RMP ELM control studies in the EAST tokamak

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ELM control is a significant issue for ITER

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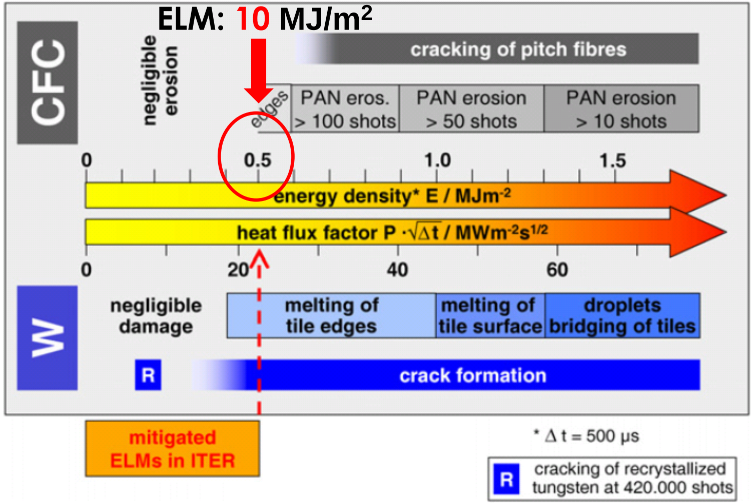
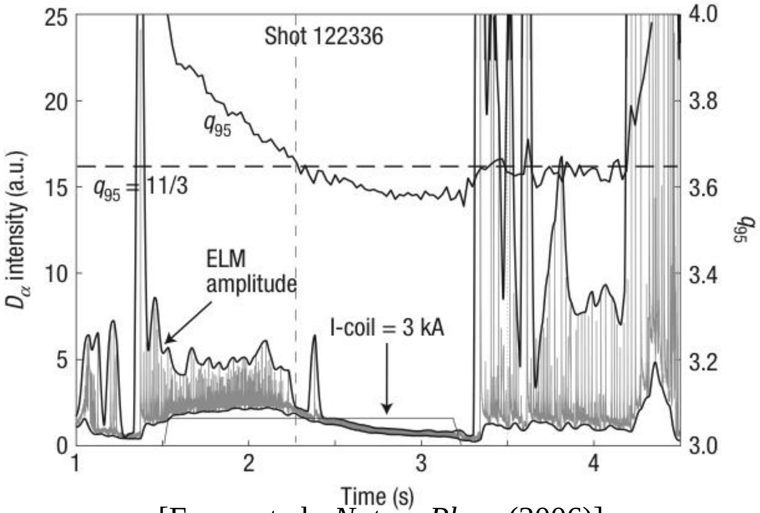


[Hawryluk et al., *NF* (2009)]

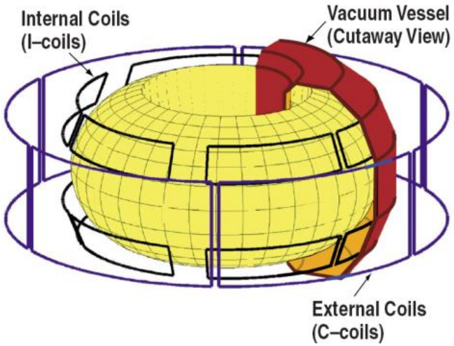


[Evans et al., *Nature Phys.* (2006)]

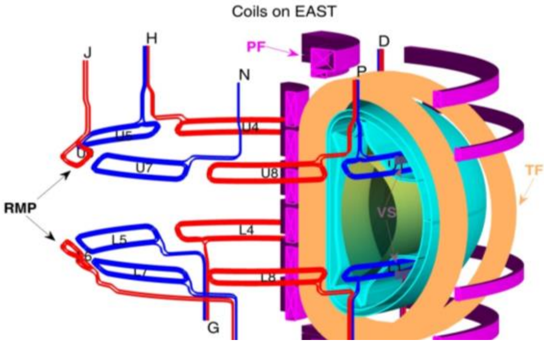
- The expected type I **Edge Localized Mode** (ELM) **size** on ITER should **be reduced** by a factor of **20** (10 → 0.5 MJ/m^2) for present wall and divertor materials.
- Resonant magnetic perturbations (**RMPs)** are one of the simplest and the most effective tools.

edge magnetic topology change ➔ pedestal reduction ➔ stabilize ELM

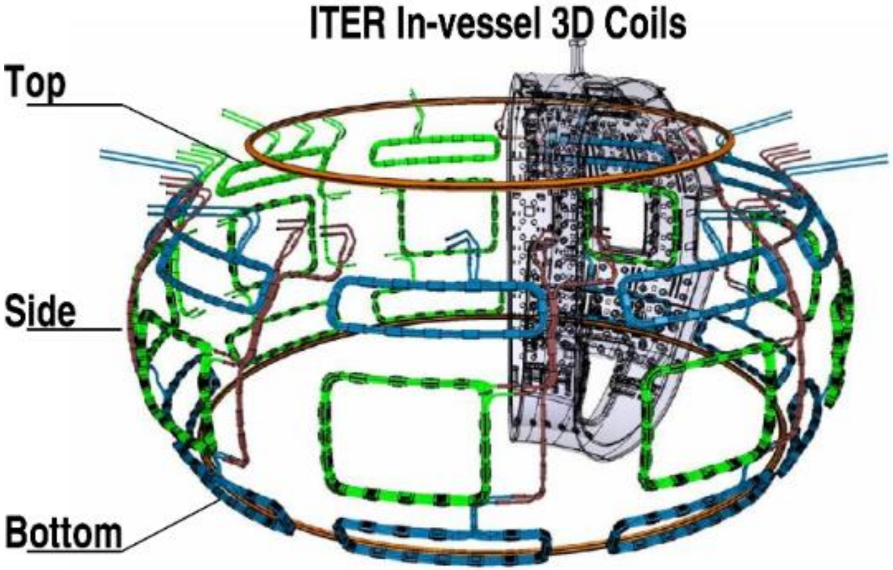
RMP coils in EAST and DIII-D in support of ELM control for ITER



DIII-D, 2x6

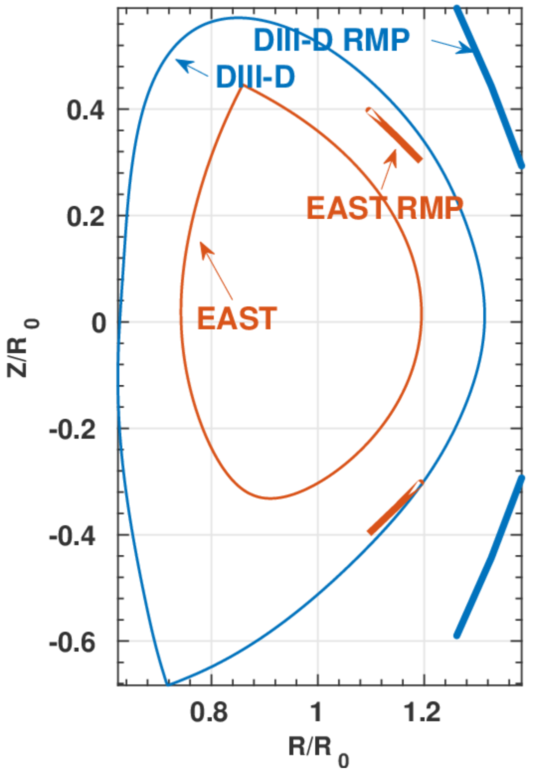


EAST, 2x8



ITER, 3x9

Previous joint experiments in DIII-D and EAST on ELM control using mixed-n RMPs



	DIII-D	EAST
General	Standard type-I ELMy H-mode:	
	q_{95}~3.5-3.8	
	β_N~1.5-2	
	$<N_e>$~$4\text{x}10^{19}\text{m}^{-3}$	
RMP coils	mixed n = 2 & 3	
	2 X 6	2 X 8
shape	LSN	USN
	R/a~2.9 (1.70/0.59)	R/a~4.4 (1.85/0.42)
$\nu_{*e,ped}$	~0.2	~0.5
$\Omega_{\Phi 0}$(krad/s)	>100	<50
Divertor	C	W

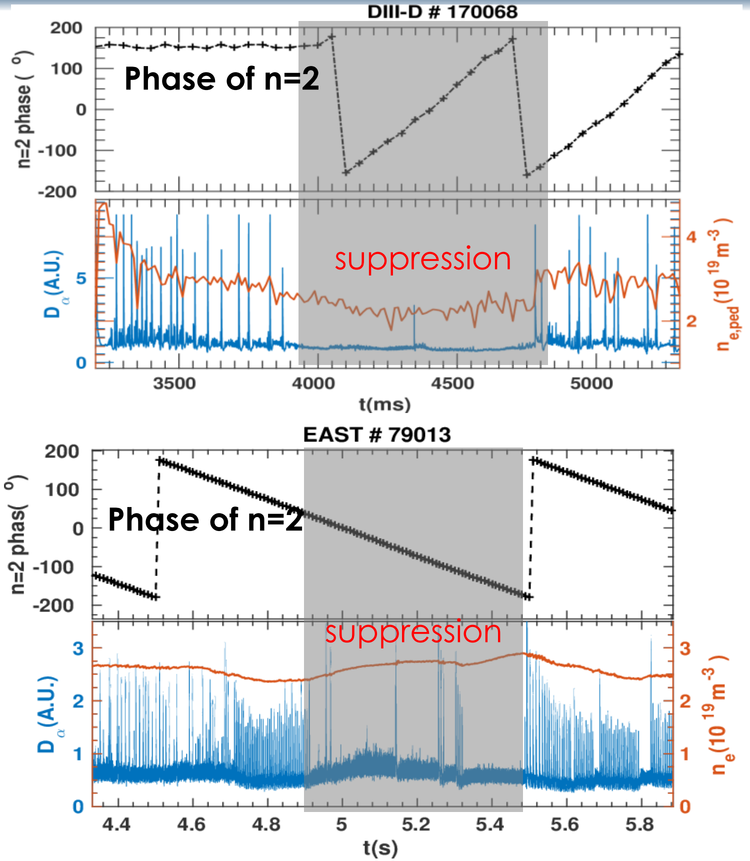
Comparison of Experimental Conditions in DIII-D and EAST

ELM Suppression Achieved Using a Rotating *n*=2 + Static *n*=3 RMP Field in DIII-D and EAST

DIII-D

Rotating n=2 + Static n=3

EAST



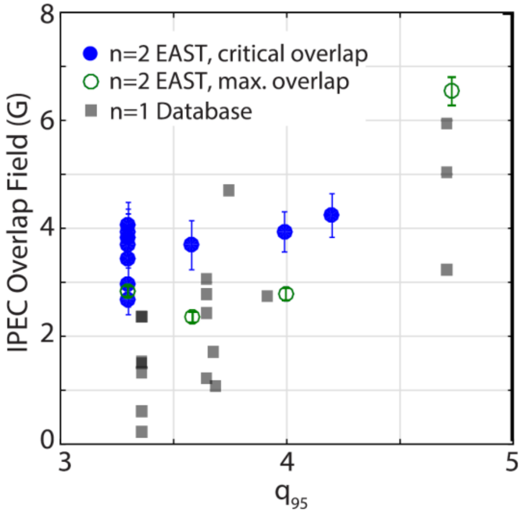
- **Reduce required coil current for ELM suppression**
- **Good for control of heat flux on the divertor while maintaining ELM suppression**
  - Periodic changes of target particle flux observed

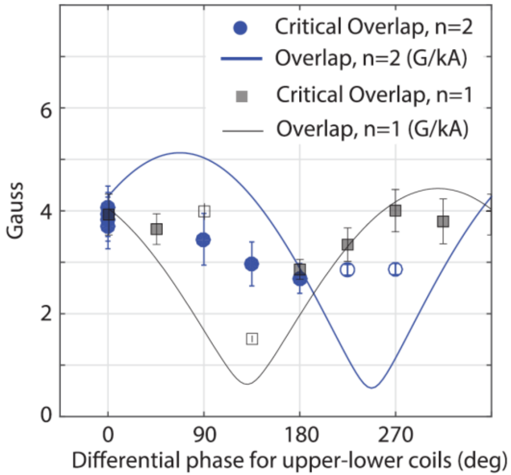
[Sun Y, APS2017, IAEA2018**]**

[M. Jia *et al.*, **Phys. Plasmas 25**, 056102 (2018)]

[S. Gu *et al*, **Nucl. Fusion 59**, 026012 (2019)]

Collaboration on n=2 RMP penetration studies in EAST

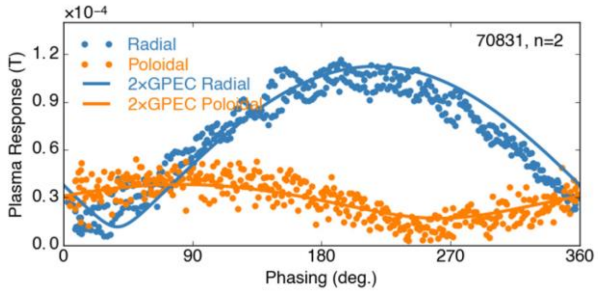


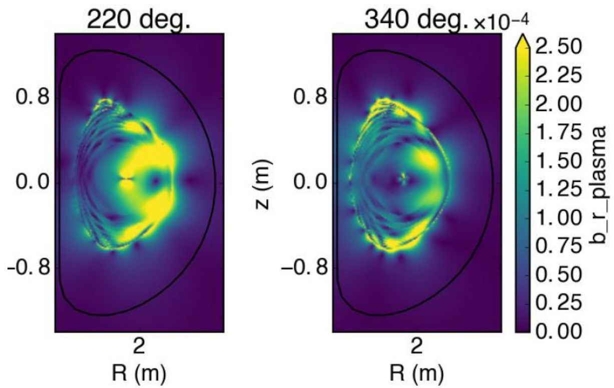


[Lanctot et al., **Phys. Plasmas 24**, 056117 (2017)]

- Thresholds for n=2 RMP are also **correlated with the "overlap" field** computed with the IPEC code
- Highlight unique requirements for **n>1 field control**

Multimode plasma response directly observed in EAST





Max Br signal

Max ELM freq.

- The n=2 plasma response was measured to be **multimodal** (**clear phase shift**) using two LFS mid-plane sensor arrays.
- GPEC ideal MHD modeling captures this transition **from single-mode to multimode**

[N. C. Logan *et al*, NF 58, 076016 (2018)]

Identification of multiple eigenmode growth rates in EAST

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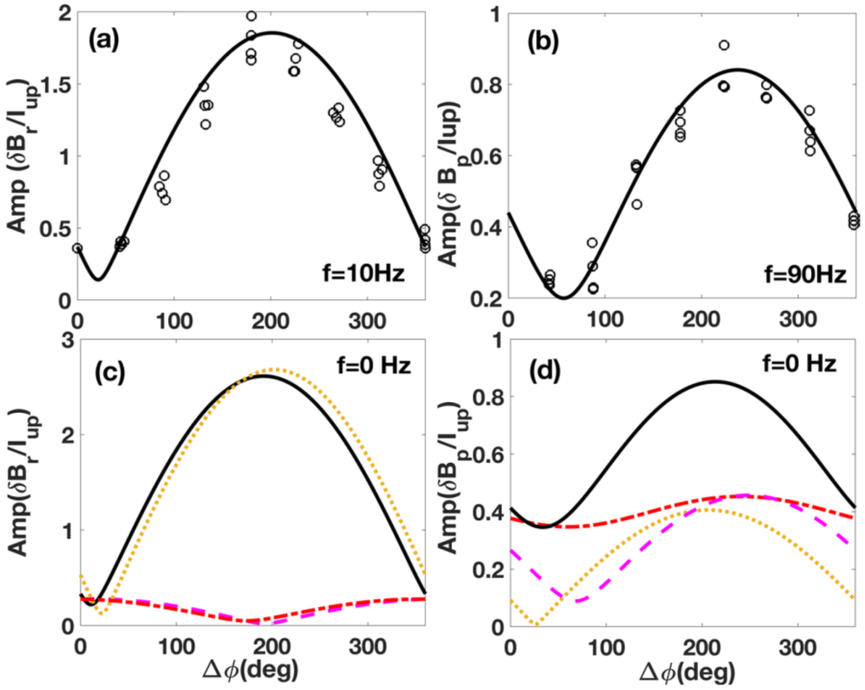

[Z.R. Wang *et al* **Nucl. Fusion 59** (2019) 024001]

- 3D MHD spectroscopy is validated in EAST
- Good correspondence between **the multimode transfer function** and experimental measurements

Previous results: Full ELM suppression achieved using low *n* RMPs in pure RF heating plasmas in EAST

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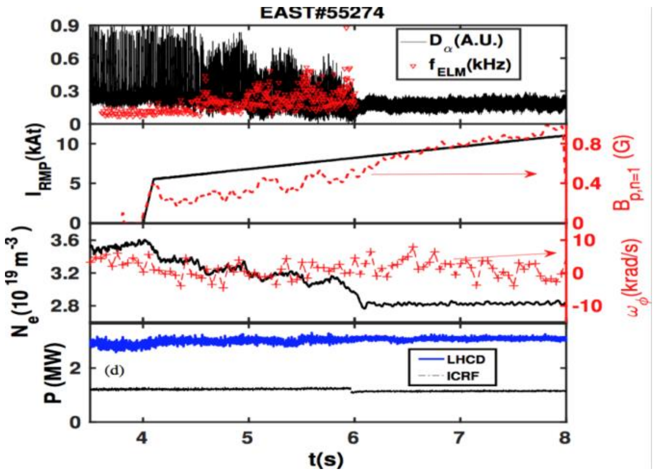

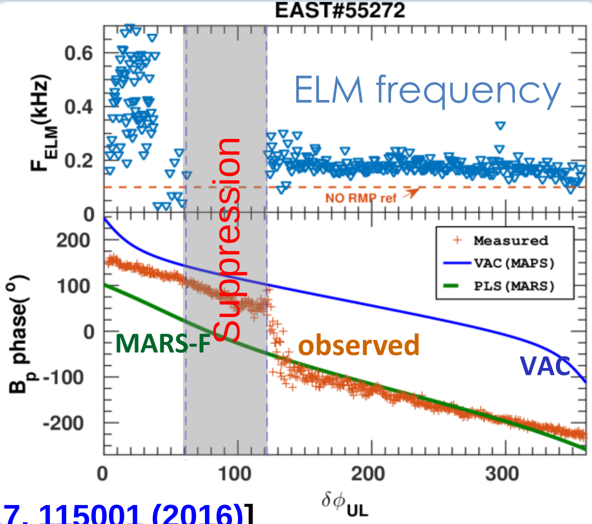

[Sun Y. *et al.*, PRL 117, 115001 (2016)]

- Full ELM suppression has been achieved in EAST
  - **RF heating, Ω_Φ~0, *n*=1,2 RMPs, $\nu_{*e,ped}$~1**
  - long pulse **fully non-inductive** operation with **W divertor ~ 20s**
  - Large range of **q_{95}~ [3.2 -6] for ELM suppression** with **low *n*** RMPs

Extend to ITER-like conditions
n=4 RMP, low torque, low q_{95}, high density, high β_N plasmas

Outlines

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- **First demonstration of full ELM suppression by *n*=4 RMP in low torque plasmas for ITER in EAST**
- Understanding of RMP ELM suppression window
- Heat flux control during ELM suppression

Challenge for accessing ELM suppression in low torque plasmas

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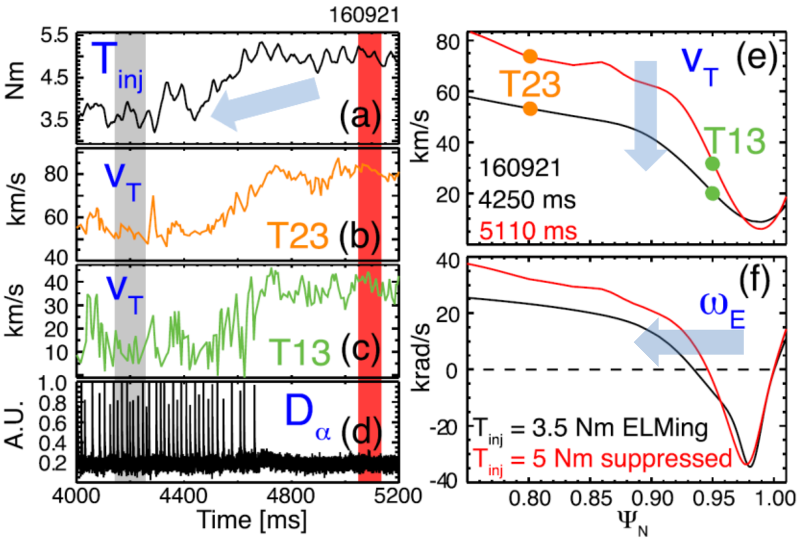
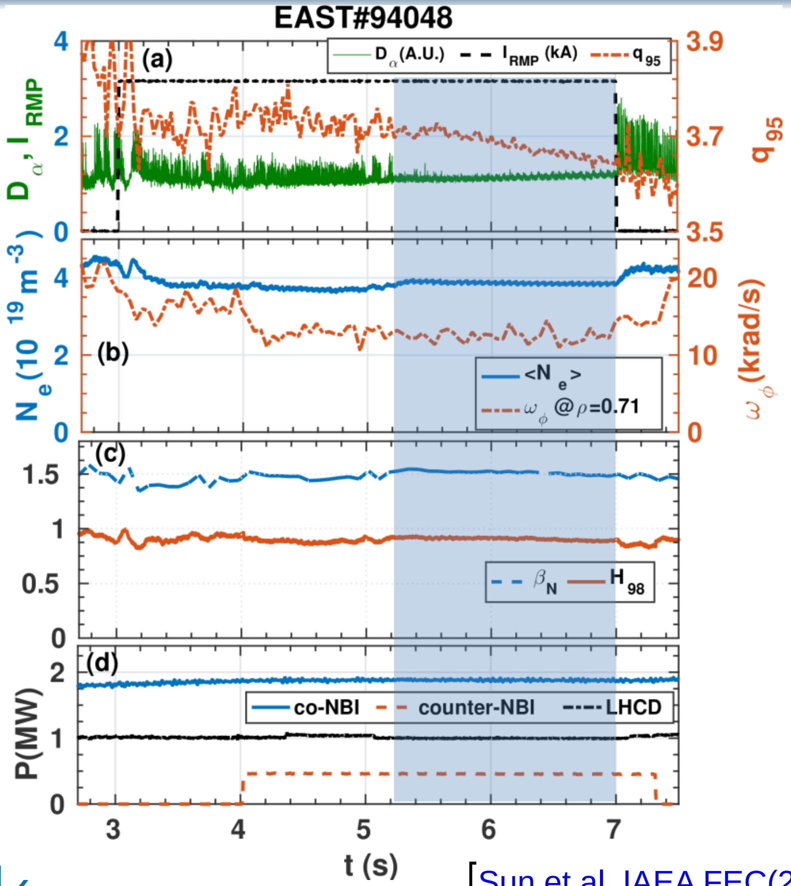


[Moyer et al. Phys. Plasmas 24, 102501 (2017)]

- ELM suppression is **lost in low torque** plasmas in DIII-D
- Possibly linked to the inward shift of **rotation zero-crossing** away from the pedestal top

New observation: Full ELM suppression by *n*=4 RMP in low torque plasmas demonstrated for the first time in EAST



- Experimental condition is close to low torque **ITER type-I ELMy H-mode**
  - **low torque** T_{NBI} **--> 0.44 N·m** (< 0.9 N·m **ITER equivalent** torque in EAST)
  - ***n*=4 RMP**
  - q_{95} ~ 3.65, $\boldsymbol{v}_{*e,ped}$~0.5, β_N~1.5
  - T_i ~ T_e ~ 1.5-2keV
- **No** obvious **drop of energy confinement**, but clear **density pump out**

[Sun et al, IAEA FEC(2021)]

Lower torque plasmas is even better for achieving ELM suppression

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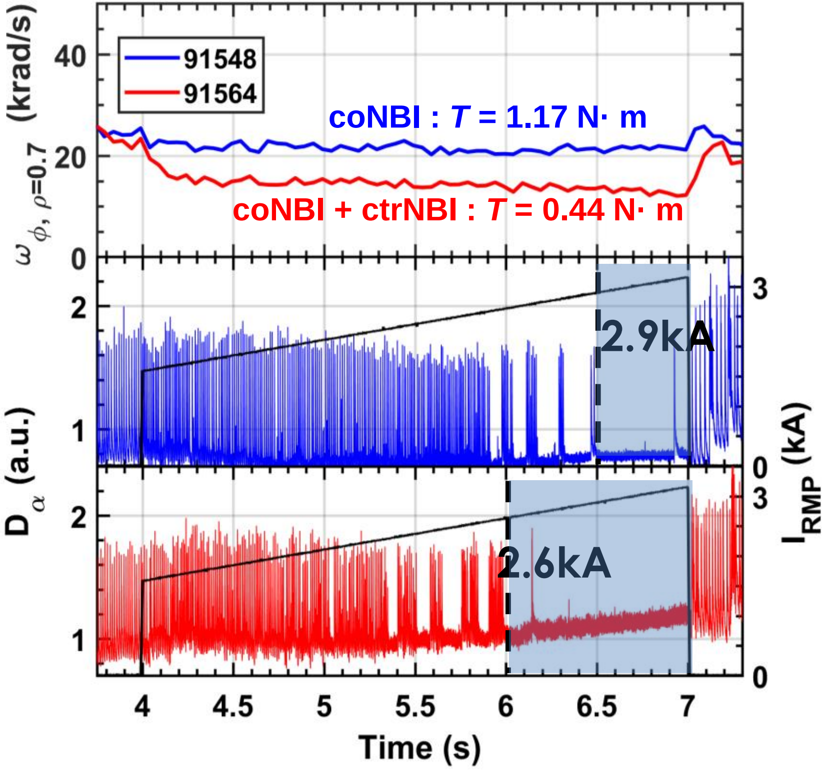

- It is **easier** to get into ELM suppression at **lower torque** plasmas
- **Threshold** RMP current for ELM suppression is reduced 10%

  2.9kA ----> 2.6kA

Two q_{95} windows identified for n=4 RMP ELM suppression

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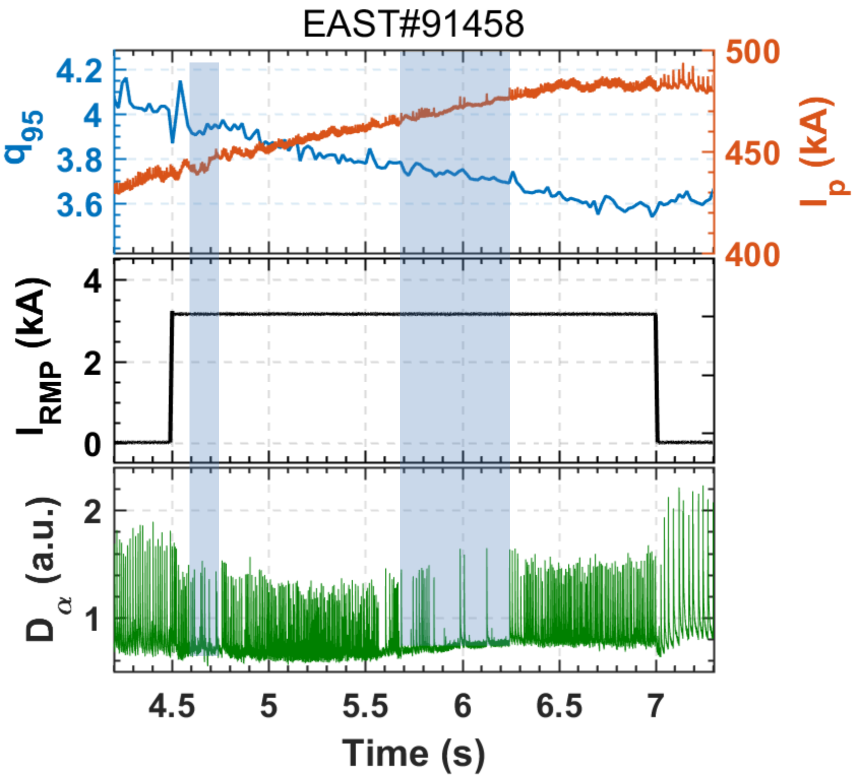
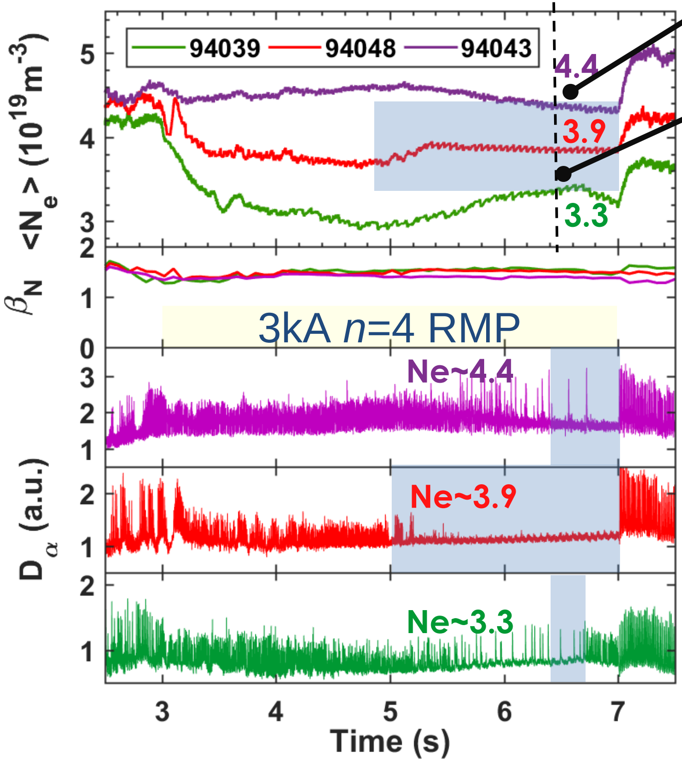
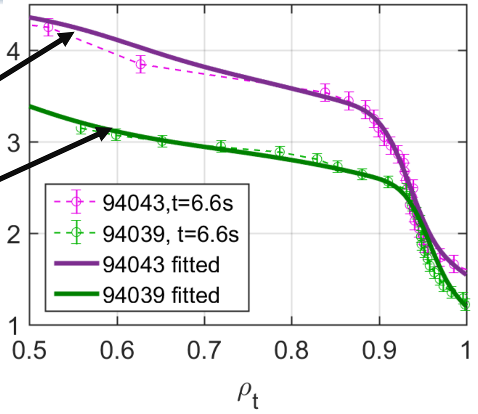


- A clear q_{95} window for ELM suppression is observed
  - **q_{95} window ~ [3.6, 3.75]**
  - Another window ~ **3.95**
- Reliable ELM suppression is only obtained with **good control of q_{95}**

Optimized density window for ELM suppression is observed





- Both **lower** and **upper density limits** for ELM suppression is observed by adjusting feedforward gas puffing
  - $\boldsymbol{N_e}$ **~** [3.3~4.4]x $10^{19}m^{-3}$ (or **[0.44-0.6]** $\boldsymbol{N_{GW}}$)
  - $\boldsymbol{N_{e,ped}}$ **~ [2.5~3.5]** x $10^{19}m^{-3}$ (or [0.33-0.47] N_{GW})

Demonstrated the advantage of *n*=4 RMP for ELM suppression

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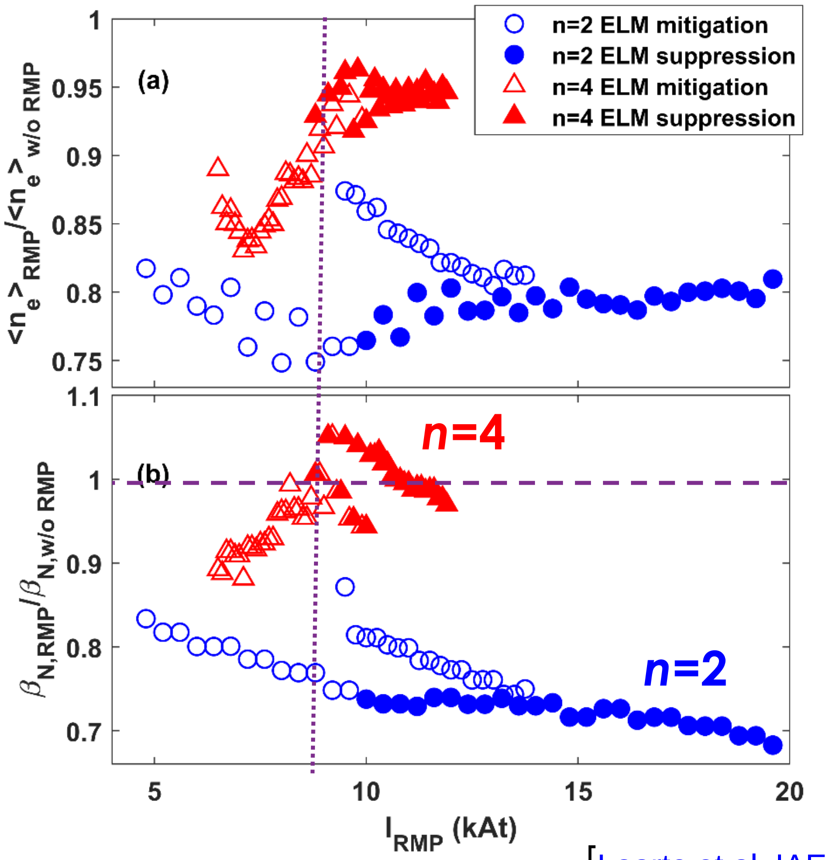

- **Threshold RMP currents** for ELM suppression are **similar**
- Impacts on plasma confinement are very different:
  - No obvious drop in stored energy and **minor** density pump out in *n*=4 case
  - **Significant drop** of stored energy and strong density pump out in *n*=2 case

↓ 20-30%

[Loarte et al, IAEA FEC(2021)]

Outlines

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- First demonstration of full ELM suppression by *n*=4 RMP in low torque plasmas for ITER in EAST
- **Understanding of RMP ELM suppression window**
- Heat flux control during ELM suppression

Spectrum effect of n=4 RMP on ELM suppression is observed

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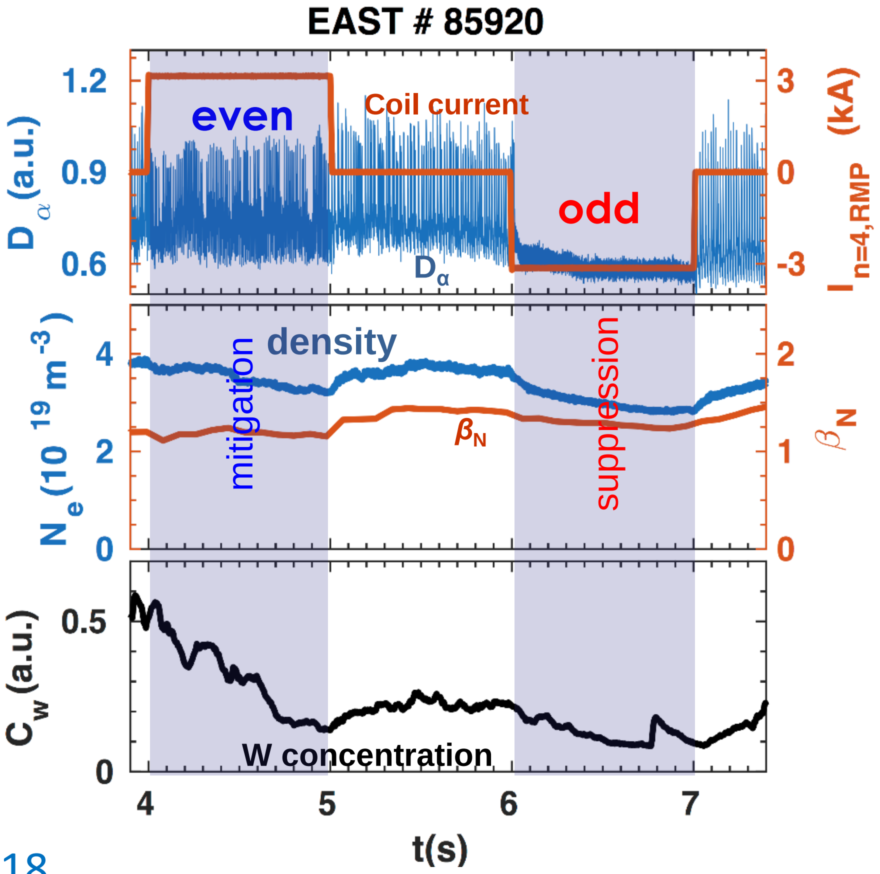

- Type-I ELMs are completely suppressed by ***n*=4 RMP** with upper-lower **odd** coil phasing, but not for the even one.
- Density pump out and rotation braking observed in both RMP spectra
- **W concentration decreased** during the application of RMP

Odd n=4 coil configuration provides stronger edge resonant magnetic field with plasma response

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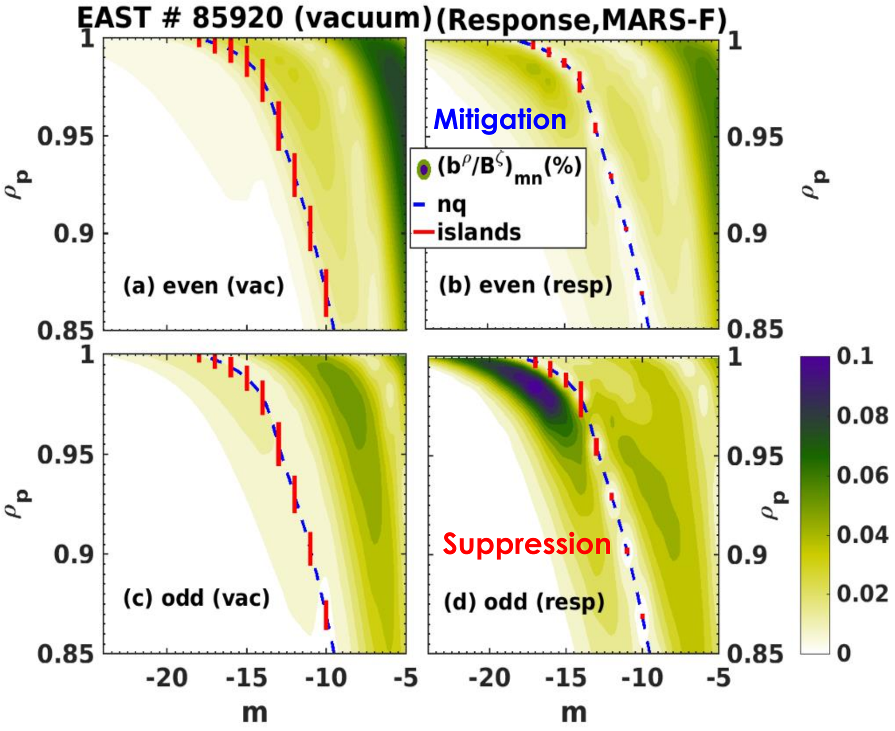
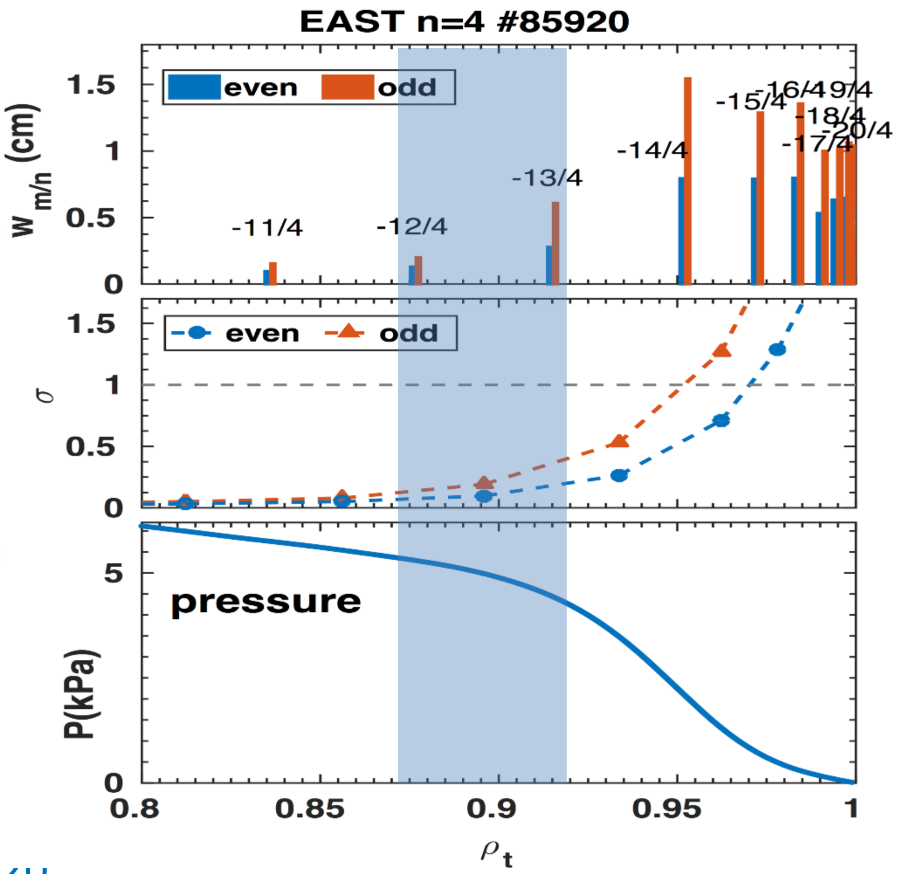


- Resonance is **stronger** for **odd** coil configuration, when resistive MHD **plasma response** is taken into account using MARS-F
  - Stronger **shielding** in the **even** case
  - Stronger **kink-like** resonant response in the **odd** case

Odd *n*=4 coil configuration provides stronger edge resonant magnetic field with plasma response



- Resonance is **stronger** for **odd** coil configuration, when resistive MHD **plasma response** is taken into account using MARS-F
  - Stronger **shielding** in the **even** case
  - Stronger **kink-like** resonant response in the **odd** case
  - **All edge** resonant harmonics are stronger in the odd case
- This explains better effect of odd n=4 RMP on ELM suppression

Modeling result demonstrates the resonant q_{95} window for n=4 ELM suppression

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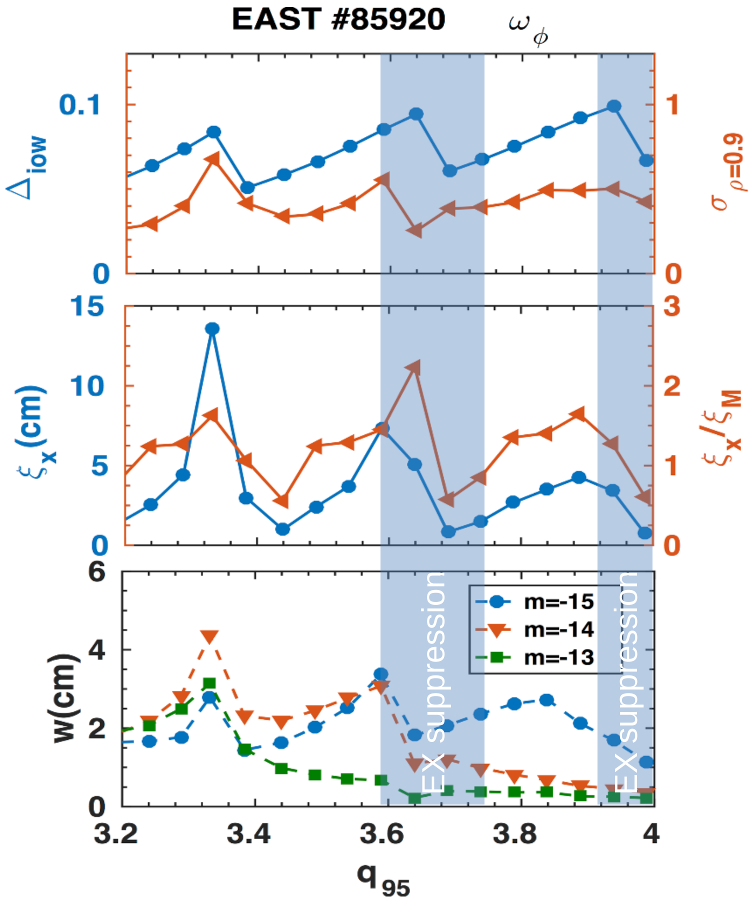
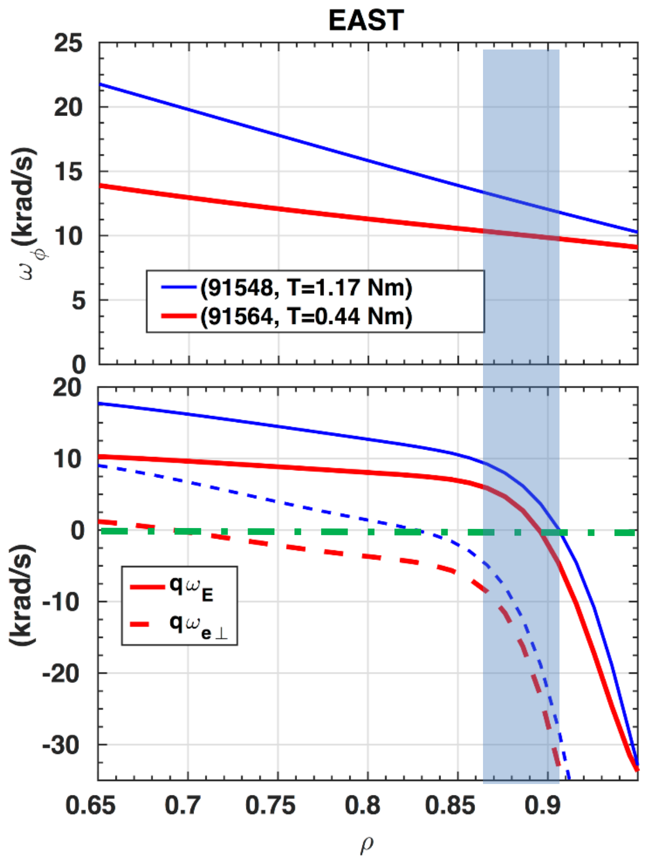


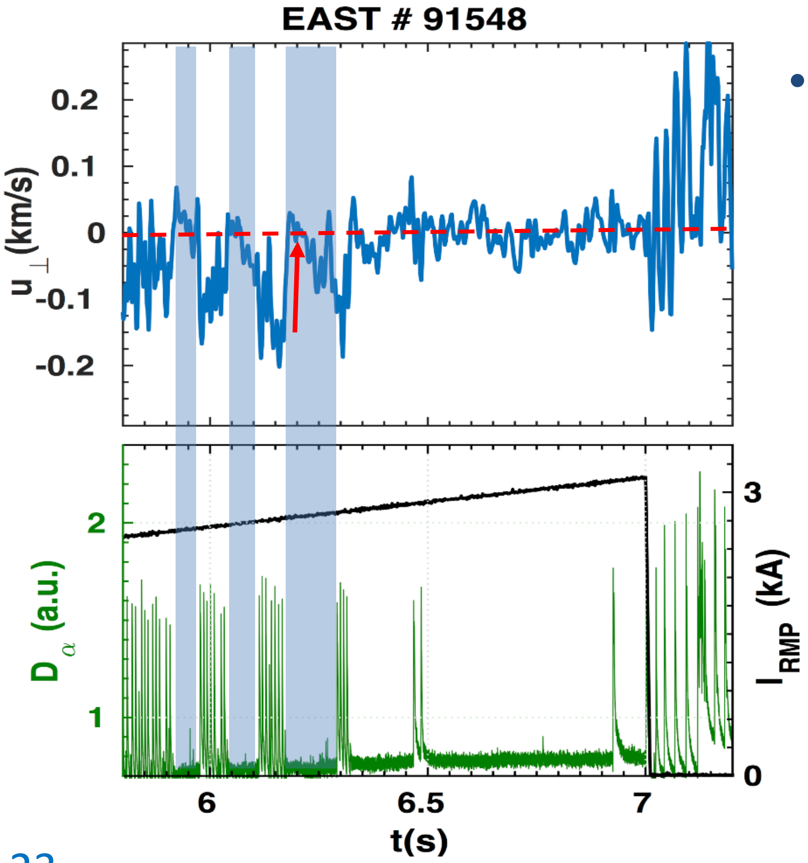
- Edge resonances, indicated by different criteria, taking into account **plasma response** using **MARS-F** code, shows a similar dependence on q_{95}
  - Stochastic layer width, Chirikov parameter near pedestal top, x point displacement, edge RMP amplitude
- Multiple resonant peaks observed in the modeling
  - 3.05, 3.35, **3.65**, **3.95**, …

Lower rotation might enhance plasma response



- The toroidal rotation is reduced to be closer to zero in low torque case
- The **zeros** of **ExB rotation** and **electron perpendicular rotation** shifted inwards
- **ExB rotation** is reduced to be **closer to zero** near the **pedestal top**

Periodic getting into and loss of ELM suppression correlated to edge perpendicular rotation



- ELM **suppression** is achieved, when edge perpendicular rotation becomes **zero**
  - $u_\perp$ is the propagating velocity of density fluctuation near the very edge ($\rho\approx1$) measured by Doppler Reflectometry
  - ELM suppression is **lost**, when $u_\perp$ drifts **away from zero**
  - ELM suppression is **sustained**, when the $u_\perp$ is **locked to zero**

Outlines

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- First demonstration of full ELM suppression by n=4 RMP in low torque plasmas for ITER in EAST
- Understanding of RMP ELM suppression window
- **Heat flux control during ELM suppression**

Challenge in control of heat flux during ELM suppression

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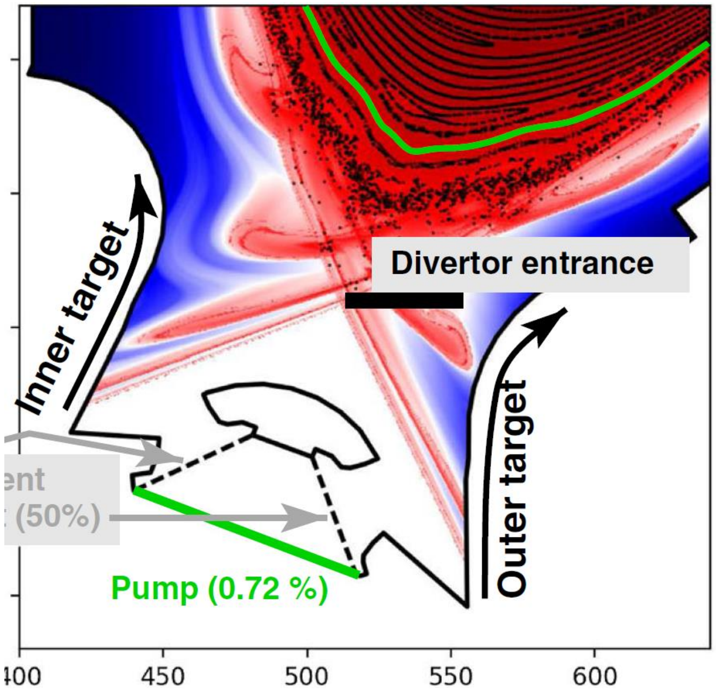
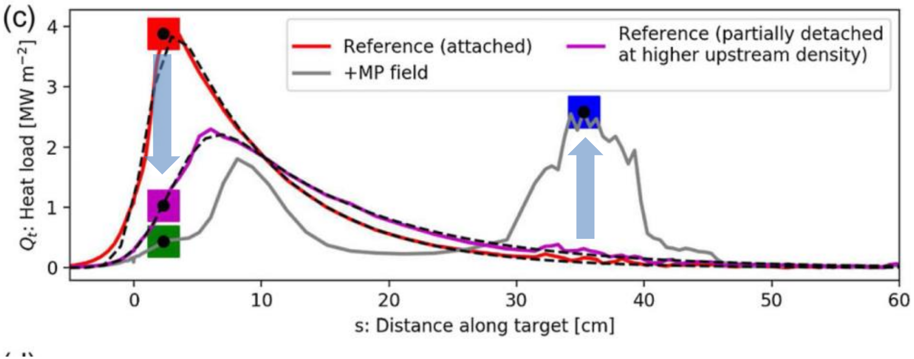
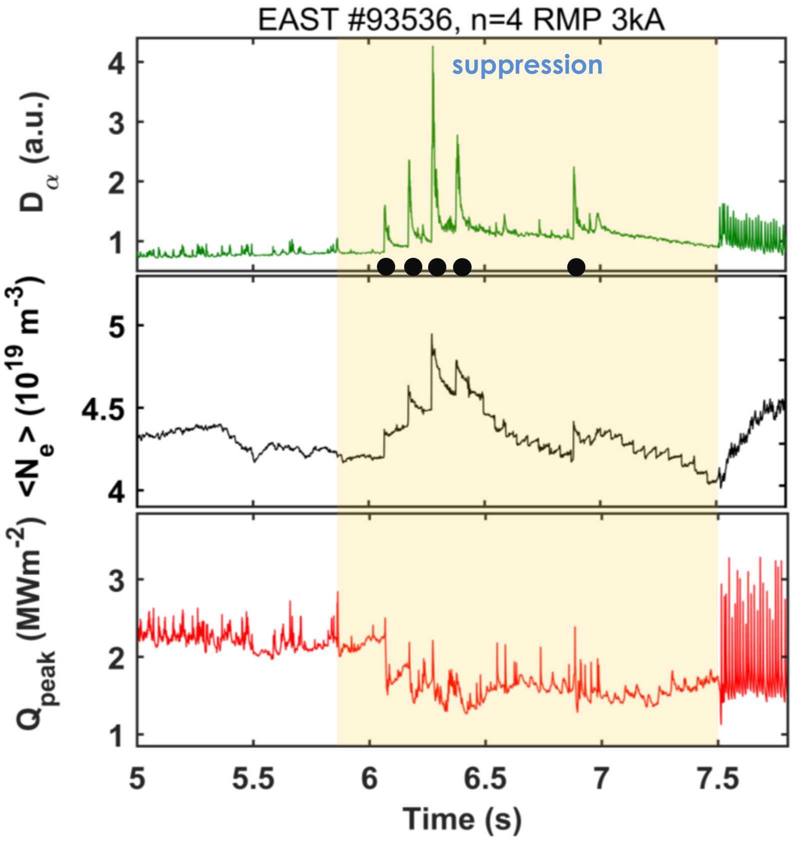




[H. Frerichs et al, Phys. Rev. Lett. 125, 155001 (2020)]

- Modeling results predicted the problem of second strike point (SSP) remains attached with increasing upstream density

RMP ELM suppression is compatible with Pellet Fueling



- **Effective fueling** is achieved using pellet injection during ELM suppression
- **No big ELMs** triggered by pellets
  - Small ELMs appears when density exceeds the threshold

Heat fluxes on both OSP and SSP are substantially reduced by injected pellets without triggering large ELMs

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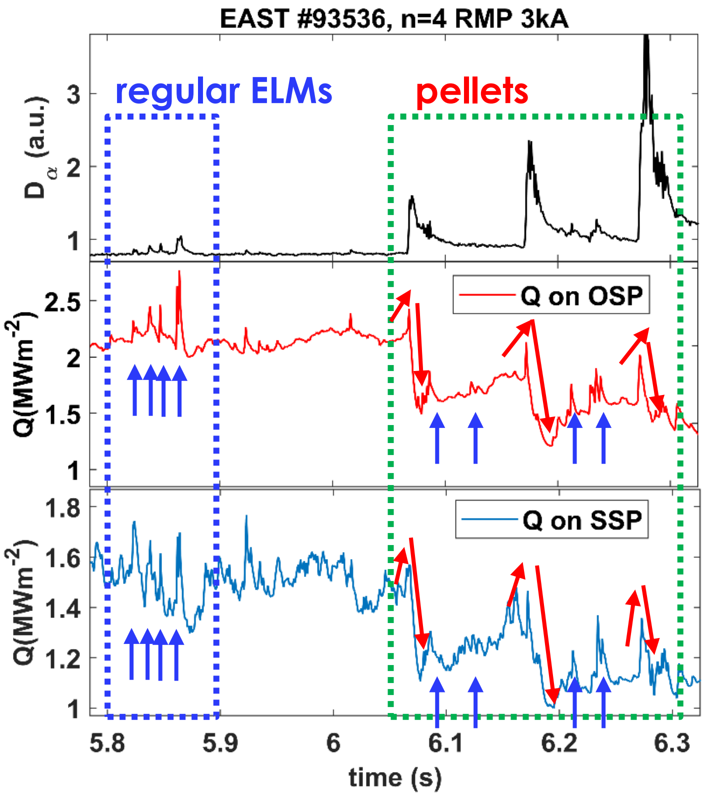

- **The heat flux on both OSP and SSP decrease after the pellet injection**
- **Effect pellets on heat flux:**
  - slight increase followed by a substantial decrease
  - small ELMs between the pellets

A similar upper density limit is observed using gas puffing fueling after ELM suppression

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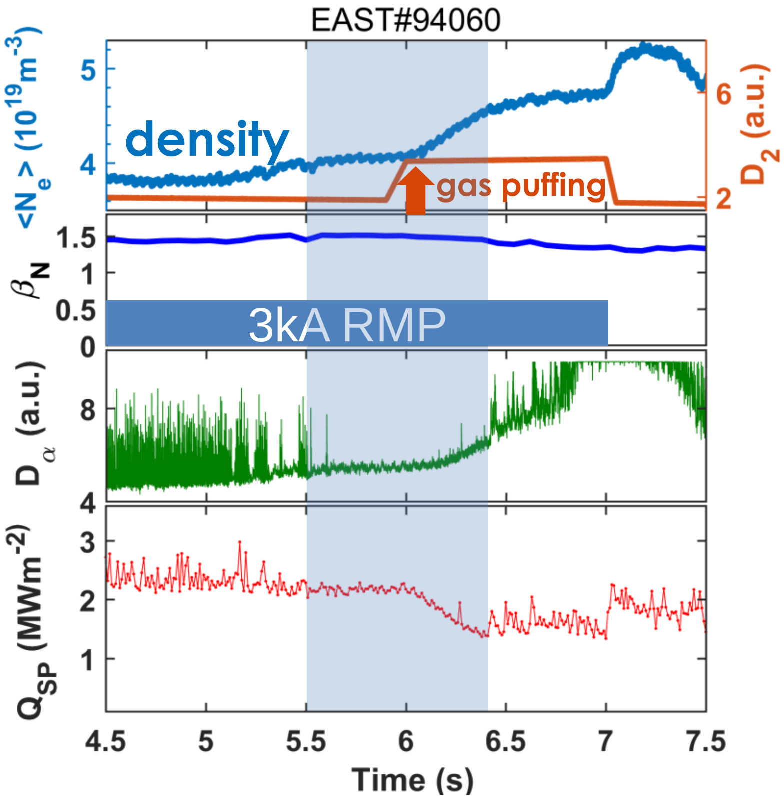

- ELM suppression sustained during gas puffing fueling before reaching the upper density limit

  Upper limit (~ **4.5×10^{19}m^{-3}** or **0.6 N_{GW}**)

- Stored energy slightly dropped (-6%) during density ramp

Heat fluxes on both OSP and SSP are reduced with gas puffing during *n*=4 RMP ELM suppression

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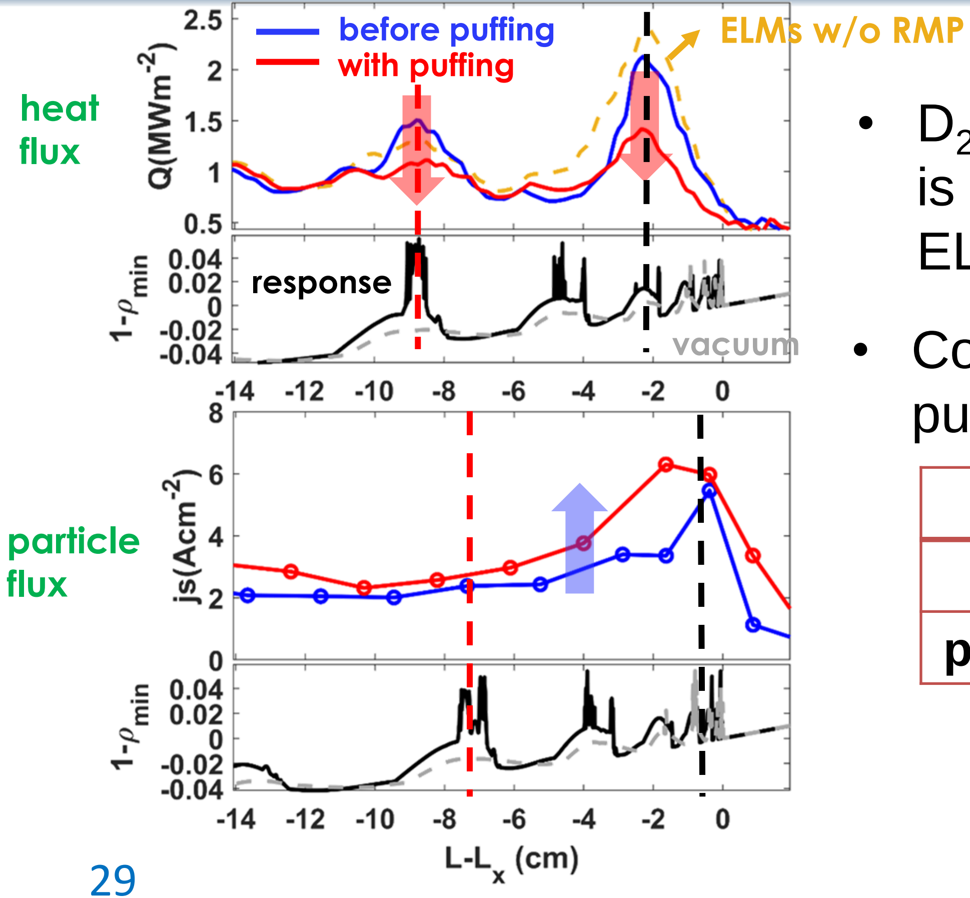

- D_2 gas puffing from mid-plane on LFS is increased during the *n*=4 (odd) RMP ELM-suppression phase
- Compared to the case before gas puffing:

	OSP	SSP
heat flux	↓	↓
particle flux	↑	↑

Heat fluxes on both OSP and SSP are reduced with impurity seeding during *n*=2 RMP ELM suppression

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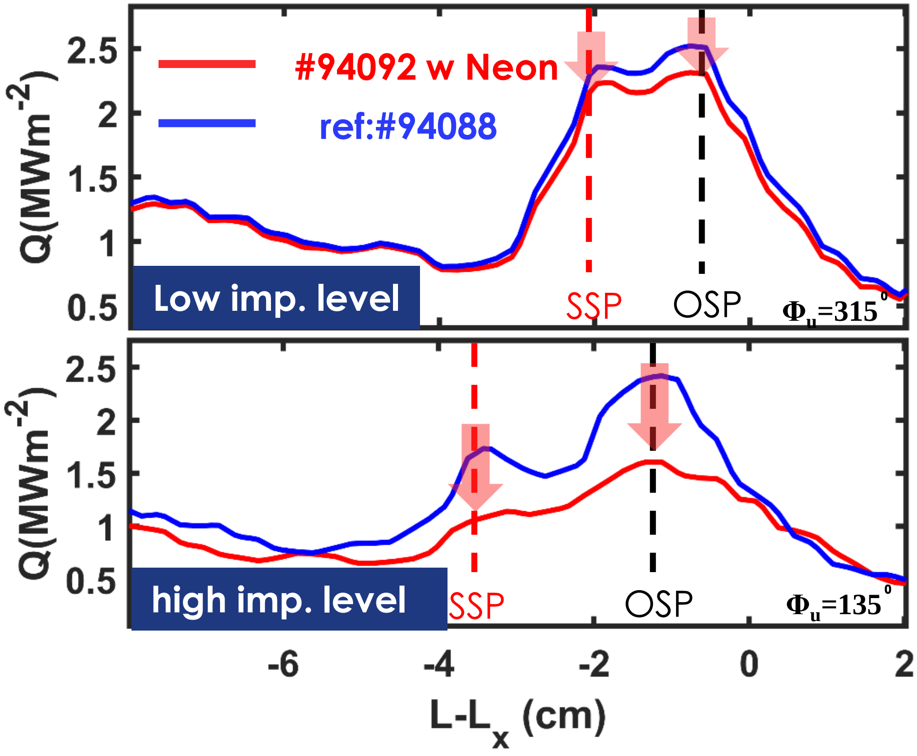

- Heat flux change compared to the case without impurity seeding:

  OSP: ↓ **SSP:** ↓

- Heat flux is **further reduced** with **increasing impurity** radiation level

Summary and conclusions

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- **Full suppression of ELMs in low torque plasmas by *n*=4 RMP has been demonstrated for ITER for the first time in EAST**
  - **low torque** (T_{NBI} ~0.44Nm) , N_e ~ 0.6 N_{GW}, q_{95} ~3.65, β_N ~ 1.5 with **W** divertor
- **ELM suppression window is consistent with the modeling of plasma response to RMP using the MARS-F code**
- **Heat fluxes on both OSP and SSP are reduced by gas puffing, pellet injection and impurity seeding during RMP ELM suppression**
- **These results expand physical understanding and demonstrate the potential effectiveness of RMP for reliably controlling ELMs in future ITER high Q plasma scenarios**