Effect of resonant magnetic perturbations on low collisionality discharges in MAST and a comparison with ASDEX Upgrade

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on behalf of

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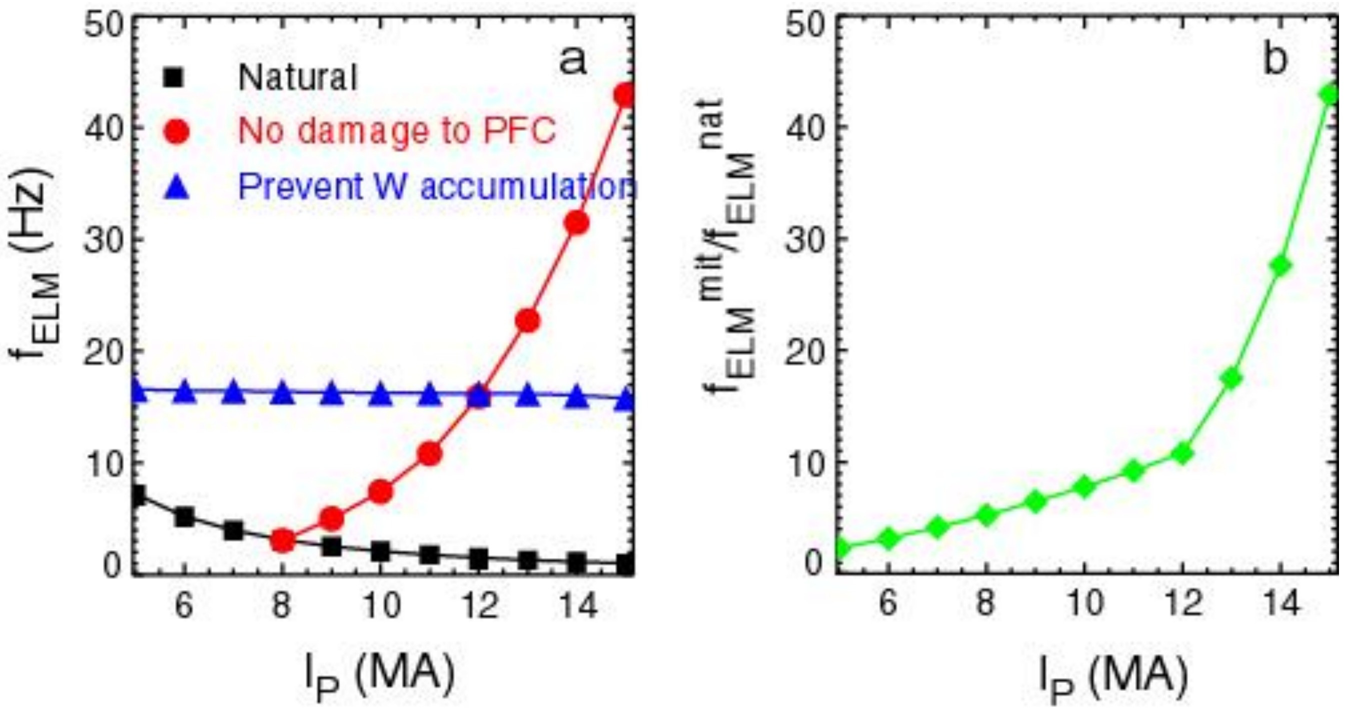
CCFE is the fusion research arm of the **United Kingdom Atomic Energy Authority**

Motivation

• The natural type-I ELMs frequency in ITER is predicted to be too low to avoid either W accumulation at low I_P or damage to PFCs at high I_P

Required increase in ELM frequency



Motivation

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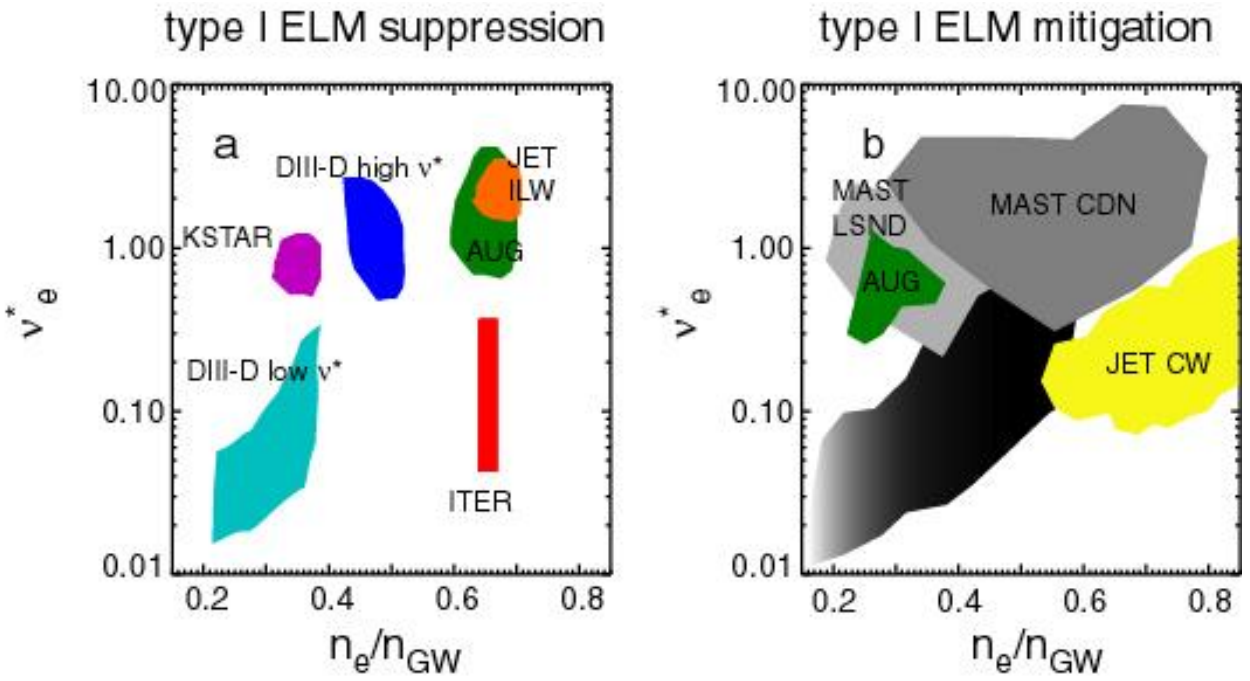
• One technique that has been shown to reduce the size of ELMs is the application of Resonant Magnetic Perturbations (RMPs)

• Need to understand how RMPs control ELMs to make predictions for ITER – a good way of doing this is by making in depth comparison across devices



Situation at IAEA 2012

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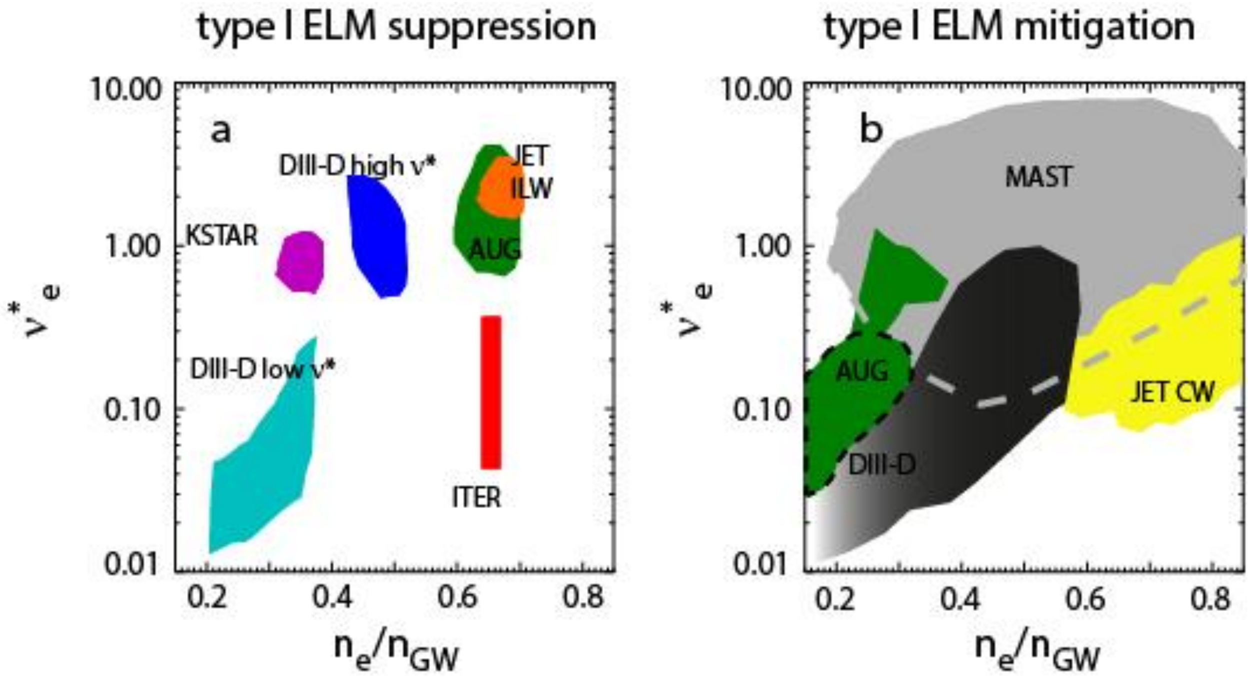
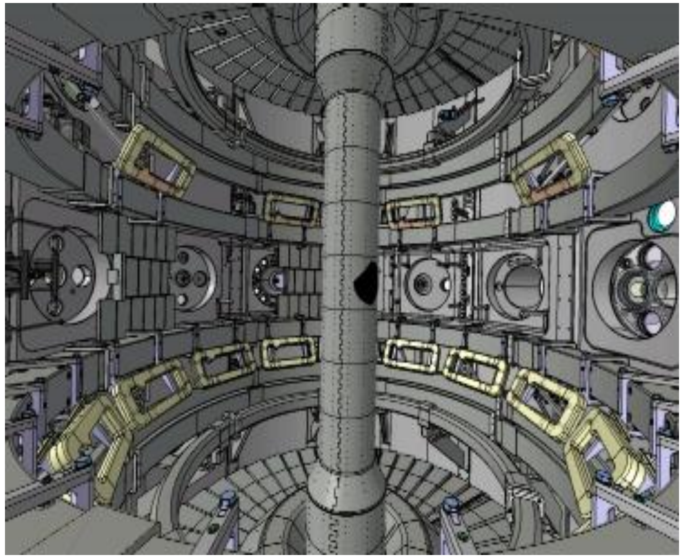


New low collisionality results from AUG and MAST

Non-axisymmetric coil system



MAST is equipped with
- 6 coils in the upper row
- 12 coils in the lower row

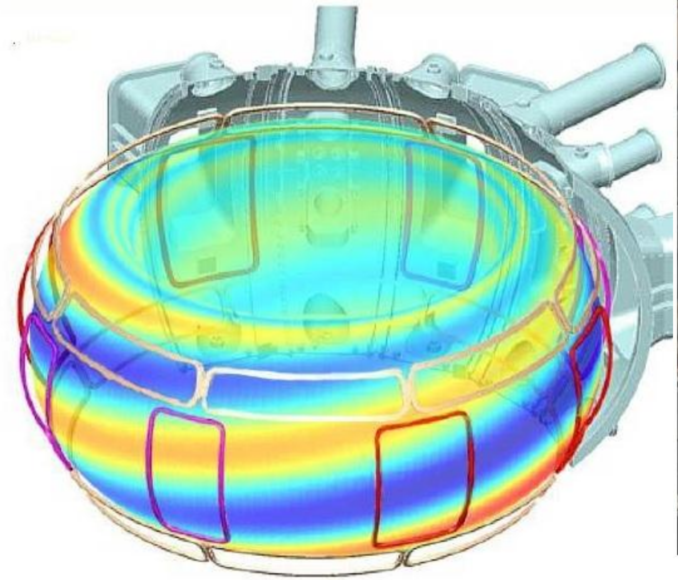
Can produce configurations

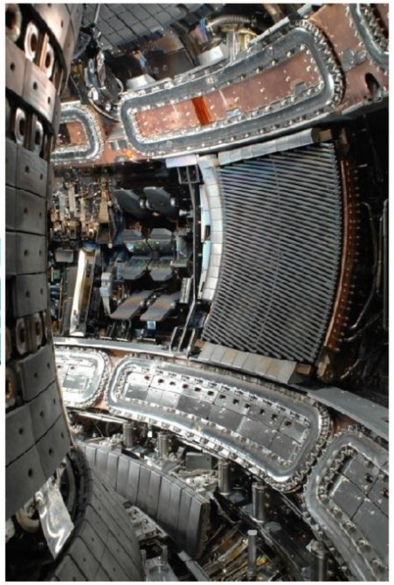
n=1,2,3,4 or 6

AUG is equipped with
- 2 rows of 8 coils each

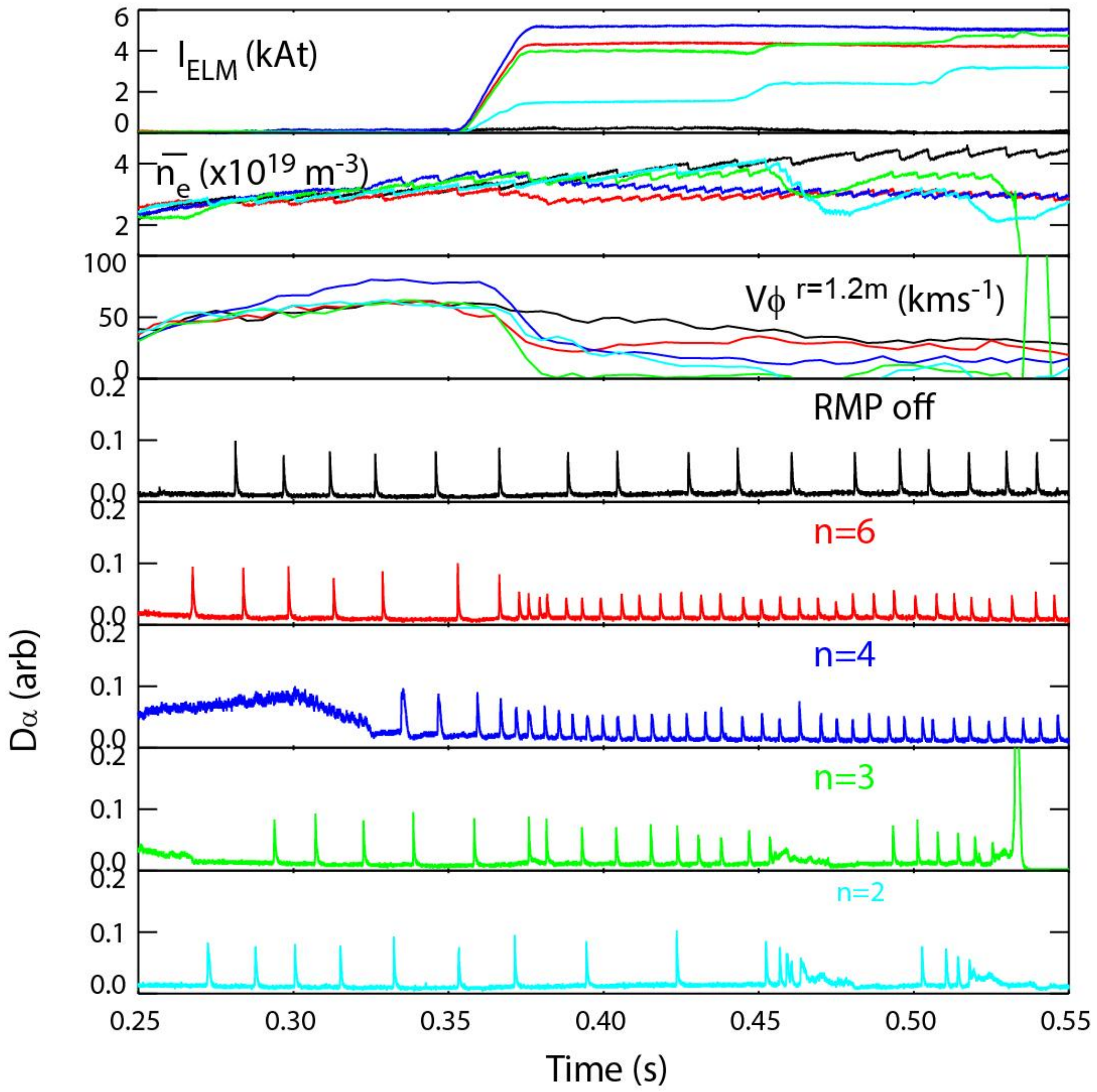
Can produce configurations

n=1,2 or 4





Examples of ELM mitigation - MAST

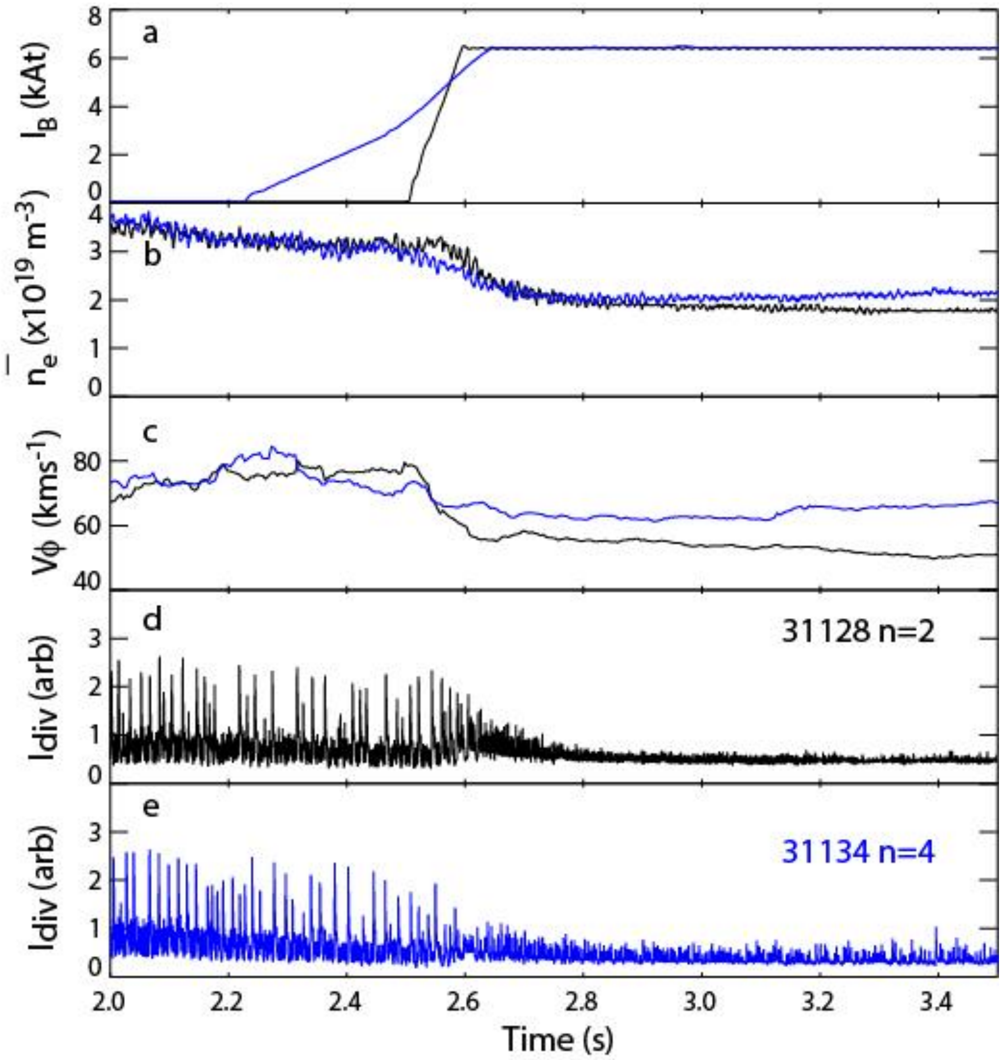


All n_{RMP} can mitigate ELMs

Very small window for n=2 between ELM mitigation and H-L transition

RMPs cause a density pump out and braking of toroidal rotation

Examples of ELM mitigation - AUG



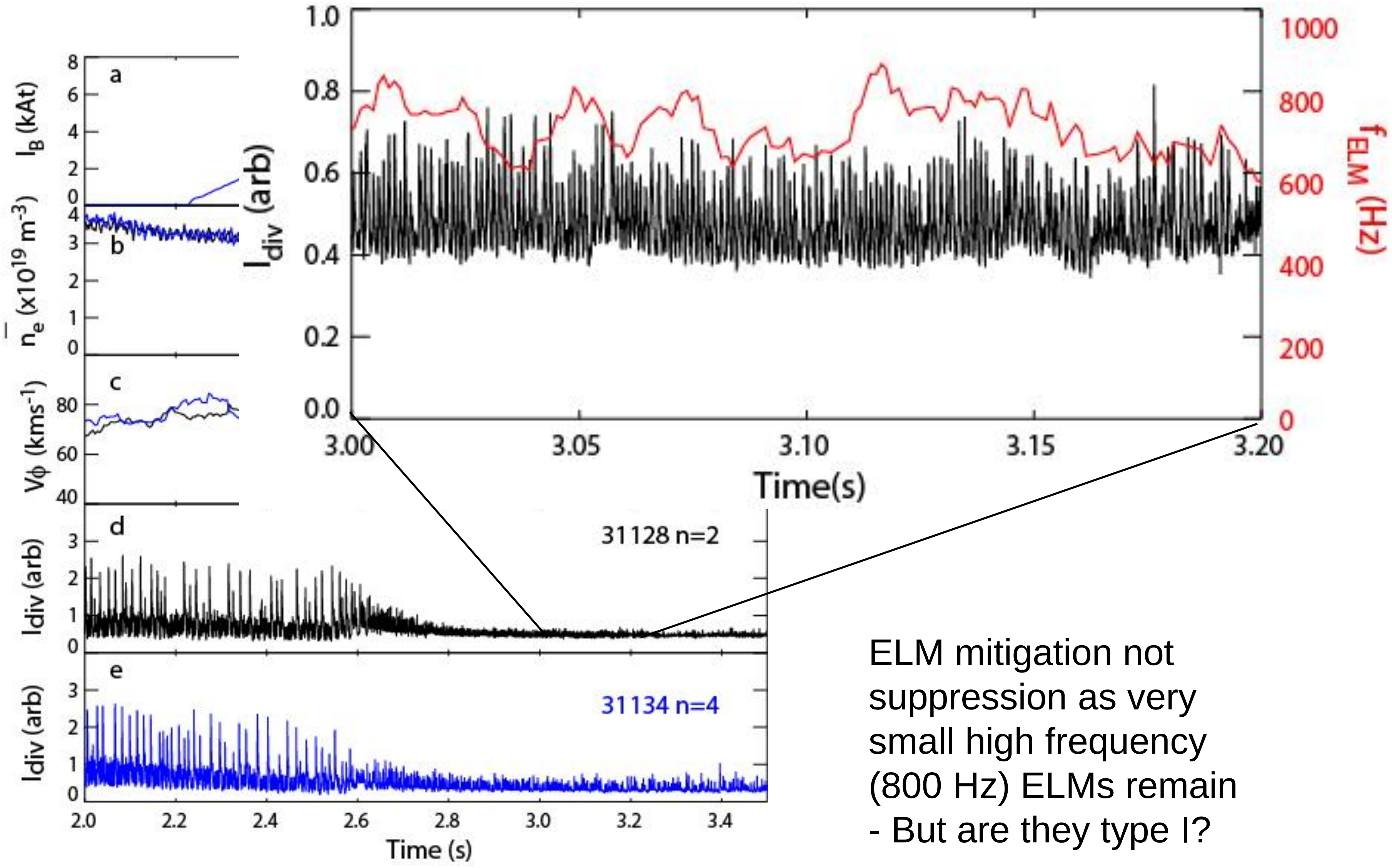
ELM mitigation has been achieved with n_{RMP}=1, 2 and n=4 magnetic perturbations

Sustained ELM mitigation demonstrated with n_{RMP}=2 and 4

RMPs cause a density pump out and braking of toroidal rotation

W Suttrop EX/P1-23

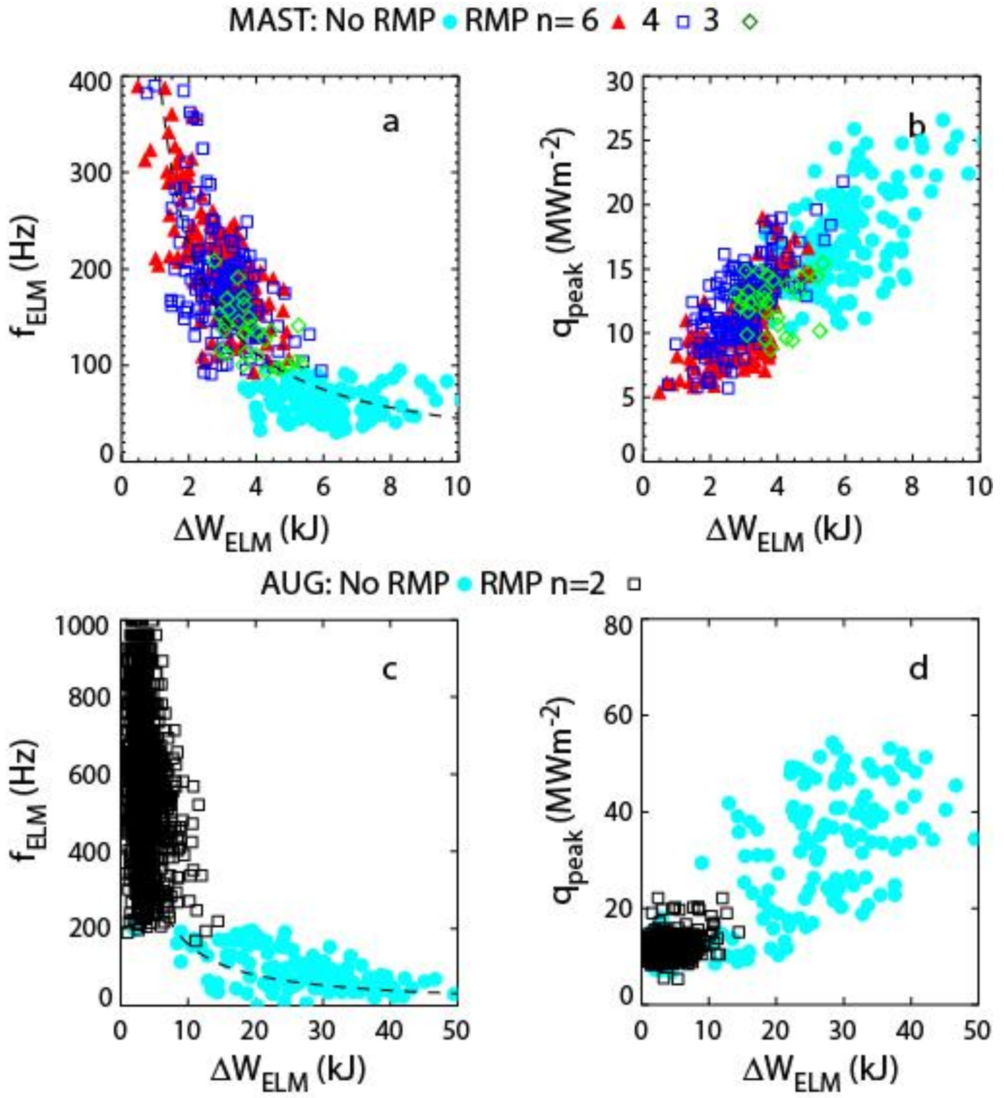
Examples of ELM mitigation - AUG



ELM mitigation not suppression as very small high frequency (800 Hz) ELMs remain
- But are they type I?

Pros of mitigation

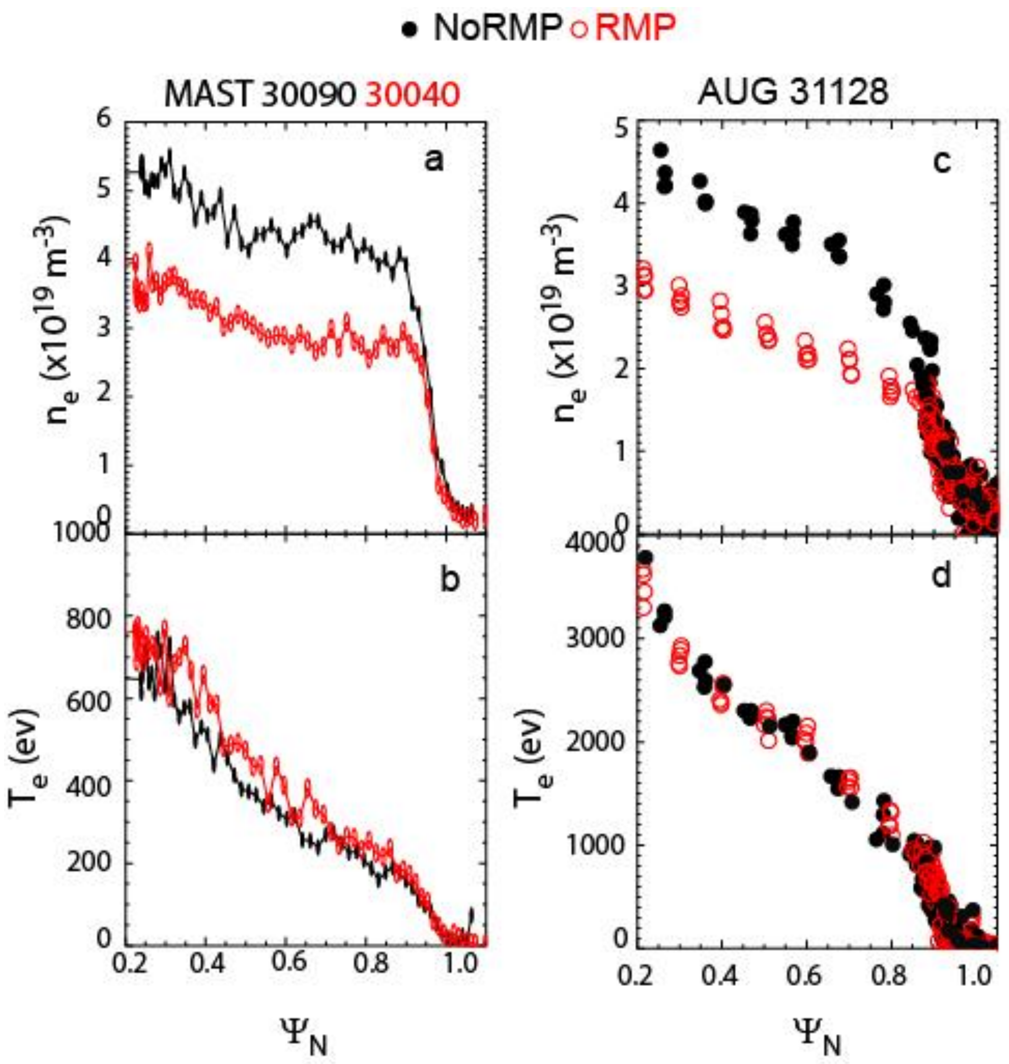
ELM mitigation decreases:



ΔW_{ELM}

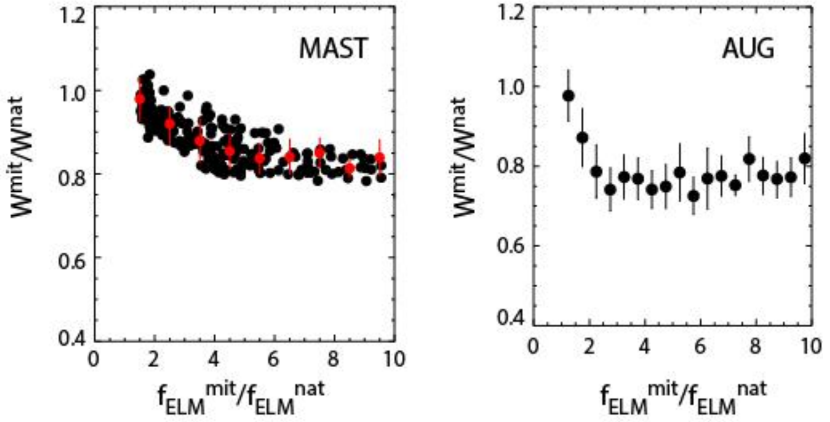
target heat load

Cons of mitigation



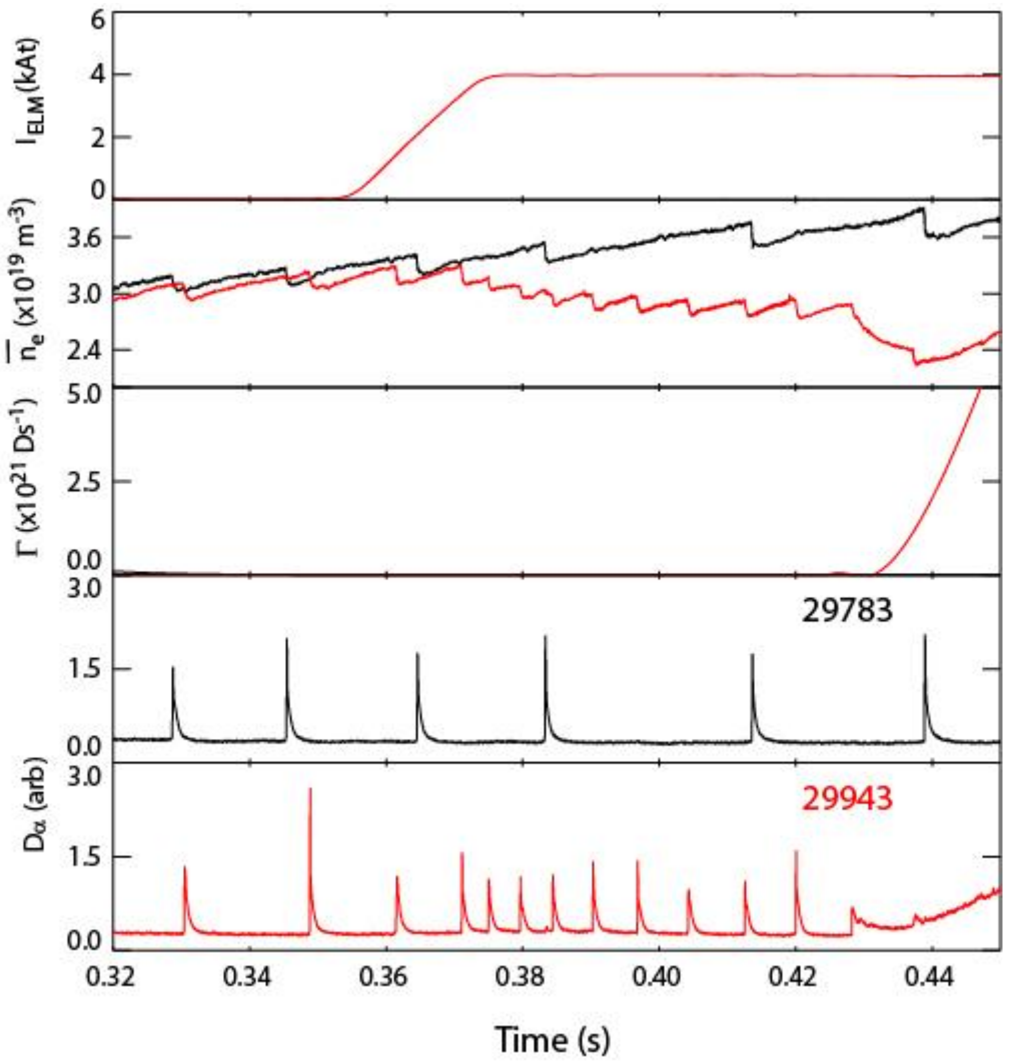
The problem is that a density pump out occurs across the entire plasma while T_e ~ constant

- leading to a large drop in confinement



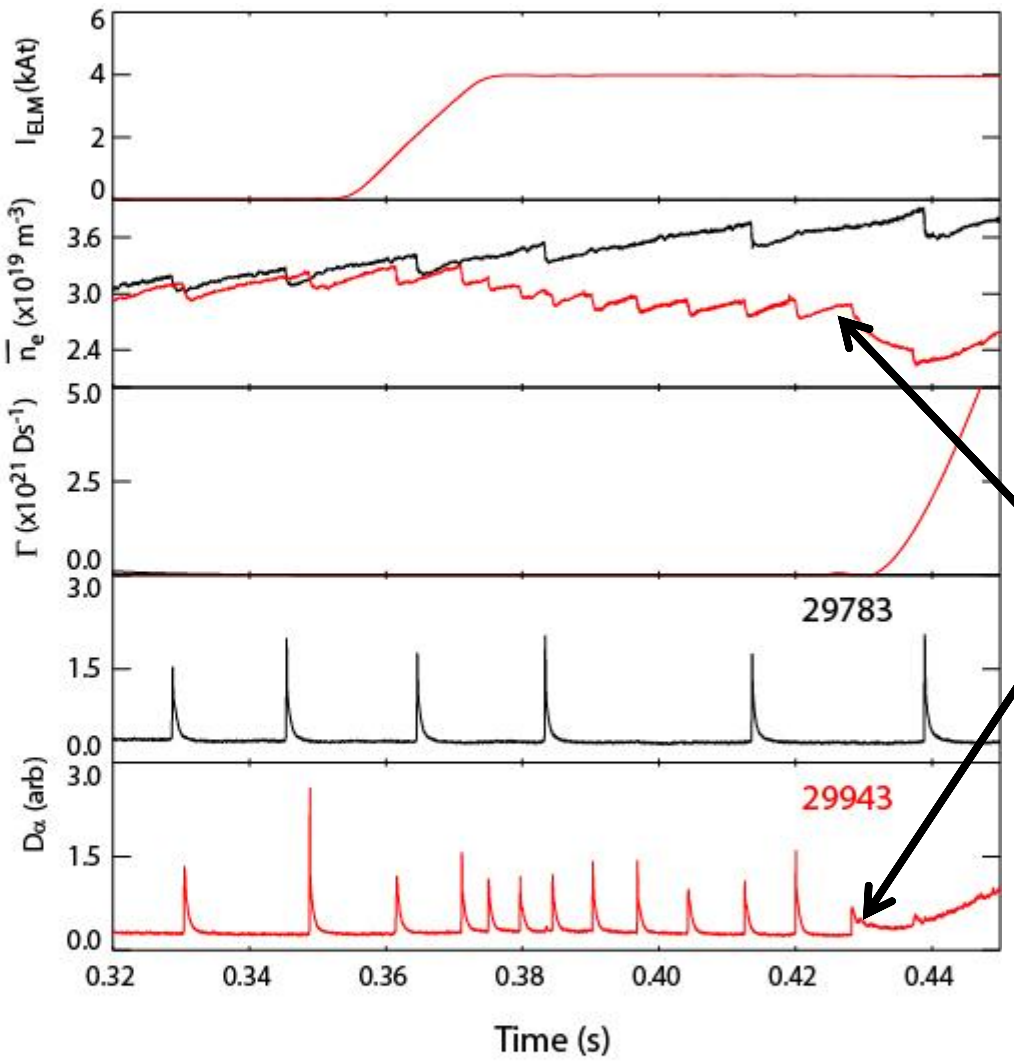
Minimising the effect of the RMPs on confinement

Minimising the density pump out - MAST



The application of RMPs to a shot that is not fuelled in the H-mode period leads to an increase in ELM frequency and reduction in the plasma density

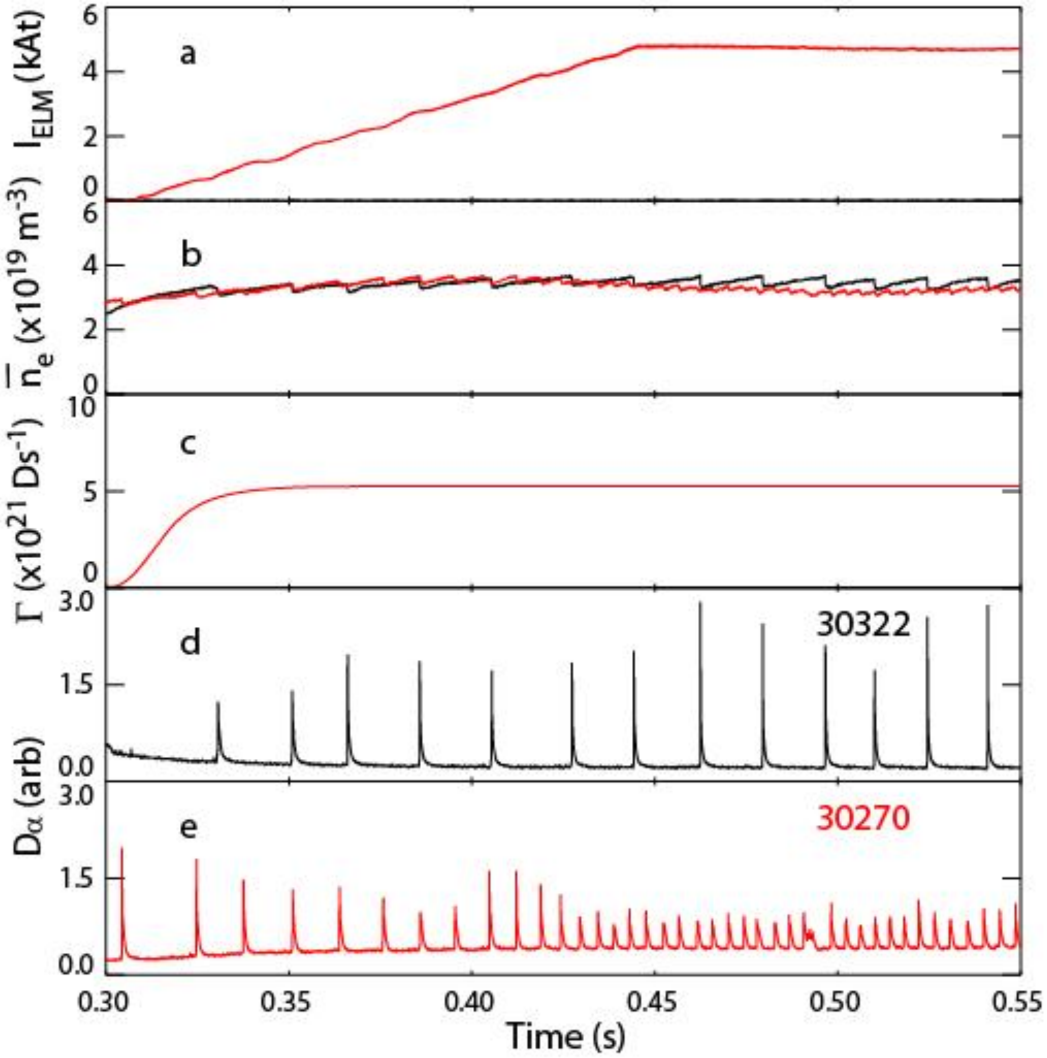
Minimising the density pump out - MAST



The application of RMPs to a shot that is not fuelled in the H-mode period leads to an increase in ELM frequency and reduction in the plasma density

The density pump out is often large enough to lead to a back transition to L-mode

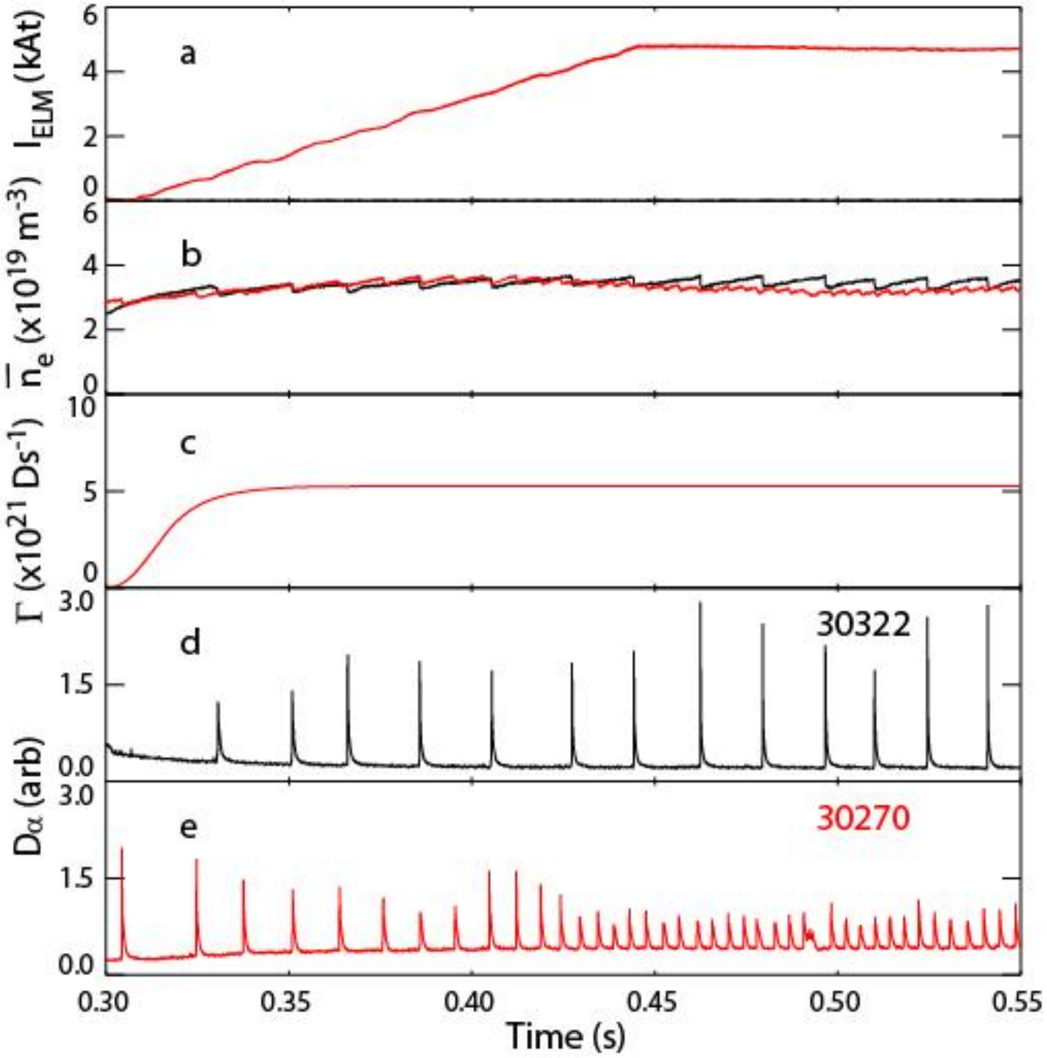
Minimising the density pump out - MAST



Application of n=6 RMPs to LSND

Using a feed forward waveform and slow I_{RMP} ramp can keep at constant density

Minimising the density pump out - MAST



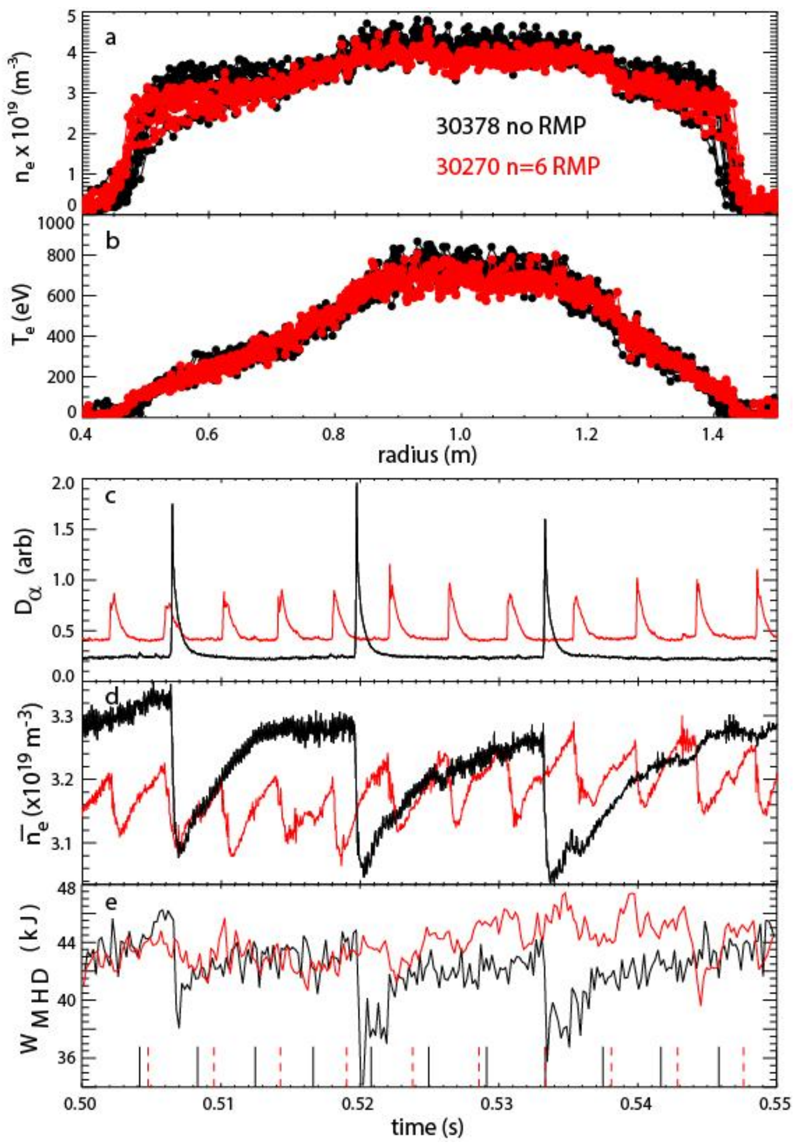
Application of n=6 RMPs to LSND

Using a feed forward waveform and slow I_{RMP} ramp can keep at constant density

Also possible using pellets

M Valovic EX/P4-36

Restoring the density - MAST



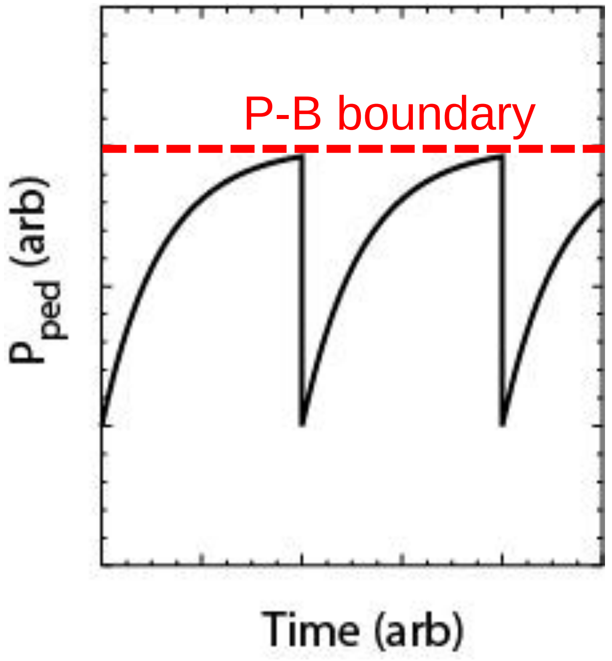
Application of n=6 RMPs to LSND

The density and temperature profiles show that not only has the core density been recovered but also the edge density

The ELM averaged line average density and stored energy are similar

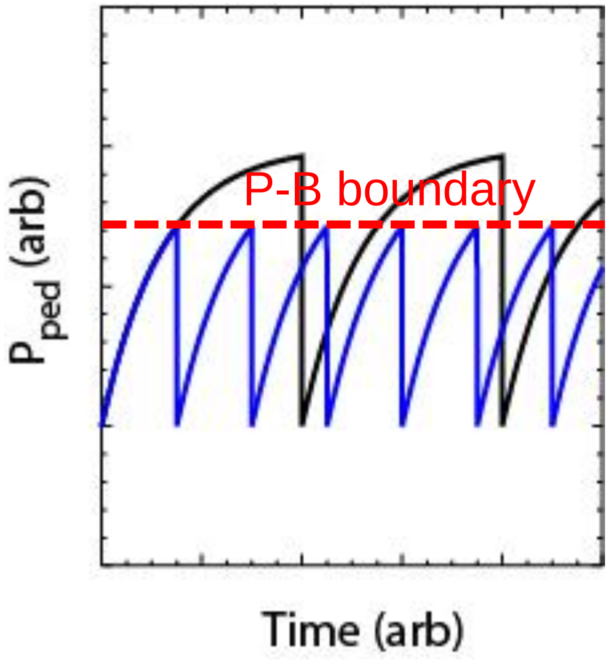
So mitigation achieved with little effect on stored energy

Pressure pedestal evolution - MAST



Natural ELM cycle – pressure pedestal evolves to a maximum value determined by the Peeling Ballooning modes stability boundary just before ELM crash

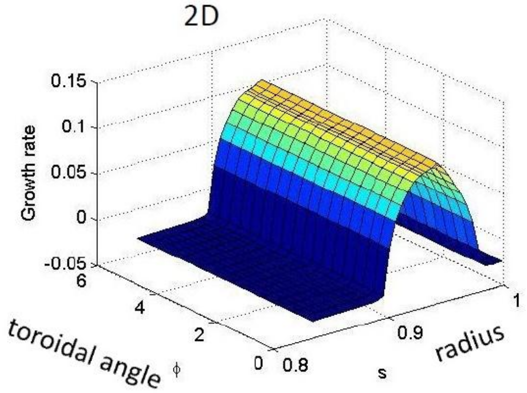
Pressure pedestal evolution - MAST

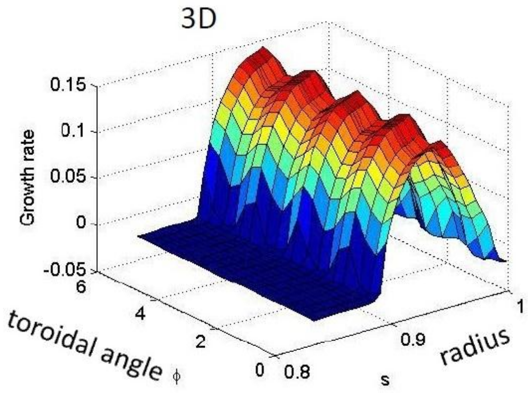


Application of RMPs leads to 3D distortions of plasma shape
-> produces regions of enhanced ballooning mode instability – reducing the PB boundary and hence triggering type I ELMs at lower P_{ped}

Infinite n ballooning stability calculated using COBRA from a VMEC equilibrium

C Ham et al., 'Tokamak equilibria and edge stability when non-axisymmetric fields are applied ' submitted to PPCF





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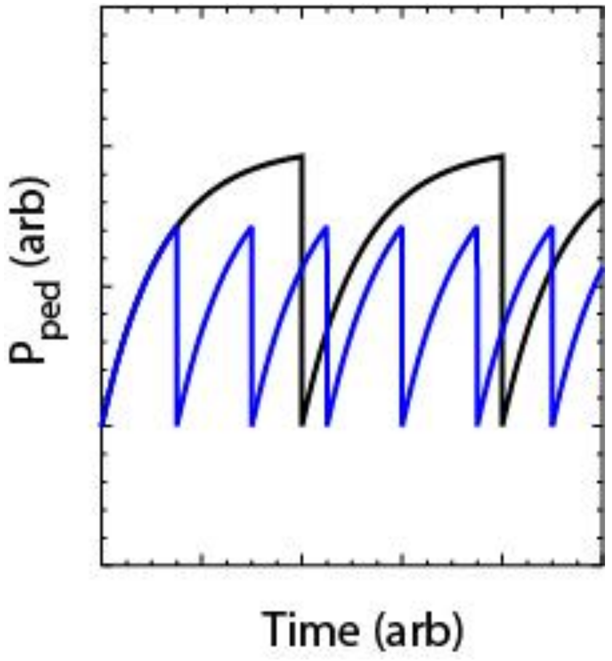

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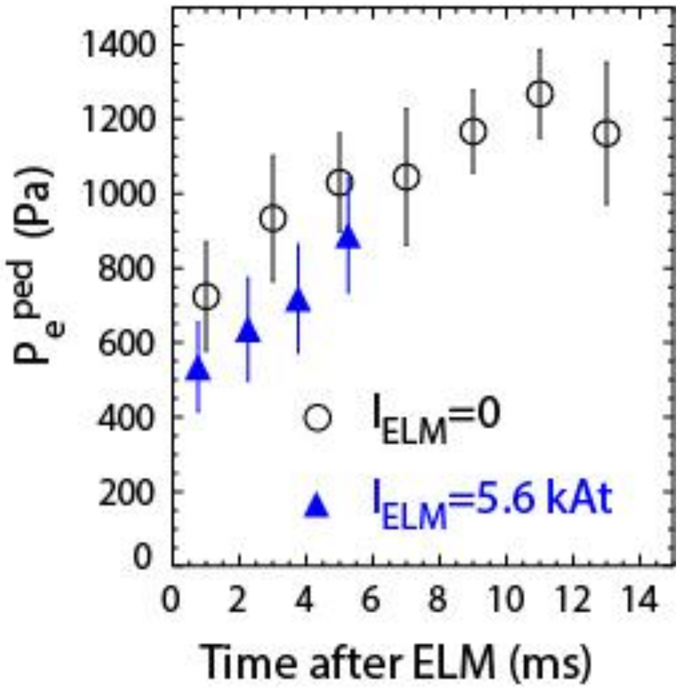
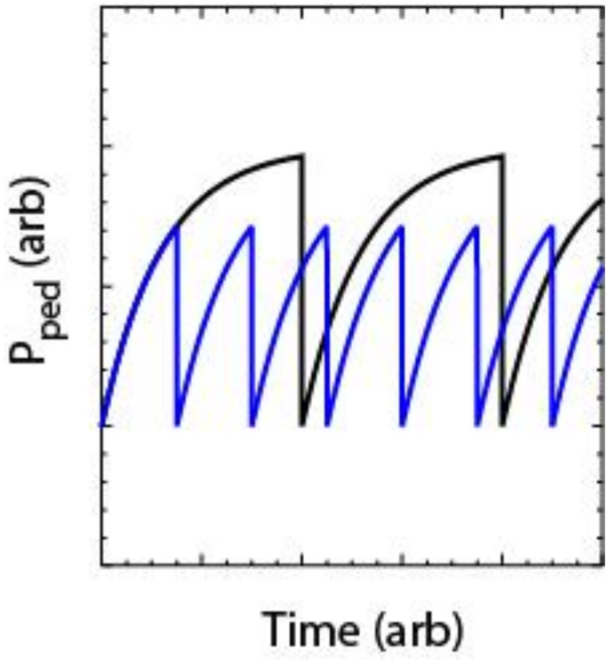
Previously observed on MAST



Pressure pedestal evolution - MAST



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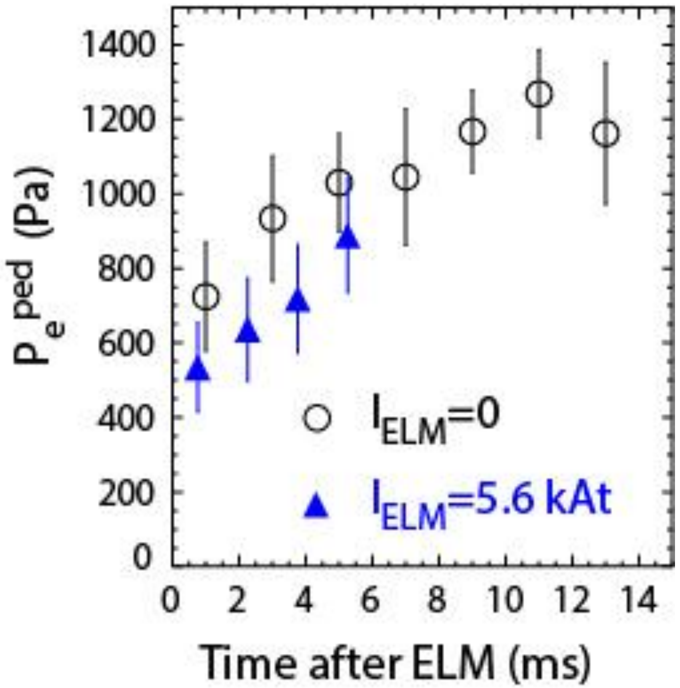
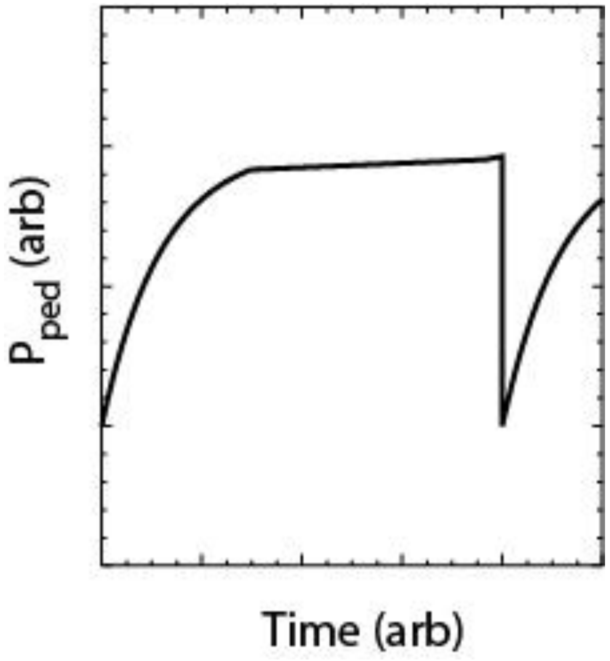


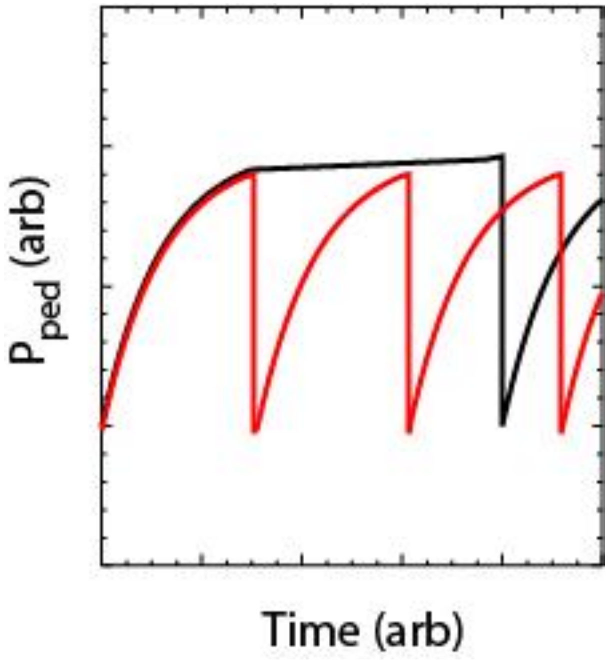
So how can P_{ped} stay the same and yet f_{ELM} increases?

Pressure pedestal evolution - MAST



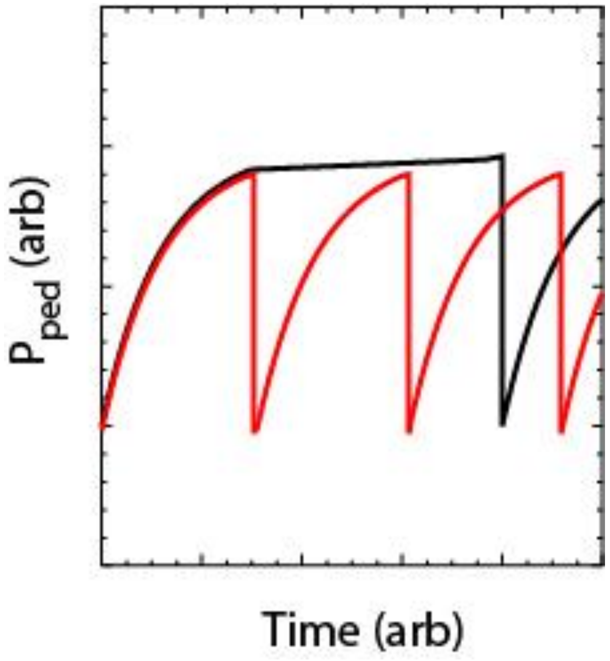
If the pedestal evolved to a saturated value early in the ELM cycle

Pressure pedestal evolution - MAST



Then could increase f_{ELM} at almost constant P_{ped}

Pressure pedestal evolution - MAST



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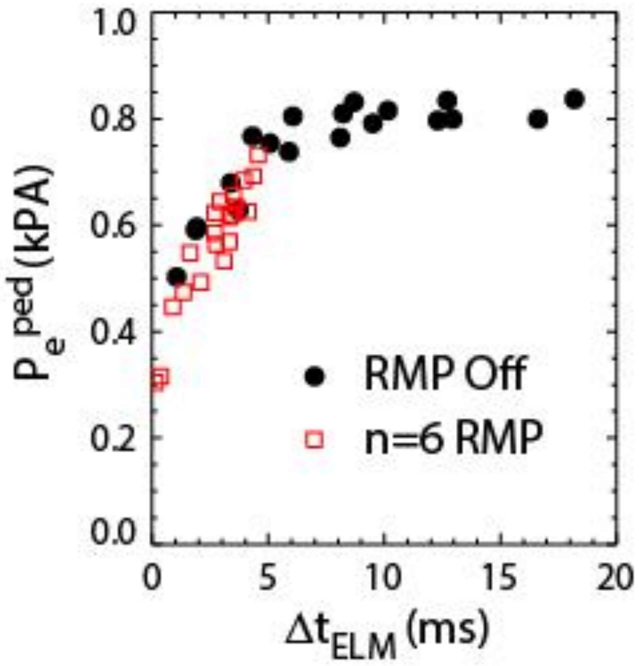
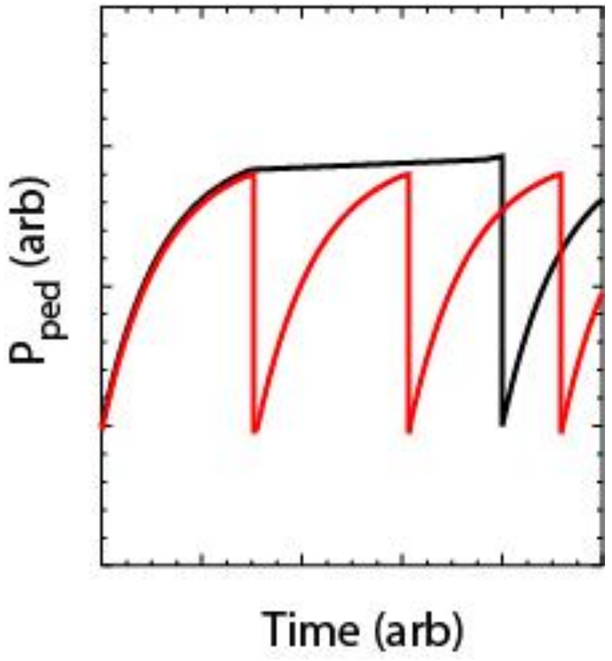


For these shots on MAST P_e^{ped} spends a large amount of times near to a saturated value during the ELM cycle and the mitigated ELMs are triggered near to the point at which the maximum is obtained

Pressure pedestal evolution - MAST



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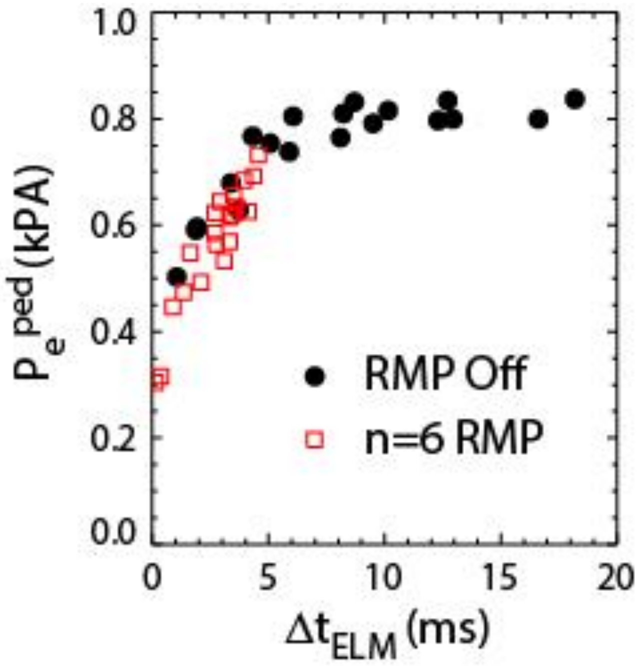
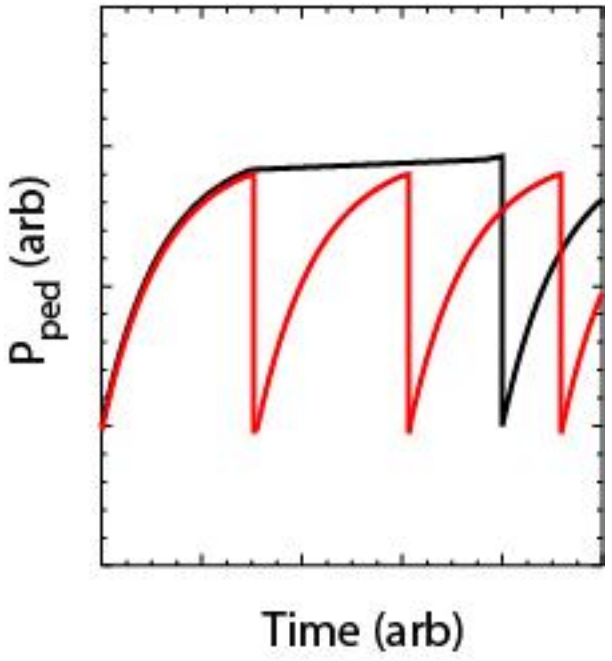


It is likely that if the frequency was increased further then the peak P_e^{ped} reached would be reduced

Pressure pedestal evolution - MAST



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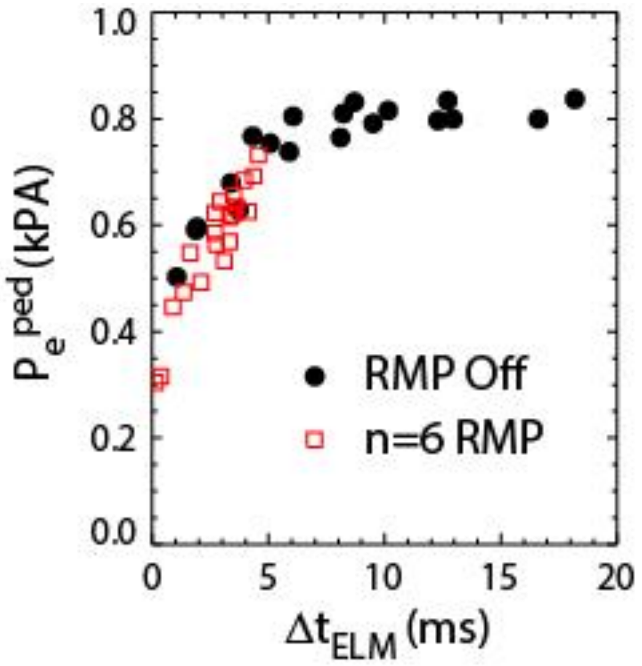
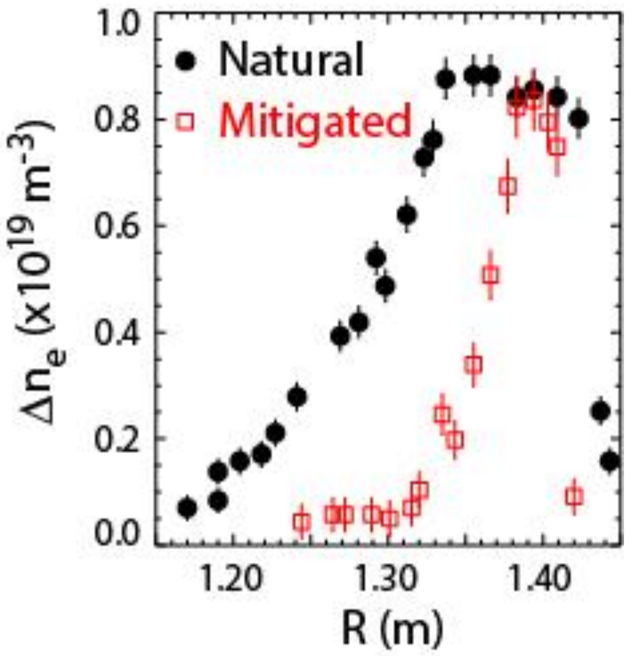


Note: Max P_e^{ped} prior to ELM AND Min P_e^{ped} after ELM are similar in natural and mitigated ELMs

So why is ΔW_{ELM} so different?

Pedestal affected area - MAST



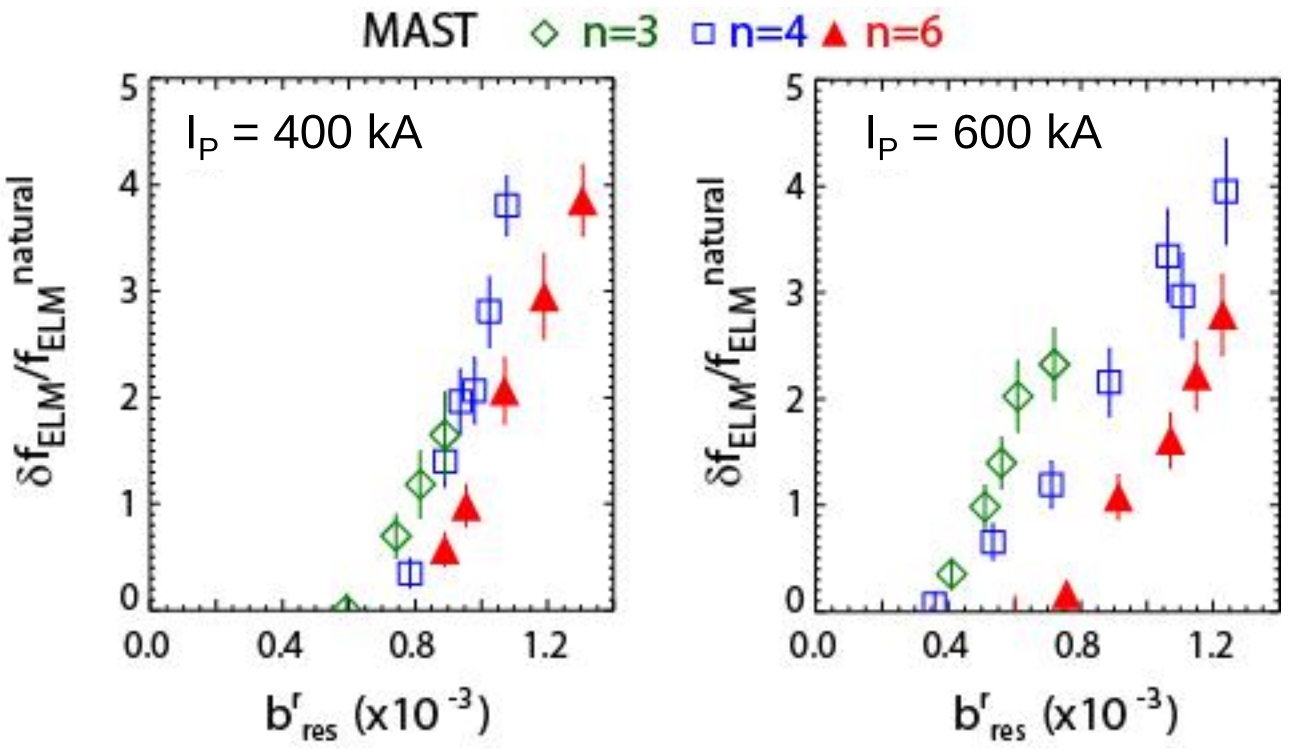
$$\Delta n_e(R) = n_e^{\text{before ELM}}(R) - n_e^{\text{after ELM}}(R)$$

The ELM affected area is much smaller for the mitigated ELMs

Parameters determining the onset of ELM mitigation

Vacuum resonant field - MAST

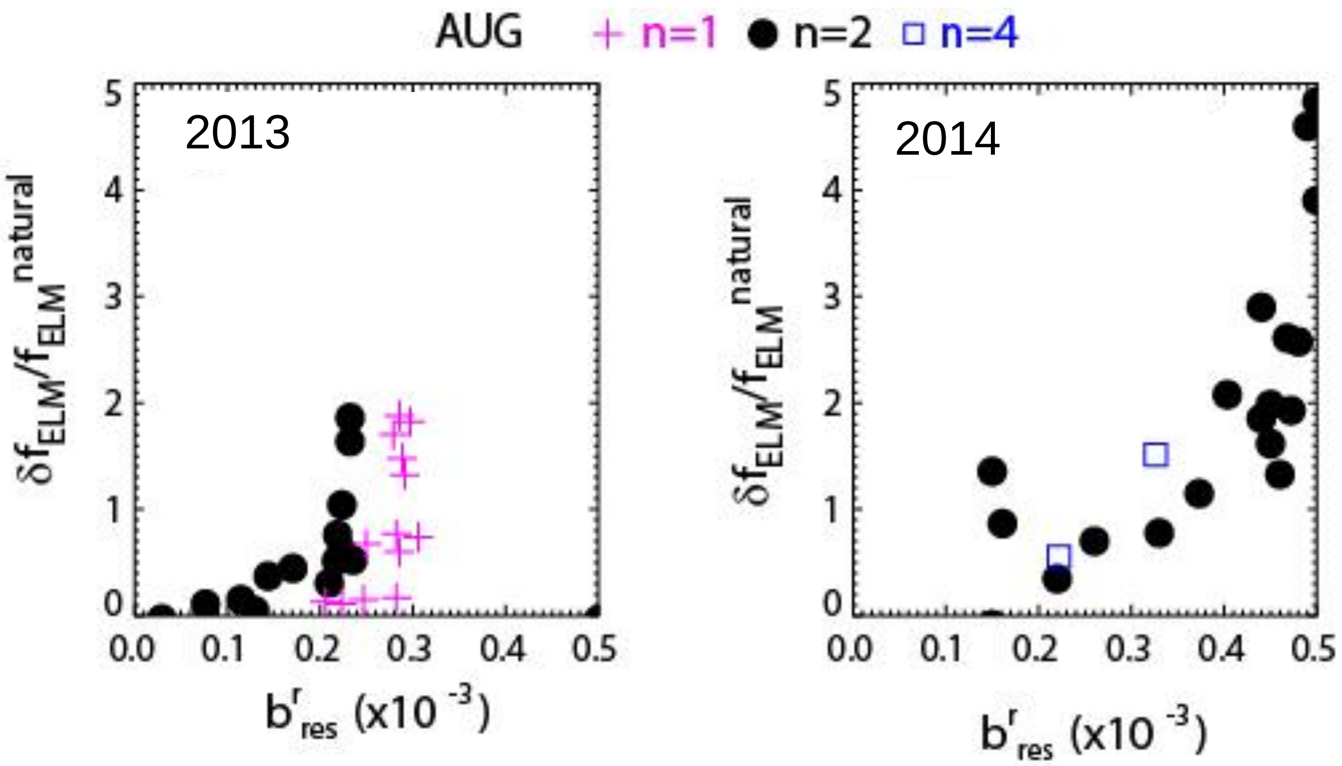
Normalised resonant radial field component (b^r_{res}) in the vacuum approximation



On MAST ELM mitigation scales ~ linearly with b^r_{res} above a threshold value

This threshold is scenario and n_{RMP} dependent

Vacuum resonant field - AUG



On AUG ELM mitigation scales ~ linearly with b^r_{res} above a threshold value which is scenario and n_{RMP} dependent

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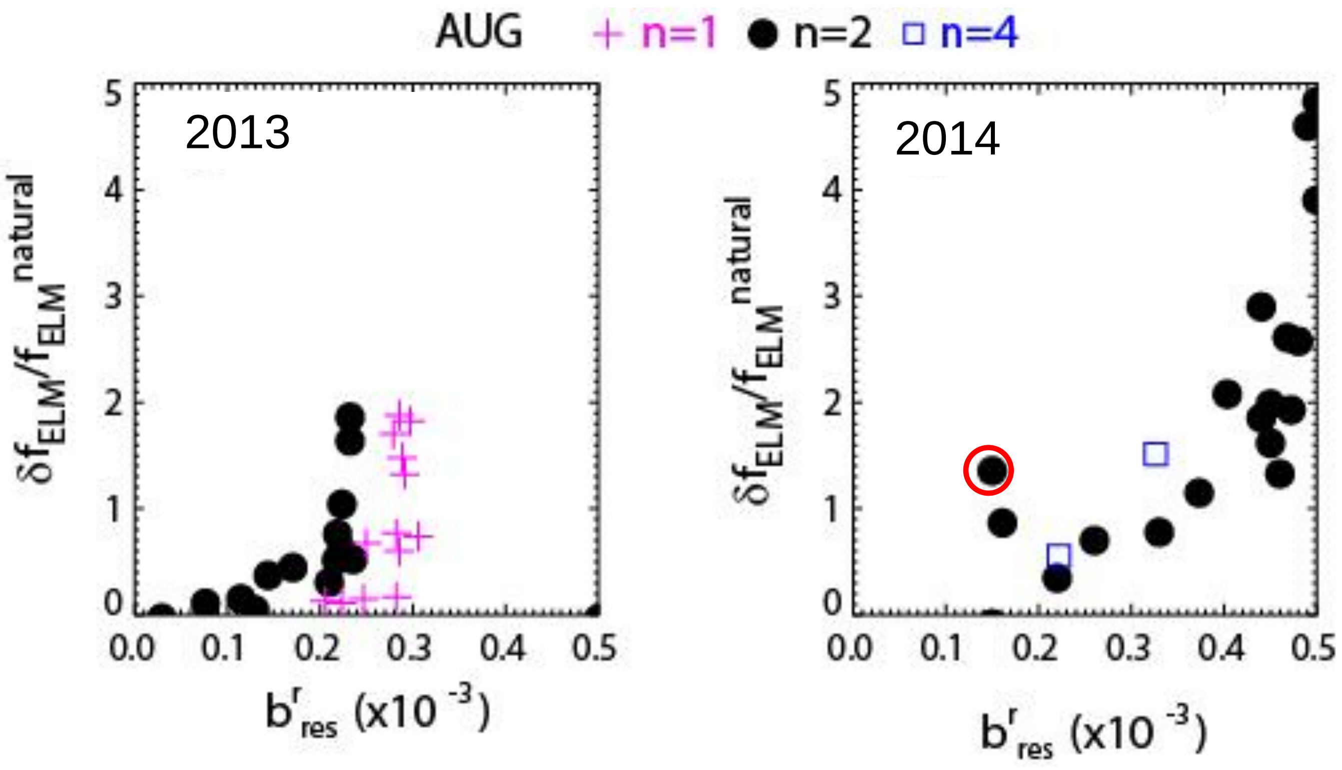
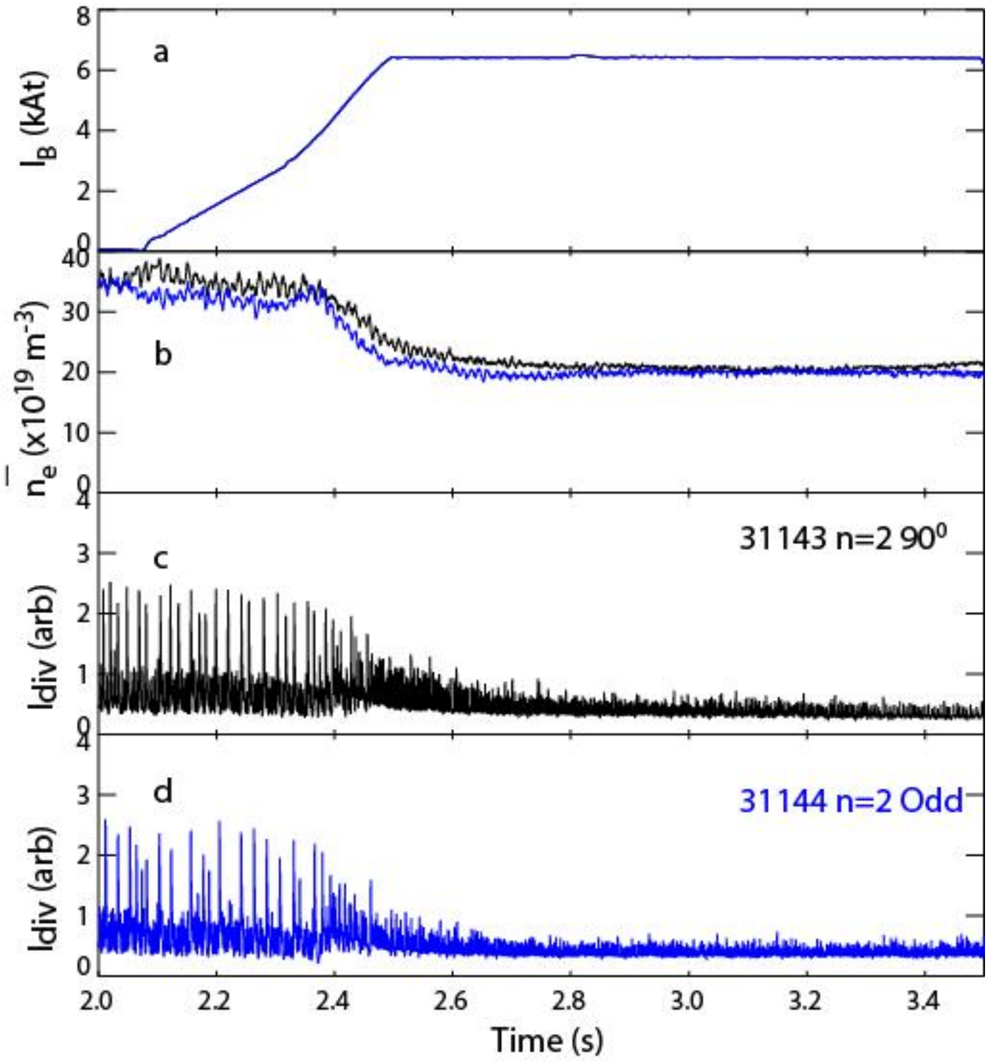


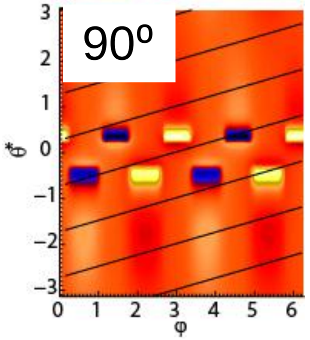
On AUG ELM mitigation scales ~ linearly with b^r_{res} above a threshold value which is scenario and n_{RMP} dependent

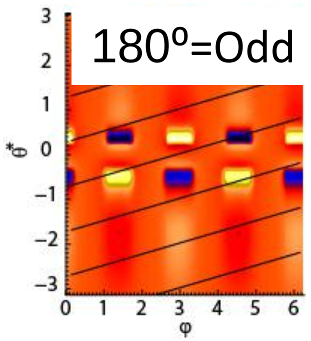
BUT there are some clear outliers

Vacuum resonant field - AUG



Differential phase scan between the currents in the upper and lower coils





-> a pitch angle/equilibrium field alignment scan

Similar increase in f_{ELM} observed at $\Delta\phi$ = 90 and 180º

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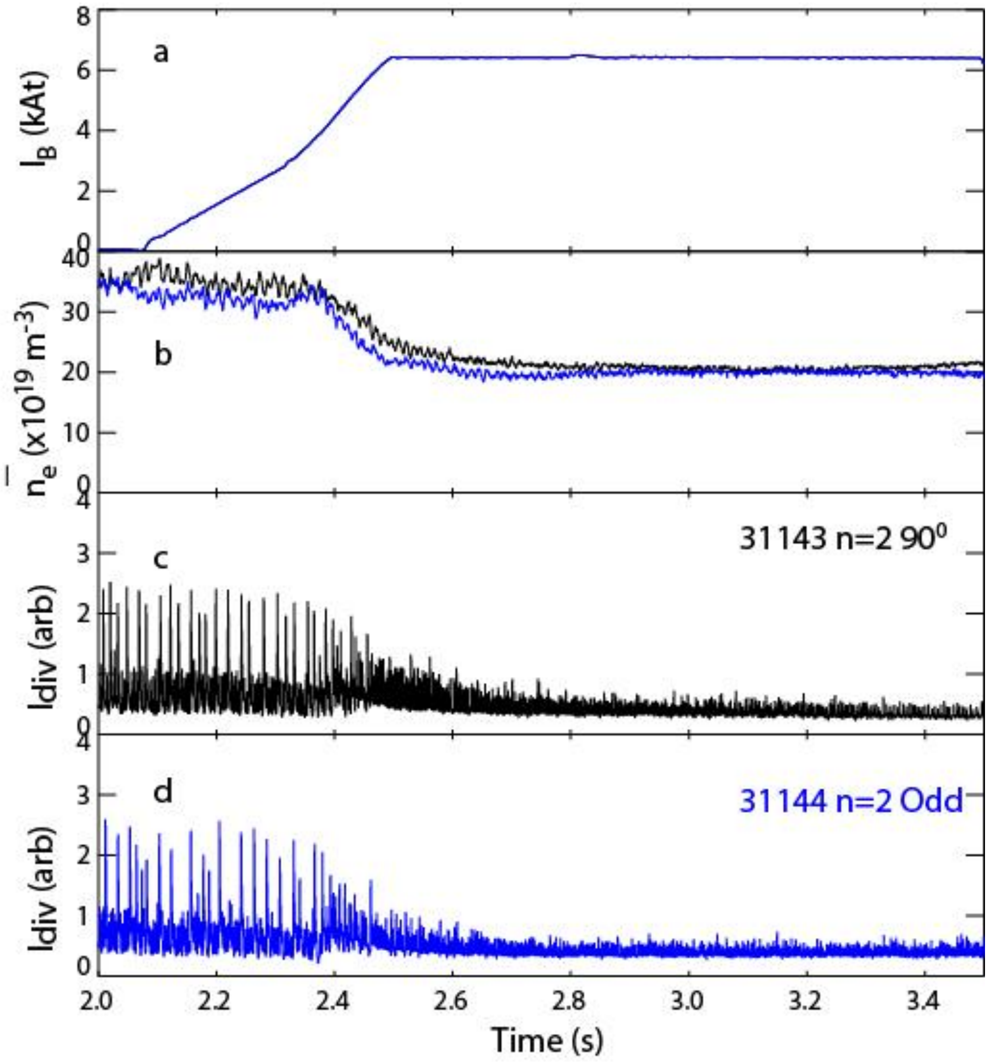
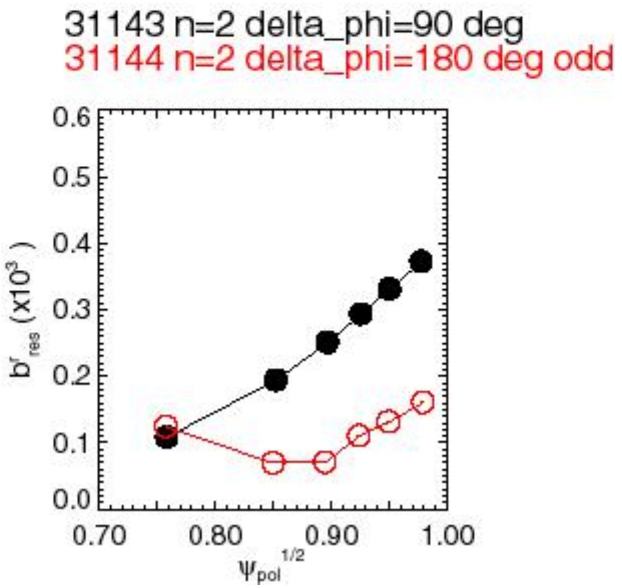
Vacuum resonant field - AUG



Similar increase in f_{ELM} observed at $\Delta\phi$ = 90 and 180º

But b^r_{res} (vacuum) very different



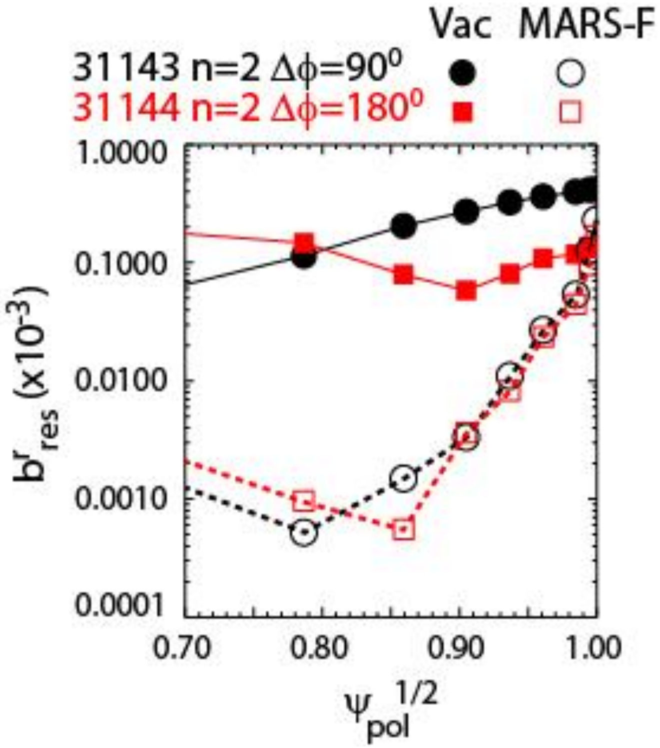
Plasma response - AUG

Included plasma effects using MARS-F, which is a single fluid linear MHD code that solves the full resistive MHD equations in full toroidal geometry

– the code allows for plasma response and screening due to toroidal rotation to be taken into account

Clear screening of resonant components

b^r_{res} now similar for 90 and 180º



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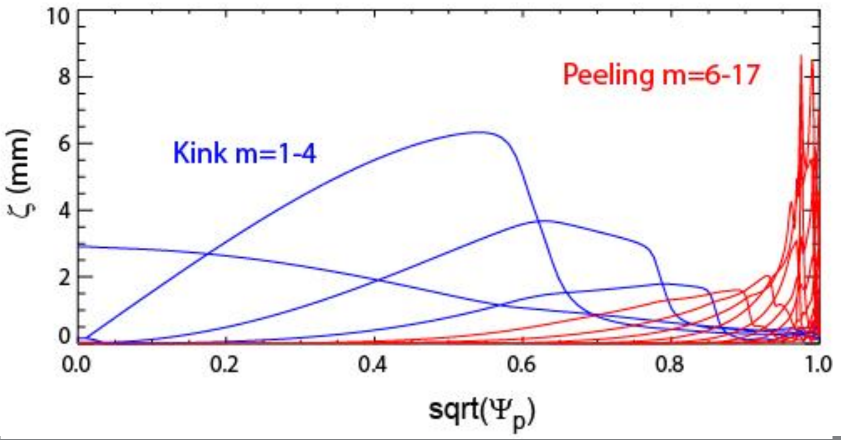
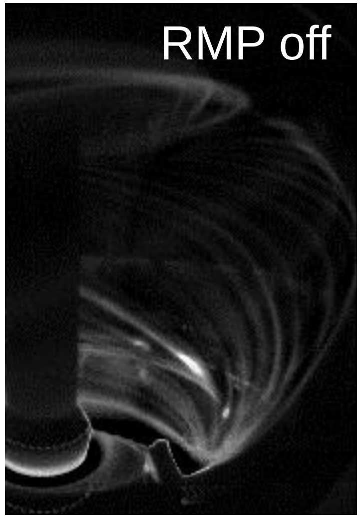
Plasma response composed of kink (core) and peeling (edge) eigenfunctions



Preliminary results indicate that maximum ELM mitigation is obtained near to where the peeling response of the plasma is maximum

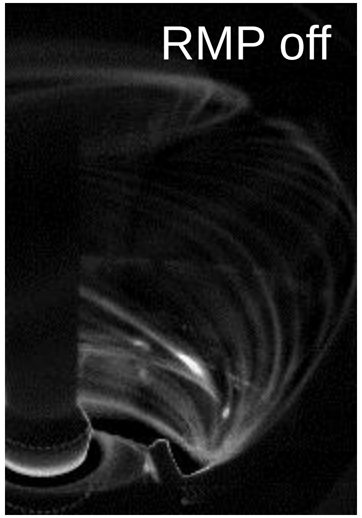
ELM type during mitigation

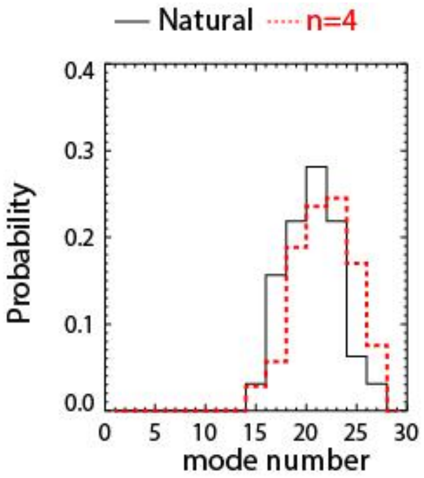
Effect of RMPs on ELM filaments - MAST

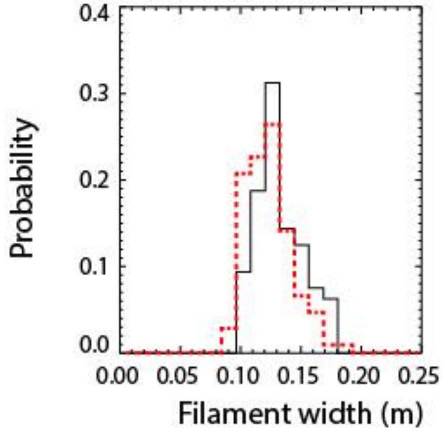


Natural and Mitigated ELMs look very similar

Effect of RMPs on ELM filaments - MAST



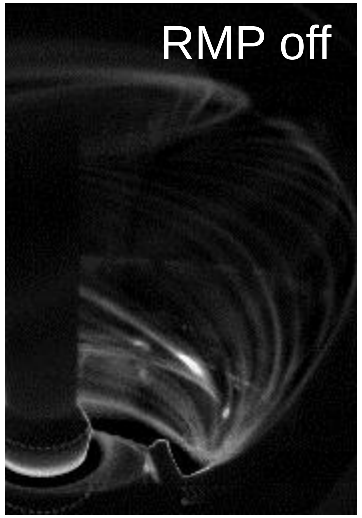


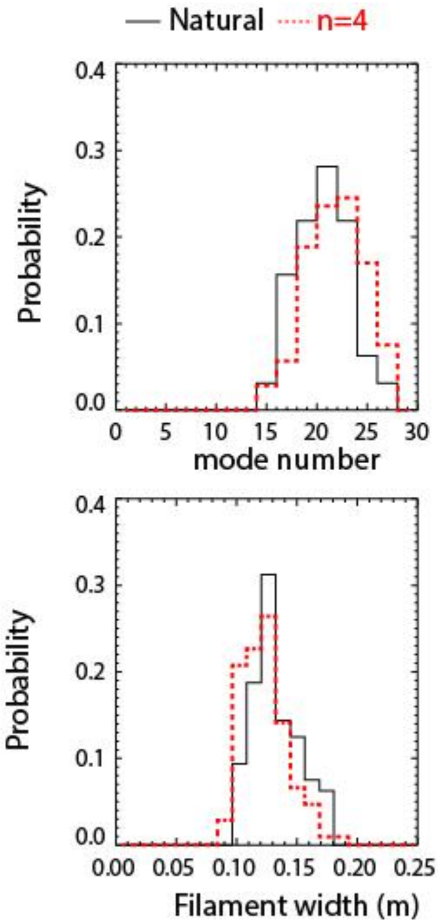


An analysis of the mode number of the filaments suggests that:

- the mitigated ELMs are still type I ELMs
- they are just smaller and more frequent

Effect of RMPs on ELM filaments - MAST





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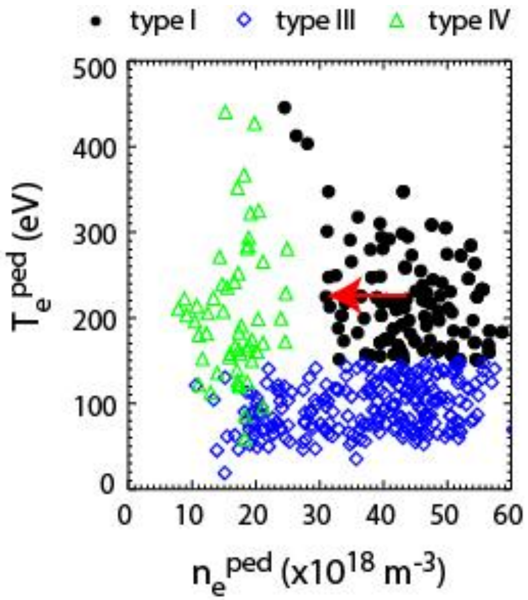
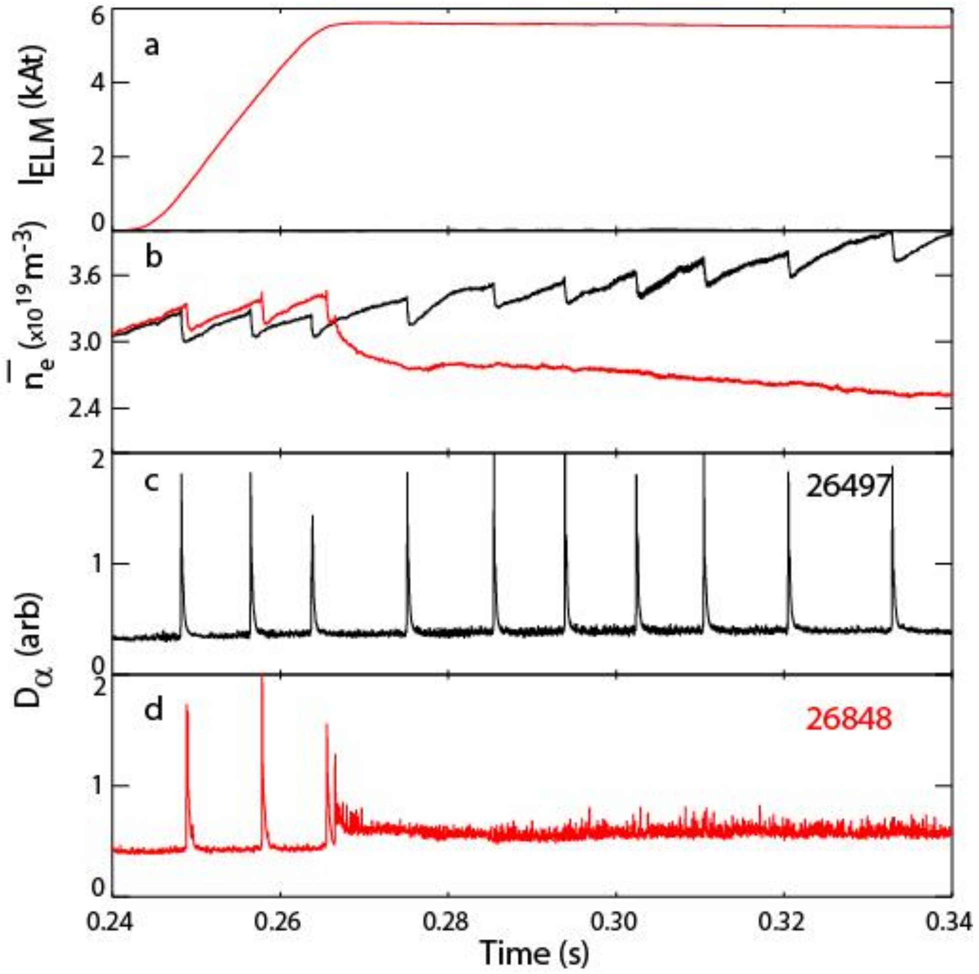
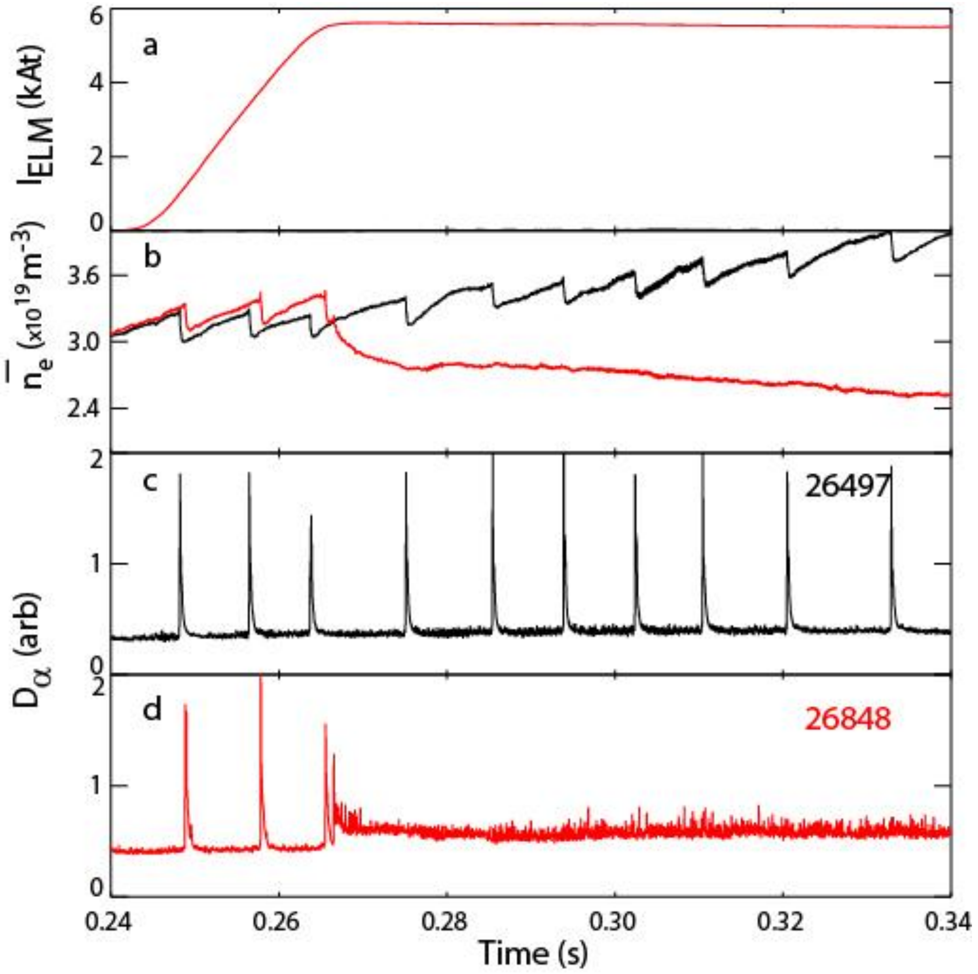


RMPs producing small ELMs on MAST

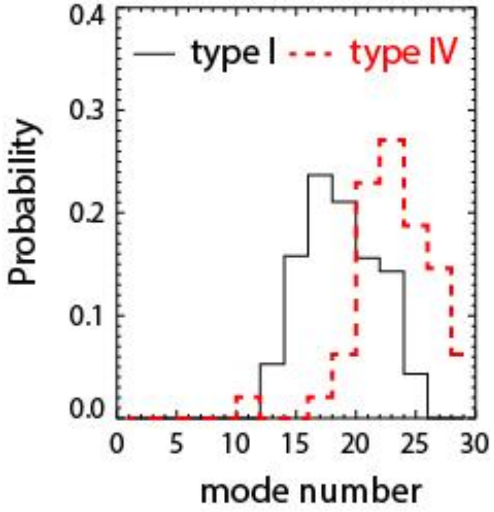


Application of n=3 RMPs to a particular discharge in MAST caused a density pump out which resulted in the establishment of a small ELM regime

RMPs producing small ELMs on MAST



Application of n=3 RMPs to a particular discharge in MAST caused a density pump out which resulted in the establishment of a small ELM regime – which had a different mode number



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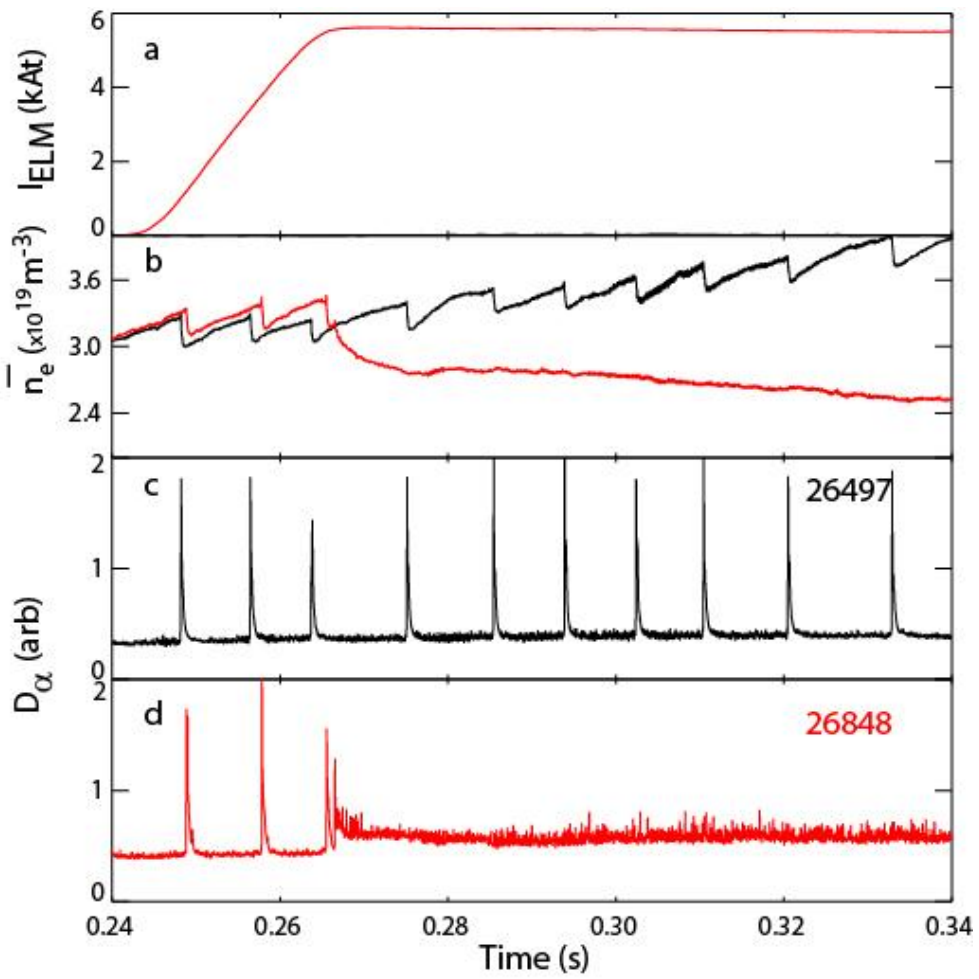
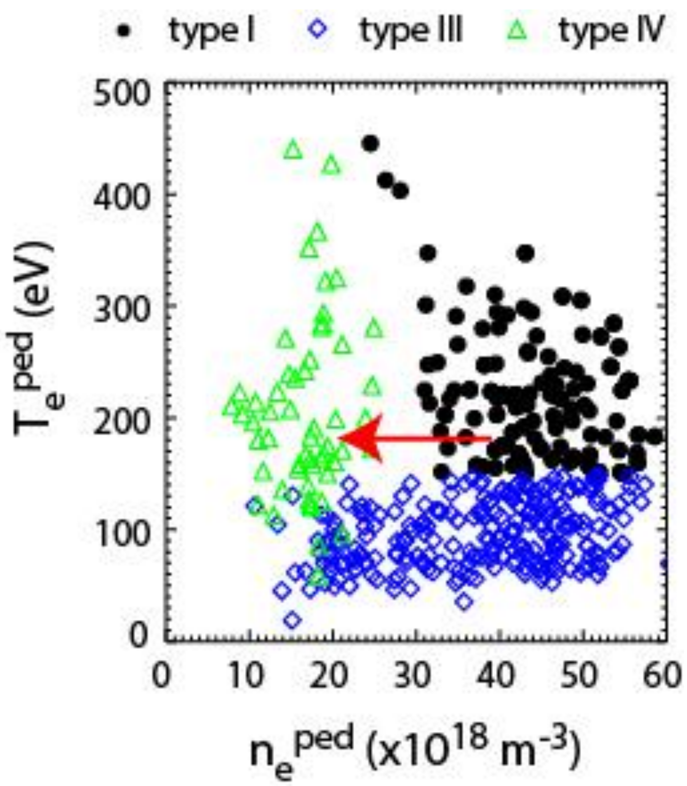


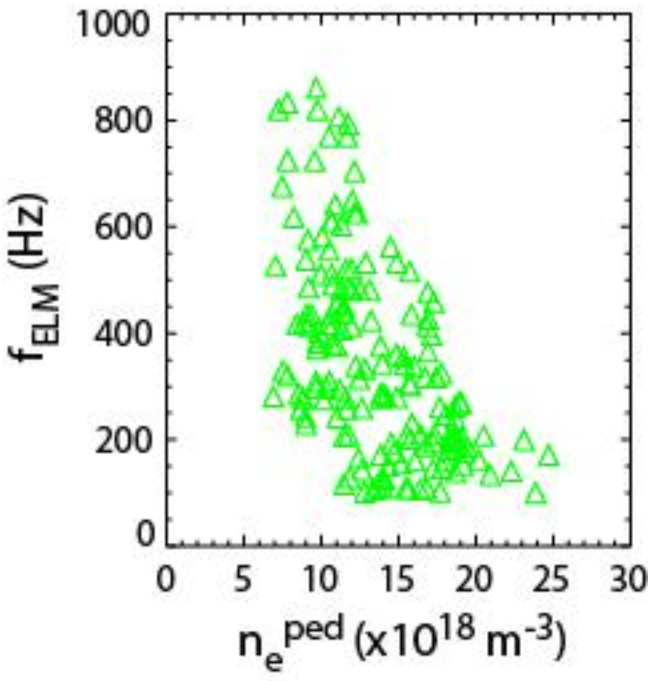
Effect of RMPs on pedestal characteristic



Pedestal characteristics compatible with type IV ELMs

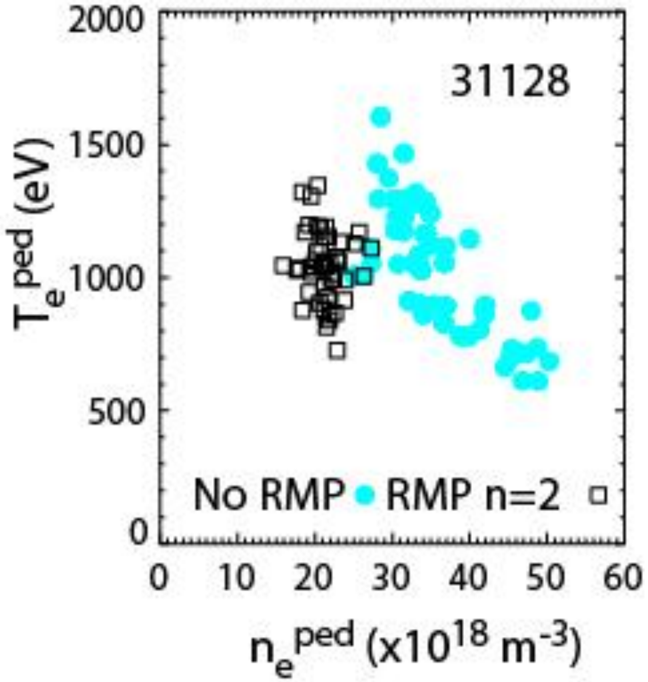
Type IV = low n_e-high T_e branch of type III

Natural type IV ELMs on MAST



Without RMPs the naturally occurring type IV ELMs frequency increases with decreasing pedestal density

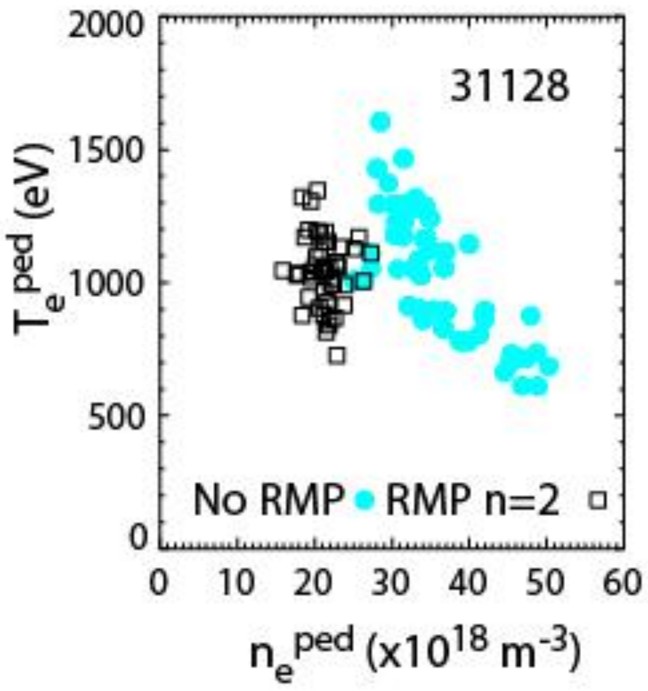
Effect of RMPs on pedestal - AUG

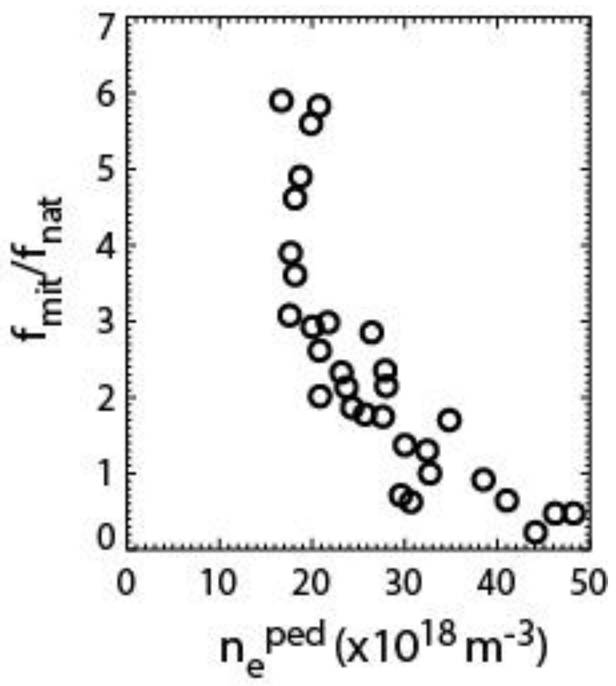


The mitigated ELMs move to the region of the Pedestal operation space typically associated with type IV ELMs

Effect of RMPs on pedestal - AUG

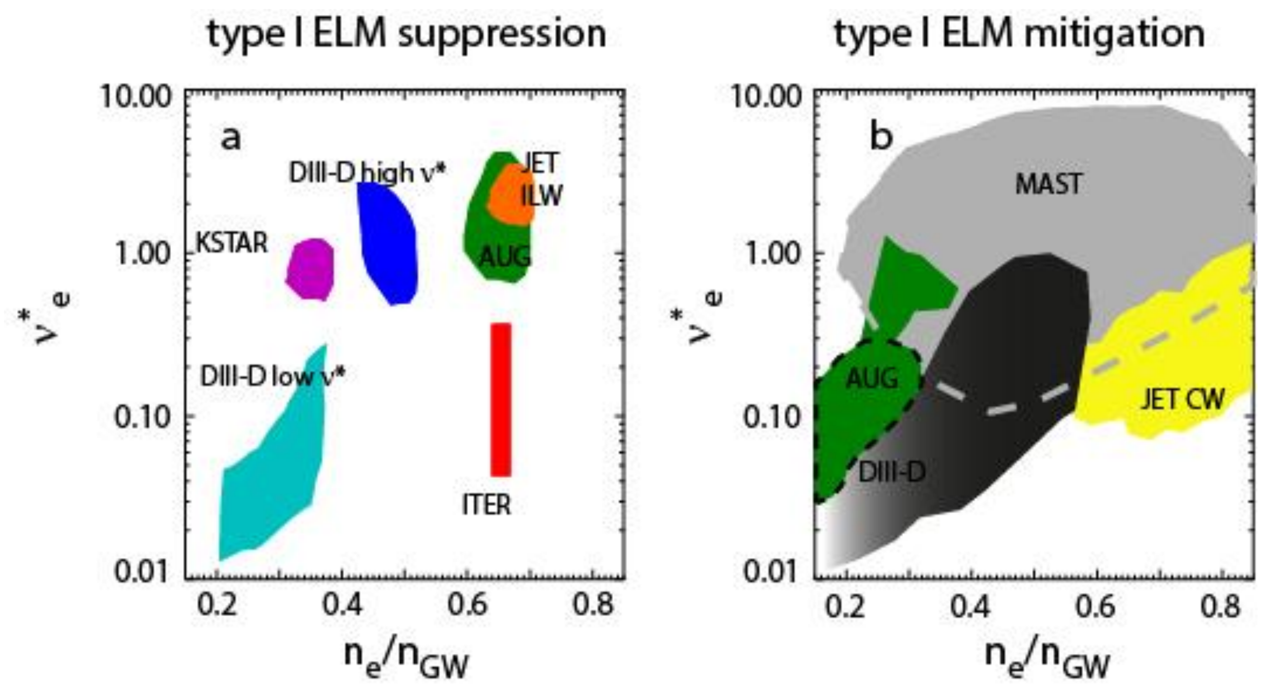
ELM mitigation increases as pedestal density is decreased



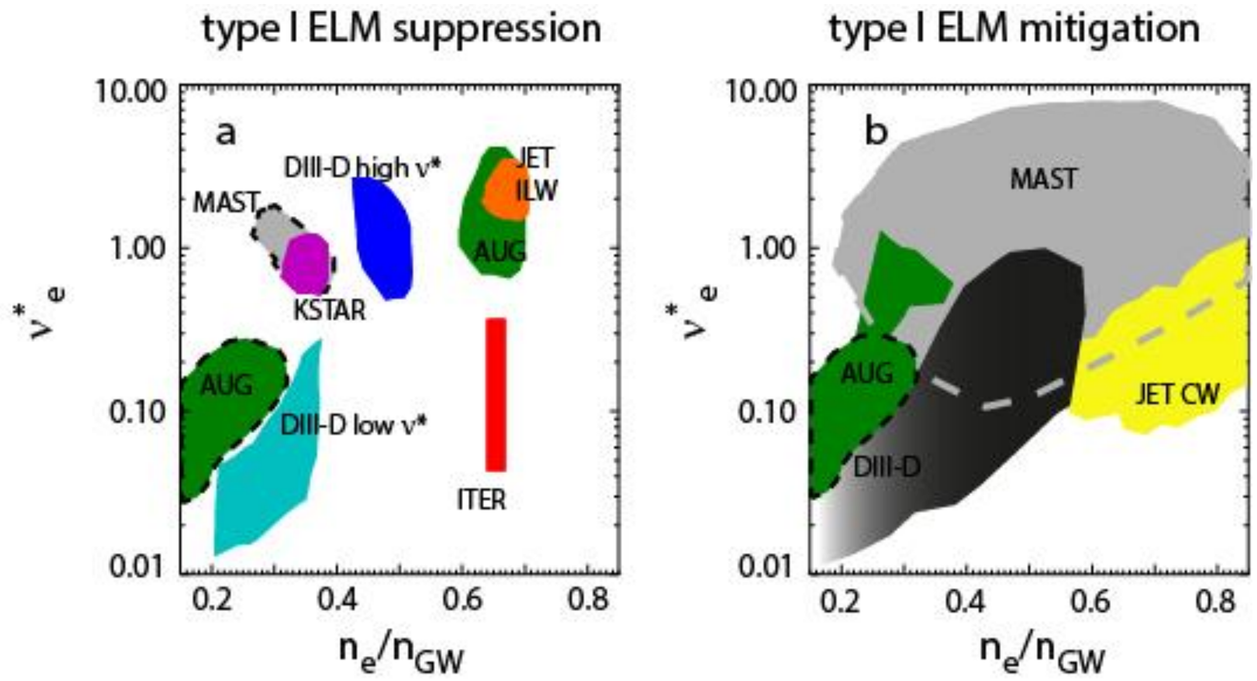


Similar to the trend observed on MAST suggesting it may be a transition to type IV ELMs

ELM mitigation or type I ELM suppression?

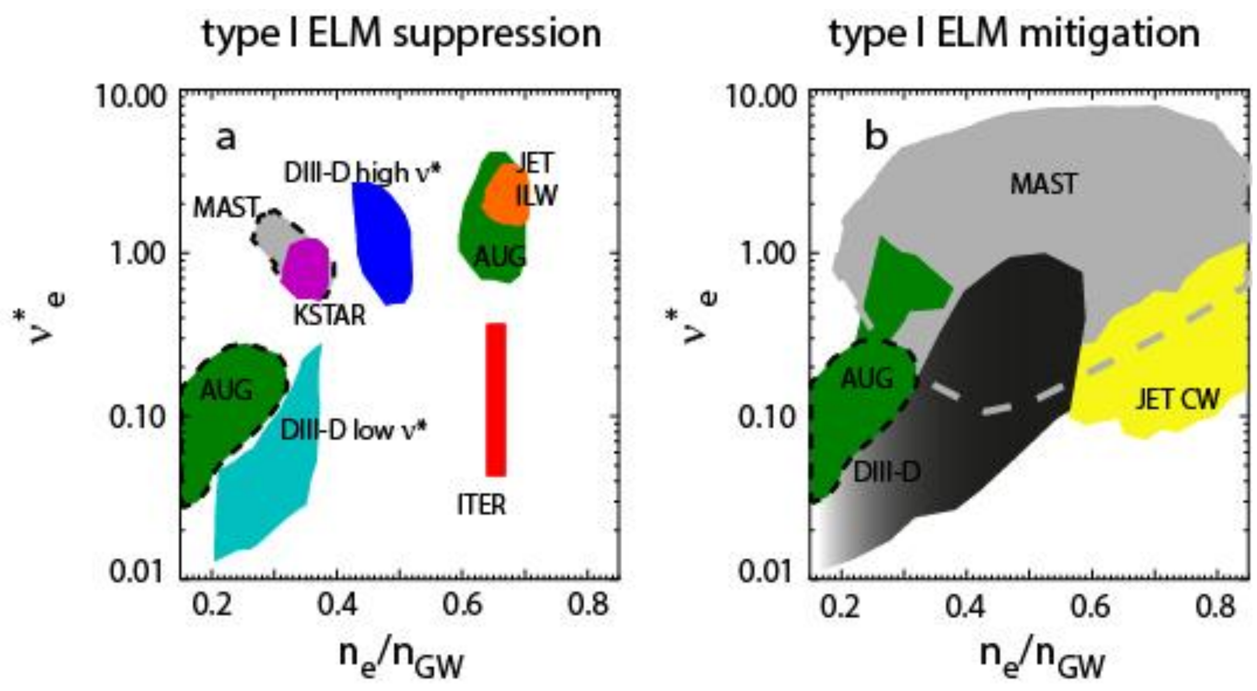


ELM mitigation or type I ELM suppression?



However in at least some of the cases it appears there is a suppression of type I ELMs and a transition to different ELM type

ELM mitigation or type I ELM suppression?



Regimes with tolerable ELMs can be established over a wide operating space in a range of devices

Summary

• **Sustained ELM mitigation has been obtained at mid to low collisionality on MAST and AUG using RMPs with a range of toroidal mode numbers resulting in**

- **smaller ELMs (ΔW) and reduced peak heat loads (q_{peak})**
- **reduction in density and stored energy**

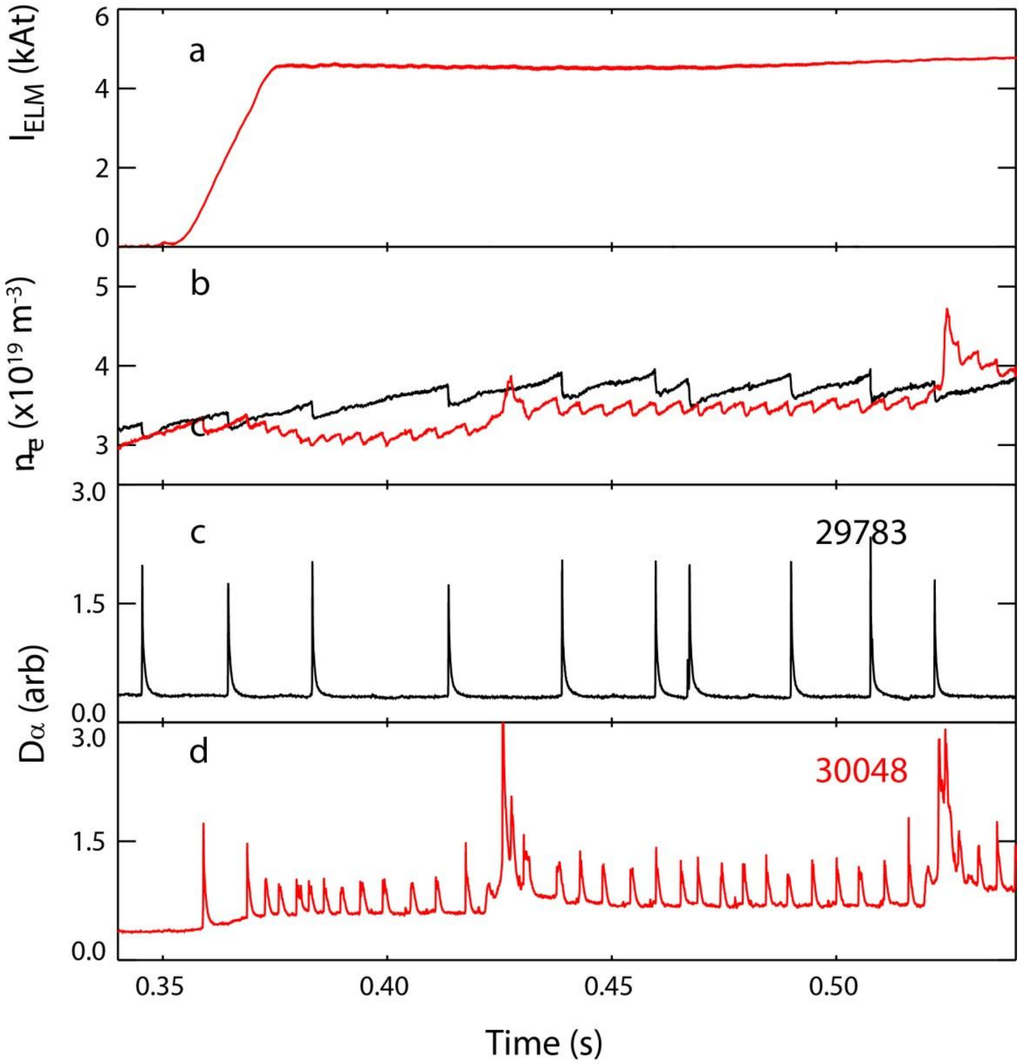
• On MAST in one type of discharge the drop in density has been eliminated resulting in reduced peak divertor heat flux with minimal drop in confinement – the smaller ELMs being a result of a change in the region of the plasma affected by the ELM.

• While the size of the resonant magnetic field component plays some role in determining the onset of ELM mitigation – this cross machine comparison has clearly indicated the need for studying the effects of the plasma response.

• There appears to be several mechanisms by which ELMs can be mitigated – increasing the frequency of type I ELMs or a transition to a different ELM regime

Backup slides

Fuelling with pellets – MAST



M Valovic EX/P4-36

Possible to refuel to densities higher than original using pellets

while still keeping mitigation

10 % drop in stored energy