XP-945: ELM Pacing By Vertical Position Oscillations

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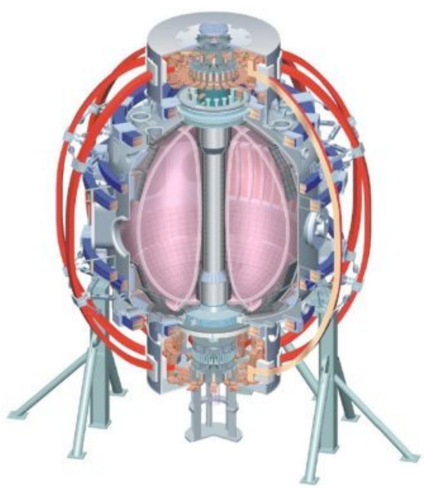

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Goal: Use Rapid Oscillations in the Plasma Position to Trigger ELMs

- Reactor-scale tokamaks need either mitigation, or complete suppression, of ELMs:
  – Suppression techniques include some RMP results, QH mode.
  – Mitigation could mean ELM pacing with 3-D fields, small-ELM regimes, pacing via pellets, or *plasma position oscillations*.

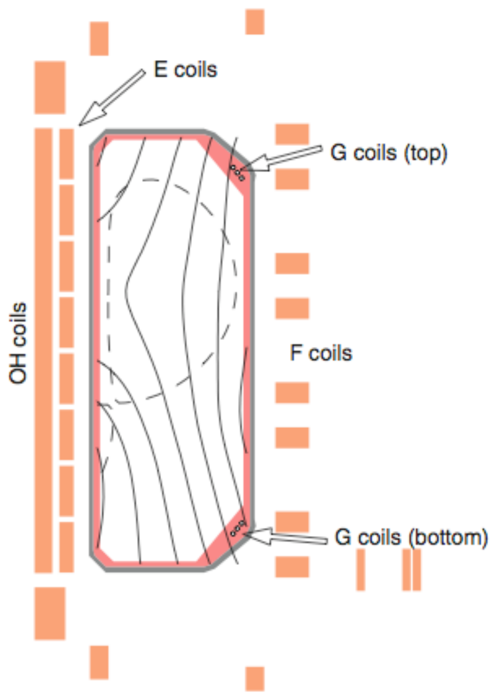
- ELM triggering via vertical position oscillations observed in at least 3 tokamaks.
  – TCV [1]: A. W. Degeling, et al., Plasma Phys. Control. Fusion **45**, 16367 (2003)
  – AUG [2]: P.T. Lang, et al., Plasma Phys. Control. Fusion **46**, L31 (2004)
    - Above two compared in [3] S.H. Kim, et al, Plasma Phys. Control Fusion **51**, 055021 (2009)
  – JET [4]: F. Sartori, et al., 35th EPS Conference on Plasma Physics

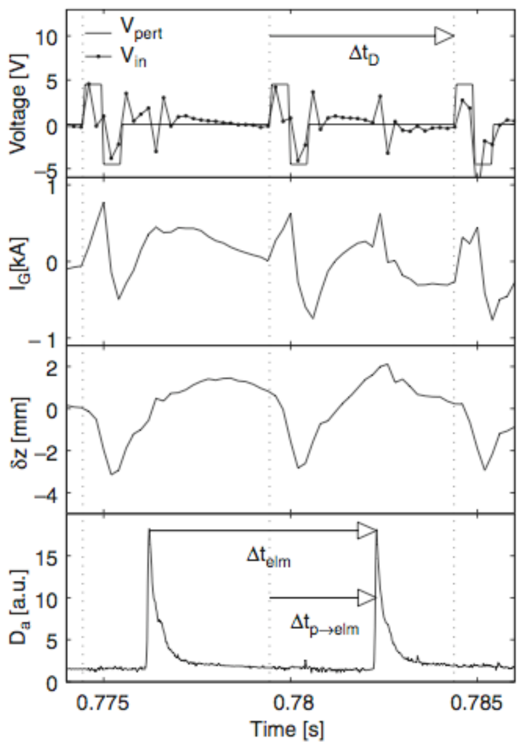
- Physics mechanism of pacing via vertical jogs remains obscure.

- Propose to test this in NSTX:
  – Support ITER needs and test concept for future ST devices.
    - Can we add any understanding to the present confused state.
  – May complement (N)RMP ELM-pacing methods.

ELM Pacing First Observed in TCV [1]

- Fast internal coils, perturbation voltage imposed on vertical control, ~140 to 300 Hz triggering, Ohmic H-mode with type-III ELMs.
- For LSN, triggered on the way UP, for USN, triggered on the way DOWN.
  - Pushing the plasma toward the divertor coil reduces the edge current.
  - Consistent with triggering when the velocity drives an increase in the edge current.
- Results consistent with model of the ELM cycle being driven by the edge current perturbation.



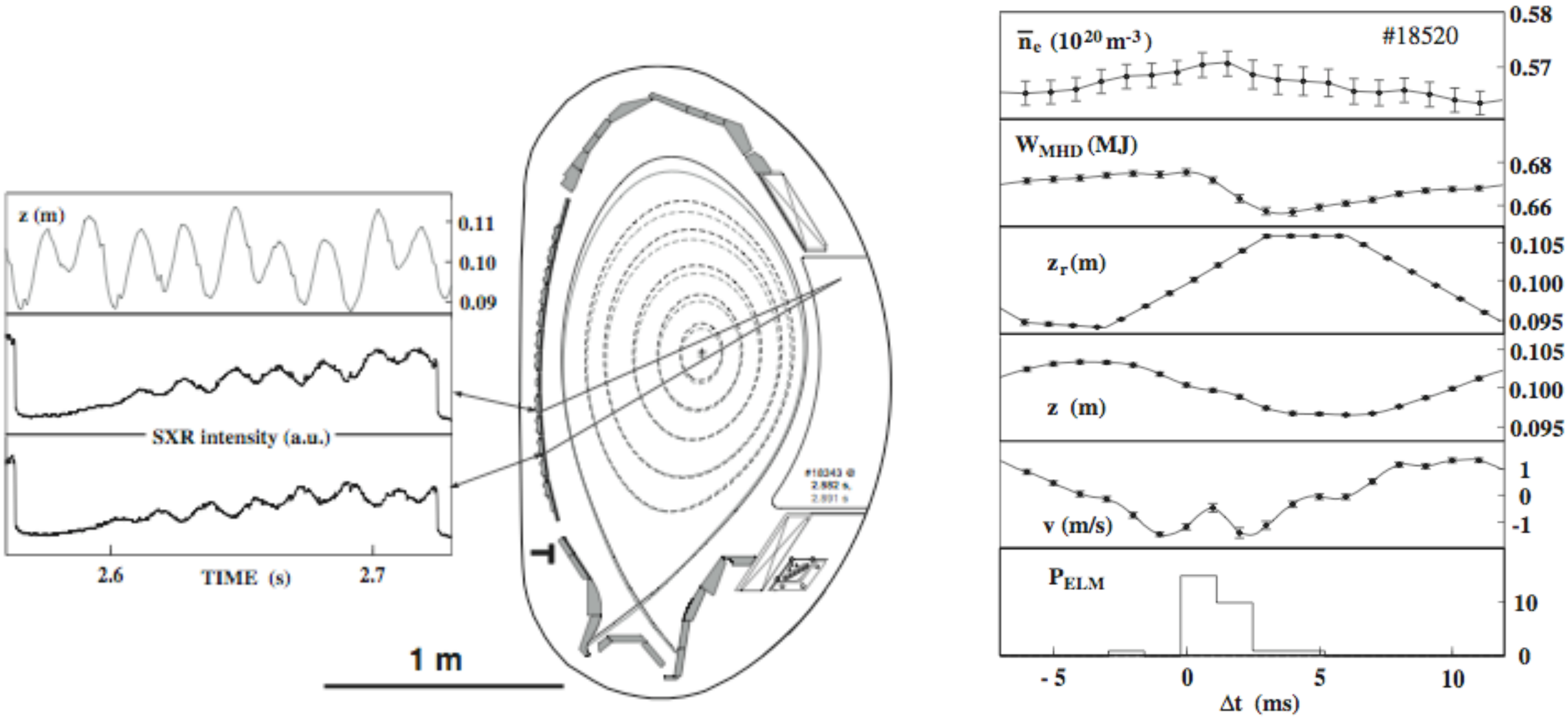


V_{pert}: External Perturbation
V_{in}: Closed Loop Response

ELM Triggered on the way UP.

AUG Also Observed Pacing [2], Though Physics Seemed Different than in TCV

- External coils, sine-wave request on the vertical position with reliable triggering achieved at ~12mm peak-to-peak, ~60 Hz triggering, NBI H-mode with type-I ELMs.
- For LSN, ELMs triggered as the plasma moves DOWN, while upward movement seemed stabilizing.
  - Opposite the TCV result!



Comparison of TCV and AUG Results in [3] Could NOT Identify a Clear Triggering Mechanism

- Confirmed with DINA-CH simulations that the edge current is decreased during triggering on AUG, but increased in TCV.
- Both configurations show a similar upper-outer separatrix deformation
  - Due to “G-Coils” in TCV, PSL in AUG
- Stability calculations for AUG indicate that the increased upper-outer squareness may reduce the pedestal stability
- Ultimately, no conclusion could be reached on the trigger physics.

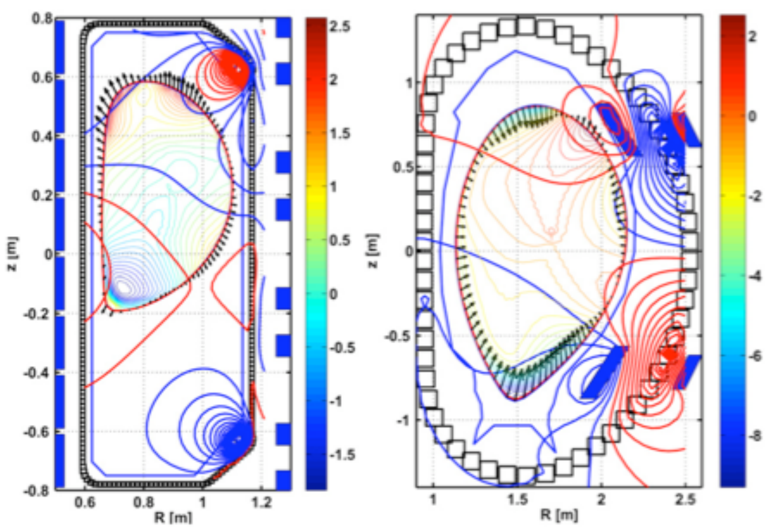


Figure 10. Flux surface deformations and vacuum flux changes are shown for upward plasma movement in TCV discharge #20333 (left) and downward plasma movement in ASDEX Upgrade discharge #18343 (right). ELMs are triggered in the experiments for these plasma movements. The arrows are amplified by a factor 20 for visibility.

Table 1. The observations in the experiments and simulations of magnetic triggering of ELMs are summarized.

Observations	TCV	ASDEX Upgrade		Comments
Plasma movement	Upward	Downward	Inward	
Type of natural ELMs	Type III	Type I	Type I	
Triggered ELMs	Observed	Observed	Not observed	
Edge current density	Increased[a]	Decreased	—	
Edge current gradient	Decreased (locally increased)	Increased (locally decreased)	—	Mixed contributions
Edge pressure gradient	Decreased	Increased[a]	—	
Plasma area	Expanded	Shrunken[a]	—	
Shape deformation	Locally expanded in upper LFS[a]	Locally expanded in upper LFS[a]	Elongated	
Squareness (upper LFS)[b]	Decreased	Increased[a]	—	Squareness decrease in TCV is not yet clearly explained
Curvature (upper LFS)[b]	—	Locally increased or decreased	Locally increased or decreased	Similar patterns
Curvature (lower LFS)[b]	—	Increased[a]	Decreased	Systematic differences in the stability margin behaviour

[a] Possible candidates for triggering ELMs.
[b] Observations from the KINX analysis [10, 14].

ELM Pacing Has Subsequently Been Achieved on JET [4]

- External coils, with user defined voltage pulse on the Vertical Stabilization (VS) controller, NBI or ICRH H-mode with low-frequency type-I ELMs, ~25-50 Hz triggering.
- Increased the ELM frequency by a factor of 5.
- Large initial ELM was moderated by triggering it earlier.
- ELMs only triggered for downward kicks (not the downward motion of an upward kick).
  - Appears inconsistent with either TCV or AUG?

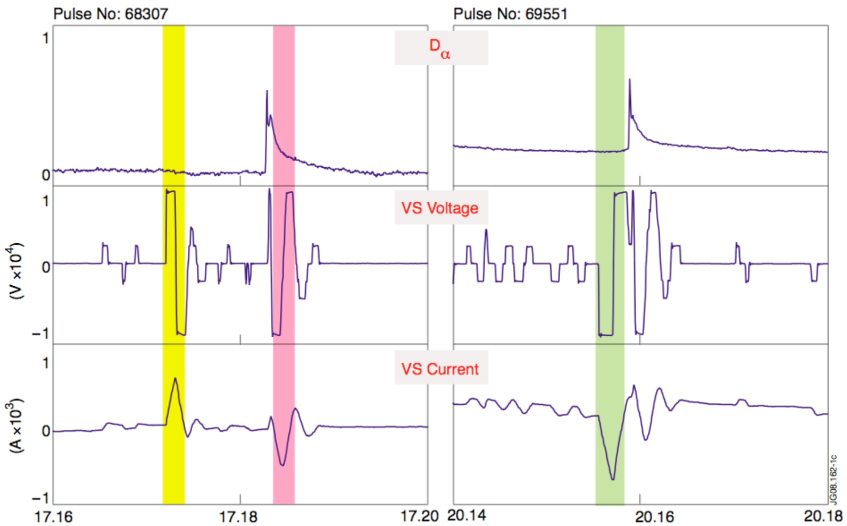
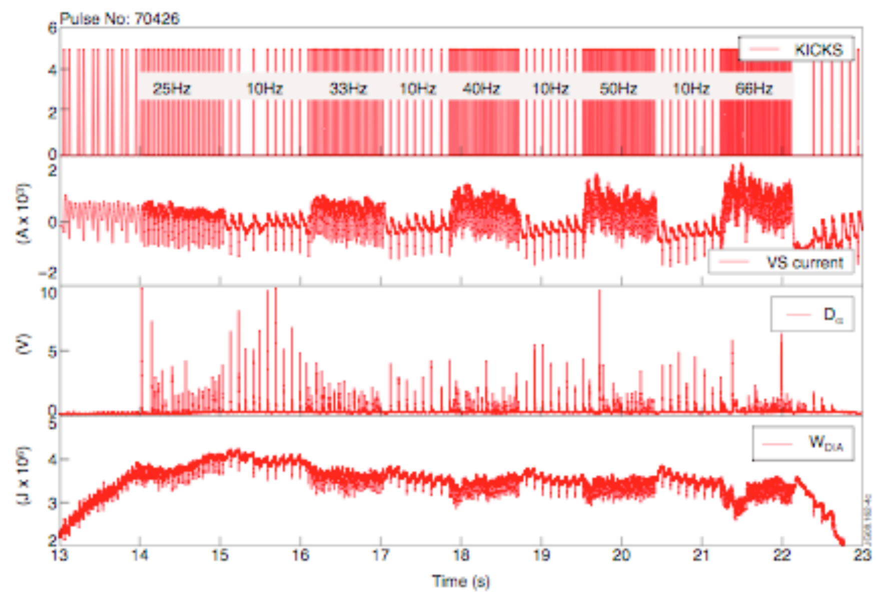


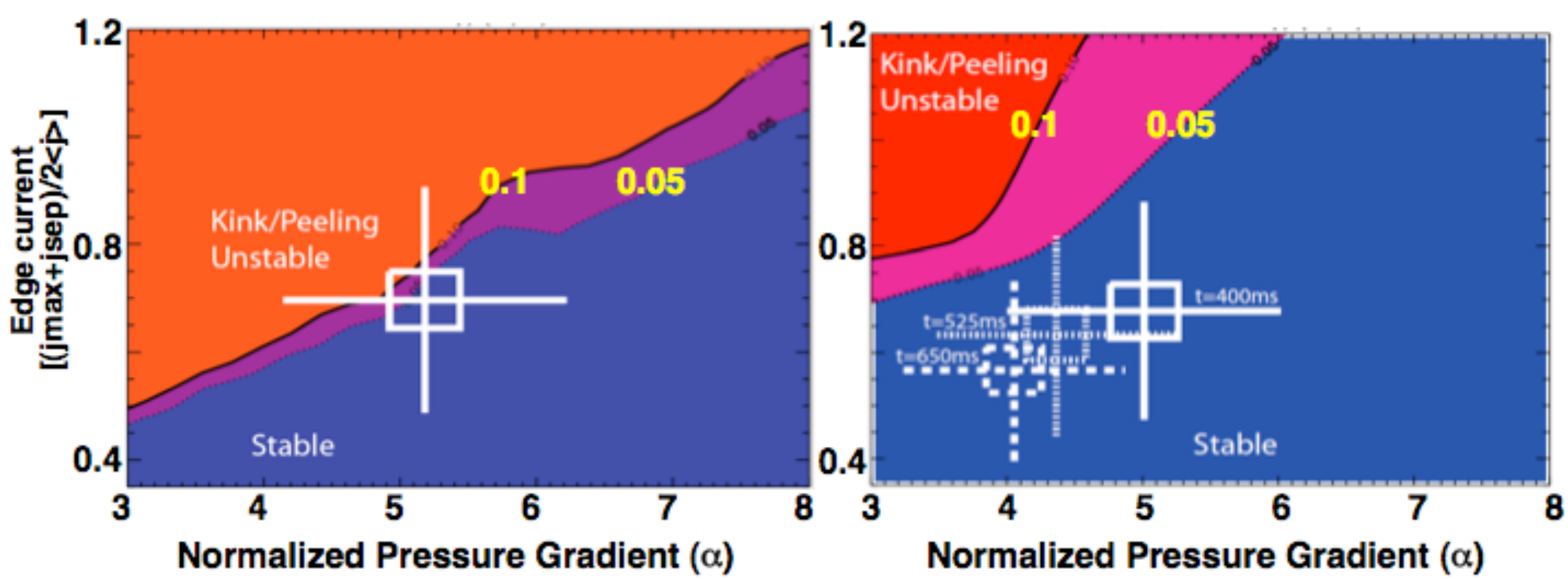
Figure 1: Voltage response to a natural ELM (pink bar), a positive kick (yellow bar), and a negative kick (green bar). The kick direction (positive/negative) is determined by the initial sign of the voltage. The following counter-kick is the VS trying to recover plasma vertical control. Note that in the natural ELM the VS applies a positive voltage briefly. This is caused by a measurement problem.



Pre-lithium edge profiles close to peeling/ballooning instability threshold (ELITE)

No lithium: $\gamma_{lin}/(\omega^*/2)$ becomes large at blue/purple/orange boundary ('varyped' EFITs)

With lithium: $\gamma_{lin}/(\omega^*/2)$ becomes large at blue/purple/red boundary ('varyped' EFITs)



Slide from R. Maingi's 2009 TTF Talk

Goal of XP-945: Demonstrate ELM Pacing with Vertical Jogs in NSTX

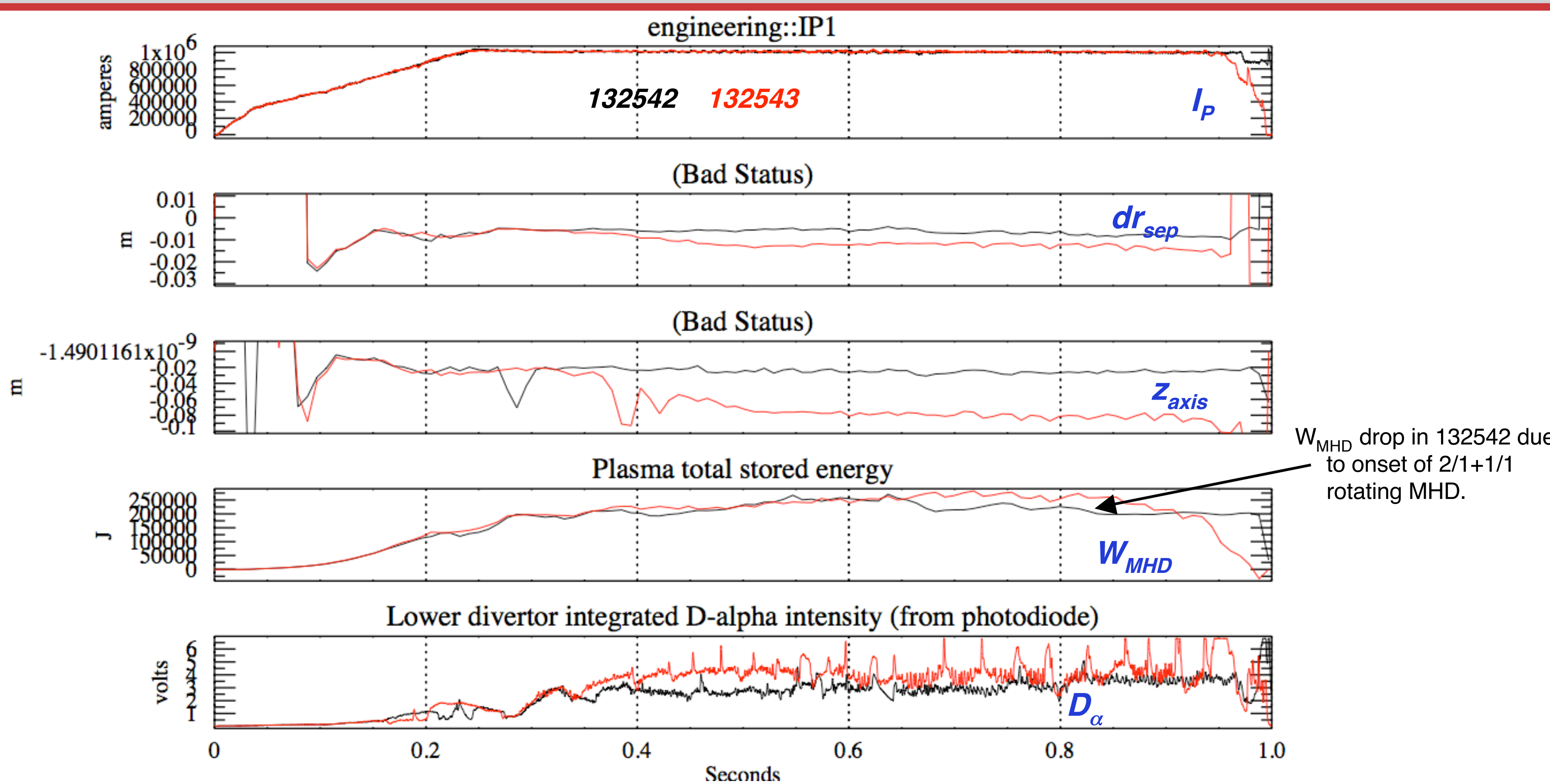
- Use 1/2 day to develop a scenario with ELM pacing via vertical jogs.

…and if this is achieved, use 1/2 day to…

- Maximize the frequency of triggered ELMs, consistent with maintaining good plasma performance

- Try to understand what leads to triggering.
  - Do we drive edge current, crossing the J_{ped} boundary?
  - Do we modify the pressure gradient?
  - Is there a threshold modification to the equilibrium shape?

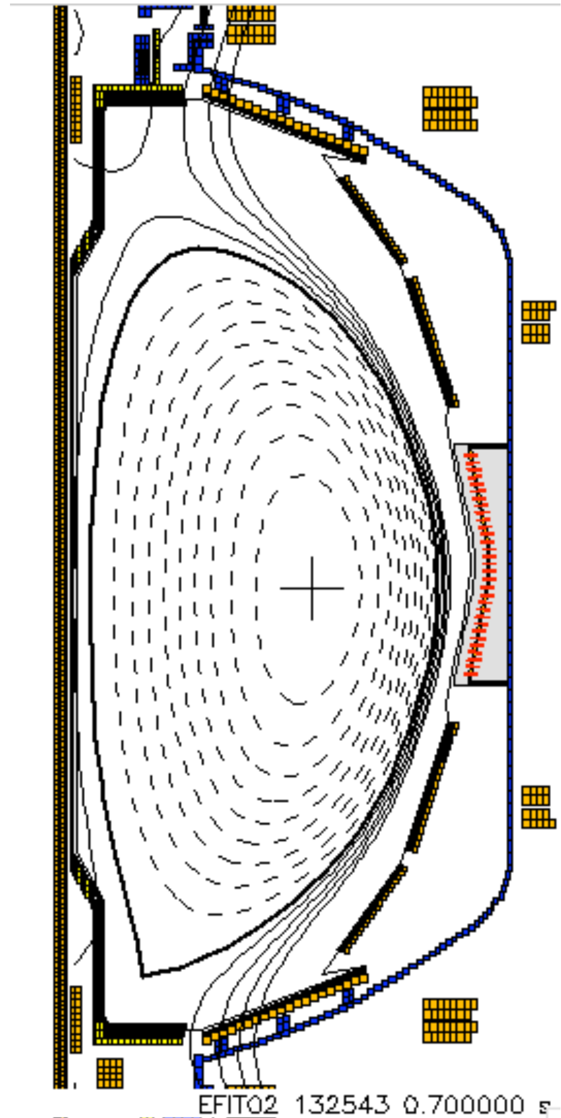
Reference Discharge (132543) Comes from the 2009 Version of XP-827, Is Similar to the Fiducial (I)



- dr_{sep} and z_{axis} are coupled in NSTX.
- Both shots have requested Z-position of 0 m (perfectly centered).
- 132542 requests dr_{sep}=-1 cm, 132543 requests dr_{sep}=-3 cm
- Isoflux "harmonizes" these inconsistent requests, but doesn't achieve either.

Reference Discharge (132543) Comes from the 2009 Version of XP-827, Is Similar to the Fiducial (II)

- Biased down
  - Reduces the risk of diverting onto the poorly conditioned upper divertor.
  - Places more power on the better diagnosed divertor.
  - Uses fiducial startup, followed by dr_{sep} rampdown to ~-1.2 cm.
- Outer gap of 10-11 cm optimized for MPTS resolution of the pedestal.
- Fairly strong shaping.
  - κ=2.1, δ_l=0.7, I_P=1000 kA
  - May be a test of the ability to jog high-κ plasmas without VDEs.
  - May need to reduce κ if vertical stability is a problem.
- Intrinsic type-I ELMs at about 30-40 Hz before Li evaporation.
  - Looks like Type-V ELMs between the type-I ELMs?
  - Lithium can eliminate ELMs…run after passivation or with small amount of Li to further reduce intrinsic frequency?
- Cases ran with various levels of heating power
  - 6MW, 132543
  - 5MW, 132547, 132550



Proposed Shot List (what is most important?)

1st 1/2 day:

- Establish Reference Discharge (4 shots)
  - Reload 132543.
  - Use 4 minute glow followed by 25 mg Li evaporation (maybe?).
  - If ELMs too frequent, either reduce input power or increase Li rate.
- Attempt to Trigger ELMs with Vertical Jogs (15 shots)
  - Modify to plasma position (z_{axis}) request with a square wave
    - parameters f_{kick}=50 Hz ($1/f_{kick}$=20 msec), amplitude A_{kick}=5cm, duration τ_{kick}=1 msec.
    - Kicks should direct the plasma down, then back centered.
  - *Should we jog dr_{sep} instead of z_{axis}, or jog then in parallel? Change any z_{axis}, dz_{axis}/dt gains*
  - Make the following modifications to pace ELMs.
    - Increase τ_{kick} until it is clear that the PF3 coils are reaching full voltage.
    - Increase A_{kick} in order to increase the magnitude of shift.
  - Repeat reference to assess intrinsic ELM frequency.

If/when pacing is observed, go to 2nd 1/2 day:

- Gate pacing on/off during a singe shot to demonstrate triggering. (2 shots)
- Study the ability to trigger ELMs over a range of f_{kick}. (5 shots)
  - Try f_{kick} values of 70, 90, 30 ($1/f_{kick}$=14 msec, 11 msec, 33 msec)
- Try to isolate transient vs. steady state effects (4 shots)
  - Attempt to run plasmas with $dr_{sep,}$ z_{axis} similar to the extremes encountered during the jogs, but with no kicks.
- Determine range of dr_{sep} over which the method works. (5 shots)
  - Take the best jogging example, and modify "steady-state" dr_{sep} request by +1cm, -1cm, and possibly other values, while keeping the "kicks".

Diagnostics and Analysis

- Diagnostics
  - MPTS for profiles
    - 60 Hz triggering can be used to align pulses to TS lasers, timing scanned.
  - Filterscopes
  - PF-3 coil currents and voltages, vessel loop voltages
  - High-n array
  - USXR with 5μm Be filters
- Analysis (presuming success in triggering)
  - Attempt to use equilibrium reconstruction to isolate (assumed) edge current perturbations.
    - Predictive code like TSC for analysis of edge currents if this fails?
  - Edge gradient analysis (tanh fits) for pedestal pressure analysis.
    - Pedestral stability analysis if it seems appropriate.