Effect of Magnetic Islands on LHD Plasma Performance

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1. Introduction

Plasmas heated by neutral beam injection (NBI) have indicated the favorable density dependence of energy confinement in the Large Helical Device (LHD) [1]. The energy confinement time τ_E is scaled by $\tau_E \propto P_{abs}^{-0.60}\,\overline{n}_e^{\,0.47}\,B_t^{0.75}$ in the configuration with a magnetic axis position R_{ax} of 3.6m [2]. Here P_{abs}, $\overline{n}_e$ and B_t are absorbed heating power, line-averaged density, and magnetic field, respectively. Therefore, an increase in $\overline{n}_e$ is a key issue in maximizing stored energy W_p., and pellet injection has a great impact on expanding the operational regime toward a high-density regime [3].

Recently, the plasma performance has been examined by controlling the widths of intrinsic magnetic islands, which seem to be generated by an error field. A remarkable improvement was observed in plasma parameters in the high-density plasmas produced by pellet injection. When the intrinsic islands were minimized, the increment of W_p amounted to about 25% and the maximum W_p of 1.03 MJ was achieved in the last experimental campaign. This paper is intended to describe this improved plasma performance, realized by minimizing the intrinsic islands and represented by the maximum W_p of 1.03 MJ.

2. Magnetic islands

In helical systems, well-nested vacuum magnetic surfaces play an essential role for plasma performance. However, the flux mapping, carried out at R_{ax} = 3.6 m and B_t = 2.75 T, showed that there were an m/n = 1/1 island and 2/1 islands in the LHD. The maximum widths of these islands are about 8 cm and 5 cm, respectively [4]. The cause of the error field is not clear, but there are a variety of possibilities, for example, ferromagnetic material located around the LHD, the large misalignment of the coils and so on.

The intrinsic islands were demonstrated experimentally to be almost simultaneously eliminated, that is, to be minimized by a perturbation coil system [4]. The perturbation coil system was installed to the LHD for the local island divertor (LID), which has been proposed for remarkable improvement of plasma confinement like H-mode in tokamaks. Thus it can also widen the widths of the vacuum magnetic islands [5].

2. Experimental Results and Discussion

The effect of the intrinsic islands on plasma performance was studied at R_{ax} = 3.6 m and B_t = 2.8 T. The port-through power of NBI and launching power of ion cyclotron range of frequency are 5 MW and 2 MW, respectively. Plasma discharges with a methane puff were conducted before this experimental series of high-density pellet plasmas, relevant to the intrinsic islands. A carbonization effect was expected from methane puffing, but its effect on our experiments was not clarified.

Figure 1 shows temporal evolutions of typical LHD discharges. Five pellets were injected from 0.5 s to 0.7 s, which increased $\bar{n}_e$ beyond the 1×10^{20} m^{-3} in this short time. While W_p behaves in an adiabatic condition at the pellet injection, it rises slowly due to confinement improvement by a density increase [6]. It was found by minimizing the intrinsic islands that W_p was improved, compared with W_p in the configuration with the intrinsic islands, and reached the maximum value of 1.03 MJ. The increment of W_p amounted to about 25 %. A large difference was also observed between $\bar{n}_e$ in the two discharges in Fig. 1(b), and this causes the difference in W_p, as predicted by the scaling law. The relation of $\bar{n}_e$ versus W_p is plotted in Fig. 2. The solid and dotted lines represent those relations predicted by the International Stellarator Scaling 95 (ISS95) [7] and one improved by a factor of 1.5, respectively. The confinement enhancement factor from the ISS95 is about 1.4 for these discharges.

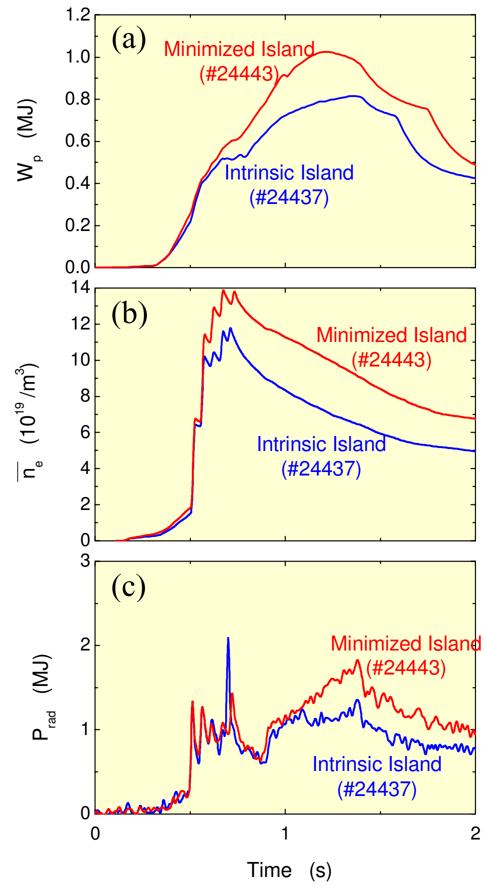

Fig. 1. Temporal behaviors of W_p, n_e and radiation power in the configurations with and without correction by a perturbation coil system.

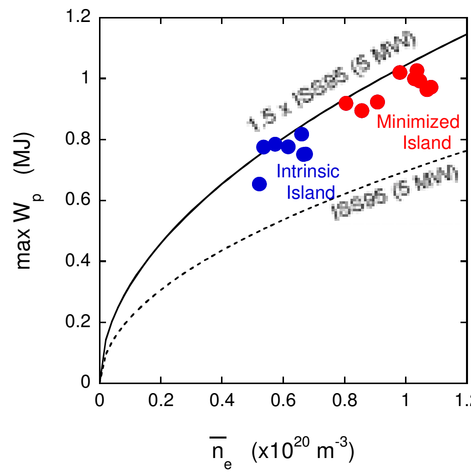

Fig. 2. Relations of n_e versus W_p in the configurations with and without correction by a perturbation coil system.

Therefore, the effect of minimization of the intrinsic islands should be recognized as the extension of preferable confinement in the higher density regime. It also should be noted that the limitation of W_p is not caused by the deterioration of confinement, but by the density limit arising from the existence of the intrinsic islands. In Fig. 1(c), the radiation power, measured by a bolometer, shows little difference between the two discharges before t ~ 1.2 sec. The emissivity profile evolutions also indicate that the intense-radiation areas are located at ρ ~ 1.0 in both cases, and the radial radiation profiles are almost the same in this period. Thus, the reason for the density increase is not attributed to impurity behavior.

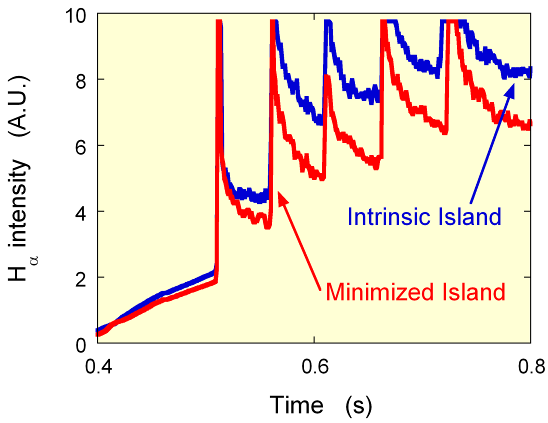

Fig. 3. H_α radiation in the discharges in the configurations with and without correction by a perturbation coil system.

A large difference was observed between the H_α radiation in the discharges with and without the minimization of the islands, as shown in Fig. 3. After the pellet injection, the H_α radiation in the discharge with the minimized islands was found to be smaller than that with the intrinsic islands, indicating that the former particle flux towards the wall is smaller than the latter particle flux. This was also demonstrated by the divertor fluxes, which were measured with Langmuir probes located on the divertor plates. Figure 4 shows the radial n_e profiles measured before and after the first and second pellet injections and those during the second pellet injections, together with the normalized rotational transform angles. An important point is that n_e in the configuration with the intrinsic islands is higher in the edge region of 4.2 m < R < 4.5 m than that with the minimized islands. Especially, the high n_e values near the last closed flux surface of R ~ 4.5 m coincide well with the high particle fluxes towards the wall when the intrinsic islands exist. In this case, the ablation of the second pellet occurs mainly in the edge region, and an increase in n_e near the plasma center becomes small. The high density in the edge region is considered to promote the ablation of the pellet, although the dependence of the ablation on n_e is weaker than that on T_e. In the case of the magnetic configuration with the minimized islands, the ablation of the second pellet occurs mainly near the plasma center, and a large increase in n_e is observed there. This is proved by the fact that n_e around R = 4 m during the ablation with the minimized islands is much higher than that with the intrinsic islands, indicating that the size of the pellet passing there is larger in the former case than that in the latter case. It should be noted that n_e around the m/n = 1/1 island is high, although the reason is not clear at this stage. The reason why the ablation is quickened in the presence of the islands is not clear either.

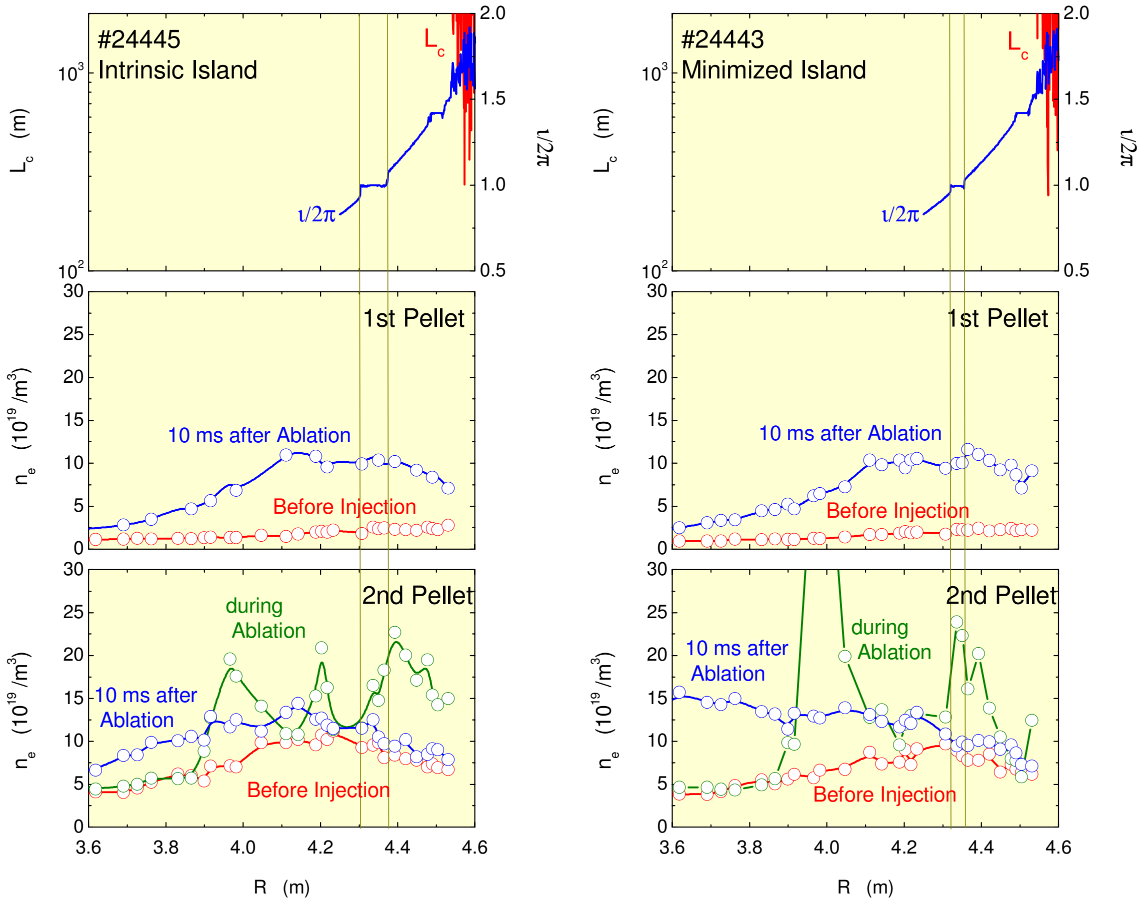

Fig. 4. Radial n_e profiles measured before and after the first and second pellet injections and those during the second pellet injections, together with the normalized rotational transform angles, in the configurations with and without correction by a perturbation coil system.

Summary

The maximum stored energy of 1.03 MJ was achieved by minimizing the intrinsic magnetic islands. When the intrinsic islands exist, the pellet ablation occurs mainly in the edge region, and a large amount of plasma flows to the wall quickly, leading to a decrease in the density, and hence, a decrease in the stored energy.

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