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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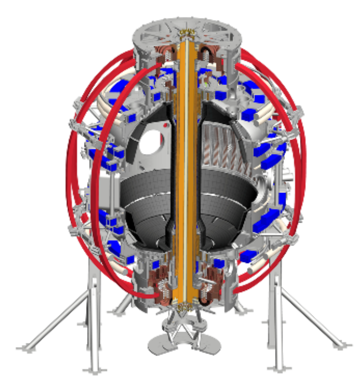


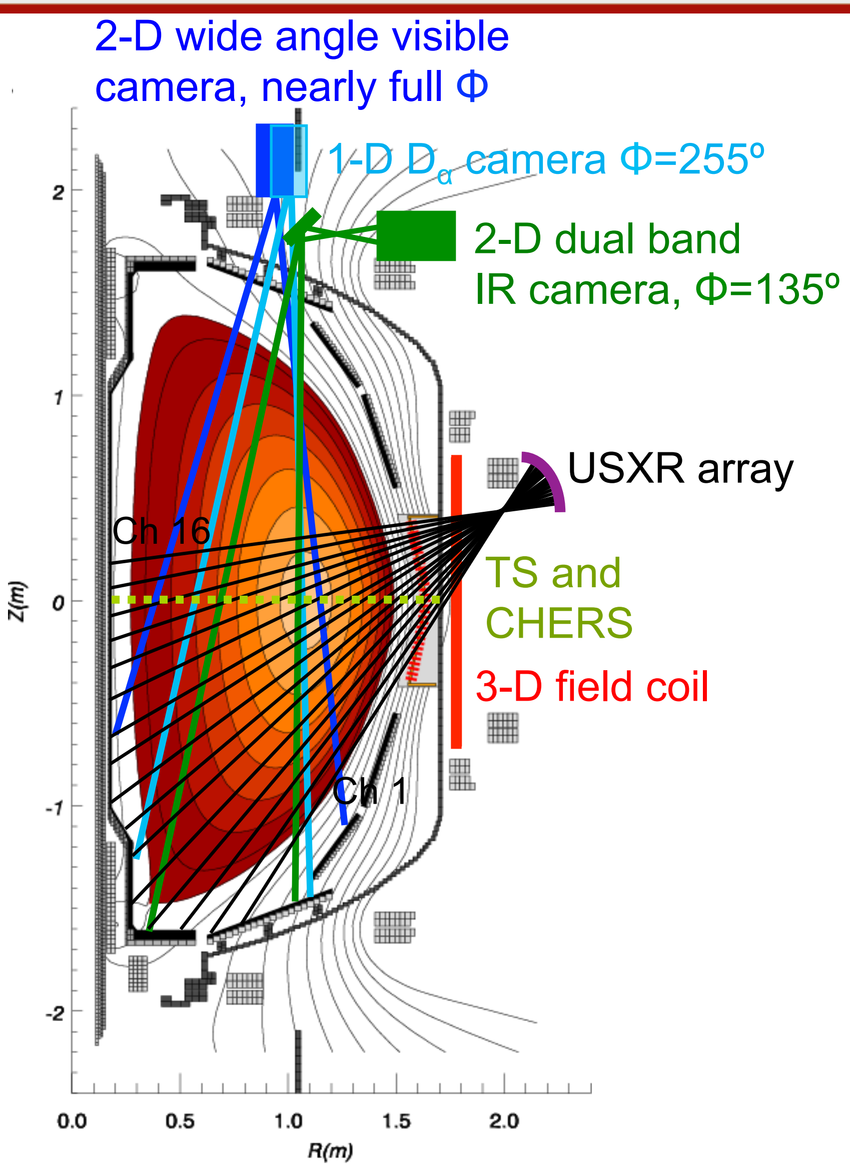
Motivation and outline

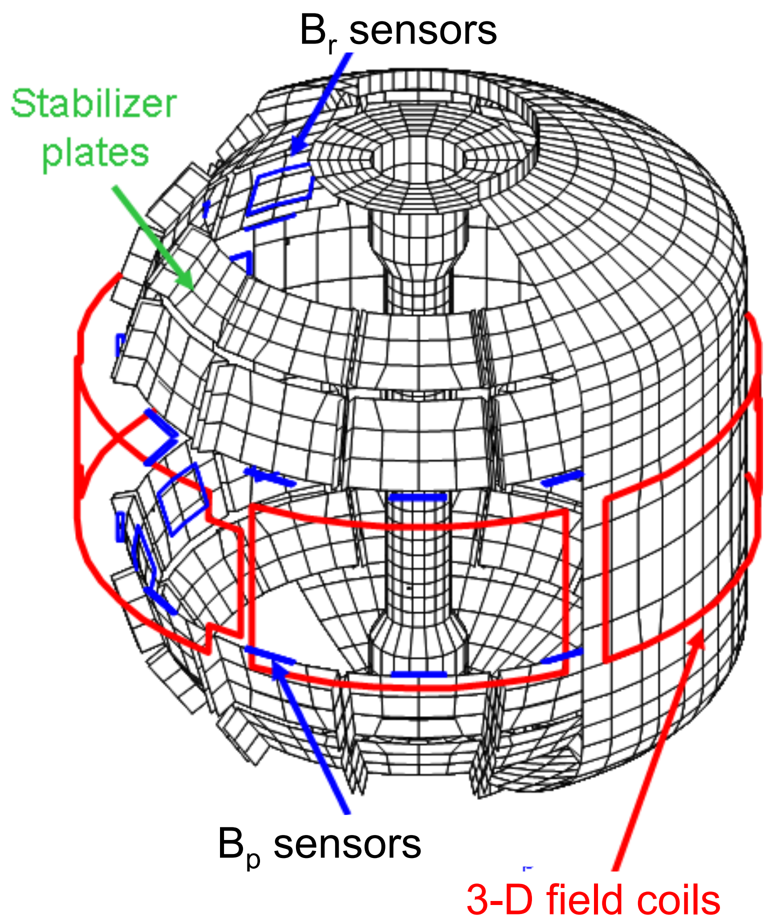
- Non-axisymmetric divertor footprints with 3-D fields are concern for future machines due to 3-D erosion and re-deposition

- 3-D footprints are strongly affected by plasma response → measurement is compared to field line tracing
  - Vacuum field line tracing
  - Ideal plasma response model (IPEC)
  - Different response for n=3 and n=1

- Understanding of common underlying physics over multiple machines is important
  - Compact size of NSTX offers a chance of wide view of divertor
  - KSTAR has 3 rows of coils → fine tuning of field spectra is possible
  - Same analysis tools (plasma response, footprint measurements, etc)

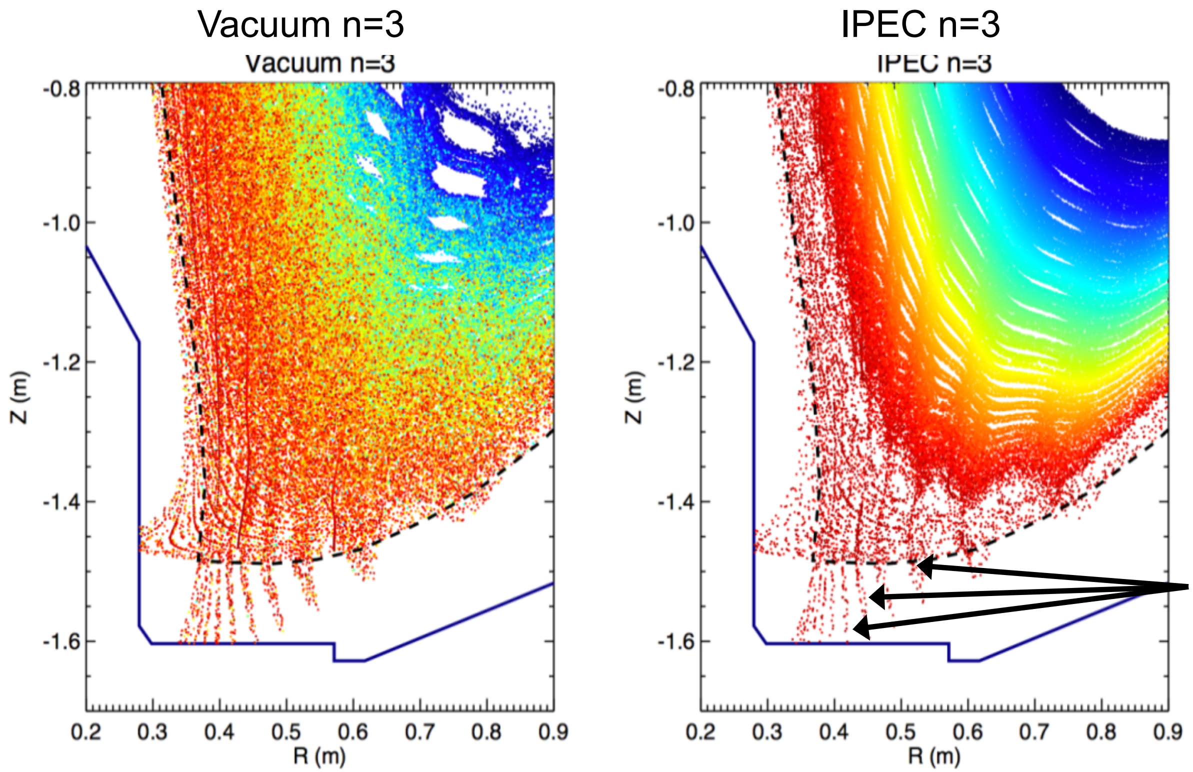
NSTX 3-D field coils and diagnostics





3-D fields (n=1, 2, 3) applied by mid-plane EFC coils

Field line tracing identifies lobes in the X-point region generated by 3-D fields, w/ and w/o plasma response

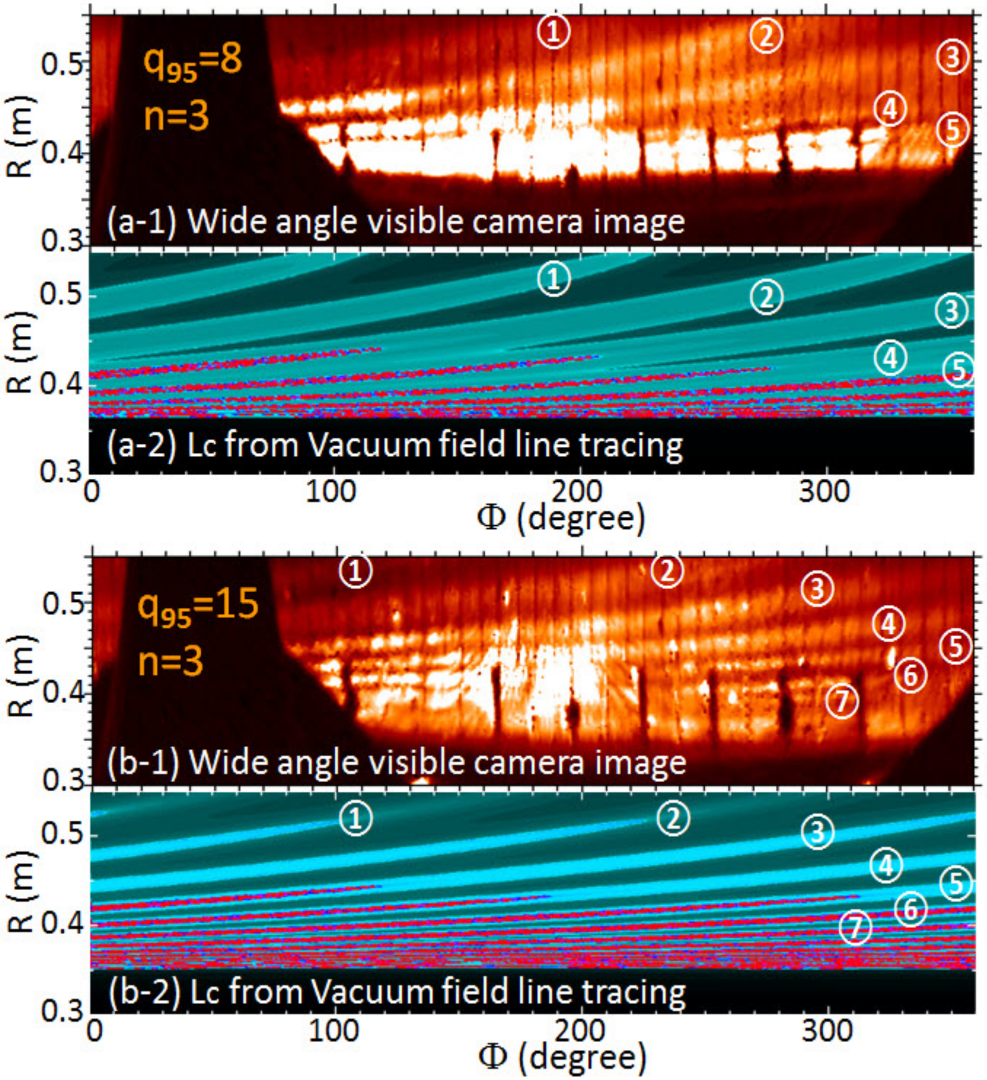


K. Kim, PPCF 57 (2015), 104002

Homoclinic tangles

- 3-D fields induce 3-D topology of perturbed field lines → lobe of homoclinic tangles
- Field line tracing simulation provides magnetic structure of 3-D lobes
  - Provide Poincare plot, divertor footprint, field line connection length profile, etc.
  - Compare results from vacuum approximation to that with ideal plasma response (IPEC)

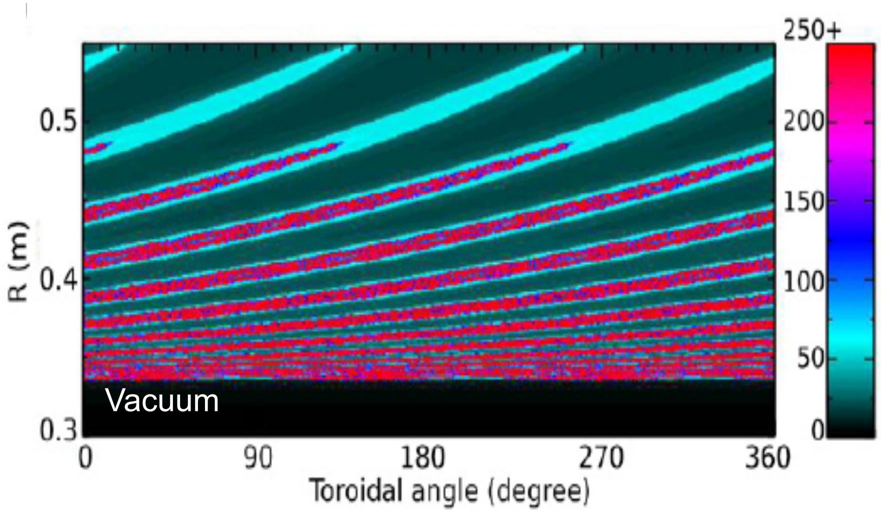
Vacuum approximation in agreement with footprints measurement for n=3 perturbation

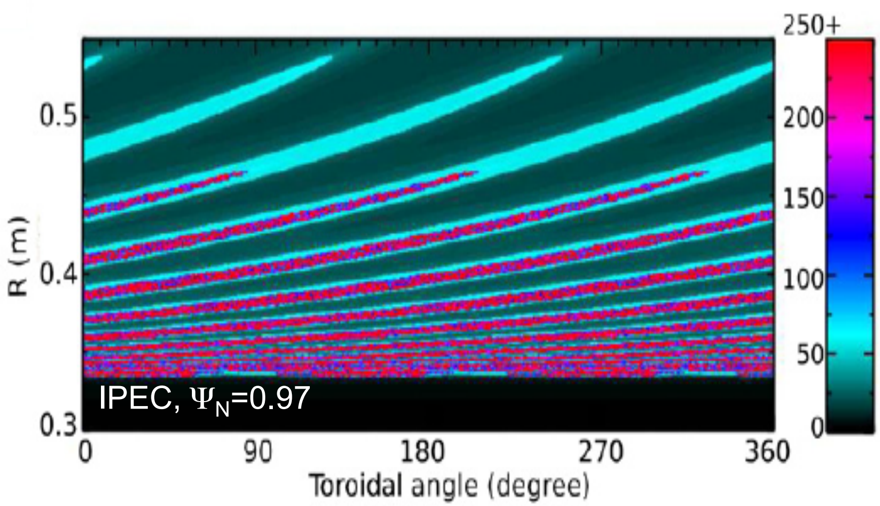


J-W. Ahn, PPCF 56 (2014), 015005

- Wide angle camera images enable comprehensive comparison to connection length (L_c) contour plot from vacuum field line tracing
- Both camera images and vacuum field line tracing produce more and narrower striations for higher q_{95}
- Good agreement between camera and vacuum field line tracing

Ideal plasma response shields applied 3D fields but overall structure is similar to vacuum result for n=3





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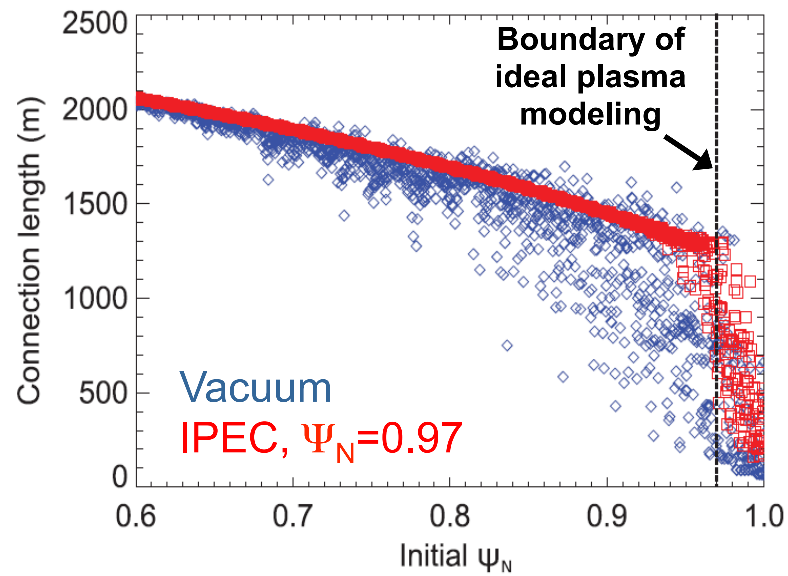
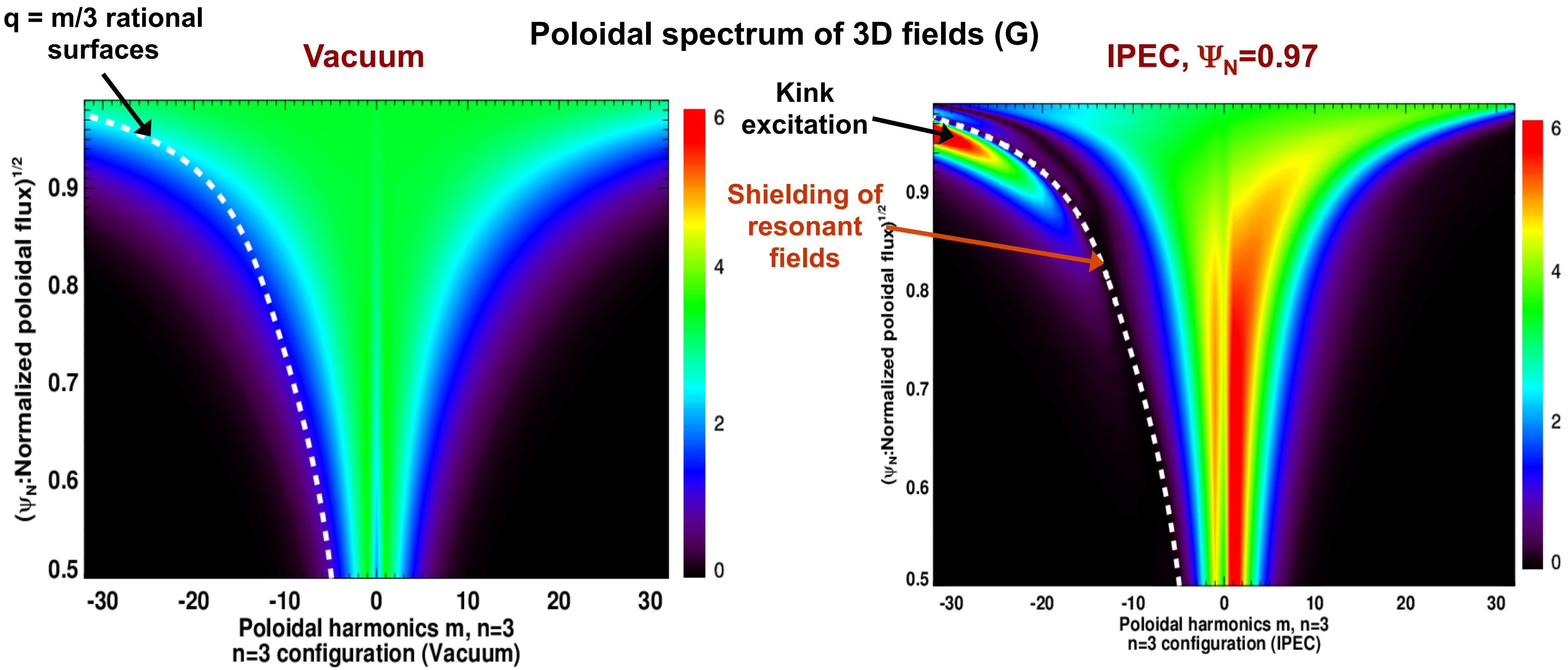


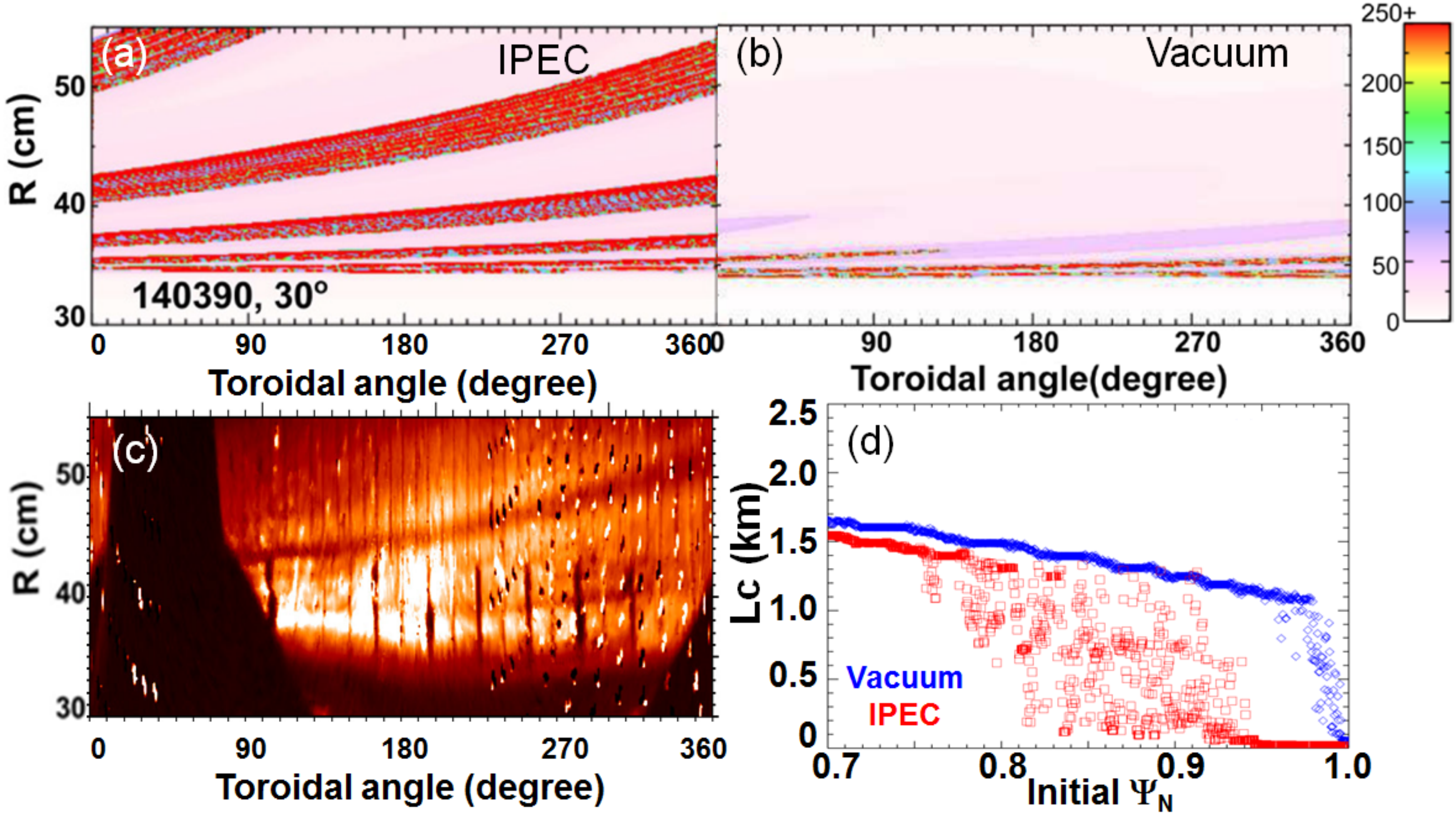
- Weakening effect from IPEC is affected by location of ideal plasma boundary
- Envelope of lobes not changed by response
- L_c profile inside separatrix shows modification of stochasticity and clear shielding effect by ideal plasma response

Shielding of resonant fields and amplification of kink response lead to weaker footprint splitting for n=3



- Resonant components are strongly shielded by ideal plasma response
- Non-resonant kink excitation is also observed
- Combined net effect is to shield the applied n=3 fields and weaken magnetic separatrix splitting

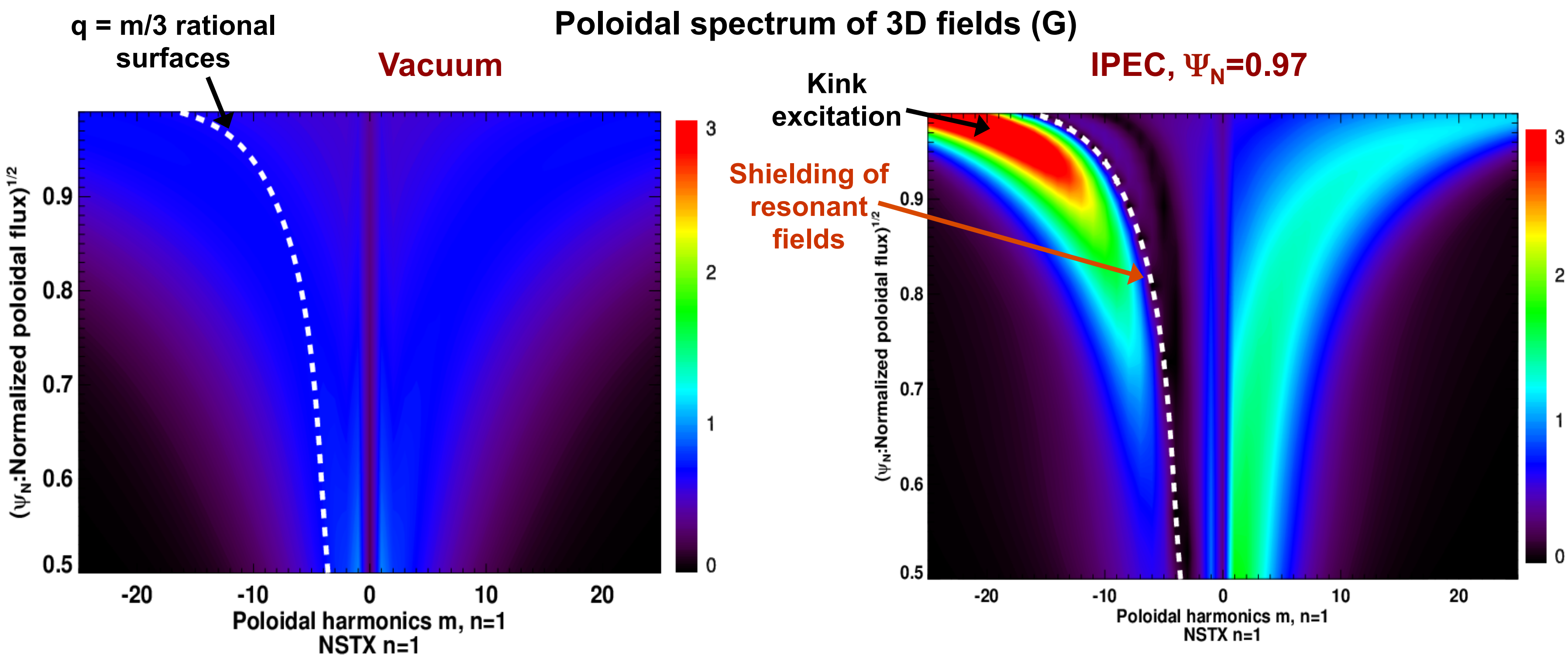
n=1 perturbation is very sensitive to plasma response – amplification of footprint splitting is observed



- Ideal plasma response dramatically amplifies n=1 separatrix splitting
  → better agrees with camera image

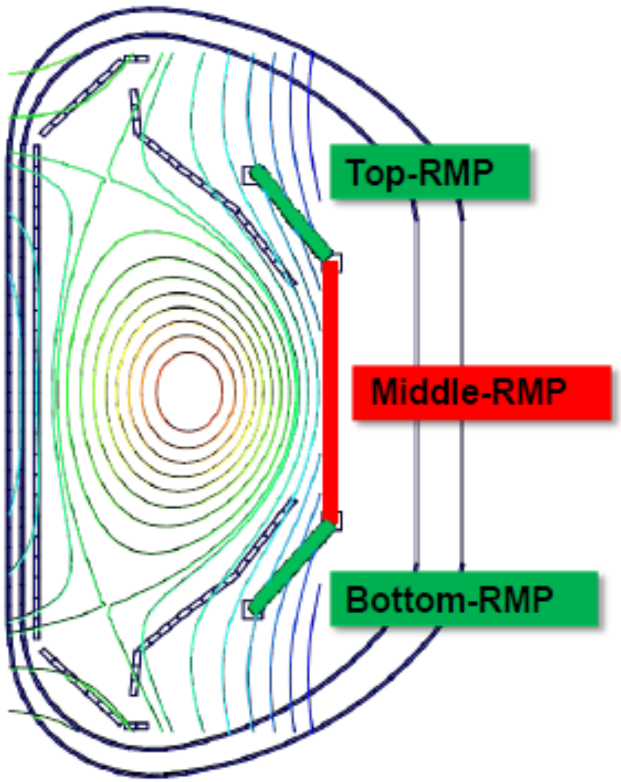
- Plasma response not only modifies amplitude, but also changes envelope of striations, unlike n=3

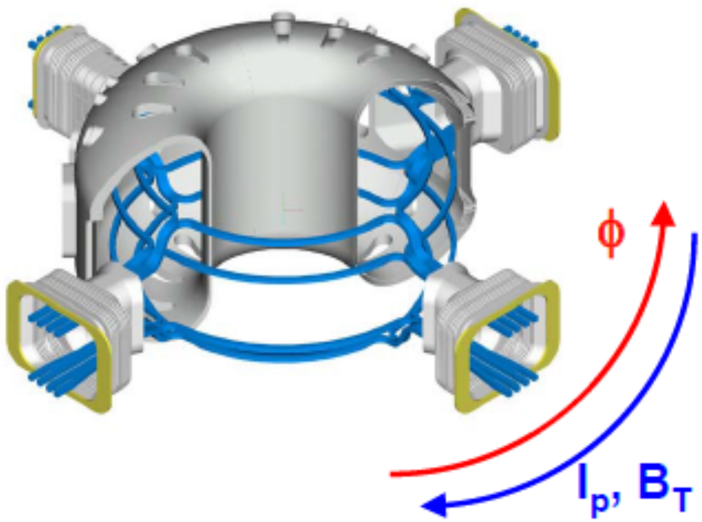
Strong kink excitation appears to be responsible for amplification of footprint splitting for n=1



- Resonant components are very weak in vacuum modeling and the ideal response only slightly shields them
- Non-resonant kink excitation is very strong
- Combined net effect is to significantly amplify the applied n=1 fields and splitting

KSTAR can produce various 3-D field configurations with 3x4 array of internal coils

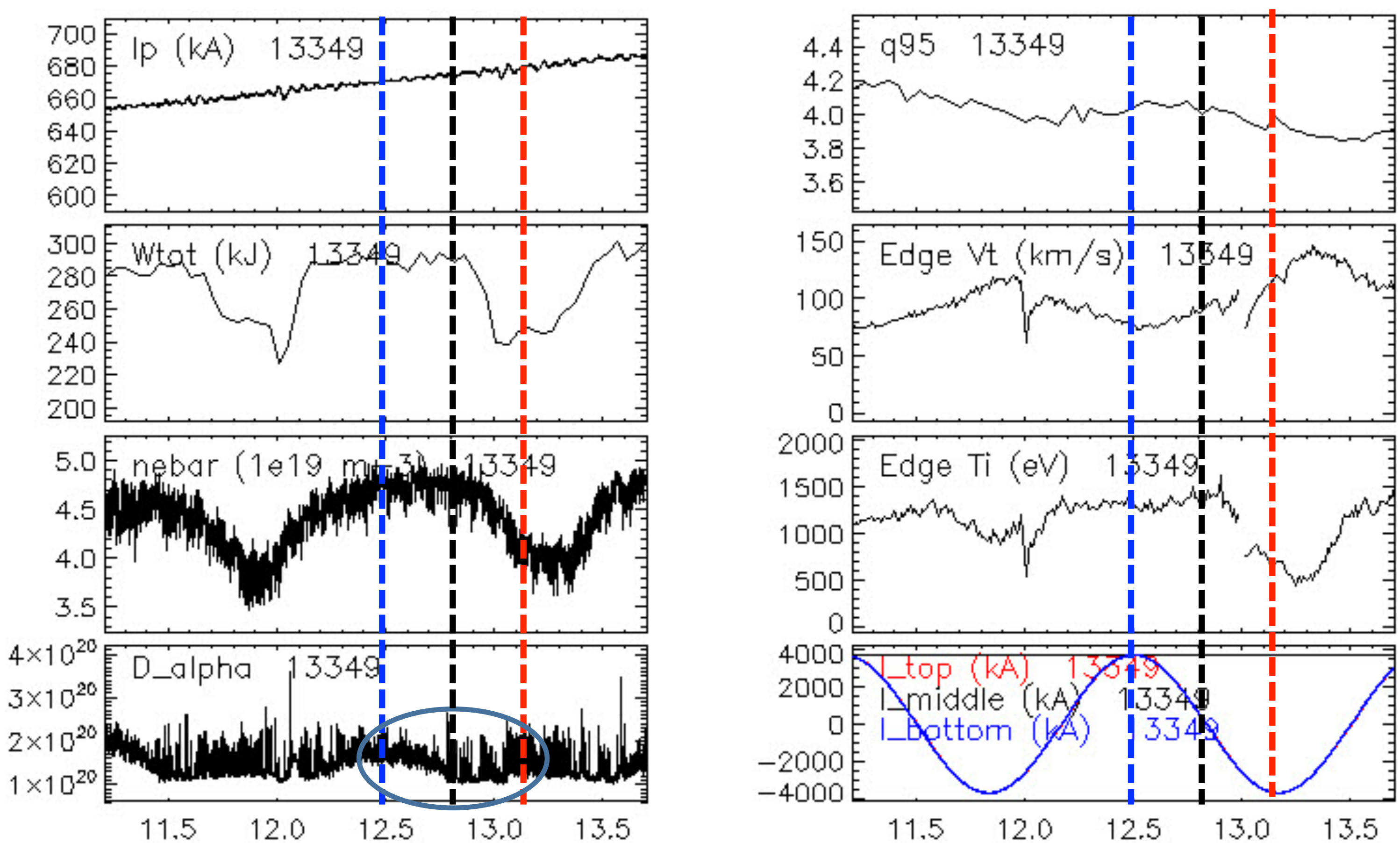




- This allows complete toroidal rotation of phase shift between upper and lower row of coils for n=1 ($\Delta\phi$ = 0 – 360^o)
- 2 phase configurations for n=2 (0^o and 90^o)

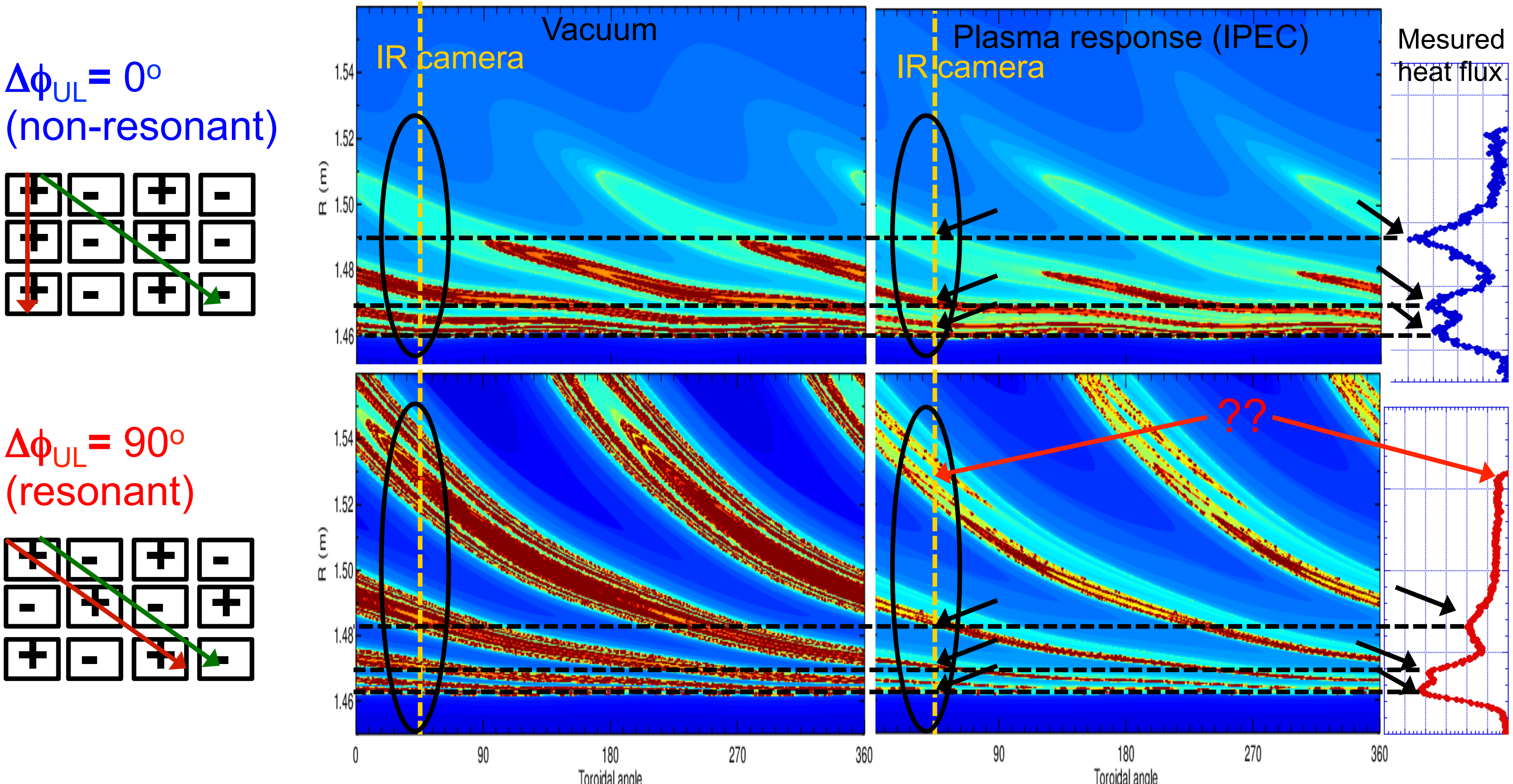
Continuous phase swing in n=2 produced obvious change in plasma parameters

n=2, $\Delta\phi_{UL}$=0° n=2, mid-plane only n=2, $\Delta\phi_{UL}$=90°



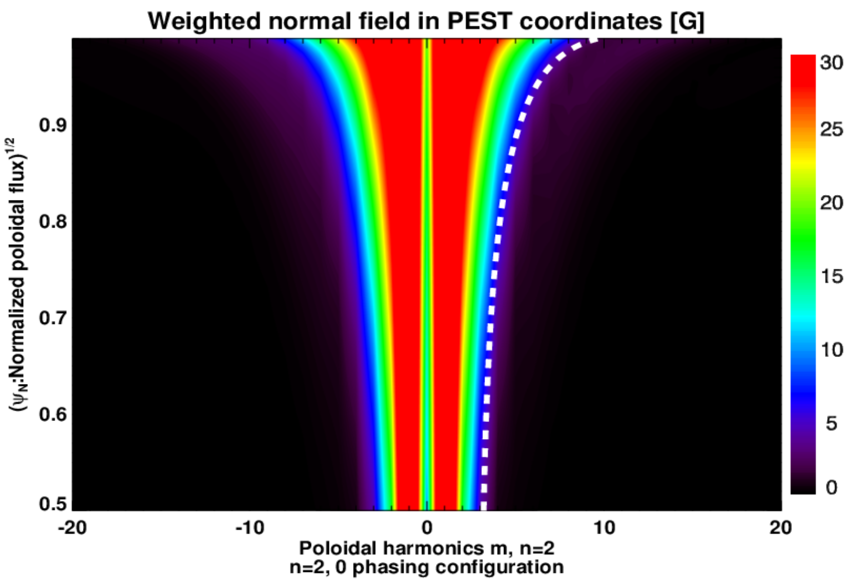
- Effect of relative phase between upper and lower row of coils ($\Delta\phi_{UL}$) on W_{tot}, density pump-out, V_t, T_i, → Change in ELM behavior

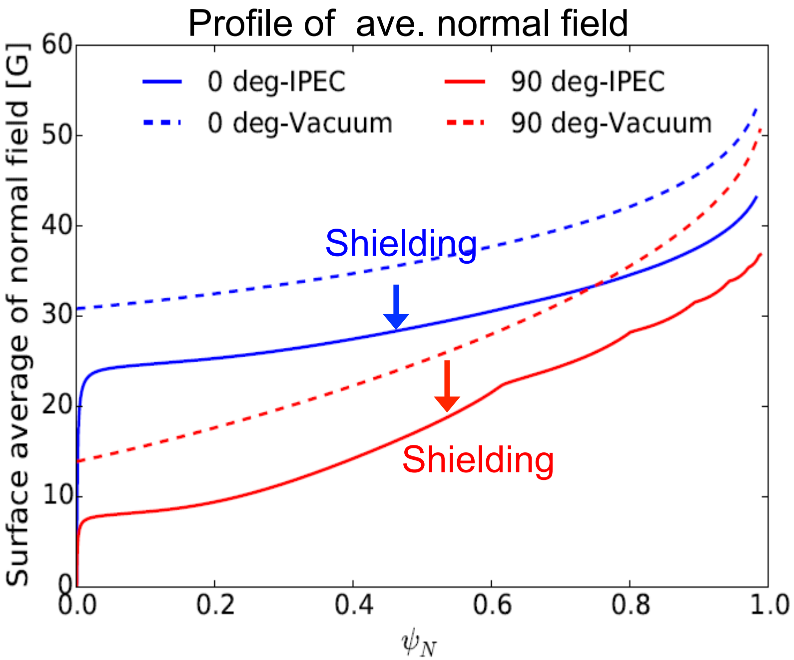
Ideal plasma response weakens divertor footprint splitting pattern and provides better agreement with measurement



- IPEC weakens splitting for both 0º and 90º phases
- Agreement of radial location of lobes between measurement and field line tracing becomes better when ideal plasma response is included
- Some lobes are not caught in measurement → transport effect?

Net effect of plasma response leads to shielding of applied 3-D fields and footprint splitting for n=2

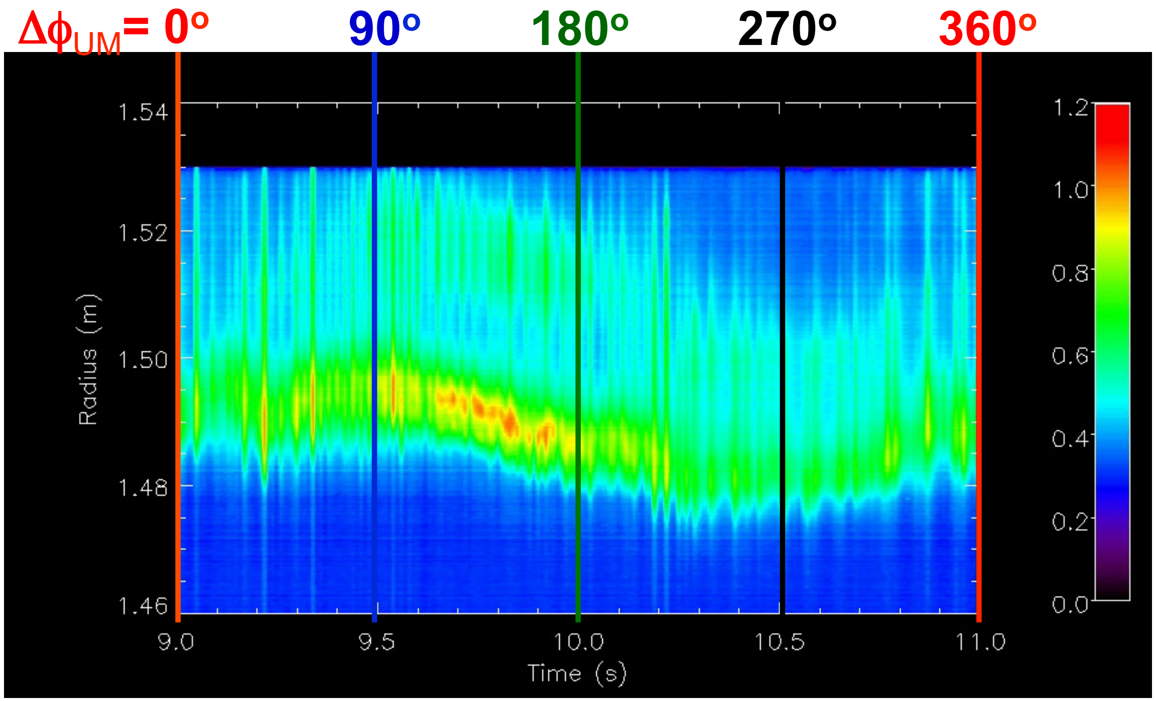


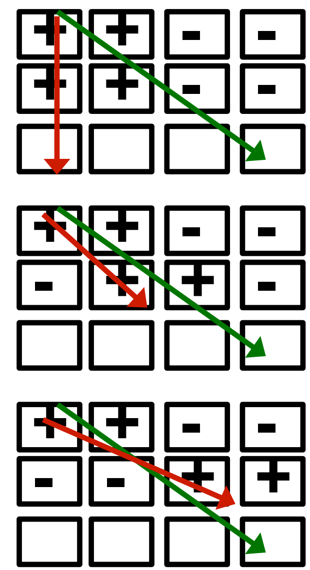


- How to quantify the net effect of resonant shielding and non-resonant excitation of 3-D fields? → calculate surface average of normal fields for whole flux surface at each radial point

- Plasma response reduces surface averaged normal fields for whole radial cross section for n=2, ie shielding of applied 3-D fields → consistent with the weakening of splitting from field line tracing

Peak heat flux and splitting becomes stronger for resonant phases of n=1



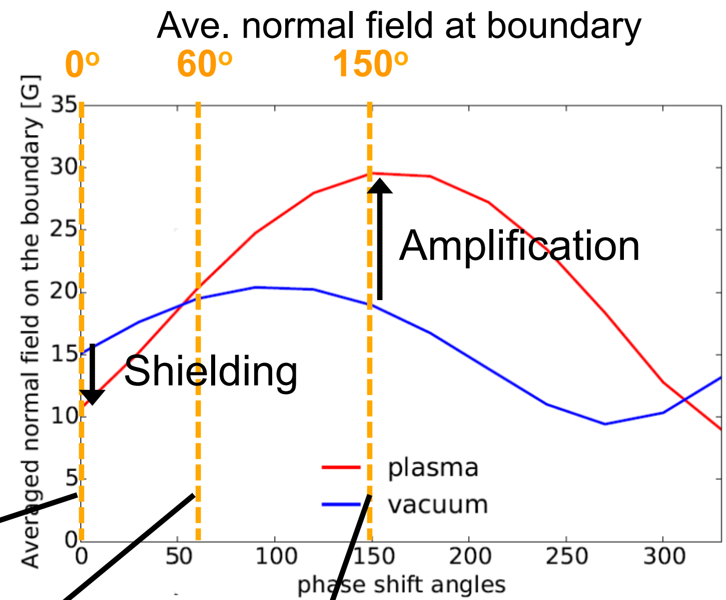


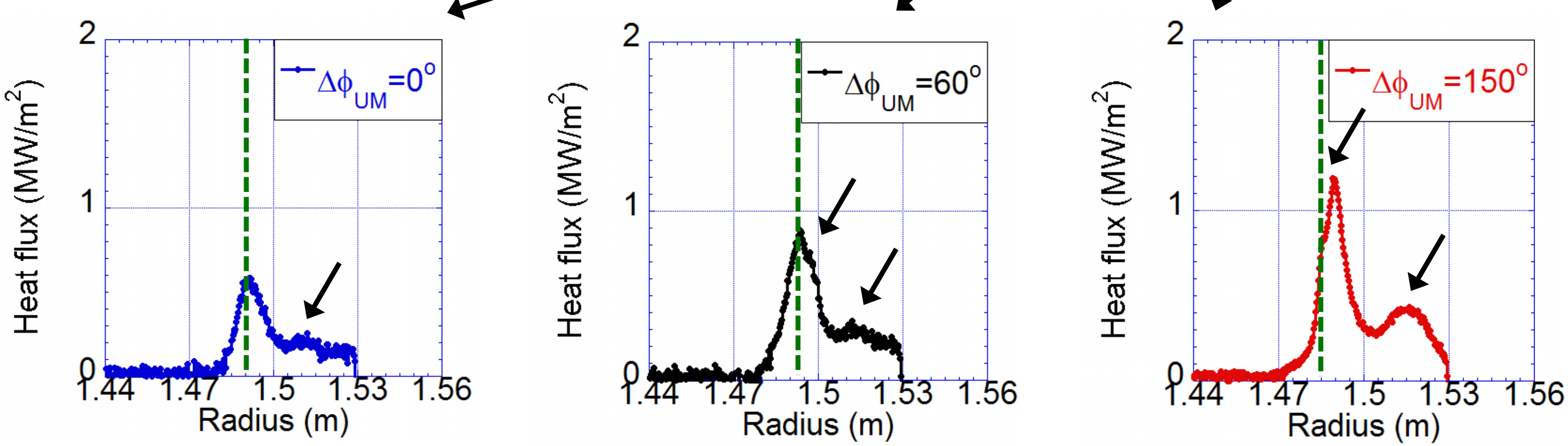
- Phase scan of n=1 fields using only upper and middle coils ($\Delta\phi_{UM}$= 0 – 360°)
- No ELM suppression (I_{upper}~3 – 4 kA, I_{mid}~2.5 kA)
- Peak heat flux increases during resonant phases ($\Delta\phi_{UM}$= 90 – 180°)

  → similar trend as for n=2
- Splitting is strongest for resonant phases ($\Delta\phi_{UM}$ ~ 90 – 180°), → Contrary to n=2 (stronger splitting for non-resonant phase, $\Delta\phi_{UL}$ ~ 0°)

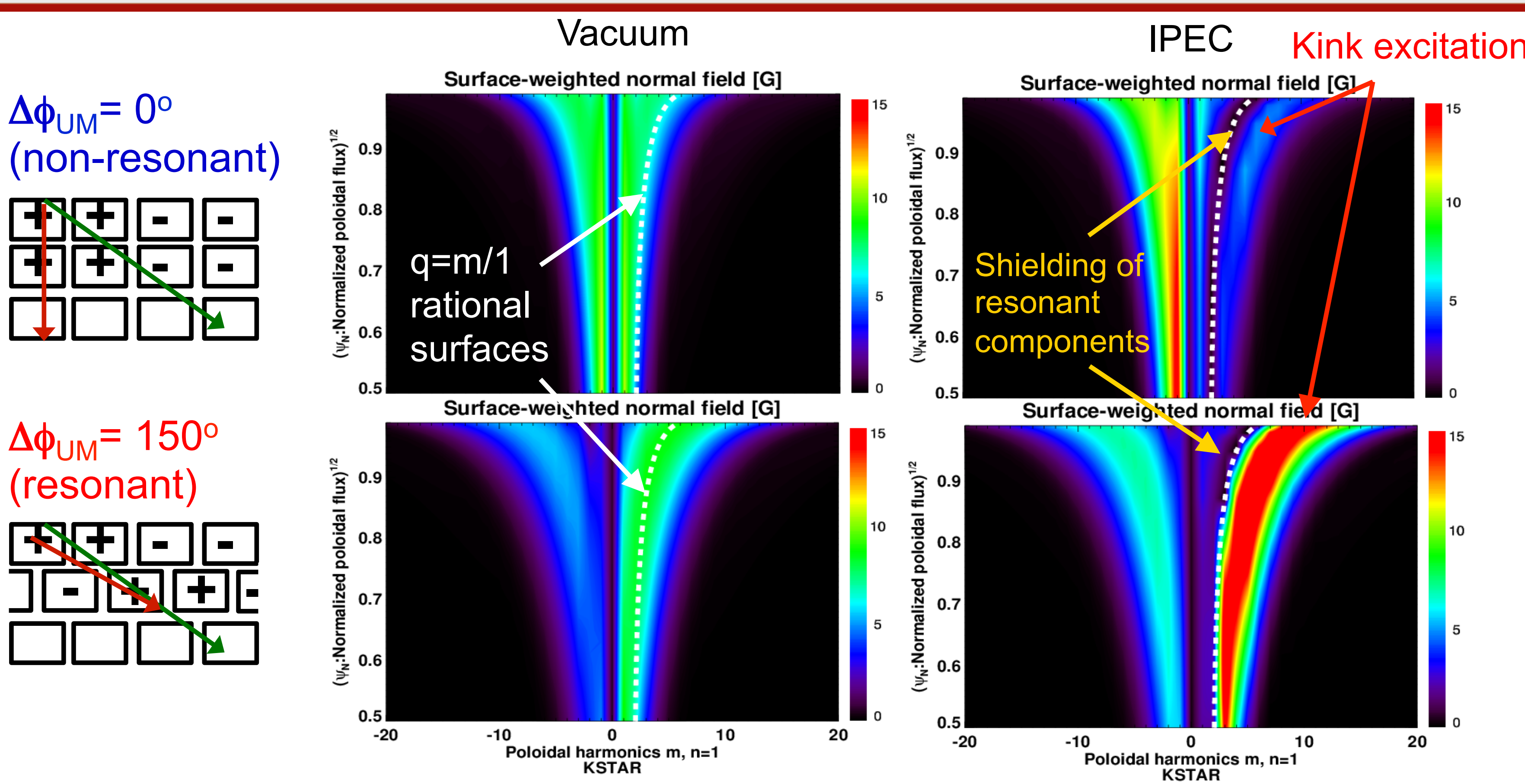
Plasma response shields or amplifies applied n=1 fields, depending on phase

- Comparison of 3-D fields at plasma boundary:
  - 0^o: shielding
  - $50 – 60^o$: ~constant
  - 150^o: amplification
- Plasma response also shifts phase
- q_{peak} and heat flux splitting better agree with plasma response case than vacuum, and become stronger with higher normal fields



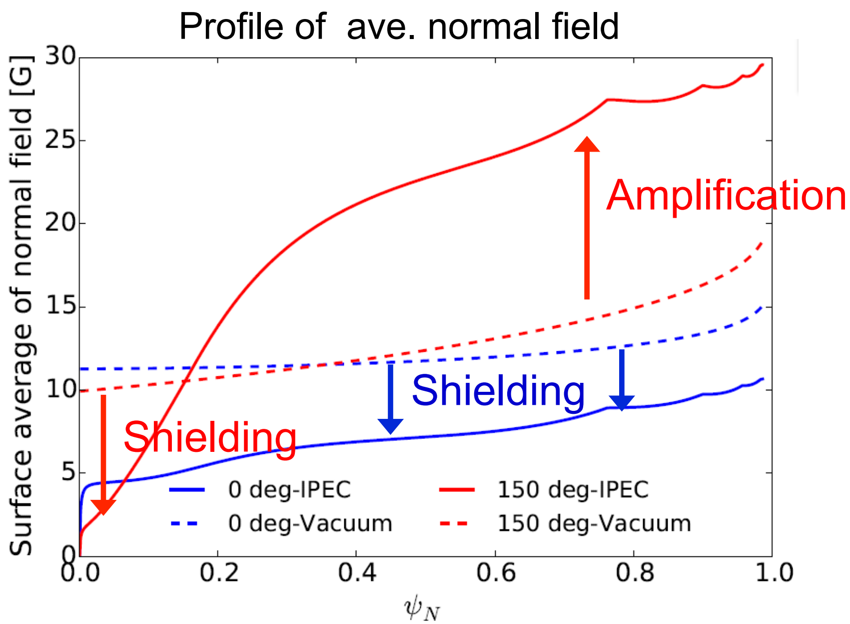


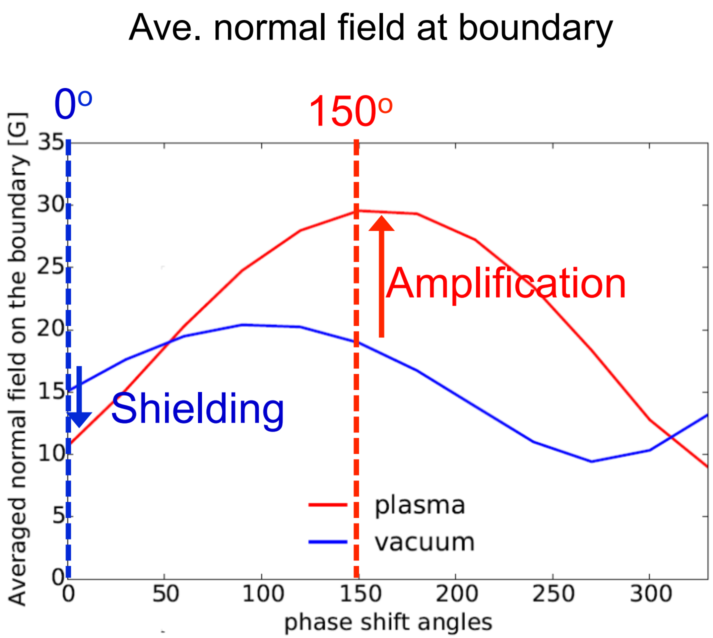
Poloidal spectrum analysis again shows similar trend for resonant and non-resonant fields as in n=2



- 0° phase is non-resonant and kink excitation is only weak
- 150° phase is very resonant → kink excitation is very strong
- Net effect is to be shown by profile of averaged normal field

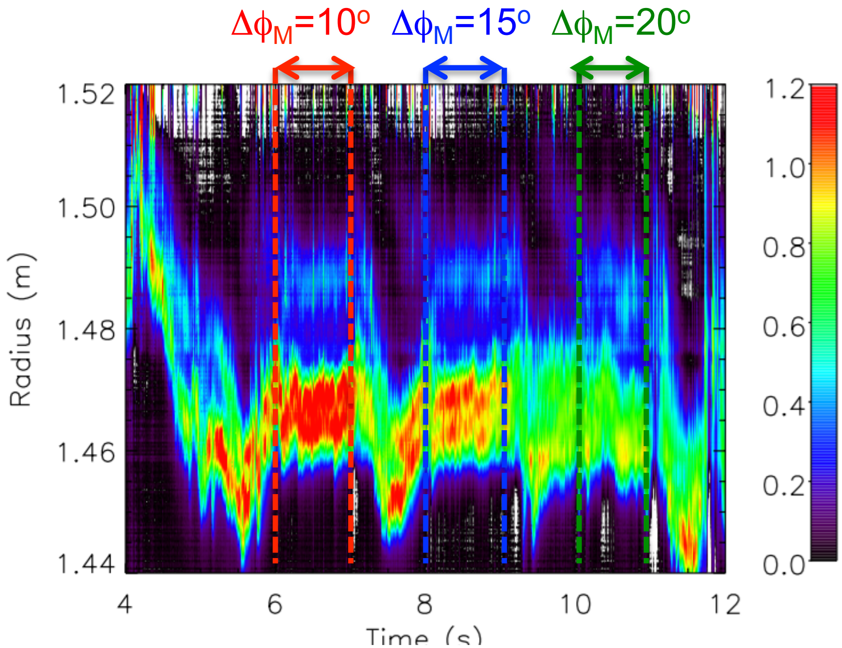
Phase variation determines plasma response to applied 3-D fields

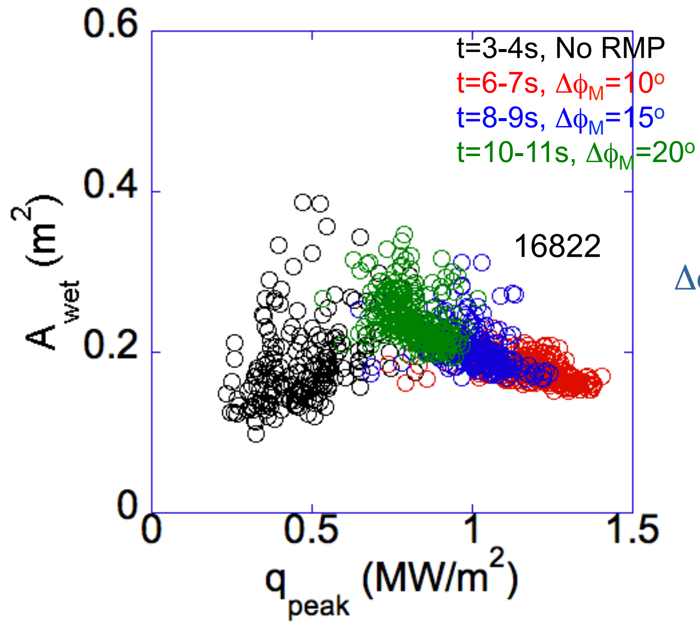


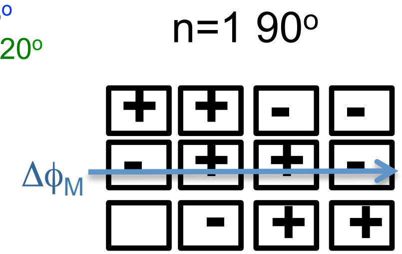


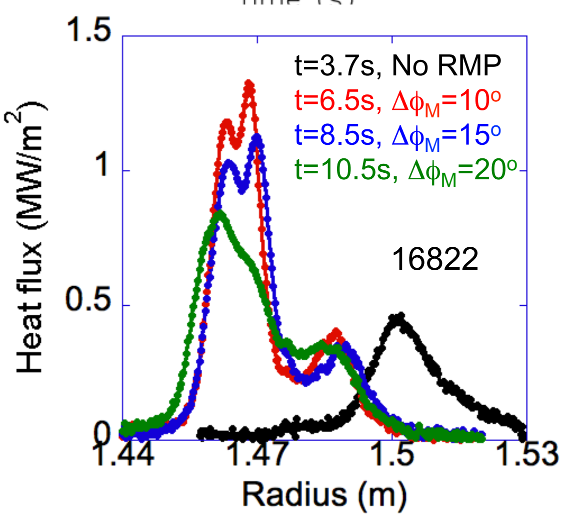
- Normal field profile is decreased by plasma response for 0° phase
- For 150°, it is mostly strong amplification but shielding occurs in the core region near magnetic axis
- Phase variation strongly affects reaction of plasma to applied fields → leads to shielding or amplification of magnetic lobes and 3-D heat and particle flux pattern

Intentionally misaligned 90° n=1 fields effectively spread heat flux to lower peak value with increasing misalignment







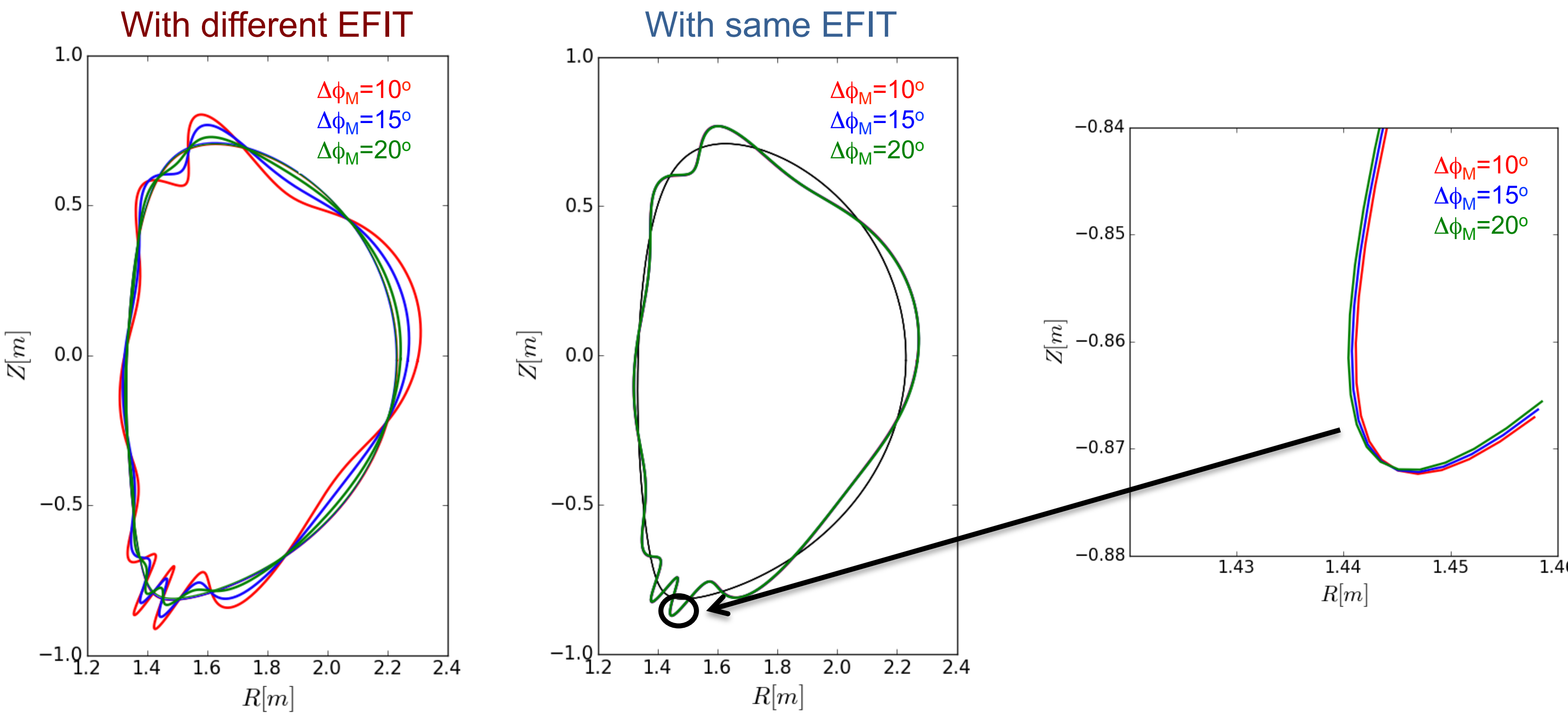


- RMP increases peak heat flux compared to no RMP case
- With increasing misalignment, wetted area increases (i.e., profile broadens) and peak heat flux decreases

Y. In, FEC 2016

However, it's not yet clear how small misalignment led to significant change in divertor footprints

Flux surface displacement from ideal plasma response (IPEC)



- Only very small (<5%) difference of external fields due to misalignment
- Plasma response (IPEC) does not produce significant difference in field structure by misalignment
- How can the difference in IR heat flux be explained? Bifurcation?

Summary and conclusions

- Applied 3-D fields can be either shielded or amplified depending on field configurations and phase, leading to modification of divertor footprints

- NSTX: wide view of divertor area allows for easier comparison to modeling
  - Ideal plasma response weakens n=3 footprint splitting, primarily due to shielding effect of resonant components. Sensitive to location of simulation boundary
  - Envelope of lobes for n=3 is not changed by plasma response
  - Ideal plasma response significantly amplifies vacuum n=1 footprints, due to strong non-resonant kink excitation

- KSTAR: three rows of coils enable to fine tune structure of applied 3-D fields
  - n=2 fields are shielded by plasma response for both 0^o and 90^o phase, therefore footprints are weakened compared to vacuum result
  - n=1 fields are either shielded or amplified depending on phase shift between upper and lower coils.
  - Slight misalignment effectively broadened heat flux profile and reduced peak heat flux, but the underlying physics is still not clear yet