Toroidal modelling of plasma response to RMP fields for HL-2M

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Outline

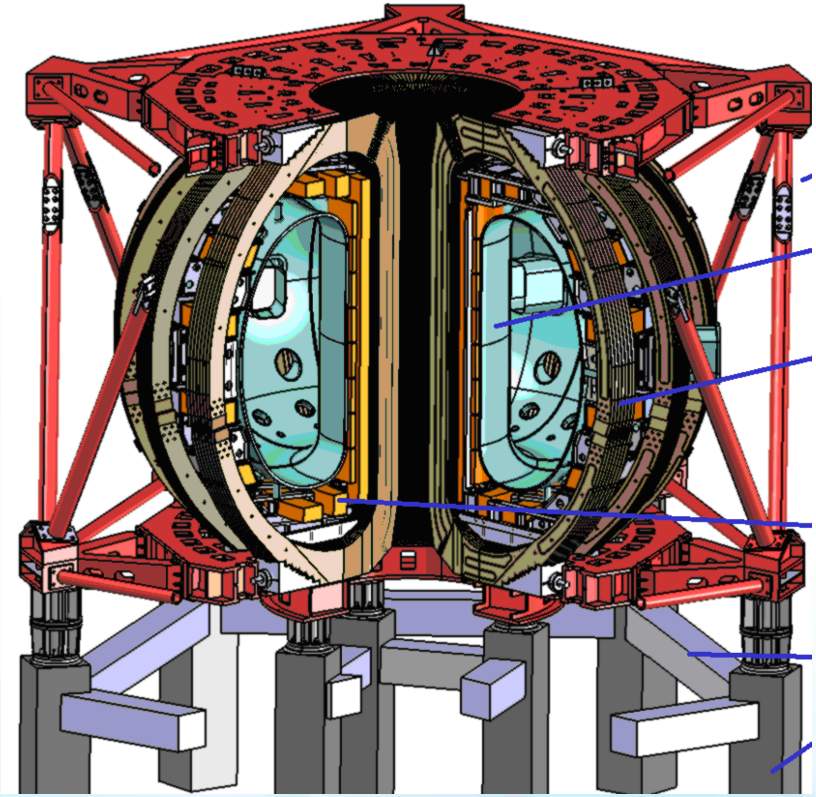
- **Introduction of RMP coil configuration on HL-2M**
- **Introduction of simulation tool: MARS-F code**
- **Numerical results**
  - Coil phasing optimization
  - Effect of RMP field on fast ion transport
- **Summary**

IntroductionHL-2M tokamak

Mission: high performance, high beta, and high bootstrap current plasma; advanced divertor configuration (snowflake, tripod), PWI at high heat flux.

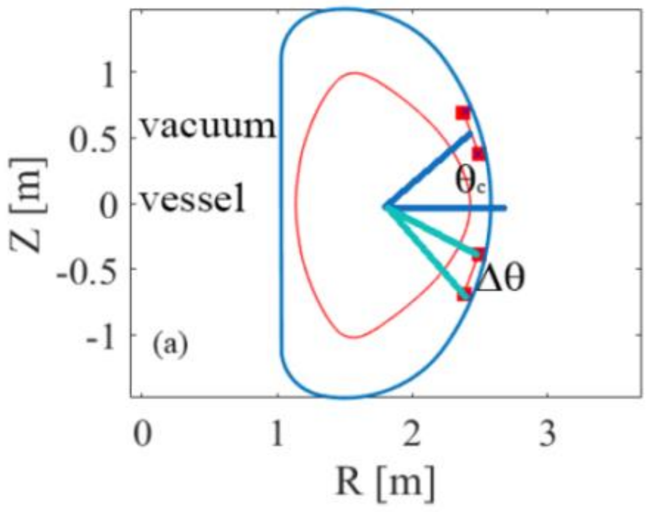
Main parameters

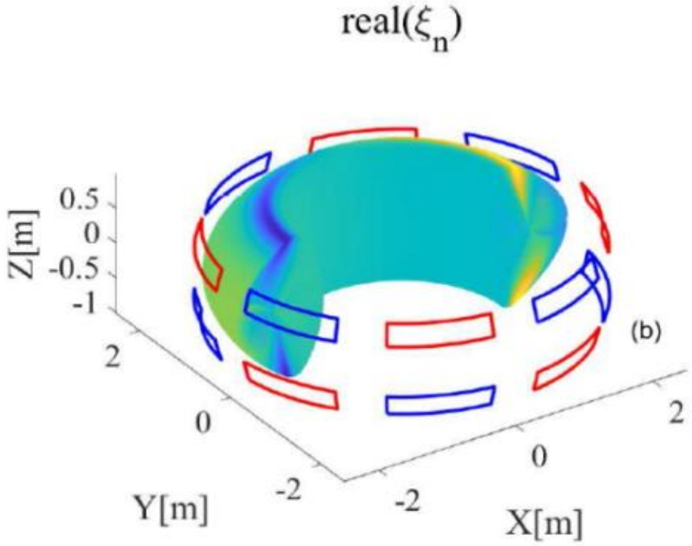
Plasma current	I_p = 2.5 (3) MA
Major radius	R = 1.78 m
Minor radius	a = 0.65 m
Aspect ratio	R/a = 2.8
Elongation	K = 1.8-2
Triangularity	δ > 0.5
Toroidal field	B_T = 2.2 (3) T
Flux swing	ΔΦ= 14Vs
Heating power	25 MW

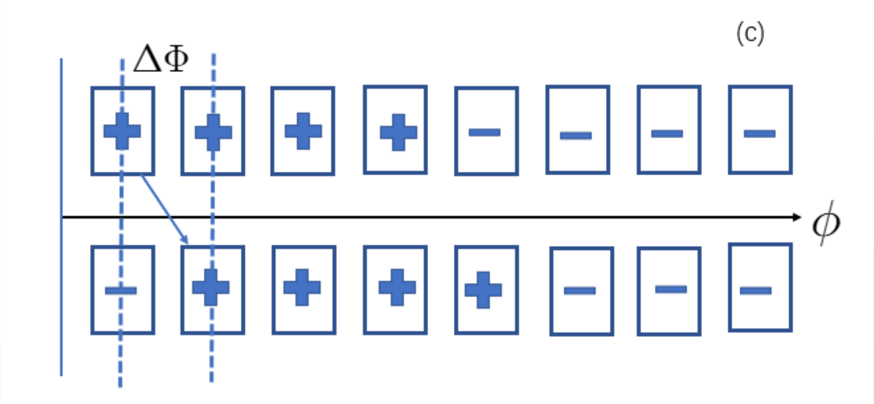

HL-2M tokamak

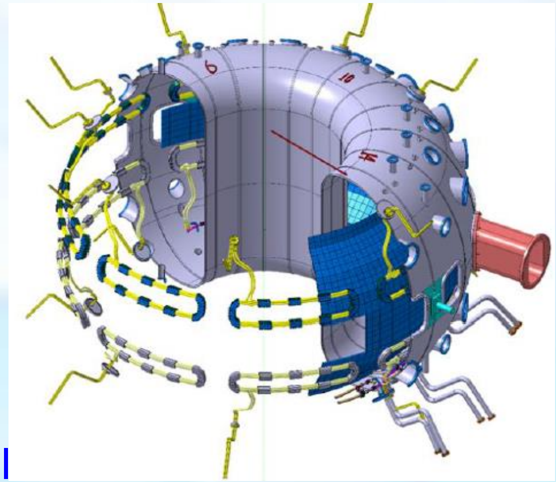
- Development of ELM control techniques is an important research topic on HL-2M.

Allows n=1,2, and 4 configurations









- Optimizing coil phasing essential for ELM control
  - Designed maximum of RMP coil current: 10 kAt
  - Allows n=1,2, and 4 configurations

Introduction of MARS-F code

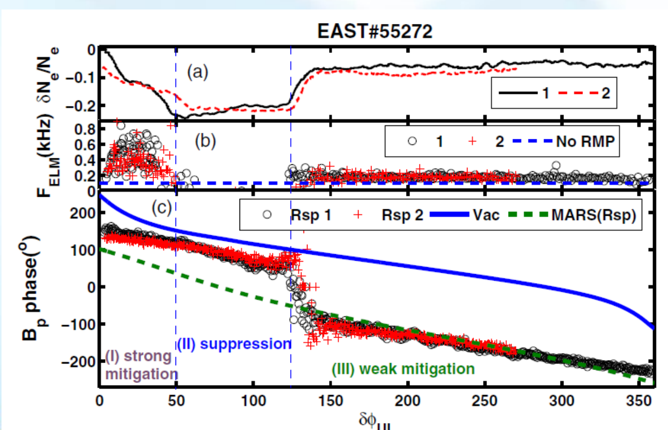
- Physical model : linear full MHD code in toroidal geometry

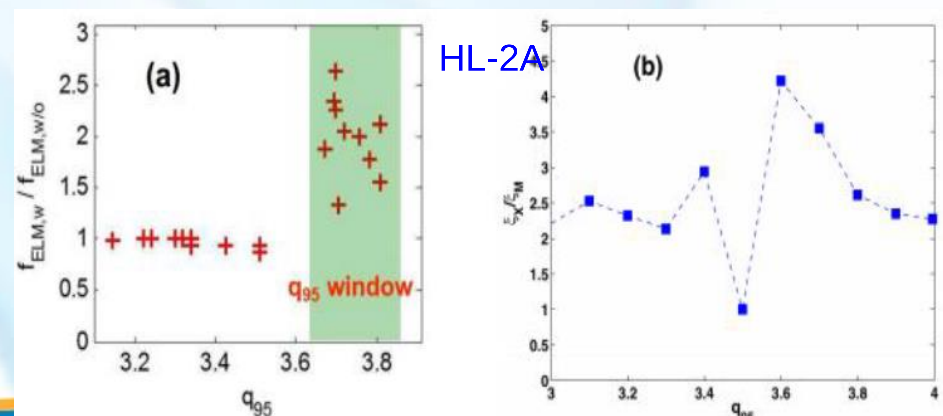
$$
\begin{aligned}
i(\Omega_{\mathrm{RMP}} + n\Omega)\xi &= v + (\xi \cdot \nabla\Omega)R\hat{\phi}, \\
i\rho(\Omega_{\mathrm{RMP}} + n\Omega)v &= -\nabla p + j \times B + J \times b \\
&\quad -\rho[2\Omega\hat{Z} \times v + (v \cdot \nabla\Omega)R\hat{\phi}] \\
&\quad -\rho\kappa_{\parallel}|k_{\parallel}v_{\mathrm{th,i}}|[v + (\xi \cdot \nabla)V_0]_{\parallel}, \\
i(\Omega_{\mathrm{RMP}} + n\Omega)b &= \nabla \times (v \times B) + (b \cdot \nabla\Omega)R\hat{\phi} \\
&\quad -\nabla \times (\eta j), \\
i(\Omega_{\mathrm{RMP}} + n\Omega)p &= -v \cdot \nabla P - \Gamma P \nabla \cdot v, \\
j &= \nabla \times b,
\end{aligned}
$$

$$\nabla \times \mathbf{b} = \mathbf{j}_{\mathrm{RMP}}, \quad \nabla \cdot \mathbf{j}_{\mathrm{RMP}} = 0$$

Y.Q.Liu, 2011, NF

- experimental validation





HL-2A

Y.W.Sun, 2016, PRL

Y.Q.Liu, 2016, PoP

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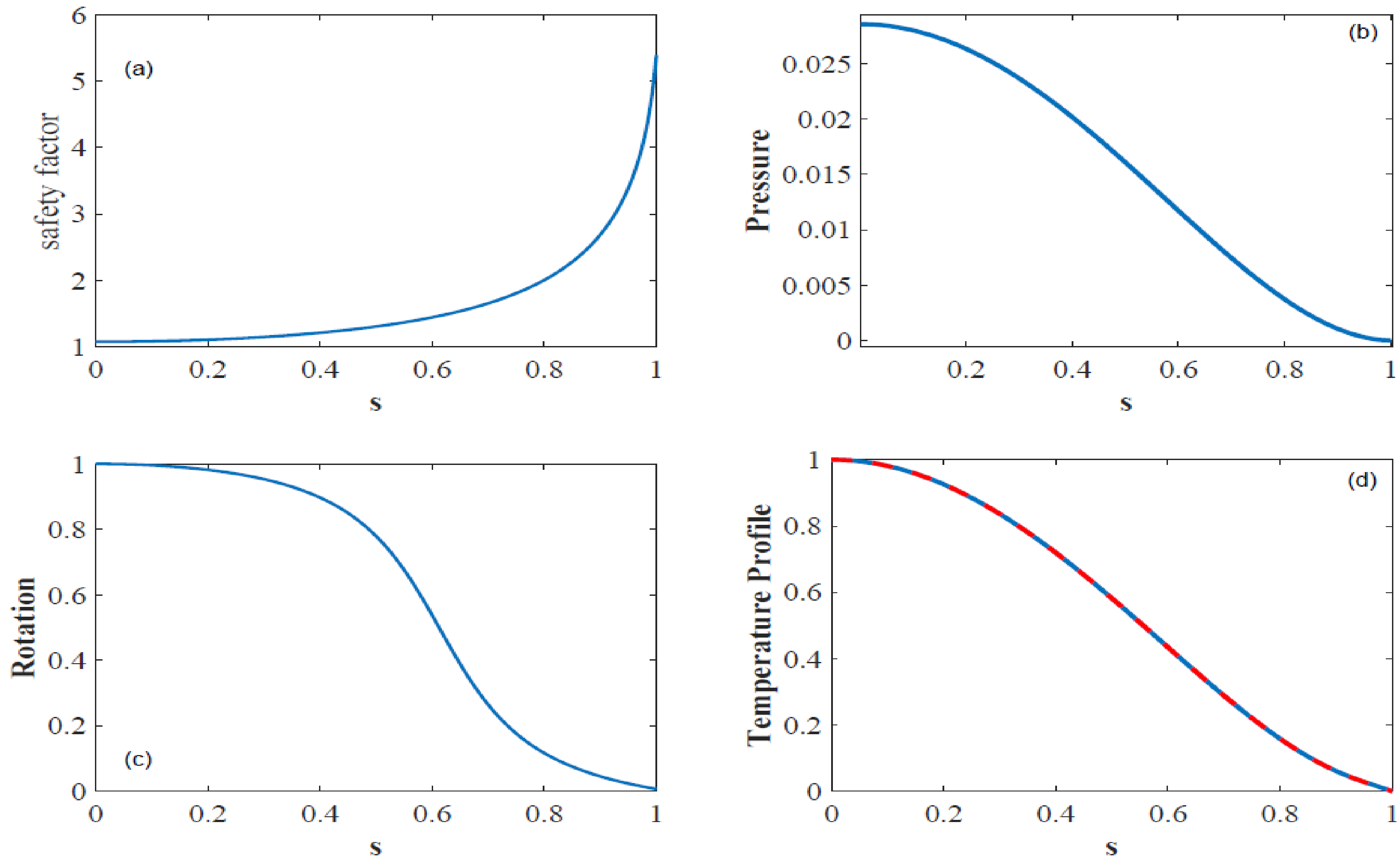
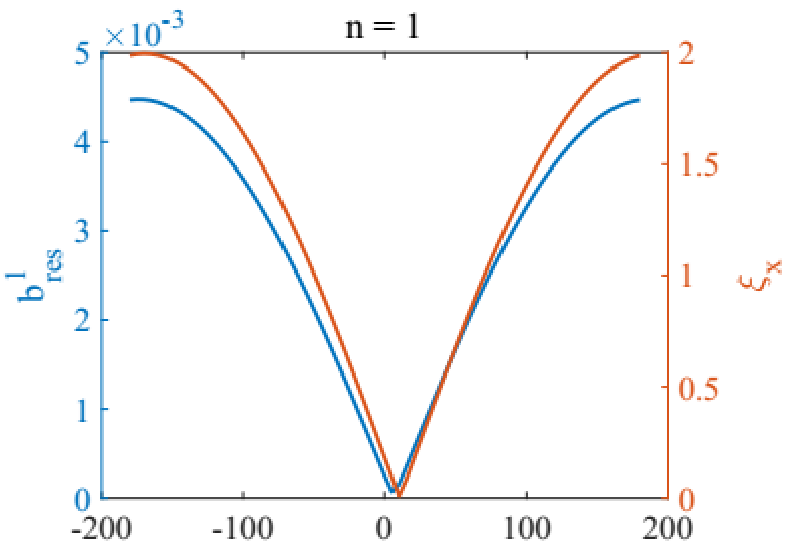
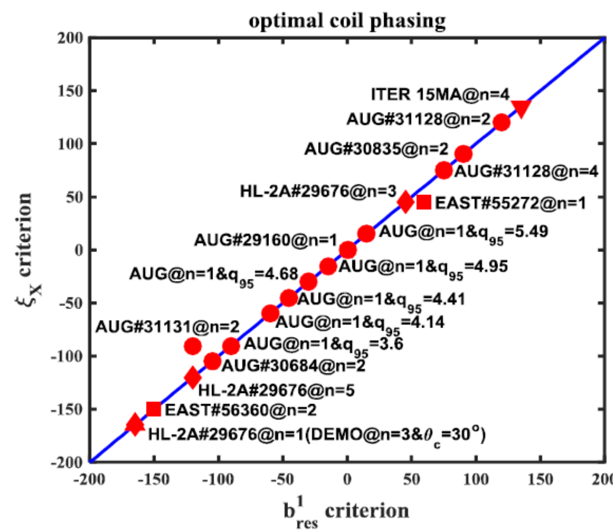
Equilibrium for a reference scenario of HL-2M



- q_0 >1, avoid the internal kink instability
- Beta_N ~1.6, much smaller than the no wall beta limit

Criteria for optimizing coil phasing $\Delta\Phi$





L.N. Zhou, NF,2018

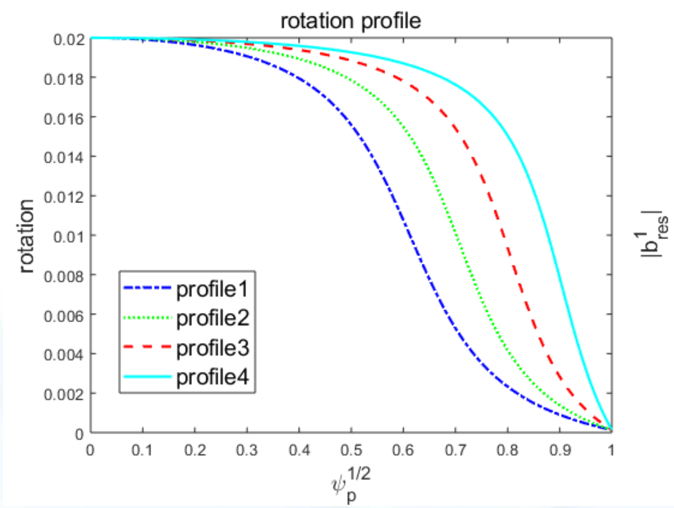
Criterion I: $b^1_{res} = \frac{1}{R_0^2}\left|\left(\frac{\boldsymbol{b}\cdot\nabla\psi}{\boldsymbol{B}\cdot\nabla\phi}\right)_{nm}\right|$ at last rational surface

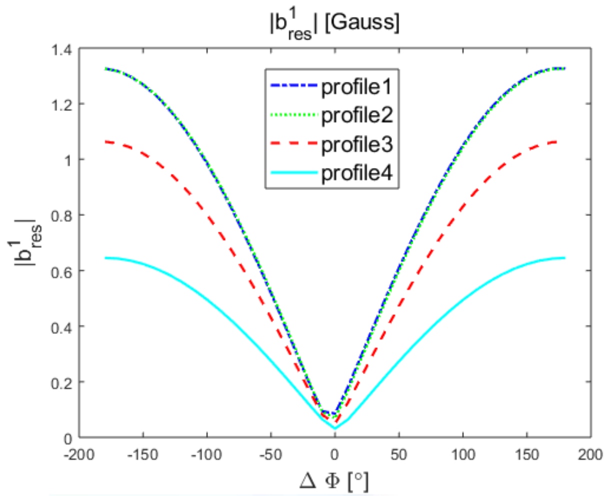
Criterion II: Displacement near X-point: ξ_X

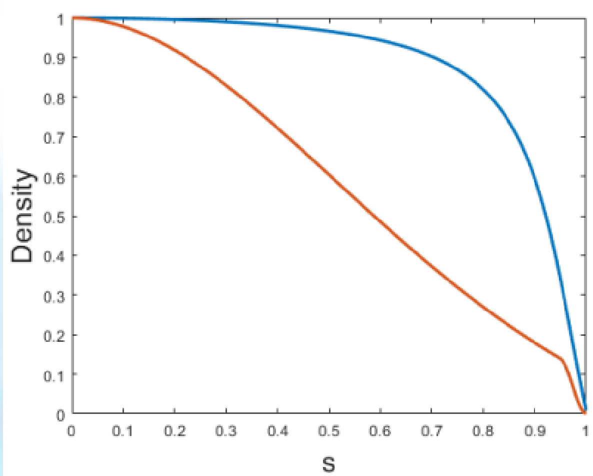
Almost the same, when linear resistive plasma response is concerned. [Y.Q.Liu, PPCF 2016]

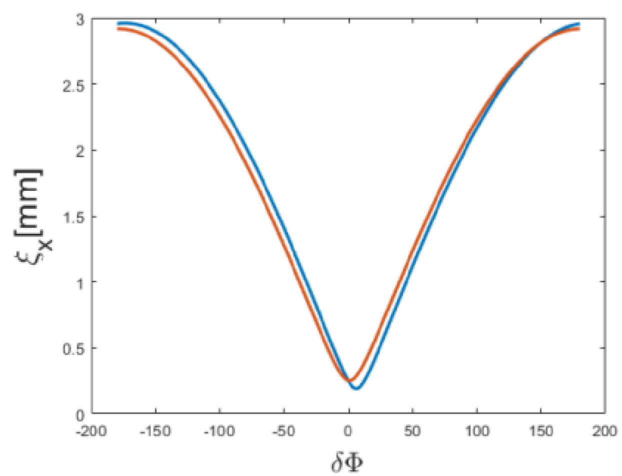
Optimal coil phasing $\Delta\Phi_{opt}$ insensitive to toroidal rotation and density profiles

- Amplitude of total RMP field depends on rotation profile at edge, due to screening effect of rotation on external field.



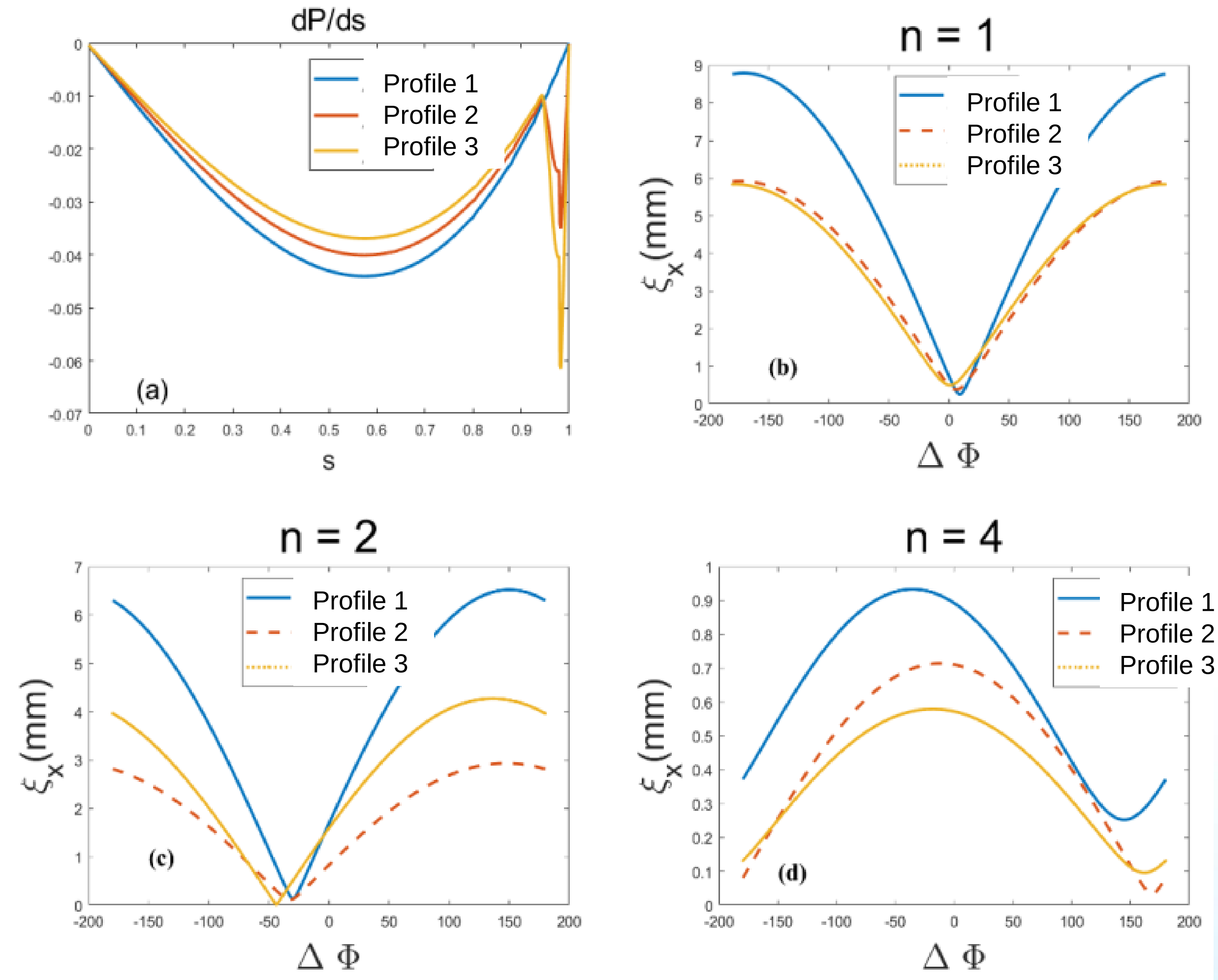






Optimal coil phasing $\Delta\Phi_{opt}$ insensitive to pressure profile

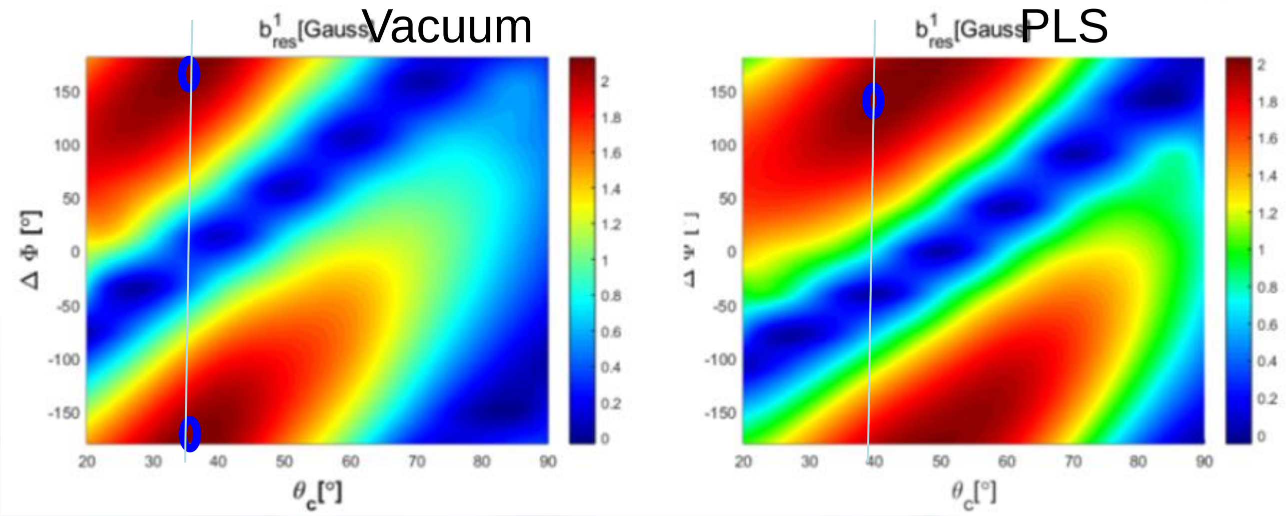
- $\Delta\Phi_{opt}$ insensitive to pressure profile at edge.
- Amplitude of displacement ne X-point decreases with increasing pressure gradient.
- (possible)Due to stabilizing effect of curvature on kink-tearing mode.
- Imply that the current coil current for ELM control may depend on the pressure gradient.



For n=1,2, and 4 configurations, the optimal phases are $\Delta\Phi_{opt} = \pm 180^o, 120^o, -50^o$

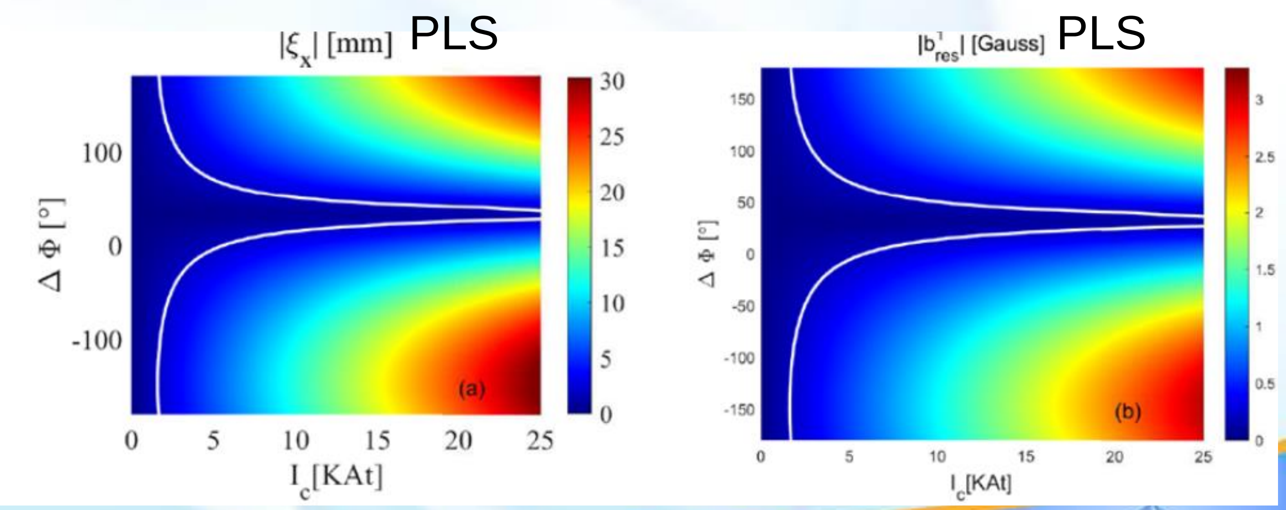
Plasma response induces the shift of $\Delta\Phi_{opt}$ at fixed coil geometry

- $\Delta\Phi_{opt}$ shifts from ~180° to ~120° ， when plasma response is considered. (n=1)



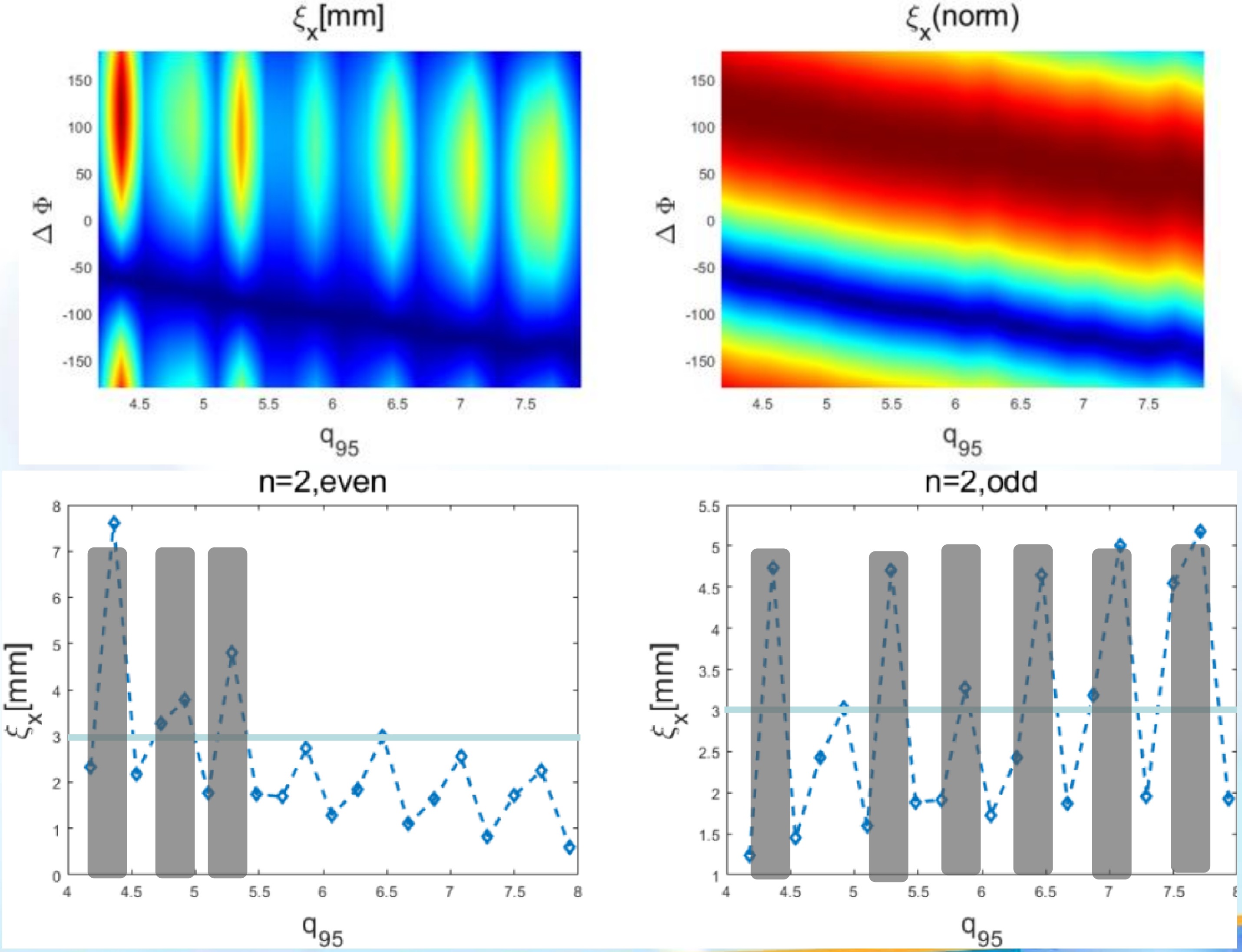
- If we simply assumed \xi_x~3 mm as the guideline for controlling ELM for HL-2M, the 10 kAt meets the requirement for ELM control, as long as avoiding the poor phasing (0~50°) for n=2

- (MAST， \xi_x~1.5mm)



Multiple effective q95 windows for ELM control

Number of effective q95 windows depends on the choice of phasing



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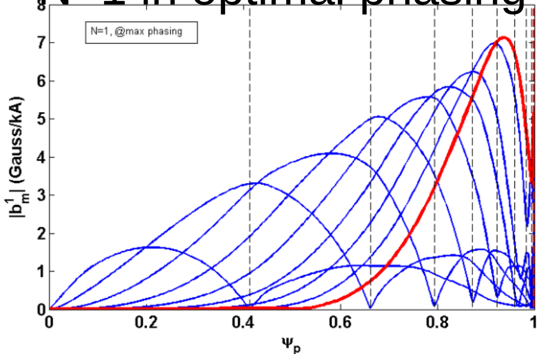
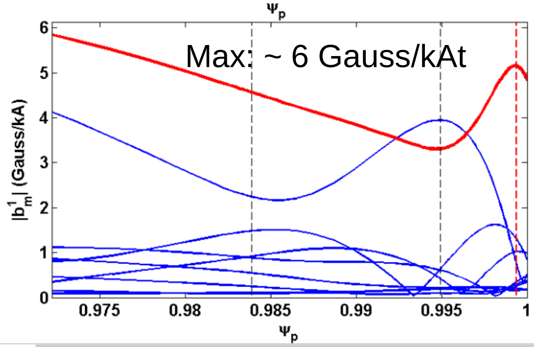
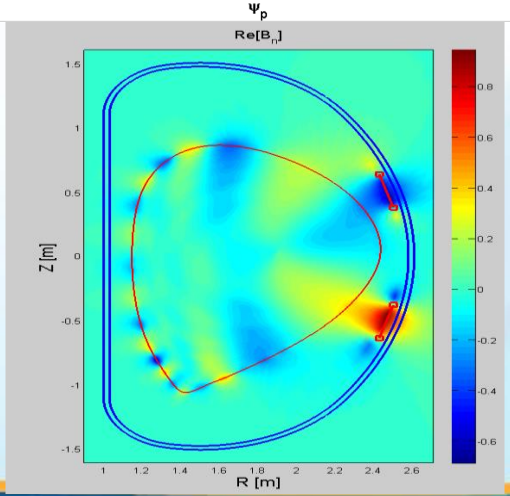
In optimal phasing, the total RMP field is amplified (n=1)

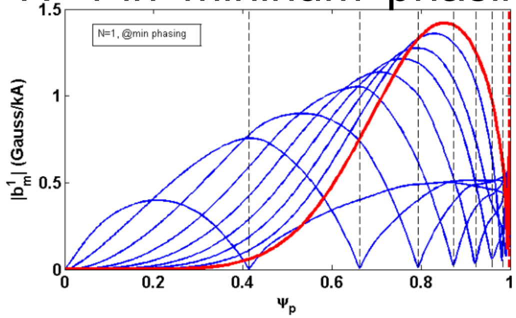
N=1 in optimal phasing

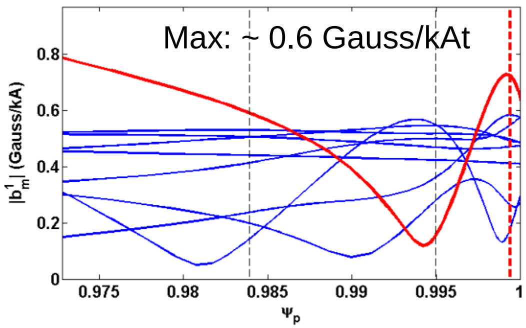


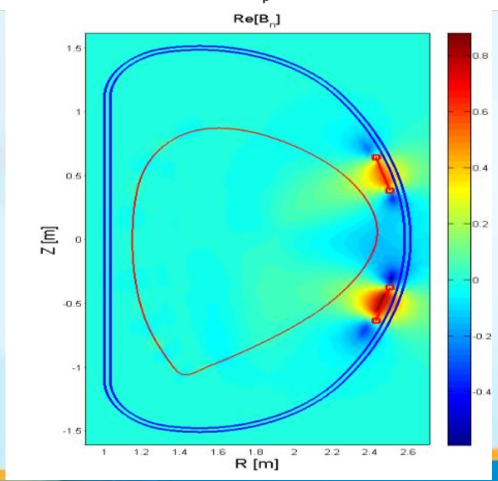


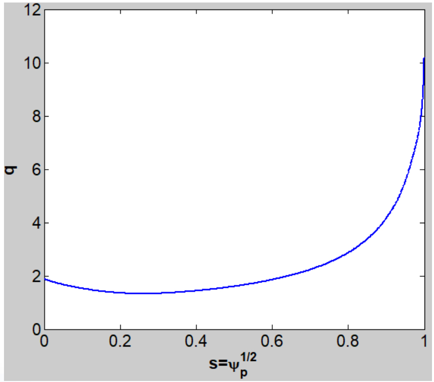


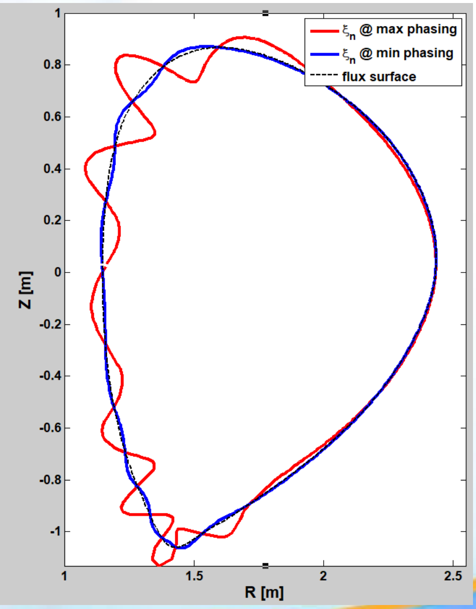
N=1 in 'mininum' phasing





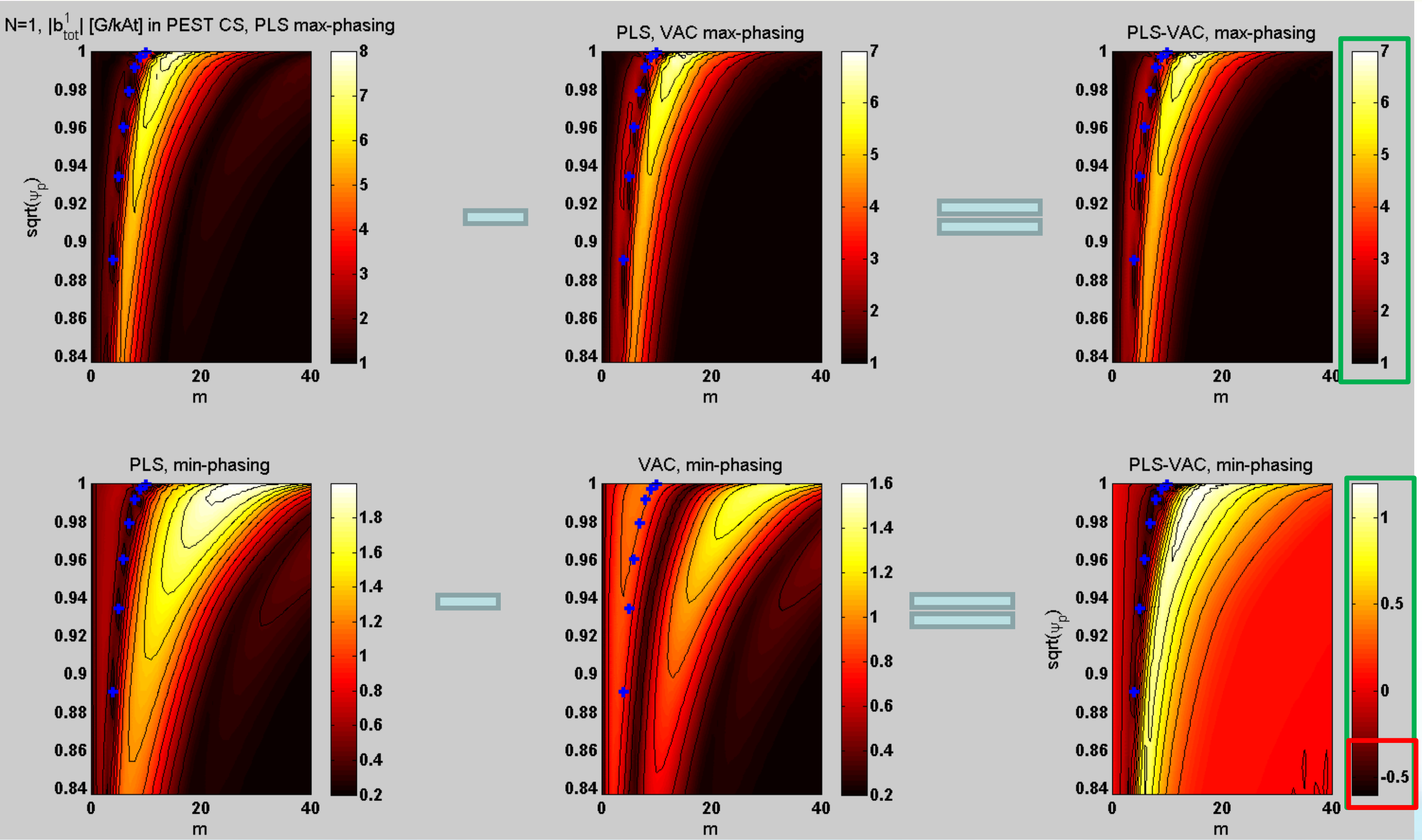






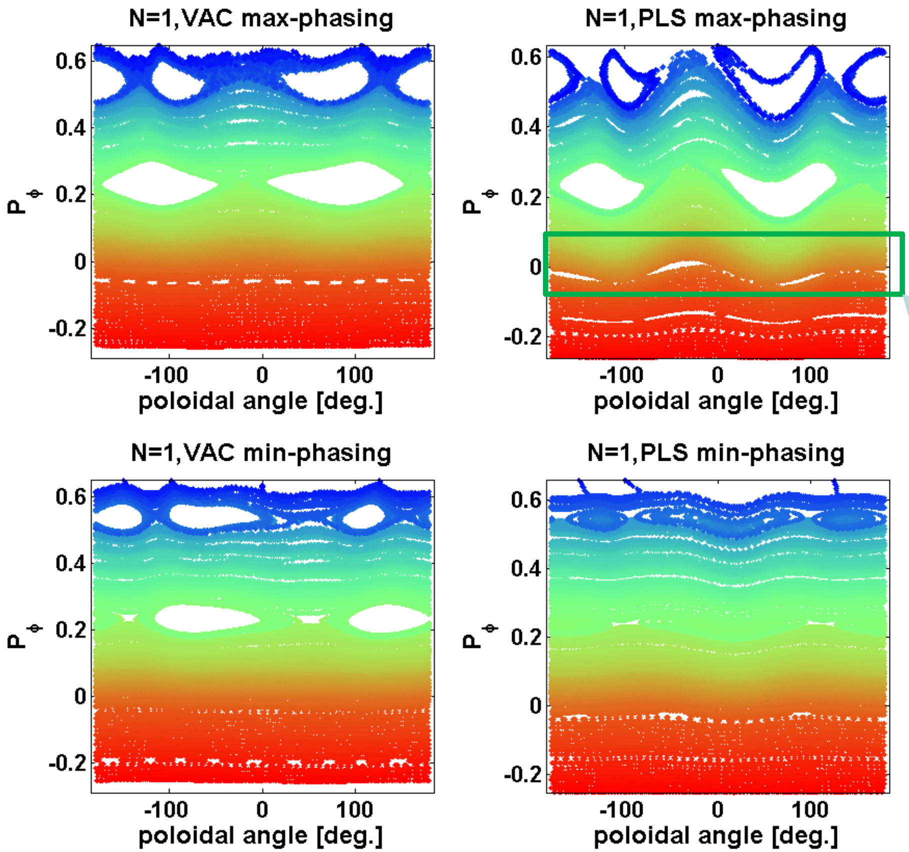
Here, a high beta (\beta_N~2.8) scenario is considered

In optimal phasing, RMP field at the plasma edge is significantly enhanced



- In optimal phasing, RMP field is generally enhanced by plasma response;
- In ‘minimum’ phasing, plasma response screen RMP field at rational surfaces, while enhances the RMP field at the non-rational surfaces for ‘m>0’ component

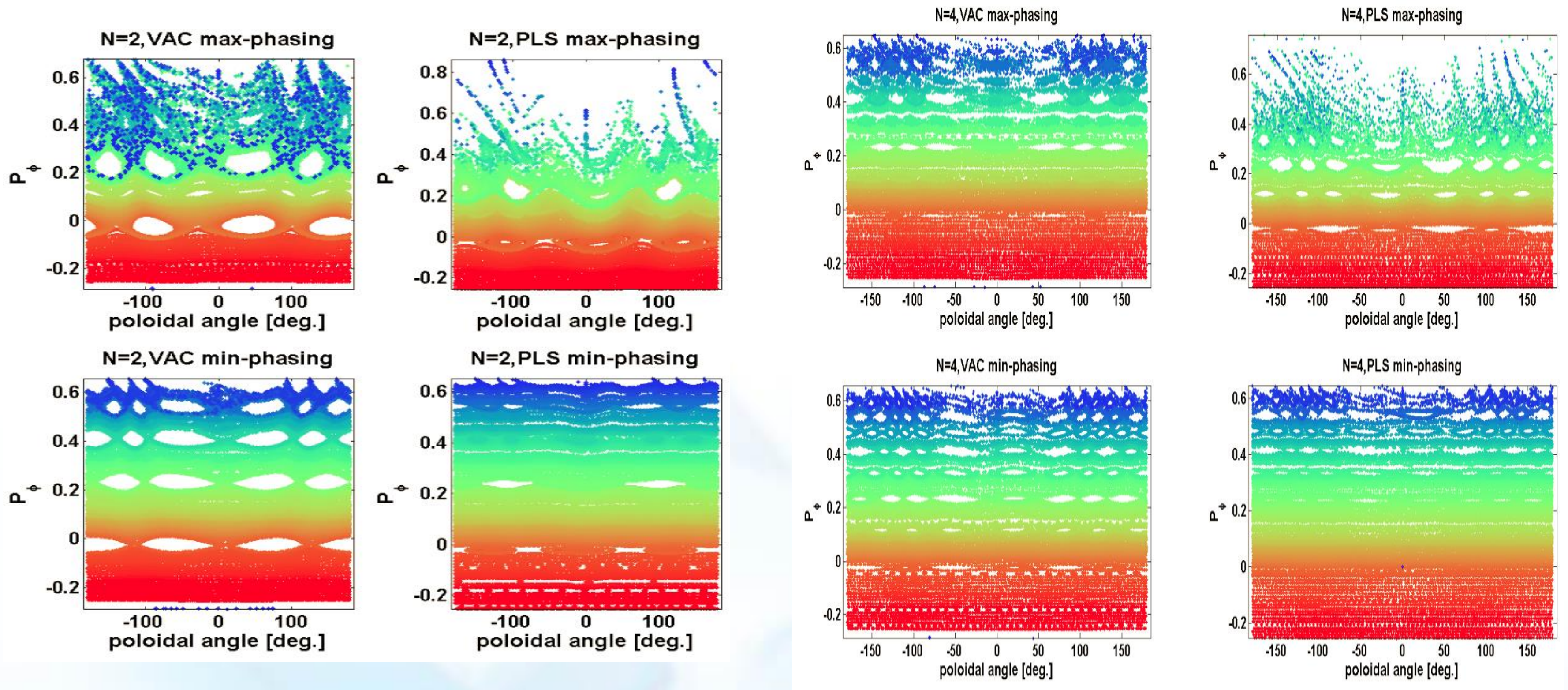
Fast ion transport significantly depends on coil phasing



- At the optimal coil phasing, when the plasma response is taken into account, the distortion of island is enhanced, which implies that more fast ions can be transported and lost
- More interesting, it seems that the island near P_\phi~0.0 (corresponding to q=1.5 rational surface) appears
- fast ion transport is much weaker at the 'minimum' coil phasing

Here, two hundred particles are launched at different (R,Z) positions, with the same kinetic energy 60 keV and pinch (ratio of parallel velocity to velocity = 0.6).

Fast ion transport significantly depends on coil phasing



- Similar, at n=2 and 4, fast ion transport is expected t o be enhanced in the optimal coil phasing for ELM control

Summary

- This work predicts the optimal coil phasing, semi-empirical threshold coil current and 'favorable' q_{95} window for ELM mitigation for HL-2M a reference scenario.

- It is found that pressure gradient and toroidal rotation at the plasma edge may play an important role on determining threshold coil current.

- At the optimal coil phasing, the plasma response amplifies the RMP field at the plasma edge and possibly enhances the fast ion transport. The results indicate that the RMP coil design for ELM control should also take into account the effect on fast ion transport.