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

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Abstract. The H-1NF heliac is a medium-sized heliac stellarator experiment with major radius R = 1 m, average plasma minor radius a = 0.15–0.2 m. Its "flexible-heliac" coil set permits extraordinary variation in the rotational transform profile and magnetic well. Experiments in low-field (B < 0.2 T) argon plasmas heated by helicon waves have yielded fundamental results on turbulent transport and confinement transitions, in particular concerning non-ambipolar flows, electric fields, and zonal flows. At higher field, (0.5 T), the device can be operated with precise (<1%) control of the rotational transform profile. Configuration scans with H-He plasmas heated by up to 100 kW of ICRF show resonance phenomena in confinement that correlate with changes in the characteristics of coherent magnetic field fluctuations.

1. Introduction

The H-1NF heliac [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 extraordinary variation in the low-shear rotational transform profile in the range $0.6 < \iota < 2.0$ and variable average magnetic well. For the experiments described in this paper, the rotational transform was in the range $1.1 < \iota < 1.5$.

H-1NF is presently operated in two modes. At low toroidal field (≤ 0.2 T), up to 100 kW of 7 MHz 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, $n_e(0) \sim 1\times10^{18}$ m^{-3} At high 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 that they can be extensively diagnosed using electric and magnetic probes and visual spectroscopy.

The ultimate design ratings of the H-1 facility are toroidal magnetic field B = 1 T and heating power P ≈ 500 kW. 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.

2. Turbulent transport and zonal flows

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

Plasmas in this operational regime exhibit spontaneous L-H confinement transitions at very low powers ~ 60 kW [4]. The L-mode plasmas show large (10-20%) coherent fluctuations in density (Fig. 1) and potential (Fig. 2), while the H-mode plasmas are relatively quiescent.

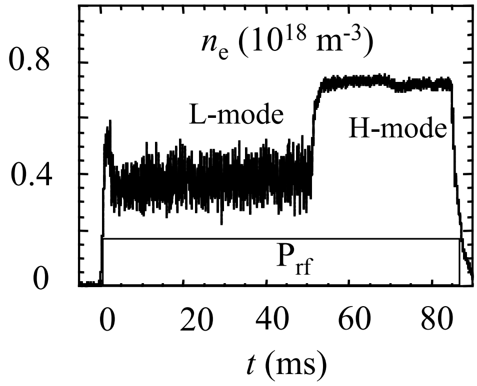

Fig. 1. L-H transition in low-field discharge in the H-1NF heliac.

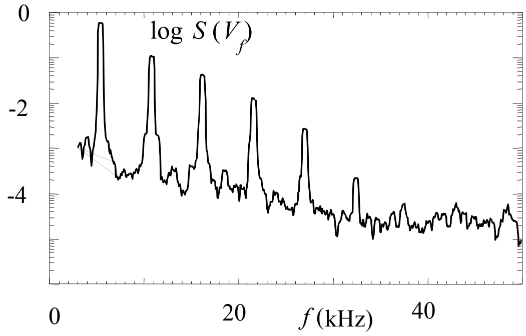

Fig. 2.Power spectrum of potential fluctuations in L-mode.

Probe studies [4-6] have shown that at the L-H transition, the fluctuation driven particle flux is reduced and the electric field shear increases. Recent experiments have examined the relative particle fluxes for the ion and electrons separately using Mach probes [6] . These results show that the ion and electron fluxes are different (Fig. 3), because of the much lower turbulent fluctuations in the ion velocity. The non-ambipolar flux combines with the neoclassical fluxes and ion orbit losses to determine the radial electric field which keeps the plasma charge neutral. At the L-H transition, the fluctuations and their associated (non-ambipolar particle flux suddenly decrease, and the resulting change of the radial electric field can be estimated from Poisson's equation to be $\Delta E_r = -(e\Gamma_{AN}\Delta t)/(\varepsilon_0\varepsilon_\perp)$, where Γ_{AN} is the non-ambipolar turbulent flux *before* the transition, $\Delta t \approx$ 1 ms is the transition time, and $\varepsilon_0\varepsilon_\perp$ 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.

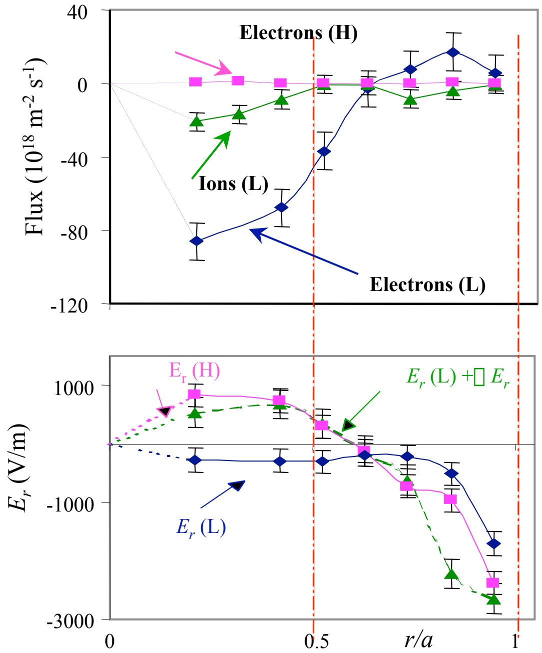

Fig. 3. Measured electron and ion fluxes and electric field profiles before and after the L-H transition, ΔE_r is the change in electric field due to the sudden suppression of the non-ambipolar turbulent particle flux at the transition.

Probe studies have also been used to identify zonal flows in low-field H-1NF discharges [7]. Strong radial electric field fluctuations at 4 kHz are poloidally symmetric, radially localised, and do not produce any fluctuation-induced particle transport. Bi-spectral analysis of the probe signals shows that summed bi-coherence is large at low frequencies, indicating that the phase coupling is strong and that spectral energy is being transferred from high to low wave numbers. Figure 4 shows an example of zonal flow generation in an H-mode discharge in which the an increase in radial electric field shear to very high values (50 kV/m^2) coincides with the appearance of low-frequency (~1 kHz) zonal flow structures with $k_r > k_{poloidal}$).

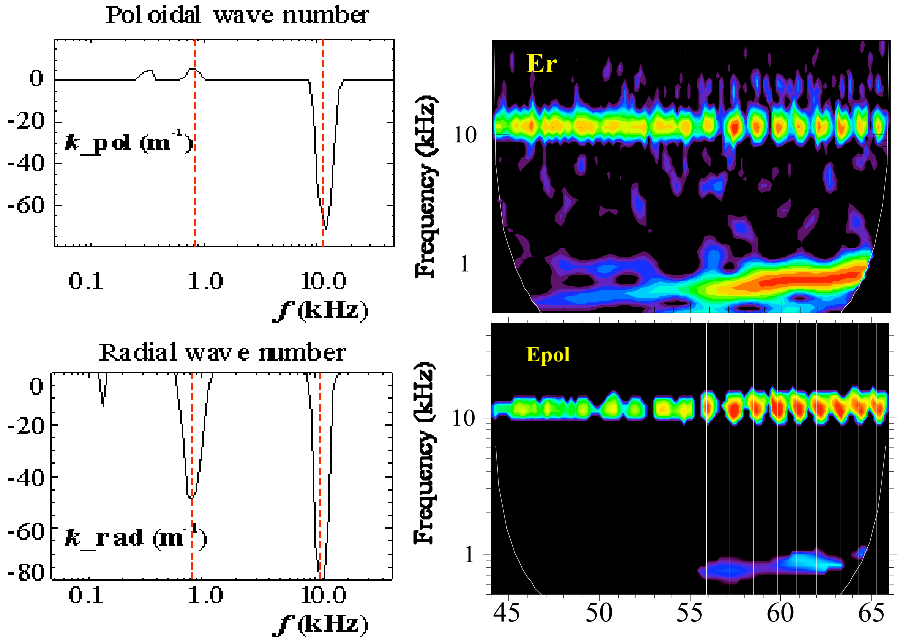

Fig. 4. Electric field spectra in low-field H-1NF discharge. A strong zonal flow appears at 1 kHz at t = 55 ms.

To extend the range of our transport studies into plasmas inaccessible to probes, we are developing a 20 -channel visible spectroscopy diagnostic [8]. Its application in our low-field partially-ionised argon plasmas is to measure an effective diffusion coefficient $D_{eff} \equiv \Gamma(r)/(dn/dr)$ using argon-ion line intensity profile measurements of $n(r)$, triple-probe measurements of $T_e(r)$ and coronal equilibrium to compute the particle flux $\Gamma(r)$ from the ionization rate. The resulting profiles of D_{eff} show that confinement improves in the outer half of the plasma in H-mode.

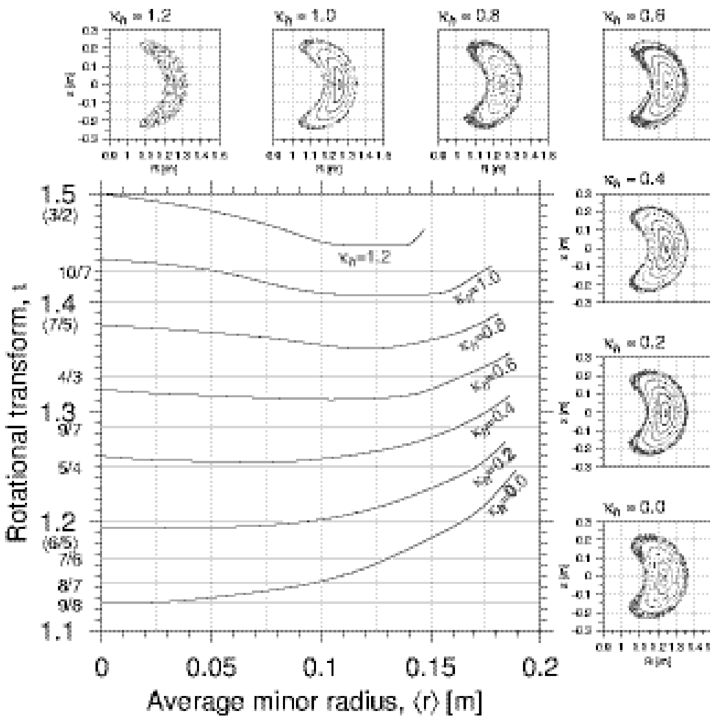

Fig. 5. Rotational transform profiles and flux surfaces for a helical winding current scan in the H-1NF heliac,

3. Configuration resonances and magnetic fluctuations

High precision scans of rotational transform (ripple in rotational transform < 0.5%) were used to study configuration effects in ICRF plasmas in fully magnetized H-He plasmas at B = 0.5T. For these experiments, the current in the helical hard core winding was used to vary the rotational transform profile over the range $1.1 < \iota < 1.5$, as shown in Fig. 5. Vacuum field studies have shown that islands at major rational surfaces (ι= 3/4, 5/4. etc.) are small (< 2 cm) [9].

Extensive transform scans with constant gas feed and heating power show a complex resonant structure in confinement as a function of rotational transform. Figure 6 shows the plasma line-average density (measured by microwave interferometry) at a fixed reference time in the discharge (the results are qualitatively similar with other choices of reference time). The largest dips in density occur near ι= 5/4 and 4/3 (where the transform profile is double valued), but there is a great deal of fine structure throughout the region of the scan. The best confinement is obtained just below the major resonances.

The resonance effect is sensitive to finite Larmor radii of plasma ions. An inset to Fig. 6 shows results for argon plasmas at B = 0.12 T (helicon heating), for which ρ_i/a ~ 0.2. Broad shallow dips in density are seen only at major resonances like ι= 3/2. These results are similar to those obtained on other low shear stellarators, such as Wendelstein 7AS [10], but show even finer structure. These results may be evidence of the effect of sets of interleaved magnetic surfaces of rational and irrational ι values, as suggested by Misguich et al [11].

The fully magnetised plasmas at 0.5 T do not exhibit the large amplitude density fluctuations seen in the low field experiments, but do have small amplitude magnetic fluctuation. Measurements of magnetic fluctuations using two external magnetic probes separated by 5 cm poloidally show that the magnetic fluctuations are also strongly sensitive to rotational transform, with maxima occurring on either side of the strongest resonance structures. The poloidal mode spectra (measured by cross-coherence signal processing techniques [12]) 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 significantly with rotational transform.

A movable magnetic probe has been used to measure radial magnetic fluctuations *inside* the plasma. Figure 7 shows that the magnetic fluctuations peak well inside the plasma in the gradient region. An additional series of rotational transform scans using the vertical field coils

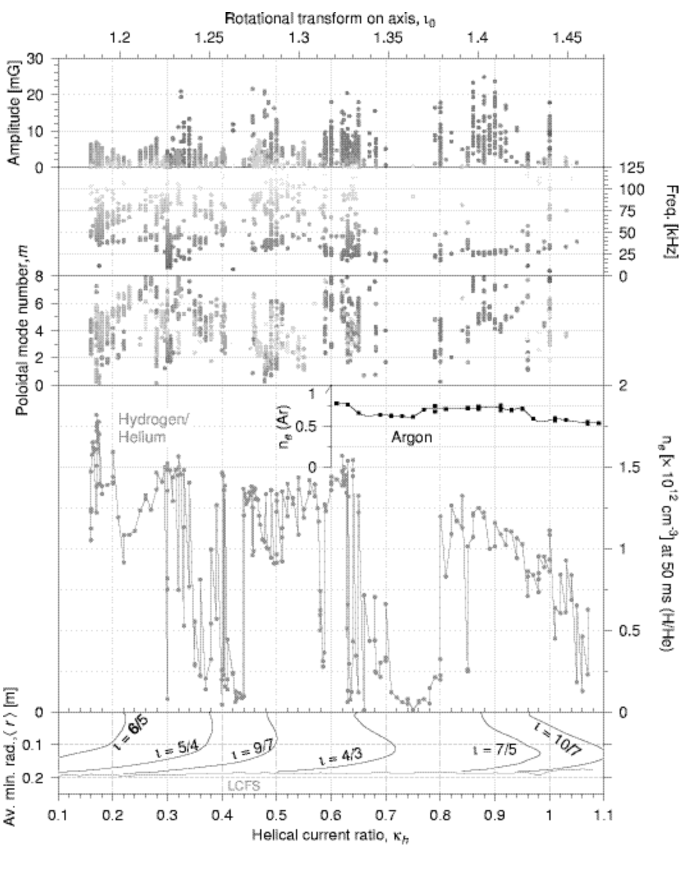

Fig. 6. Density and magnetic fluctuation spectral characteristics at reference time (50 ms) in sequence of discharges in rotational transform scan realised by variation of the helical hard-core coil current. The top plots show the amplitudes of coherent frequency components and apparent poloidal mode numbers, with the grey-scale coding of frequency. The bottom plot shows the progression of major resonances across the rotational transform profile. An inset shows the results of a scan at low field, where finite Larmor radius effects are important.

to vary the transform over a narrow range was used to track the motion of the localisation of the magnetic fluctuations. When the magnetic fluctuation data are plotted as a function of rotational transform, the amplitudes peak near the ι= 7/6 surface.

4. Future plans

Experiments on H-1NF in the immediate future will feature imaging studies of zonal flows, internal measurements of magnetic fluctuations over a wide range of rotational transform profiles at 0.5 T, and extension of detailed studies of turbulence to plasmas at B = 0.5 T with 200 kW of ICRF power and 200 GHz of 28 GHz ECH.

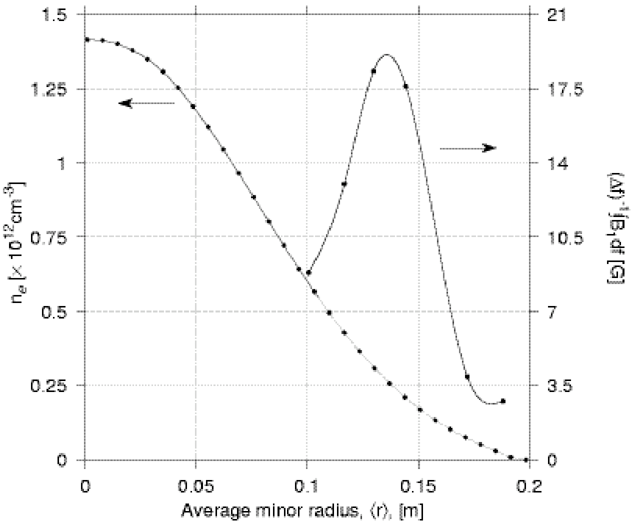

Fig. 7. Profile of radial magnetic fluctuations measured with scannable magnetic probe in a configuration with ι(0) =1.12, ι(a) = 1.25. Shown for comparison is the density profile measured with FIR interferometry [13].

Acknowledgments

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