Shielding and amplification of non-axisymmetric divertor heat flux by plasma response to applied 3-D fields in NSTX and KSTAR

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Non-axisymmetric divertor heat flux is one of the primary concerns with the application of 3-D fields for ELM control in ITER, as they will cause asymmetric erosion and re-deposition of divertor material. Not only in attached divertor conditions, it is also important when 1) the applied 3-D fields burn through detached divertor plasma or 2) heat flux at outer lobes in the far SOL increases by 3-D fields even though plasma in the near SOL remains detached, as seen in NSTX [1, 2]. Understanding of underlying physics processes that determine 3-D divertor footprints is therefore crucial for ITER's long pulse operation scenario in the presence of 3-D fields. It has been recently found that plasma response plays a key role in the formation of 3-D lobe structure and divertor footprints by the applied 3-D fields in NSTX (mid-plane coils only, up to n=3) and KSTAR (upper, middle, and lower row of coils, up to n=2).

Work in NSTX showed [3] that ideal plasma response from IPEC can significantly shield or amplify vacuum footprints from field line tracing. The spherical tokamak geometry of NSTX enables measurement of divertor footprints with almost full toroidal and radial coverage of lower divertor plates. Figure 1 shows footprints with n=1 magnetic perturbations in NSTX. Experimentally observed footprint by a wide angle visible camera is illustrated in figure 1(c). The connection length (L_c) profile for the case of vacuum approximation (blue, figure 1(d)) shows that L_c rapidly decreases only at the very plasma edge (Ψ_N~0.97). This corresponds to the very weak vacuum footprint splitting shown in figure 1(b). However, ideal plasma response dramatically amplifies modeled splitting, see figure 1(a), and this produces a better agreement with the camera image demonstrated in figure 1(c). Accordingly, the L_c profile begins to decrease (figure 1(d)), in a significantly deeper region, Ψ_N~0.75, which is a

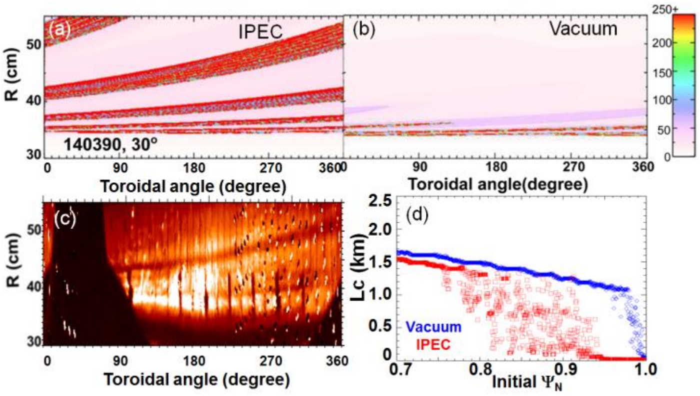

Figure 1 Divertor footprints in the presence of applied n=1 magnetic perturbations in NSTX. (a) and (b) are contour plot of connection lengths from field line tracing with and without ideal plasma response, respectively. Plot (c) is the experimentally observed footprint from a wide angle visible camera. Plot (d) shows the profile of connection length for the vacuum (blue) and ideal plasma response (red) case.

consequence of strong amplification of applied n=1 fields. However, for the case of n=3 in NSTX, applied 3-D fields are primarily shielded by ideal plasma response; the shielding effect of resonant fields is greater than the amplification effect of non-resonant fields.

Shielding of applied 3-D fields has been also observed in KSTAR by ideal (IPEC) plasma response modeling. AC waveforms were used to produce time varying spectrum of 3-D fields that continuously changed alignment with equilibrium pitch. Two distinctive phases of n=2 perturbations were closely examined; resonant (90^o phase) and non-resonant (0^o phase) configurations. It was revealed that deep penetration of applied n=2 fields is inhibited by the shielding effect of resonant components even with kink excitation of non-resonant components in both phases. Figure 2 shows poloidal spectrum of n=2 fields with 90^o phase in KSTAR. As in NSTX, non-resonant components of the applied n=2 fields are amplified due to kink excitation, see figure 2(b), while resonant components, *i.e.* the field components along the white dashed line in figure 2(a), are strongly shielded. This shielding effect wins over the amplification effect of non-resonant fields, producing the end result that the applied n=2 fields are significantly screened; see figure 2(c) for comparison of radial profile of total perturbation for the vacuum and IPEC case, which shows screening of vacuum fields by plasma response. 90^o phase produces strong density pump-out as well as significant reduction of stored energy (W_{tot}). However, toroidal rotation speed (V_t) in the edge is not reduced, which should have created effective screening effect. On the contrary, 0^o phase did not produce noticeable drop in density and W_{tot} but reduced V_t significantly. The decrease of V_t leads to relatively weaker shielding compared to the 90^o case, which is consistent with the comparison to poloidal spectrum and L_c profile data between the two phases.

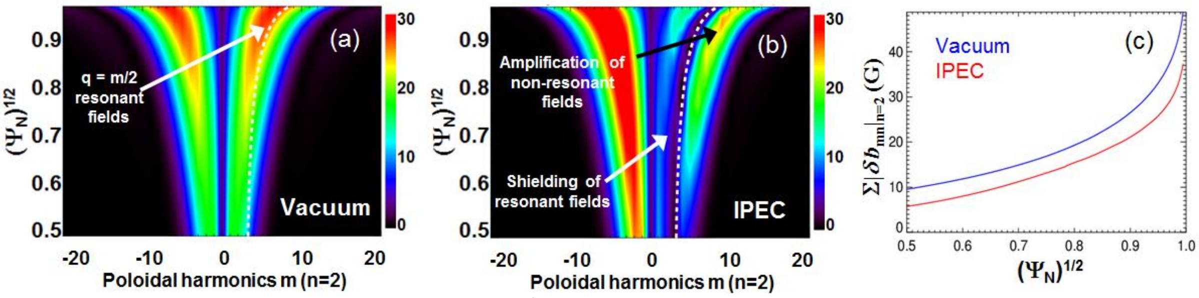

Figure 2 Poloidal spectrum of n=2 fields with 90^o phasing in KSTAR. Plot (a) is for the vacuum case and (b) is for the ideal plasma response case from IPEC. Strong shielding of resonant fields and excitation of non-resonant fields are observed when the plasma response is taken into account. Plot (c) is radial profile of total perturbation, sum over m=[0, 20], for vacuum and IPEC, showing net shielding effect of applied fields by plasma response.

Radial location of lobes in the measured heat flux profile shows good agreement with that from the field line tracing for both 90^o and 0^o phases in KSTAR. Observed heat flux splitting for the 90^o phase is stronger than 0^o even though the shielding effect is stronger for 90^o. This can be due to the fact that the original vacuum penetration for the 0^o phase is much weaker, so that less field lines leak out of the stochastic region than in the 90^o case even after taking account of the shielding effect of plasma response.

In summary, the role of plasma response to the applied and intrinsic 3-D fields in setting non-axisymmetric divertor heat flux pattern in tokamaks has been studied with data from NSTX and KSTAR. This work was supported by the US Department of Energy, contract numbers DE-AC05-00OR22725 (ORNL), DE-AC02-09CH11466 (PPPL), DE-FC02-04ER54698 (GA), and DE-AC52-07NA27344 (LLNL), and DE-SC0013911 (UW).

Reference

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