Investigating ELM Pacing with Vertical Oscillations on DIII-D

by

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November 2, 2021

ELM Pacing

<u>ELM Pacing</u> is when the plasma is perturbed intentionally in order to trigger ELMs in a controllable way

Why would we want to trigger ELMs?

ELM Pacing - Effects of ELMs

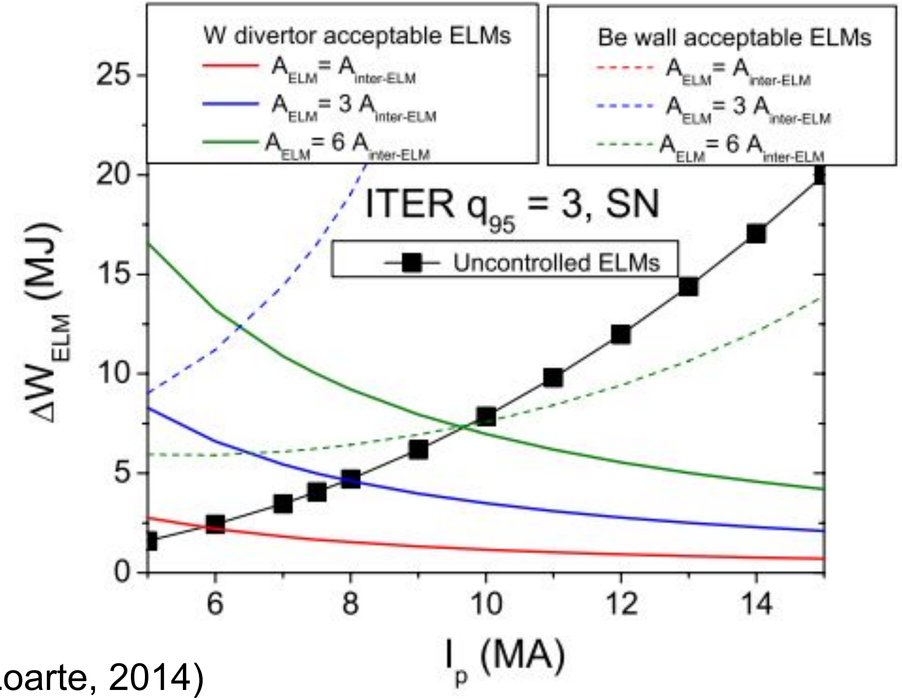
Positive

- Flush out impurities that build up in core (due to increased confinement of H-mode)
- Prevent uncontrolled density buildup in core
- Both of which could otherwise lead to reduced performance and disruptions

Negative

- Places limit on pedestal height
  - Which limits plasma performance
- Large Transient Heat Flux!
  - Extrapolation to ITER-size device shows that giant ELM heat fluxes will be unacceptably destructive to divertor

ELM Pacing - Effects of ELMs



(Loarte, 2014)

Negative

- **Places limit on pedestal height**
  - **Which limits plasma performance**
- **Large Transient Heat Flux!**
  - **Extrapolation to ITER-size device shows that giant ELM heat fluxes will be unacceptably destructive to divertor**

ELM Pacing Mitigates ELM Negatives by increasing f_{elm}

Main Goal of ELM Pacing: **Reduce** ELM size (and resulting heat flux to divertor) by **increasing** ELM frequency

ELM Pacing Techniques

- **Resonant Magnetic Perturbations**
- **Pellet Injection**
- **Vertical Plasma Oscillations ("Kicks"/ "Jogs")**

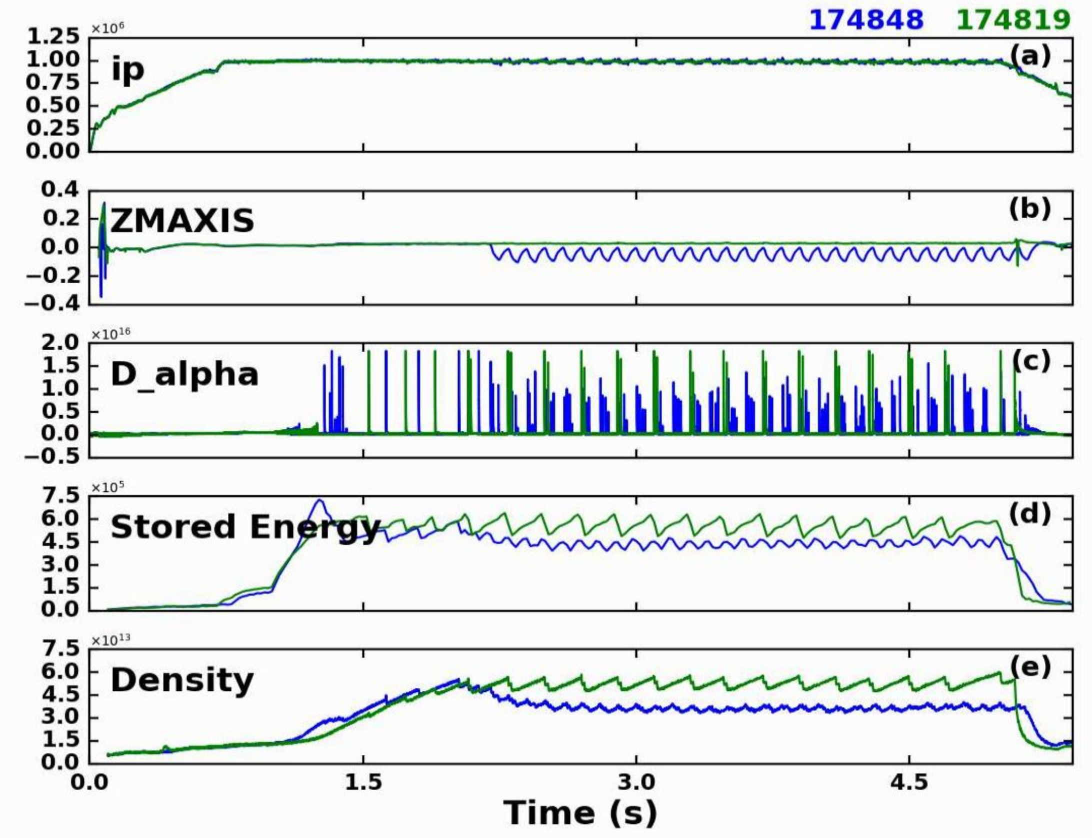
Focusing on Shot #174848 Which had 20Hz Vertical Plasma Oscillations

Questions we want to answer

- Is ELM Pacing achieved?
- How do the kicks trigger ELMs?
- How do the kicks affect other plasma parameters?

Shot Parameters I_p~ 1MA β_N~1.2 q_{95}~5 B_t~-2.1T

With Kicks | Reference



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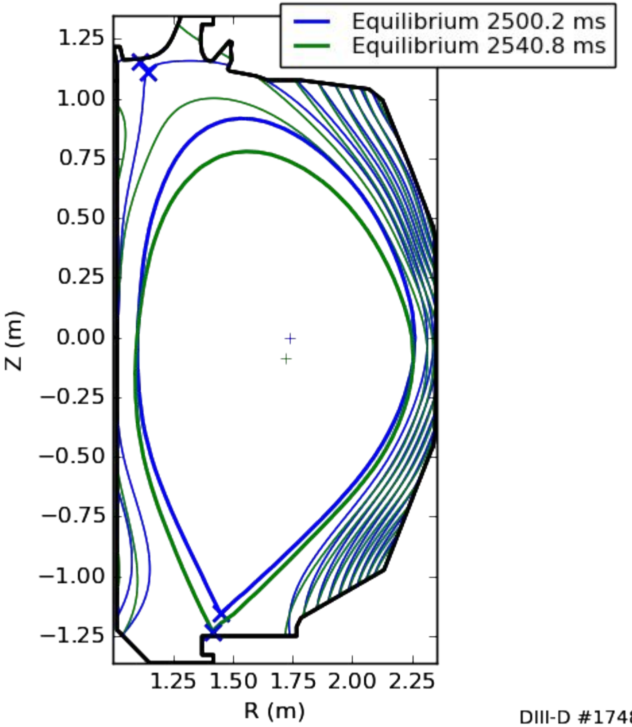
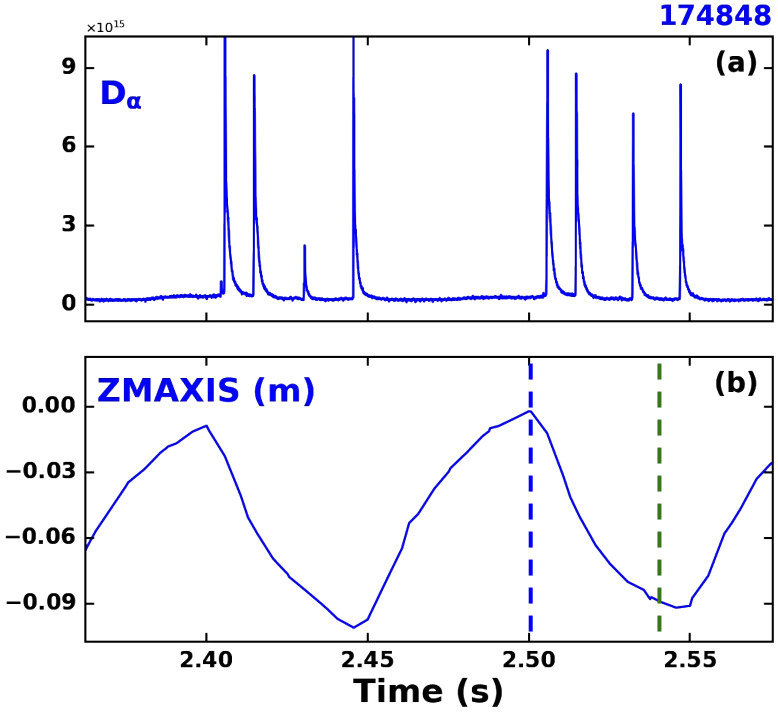
Plasma shape compresses from downward kick

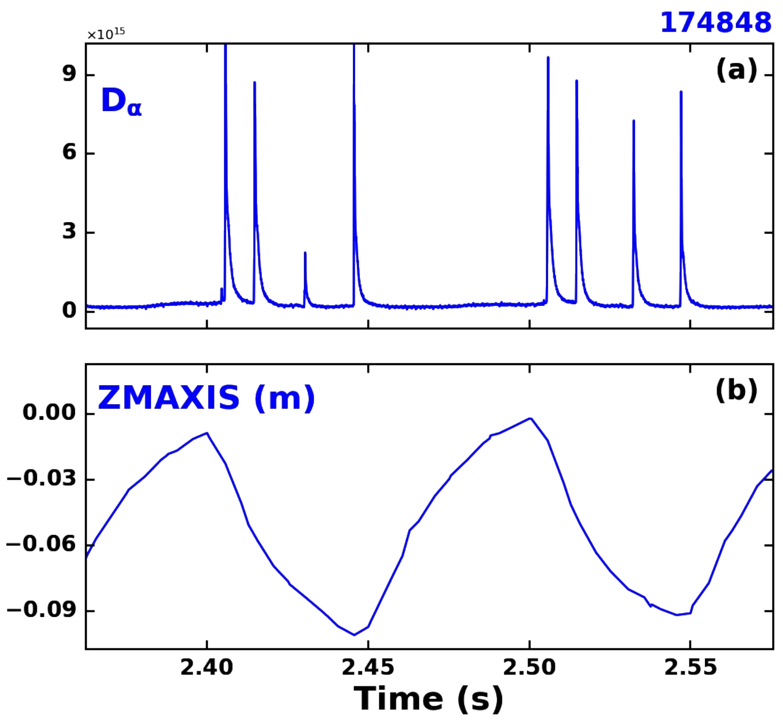


DIII-D #174848 EFIT03 ms



Observed ELM Behavior - Triggering and Pacing

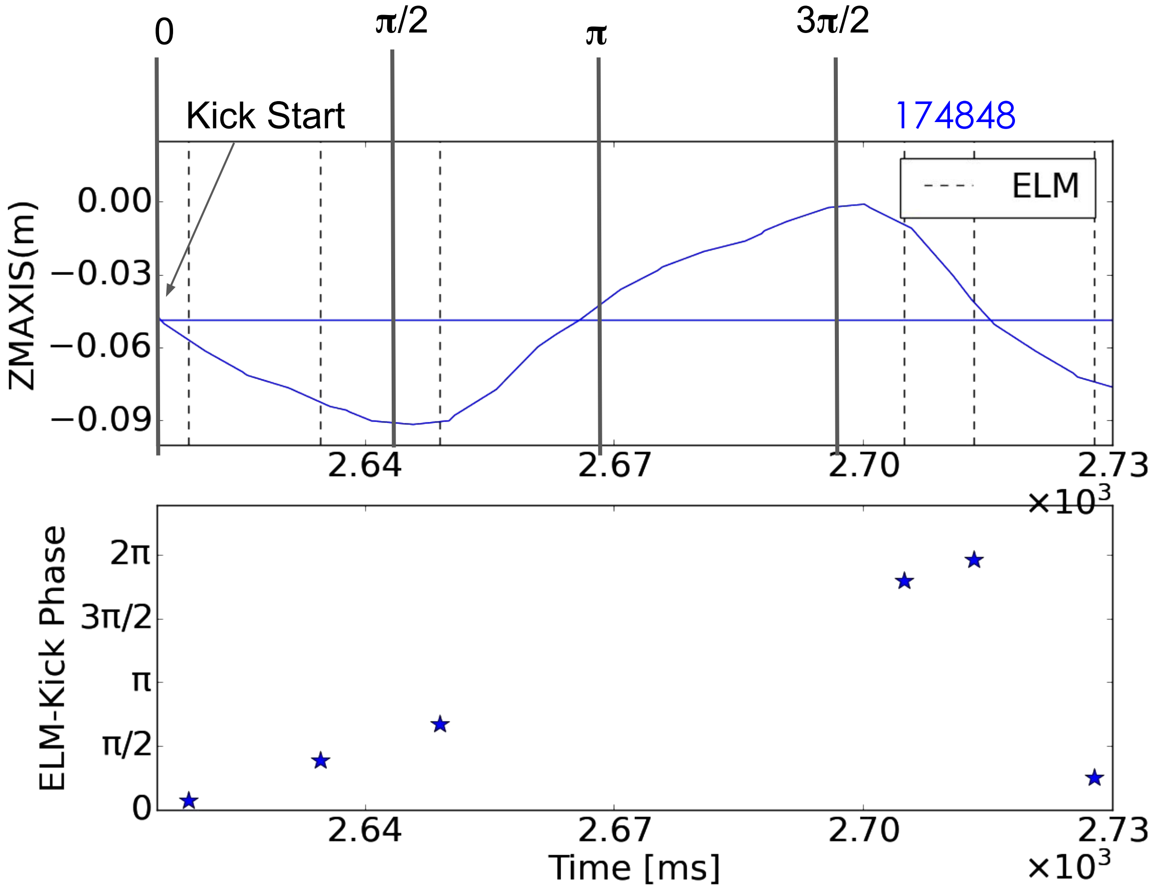
- Qualitatively, ELMS triggered as plasma is moving down
    - Similar to NSTX, JET
- Multiple ELMs triggered consistently with each kick
    - Similar behavior is seen in other experiments (KSTAR, ASDEX-U)



Define ELM-Kick Phase as 0 if ELM occurs when ZMAXIS at Average position and moving down, increases to 2π

Define start of kick as when magnetic axis is at average Z position and moving down

Define ELM that occurs at that point as having 0 ELM-kick phase, phase increases up to 2π



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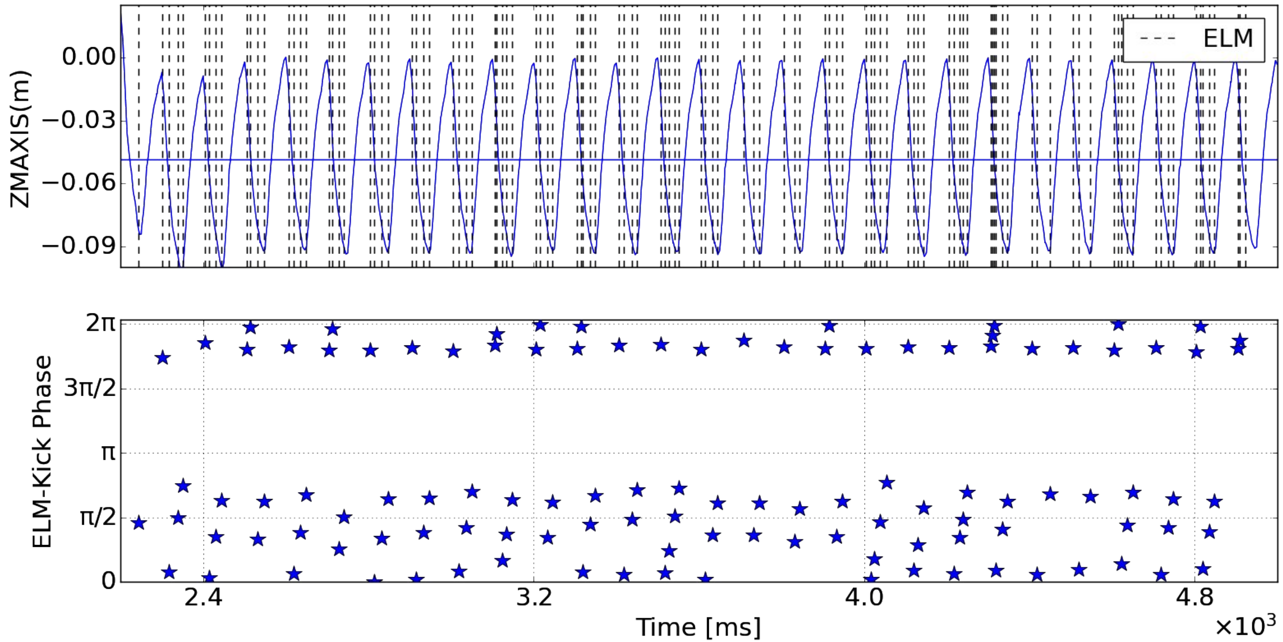
Phase consistently between $[0,\pi/2]$ and $[3\pi/2, 2\pi]$

Indicates quantitatively that ELMs are occurring mainly as plasma is moving down



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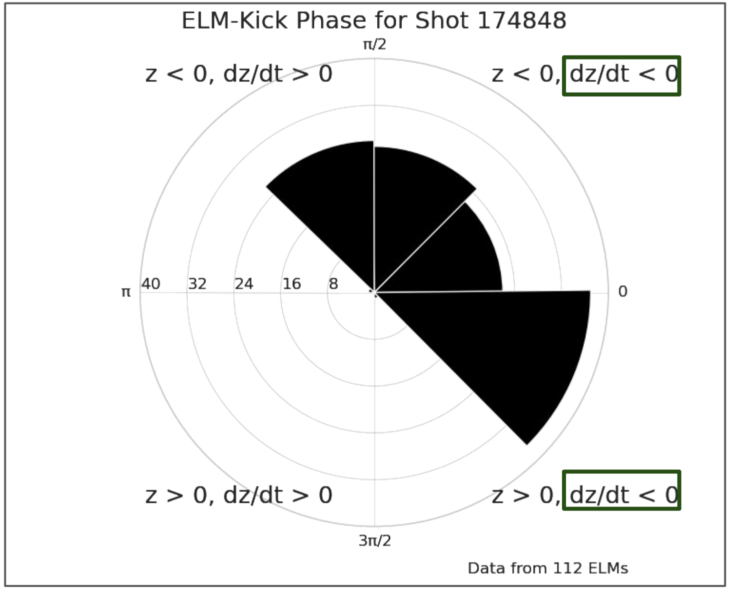
78% of ELMs Occurred while plasma was moving downwards => ELMs correlated with the kicks

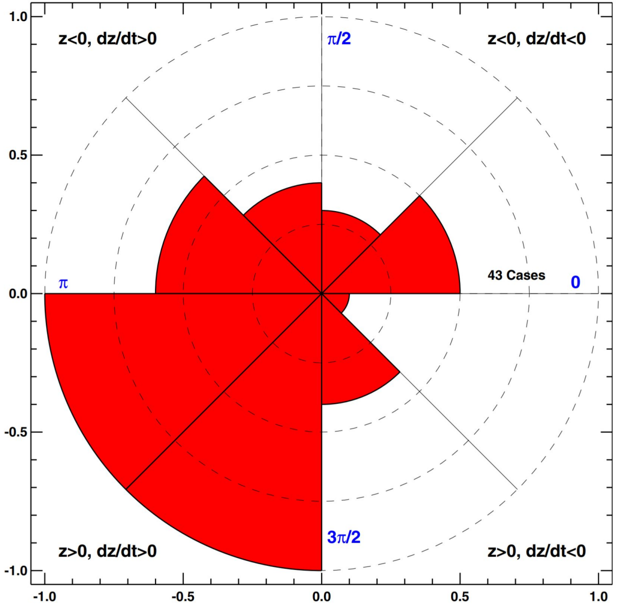
- Similar direction to results from vertical kick experiments in ASDEX-U and JET

- ELM triggering in opposite direction was observed in TCV, KSTAR and NSTX vertical kick experiments

DIII-D



NSTX[1]

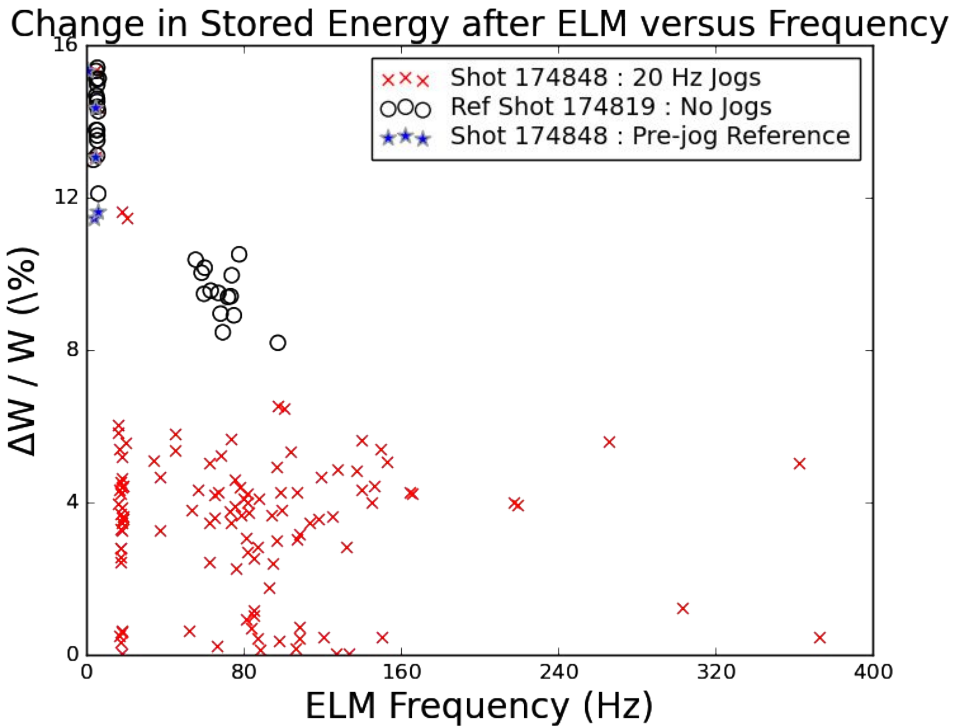


[1]Gerhardt 2010

ELM Pacing Effect on ELM Size - Stored Energy

ELM size defined as change in plasma stored energy ΔW/W

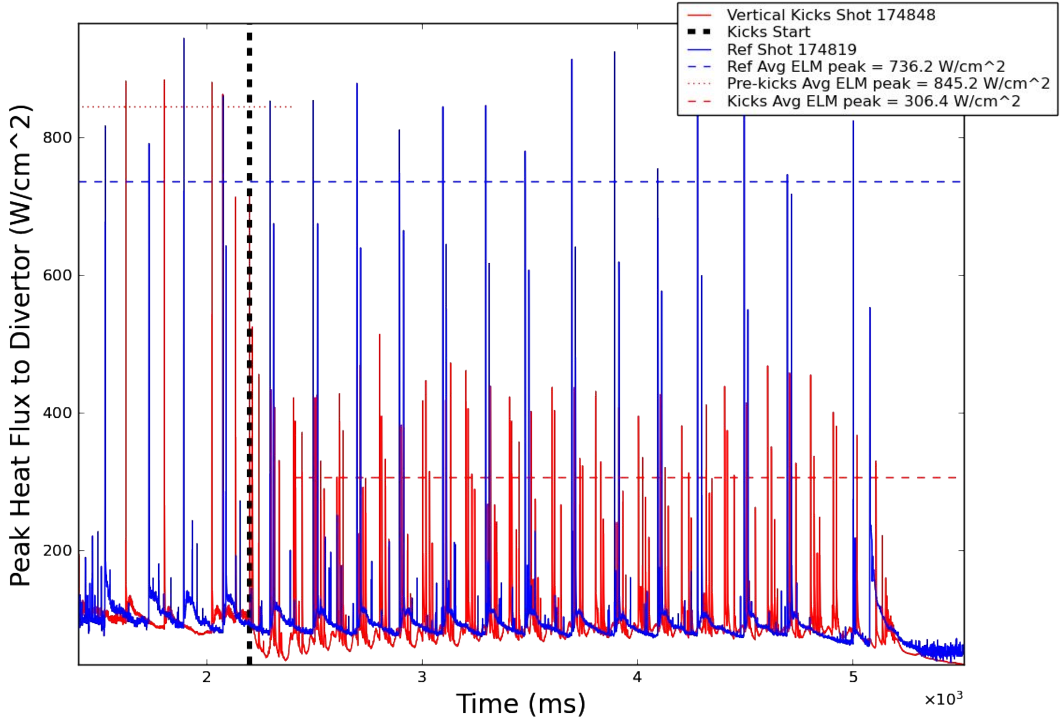
Clearly see a decrease in ELM size in the vertical kicks experiment as compared to reference with no kicks and pre-kicks reference period in shot 174848



ELM Pacing Effect on ELM Size - Divertor Heat Flux

Kicks cause decrease in the peak heat flux to divertor from ELMs (as measured by IRTV system)

- **~300 W/cm^2 peak flux for Shot 174848 (during kicks)**
  - Decreases with increasing ELM freq.
- **~ 750 W/cm^2 peak flux for reference Shot 174819**



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ELM Pacing with vertical oscillations appears to be achieved in Shot 174848

- **ELM triggering correlated with the kick frequency ✔**
- **ELM Size as measured by stored energy loss is reduced ✔**
- **Peak heat flux due to each ELM is reduced ✔**

By what mechanism does jogging trigger ELMs?

- **Literature from similar experiments suggest that vertical oscillations could perturb the edge current density enough to trigger ELMs**
- **But, exact mechanism is not yet shown definitively in experiments (edge current density difficult to measure)**

$$\delta J_\phi = \frac{1}{2\pi r_0 w_r}\left(\delta I_\phi^{w_r} - I_\phi^{w_r}\frac{\delta w_r}{w_r}\right)$$ (Artola, 2018)

Change in edge Current Density

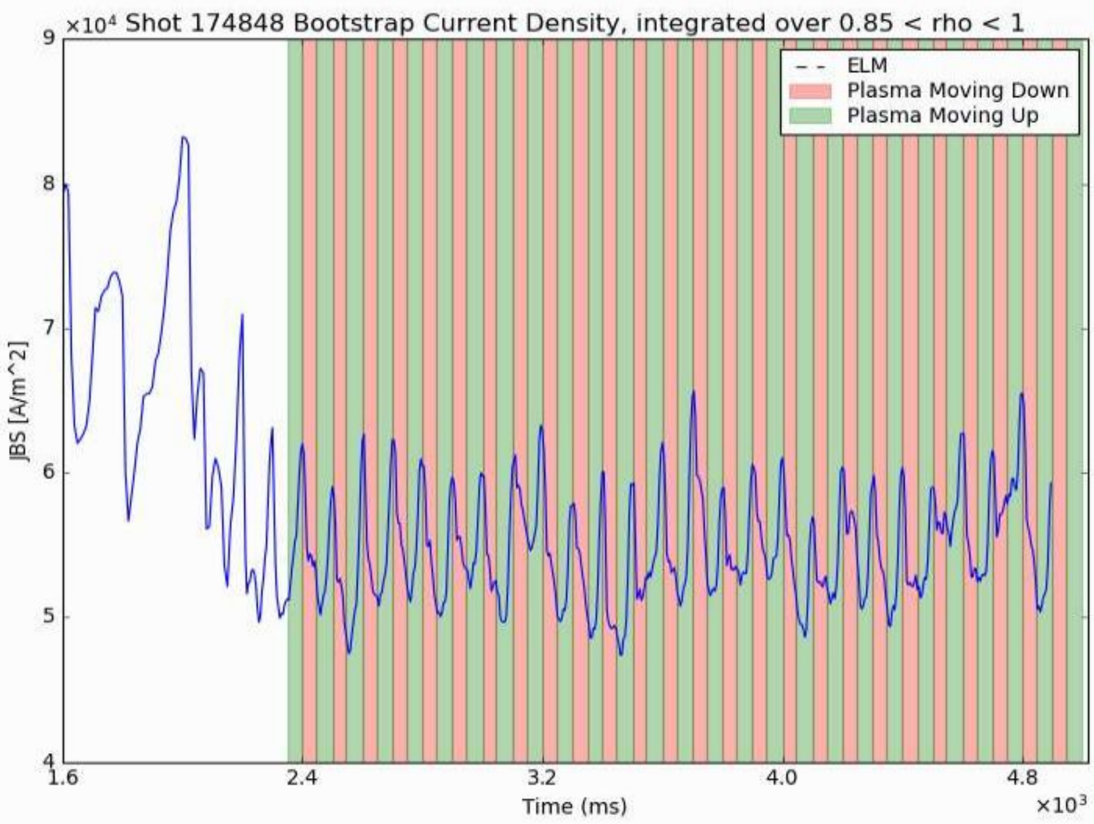
Change in total edge toroidal current

Redistribution of total edge toroidal current

J_ϕ	Edge current density
$I_\phi^{w_r}$	Total toroidal current contained in edge
w_r	Width of edge region
r_0	Radius of core plasma region

Sauter Model for Bootstrap Current shows edge current decreasing in downward kicks in DIII-D Shot 174848

- **Multiple ELMs occur on downward kick**
- **ELMs reduce pedestal gradients**
- **Sauter J_{Boot} ~ edge T,n gradients**



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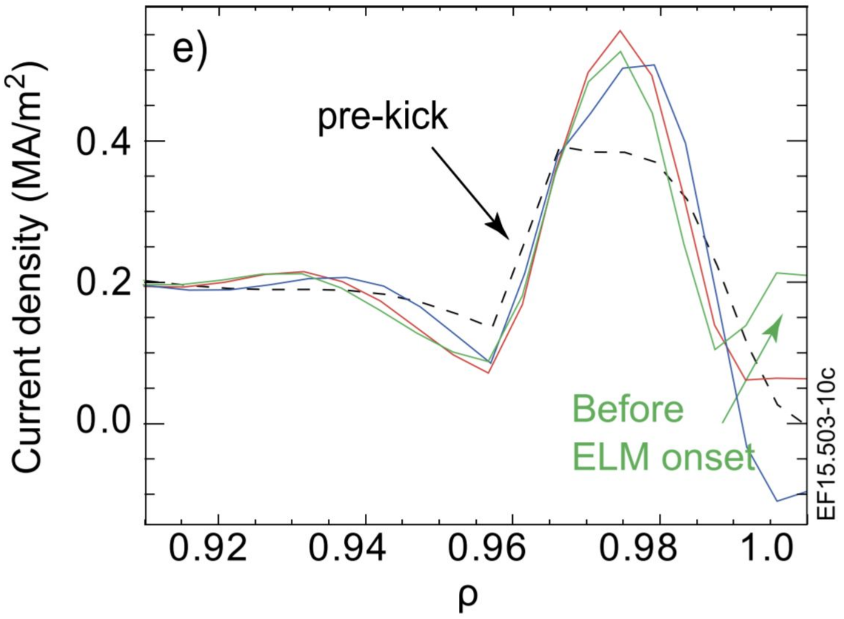
Simulations of Similar Experiments Predict Increased J_{edge}

- **JET vertical kick experiment showed similar behavior as Shot 174848 (ELM triggered on downward motion)**
- **Simulation of downward plasma movement predicts increase in current density near separatrix**
- **This would not be visible to us experimentally with current diagnostics capabilities (no edge MSE, Li beam was not used)**



(De La Luna, 2016)

Conclusions and Future Work

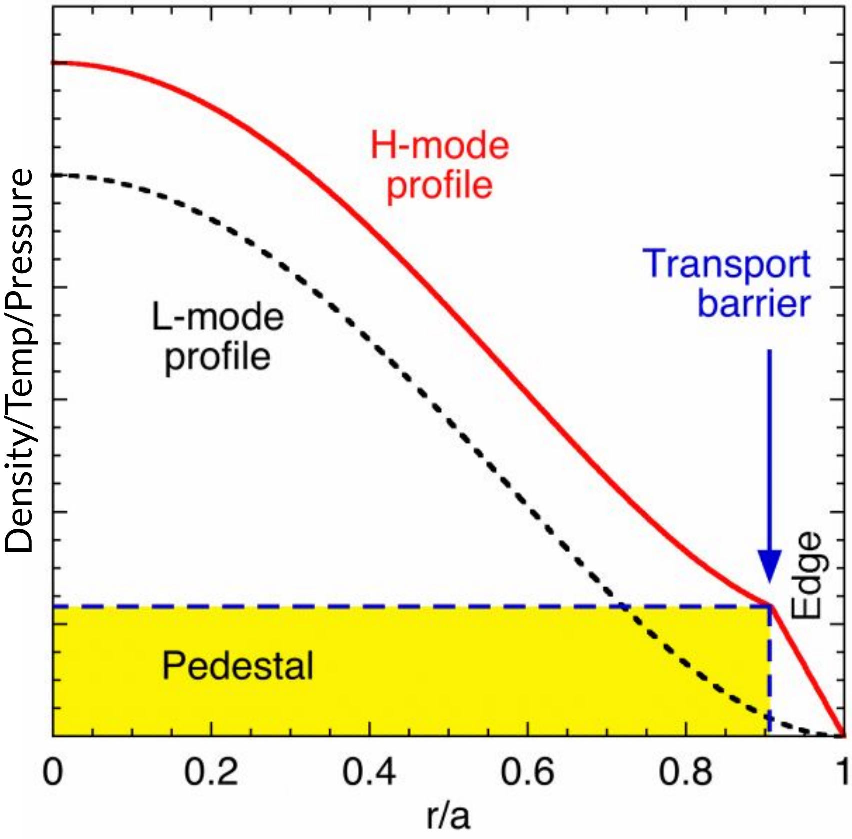
- **ELM pacing via vertical oscillations is shown on DIII-D**
  - ELMs triggered with higher frequency
  - ELM peak heat flux was reduced
- **ELM triggering mechanism not obvious from experimental measurements**
  - Plan to investigate stability boundary at various points in kicks using ELITE

Acknowledgements: Oak Nelson, Florian Laggner, OMFIT

Backup

Background - What is an Edge Localized Mode (ELM)?

- **Type I ("giant" ELMs) can be modelled as ideal MHD instability localized near edge of plasma**
  - Coupling between peeling (**J**-driven) and ballooning (**∇P**-driven) instabilities
- **Occurs periodically during ELMy H-mode operation**
- **Causes enhanced transport of plasma out from core**



http://fusionwiki.ciemat.es/wiki/Pedestal

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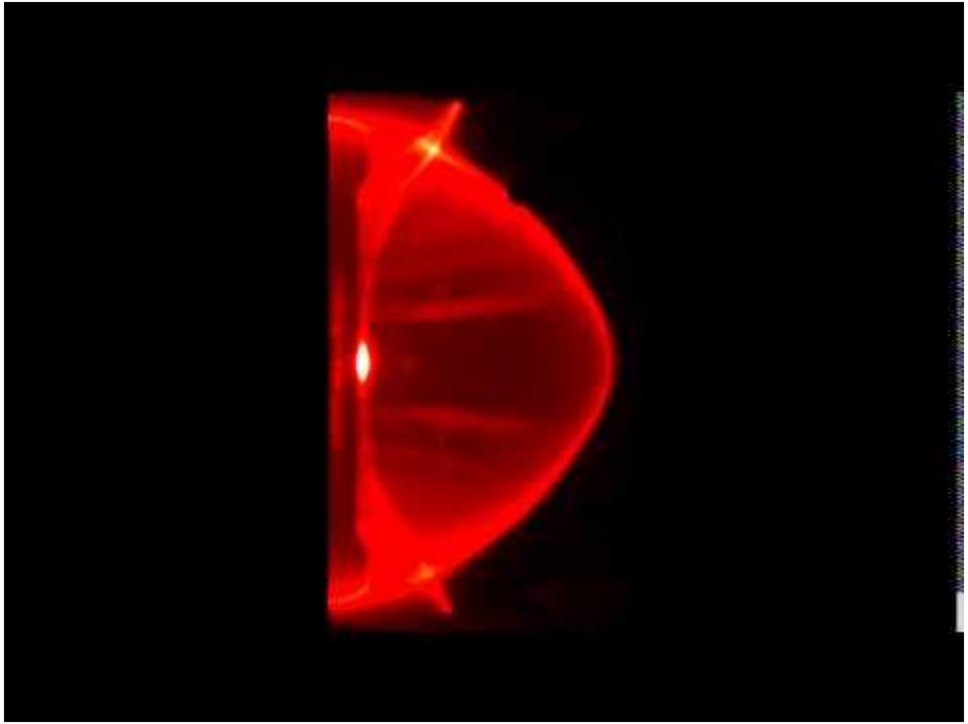

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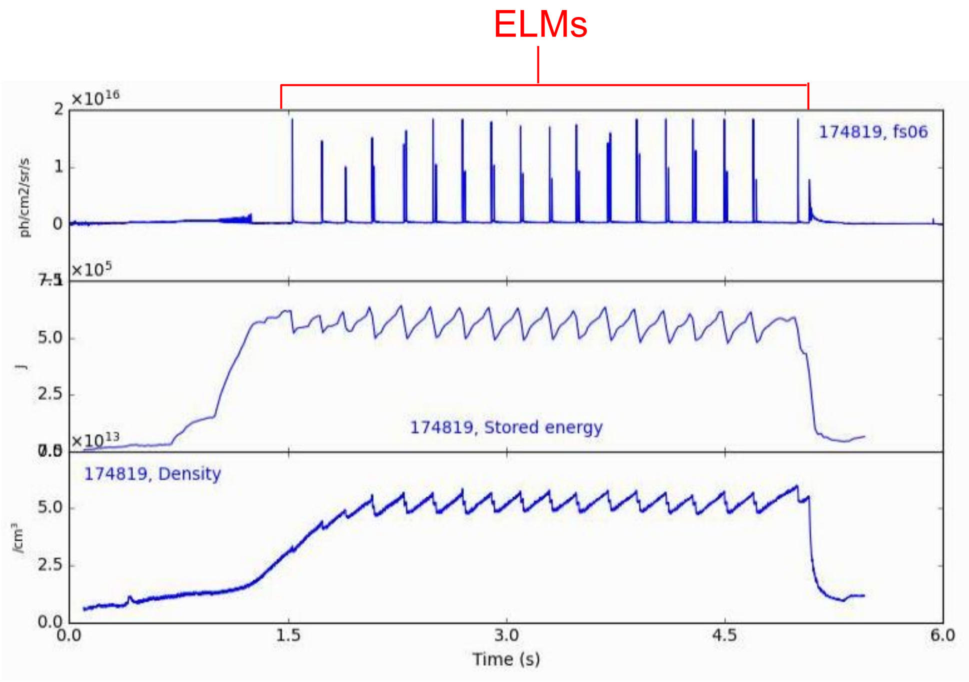

- Typically observed in experiments as a spike in D_α emission
- Accompanied by a rapid decrease in stored plasma energy and plasma density
- This lost energy goes to the walls and divertor
  - Leads to large transient heat fluxes

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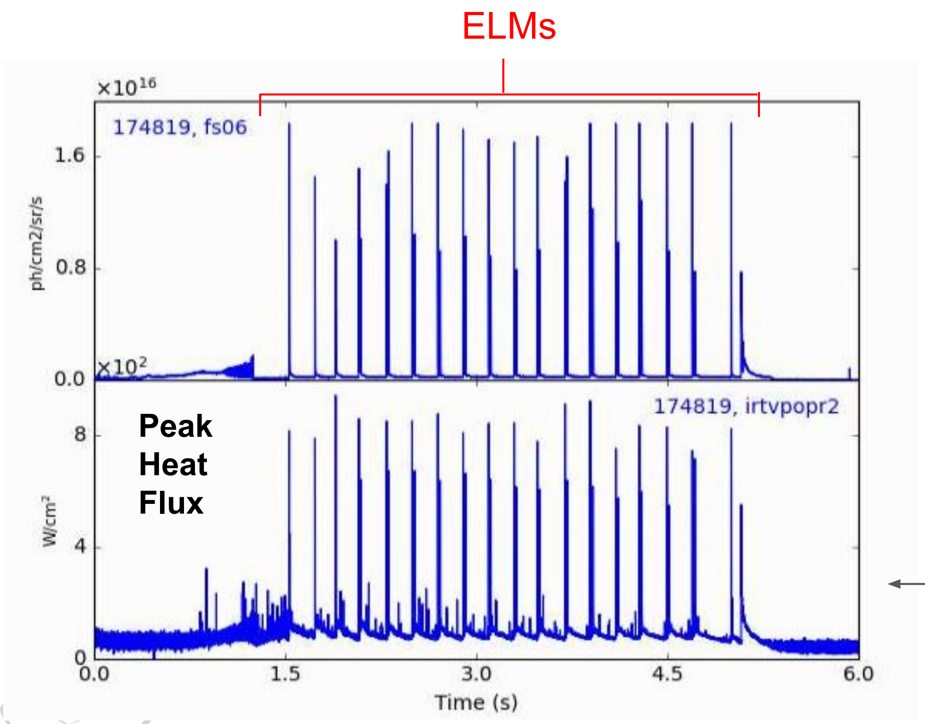

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3 Mechanisms for Total Edge Current to Change: Local Change in external flux, motion through ∇B, Shape Change

$$\delta I_\phi^{w_r} = \frac{4\pi}{\mu_0 R_0}\left[\delta\psi_{\rm ext}(a) - B_\theta(r_0) R_0 \delta w_r - \eta J_\phi \delta t\right]$$

$$\delta\psi_{\rm ext} \approx \delta\psi_{\rm ext}(\mathbf{r}_0) + \delta\mathbf{r}\cdot\boldsymbol{\nabla}\psi_{\rm ext}$$

1 | 2 | 3

Can be considered small in ideal plasma

1	Local Change in External Flux (such as from coil currents changing
2	Change in flux due to motion of plasma through inhomogeneous **B** field
3	Change in plasma shape (compression, etc)

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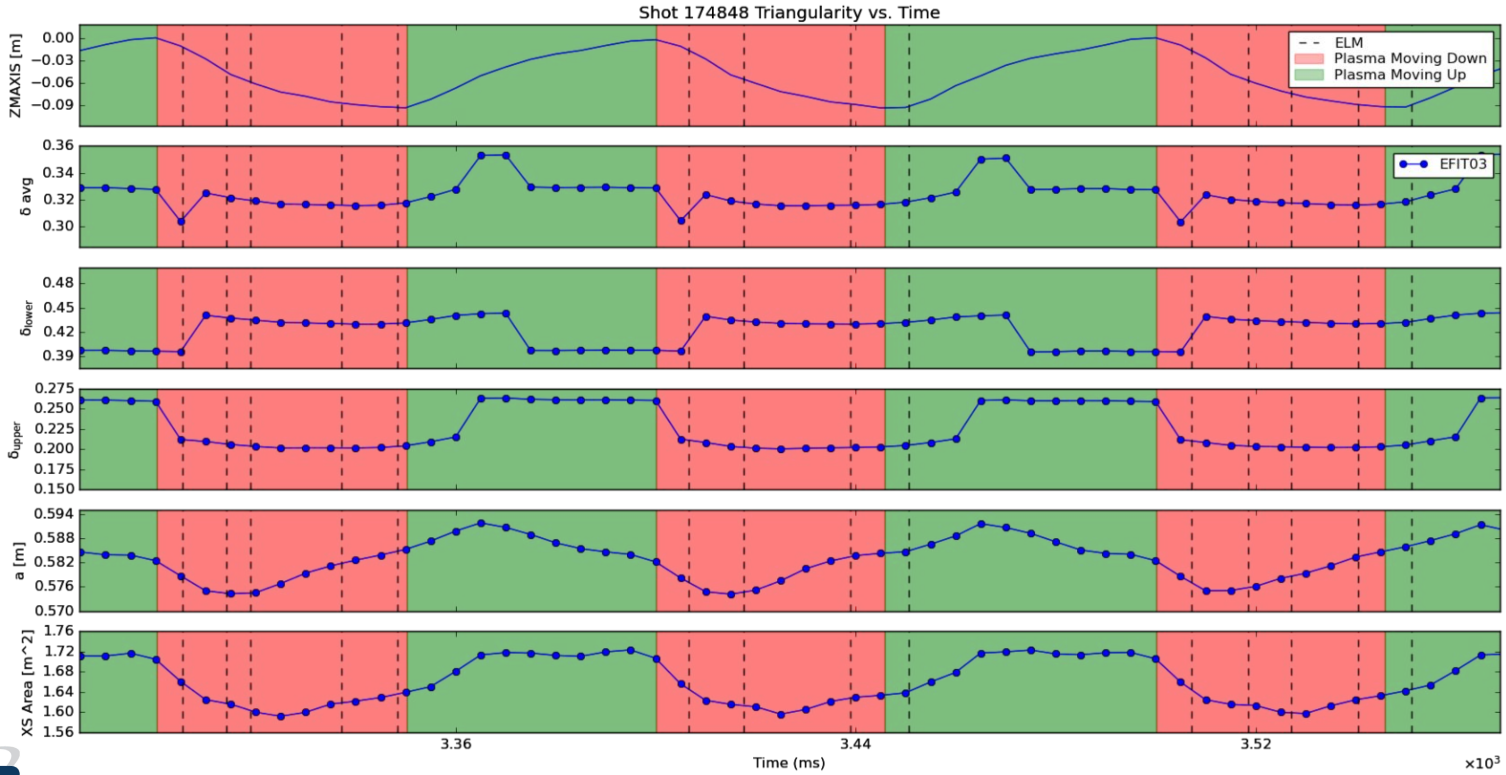
Shape Changes During Oscillations - Decreased XS Area, Decreased δ^{upper}



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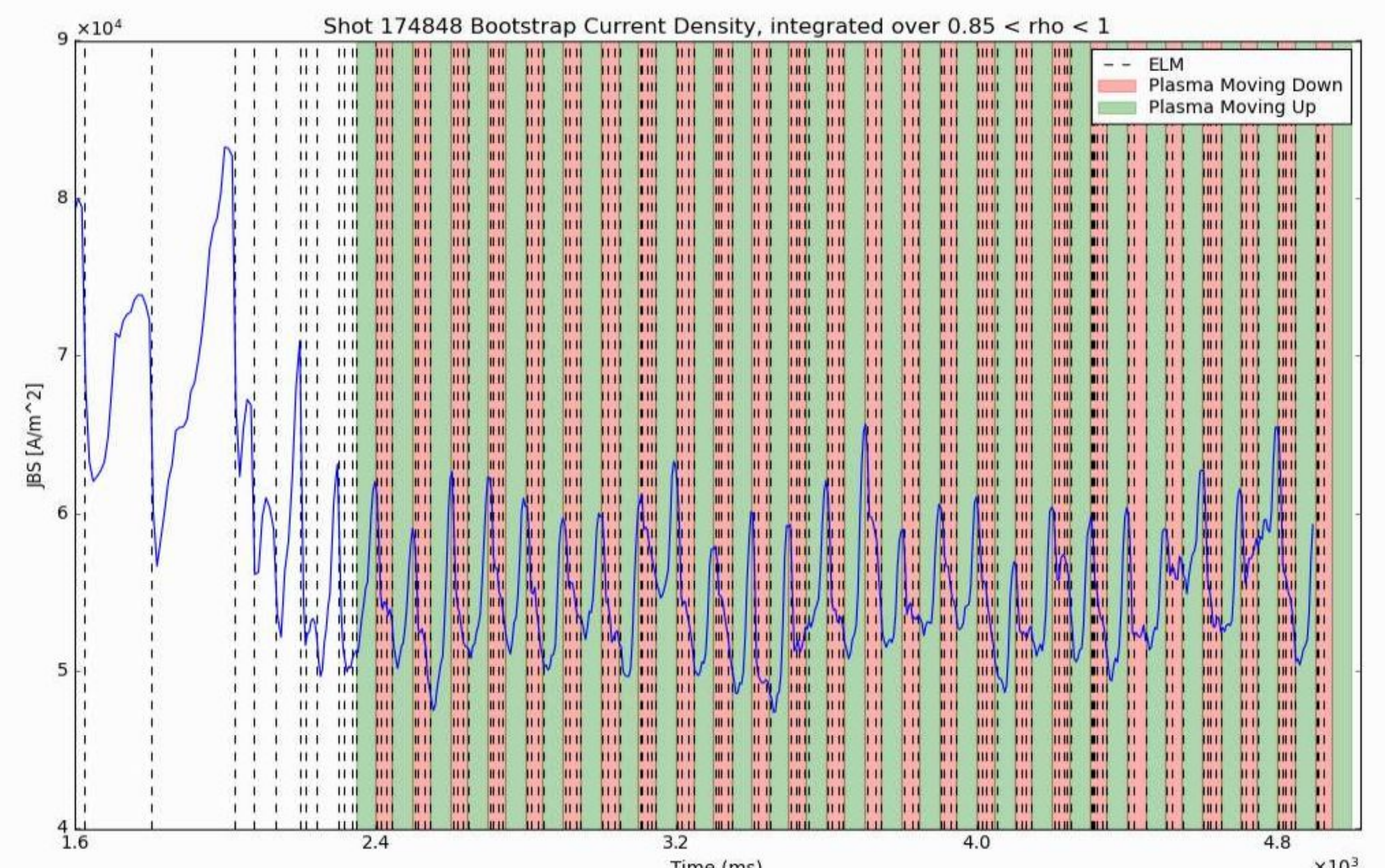
Bootstrap Current Plot with ELMs overlaid

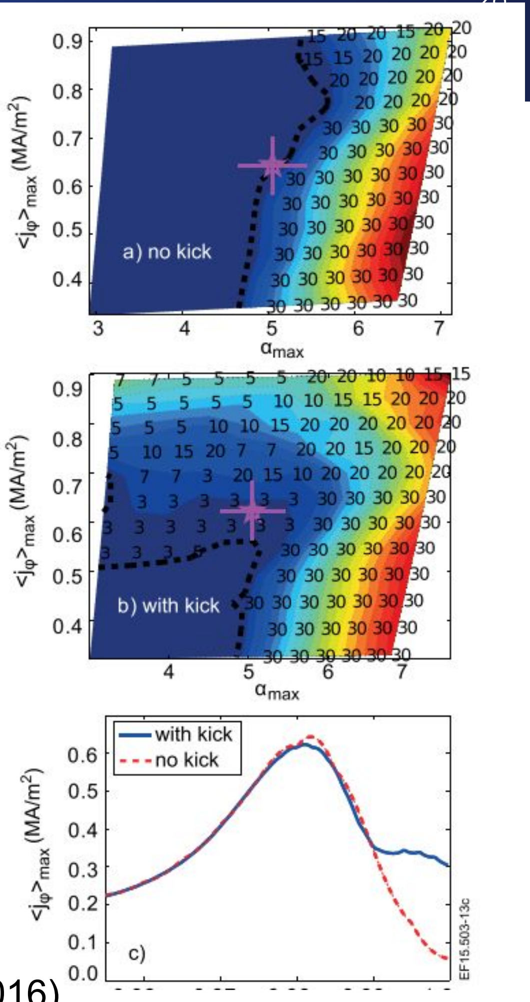


Stability Analysis With Simulated J_{edge} for a similar JET shot

Stability results with an artificially added current at edge, from simulation predictions

Plasma marginally stable without added current, but unstable with added current

This is stability of a time slice right before an ELM is triggered during a vertical oscillation moving downwards



(De la Luna 2016)

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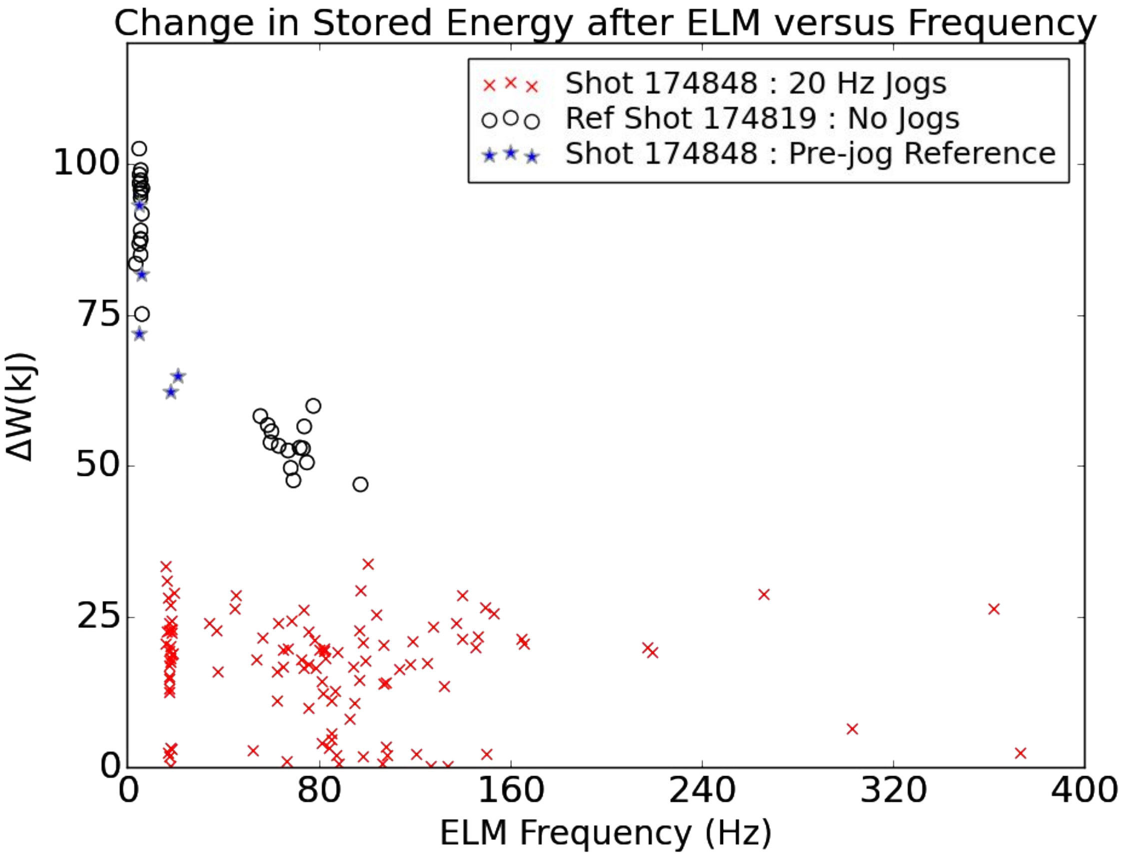
Absolute dW Values vs ELM Frequency



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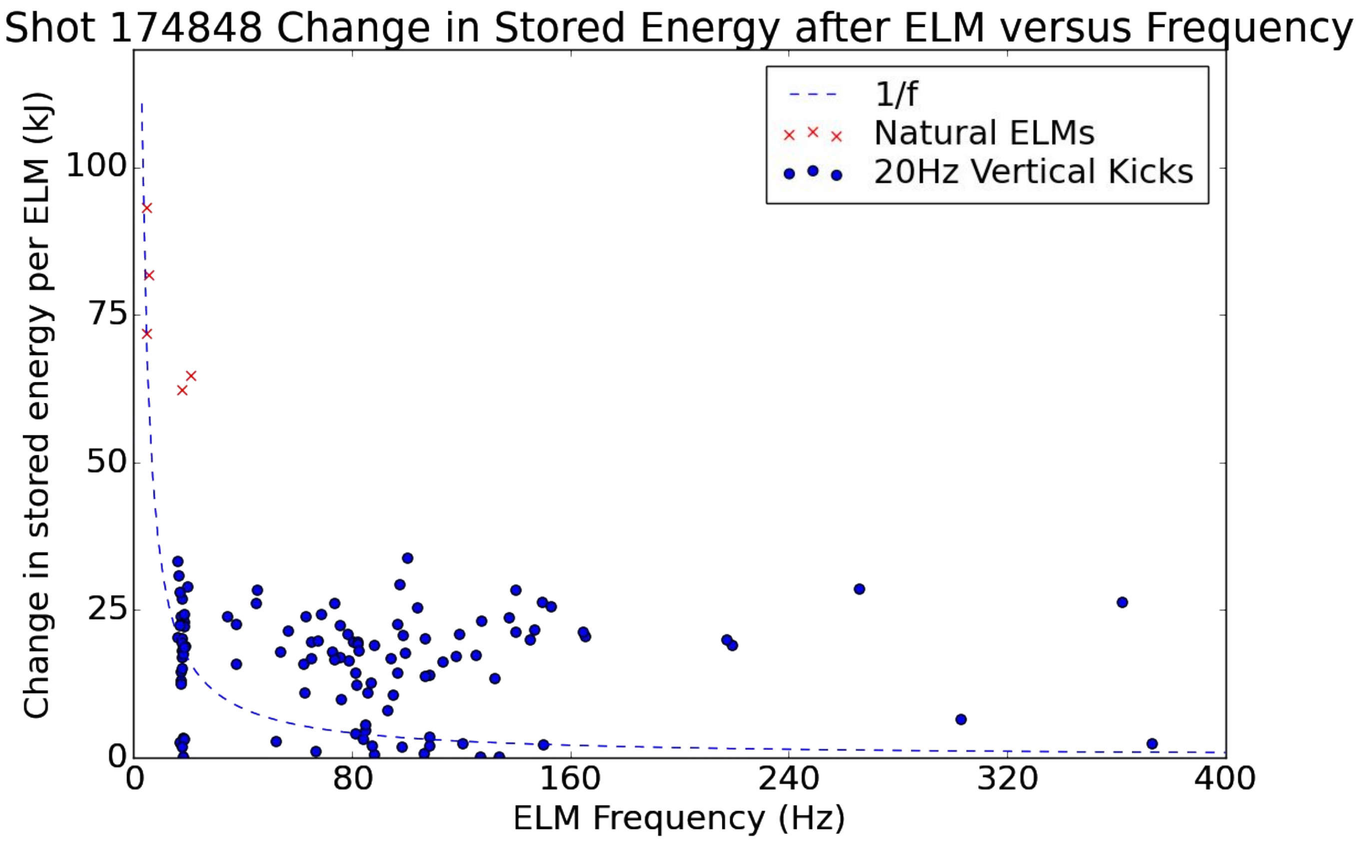
Absolute dW Values vs ELM Freq. for Shot 174848 Only



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