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Characteristics of Pellet Penetration and Related Performance Improvement in LHD

H.Yamada, R.Sakamoto, S.Sakakibara, S.Morita, K.Tanaka, K.Narihara, S.Masuzaki, K.Y.Watanabe, B.J.Peterson, M.Osakabe, S.Murakami, L.R.Baylor*, S.K.Combs*, M.Goto, K.Ida, H.Idei, O.Kaneko, K.Kawahata, A.Komori, S.Kubo, J.Miyazawa, H.Nakanishi, Y.Narushima, S.Ohdahi, N.Ohyabu, M.Shoji, K.Toi, T.Tokuzawa, K.Tsumori, LHD Experimental Group

National Institute for Fusion Science, Toki, 509-5292, Japan
** Oak Ridge National Laboratory, Oak Ridge, TN 37831-8071, USA*

1. Introduction

The Large Helical Device (LHD) is a large superconducting heliotron with a nominal major radius of 3.9 m and a minor radius of 0.6 m. Confinement characteristics of net-current free plasmas have been investigated in the extended parameter regimes which have been realized by large dimension, strong magnetic field close to 3 T and high heating power up to 5 MW. Gas puffing has been widely used to raise plasma density, however the particle sources are strongly localized at the surface. Deterioration of fueling efficiency of gas puffing has been enhanced by a thick ergodic layer lying between the last closed magnetic surfaces and divertors. This leads to requirement of strong gas puffing to sustain the plasma density and consequently generated excess neutrals limit the operational regime. Therefore deep fueling which has high fueling efficiency would be mandatory. Deep fueling may also be useful to create peaked density profiles believed favorable for confinement.

Pellet injection is an established and promising technique fulfilling these requirements. The pellet injector for LHD is a single-gas gun with 5 barrels [1]. The pellet size is 3 mm in diameter and 3 mm long, which has approximately 9×10^{20} hydrogenic atoms and electrons. The density increase is expected around $3\times10^{19}\mathrm{m}^{-3}$ per pellet if the efficiency is 100 %. The pellets are launched from the low magnetic field side with the velocity of 1 km/s. The pellet injection in LHD has greatly extended the operational regime of NBI heated plasmas [2], in particular, density up to $1.1\times10^{20}\mathrm{m}^{-3}$.

Energy confinement in LHD has indicated a significant enhancement from the scaling law ISS95 [3] by 60 % and this improvement significantly relies on formation of pedestals [4-5]. Dynamical processes observed in a transient phase during and after pellet injection are discussed with relation to the fueling efficiency and confinement enhancement for NBI heated plasmas. The magnetic geometry in this study is focused on the inward shifted configuration which is characterized by the magnetic axis R_{ax} =3.6m and shows the best confinement performance.

2. Intrinsic Density Dependence of Energy Confinement Time

Significant positive density dependence has been established in helical experiments, which suggests gyro-Bohm nature in transport. Since the present scenario towards a helical reactor relies on high density operation, extrapolation of density dependence is tremendously important in engineering development as well. LHD offers important data because LHD has a large volume and modest heating power density. From the tokamak experience, larger plasmas often show a saturation of confinement in the lower density regime.

Figure 1 shows the change of stored energy in the density scan with almost constant absorbed heating power. Since the heating power is constant, the stored energy in the ordinate is equivalent to the energy confinement time. It is found that an energy confinement time increases with density beyond $2\times10^{19}\mathrm{m}^{-3}$, that is the prediction of saturation from the empirical scaling in tokamaks [6]; $\bar{n}_e^{sat} = 10\ V^{-0.45} P_{abs}^{0.55} M^{0.6} Z_{eff}^{-0.4}$, where V is the volume of plasmas in m^3. More in detail, the usual gas fueled discharges how deterioration around $3\times10^{19}\mathrm{m}^{-3}$. This may be due to excess neutrals from strong gas puffing to build up density in a limited pulse length. In this situation, plasma can be heated up by turning off the gas puff. After turning off the gas puff, saturated stored energy increases again, which we call reheat. This recovery of the stored energy is attributed to the pedestal component, which indicates that degraded confinement in the pedestal by excess neutrals recovers the intrinsic characteristics by eliminating the cause.

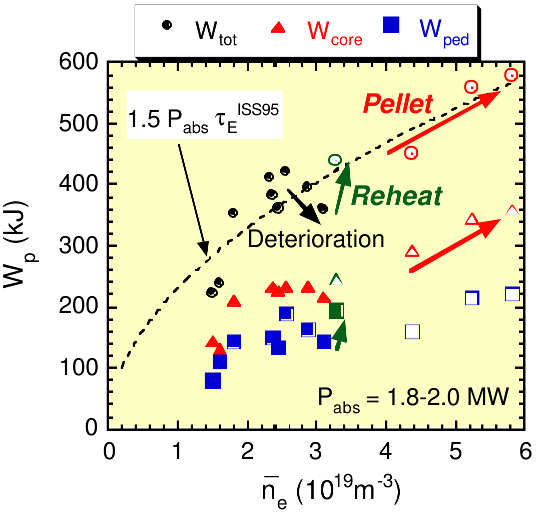

Fig.1 Stored energy as a function of density with approximately fixed absorbed power of NBI.

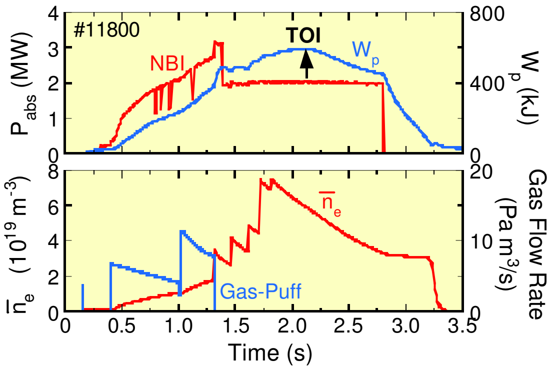

Fig.2 Typical waveforms of a pellet injected discharge. TOI is the time of interest used as the data in Fig.1

Pellet injection greatly extends the operational regime in the higher density side. Figure 2 is typical waveforms of a pellet injected discharge where 5 pellets are injected. In contrast to the reheat, confinement improvement in pellet injected discharges is highlighted in the core region. This density scan indicates that the recovery of intrinsic confinement is related to the fueling condition to avoid excess neutrals. Local heat transport analysis suggests that the heat conduction coefficient at two thirds radius decreases with the density up to $2.5\times10^{19}\mathrm{m}^{-3}$ and saturates above it. While the density profile in gas-fueled discharges is flat with a slight hollowness, pellet-fueled discharges show more peaked profile, which can explain a further confinement improvement in spite of the same local heat conduction coefficient in the core.

3. Pellet Penetration and Fueling Efficiency

Although particles are fueled directly into the plasma by pellet injection, the fueling efficiency is typically 50-90% in the LHD experiments. Existence of prompt missing particles has been reported in tokamak experiments, in particular, for the case of low-field side launching [7]. This mechanism is closely related to the motion of high density plasmoid generated by ablated pellets in a short time scale of the order of 100 µs.

Figure 3 shows an expanded view of waveforms at the pellet injection. The time frame is 1.5 ms. Fine structures and spikes in the signals of the central line density and H_α directly coming from ablation are well correlated with each other. The rotational transform where the pellet is passing indicates that the ablation starts just at the last closed flux surface inside the ergodic region. The largest dip observed every signal seems to be related to the major rational surface of unity. The middle graph shows magnetic fluctuation. A coherent mode with the resonance in the core is excited and slows down with disappearing.

The bottom waveforms are the H_α signal in different toroidal positions. The waveform close to the pellet injection position apart 36 degrees in toroidal direction is very similar to the ablation H_α in the top figure. The signal separated by 72 degrees has one sharp peak accompanied by another broad peak. The direct response of ablation is very tiny at the toroidally opposite position located 180 degrees apart and a large-buildup after the pellet injection is observed. This abrupt enhancement of H_α just after the pellet injection could be connected to density redistribution and missing particles.

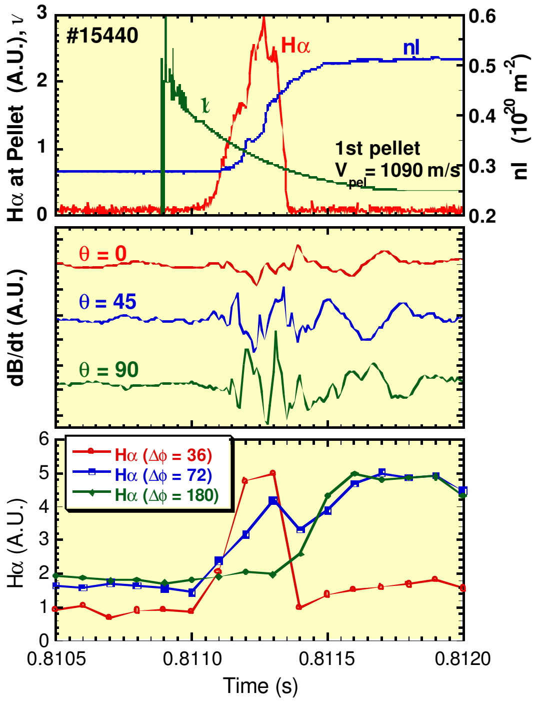

Fig.3 Waveforms in the pellet ablation phase.

4. Transient Confinement Improvement

An element of confinement characteristics can be seen dynamically in the transient phase after pellet injection. Figure 4 shows waveforms of the high-beta attempt shot at low magnetic field of 1.3 T. 5 pellets are injected within 80 ms and the density is raised rapidly. Then diamagnetic stored energy starts to increase, which is accelerated with additional NBI in this discharge. Dots show the stored energy estimated from the profile measurement of T_e and n_e and assumption of the same ion temperatures. The kinetic estimate usually agrees quite well with the diamagnetic measurement. However, a systematic discrepancy has been often observed in the transient phase after the pellet injection. This suggests that the ion temperature is higher than the electron temperature. An increase in the stored energy stops at 1.05s and the density decay rate also changes at the same time, which suggests deterioration of particle confinement. This event is correlated with the start of bursts in H_α and magnetic fluctuation. A mode analysis of magnetic fluctuations suggests that the large coherent modes with $m \geq 2$ although the Mercier

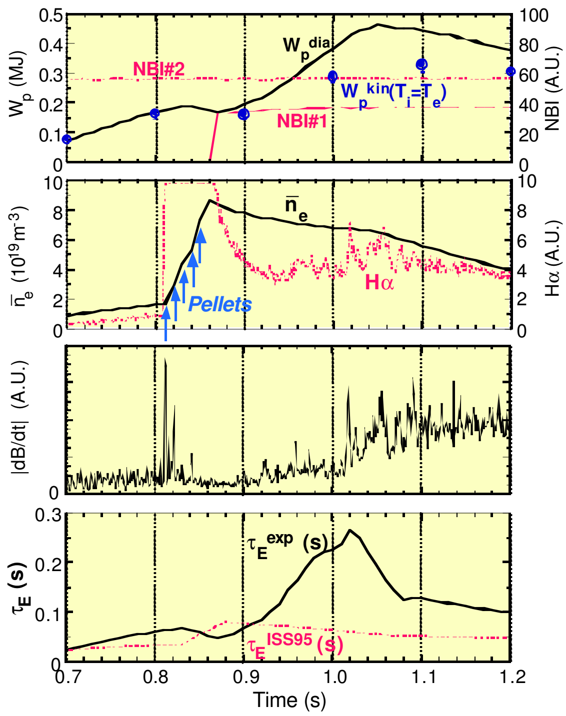

Fig.4 Waveforms in transiently improved confinement phase after a pellet injection.

criterion indicates that the pedestal part is still stable against the ideal interchange mode in the burst phase. Correlating bursts are observed in the particle flux onto the divertor plate, the light impurity line emissions and the line density as well. The bottom frame in Fig.4 shows that energy confinement time including the time derivative indicates significant enhancement of a factor of up to 4. This tremendous improvement, which cannot be explained by the density increase, lasts during the quiescent phase of H_α and magnetic fluctuation. After the event of bursts, confinement settles down to usual level characterized by the factor of 2 improvement.

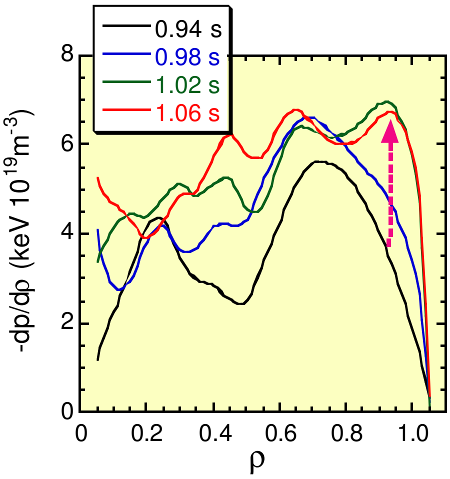

Fig.5 Evolution of pressure gradient profile after a pellet injection.

The temperature drops instantaneously by pellet injection. This process looks adiabatic. Then plasma is heated up again. The ratio of increase is larger in the peripheral region than in the core. In other words, a pedestal which is destroyed by pellet injection recovers quickly. However, it is clearly found that the pedestal temperature is limited at a certain level while the central temperature continues to increase. Figure 5 shows the evolution of the electron pressure gradient profile. A pedestal pressure is significantly reduced by pellet injection and recovers in 0.1s. However, it is stuck after 1.02s which coincides with the bursts of fluctuation in a various plasma parameters.

There is every possibility that the bursts in H_α and magnetic fluctuation are a sort of ELM limiting pressure gradient at the edge. As long as there is room for pedestal pressure, confinement is much improved since a pedestal pressure recovers so fast. However once the edge pressure reaches a certain level, it cannot increase further. Then global confinement is determined by transport in the core. These observations can be also seen in the operation with the higher magnetic field, which suggests that limitation of pedestal pressure cannot be simply explained by β or $\nabla\beta$ alone.

5. Summaries

Pellet injection has expanded the operational regime of density with keeping a favorable dependence of confinement. Reduction of excess neutrals and peaked density profile play essential roles. A transient behavior after the pellet injection has expanded the understanding of confinement improvement due to pedestal formation from the static state to dynamical behavior. Instabilities to limit the pressure gradient at the pedestal have been observed. Ununiform particle flux has been observed in the time scale of 100 μs, which may be related to prompt missing particles from the ablated pellet.

Aknowledgements

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