Shape and Evolution of the Electron Temperature Profile in LHD

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Abstract. With a multi-point (200) repetitive (50-200 Hz) Thomson scattering system, we studied the shape and evolution of the electron temperature (T_e) profiles of the plasma confined in LHD. We first survey various shapes of the observed T_e profiles and then describe two notable findings in some detail: (1) A pedestal often appeared on T_e profiles around the $\iota/2\pi=1$ surface, but its correlation with confinement was weak; (2) A magnetic island generated by an external error field changed its size in plasma. Normally the island shrank in plasma, but grew upon a hydrogen pellet injection.

1. Introduction

The Large Helical Device (LHD) [1,2] is a super conducting magnet system for fusion relevant plasma confinement. An appropriate combination of the electric currents in a pair of toroidal helical coils (L/M=2/10) wound with an optimized winding law and three pairs of poloidal coils would generate the magnetic field configuration whose horizontally elongated poloidal cross section looks as shown in Fig.1 (A). In the absence of plasma (vacuum), a substantially wide space is filled with almost completely nested magnetic surfaces bounded by a stochastic magnetic field region. The practically obtained magnetic field deviates slightly from this designed field because of an inevitable small construction error, Earth's magnetic field and ferromagnetic material around LHD. The error field thus caused resonates on low order rational magnetic surfaces and generates vacuum islands as shown in Fig.1 (B). In the

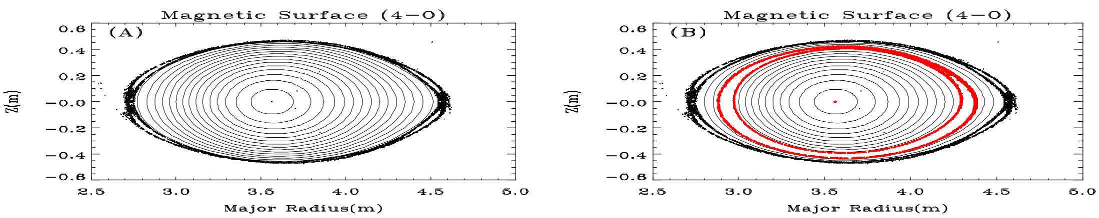

Fig1. Poloidal cross sectional views of magnetic field lines in LHD. (A) Ideal designed field lines. (B)Practical field lines with an external error field added. Thomson scattering measurement was carried out along the major radius on the z=0 plane.

presence of plasma, plasma currents such as Pfirsch-Schlüter (P-S), bootstrap, beam-driven, and RF-driven currents may be generated even if no external toroidal electric field is applied. These plasma currents may generate an ‘error field’ [3], which is a particular feature of three-dimensional devices like LHD. This internal ‘error field’ adds to a vacuum error field *incoherently*. Contrary to this, the pressure driven current on/near a rational surface will interact *coherently* with the island lying on the same surface: the perturbed current modifies the island geometry, the modified island changes the pressure distribution, and the changed pressure distribution modifies the current distribution. This closed loop interaction will cause, in some cases, a small seed island to grow to a large fraction of the plasma size and substantially deteriorate the plasma confinement, as is observed in tokamaks as the neoclassical tearing mode [4]. Thus, even if good vacuum magnetic surfaces are realized in a helical device, they may be destroyed in plasma by the above mechanisms, and therefore it is important to scrutinize the goodness of the magnetic surfaces in confinement experiments. Provided that electron temperature (T_e) is almost constant on each magnetic surface, a highly space-resolved T_e profile will reveal the presence of an island as a flat region or a bump as was demonstrated by the LIDAR installed on JET [5]. Moreover, the fine T_e profile will help us to find a transport barrier localized at a very narrow region as the RTP tokamak group demonstrated [6]. In the above view, we constructed a multi-point (200) and high repetition rate (50-200 Hz) Thomson scattering diagnostic [7] to measure fine T_e and density (n_e) profiles of LHD plasma along a major radius passing the magnetic axis. The spatial resolution ranges from 20 mm (at R= 4.5m) to 40 mm (at R= 2.5m). In the following, we first display various shapes of the T_e profile observed in LHD, and then describe two notable observations: (1) formation of a pedestal on the T_e profile, and (2) the response of an error field island in plasma.

2. T_e profile Morphology

In order to examine defects on the nested magnetic surfaces and to grasp the rough confinement properties of LHD, we surveyed all T_e profiles obtained in the 1999 Experiment. Here we pick up some of the representative T_e profiles in Fig.2 together with n_e and the calculated heat deposition profiles (q_e) and give brief remarks. At present, the n_e profiles give

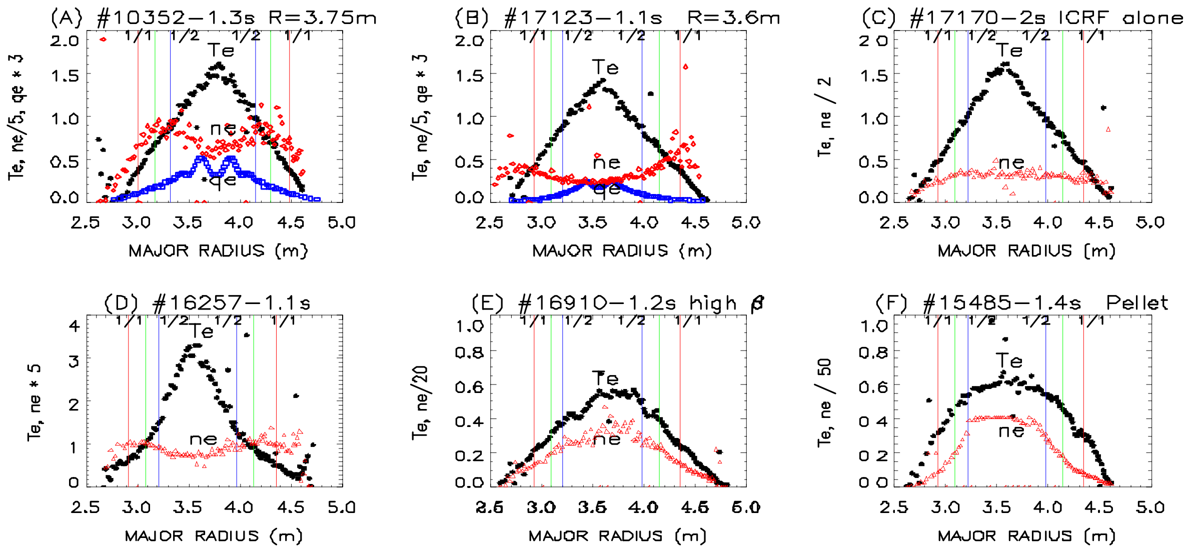

Fig.2. Various shapes of T_e profiles together with n_e and q_e profiles. Vertical lines indicate the positions where i/2p=1/1, 2/3, 1/2. (A) NBI plasma with R_{ax}=3.75m. (B)NBI plasma with R_{ax}=3.6m. (C) Plasma sustained by ICRF alone. (D) NBI plasma with centrally focused ECH.(E) High b plasma. (F) NBI plasma after pellet injection. Units are T_e (keV), n_e ($10^{19}m^{-3}$), and q_e (MW/m^3).

only rough information. For low n_e plasmas, for which the central T_e scatter largely, several successive data are averaged to lower the statistical noise. (A) The T_e profile of NBI-heated plasma with magnetic axis R_{ax}=3.75m. (B) The T_e profile of NBI-heated plasma with R_{ax}=3.6m. It is interesting that the two T_e profiles are peaked though the q_e profiles have a hollow center. A transport code shows that the inward-shifted plasma, (B), has better confinement. The apparent boundaries of the T_e profiles extend further ~ 0.05m beyond the last closed magnetic surface. (C) A T_e profile of plasma heated and maintained by ICRH alone. It is surprising that the T_e profile shape is very similar to that of the NBI plasma. On the almost straight slopes of these three T_e profiles, we can notice small flat regions around $\iota/2\pi=1$. (D) A very peaked T_e profile of NBI plasma with a centrally focused ECH. All T_e profiles shown above are of peaked shapes, indicating good confinement in the preserved well nested magnetic surfaces. These peaky profiles were observed for low β or low-density plasma. (E) A T_e profile of plasma formed in a low magnetic field of B_0=0.75 T with the average beta β> 2 %. We can notice the outward shift and flattening of the peak, a large island of ~0.15m width at ~1/3 of the minor radius, and the extension of the boundaries. (F) A round T_e profile after pellet injection. This shape persisted for a time much longer than the confinement time. We can notice a large flat region at the outer $\iota/2\pi$~1 position.

3. Appearance of Pedestal

Closely looking at T_e in Fig.2(B), we can notice a bend in the almost straight slope around the outer $\iota/2\pi=1$ position. Sometimes, this bend developed as shown in Fig.3(A) [8], which looks like the pedestal observed in tokamaks. A pedestal on a T_e profile implies the spatial change of transport property and therefore is important for finding a confinement improvement. Notable features concerning the pedestal are: (1) it appears near the $\iota/2\pi$= 1 surface within an uncertainty of 0.05 m; (2) this pedestal shape seems to be more pronounced in helium discharges than in hydrogen discharges. To avoid a human bias introduced in choosing sample data, we made a statistical analysis of all T_e profiles obtained in the 1999 Experiment. We modeled T_e profiles by a pentagon with five vertices and two temperatures, T_p and T_c as shown in Fig.3(A). This model shape includes a triangle shape as a special degenerate case. Of about 23000 T_e profiles which have diamagnetic energy W_p>200 kJ, 7900 profiles were well fitted to this shape with the normalized residue less than 2. The T_p vs. T_c relations for the data thus selected are shown in Fig.3(B) and (C) for hydrogen and helium discharges, respectively. The points below the lines correspond to T_e profiles with a pedestal. On the average, T_e profiles in helium discharges have a more pronounced pedestal than in hydrogen discharges. This fact tempts us to conjecture that the formation of the pedestal is related to atomic processes such as charge exchange and radiation energy loss. This is in accord with the appearance of the pedestal at the edge of the plasma, where the atomic processes are taking place predominantly. In the decaying phase of plasma, when the $\iota/2\pi=1$ surface was out of the plasma, a pedestal occasionally appeared around the next low order rational surface ($\iota/2\pi=2/3$), indicating a relation between the rational surfaces and the pedestal. The proximity

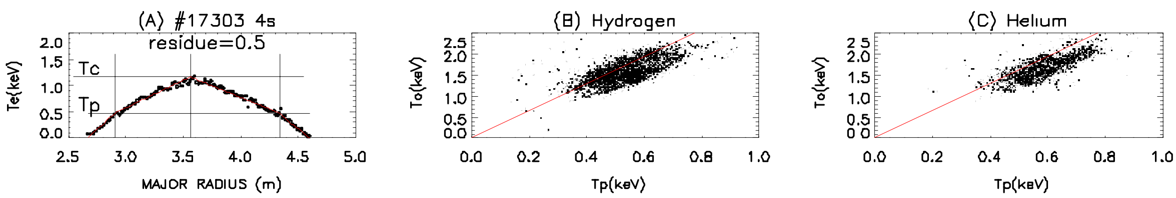

Fig3. (A) A model shape for T_e profile. T_p vs. T_c relations for (B) hydrogen and (C) helium plasma.

of the pedestal to the rational surfaces poses a question whether the pedestal really has no poloidal structure (m=0). This should be checked experimentally in the future. The pedestal seemed to be formed in the early phase of plasma evolution, and once formed, it was preserved during the plasma discharge. A point of curiosity is whether the pedestal structure helps to improve the confinement property. The correlation between diamagnetic energy W_p and T_p/T_c, which is a measure for the degree of pedestal, Corr(W_p , T_p/T_c)= 0.10(0.16) for hydrogen(helium) discharges. Correlations among the relevant parameters are: Corr(W_p,$<n_e>$)=0.64(0.63); Corr(T_c,$<n_e>$)=-0.47(-0.45); Corr(T_p, $<n_e>$)=-0.27(-0.27); Corr(T_e, T_p)=0.69(0.83); Corr(W_p, T_c)=0.29(0.33); Corr(W_p, T_p)=0.38(0.46).

4. An Error Field Island in Plasma

As already mentioned, we can often notice flat regions in the T_e profiles at the locations where $\iota/2\pi$~1. At the same position, in the absence of plasma, there is an m/n=1/1 island, as was demonstrated by an electron beam mapping method [1]. At the toroidal position where the Thomson scattering was carried out, the poloidal cross section of the island is estimated to look as shown in Fig.1(B). Interestingly, the size of the island estimated from the width of the flat region on the T_e profile was smaller than the vacuum island size and changed in different plasma parameters. This fact implies that currents were induced in the plasma or the surrounding conductor to alter the island size. An example of the island evolution is shown in Fig.4.

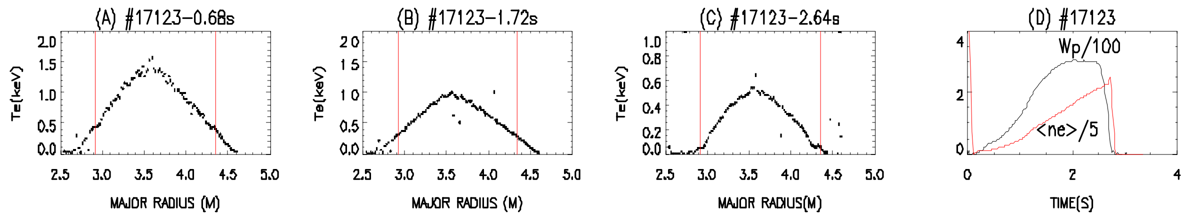

Fig.4 T_e profiles at (A) 0.68s, (B) 1.72s and (C) 2.64s of NBI plasma with R_{ax}=3.6 m. The vertical lines show i/2p=1 positions. The time variations of W_p(kJ) and $<n_e>$ ($10^{19}m^{-3}$) are shown in (D).

(A) When n_e rose enough to yield Thomson scattering signals, the island width was already smaller than the vacuum size. The reduced island changed its size from time to time until t~1.5 sec. (B) In the period 1.6s < t <2.6 s, the island almost disappeared. (C) In the last phase, the island reappeared with the width and phase consistent with the vacuum island. In general, the island is smaller in the higher density and in the lower magnetic field. What plasma current is responsible for the island reduction? The NBI-driven current is rejected, because co, counter and balanced NBI modes introduced no appreciable difference. If an internal global current and the resultant error field is responsible, the phase ∂f the field with respect to the external error field will distribute as ϕ={a constant+$2\pi/10$*n, n=0,9} with an equal probability because of the C_{10} symmetry of LHD. This will cause the island to show up with different shapes and phases shot by shot, which is not in accord with the observations. Thus, only the pressure-driven currents on/near the rational surface, which can *coherently* interact with the island, seem to explain the observations. Theories [9,10] predict that two kinds of currents are involved. A part of the P-S current governed by the restive interchange effect works to stabilize/destabilize an island depending on whether the resistive interchange mode is stable/unstable. A self-consistent bootstrap current profile makes the island to grow if the condition $dp/d\iota\,\Delta_0 > 0$ is satisfied. Here Δ_0 is a geometrical constant to determine the magnitude and direction of the bootstrap current. In tokamaks, the destabilizing bootstrap current effect exceeds the stabilizing resistive interchange effect, leading to the growth of the island. In LHD, the situation is a little more complicated. For the normal operation $dp/d\iota < 0$ everywhere, but the resistive interchange effect and the Δ_0 profile depend on the magnetic configuration, e.g., R_{ax}. For the R_{ax}=3.75m configuration, both resistive interchange effect and bootstrap current work to stabilize the n/m=1/1 island, whereas for the R_{ax}=3.6m configuration, they both work to destabilize the island. These are not in accord with the observation that the island shrank in both R_{ax}=3.75 m and R_{ax}=3.6 m configurations in almost all cases. A more refined theoretical model is needed. The response of the island to hydrogen ice pellet injection was diverse. In one case, after pellet injection, the island changed its phase by $\pi/2$ as shown in Fig.2(F). In another case, the island just grew preserving its phase. The error field generated by a pellet-driven current might be added *incoherently* to the external error field. Obviously, the change in plasma parameters due to the pellet injection modified the bootstrap plus P-S currents on the rational surface, thus complicating the problem extremely.

4.Conclusions

- The T_e profile of plasma confined in LHD showed smooth and peaked shapes, demonstrating that the three dimensional well nested flux surfaces in vacuum were preserved in the presence of plasma up to at least β~1%.
- A pedestal often appeared on the T_e profile around $\iota/2\pi$=1, but its correlation with confinement was weak.
- The external error field island almost always shrank in plasma, indicating a *coherent* interaction between the island and the currents flowing on/near the rational surface. The existing theory cannot explain the observation.
- The response of the island to pellet injection was diverse, indicating that the field generated by pellet-driven current was added *incoherently* to the external error field.

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