Redistribution of three-dimensional divertor footprint induced by time-varying resonant magnetic perturbations on EAST

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Introduction

One of the main concerns for future ITER H-mode operation is the control of heat and particle fluxes to the plasma facing components (PFCs)[1, 2]. The transient heat and particle fluxes to the divertor plates, mainly induced by the type-I edge localized modes (ELMs) can be controlled by applying resonant magnetic perturbations (RMPs). The RMP ELM suppression was first achieved on DIII-D and then reproduced on KSTAR, EAST and recently on ASDEX-Upgrade. Other devices have reported ELM mitigation effects with RMPs. But there still problems from localized stationary heat and particle loads under fixed RMP application. Because stable and unstable separatrix manifolds will form homoclinic tangles and intersect with the divertor target plates. Non-axisymmetric helical striations are created on the divertor plates and the so-called strike point splittings introduce additional paths for heat and particles striking on the divertor plates. The localized stationary heat and particle load on the divertor target may exceed thermal stress limits and leads to excessive localized erosion, especially in the long pulse operation case. To avoid it, the distribution of heat and particle fluxes needs a dynamic control, which can be achieved by time-varying RMP fields.

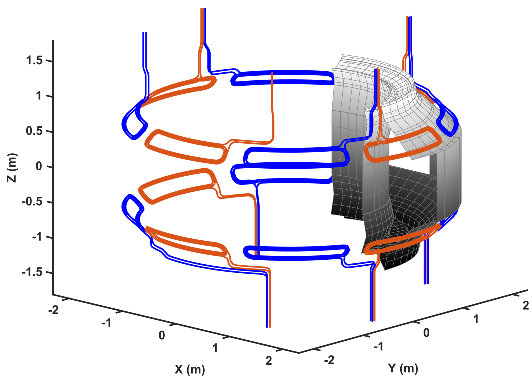

Figure 1: *RMP coils on EAST*

The Experimental Advanced Superconducting Tokamak (EAST) with ITER-similar low-torque heating, RMP coils and plasma configurations can be a good platform for testing the effect of time-varying RMP fields on both ELMs and divertor power loads. The shape and position of the EAST RMP coils is shown in Fig. 1. There are two up-down symmetric RMP coilarrays closely outside the vacuum vessel wall facing the hot plasmas. Each coil array has eight 4-turn coils distributed along the toroidal direction. The current of k^{th} coil (coil center at $\phi_{\rm k}$) in upper (s = U) or lower (s = L) array is given by $I_{\rm s,k} = A\cos(n\phi_{\rm k} - \phi_{\rm s})$, in which A is the amplitude. The flexible power supply and control system can provide A up to 2.5 kA. Rotating the coil current in both array with same frequency will produce a rigid rotating RMP field. Rotating the coil current (continuously or in steps) in only one array will produce a phase difference $d\phi_{UL} = \phi_U - \phi_L$ scan (spectrum scan) RMP field.

TOP2D code[3] is used for the magnetic topology and footprint modeling, which can calculate under both vacuum (VAC) or plasma response (PLS) cases. The plasma response is calculated by MARS-F, in which single fluid resistive full magnetohydrodynamic equations are used.

Experimental observations under time-varying RMPs

A rotating spiral pattern of the particle flux was observed in shot 52342 using rigid rotating n=1 RMP field[4]. Three full toroidal cycles of the 10 kAt (2.5kA $\times$ 4turns) n=1 RMP field with $d\phi_{\rm UL} = 0^\circ$ were applied from 3.2 s to 3.5 s. Figure 2 shows the particle flux js in A/cm^2 temporal evolution at one toroidal angle on the lower outer divertor plate. L in centimeter measures the poloidal distance along target from one point on the divertor to the corresponding divertor corner ($L = 0$). Overlapped contours are temporal evolution of magnetic footprint formed by two magnetic surfaces of square root of normalized poloidal magnetic flux $\rho = \sqrt{\psi_{pN}}$=1 and 1.06. There is a good agreement between the modeled magnetic footprint and the experimental observations, which is more clear in

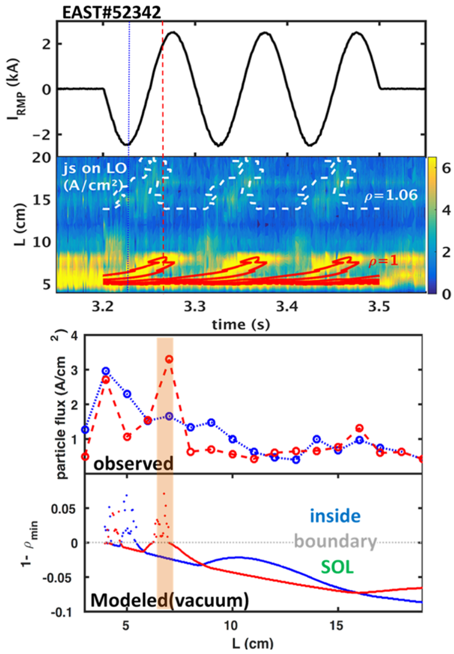

Figure 2: *The particle flux temporal evolution with the rigid rotating RMP field is consistent with the numerical modeling of magnetic footprint.*

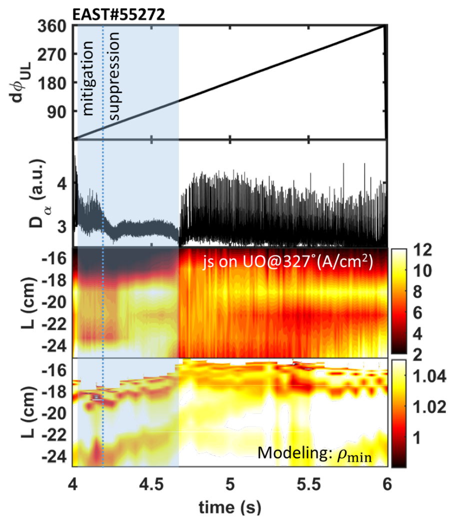

Figure 3: *n=1 RMP spectrum scan and the effect on ELMs and the particle flux on the upper outer divertor plates. The modeled footprint temporal evolution is compared.*

the lower subgraph showing the comparison between profiles of the observation and the penetration depth $1-\rho_{min}$ of two time slices marked in the upper subgraph.

The temporal evolution of particle flux is also observed in shot 55272 with a continuous spectrum scan of $n = 1$ RMP fields[4], which is shown in Fig. 4. $d\phi_{UL}$ changed two periods from 0 to 360° continuously. The plasma behavior in the two periods are highly repeated so only one period from 4 s to 6 s are shown. Due to the RMP spectrum effect, a nonlinear transition from mitigation to suppression of the ELMs has been reported in Ref.[5]. The particle flux temporal evolution measured at one toroidal angle on the upper outer divertor plates is compared with the modeled time-varying magnetic footprint at the same toroidal angle. It also shows a qualitative consistency with the measured particle flux in terms of the modeled strike point splitting patterns. During ELM suppression (4.3 s, 4.5 s and 4.7 s) and mitigation (4.0 s and 4.3 s) phases, the footprint area defined by the intersection of the deformed separatrix of $\rho = 1$ are modeled and shown in Fig. 4. It indicates that the magnetic footprint can be redistributed in a wide toroidal angle on the lower outer divertor with only one coil array current rotating.

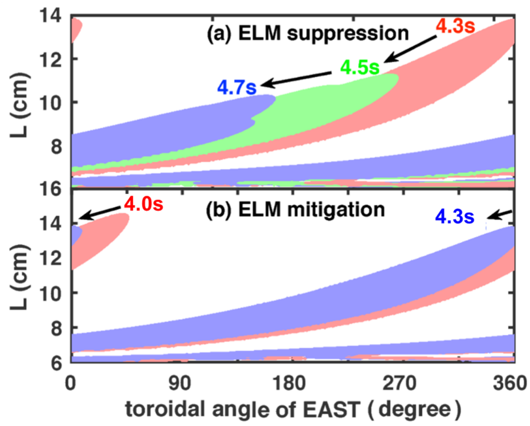

Figure 4: *Modeled magnetic footprint on the lower outer targets during ELM suppression and mitigation phases in shot 55272.*

The RMP spectrum effect on the heat flux distribution is observed in EAST shot 71204 as shown in Fig. 5. The 10 kAt $n = 1$ RMP fields with spectrum scan in steps was applied. The step with $d\phi_{UL} = 270°$ and the other one with $d\phi_{UL} = 180°$ are compared. They have different effect on the ELMs and only heat flux splitting is observed in the later steps with better ELM-control effect.

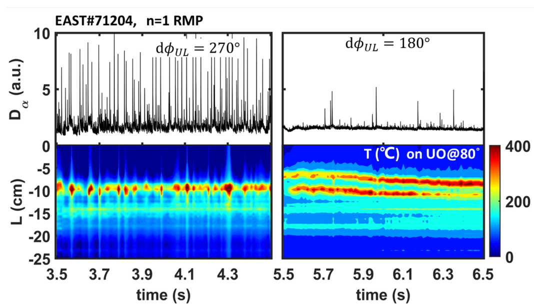

Figure 5: *The RMP spectrum effect on ELMs and heat flux distributions in shot 71204*

Effect of plasma responses on magnetic footprints

The plasma response is found to influence the penetration depth of field lines connected to the footprint patterns on divertor target under the application of the RMP field and then to influence the particle flux distribution on the divertor target. As an example, the plasma response effects in EAST shot 56366 with a spectrum step-scan n=2 RMP field are shown. $\mathrm{d}\phi_{\mathrm{UL}} = 270^\circ$ and $\mathrm{d}\phi_{\mathrm{UL}} = 90^\circ$ are two obvious cases of amplifying and screening effects respectively. The value of $\rho = \sqrt{\Psi_{\mathrm{pN}}}$ of the upper X-point is 1.044. So the contour lines with $\rho_{\min} = 1.044$ is of footprint formed by the deformed upper separatrix. As shown in Fig. 6, the footprint contours for the VAC and PLS cases are compared in (a) and (c). The corresponding field line penetration depth $1-\rho_{\min}$ profiles at one toroidal angle are compared with the measured particle flux profiles at the some position are compared in (b) and (d). The peak positions on the profile are not changed by the plasma response. But the $\rho_{\min}$ value of each peak has been changed. Under $\mathrm{d}\phi_{\mathrm{UL}} = 270^\circ$ spectrum there is an amplifying effect that makes field lines closer to LCFS connect to the divertor. On the contrary, under $\mathrm{d}\phi_{\mathrm{UL}} = 90^\circ$ spectrum, the $1-\rho_{\min}$ profiles in (d) indicate that the plasma response has a screening effect that makes field lines closer to LCFS no longer connect to the divertor. It also means that after considering the effect of plasma response the field lines connected to the divertor could not penetrate deep into SOL, as a result there will be less charged particles from the plasma region being converted to the divertor.

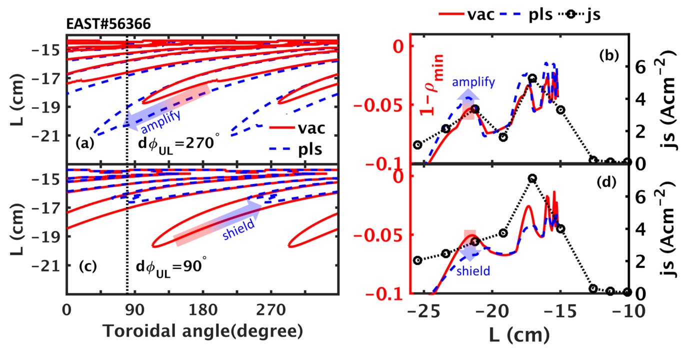

Figure 6: *The plasma response effect changes the field line penetration depth in shot 56366*

Conclusion

Both particle and heat fluxes can be more evenly distributed on the divertor plates by rotating RMPs or changing the spectrum. Plasma responses also play an important role in the magnetic footprint distribution. Power load distribution can be controlled simultaneously with good ELM-control background. For this purpose, a clear ELM-control window and skillfully designed time-varying schemes combining both rotating and spectrum scanning RMPs are required.

References

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