The Role of Shaping in the Sawtooth Instability

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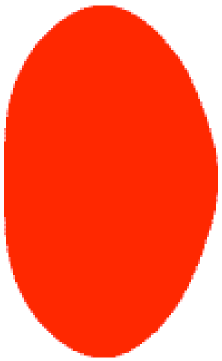

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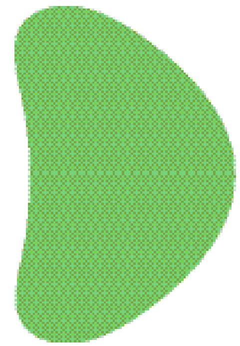

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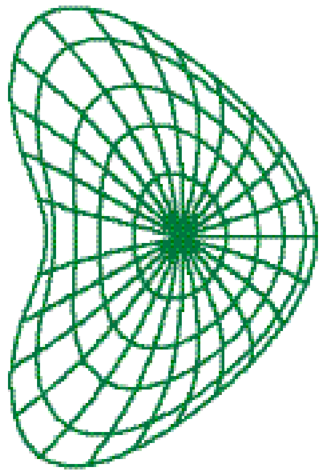
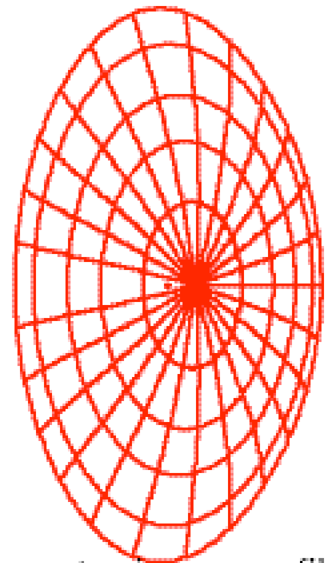
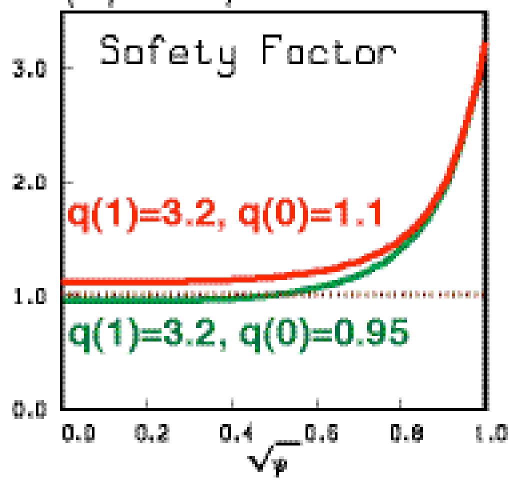
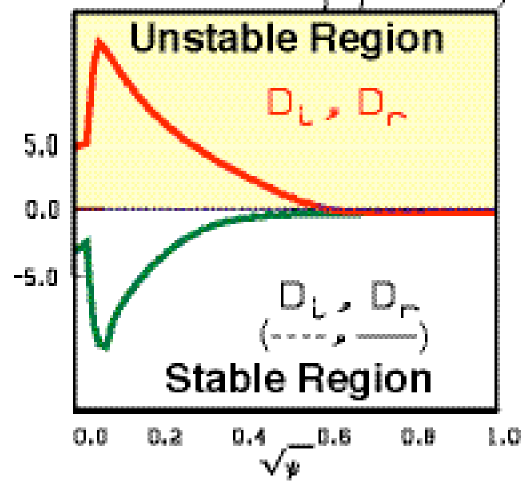
Core Stability of Bean and Oval Shapes





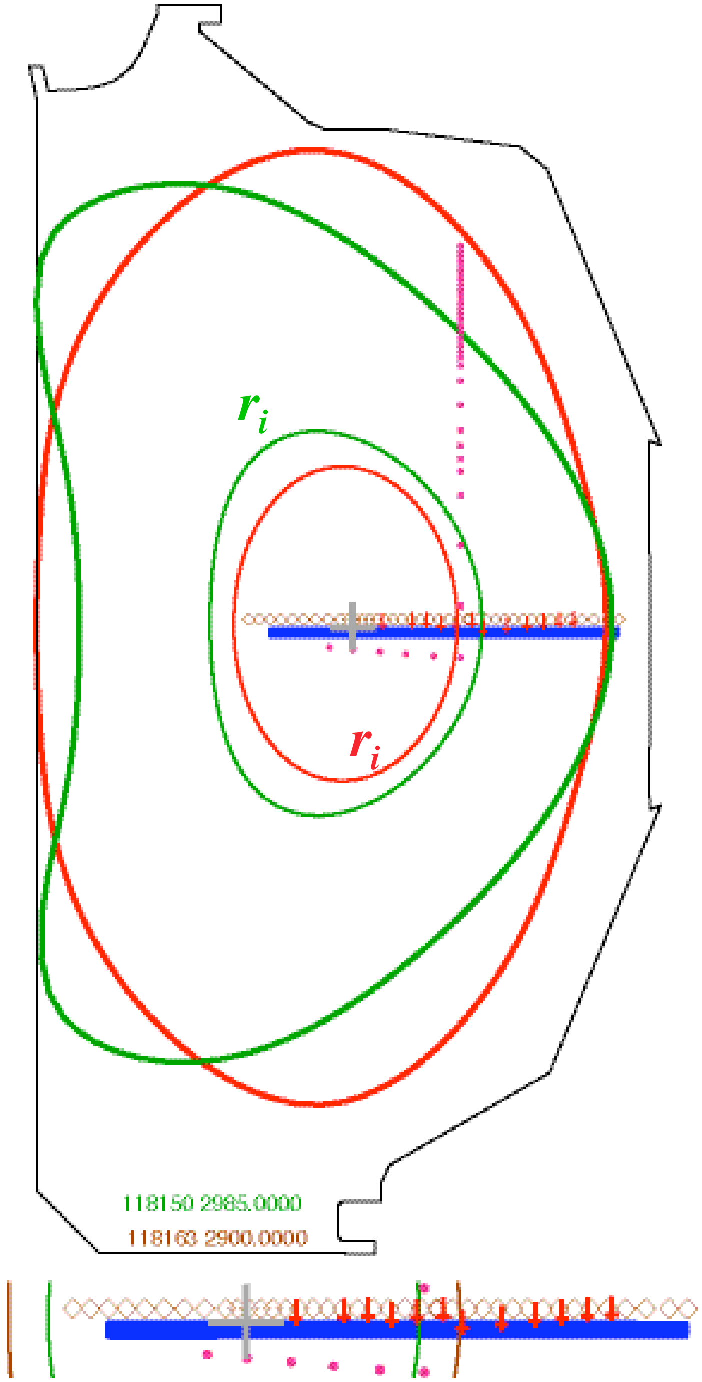
(D_l & D_r are essentially the same for monatonic q profiles.)





Shaping can move the interchange stablity boundary (Mercier Criterion) across q=1, separating the role of interchange and internal kink instabilities in the sawtooth collapse.

Plasma boundary shape and shape at sawtooth inversion radius

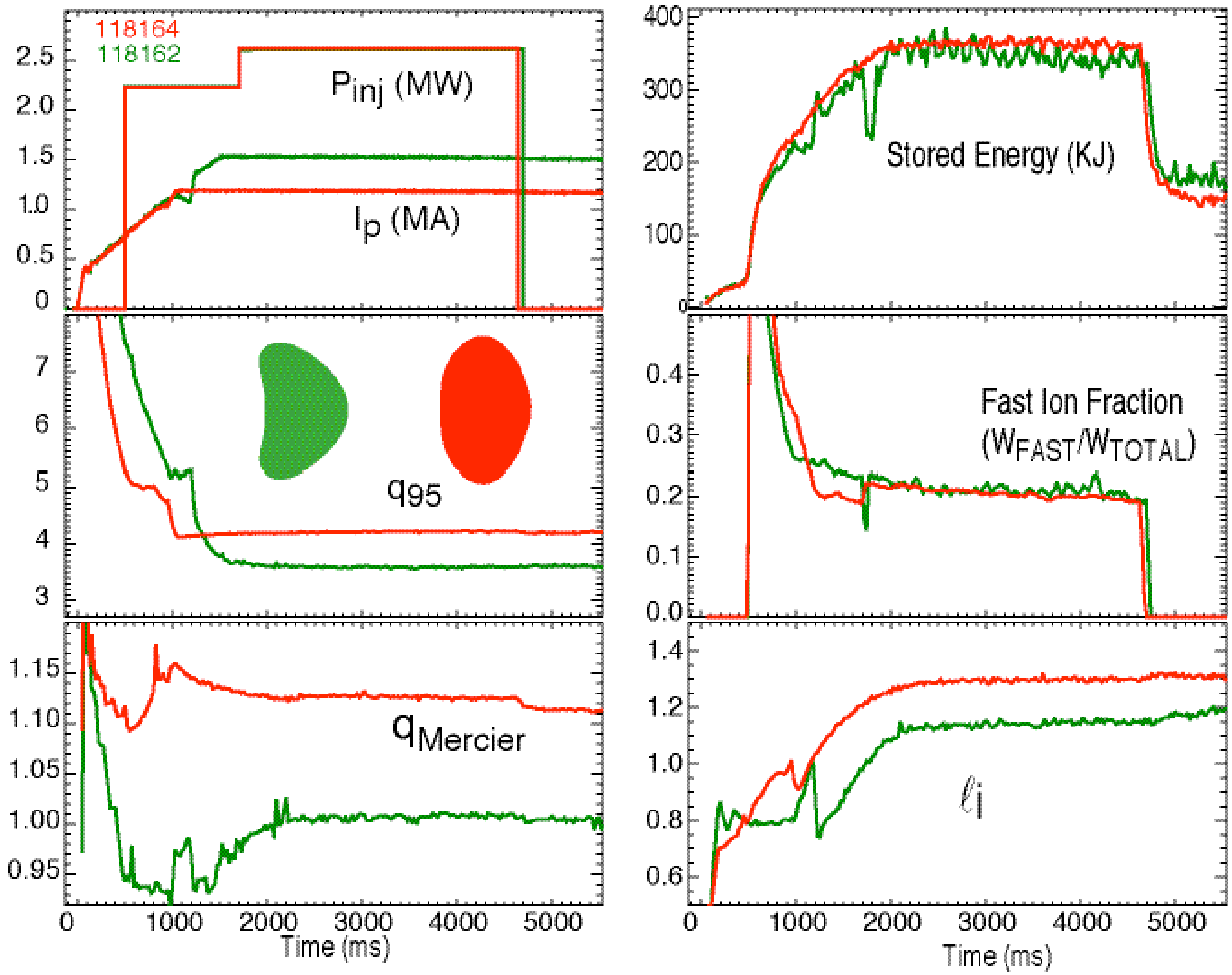


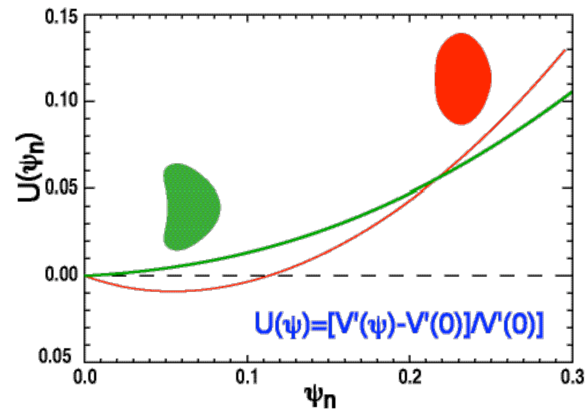
Principal Diagnostics:

The magenta solid circles are Thomson Scattering (n_e, T_e). The upside-down red daggers are CER (T_i) locations. The blue bar is the MSE (B_Z/B_T) range of locations. The brown diamonds are ECE (T_e) locations.

Discharge Evolution

We always use an early beam and grow the plasma as the current rises to promote early sawteeth. Two levels of plasma current have been used in each shape.





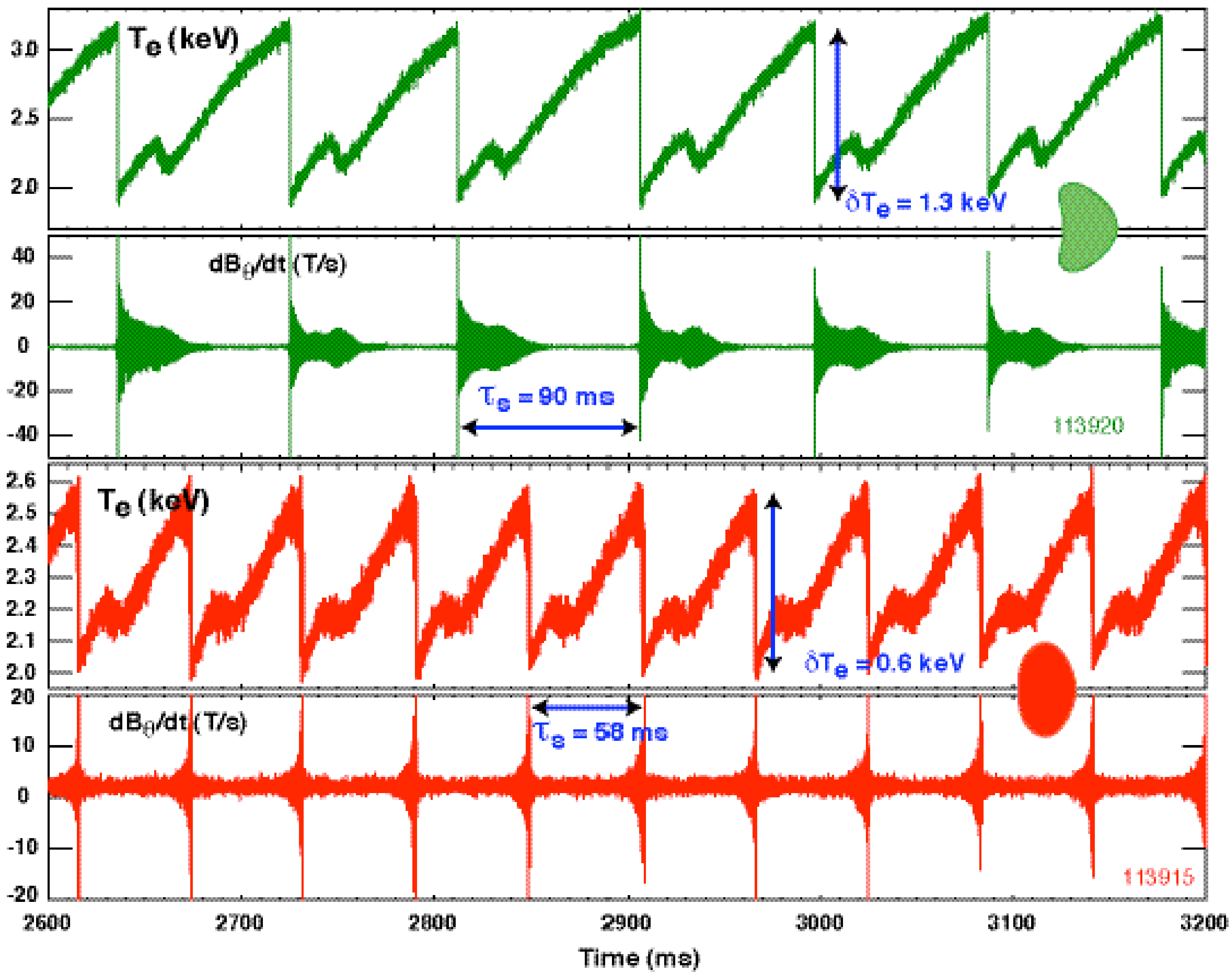
Resulting beans have a central magnetic <u>well</u>. The ovals have a central magnetic <u>hill</u>.

Some Plasma Parameters

Parameters of Interest				
	bean 1	bean 2	oval 1	oval 2
Shot	113920	118162	113915	118164
I_P (MA)	1.38	1.52	0.88	1.18
B_T (T)	1.79	1.85	1.80	1.85
V (m^3)	17.5	17.6	20.1	20.1
$<n_e>$ ($x10^{19}$ $m^{3)}$	2.0	2.5	1.9	2.75
β_P	0.22	0.24	0.45	0.38
β_{P1}	0.16	0.19	0.41	0.33
ℓ_i	1.24	1.15	1.41	1.29
W^{mhd} (MJ)	0.25	0.34	0.24	0.37
τ^*_e (ms), τ^{th}_e (ms)	93	127, 75	90	140, 75
τ_S (ms)	90	154	59	80
q_{95}	3.9	3.6	5.4	4.2
r_i (normalized inversion radius)	0.38	0.44	0.28	0.35
W^{fast}/W^{mhd}	0.27	0.13	0.25	0.11
reconnection δB_θ (G)	219	293	85	129

In the bean plasma current is limited by coil current limits. In the oval the limitation is our requirement that the two plasmas are made with the same poloidal power supply configuration so that the shape can be switched on a shot-to-shot basis. This allows us to minimize systematic errors.

The Sawteeth - In Beans and Ovals



Outline

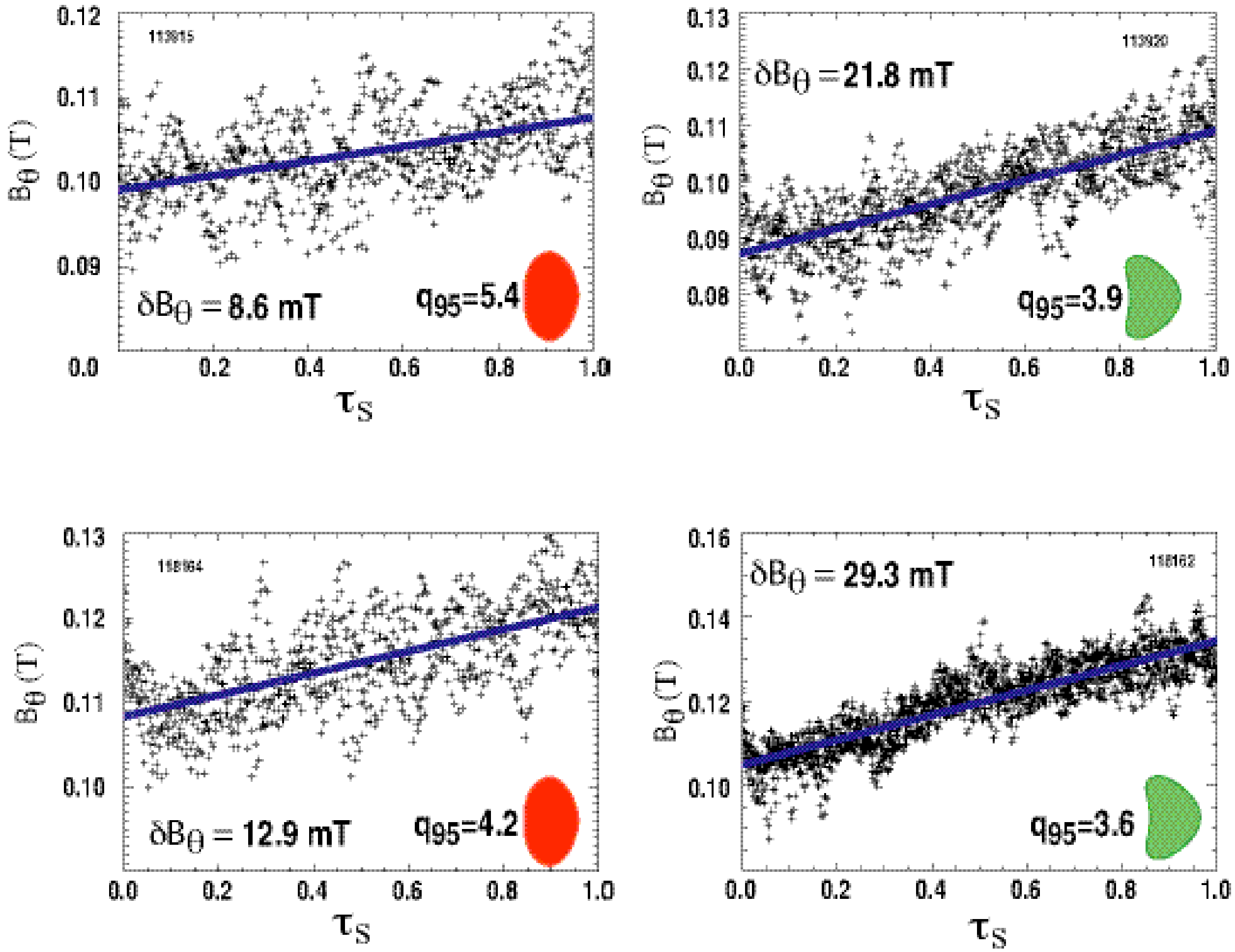
The Crash

1. ideal or resistive
2. interchange or kink

The Sawtooth Ramp

1. equilibrium evolution
2. ion behavior
3. transport rates
4. response to ECH

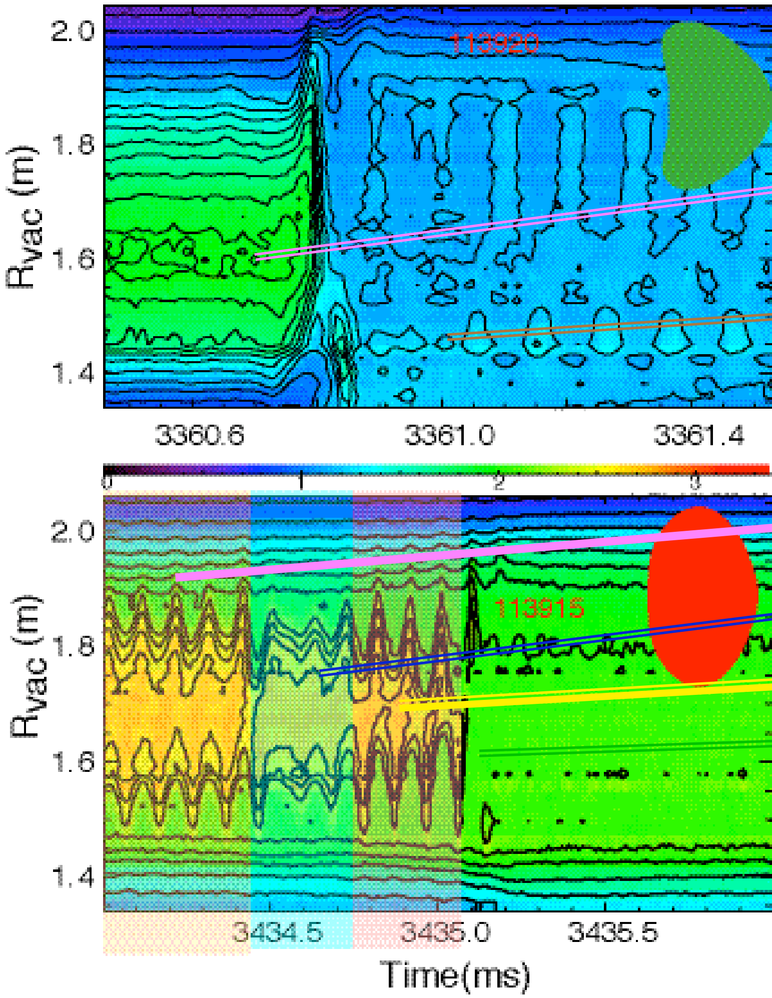
Reconnection - average over 7 sawteeth and do a linear fit. Reconnection larger in beans.



Chose MSE channel with largest change. Reconnection is seen as an identifiable event in the MSE signal in the bean, but not in the oval.

Results inside/outside magnetic axis differ only a few percent.

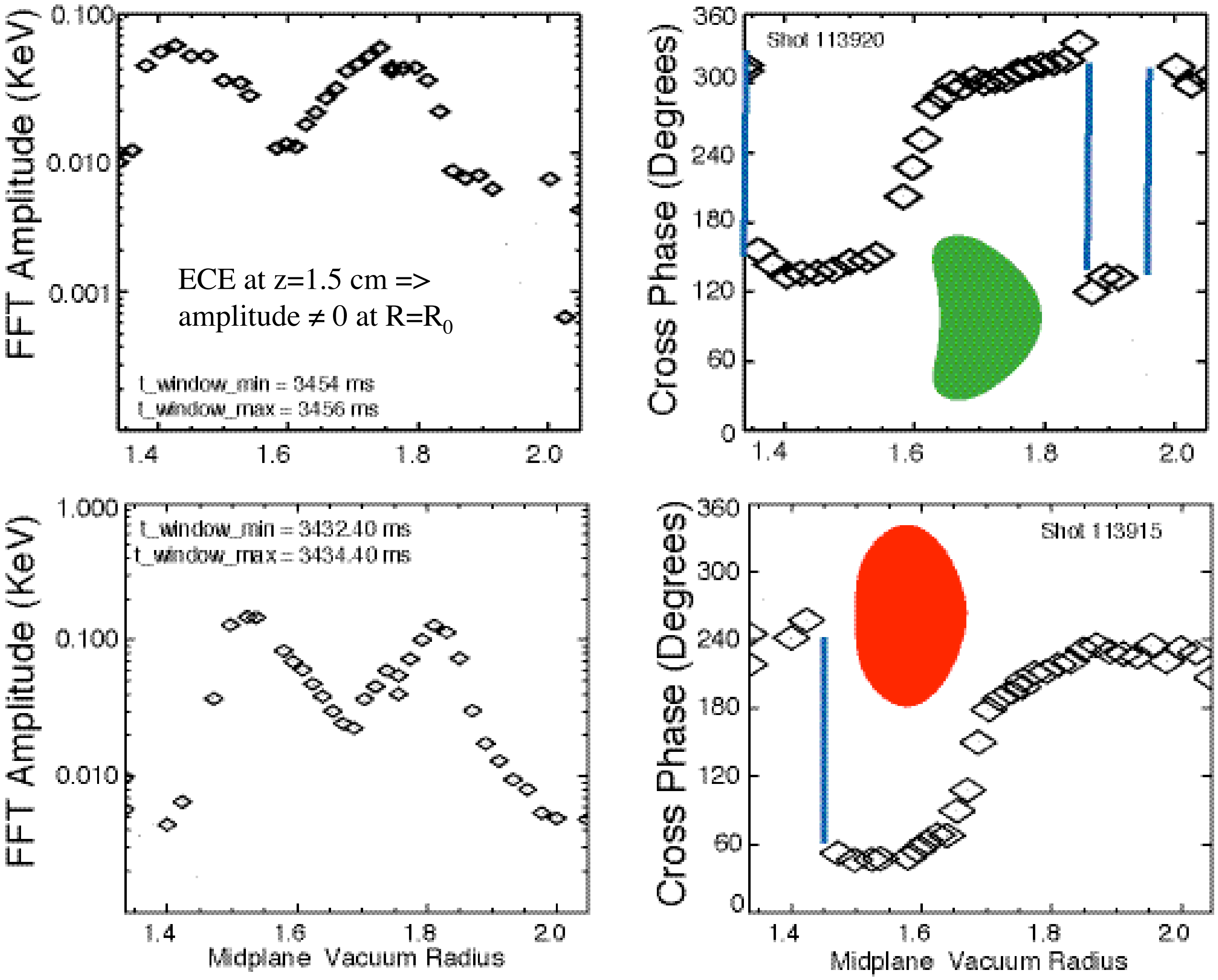
The crash as an ECE color map.



No Structure (Hot Core)
=> Crash
=>Helical State
Crash time ~ 40 µs

Saturated State
=> Mixing
=>The End is Near
=> ~Axisymmetric State.
By an equivalent definition
Crash time ~ 70 µs

Examine FFT of Cross Correlation of ECE signals with magnetic n=1 signal.

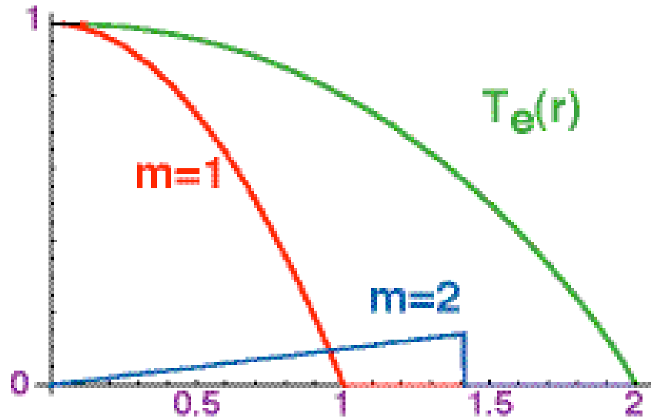


<u>No coherent structure before crash.</u> Double island structure *after* crash (inboard / outboard 180° phase jumps).

Single inboard phase jump => unique signature of quasi-interchange.

FFT Model => Quasi-Interchange

Components of model:
n=1 eigenfunction and a
temperature profile



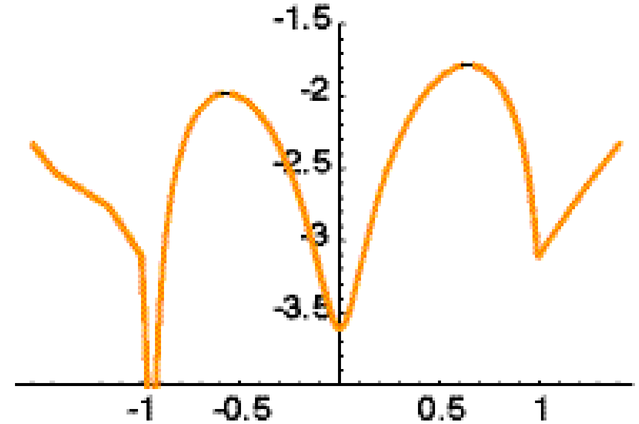
Signal will be
$\xi(r,\theta,t)\cdot T_e'(r,t)$

$$\xi(r,\theta,t) = \xi_1(r)\mathrm{Cos}[\theta - t] + \xi_2(r)\mathrm{Cos}[2\theta - t]$$

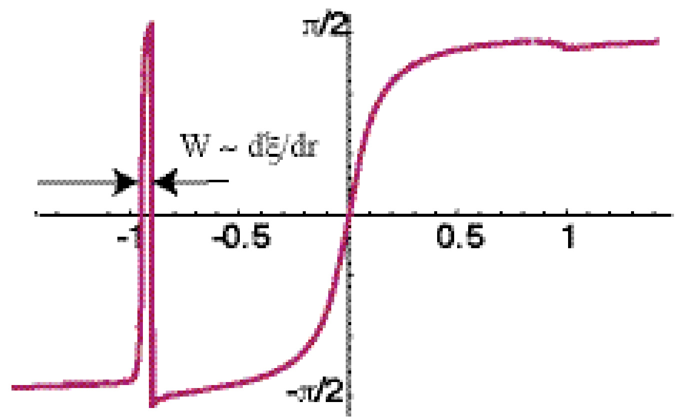
Phase jump from Cos terms and jump back is from Sin terms. The separation depends on slope of the m=1 component as it intersects the m=2 component of ξ. If the m=1 component is kink-like (top hat) the terms cancel and the phase jump does not occur.

=>

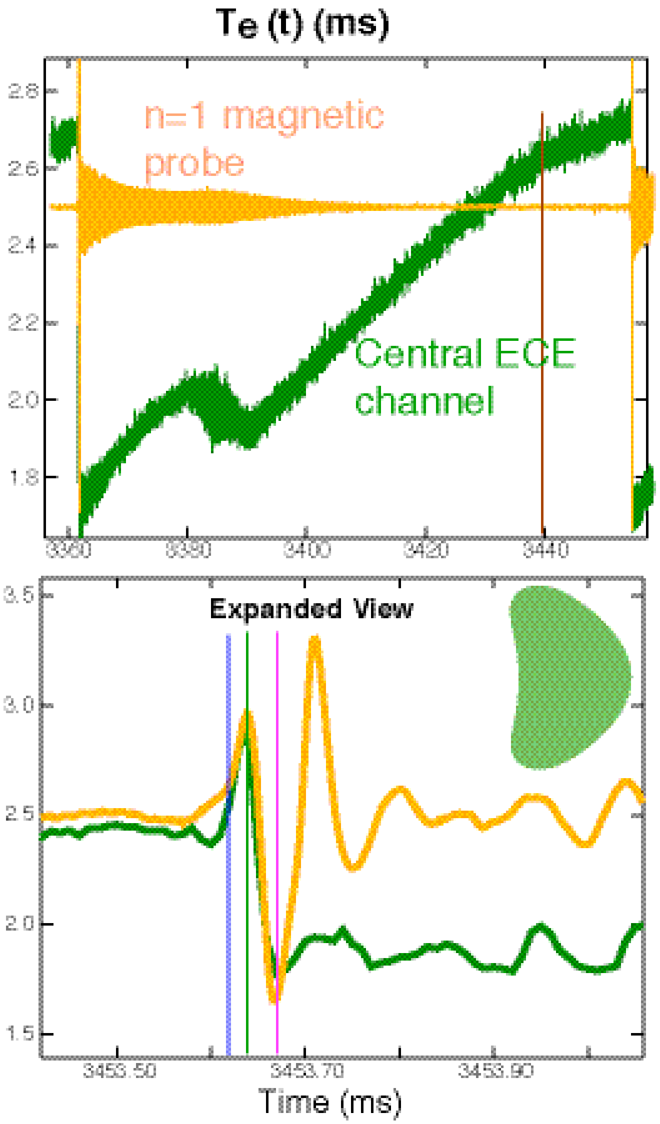
Log(FFT Amplitude)

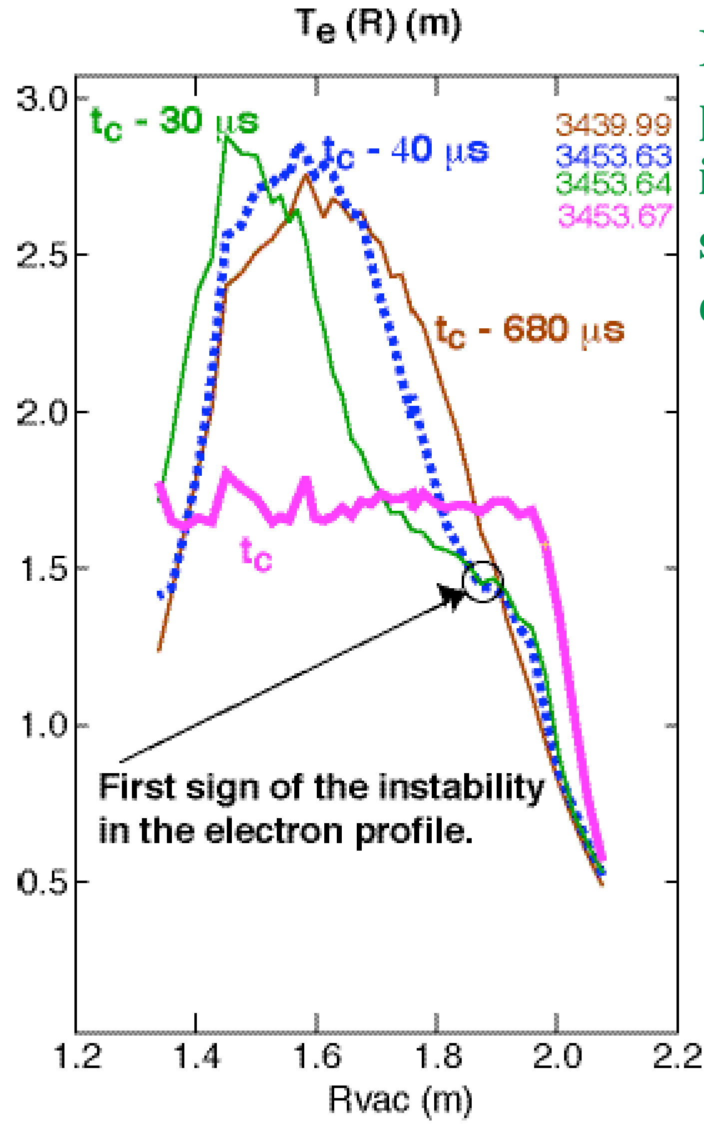


FFT phase



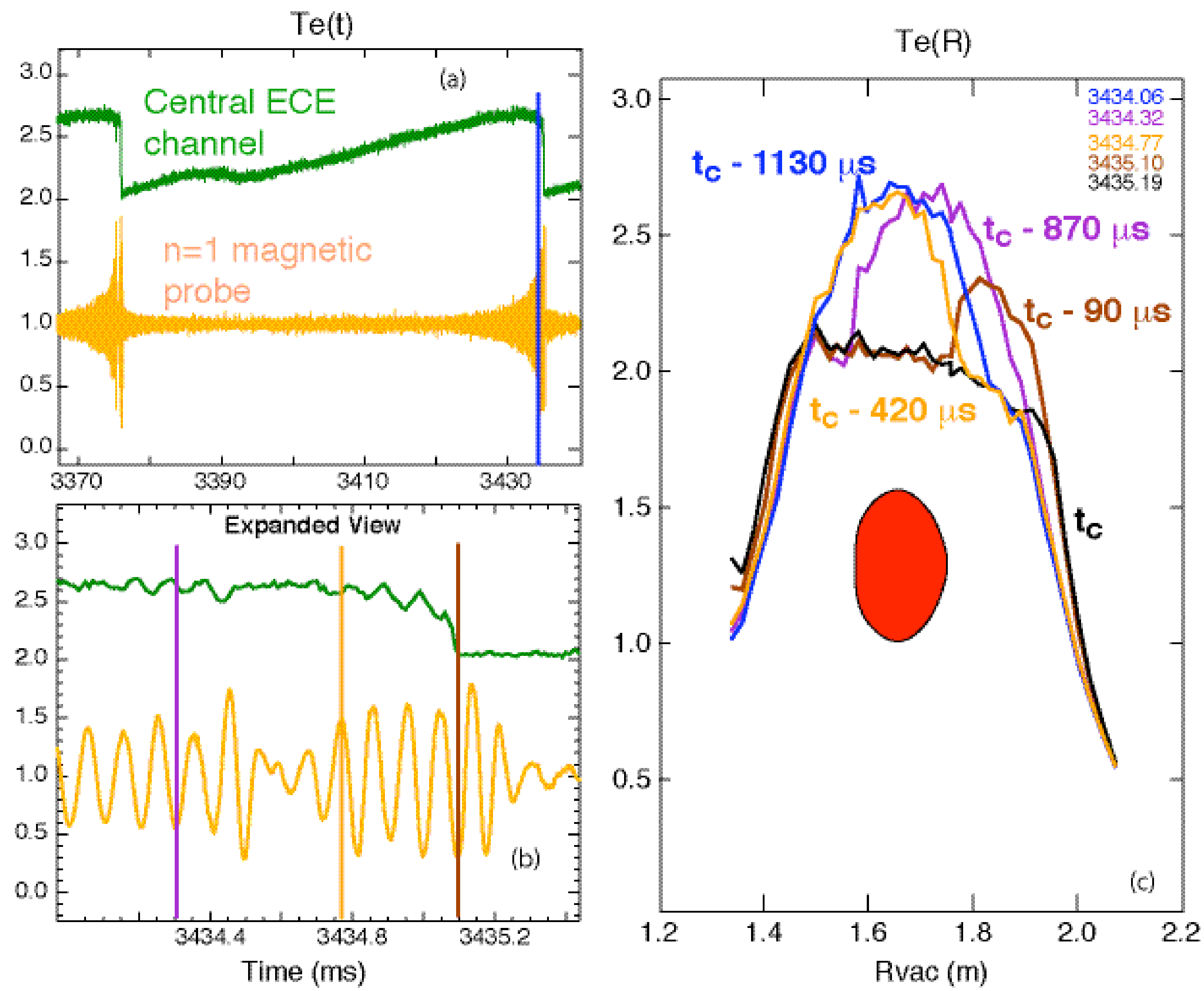
ECE Profiles and End of Sawtooth





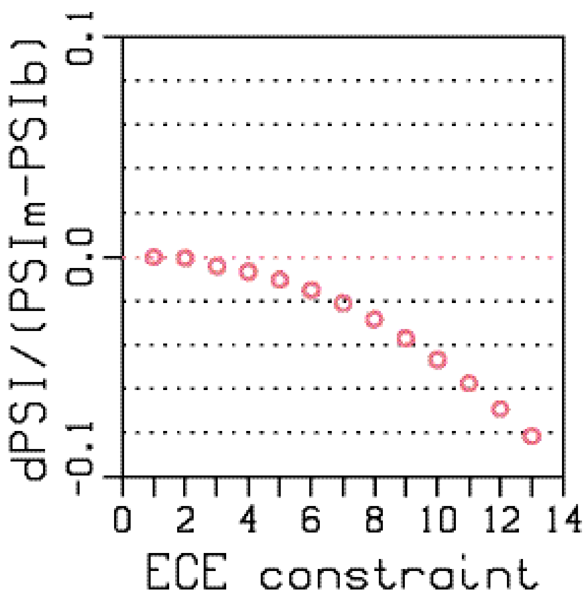
In the bean the profile just caves in from the low field side. No precursor detected.

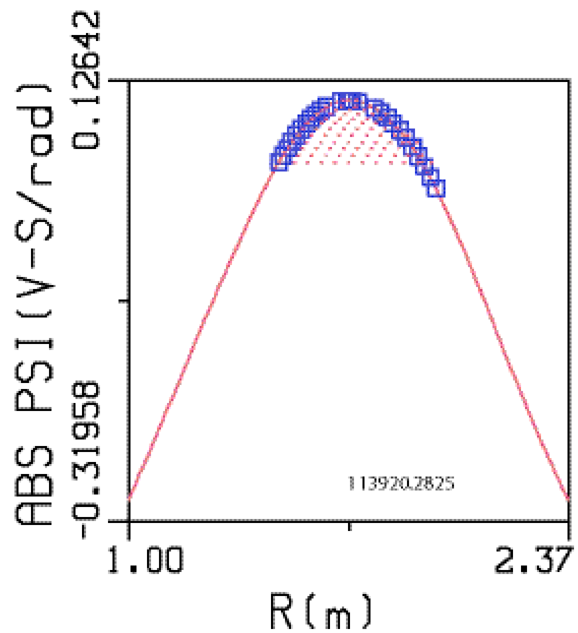
ECE Profiles and End of Sawtooth

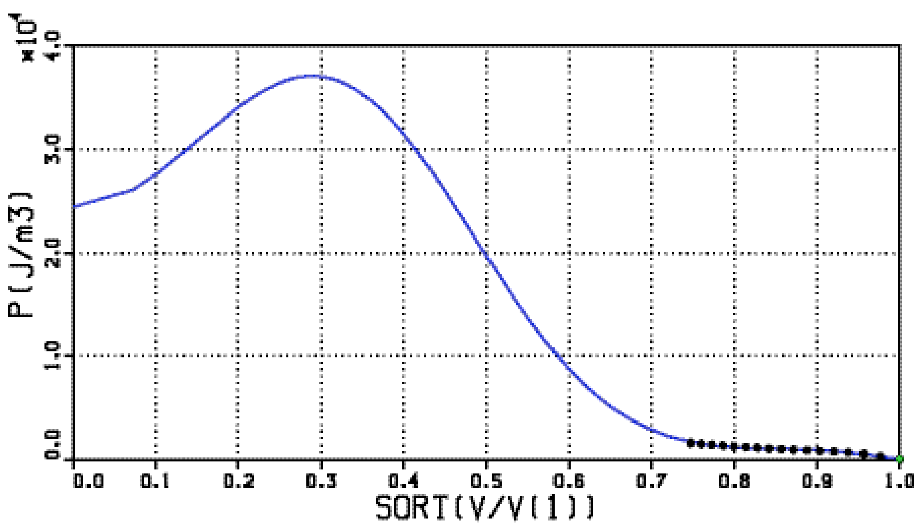


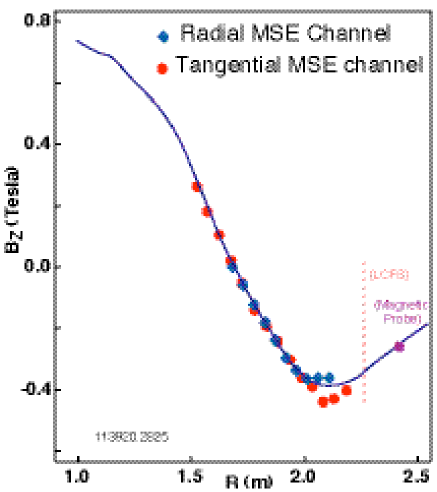
Rotating structure is altered about 600 ms before the crash is completed.
Probably not tearing until after t_c - 420 μs.

ECE-constrained equilibrium using MSE and outer pressure

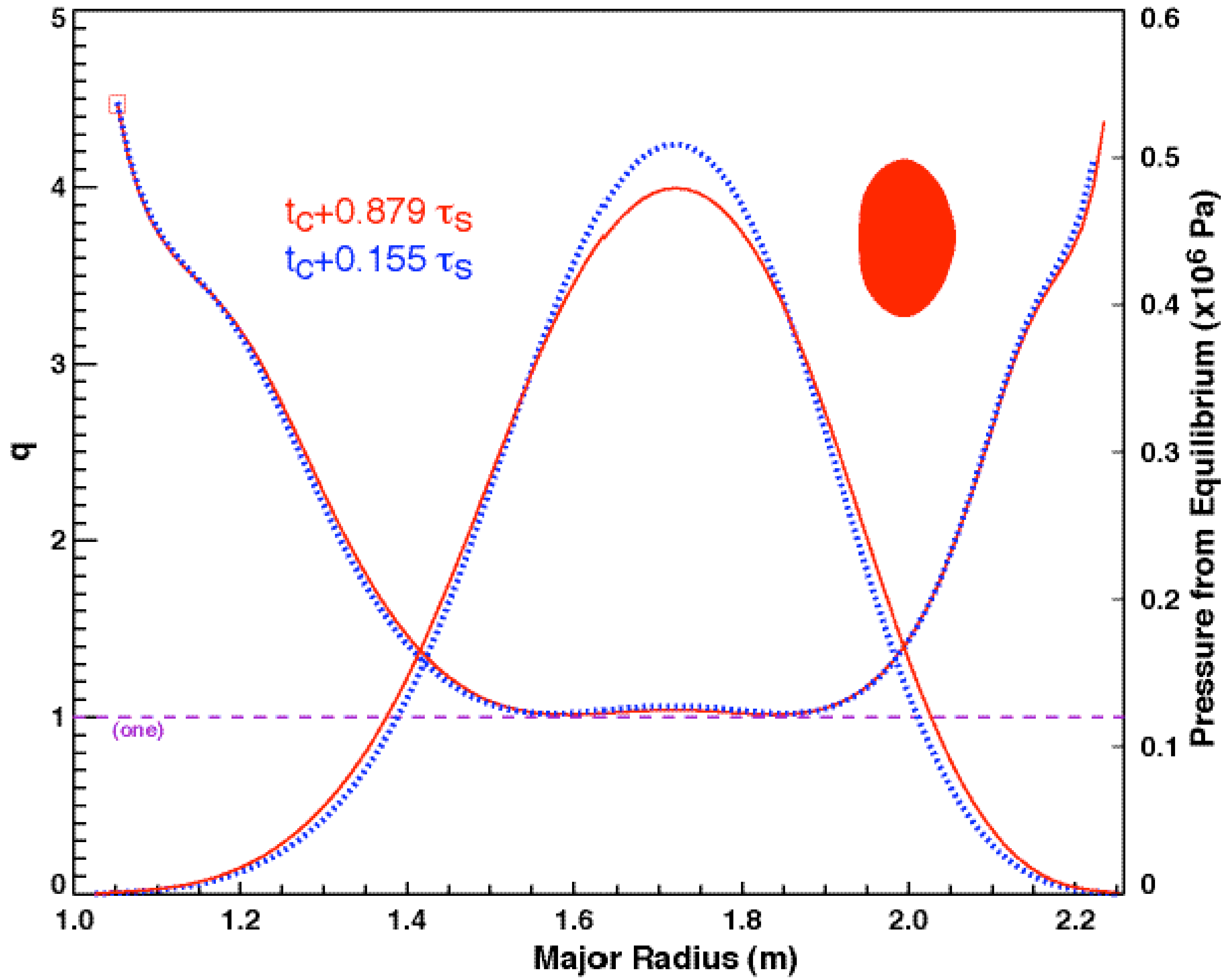




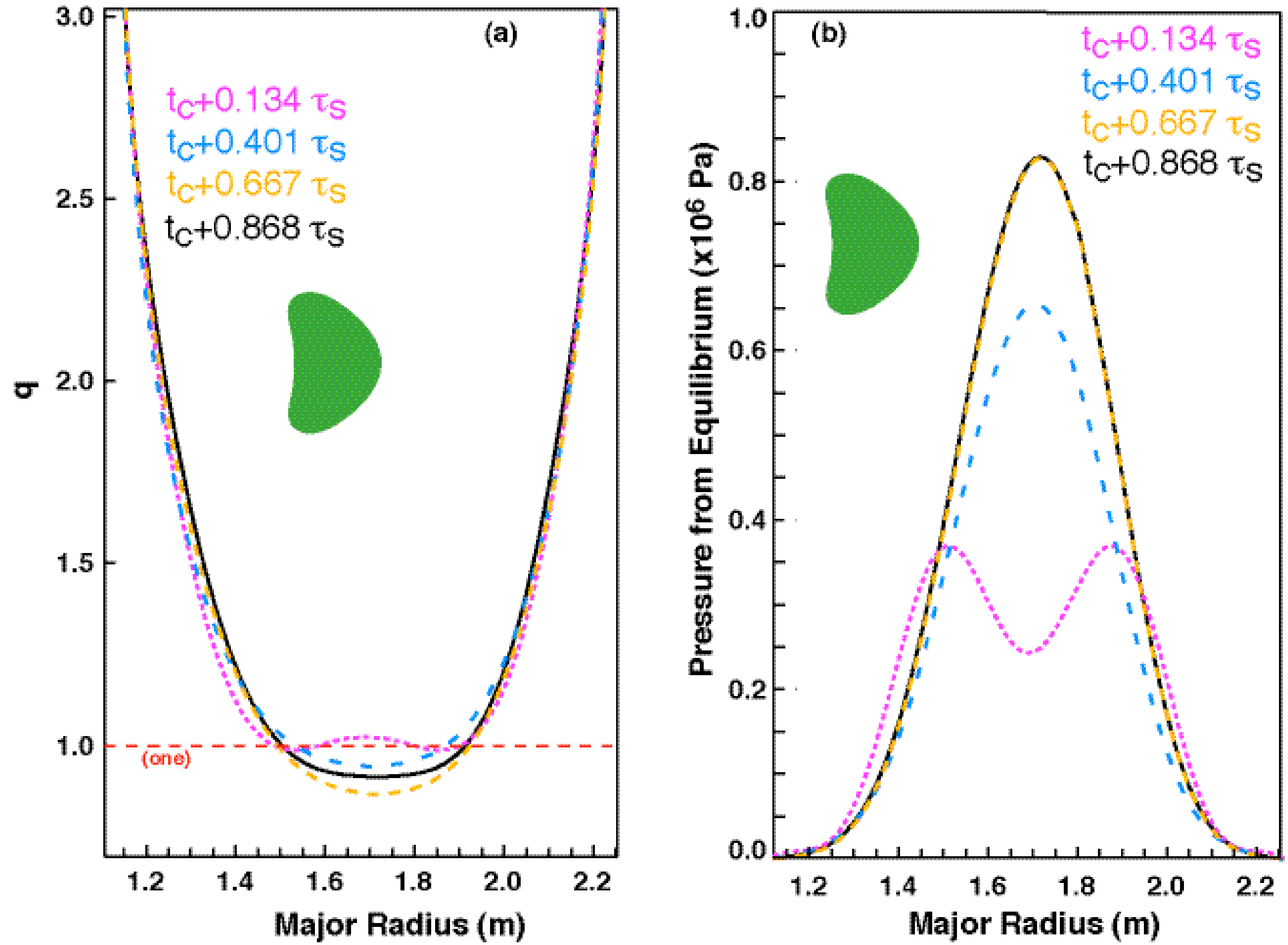




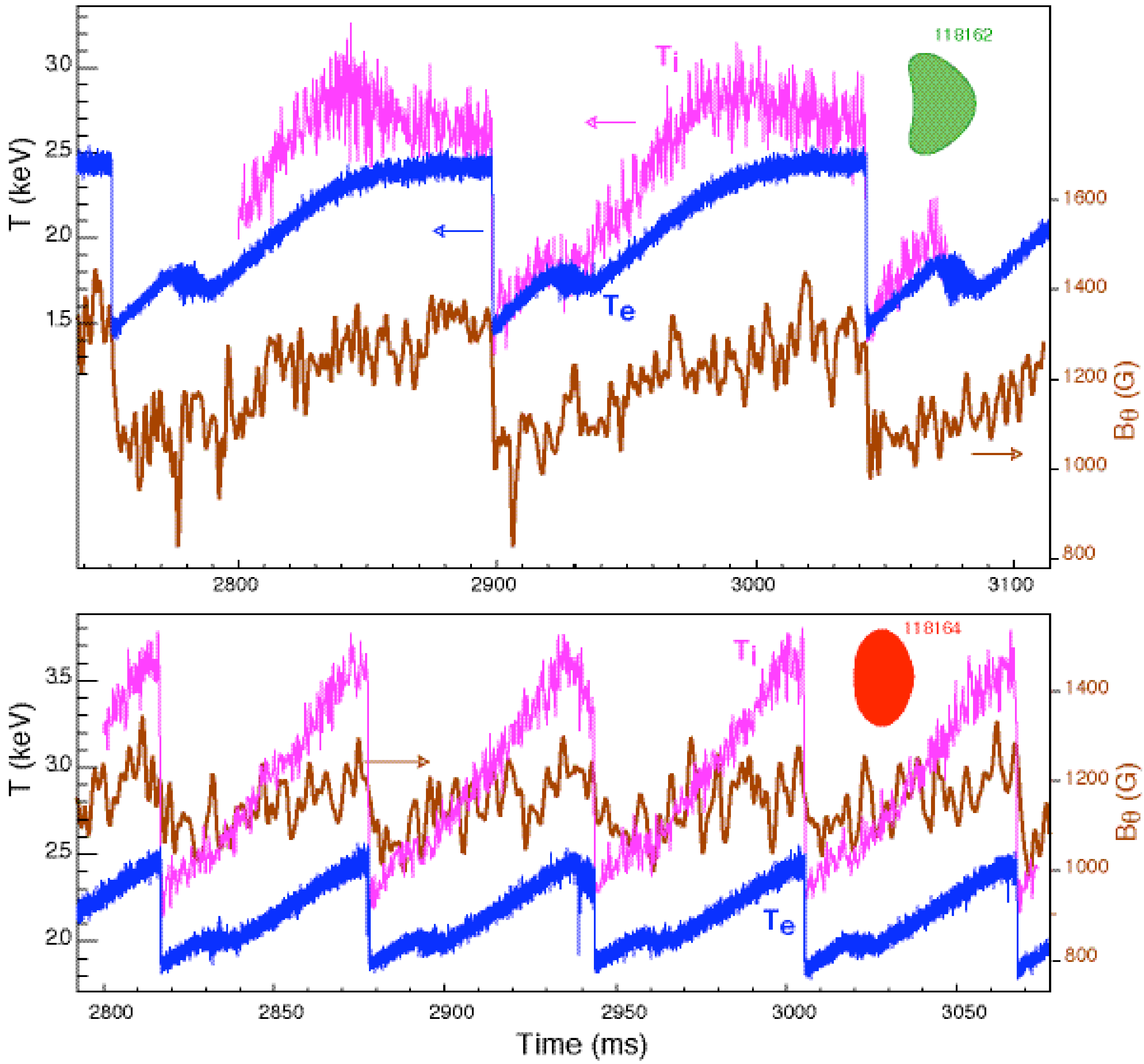
Oval equilibrium does not develop shear



Bean equilibrium does develop shear



Characteristic Behaviors during Sawtooth Ramp



Bean

$T_i \approx T_e$

T_i, v_ϕ roll over

dB_θ/dt crashes

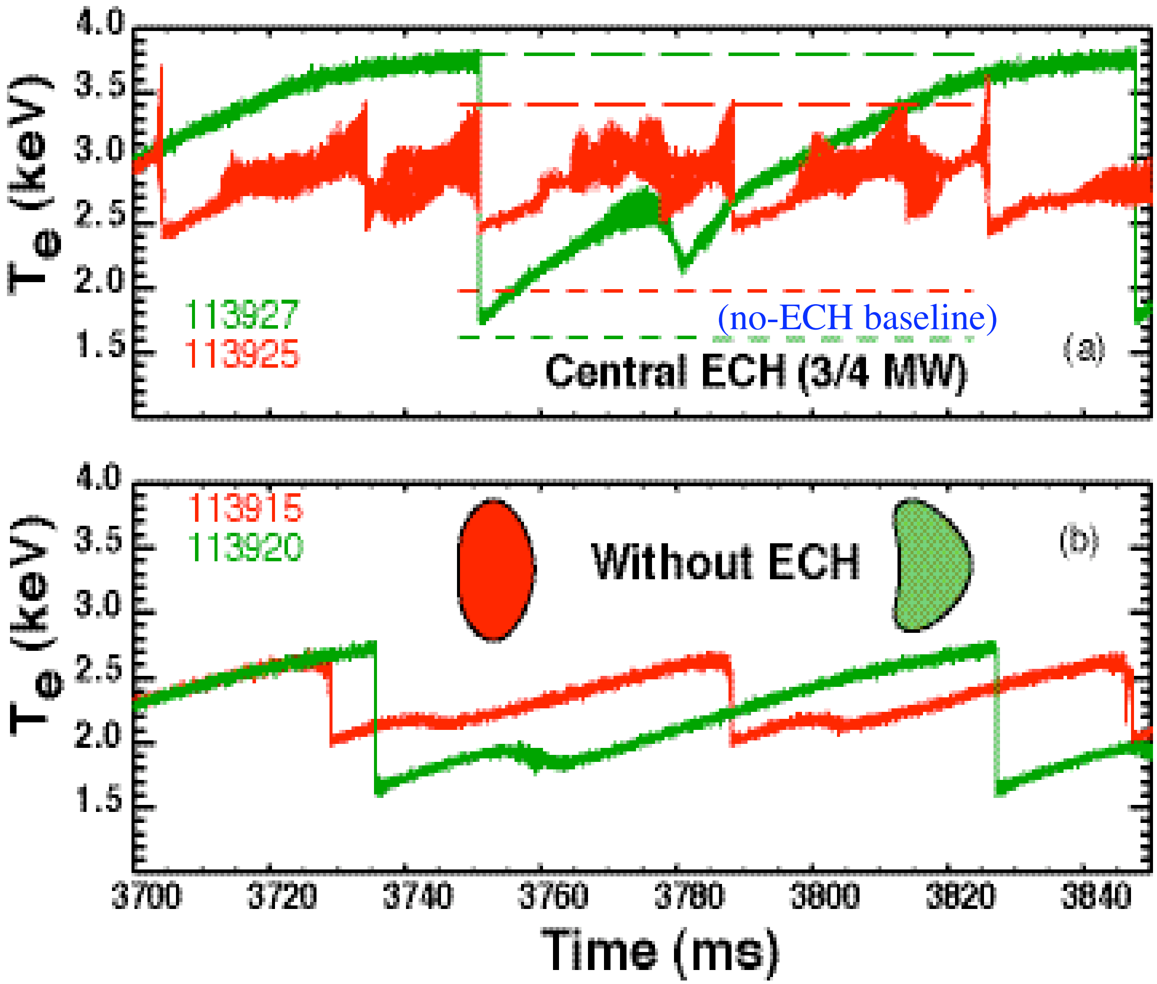
Oval

$T_i > T_e$

T_i does not roll over (relative to T_e)

dB_θ/dt meanders

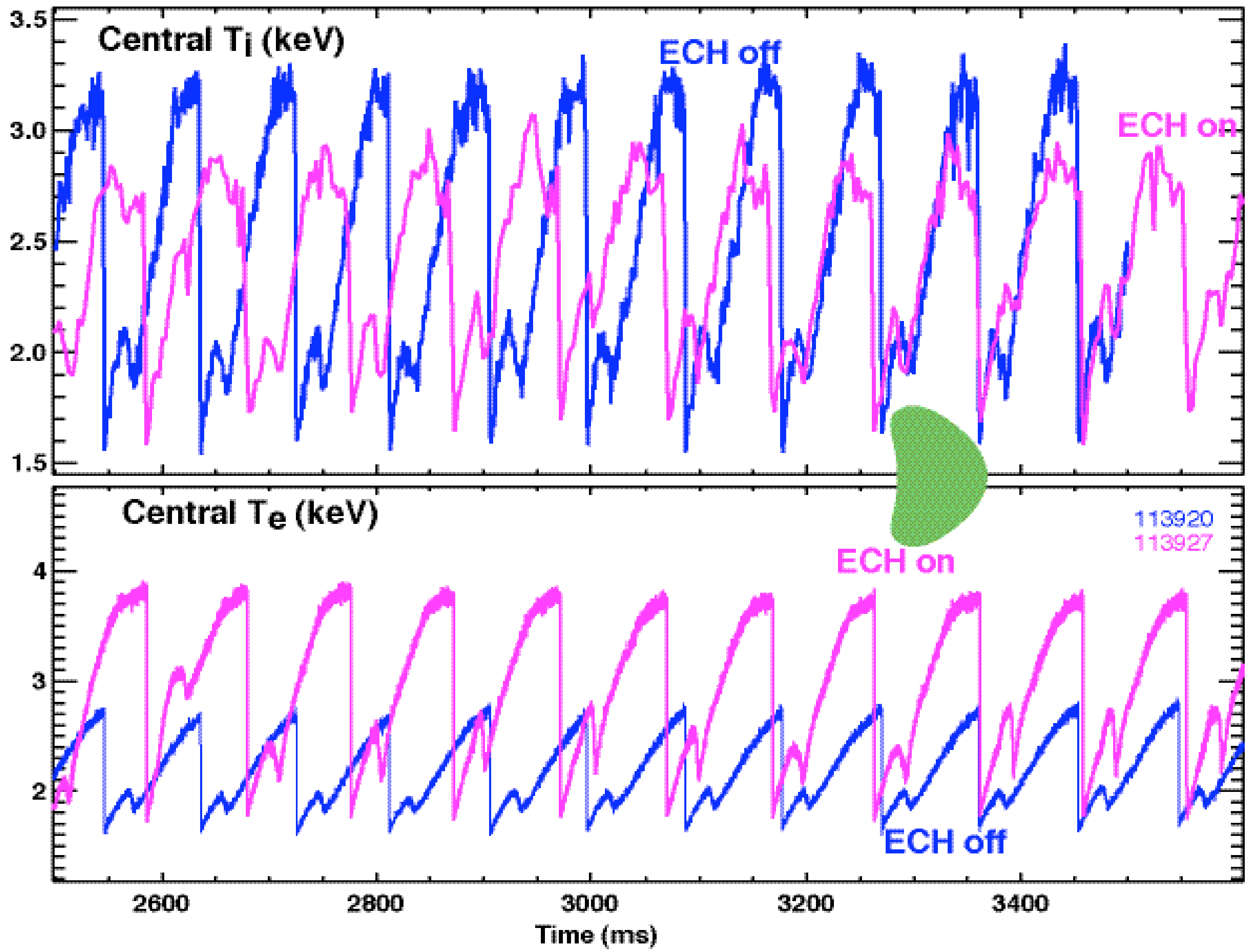
Response to Central ECH



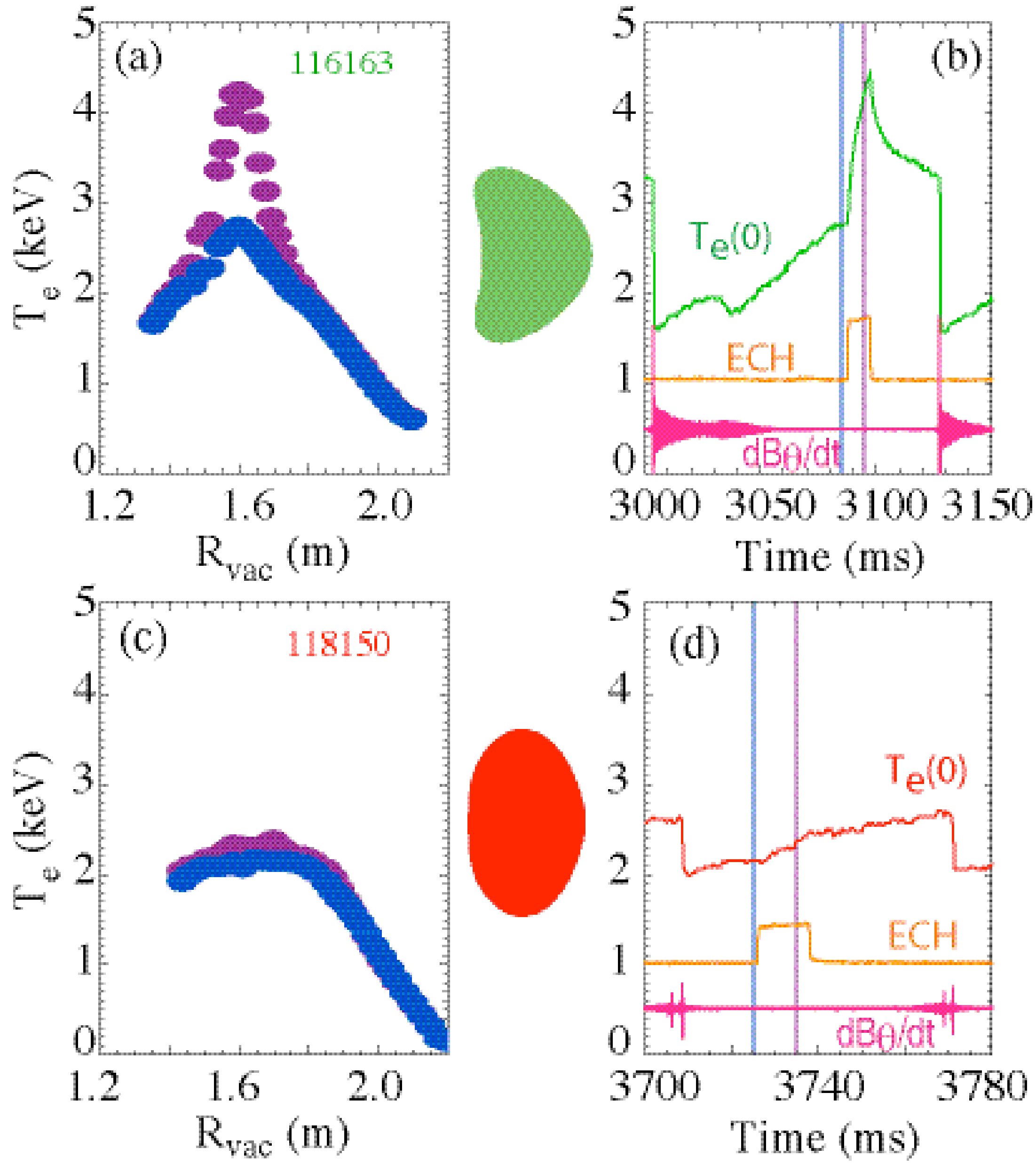
<u>Bean:</u> Sawtooth amplitude increased, baseline preserved. Sawteeth remain regular.

<u>Oval:</u> Sawtooth amplitude not increased, baseline rises. m=1 activity greatly increased, Period and partial reconnections irregular.

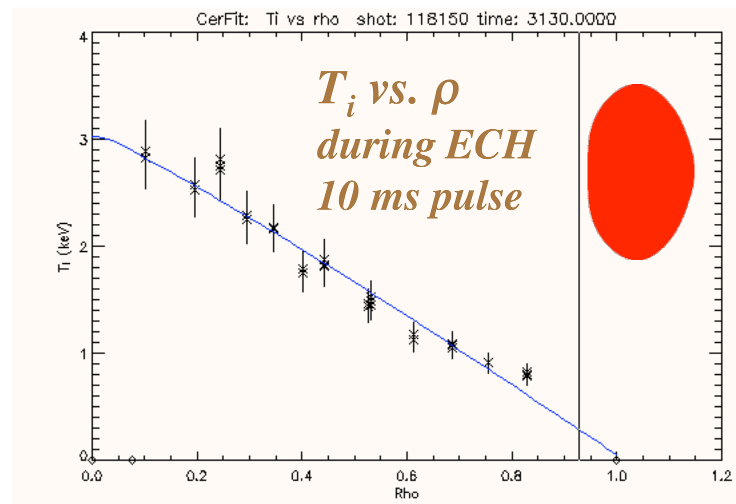
Sustained ECH attenuate ion sawteeth and aggravates rollover in beans



Impulse Response



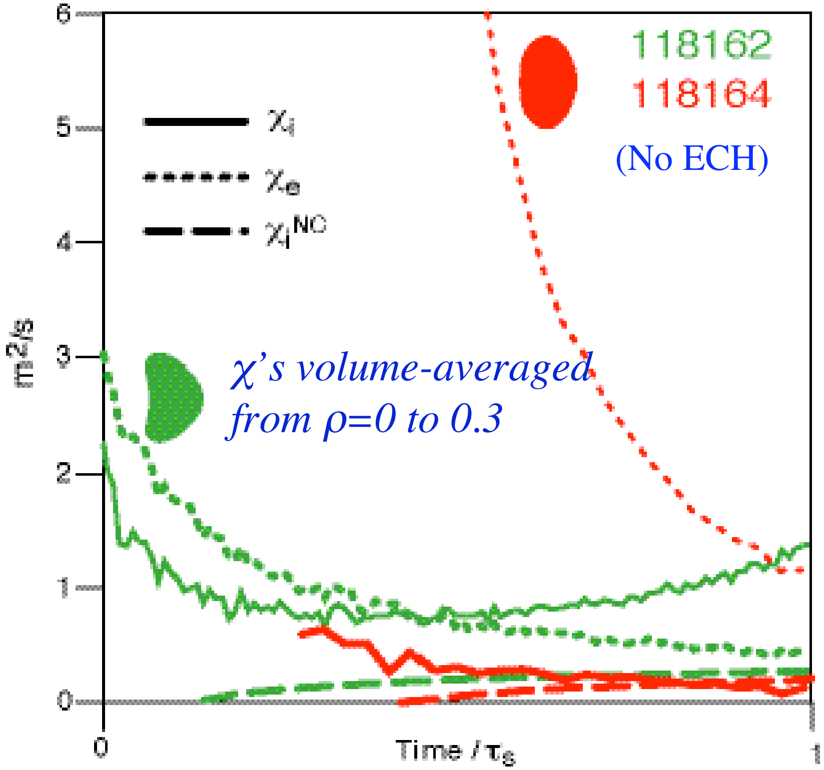
Electrons respond locally.



Electrons do not respond!

However ∇T_i is just fine.
L_{Ti} ~ a inside r_i before, during, & after ECH pulse

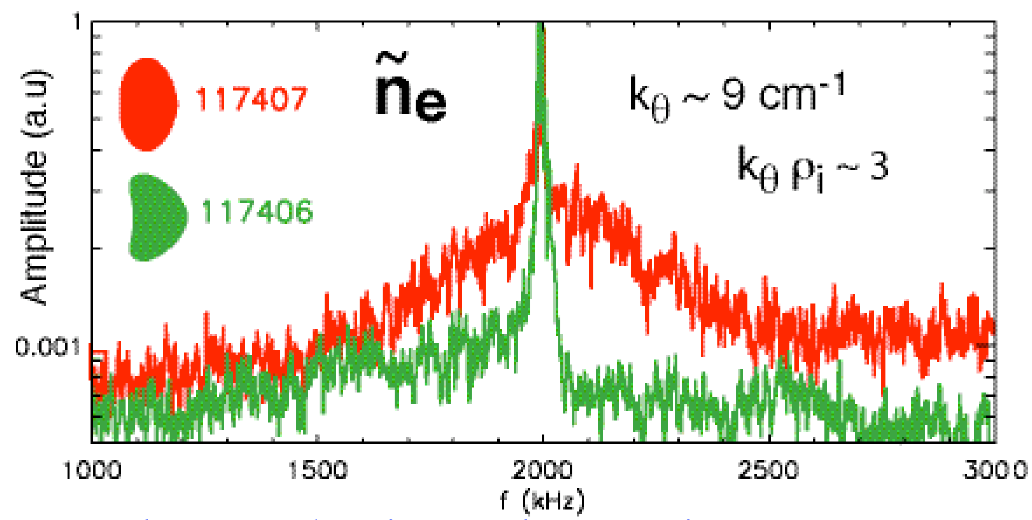
Central Thermal Diffusivities



Transport analysis averages over a few sawteeth to create repeated identical sawtooth periods.

Oval: χ_e is as large as needed to eliminate ∇Te. χ_i at the neoclassical level **Bean:** χ_e and χ_i are typical of values seen in core of tokamak plasmas. χ_e rises late in the period when T_i rolls over.

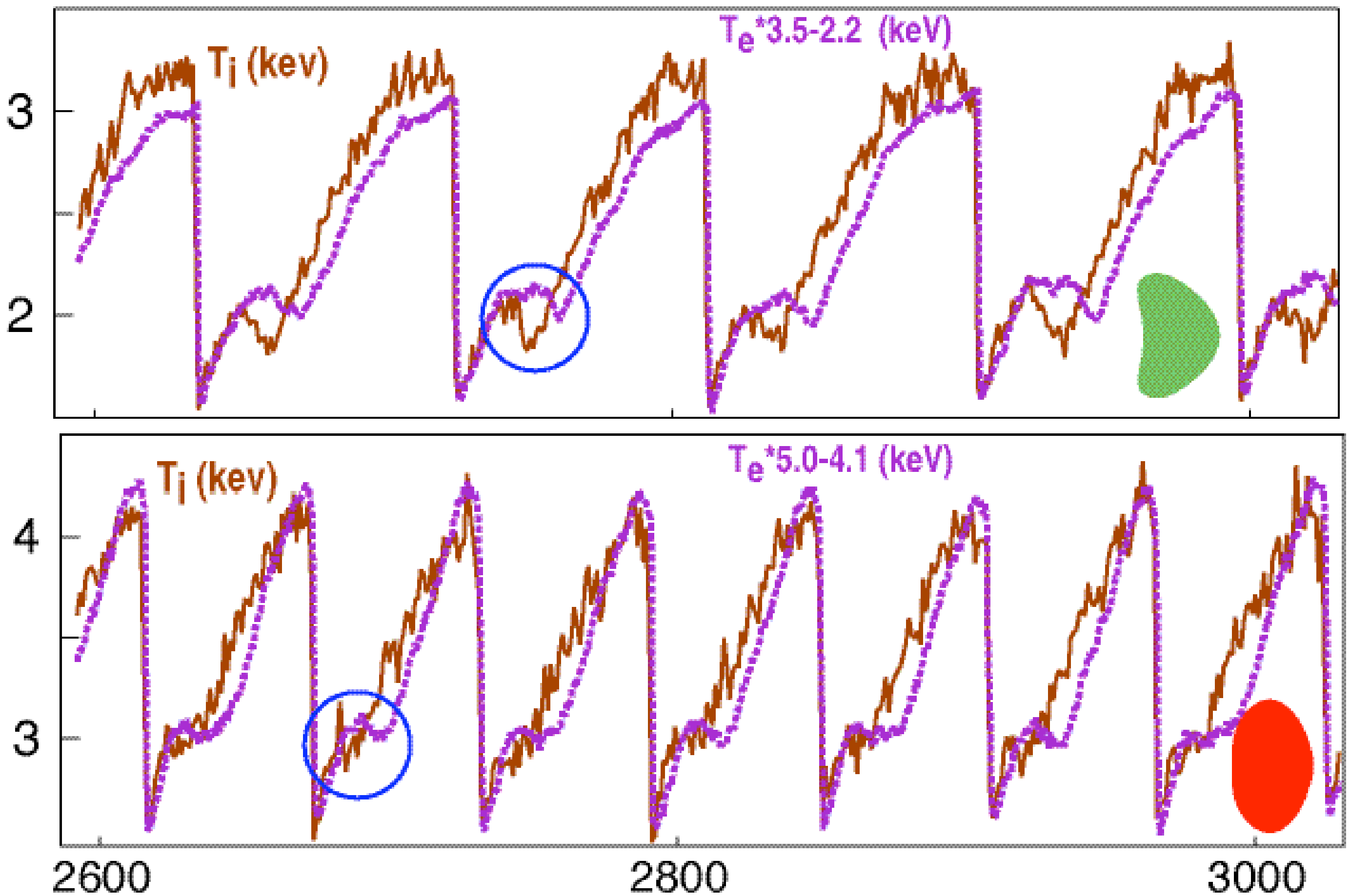
Density Fluctuation Spectra



Note: when ECH is added, central power density to electrons is increased by a factor of 25 so χ_e is ~ 100 m^2/s.

Relaxation Event Appears To Be Key In The Evolution

Prior to relaxation event electron confinement in the bean is as bad as it is in the oval.
Prior to the relaxation event, both shapes have little or no shear.



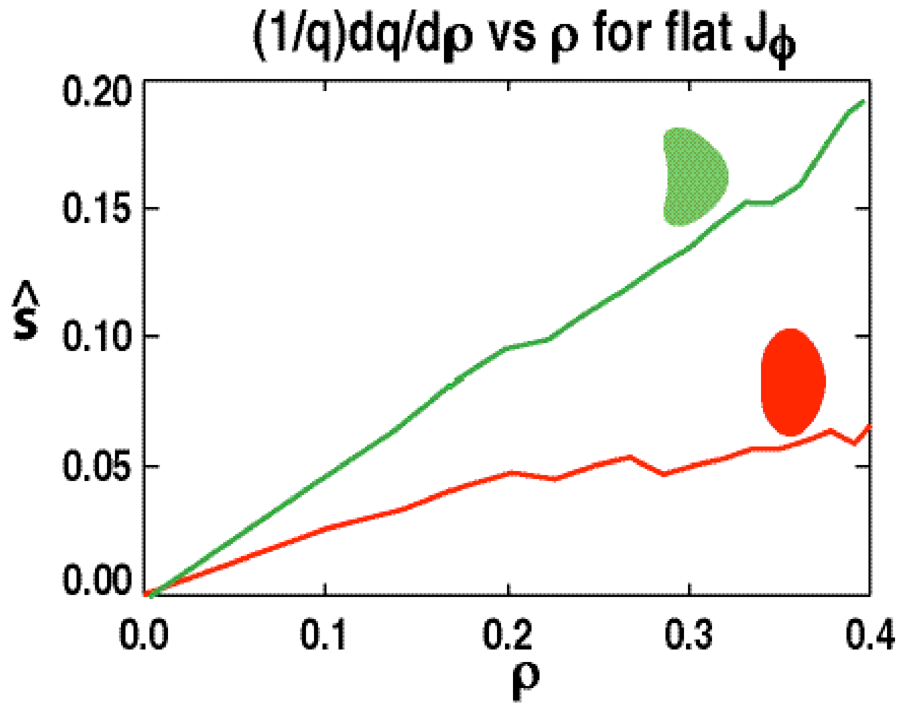
Bean
Ions recover before electrons.

Oval
Ions recover before electrons but even earlier than in the bean.

T_e at the radius of the T_i measurement, scaled to overly the ion waveform

Shaping causes shear when J_ϕ is flat.

- *We have been considering shear as a secondary quantity in a causal sense, because the bean develops shear but the oval does not.*
- *Assume the relaxation event has the current adjusting to the new T_e and at the end of this event the current profile is perfectly flat inside r_i.*
- *Because of the triangularity of the inner surfaces in the bean, there will be considerably more shear than in the oval. If χ_e depends strongly on shear, T_e may begin to peak in the bean leading to increased shear => a bootstrap process.*



(VMEC model equilibrium with p'=0)

Conclusions

- In both the bean and oval, reconnection occurs. After the sawtooth crash both have reconnected to have a central region with $q \approx 1$ and little shear.
- The Mercier criterion is not satisfied in the oval plasmas. (Something akin to the Mercier criterion seems to be satisfied for electron pressure.)
- The oval plasma develops a quasi-interchange n=1 instability. By contrast, the bean instability is an internal kink.
- From ECH results, the bean is crash is not a result of pressure (β_{p1}). In the oval, adding central pressure makes the behavior chaotic. This same chaotic behavior is seen in the bean prior to the relaxation event.
- The rollover in T_i seen in the bean is aggravated when ECH is added. The rollover may simply be an inverse dependence of χ_i on T_e.
- $\omega_{*i} \ll \gamma_{mhd}$ in the oval -- unimportant ; $\gamma_{mhd}^{-1} \sim 4\ \mu s$
- $\omega_{*i} \sim 1/2$ -- 1 (γ_{mhd}) in the bean ?? important; $\gamma_{mhd}^{-1} \sim 30\ \mu s$
- || current evolution appears neoclassical (preliminary) during ramp
    - (anomalous during relaxation event)