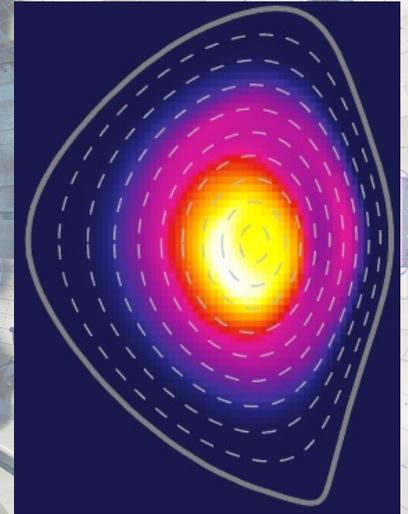


# MHD and Scenario Development in Negative Triangularity

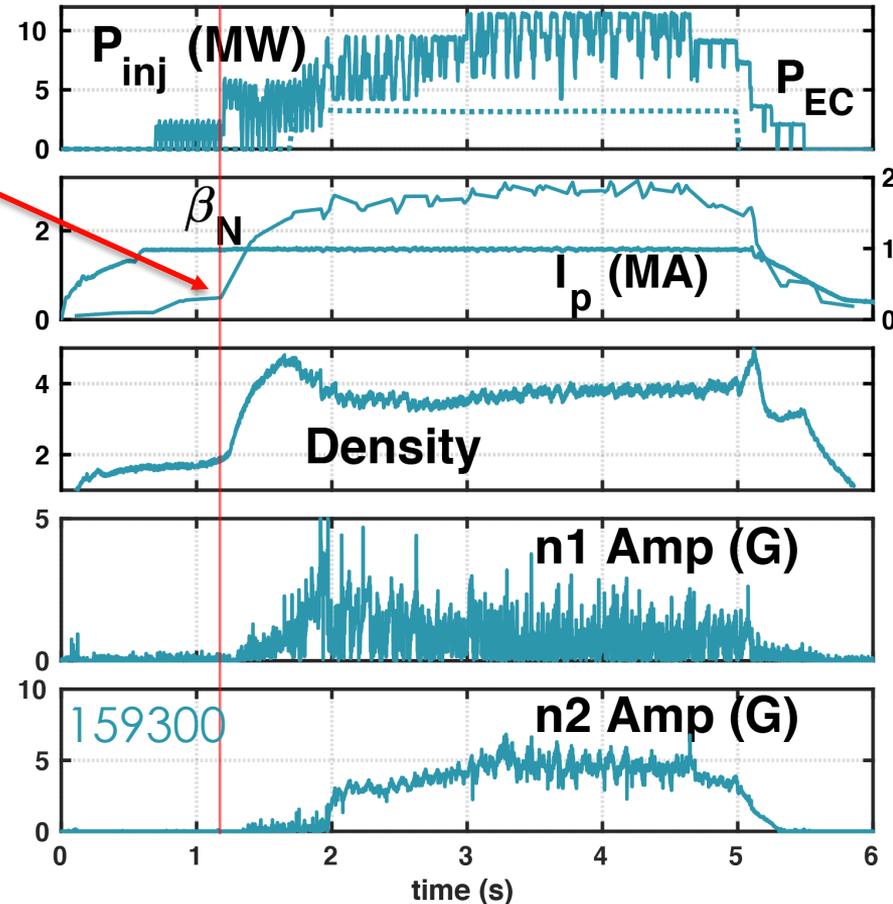
**W. Boyes**

F. Turco, J. Hanson, G. Navratil,  
Nathan Richner, Max Austin,  
Alessandro Marinoni, Alex  
Saperstein, Siye Ding and the DIII-D  
team



# Discharges formed with “late heating” access sawtooth and ELM free operation at high normalized pressure

- Access taken from a **hybrid scenario** plasma
- Form sawtoothing L mode plasma
- Blast heating once  $I_p$  ramp has concluded,  $I_i$  high, flat q shear
- Discharges at fusion relevant BetaN recover **hybrid scenario MHD**
- Beam programming to obtain trustworthy MSE
  - Swings in  $P_{inj}$  of 7.3-10.3 MW vary betaN 2.6-2.9



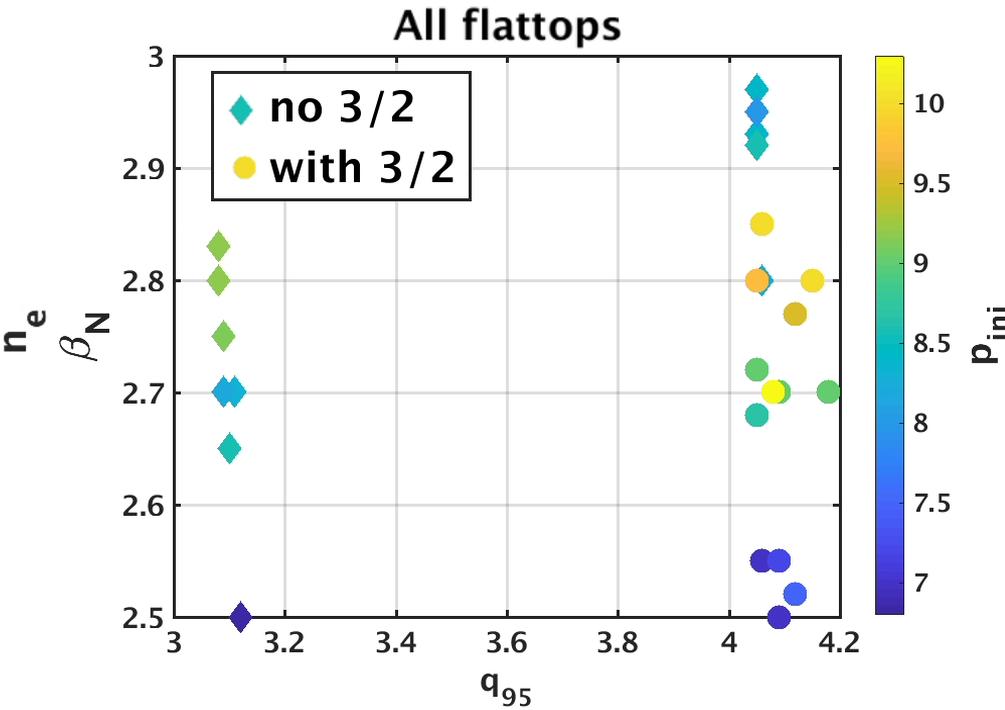
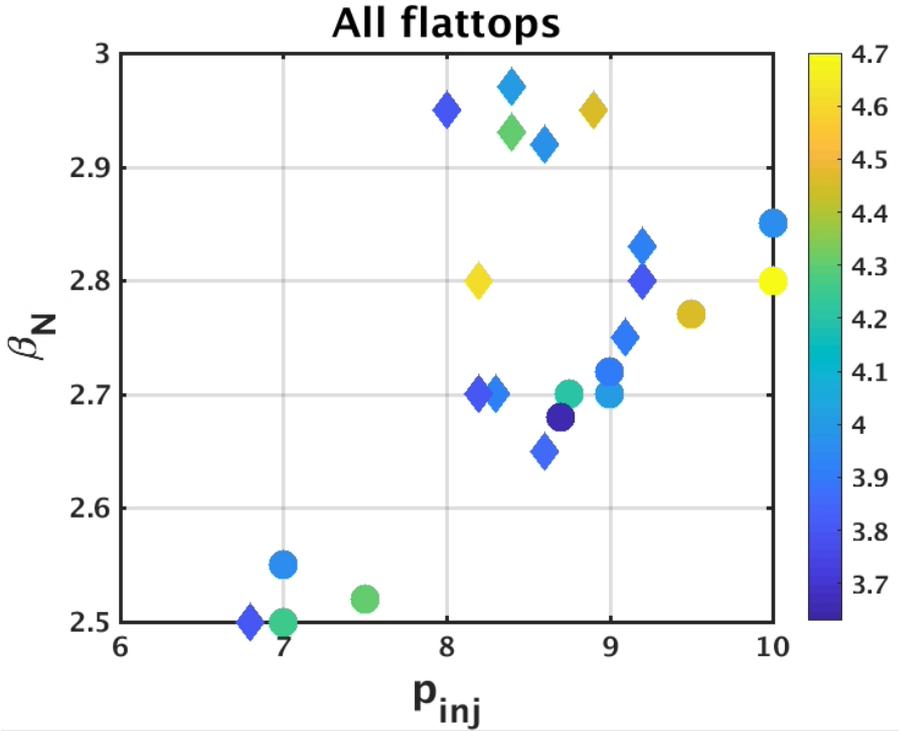
# Contents

- **Overview of experiments**
- **MHD/Disruption phenomenology**
- **Initial ideal limits**
- **Halo current/MHD rotation scaling**

# Contents

- **Overview of experiments**
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# Parameter space scanned over q95s with fixed access

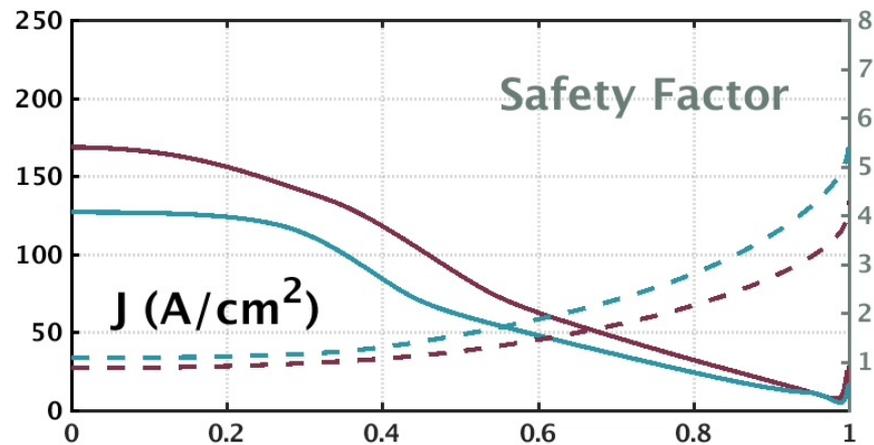


\*Symbols represent averages over BetaN flattops with stationary parameters  
 Durations 300ms-2.5s

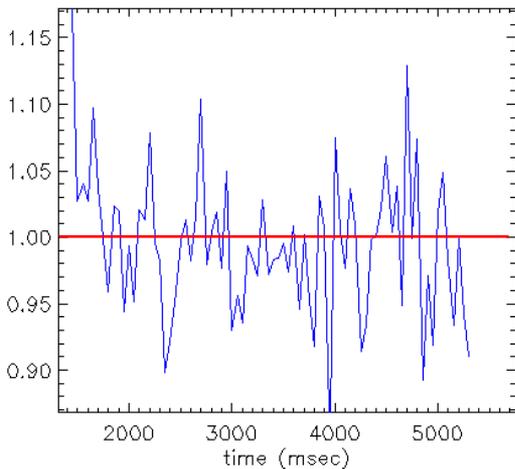
# Series of kinetic reconstructions performed for multiple shots to resolve evolution and ideal limits

With similar access,  $n_e \sim 3.9$ , and flat top  $p_{inj} \sim 10\text{MW}$ :

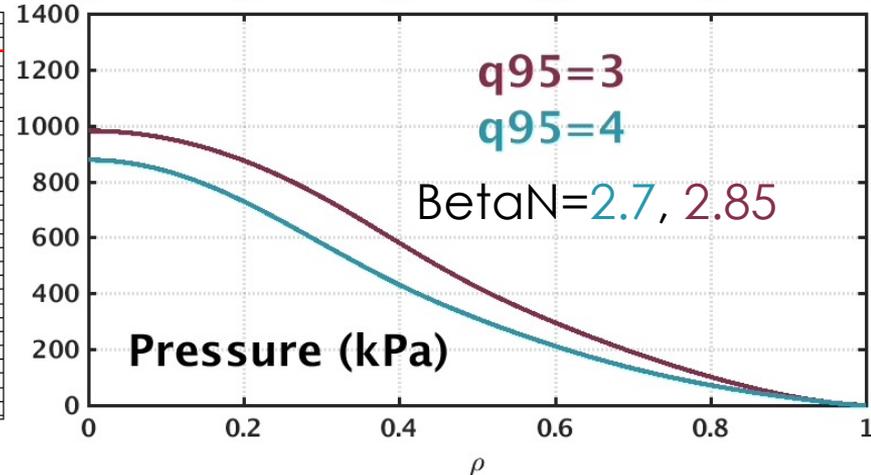
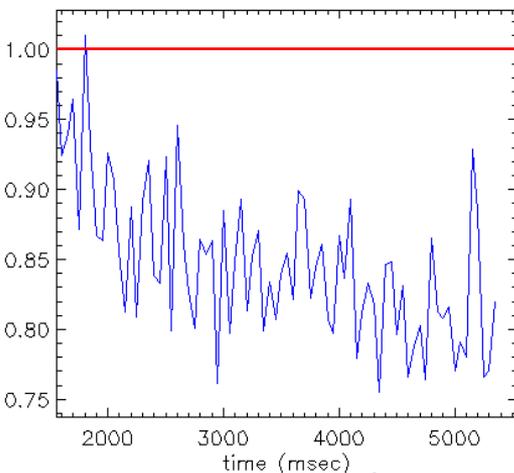
- $q_{min} \sim 0.8-0.9$  in  $q_{95}=3$  cases
- $q_{min} \sim 0.9-1$   $q_{95}=4$



$q_{min}$  from  $q_{95}=4$

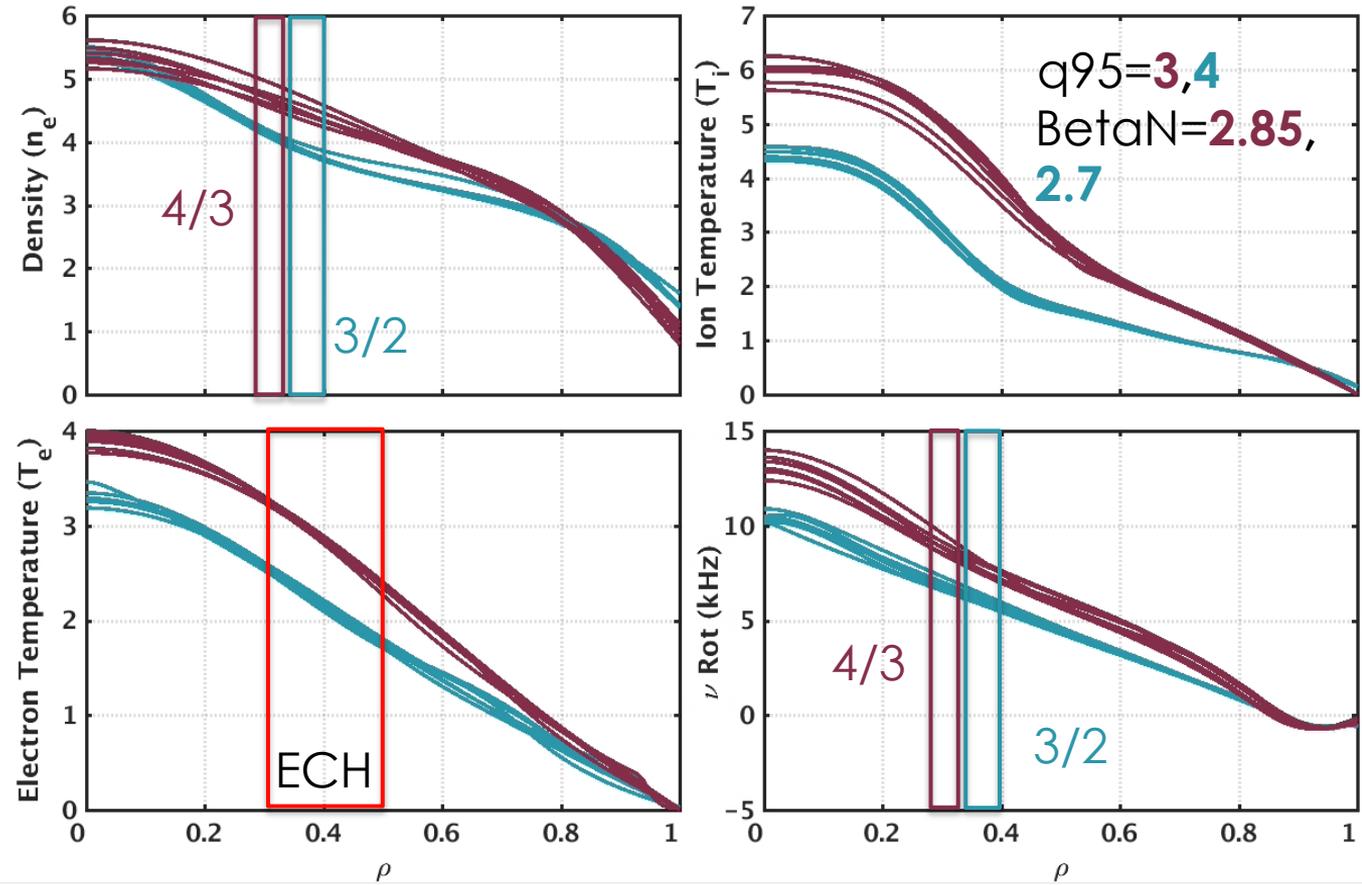


$q_{min}$  from  $q_{95}=3$



# Kinetic profiles from $q_{95}=3, 4$ reflect expected trend with $I_p$

- Momentum confinement varies with  $I_p$
- 3/2 tearing mode may have visible effect on  $n_e$  profile shape



# Contents

- Overview of experiments
- **MHD/Disruption phenomenology**
  - Where are my sawteeth?
- Initial ideal limits
- Halo current/MHD rotation scaling

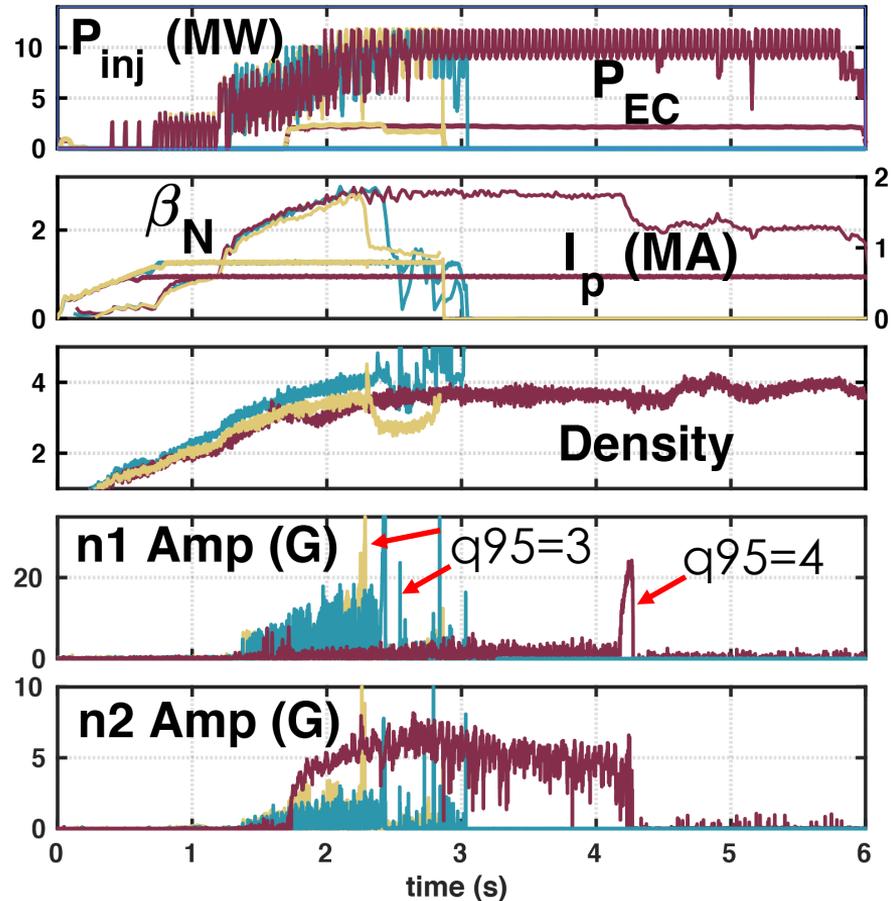
# MHD phenomena and disruption causes differ between $q_{95}=3,4$

- Flattops at  $q_{95}=3$  feature fishbones, 4/3 TM bursts
- Flattops at  $q_{95}=4$  have only 3/2 TM
  - No seeds for  $n=1$  NTMs!
- TMs at  $q_{95}=3$  similar to low torque IBS;  $q_{95}=4$  resemble hybrid scenario
- Three shots at  $q_{95}=3$  with all co NBI and EC probably suffer error field penetration
  - Disrupt before encountering rotating 2/1 TMs

(# cases)	$q_{95}=3$	$q_{95}=4$
2/1 TM	grows, <b>disrupts</b> (2)	saturates, locks (1)
3/2 TM	grows, <b>disrupts</b> (2)	saturates, benign (10+)

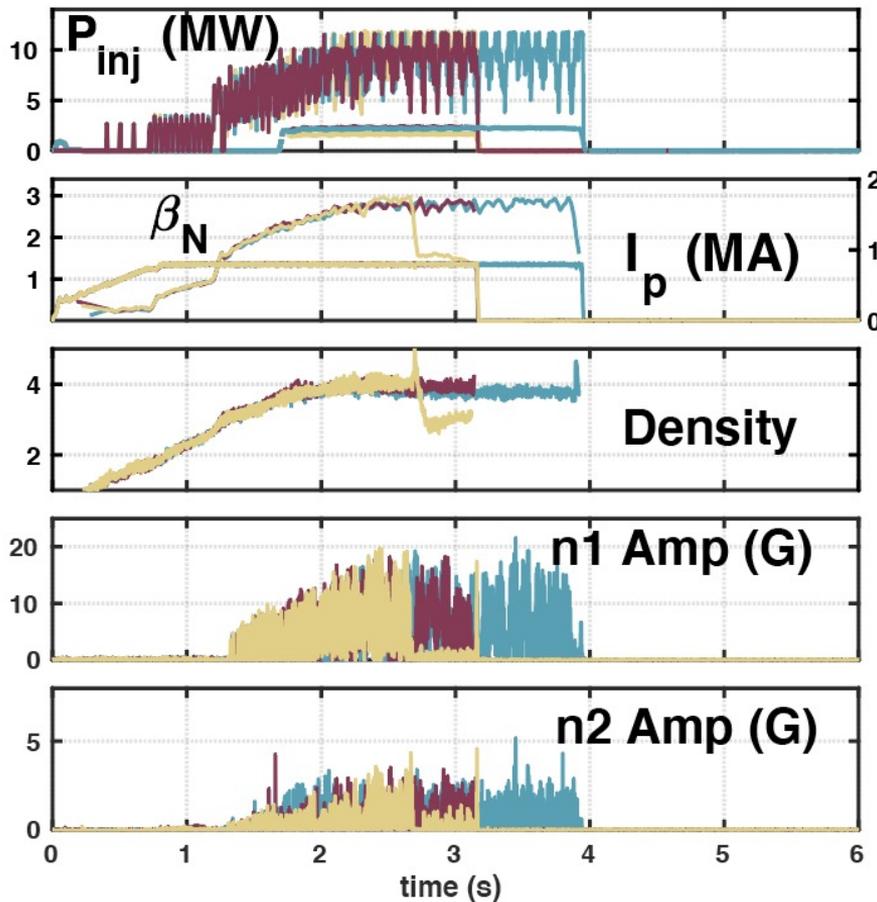
# Observed 2/1 TMs

- $q_{95}=3,4$  cases encounter modes at  $\beta_N > 2.8$  (~90% of ideal limits)
- $q_{95}=4$  case locks and does not disrupt over 1.5s
- $q_{95}=3$  cases grow, lock, and disrupt quickly
- $\beta_N$  limited by unknown transport in most NT plasmas, but these suggest a tearing limit is not far
  - Need better statistics



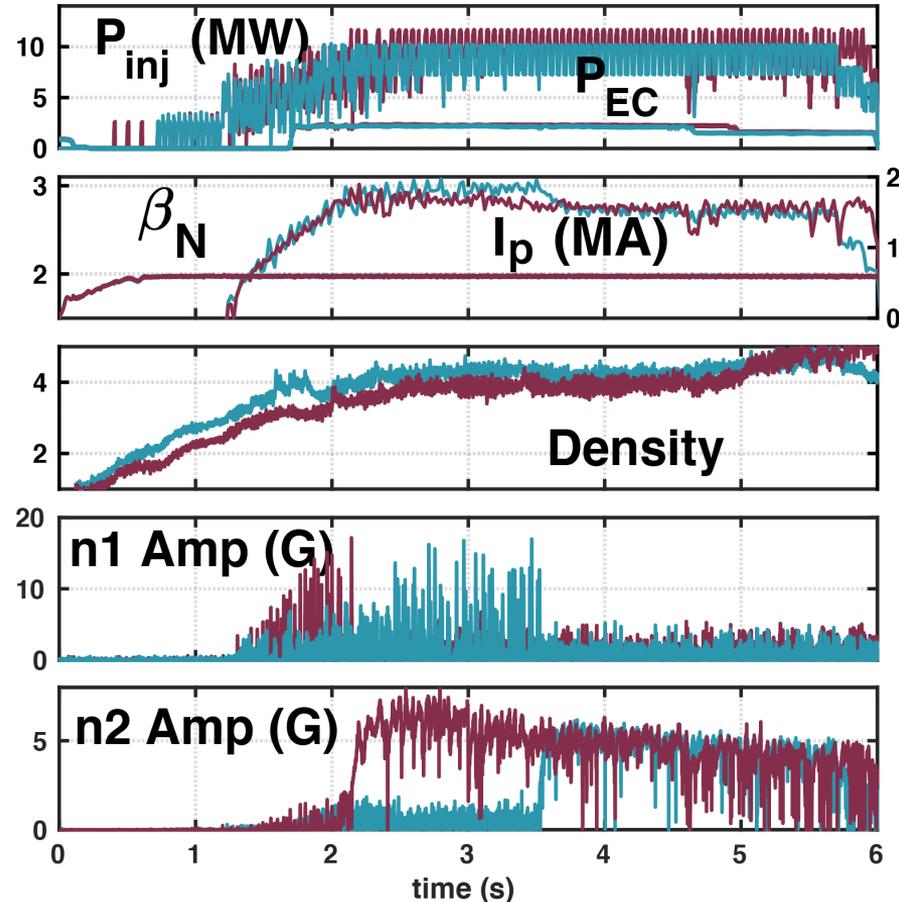
# EF penetration most likely cause of disruptions at q95=3

- **EF correction was not optimized for this shape or scenario**
  - Traces of Ni, Al, and Fe in these not long before disruptions...
  - But NT may care less about impurities
  - Could be shape control



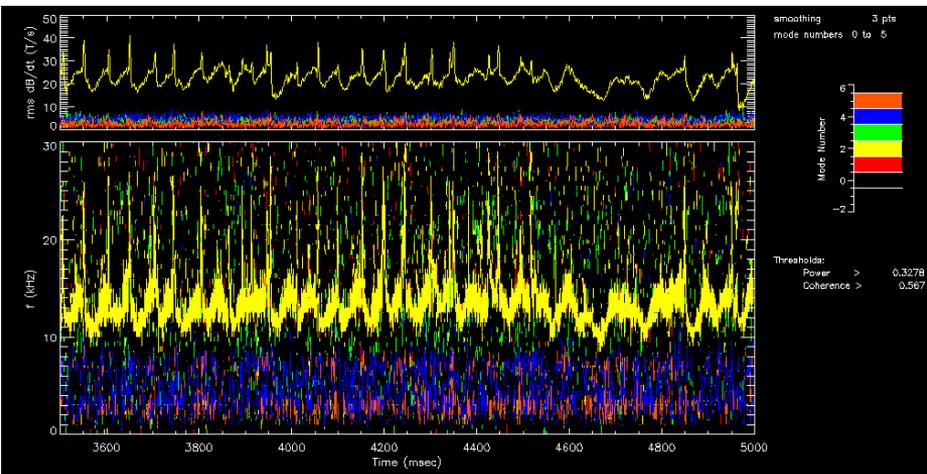
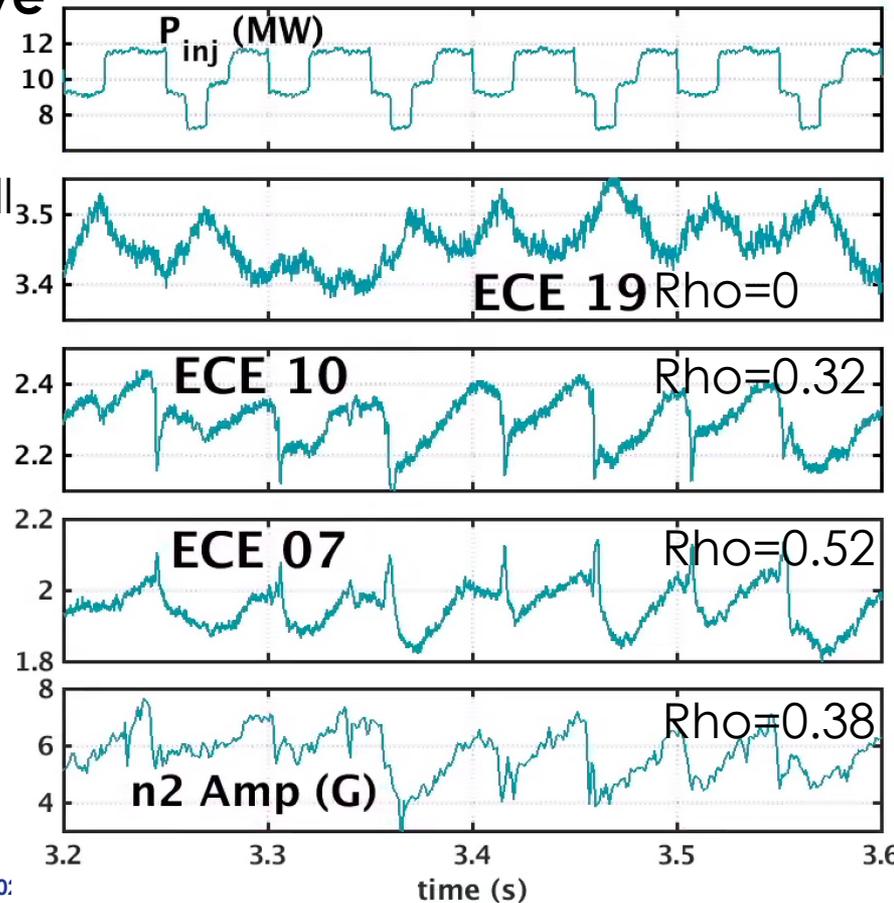
# Sawteeth and Fishbones

- **Correlation with  $n=2$  onset and disappearance of fishbones**
  - Flux pumping raising  $q_{\min}$
  - or fast ion pressure broadening, NBCD redistributed
  - or something else
- **No sawtooth crashes at either  $q_{95}$  in these experiments**
- **A hybrid state may yield lower disruptivity and enhanced MHD stability just as in PT**
  - $n=2$  confinement loss must be minimized



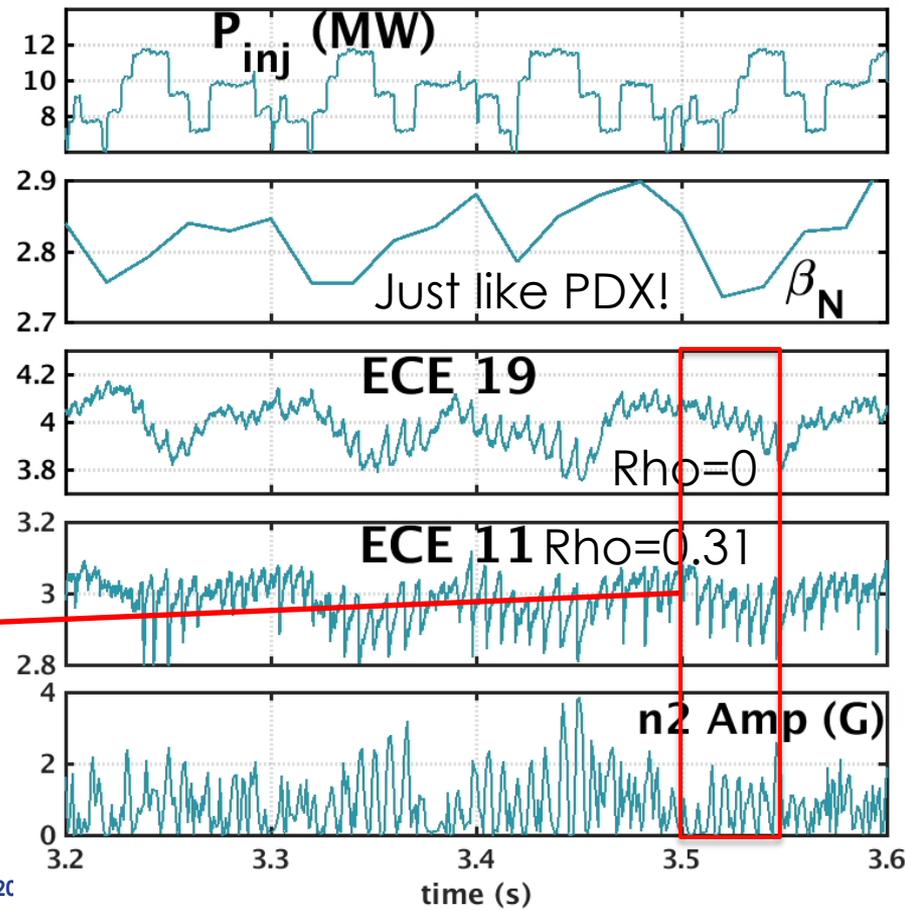
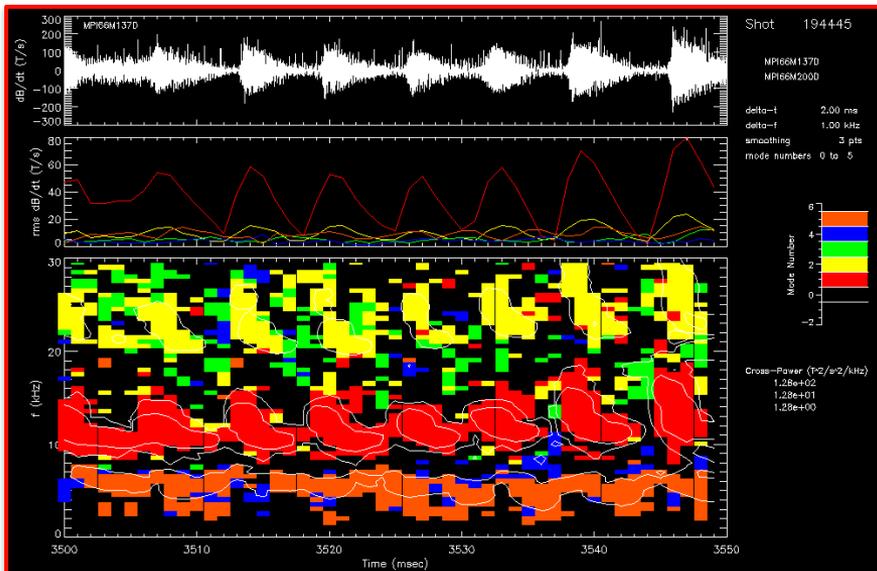
# Crashes in $T_e$ at $q_{95}=4$ arise from modulated 3/2 TM

- **TM amplitude crashes are suggestive of flux pumping (Petty 2009, Luce 2004)**
  - Probably required to generate small voltage
- **Combined with absence of fishbones, likely means  $q_{\min} > 1$**



# No sawteeth during n=3 at q95=3, higher ne q95=4

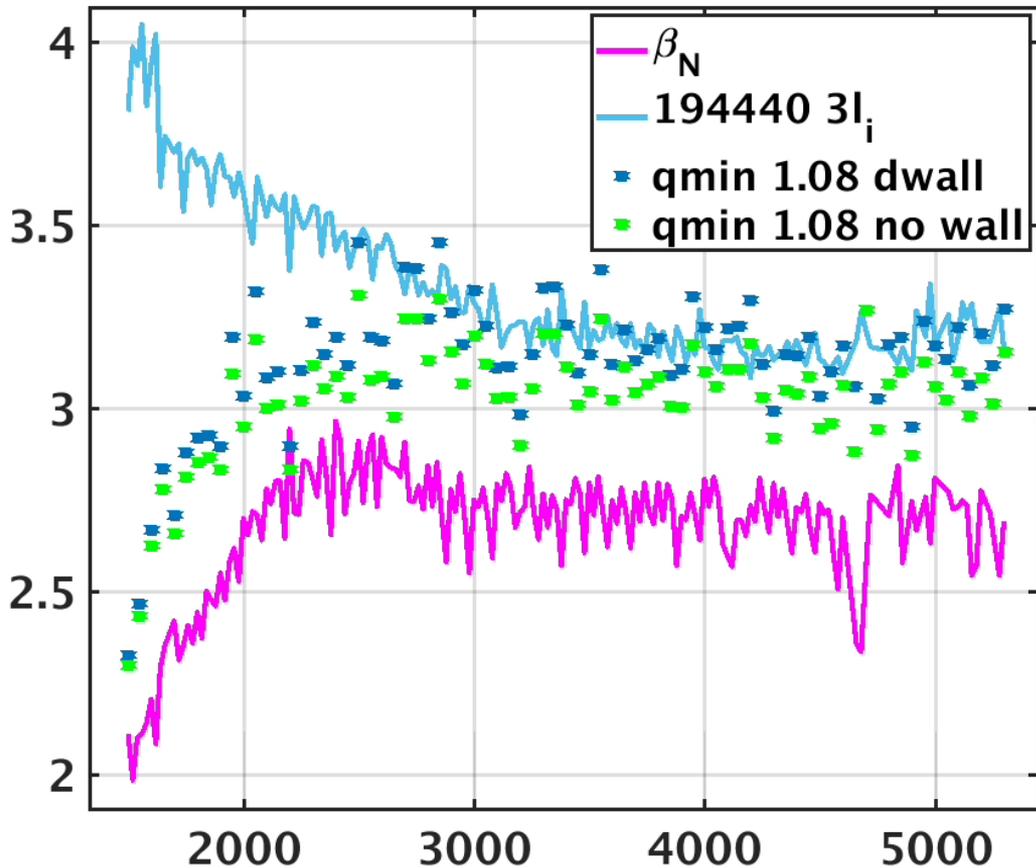
- Fishbones compete with modulated 4/3 bursts
- Crashes at  $\rho \sim 0.3$
- Possible 4/3 TM flux pumping, akin to some PT hybrids



# Contents

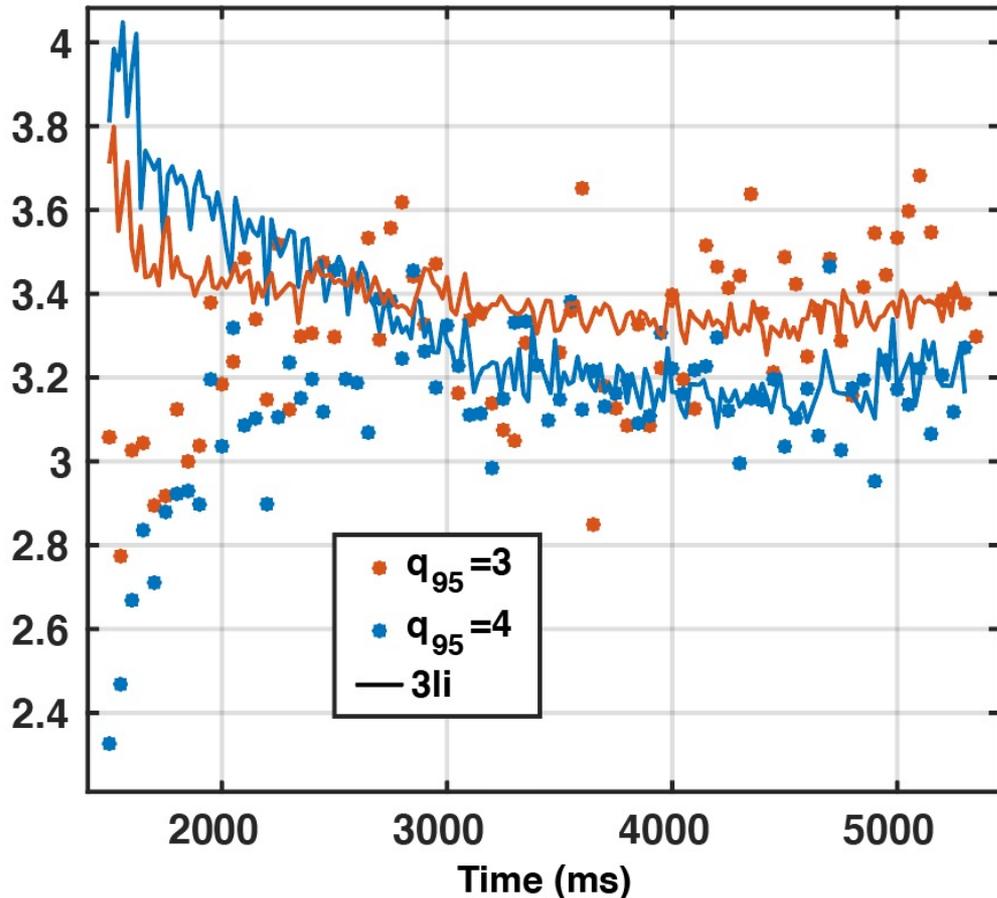
- Overview of experiments
- MHD/Disruption phenomenology
- **Initial ideal limits**
- Halo current/MHD rotation scaling

# Cases at $q_{95}=4$ with $3/2$ consistent with previous $n=1$ limits



- **No wall limits (Corsica, DCON) approximated by  $3I_i$** 
  - *Boyes et al. NF 2023*
- **Ideal wall  $\sim 1.05 \times$  No wall limits**
- **User choice of  $q_{\min}$  and shear makes a difference in limit calculation**
  - Working to minimize  $q_{\min}$
- **Future work to examine kink structure, corroborate with GATO**

# Initial $n=1$ limit calculations see no strong trend with $q_{95}$



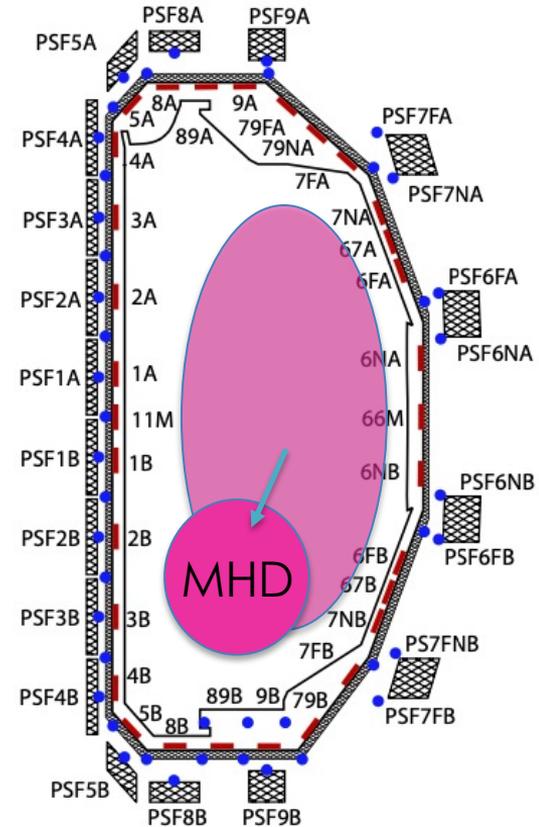
- **Given similar profile shapes & BetaNs, this may not be surprising**
  - Coarse trend with  $I_i$  is observed
- **We do not observe many 2/1 tearing modes in experiment in either case**
  - Insufficient to indicate ideal limit proximity
- **Future work includes comparing limits with similar TMs**

# Contents

- Overview of experiments
- MHD/Disruption phenomenology
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# Disruptions observed in $q_{95}=3,4$ cases

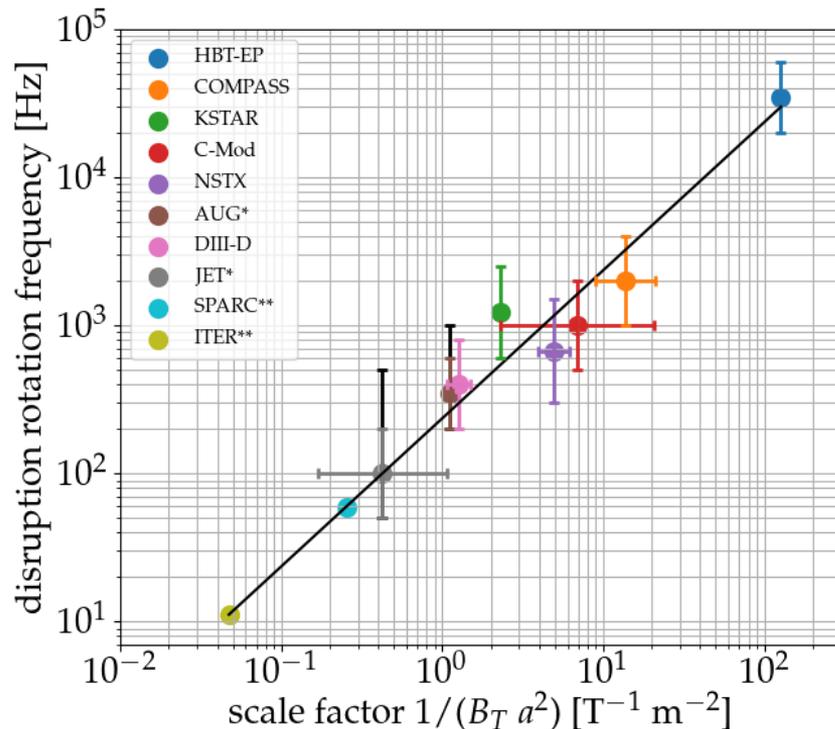
- VDE moves down toward xpoint, as expected
- Secondary MHD event transpires, likely due to rational surface passing through LCFS
- MHD structure rotates substantially in disruption
- Halo currents (HCs) can cause EM stresses on machine components



# Multimachine rotation scalings suggest danger in ITER

- Scalings predict HC/MHD rotation may be resonant with structures in ITER<sup>1,2</sup>
- These have been extended to SPARC, HBT-EP<sup>2</sup>

Does NT have any effect on the HC/MHD poloidal rotation frequency?



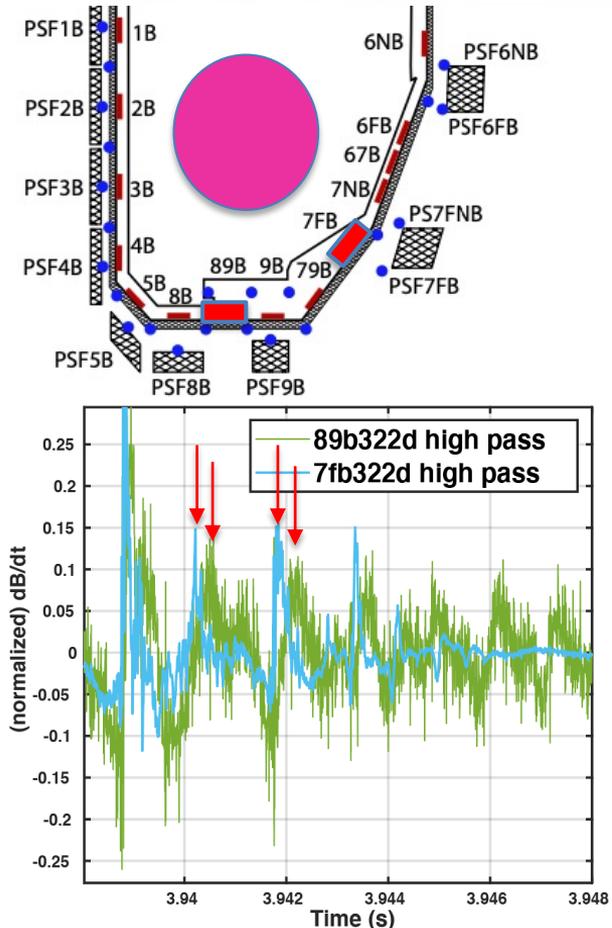
Courtesy of A. Saperstein<sup>2</sup>

1: Myers NF 2018

2: Saperstein NF 2022

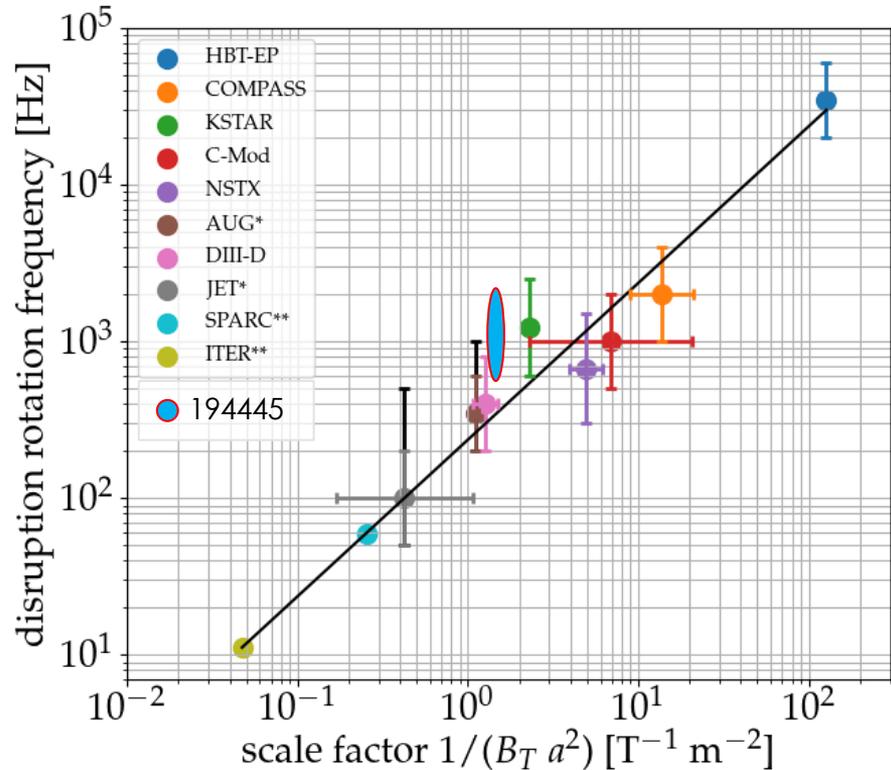
# Work in progress analyzing q95=3 disruption MHD

- I'm using phase lag between bdot magnetics sensors to approximate mode rotation
- Comparing cross correlation analysis of high pass filtered signals to by-eye in review plus
  - Temporal lags vary since mode spins up
- **Assumptions**
  - m ignored
  - Plasma cross section  $\approx \pi a^2$
  - Rotation is poloidal



# NT does not seem to change $f_{pol}$

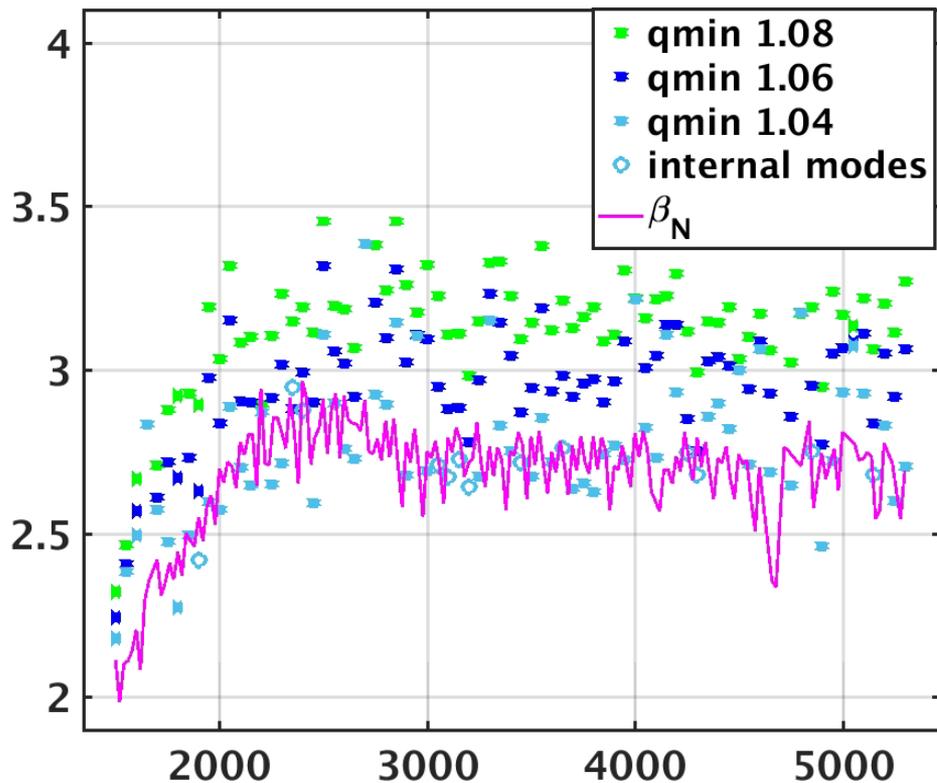
- **Initial estimates**  $f_{pol} = [0.6 - 2kHz]$ 
  - Individual fluctuations vs cross correlation over multiple
- **Future refinements:**
  - Cross correlating multiple sensor pairs
  - Attempting to estimate  $m$
  - Adding more NT shots



# Takeaways

- **NT plasmas at  $q_{95}=3,4$  have been sustained stationarily and stably in experiment at relevant  $\beta_N=2.7-2.9$** 
  - Hybrid scenario MHD phenomena
  - Few disruptions; most at  $q_{95}=3$  and caused by EF penetration
  - Conditions extrapolate to reactor relevance
- **Neither ideal limit calculations nor occurrence of 2/1 TMs show strong trends with  $q_{95}$** 
  - Ideal wall limits  $\beta_N \sim 3.1-3.4$
  - 2/1 modes onset  $\beta_N > 2.8$
- **Halo current poloidal rotation scales like PT DIII-D plasmas**

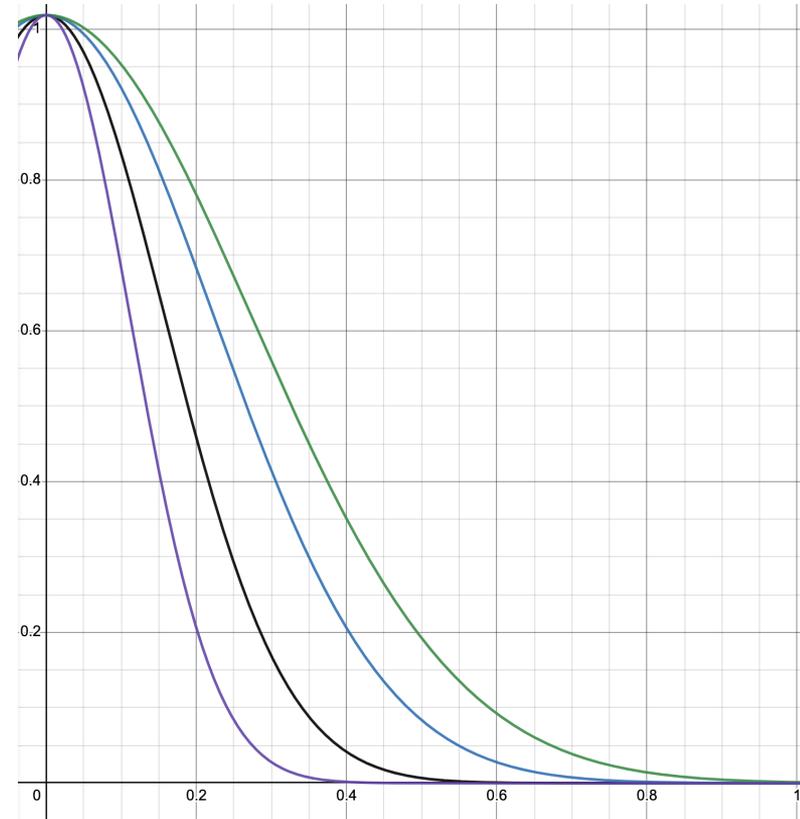
# Extra: $q_{\min}$ affects ideal limit calculations



- **The choice of  $q_{\min}$  should approximate experiment**
  - Given lack of  $n=1$  sawteeth, choice is not clear
- **Low  $q_{\min}$  may cause DCON to find internal modes erroneously**

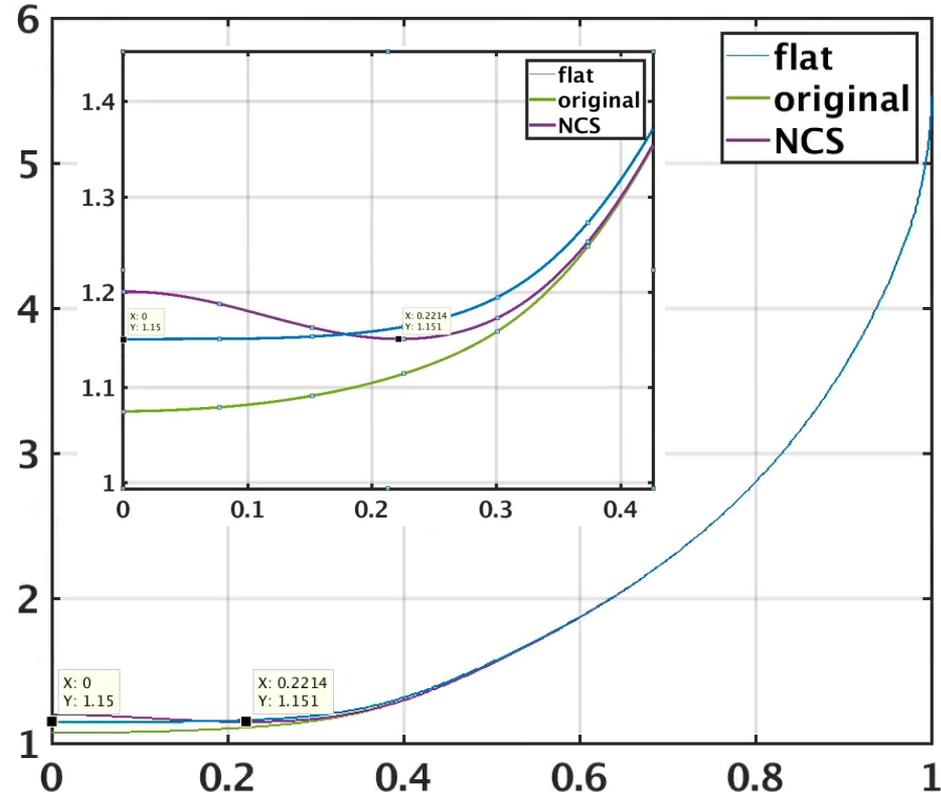
# Extra: New method developed to modify q profile very quickly

- Spline method was slow and could produce unrealistic profiles
- Multiplication by a linear function can modify q at undesirably high radius
- My new method multiplies by a gaussian function in matlab, preserving differentiability (important for PEST3, RDCON)
  - Scans denominator ( $\sim$ variance) to fit  $q_{\min}$  within tolerance
  - $q_0$  specified to impose shear in NCS ( $q_{\min} \neq q_0$ ) case



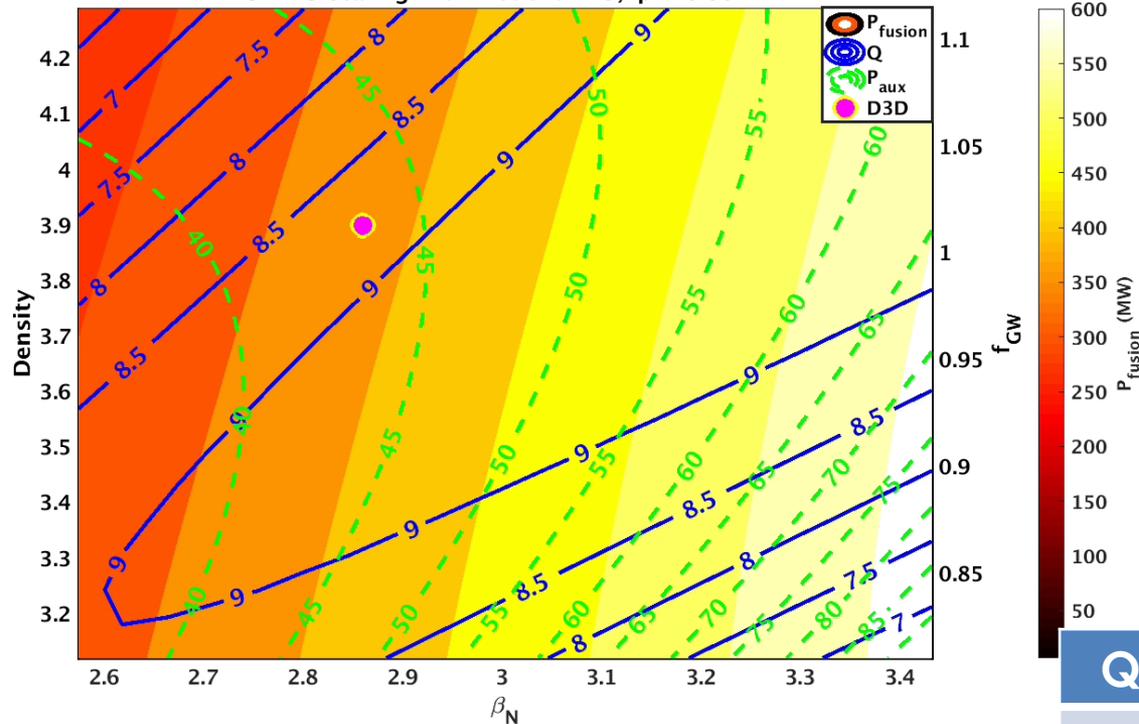
# Extra: Limits conditionally to core q shape

- Method can produce either NCS or flat profiles in the core automatically, with specified negative shear (positive shear coming soon)
- Specifying shear important for avoiding erroneous internal modes in ideal codes
- Similarity of BetaN limits ( $n=1$ ) for these profiles depends on  $q'$ ,  $p'$  alignment



# Scalings: q95=3 to NTARC (B=9T)

194445 scaling with model  $\epsilon=2.9$ ,  $I_p=10.00$  MA

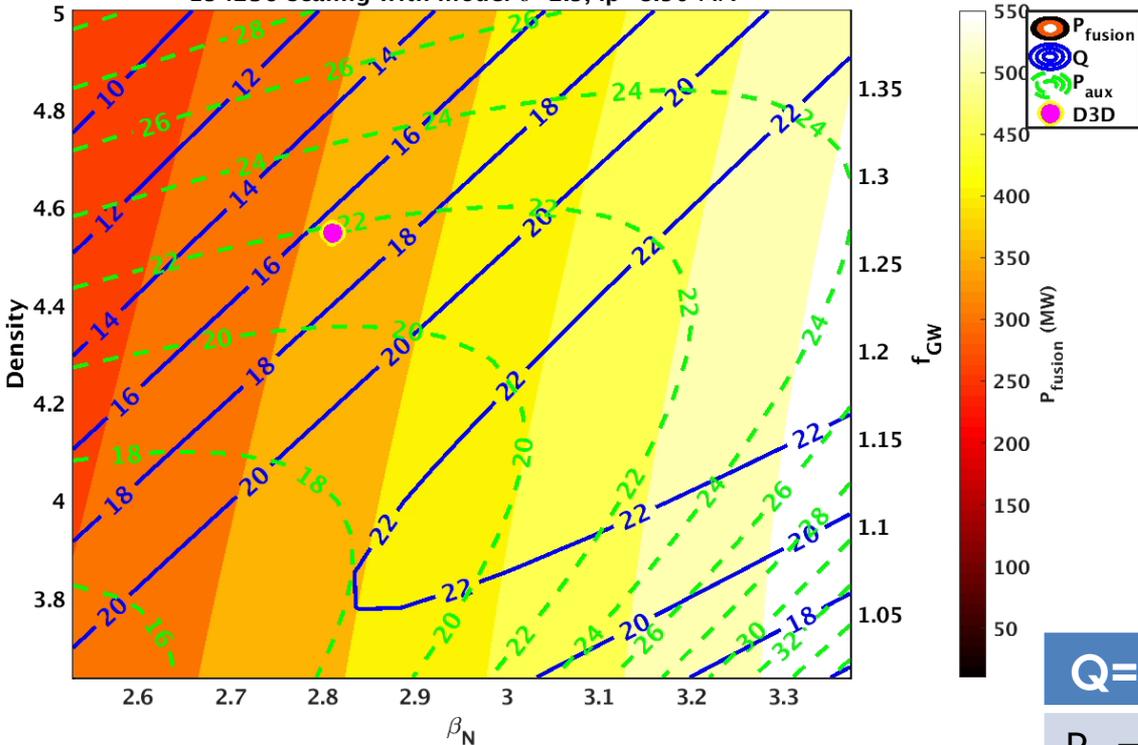


- q95 scary, but experiments ran that low at decent power
- BetaN is very conservative, more optimization to be done

<b>Q=9.1</b>	<b>P<sub>fus</sub>=420MW</b>	<b>P<sub>aux</sub>=46MW</b>
B <sub>N</sub> =1.4	f <sub>GW</sub> =1.01	f <sub>loss</sub> =0.27
R=3.6m	T <sub>i0</sub> =12.3 keV	q95=2.52

# Scalings: q95=4 without 3/2 TM to ARC

194236 scaling with model  $\epsilon=2.9$ ,  $I_p=8.50$  MA

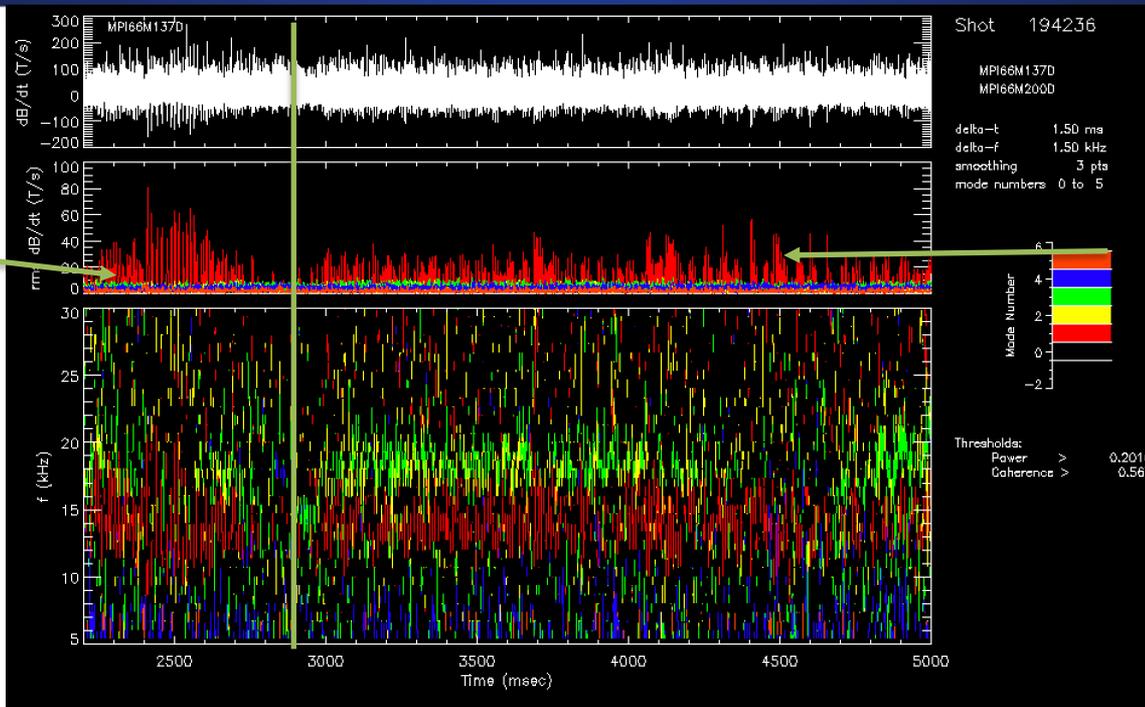


- **fGW is too high, starting plasma is fairly collisional**
  - NT may not care, according to DIII-D experiments

Q=16.6	P <sub>fus</sub> =362MW	P <sub>aux</sub> =22MW
B <sub>N</sub> =1.33	f <sub>GW</sub> =1.3	f <sub>loss</sub> =0.38
R=3.6m	T <sub>i0</sub> =12.1 keV	q95=2.85

# Possible new NT Hybrid at $q_{95}=4$ , with 4/3 TM

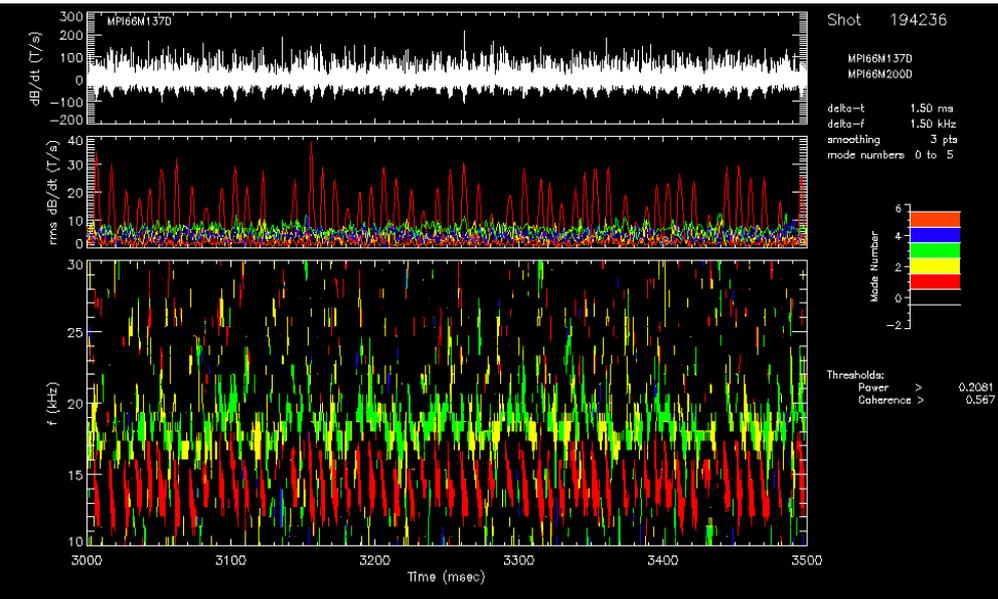
Larger amplitude, slower fishbones



Lower amplitude, intermittent fishbones for the duration of the 4/3

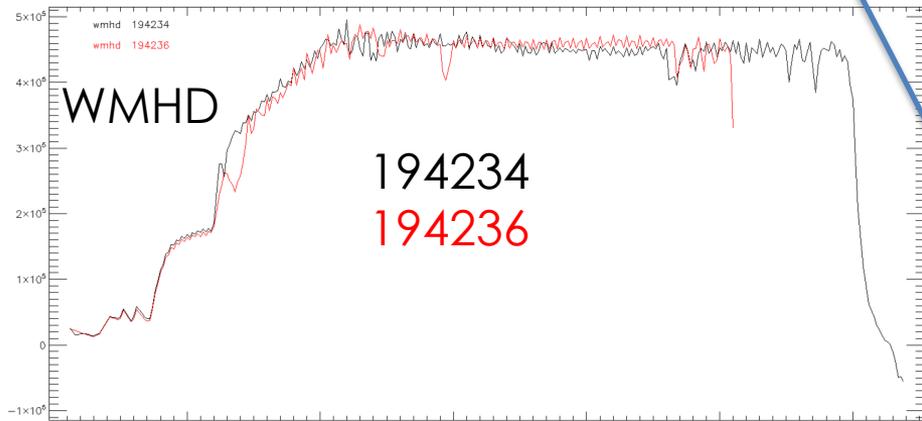
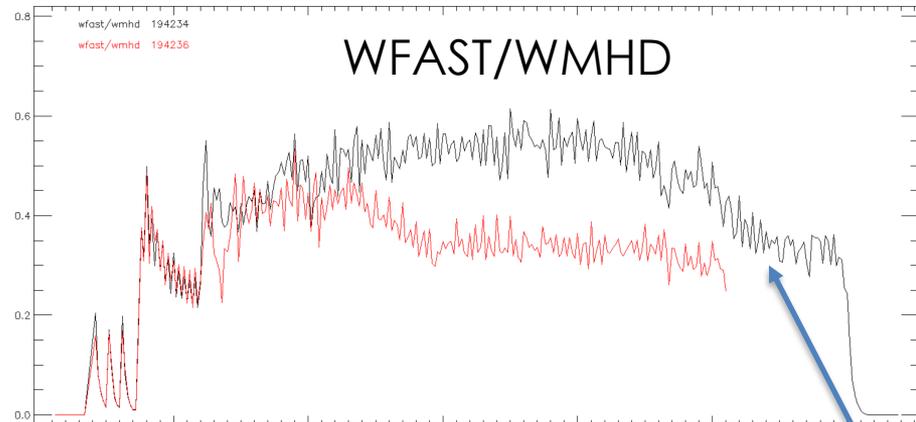
- This shot strongly resembles past hybrids and some of my  $q_{95}=3$  cases.

# 194236



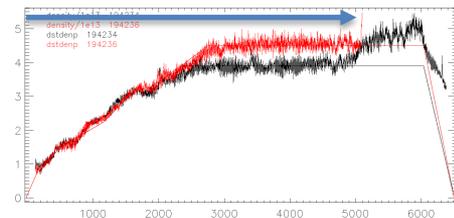
- **Clear modulated fishbones and lack of sawteeth**
- **This shot had higher ne than the others, might be part of accessing the 3/2 or 4/3 hybrid varietal, like in PT**
- **Compare to 131265, 194445**

# Phenomenology is now the same between q95=3,4 cases

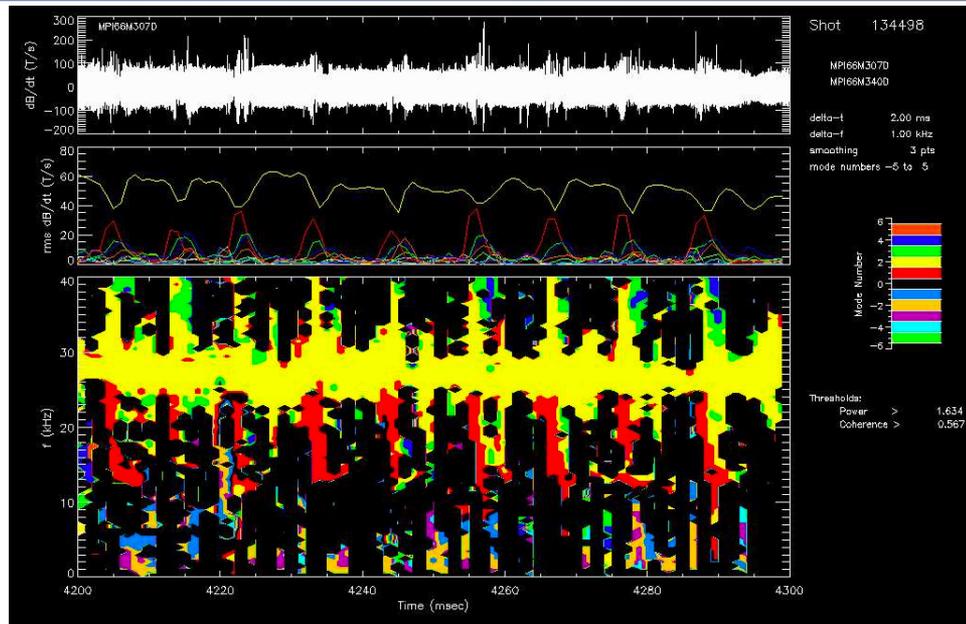


- Clear improvement in fast ion confinement without 3/2, and at higher  $n_e$
- Cases with 4/3 don't seem to lose fast ion confinement nearly like cases with 3/2
  - Could this be differences in island overlap with fast ion orbits?
  - Caveat: **red** has 20% less NBI injected power

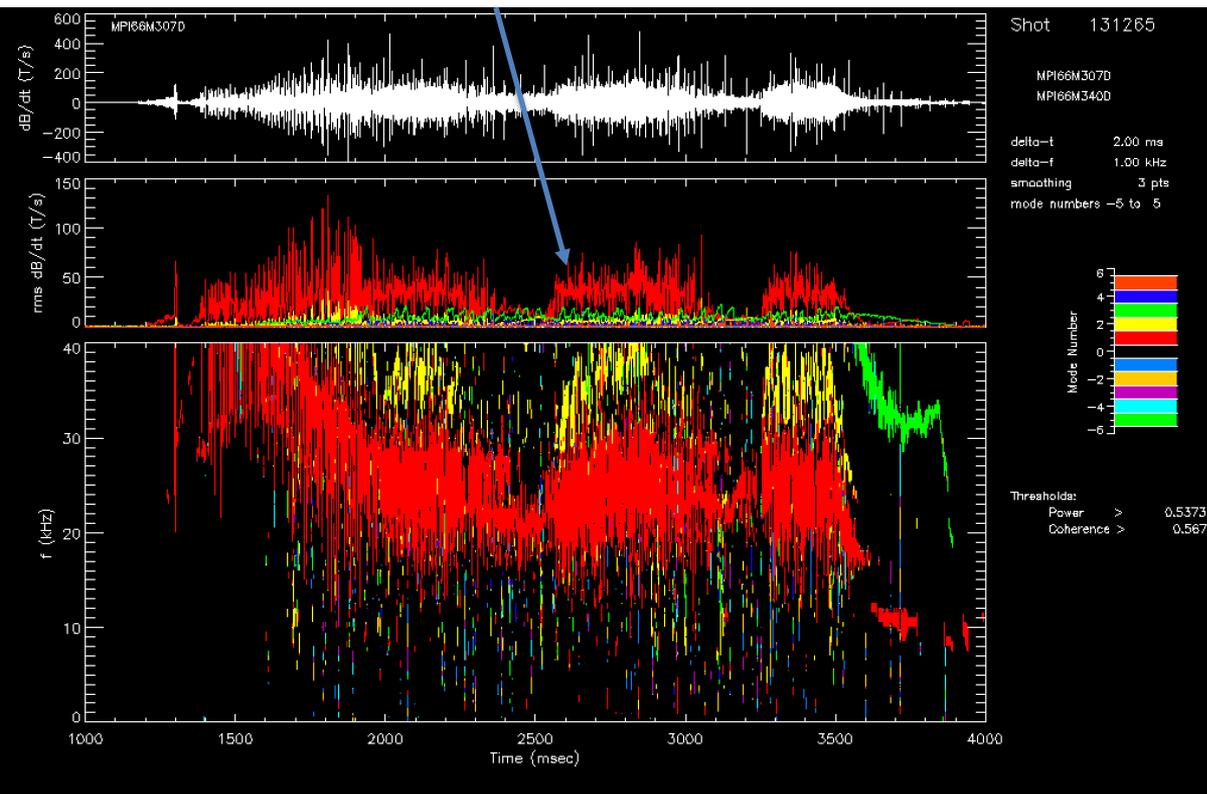
Also, density effect Balance becomes similar once  $n_e$  rises in 3/2 case



- 3/2, spinning quickly.  
Nonegligible multi n activity from ELMs
- TM amplitude modulated here by elms

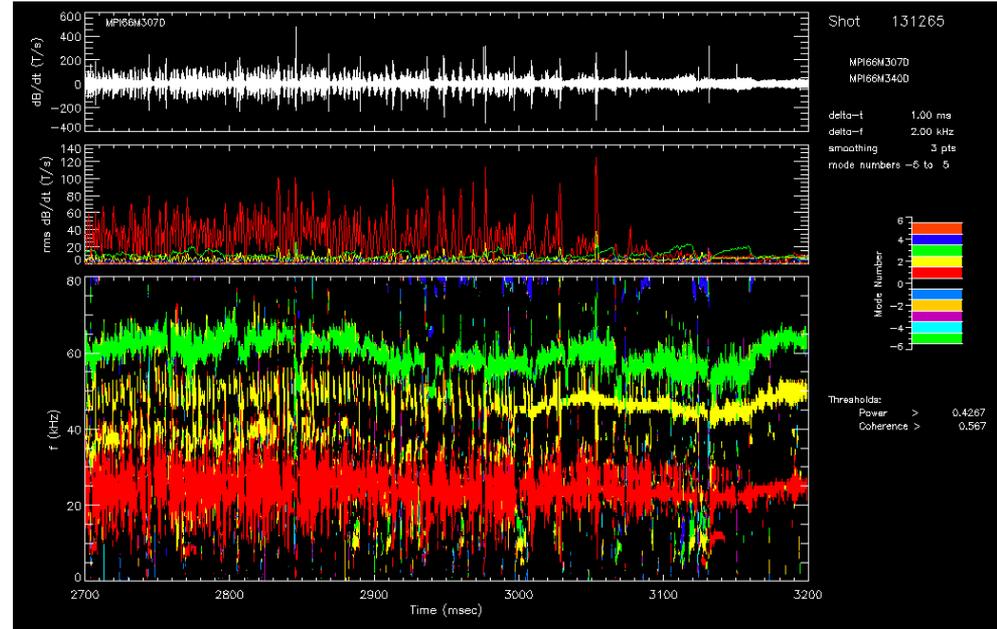


Artifact of  $dt=2$ . becomes clearly fishbones at  $dt=1$

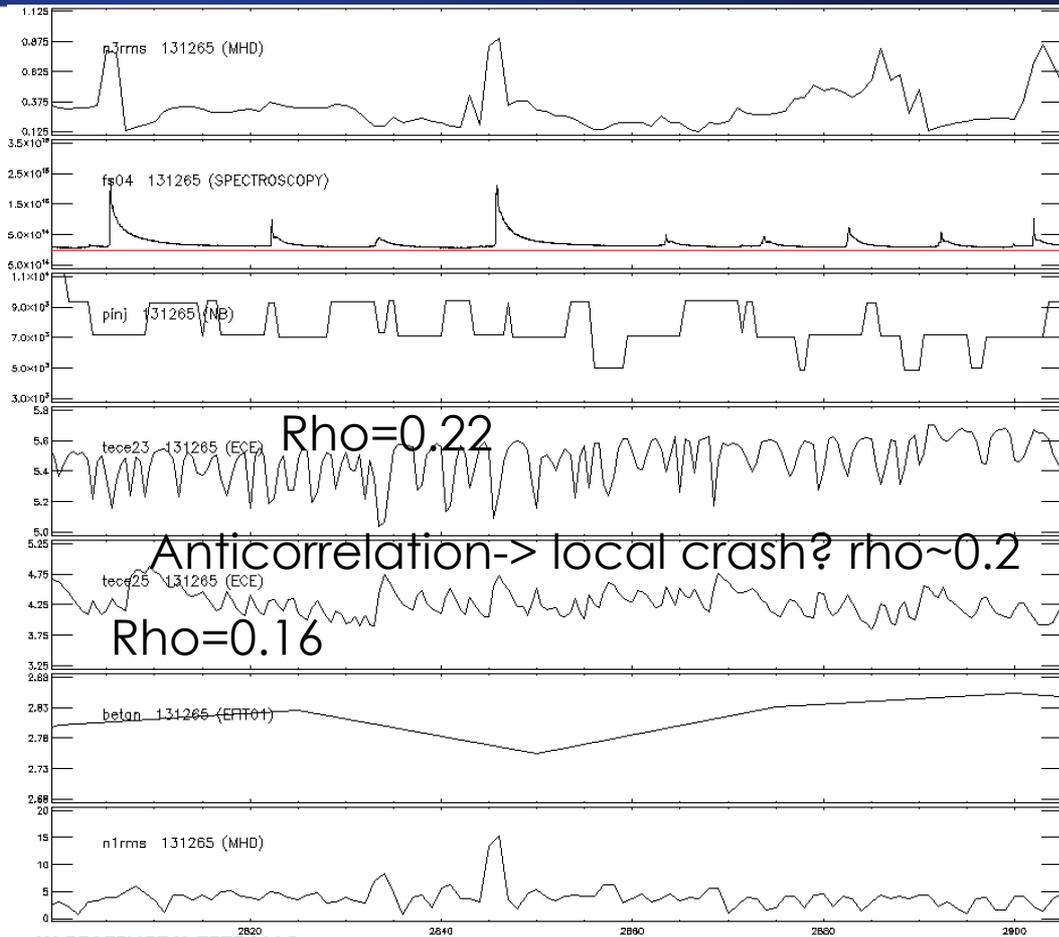
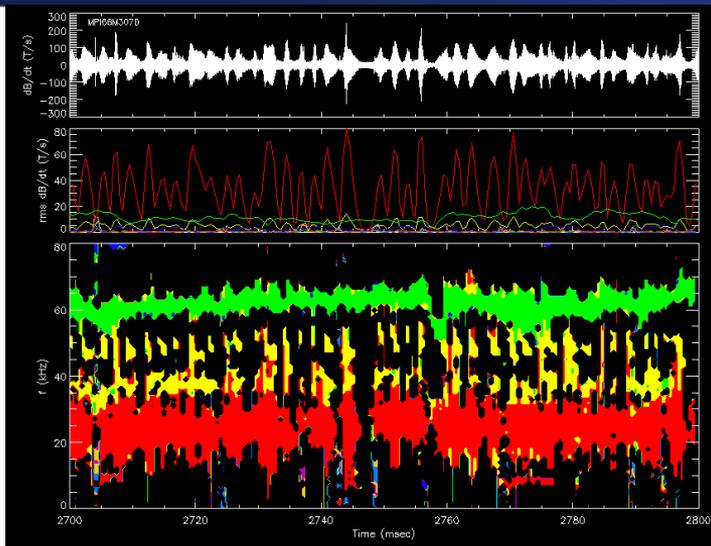


- This looks scarily similar to 194445
- Nice performance, gets up to  $Te \sim 6-7$ ,  $Ti \sim 9$ !
- Seem to get fishbones and then 4/3 interactions with big ELMs

- TEce sees elms
- 4/3 is modulated sorta like my NT shot
  - Rotation locates it at  $\rho \sim 0.38$  like in mine
- Competition between fishbones and 4/3
- No sawteeth that I can find, correlated fishbones with Te crashes here
  - Careful of ne cutoff in ece

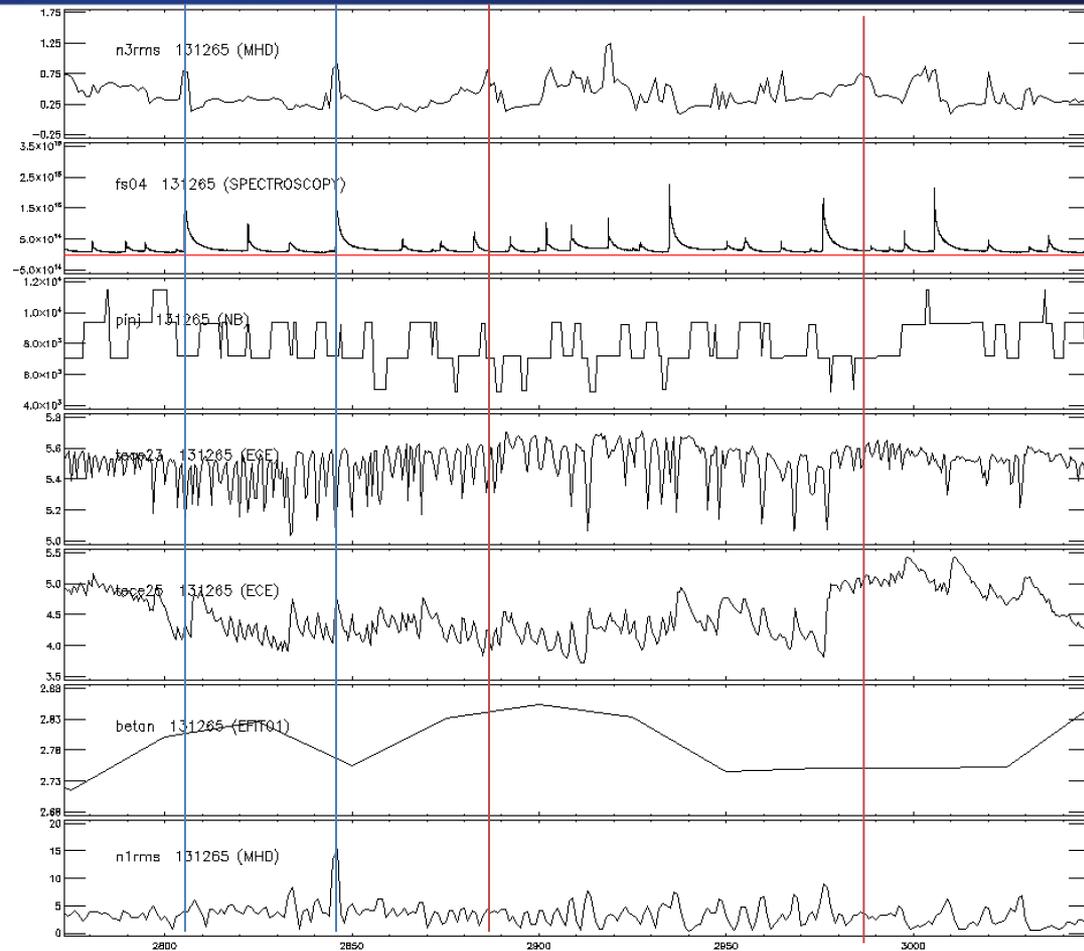


# ECE signal from fishbones visible $\rho \sim 0.2$

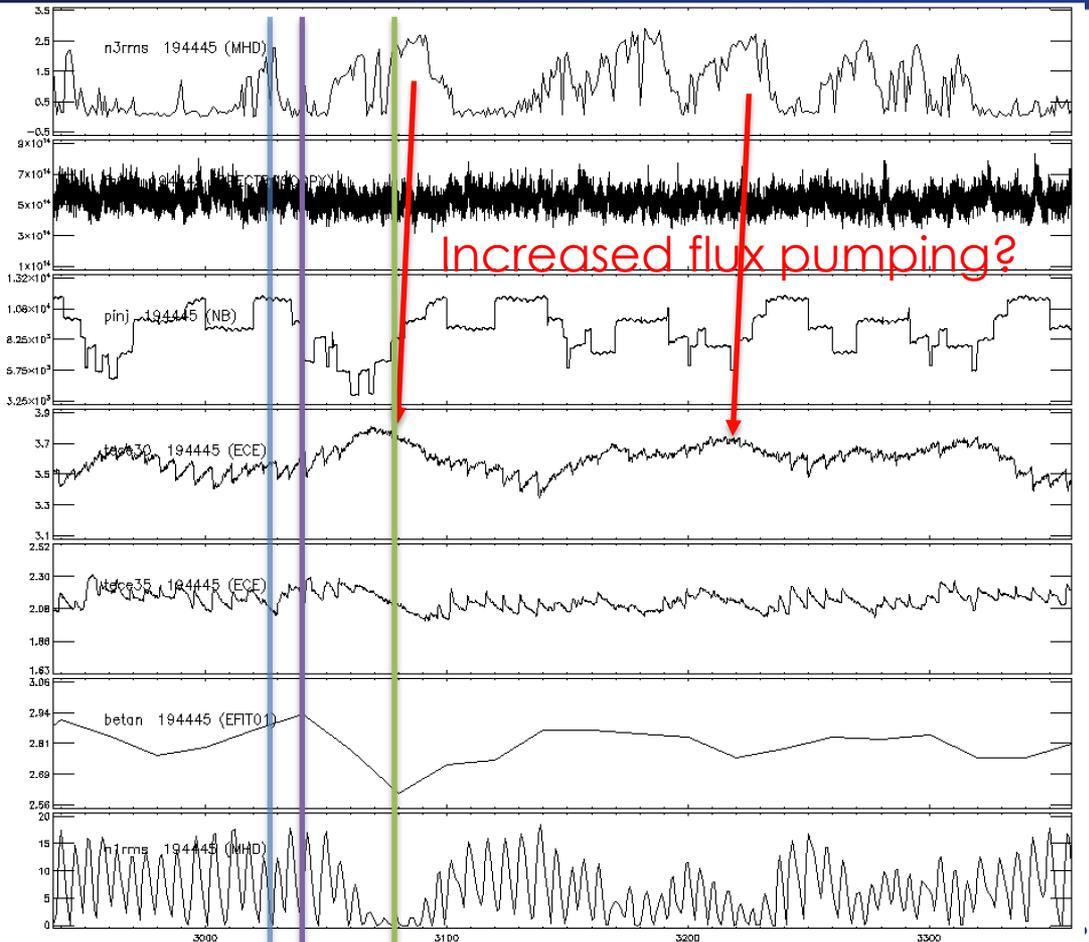


# Some ELMs talk to 4/3 mode, but not all

- **4/3 seems to burst on its own, sometimes coupling to ELMs, other times not**
  - character is different-  
> ELM coupled closer to impulse event
  - Vs gentler modulation
- **Not correlated with Pinj**
- **Same Te crashing with fishbones (n=1), not just ELMs**



# 194445 is similar, but for lack of ELMs

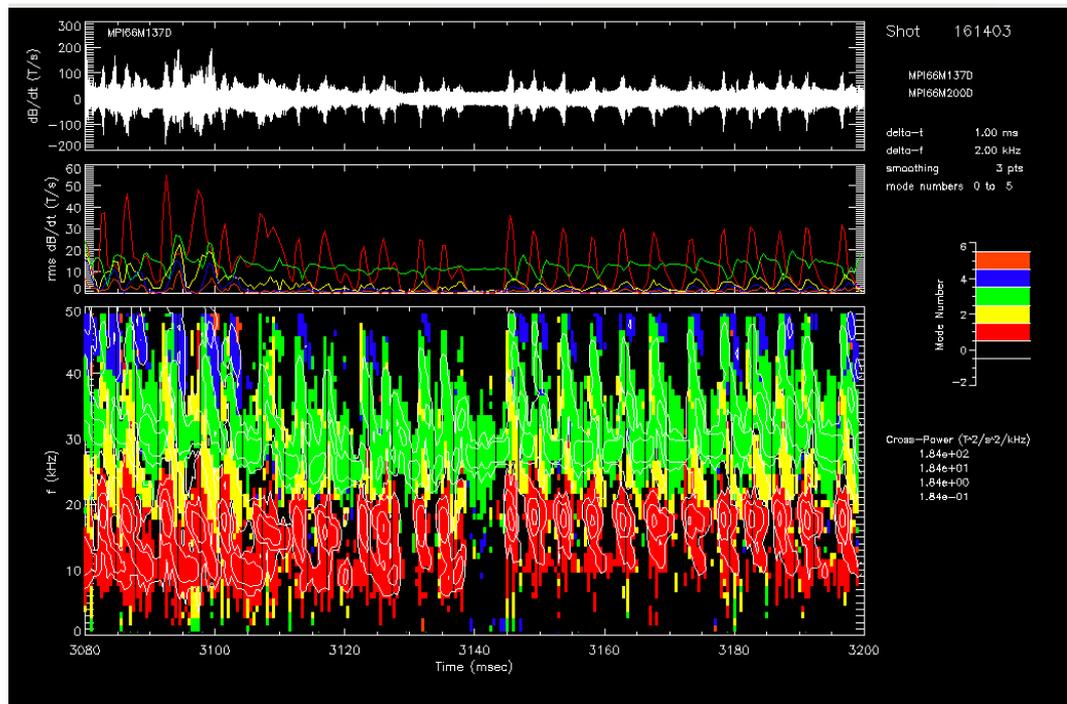


- **Fishbone inversion between  $\rho = 0.3$  and  $0.4$**
- **$4/3$  is  $\sim 6.5$  kHz,  $\rho \sim 0.35$** 
  - Despite
- **Pinj, BetaN,  $4/3$  modulations are phase delayed**
  - I bet steady beam power would maintain  $4/3$ , eliminate fishbones, as in other hybrid examples

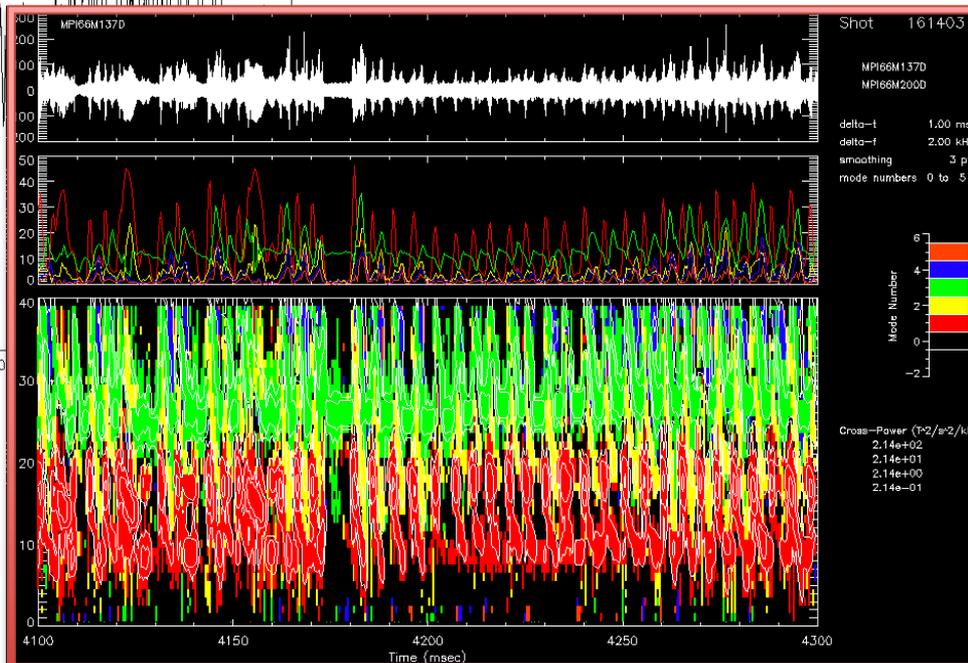
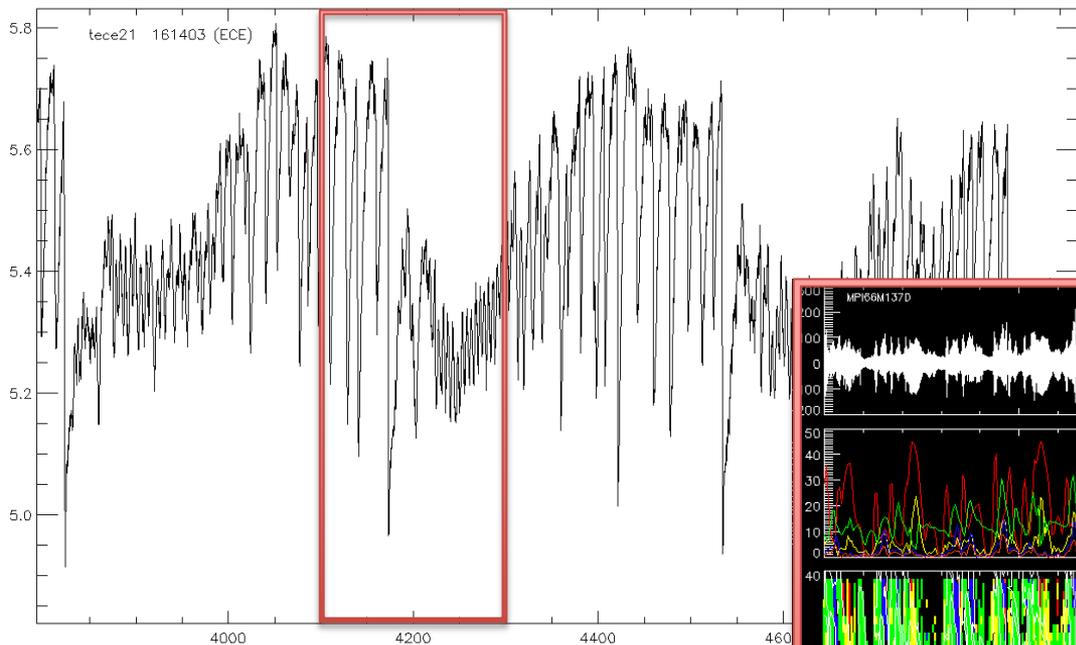
# Hybrid with 4/3 TM 161403

- **4/3 TM talks to sawtooth, which is present**

- This produces chirping similar to what I have in 3/2 mode
- Chirping correlates with sawteeth on modespec
- crashes at  $\rho \sim 0.25$  in TECE



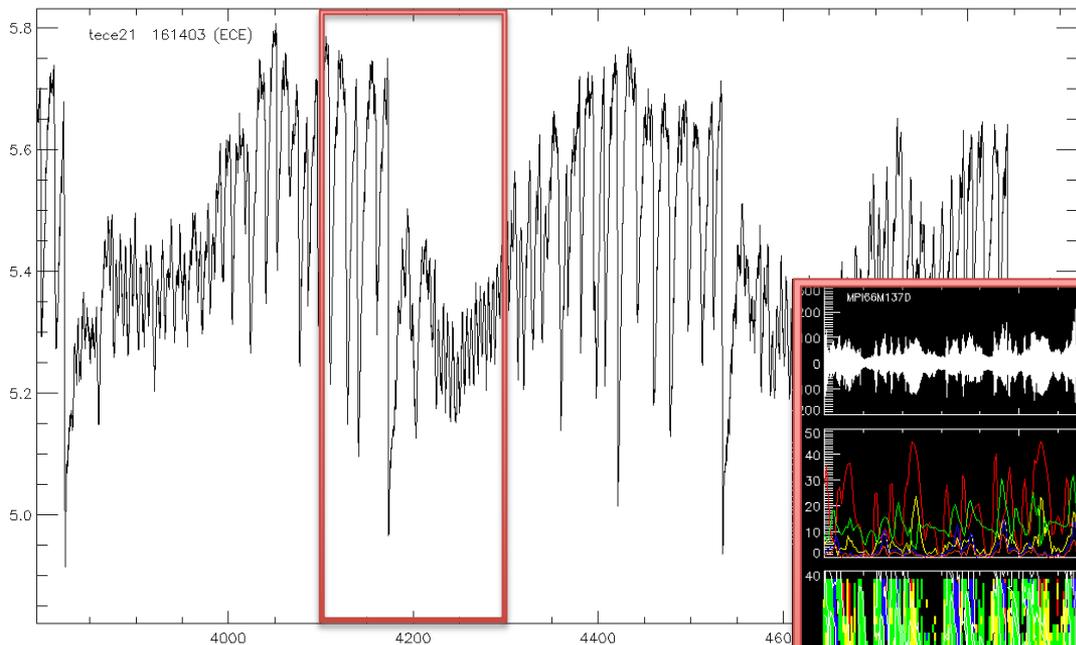
# Fishbones “ring” in amplitude



Sawteeth change character

- Large and irregular to small and regular
- Indicator of  $q_{min}$ ?

# Fishbones “ring” in amplitude

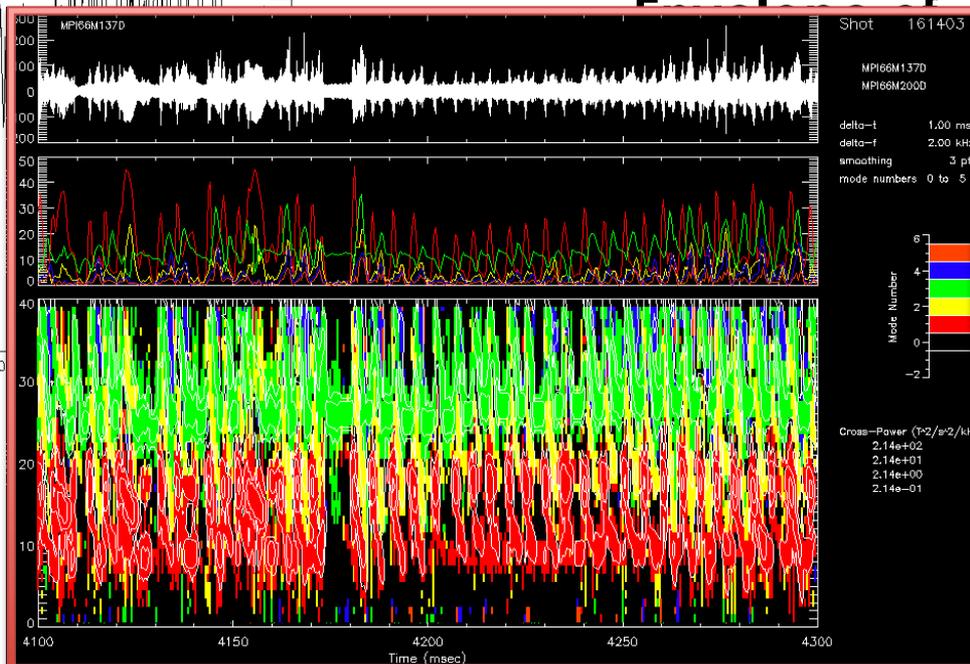


- Crashes correlated with sawteeth on modespec

Sawteeth change character

- Large and irregular to small and regular
- Indicator of  $q_{min}$ ?

57



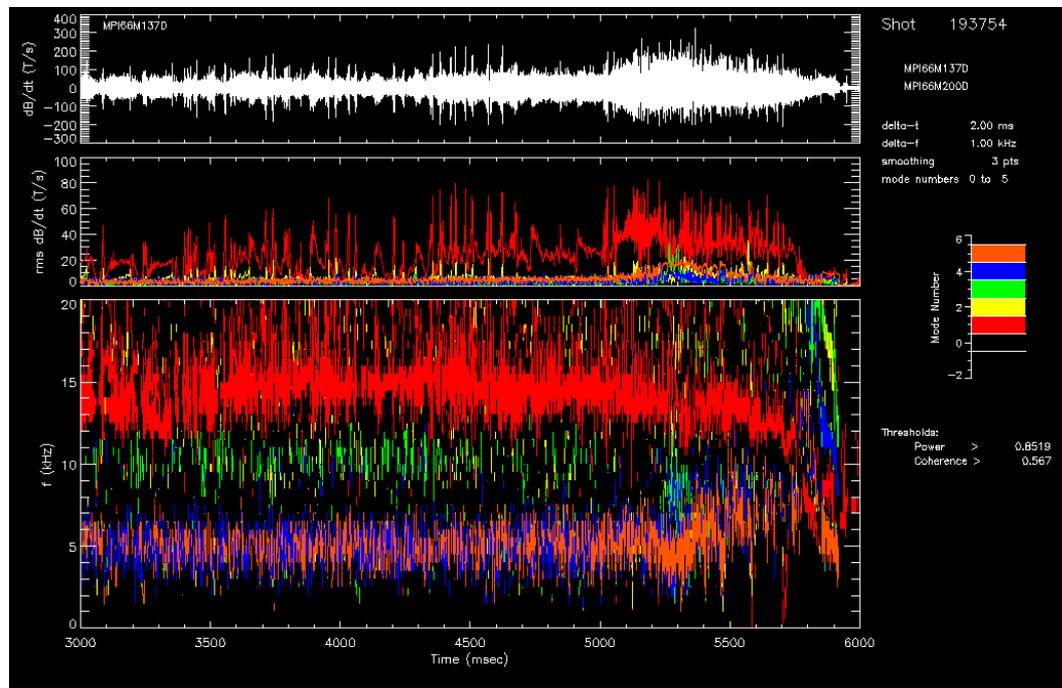
go

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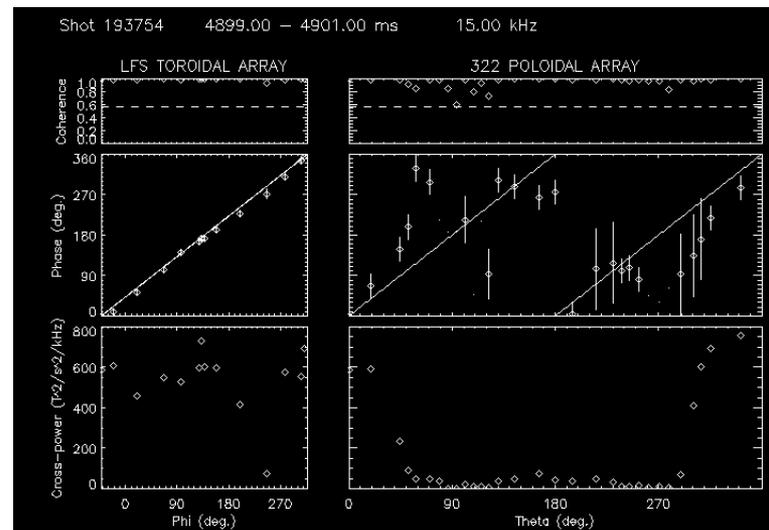
e

# What is this “long lived mode” (LLM)?

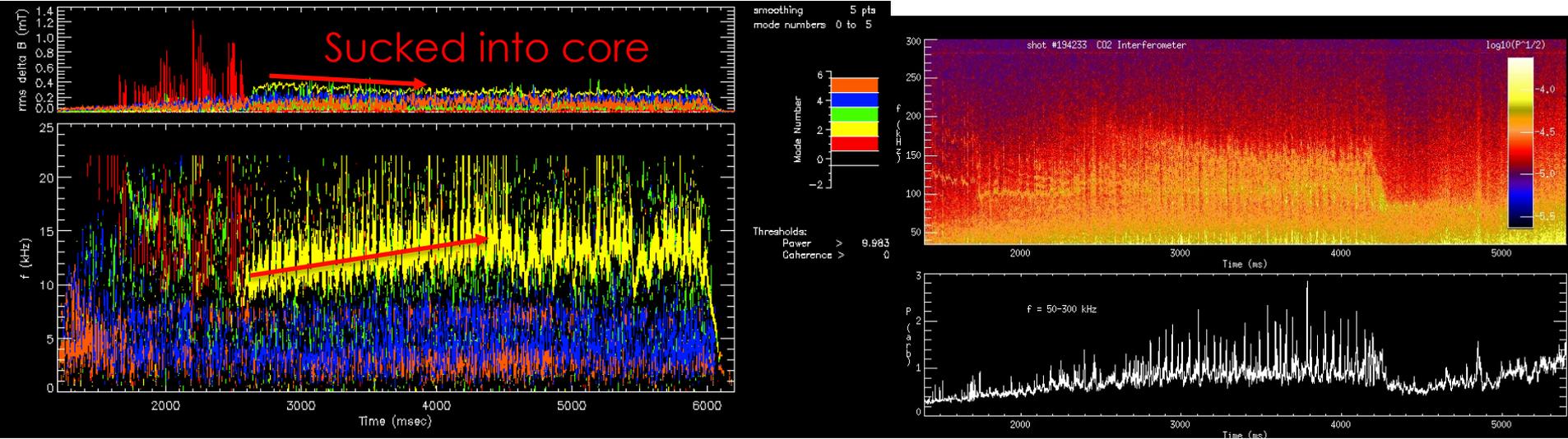
- Seen in ATs by Chapman, and kstar hybrids by Na
- Would be worth looking at phase inversion in SXR
- Looks like it's an  $n=1$  ideal internal kink mode, but does not crash... odd
  - No  $q=1$  surface, (no negative helical flux) so we don't have reconnection
  - Otherwise, we'd get the resistive kink  $\rightarrow$  sawteeth
  - I don't think I have this
- Chapman I. T. et al 2010 Nucl. Fusion 50.4 045007
- Internal kink 1/1 growth rate here for  $q$  profiles  $\rightarrow$  could guide my  $q$  profile scans
- dWmhd produces finite kink growth rate with  $q_{min} > 1$ , but field line bending forces saturation at some finite  $ksi$
- If LLM is present, causes fast ion loss. Often transitions to fishbones - maybe like mine? Could explain  $n=1$  without crashes



- High betat, betaN shot at  $q_{95}=2.7$  has huge sawteeth

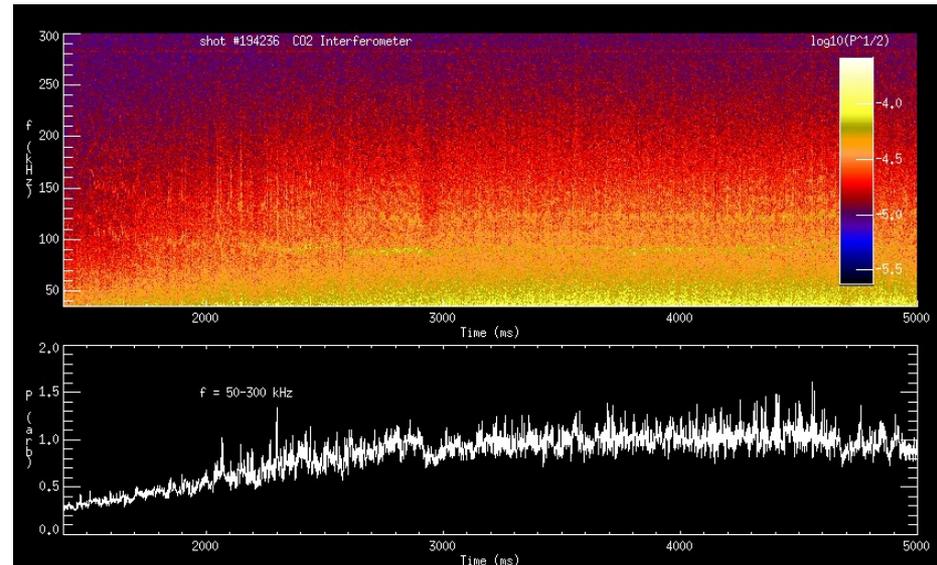
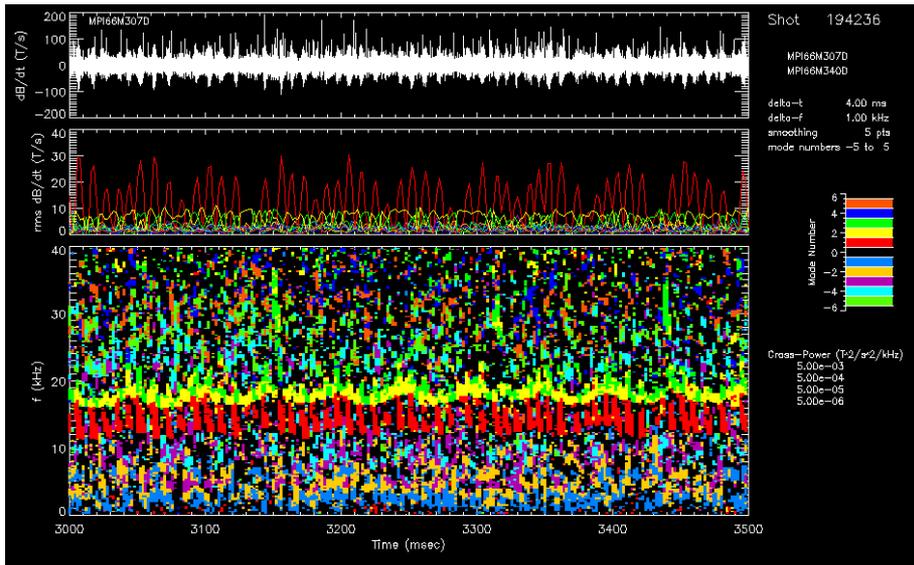


# Extra: Cases at q95=4 with chirping 3/2 TM



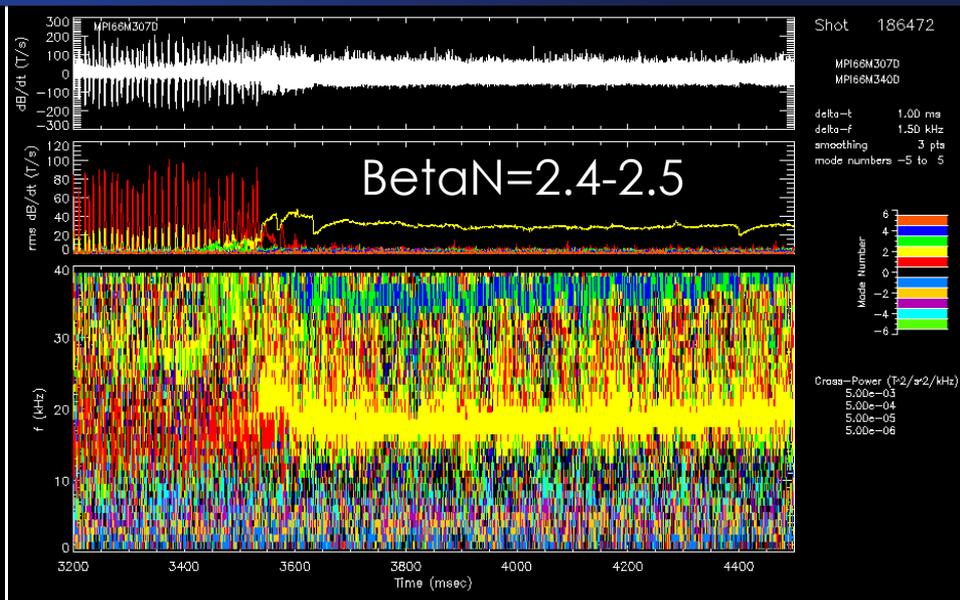
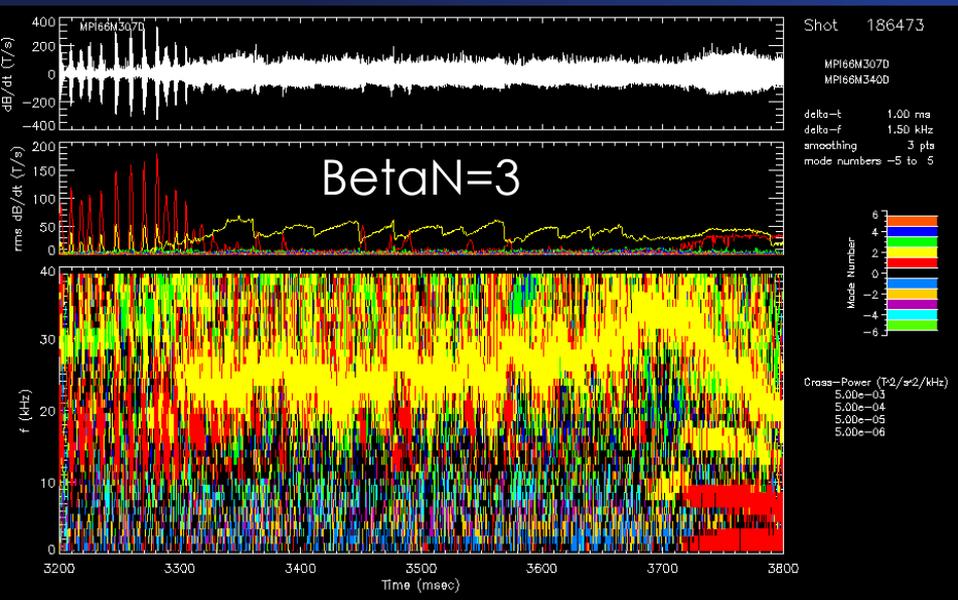
- Flux pumping may be happening -> removal of  $n=1$  activity
  - Future work to prove this, comparing neoclassical J prediction and observed J
- Looked for seeds (with N. Richner) of the 2/1 TM, found nothing convincing
  - Need to look at proximity to ideal limits,  $\delta a'$

# Extra: Fast ion phenomenology q95=4 without TM



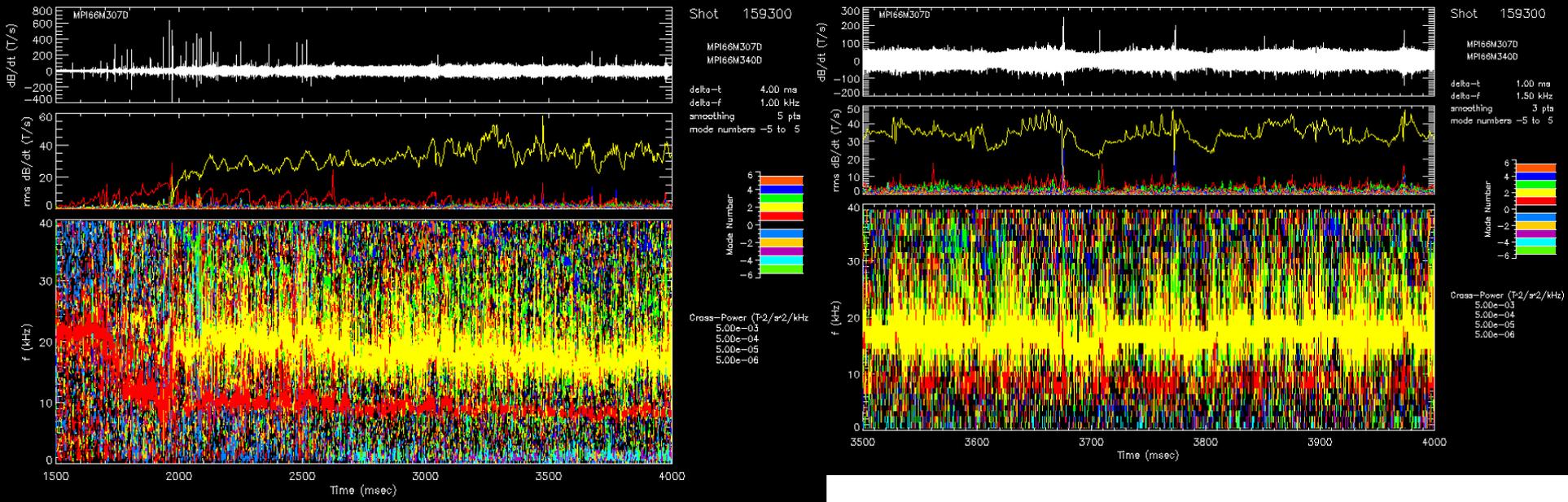
- One low Ip case without 3/2 TM runs at higher  $n_e \sim 4.5$  and does not see large spikes from coupling
- Only significant MHD is fishbone-ing

# Extras: Previous NT shots see less interaction with $q=1$



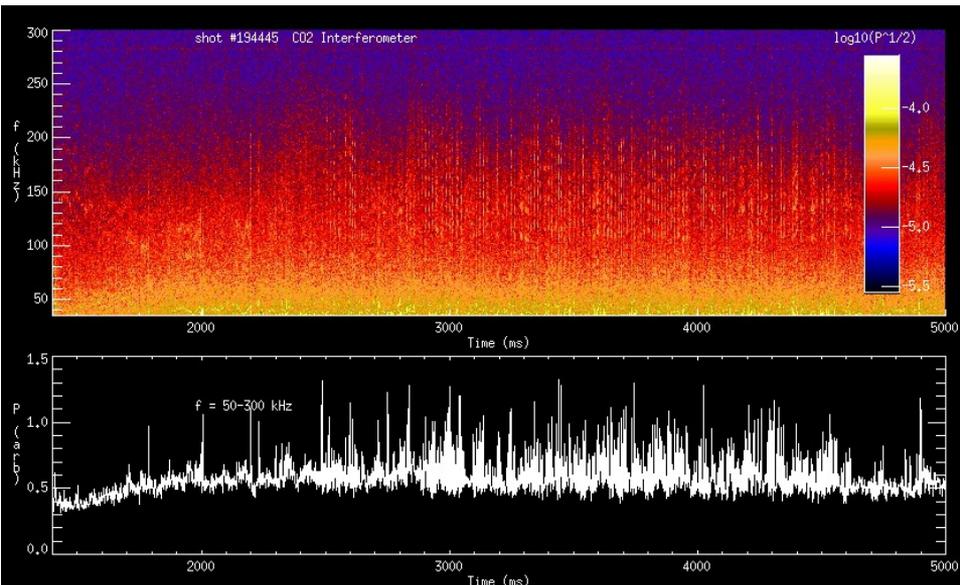
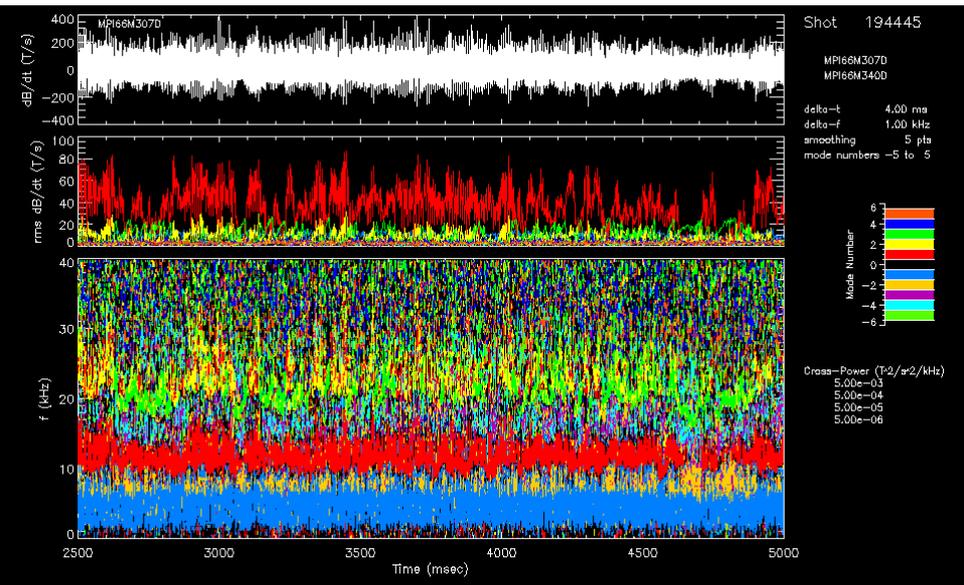
- **These are not exactly comparable to new cases**
  - Larger shape, 50% more  $I_p$  (0.6MA  $\rightarrow$  0.9MA), higher  $n_e$ , higher rotation
  - H98y2, TauE, betaN higher,  $q_{95}$  higher

# Extra: Reference hybrids look similar



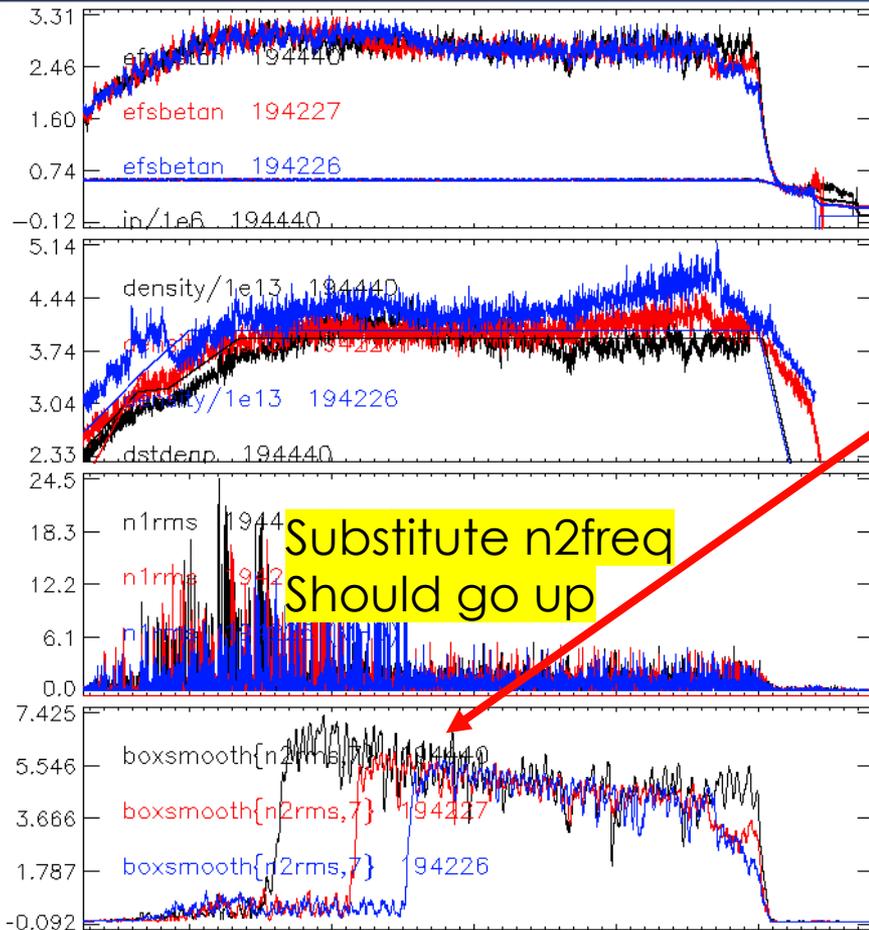
- Interaction, bursts from  $q=1$  surface aren't gone in PT hybrid plasmas
- $q_{95}$  in reference is  $6.1 \rightarrow q$ ,  $n=2$  evolution, flux pumping strength likely different

# Extra: q95=3 cases see fishbones



- Fishbone activity observable in all q95=3 cases
- Each of these need half or less anomalous fast ion diffusion vs q95=4 with TM

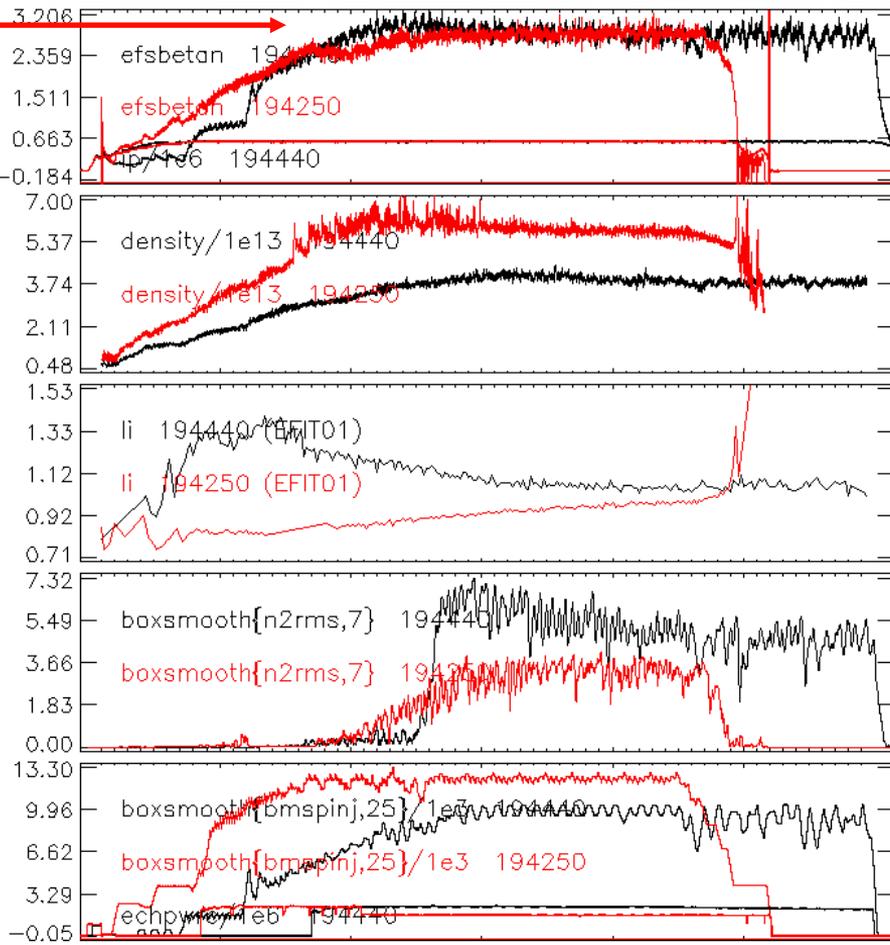
# Flux pumping: q profile moves with or without 3/2



- Access varied to encounter 3/2 earlier in flattop- ne lowered
- Decline in  $n=2$  amplitude is very reproducible despite onset time
- Suggests that  $q$  profile ( $q=3/2$  surface) trajectory proceeds with or without 3/2 mode

# Flux pumping: Shot 194250

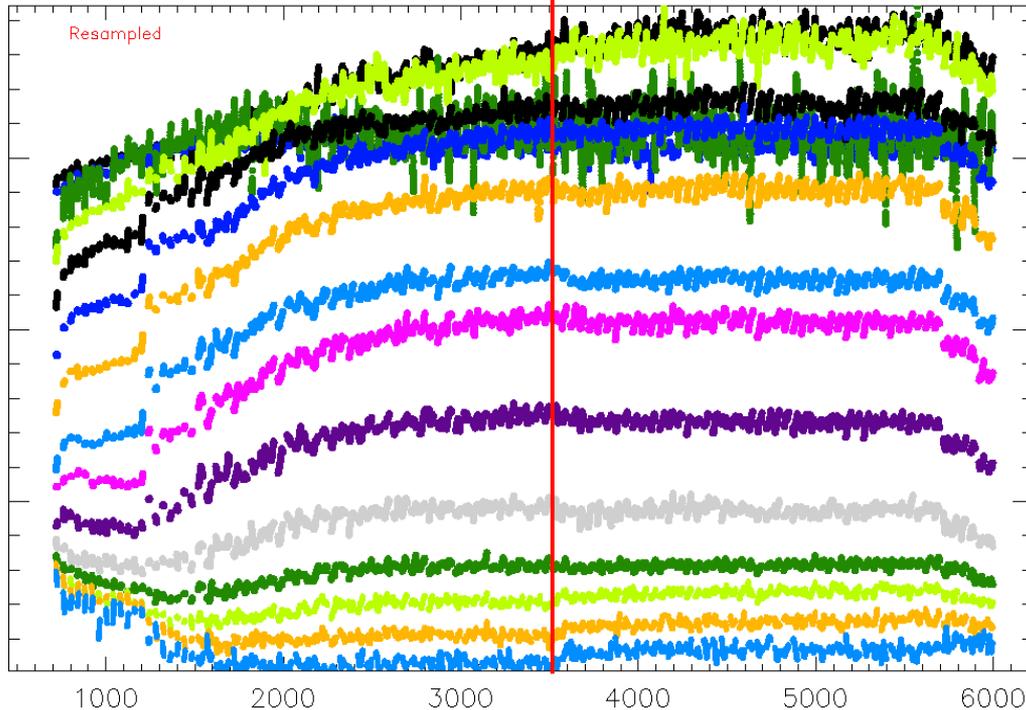
Mystery  
BetaN  
limitation  
despite  
Pinj, ne,  
access



- Probably not flux pumping  $\rightarrow$  3/2 not sufficient alone
- Access (early vs late heating) means  $q=1$  is probably never in the plasma
- $q=1$  sawtooth precursor possibly required for flux pumping is therefore missing

# Flux pumping: Raw MSE Shot 194440

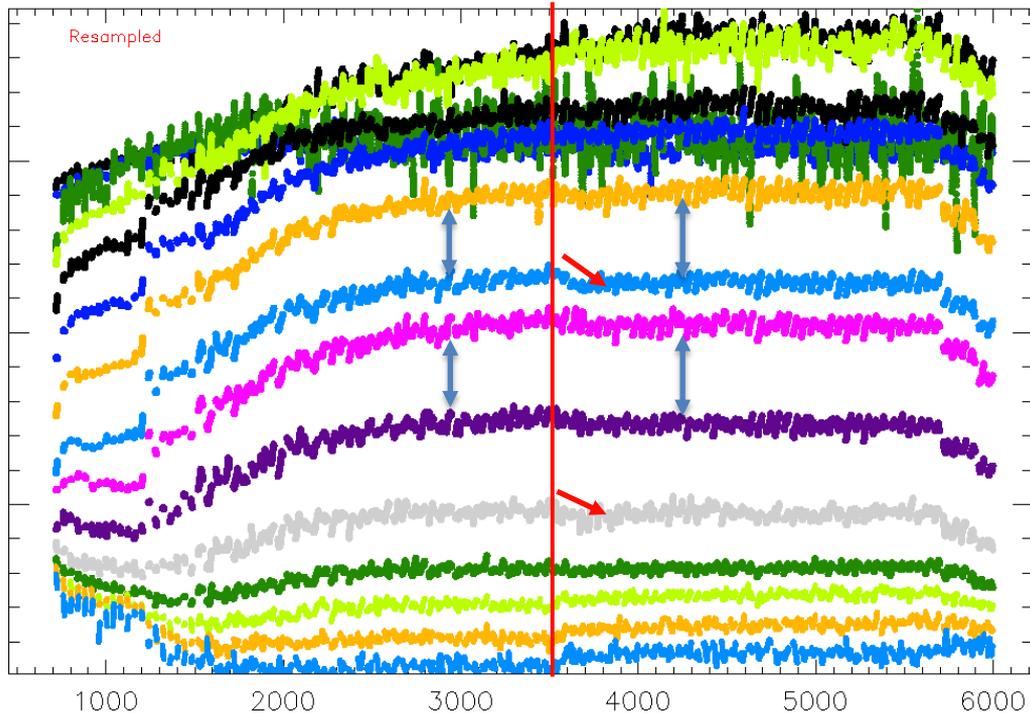
3/2 onset



- Flux pumping can sometimes be seen on Raw MSE as separation of channels in time
- TM drops BetaN from 3 to 2.7, which also moves surfaces

# Flux pumping: Raw MSE Shot 194440

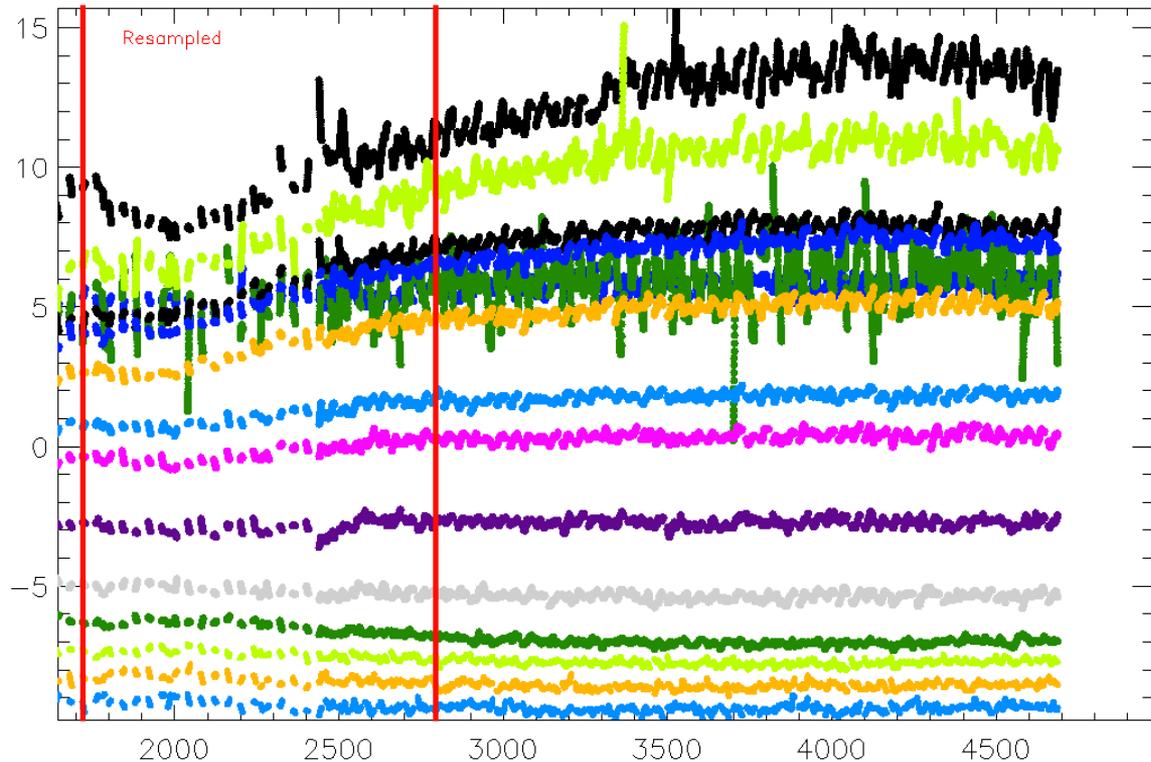
3/2 onset



- Flux pumping can sometimes be seen on Raw MSE as separation of channels in time
- TM drops BetaN from 3 to 2.7, which also moves surfaces -> can cause movement in channels
- Disentangling the two is... tricky and not conclusive

# Flux pumping: Shot 194250

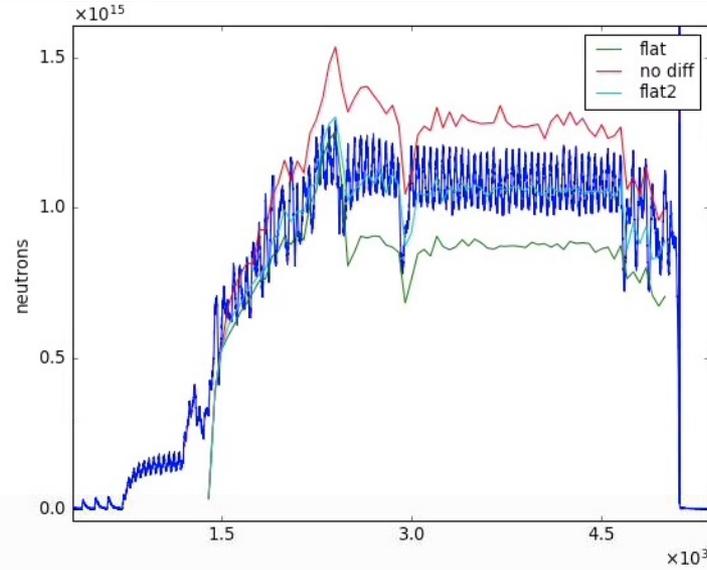
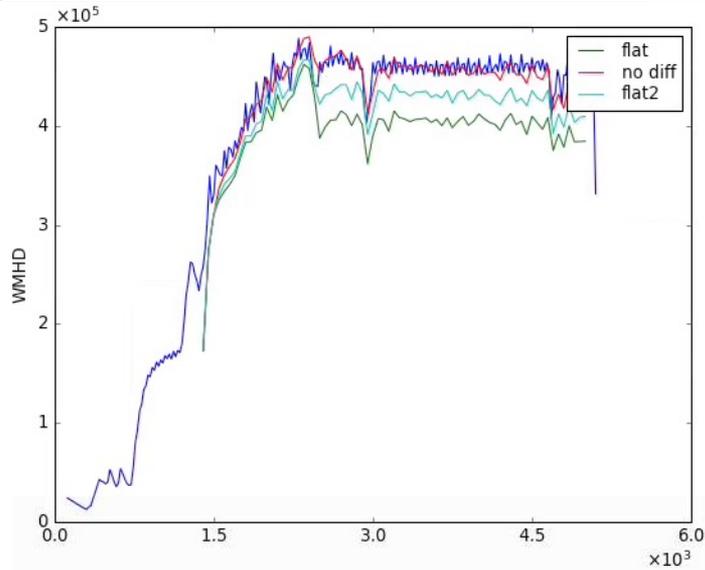
3/2 onset



Max 3/2 amp

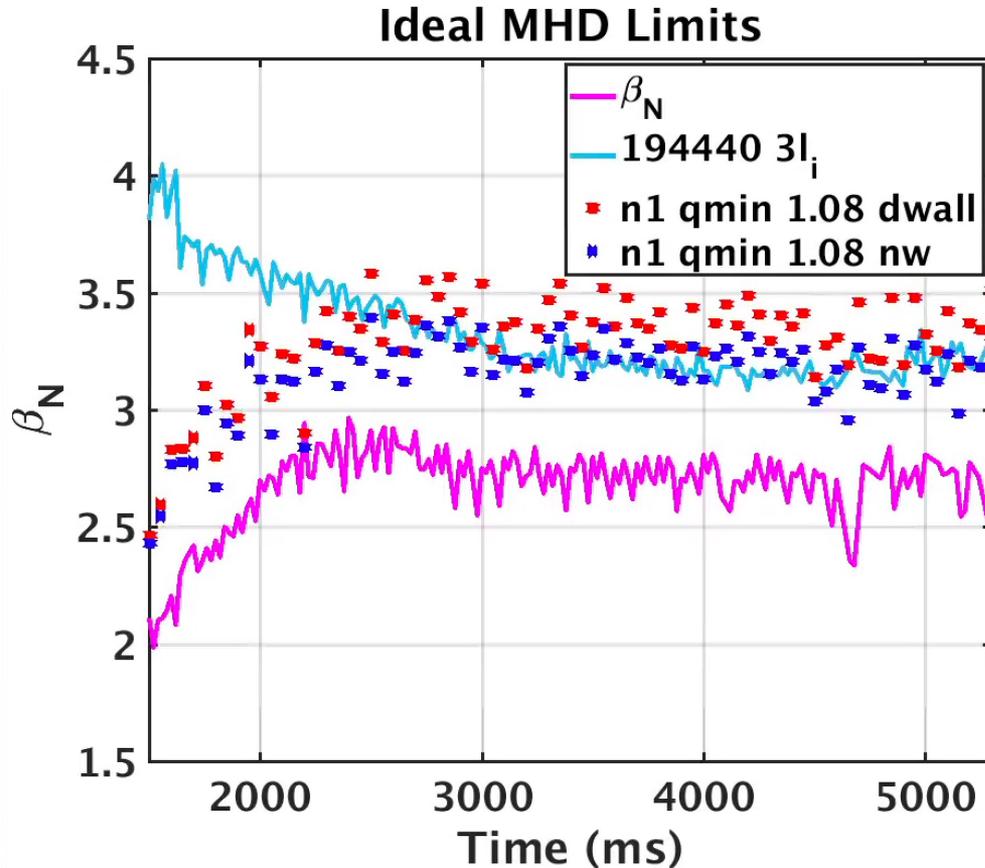
- Probably not flux pumping  $\rightarrow$  3/2 not sufficient alone
- Li trajectory  $\rightarrow$  no  $q=1$  in the plasma, no sawtooth precursor

# Extra: Strange nubeam results due to low $W_{\text{thermal}}$



- **Case without 3/2 TM, at higher  $n_e$ , has fishbones.**
- **TDEM/Nubeam does not need anomalous diffusion here to match WMHD (red), but neutrons are wrong**
- **Flat top value from NT with 3/2 is too high (10k, green) suggesting lower  $n_e$  and/or TM does damage to fast ion confinement**

# Ideal limits from previous method match 3li well



- This iteration of the method did not ensure monotonicity
- Adjusted method attempts to remove variations (or masking of variations) in limits due to q profile shape variation