First demonstration of full ELM suppression in low input torque plasmas for ITER using n=4 RMP in EAST

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Integrated ELM and divertor flux control using RMPs with low input torque in EAST in support of the ITER Research Plan

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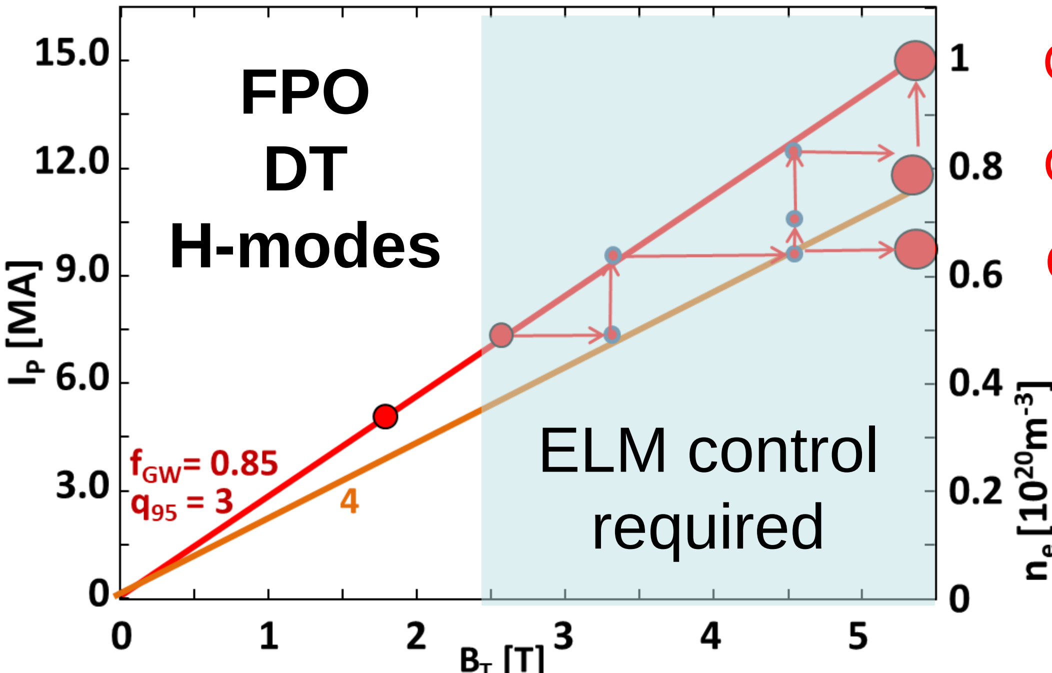
ELM control and ITER Research Plan (IRP)

- ELM control is essential for execution of ITER Research Plan
- ELM mitigation (reduction of q_{ELM}) and suppression (q_{ELM} ~ 0). Reducing q_{ELM} by mitigation uncertain → Focus on suppression
- Compatibility with wide range of high Q scenario requirements (low normalized input torque, radiative divertor operation, pellet fuelling, …) → ITER Technical Report (ITR-20-008)



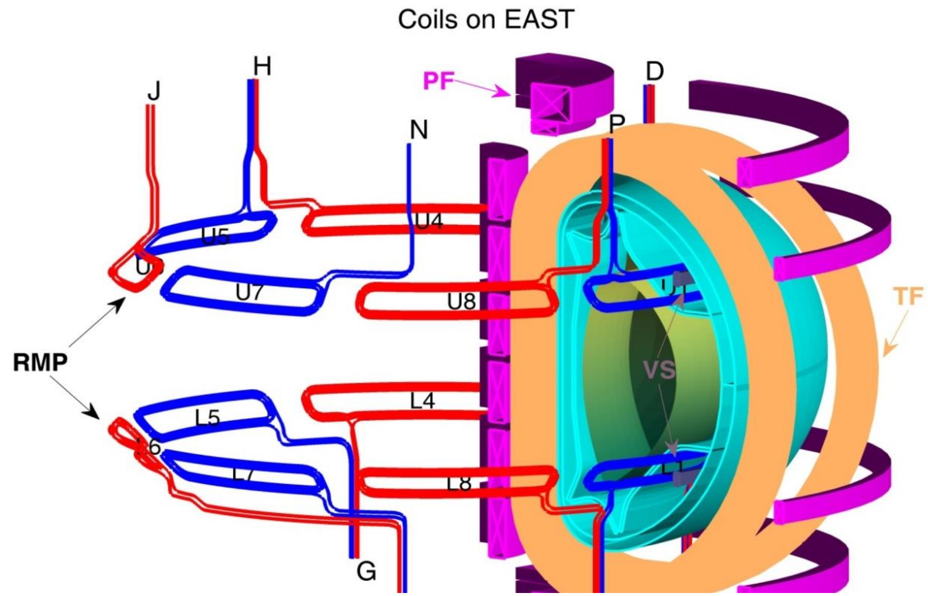
Q = 10 15 MA/5.3 T

Q = 5 long pulse ~ 12.5 MA/5.3 T

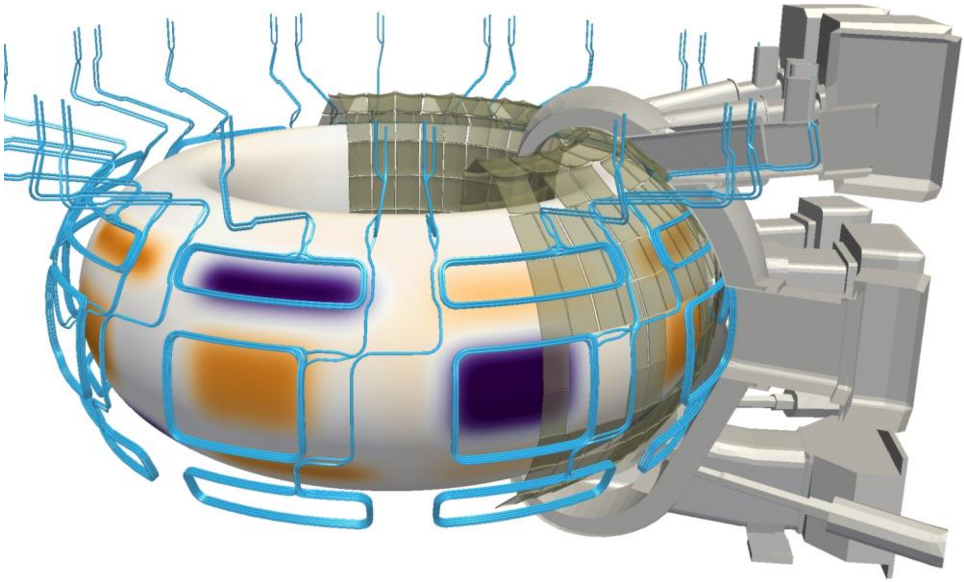
Q = 5 steady-state ~ 10 MA/5.3 T

ELM control (RMP) R&D in EAST for ITER

- EAST RMP coils cover same toroidal mode number as ITER (up to $n = 4$)
- Unique capabilities to access ELM suppression in dominant RF-heated H-modes with low input torque and W divertor



EAST, ***n* = 4**



ITER

***n* =** 1, 2, **3, 4** ELM control

ELM control (RMP) R&D in EAST for ITER

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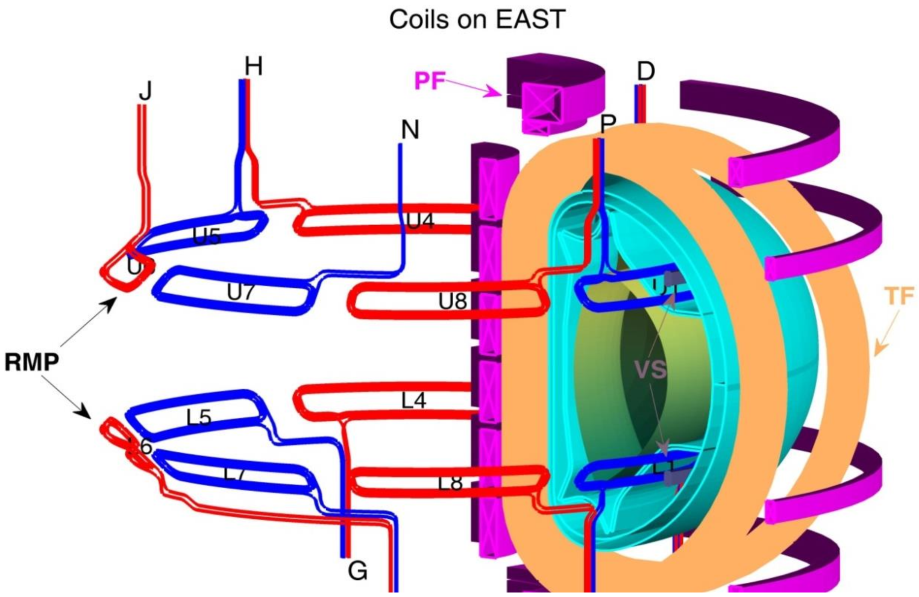
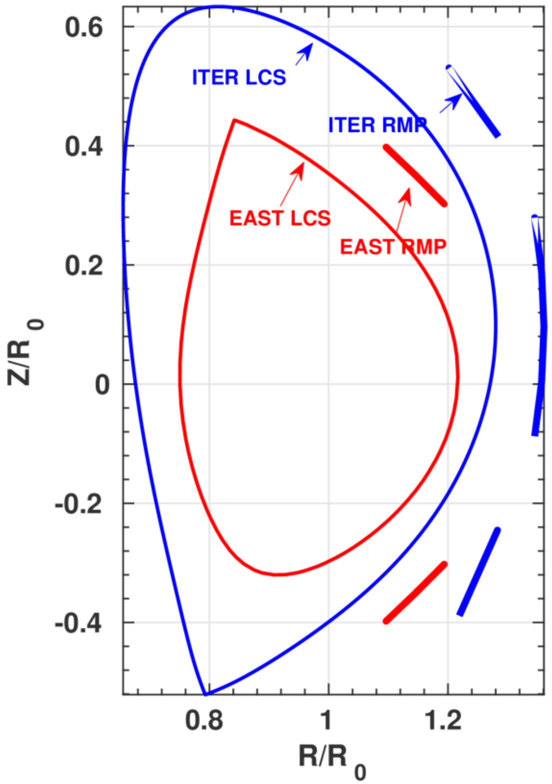
- Unique capabilities to access ELM suppression in dominant RF-heated H-modes with low input torque and W divertor



EAST, ***n* = 4**



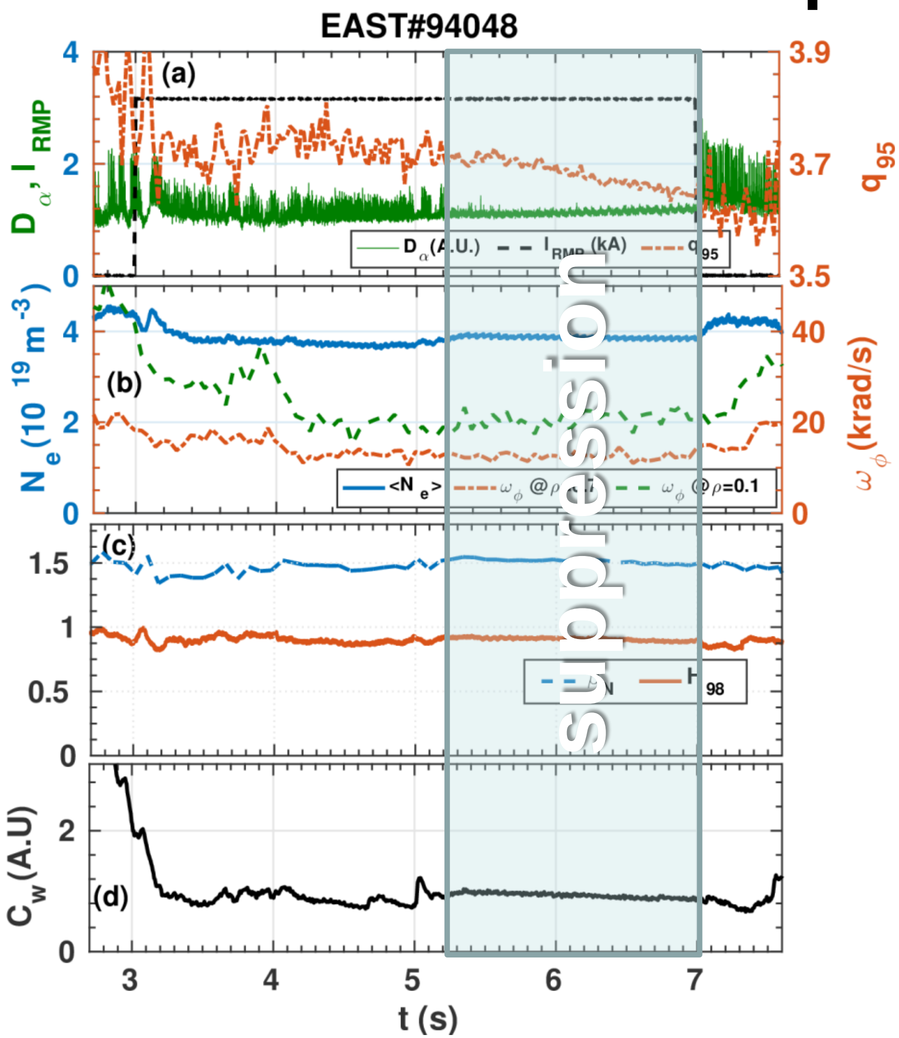
Outline

- First demonstration of full ELM suppression by n = 4 RMP in low torque plasmas in EAST
- RMP ELM suppression window with n = 4 (torque, q_{95}, density, spectrum, edge rotation, …)
- Compatibility of RMP suppressed H-mode with ITER high Q scenario requirements
  - High energy and particle confinement
  - Gas and pellet fuelling
  - Stationary divertor heat flux control

First demonstration of full ELM suppression by n = 4 RMP in low torque plasmas in EAST

ELM suppression by *n* = 4 RMP in EAST

Demonstrated in EAST for first time and in low input torque plasmas

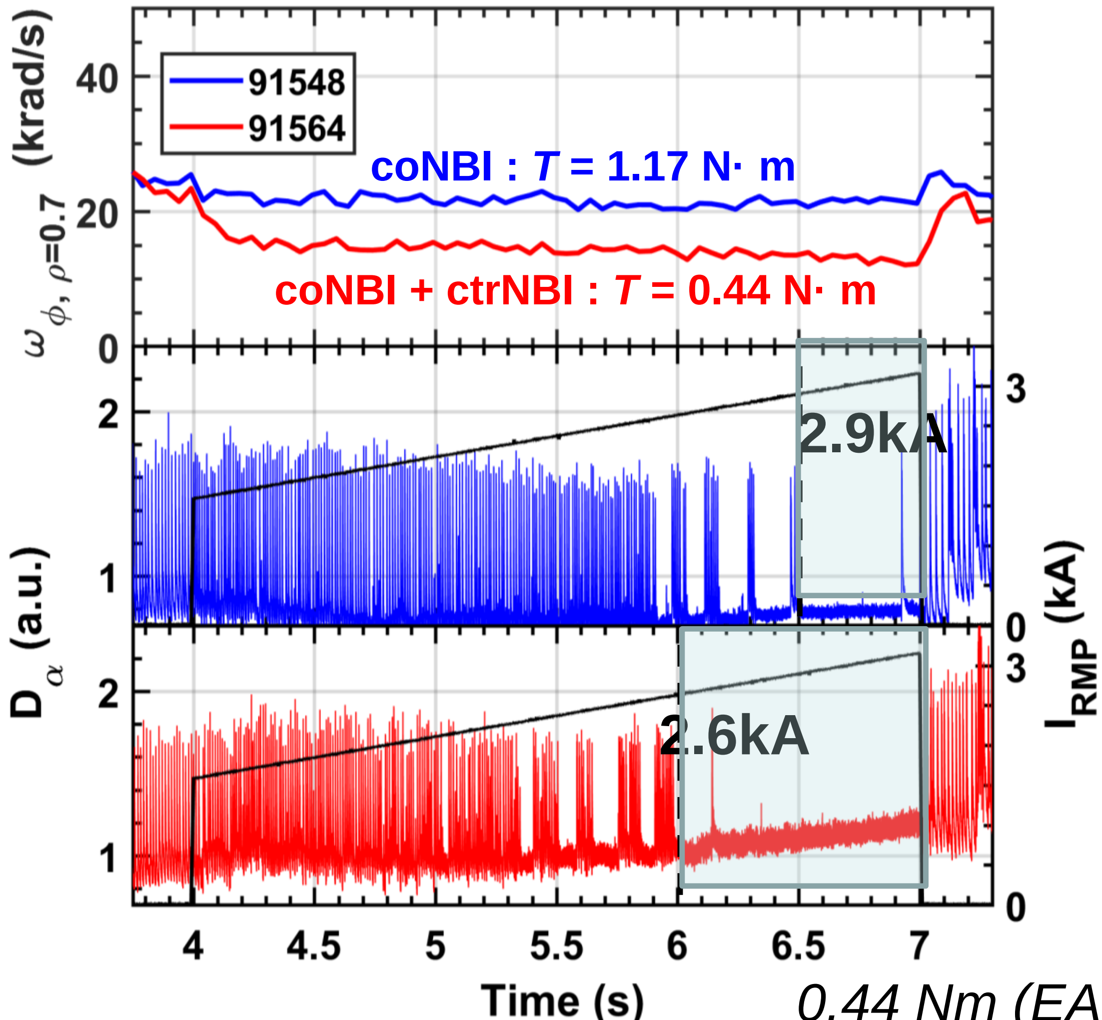


- ❑ Conditions similar to high Q **ITER H-modes**
  - ➢ **low torque** T_{NBI} → **0.44 N·m** (< 0.9 N·m **ITER 33 MW-NBI equivalent)**
  - ➢ q_{95} ~ 3.65, $\nu_{*e,ped}$ ~ 0.5, β_N ~ 1.5
  - ➢ T_i ~ T_e ~ 1.5-2 keV
- ❑ **No drop in energy** confinement
  - ➢ Small density pump out
  - ➢ Low W concentration during RMP application

RMP ELM suppression window with *n* = 4
(torque, q_{95}, density, spectrum, edge rotation, …)

Impact of torque on n = 4 ELM suppression

Lower torque input favours access to ELM suppression with n = 4 RMP in EAST unlike other experiments



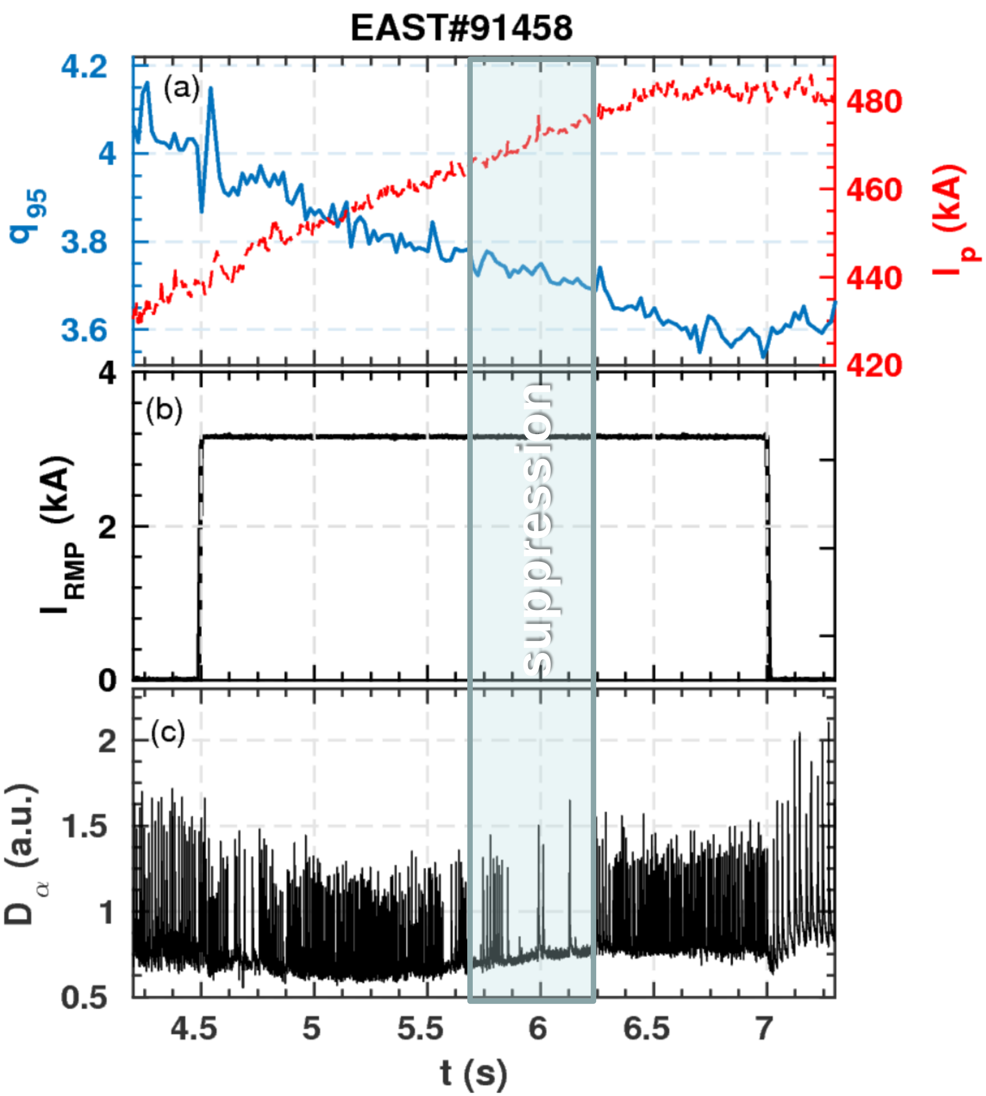
- co-/counter- NBI used to vary input torque
- Lower torque input favours access to ELM suppression

Threshold RMP current for ELM suppression reduced 10%

2.9 kA vs. 2.6 kA

0.44 Nm (EAST) → 16.5 NBI (1 MeV) (ITER)

q_{95} window for n = 4 ELM suppression

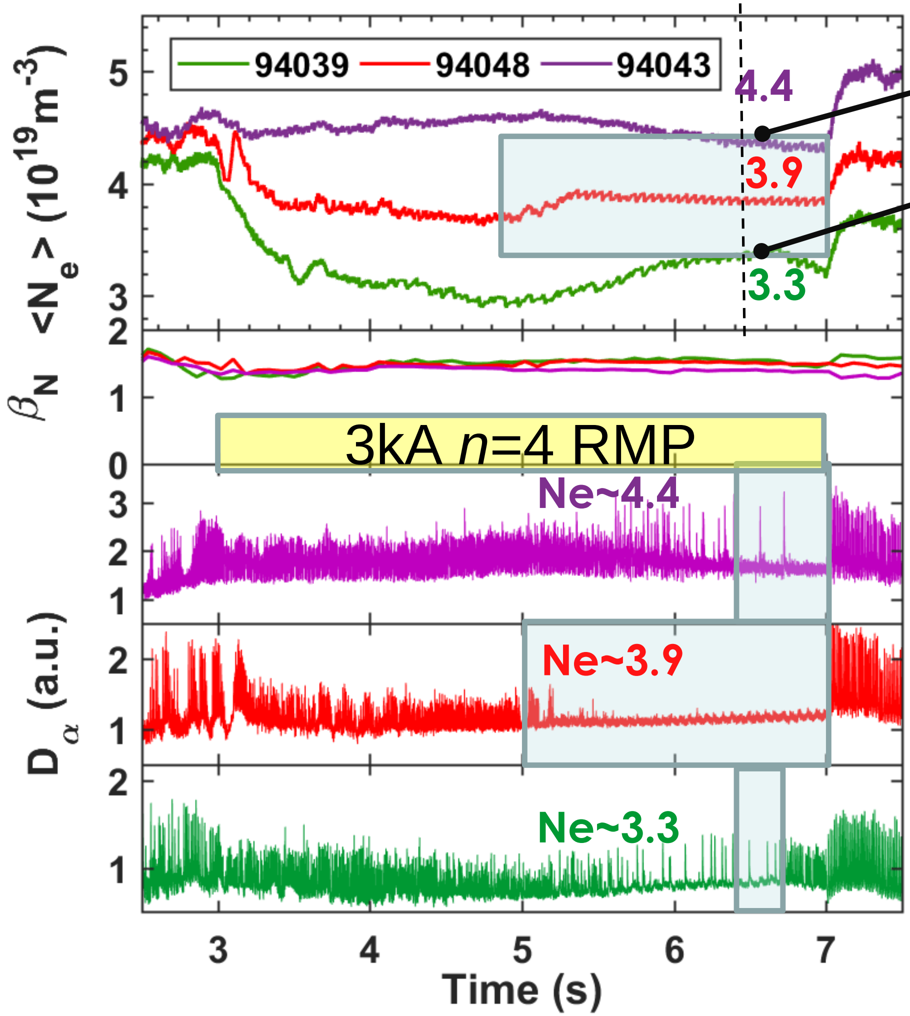


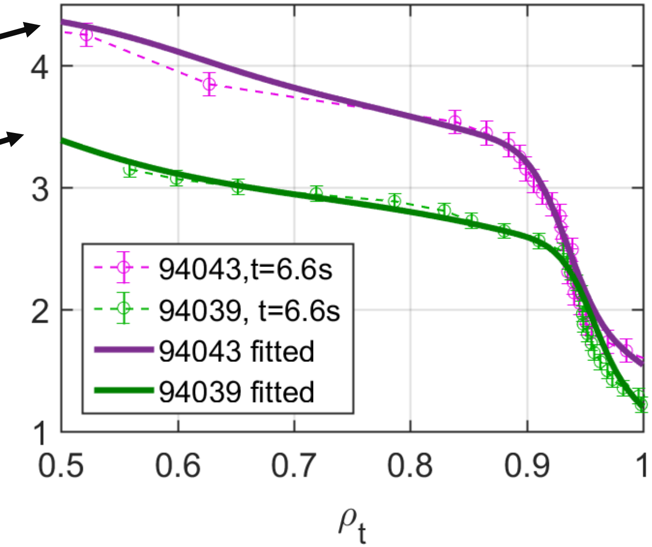
- Clear q_{95} window for ELM suppression

  $$q_{95} \sim [3.6, 3.75]$$

- Reliable ELM suppression obtained with good control of q_{95}/RMP perturbation alignment
- Supports flexibility of perturbation phase control included in ITER design

Density window for n = 4 ELM suppression





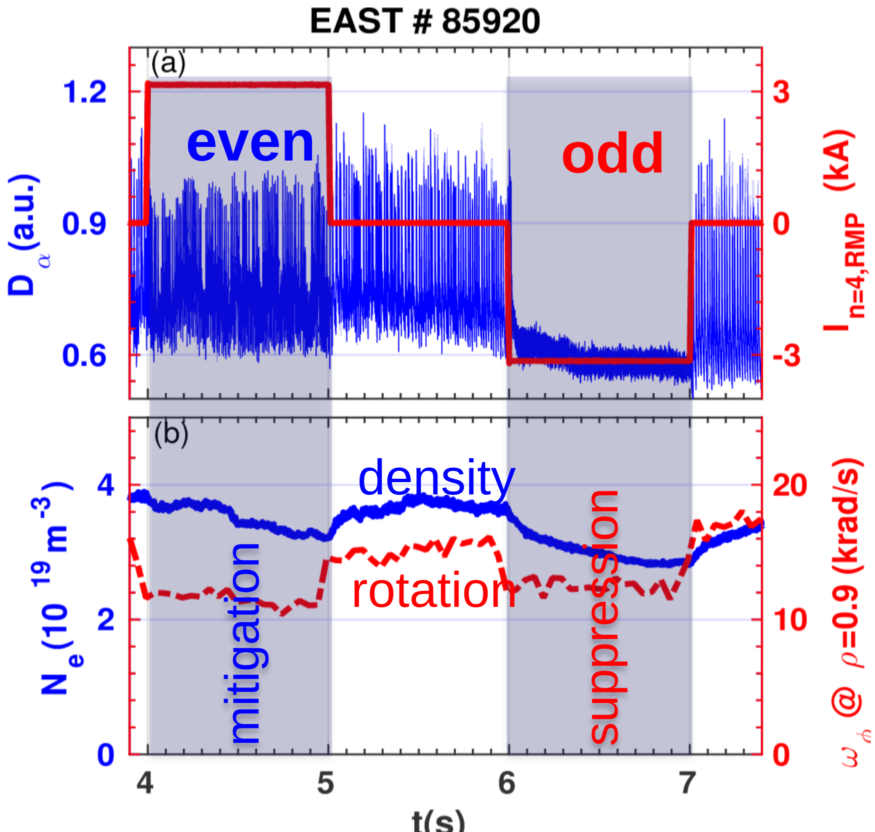
- ❑ **High** and **low** density limits observed for ELM suppression

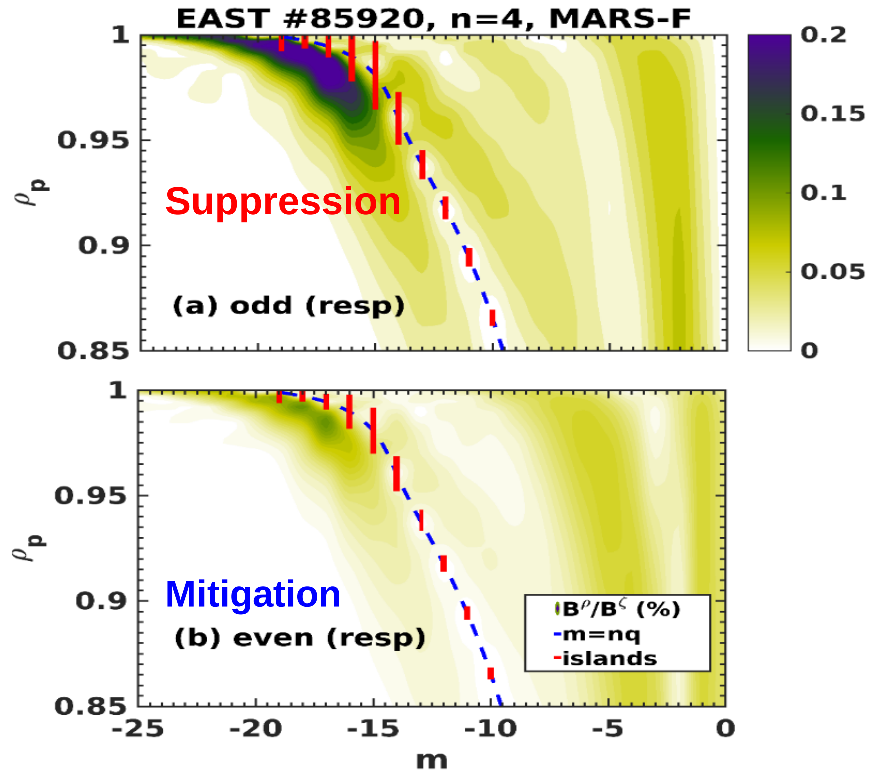
  - ➢ **N_e** ~ [3.3 - 4.4] 10^{19}m^{-3} **([0.44 - 0.6] N_{GW}**
  - ➢ **$N_{e,ped}$** ~ [2.5 – 3.5] 10^{19}m^{-3} **([0.33-0.47] N_{GW})**

Physics for density window needs understanding for ITER extrapolation

RMP spectrum and *n* = 4 ELM suppression

- ELM suppressed only by *n* = 4 RMP up-low odd coil phasing
- Plasma response (MARS-F): Stronger shielding (even) and Stronger kink-like resonant response (odd) → all edge resonant harmonics stronger for odd phasing





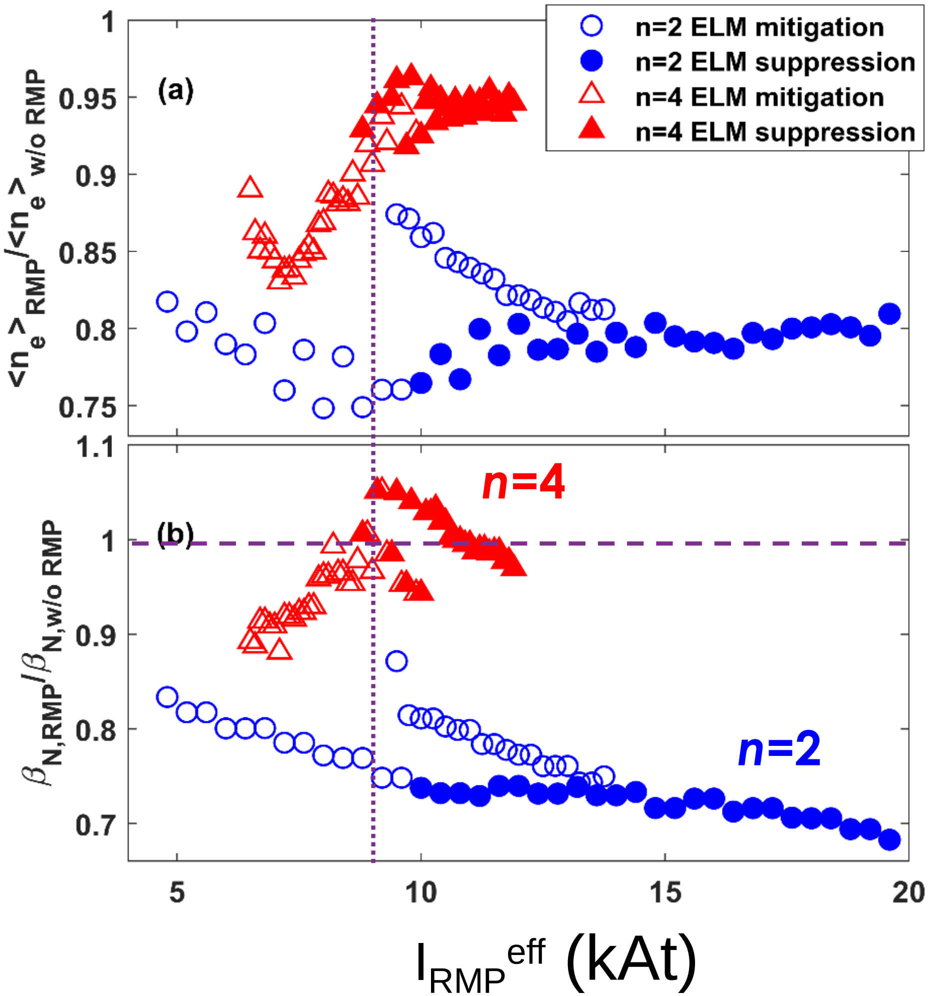
Multiple q_{95} resonant peaks in modeling : 3.05, 3.35, **3.65**, **3.95**, …

Compatibility of RMP suppressed H-mode with ITER high Q scenario requirements

High energy and particle confinement

High energy and Particle confinement with n = 4

- ELM suppression with n = 4 RMPs → small (if any) impact on energy and particle confinement (unlike with n = 2)



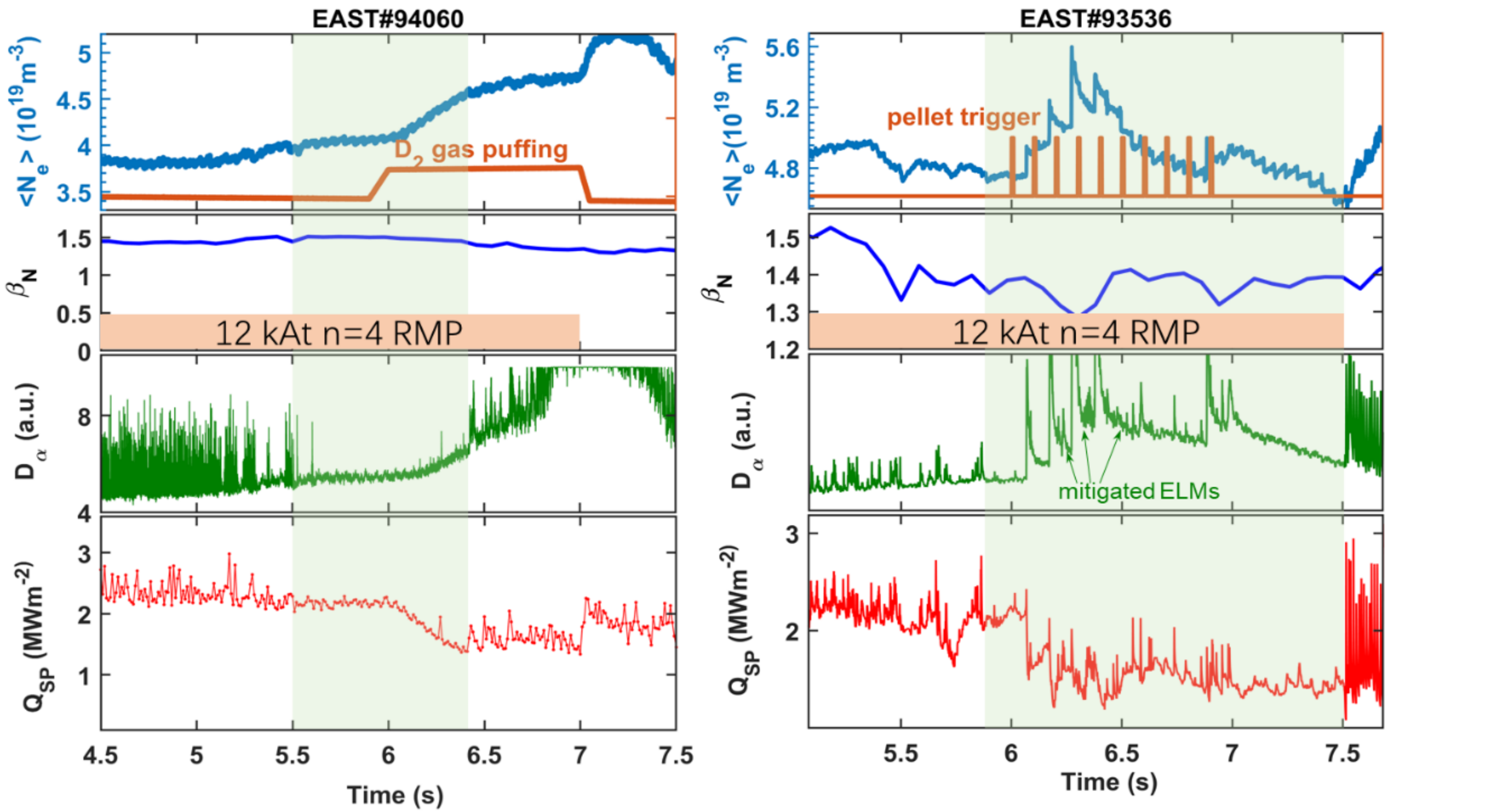
- Same RMP coil threshold for ELM suppression for n = 2 and n = 4
- Energy confinement
  ↓ 25 - 30 % n = 2
  no change n = 4
- Particle confinement
  ↓ 20 - 25 % n = 2
  ~ 5 % n = 4

Supports use of high n RMPs for ELM control in ITER

Gas and pellet fuelling

Gas & pellet fuelling - *n* = 4 suppressed-ELM H-modes

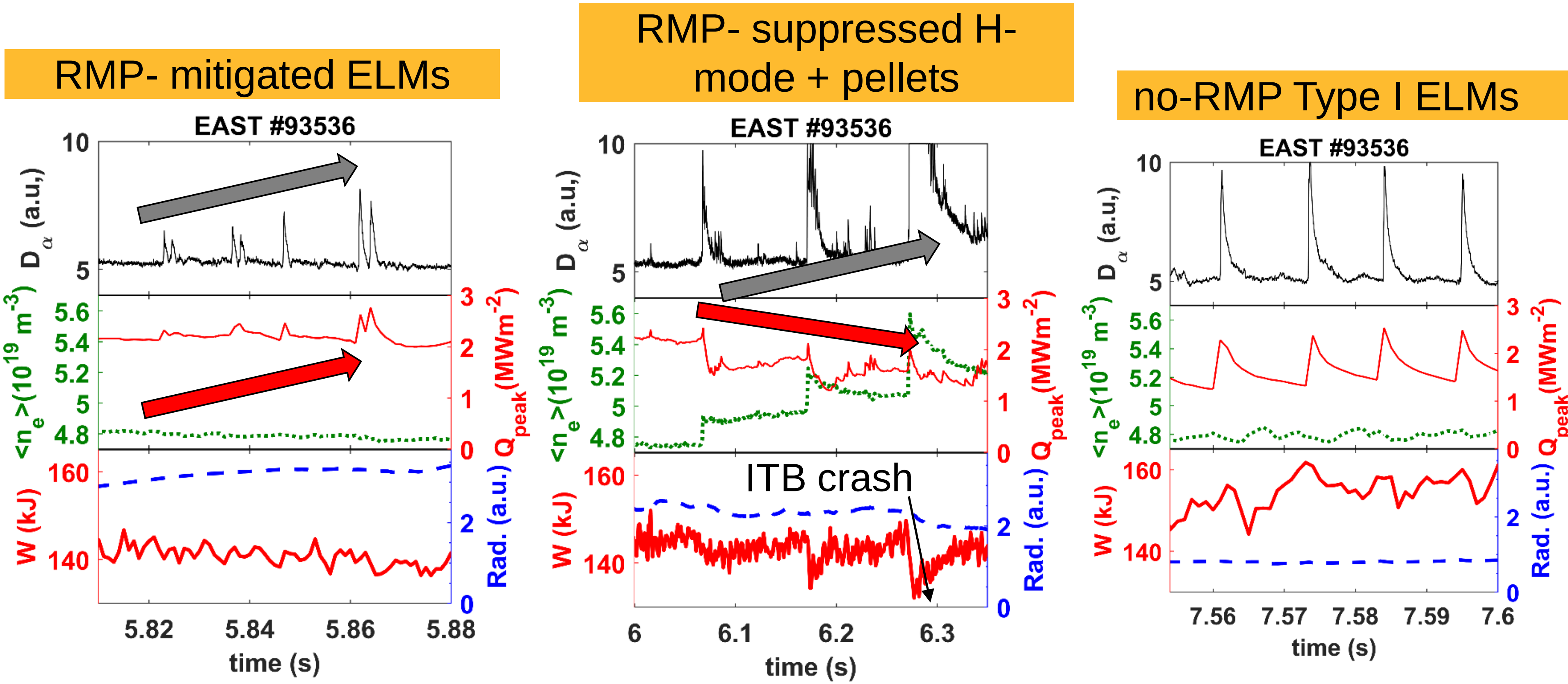
- ❑ Fuelling by gas or pellets used to vary plasma density in suppressed-ELM H-modes ($N_e > 0.6\ N_{GW}$ → mitigated ELMs)
- ❑ LFS shallow penetration pellets causes MHD events ≠ ELMs



Compatibility of ELM suppression and shallow pellet fuelling key issue for ITER

Pellet-triggered MHD in *n* = 4 suppressed-ELM H-modes

- ❑ Pellets cause plasma energy drop due to core MHD (ITB crash) → edge power fluxes very low ≠ ELMs (similar to AUG findings)



- ❑ Density increase by pellets reduces outer divertor peak heat flux

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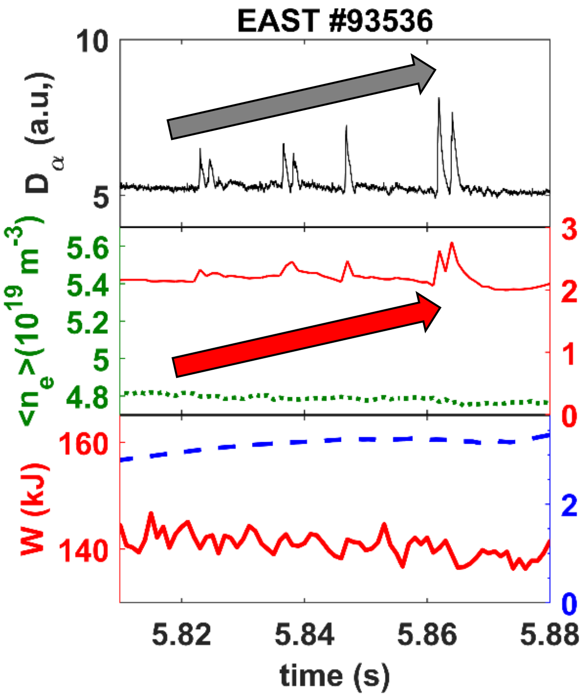
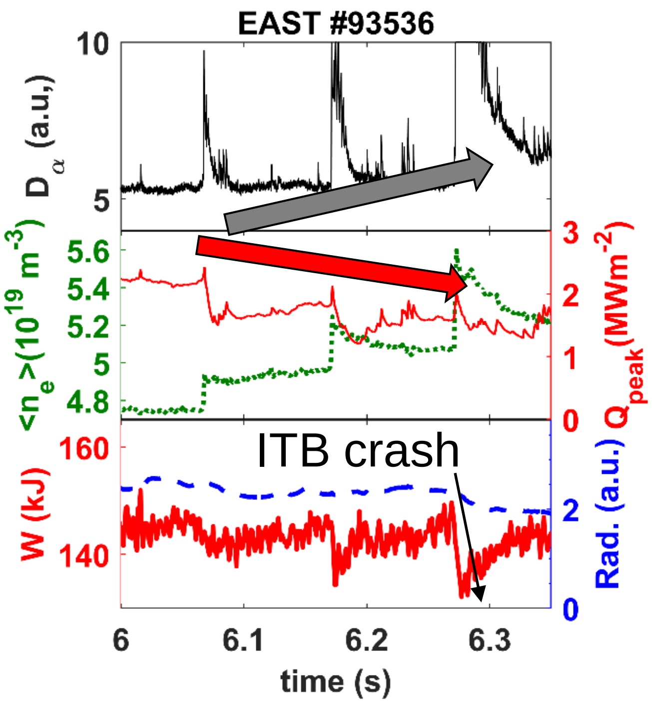
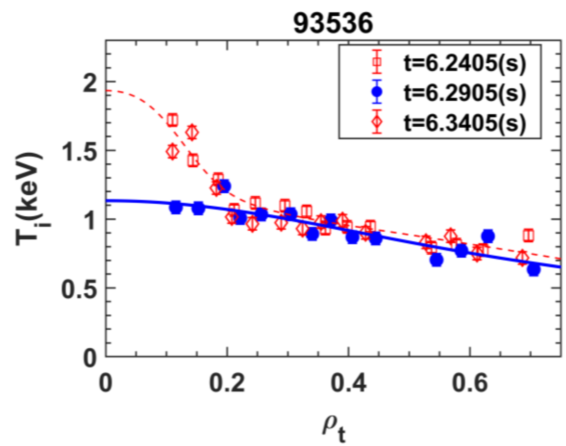
RMP- mitigated ELMs



RMP- suppressed H-mode + pellets



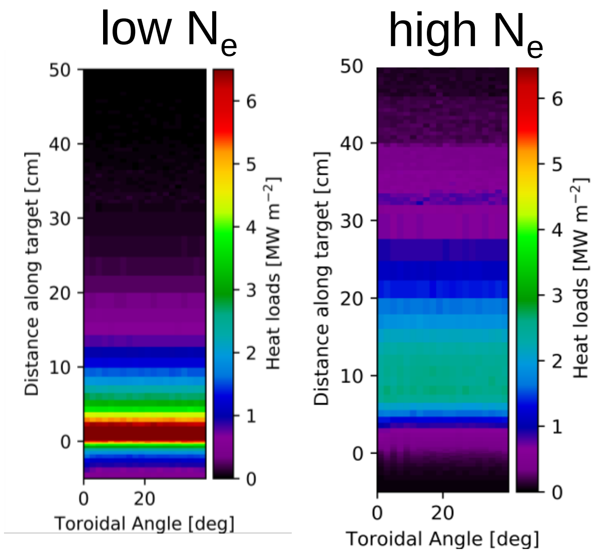


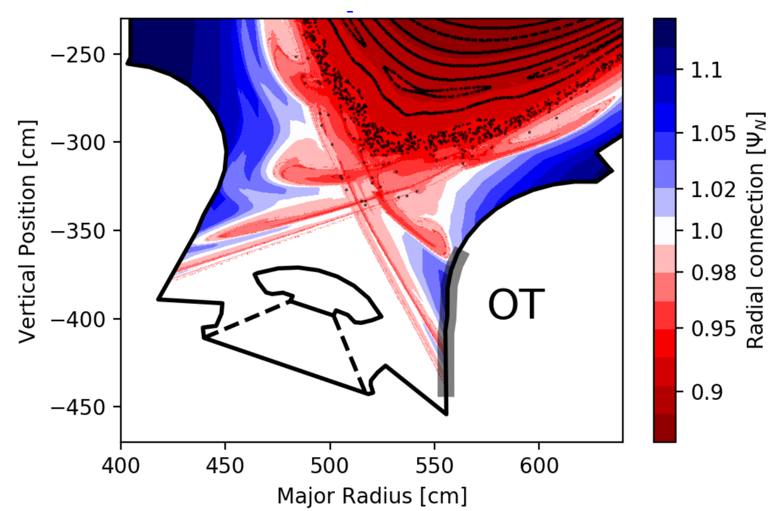
- ❑ Density increase by pellets reduces outer divertor peak heat flux

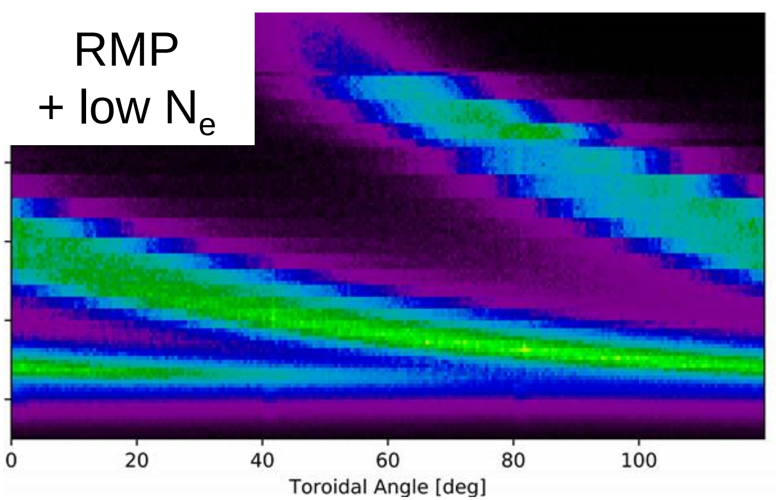
Stationary divertor heat flux control

Control of divertor heat flux with RMPs

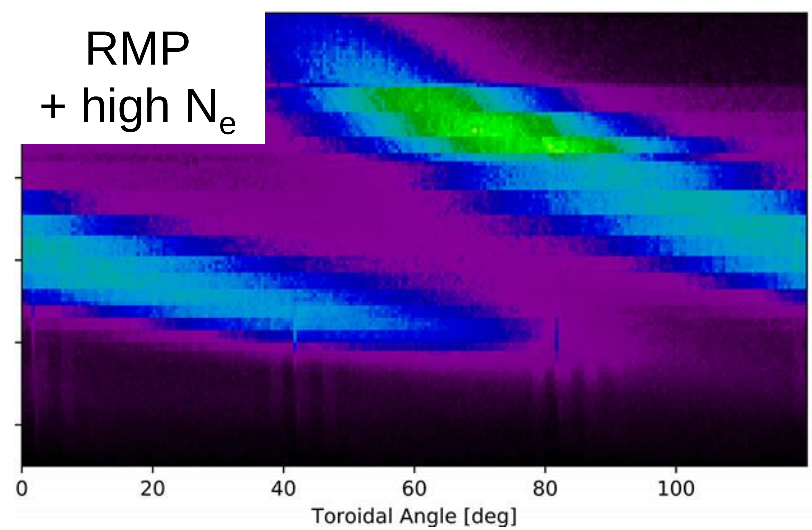
- 3-D magnetic field structure (RMPs) impacts access to high recycling/radiative divertor conditions for off-separatrix lobes





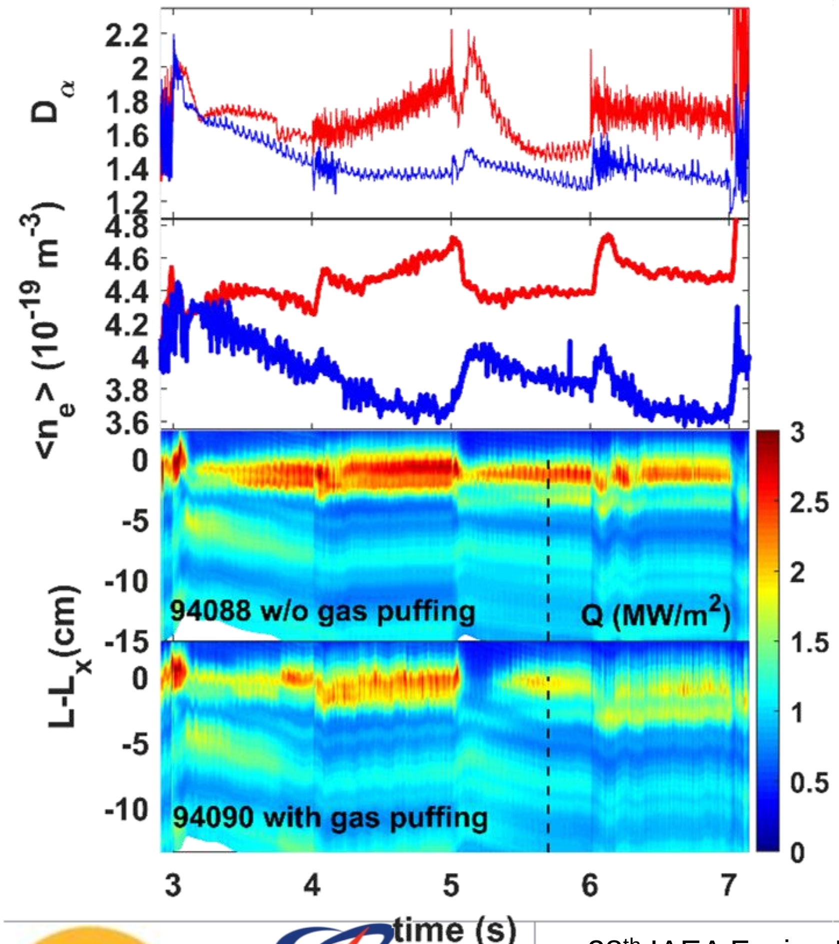


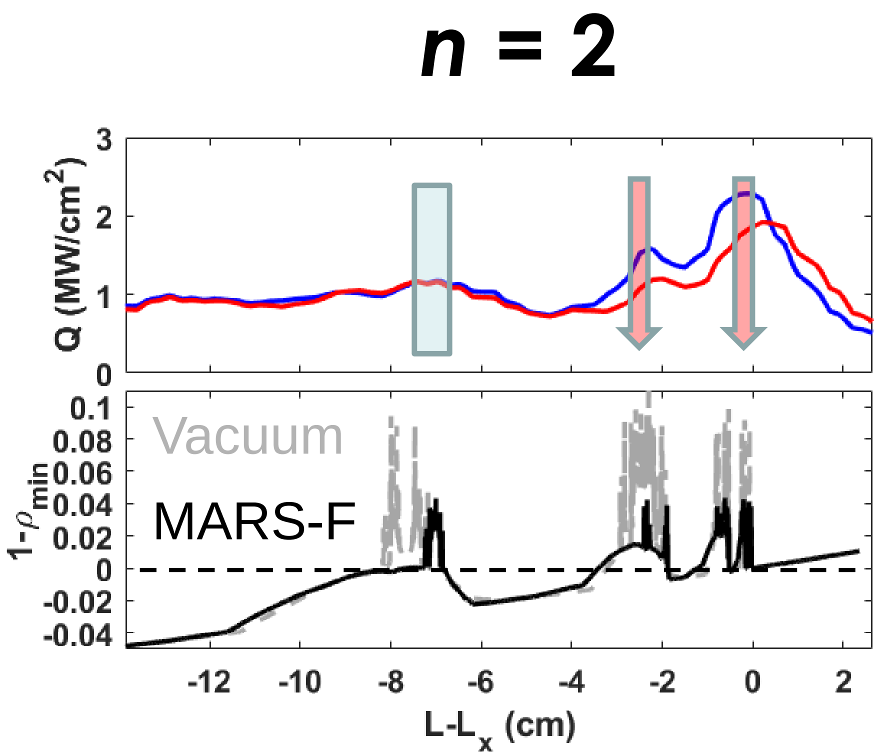
ITER PFPO-1 EMC3-Eirene modelling [H. Frerichs, PRL 2020 and this conference]



EAST divertor heat flux control with n = 2 RMPs

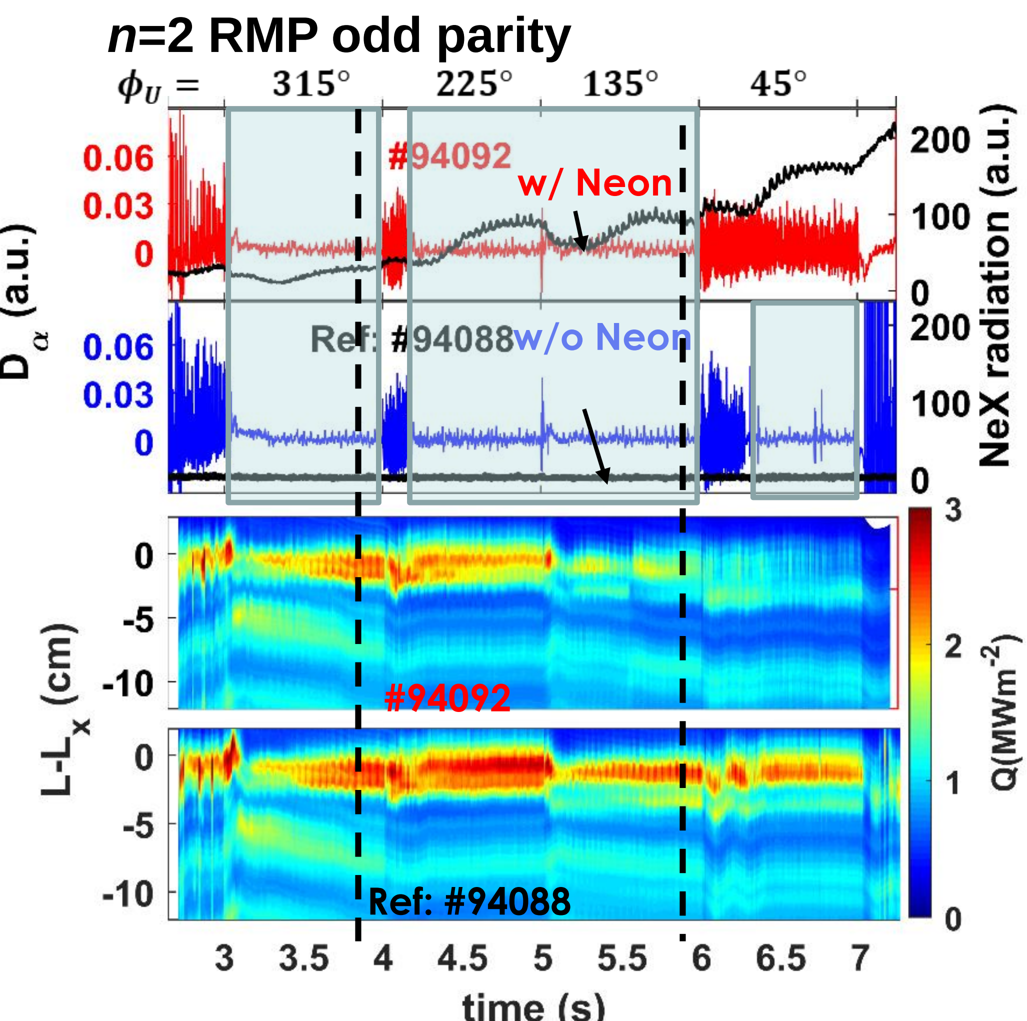
- Near-separatrix q_{div} reduction by gas fuelling but no effect on off-separatrix lobes for suppressed-Elm H-modes

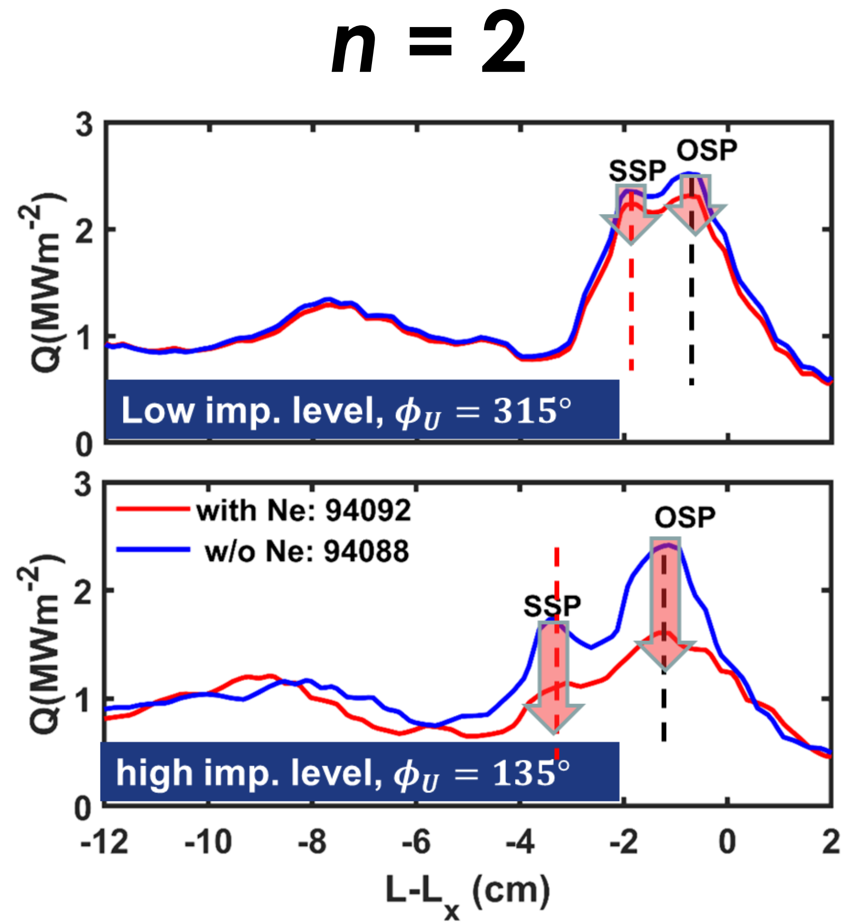




EAST divertor heat flux control with *n* = 2 RMPs

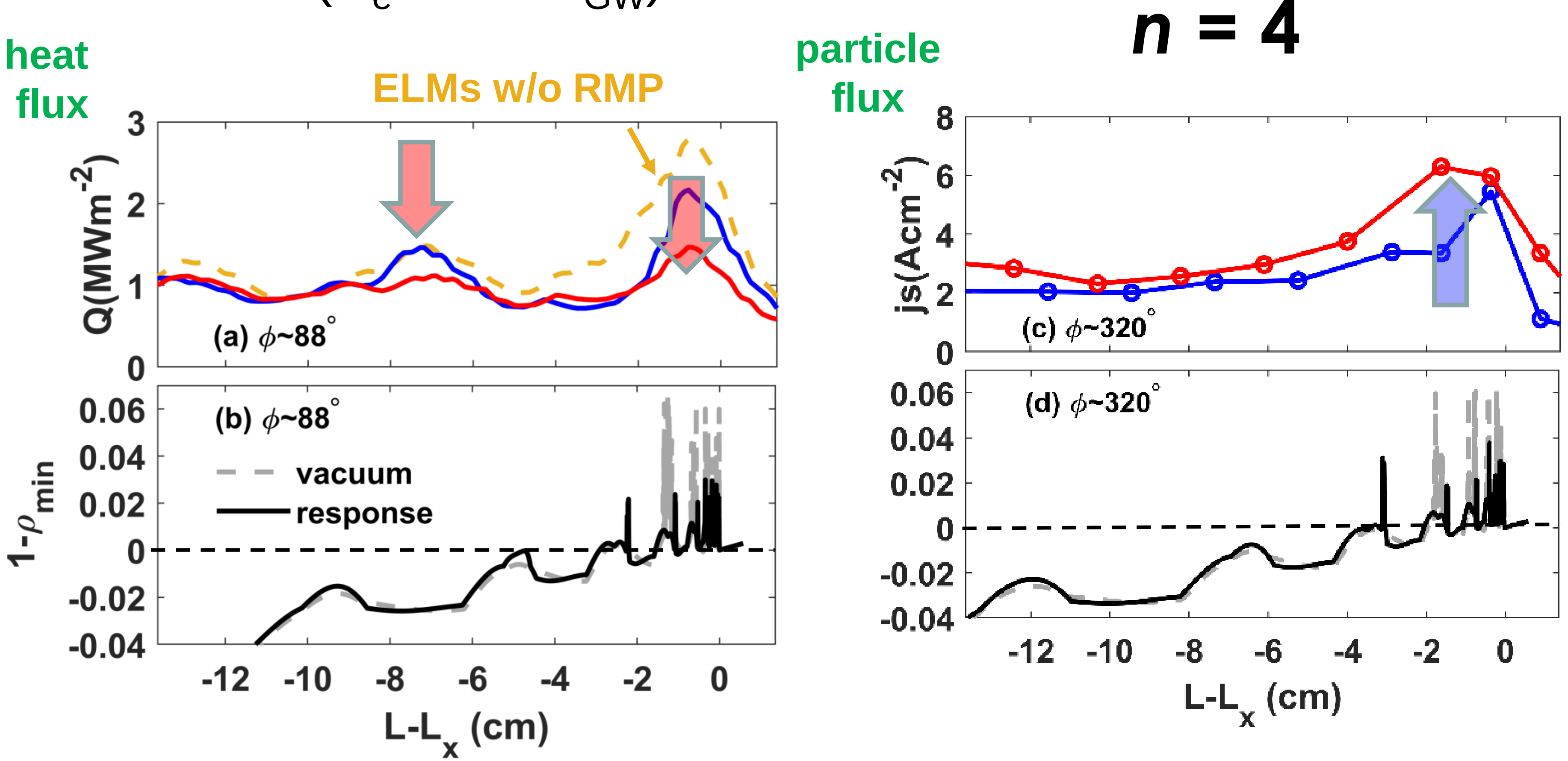
- Similar results obtained with divertor Neon seeding → off-separatrix power fluxes unaffected by seeding





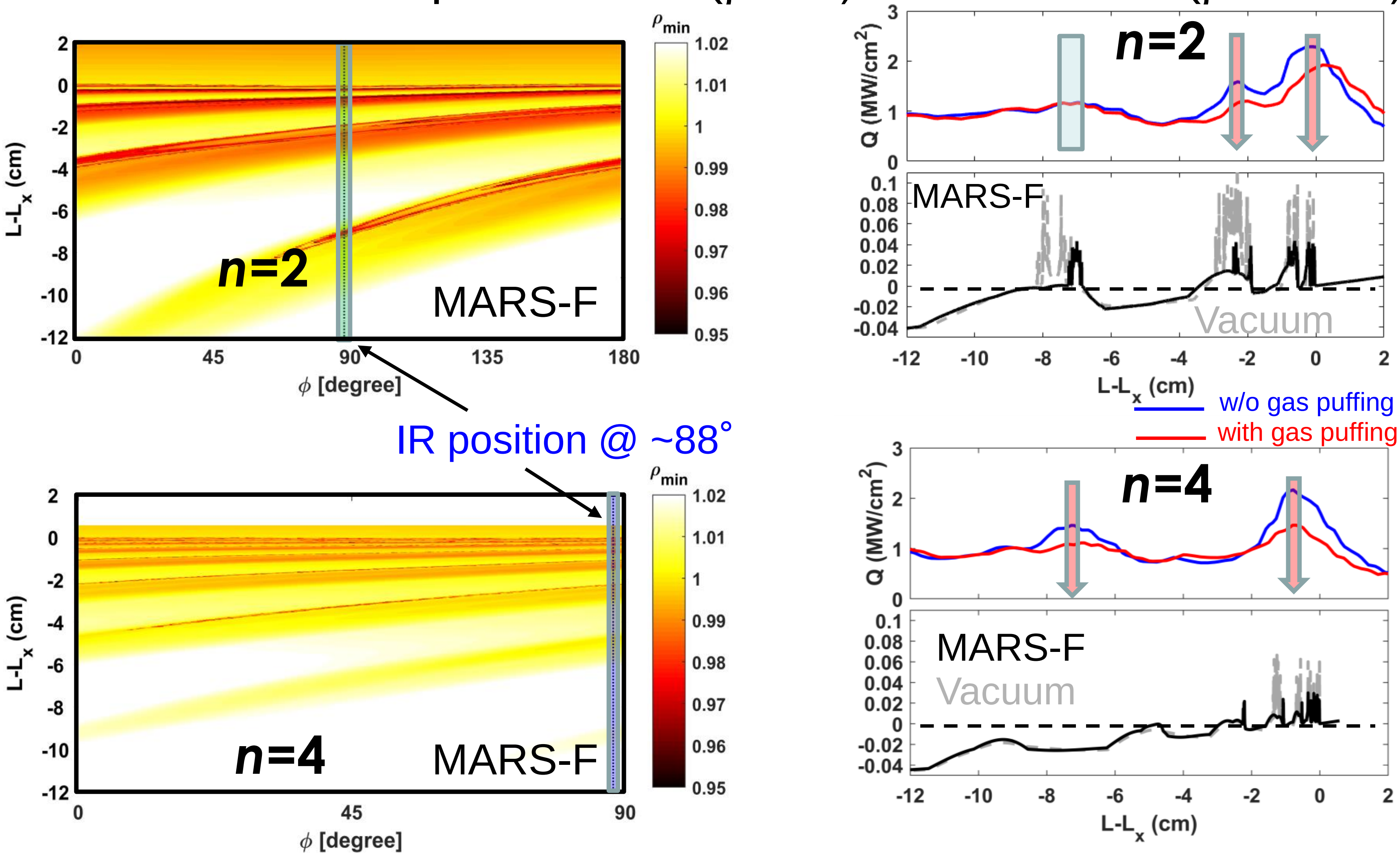
EAST divertor heat flux control with *n* = 4 RMPs

- Gas fuelling reduces heat at both near-separatrix and off-separatrix lobes for $n = 4$
- Divertor remains in high recycling regime for ELM-suppressed conditions ($N_e \leq 0.6\ N_{GW}$)



EAST divertor heat flux control and plasma response

- Off-separatrix lobe heat flux reduction for n = 4 consistent with shallower field line penetration ($\rho \approx 1$) versus n = 2 ($\rho \approx 0.98$)

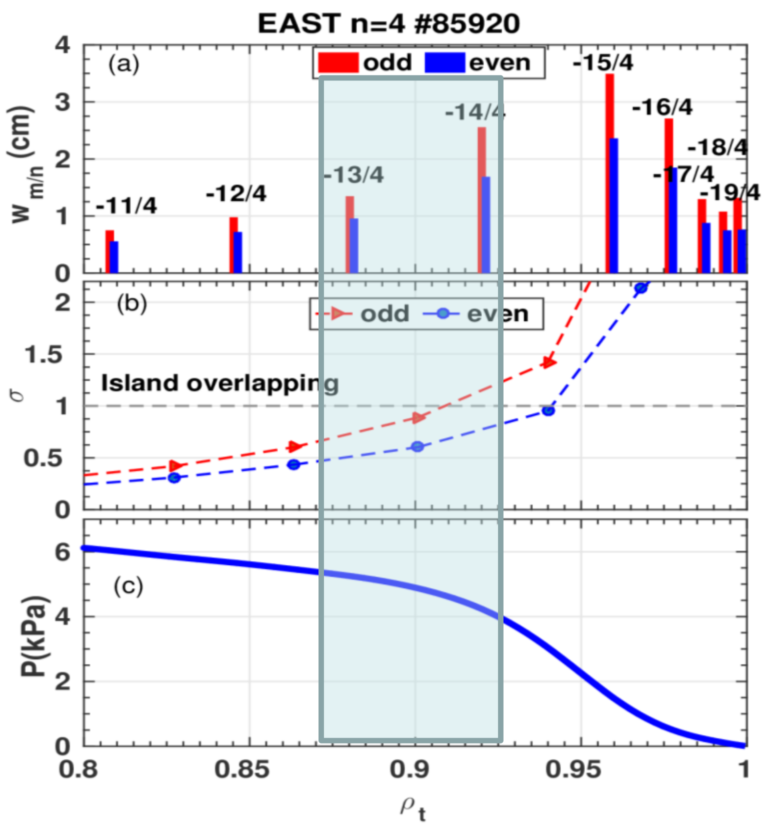


Summary and Conclusions

- Full suppression of ELMs in ITER-like low input torque plasmas with *n* = 4 RMPs demonstrated for 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 and low n_W
  - ELM suppression window is consistent with modelling of plasma response to RMP using MARS-F code
- *n* = 4 RMP suppressed ELM H-mode provides a promising integrated scenario for ITER high Q operation
  - High energy & particle confinement with suppressed ELMs
  - Compatibility with pellet fuelling (without ELM triggering)
  - Control of divertor heat flux by high recycling/radiative divertor operation for separatrix and off-separatrix lobes
- Further R&D required to strengthen physics basis for extrapolation to ITER and to optimize further scenario at EAST

Back-up slides

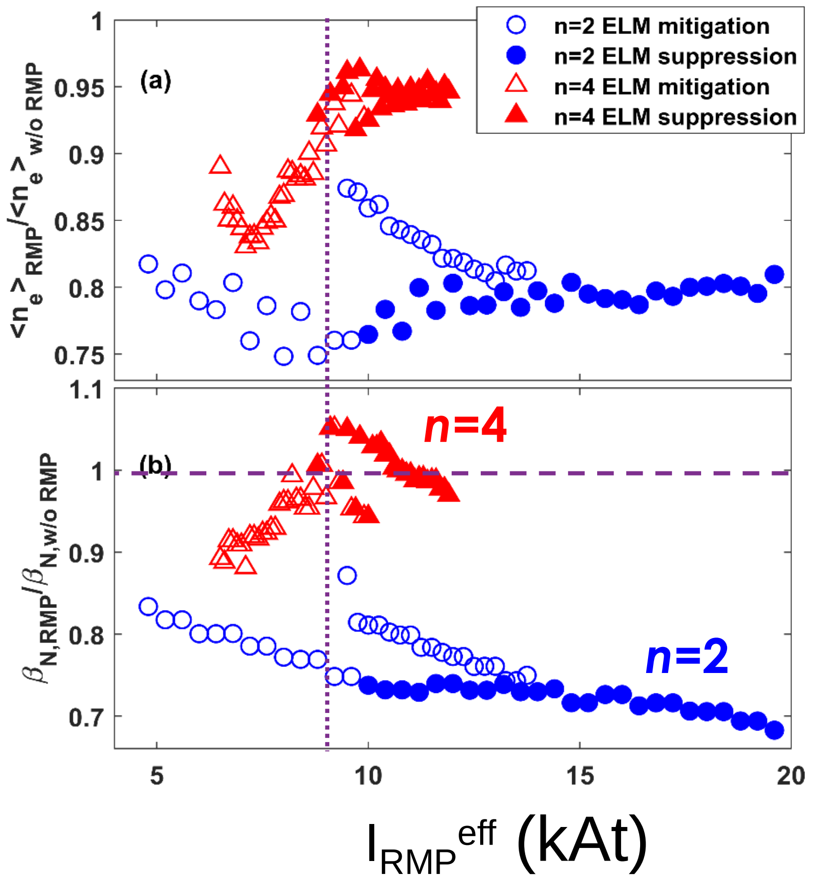
Odd *n*=4 coil configuration provides stronger edge resonant magnetic field with plasma response



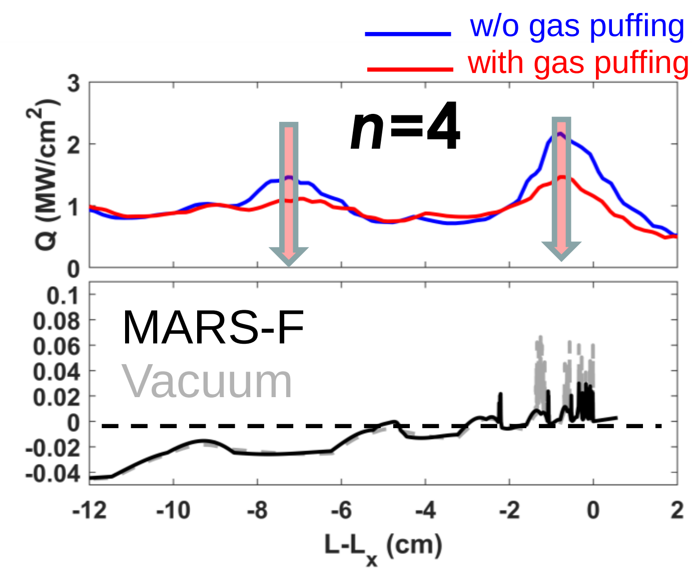
- Resonance is **stronger** for **odd** coil configuration, when resistive MHD **plasma response** is taken into account using MARS-F
  - Stronger **shielding** in the **even** case
  - Stronger **kink-like** resonant response in the **odd** case
  - **All edge** resonant harmonics are stronger in the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

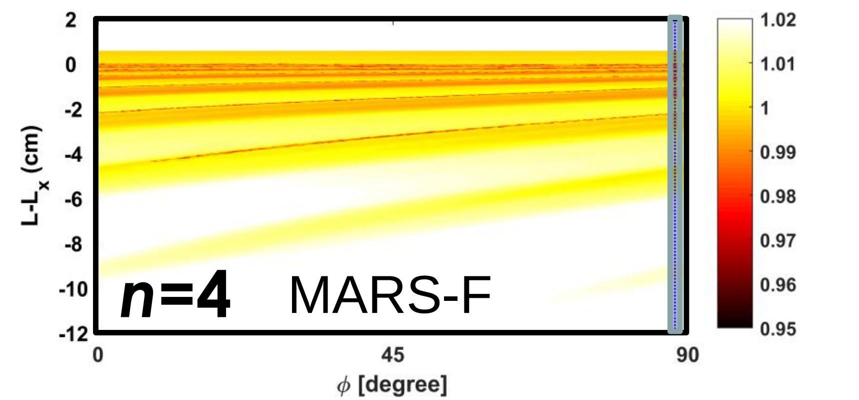
Optimum ITER high Q scenario integration of ELM suppression with *n* = 4 RMP in EAST

- ❑ High energy and particle confinement maintained

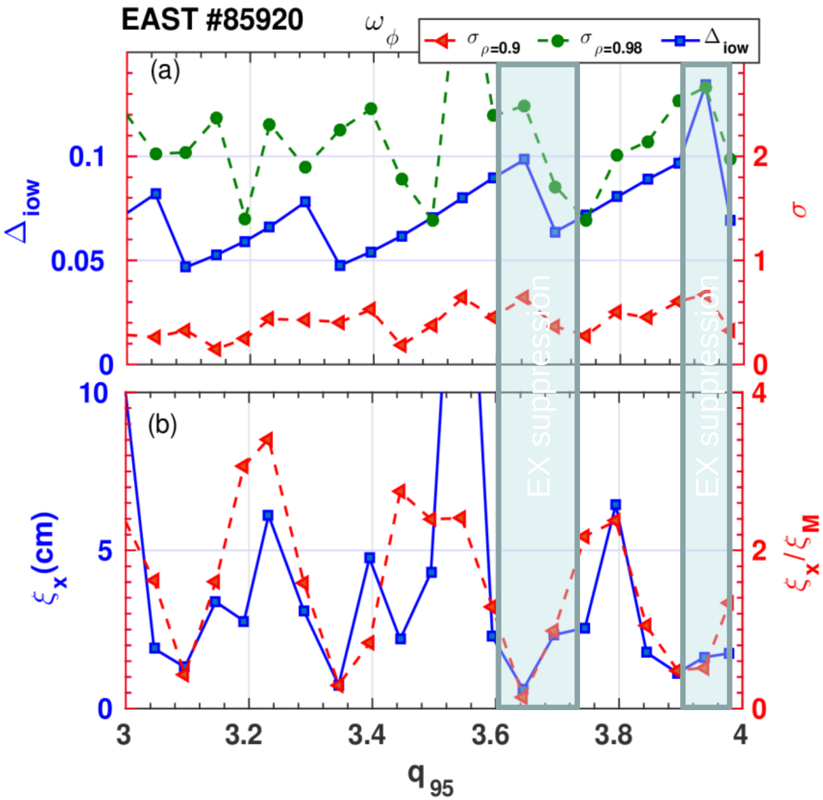


- ❑ Good control of divertor power fluxes (separatrix + off-separatrix)





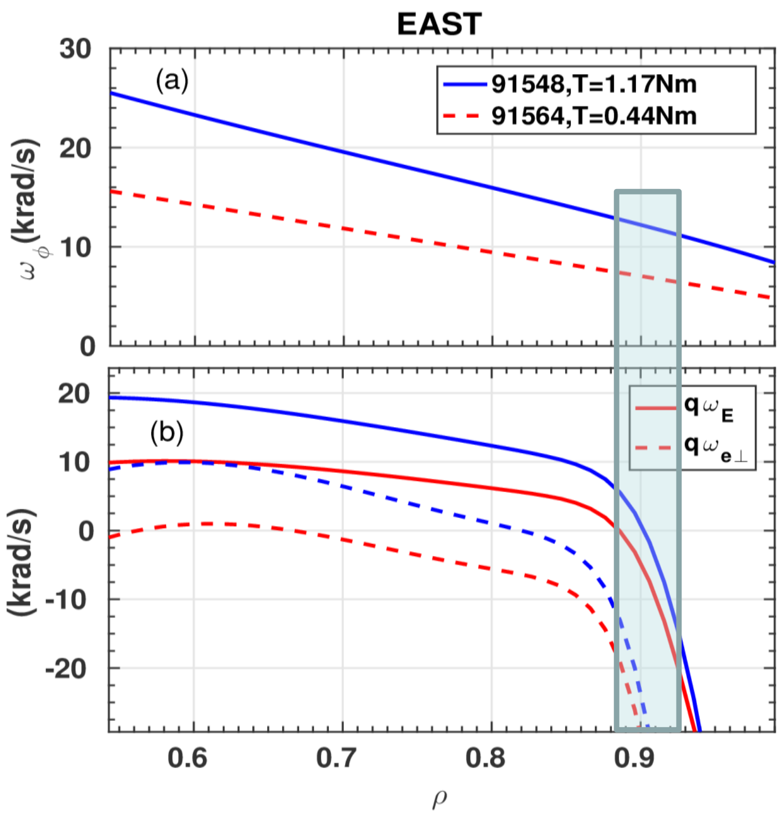
Modeling result demonstrates the resonant q_{95} window for n=4 ELM suppression

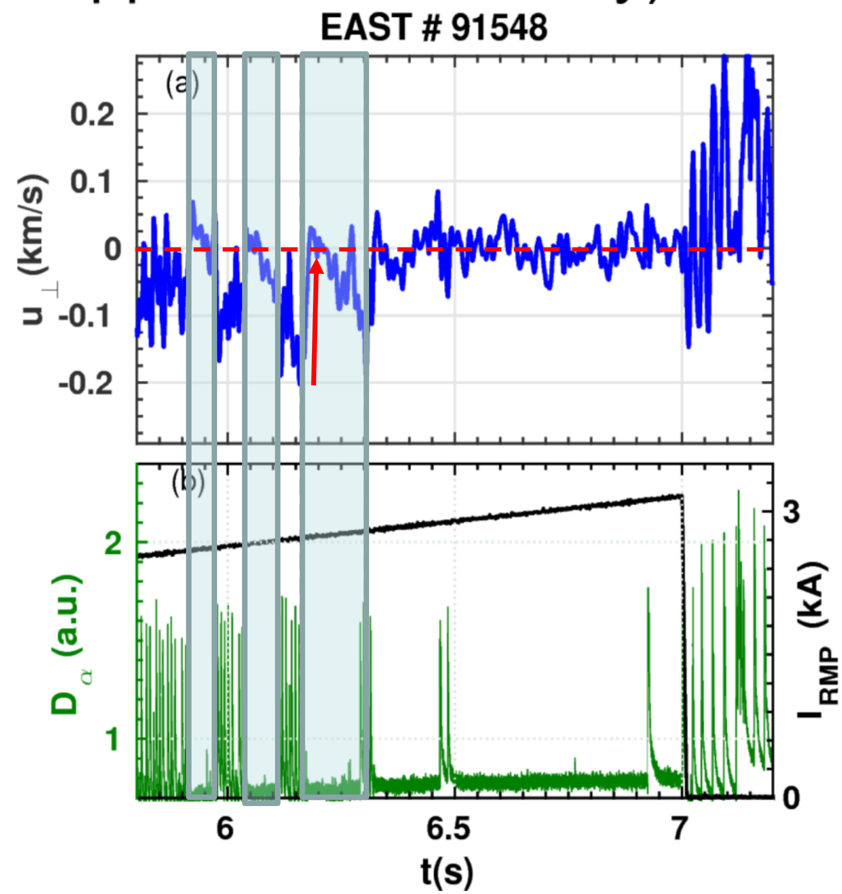


- Edge resonances, indicated by different criteria, taking into account **plasma response** using **MARS-F** code, shows a similar dependence on q_{95}
  - Stochastic layer width, Chirikov parameter near pedestal top, x point displacement, edge RMP amplitude
- Multiple resonant peaks observed in the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

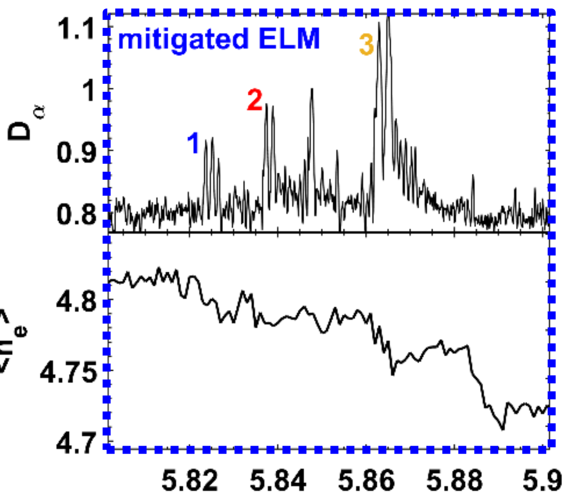
ELM suppression with n = 4 and rotation

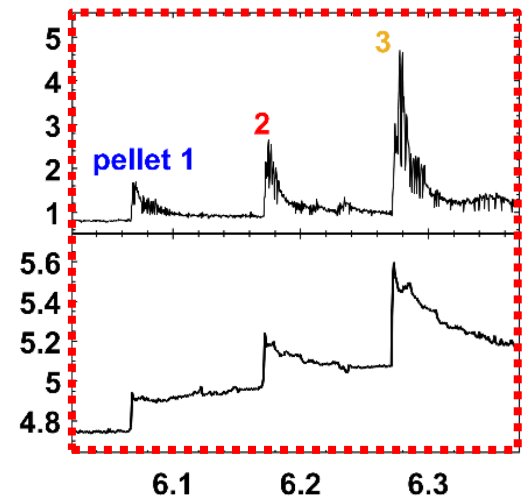
- Co-/counter-NBI used to explore physics of rotation impact on ELM suppression → low ExB (and not $v_{\perp,e}$) in pedestal during suppression (AUG, DIII-D, …)
- $u_\perp$ (density fluctuation at ρ≈1 by Doppler Reflectometry) = 0 during ELM suppression



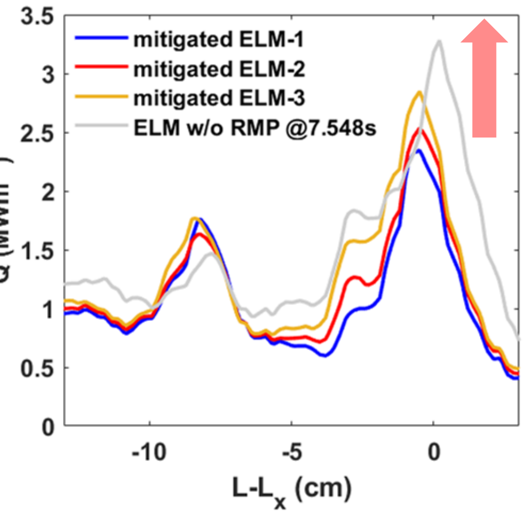


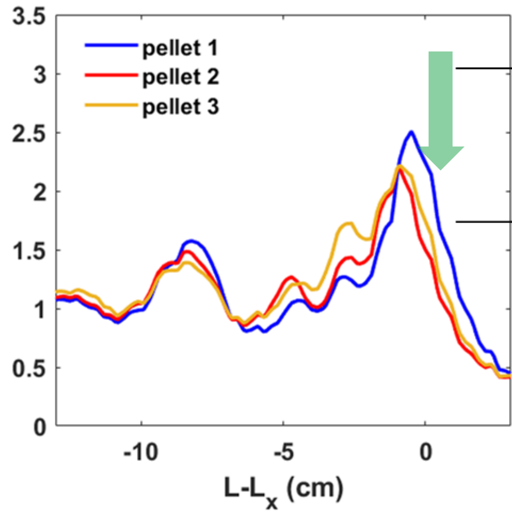
Details on pellet induced events with RMPs





- Large D_α spikes followed pellet injections are **MHD pellet-specific activities**, rather than large ELMs
- The **power flux magnitude** with increased D_α size are:





spikes from	D_α size	power flux magnitude
mitigated ELMs	↑	↑
injected pellets		↓