NSTX

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ELM Pacing Via Vertical Position Jogs in NSTX

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1: PPPL, 2: ORNL, 3: Columbia University, 4: The Johns Hopkins University

17th Pedestal and Edge ITPA Group Meeting
PPPL

Thanks for squeezing the talk in at the last minute.

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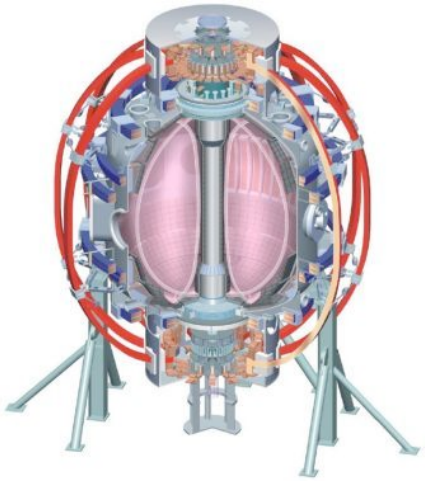

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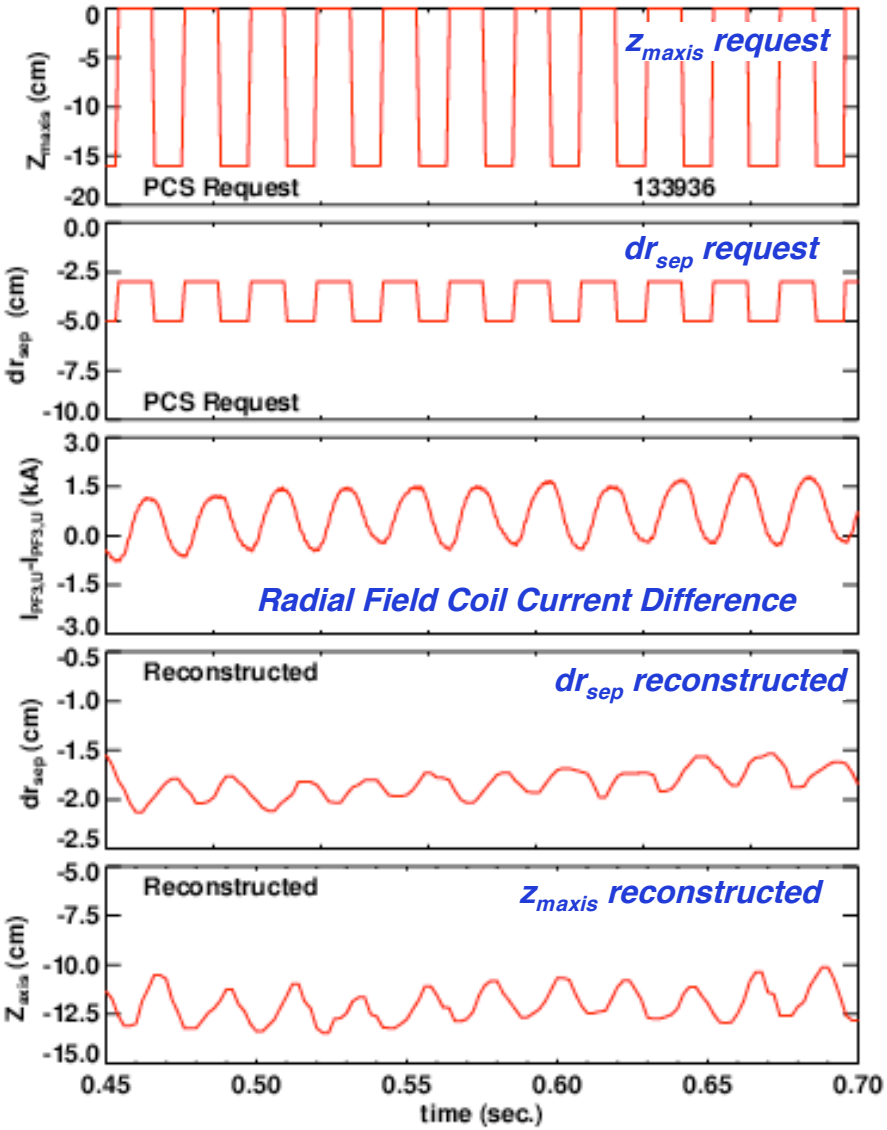
Goal: Use Rapid Oscillations in the Plasma Vertical Position to Trigger ELMs

- 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.
  - Perturbations to edge current?
  - Modifications of the boundary shape?
  - Something else?
  - All of the above?
- Propose to test this in NSTX:
  - Support ITER needs.
  - Test concept for future ST devices.
  - Attempt to understand something about ELMs.

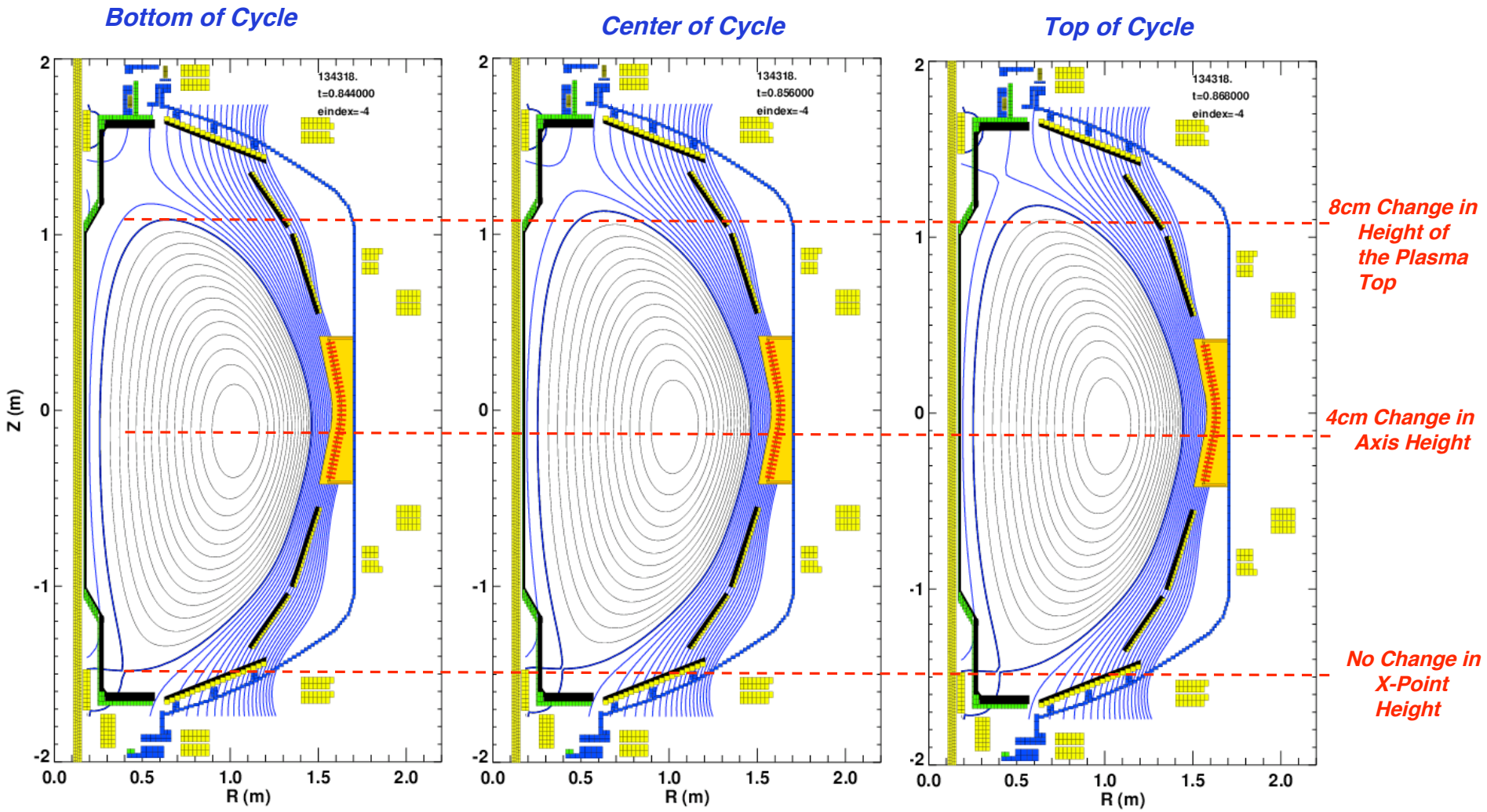
Plasma Can Be Jogged Using Step Requests in Axis Vertical Position, dr_{sep}, or Both Synchronously.

- NSTX uses the General Atomics PCS
  - rtEFIT and ISOFLUX for shape control.
  - No explicit voltage perturbations on rail field coils.
- NSTX has a 1.6cm thick stainless steel vessel.
  - Tends to shield the radial field perturbations.
- Apply synchronous jogs in dr_{sep} and z_{maxis} to drive motion.
  - dr_{sep} and z_{maxis} are strongly coupled in NSTX due to the coil locations.
  - Request large & rapid excursions in these parameters to overdrive the motion.
- Considering adding an explicit voltage perturbation to the radial field coils for FY-10.



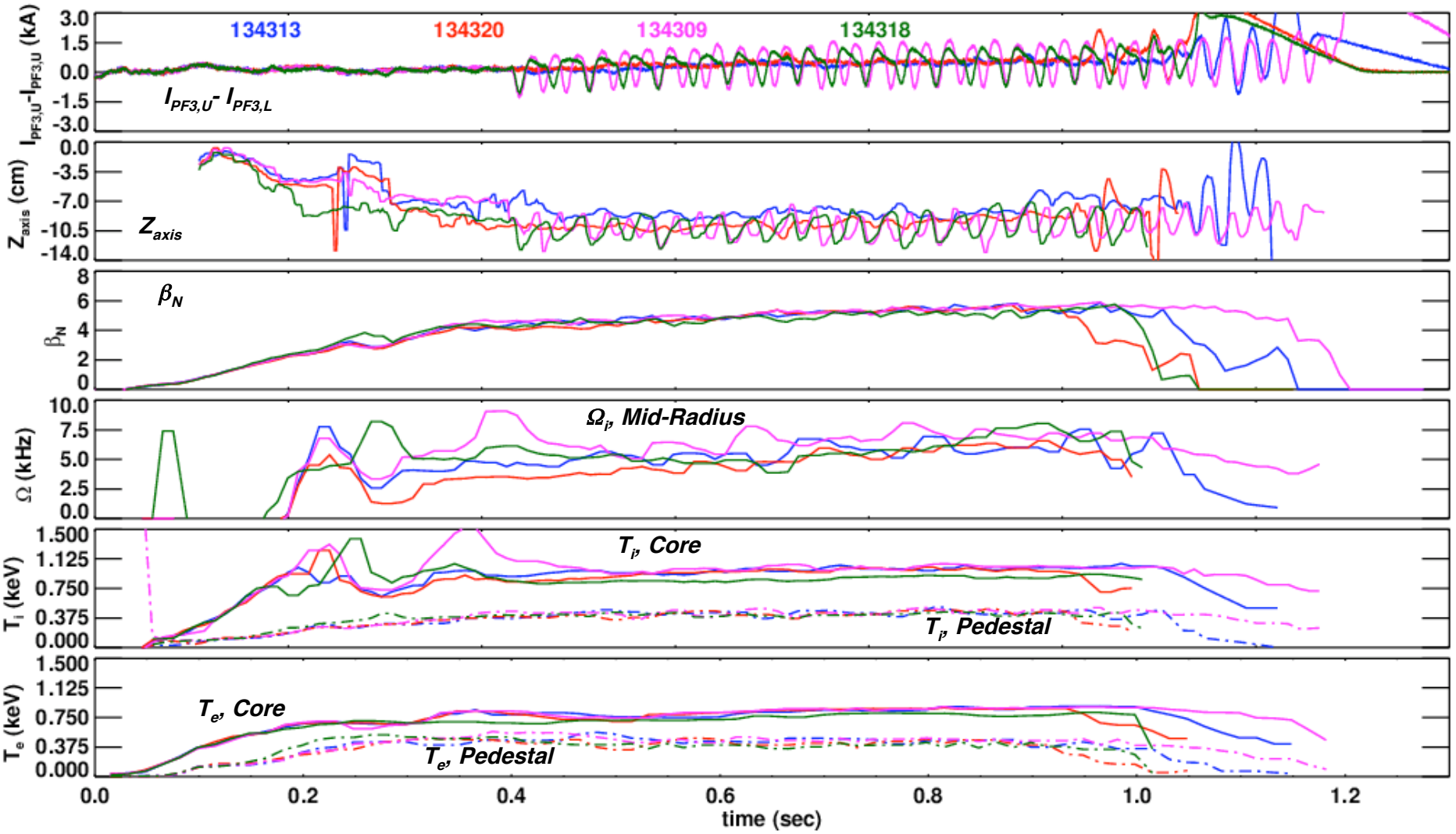
Jogs Lead To Large Shift in Plasma Top, but X-Point is Fixed

134318: 30 Hz Jogs in dr_{sep}



Global Plasma Parameters are Remarkable Unaffected by *Careful* Jogs

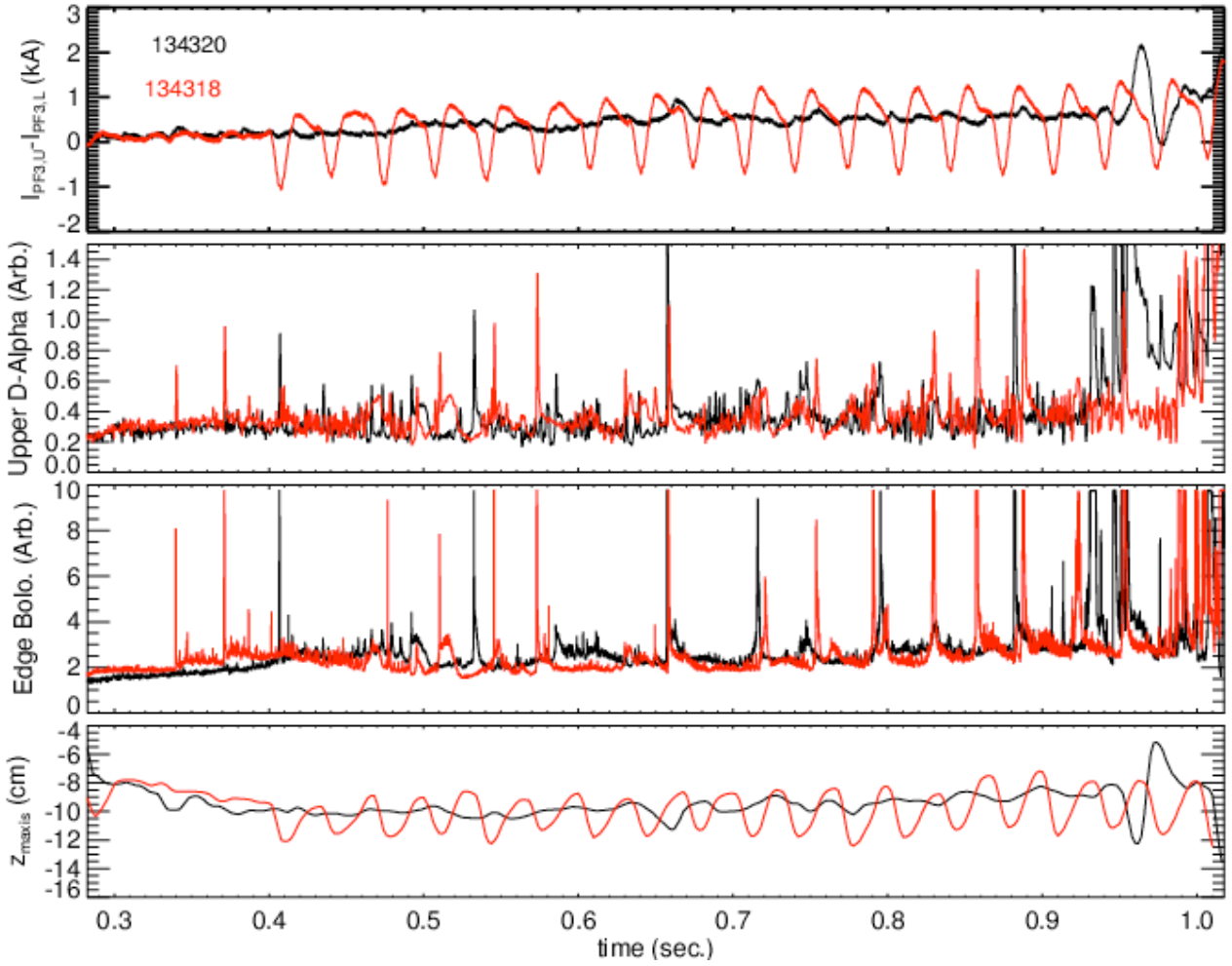
134313: Reference ***134320: Reference*** ***134309: 45 Hz jogs*** ***134318: 30 Hz jogs***



30 Hz Jogging Observed to Increase/Synchronize ELM Frequency in ELMy Discharges

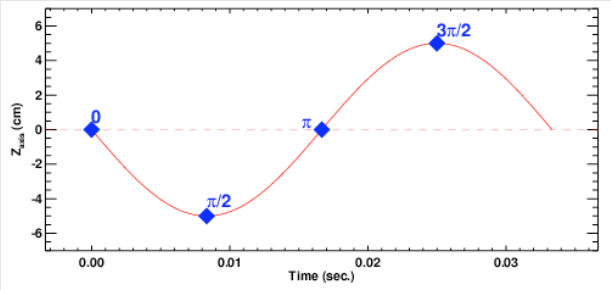
134320: Reference, 6 ELMs in 0.5 sec.→f_{ELM}= 12 Hz

134318: Jogging Case, 12 ELMs in 0.5 sec.→f_{ELM}= 24Hz



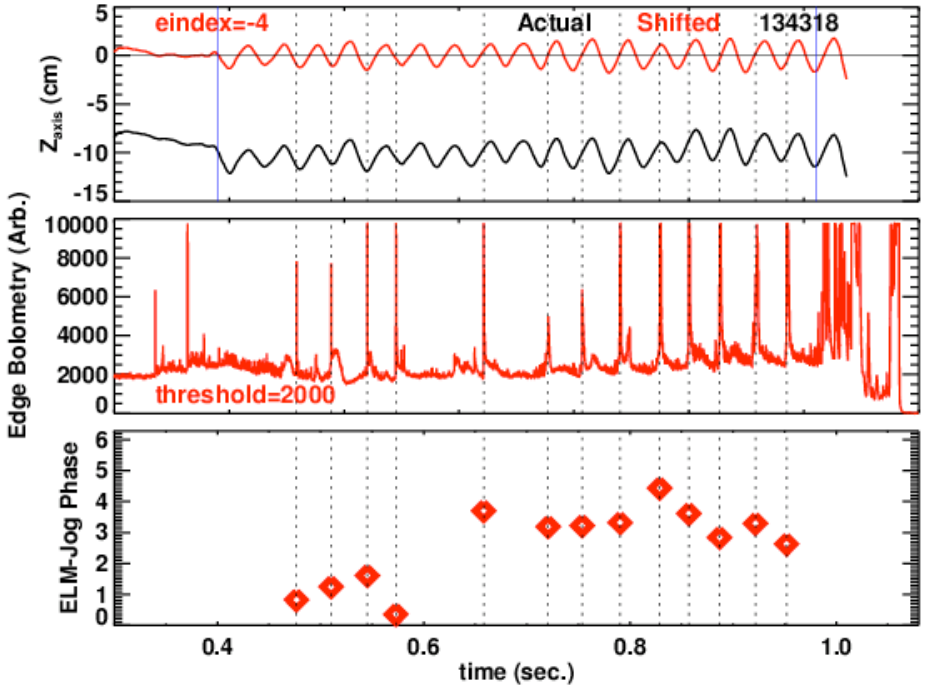
At 30 Hz, ELMs most likely to be Triggered As the Plasma Moves Up

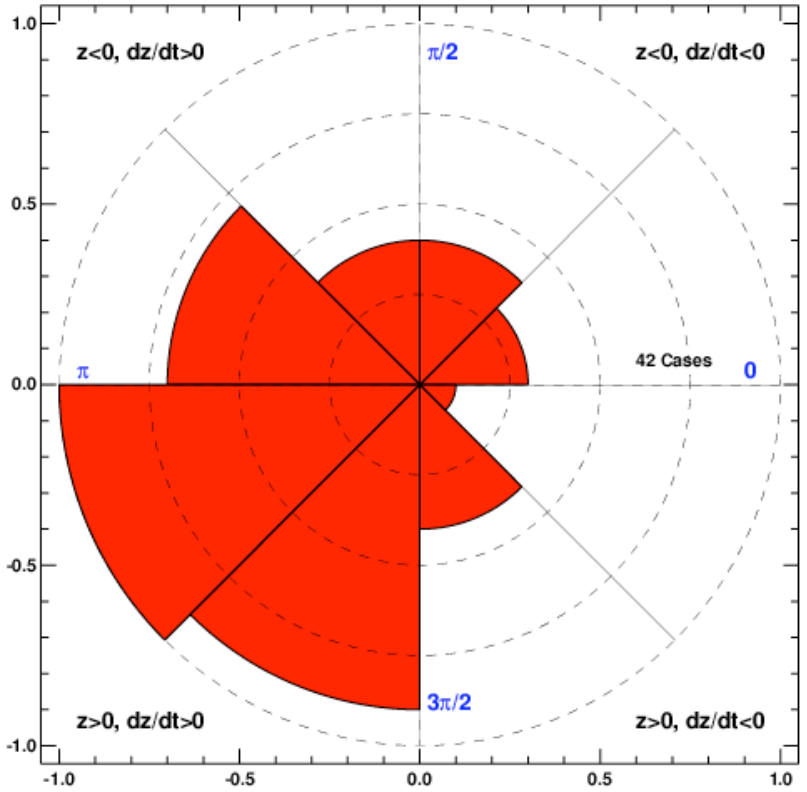
Definition of Phase Within Jog Cycle



- 42 ELMs during jogging phase of 4 shots, 30 Hz Jogging.
  - 134314,134318,134312,134310
- ELMs most likely to be triggered as the plasma moves up.
- ELMs unlikely to be triggered as the plasma moves down.

ELMs have Preferential Phase w/ Respect to Jogs after t=0.6





45 Hz Jogging Induces Rapid ELMs

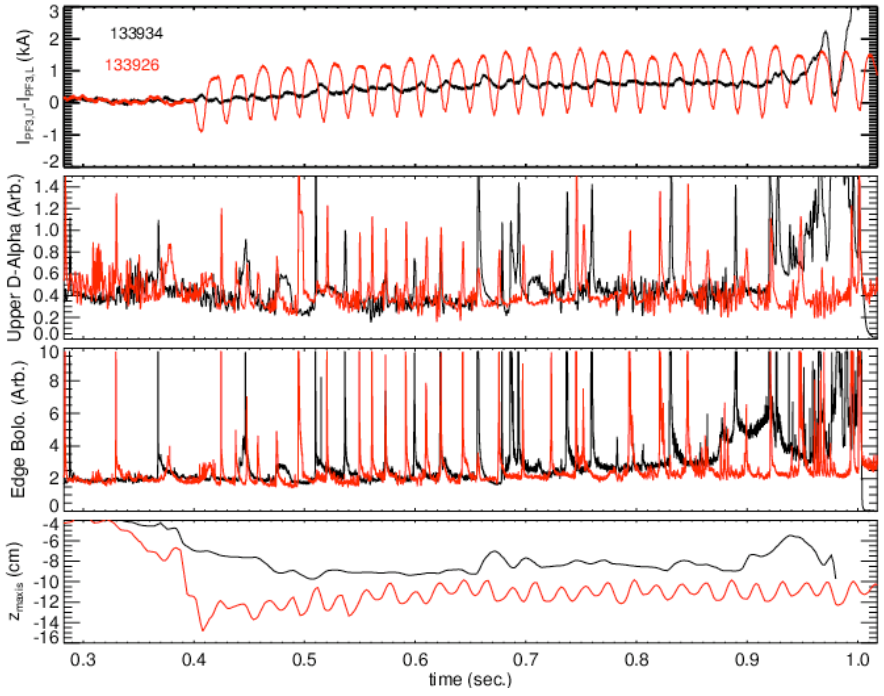
133934: Reference, ~12 ELMs in 0.5 sec.

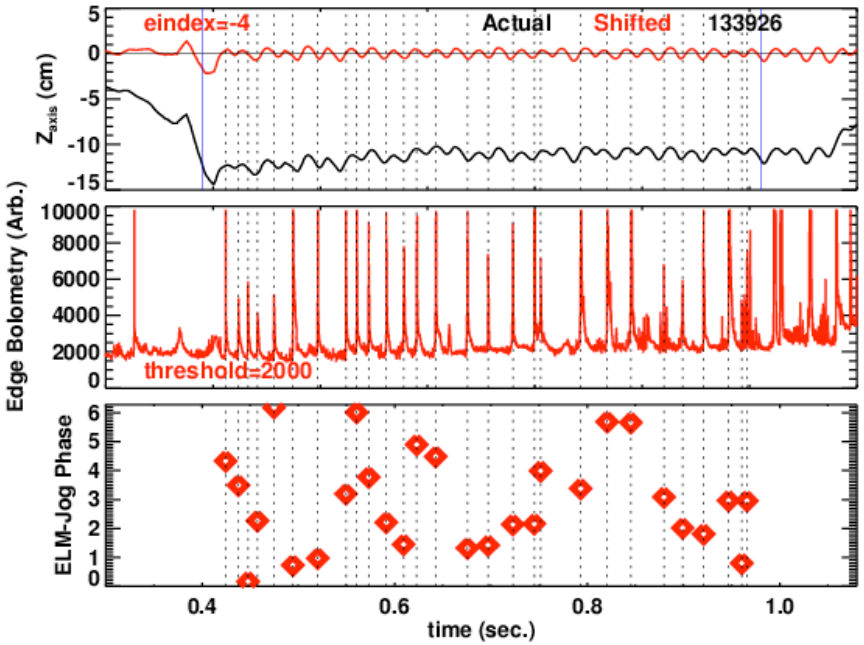
133926: Jogging Case , ~26 ELMs in 0.5 sec.

ELMs ~twice as rapid with 45 Hz jogs

~2 cm oscillation in the plasma centroid

ELM Phase with respect to the vertical motion is not simple

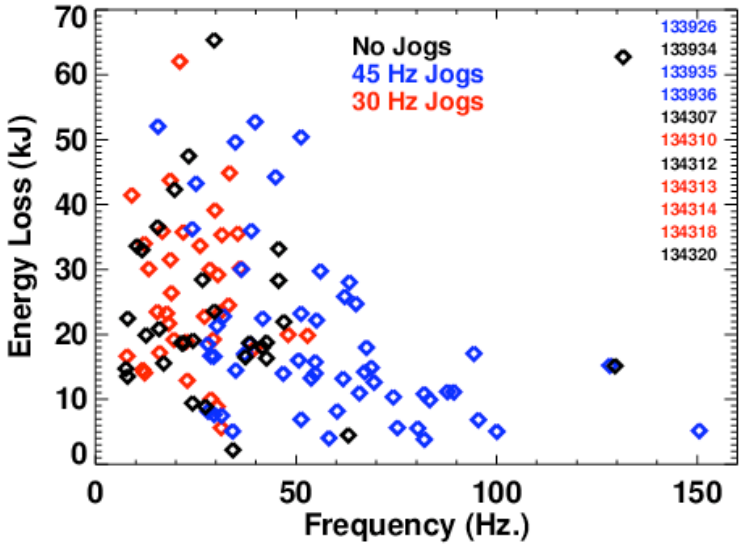


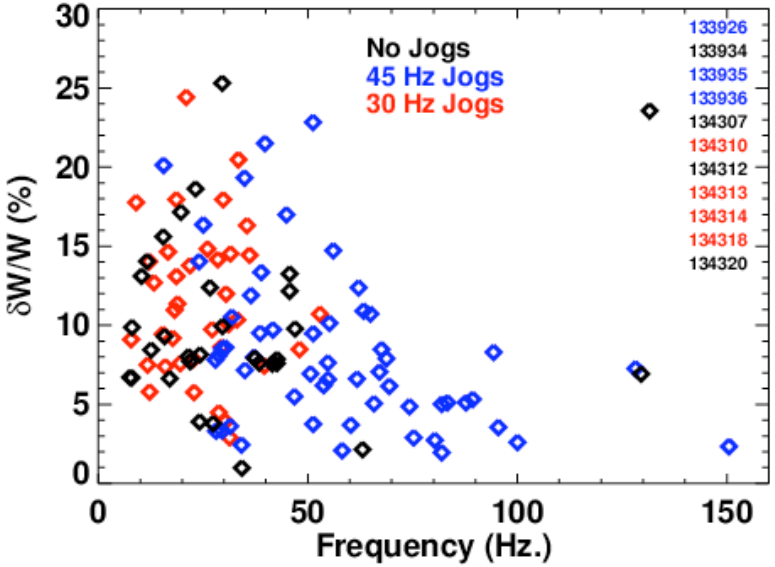


Jogs may trigger ELMs via more than one mechanism?

Faster ELMs Reduce the Stored Energy Loss per ELM

- Calibrate diamagnetic flux against stored energy from equilibrium reconstructions.
- Little decrease in ELM size for the 30 Hz Jogs
- Jogs at 45 Hz observed to reduce the typical ELM size.
- IR camera confirms that ELM energy loss not reduced for 30 Hz pacing.
  - Pacing exacerbated transient loading in this case.



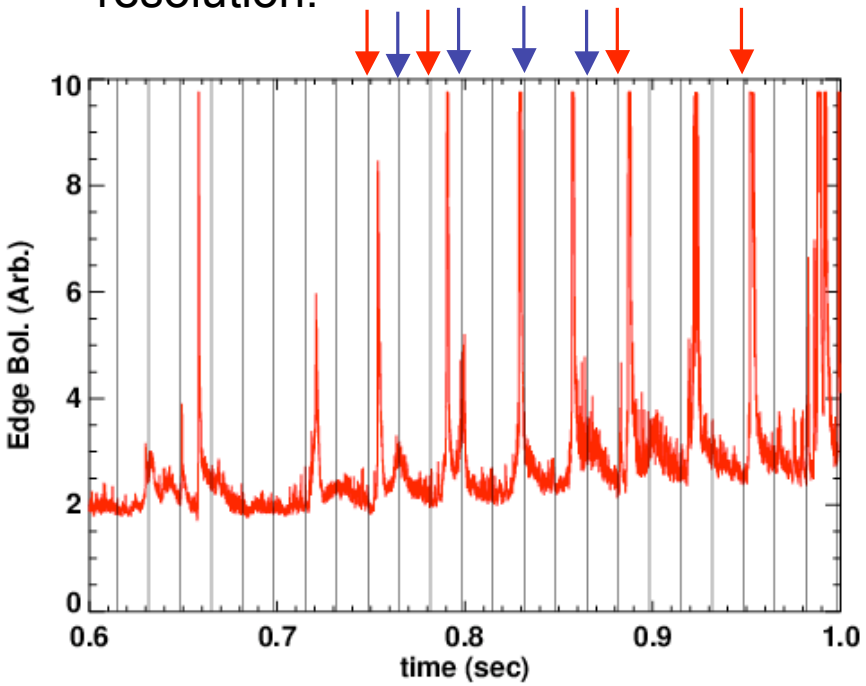


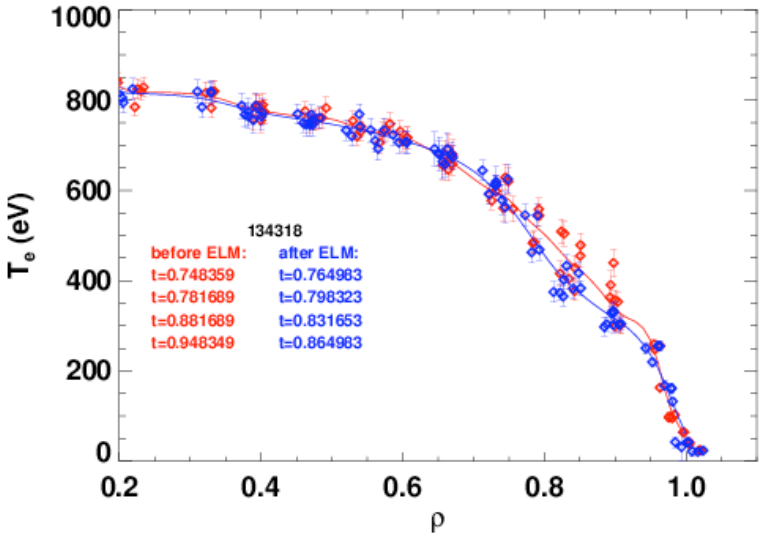
Conclusions And Next Steps

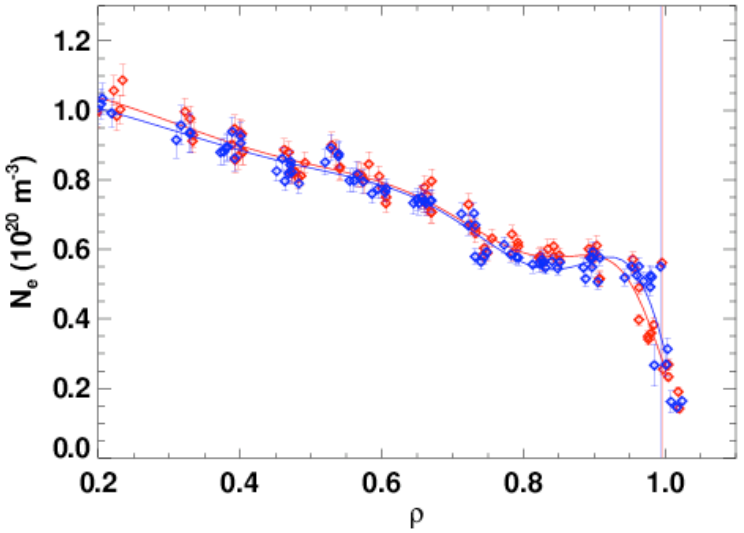
- NSTX has demonstrated ELM pacing via vertical jogs.
  - The NSTX plasma can be vertically jogged.
  - The jogs can be consistent with high performance.
  - The jogs can trigger and pace ELMs.
  - The most rapid ELMs are smaller than the natural ones.
- Next Steps: follow-up experiment for 2010.
  - Test upward kicks?
  - Explicit scan of equilibrium dr_{sep} during kicks?
  - Try in a moderate triangularity discharge?
  - Improved profile measurements during kicks: scan kicks relative to MPTS?
    - Get data of sufficient quality for stability analysis.
    - Large vessel currents may make this analysis difficult.
  - Add explicit voltage perturbations to PF-3 coils?
  - Add kicks to plasma with 3D fields.
    - Observed to facilitate triggering in JET.

Small But Measurable Changes in the Profiles After the ELMs

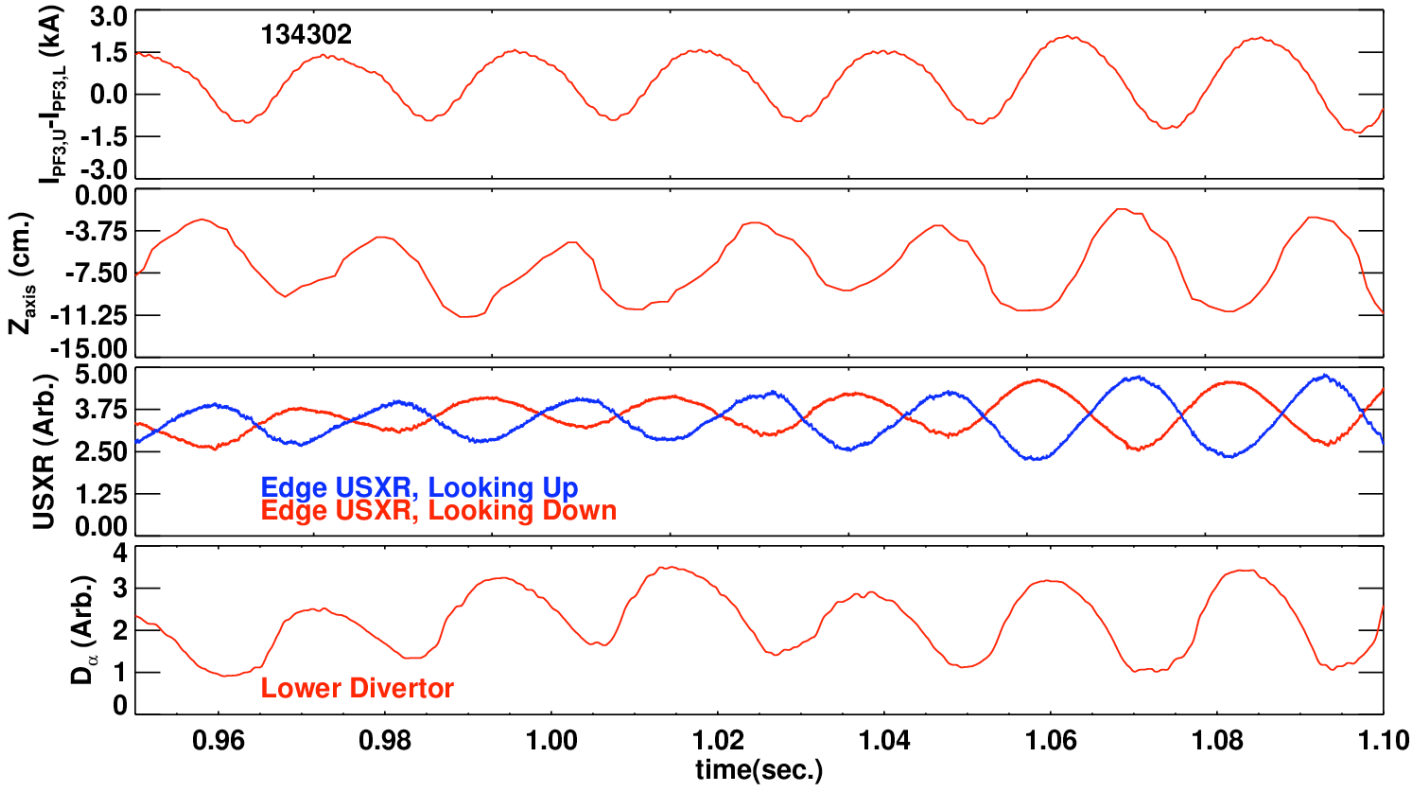
- Map data to ρ, the sqrt of the normalized poloidal flux.
  - Enforce $T_{e,sep}$=40 eV
- Biggest difference across the ELM is a reduction in in the pedestal temperature.
- Next time: stagger jogs w/ respect to MPTS, so achieve better temporal resolution.







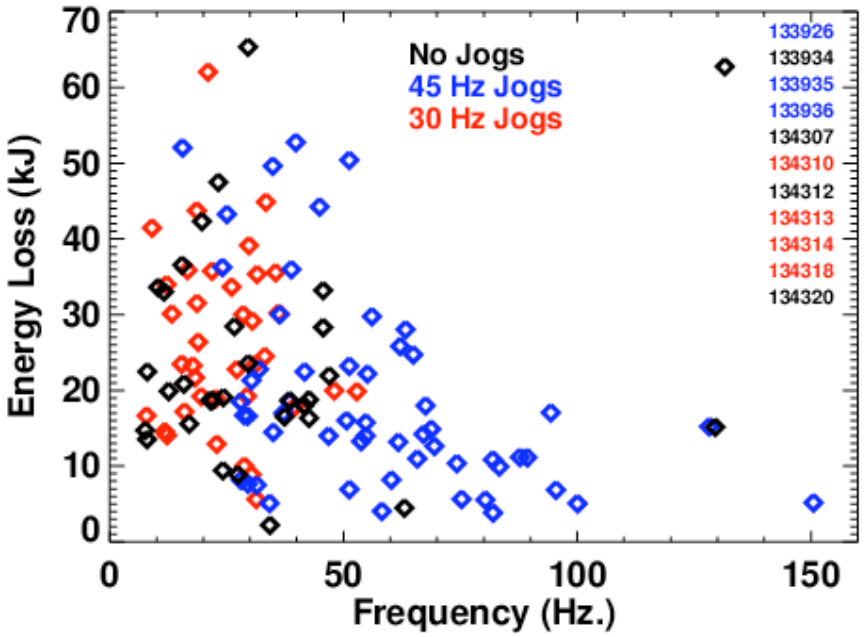
Kinetic Measurements Confirm Reconstructed Jogging Phase



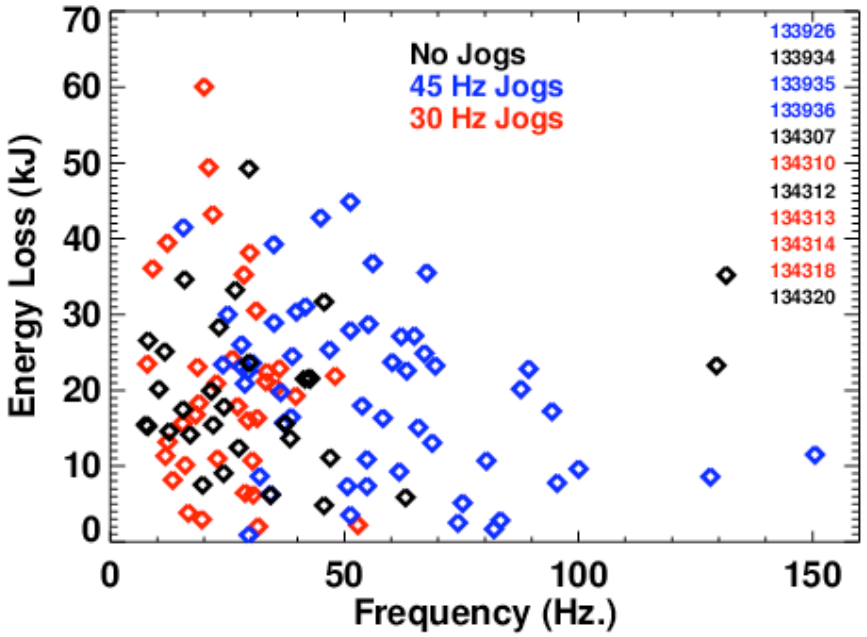
- Want to confirm the reconstructed vertical motion using kinetic data.
- Discharge with jogs, but no triggered ELMs (due to Li conditioning?)
- Edge USXR, with 10μm filter, sensitive to the plasma edge.
- When plasma moves up, the USXR chord looking up shows more signal.
- Lower divertor D_α increases when reconstructions shows the plasma moving down.

Stored Energy Loss From Fast Fdia and Equilibrium Reconstruction Yield Similar Trends

From Fast Calibrated Fdia



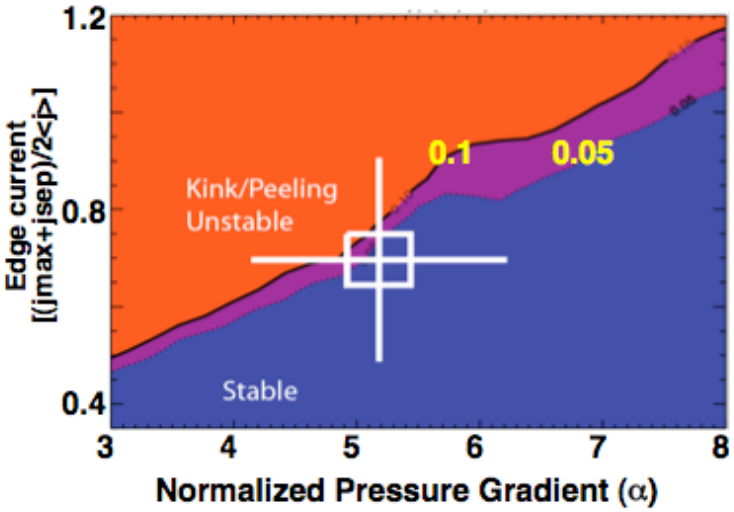
From Fast Equilibrium Reconstruction



A Potential Explanation From A Peeling-Ballooning Perspective

- *Peeling-Ballooning Theory*: ELMs are destabilized in NSTX when the edge current becomes too large.
- *From Reconstructions*: The jogs create (small) perturbations in the edge current.
- *Thesis*: The sum of the temporally evolving edge bootstrap current and oscillating edge currents causes the total current to cross the stability boundary ELM!
- May explain the difficulty in triggering ELMs with Li coated PFCs.
- Introduces new time-scales and requirements:
  - Size of the edge current perturbations compared to the bootstrap current.
  - Time scale of jogs compared to the resistive current evolution.
- Unclear that this thesis can be proven/disproven by data.
- Even if true, can be only part of the story.

Maingi et al, PRL 2009



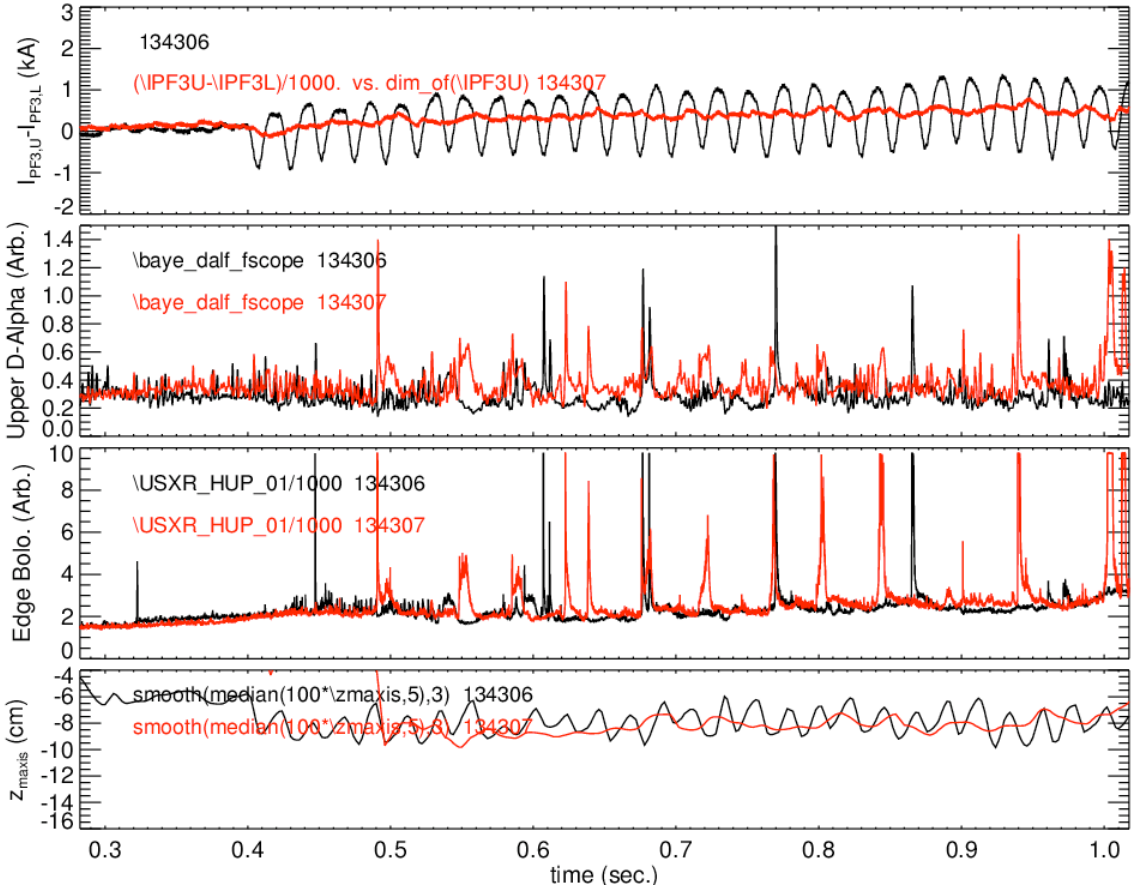
More Difficult to Trigger ELMs When Lithium Conditioning is Present

Shots taken morning after heavy Li conditioning

Equilibrium dr_{sep} also less negative than other cases

134306: Jogging ***134307: Reference***

Jogs are unable to generate ELM in this cases…because of Li or dr_{sep}?

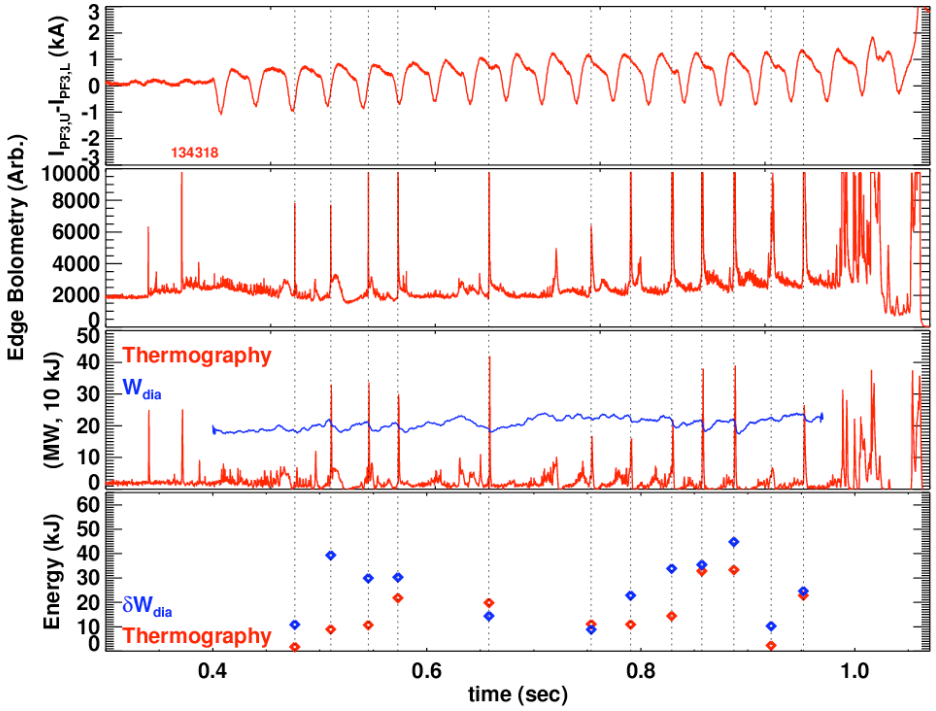


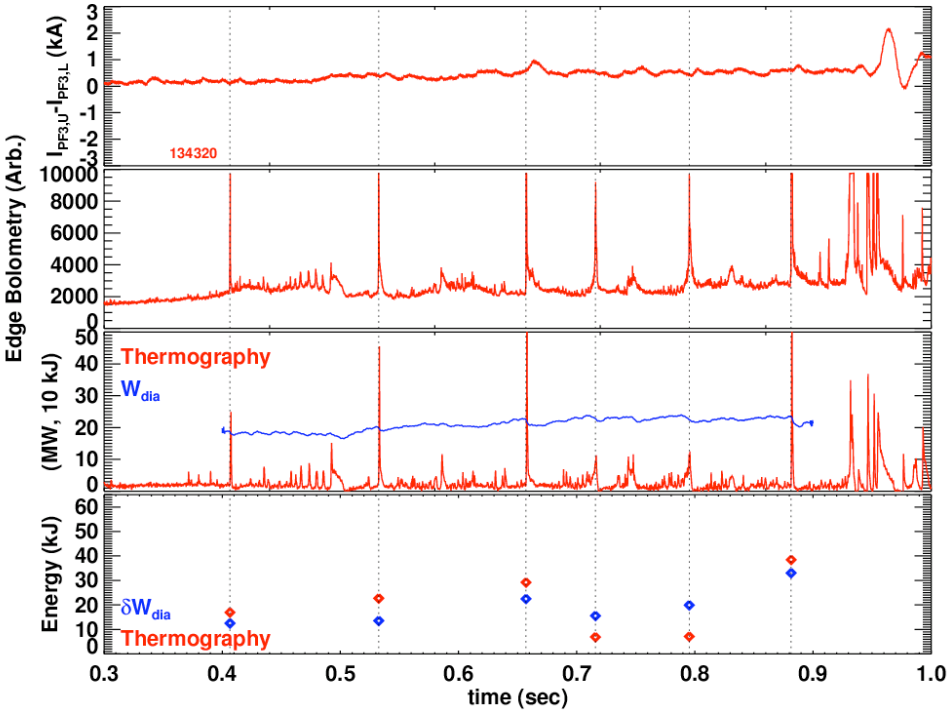
Magnetic Triggering Techniques Have Been Reliable in this Condition

IR Thermography Confirms That ELMs Paced at 30 Hz are Not Particularly Smaller

Reference Shot: 134318
$\langle \delta W_{IR} \rangle$= 16 kJ, $\langle \delta W_{dia} \rangle$=25 kJ
Mean ELM Frequency: 26 Hz
$\langle P_{IR} \rangle$=402 kW, $\langle P_{dia} \rangle$=643 kW

Reference Shot: 134320
$\langle \delta W_{IR} \rangle$= 20 kJ, $\langle \delta W_{dia} \rangle$=19.5 kJ
Mean ELM Frequency: 12.6 Hz
$\langle P_{IR} \rangle$=255 kW, $\langle P_{dia} \rangle$=246 kW



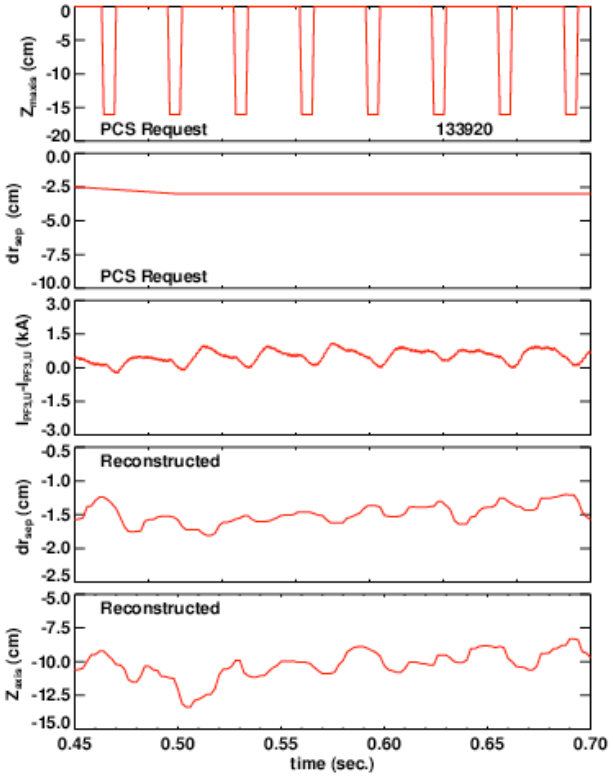


In this case, the pacing would exacerbate the transient loading problem.

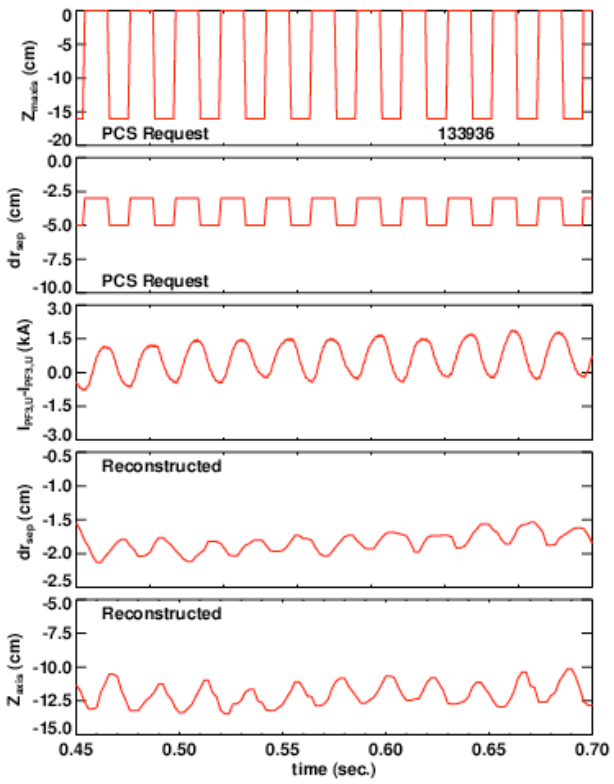
Camera Data Courtesy of J.-W. Ahn, ORNL

Plasma Can Be Jogged Using Step Requests in Axis Vertical Position, dr_{sep}, or Both Synchronously.

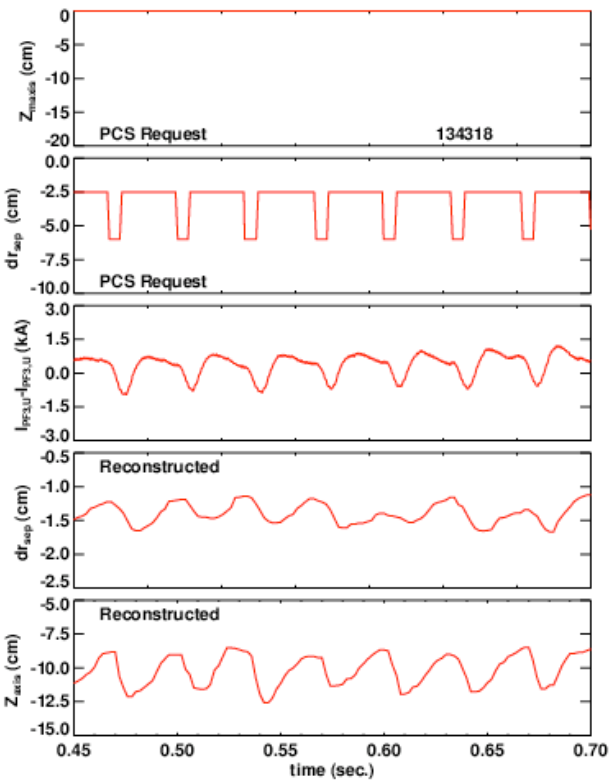
133920: Jogs in Z_{axis} alone, 30 Hz



133936: Jogs in Z_{axis} and dr_{sep}, 45 Hz



134318: Jogs in dr_{sep} alone, 30 Hz



- Final configuration used jogs in dr_{sep} alone, as these allowed a rapid response.
- Considering adding an explicit voltage perturbation to the radial field coils for FY-10.

Boundary shapes from this case on previous slide

Most Type-I ELMs Do Not Cause Vertical Control Oscillations

Reference Shot: 134320

~ 0.5 V oscillations in Upper Lower Voltage

~No Oscillations on the coil differential voltage.

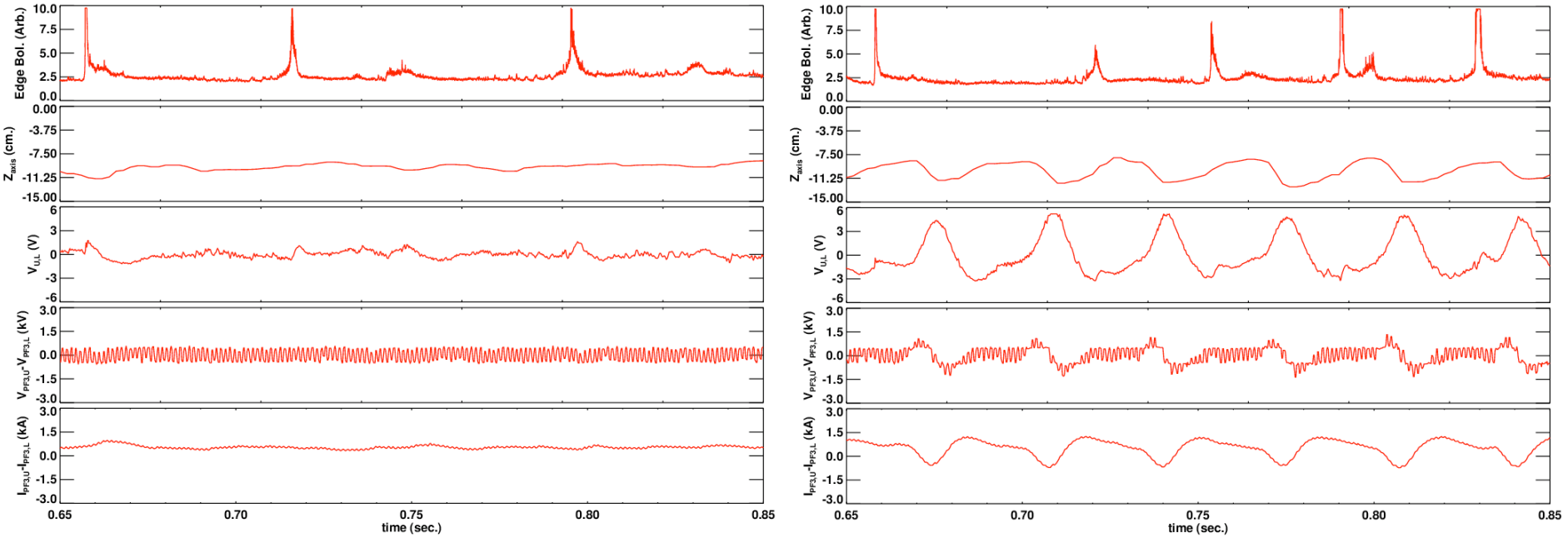
~ No Oscillations in the coil differential current.

Jogging Shot: 134318

~6 V oscillations in Upper Lower Voltage

~2 kV Oscillations on the coil differential voltage.

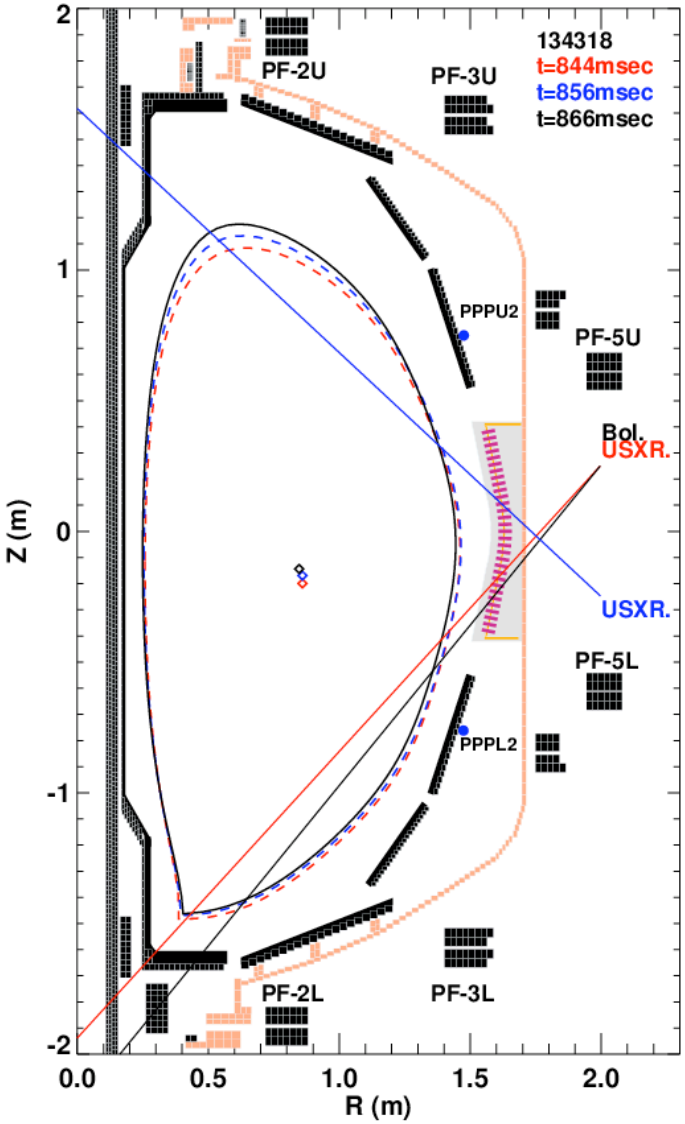
~3kA Oscillations in the coil differential current.



Cannot define required vertical perturbation for ELM triggering as a fraction of that from an intrinsic ELM [2],[4]

Questions & Answers

- Can the plasma be rapidly jogged in NSTX, given the thick continuous stainless steel vessel?
  - Yes: Requesting large jogs in dr_{sep} can produce rapid jogs in plasma vertical position
- Can ELMs be triggered by the jogs?
  - Yes: For instance, discharge with ~15 Hz ELMs can have them accelerated to ~30 Hz.
- What characteristics of the equilibrium allow best triggering?
  - Preliminary: It appears that more strongly biased down plasmas have ELMs triggered more easily.
- Do the jogs adversely impact confinement, stability, and overall performance?
  - No: stored energy and rotation are not adversely impacted as long as the average dr_{sep} is not made too negative.
- Can we learn anything about ELM physics from these experiments?
  - Maybe…

Background: First Attempts at ELM Triggering Via Jogs in NSTX in 2009

- Tried experiments on two days.
  - 27 shots on June 1st
    - Developed jogging technique and found evidence of pacing.
    - 45 Hz data taken this day.
  - 20 shots on June 12th
    - This immediately after very heavy Li usage the previous evening.
    - 30 Hz data taken this day.
- NSTX has a continuous 1.6 cm thick stainless steel vacuum vessel.
  - Not immediately clear that the plasma could be moved sufficiently rapidly.
- Use GA PCS with rtefit & isoflux shape control.
  - Apply jogs as square waves in requests for either dr_{sep} or z_{axis}