Observation of Edge Harmonic Oscillation in NSTX and Theoretical Study of Its Active Control Using HHFW Antenna at Audio Frequencies

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Abstract:

This paper presents two important topics in the tokamak ELM control using the non-axisymmetric (3D) magnetic perturbations: Experimental observations of the edge harmonic oscillation in NSTX (not necessarily the same as EHOs in DIII-D), and theoretical study of its external drive using the high harmonic fast wave (HHFW) antenna as a 3D field coil. Edge harmonic oscillations were observed particularly well in NSTX ELM-free operation with low $n = 1$ core modes, with various diagnostics confirming $n = 4 \sim 6$ coherent oscillations in 2-8kHz frequency range. These oscillations seem to have a favored operational window in rotational shear, similarly to EHOs in DIII-D QH modes . However, in NSTX, they are not observed to provide particle or impurity control, possibly due to their weak amplitudes, of a few mm displacements, as measured by reflectometry. The external drive of these modes has been proposed in NSTX, by utilizing audio-frequency currents in the HHFW antenna straps. Analysis shows that the HHFW straps can be optimized to maximize $n = 4 \sim 6$ while minimizing $n = 1 \sim 3$. Also, IPEC calculations show that the optimized configuration with only 1kAt current can produce comparable or larger displacements than the observed internal modes. If this optimized external drive can be constructively combined, or even resonated, with the internal modes, the edge harmonic oscillations in NSTX may be able to produce sufficient particle control to modify ELMs.

1 Introduction

Edge localized modes (ELMs) can generate unacceptable heat loads to plasma facing components in a reactor scale tokamak or spherical torus, and therefore ELM control is a critical issue in ITER. One promising concept is the application of steady non-axisymmetric (3D) fields to maintain the pedestal pressure below the edge stability boundary [1-3],

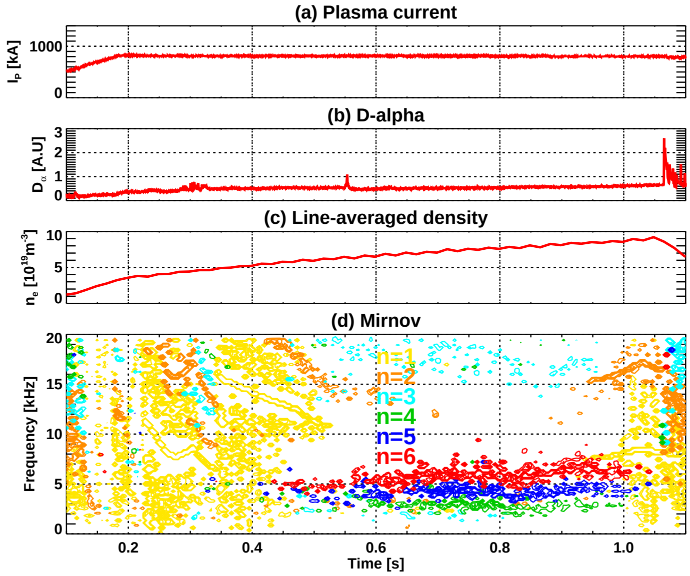


FIG. 1: An example of the edge harmonic oscillations observed in NSTX (#138239). One can see the clearly separated $n = 4 \sim 6$ harmonic oscillations in the ELM-free state at $t = 0.6 \sim 1.0s$, with $2 - 8kHz$ frequency range, from the (d) Mirnov oscillations.

as well as to provide sufficient particle transport without ELMs. However 3D coil requirements are often demanding in cost and engineering, and thus it is also valuable to minimize the coil requirements and/or to find an alternative means of ELM control, such as the operation in the quiescent H (QH) mode [4]. The QH mode utilizes naturally arising 3D fields in the edge, called edge harmonic oscillations (EHOs), instead of externally driven 3D fields. However, the QH mode requires strong rotational shear [5], and thus the operational window is possibly limited, or external 3D field coils are required again to control the rotational shear [5,6]. These requirements may be mitigated if internal and external drive of 3D fields can be constructively combined. This paper covers two important topics for this vision: Experimental observations of the edge harmonic oscillation in NSTX (not necessarily the same as those observed in the DIII-D QH mode), and theoretical study of its audio-frequency active control using the existing NSTX [7] high harmonic fast wave (HHFW) antenna [8] as a 3D field coil, to amplify the internally arising harmonic oscillations, in order to provide externally adjustable particle transport and ELM control.

2 Observation of Edge Harmonic Oscillation in NSTX

In ELM-free operation in NSTX associated with strong lithium deposition, clear edge harmonic oscillations were reproducibly observed during operation with $\sim 4MW$ of neutral beam injection (NBI) power, $I_P \sim 800kA$ plasma current, and $B_T \sim 4.5kG$. These

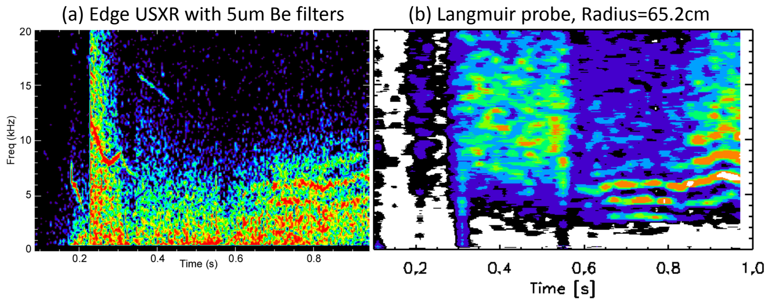


FIG. 2: Edge harmonic oscillations observed from (a) the edge USXR, and (b) the Langmuir probes in the far SOL, with the similar frequency range $2 \sim 8kHz$, in the discharge #138239.

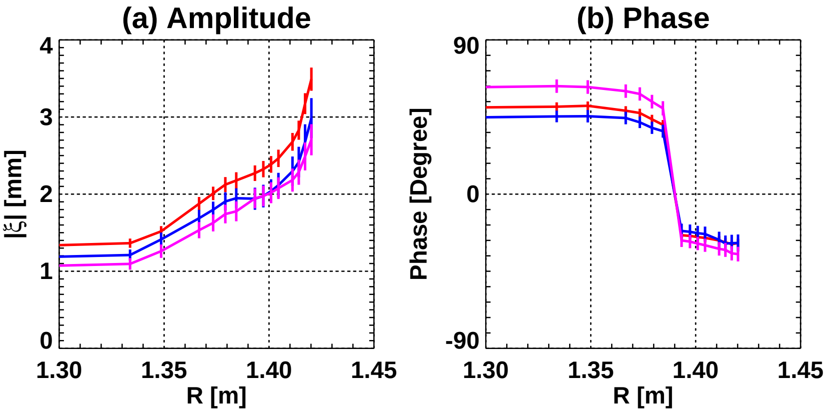


FIG. 3: Plasma displacement profiles associated with the edge harmonic oscillations in NSTX, measured by reflectometer in the discharge #138752. (a) The amplitude shows the edge localized nature and (b) the phase shows the coherent nature of the modes.

oscillations, which share some characteristics with the n=1 dominated modes observed in small-ELM regimes in NSTX [9], were first widely observed on Mirnov coils. Figure 1 shows an example of discharges and observations, where one can see clearly separated harmonic oscillations from the Mirnov, with $2 \sim 8kHz$ and toroidal harmonics $n = 4 \sim 6$, in long ELM-free periods with low core $n = 1$ modes.

Other diagnostics in NSTX also found these oscillations. The edge ultra-soft x-rays (USXR) channel [10], using the thinner, $5\mu m$ Be filter, found the oscillations with the similar frequency range as shown in Figure 2 (a). Also, Langmuir probes [11], in Figure 2 (b), showed that the oscillations are stretched out to the far scrape-off layer (SOL) region. The USXR and Langmuir probes indicate that the oscillations are noticeable especially in the edge including the far SOL and may be localized in the edge region.

The edge-localized nature of the modes becomes evident by reflectometer [12], which can resolve the plasma displacement profile by measuring density fluctuations, as shown

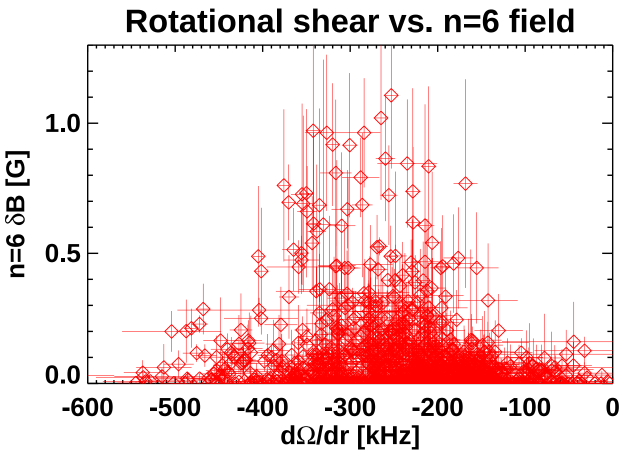
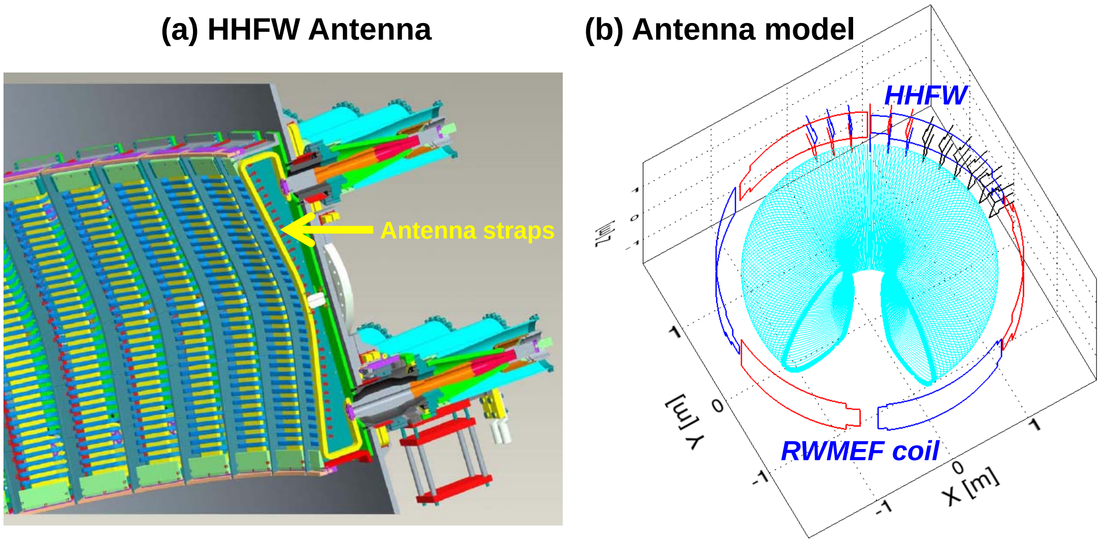


FIG. 4: Statistical analysis indicating the $n = 6$ of the edge harmonic oscillations in NSTX may have a favorable range of the rotational shear.

in Figure 3. One can clearly see the modes are localized at $R > 1.35m$, which corresponds to the NSTX pedestal, with the mode amplitudes up to $3 \sim 4mm$. Another observable feature is the coherent nature of the modes. As can be seen from Figure 3 (b), the $n > 3$ modes are highly coherent for their toroidal phases in entire spatial region within only a few %. Note that it is also interesting to see the $n > 6$ mode from the reflectometry, while the $n > 6$ is beyond the covering range of the Mirnov. The $n = 6$ mode amplitude is still the largest in the reflectometry, but this $n > 6$ observation indicates that the NSTX edge harmonic oscillations may be the collection of the coherent toroidal harmonic modes covering the wider n than $n = 4 \sim 6$.

The edge harmonic oscillations found in NSTX are not necessarily identical to the EHOs in DIII-D driving the QH mode, but seem to have similar stability characteristics. The EHOs on DIII-D are understood as the low n peeling modes destabilized by strong rotational shear and non-linearly saturated by regulating back the rotation shear [5]. The edge harmonic oscillations in NSTX are also mostly the low n's, indicating that they may also be associated with peeling modes. Moreover, the stability analysis using the DCON code [13] indicates that the studied discharges are close to the marginal stability for $n > 3$ and thus would be easily destabilized if any non-ideal MHD mechanism is involved. In NSTX, the edge harmonic oscillations become apparent in particular operating conditions, such as the beam power $\sim 4MW$ as mentioned earlier in the paper, but those conditions could be favorable to particular kinetic parameters such as the rotational shear. Indeed, although the correlation is not so strong, the statistical analysis for ~ 30 discharges on the Mirnov shows that the $n = 6$ mode amplitudes, for instance, have a favorable range of the rotational shear, as can be seen in Figure 4.

The stability and statistical analysis suggest that the edge harmonic oscillations in NSTX may have similar characteristics to the EHOs in DIII-D. However, these oscillations did not provide any utility on performance in NSTX, any clear particle and impurity control, as the density kept rising as already shown in Figure 1 (c). It will be interesting



(a) HHFW Antenna (b) Antenna model

FIG. 5: The actual design of the HHFW antenna in (a), and the filament model of the antenna straps in (b), compared to the existing RWMEF coils. The color codes in (b) actually shows the finally optimized configuration for $n = 4 \sim 6$, as described in the paper.

to see if 3D field perturbations can be used to adjust the rotational shear to a favorable level and if the edge harmonic oscillations can be strengthened enough for the particle control, similarly to the non-resonant magnetic field (NRMF) application for the EHOs in the DIII-D QH mode. This can be studied in the future, but here we studied a different utilization of 3D fields; Coupling the external 3D field drive to these naturally arising internal modes. This will be described in the next section.

3 Study of Edge-Harmonic Mode Control Using HHFW Antenna

The edge harmonic oscillations in NSTX could potentially be used for particle and ELM control if the modes could be amplified by external means such as 3D field coils, directly rather than indirectly, unlike the NRMF control of the rotational shear. R. Goldston proposed the utilization of HHFW antenna for this and to couple external 3D fields to the internal modes using audio-frequency currents in the antenna straps. The HHFW antenna locations are localized within a 90 degree toroidal section and so they can effectively drive high n modes in the edge. Figure 5 illustrates the localized feature of the HHFW antenna, compared to the existing NSTX 3D coils. Also there are 24 antenna straps in total, which can give the high flexibility in producing the 3D field spectrum and for its optimization.

For optimization, first the dominant external field for plasma is identified using the

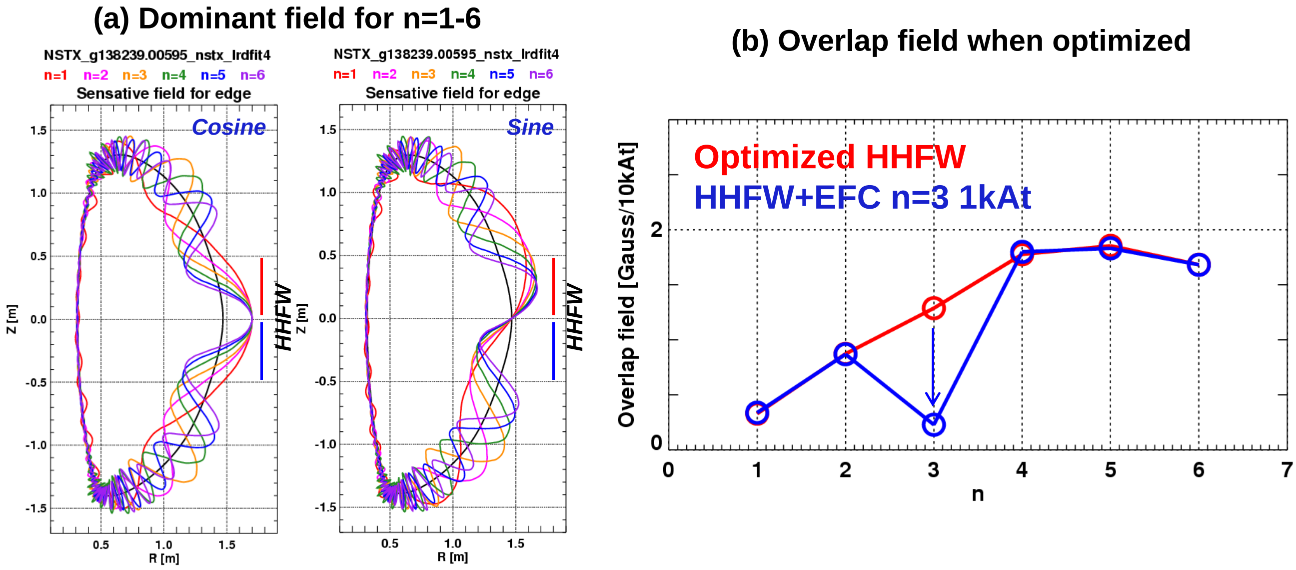


FIG. 6: IPEC analysis for the (a) dominant $n = 1 \sim 6$ *external field measured on the plasma boundary, and the (b) overlap with the dominant field when the configuration is optimized for high* $n = 4 \sim 6$. *In principle, the RWMEF coil can be used to reduce* $n = 1 \sim 3$ *further, as illustrated in (b).*

Ideal Perturbed Equilibrium Code (IPEC) [14], and the best configuration is chosen to produce the dominant external field for $n = 4 \sim 6$ as closely as possible while minimizing $n = 1 \sim 3$ fields. This can be quantified by the overlap field with the dominant external field on the boundary, which is the effective measure of the efficiency on the dominant field drive [15,16]. Figure 6 shows (a) the dominant external field for $n = 1 \sim 6$ and (b) the overlap with the dominant field for each n when optimized. The dominant field structure, especially the sine part, already shows that the coupling with the HHFW antenna should be more efficient for the higher $n = 4 \sim 6$ due to the localized antenna at the midplane. The optimized configuration, as illustrated in the previous Figure 5, with the color codes, is selected from $20 - 30$ different combinations of the positive (the red in Figure 5), the negative (the blue) polarities, otherwise inactivated (the black), in each 24 antenna strap. In principle, the configuration can be further optimized using different currents in each strap, but practically the limited power supplies will require the equivalent currents in straps. Also even RWMEF coils can be combined to minimize low n modes, if driving frequencies are sufficiently low, as shown in Figure 6 (b).

With the optimized configuration, quantitative IPEC calculations for driven radial displacement are compared with the quantitative reflectometer measurements in Figure 7. The calculations show that when the HHFW antenna configuration is optimized, only the 1kA current in the antenna straps can drive much larger displacements for $n = 5$ and comparable ones for $n = 6$, than the observed edge harmonic oscillations. This current is within the normal range of RF frequency currents in NSTX HHFW application.

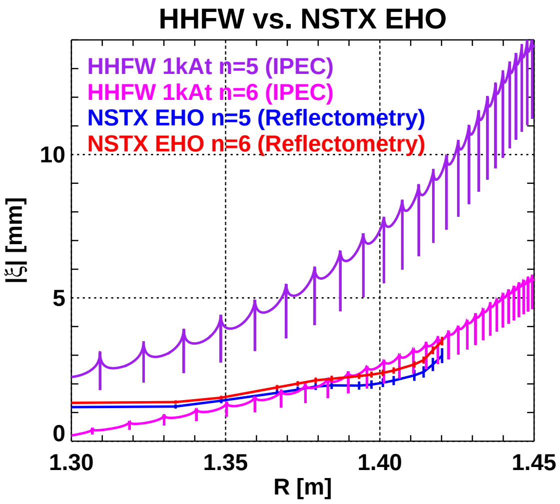


FIG. 7: The externally driven displacements by the optimized HHFW antenna configuration, predicted by IPEC, and the internally driven displacements by the edge harmonic oscillations in NSTX, measured by reflectometry.

Therefore, if this external drive of the high n modes can be constructively tuned, or even resonated, with the internally arising modes, the edge harmonic oscillations in NSTX may be able to provide sufficient particle transport, to change the pedestal structure and to control ELMs.

4 Concluding Remarks

The observation of the edge harmonic oscillation in NSTX, and the theoretical study of its active drive using HHFW antenna as a 3D coil are presented and discussed. The possibility of implementing a drive system will be examined in NSTX-U first, and successful application may provide a pathway to AC drive of peeling-ballooning modes for edge particle and ELM control in future devices, including ITER. Also, if the externally driven 3D field can be constructively combined with the internally driven oscillations as suggested in this paper, it will be a very useful and unique tool for the ELM control in tokamaks by mitigating the demanding 3D coil requirements and the limited operating conditions, compared to only the external or only the internal 3D field utilization.

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