The Relationship of Locked Modes to Edge Current Density

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The Relationship of Locked Modes to Edge Current in DIII-D [1] E.A. LAZARUS, Oak Ridge National Laboratory, M.S. CHU, T.H. OSBORNE, R.J. LA HAYE, General Atomics, B.W. RICE, Lawrence Livermore National Laboratory — Locked modes are a familiar problem in low density discharges [$\bar{n}_e(R_0/B_\mathrm{t})q^* \approx 8$] for elongated plasmas. In a series of limiter discharges we found the following phenomenology for a particular series. Discharges which were maintained at approximately constant shape during the I_p ramp encountered a locked mode at $q_\ell \approx 3$ leading to a disruptive termination with a probability of approximately 80%. Discharges for which κ was initially increased to a larger value than the desired value of 1.6 and later reduced follow a different trajectory in that $q_\ell = 3$ is not reached in the I_p ramp, but in the flattop where κ is reduced to its final value. These discharges avoided the locked mode with 100% reliability. The current density is measured with a motional Stark effect diagnostic. At the time $q = 3$ is reached, the edge current density is somewhat higher in the former cases. Experimental results and resistive stability analysis will be presented.

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☐ Prefer Oral Session
☒ Prefer Poster Session

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Locked modes are a familiar problem in low density discharges [$\bar{n}_e(R_0/B_t)q^* \approx 80$] for elongated plasmas. In a series of limiter discharges we found the following phenomenology for a particular series. Discharges which were maintained at approximately constant shape during the I_p ramp encountered a locked mode at $q_\ell \approx 3$ leading to a disruptive termination with a probability of approximately 80%. Discharges for which κ was initially increased to a larger value than the desired value of 1.6 and later reduced follow a different trajectory in that $q_\ell = 3$ is not reached in the I_p ramp, but in the flattop where κ is reduced to its final value. These discharges avoided the locked mode with 100% reliability. The current density is measured with a motional Stark effect diagnostic. At the time $q = 3$ is reached, the edge current density is somewhat higher in the former cases. Experimental results and resistive stability analysis will be presented.

DIII—D Locked Mode Criteria

- **There are several rules-of-thumb used to indicate a threat of locked modes:**

1. **DITE < 9, where DITE =** $\dfrac{\overline{n_e}}{B_t / R}\, q_*$ **and**

$$q_* = \frac{a^2 B_t}{\frac{\mu_0}{2\pi} R I_p} \left(\frac{1+\kappa^2}{2} \right) \left[1 + \varepsilon^2 \left(1 + \frac{\left(\beta_p + \ell_i/2\right)}{2} \right) \right]$$

$$\left[1.24 - 0.54\kappa + 0.13\delta + 0.3\left(\kappa^2 + \delta^2\right)\right]$$

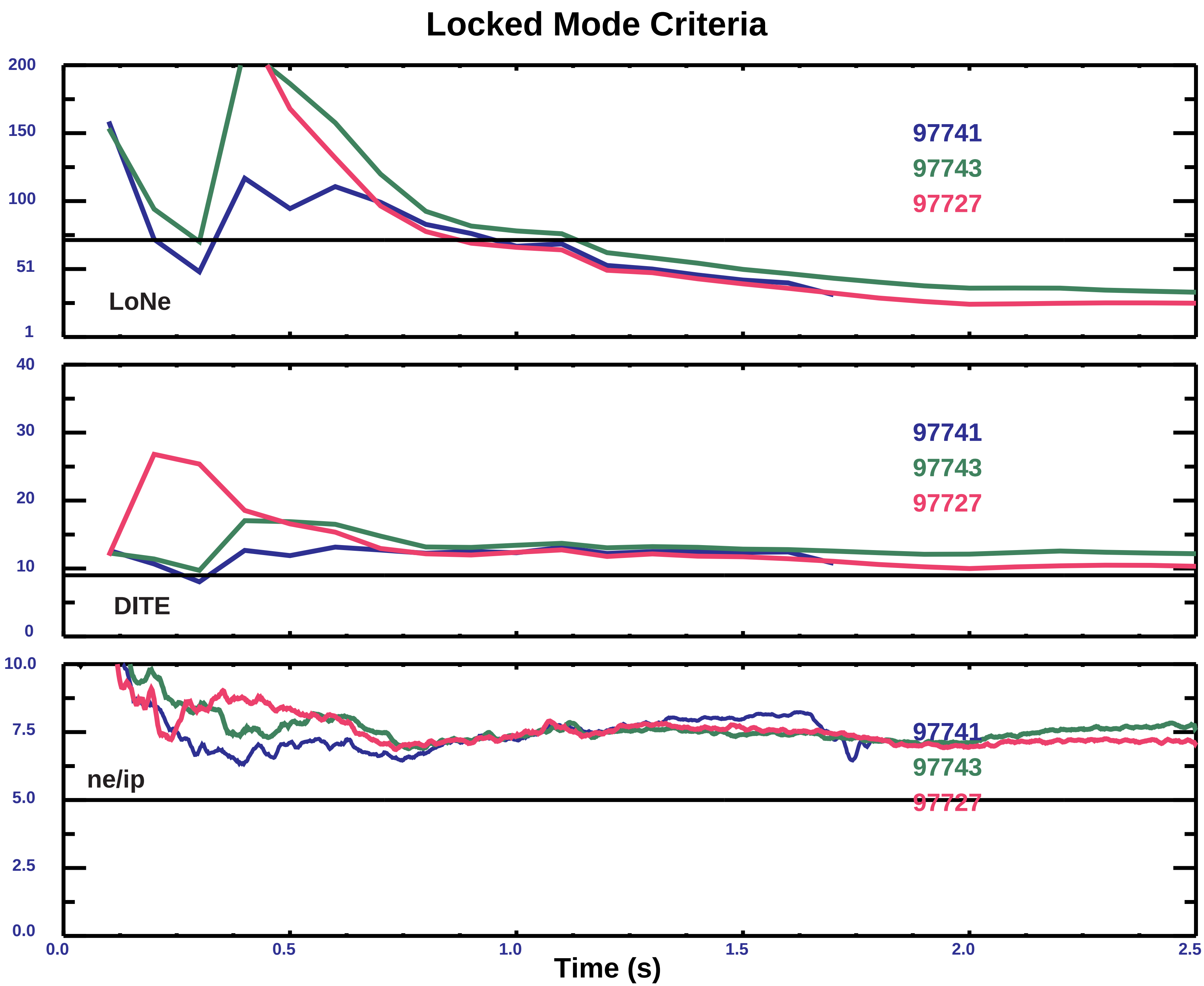
2. **LoNe < 72, where LoNe = (DITE)•q_***

3. **“ne/ip” > 5, is the vertical line-integrated density (“DENV2”) divided by plasma current.**

- **Attempts to replace q_* with q_ψ seem to destroy the valididity of these empirical criteria.**

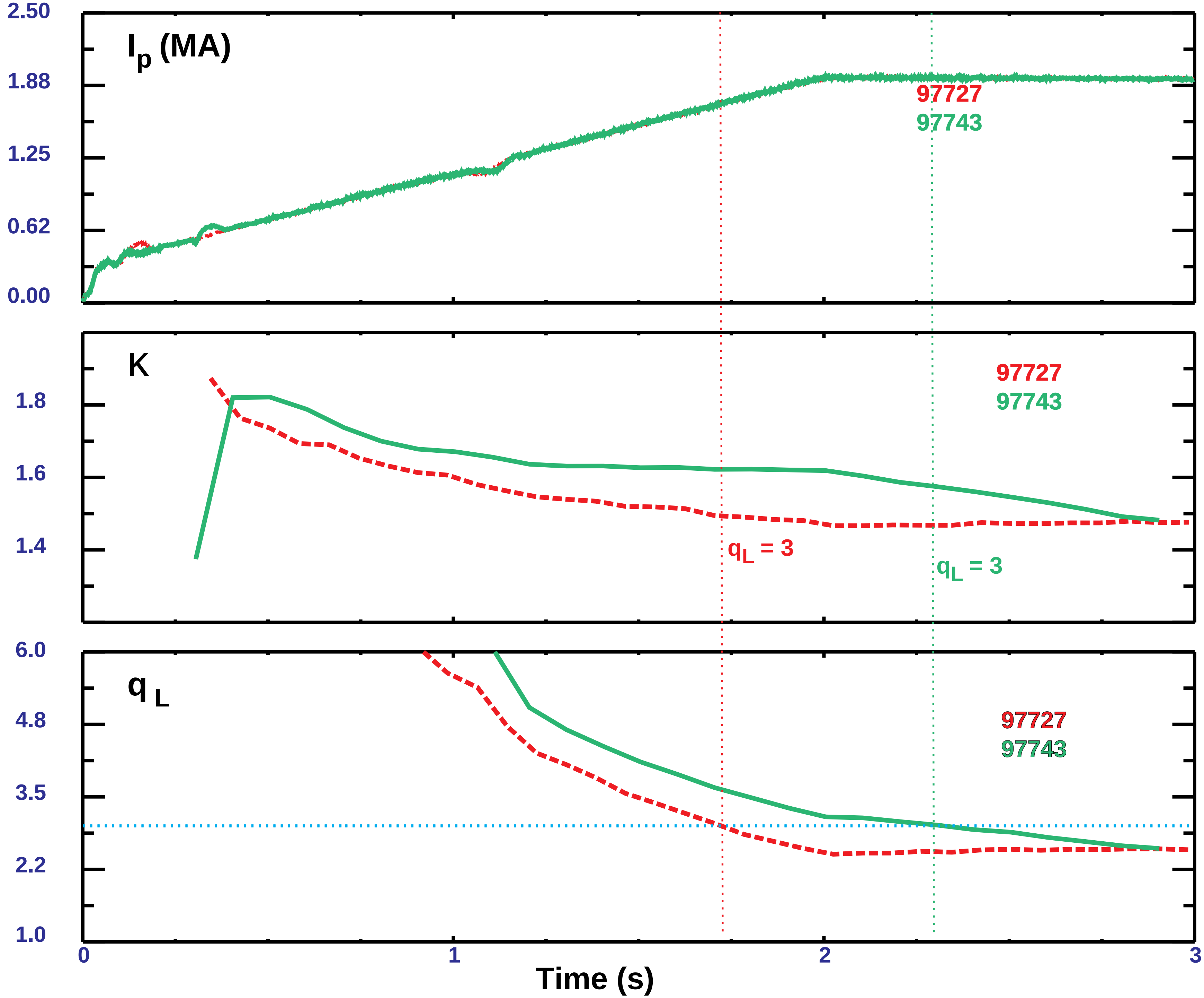
- **While the LoNe can be violated, the plasma will not accept heating and locks at the first attempt to raise β.**
- **Even ignoring these exceptions, it seems to me stunning how frequently locked mode difficulties correlate with LoNe just touching 72 (from above) during plasma rampup.**

- **The goal of the experiment was to produce low β plasmas which would exhibit a classical tearing mode at low q (<2.5) but would have low enough density for ECE to be operable. It turned out that the plasma was remarkably robust for q > 2.25 and tearing modes were difficult to generate with impurity and/or D_2 puffing.**
- **While the latter type were 100% successful in passing through q=3, an error (such as mistiming the κ evolution would reproduce the locked mode behavior of 97741 discussed below.**

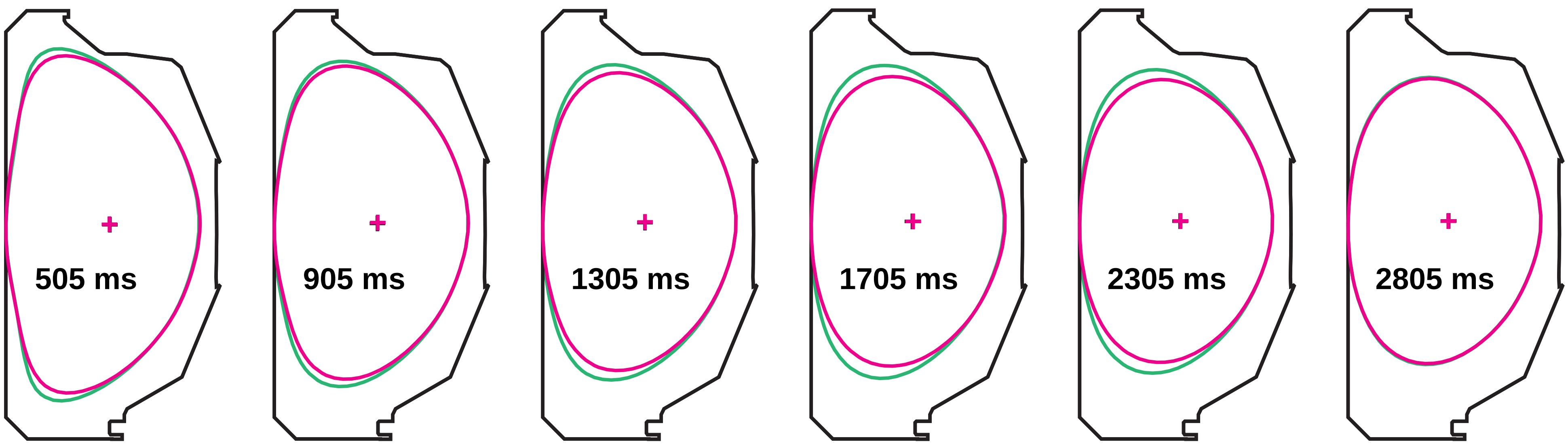

Locked Mode Criteria
200
150
100
51
1
LoNe
97741
97743
97727
40
30
20
10
0
DITE
97741
97743
97727
10.0
7.5
5.0
2.5
0.0
ne/ip
97741
97743
97727
0.0
0.5
1.0
1.5
2.0
2.5
Time (s)

Time Evolution of Shape

- In this discussion we will focus on three plasmas:
  1. 97741 is in a category of low-density discharges where 80% (8 of 10) developed a locked mode and disrupted – all at about the same time, corresponding to $q_l \geq 3$.
  2. 97727 is one of the two discharges with this same evolution , which did not disrupt
  3. 97743 is a different evolution of plasma shape which delays passing through q=3 until I_p is in the flat top.
- I hope to preserve this color- coding - – no guarantees
- First we examine the evolution of the latter two discharges.



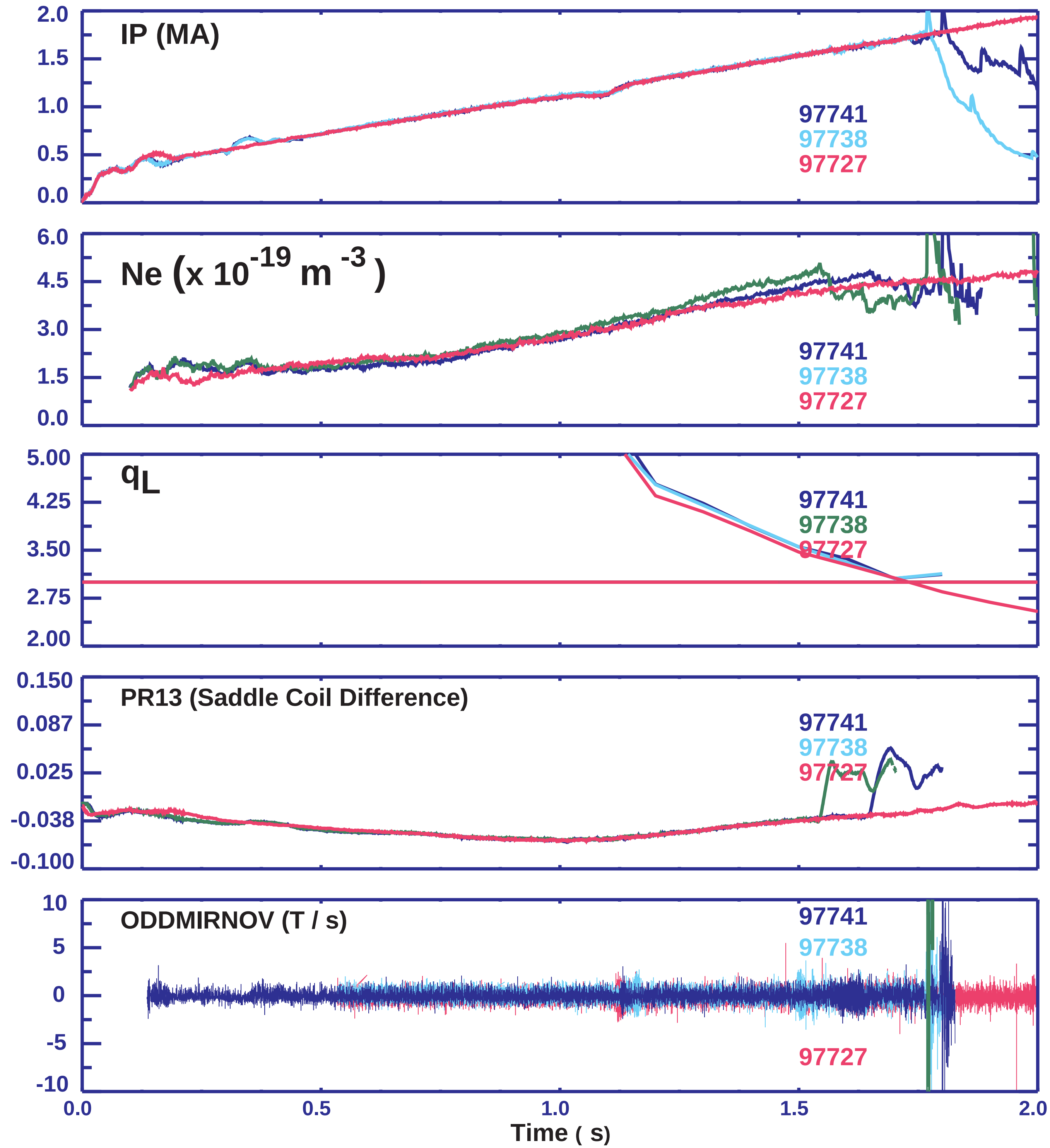
2.50
1.88
1.25
0.62
0.00
Ip (MA)
97727
97743
K
1.8
1.6
1.4
97727
97743
qL = 3
qL = 3
6.0
4.8
3.5
2.2
1.0
q L
97727
97743
0
1
2
3
Time (s)



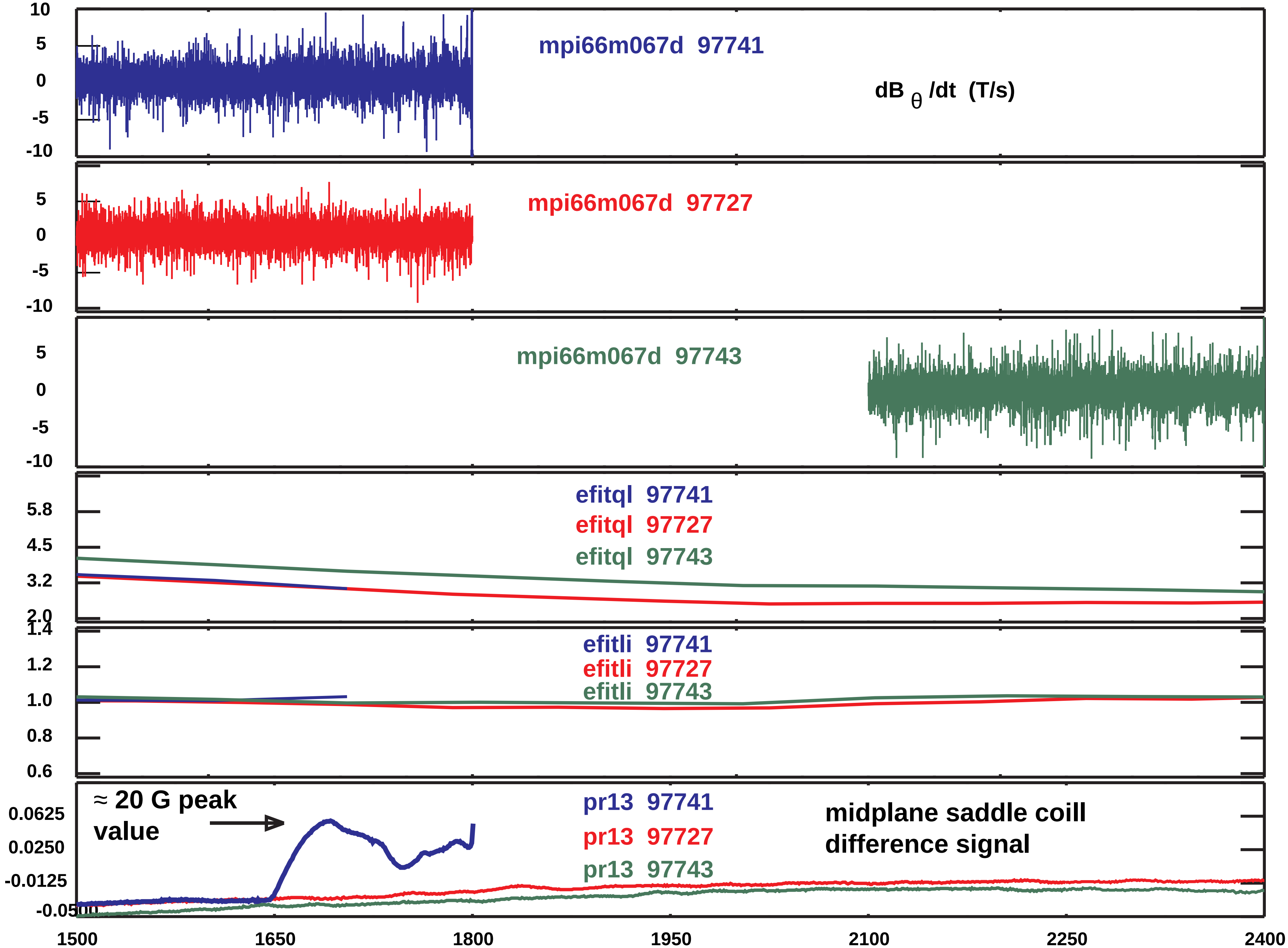
SHAPE EVOLUTION FOR 97743 AND 97727

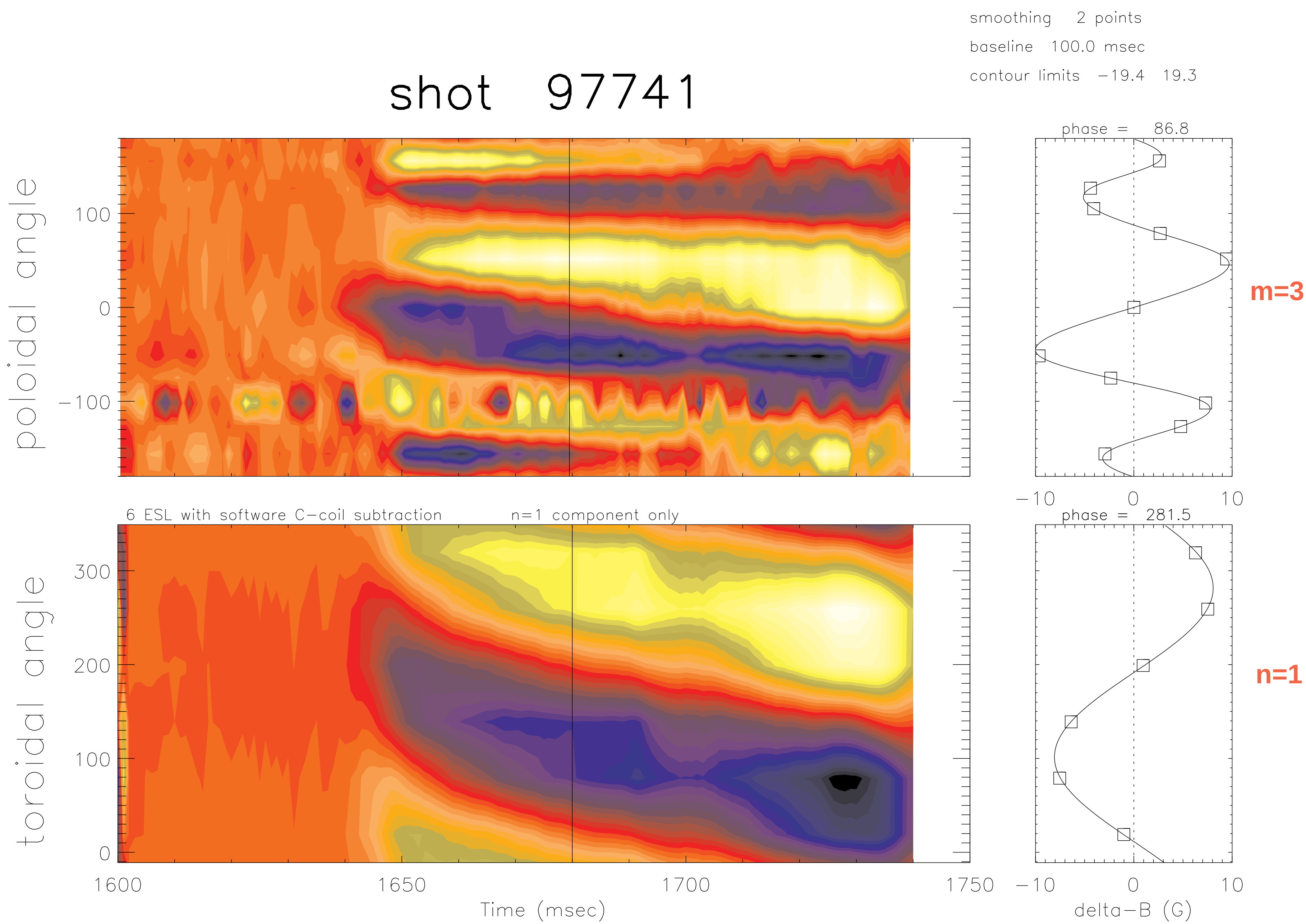
Disruptive Behavior

- There is little difference in the dB_θ /dT signals prior to or even beyond the onset of tle locked mode as evidenced in the figure below
- The next figure shows the typical time evolution of the plasmas encountering LM disruptions, along with the counter example, 97727.
- All the disruptions of this type begin with a positive spike in I_p, indicating a peaking of the current profile.
- The analysis of saddle coils (toroidal and poloidal arrays) for 97741 (3rd figure below) shows an m/n=3/1 mode beginning to grow at about 1462 ms and its rotation is completely stopped at 1680 ms
- A careful examination of the saddle coil signals for 97727 and 97743 shows no evidence whatsoever of an external perturbation as the plasma passes through q_L=3.



IP (MA)
97741
97738
97727
2.0
1.5
1.0
0.5
0.0
Ne (x 10^{-19} m $^{-3}$)
6.0
4.5
3.0
1.5
0.0
q_L
5.00
4.25
3.50
2.75
2.00
PR13 (Saddle Coil Difference)
0.150
0.087
0.025
-0.038
-0.100
ODDMIRNOV (T / s)
10
5
0
-5
-10
0.0
0.5
1.0
1.5
2.0
Time (s)

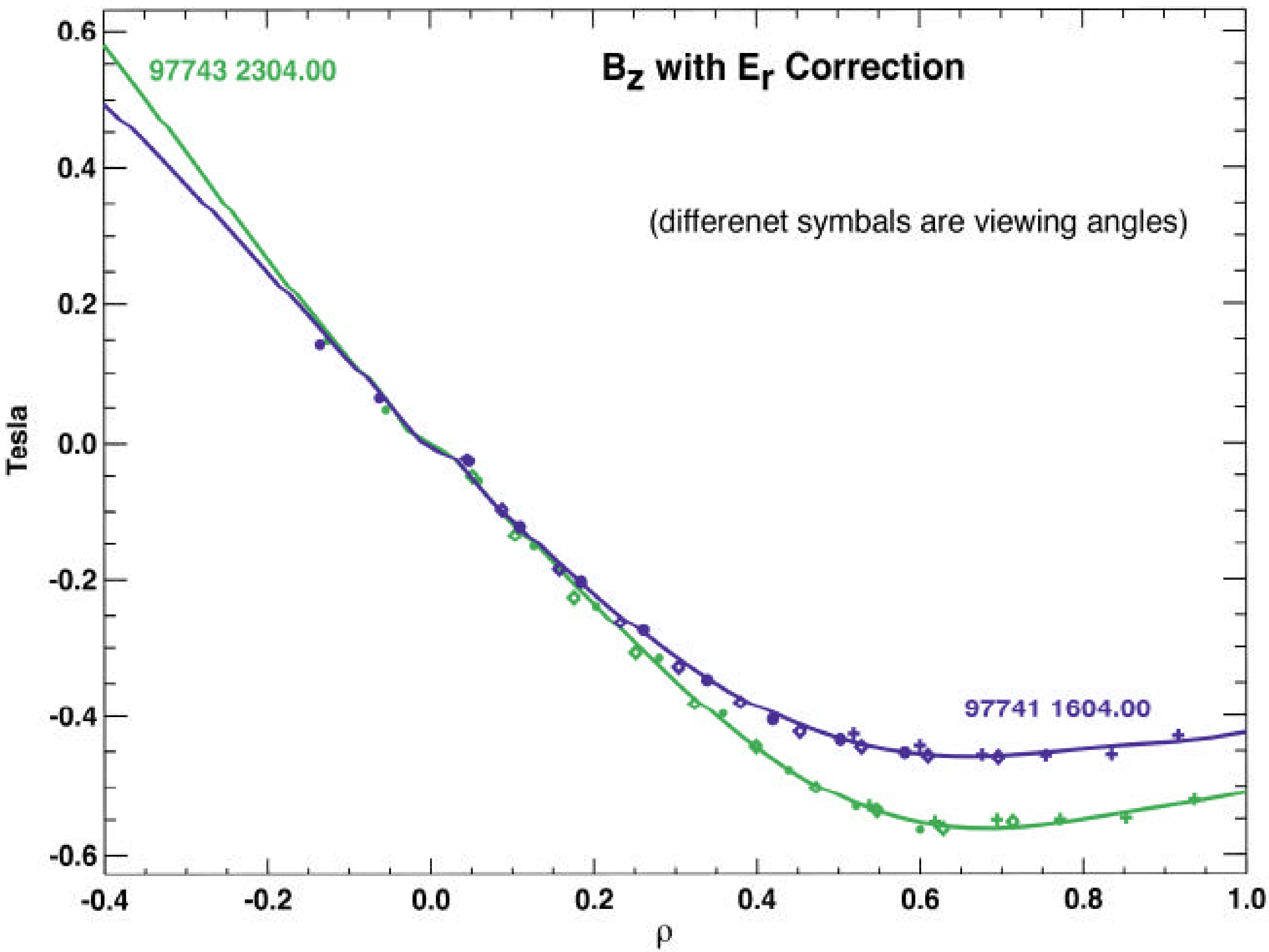

mpi66m067d 97741
dB θ /dt (T/s)
mpi66m067d 97727
mpi66m067d 97743
efitql 97741
efitql 97727
efitql 97743
efitli 97741
efitli 97727
efitli 97743
≈ 20 G peak
value
pr13 97741
pr13 97727
pr13 97743
midplane saddle coill
difference signal
10
5
0
-5
-10
5.8
4.5
3.2
2.0
1.4
1.2
1.0
0.8
0.6
0.0625
0.0250
-0.0125
-0.0500
1500
1650
1800
1950
2100
2250
2400



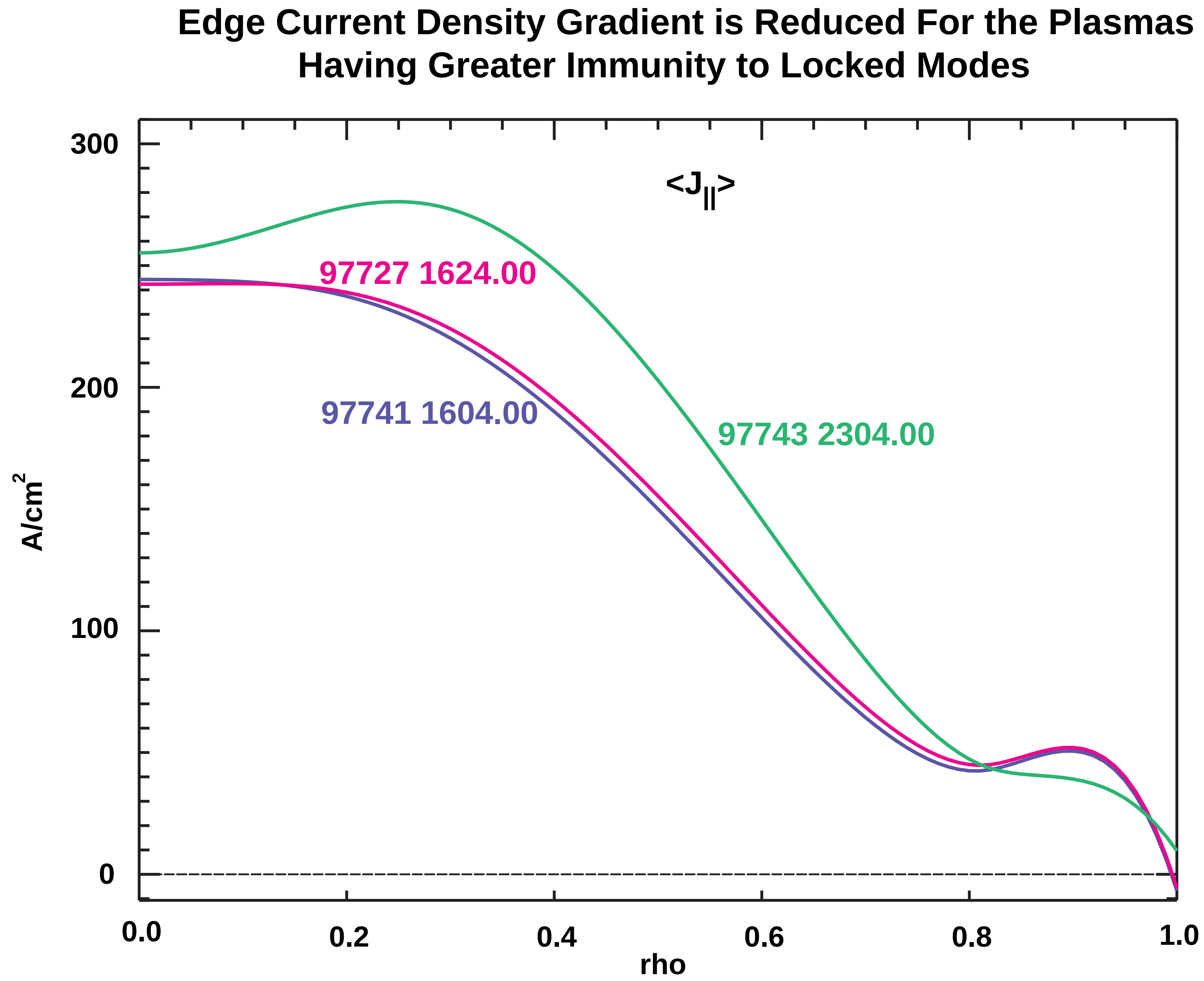
smoothing 2 points
baseline 100.0 msec
contour limits −19.4 19.3
shot 97741
phase = 86.8
poloidal angle
100
0
−100
m=3
−10
0
10
6 ESL with software C−coil subtraction
n=1 component only
phase = 281.5
toroidal angle
300
200
100
0
n=1
1600
1650
1700
1750
Time (msec)
−10
0
10
delta−B (G)

ANALYSIS OF CURRENT PROFILE

- The 30 Left beam is pulsed (10 ms on / 90 off) to obtain MSE and CER data. This is a small enough perturbation that it is not seen in the diamagnetic flux. β_p is $\approx$ 0.09 for these plasmas.
- This limits our profile analysis to these small windows. For the particular shots to be compared: 97741 and 97743 the times are respectively 35 ms prior to the onset of the locked mode and 35 ms prior to reaching $q_L = 3$.
- The analysis is based on n_e (Thomson), T_e (Thomson and ECE, T_I (CER), Z_{eff} (Visible Bremstrahlung), B_z (MSE) and a large array of external magnetic diagnostics. (The MSE data and fit are shown below.)
- We have taken care to treat the analysis identically for each shot, reducing the possible effects of systematic errors on the resulting edge current density.
- We also analyzed 97727, which should look very similar to 97741.



B_Z with E_r Correction
97743 2304.00
97741 1604.00
(differenet symbals are viewing angles)
Tesla
ρ
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0



Edge Current Density Gradient is Reduced For the Plasmas Having Greater Immunity to Locked Modes
<J||>
97727 1624.00
97741 1604.00
97743 2304.00
300
200
100
0
A/cm2
0.0
0.2
0.4
0.6
0.8
1.0
rho

Discussion and Conclusions

- We have observed a marked difference in the probablility of developing a locked mode in the neighborhood $q_L \geq 3$ depending on the plasma shape trajectory relative to the I_p ramp.
- If the safety factor evolves through q=3 in the I_p flattop, allowing more time for current to soak in, the probability (in Ohmic plasmas) decreases to near zero. Of course, this is done infrequently as the Ohmic flux consumption is increased.
- A kinetic analysis of the equilibrium shows that this slower evolution results in a lower $\nabla J_{\backslash\backslash}$ near the boundary consistent with expectations based on stability theory.
- Stability analysis is incomplete at this time.
- Such discharges seemed so bulletproof at q<2.5 that a small effort was made to use further vertical compression to get q<2. It was like hitting a brick wall – the lowest q_L we could reach was 2.12