Plasma response to resonant magnetic perturbations and its application in ELM control

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Contents

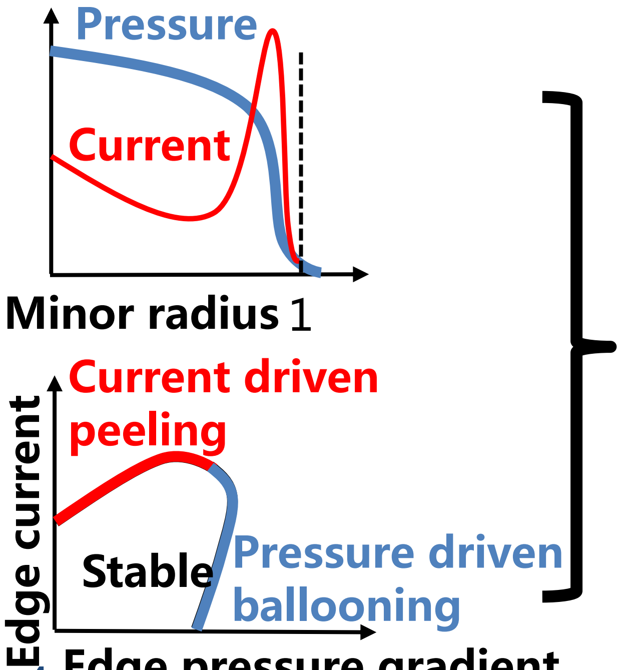
01

Background & Motivation

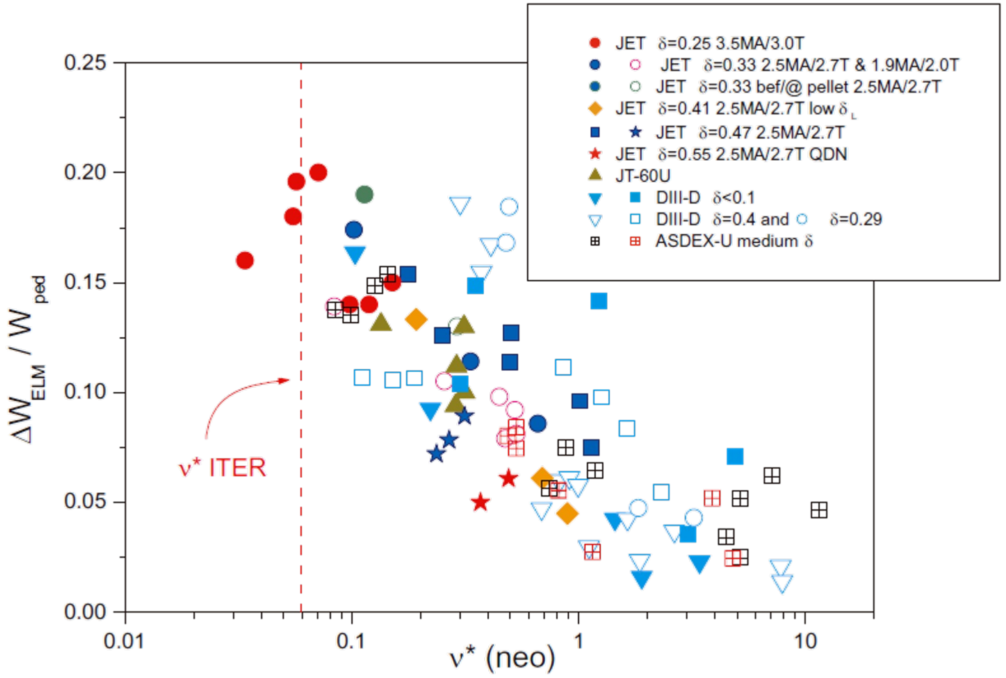
- Edge localized mode must be controlled in tokamak
- RMP is one effective technique to control ELMs
- Plasma response is the key point to understand the physical mechanism of ELM control
- Unsolved problem in the past

Edge localized mode must be controlled in tokamak (mitigation or suppression)

- **Edge localized mode (ELM)**
  - Periodic crash event driven by edge current and pressure gradient in an H-mode plasma
- **Unacceptable level of damage to future fusion devise**
  - Huge amount of energy loss (~20MJ) per ELM expected in standard H-mode operation for ITER



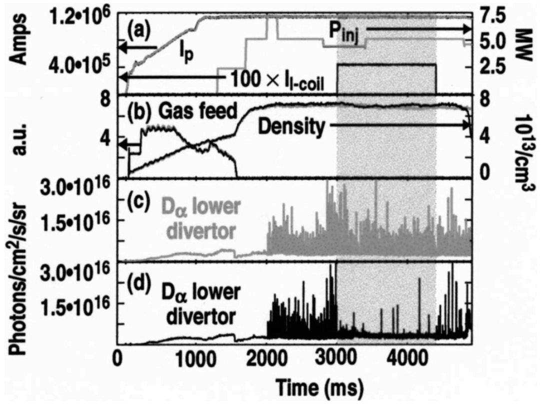
ELM



A. Loarte, 2003, PPCF

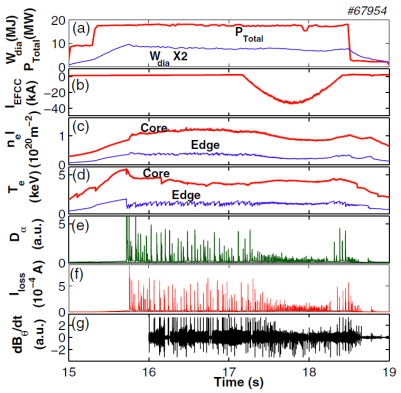
Resonant magnetic perturbations (RMPs) is one of the most effective technique to control ELMs

DIII-D



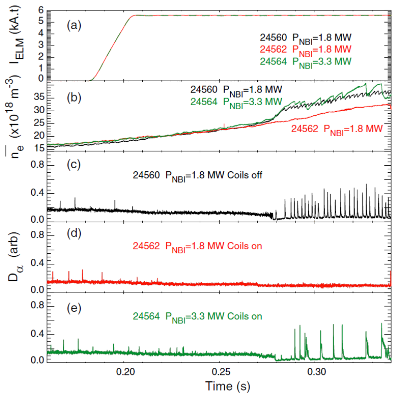
T. E. Evans, 2004, PRL

JET



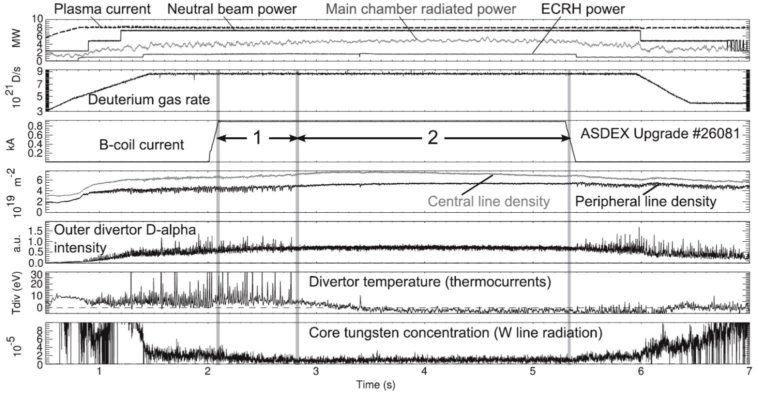
Y. Liang, 2007, PRL

MAST



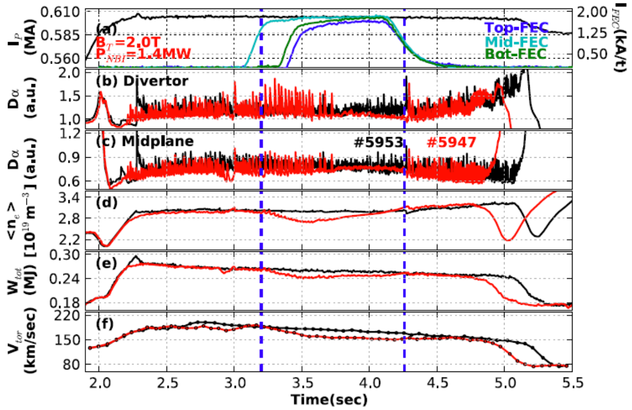
A. Kirk, 2011, PPCF

ASDEX Upgrade



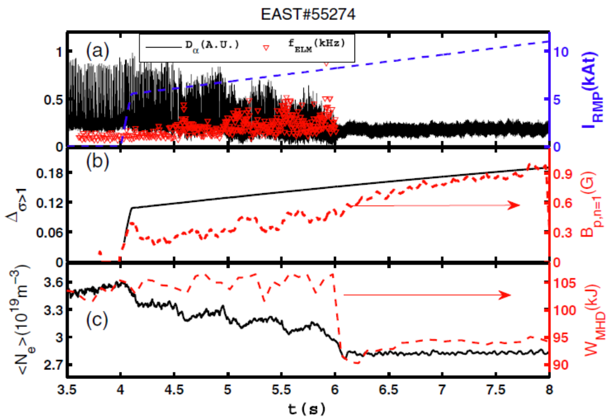
W. Suttrop, 2011, PRL

KSTAR



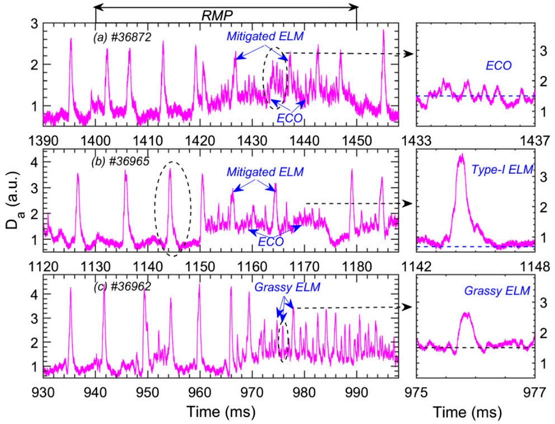
Y. M. Jeon, 2012, PRL

EAST



Y. Sun, Y. Liang, Y. Q. Liu, **S. Gu**, et al, 2016, PRL

HL-2A



T.F. Sun, 2021, NF

Plasma response is the key point to understand the physical mechanism of ELM control

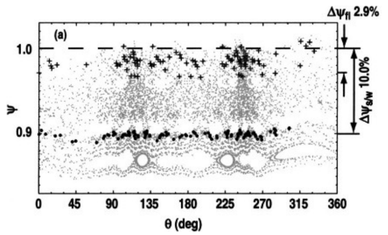
Vacuum

Fail in quantitative comparison

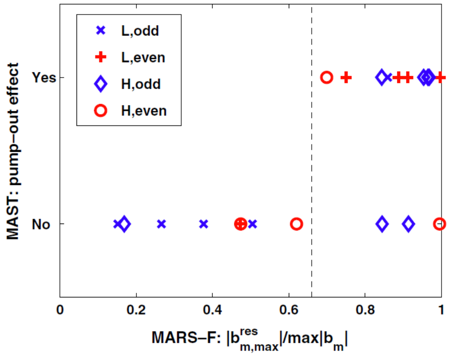
Plasma response

Multi-mode

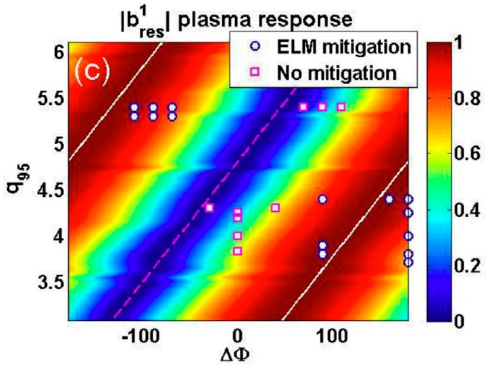
Non-linear



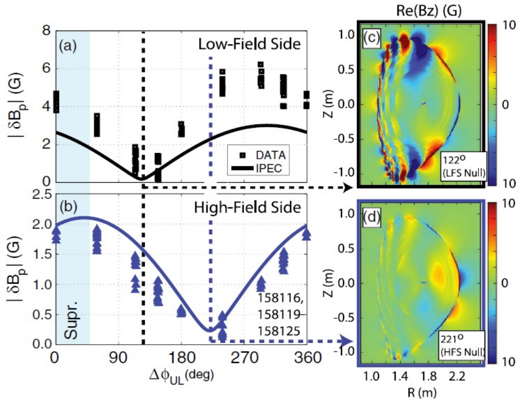
T. E. Evans, 2004, PRL



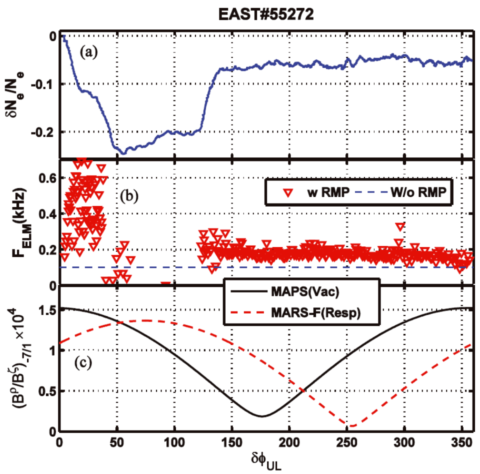
Y. Q. Liu, 2011, NF



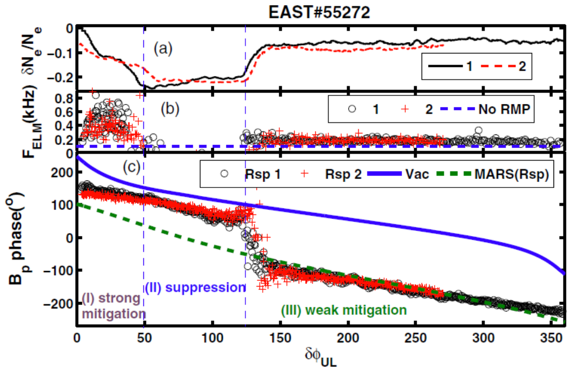
L. Li, 2016, NF



C. Paz-Soldan, 2015, PRL



X. Yang, 2016, PPCF



Y. Sun, Y. Liang, Y. Q. Liu, **S. Gu**, et al, 2016, PRL

Unsolved problem in the past

- Plasma response on EAST
  - Measurement?

Measurement and simulation of plasma response on EAST

- Multi-mode & ELM control
  - Relationship?
  - Physical mechanism

Influence of multi-mode plasma response on ELM control

- Non-linear & ELM control
  - Relationship?
  - Physical mechanism

Plasma response to mixed-n RMP and its influence on ELM control

- Influence of plasma shape
  - On plasma response?
  - On ELM control?

Influence of plasma shape on plasma response to RMPs

02

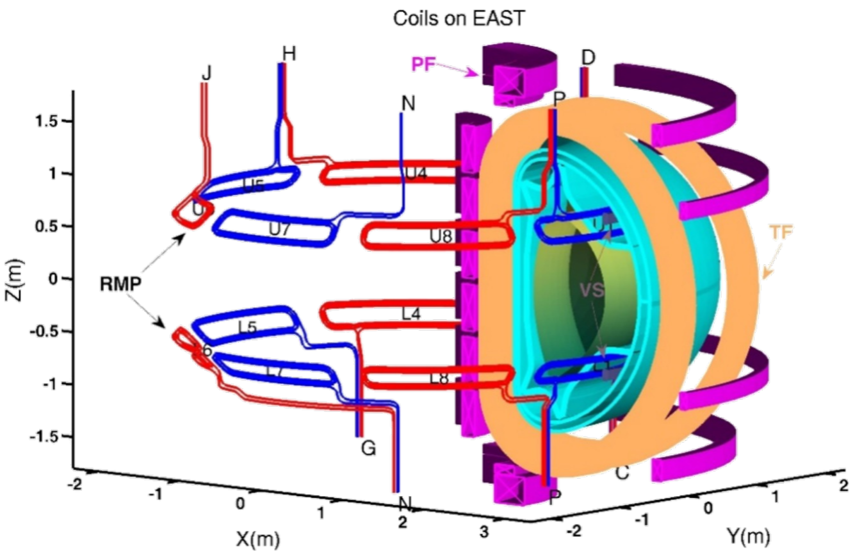
Plasma response measurement on EAST

RMP system on EAST

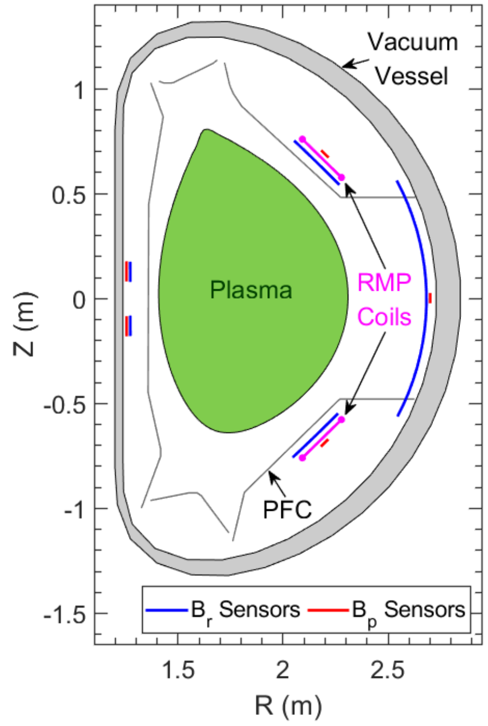
Develop the 3D magnetic plasma response measurement system in EAST

RMP system on EAST

- **3D coils on EAST**
  - Number of coils：8(U)+8(L)=16
  - Number of power supplies：8
  - Maximum current：2.5kA x 4 turns
  - Applied field：n=1~3 rotating、n=1~4 static



- **Magnetic diagnostics for 3D physics**
  - 5 array magnetic probes （B_p signal）
  - 5 array saddle loops （B_r signal）



EAST has flexible 3D coils and abundant 3D diagnostics

Develop the 3D magnetic plasma response measurement system in EAST

Sensor measurement

B^{sensor}

Subtract vacuum filed

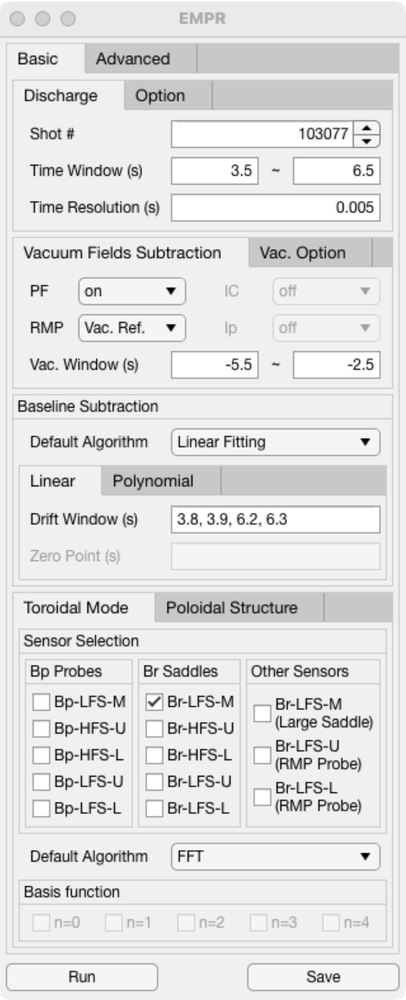
$B^{\text{plas}} = B^{\text{sensor}} - B^{\text{vac}}$

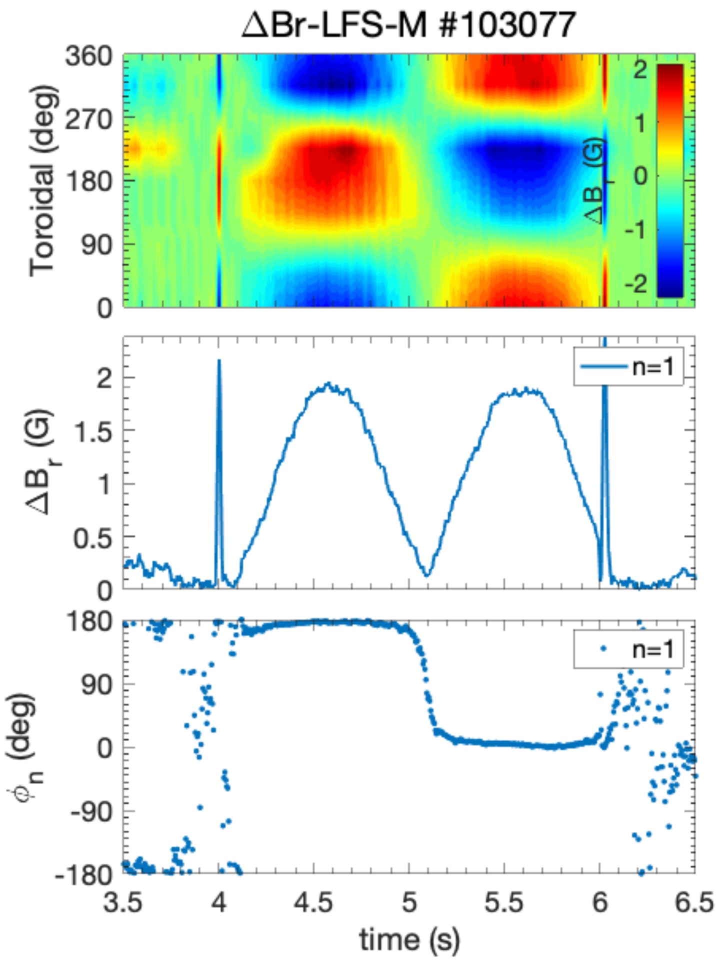
Subtract baseline

$\delta B^{\text{plas}} = B^{\text{plas}} - B_0^{\text{plas}}$

Fourier decomposition

$\delta B^{\text{plas}} = \sum_n B_n \cos(n\phi - \varphi_n)$





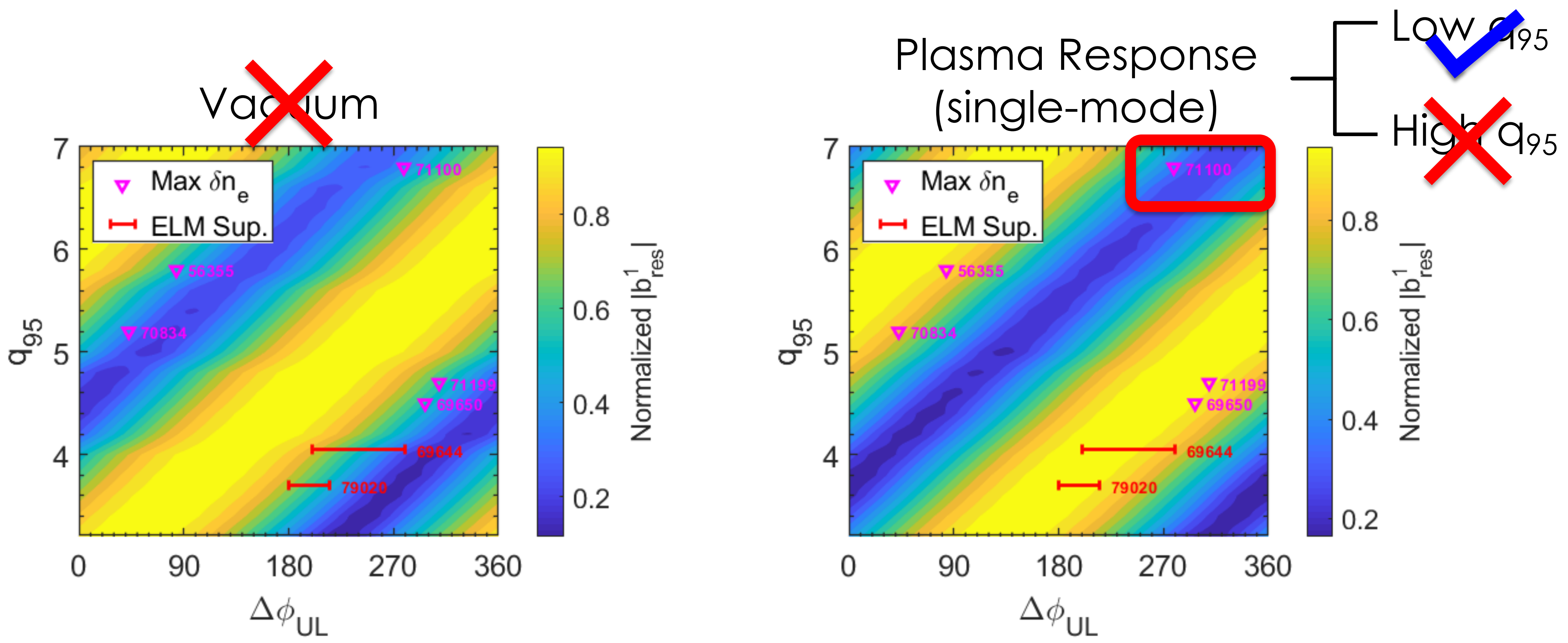
03

Effects of multi-mode plasma response on ELM control

- Insufficient understanding for ELM control with single-mode plasma response analysis
- Multi-mode plasma response extraction using SVD
- Plasma response of the dominate mode alone cannot explain the ELM control effect
- Multi-mode plasma response affect ELMs control through Pedestal top components
- Criterion
- PT-mode is associated with ELM control

Insufficient understanding for ELM control with single-mode plasma response analysis

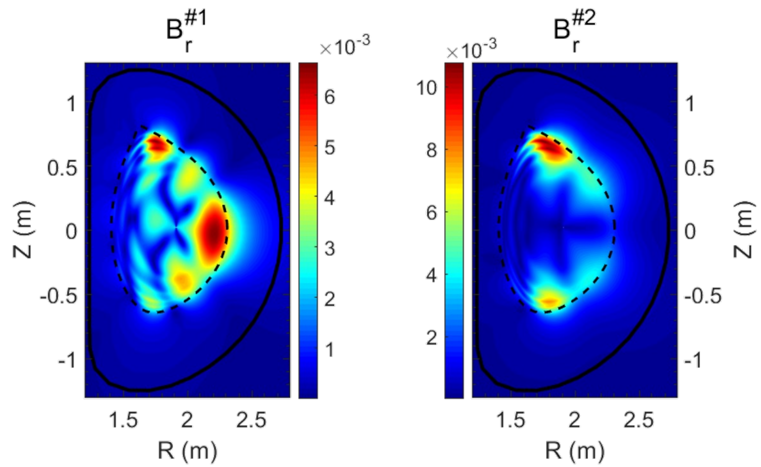
- **The single-mode criterion loses efficacy in EAST high q_{95} regime**



Multi-mode plasma response extraction using SVD

- **Plasma response to external applied 3D field can be represented by**
  - $\delta B(r,\theta,\phi) = \sum_n B_n(r,\theta) e^{-in\phi}$

Single toroidal harmonic: $\delta B(r,\theta,\phi) \Leftrightarrow B_n(r,\theta)$

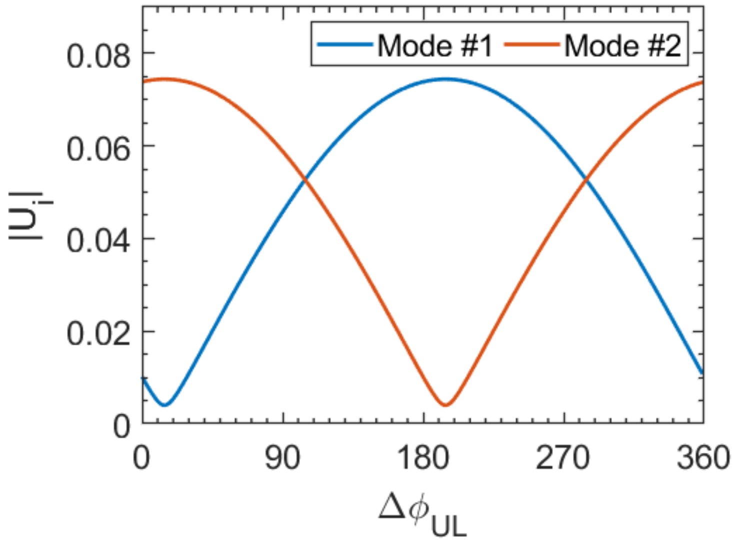


- **Multi-mode plasma response extraction using SVD**
  - $A = USV^H$

Spatial structure

$\Delta\phi_{UL}$

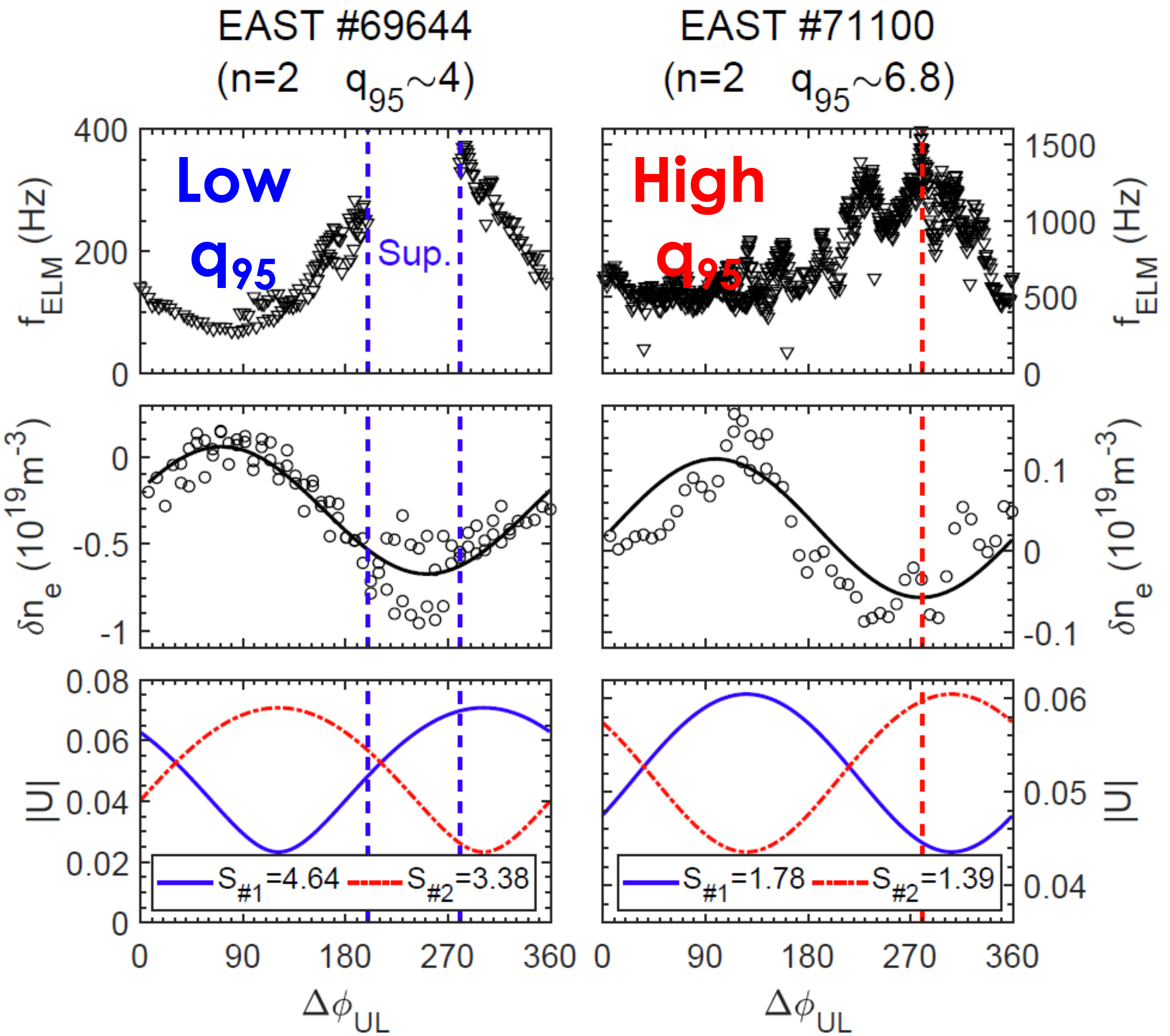
- $$A = \begin{pmatrix} \overbrace{A_{1,1} \; A_{1,2} \cdots A_{1,Y}}^{\Delta\varphi_{UL}\,1,mesh\,1} & \overbrace{A_{2,1} \; A_{2,2} \cdots A_{2,Y}}^{\Delta\varphi_{UL}\,1,mesh\,2} & \cdots & \overbrace{A_{X,1} \; A_{X,2} \cdots A_{X,Y}}^{\Delta\varphi_{UL}\,1,mesh\,X} \\ \overbrace{A_{1,1} \; A_{1,2} \cdots A_{1,Y}}^{\Delta\varphi_{UL}\,2,mesh\,1} & \overbrace{A_{2,1} \; A_{2,2} \cdots A_{2,Y}}^{\Delta\varphi_{UL}\,2,mesh\,2} & \cdots & \overbrace{A_{X,1} \; A_{X,2} \cdots A_{X,Y}}^{\Delta\varphi_{UL}\,2,mesh\,X} \\ \vdots & \vdots & \ddots & \vdots \\ \overbrace{A_{1,1} \; A_{1,2} \cdots A_{1,Y}}^{\Delta\varphi_{UL}\,M,mesh\,1} & \overbrace{A_{2,1} \; A_{2,2} \cdots A_{2,Y}}^{\Delta\varphi_{UL}\,M,mesh\,2} & \cdots & \overbrace{A_{X,1} \; A_{X,2} \cdots A_{X,Y}}^{\Delta\varphi_{UL}\,M,mesh\,X} \end{pmatrix}_{M\times 2N}$$
- S Amplitude of each mode
- V Spatial structure of each mode
- U $\Delta\varphi_{UL}$ dependence of each mode



Plasma response of the dominate mode alone cannot explain the ELM control effect

- The dominate mode is related to ELM control at low q_{95}

- The secondary mode is related to ELM control at high q_{95}

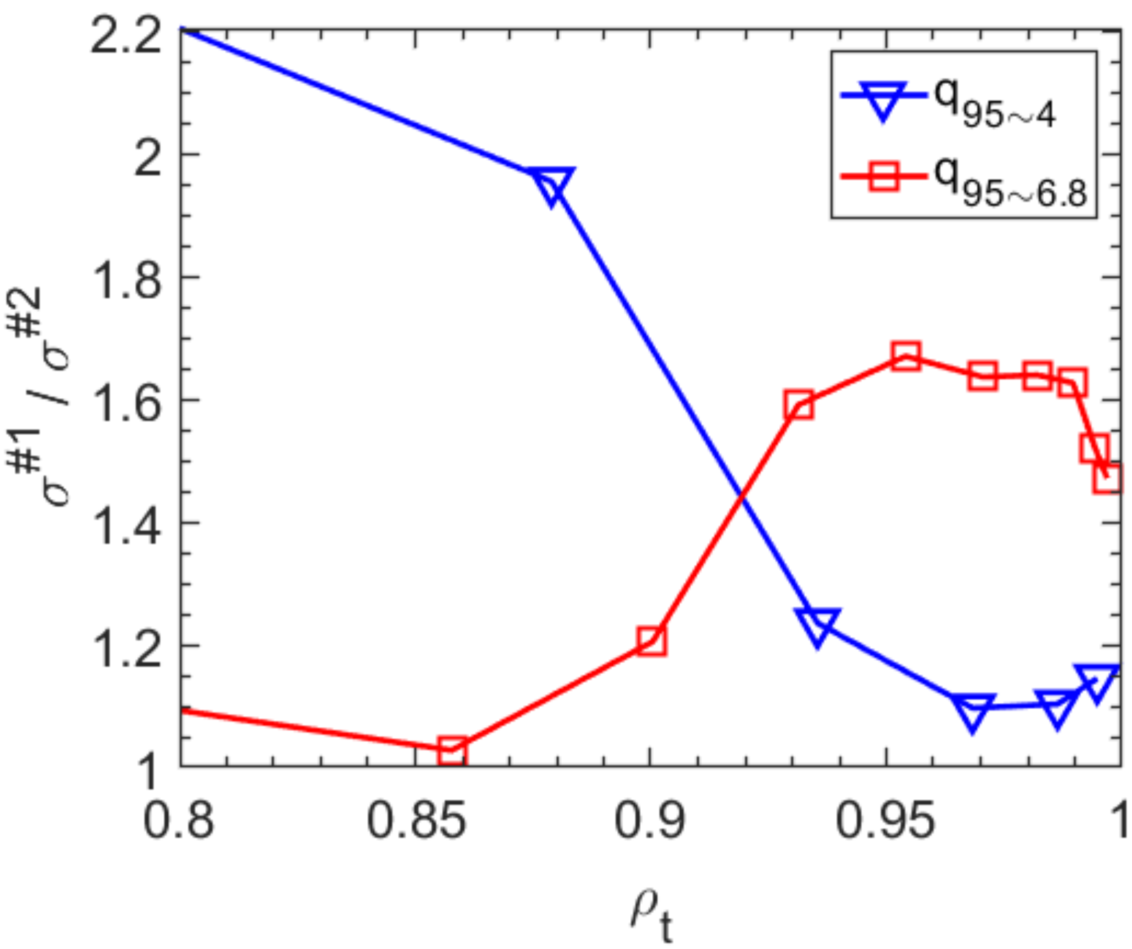


Multi-mode plasma response affect ELMs control through pedestal top components

- **Low q_{95}**
  - Resonant components of the dominant mode stronger on pedestal top
  - Resonant components of the secondary mode stronger on pedestal foot

- **High q_{95}**
  - Resonant components of the dominant mode stronger on pedestal foot
  - Resonant components of the secondary mode stronger on pedestal top

- **The ratio of Chirikov parameter σ of these two modes shows the difference clearly**
  - $\sigma = \frac{w_{m_1/n_1} + w_{m_2/n_2}}{2|\rho_2 - \rho_1|}$



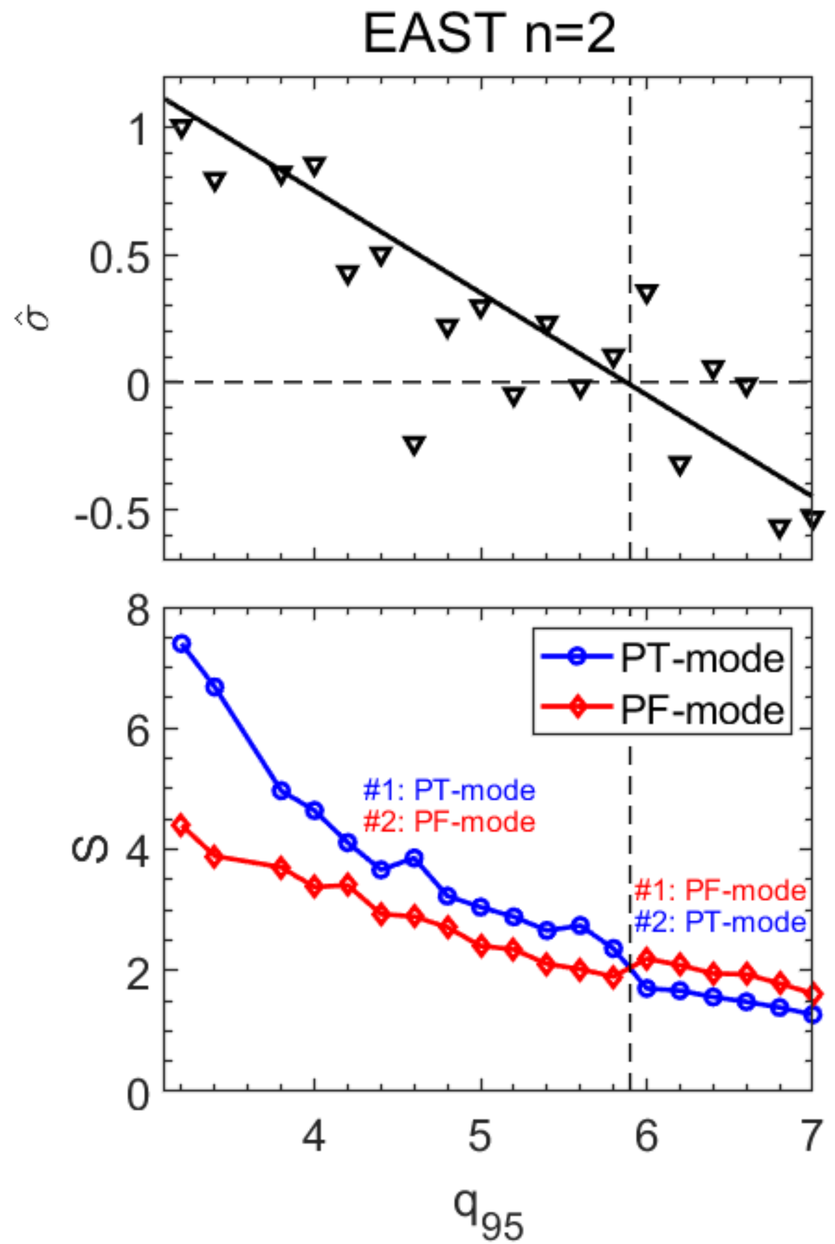
Mode with greater resonance or stochasticity at the pedestal top region is associated with ELM control

Criterion

- New criterion: $\hat{\boldsymbol{\sigma}} = \frac{\langle \sigma_{PT}^{\#1} \rangle}{\langle \sigma_{PT}^{\#2} \rangle} - \frac{\langle \sigma_{PF}^{\#1} \rangle}{\langle \sigma_{PF}^{\#2} \rangle}$

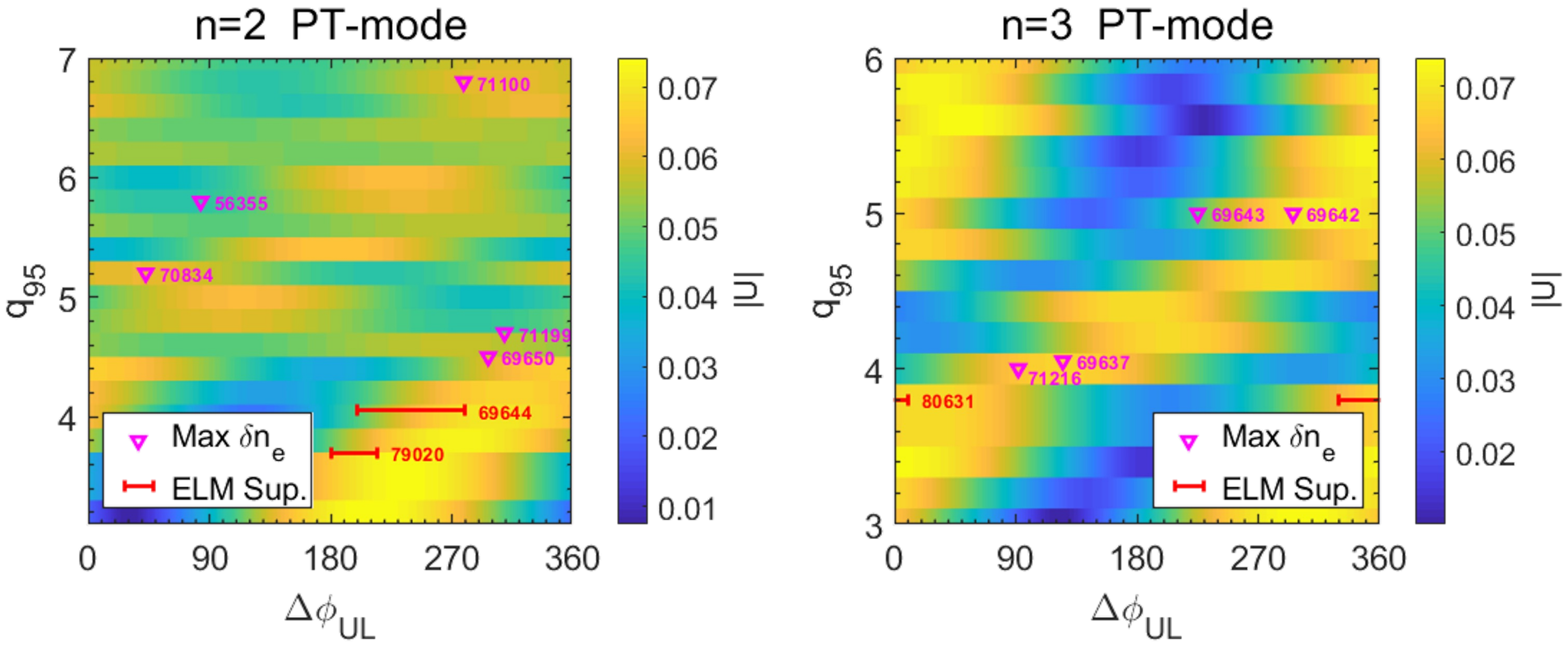
- $\hat{\boldsymbol{\sigma}} > \mathbf{0}$, resonance stronger on pedestal top, PT-mode (pedestal top mode)

- $\hat{\boldsymbol{\sigma}} < \mathbf{0}$, resonance stronger on pedestal foot, PF-mode (pedestal foot mode)



PT-mode is associated with ELM control

- **PT-mode can be used to explain and optimize ELM control**



Summary

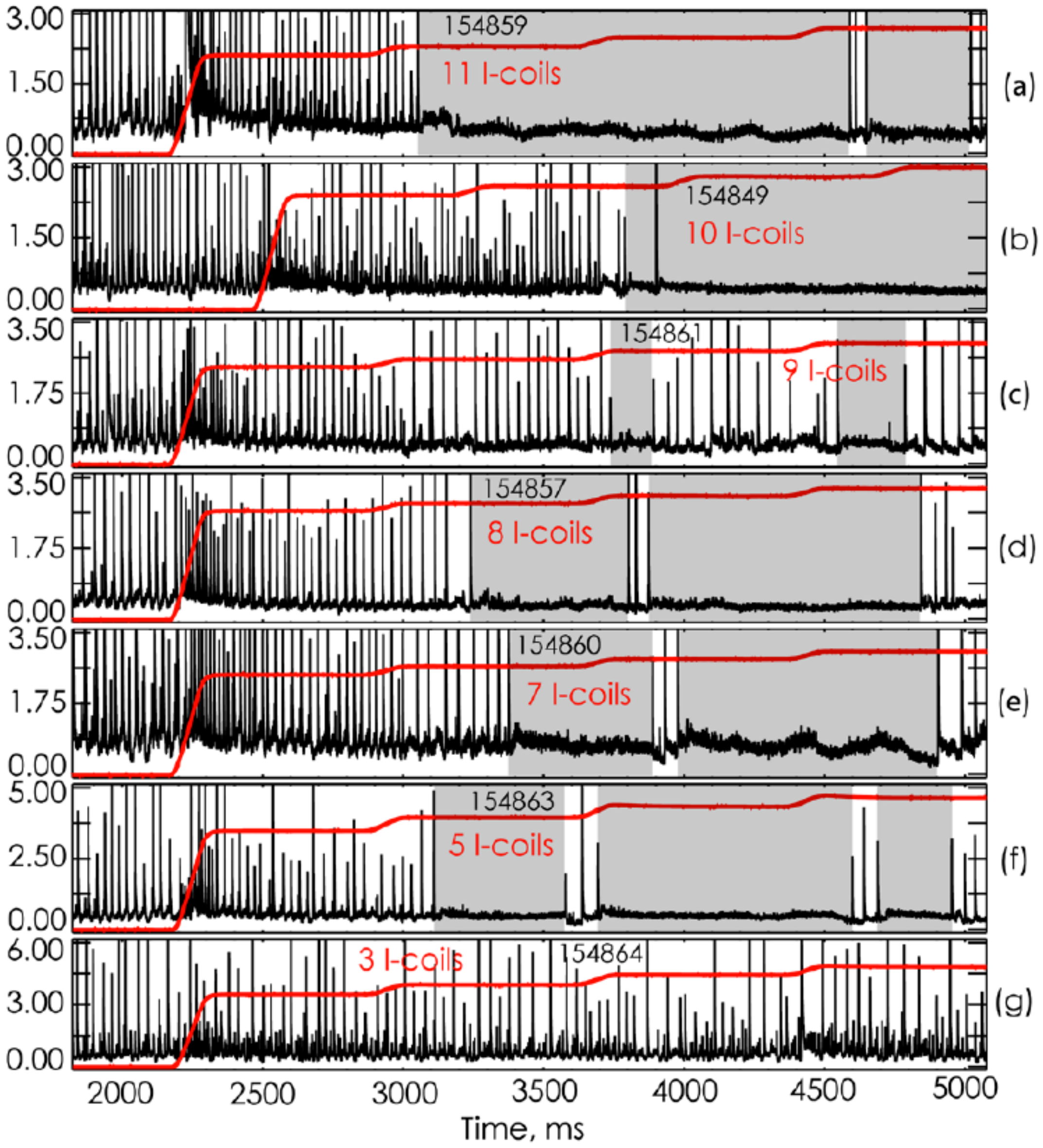
- **Propose a new method for multi-mode plasma response extraction using SVD**
- **Propose a new criterion for controlling ELMs based on multi-mode plasma response**
  - $\hat{\boldsymbol{\sigma}} = \frac{\langle \boldsymbol{\sigma}_{PT}^{\#1} \rangle}{\langle \boldsymbol{\sigma}_{PT}^{\#2} \rangle} - \frac{\langle \boldsymbol{\sigma}_{PF}^{\#1} \rangle}{\langle \boldsymbol{\sigma}_{PF}^{\#2} \rangle}$
    - $\hat{\boldsymbol{\sigma}} > \mathbf{0}$, resonance stronger on pedestal top, mode associated with ELM control
- **It reveals that mode with greater resonance or stochasticity at the pedestal top region is associated with ELM control**

04

Plasma response to mixed-n RMP and its influence on ELM control

Introduction

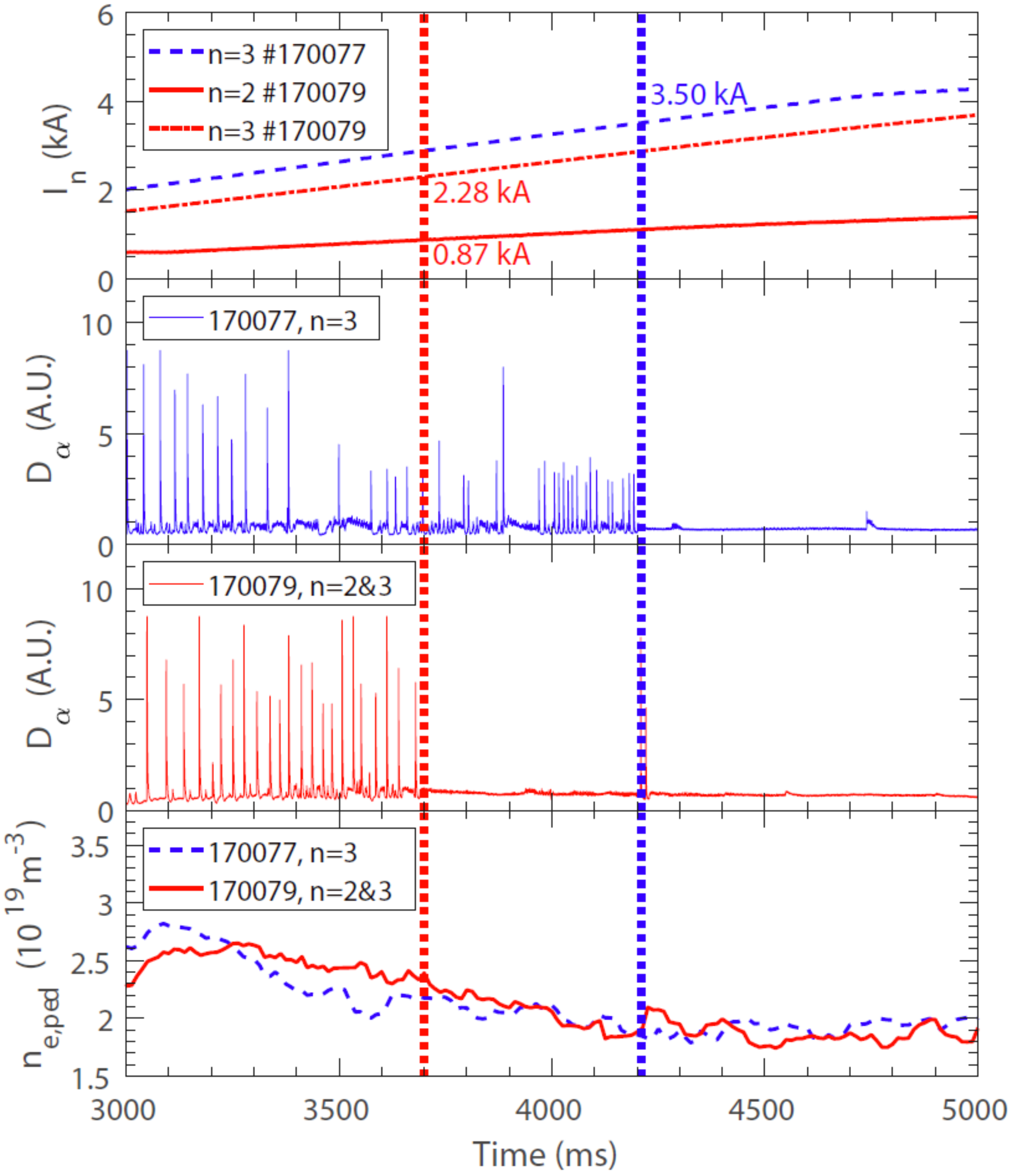
- **ELM control using mixed-n RMP**
  - ELM can be suppressed with reduced coils RMP
  - Physical mechanism of ELM control using mixed-n RMP



D. M. Orlov et al, 2016, NF

Mixed-n RMP lower the threshold of ELM suppression

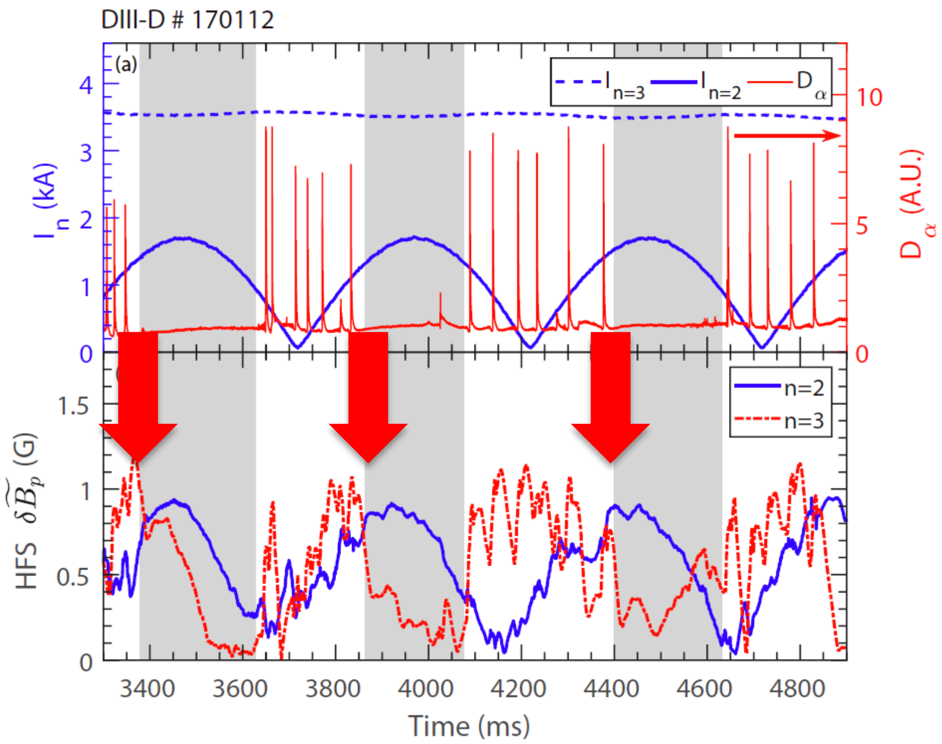
- **ELM suppression threshold**
  - n=2：no suppression
  - n=3：3.50kA
  - Mixed-n：$I_{n=2}$=0.87kA, $I_{n=3}$=2.28kA
- **Power supply**
  - Maximum current reduced by 13%
- **Energy consumption**
  - Energy consumption reduced by 54%



Mixed-n RMP offers a better way to control ELMs

Non-linear jump during the transition from ELM mitigation to suppression

- **Non-linear jump of plasma response is observed from during the transition from ELM mitigation to suppression**
  - n=3 jump of plasma response → n=3 mode structure change & edge components penetrate→ ELM suppression
  - n=2 linear response → help n=3 components penetrate → lower the threshold

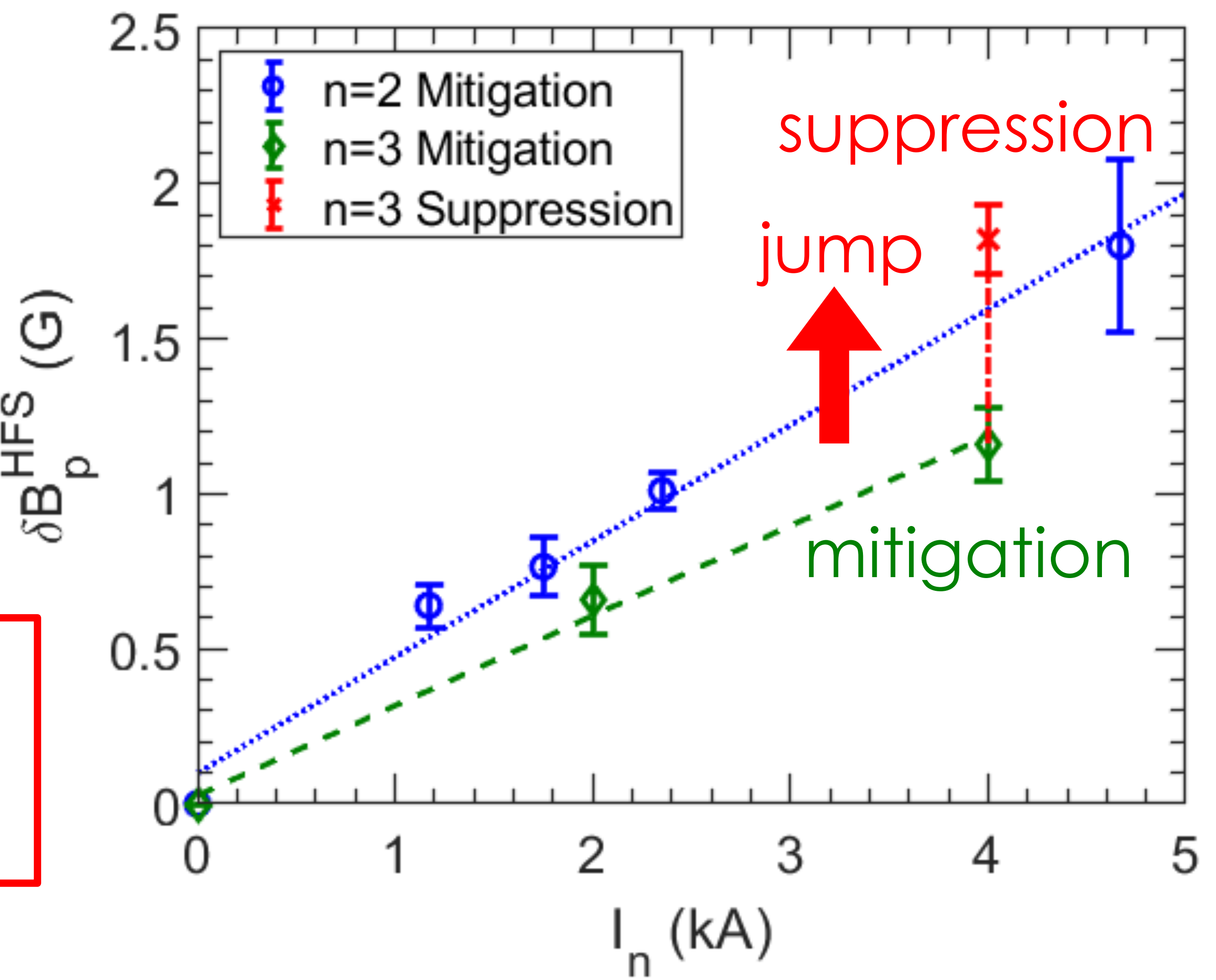


Non-linear jump of n=3 components is the key to suppress ELMs

Non-linear jump of plasma response during ELM suppression

- **n=3 —— non-linear**
  - Jump from mitigation to suppression
- **n=2 —— linear**
  - No ELM suppression

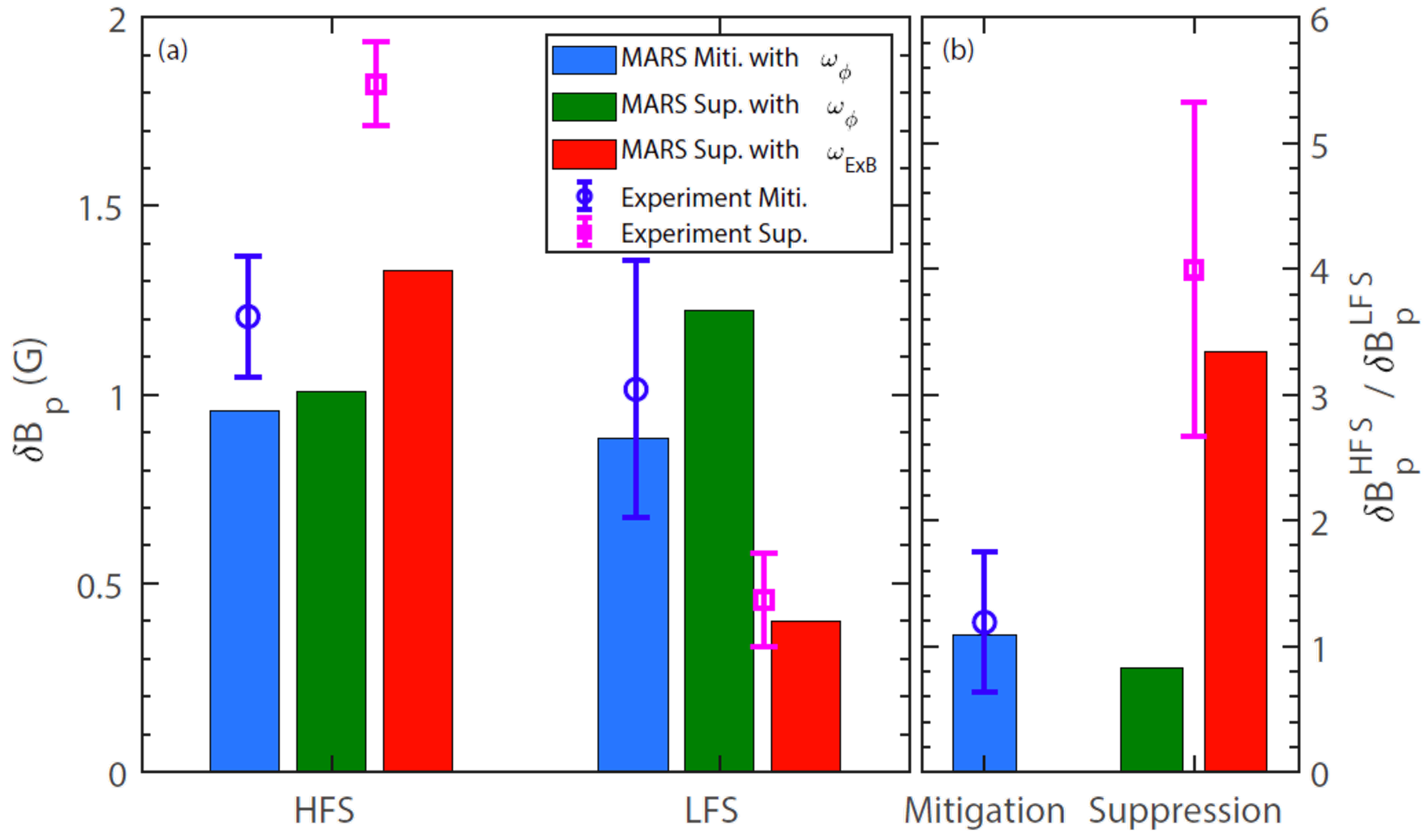
n=3 non-linear jump of plasma response is the key to ELM suppression



Simulation of plasma response on HFS and LFS

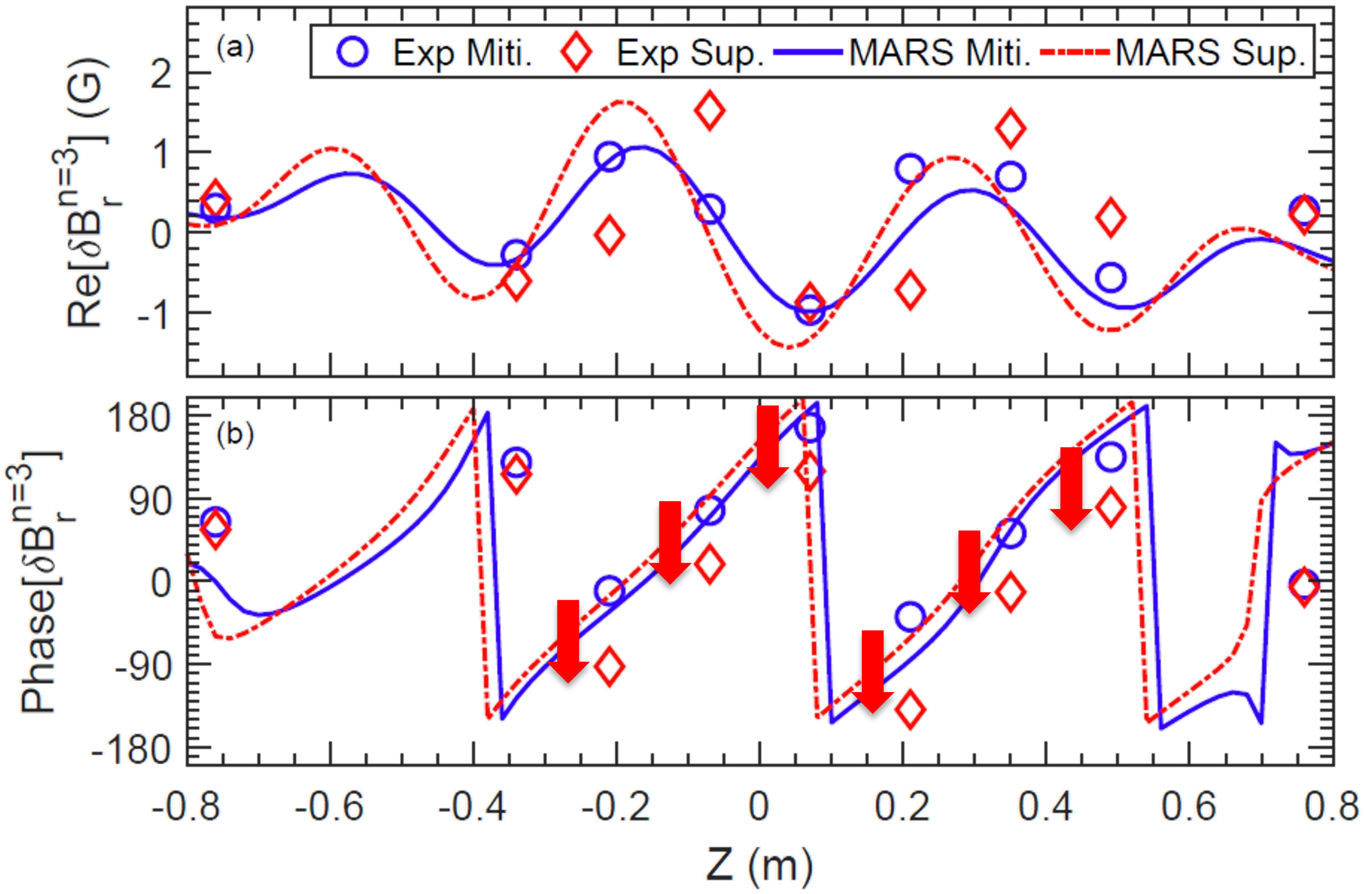
- **ELM mitigation**
  - √ shielding: toroidal rotation
- **ELM suppression**
  - × shielding: toroidal rotation
  - √ penetrating: $\boldsymbol{E}\times\boldsymbol{B}$ rotation

Edge components penetration
↓
ELM suppression



Linear fluid model is insufficient for plasma response during ELM suppression

- **HFS mode structure**
  - ELM mitigation: good agreement in both phase and amplitude
  - ELM suppression: 90-degree phase difference between measurement and simulation

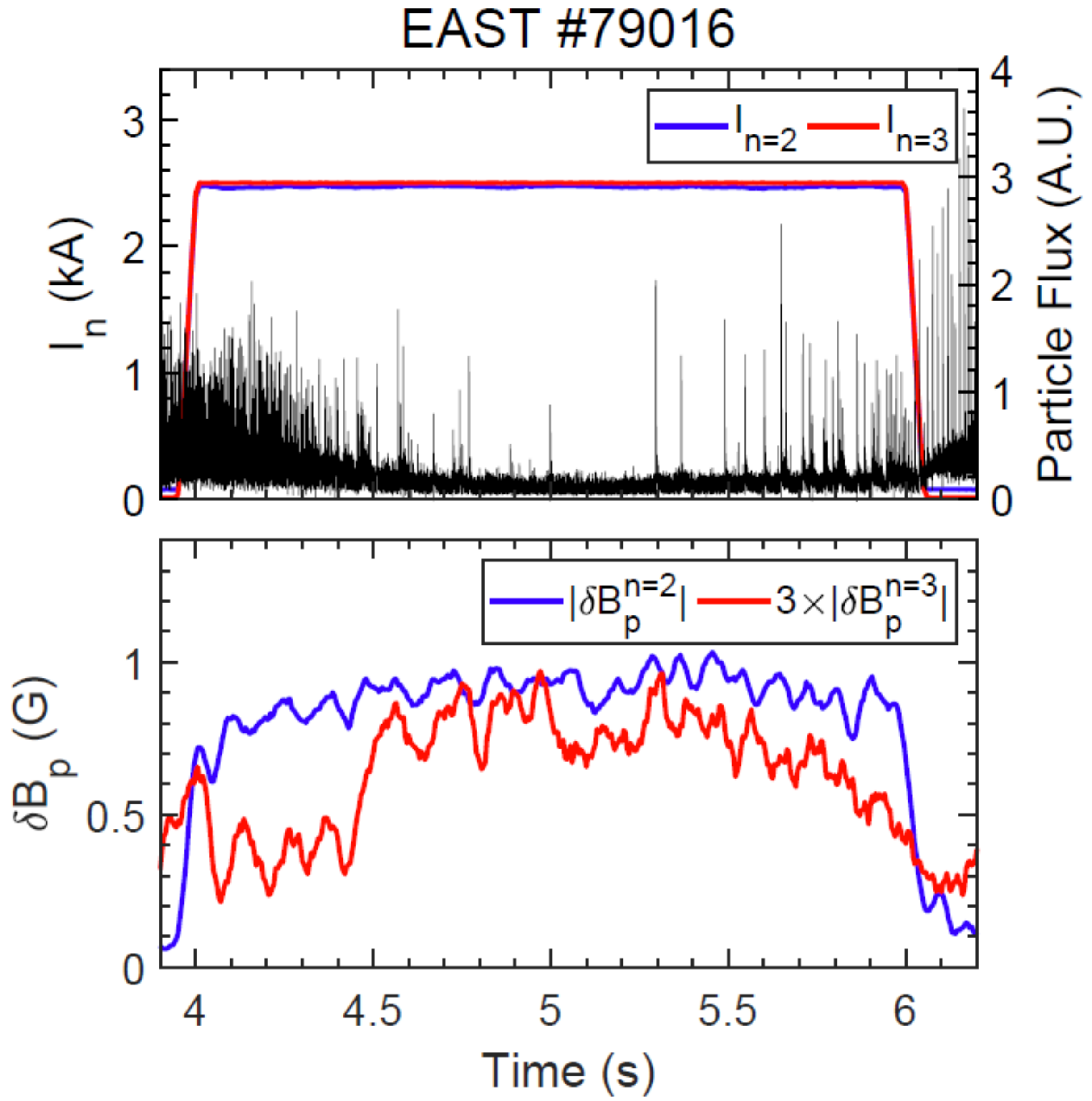


Non-linear plasma response should be taken into consideration for ELM suppression

ELM suppression using mixed-n RMP on EAST

- **ELM mitigation -> suppression**
  - n=2 linear plasma response
  - n=3 non-linear jump

- **Similar to results on DIII-D**
  - n=3 components play the key role in ELM suppression



Summary

- **Mixed-n RMP lower the threshold of ELM suppression**
  - Maximum current reduced by 13%
  - Energy consumption reduced by 54%
  - Mixed-n RMP offers a better way to control ELMs

- **Demonstrate that non-linear plasma response and edge components penetration is the key point to suppress ELMs**
  - n=3 jump of plasma response → n=3 mode structure change & edge components penetrate→ ELM suppression
  - n=2 linear response → help n=3 components penetrate → lower the threshold

05

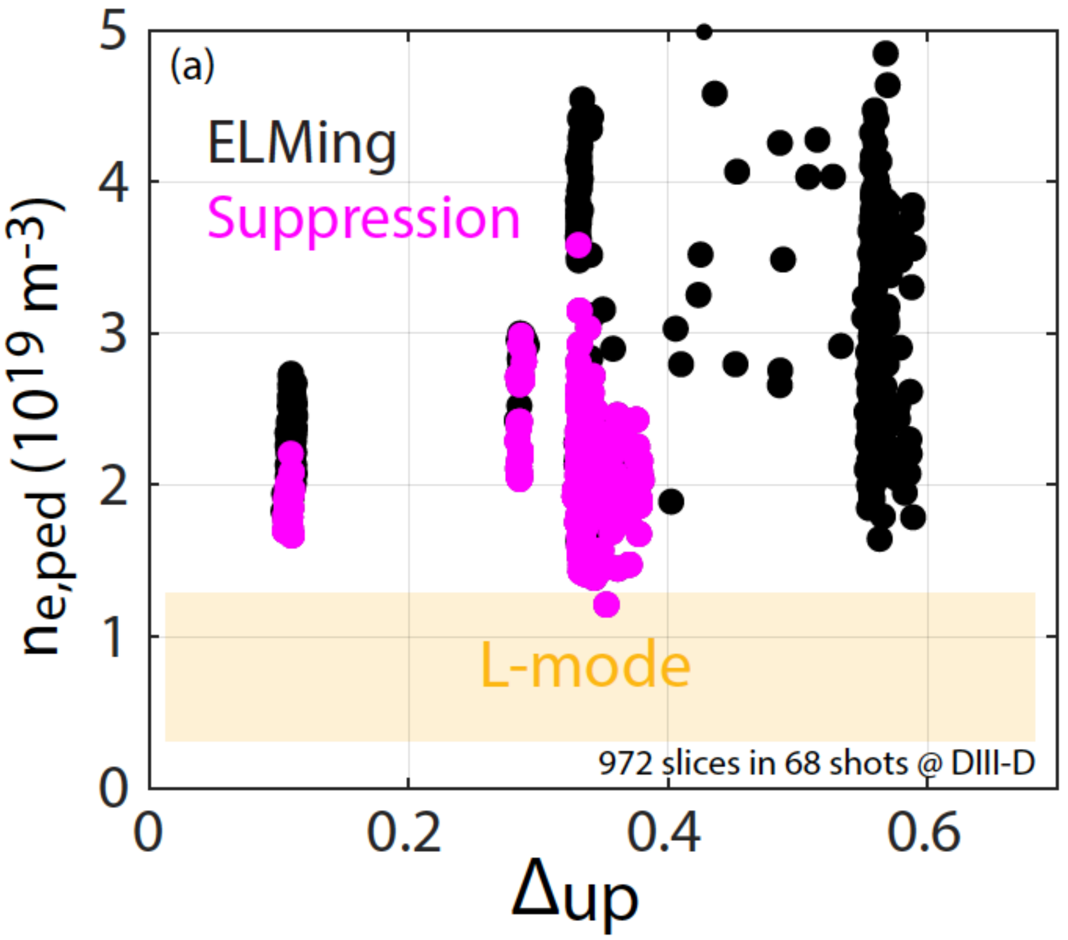
Influence of triangularity on the plasma response to RMPs

- Plasma response provide explanation for inability to access ELM suppression at high triangularity in DIII-D
- Research methods: Plasma response simulation vs experimental observation based on varying triangularity equilibria
- The resonant coupling is correlated with ELM suppression access in DIII-D
- Resonance decreases with triangularity in both EAST and AUG
- Validation between experiments and simulation support the reliability in plasma response simulation
- The multi-mode plasma response provides another way to understand ELM control effects
- Conclusion & Implication

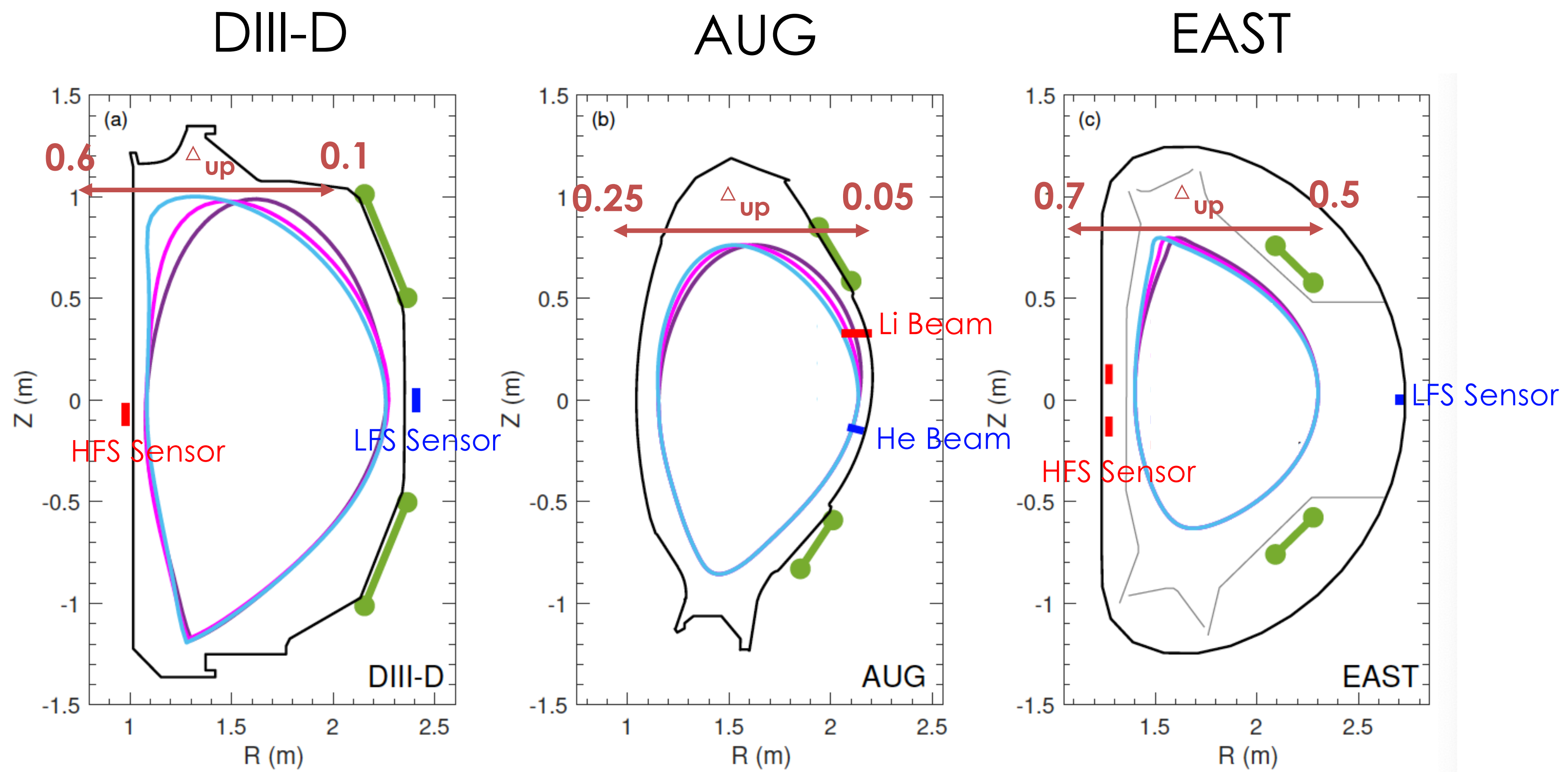
Plasma response provide explanation for inability to access ELM suppression at high triangularity in DIII-D

- **ELM is easier to be suppressed at low or moderate triangularity in DIII-D**

- **Possible hypotheses**
  - Resonant coupling is reduced at high triangularity as compared to that at low triangularity



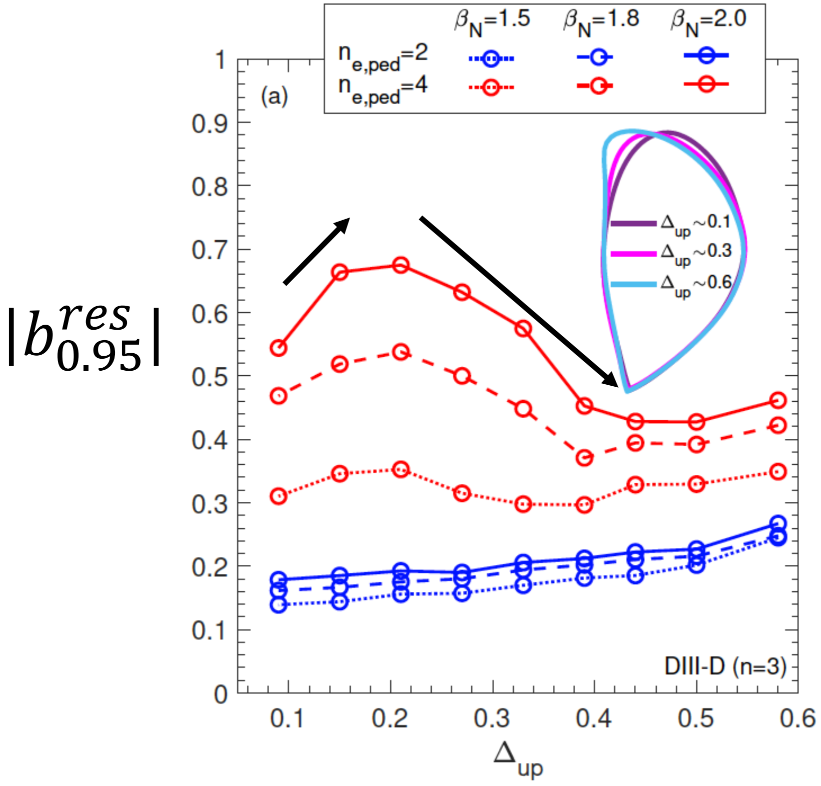
Research methods: Plasma response simulation vs experimental observation based on varying triangularity equilibria

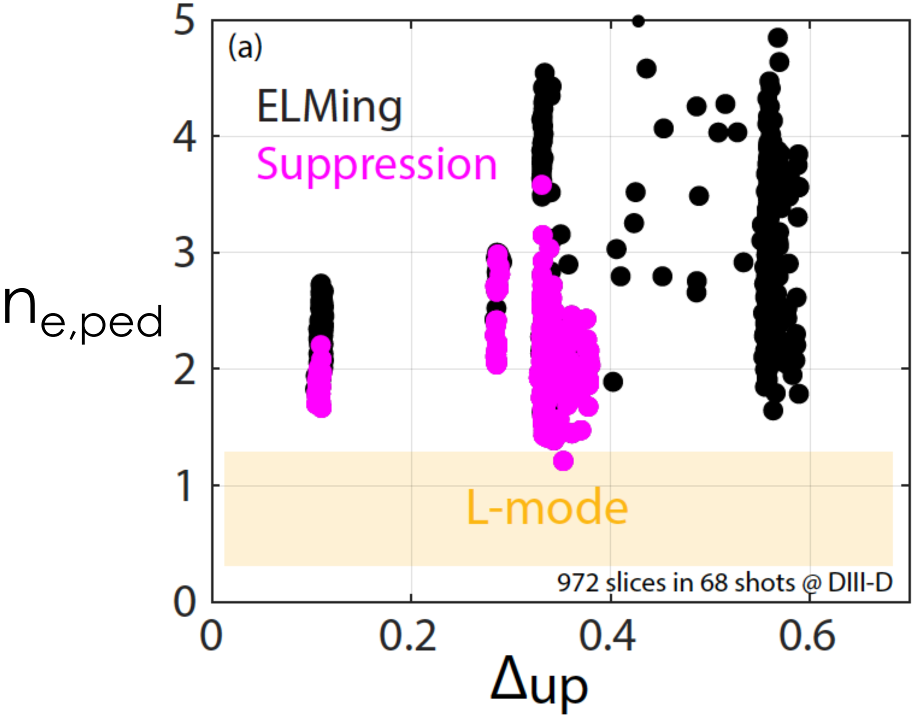


Computed resonant coupling and experimental data will be compared for each device

The resonant coupling is correlated with ELM suppression access in DIII-D

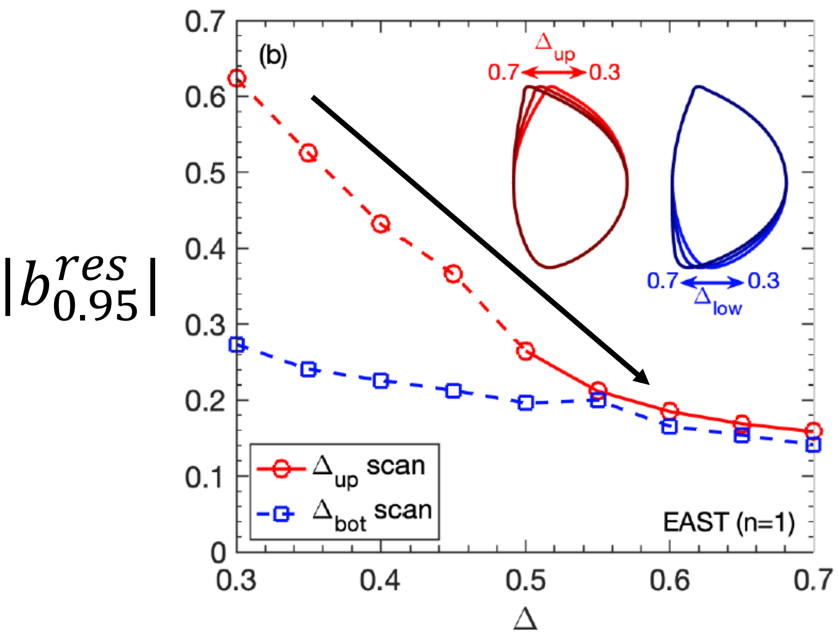
- ELMs are easier to be suppressed at low or moderate triangularity
- Linear model cannot explain loss of suppression



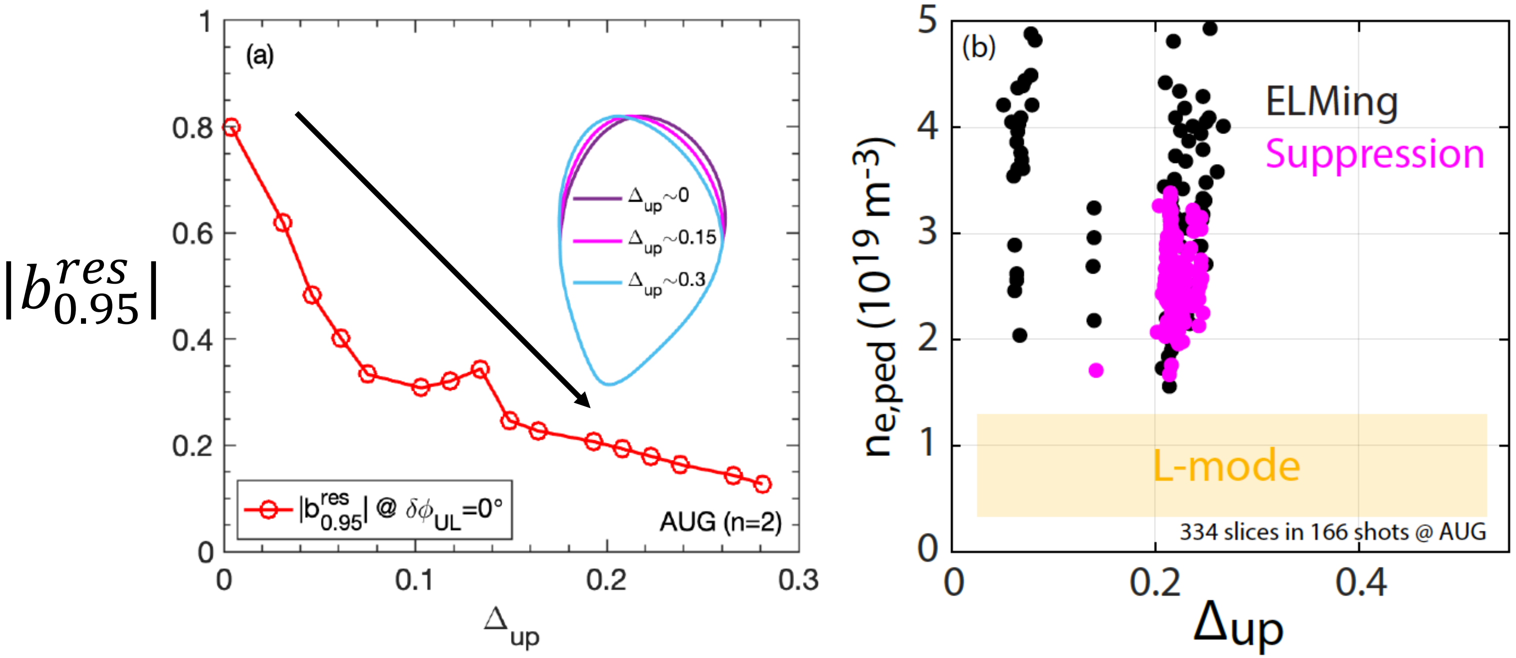


Resonance decreases with triangularity in both EAST and AUG

EAST



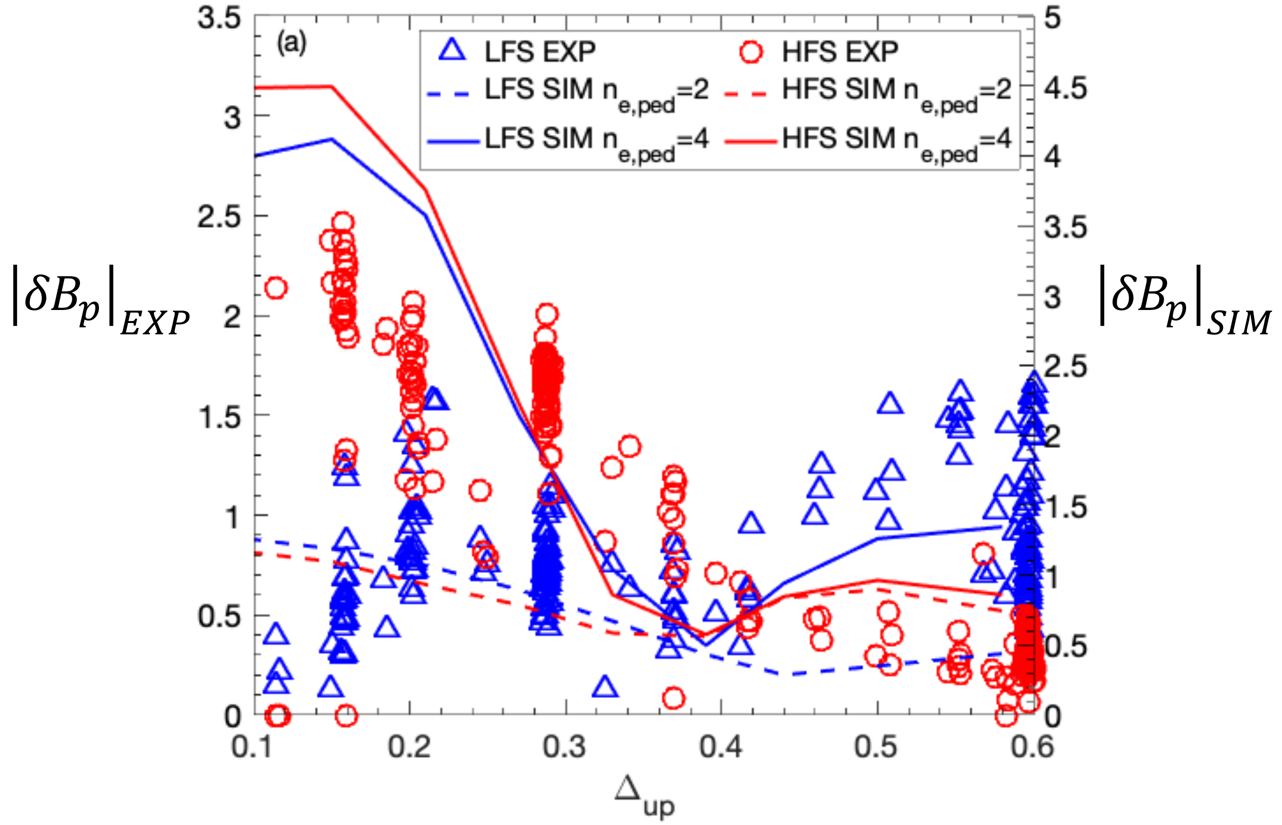
AUG

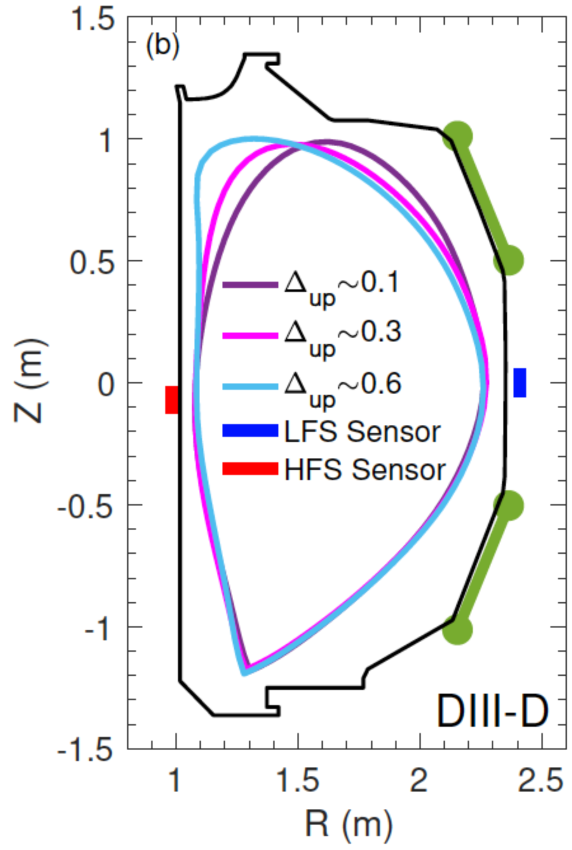


The experimental trend in AUG is opposite
Further 3D stability analysis is required

Validation between experiments and simulation support the reliability in plasma response simulation

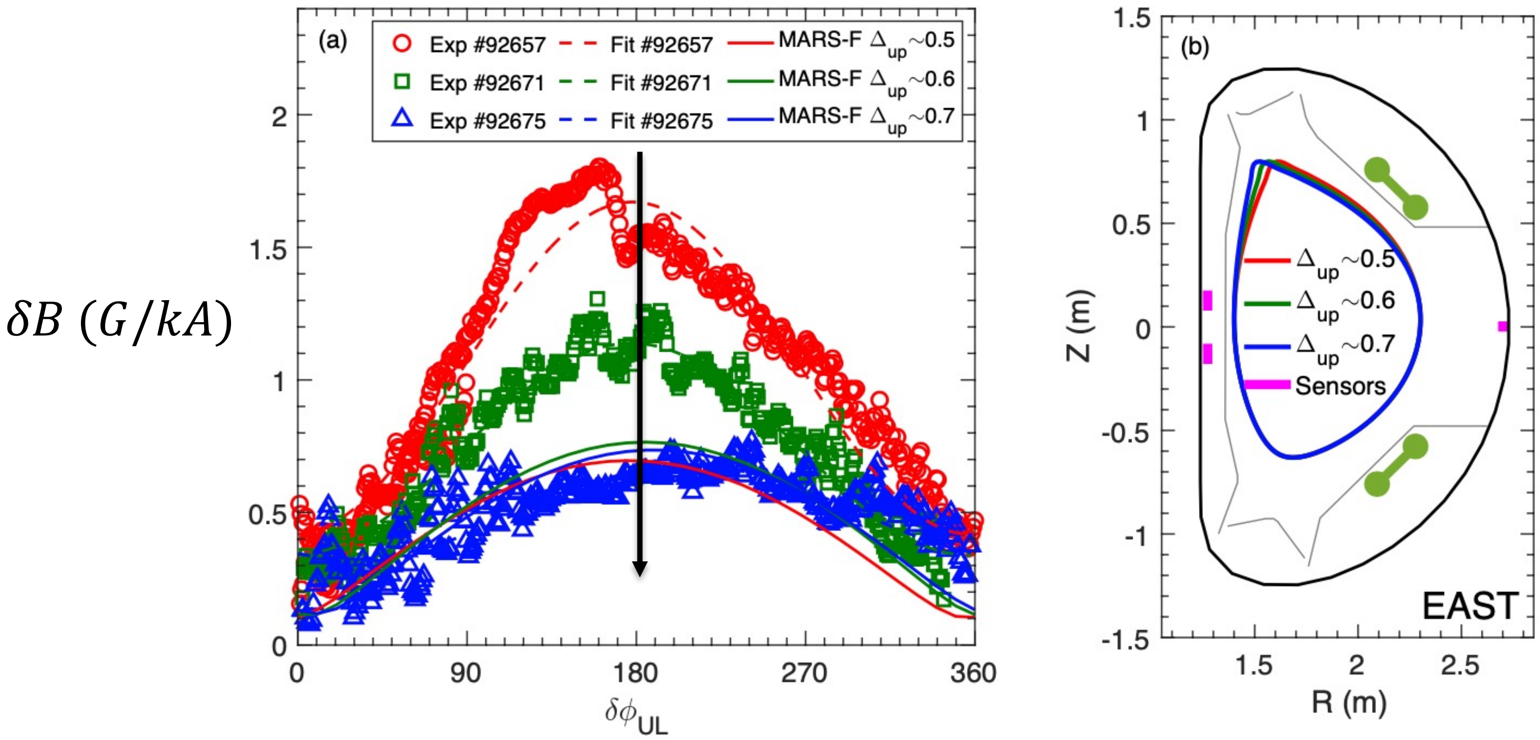
- **The magnetic plasma response shows good agreement in trends between experiment and simulation in DIII-D**





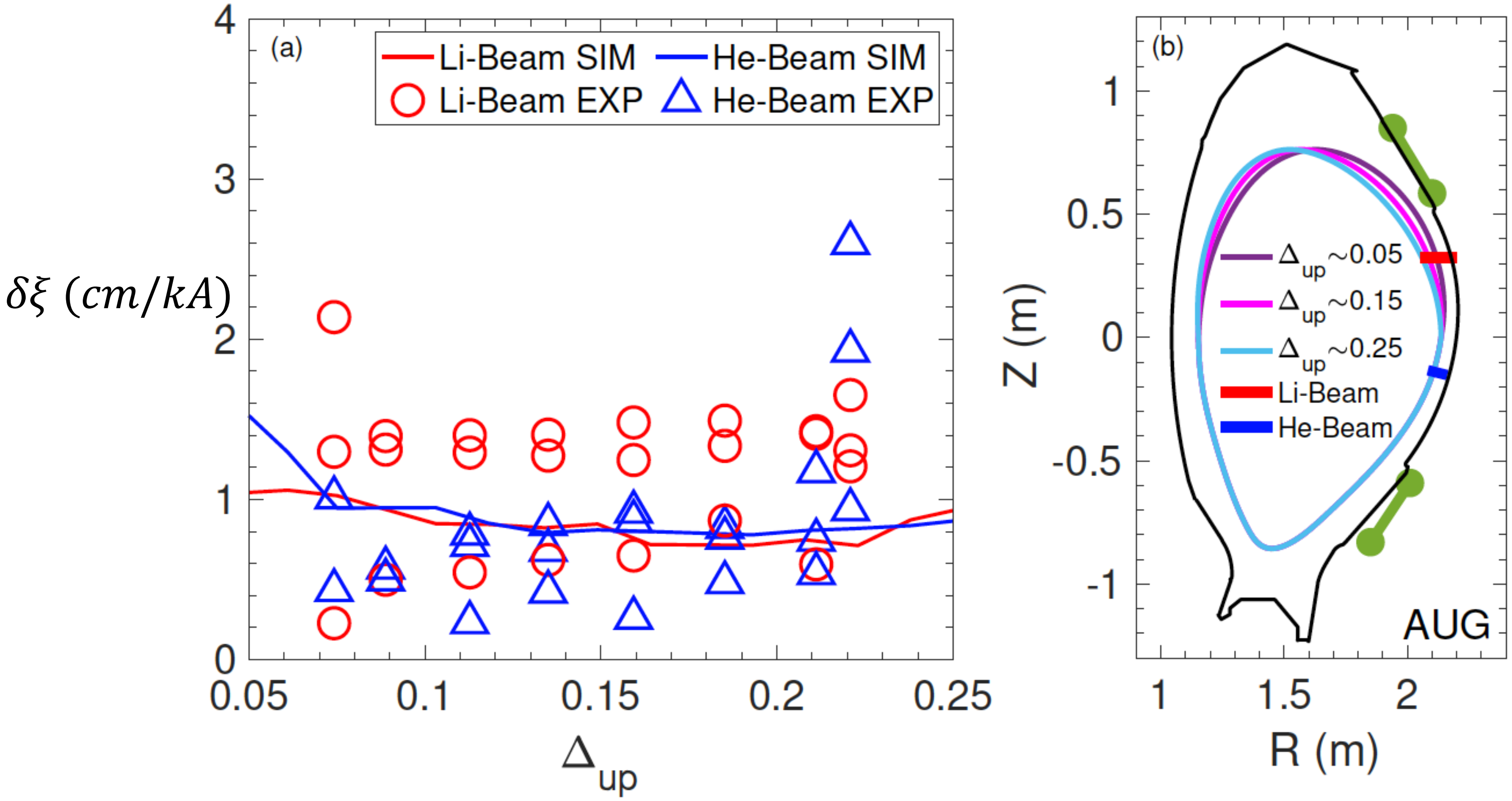
The inboard magnetic plasma response measured in EAST deceases with triangularity

- The simulated and measured plasma response shows good agreement in phasing dependence
- Amplitude is not captured



The outboard displacement shows good agreement between experiment and simulation in AUG

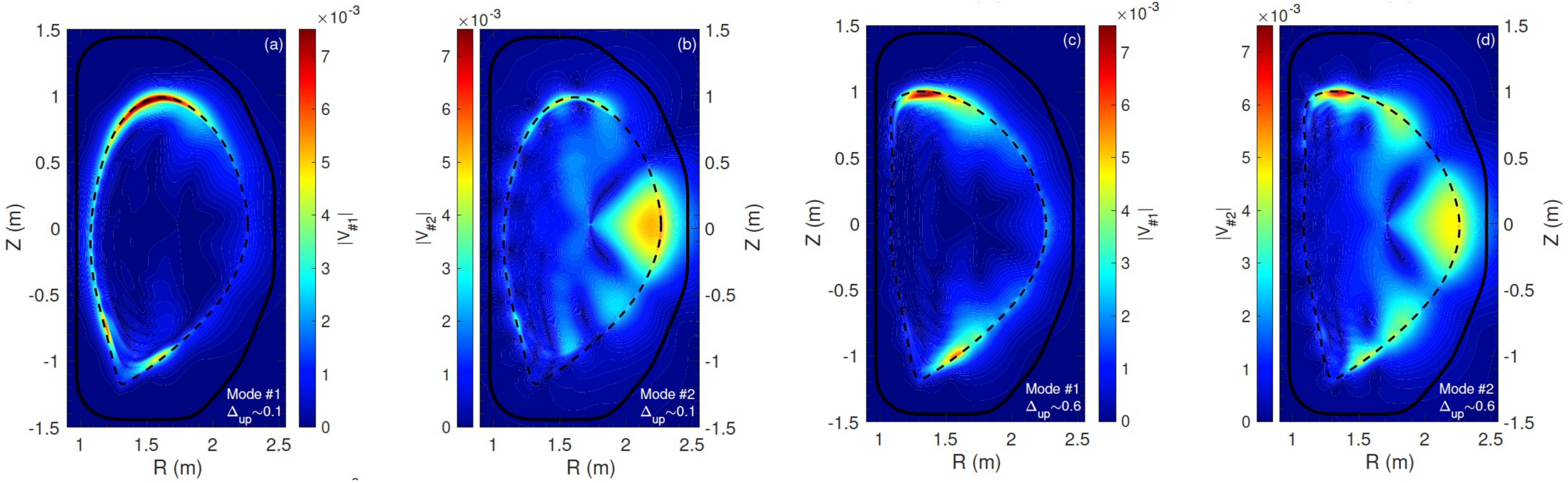
- The LFS displacement is insensitive to triangularity
- No sensor on HFS



SVD structure of plasma response is not sensitive to triangularity but amplitude is

- Multi-mode plasma response extracted using SVD

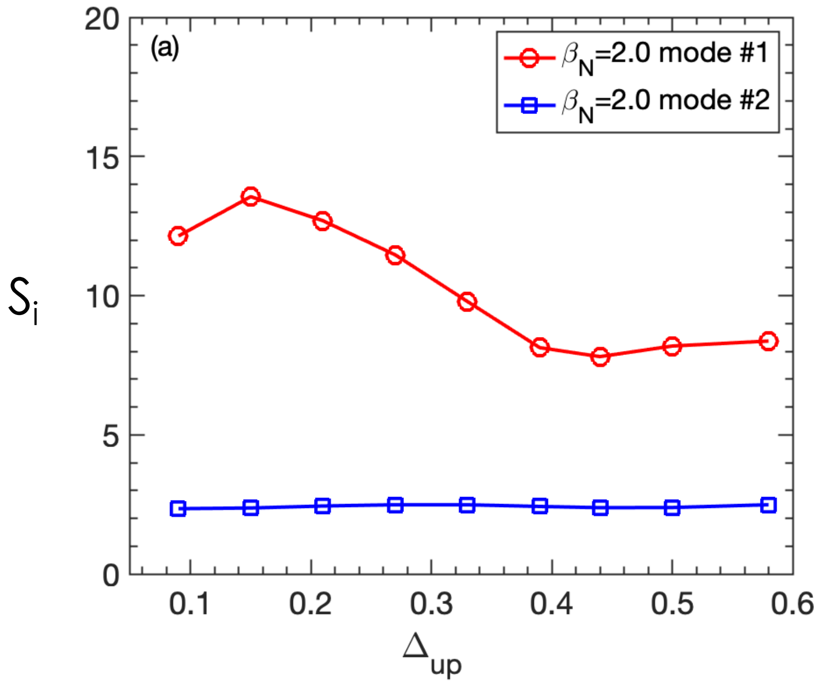
Δ_{top}=0.1 (DIII-D n=3) **Δ_{top}=0.6 (DIII-D n=3)**



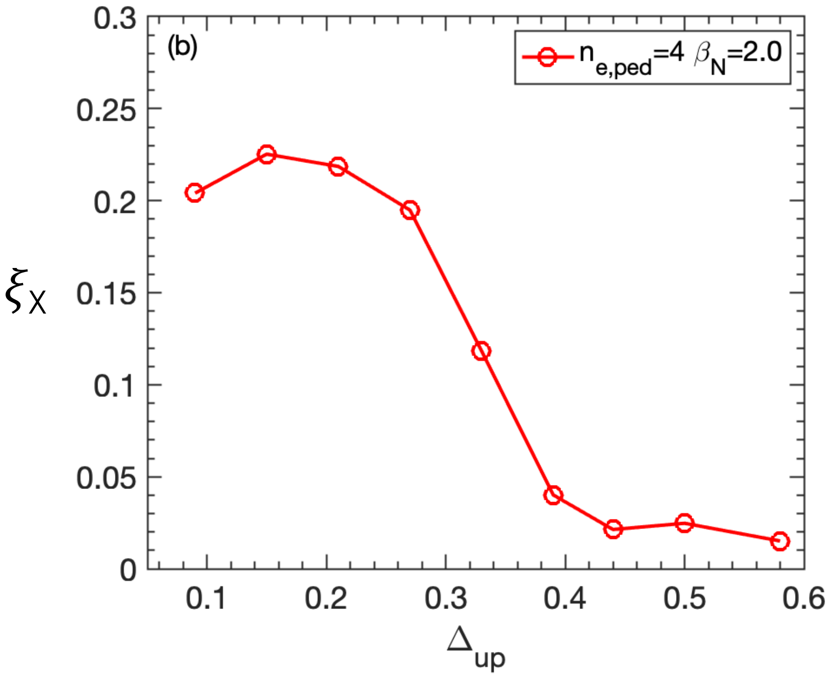
The multi-mode plasma response provides another way to understand ELM control effects

- The dominate mode reveals similar trends with X-point displacement and edge resonance

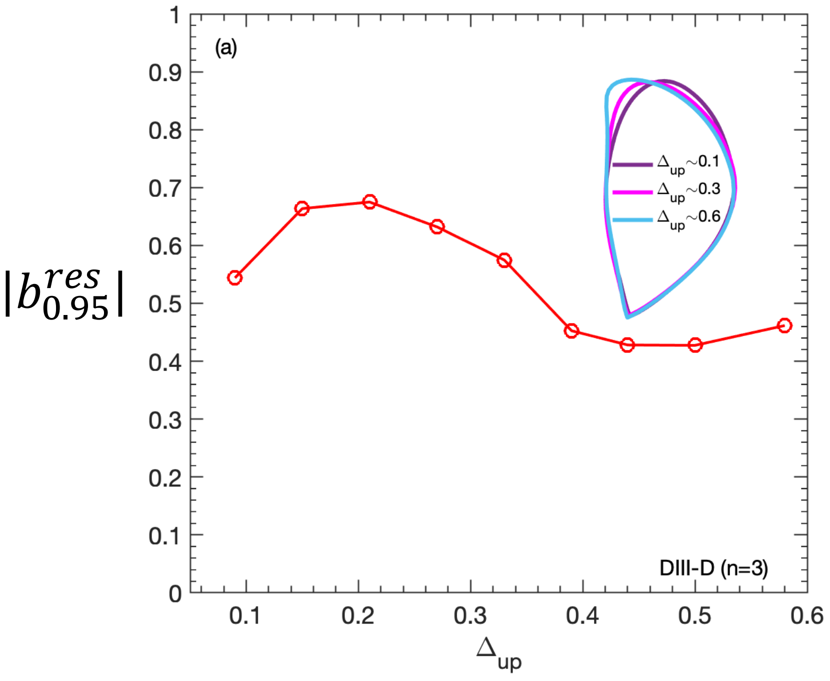
Multi-mode response



X-point displacement



Edge resonance

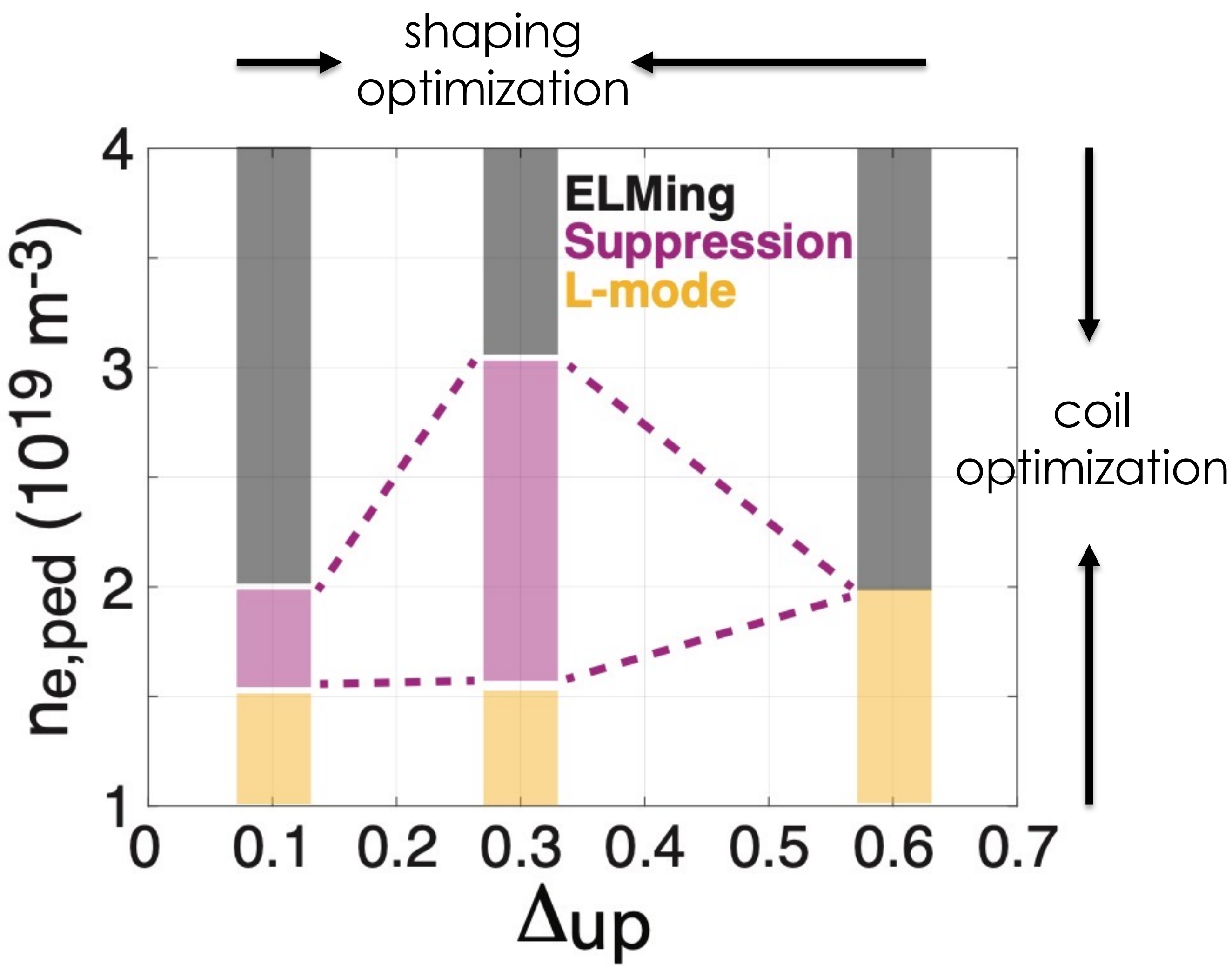


Summary

- The plasma response decreases with triangularity
  -> shaping optimization should be taken into consideration for ELM control

- The plasma response is strongly reduced at high triangularity
  -> More current and further coil optimization is required for better control ELMs at high triangularity

- Linear model only provide partial understanding for ELM control
  -> nonlinear model is needed



06

Influence of up-down asymmetry on the plasma response to RMPs

The plasma shape significantly affect RMP-ELM control

KSTAR experiments show ELMs suppressed only at LSN

Plasma response help to understand the dR_{sep} effects on ELM control in KSTAR

EAST experiment allows validation of plasma response

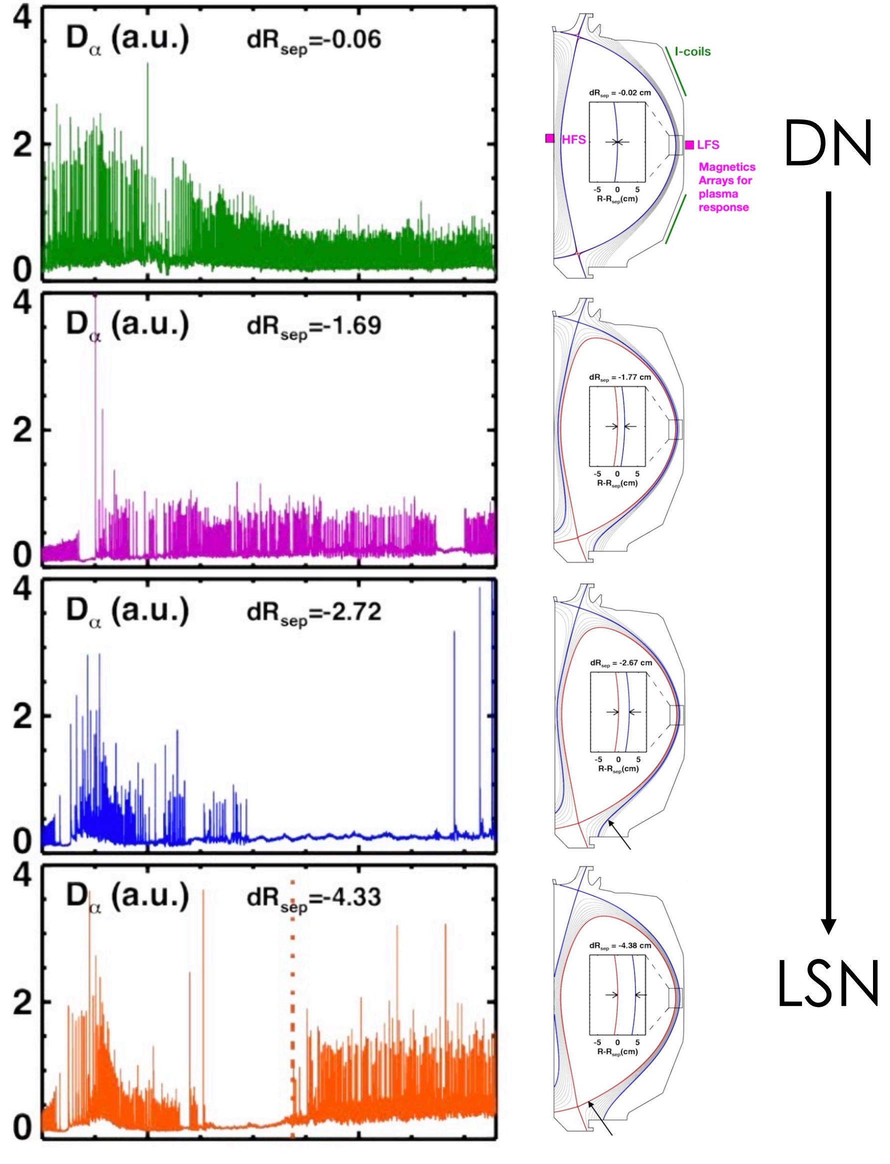
Validation of plasma response modeling shows good agreement between experiment and simulation

2D pattern of edge resonance shows it lower at DN and shifted with dR_{sep}

Shape optimization helps to maximize access to RMP-ELM suppression in EAST

Background & Motivation —— The plasma shape significantly affect RMP-ELM control

- **Future tokamak requires effective control of transient heat loads caused by edge localized mode (ELM)**
  - Resonant magnetic perturbation (RMP) is one robust technique to control ELMs
- **Recent experiments found RMP-ELM control significantly affected by the plasma shape[1-3]**
  - DIII-D: ELMs suppressed at LSN, but not DN
  - KSTAR: ELMs suppressed at LSN, but not DN
  - EAST: ELM suppressed at LSN or USN, but not DN



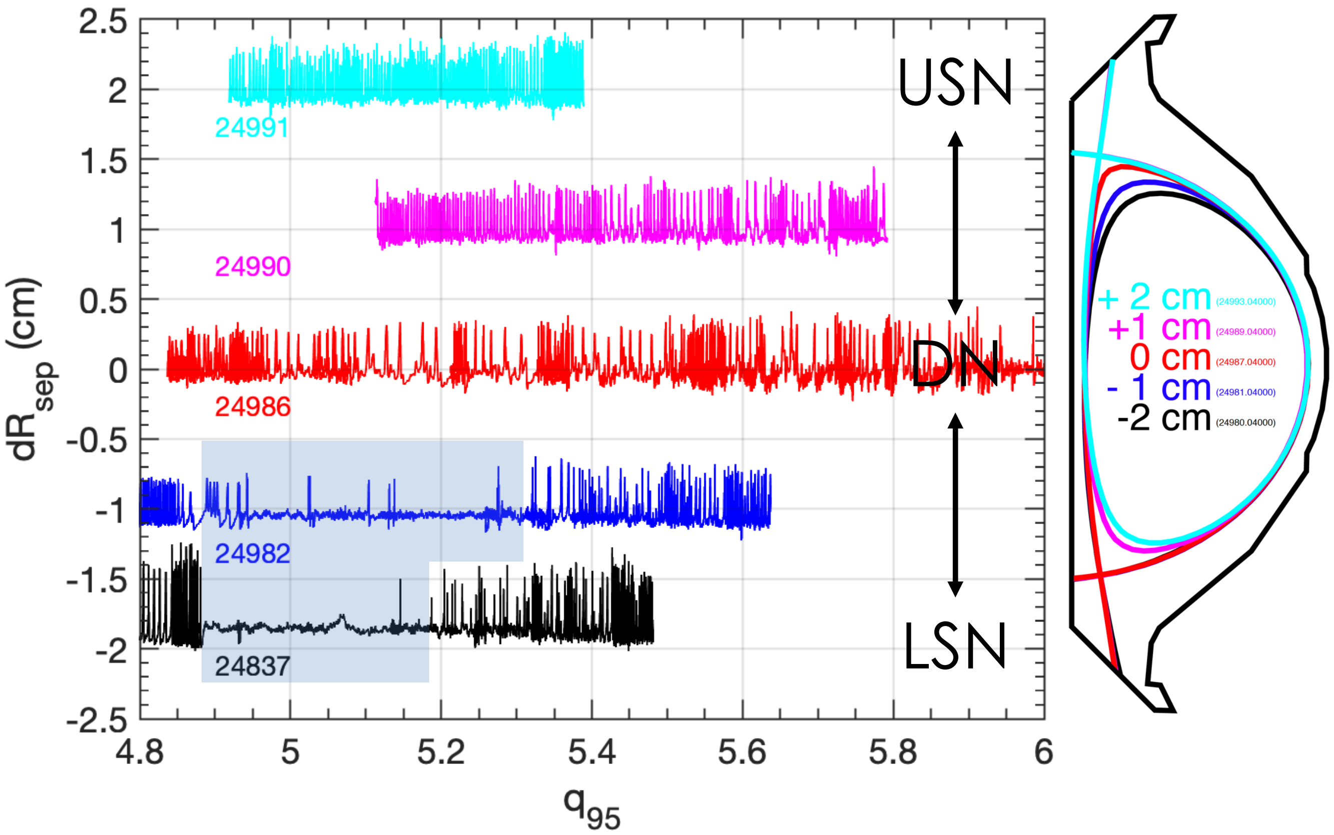
M. Shafer *et al*, IAEA (2021)

[1] W. Suttrop *et al*, PPCF 59 014049 (2017)
[2] C. Paz-Soldan *et al*, NF 59 056012 (2019)
[3] S. Gu *et al*, NF 62 076031 (2022)

DIII-D NATIONAL FUSION FACILITY KSTAR ASIPP

KSTAR experiments show ELMs suppressed only at LSN

- **Summary of experimental observation in KSTAR 2020**
  - ELMs suppressed only at LSN
  - ELMs suppressed at q_{95}~5 (4.9~5.3)
  - No suppression observed at DN

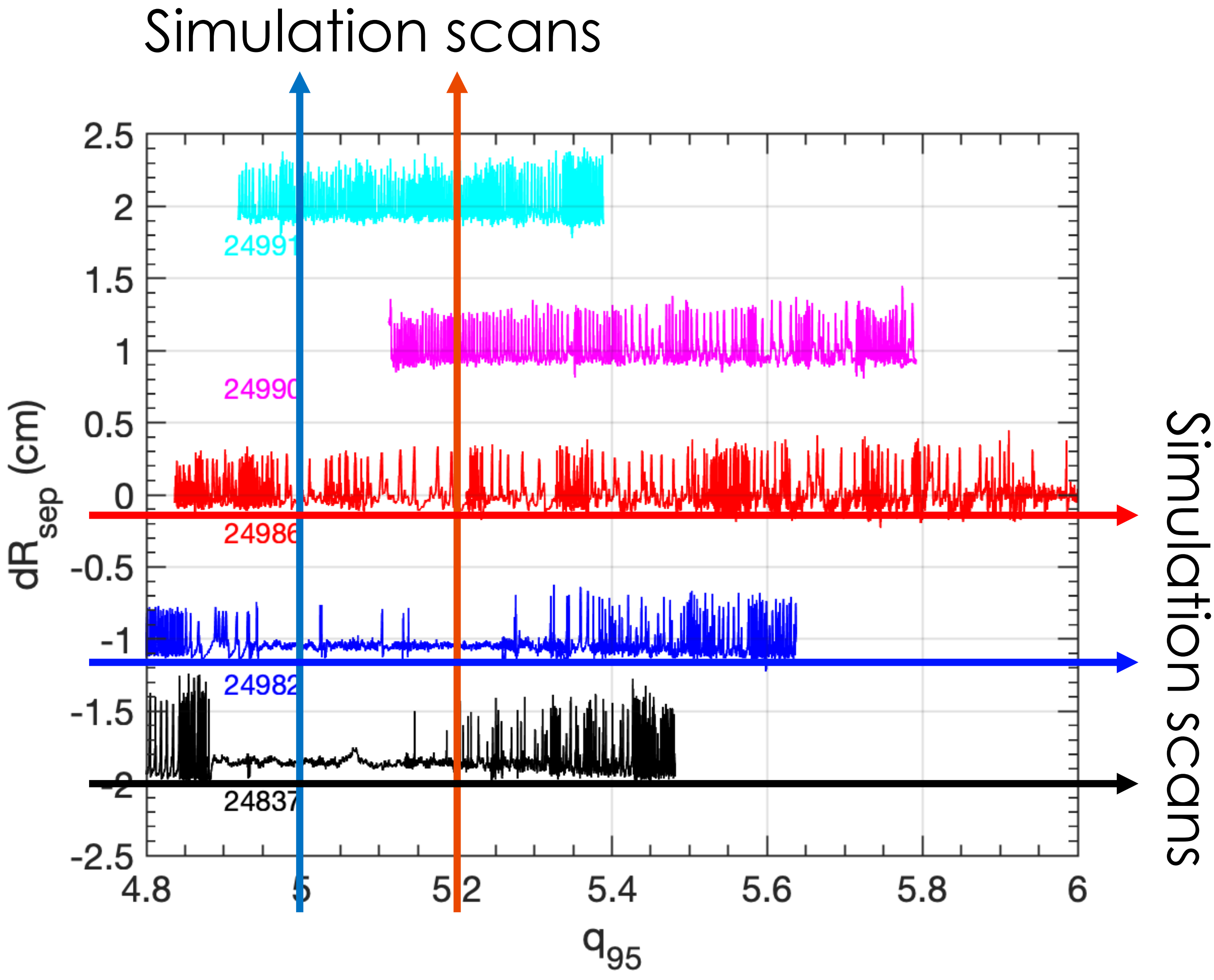


Note: D_α signal re-baselined by dR_{sep} value

KSTAR

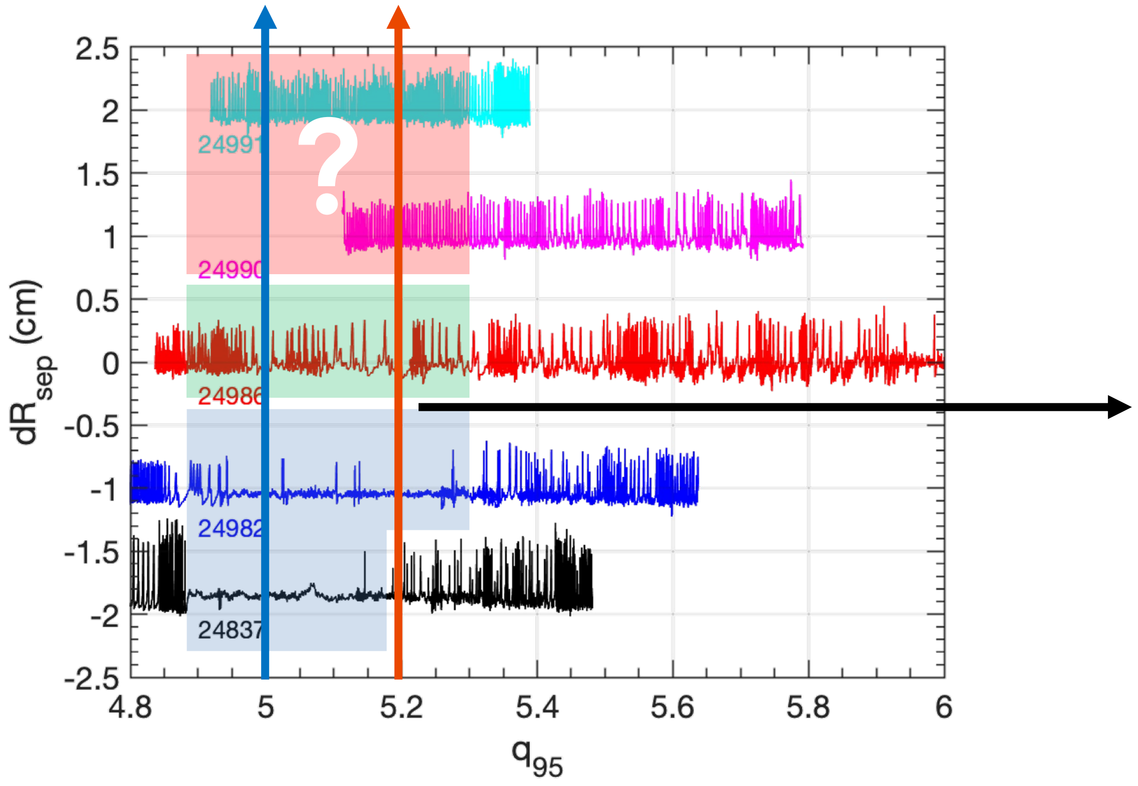
Numerical modeling approach —— dR_{sep} and q_{95} scan in plasma response simulation using MARS-F code

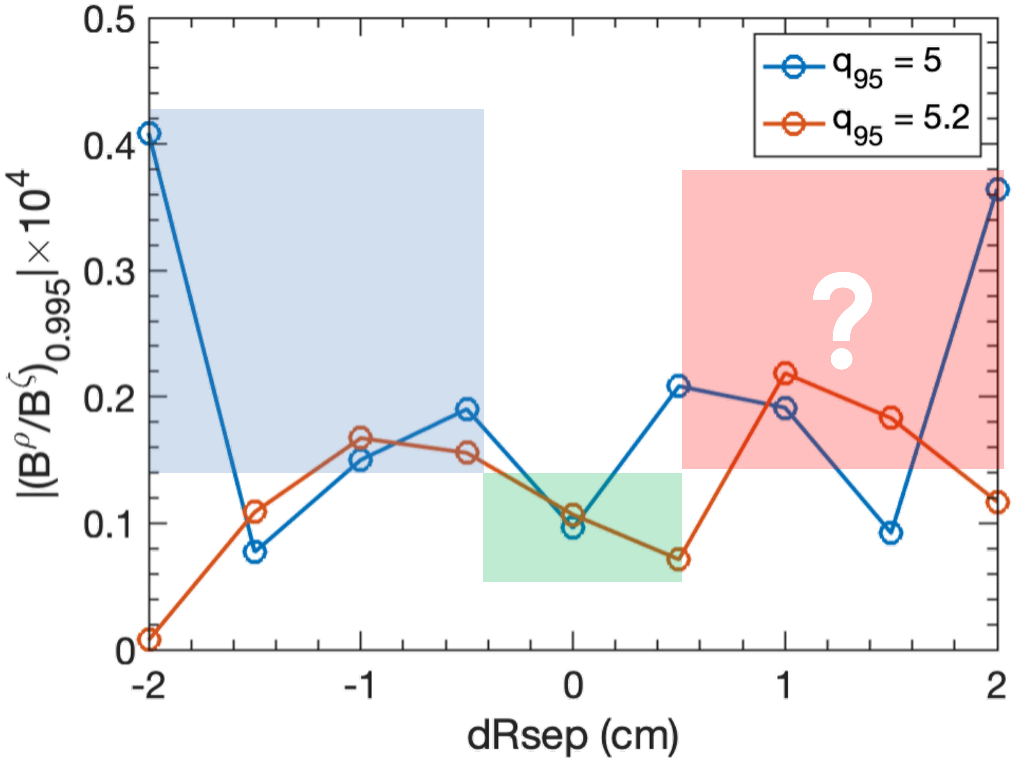
- **MARS-F simulation**
  - Single-fluid linear resistive MHD
- **Plasma response examined in 2 dimensions (dR_{sep} & q_{95})**
- **Focus on**
  - q_{95} ~ 5.0, 5.2
  - dR_{sep} ~ 0, -1, -2 cm



Plasma response help to understand the dR_{sep} effects on ELM control in KSTAR

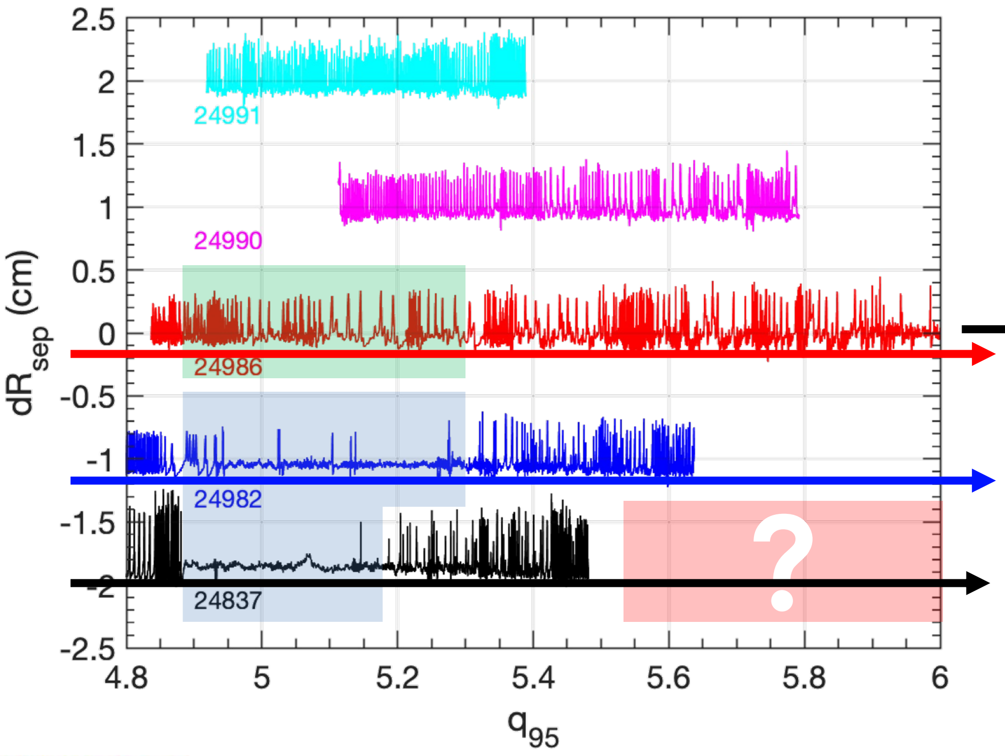
- **The edge resonance is greater at LSN compared to that at DN**
- **Cannot explain the inability of ELM suppression at USN**
  - Divertor condition – L-H threshold not symmetric

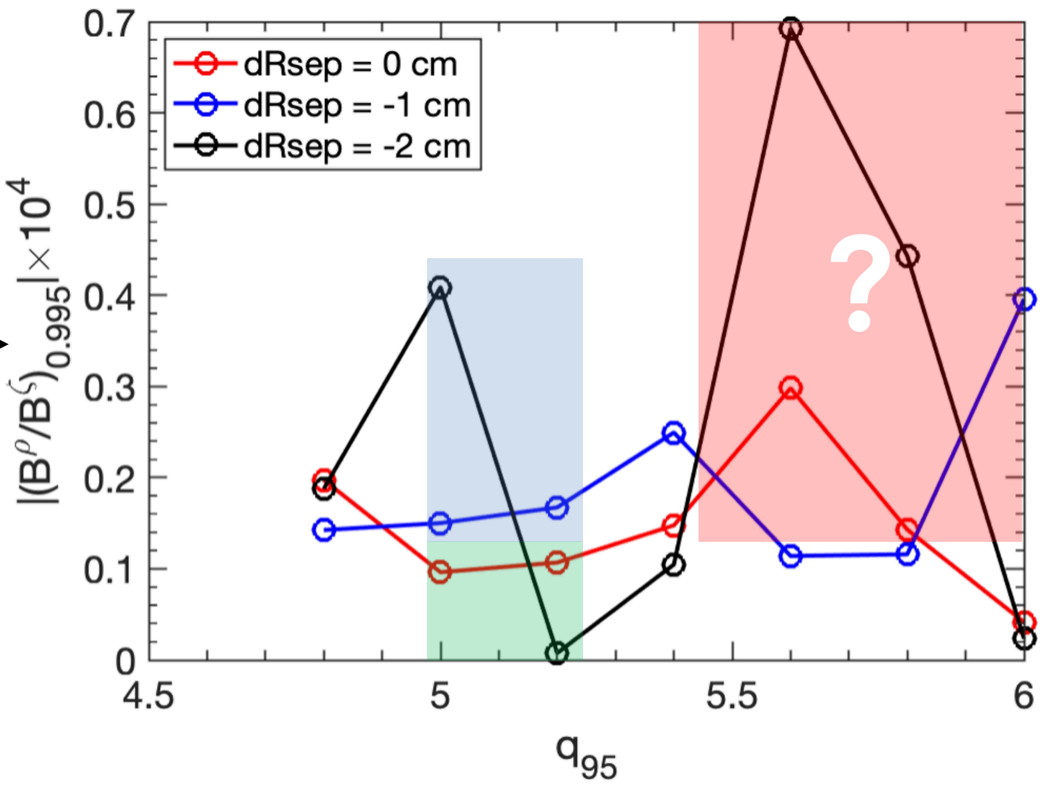




Plasma response help to understand the dR_{sep} effects on ELM control in KSTAR

- The edge resonance is greater at LSN compared to that at DN
- Plasma response simulation indicate a second window

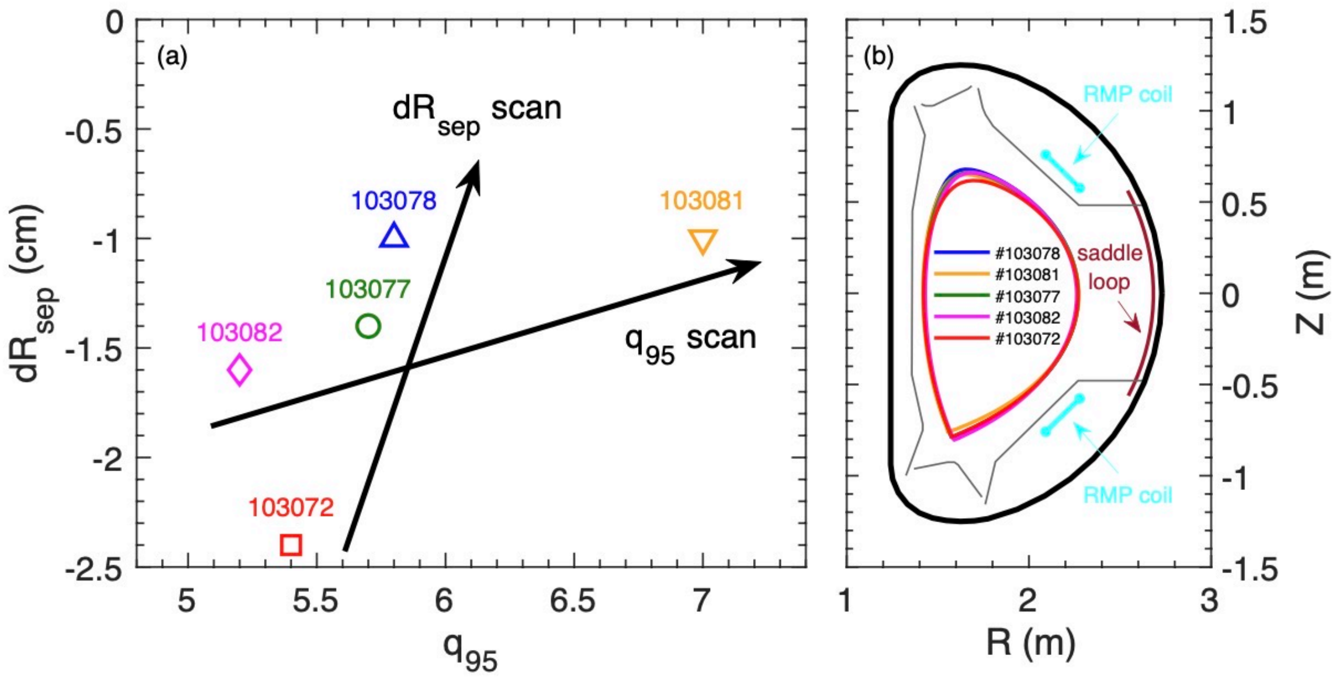




KSTAR

EAST experiment allows validation of plasma response

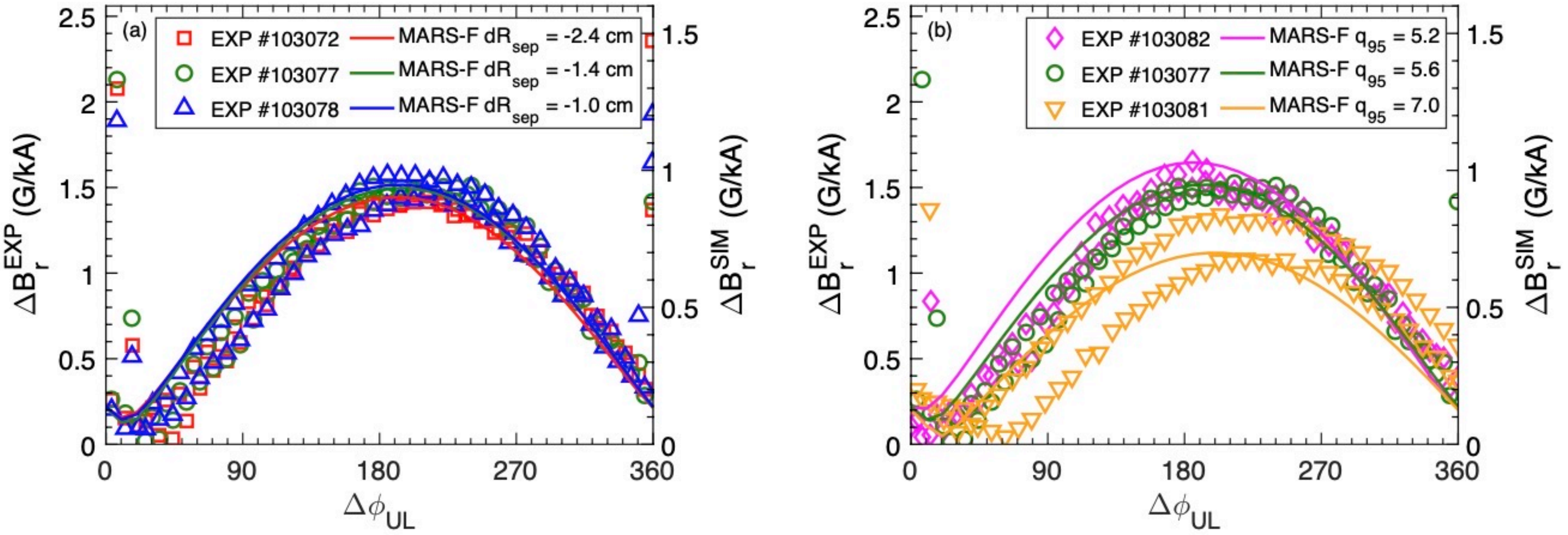
- Magnetic sensors on EAST provide good measurement of plasma response
- n=1 phasing scan in experiment allows validation of plasma response at different dR_{sep} and q_{95} values



ASIPP

Validation of plasma response modeling shows good agreement between experiment and simulation

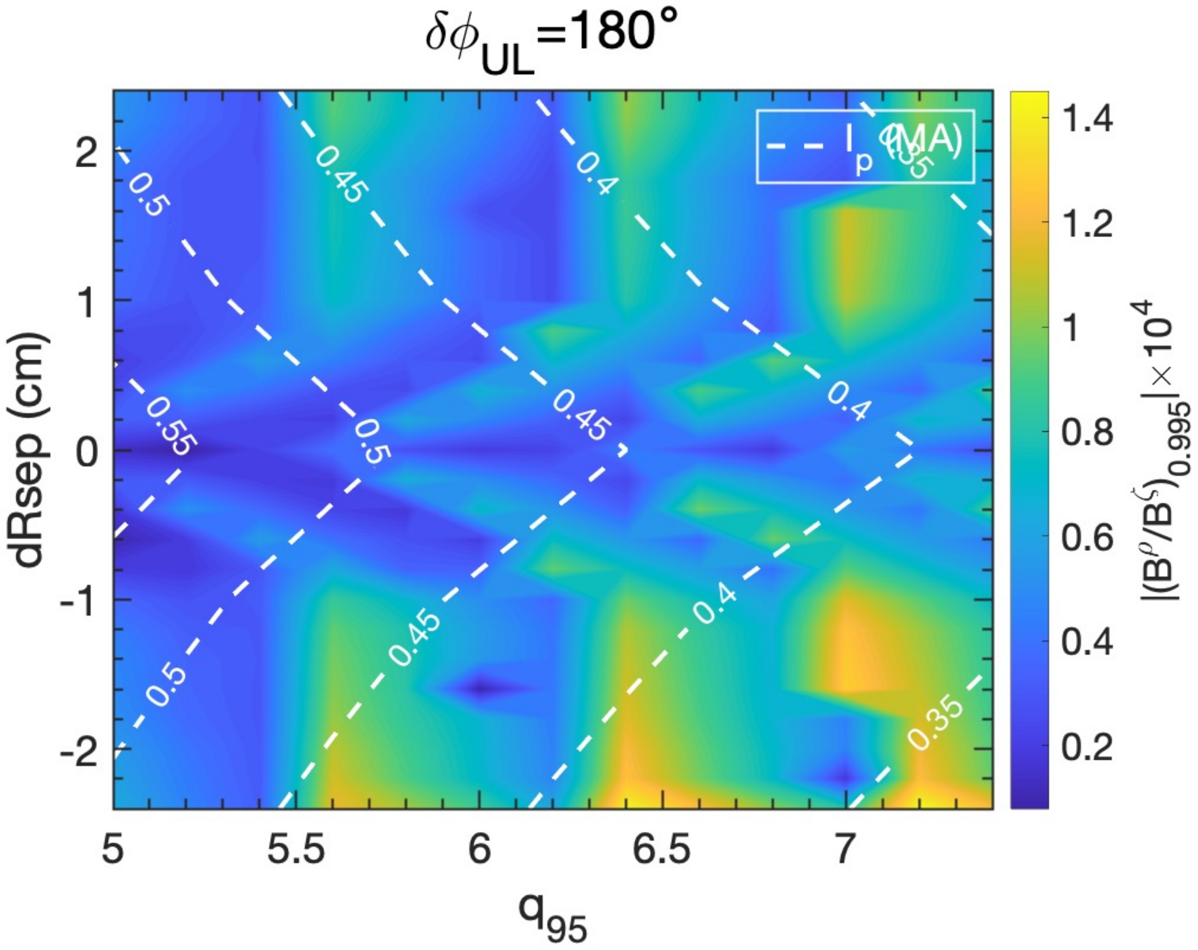
- **Good agreement between experiment and simulation**
  - Phasing dependence well represented
  - Relative amplitude matches



ASIPP

2D pattern of edge resonance shows it lower at DN and shifted with dR_{sep}

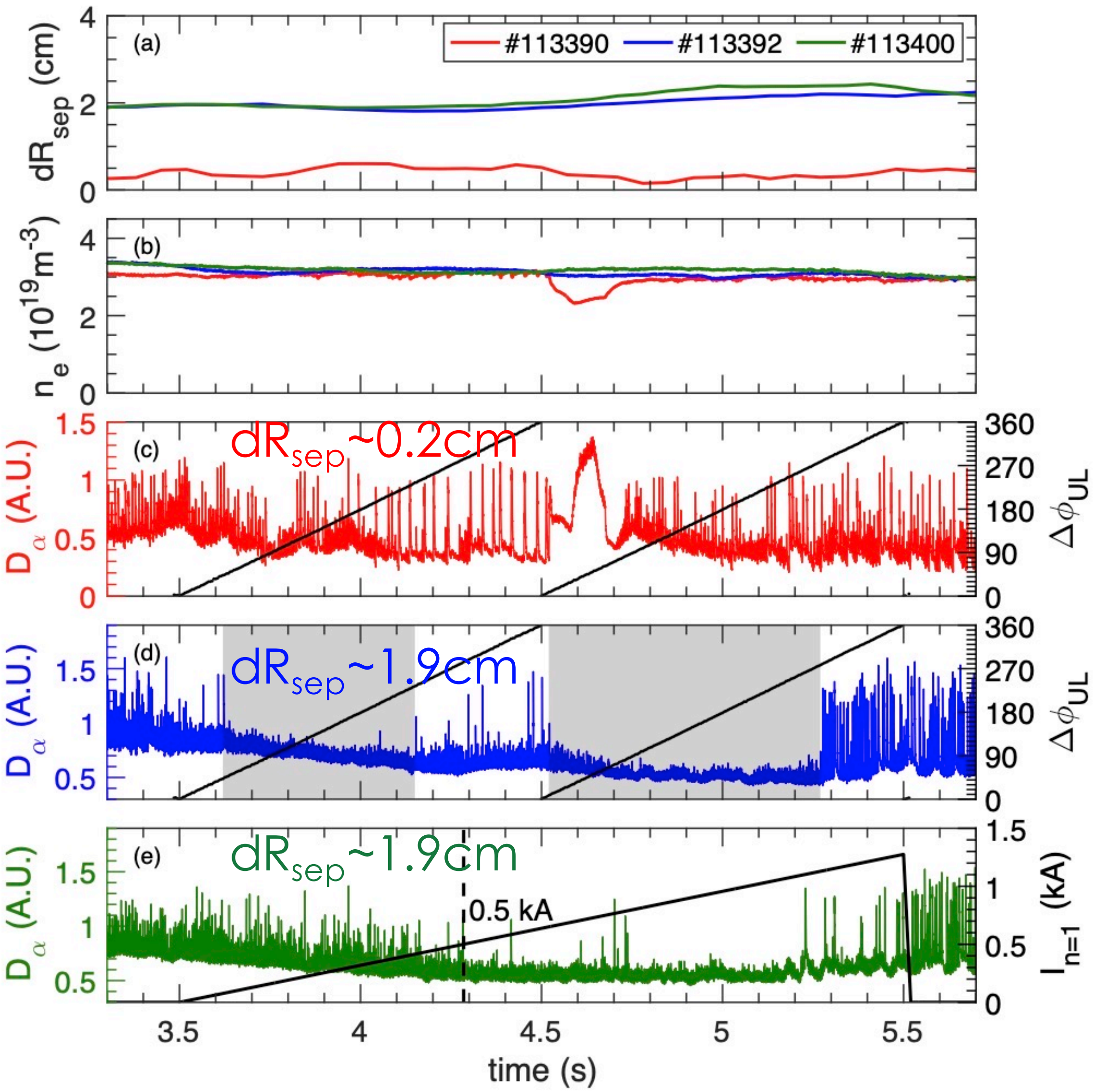
- **Resonance lower at DN**
  - More difficult to suppress ELMs at DN
- **Constant Ip line shifted**
  - dR_{sep} optimization requires plasma current control
- **2D pattern shifted**
  - q_{95} window shifted with dR_{sep}



ASIPP

Shape optimization helps to maximize access to RMP-ELM suppression in EAST

- **Improve RMP-ELM control through plasma shape optimization**
- **Expand phasing window of ELM suppression to 270°**
- **Reduce ELM suppression threshold to I_{thres}~0.5 kA**
  - Reduced by 75% compared to previous results



ASIPP

Summary

- **The plasma response provides a candidate explanation for the inability to access ELM suppression in DN shapes**
  – Edge resonant coupling is reduced as plasma shape approaches DN

- **Shape optimization helps to maximize access to RMP-ELM suppression**
  – ELM suppression threshold significantly reduced

07

Summary

Summary

- **Measurement and simulation of plasma response on EAST**
  - Develop the 3D plasma response measurement system on EAST
- **Influence of multi-mode plasma response on ELM control**
  - Propose a new method for multi-mode plasma response extraction using SVD
  - Propose a new criterion for controlling ELMs based on multi-mode plasma response
    - Mode with greater resonance or stochasticity at the pedestal top region is associated with ELM control
- **Plasma response to mixed-n RMP and its influence on ELM control**
  - Mixed-n RMP lower the threshold of ELM suppression
  - Demonstrate that non-linear plasma response and edge components penetration is the key point to suppress ELMs
- **Influence of plasma shape on the plasma response to RMPs**
  - The plasma response provides a candidate explanation for the inability to access ELM suppression in high triangularity or DN shapes
  - Shaping optimization should be taken into consideration for ELM control

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08

Questions?