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CONFINEMENT IMPROVEMENT BY PARTICLE FUELING OPTIMIZATION

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The method to improve the energy confinement time by using a particle fueling optimization is proposed. The combination of a pellet injection and an interrupted neutral beam injection reduces the particle deposition at the plasma periphery. It is expected that the global confinement time is improved due to the suppression of the reduction of electron temperature at the plasma periphery if the particle deposition at the plasma periphery is reduced by some appropriate methods, e.g. combination of fueling by pellet injection and particle exhaustion by a divertor or a pump limiter. It is also shown that higher neutron production rate and lower tritium handling amount can be expected by employing pellet injection for fueling.

Keywords: Energy Confinement, Fueling, Pellet Injection, Interrupted NBI, Neutron Production, Tritium Handling.

粒子補給の最適化による閉込め特性の改善

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粒子補給の最適化によるエネルギー閉込め時間の改善の方法を提案する。ペレット入射と断続中性粒子入射加熱の組合わせによりプラズマ周辺部での粒子補給量を低減出来，エネルギー閉込め時間が改善された。ペレット入射による燃料補給とダイバータあるいはポンプリミターによる粒子排気を用いることにより，プラズマ周辺部への粒子補給量が低減され，ひいては周辺部の電子温度の低下が防げられ，エネルギー閉込め時間が改善されると期待出来る。ペレット入射により，より高い中性子発生率と，より低いトリチウム・インベントリーが期待出来ることも示されている。

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1. Experimental Base

Degradation of confinement time from the INTOR scaling is widely observed in high density beam-heated tokamak discharges {1}. It is shown that this degradation can be suppressed by direct particle fueling with D_2 pellet injection in Doublet III tokamak (pellet radius r_p=0.65 mm, velocity v_p=800 m/s) {2,3}.

1.1 Joule heating case

Even in Joule-heated divertor configured discharges, the energy confinement time is not increase linearly with the density if the plasma is fueled by conventional gas puffing as shown in Fig. 1. Figure 1-a) shows that, in the gas-fueled discharges, the neutral pressure at the divertor and the particle recycling level represented by D_α emission both at primary limiter (D_α^{LIM}) and the divertor region (D_α^{MID}) are increase nonlinearly with the line-averaged electron density of the main plasma, $\bar{n}_e$. Consequently, the energy confinement time is saturated around 60 ms when the density is raised above 4×10^{13} cm^{-3} as shown in Fig. 1-b).

In contrast to that, the pellet fueled confinement times continue to improve with increased density. This is probably due to the fact that in the pellet fueled discharges both the edge pressure and the limiter recycling light are maintained at relatively low levels (Fig. 1) and/or the successful density rise at the plasma center which has good confinement properties.

1.2 Beam heating case ($H^0 \rightarrow D^+$; E_0 = 73 KeV)

In neutral-beam heated limiter discharges, the energy confinement time shows transient improvement for first 60 ms, but then drops below Joule-heating level, reaching a value which equal to that in a comparable gas-fueled plasma as shown in Fig. 2-a). This is due to the build-up of fast ions from the beam that enhance the pellet ablation at plasma periphery.

A scheme was tested to eliminate this effect and to enhance pellet penetration by briefly interrupting the neutral beams just before each pellet was injected. This is based on the relatively fast slowing-down time of fast ions in the edge plasma which is less than 10 ms, and on the expected dependence of the ablation on the fast ion population. The energy confinement time and pellet penetration are improved over the continuous beam case for delay times (time from beam turn-off to pellet injection: Δt) greater than 8 ms. Further delay shows little additional improvement (Fig. 2-b)). Temporal deviation of the energy spectrum of charge-exchange neutrals coming from the plasma edge shows fast decay, <5 ms, of lower energy components ($E_0/2$, $E_0/3$) after every beam turn-off.

A comparison of pellet ablation profiles for continuous vs. interrupted beam (Fig. 3) shows that there is no significant difference in pellet penetration. However, the pellet ablation in the outer 10 cm of the plasma is reduced by interrupting the beam. The reduction in the edge ablation with improved penetration results in lowered edge density and slower central density decay time as measured by the visible bremsstrahlung array. Density profile information from this visible bremsstrahlung emission measurement shows that there is no difference between the profiles for Δt=4 ms and 18 ms of interruption of neutral beam injection shown in Fig. 2-b) except at peripheral region (Fig. 4). Both profiles are normalized at core plasma region. This reduction of edge ablation and thus suppression of peripheral cooling may account for the maintained improvement of the energy confinement time by keeping edge recycling lower. Peripheral cooling is considered to lead to strong temperature gradient and to the enhancement of the heat conduction loss.

2. Particle fueling optimization

2.1 Optimization for confinement improvement

Above experimental results imply that the control of edge fueling (keeping the peripheral plasma in low density and high temperature) is most responsible to improve energy confinement characteristics. In this scheme, it is shown by 1-D tokamak code simulation that any change in transport characteristics ($\chi_e=5\times10^{19}/n_e$, $\chi_i=4\chi_{HH}$, $D_A=1/4\cdot\chi_e$) before and after pellet injection are not necessary to improve the confinement as shown in Fig. 1 {4}. The pellet is not necessary to penetrate up to the plasma center, but it is necessary to reduce pellet ablation at plasma periphery.

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For a discharge of long duration, the combination of pellet fueling with interrupted beam, if necessary, and divertor or pump limiter for exhaustion of excessive particles is the most promising method. The slowing down time of fast ion in peripheral plasma (e.g. T_e=1 KeV; n_e=10^{13} cm^{-3}) is about 100 ms in large tokamaks.

If one fuels plasma by gas-puffing, it is necessary to distribute the locations of the puff systems in toroidal/poloidal direction in order to reduce strong localized cooling.

2.2 Neutron production

The neutron production rate is drastically enhanced ($\sim \times 10$) by direct pellet fueling to hot core plasma even if the energy confinement time degrades {2,3}. This is presumably due to the maintained peaked-profile with high density at central hot core region. A simulation of pellet fueled limiter discharge for JT-60 shows that the thermal Q value, Q_{th}, assuming D-T reaction can easily exceed unity with 20 MW beam heating, even though the pellets are injected before beam injection, whereas it is difficult to reach $Q_{th} \sim 0.9$ by using comparable gas-fueled discharge {5}.

Pellet fueling is competent for obtaining high Q_{th} values.

2.3 Tritium handling

High fueling efficiency ($90 \sim 100$ %) for pellet fueling is also observed in D-III {3}. This value is more than $2 \sim 3$ times higher than that of gas-puff case. Therefore the total handling amount of tritium can be lessen by applying pellet injection.

Acknowledgement

The author is grateful to Doublet III operations and physics groups for their great helps and fruitful discussions. Figure 4 is based on the analysis done by Miss S. Wojtowicz. He also acknowledges the continuing encouragements of Drs. M. Tanaka, M. Yoshikawa, K. Tomabechi and S. Mori.

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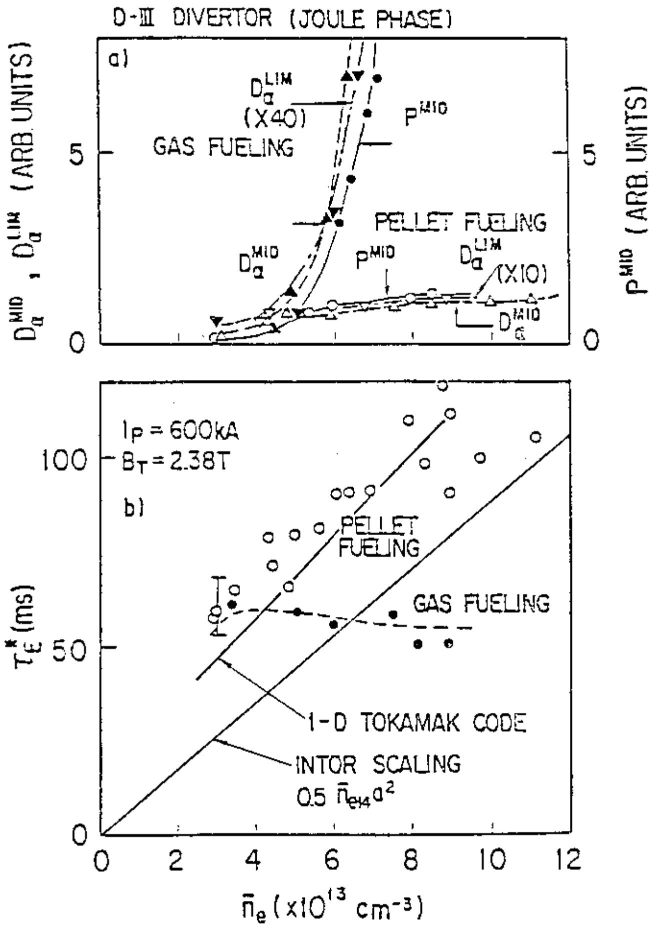

Fig. 1 Comparison of a) particle recycling at limiter and divertor as inferred from D_α^{LIM} and D_α^{MID} and neutral pressure at divertor and b) the energy confinement time between gas- and pellet-fueled discharges as functions of $\bar{n}_e$. Open symbols denote pellet-fueled, and solid symbols gas-fueled discharges. Results of 1-D tokamak code simulation is also presented {4}.

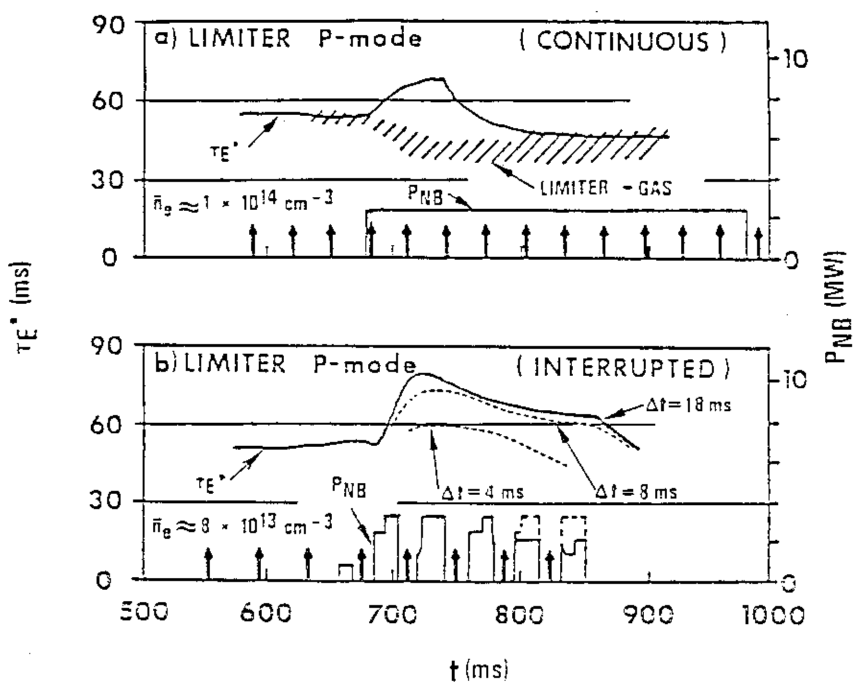

Fig. 2

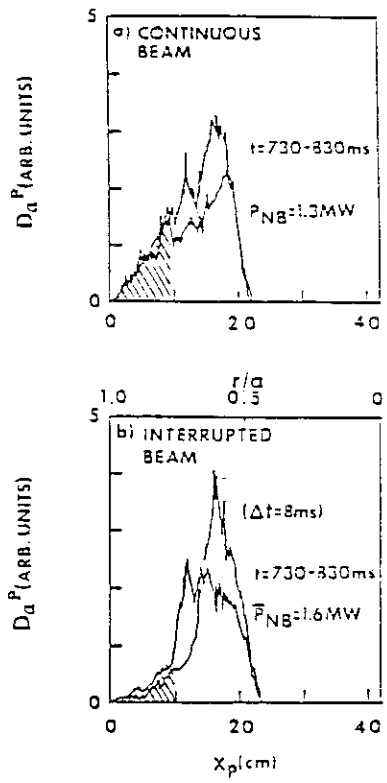

Fig. 3

Fig. 2 Comparison of temporal deviation of average energy confinement time for a) continuous-beam case and b) interrupted-beam case for Δt = 4, 8 and 18 ms. Pellet injection times are shown by arrows except for Δt = 4 and 18 ms {2}.

Fig. 3 D_α signals coming from pellet to 90° filtered photodiode ($D_\alpha{}^P$) as pellet ablation profiles: a) for continuous 1.3 MW beam heating and b) for interrupted beam heating (average beam power of 1.6 MW; Δt = 8 ms) in Fig. 2. Penetration is measured from limiter surface, x_p, deduced from measured pellet velocity (800 $m \cdot s^{-1}$). These pellets are injected between t = 730 and 830 ms in both cases {2}.

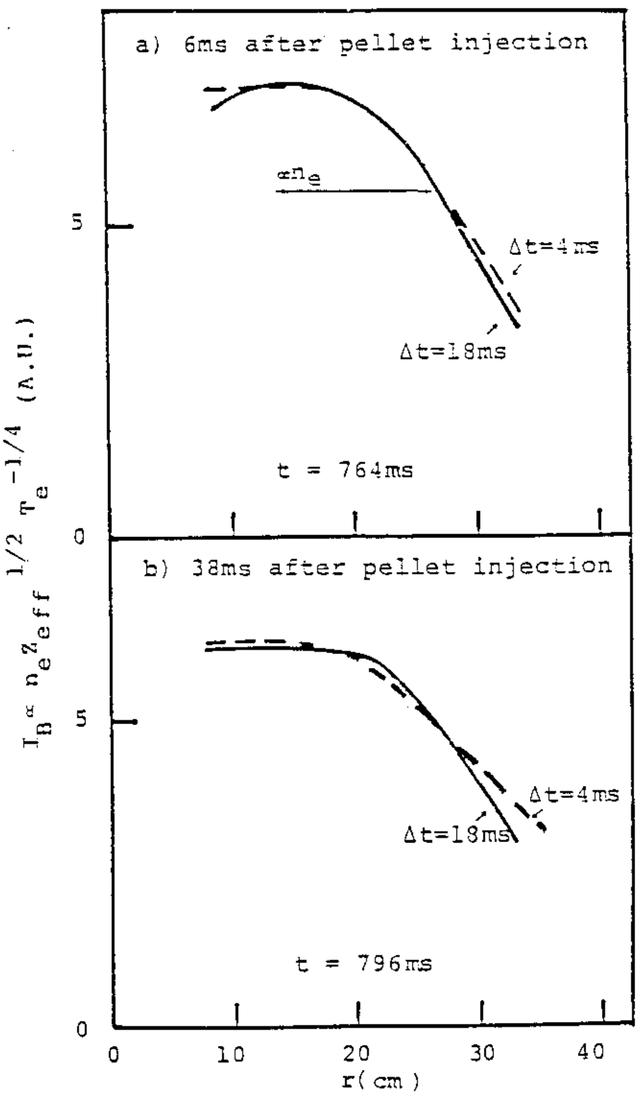

Fig. 4 Comparison of radial profiles of square root of abel-inverted bremsstrhlung emission, I_B, as a relative density profiles for Δt = 4 ms and 18 ms for discharges in Fig. 2. (a) 6 ms and b) 38 ms after last pellet injection.)