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Confinement Transitions in the H-1 Heliac

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Abstract

Experiments at low magnetic field (< 0.2 T) in the H-1 heliac show transitions in confinement at low temperature and low heating power ~ 50 kW. These transitions exhibit many of the features seen in L-H transitions in large tokamaks and stellarators: steepening of the density gradient, increases in the radial electric field, suppression of turbulence, and increased ion energies. Future experiments in H-1 will attempt to extrapolate these phenomena to higher magnetic fields $0.5 < B < 1$ T and heating power $P > 0.5$ MW and study confinement in finite-pressure helical-axis plasmas.

Keywords:

helical-axis stellarator, heliac, improved confinement, electric field, turbulence

1. Introduction

The H-1 device[1] in the Institute of Advanced Study at the Australian National University is a flexible heliac[2] with major radius $R = 1$ m, average plasma radius $\langle a \rangle \approx 0.2$ m, and $M = 3$ field periods. Adjustment of the relative currents in the circular and helical hard core windings permits variation of the low-shear rotational transform profile from $\iota \approx 0.6$ to 2. While H-1 is designed ultimately to operate at magnetic fields up to $B = 1$ T with total plasma heating power $P \geq 0.5$ MW, it is limited during its initial period of operation by the present magnet power supply and heating systems to $B \leq 0.25$ T and $P = 100$ kW. Nevertheless, experiments with low-power, low-temperature "model" plasmas have demonstrated confinement transition phenomena similar to those seen in larger tokamaks and stellarators with high power plasma heating[3]. This regime has the advantage that material probes can be used to diagnose the plasma in detail.

2. Confinement Transitions

This series of confinement experiments were conducted primarily in argon, although helium and neon show similar behavior. The plasmas were initiated and maintained with 50–100 kW of helicon wave heating at $f = 7$ MHz. At magnetic fields that exceed a critical value (that is experimentally found to depend on the rotational transform and/or shear[4]) the density spontaneously increases by a factor ~1.5 in ~1 ms, as shown in the trace in Fig. 1. This increase in average density is accompanied by a steepening of the density profile and changes in the plasma potential that increase the radial electric field in the outer part of the plasma, as illustrated in Fig. 2.

Figure 2 shows that the maximum value of $|E_r|$ and its gradient occurs just outside the maximum in the density gradient, but it should be noted that in these plasmas, the ion Larmor radius is ~0.2–0.3 of the plasma minor radius, which limits the effective resolution of the measurements. Study of a variety of discharges suggests that, globally, the radial electric field

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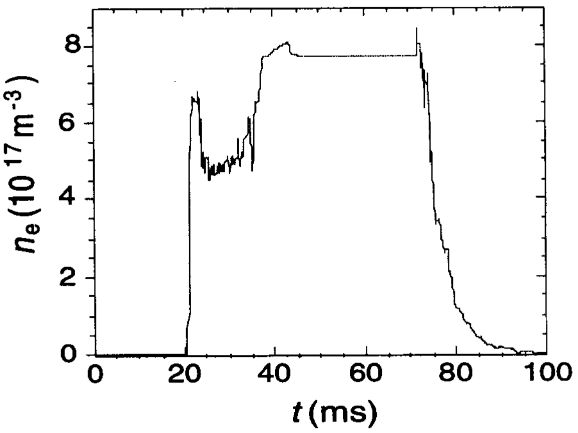

Fig. 1. Time trace of the line-average density in an H-1 discharge with B = 0.615 T in a magnetic configuration with $\iota \approx$ 1.41. The confinement transition occurs at $t \approx$ 40 ms.

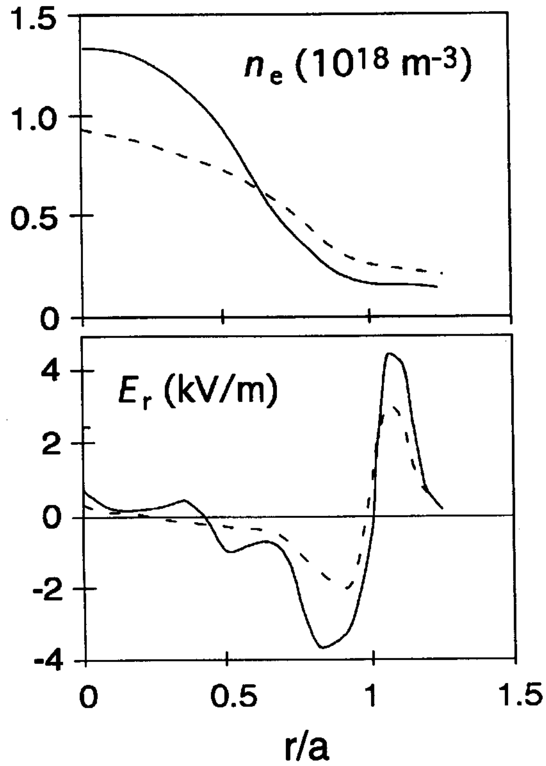

Fig. 2. Radial profiles of plasma density (n_e) and radial electric field (E_r) in H-1. Profiles taken 5 ms before (dotted) and 5 ms after (solid) transition to improved confinement. The plasma boundary r/a = 1 is determined by the last closed magnetic flux surface, and is also the location of the helicon wave antenna.

increases in proportion to the ion pressure gradient, and that the bulk plasma rotation is negligible compared to the poloidal E × B rotation in both the low and high confinement modes[5]. Modelling studies suggest that the radial electric field is consistent with ambipolar ion and electron fluxes when both diffusive and direct particle losses are included[6].

Substantial plasma turbulence and turbulent transport is observed in the plasma before the transition, but these subside when the density jump occurs. Figure 3 shows the turbulent particle transport as measured by multiple Langmuir probes (which measure the plasma density and potential fluctuations, and their mutual coherence and phase[4]) before and after transition; the portion of the transport due to fluctuations drops by two orders of magnitude. Note that this measurement does not measure the underlying, non-turbulent transport due to diffusion and direct particle losses (both large because of the low magnetic field and large ion Larmor radii). The global nature of the fluctuations in the low confinement mode (poloidal mode number m = 1 or 2, large coherence lengths) causes the fluctuation-induced transport to peak at mid-radius.

Improvement in the heating and confinement of the ions is also observed at the transition. Figure 4 shows that the profile of ion temperature (average ion

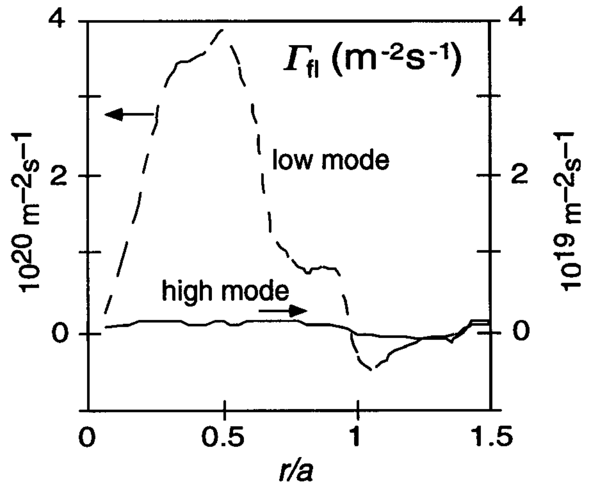

Fig. 3. Fluctuation-induced particle flux in H-1 discharges below and above confinement transition threshold, as measured by Langmuir probes. Note that this measurement only includes the contribution of the turbulence, not the underlying non-turbulent flux. The background noise level is ~ 10^{-3} times the peak value, and the flux drops by a factor of 100 at the transition.

energy measured by a retarding-field energy analyzer) rises in the high confinement mode. The electron temperature profile (Fig. 5) is hollow both in the low and high modes — presumably because the proxmity of the rf heating antenna and the non-resonant helicon heating scheme.

The energy and particle content of the plasma both increase by factors ~1.5 in the high confinement mode, while the coupled rf power (as measured from the coupling resistance) remains constant. Thus, the apparent confinement times (~1 ms) are increased with the transition. However, the low plasma temperatures and the presence of substantial neutral densities in these plasmas make more precise energy and particle balances very difficult, and the limited power and magnetic field available in H-1 at present make scaling studies impractical.

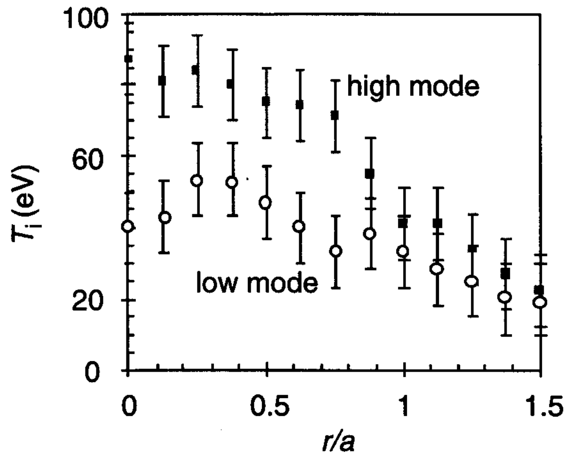

Fig. 4. Ion temperature (measured with retarding-field energy analyzer) in low and high confinement modes.

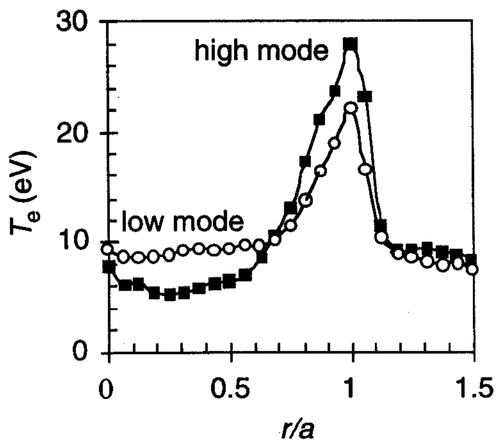

Fig. 5. Electron temperature (measured with Langmuir probes) in low and high confinement modes.

Additional experiments have shown a variety of phenomena that occur in some transitions, including dithering transitions and discharges in which the turbulence persists in the high confinement mode, but with fluctuation-induced particle flux that actually flows inward in the inner region of the plasma; this reversal has been shown to be approximately uniform around the flux surfaces[7].

3. Discussion

These experiments have demonstrated that the low-power, low temperature plasma in H-1 can serve as an accessible experimental paradigm for the study of magnetic confinement with strong radial electric fields. The results show many of the phenomena seen during confinement transitions in larger devices with 10–100 times the heating power, suggesting that at least some of the underlying physics is similar.

An important challenge is to increase the plasma parameters to bring these experiments closer to fusion plasma conditions. In December, 1997, H-1 will be shut down for 6-8 months to permit the installation of a new magnetic field power supply which will provide magnetic fields up to $B = 1$ T. Operation at $B = 0.5$ and 1 T will permit ECH with a 200 kW, 28 GHz gyrotron that has already been installed and tested in collaboration with teams from Kyoto University and the National Institute for Fusion Science in Japan. Additional ICRF power (~250 kW) will also become available. The availability of two heating schemes will permit much more flexible studies of confinement and electric field effects. The increase in power will permit experiments at higher plasma temperature and pressure, and ultimately, flux surface fragility at finite pressure, and stability phenomena such as ballooning modes.

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