# DEPENDENCE OF RMP PENETRATION THRESHOLD ON PLASMA PARAMETERS AND ION SPECIES IN HELICAL PLASMAS

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**Abstract**

We investigate the penetration threshold of the RMP (Resonant Magnetic Perturbation) by the external coils in the LHD (Large Helical Device) for the various plasma aspect ratio configurations. In a configuration of the LHD, the threshold dependence on the density is qualitative similar with that in Ohmic tokamak plasmas, and the beta dependence is opposite to the tokamaks. The qualitative dependence on the collisionality is opposite to that in a high plasma aspect configuration, which is a quite unique property, and first found in the LHD. Also, we investigate the threshold on the ion species, and find that the threshold in the deuterium discharges is quite smaller than that in the hydrogen ones. In the above cases, the RMP penetration thresholds are higher as the poloidal rotation is faster, which is qualitatively consistent with the torque balance model between the electro-magnetic and the poloidal neoclassical viscous torque.

## 1. INTRODUCTION

Existence of the intrinsic RMP, which is same with "error field", induces the magnetic island and leads to the degradation of plasma confinement in helical plasmas. On the other hand, in tokamaks, it induces the locked-mode instability, which sometimes leads to a disruption, and in the other time it becomes a "seed island" on the neoclassical tearing instability, which limits the operational beta value. However, even if the RMP is externally imposed, the island does not always appear in plasmas. In the LHD [1], which is one of the largest helical devices in the world, the island sometimes appears and in the other times does not exist in the plasma region depending on the plasma parameters [2, 3]. In the LHD, it is reported that there is a threshold of the RMP penetration, which means that the island is not observed when the amplitude of the external RMP does not exceed a value (threshold), but it appears when the amplitude is beyond the value [4, 5]. In tokamaks, the locked mode instability does not always appear when the tearing instability is expected unstable and the external RMP is applied. The locked mode instability is often observed when the amplitude of the RMP is beyond a value (threshold), too. The above phenomena are observed under the condition that the external RMP does not rotate in time. Even in the case that the RMP rotates, it is reported that the RMP is shielded or decreases in the plasma when the amplitude is below a value, and the RMP is amplified when the amplitude is beyond the value [6]. Especially, in ITER, the tolerance of the error field to avoid the locked mode instability is much concerned because the locked mode and the disruption as the post process is expected in Ohmic discharges. Here the minimum amplitude of the RMP to induce the locked mode instability is considered as the threshold of the RMP penetration. The construction of an empirical scaling on RMP penetration threshold has been tried based on the experiments in the multi-devices for long time [7, 8]. On the other hand, the theoretical models of the RMP shielding mechanism by the plasmas and the determination of the RMP penetration threshold are investigated [9, 10]. However, the empirical scaling of the RMP penetration threshold and the theoretical model on the determination of the threshold should be investigated to further improve the prediction accuracy.

In the LHD, the RMP shielding mechanism and the determination model of the penetration threshold are intensively investigated [2-5, 11, 12, 13] since the RMP shielding phenomena were newly observed in the LHD [14]. In Ref.[3], The healing and growing (shielding and penetration) condition of the external RMP are summarized in the beta value and collisionality spaces, and the bootstrap current modified by the island is considered as the shielding effect. But, the effect of the bootstrap current does not explain the experiment results.

In Ref.[11], the observation of the time evolution of the poloidal flow at the transition phase of the island healing/growing suggests that the evolution of the poloidal flow at the outside of the resonant rational surface is strongly related with the RMP shielding threshold. In Ref.[5, 12], it is reported that, by investigating the dependence of the RMP penetration/shielding threshold on the magnetic configurations, the plasma aspect ratio dependence of the penetration threshold is strongly related with the increase of the magnetic shear and the decrease of the magnetic hill parameter, and the magnetic axis location dependence is consistently explained by the effect of the neoclassical viscos torque.

In this paper, in order to contribute the improvement of the accurate prediction on the RMP penetration threshold in the Ohmic tokamak discharges, in the LHD plasmas without any external torque, the empirical scaling of the the RMP penetration threshold on the electron density and the beta value is constructed, which is shown in section 3.1. And the RMP penetration threshold dependence on the collisionality for the various plasma aspect ratio configurations are compared in order to improve the database of the penetration threshold dependence on the magnetic configurations, which is shown in section 3.2. Furthermore, in the recent deuterium experiments, the RMP penetration threshold is investigated, and it is compared with that in the hydrogen plasmas from viewpoint of the ion species dependence of the RMP penetration threshold, which is shown section 3.3. We believe that the above results contribute to not only the understanding of the RMP shielding mechanism in the helical plasmas but also the improvement of the accuracy of the prediction on the RMP penetration threshold on the Ohmic tokamak plasmas trough the investigating the unified theoretical model to determine the penetration threshold. In section 4, we will discuss the results in section 3 from viewpoint of the relationship between the RMP penetration threshold and the plasma poloidal velocity, and give a brief summary.

## 2. EXPERIMENT SETUP

The LHD is a heliotron device with a pair of helical coils and three pairs of poloidal coils. The typical major and minor radii are 3.6m and 0.65 m, respectively. The helical coils consist of three layers winding coils built in minor radial direction. We can change the plasma aspect ratio and the magnetic shear, the magnetic hill parameter due to change the minor radial location of the helical coil current center and/or the helical coil pitch parameter, $\gamma_C \equiv (M/l)/(R_C/a_C)$, where $M$ and $l$ are the toroidal field period and the number of poles of the helical coils, and $R_C$ and $a_C$ are the major and the minor radius of the helical coil winding law, respectively. In this paper, the plasma aspect ratio, $A_p$, changes from 5.7 to 7.1 ($\gamma_C$=1.254~1.174). The central rotational transform changes from 0.33 to 0.57, but the edge rotational transform is kept around 1.65. The magnetic hill parameter increases with the increase of plasma aspect ratio. And the $m/n$=1/1 resonant rational surface move from 0.85 to 0.73 as the function of the normalized minor radius [5]. Here $m$ and $n$ are the poloidal and toroidal mode numbers. LHD equips ten pairs of coils with normal conductors set at the top and bottom (RMP coils), which can produce a magnetic field of $m/n$ = 1/1 and/or 2/1 modes with some different phase. In this study, the perturbation field with $m/n$=1/1 is imposed by RMP coils.

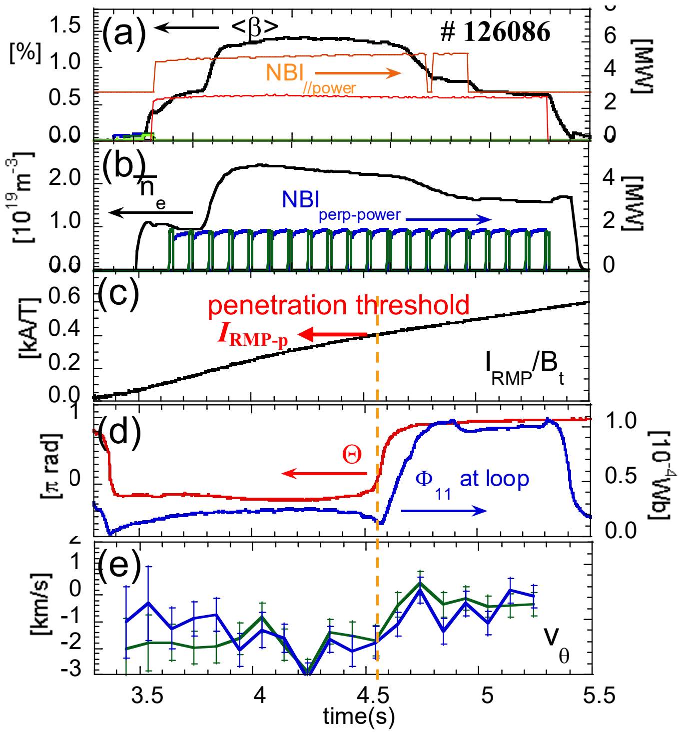


*FIG.1. Typical discharge waveform for RMP rump-up experiment. (a) the volume averaged beta and tangential NBI port-through-power, (b) the line averaged electron density and perpendicular NBI port through power, (c)the externa RMP coil current, (d)The phase (defined by the poloidal location of the island's O-point at a toroidal cross-section) and amplitude m/n=1/1 RMP component induced by plasma, Θ and Φ, (e) the poloidal flow velocity around the resonant rational surface. The vertical dashed line corresponds to the time when the external RMP penetrates into plasma.*

We carried out ramp-up RMP experiments. The typical discharge time and operational magnetic field is 2s and 1.38T, respectively. Figure 1 shows a typical waveform of the rump-up RMP experiment. The plasmas are initiated by ECH, and it is maintained by the balanced tangential NBI in order to reduce the external torque as shown in Fig.1(a), which is similar condition with the Ohmic tokamak plasmas. The perpendicular NB with the positive ion sources are intermittently injected to measure the poloidal and toroidal plasma flow velocities, as shown in Fig.1(b). During the discharge with almost constant density and heating power as shown Figs.1(a) and (b), the external RMP coil current is increased as shown in Fig.1(c). Here the externally imposed RMP does not rotate. The RMP current was ramped up with 0.3 kA/s. In Fig.1(d), at t~4.55s, the phase of the RMP induced by plasmas, which is measured by 2 pair saddle coils set located in different toroidal section, suddenly changes and a flat structure around the resonant rational surface suddenly appears in the electron temperature radial profile. In this paper, the RMP coil current ($I_{RMP\text{-}p}$) is identified as an index of the RMP penetration threshold as shown in Fig.1(c). Figure 1(d) shows the time evolution of the poloidal rotation speed around the resonant surface.

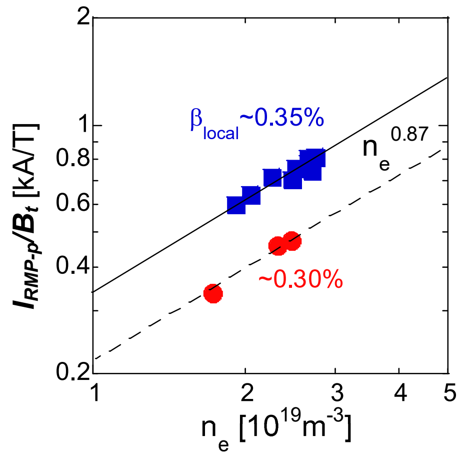


*FIG. 2. RMP penetration threshold as the function of the density at the rational surface in the LHD with $A_p$=5.7 for the m/n=1/1 mode. Here $\beta_{local}$ ~0.35% (■) and ~0.30% (●) are shown.*

## 3. RMP PENETRATION THRESHOLD DEPENDENCE IN THE LHD

### 3.1. Comparison between balanced NBI helical plasmas and Ohmic tokamak plasmas

As shown in section 1, in Ohmic discharges of tokamaks, they are constructing the following RMP penetration threshold scaling [15], and checking the validation through the multi-device experiments for the various density ($n_e$) and beta ($\beta_N$) regimes from the viewpoint of the avoidance of the locked mode instability in ITER operation.

$$B_{pen} / B_t \propto n_e^{1.4\pm0.13} B_t^{-1.8\pm0.16} R^{0.81\pm0.24} \beta_N^{-0.86\pm0.14}$$

Here $B_{pen}$ denotes the amplitude of the RMP penetration threshold, and $B_t$ and R are the toroidal magnetic field strength and the major radius, respectively. We investigate the RMP penetration threshold dependence on the density and the beta value in the LHD with $A_p$=5.7 for the $m/n$=1/1 mode. The $A_p$=5.7 configuration corresponds to a high confinement performance configuration in the LHD experiments. Figure 2 shows the penetration threshold as the function of the density at the resonant rational surface. Here the plasmas are heated by the balanced tangential NBI, which corresponds to the similar condition of tokamak's Ohmic discharges in the sense that there is no external torque. The collisionality belongs to the plateau regime. The penetration thresholds for the cases that the beta value at the $m/n$=1/1 resonant rational surface ($\beta_{local}$) is around 0.35% and 0.30%, are shown by ■ and ●, respectively. From Fig.2, the power law of the penetration thresholds on the collisionality is same independent of beta regimes, which is qualitatively same with that of tokamaks, but it has quantitatively weak dependence ($\propto n_e^{0.87}$) on the density with tokamaks ($\propto n_e^{1.4}$). On the other hand, the threshold in the LHD is larger as the beta increases, which is different from tokamaks.

### 3.2. Plasma aspect ratio dependence of the penetration threshold

In Ref.[5], the penetration threshold dependence on the plasma aspect ratio is investigated under the almost same beta and collisionality regimes in the LHD. There we found that the RMP penetration threshold decreases with the increase of the plasma aspect ratio. Now we investigate the penetration threshold dependence on the collisionality of ion for the various aspect ratio plasmas, and the results are shown in Fig.3. Here $\nu_{i*b}$=1 means the ion collisionality boundary between the plateau and the banana regimes. It should be noted that $\beta_{local}$ ~0.35%, which corresponds to around 1.0% as the volume averaged beta value. This beta regime is less than that in Ref.[5].

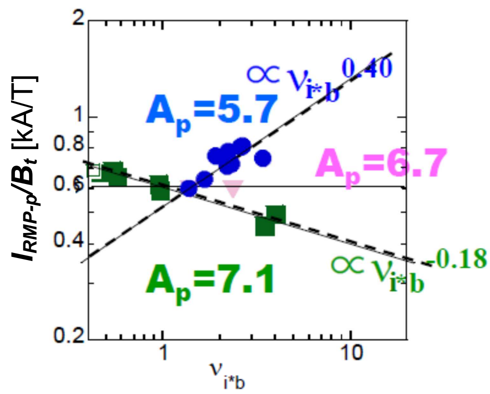


*FIG. 3. RMP penetration threshold dependence on collisionality for various $A_p$ configurations in the LHD. $\nu_{i*b}$=1 means the boundary of the plateau and the banana regimes. $A_p$=5.7, 6.7 and 7.1 are shown by ●, ▼ and ■, respectively.*

The most impressive results in Fig.3 is that the penetration threshold dependence on the collisionality in the low plasma aspect configuration is opposite in the high aspect one. Only in a high collisional regime, $\nu_{i*b}>2$ (almost plateau regime), the threshold dependence on the plasma aspect ratio in Ref.[5] is reproduced. In a low collisional regime, $\nu_{i*b}<1$ (almost $1/\nu$ regime), another dependence appears. This result would lead to the reconsideration of the statement that the increase of the magnetic shear and the decrease of the magnetic hill parameter should strongly affect the penetration threshold [5] because both the magnetic shear and the magnetic hill parameter little changes when the beta value is kept and the collisionality changes.

### 3.3. Ion species dependence of the penetration threshold

Recently, the deuterium experiments start in the LHD [1]. Here, in the deuterium discharges, the ions injected by the balanced NB and the perpendicular NB are deuterium in addition to the working gas supplied by gas-puff systems. We compare the RMP penetration thresholds in the deuterium and the hydrogen discharges in the almost same beta regime. Figure 4 shows the threshold dependence on the collisionality in the hydrogen and the deuterium discharges. The magnetic configuration is same with that in Fig.2 ($A_p$=5.7). From Fig.4, the penetration threshold in the deuterium discharge is smaller than that in the hydrogen one. This result means that the deuterium plasmas are affected with the smaller external RMP than in the hydrogen, which leads to the unfavourable property because the tolerance of the error field to prevent the degradation due to the appearance of magnetic island in the deuterium discharges is smaller than that in the hydrogen ones.

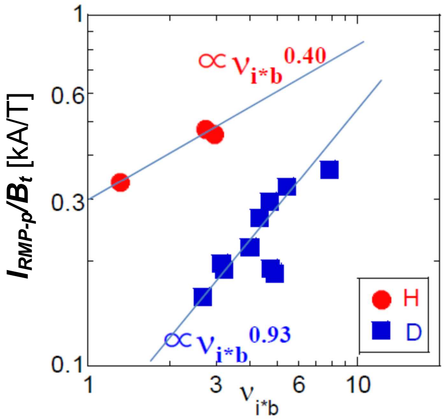


*FIG. 4. RMP penetration threshold as the function of the collisionality in the LHD with $A_p$=5.7 and $\beta_{local}$~0.3%. Here the deuterium and hydrogen discharges are shown by ■ and ●, respectively.*

## 4. DISCUSSION AND SUMMARY

Here we consider the reason why the RMP penetration threshold dependence on the collisionality appears for the various magnetic configurations and ion species, as shown in section 3.2 and 3.3. The most popular model on the shielding mechanism of the external RMP is a balance between the electro-magnetic and the viscous torque [9], which is based on the following scenario. When the plasma is rotating with a relatively large speed, the large difference between two Alfven resonant surfaces due to the large plasma speed prevents the reconnection of the magnetic field lines because the Alfven resonance does not overlap with the resonant surfaces [16]. When the external RMP exists, the plasma rotation is driven by a viscosity torque and it is decelerated by the electro-magnetic torque by the externally imposed RMP and its driving perturbed plasma current. Then when the the electro-magnetic torque is beyond the viscos torque, the plasma rotation is decelerated and the external RMP penetrate the resonant rational surfaces. According to a model in helical plasmas without an external torque [16], the poloidal neoclassical viscosity is considered dominant. When the the electro-magnetic torque is beyond the viscos torque, the plasma poloidal rotation decelerated and the RMP penetrates. The neoclassical viscous torque is expressed by the product of a poloidal rotation speed, and a viscosity coefficient, and the electro-magnetic one is roughly proportional to the square of the externally imposed RMP coil current. The imposed RMP coil current, when RMP penetrates, corresponds to the index of the penetration threshold, $I_{RMP\text{-}p}$. On the contrary, the neoclassical poloidal rotation and the viscous coefficient are considered to depend on the ion species and the configuration through the helical ripple in the magnetic field strength, the rotational transform and so on.

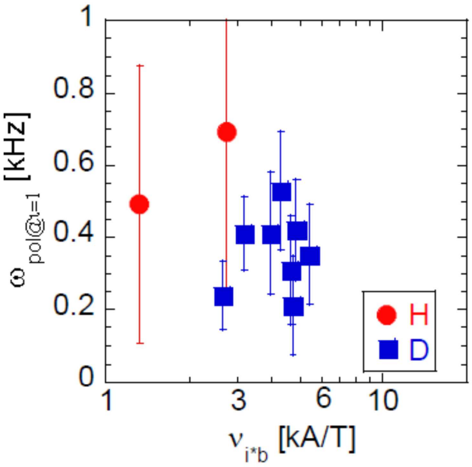


*FIG.5. Poloidal rotation frequency at the m/n=1/1 resonant rational surface as the function of the collisionality. Here the deuterium and hydrogen discharges are shown by ■ and ●, respectively.*

Figure 5 shows the poloidal plasma rotation ($\omega_{pol@\iota=1}$) of the plasma at the rational surface just before the penetration as the function of the collisionality in the deuterium and hydrogen discharges. The dataset is included by that of Fig.4. This figure shows that the poloidal rotation in the deuterium discharge is much smaller than that in the hydrogen ones when we compare them at the same collisionality, which would lead to the reduction of the penetration threshold. Next, we plot the penetration thresholds of Fig.3 ($A_p$=7.1;◇, $A_p$=5.7; ○) and Fig.4 (H;●, D;■) as the function of the poloidal rotation as shown in Fig.6. In the all cases, the RMP penetration thresholds increases as the poloidal rotation is faster, which is qualitatively consistent with the torque balance model between the electro-magnetic and the poloidal neoclassical viscous torque [17, 18]. Then the main reason why the penetration threshold in the deuterium is lower than that in the hydrogen is considered that the poloidal rotation in the deuterium is slower than that in the hydrogen. Figure 7 shows the poloidal rotation frequency at the resonant surface as the function of an index of the neoclassical flow. Because the poloidal rotation speed is proportional to $T_e*(n_e'/n_e+2T_e'/T_e)$ according to Ref.[18], $T_e*(n_e'/n_e+2T_e'/T_e)$ is defined as the index of the neoclassical flow here. Figure 7 shows that the poloidal rotation frequency increases with the increase of the index of the neoclassical flow, which shows that the observed poloidal rotation is driven by the neoclassical viscosity. Then the poloidal rotation of the deuterium discharges is smaller than that of the hydrogen ones because the electron temperature is lower than that in the hydrogen discharges at the almost same collisionality.

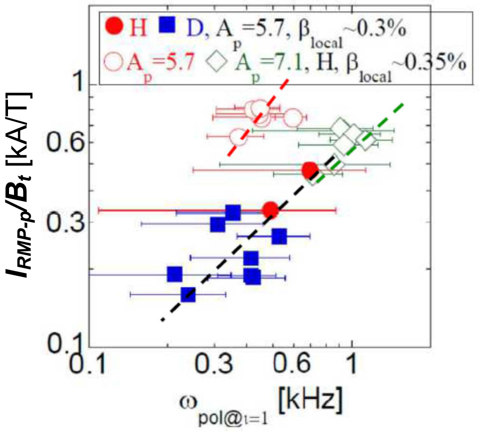


*FIG.6. RMP penetration threshold as the function of $\omega_{pol@\iota=1}$ in the LHD with $A_p$=5.7~7.1 and $\beta_{local}$=0.3~0.35% as shown in Figs.2 and 3.*

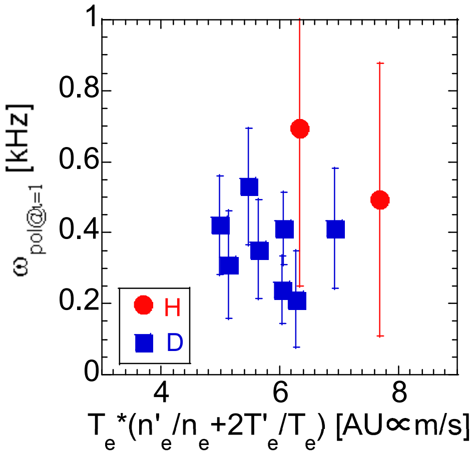


*FIG. 7. Poloidal rotation frequency at the m/n=1/1 resonant rational surface as the function of an index of the neoclassical flow. Here the deuterium and hydrogen discharges are shown by ■ and ●, respectively.*

The opposite dependence of the penetration threshold on the collisionality in the various plasma aspect configurations would come from the poloidal rotation dependence on the collisionality. It is known that the neoclassical poloidal viscosity is proportional to the non-axisymmetric neoclassical radial particle flux [19], which has different dependence on the collisionality and the magnetic field ripple component [20, 21]. That is, the poloidal rotation dependence on the collisionality in the 1/ν and the plateau regimes would be quite different. The quantitative evaluation of the dependence of the poloidal rotation speed on the collisionality and the collisional regime is a future subject.

We investigate the penetration threshold of the RMP by the external coils in the LHD for the various plasma aspect ratio configurations. In a good confinement configuration ($A_p$=5.7) of the LHD without external toroidal and poloidal torque input like a unbalance NBI, the threshold dependence on the density is qualitative similar with that in Ohmic tokamak plasmas, and the beta dependence is opposite to the tokamaks. Further, the qualitative dependence on the collisionality is opposite to that in a high plasma aspect configuration, which is a quite unique property comparing with the tokamaks, and first found in the LHD. Also, we investigate the threshold on the ion species, and find that the threshold of deuterium is quite smaller than that of hydrogen. In the above all cases, the RMP penetration thresholds are higher as the poloidal rotation is faster, which is qualitatively consistent with the torque balance model between the electro-magnetic and the poloidal viscous torque. However, it is still unclear how the poloidal rotation speed is determined except for the ion species dependence. Next, we should make clear how the poloidal rotation speed and/or the viscosity coefficient for the various plasma aspect ratio LHD configuration and tokamaks.

In Ohmic tokamak plasmas, the anomalous viscos torque is expected much dominant comparing with the neoclassical viscos torque [17, 18]. However, the prediction of the RMP penetration condition in helical plasmas with the high accuracy would lead to the systematic understanding of the penetration mechanism in torus plasmas because in the higher collisionality region in the LHD, there is a possibility that the anomalous viscosity is dominant instead of the neoclassical viscosity as the viscous torque.

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