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Experimental observations of plasma edge magnetic field response to resonant magnetic perturbation on the TEXTOR Tokamak

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Abstract
The plasma response to a resonant magnetic perturbation (RMP) is experimentally measured on the TEXTOR tokamak using a fast movable magnetic probe. It is shown that, due to the plasma response, the magnetic field significantly differs from the vacuum field. Clear linear and non-linear responses to RMP are observed by varying the intensity of these perturbations or the plasma edge safety factor. Both the radial profile evolution and the dependence of plasma response on the edge safety factor show a stronger resonant effect when the RMP rotates at 5 kHz in the counter-current direction.

(Some figures may appear in colour only in the online journal)

1. Introduction
Resonant magnetic perturbation (RMP) physics has attracted a great deal of interest through its involvement in several important issues in magnetic fusion research. An RMP field has been shown to be effective in the suppression and active control of type-I edge-localized modes (ELMs) \cite{1, 2} and the RMP coil system will be one of the ELM control methods in ITER \cite{3}. Also, RMP physics is directly involved in mode locking \cite{4–8} and field penetration processes \cite{9–13}, both being potential dangers for a fusion reactor. All these topics are directly related to the interaction between plasma and external applied perturbations, i.e. plasma response to RMP.

One effect of the plasma response to an RMP is the occurrence of surface currents on rational surfaces. Such currents can modify the original RMP vacuum field topology. When a mismatch exists between the RMP rotation frequency and the magnetohydrodynamic (MHD) frequency at low RMP amplitudes, these currents can shield the RMP field from the plasma \cite{12, 14–16}. The MHD frequency \cite{12, 15, 17} is defined by

\[
    f_{\text{MHD}}(r_s) = \left[ \frac{m}{2\pi r_s} \left( E_r + \frac{\nabla p_e}{en_e} \right) / B_\phi \right]_{r=r_s},
\]

where \( r_s \) denotes the position of the corresponding rational surface. For the same rotation mismatch, this screening effect breaks down and the \( \delta B_r \) field penetrates into the plasma when the RMP amplitude increases to a certain level for fixed plasma parameters. If the perturbation is high enough, the island can be formed by \( \delta B_r \) and the perturbation can be amplified in some cases \cite{9, 18, 19}.

Plasma response to RMP has been investigated in several ways. A set of MHD theories about plasma response to RMP has been developed in a slab or cylindrical geometry, which can be found in \cite{12, 14, 20–22}. Numerical calculations have been performed to simulate the plasma response to
The toroidal magnetic field system consists of 16 helical coils located at the high-field side of magnetic perturbations on the tokamak plasma. The DED the beam-heated L-mode plasma and even more different from the Ohmic discharges throughout the experiment, the rotation reconstruction is around 0.1. It is necessary to point out that in 360 kA, giving the edge safety factor range $q_a$ tokamaks [5, 9, 13, 16, 32]. An important point about this Experimental studies have also been carried out on several radius RMP, which can be found in [23–31] and references therein. Nucl. Fusion Section4 presents the radial profile of the poloidal field. The dependence of plasma response on RMP intensity is measured. By inserting the probe inside the plasma, one can obtain radial profiles of the local magnetic field. The dependence of plasma response on RMP frequency and on the target plasma can be investigated through compared multiple shots. In this paper, the poloidal component of the local magnetic field and plasma response part from the FMMP are shown. This paper presents the very recent experimental data from the FMMP. The result, mainly $\delta B$, is the dominant component of the corresponding field of the surface current. More modelling work is needed to improve the understanding of the experimental observation. This paper is organized as follows. In section 2, the RMP system on TEXTOR and FMMP designed for this experiment will be introduced. The experimental results are described in section 3, which shows plasma response measurements when the magnetic probe is located outside the bulk plasma. Section 4 presents the radial profile of the poloidal field. The results are discussed and a summary is given in section 5.

2. Experimental setup

The experiment was carried out on the TEXTOR tokamak, which is a circular, medium-sized, limiter tokamak with major radius $R_0 = 1.75$ m and minor radius $a = 0.47$ m [33]. A toroidal magnetic field $B_T = 1.6$ T was applied in the experiment while the plasma current $I_p$ varied from 180 to 360 kA, giving the edge safety factor range $q_a = 2.93–5.85$. The value of the edge safety factor is based on the cylindrical calculation [38]. Since TEXTOR has a circular cross-section and Ohmic plasmas were used for all discharges presented in this paper, the $q_a$ values are quite reliable. The magnetic reconstruction in several shots shows that the difference in $q_a$ value between the cylindrical calculation and equilibrium reconstruction is around 0.1. It is necessary to point out that in the Ohmic discharges throughout the experiment, the rotation profiles and the intrinsic rotation levels are quite different from the beam-heated L-mode plasma and even more different from the H-mode plasmas.

TEXTOR is equipped with a dynamic ergodic divertor (DED) system [34] with the purpose of studying the effect of magnetic perturbations on the tokamak plasma. The DED system consists of 16 helical coils located at the high-field side (HFS), producing a dc or ac RMP field. Three basic DED mode configurations are possible: $m/n = 12/4, 6/2, 3/1$, while the DED frequency can be chosen in the range 1–10 kHz for ac operation. The fast rotating RMP field is the uniqueness of the TEXTOR tokamak.

In this experiment, the DED system is operated in $m/n = 3/1$ mode with a frequency of $\pm 5$ kHz. Here $+5$ kHz implies that the magnetic perturbation is rotating in the counter direction of the plasma current, i.e. the direction of electron diamagnetic drift, while $-5$ kHz means rotation in the co-current direction. The opposite currents flowing in the two sets of coils (figure 1(a)) create a helical perturbation field. The 3/1 mode configuration of the DED produces strong sidebands with poloidal mode numbers $m = 1, 2, 3$ and 4 (see figure 1(b)). This allows the study of the plasma response at different rational surfaces ($q = 2, 3, 4, \ldots$). The last resonant surface mainly chosen to perform the experiment is the $q = 3$ or 4 surface.

FMMP is a special diagnostic designed to measure the plasma response to an ac DED perturbation. The probe system consists of nine magnetic pick up coils combined with a supporting structure. It is installed at the low-field side (LFS) on TEXTOR. These nine coils are divided into three groups in the radial direction which can measure the local perturbed field in the three directions of space. Only the poloidal field is presented here due to signal quality. The size of each probe group is $5 \times 25 \times 25$ mm³. The distance between neighbouring coil groups is 5 mm. The probe can be inserted into the plasma with a speed of up to 0.8 m s⁻¹ for edge profile measurements. The probe system including the amplifiers has a frequency bandwidth of 110 kHz. The effective area of the poloidal coil $N_S$ is 0.0137 m², while $N_S$ is 0.0199 m² for the toroidal coil and $N_S$ is 0.0506 m² for the radial coil, respectively. More details of the FMMP can be seen in figures 1(a) and (c).

One discharge measuring the plasma response to a DED field is presented in figure 2. Basic plasma parameters in this discharge are $B_T = 1.6$ T, $I_p = 290$ kA, line-averaged electron density $n_e = 1 \times 10^{19}$ m⁻³ and edge safety factor $q_a = 3.6$. The plasma density and current have achieved flat-top phase before applying DED. In all discharges presented in this paper, the toroidal field and electron density are kept almost the same. But the plasma current is scanned from 180 to 360 kA and DED parameters are modified in different discharges. For shot #113891, the DED frequency is $-5$ kHz. The phase (θ) here means the phase difference between the magnetic signal and the DED current in the temporal domain after taking the Fourier component at $5$ kHz. The vacuum phase could be zero or $\pi$ due to the possible opposite DED coil current directions in different campaigns. The phase difference between the magnetic signal and the vacuum field (θv, solid curve in figure 2(c)) is a physically meaningful quantity. Later in this paper, all absolute phase measurements will be substituted by such phase differences ($\delta \theta = \theta - \theta_v$). The amplitude of the local magnetic field shown in figure 2(b) may give rise to a confusion since it is lower than the plasma response amplitude. In fact, the FMMP measures the local magnetic field contribution from both vacuum field and plasma response field, which can be expressed as $\delta B = \delta B + \delta B_p$ . After taking each term’s $5$ kHz Fourier component, it can be written as $|\delta B|e^\theta = |\delta B|e^\theta + |\delta B_p|e^\theta$. In the experiment,
the $\delta B_\parallel$ term is obtained from a vacuum reference shot and both its amplitude and phase are shown as solid curves in figures 2(b) and (c). In another shot with plasma (e.g. #113891), the local magnetic field is measured. By subtracting the vacuum part from the total local field, a pure plasma response is obtained and is shown as dashed–dotted curves. For this shot, the amplitudes of $\delta B_\parallel$ and $\delta B_\perp$ are similar and their phases are nearly opposite. Therefore, $|\delta B|$ (solid curve in figure 2(b)) is much lower than $|\delta B_\parallel|$.

Each discharge can be divided into two main phases. In phase 1, the DED current ramps up. In this process, the probe is located outside the plasma (see figure 2(d)) measuring the local field. These two terms can be separated with the help of the vacuum reference values. In phase 2, the probe is inserted into the plasma, obtaining edge profiles of the local field. There is a short time between these two phases in order to ensure a steady state of plasma equilibrium. DED current, plasma current and DED frequency are changed between shots to measure systematic changes of the plasma response.

3. Linear and non-linear plasma response to RMP

In this section, experimental results from phase 1 referred to in the last section are presented. The probe is stationary, located about 6 cm outside the plasma edge (figure 2(d)). With the linear increase in DED current, the amplitude of the vacuum field increases linearly and the phase of the vacuum field is held near zero. Later in this paper, most attention will be paid to the plasma response term. For shot #113891, the plasma response amplitude $|\delta B_\parallel|$ increases nearly linearly and its phase $\theta$ is held at a certain value near $-\pi$. However, the dependence of plasma response on the DED current changes with the target plasma.
3.1. Experimental observation of the plasma response to \(-5\) kHz DED

Different plasma responses are observed for different \(q_{a}\) values as a function of the DED coil current (figure 3). Firstly, \(|\delta B_{0}|\) at \(q_{a} = 3.4\) (dashed curve in figure 3(a)) is much higher than that at \(q_{a} = 4.58\) (solid curve in figure 3(a)). This could be due to the harmonic sidebands of \(3/1\) DED configuration, where the \(m = 2, 3\) components are stronger than the \(m = 4\) component. Additionally, for \(q_{a} > 4\), the plasma response of the \(3/1\) surface may already screen part of the \(4/1\) component from the DED field. Secondly, the slope of \(|\delta B_{0}|\) at \(q_{a} = 4.58\) and 3.4 is nearly constant and the phase is constant. This is clearly a linear plasma response to RMP. Meanwhile, the slope of \(|\delta B_{0}|\) at \(q_{a} = 3.1\) and 4.21 changes after the DED current achieves a certain value (near 0.6 kA here). This is associated with the change in the phase of the plasma response, \(\delta \theta\), which changes continuously with the linearly increasing DED current. This implies a non-linear plasma response to the RMP. The slope of \(|\delta B_{0}|\) at \(q_{a} = 3.1\) decreases when the non-linear response appears, while it increases for \(|\delta B_{0}|\) at \(q_{a} = 4.21\). Thirdly, the DED current threshold of such a transition (from linear response to non-linear response) depends on the edge safety factor. The difference between linear and non-linear response may be due to the RMP penetration at the outermost rational surface for non-linear response. In the linear phase, the response current on the surface always screens the RMP. When the DED current reaches some threshold, RMP penetration seems to take place. This may lead to the phase change of non-linear response. The edge safety factor is higher above the nearest smaller integer, implying a deeper inside surface of the most external surface. In this case, mode penetration does not happen even when the DED current reaches the plateau value.

The dependence of \(\delta \theta\) on \(q_{a}\) is presented in figure 4. For each \(q_{a}\) value, one discharge is performed. Three curves are shown, corresponding to three values of the DED current during its ramp-up: 0.3, 0.5 and 0.8 kA. For some \(q_{a}\) values, \(\delta \theta\) does not change while the DED current varies from 0.3 to 0.8 kA. Such \(q_{a}\) regions can be named linear regimes (e.g. \(q_{a} = 3.4\)–3.8). In contrast, there exist non-linear regimes (e.g. \(q_{a} = 4\)–4.3) where \(\delta \theta\) varies with the DED current. There is a periodic appearance of linear and non-linear regions in the \(q_{a}\) region of 3–6. Generally, when the outermost resonant surface is relatively far from the plasma edge, e.g. the \(q = 3\) surface for \(q_{a} = 3.4\)–3.8, the plasma response is linear. The only exception is that the \(q_{a}\) region of 5–5.4 is not a clearly non-linear region but between a linear and a non-linear region. This could be due to the relatively weak \(m = 5\) resonant component.

The phase difference between neighbouring linear regimes should be noted (near \(\pi\) here). This seems to be an implication that the phase of plasma response is determined by the outermost resonant surface. For the linear regimes, if screening effects are dominant, then the poloidal phase of the response field is imposed by the DED. Since the DED coils are located on the HFS, the phase of the screening currents on the HFS should not depend on the number \(m\) of the outermost rational surface. However, the helical current and the corresponding field have a poloidal mode number \(m\) and it changes between even and odd regularly. Depending on the even or odd \(m\) number, the phase observed from the LFS will be either the same as DED or shifted by \(\pi\).

As discussed earlier in this section, the reason for the appearance of a non-linear region is probably the RMP penetration at the outermost resonant surface as the DED current increases, while linear regions appear due to the deeper position of the resonant surface and dominance of the screening effect. One possible explanation for the periodic nature of the plasma response phase in figure 4 is that the phase is dominated by the outermost resonant surface. As \(q_{a}\) grows (e.g. \(q_{a} = 3.1\)–3.5), the outermost resonant surface moves further inside and a linear response is observed. When a new resonant surface is introduced (e.g. \(q_{a} = 3.8\)–4.1), the new outermost surface is near the plasma boundary and a non-linear response is observed. The fact that the region \(q_{a} = 5\)–5.4 is more likely to be linear is mainly due to the weak \(m = 5\) harmonic of the DED spectrum, which cannot penetrate into the plasma.

For part of discharges with \(-5\) kHz DED, the MHD activity is analysed using poloidal Mirnov coils. No mode is observed before DED application. After the DED is applied,
for the $q_a < 3.2$ region, which is non-linear, only one mode is observed, i.e. 2/1 mode at 5 kHz. For $q_a = 3.5–3.8$ region (linear), only 3/1 mode at 5 kHz is observed during the DED phase. For the discharge with $q_a = 3.4$, which is right in between those two regions, it is observed that the dominant mode changes from 2/1 mode to 3/1 mode as the DED current increases. Both modes are at 5 kHz with some weak sideband harmonics, e.g. 10 kHz and 20 kHz. No clear modes are observed for the discharges with $q_a > 3.8$ for the −5 kHz DED case.

The scan is also performed in the +5 kHz DED case where such linear and non-linear response regimes can also be seen for $q = 3, 4$ surfaces (figure 5). Some main features for the +5 kHz case are (1) linear regions can be seen for $q_a = 3–3.4$ and $q_a = 3.9–4.2$, while when $q_a > 4.2$ it is non-linear. For $q_a = 3.5–3.9$, it is a weak non-linear region similar to $q_a = 5–5.4$ in the −5 kHz case. (2) For neighbouring linear regions, the phase difference is nearly 0.7π. (3) For $q_a > 4.2, 2/1$ mode can be excited, which cannot be seen in the −5 kHz case. However, it is not so reproducible due to more locked mode discharges and more disruptions. These differences could be partly understood as better agreement between DED frequency and MHD frequency. Easier mode penetration is expected in the +5 kHz case.

3.2. Comparison of the plasma response amplitude in the presence of the ±5 kHz DED

The dependence of the plasma response amplitude on $q_a$ is compared. The results are presented in figure 6. The x-axis ($q_a$) is divided into two parts. This is mainly because the $|δB|/|B_0|$ value is too low for high $q_a$. So the scaling of the y-axis is adjusted to be more readable in figures 6(b) and (d).

For the −5 kHz case in figure 6, $|δB|$ always decreases as $q_a$ increases. When $q_a$ reaches an integer value of 4 and/or 5 (i.e. a new resonant surface is introduced), a more significant change can be observed. However, there is no obvious change when the $q = 3$ surface is introduced. This can also be explained by both possibilities mentioned in section 3.1. If the last rational surface is dominant, the dependence of $|δB|$ on $q_a$ can be understood from the amplitudes of different harmonics (figure 1(b)). Since there is no big difference between the $m = 2$ and 3 terms, there will be no significant decrease observed when the 3/1 surface is introduced, and a strong decrease can be seen when the 4/1 or 5/1 surface occurs. But it is not necessary that the ratio of $|δB|$ between the $q = 2$ and 3 surfaces should follow that of the vacuum DED spectrum. This is mainly because the spectrum is the amplitude of those harmonics at the plasma edge ($ρ/ρ_0 ∼ 0.95$ in figure 1(a)) and the probe measures at a position several centimetres away from the last closed surface. The radial decay of each harmonic depends on the number $m$. So the decrease in $|δB|$ at different $q$ values only qualitatively follows the DED spectrum. Another mechanism, as mentioned at the beginning of section 3.1, could contribute to the understanding of this point, that is the resonant surfaces in the core (e.g. $q = 3$) already screen part of the resonant field at the outermost resonant surface (e.g. $q = 4$) due to mode coupling effects, so that the screening field from the outermost surface itself does not have to be as strong as the DED spectrum. If multiple surface interactions create a dominant effect here, the plasma response will be determined by the combination of all harmonics and will not be easy to predict. Modelling would be needed to support the discussion.

The plasma response to the +5 kHz DED behaves differently from the −5 kHz case. $|δB|$ shows peaked values around $q_a = 3$ and $q_a = 4$, and is much weaker between the peaks. This can be understood from the difference between the DED frequency and the MHD frequency. Generally, RMP penetration occurs at the lowest DED current when the frequency matches the mode’s MHD frequency [13]. In this Ohmic experiment, the +5 kHz field rotates in the counter-current direction and is closer to the MHD frequency than in the −5 kHz case. For instance, based on the calculation from the 4FC code [29], the 3/1 MHD frequency is about 4.85 kHz and that for 2/1 mode is 3.4 kHz in the counter-current direction, i.e. the same direction and a very similar magnitude as the DED frequency for 3/1 mode [35]. Thus, RMP penetration is more likely to occur for the +5 kHz case. The peaks exist because the response field decreases fast when moving away from the resonant surface, since the penetration current is basically bipolar [37]. Another fact is that 2/1 mode penetration has only been observed in the +5 kHz DED case. No 2/1 mode penetration can be seen in the −5 kHz DED case even when the DED current reaches the technical limit. Typical effects of 2/1 field penetration on the plasma response field signal are as follows. (1) Right after penetration, $|δB|$ will be 3–4 times higher than that before penetration. (2) A phase jump with a typical value from 50° to 100° will occur when mode penetration happens. It is quite interesting from the modelling [36] that for 2/1 mode penetration, it is a very sharp (with a typical time scale of resistive diffusion time) change both for island width and frequency locked to RMP. However, 3/1 mode penetration is a slow effect compared with 2/1 mode penetration. This leads to some difficulties in the experimental observation of 3/1 mode penetration. Detailed results can be seen in [36]. More investigation of mode penetration will be left for a future work.
4. Radial profiles of plasma response fields

In section 3, plasma response to RMP was measured outside the plasma. This section mainly investigates phase 2 described in the last paragraph of section 2. This work is done by inserting the probe into the plasma while the DED current is kept constant. At the deepest position, the probe is about 4 cm inside the plasma edge.

Figure 7 shows the radial profile of the poloidal components for both the total field and the plasma response field. The target plasma and DED setting are explained in section 2. The measured field oscillates at $-5\, \text{kHz}$, in agreement with the DED frequency of $-5\, \text{kHz}$. A full picture of this field in one or more periods can be reproduced by a contour plot.

One example of such a contour plot is shown in figure 8. Here, the x-axis shows the time scale of a 5 kHz ac period, where 0.2 ms is one full period. Consistent with the amplitude and phase of the local field measured in figure 7, the poloidal component of $|\delta B|e^{i\omega t}$ (figure 8(a)) significantly differs from that of the vacuum DED field (figure 8(b)), where $\omega$ is the RMP frequency. This difference from the vacuum field clearly indicates the existence of sheet current on the rational surface ($\sim 221.3\, \text{cm}$ here), which dominates the discontinuity of the magnetic field. At a certain radial position, the poloidal component of the total field is even reduced to zero. This means under this target plasma, the surface current on this surface makes nearly perfect compensation, i.e. strongly screening the $\delta B_r$ field, which creates the island in the penetration case. The ‘island’ should be suppressed to a very small size. Although the details of the phase inversion would strongly depend on...
the interplay among all surface currents on multiple surfaces, the measuring of poloidal field presented here gives rise to a possible way to identify the position of the rational surface.

For this discharge, by taking the gradient of the poloidal magnetic local field, the centre position of the rational surface can be identified as \( R = 221.3 \) cm. This is based on the assumption that the point which has the highest gradient can be considered as the centre position of the rational surface. Meanwhile, the position of the \( q = 3 \) surface obtained by the DIVA [36] code (solving the Grad–Shafranov equation) is \( R = 220.4 \) cm. This mismatch may come from the equilibrium calculation, since there is no current profile measurement. And the rational surface described by the phase jump of \( \delta B_\theta \) seems quite plausible.

It is natural to expect the linear and non-linear nature of the plasma response to depend on the DED current for fixed plasma parameters and fixed DED frequency. On increasing the flat-top values of the DED current with a fixed target plasma, the plasma response should vary from linear to non-linear. Such a DED current scan is carried out. In order to study the detailed evolution process of the plasma response, the radial profiles of plasma response are measured with different initial values (depending on the DED current). In this scan, the main parameters are \( B_T = 1.6 \) T, \( I_p = 250 \) kA, \( \bar{n}_e = 1 \times 10^{19} \) m\(^{-3} \), \( q_o = 4.2 \), \( f_{\text{ded}} = -5 \) kHz and \( I_{\text{ded}} \) is scanned from 0.2 to 0.7 kA. The same scan but with the +5 kHz DED is also performed for comparison. The results are presented in figure 9. In both scans, the position of the last closed surface is kept the same as in all the discharges presented in this paper (~223 cm).

In the -5 kHz DED case, \( |\delta B_\theta| \) increases with the DED current. When \( R \) is close to 230 cm, changes in \( \delta \theta \) values at different DED currents partly reproduce the process from a linear response to a non-linear response (see square points in figure 3). In this DED current scan, the non-linear response occurs before \( I_{\text{ded}} \) achieves 0.5 kA.

Still for the -5 kHz case and for \( I_{\text{ded}} = 0.3 \) kA, a \( \pi \) shift is observed in \( \delta \theta \) as \( R \) goes from 220 cm to 230 cm. One possible explanation is that the probe crossed the whole 4/1 surface during the insertion, assuming that the 4/1 mode is dominant here. For higher DED currents, there is no full \( \pi \) shift in \( \delta \theta \). This may be due to the increased island width for higher DED currents, so the non-linear effect could play some role. However, in all discharges, no island overlapping was observed, and not even more than one surface can be covered by the range which the probe can measure. Although the initial phases before the probe insertion are different, the final phases for all DED currents are almost the same (near \( \pi \) here). This value is consistent with the result in figure 4. In figure 4, for the linear regime between \( q_a = 4 \) and 5, the constant phase is near 0, while it is near \( -\pi \) for the linear regime between \( q_a = 3 \) and 4. Both values are the same considering the 2\( \pi \) shift.

In the +5 kHz DED case, with DED current ranging from 0.3 kA to 0.5 kA, \( |\delta B_\theta| \) slightly increases with the DED current and \( \delta \theta \) remains nearly constant. When \( I_{\text{ded}} = 0.7 \) kA, a 2/1 mode penetration occurs with a threshold of about 0.6 kA. \( |\delta B_\theta| \) increases nearly by a factor of 3 and \( \delta \theta \) changes by about \( \pi /3 \) right after mode penetration.

5. Discussion and summary

Experimental measurement results of the plasma response to resonant magnetic perturbations are presented in this paper. Two possibilities, single surface dominant or multi-surface dominant, can be used to explain the dependence of the plasma response on \( q_a \) (figures 4–6). One possible solution is to simulate this dependence numerically. In order to check
both possibilities, each Fourier harmonic has to be calculated, especially as the input of the four-field MHD code 4FC. Some preliminary work with the help of the 4FC code has been done [35], mainly showing the simulation of mode penetration. More efforts will be undertaken in the future.

Measurements of the magnetic field inside the plasma give direct information on the existence of helical response (to the RMP field) currents on resonant surfaces which can modify the vacuum RMP field. One has to note that the plasma response to the RMP discussed in this paper is different from the plasma response to the tokamak vacuum field which is defined in the Grad–Shafranov equation. Just like the ac RMP field, the response current should also be an oscillating ac current. This response current can be calculated from the gradient of the poloidal response field presented in this paper. However, since it is not sure whether the effect from a single surface or multiple surfaces is dominant, there is some difficulty in calculating the response current, especially for the non-linear response case.

As mentioned in the comparison of +5 and −5 kHz DED experiments, it is expected that RMP penetration is more likely to occur in the +5 kHz than in the −5 kHz case. It is observed in this and previous experiments that more field penetration occurs in the +5 kHz case. It is natural to expect a stronger screening effect in the −5 kHz case. In order to confirm the screening or field penetration state, the radial field δB needs to be determined, which is the source of island formation. The signal of the radial local field is not yet available for technical reasons. This problem is foreseen to be fixed in the next campaign, giving more detailed measurements from the FMMP.

Since one rational surface is observed during the probe insertion, there is a strong motivation to design a new experiment with higher qa, especially since no more than one surface has been covered to date (described in section 4). This effort may make it possible to observe multiple surfaces in the edge region where the probe can measure. Another option is to try 6/2 or even 12/4 mode DED since more resonant surfaces will be introduced. If multiple surfaces are detected, it is even expected that by increasing the DED current, different surfaces could overlap due to the increase in the island width. This may give a direct observation of the magnetic chaos. The main difficulty here is that the magnetic signal from higher m harmonics may be too weak for the probe to detect. This part is under preparation for the coming campaign.

In order to investigate the plasma response to RMP under different rotation levels, it is scheduled to perform the FMMP experiments by making use of the two tangential NBIs on TEXTOR. Beta scan and torque scan can be carried out. This part will extend the experimental observation to the H-mode like regime. The disadvantage of the beam experiment is that it will not be able to insert the FMMP into the plasma. Only ‘phase 1’ described in section 2 can be performed. Therefore, the edge profile cannot be compared with the Ohmic case, which is presented in this paper.

In conclusion, the plasma response to resonant magnetic perturbation has been investigated experimentally using the fast movable magnetic probe on TEXTOR. Linear and non-linear plasma responses are observed, depending on the parameters of the perturbation field and location of the resonant surface. A much stronger resonant effect is observed in the +5 kHz ac RMP case due to a smaller frequency difference between MHD frequency and the RMP rotation frequencies. Profiles of the poloidal component of the response field are presented, showing that the plasma response can significantly change the plasma edge field from the vacuum calculation. These experimental results can be compared with modelling work and allow the validation of the models before their further application to ELM control modelling. The data presented in this paper provide a set of experimental proofs that the vacuum assumption, which is the principle for the design of an ELM control coil system in ITER, is not always correct. The edge ergodization effect of RMP, currently being considered a possible physical mechanism to explain the ELM control by RMP, has to take the plasma response into account.
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