Improved Particle Confinement Mode in the H-1 Heliac Plasma

M. G. Shats, D. L. Rudakov, B. D. Blackwell, G. G. Borg, R. L. Dewar, S. M. Hamberger,
J. Howard, and L. E. Sharp
Plasma Research Laboratory, Research School of Physical Sciences and Engineering,
Australian National University, Canberra, ACT 0200, Australia
(Received 9 September 1996)

The first experimental observation of the sudden transition to the improved particle confinement mode in the H-1 heliac is reported and shows a clear dependence on magnetic configuration. In a low-temperature plasma a transition to improved confinement followed by a twofold increase in the electron density is observed when the magnetic field exceeds a critical value $B_{\rm cr}$. At $B \approx B_{\rm cr}$ the transition occurs spontaneously (within 1 ms). This $B_{\rm cr}$ strongly decreases with increasing rotational transform. The improvement in confinement correlates with the suppression of the fluctuations and fluctuation-induced particle flux and with the increase in the radial electric field. [S0031-9007(96)01636-5]

PACS numbers: 52.55.Hc, 52.25.Fi, 52.25.Gj

Sudden transitions to improved confinement modes have been a focus of toroidal confinement research for more than a decade since the discovery of the H mode in 1982 in a divertor tokamak [1]. Recently, L-H transitions have also been observed in stellarators [2–4] and in a linear machine [5]. The great variety of plasma situations in which the transition to improved confinement is observed suggests that there may be some universal mechanism responsible for the formation of a transport barrier and the decrease in the particle outflow [6]. Typically, the formation of the transport barrier and the suppression of fluctuations during the transition are followed by the development of a steep density gradient and an increase in the radial electric field at the plasma edge [6]. These characteristics of the transition are observed in different magnetic configurations, at different collisionalities, and at both high [7] and low [5] electron and ion temperatures.

In this Letter we report the first experimental observations of L-H transition in a high rotational transform, low-shear stellarator (the H-1 heliac), whose critical conditions depend strongly on the magnetic configuration. We show that the onset appears to be consistent with the theory of Shaing *et al.* [8] for stellarators and should thus allow the results to be extrapolated to larger stellarators.

H-1 is a three-field period toroidal heliac [9,10] (helical axis stellarator) with major radius $R_0 = 1.0$ m, mean minor radius $\langle a \rangle \approx 0.2$ m, externally controllable rotational transform $\iota(r/a = 0) = 0.6{-}2.0$ and low vacuum magnetic field shear ($\Delta\iota/\iota \approx 0.03{-}0.06$). In the described experiments H-1 is operated at low magnetic fields ($B_0 \leq 0.2$ T, where B_0 is the magnetic field at the magnetic axis) where plasma is produced in argon by up to 60 kW of radio frequency power at 7 MHz [11]. Radial profiles of the electron density, electron temperature, plasma potential, and fluctuation-induced particle flux are measured by a triple Langmuir probe [12,13] and probe arrays. Line-average plasma density is monitored using a microwave interferometer and the plasma energy measured by a diamagnetic loop. Plasma in this experiment is current-free, with net toroidal current as measured with Rogowski coil less than 40 A. Central electron temperature varies from 6 to 15 eV in a wide range of experimental conditions. Chord averaged electron density is in the range between 0.6 and 1.5×10^{18} m^{-3}.

We observe two distinctly different modes of plasma confinement. At magnetic fields below some critical value $B < B_{\rm cr}$, the discharge is dominated by strong coherent fluctuations ($\tilde{n}/n = 0.15{-}0.4$, $\tilde{\varphi}/T_e \sim 1$) [14] with frequencies of $f = 3{-}12$ kHz and poloidal mode numbers of $m = 1$ or 2. If the magnetic field exceeds critical value, a sudden improvement in particle confinement is observed. The fluctuation level in this mode drops by an order of magnitude, while both central and average densities are increased by a factor of 1.5–2.2. When the magnetic field is near the critical value $B \approx B_{\rm cr}$ we observe spontaneous transitions between these two modes of confinement. The critical magnetic field for the transition changes with the rotation transform ι, controlled in these experiments by varying the current in the helical winding in the range from $\iota(r/a = 0.5) = 1.15$ to 1.41. The critical magnetic field for the transition decreases with ι by a factor of more than 2, as shown in Fig. 1.

Figure 2(a) shows a typical time evolution of the average electron density during spontaneous transition at $B \approx B_{\rm cr}$ for a magnetic configuration with $\iota(r/a = 0.5) = 1.41$. Average density increases by about 50% after the transition. Diamagnetic signals (not shown) also exhibit a similar increase while electron temperature does not significantly change from its initial value of 8 eV. Figures 2(b) and 2(c) show the time evolution of the ion saturation current $I_{\rm s}$ and plasma potential $V_{\rm pl}$ in the region 2 cm inside the last closed flux surface (LCFS). Increase in $I_{\rm s}$ correlates with the decrease in the fluctuation level and with the change of the plasma potential to a more negative value. This transition occurs on a time scale of about 1 ms. Figure 3 shows radial profiles of the electron density, plasma potential, and a radial electric field before

0031-9007/96/77(20)/4190(4)$10.00

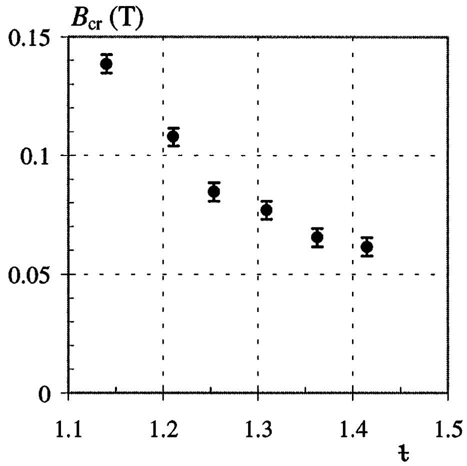

FIG. 1. Critical magnetic field B_{cr} for the transition versus the rotational transform $\iota(r/a = 0.5)$.

and after the transition of Fig. 2. Density increase is observed everywhere inside the LCFS while the plasma potential becomes more negative in the region $r/a < 0.9$. The radial electric field (computed from V_{pl}) becomes more negative (directed inward) increasing after the transition by a factor of 2 in the region about 3 cm inside the LCFS. The radial gradient of the electric field also grows in this region. The value of the radial electric field, averaged over the ion Larmor radius ($\rho_i \sim 1-1.6$ cm) is about $E_r \approx -3$ kV/m in the region inside the shear layer. This value of E_r does not significantly change during a configuration (ι) scan and stays typically in the range $E_r \approx -(2.7-3.3)$ kV/m. Such radial electric fields should produce significant poloidal plasma flow near the plasma periphery. We used a Mach probe (a double Langmuir probe with direction-sensitive electrodes) [15] to check for any ion flows in the poloidal direction. Our measurements indicate the presence of poloidal flows that appear in the plasma region $r/a \sim 0.8-1$. In the high confinement mode the ratio of the ion saturation currents to the probe tips facing upstream and downstream is

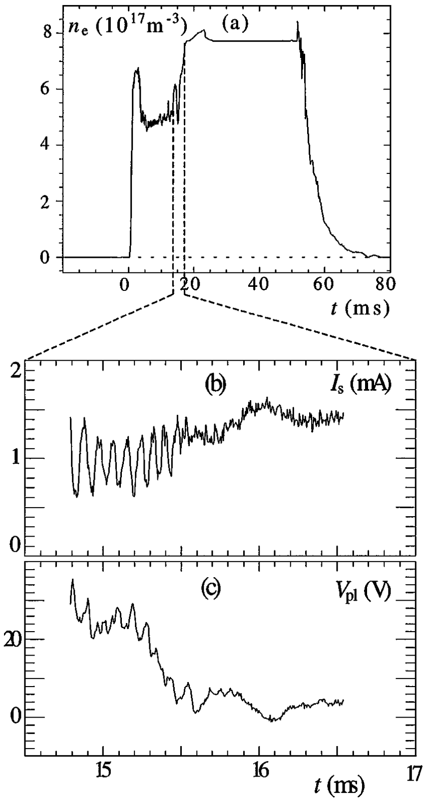

FIG. 2. Temporal evolution of the line-average density (microwave interferometer) (a), ion saturation current (b), and plasma potential (c) during a spontaneous transition at $B_{cr} = 0.0615$ T in the magnetic configuration with $\iota \approx 1.41$. Note the different time scale for I_s and V_{pl}.

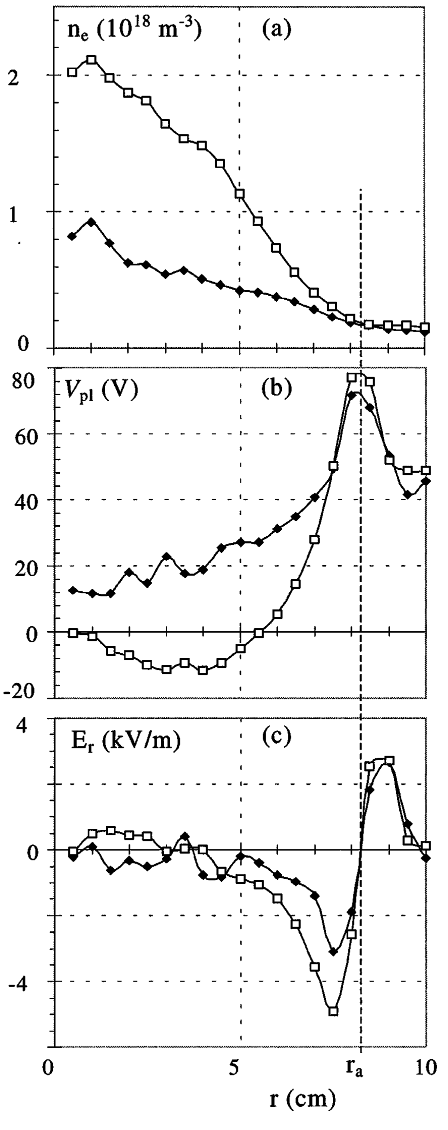

FIG. 3. Radial profiles of the electron density (a), plasma potential (b), and radial electric field (c) 5 ms before (solid diamonds) and 5 ms after (open squares) the transition shown in Fig. 2.

$I_{\mathrm{up}}/I_{\mathrm{down}} = 1.5-2$ (this ratio is equal to unity if there is no flow). In the low confinement mode this asymmetry is smaller (1.1–1.3). In both cases the direction of the flow corresponds to that of the electron diamagnetic and $\boldsymbol{E} \times \boldsymbol{B}$ drift.

Two steady-state discharges corresponding to low and high confinement modes are illustrated in Fig. 4 for $B = 0.046\ \mathrm{T} < B_{\mathrm{cr}}$ and $B = 0.077\ \mathrm{T} > B_{\mathrm{cr}}$. As in spontaneous transition, we observe a twofold increase in the central density [Fig. 4(a)] and a decrease in the fluctuation relative level [Fig. 4(b)]. We also measure a fluctuation-driven particle flux as $\Gamma = (k/B)\langle \tilde{n}\tilde{\varphi}\rangle$, where k is the fluctuation poloidal wave number and $\langle\,\rangle$ denotes a cross correlation between density and potential fluctuations. This flux [Fig. 4(c)] has a maximum at $r/a \approx 0.5$. At $B > B_{\mathrm{cr}}$ this particle flux decreases by a factor of 100. The observed suppression of the fluctuations and of the fluctuation-driven flux can account for the increase in the electron density and the improvement in particle confinement. We also observe that the e-fold decay time in the mean electron density after switching off the radio frequency power changes from $\tau \approx 0.4$ ms when $B < B_{\mathrm{cr}}$ to $\tau \approx 2.5$ ms when $B > B_{\mathrm{cr}}$. According to a simple particle balance this increased decay time is an indication of the improvement in the particle confinement since the ionization processes are similar in both regimes.

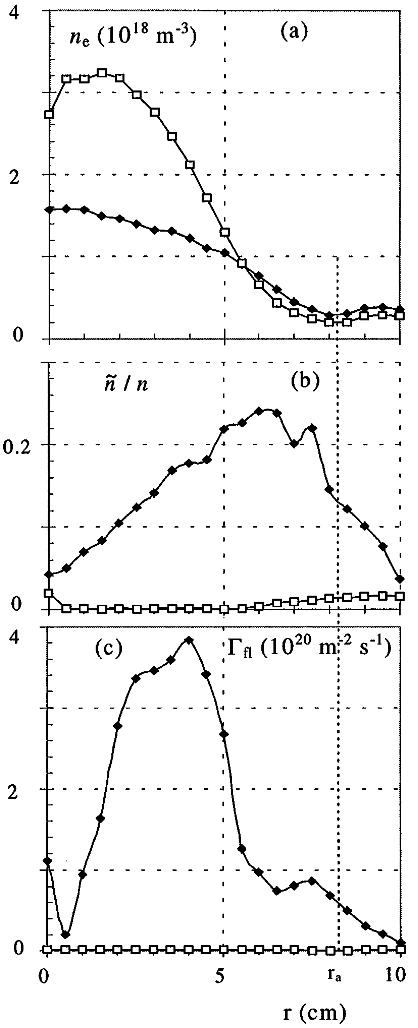

FIG. 4. Radial profiles of the electron density (a), relative level of the density fluctuations (b), and fluctuation-induced flux (c) at the magnetic field below ($B = 0.75B_{\mathrm{cr}}$) (solid diamonds) and above ($B = 1.25B_{\mathrm{cr}}$) (open squares) the critical field in the configuration with $t \approx 1.41$.

Many of the observed characteristics of the transition from low to high confinement are similar to those observed during L-H transition on other machines [6]: fast (1 ms or less) change to higher densities, steeper density gradients, more negative plasma potentials, more negative electric fields, and steeper electric field gradients in the plasma edge after the transition. The suppression of the fluctuations and fluctuation-driven particle flux is also a commonly observed feature of L-H transition. All these allow us to conclude that we are observing a similar phenomena on the H-1 heliac.

Observation of the critical magnetic field as a necessary condition for the transition as well as dependence of B_{cr} on the rotational transform has not been previously reported. The existence of the critical magnetic field and $B_{\mathrm{cr}}(\iota)$ dependence seems to be consistent with the recent theory [8] in which the bifurcation theory of L-H transition has been extended to stellarators. Ion collisionality parameter $\vartheta_i^* = \nu_{\mathrm{i}} L_{\|}/V_{\mathrm{ti}}$, (where ν_{i} is the ion collision frequency and $L_{\|} \approx 0.3$ m is a parallel connection length and V_{ti} is an ion thermal velocity) is about 2 in our experiment (taking $n_{\mathrm{e}} = 1.5 \times 10^{18}\ \mathrm{m}^{-3}$ and $T_{\mathrm{i}} = 0.5T_{\mathrm{e}}$), so that the comparison with the theory [8] is valid. According to [8], the bifurcation occurs when the poloidal Mach number ($M_{\mathrm{p}} \approx V_{\mathrm{p}}B/V_{\mathrm{ti}}B_{\mathrm{p}}$, where V_{p} is a poloidal plasma rotation velocity, B_{p} is the poloidal component of the magnetic field) reaches either unity (tokamak-like case) or $M_{\mathrm{p}} \sim |m - nq|/m = |1 - 1/\iota^2|$, where m and n are poloidal and toroidal mode numbers, respectively. The distinctive feature of heliacs is that this second resonance can be reached at relatively low M_{p} because $\iota > 1$ for most practically important magnetic configurations [10]. If we compare two configurations at $\iota = 1.15$ and 1.41 (Fig. 1), the corresponding resonant poloidal Mach numbers are $M_{\mathrm{p}}(\iota = 1.15) \sim 0.24$ and $M_{\mathrm{p}}(\iota = 1.41) \sim 0.52$. The ratio of the $\boldsymbol{E} \times \boldsymbol{B}$ rotation velocities in these configurations (sine E_{r} does not change much with ι, as stated earlier) at critical magnetic fields is $V_{E\times B}(\iota = 1.41)/V_{E\times B}(\iota = 1.15) \approx B_{\mathrm{cr}}(\iota = 1.15)/B_{\mathrm{cr}}(\iota = 1.41) \approx 2.2$. The ratio of the theoretical resonance Mach numbers is $M_{\mathrm{p}}(\iota = 1.41)/M_{\mathrm{p}}(\iota = 1.15) = 2.17$ which is very close to our experimental estimate. On the other hand, $V_{E\times B}$ estimated from the experimental data should not be used as poloidal rotation velocity since a contribution of the ion pressure gradient to the poloidal momentum balance is not known. Our measurements using the Mach probe show that the poloidal Mach number, estimated within uncertainty of the ion temperature (we take $T_\mathrm{i} \sim 0.5T_\mathrm{e}$ in our estimates), can be greater than unity after the transition. This suggests that a "tokamak-like" bifurcation at $M_\mathrm{p} = 1$ is also possible. However, the "stellarator-type" bifurcation (where, in fact, we use ratios rather than the absolute values of velocities in our estimate) better explains the strong experimentally observed ι dependence (Fig. 1). Additional measurements of the poloidal rotation velocities using spectroscopic methods with high spatial resolution as well as ion temperature gradient measurements are necessary to clarify this issue.

The observed abrupt reduction in the fluctuation level and in the fluctuation-induced particle flux could be explained theoretically by a mechanism of turbulence stabilization by sheared $\boldsymbol{E} \times \boldsymbol{B}$ flow [16]. Our observations demonstrate the suppression of the fluctuations everywhere inside the LCFS, in contrast to the experiments on DIII-D and TEXT tokamaks [17,18] where fluctuations decreased in a localized zone corresponding to the location of the sheared rotational flow. This difference may be due to the fact that in the present experiment the observed fluctuations have all the features of coherent global modes rather than of developed turbulence with short radial correlation lengths seen in tokamaks. The causality between the suppression of the fluctuations and the development of more negative radial electric field is not quite clear but there are indications that the change in the plasma potential precedes the drop in the fluctuation level, as shown in Figs. 2(b) and 2(c). Further measurements of the radial (de)correlation of the fluctuations will give more details on the actual mechanism of the fluctuation suppression in the H-1 heliac.

In conclusion, we have observed transform-dependent transitions to the improved particle confinement regime in the H-1 heliac. It is possible that the intrinsic nonambipolarity of the electron and ion fluxes in H-1 [19] (which leads to a formation of the radial electric field), higher rotational transform (compared with other machines), low ion temperature, and higher ion mass ($m_\mathrm{i} = 40$ in our experiments with argon plasma) make this transition easier than in other experiments. Further measurements in the discharges with different working gases and at higher temperatures might confirm this.

[1] F. Wagner *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).
[2] V. Erckmann *et al.*, Phys. Rev. Lett. **70**, 2086 (1993).
[3] F. Wagner *et al.*, Plasma Phys. Controlled Fusion **36**, A61 (1994).
[4] K. Toi *et al.*, Plasma Phys. Controlled Fusion **36**, A117 (1994).
[5] O. Sakai, Y. Yasaka, and R. Itatani, Phys. Rev. Lett. **70**, 4071 (1993).
[6] K. H. Burrel, Plasma Phys. Controlled Fusion **36**, A291 (1994).
[7] R. J. Groebner, K. H. Burrel, and R. P. Seraydarian, Phys. Rev. Lett. **64**, 3015 (1990).
[8] K. C. Shaing, C. T. Hsu, and P. J. Christenson, Plasma Phys. Controlled Fusion **36**, A75 (1994).
[9] S. M. Hamberger *et al.*, Fusion Technol. **17**, 123 (1990).
[10] M. G. Shats *et al.*, Nucl. Fusion **34**, 1653 (1994).
[11] B. D. Blackwell *et al.*, Trans. Fusion Technol. **27**, 282 (1995).
[12] S. Chen and T. Sekiguchi, J. Appl. Phys. **36**, 2363 (1965).
[13] M. A. Meier *et al.*, Rev. Sci. Instrum. **66**, 437 (1995).
[14] M. G. Shats *et al.*, Trans. Fusion Technol. **27**, 286 (1995).
[15] B. J. Peterson *et al.*, Rev. Sci. Instrum. **65**, 2599 (1994).
[16] H. Biglari, P. H. Diamond, and P. W. Terry, Phys. Fluids B **2**, 1 (1990).
[17] E. J. Doyle *et al.*, Phys. Fluids B **3**, 2300 (1991).
[18] Ch. P. Ritz *et al.*, Phys. Rev. Lett. **65**, 2543 (1990).
[19] S. L. Painter and H. J. Gardner, Nucl. Fusion **33**, 1107 (1993).