a movable magnetic probe. These studies are complicated by probe effects—the insertion of the probe inside a the plasma causes the density to drop—and so the results must be interpreted cautiously. Figure 9 shows a plot of radial magnetic field fluctuations at the time of interest near the density maximum as a function of the radius for a nominal configuration (the bottom-most curve in figure 7), which is compared for reference to the electron density profile as measured by tomographic FIR interferometry [18]. The fluctuations appear to peak in the gradient region at a normalized radius of 0.7, with a maximum of \( \sim 20 \) G. This peak falls near the \( \ell = 6/5 \) resonance for this configuration.

Since the magnetic fluctuation frequencies are low (typically most of the signal energy is \( \leq 50 \) kHz), it may be appropriate to consider a magnetic island model. Using an analytical estimate [19] for the size of the magnetic island width corresponding to such a perturbation yields

\[
\delta \approx 4 \left( \frac{R_0}{mtr_s} \right)^{1/2} \sim 8 \text{ cm}
\]

assuming a mode number \( m = 4-6 \) and shear as shown in figure 8. This is comparable to the width of the radial magnetic fluctuation peak in figure 9. Such a macroscopic island could reduce confinement by decreasing the effective confinement volume.
The observations of fluctuation activity in H-1NF when resonances are located in the pressure-gradient region, coupled with the experimental identification of similar fluctuations in other currentless stellarator/heliotron devices (Heliotron-E [21], ATF [22], CHS [23], LHD [24], W7AS [25]) as resistive interchanges, make it tempting to conclude that the H-1NF fluctuations are also interchanges. However, in H-1NF, the magnetic fluctuations are correlated with an apparent decrease in confinement that has not been attributed to the interchanges seen in the other experiments. This could be a consequence of the reversed shear in many of the H-1NF configurations studied here.

The importance of shear reversal in the H-1NF experiments suggests a possible point of comparison and contrast with reversed-shear tokamaks. For example, in the JET device [15], transitions to enhanced confinement with transport barriers have been regularly obtained by driving the shear reversal point close to major integer resonances such as $q = 2$.

In the experiments on H-1NF described here, both the confinement and the fluctuations begin to decrease just below resonances such as $t = 6/5$ and $5/4$. Here, the zero shear radius is in the core of the plasma, $\rho (t' = 0) < 0.5$. However, at higher $t$ resonances such as $9/7$ and $4/3$, $\rho (t' = 0) > 0.5$, and confinement is maintained with $t$ just below the resonance. This suggests that the degree of shear reversal and location of the zero shear point relative to the pressure profile are important to both equilibrium and stability.

5. Future plans

To extend the range of our transport studies into parts of the low-field heliac plasmas inaccessible to probes, we are developing a 20-channel visible spectroscopy diagnostic [26]. Its first application is to measure an effective diffusion coefficient $D_{\text{eff}} = \Gamma (r) / (dn / dr)$ using argon-ion line intensity profile measurements of $n_e (r)$, argon-neutral atom line measurements of the neutral density profile, triple-probe measurements of $T_e (r)$ and coronal equilibrium to compute the particle flux $\Gamma (r)$ from the ionization rate.

Future experiments will address this question with more detailed studies of the poloidal and toroidal spectra and correlation lengths of the magnetic fluctuations, and Langmuir probe turbulent transport measurements in the outer part of the plasma. Additional heating power ($\sim 200$ kW, 28 GHz ECH, and $<200$ kW ICRF) is now becoming available, and will ultimately allow the confinement and fluctuation studies to be extended to higher temperature plasmas.

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