Optimization of ELM control using RMPs with minimal fast-ion loss

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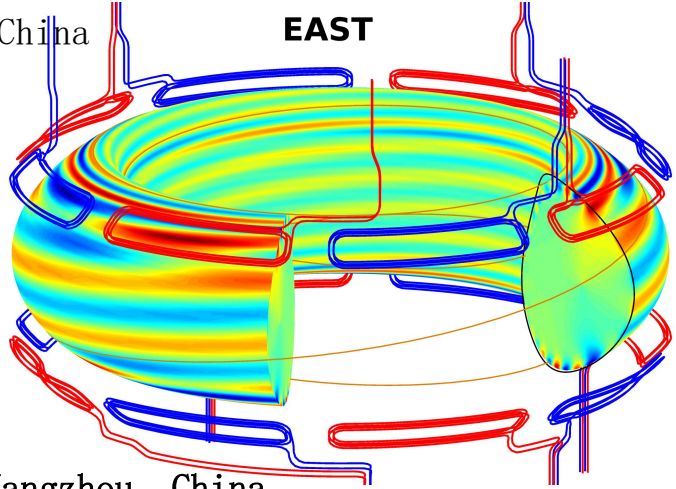

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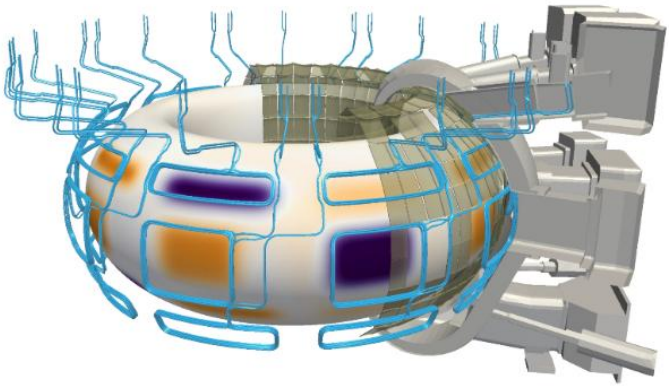
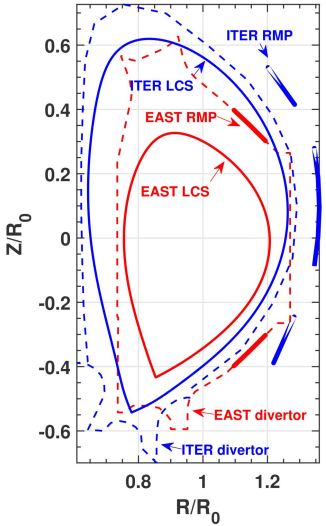
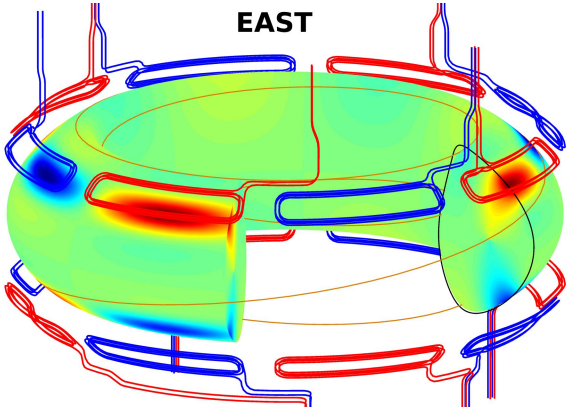
RMP coils in EAST in support of ITER research

ASIPP



ITER, n = 3, 4

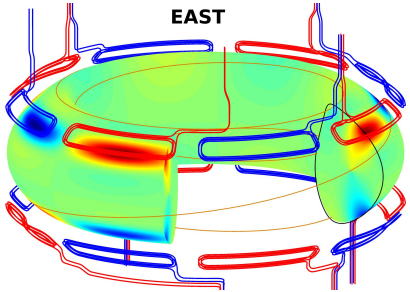


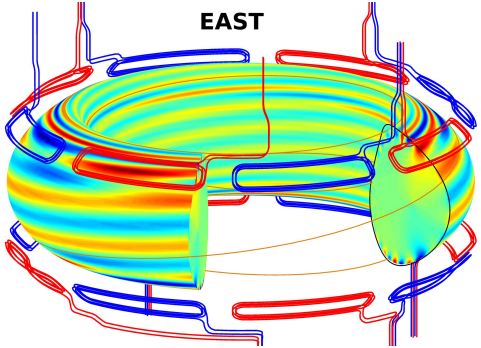


EAST, n = 1–4

- RMP ELM control required in ITER
- EAST RMP covers the **same toroidal mode number** up to n=4

Key issue for understanding 3D physics

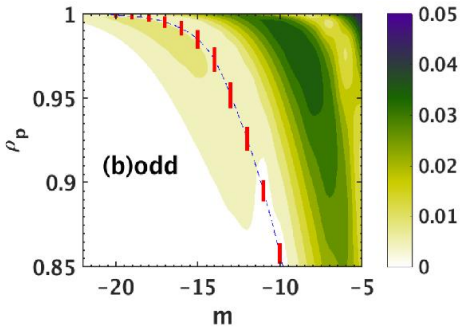


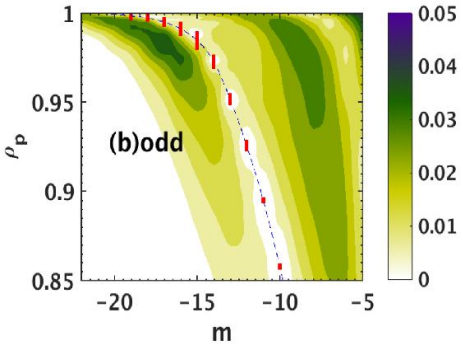


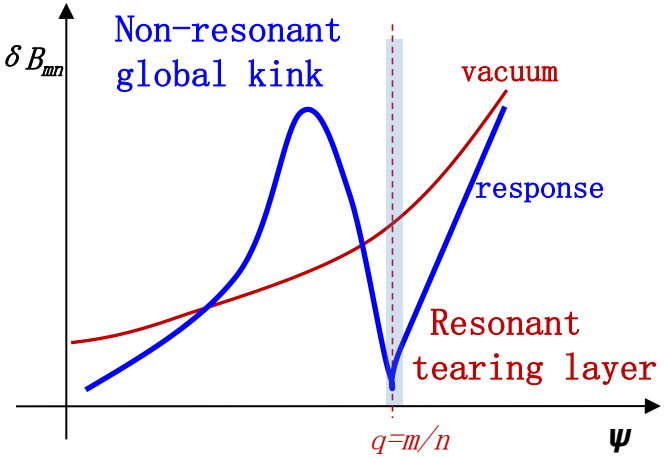
Vacuum

Plasma response to RMP

Response





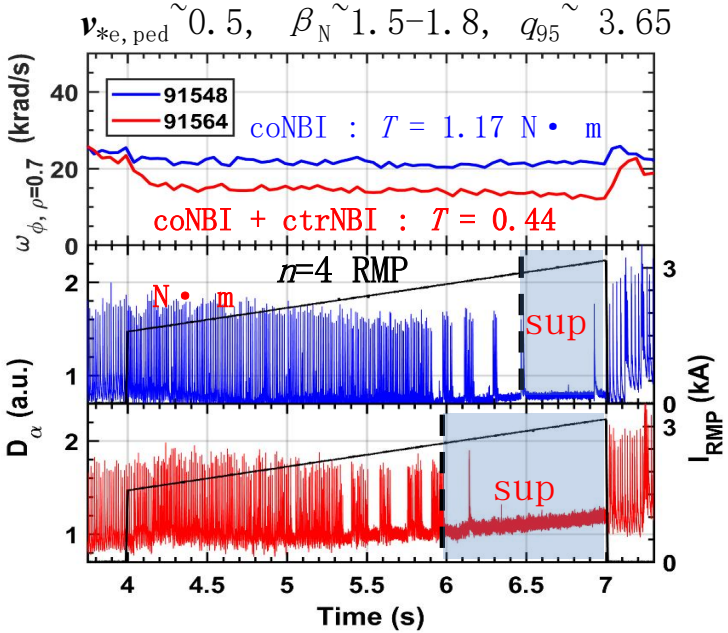


Outlines

ASIPP

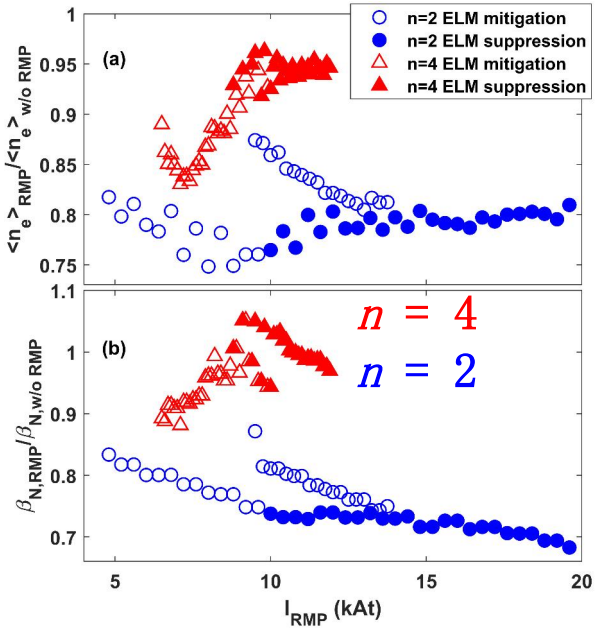
- Resonant RMP on ELM suppression
- Non-resonant RMP on fast-ion loss
- Optimized RMP ELM suppression with minimal fast-ion loss

ELM suppression achieved by n=4 RMPs in ITER-like low torque plasmas in EAST



[Sun Y. *et al.*, *NF* 61, 106037 (2021)]

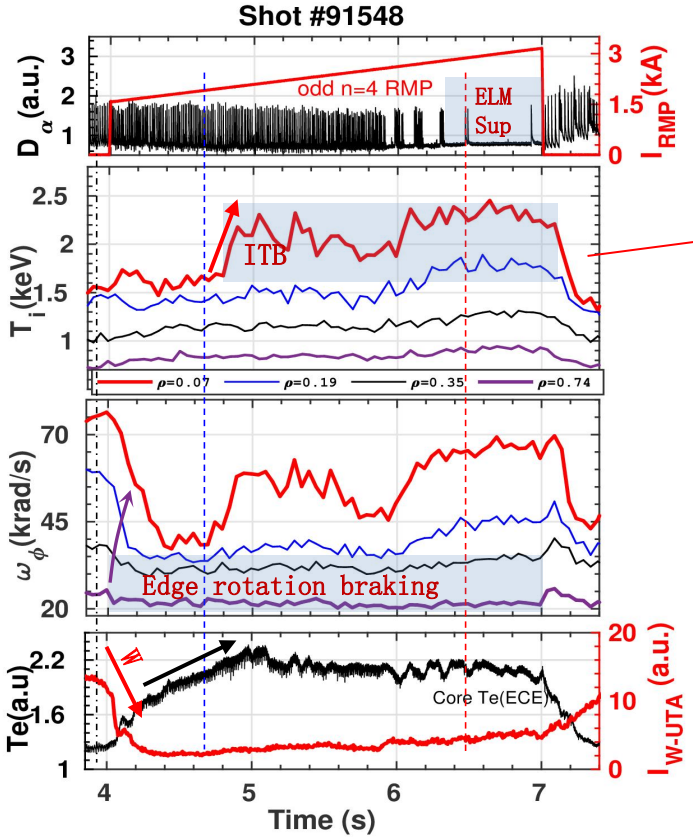
- Experimental condition is close to low torque ITER type-I ELMy H-mode

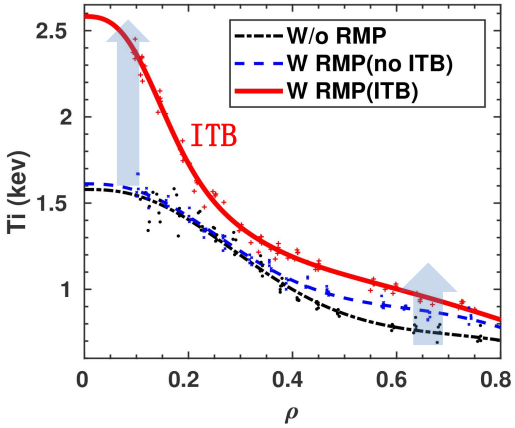


[M. Jia *et al*, *NF* 61, 106023(2021)]

- Advantages of n = 4 RMPs
  - No obvious drop of energy confinement
  - Avoidance of W accumulation

Enhanced core confinement via triggering ITB during the application of *n*=4 RMPs



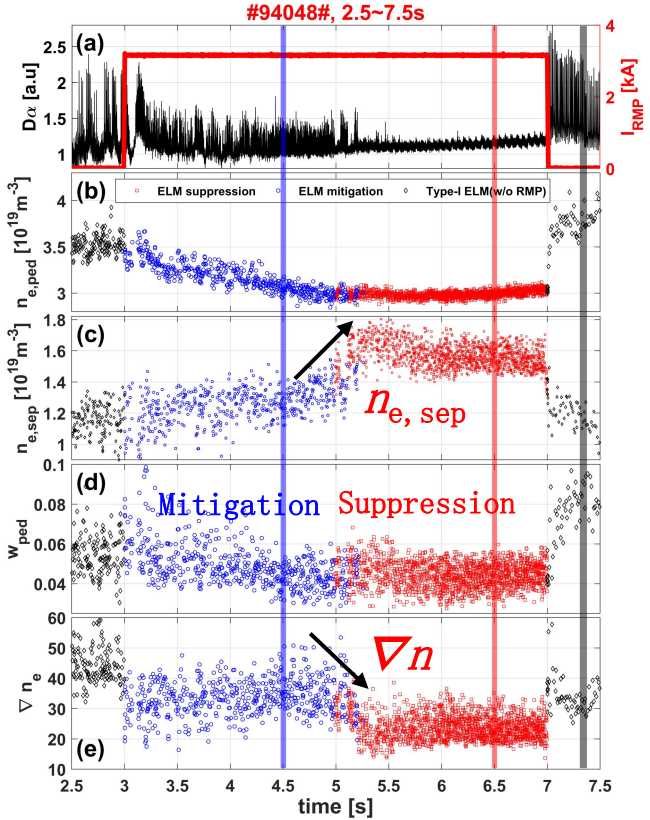


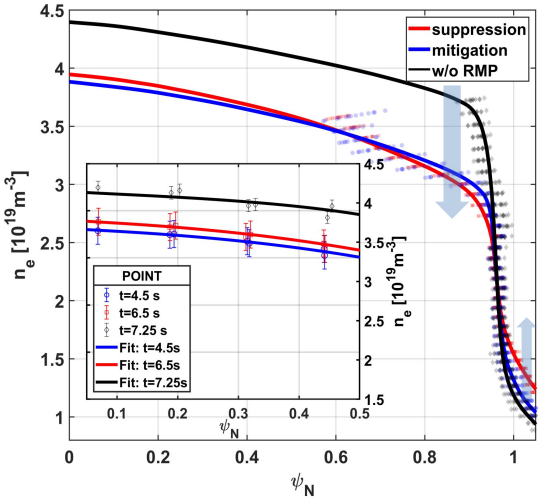
- ITB was triggered reproducibly during the application of *n*=4 RMP ELM control
- ITB can be stably sustained by RMP

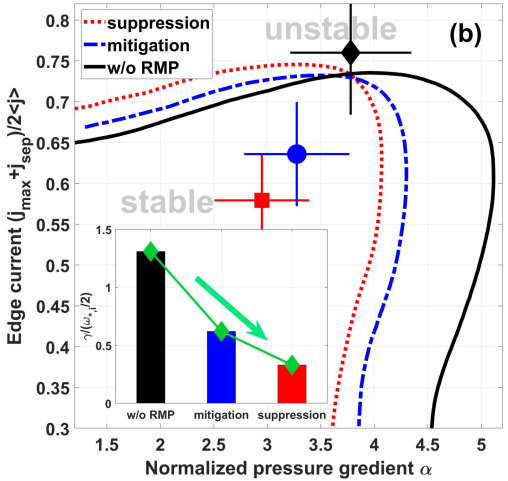
Simultaneously control of double transport barriers with low core W

[Sheng H. *et al*, PRX-Energy 4, 043012(2025)]

RMP ELM suppression strongly depends on the modification of pedestal profiles



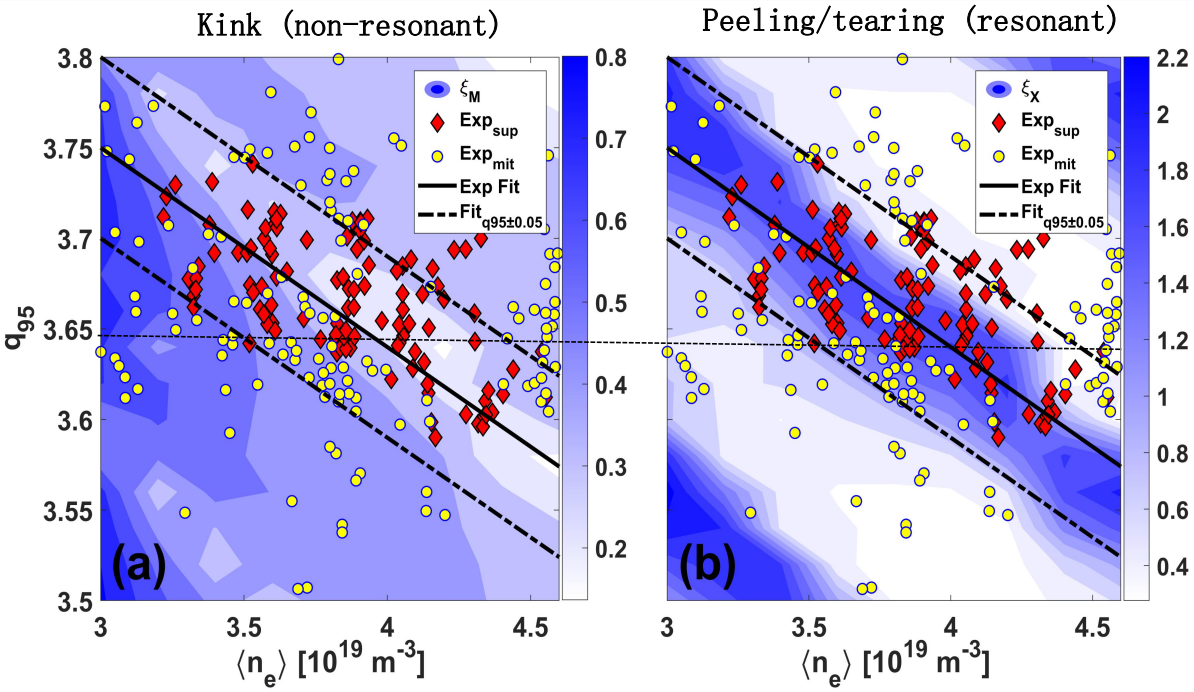




- Reduced pedestal gradient due to increase of $n_{e,\ sep}$ during the transition from ELM mitigation to suppression
- Peeling-ballooning modes are stabilized by the reduction of pedestal current and pressure gradient induced by RMPs

[Wu X *et al* NF 65, 076031 (2025)]

Resonant component plasma response plays the dominant role in achieving ELM suppression



[Sun Y. *et al*, FEC(2025)]

- Resonant response in [q_{95}, n_e] window aligns well with ELM suppression
- Non-resonant kink response shows a different dependence

Outlines

ASIPP

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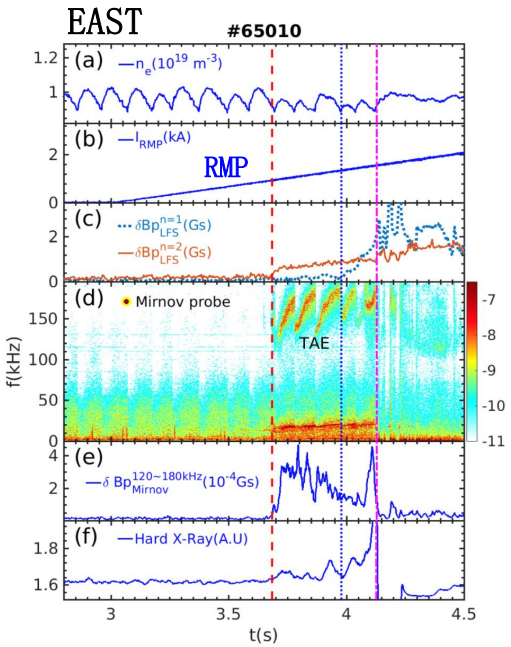
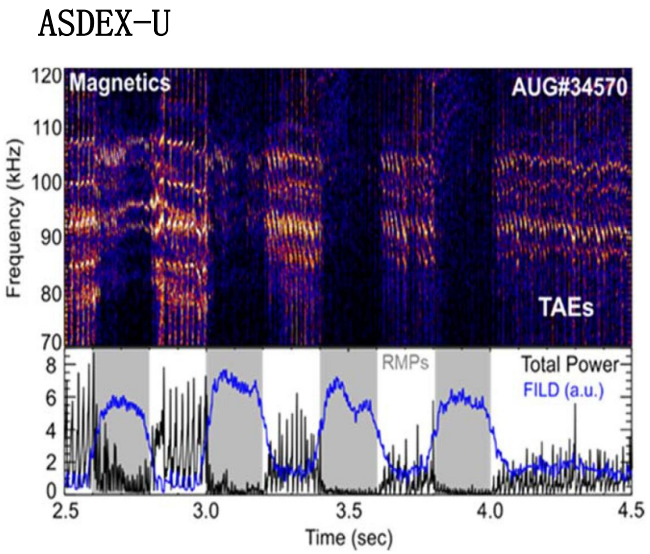
- Non-resonant RMP on fast-ion loss
- Optimized RMP ELM suppression with minimal fast-ion loss

RMP effects on AE and fast particle loss

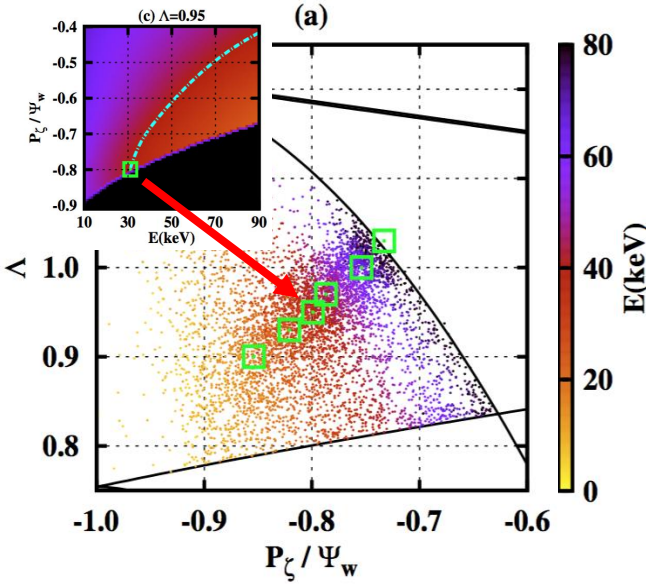
ASIPP



[Chu et al, NF 58, 104004(2018)]



[Garcia-Munoz *et al*, PPCF 61, 054007(2019)]

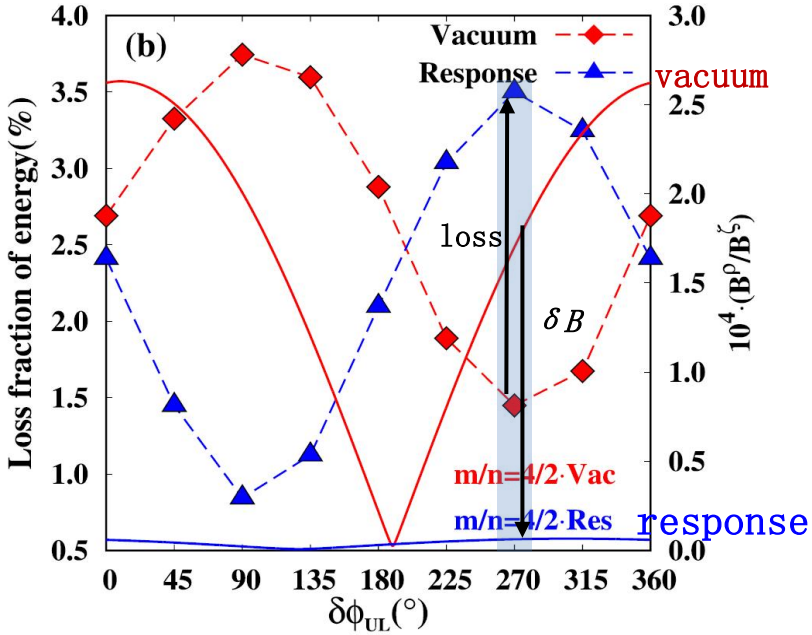


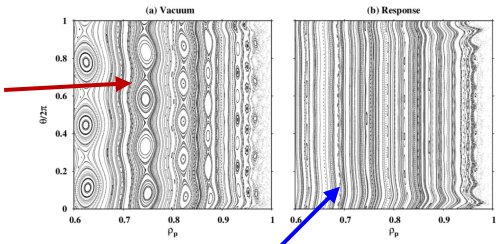
[He *et al*, NF 59, 126026 (2019)]

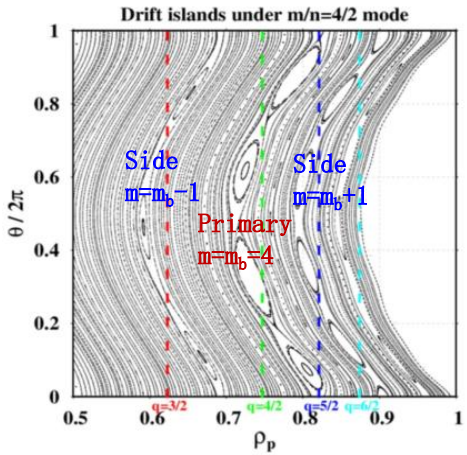
- RMP causes the changes of **the stability of AE**
- Various **resonant effects** have been identified

→ Phase space profile control

Non-resonant RMP side bands enhanced fast-ion loss







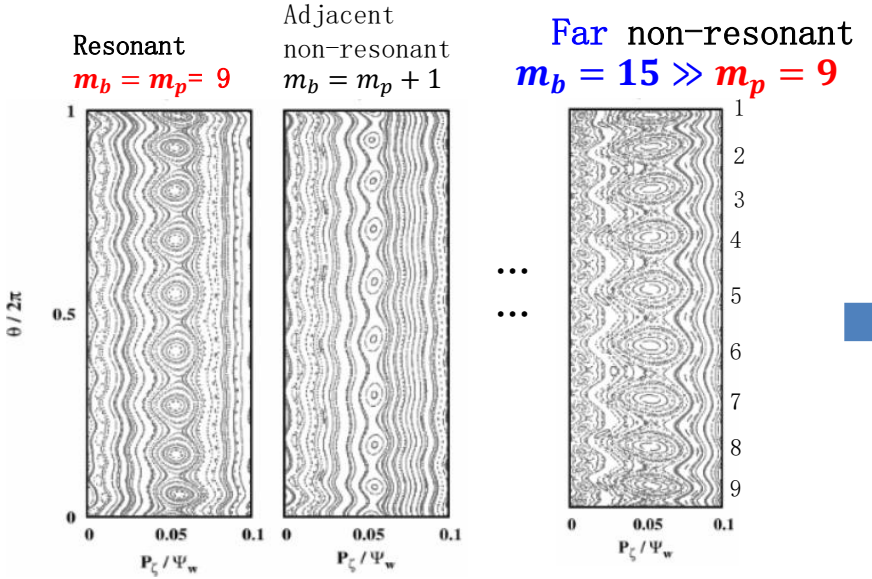
[He K. *et al*, NF 60, 126027 (2020)]

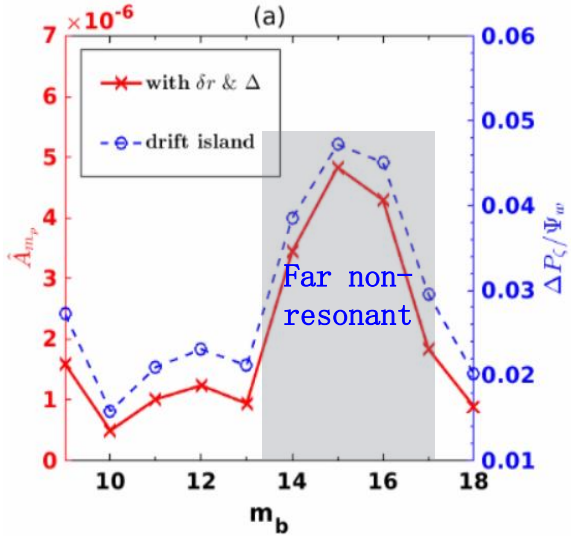
- Plasma response can significantly shield the resonant components of RMPs
- RMPs with plasma response **enhanced EP loss** due to **side band resonances**

Far non-resonant RMP components effect on fast-ion loss during the application of n=4 RMPs

Drift islands (n=4):

$m_p = 9$





Contributed RMP harmonics

$$\widehat{B}_{m_p} = \frac{1}{2\pi}\int_0^{2\pi} e^{-im_p\theta_p}\left[\sum_{m_b} B_{m_b}(\psi)e^{i(m_b\theta - n\Delta)}\right]d\theta_p$$

In orbit coordinates

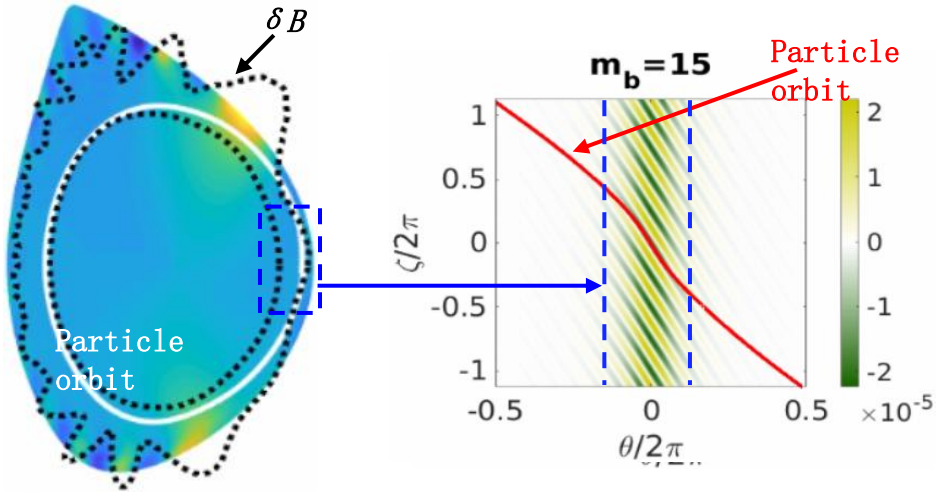
In flux coordinates

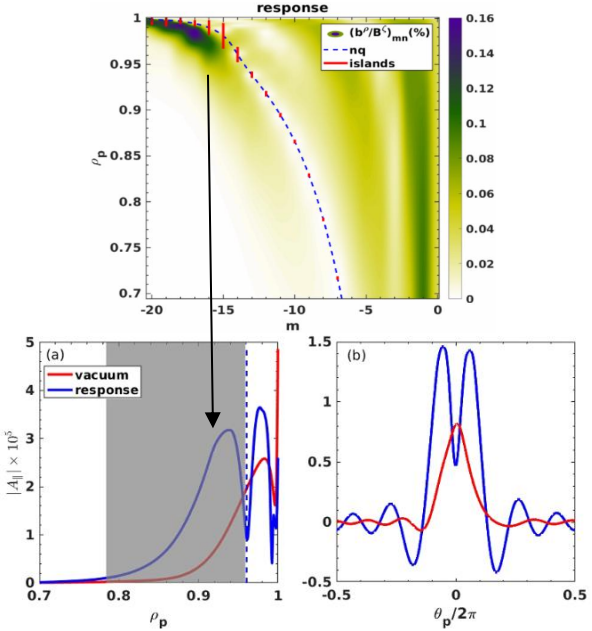
[Zhang YN *et al*, NF 64, 046012 (2024)]

- Significant fast-ion loss even with strong shielding effect

Why far non-resonant harmonics matter

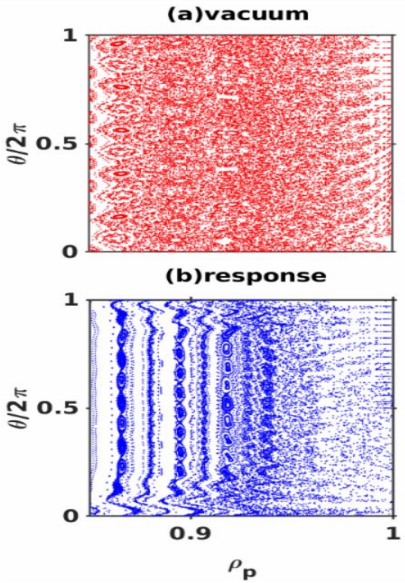
Experienced field: $\sum_{m_b} B_{m_b}(\psi) e^{i(m_b\theta - n\Delta)}$

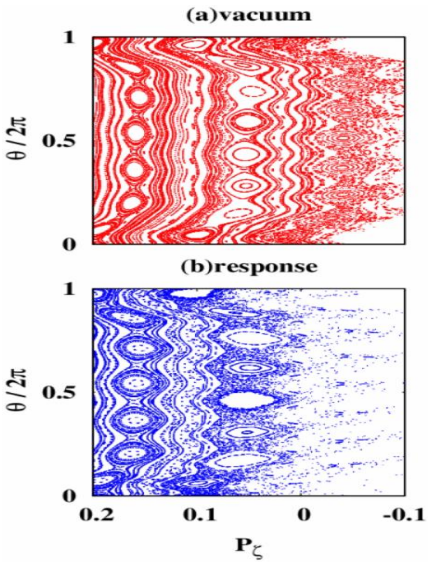


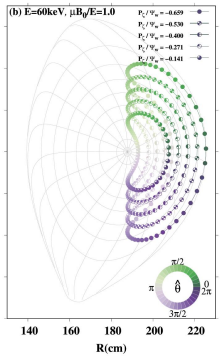


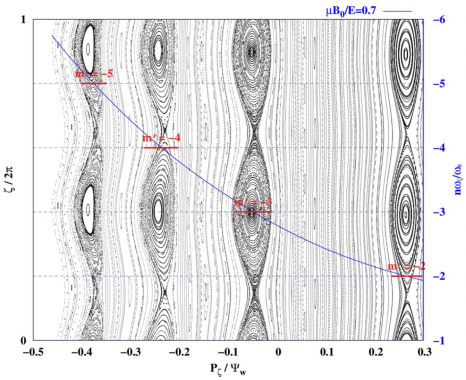
- Edge non-resonant RMPs resonant with fast-ions with **finite orbit width and variation of toroidal drift**
- **RFA effects** due to kink mode response further enhance the non-resonant harmonics, although there is a shielding of resonant harmonics

Magnetic topology .VS. particle orbit topology









Magnetic islands

Drift islands

[He K. *et al*, NF 65, 106022 (2025)]

$$w_{mn} = 4\sqrt{\left|\frac{b_{mn}}{nq'/q}\right|}_{q=m/n}$$

$$\Delta P_\zeta = 4\sqrt{\frac{2n\boxed{h_{m'n}}}{\partial\dot{Q}(\mu,P_\zeta,E)/\partial P_\zeta}}$$

Spectrum in orbit coordinates

$$\boxed{h_{m'n}(\mu,P_\zeta,J)}$$

- Non-resonant RMP contributes to the drift islands
- Drift island width can be evaluated using an action-angle transform

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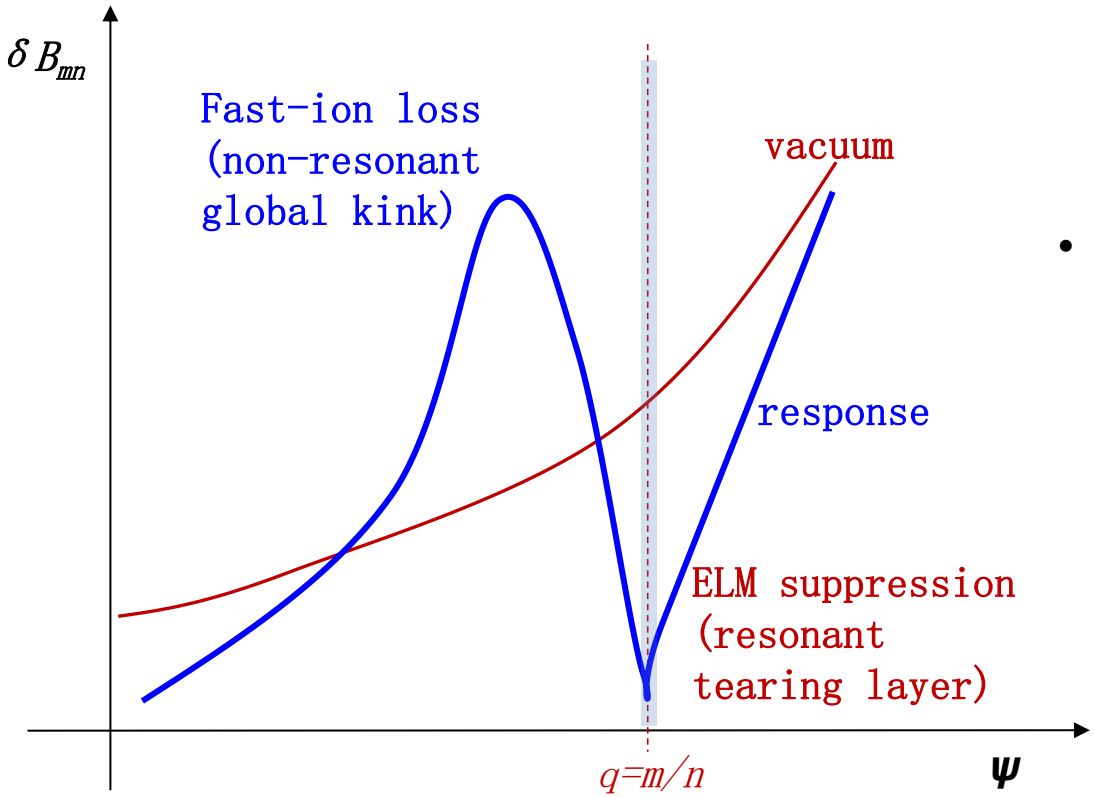
Summary of physics in different scales



- Helicity of field line is different from helicity of particle orbits

Optimization of n=2 RMP spectrum for ELM control with minimal fast-ion loss

ASIPP

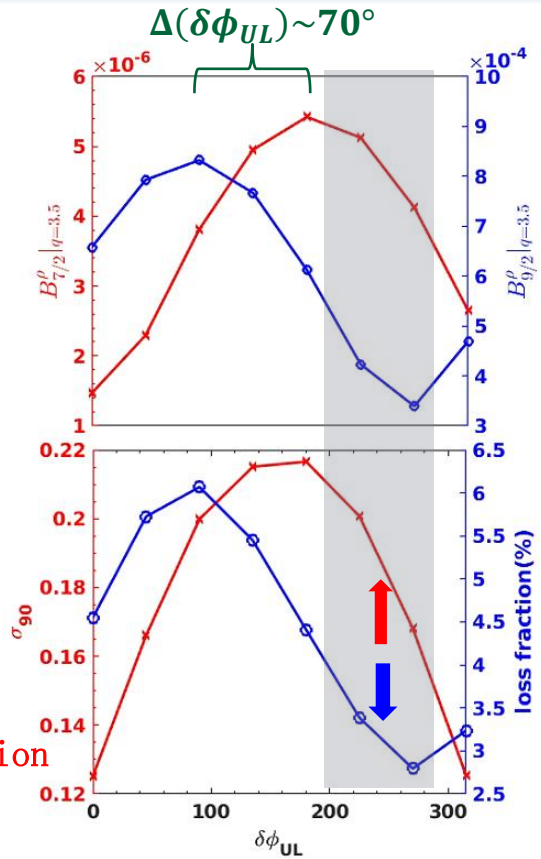
Resonant component m/n

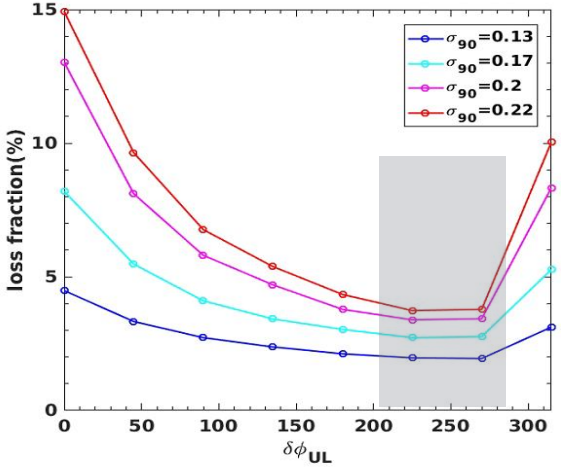
Non-resonant component (m+2)/n

Pedestal top resonance

ELM suppression

Fast-ion loss

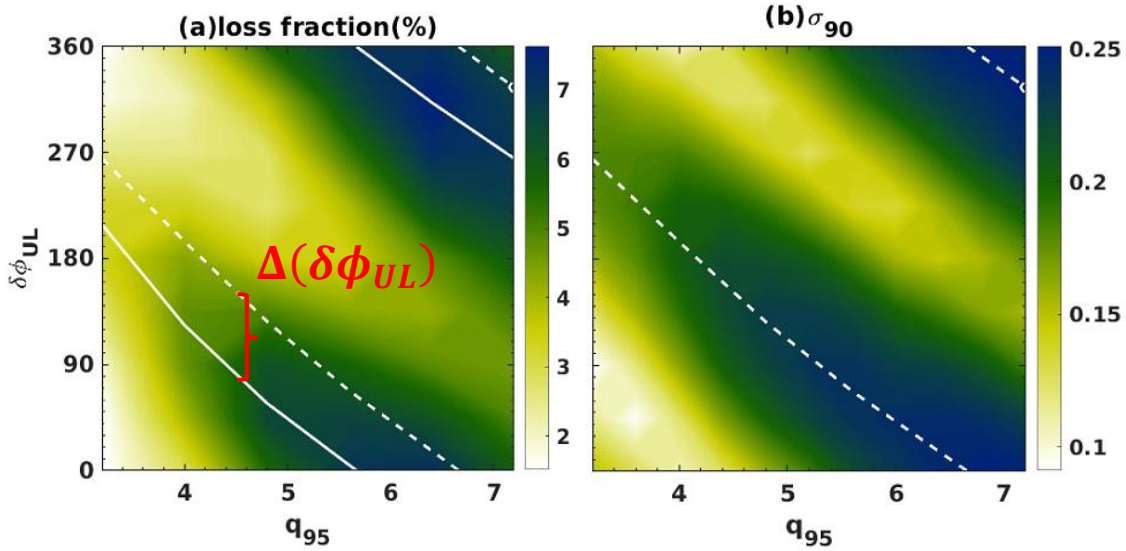


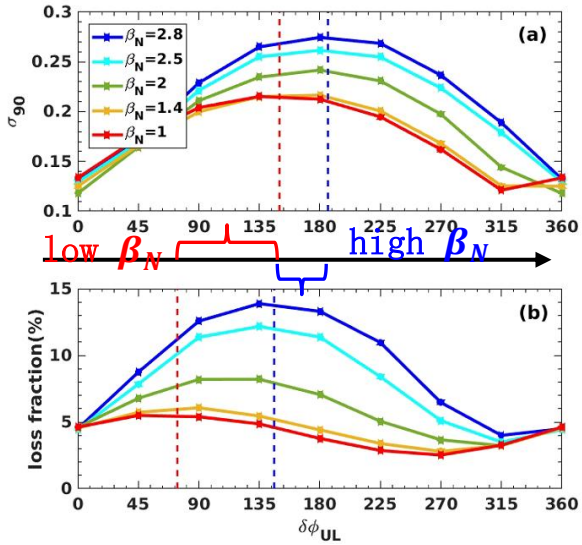


- Separation of phasing peaks with strongest resonant and non-resonant harmonics allows an optimization
- The **reduction** of fast-ion can be **a factor 2-4** for the same edge resonance level for RMP ELM suppression

[Zhang YN *et al*, NF **66**, 046023 (2026)]

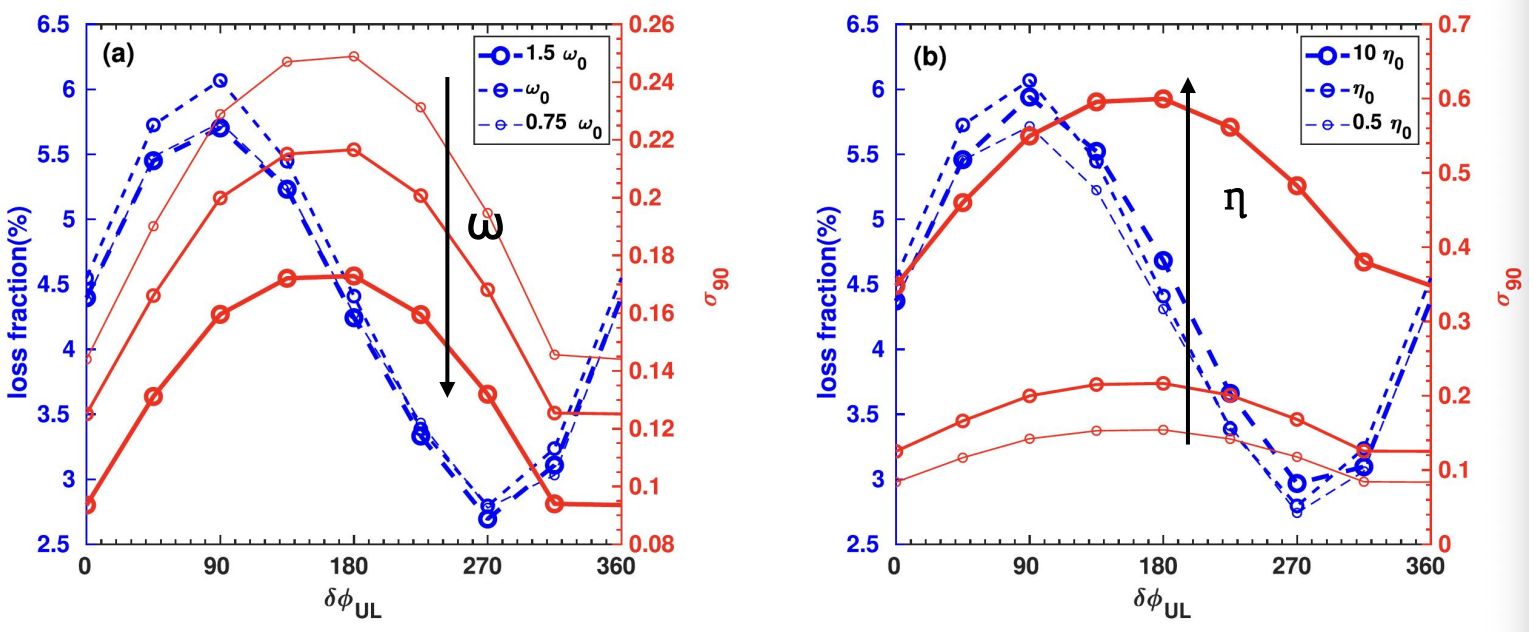
The optimization is applicable for different operational scenarios





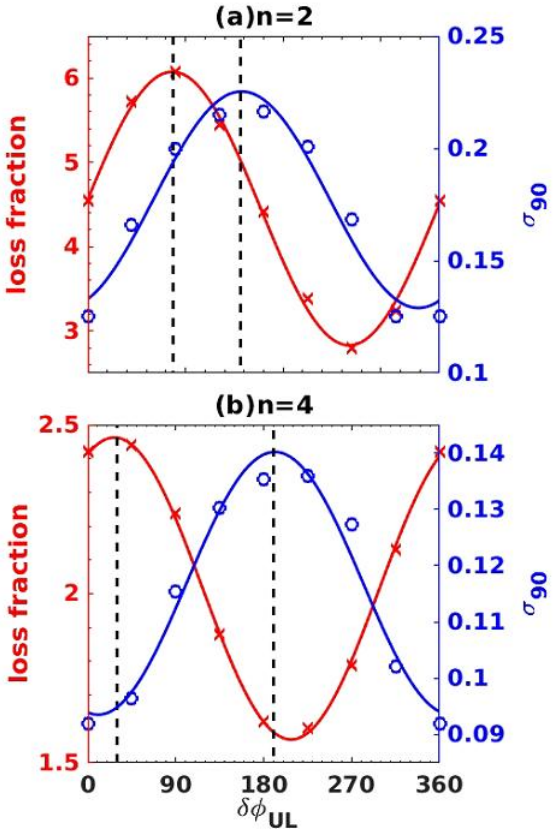
- The phasing difference $\boldsymbol{\Delta(\delta\phi_{UL})}$ between maximal edge resonance and fast-ion loss **keeps almost constant** in a large range of q_{95}
- Optimization becomes more challenging in **advanced scenario** due to RFA

Layer physics dominants the resonant response

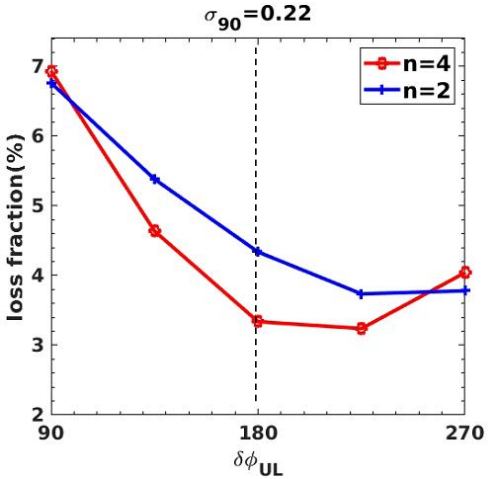


- Resonant tearing layer response is sensitive to layer quantities, such as **rotation** and **resistivity**

Another advantage of *n*=4 RMPs for ELM suppression



- *n*=4 RMPs is **naturally optimized** for the phasing with maximal edge resonance and minimal fast-ion loss
- Minimal level of fast-ion loss for the n=4 case is **smaller** than the n=2 case for the same level of edge resonance



Summary and conclusion

- **RMP ELM suppression** window observed in the EAST experiments can be well understood by the **resonant tearing-like layer physics** plasma response
- **Non-resonant kink-like** plasma response dominants the **fast-ion loss** in the simulation
- **Optimized RMP spectrum** for ELM suppression with minimal fast-ion loss has been identified, utilizing the different plasma response in resonant and non-resonant harmonics
- **Advantages of *n*=4 RMPs** for ELM suppression in both energy confinement and fast-ion loss has been identified