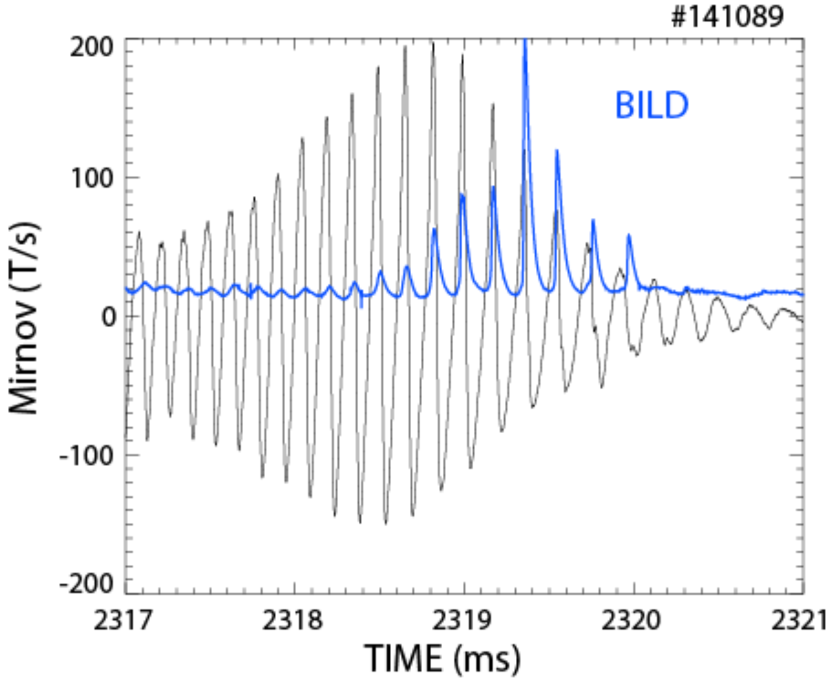
The Intriguing Nonlinear Dynamics of Off-axis Fishbones



Bill Heidbrink

R. Fisher, M. Garcia-Munoz, G. Matsunaga, G. McKee, R. Moyer, C. Muscatello, M. Okabayashi, D. Pace, K. Shinohara, W. Solomon, M. Van Zeeland, Y. Zhu

"Characteristics of off-axis fishbones," W.W. Heidbrink et al., PPCF (2011)

"Off-axis fishbone-like instability and excitation of resistive wall modes in JT-60U and DIII-D," M. Okabayashi et al, PoP (2011)

DIII-D NATIONAL FUSION FACILITY

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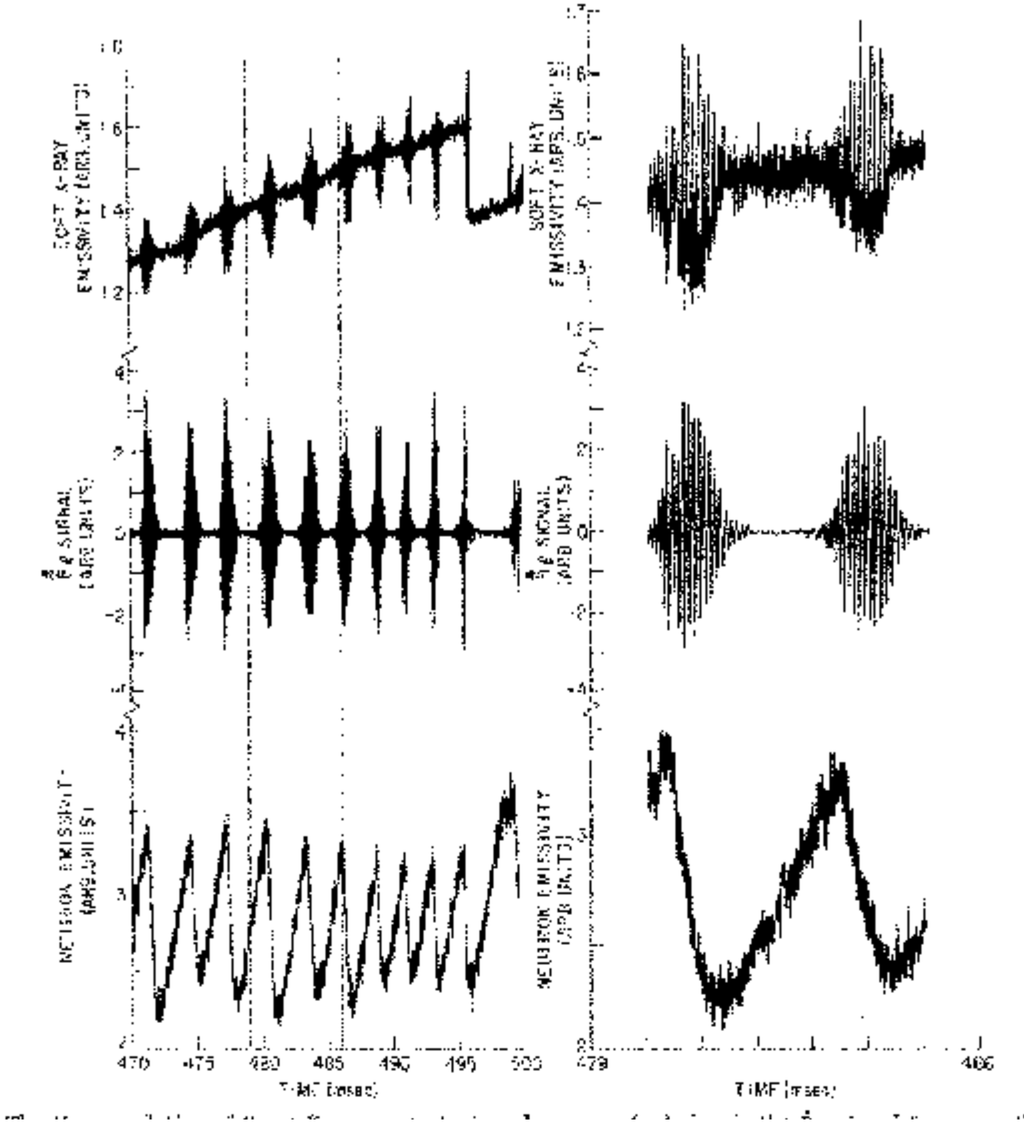
Outline

- Introduction: Off-axis fishbones are energetic particle modes (analogous to PDX fishbones)
- Mode Characteristics
- Fast-Ion Measurements

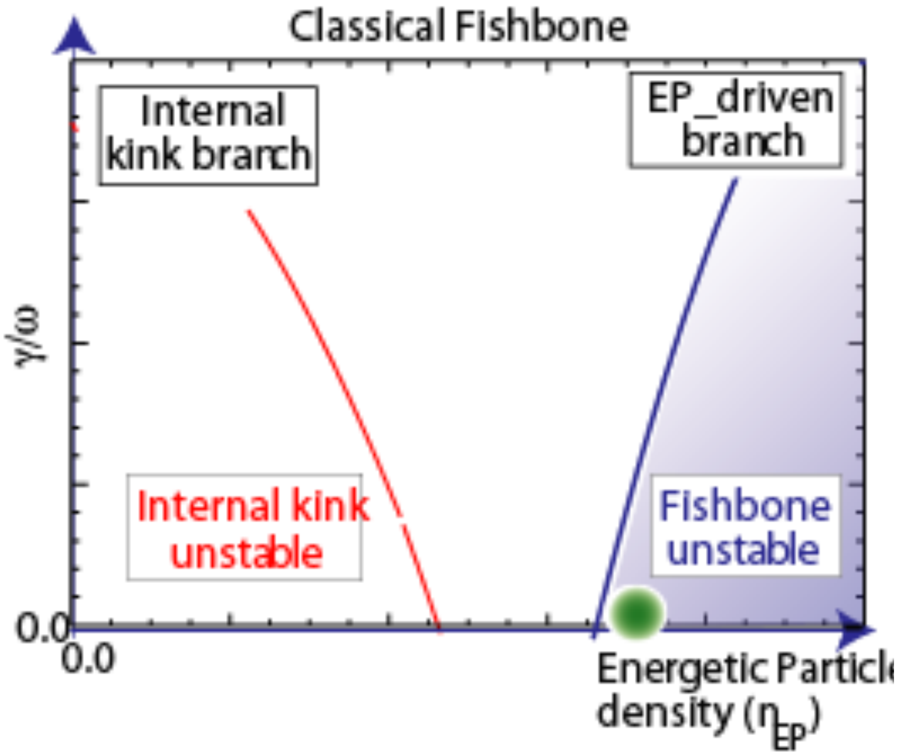
Fishbones were discovered on PDX



McGuire, PRL 50 (1983) 891

- Deuterium neutral beam injection at a perp. angle → lots of trapped particles
- Bursts at precession frequency of trapped beam ions
- Beam ions ejected at each burst in a "beacon"
- Neutrons drop → reduction in confined beam ions
- Mode structure of (n,m)= (1,1) internal kink

PDX fishbones were an energetic-particle mode (EPM) branch of the internal kink



- "Sawtooth" instability is the MHD branch of the internal kink
- At modest EP density, trapped energetic particles stabilize the sawtooth instability
- Too many energetic particles destabilizes the EPM branch

idea popularized by Porcelli, PPCF 33 (1991) 1601

Off-axis Fishbones occur in High Beta plasmas with $q_0 > 1$

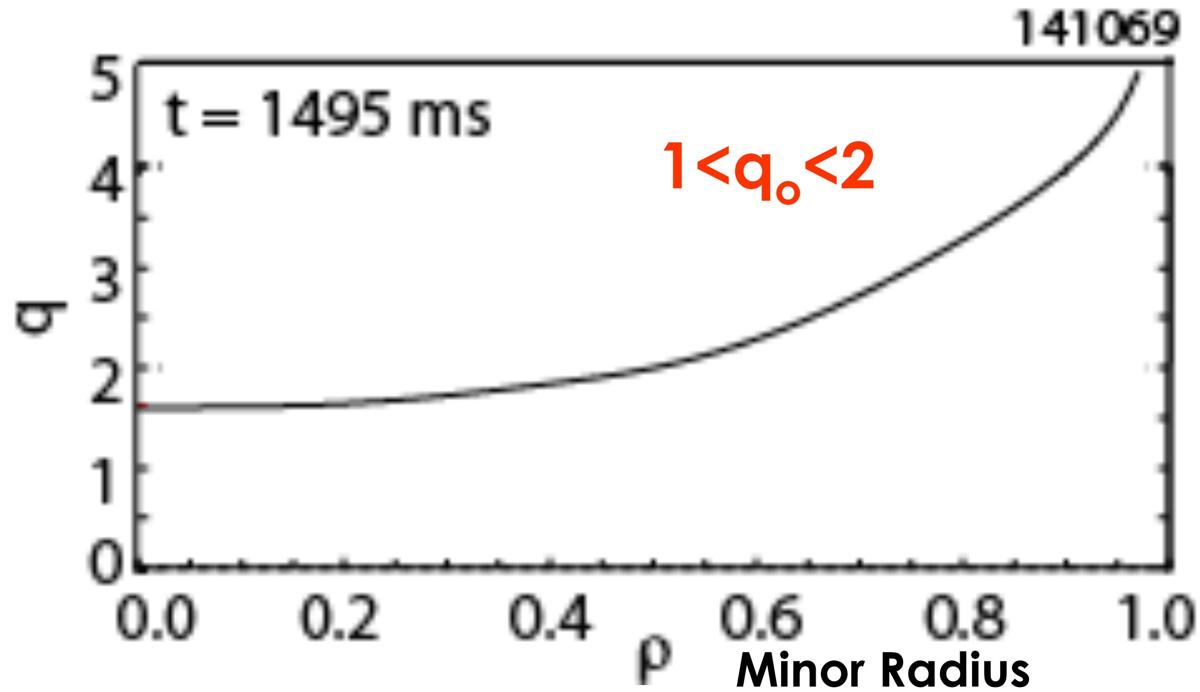
B_T= 1.7 T

I_p= 1.07 MA

H-mode

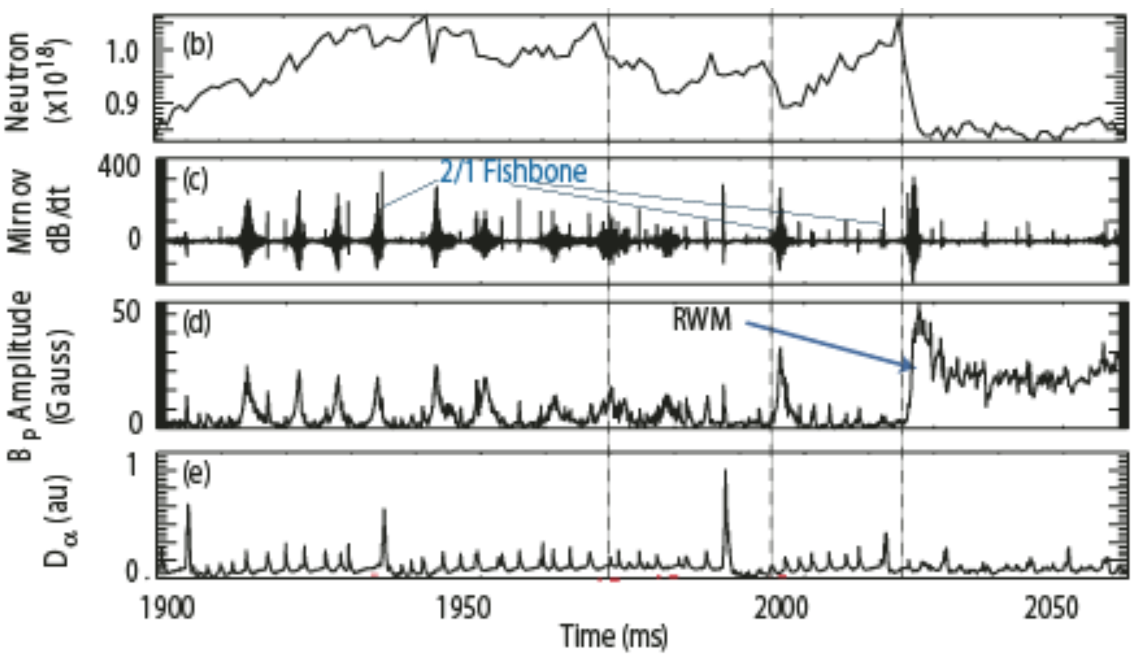
b_N=2.6

n_e= 4e19 m^{-3}



Classic (PDX) fishbone was an internal kink (q_0<1)

Off-axis Fishbones can trigger Resistive Wall Modes (RWM)

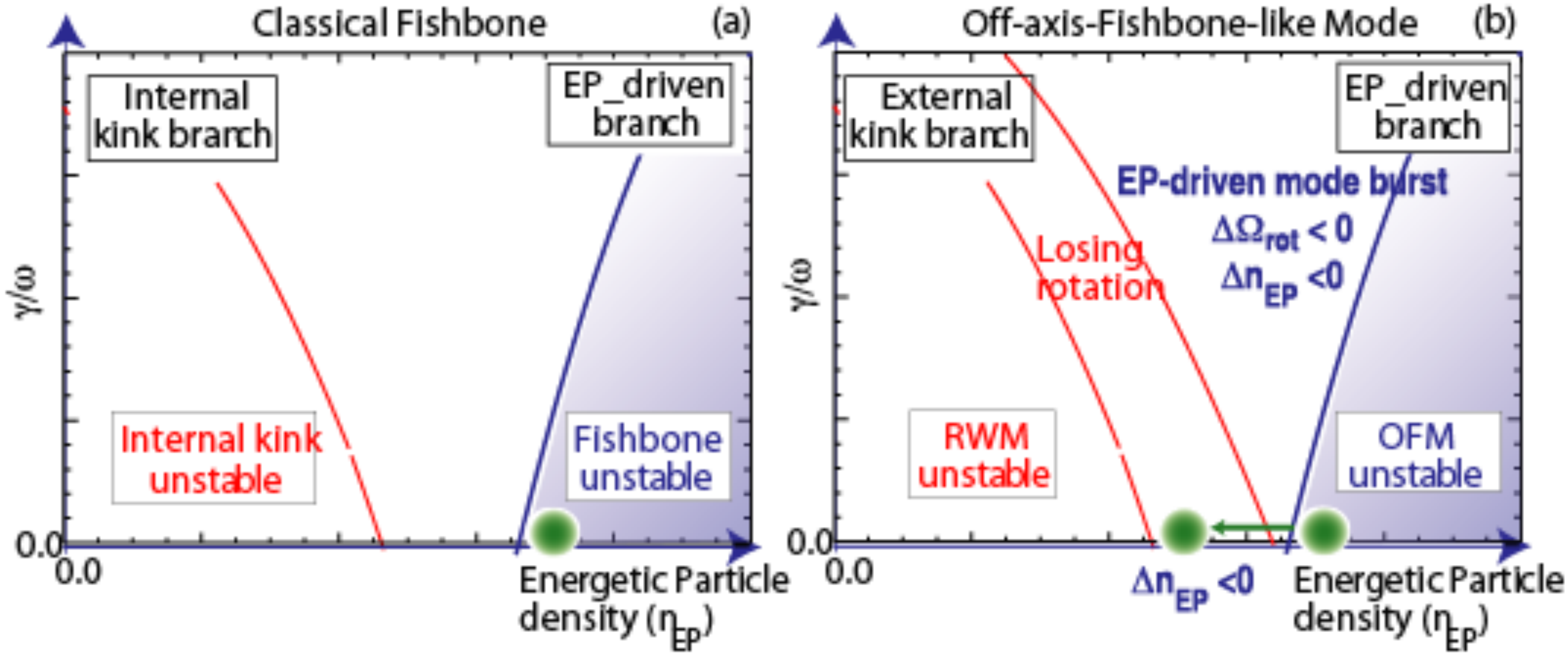


Okabayashi, NF 49 (2009) 125003

- Also happens in JT-60U [Matsunaga, PRL 103 (2009) 045001]

- Want a high β plasma for fusion → drives external kinks
- RWM is an MHD external kink that's modified by the wall
- Fast ions & toroidal rotation help stabilize RWM
- Fishbones cause reduction in both → triggers RWM

Hypothesis: the off-axis fishbone is an external kink EPM

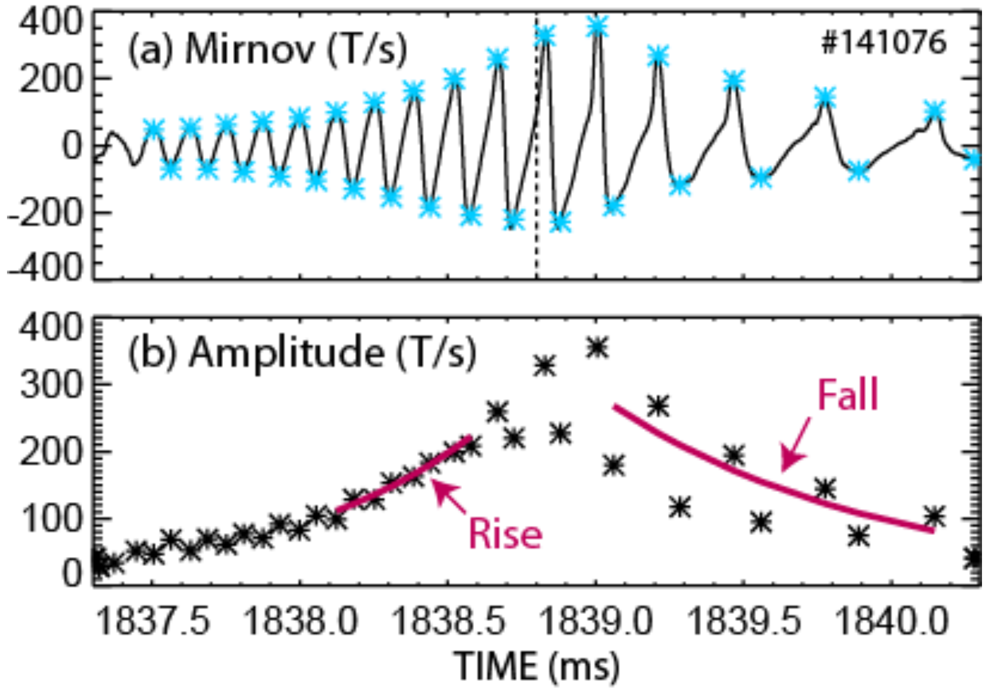


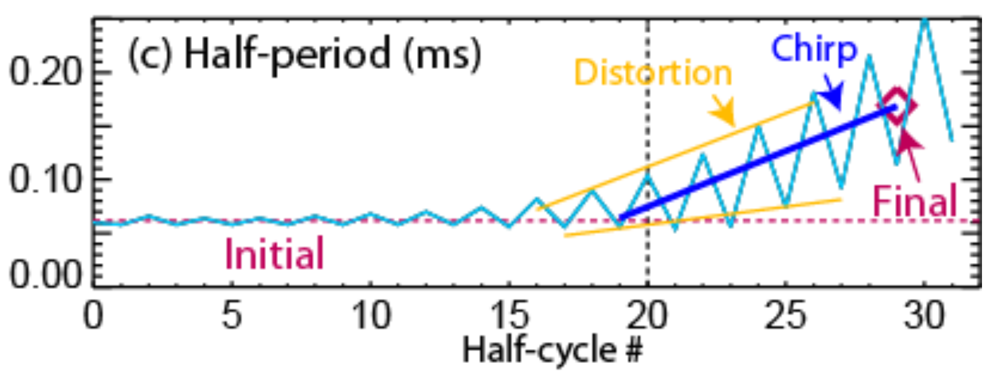
Okabayashi, PoP (2011)

Outline

- Off-axis fishbones are energetic particle modes (analogous to PDX fishbones)
- Mode Characteristics
- Fast-Ion Measurements

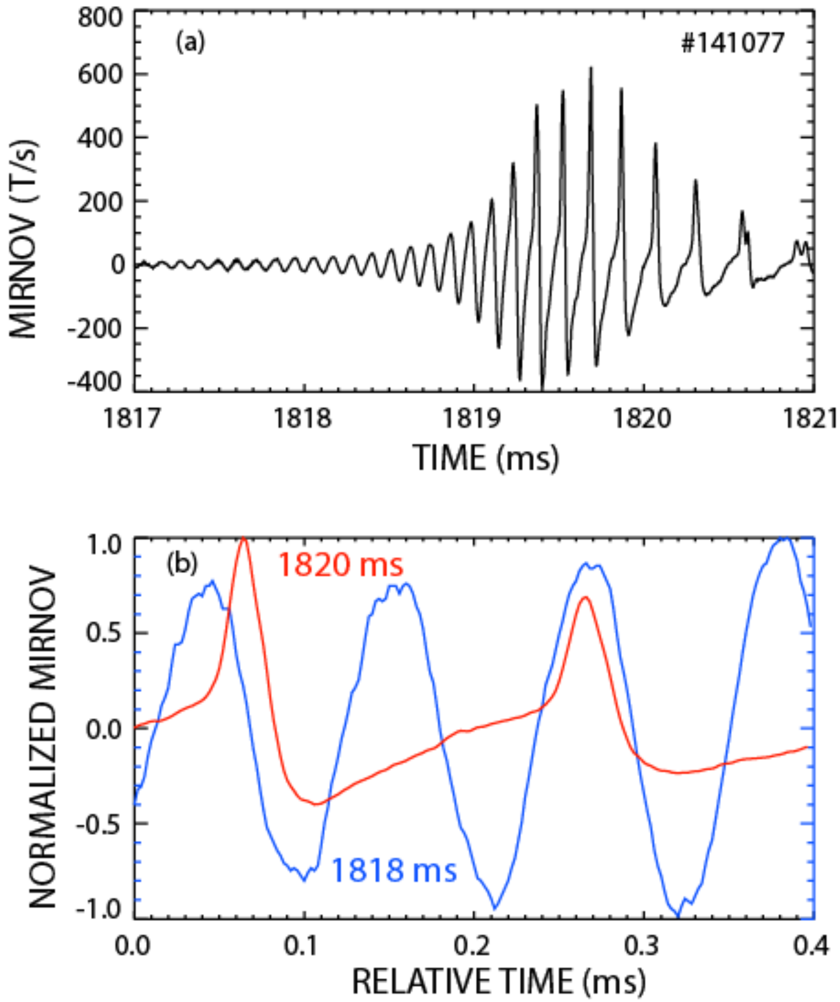
Analyze Mirnov coil signal & form a database of 513 bursts

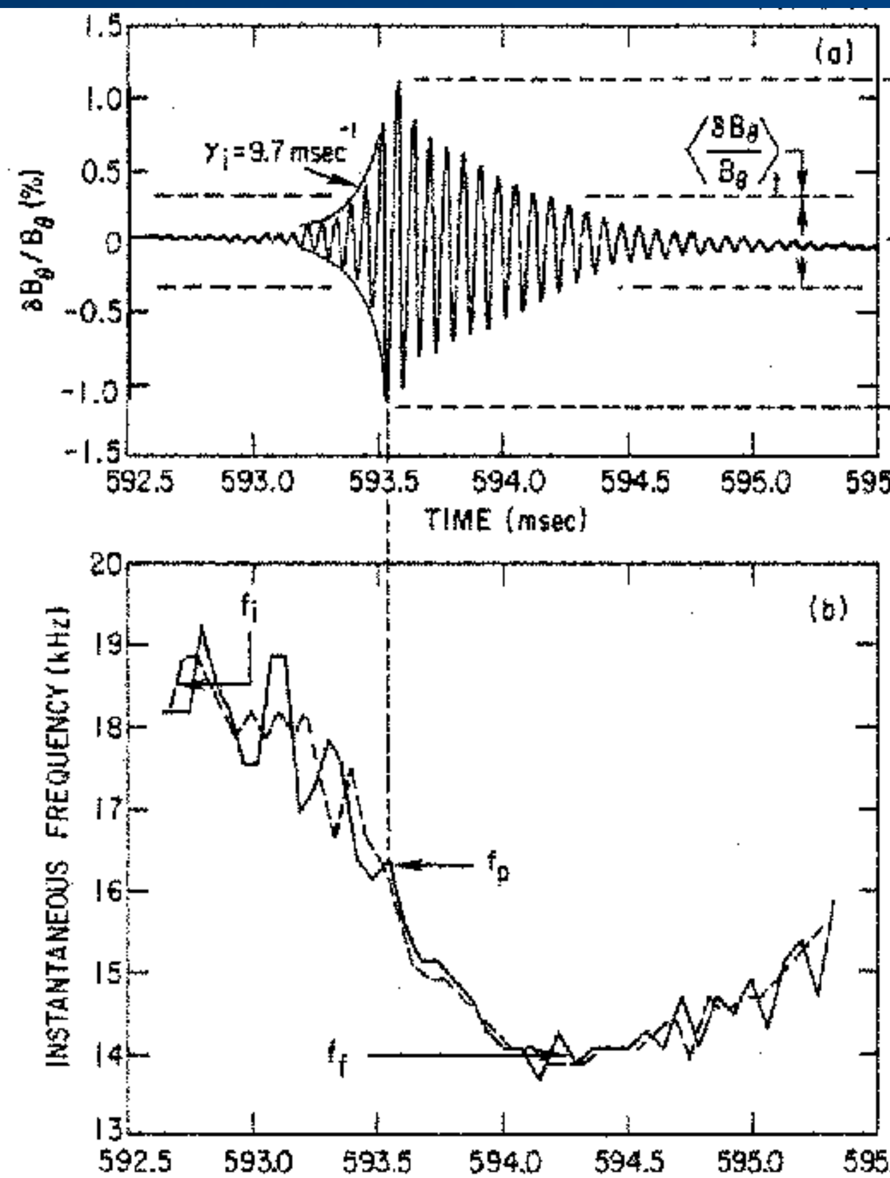




- Amplitude rises and falls—fit to exponentials
- Infer initial frequency, final frequency, and chirping rate from half-period
- Waveform distorts from a sine wave—use difference in half-period to measure distortion

Chirping like PDX; Distortion different

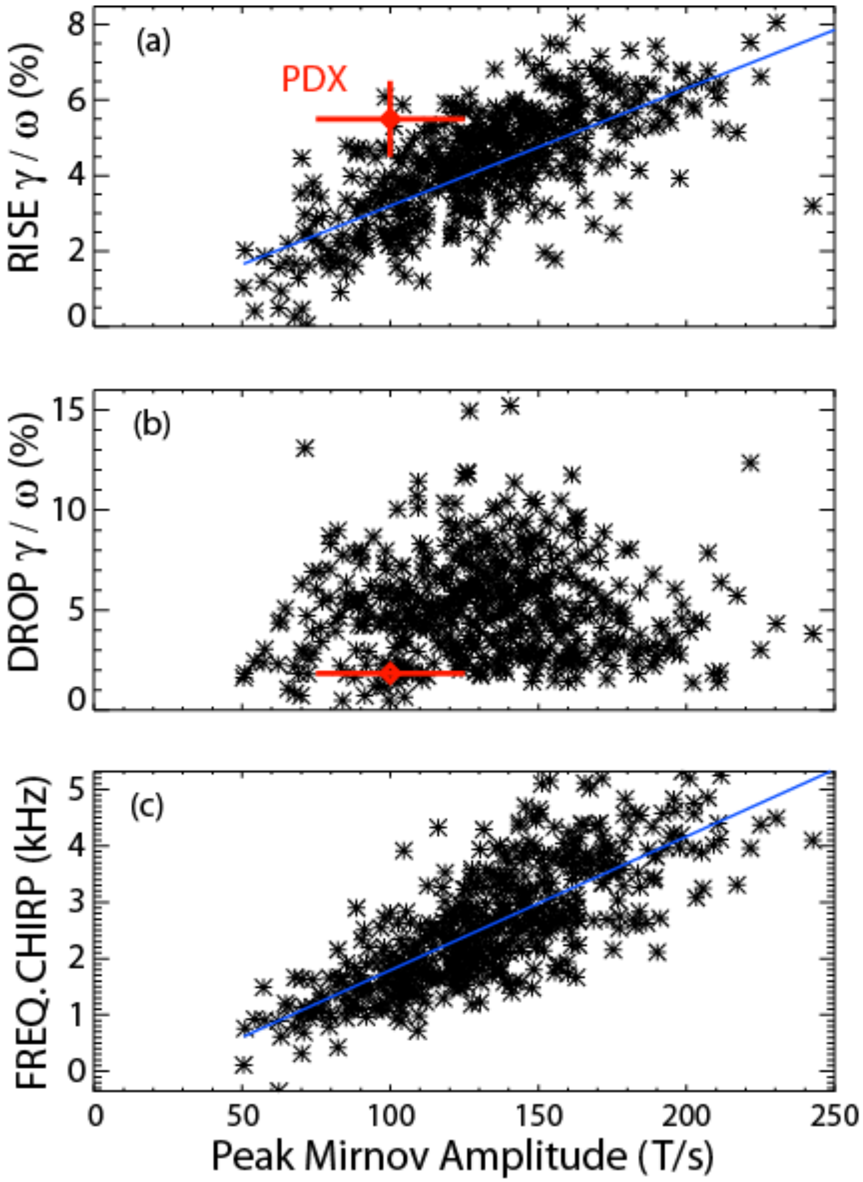




Buchenauer, Ph.D. Thesis

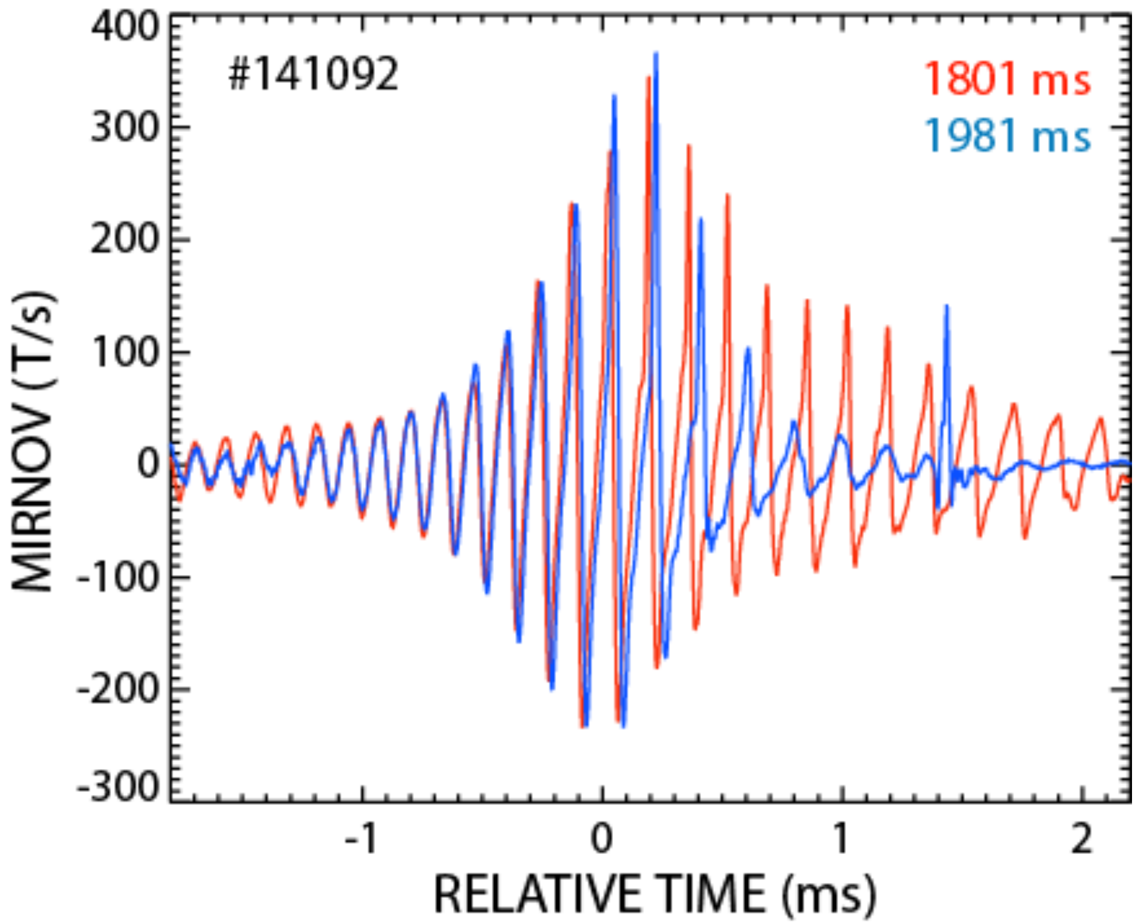
TIME (msec)

Rise like PDX; Decay different

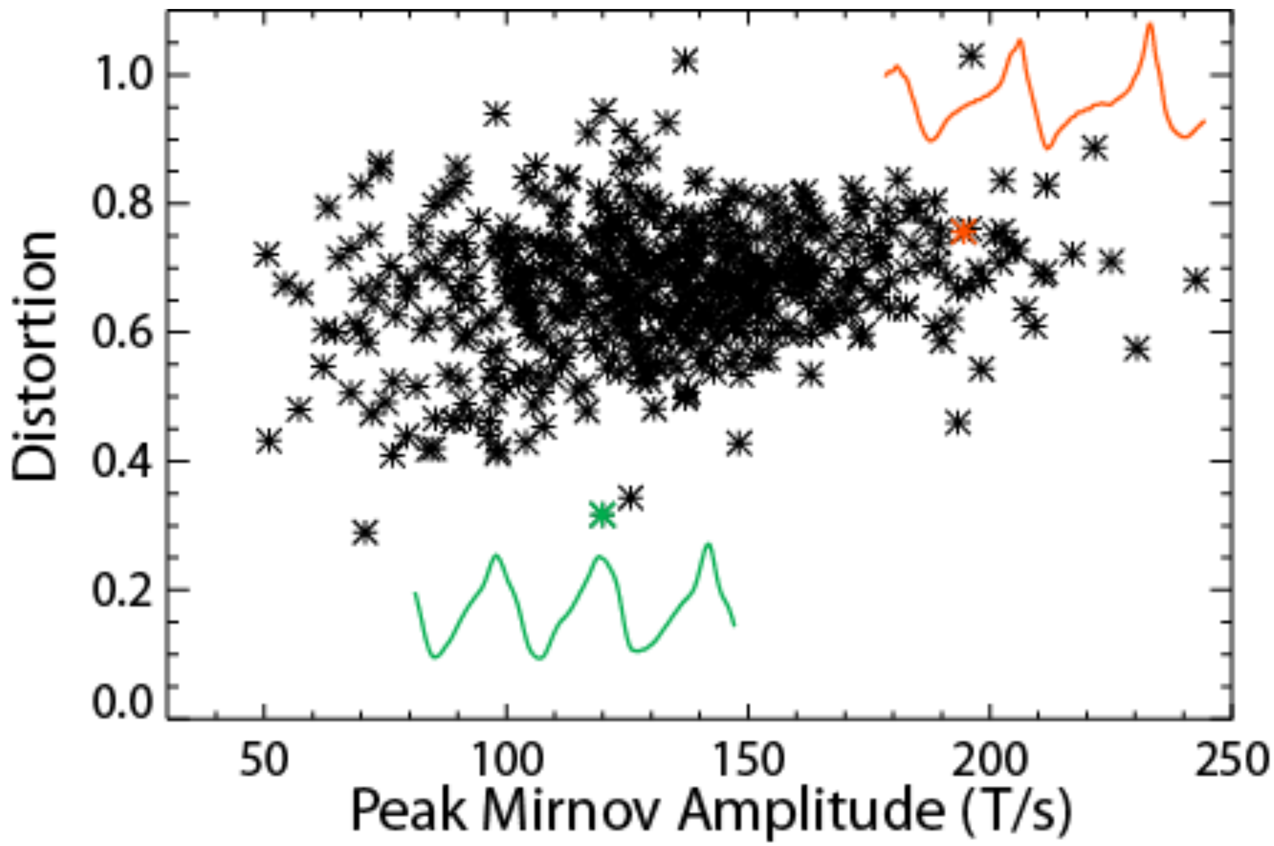


- Growth rate increases with amplitude (like PDX)
- Decay faster than PDX & far more variable
- Chirp rate increases with amplitude (like PDX)
- Fractional frequency change ~40% (like PDX)

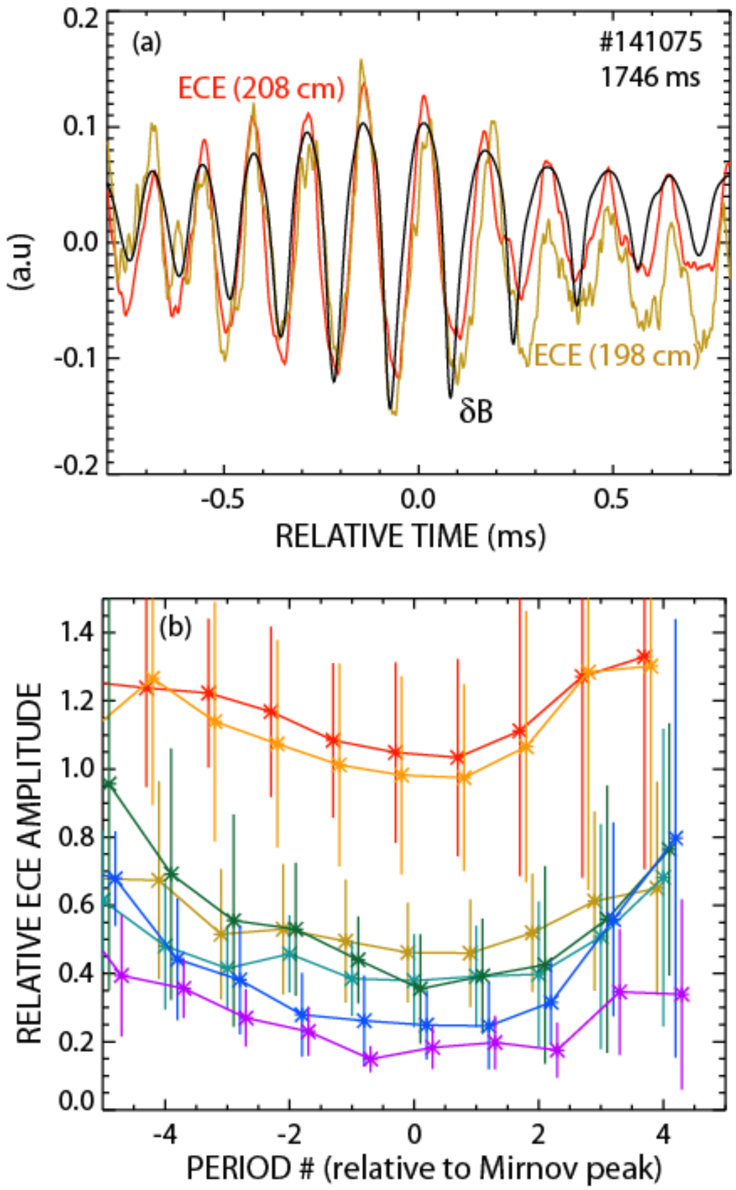
The decay phase is highly variable



All the bursts have strong distortion at peak amplitude

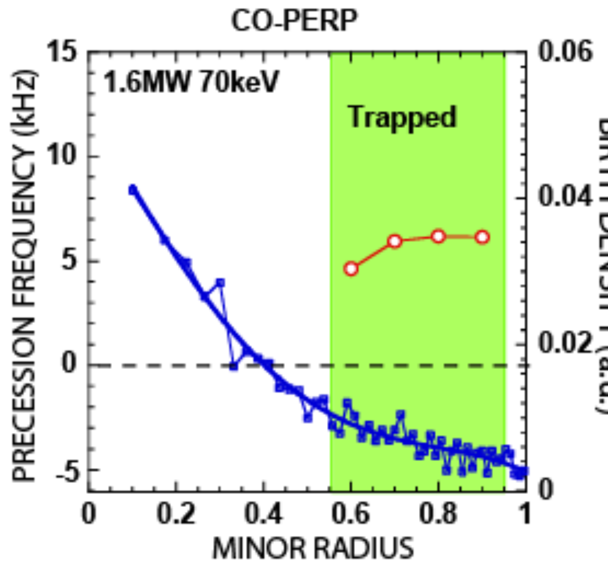


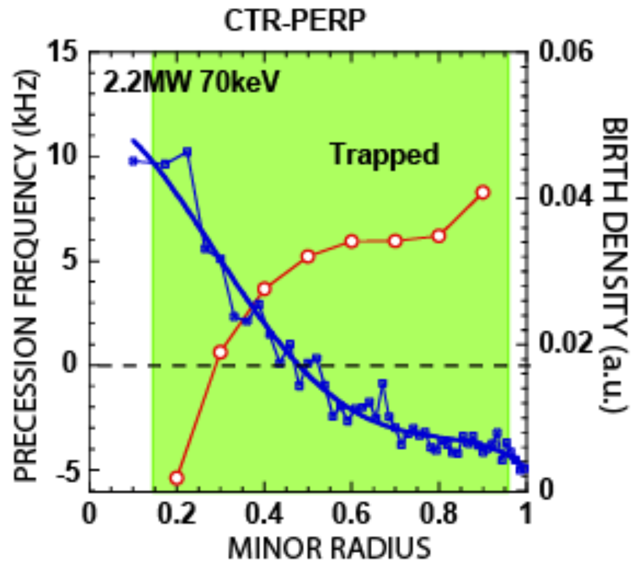
Mode structure changes during the burst

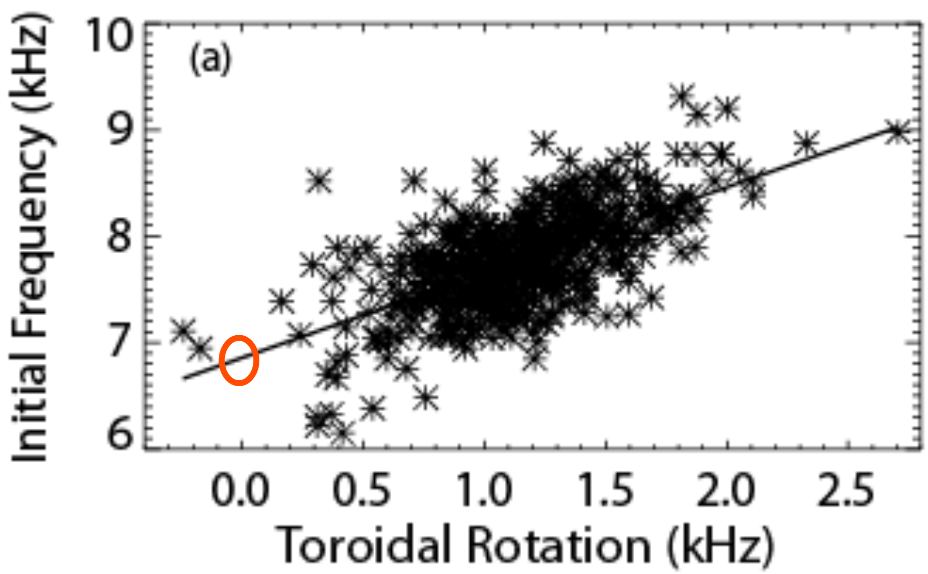


- The eigenfunction peaks near the q=2 surface
- Change in structure: Called "non-perturbative" by theorists
- Expected for an Energetic-Particle Mode

Mode frequency ~ precession frequency





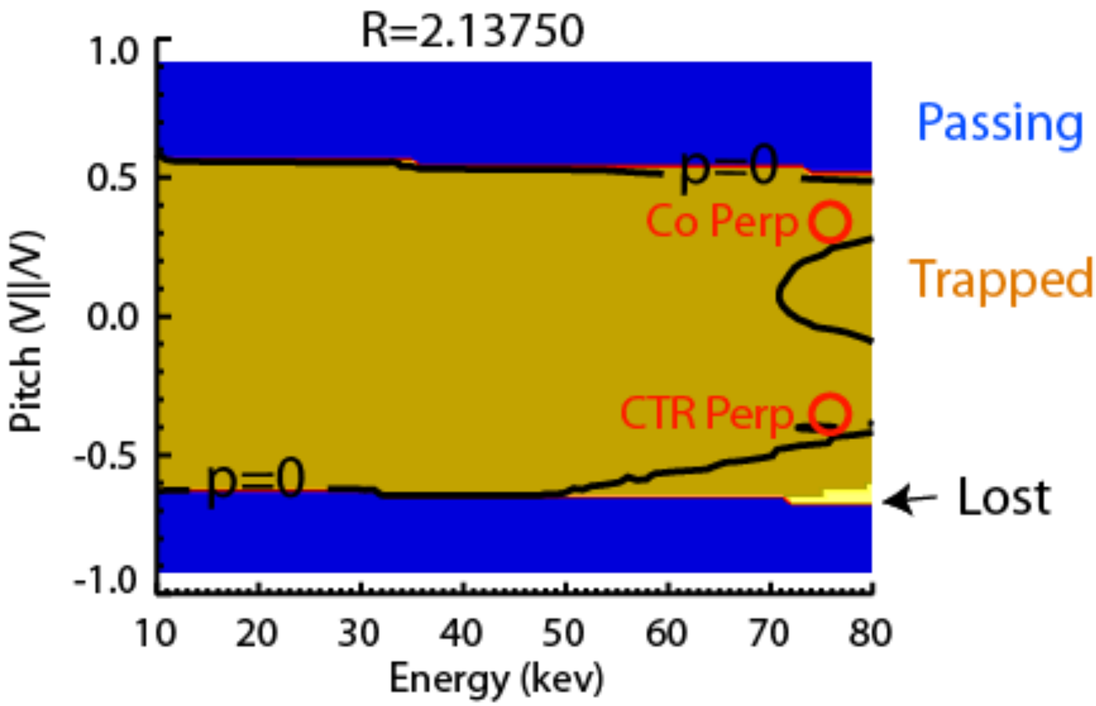


- **Rotation frequency adds to precession frequency**
- **Intercept = precession frequency**

Outline

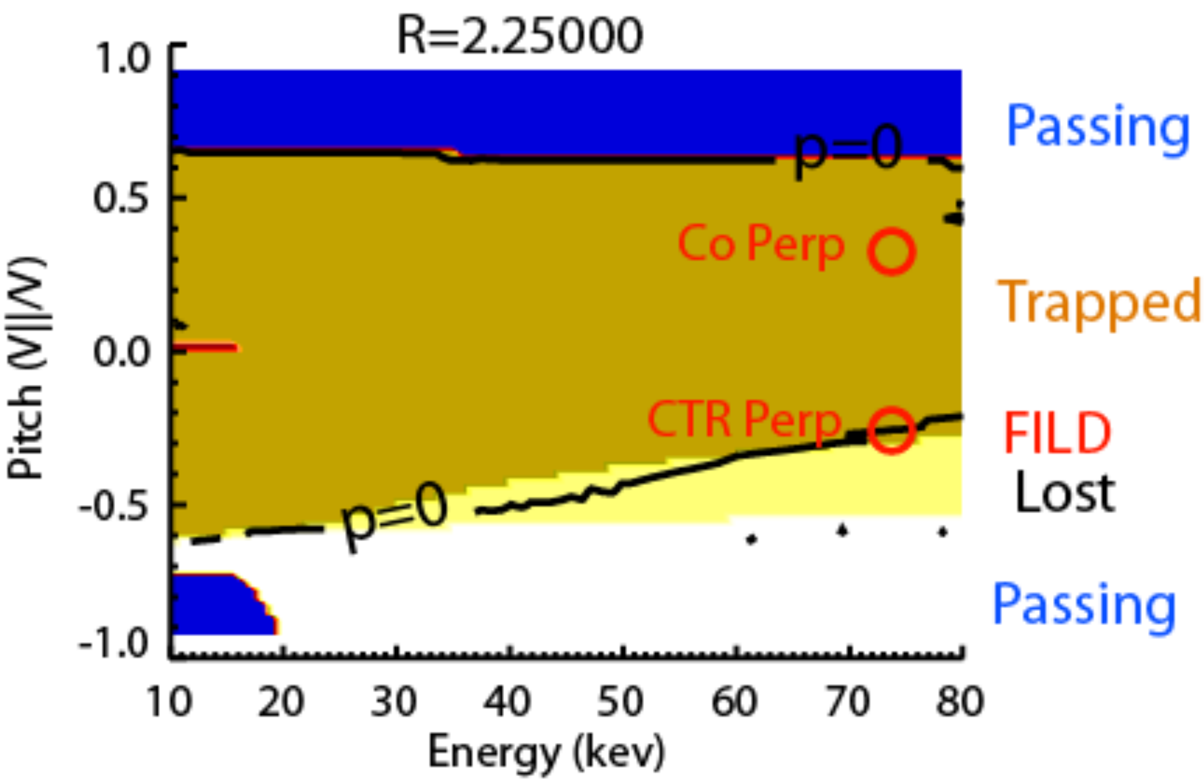
- Off-axis fishbones are energetic particle modes (analogous to PDX fishbones)
- Mode grows & chirps like PDX fishbone but decay & distortion are different
- Fast-Ion Measurements

Perpendicular beams are born near the resonant frequency



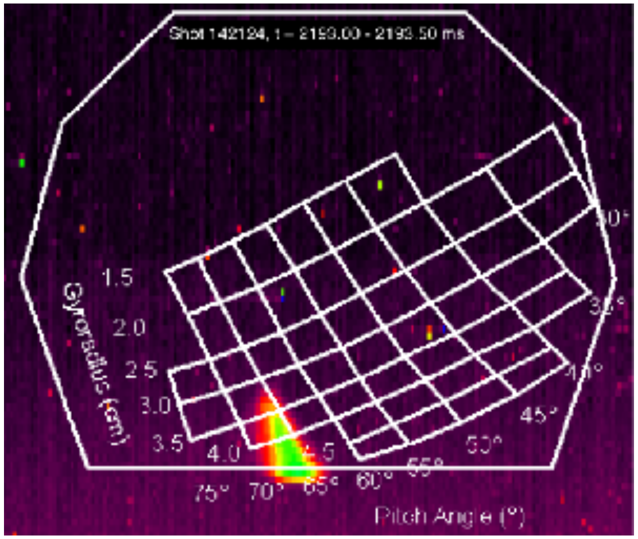
- ***The p=0 curves represent the $w=w_{pre}$ resonance***
- ***Red circles represent center of deposited ions***

Counter-perp beam ions are expelled onto the loss orbit measured by FILD



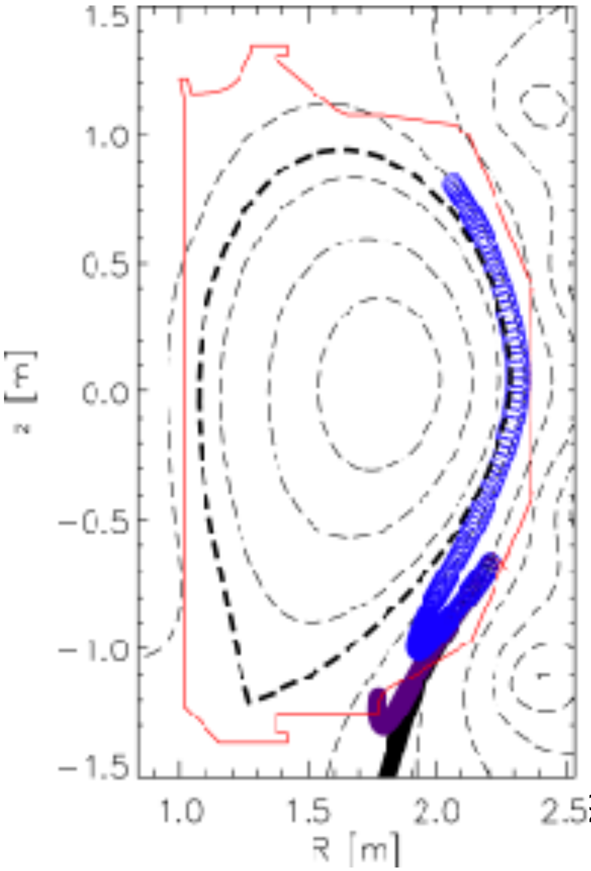
- Deposition, resonance, and measured loss orbit coincide at large major radius

Fast-ion Loss Detector (FILD) measures lost trapped ions at fishbone burst

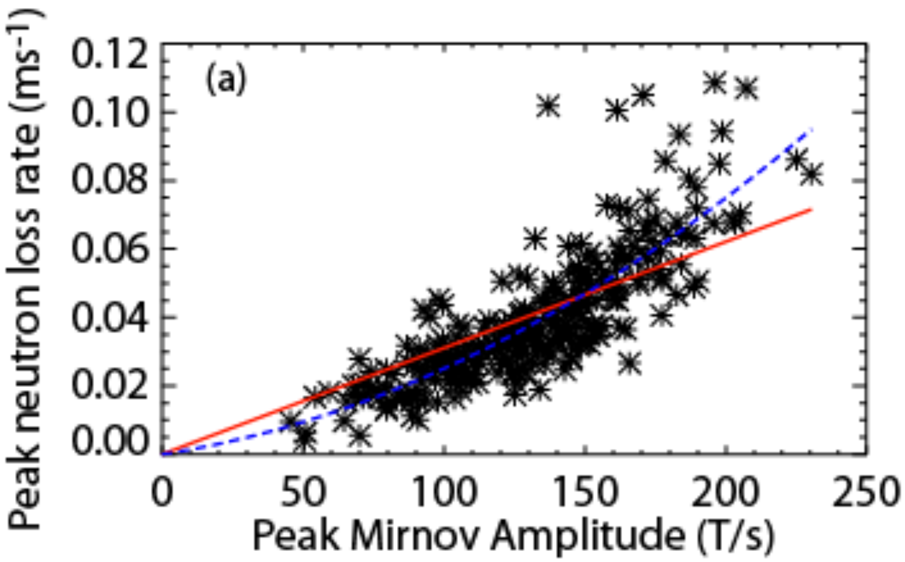


- Bright spot for ~80 keV, trapped fast ions

- Loss orbit resembles banana orbits deposited by perpendicular beams

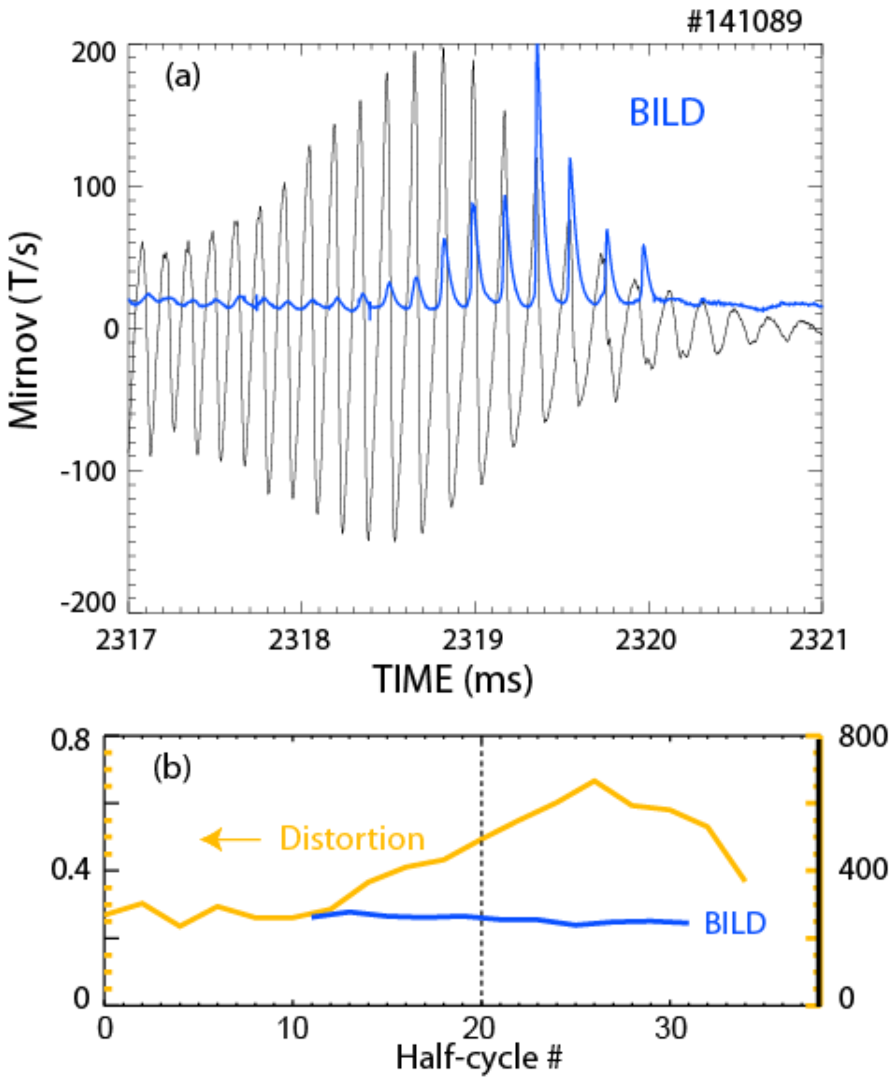


Neutron data: Losses increase with increasing mode amplitude



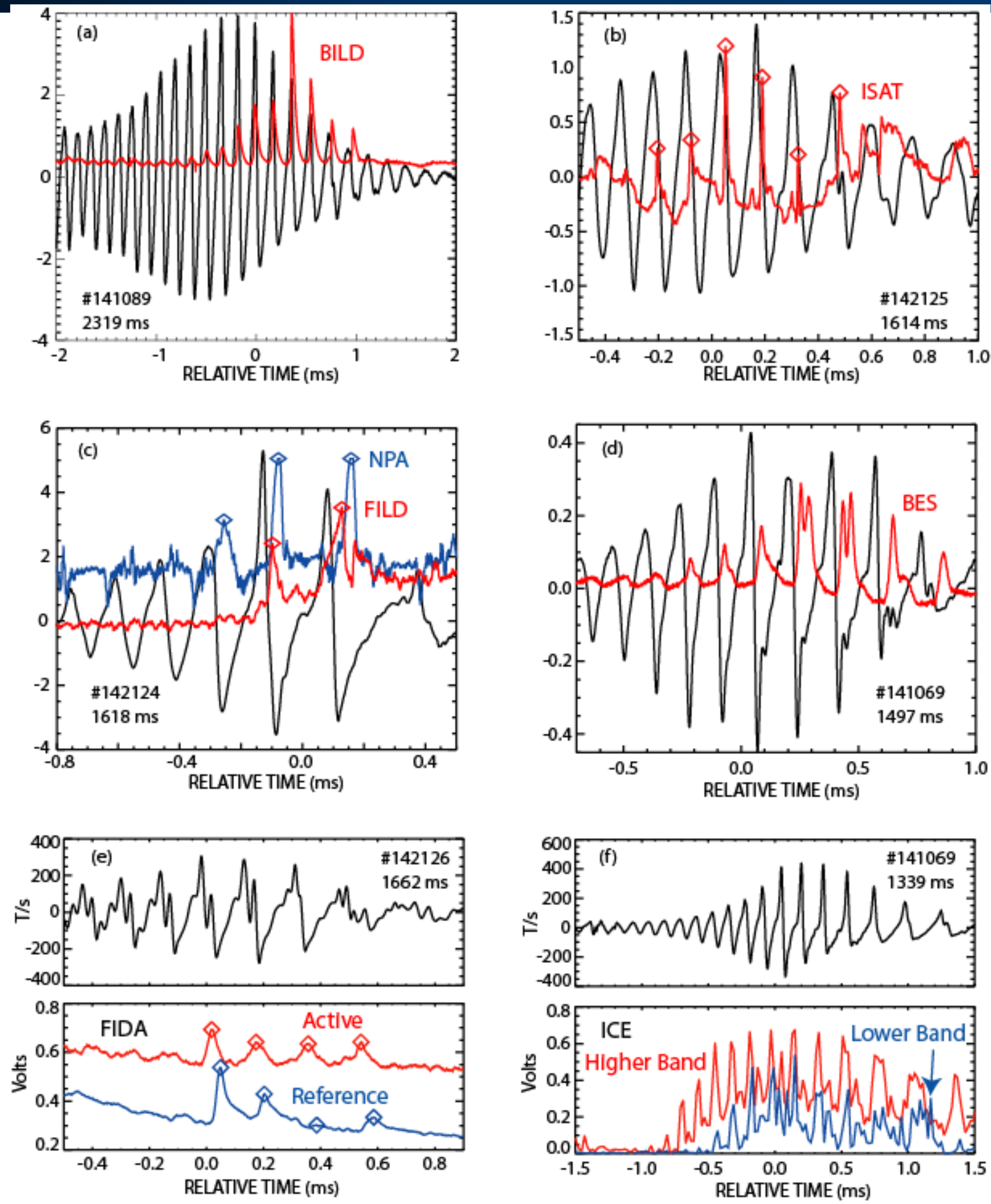
- Linear dependence predicted for convective losses (PDX fishbone)
- Like PDX, losses also scale with frequency chirp
- Peak loss occurs at time of maximum amplitude
- ~50% of trapped fast ions are lost

Losses have a definite phase relative to the mode



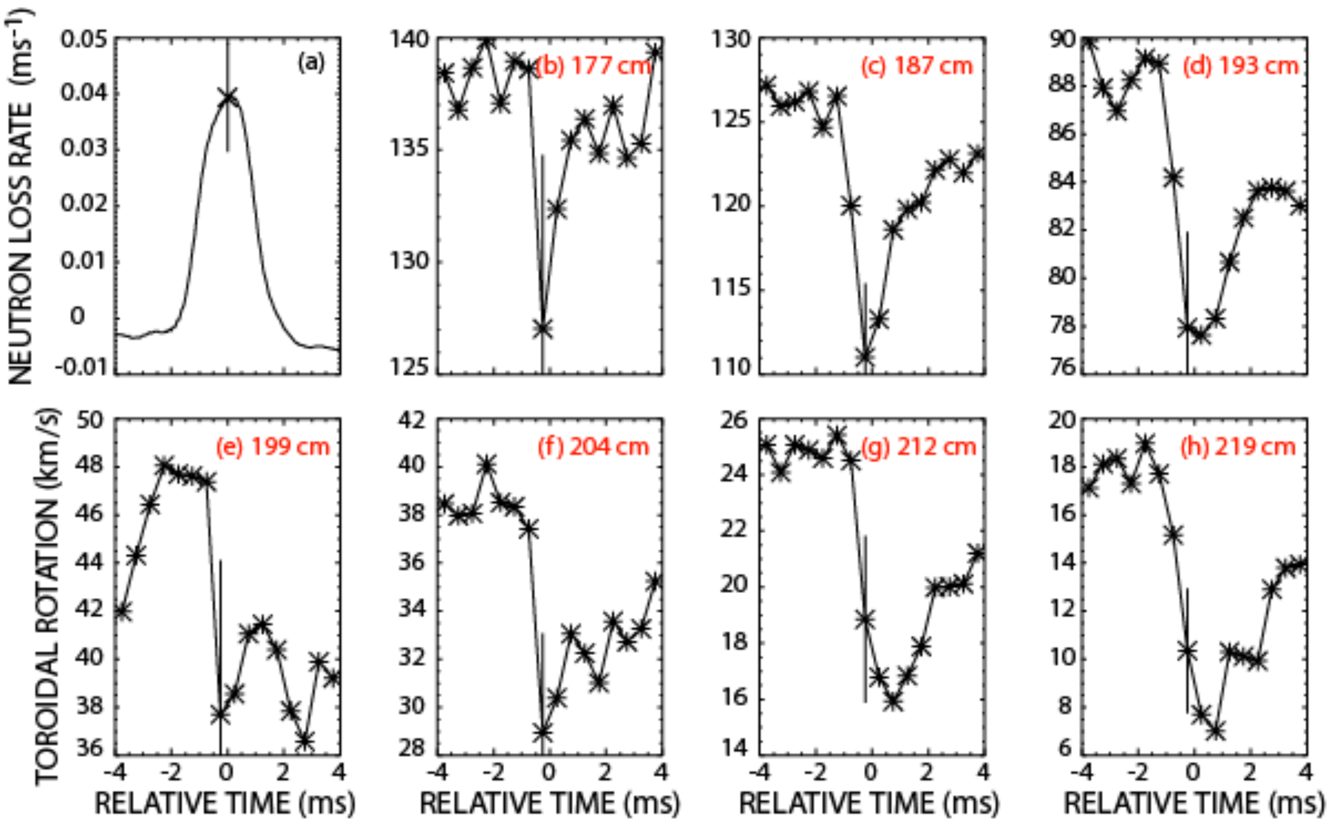
- BILD=Beam-ion Loss Detector
- Like "beacon" measured for PDX fishbones
- Probably caused by E_q x B_f convective transport (White's "mode-particle pumping" theory)

All seven loss diagnostics observe the "beacon"



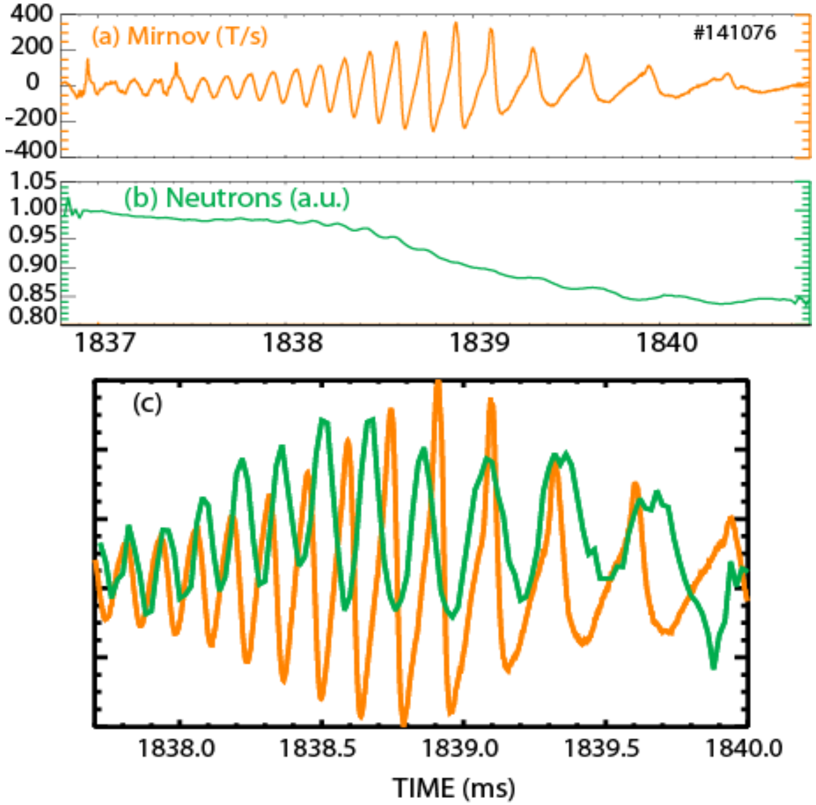
- ISAT (Langmuir probe)
- NPA (Perp neutrals)
- BES (Edge fast-ion D-alpha light)
- FIDA (edge fast-ion D-alpha light)
- ICE (ion cyclotron emission)—lost fast ions drive magnetoacoustic waves in the plasma scrapeoff

Non-ambipolar losses cause sudden drop in electric field → toroidal rotation

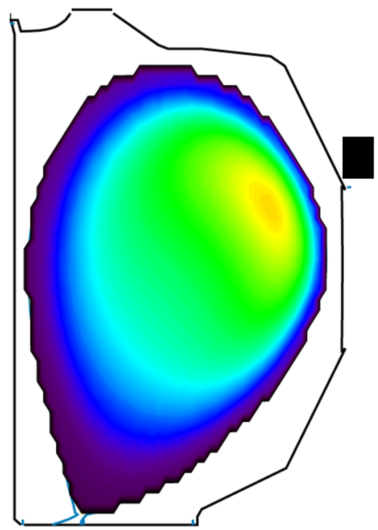


- **Conditionally average 16 similar bursts**
- **Losses act like a torque impulse—a negative beam blip** ***(deGrassie PoP 2006)***
- **Magnitude consistent with neutron drop**

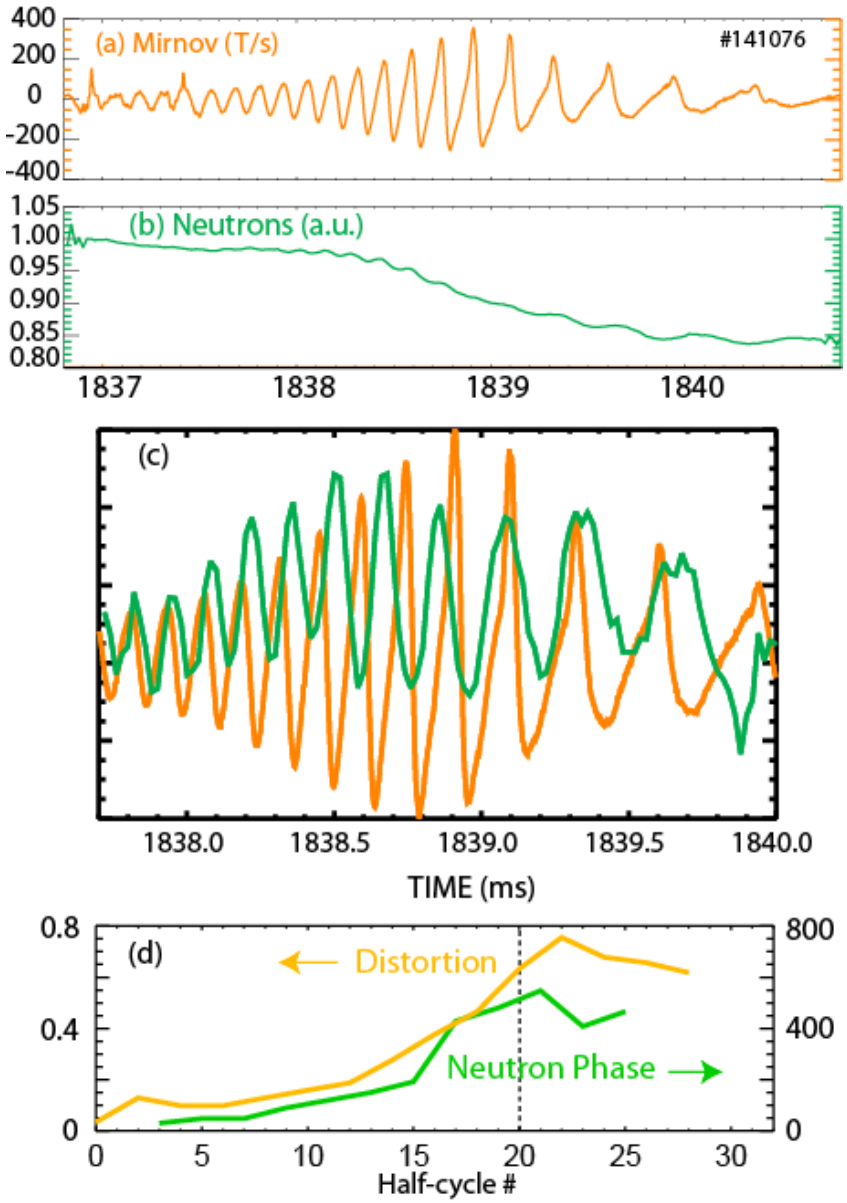
Neutrons measure internal fluctuations in fast-ion density



- Fluctuations caused by motion of confined fast ions relative to scintillator



Phase of neutron oscillations slips relative to mode

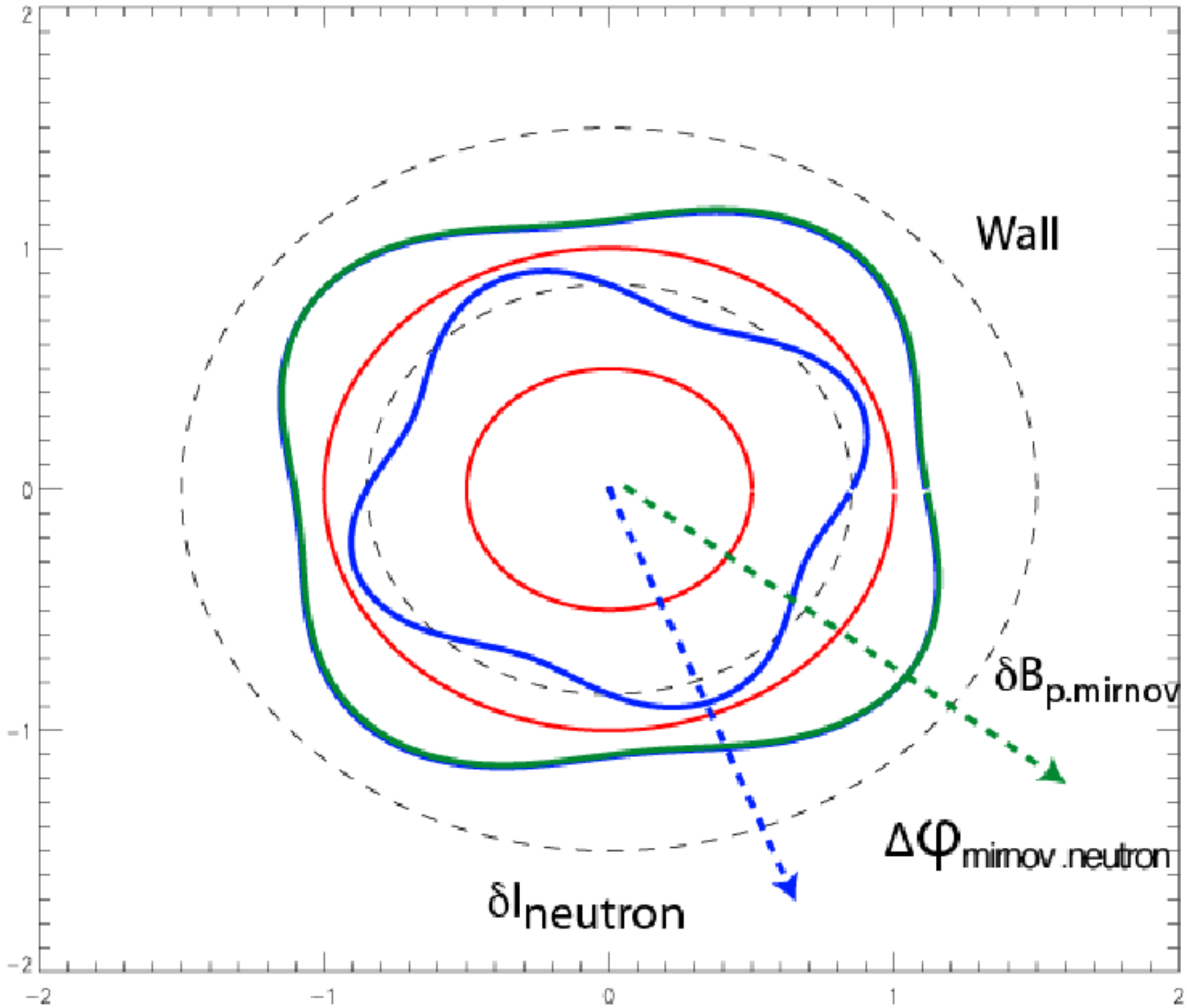


- Fluctuations caused by motion of confined fast ions relative to scintillator
- Detrend neutron signal to observe oscillations clearly
- Initially fast ions oscillate with mode
- Phase slips over 360°
- No slip in internal fluctuations

Comparison with PDX Fishbones

Off-axis	PDX
f_{pre} resonance	f_{pre} resonance
Df/f ~ 40%	Df/f ~ 40%
Growth g/w ˜ 5%	Growth g/w ˜ 5%
Decay faster & variable	Decay slower
Predator-prey burst cycle	Predator-prey burst cycle
Losses in "beacon"	Losses in "beacon"
Losses ~ linear w/ B_{max}	Losses ~ linear w/ B_{max}
Loss rate ~ chirp rate	Loss rate ~ chirp rate
Strong distortion of wave	Weak distortion of wave
Neutron phase slip	Constant neutron phase

Two obvious differences: external/internal & single/multiple sources



- Off-axis fishbones could drag on wall
- PDX fishbones had one angle of injection (greater anisotropy in velocity space) → whole population stays in phase?

Conclusion

- Off-axis fishbones have many similarities to PDX fishbones
- They probably are an EPM branch of the external kink
- The mode distortion, decay phase and neutron phase slip differ markedly from PDX fishbones (and other chirping modes)
- Unusual nonlinear evolution is an interesting challenge for theory

Two types of comparison with theory

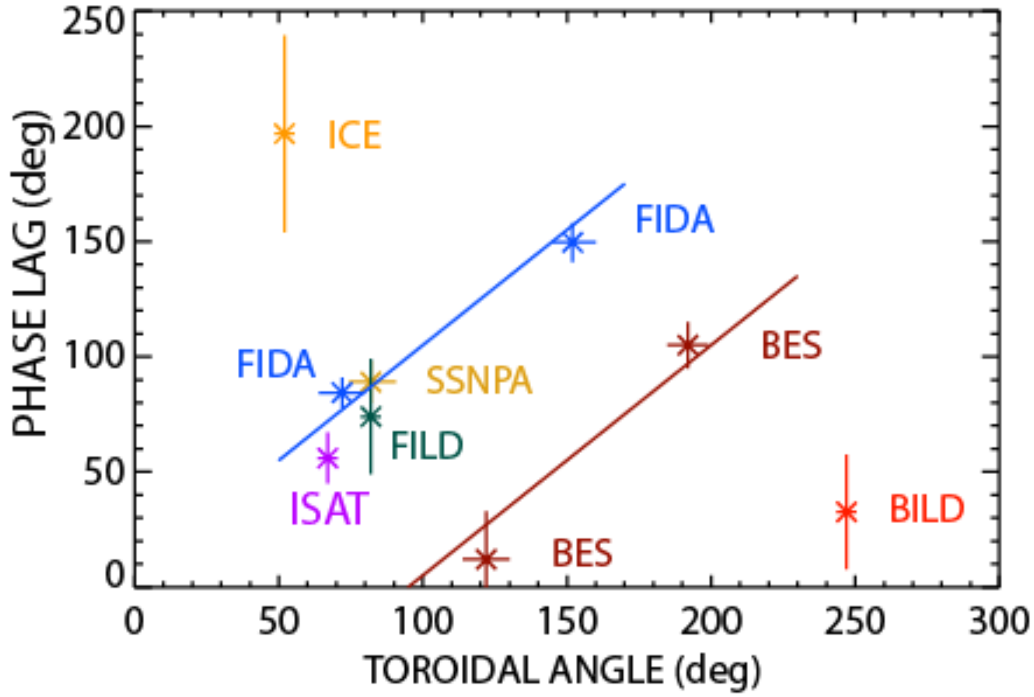
Wave-Particle Consistency Check

- Model instability by matching to fluctuation data
- Calculate effect on fast-ion distribution function with an orbit-following code
- Compare predicted distribution with fast-ion data

Complete Predictive Modeling

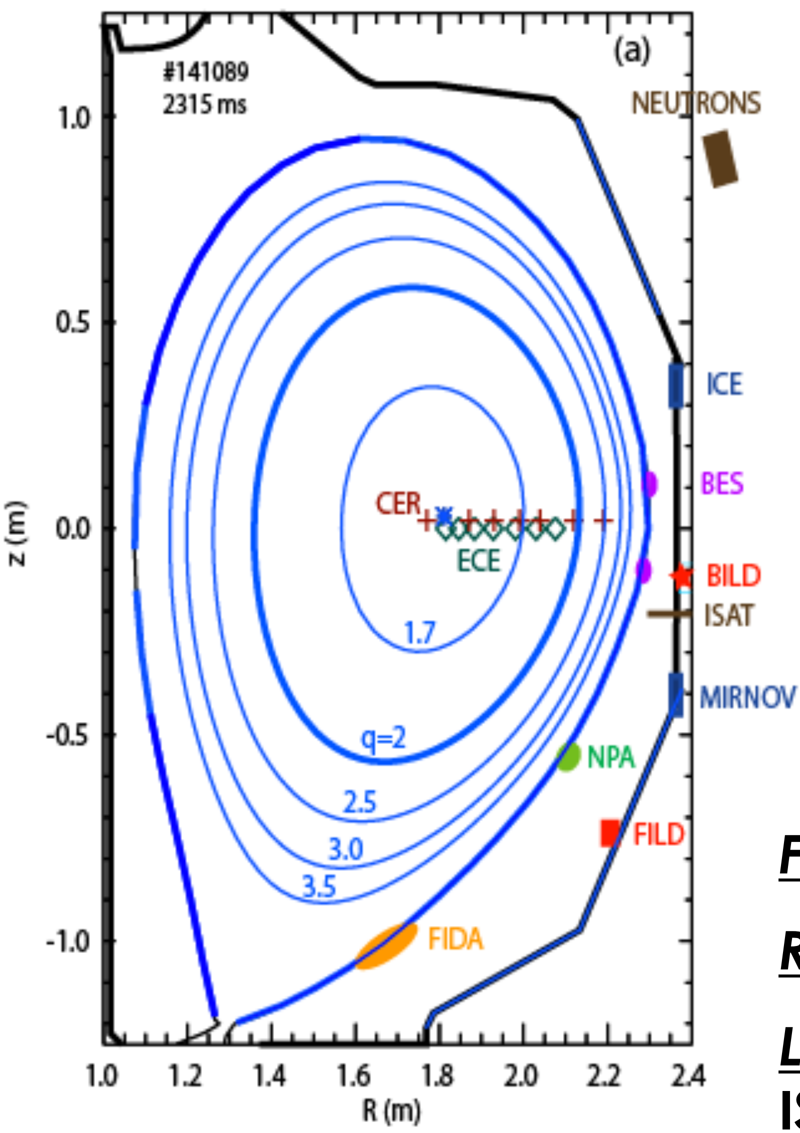
- Compute full nonlinear evolution of instability & fast-ion response self-consistently

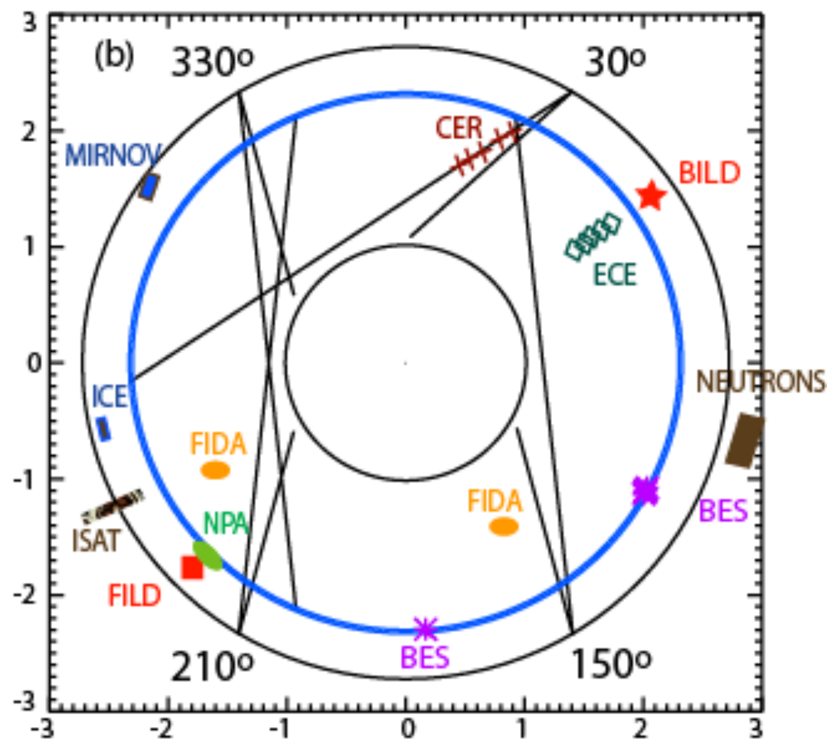
The phase of the "beacon" differs for different loss diagnostics



- The phase is fixed (relative to the mode) for every diagnostic
- Diagnostics that measure the same quantity have the expected n=1 toroidal phase shift
- Different diagnostics measure different part of bounce motion → different phase
- Same effect on PDX

Many instruments diagnose the instability



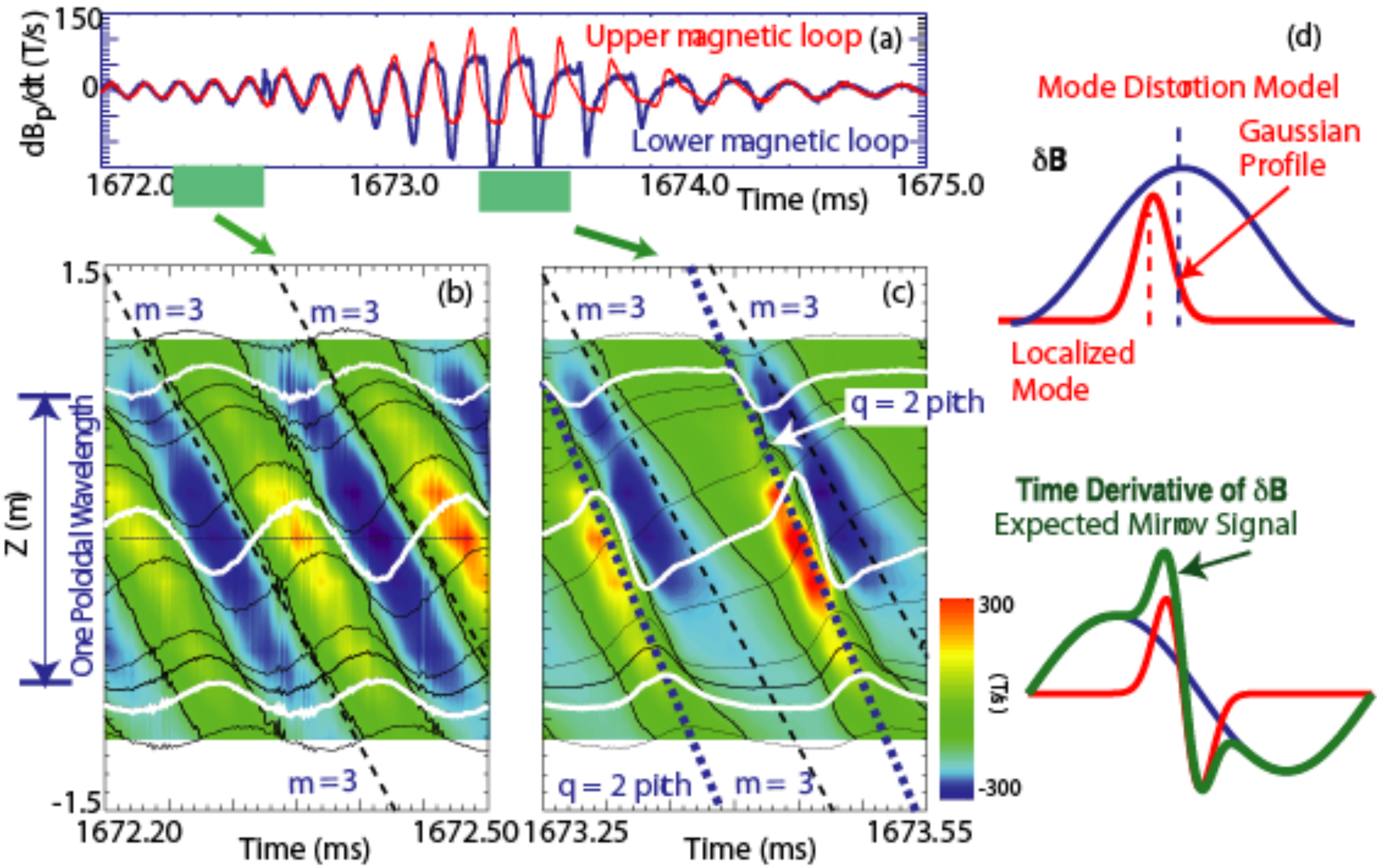


Fluctuations: **Mirnov, ECE**

Rotation: **CER**

Losses: **BILD, FILD, NPA, BES, FIDA, ICE, ISAT**

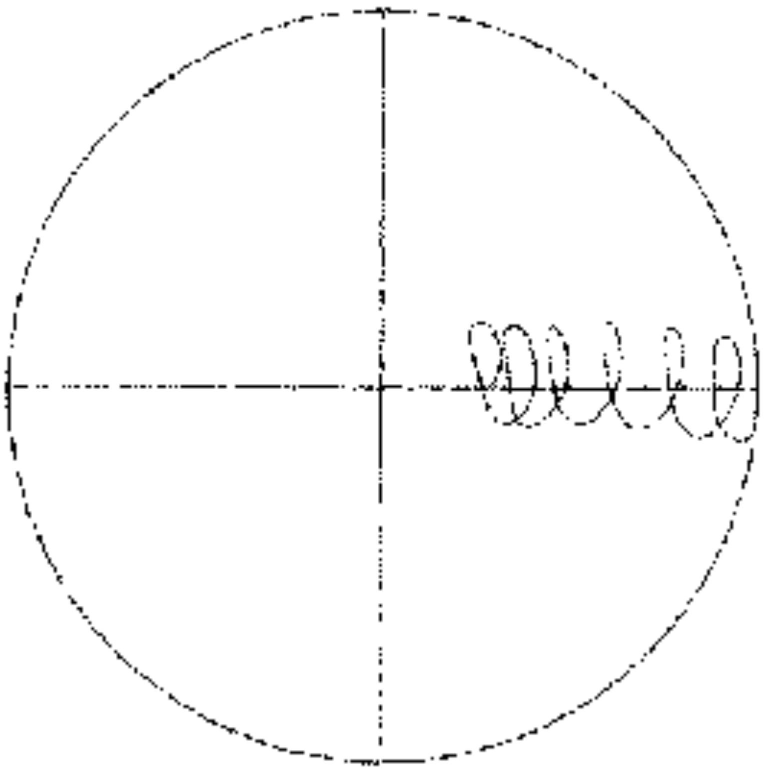
Poloidal Mirnov data→ distortion has q=2 pitch



Okabayashi, PoP (2011)

Resonance at the precession frequency determines the type of loss orbit

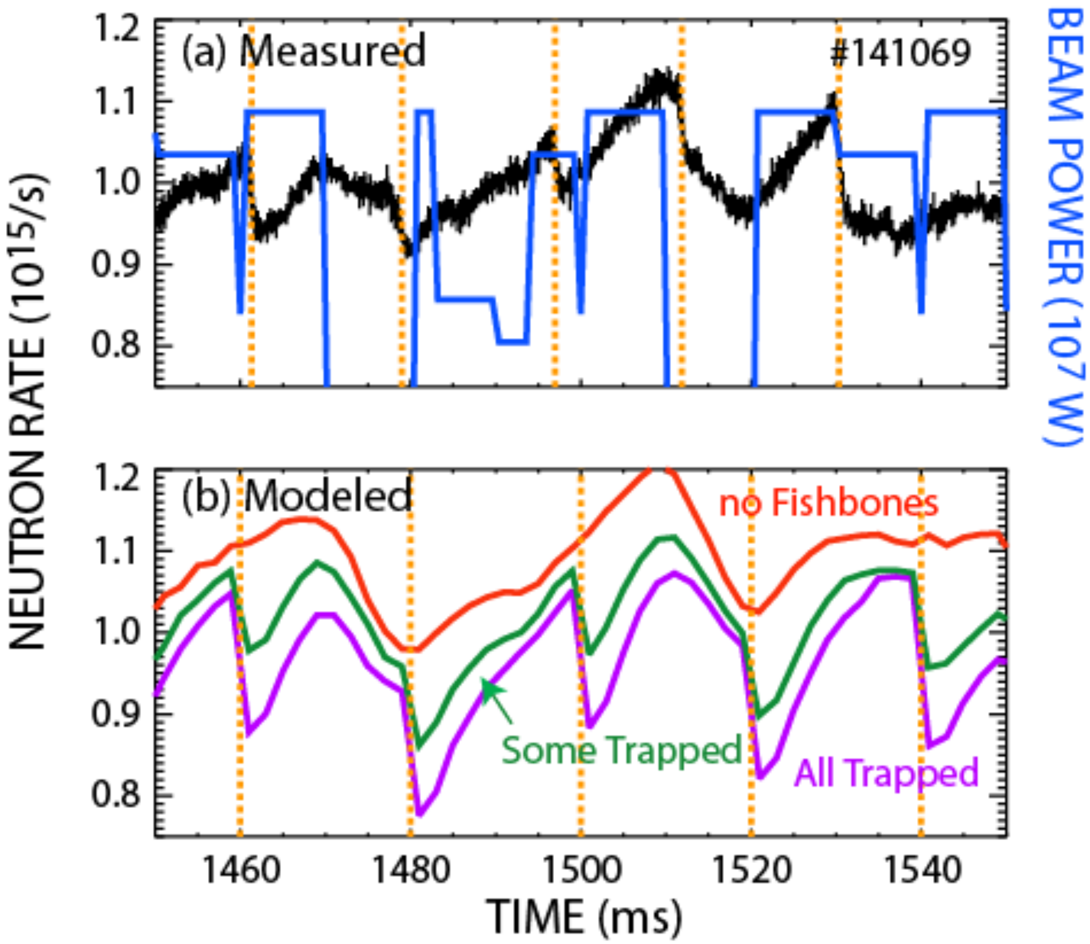
Calculated Fishbone Loss Orbit



White, Phys. Fluids (1983)

- The mode extracts energy from the fast ions → fast-ion energy decreases
- Low frequency → 1st & 2nd adiabatic invariants are conserved
- μ conservation → particle must move out (to lower B)
- Main loss mechanism: convective E x B radial transport

Approximately 50% of the trapped fast ions are lost at a burst



- Use TRANSP code to predict neutron rate
- Most reactions are "beam-plasma"
- Expelling all trapped fast ions at each burst overestimates neutron drop