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Rotating MHD Analysis for Disruption Event Characterization and Forecasting

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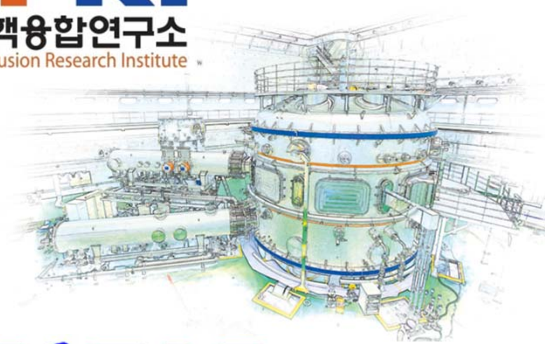

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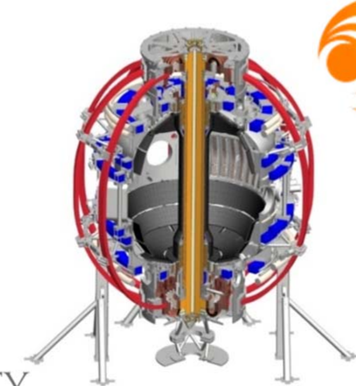

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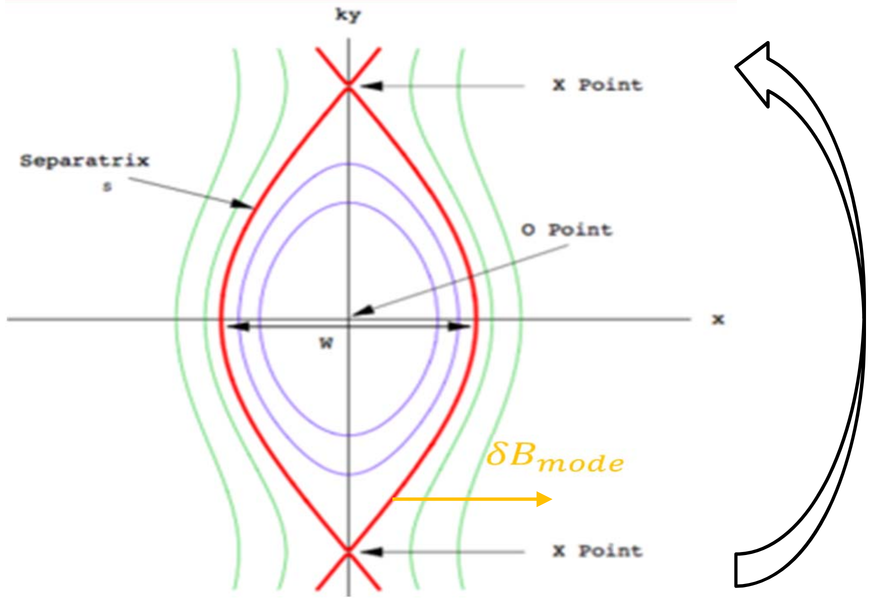
NSTX-U

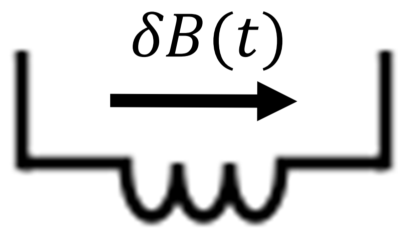
Automated identification of rotating MHD modes can be a practical tool for disruption forecast efforts

- Motivation:
  - Validate the automated identification of rotating MHD instabilities in a tokamak plasma
  - Develop a disruption warning level based on rotating MHD activity

- Talk Outline
  - Analysis and automated identification of rotating MHD
  - Set of criteria used to determine a warning level for disruptions
  - NSTX examples of varying plasma activity the code is tested on
  - Summary & next steps

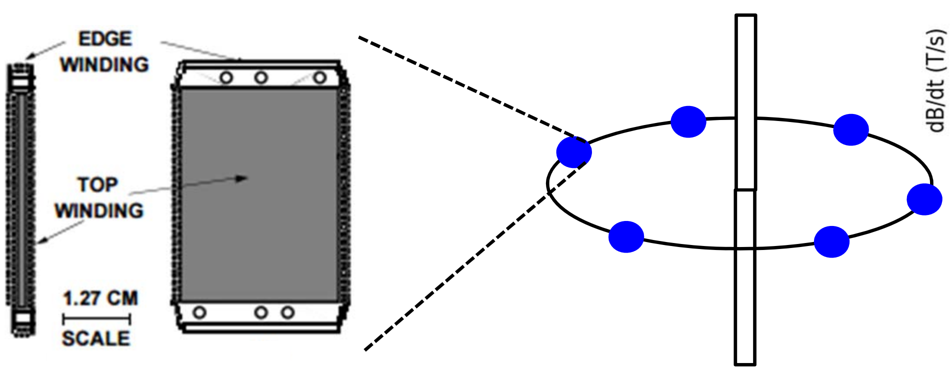
Toroidal magnetic probes measure amplitude of magnetic field perturbations from modes

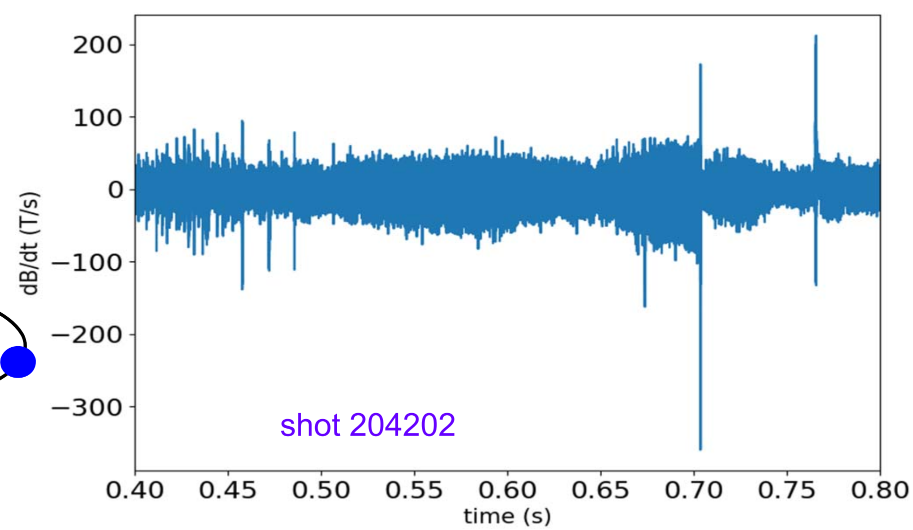




- Mode rotation can be detected by magnetic “pick up” coils placed toroidally around the tokamak

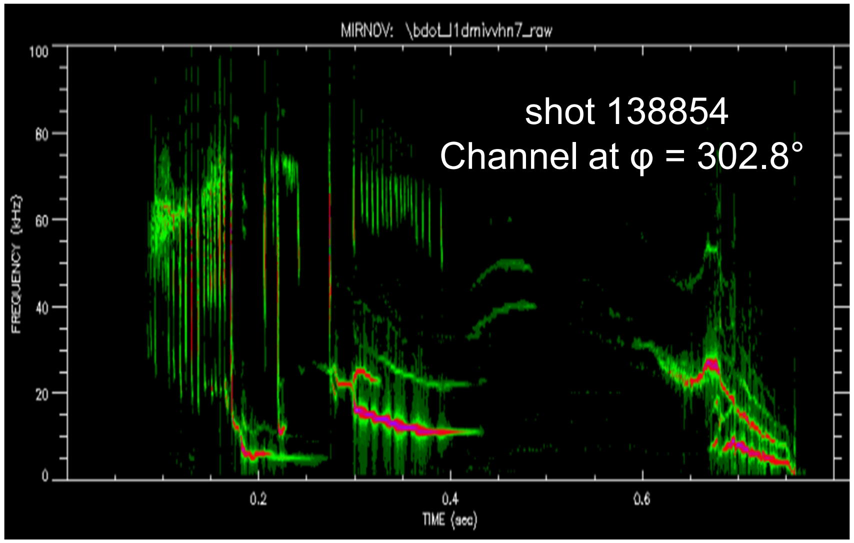
- Error fields and current gradients drive formation of magnetic islands

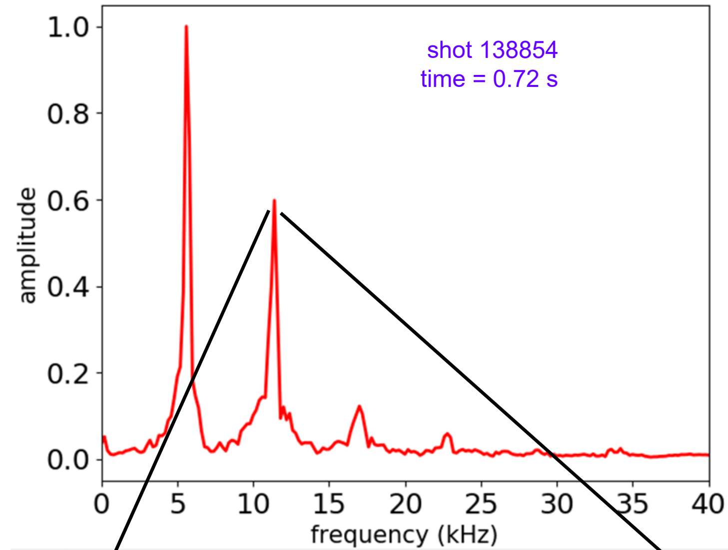


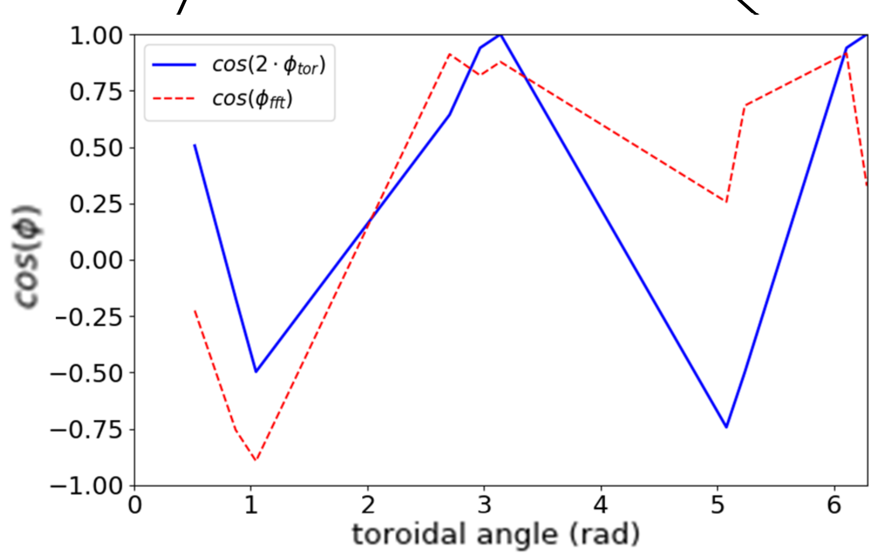


Spectral decomposition of probe signals used to identify the mode number and rotation frequency

- Consecutive short time FFTs give the phase and amplitude of a signal in frequency and time





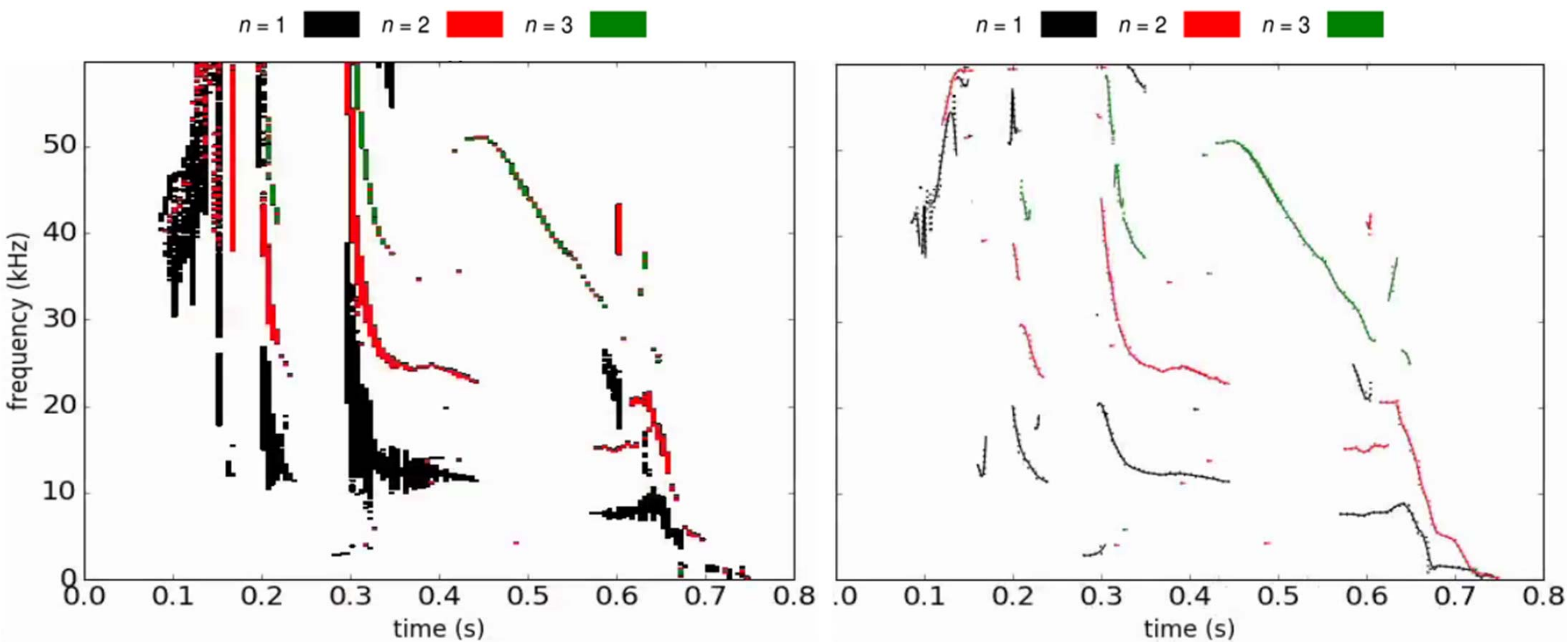


- The phase shifts at every frequency and time point for the channel array should match with the expected toroidal angle dependence of the predominant n mode.

Simplified generated spectrogram for further analysis of rotating MHD modes

- Selected peak amplitude frequency from bandwidth
- Performed smoothing fit on frequency curves

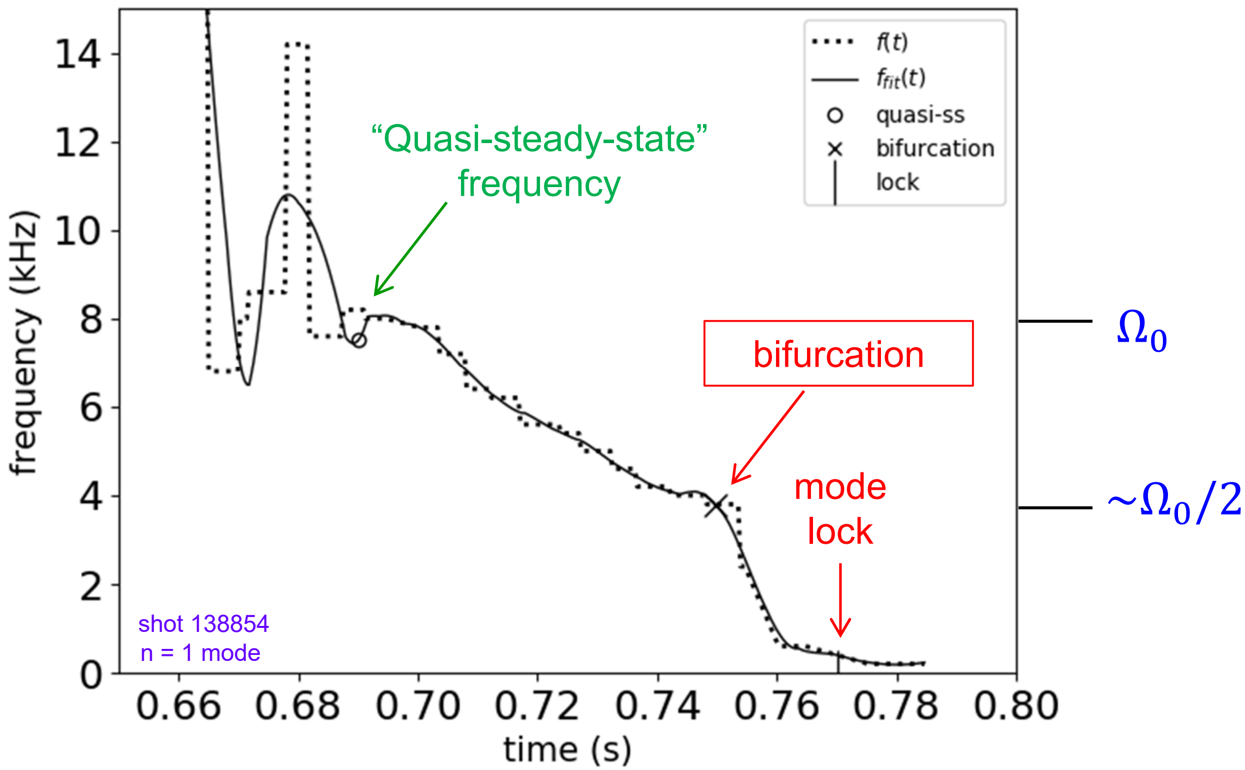
Spectogram → Rotating MHD Events



shot 130198

Rotating MHD modes create a friction in the plasma that leads to slowing of the modes and potential locking

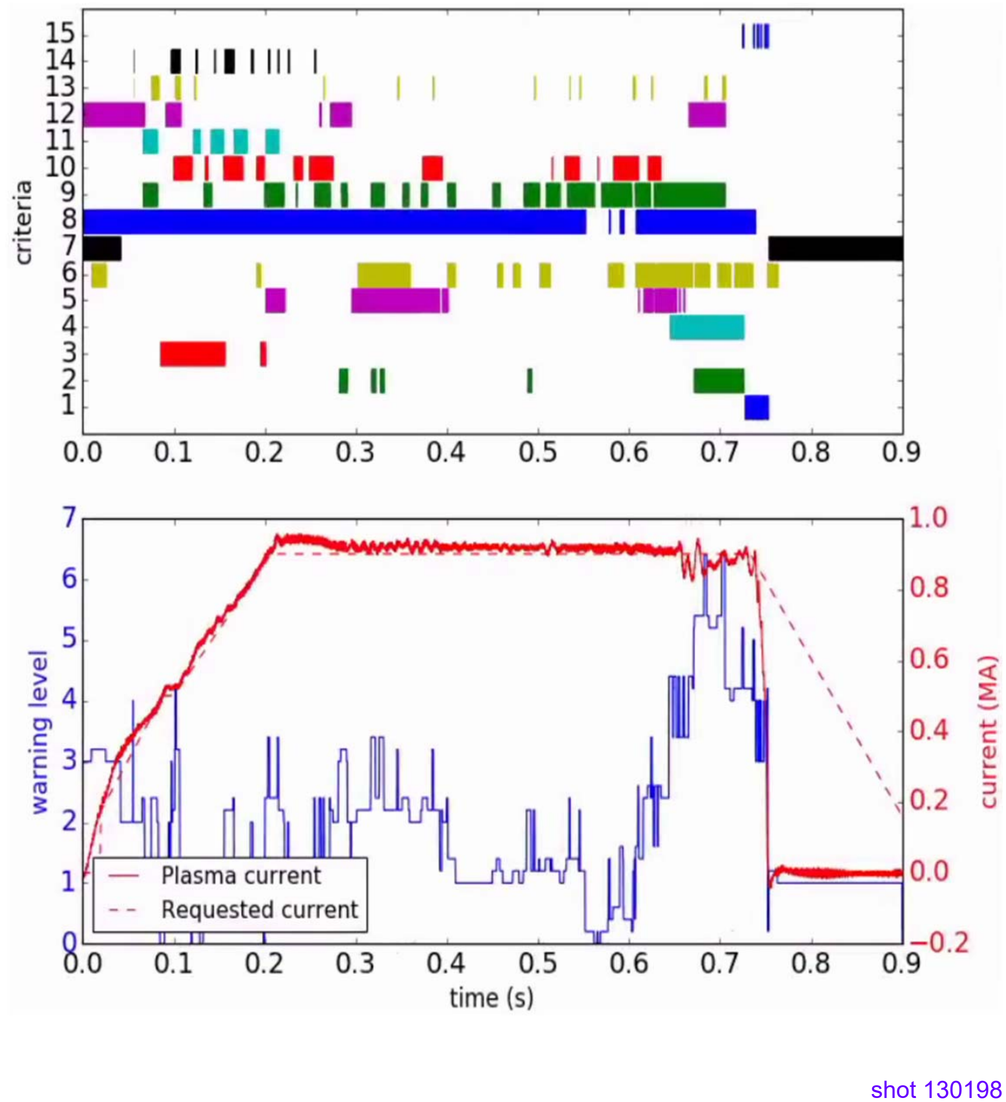
- Natural frequency of mode rotation is reached due to a force balance of drag and driving auxiliary heating
- In the process of slowing down the mode can lose force balance leading to a frequency bifurcation



Severity of mode determined from criteria based on rotating MHD analysis and relevant plasma signals

- Low frequency magnetic probes
- Rotation Profiles
- β_N and internal inductance
- Mode amplitude
- Past bifurcation
- Magnitude of frequency

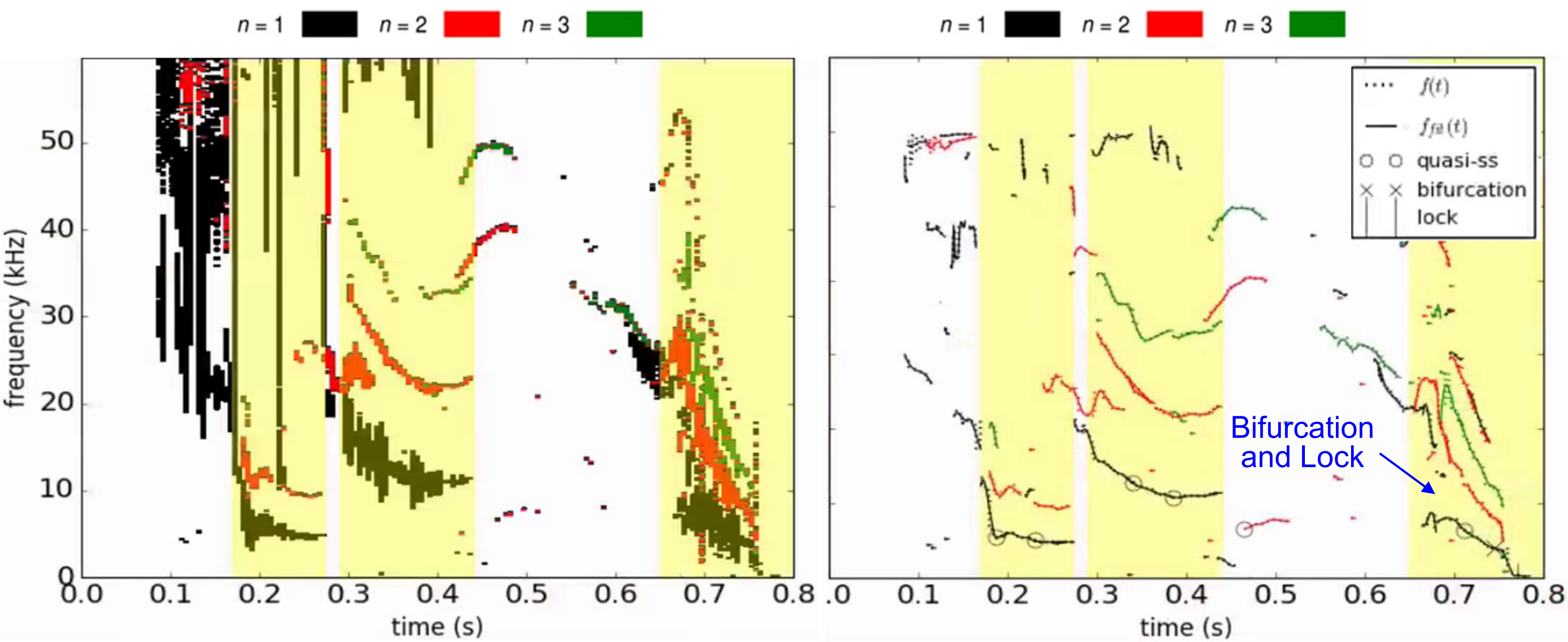
Criteria	Description
15	Locked n=1 strong
14	Outer core rotation
13	Mid core rotation
12	Low core rotation
11	Dec. outer rotation
10	Dec. mid rotation
9	Dec. core rotation
8	Low li
7	β_N/li range
6	Decreasing β_N
5	Strong mode
4	Bifurcation
3	High-freq
2	Low-freq
1	Lock freq



- Criteria cover magnetic and kinetic properties of the plasma relevant to rotating MHD mode evolution
- Summed criteria with the appropriate weights to generate disruption warning level

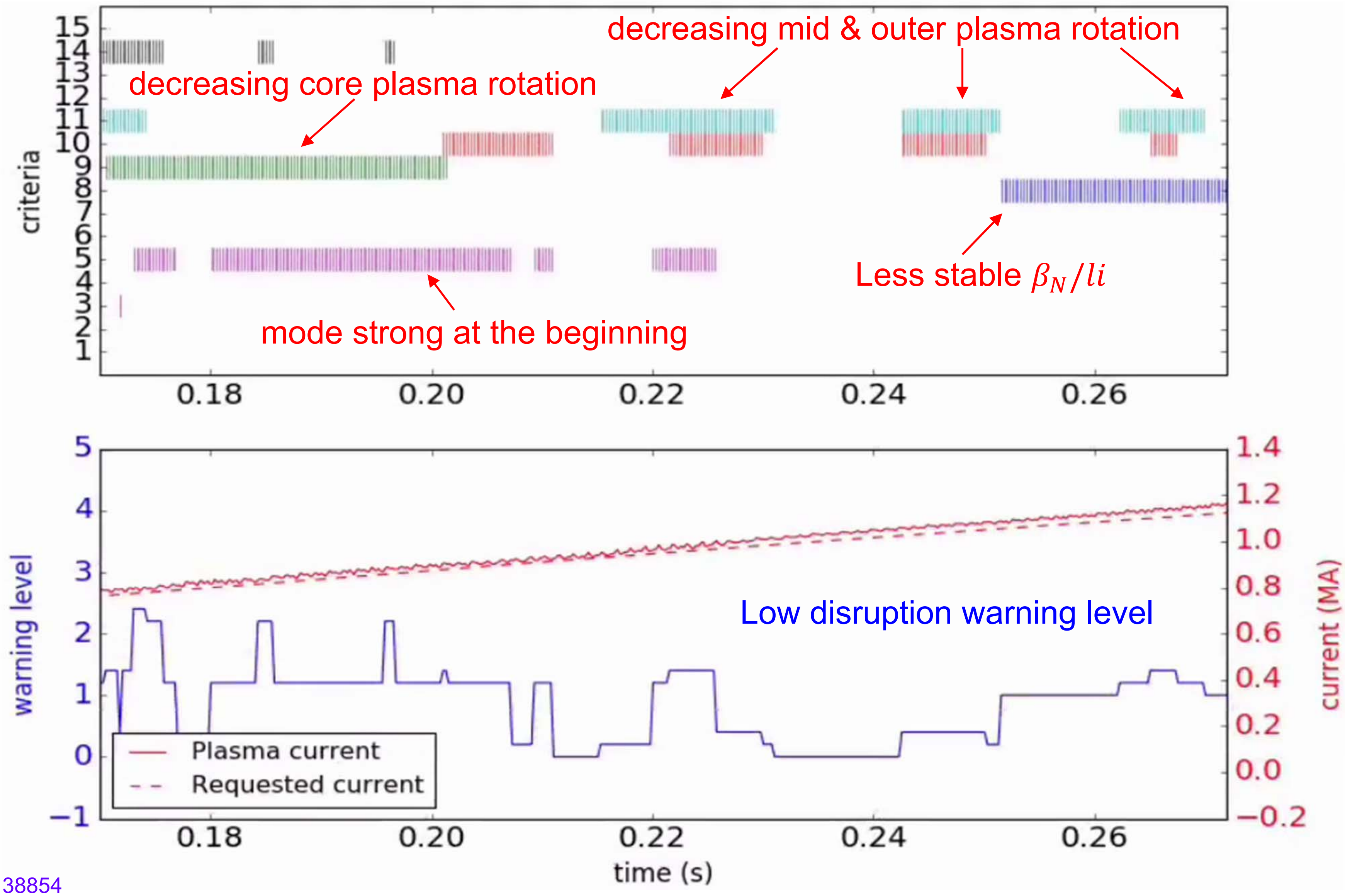
Example 1: Archetypal mode bifurcation and locking

- Separate into three periods of mode activity
  - During startup
  - At start of flat top
  - At start of ramp-down



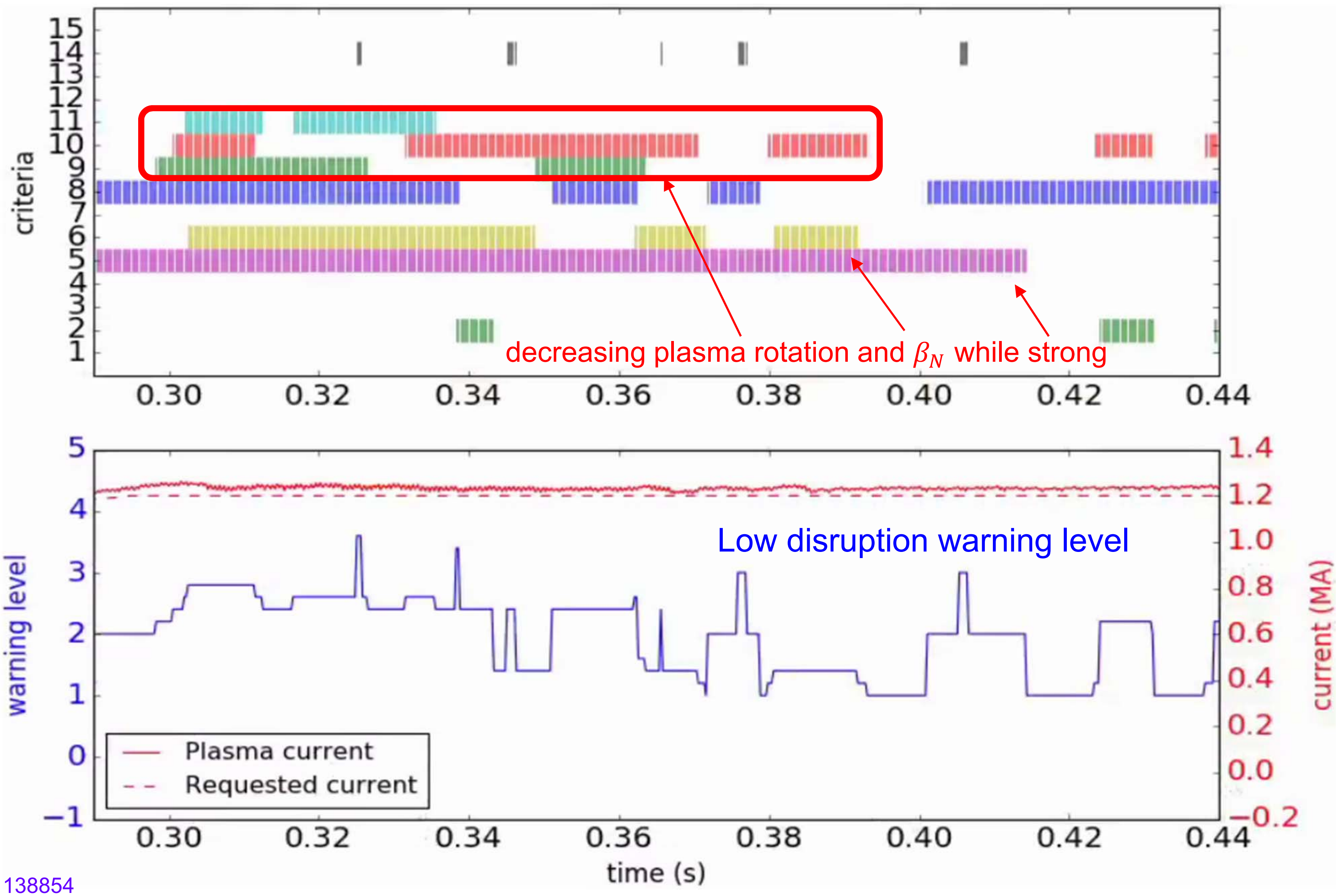
shot 138854

1st Period: Safe mode and plasma activity is shown by relatively low disruption warning level



shot 138854

2nd Period: Modes lead to dip in plasma rotation but plasma recovers and warning levels remain low



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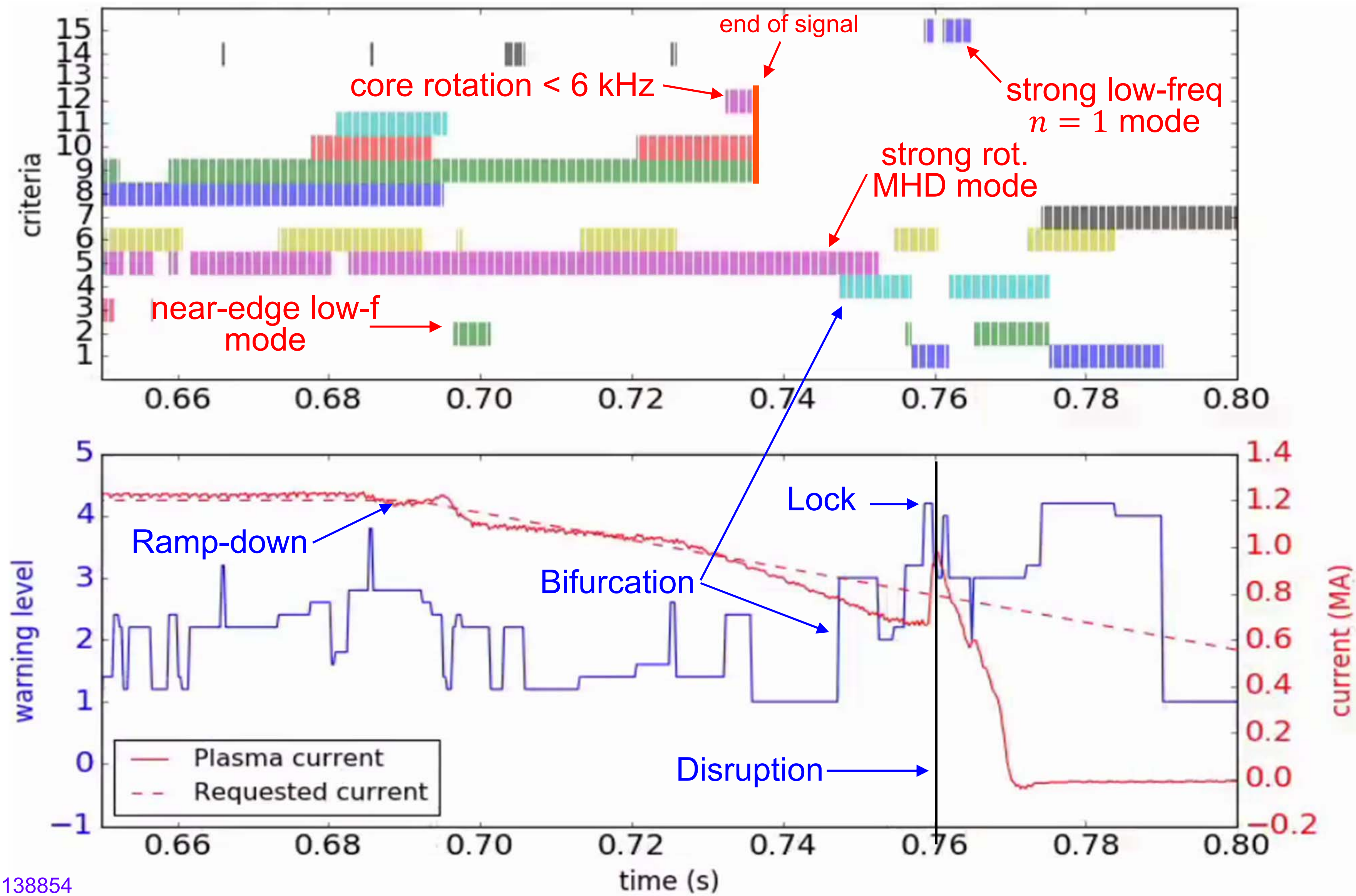
3rd Period: Warning level increases as plasma bifurcates, locks, and disrupts



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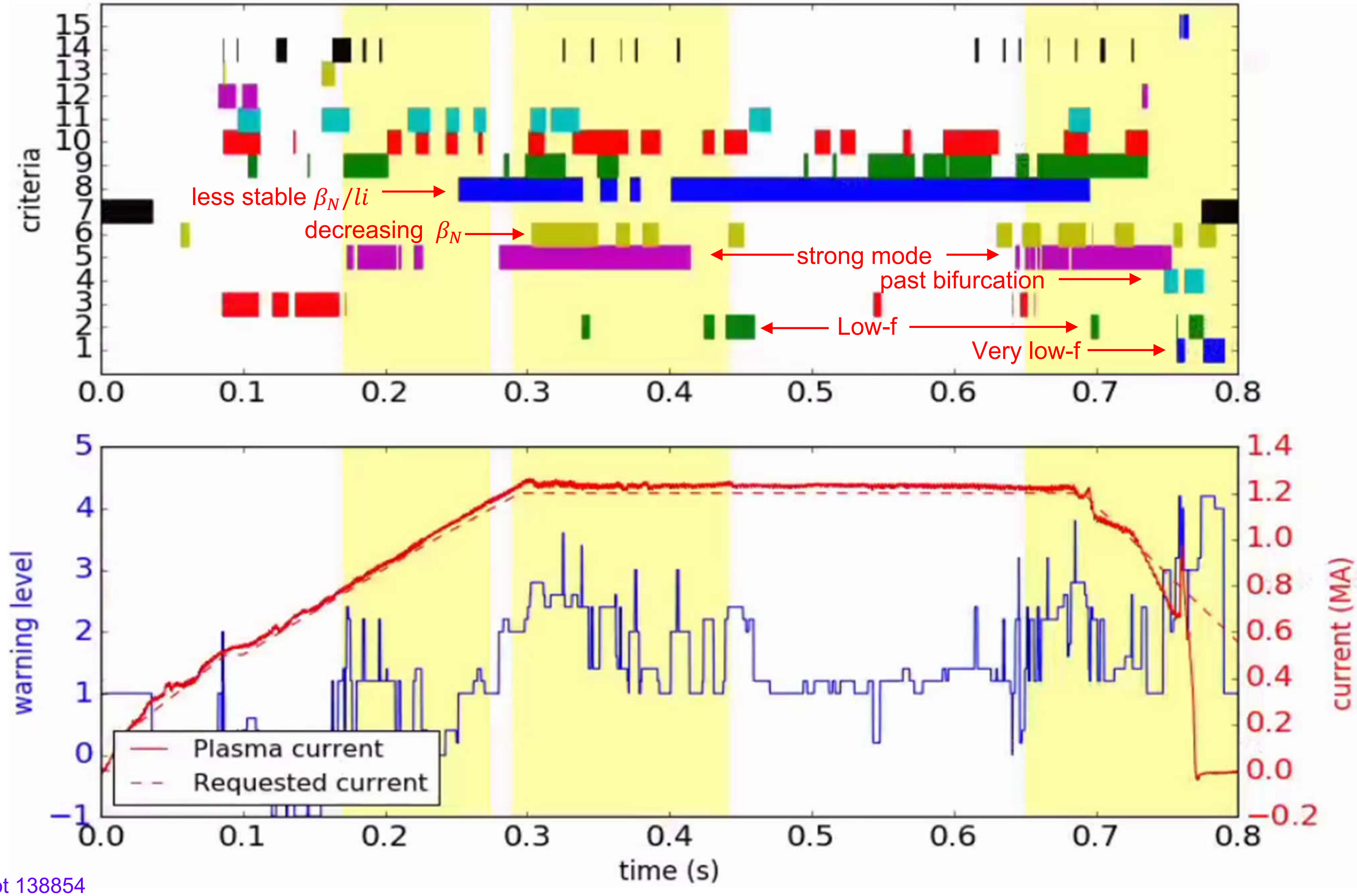
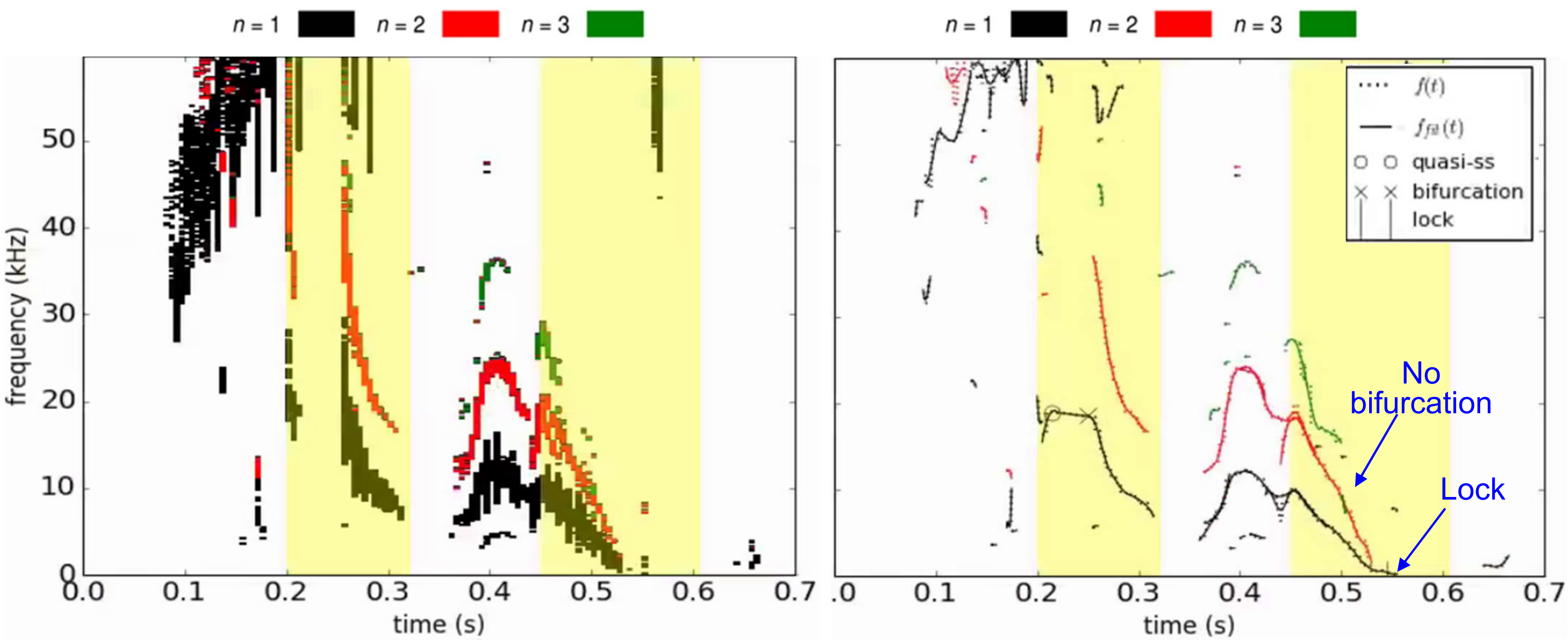
Example 1: Complete shot overview of warning levels shows relative severity of mode activity



shot 138854

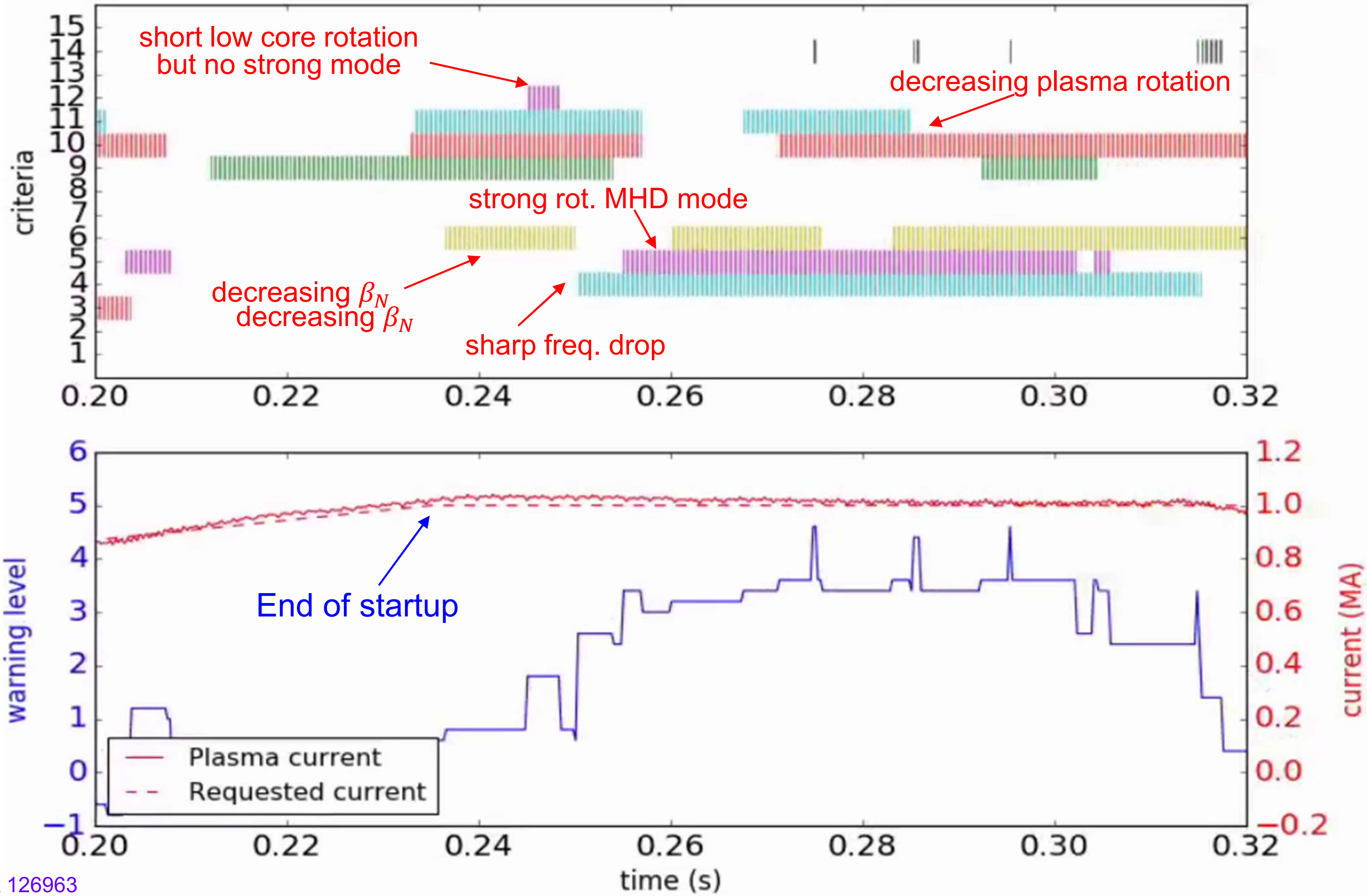
Example 2: Mode slowing and locking without bifurcation

- Bifurcation may be avoided if island size reduces through mode evolution
- Separate into 2 regions:
  - Sharp decrease in mode rotation frequency
  - Slowing and locking without a bifurcation (then disrupts)



shot 126963

1st Period: Sharp drop in mode rotation leads to increase in warning level



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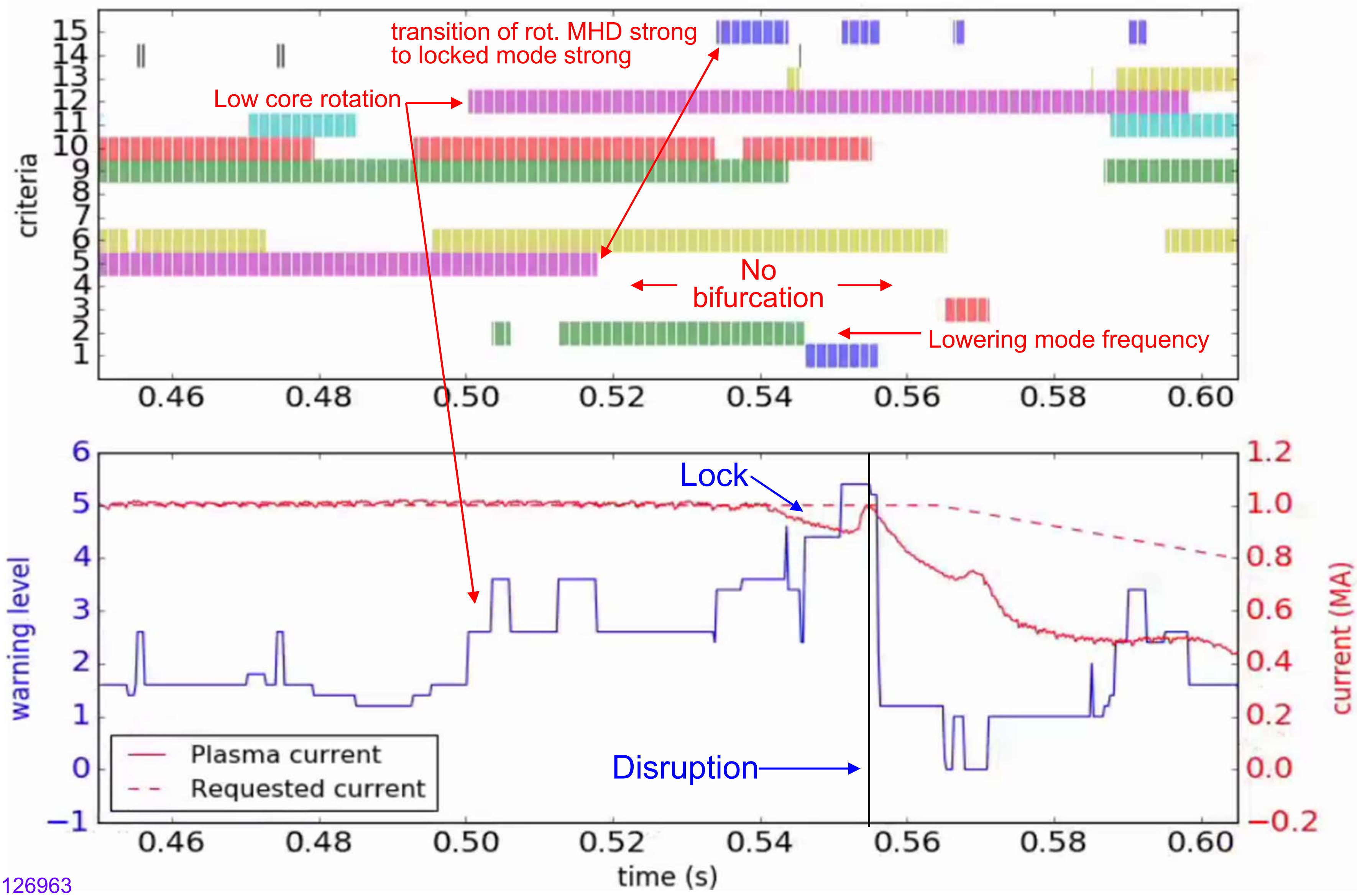
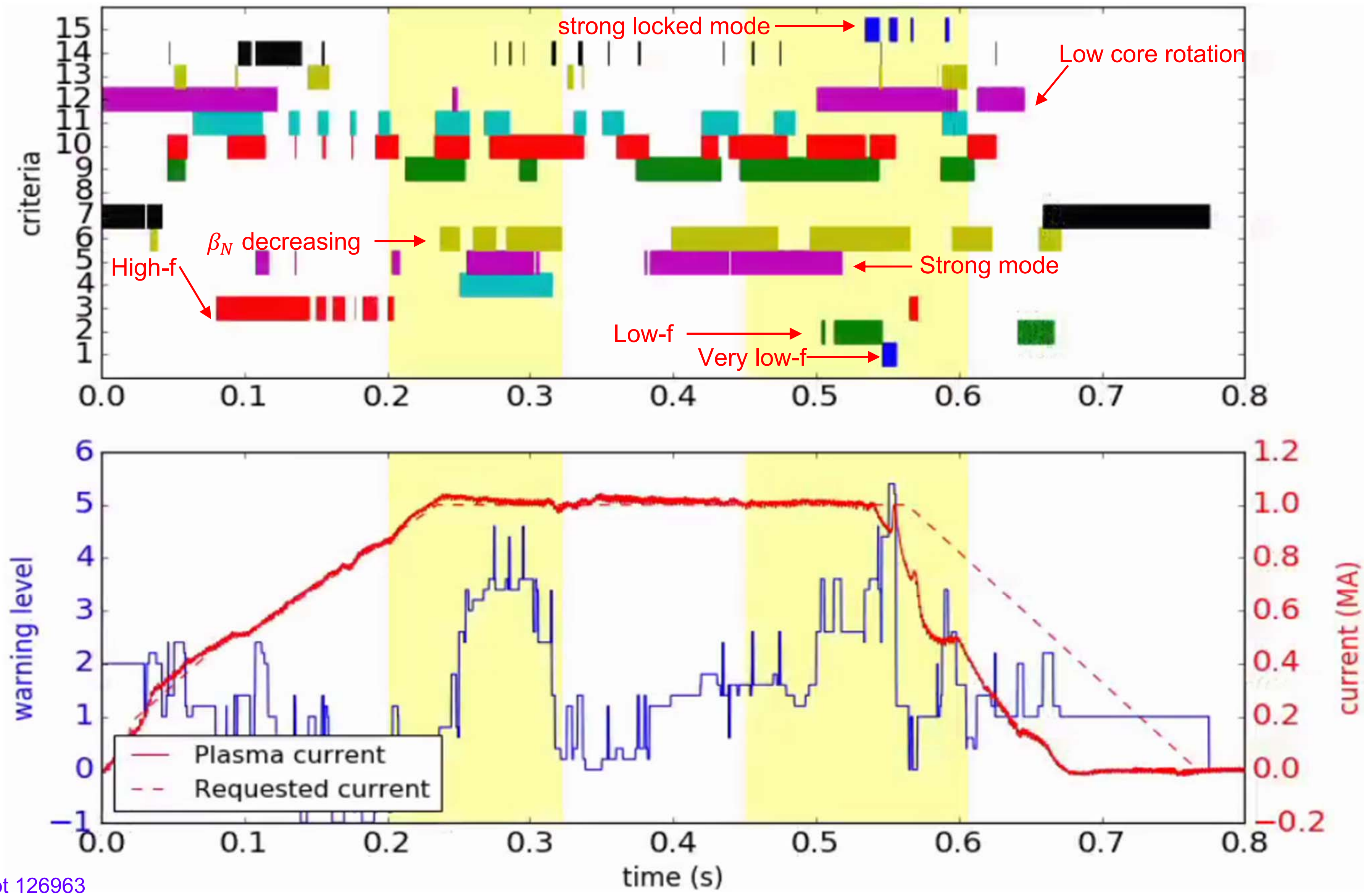
2nd Period: Rising warning level without bifurcation due to low plasma and mode rotation



shot 126963

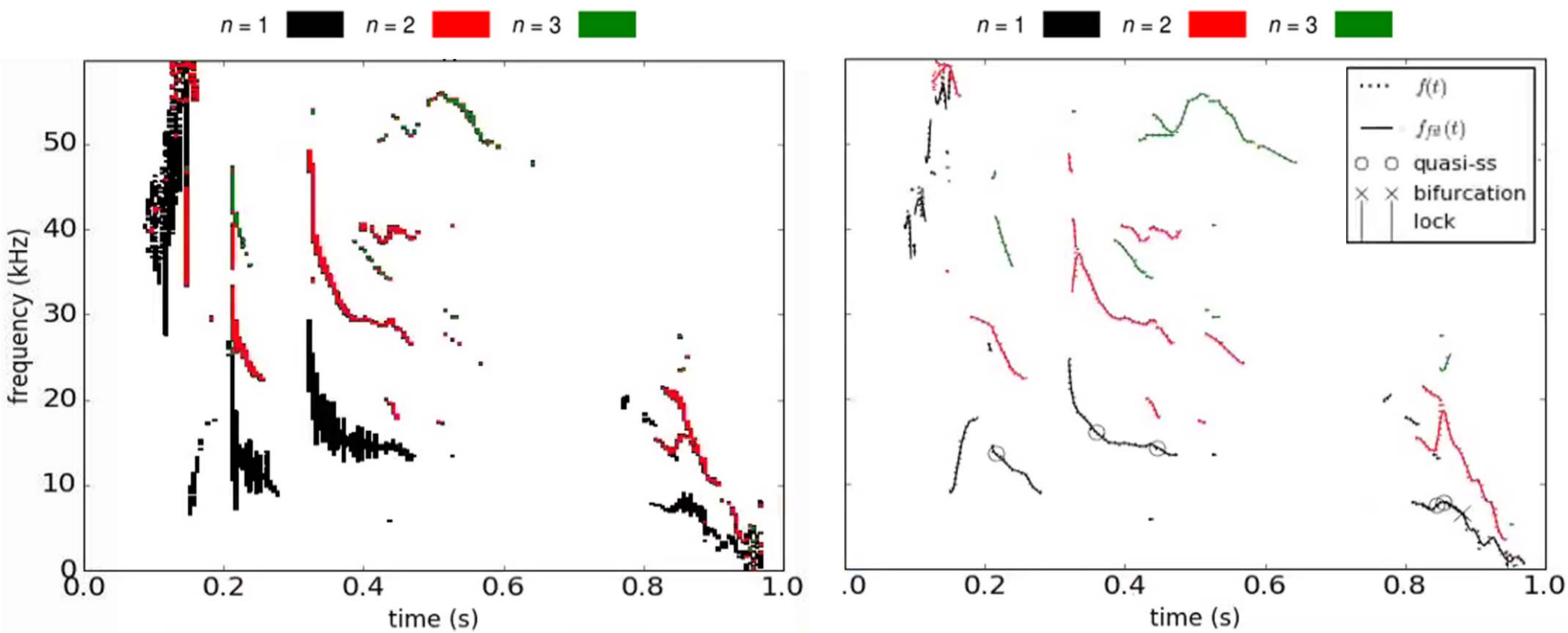
Example 2: Complete shot overview of warning levels shows relative severity of mode evolution



shot 126963

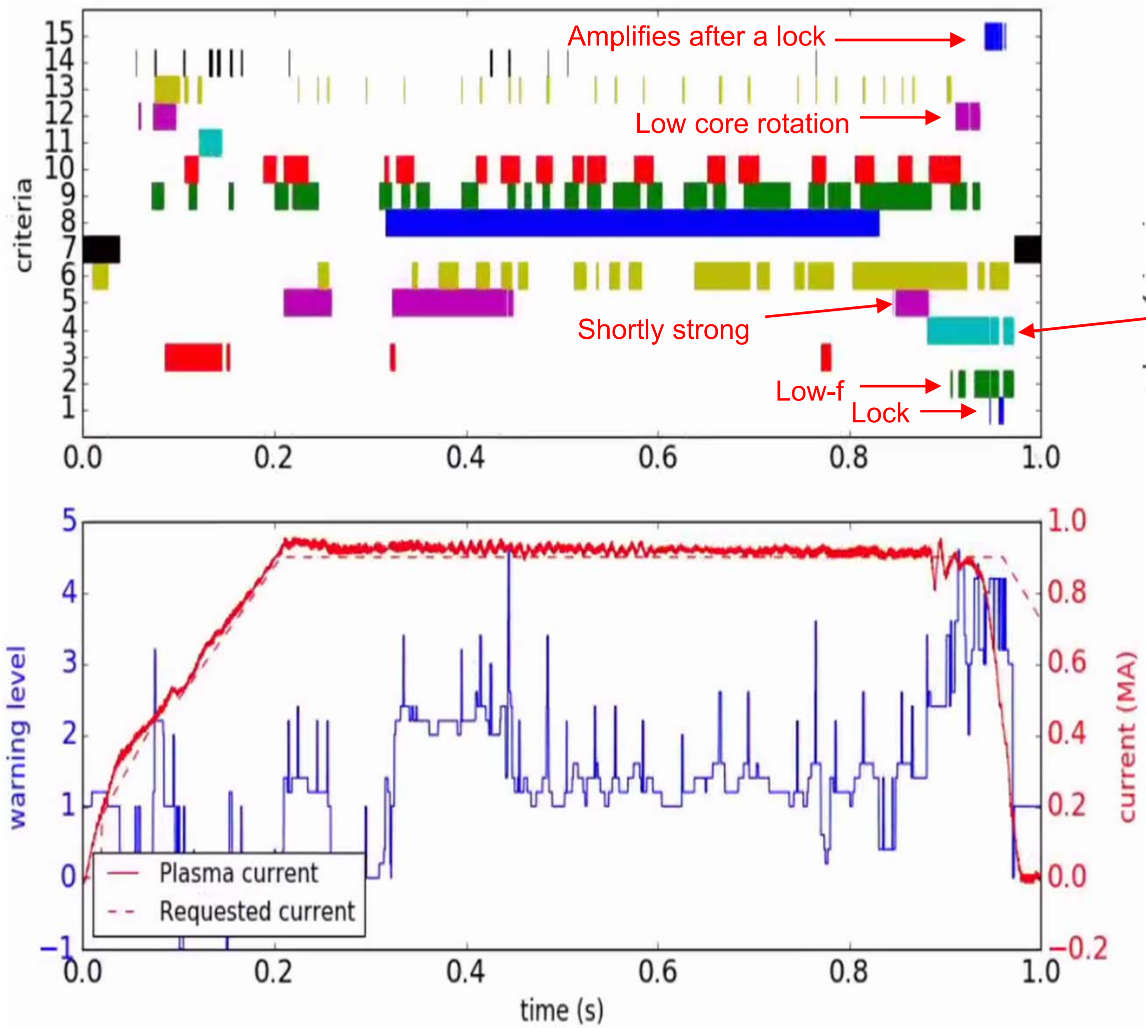
Example 3: Tearing mode approaching marginal island width

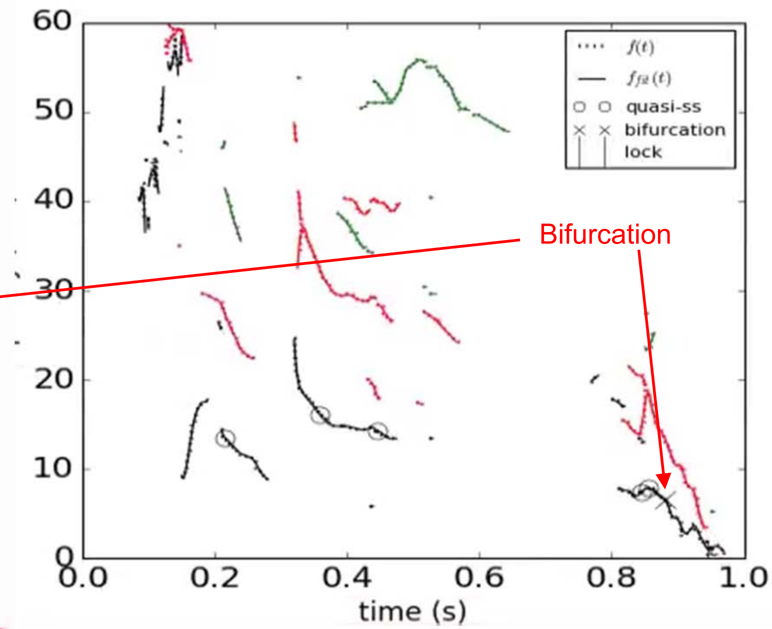
- More subtle case as the aim is to stabilize the mode with decreasing island size
- Locked modes amplify after plasma rotation is low enough



shot 130190

Example 3: Warning level increases primarily by lowered plasma rotation and mode frequency even at low amplitude



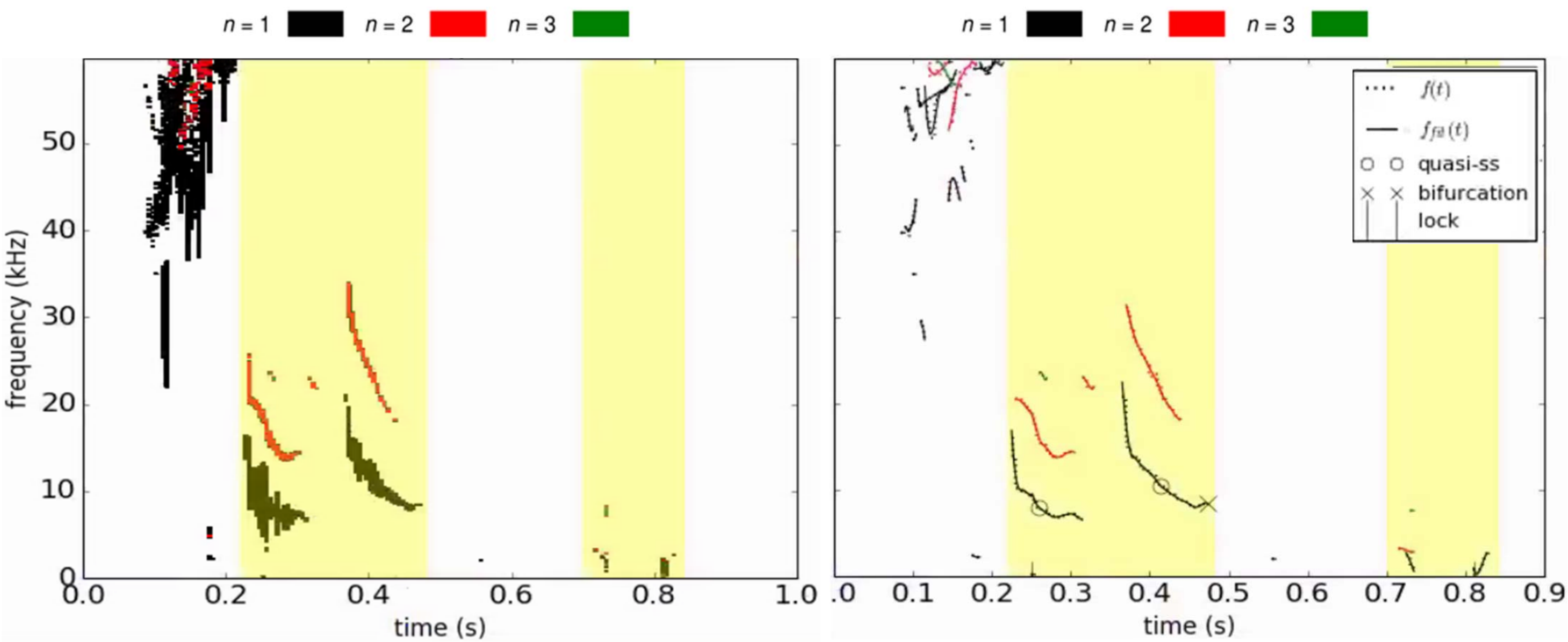


- Rising warning level to disruption

shot 130190

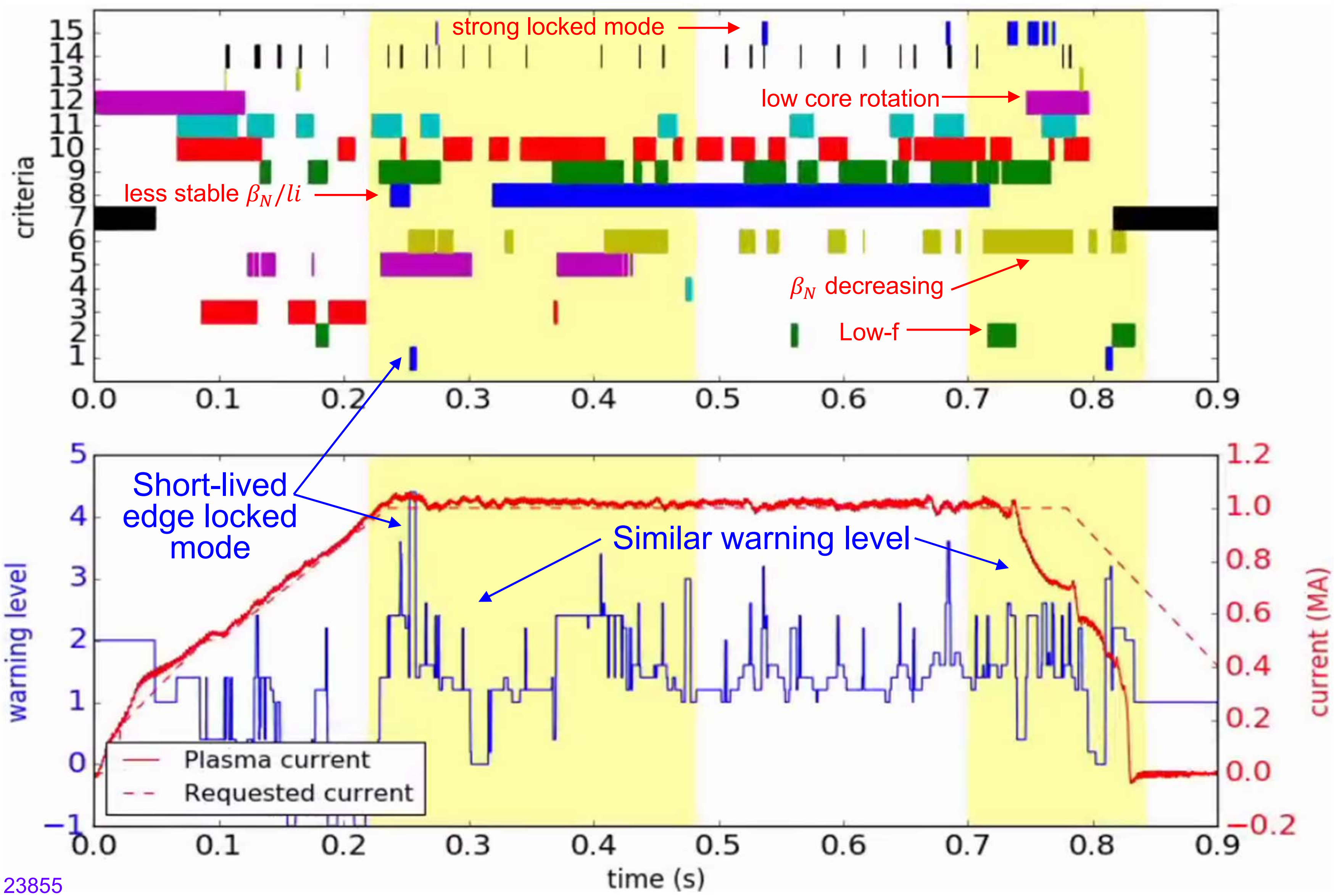
Example 4: Rotating MHD modes disappear and plasma disrupts

- The spectrogram follow a similar pattern for locked mode predominant shots
  - Rotating MHD modes disappear after startup
  - Very low-f mode activity near disruption



shot 123855

Example 4: Rotating MHD event warning levels correctly miss locked mode induced disruption



shot 123855

New automated identification of rotating MHD modes in DECAF is showing good success for disruption forecasting

Summary

- Developed a tool for analysis of rotating MHD mode activity in a tokamak plasma
- Used the tool to generate preliminary criteria for determining disruption warning levels. Tested in a variety of cases.

Next steps

- Improve the identification of the bifurcation event with known physics models
- Optimize the rotating MHD analysis parameters for improved identification of the mode
- Couple the rotating MHD event to other events in DECAF (e.g. reduced RWM model)
- Improve the definition, and optimize the logic and weights of the criteria for improved disruption forecasting

Thank you for listening

Any Questions?

BACKUPS

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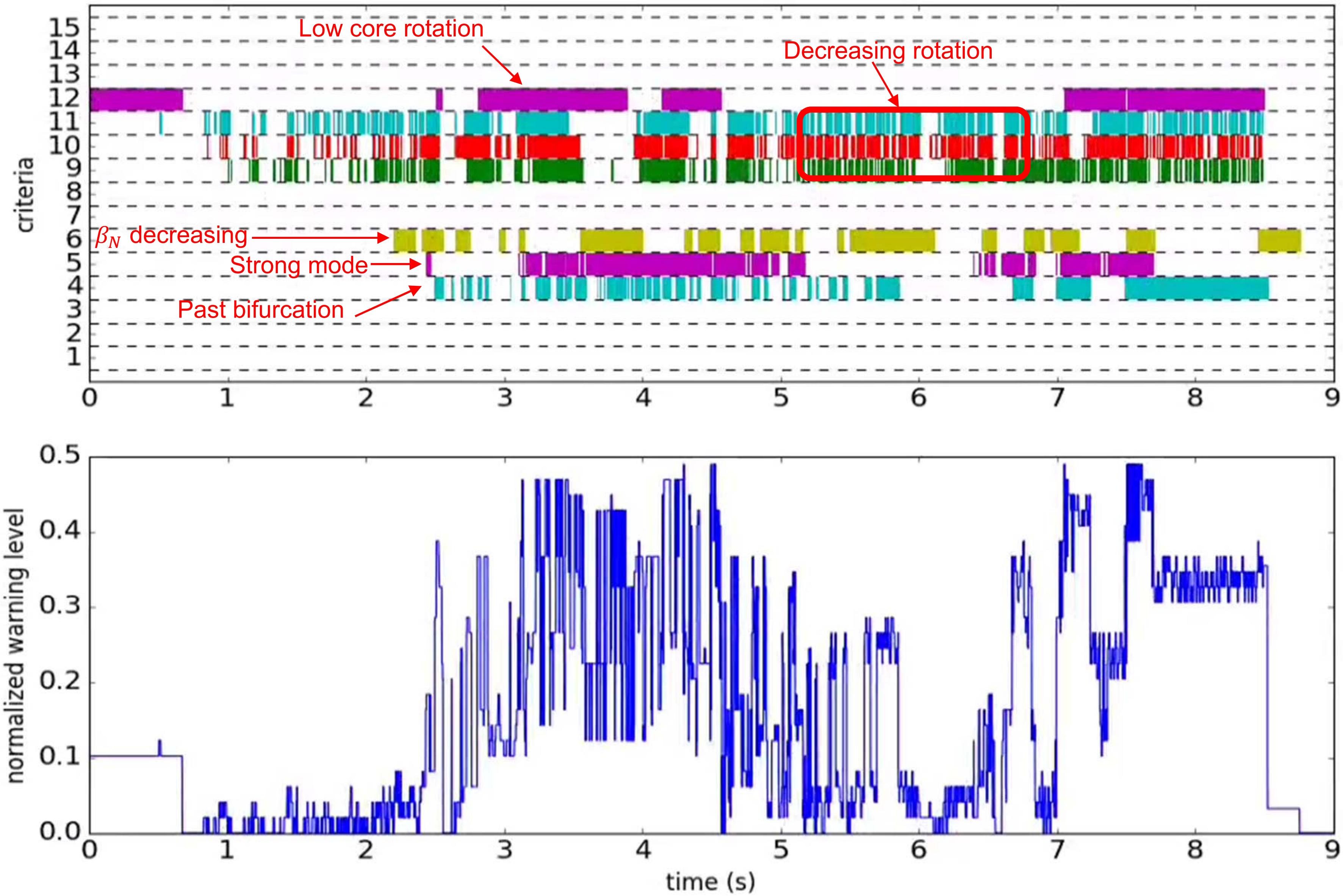
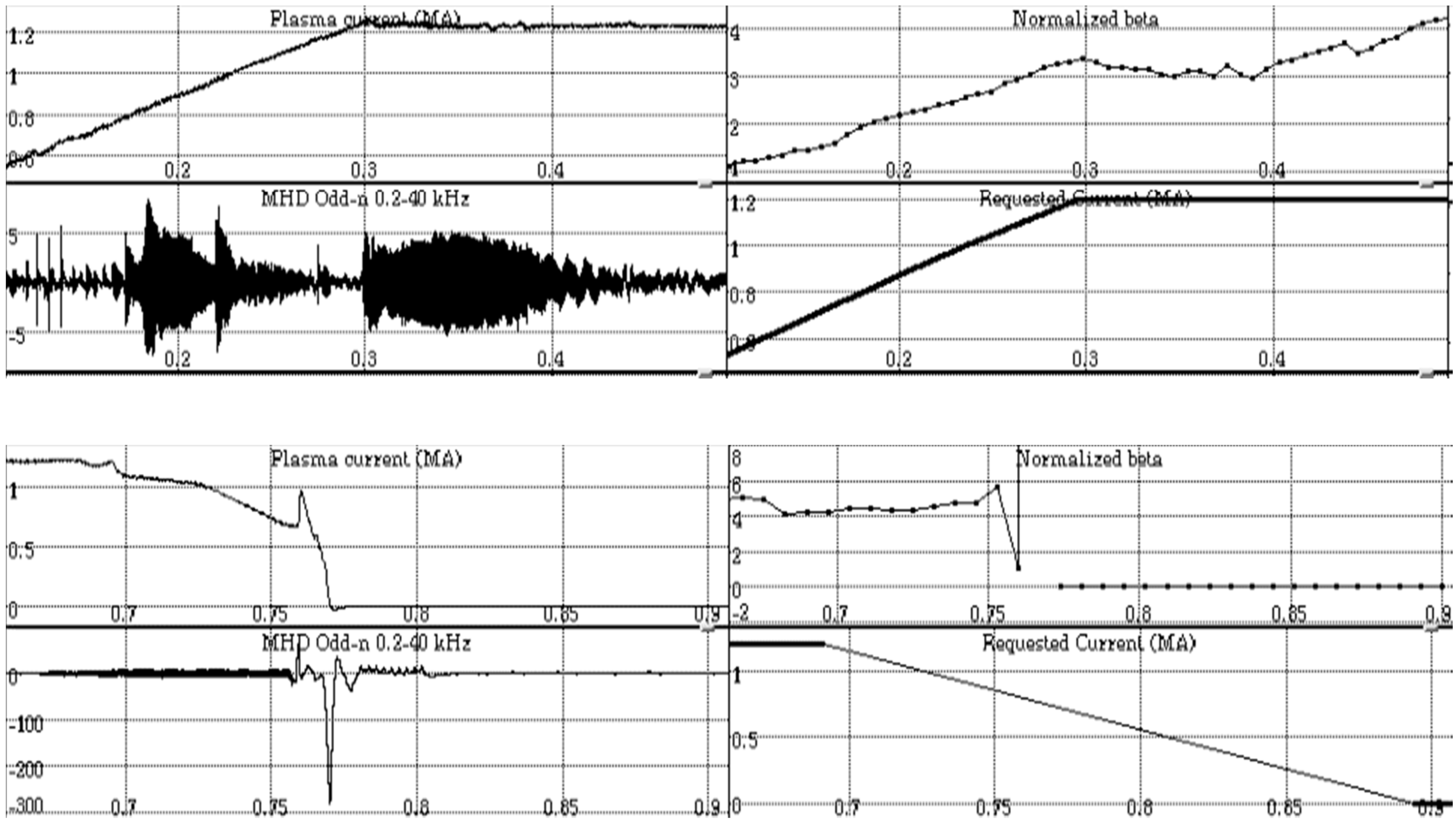


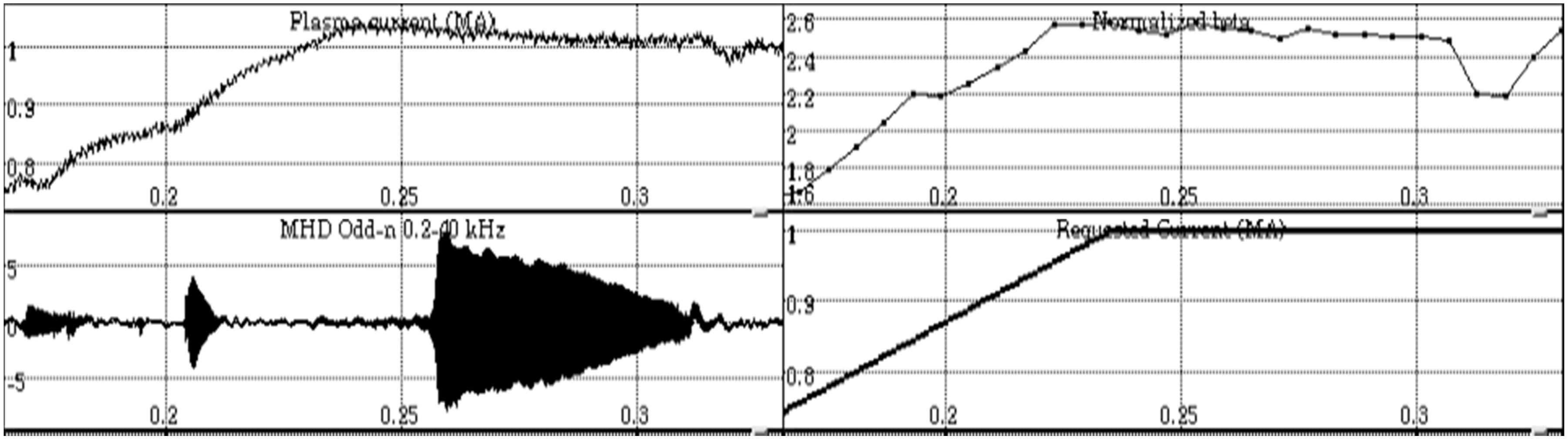
Low core rotation
Decreasing rotation
β_N decreasing
Strong mode
Past bifurcation
criteria
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
normalized warning level
0.5
0.4
0.3
0.2
0.1
0.0
time (s)

Shot 138854

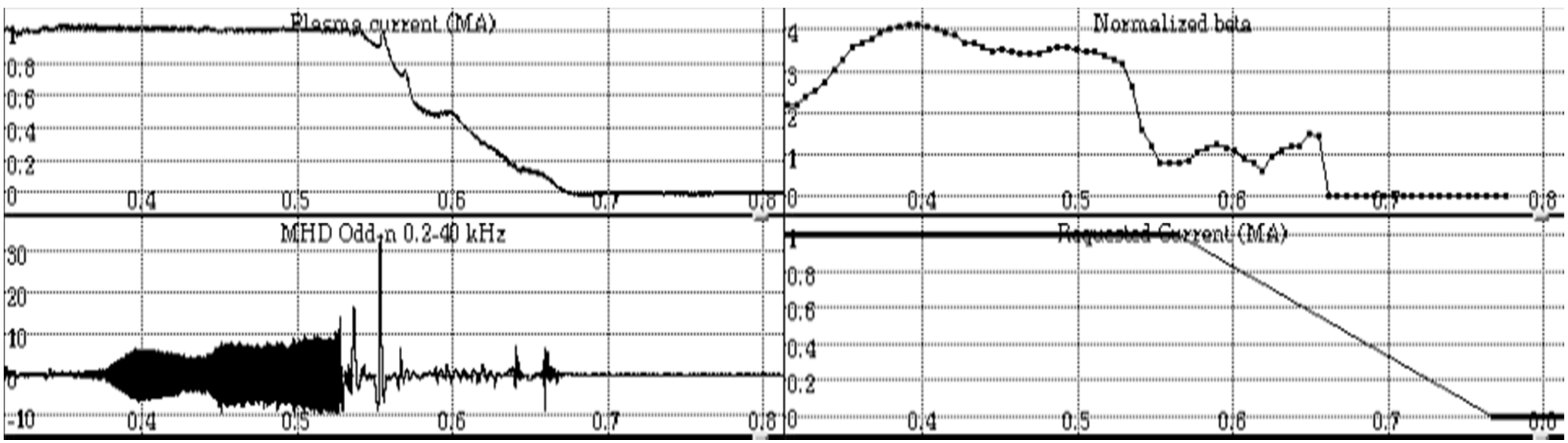


Plasma current (MA)
Normalized beta
MHD Odd-n 0.2-40 kHz
Requested Current (MA)
Plasma current (MA)
Normalized beta
MHD Odd-n 0.2-40 kHz
Requested Current (MA)

Shot 126963



Plasma current (MA)
Normalized beta
MHD Odd-n 0.2-40 kHz
Requested Current (MA)

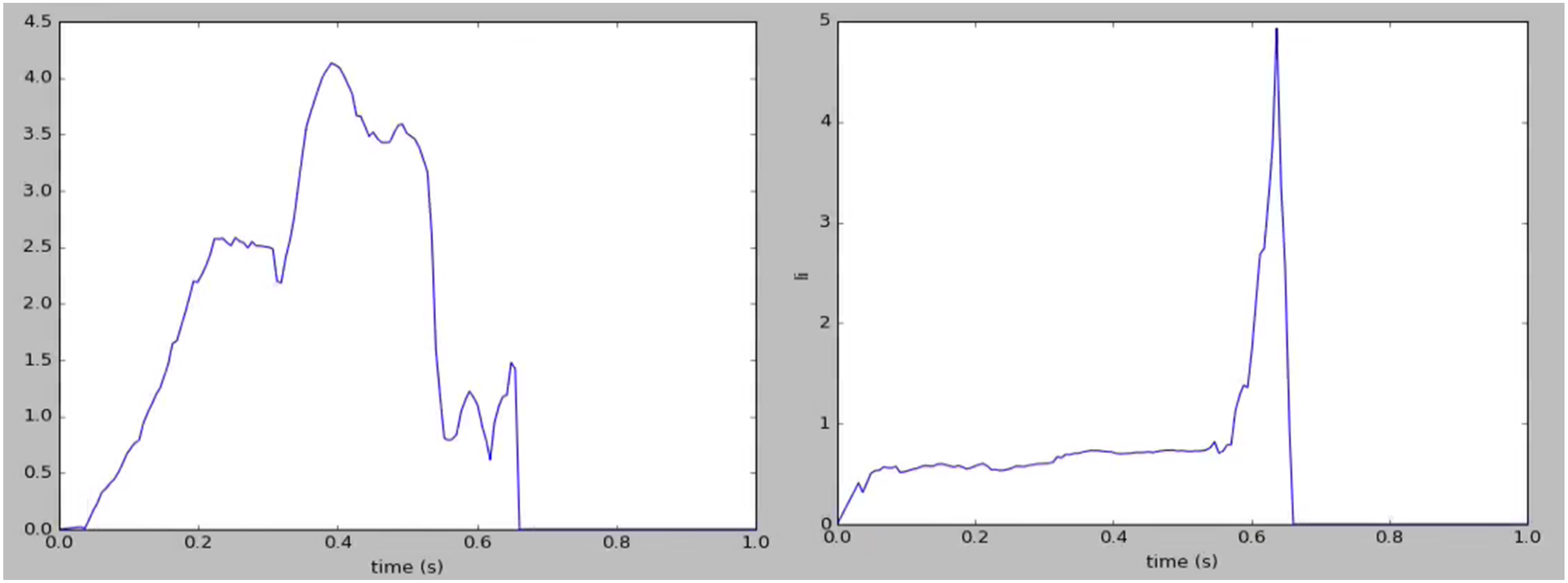


Plasma current (MA)
Normalized beta
MHD Odd-n 0.2-40 kHz
Requested Current (MA)

Shot 126963

- Low betaN shot with increasing li (betaN/li outside of stable range)

β_N li



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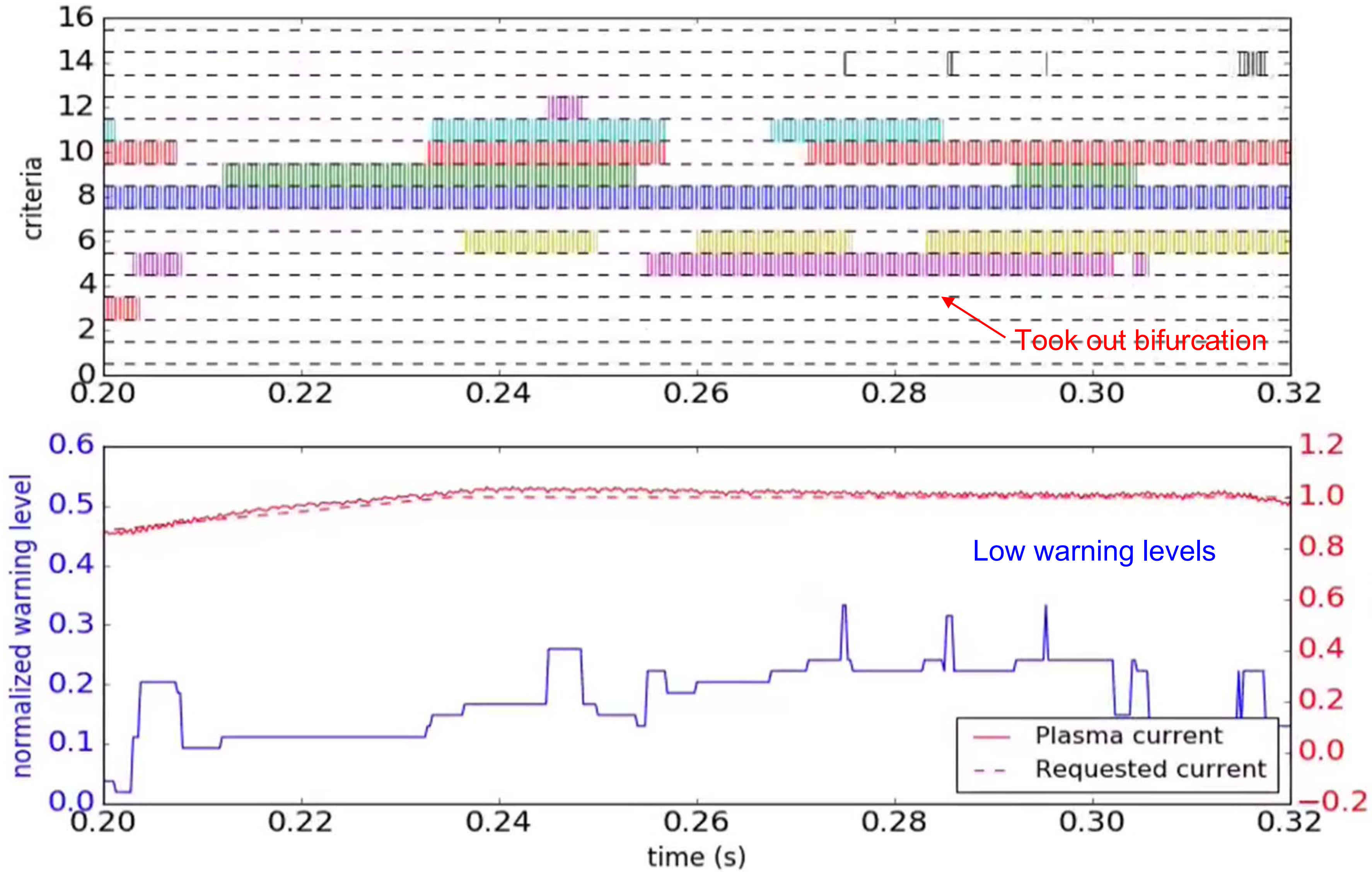
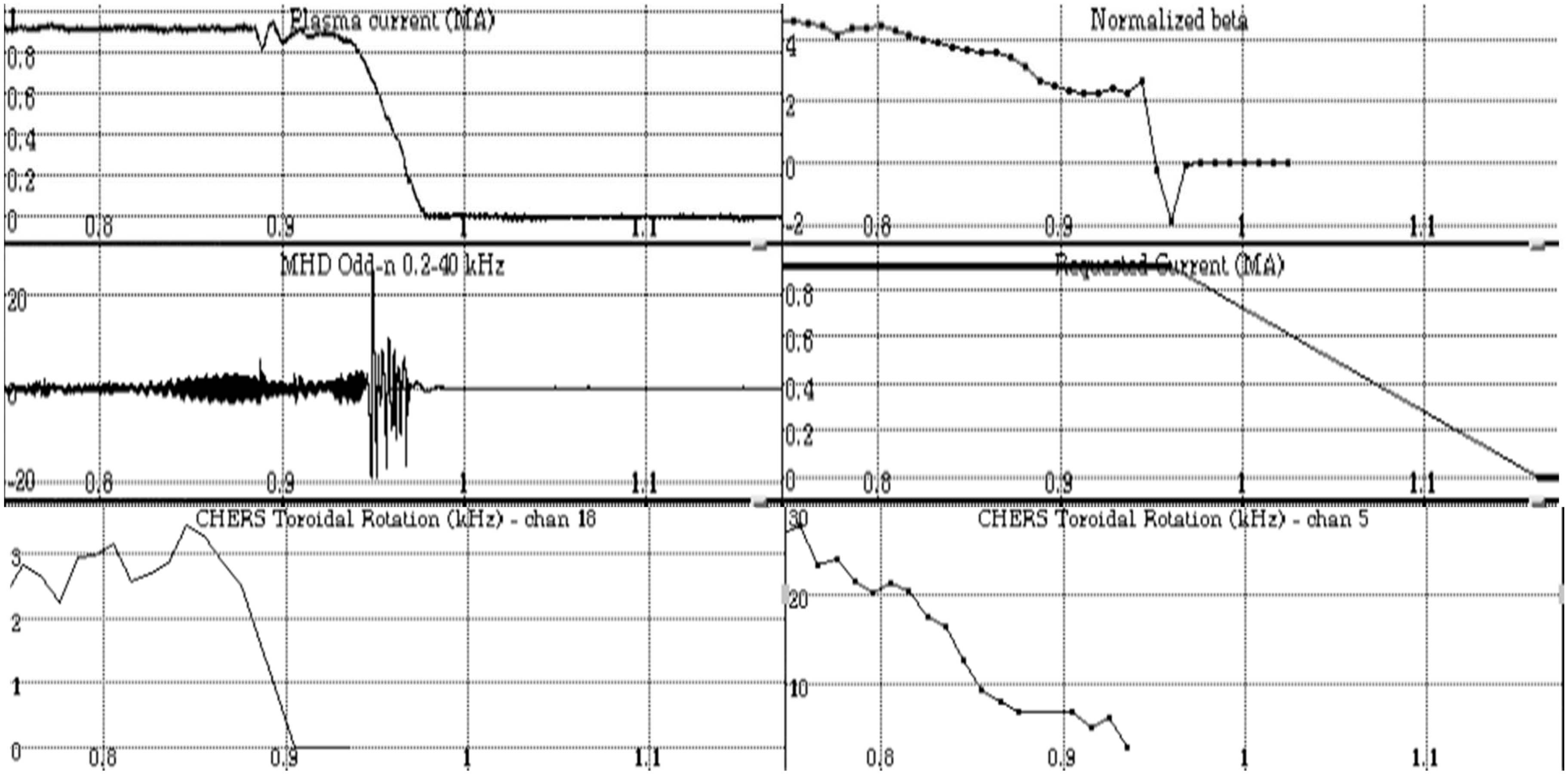
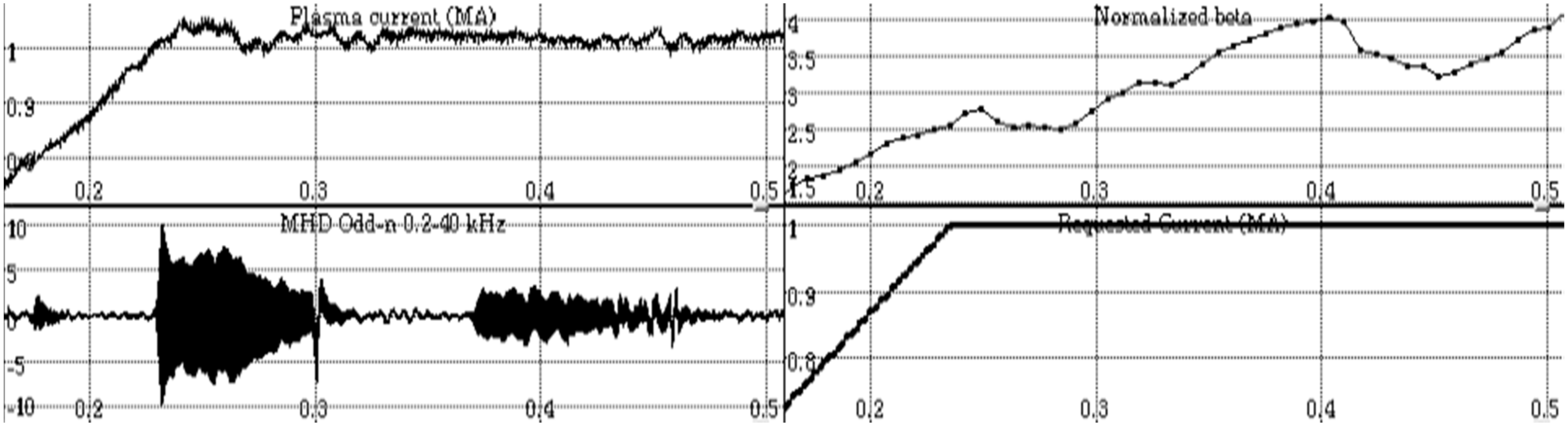


16
14
12
10
8
6
4
2
0
criteria
Took out bifurcation
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.6
0.5
0.4
0.3
0.2
0.1
0.0
normalized warning level
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
current (MA)
Low warning levels
Plasma current
Requested current
time (s)

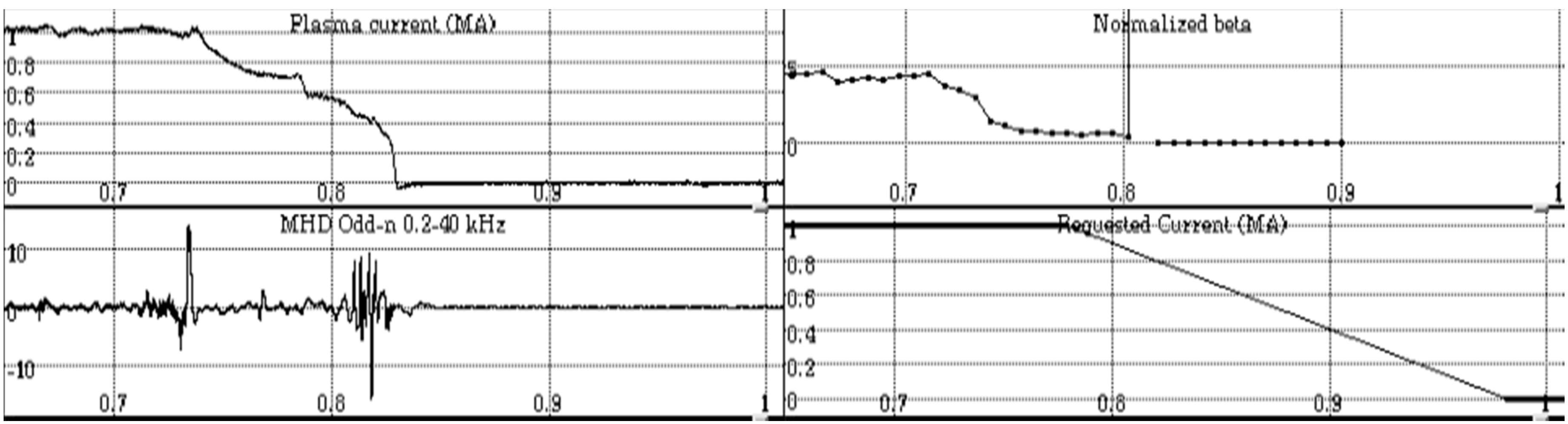
Shot 130190


Plasma current (MA)
Normalized beta
MHD Odd-n 0.2-40 kHz
Requested Current (MA)
CHERS Toroidal Rotation (kHz) - chan 18
CHERS Toroidal Rotation (kHz) - chan 5

Shot 123855



Plasma current (MA)
Normalized beta
MHD Odd-n 0.2-40 kHz
Requested Current (MA)



Plasma current (MA)
Normalized beta
MHD Odd-n 0.2-40 kHz
Requested Current (MA)

Torque balance of plasma rotation shows frequency bifurcation due to mode drag

- The drive torque T_{aux} from neutral beam injection
- The drag torque from plasma viscosity is expected to be negative and proportional to the angular speed of the plasma (like friction):

$$T_{2D} = -\frac{(I\Omega)}{\tau_{2D}}$$

- The EM drag torque is more complicated and depends on whether the plasma slips with respect to the magnetic flux

- "No slip":

$$T_{mode} = -\frac{k_1}{\Omega}$$

- "Slips":

$$T_{mode} = -k_1\Omega$$

- k_1 is proportional to the island width of TM

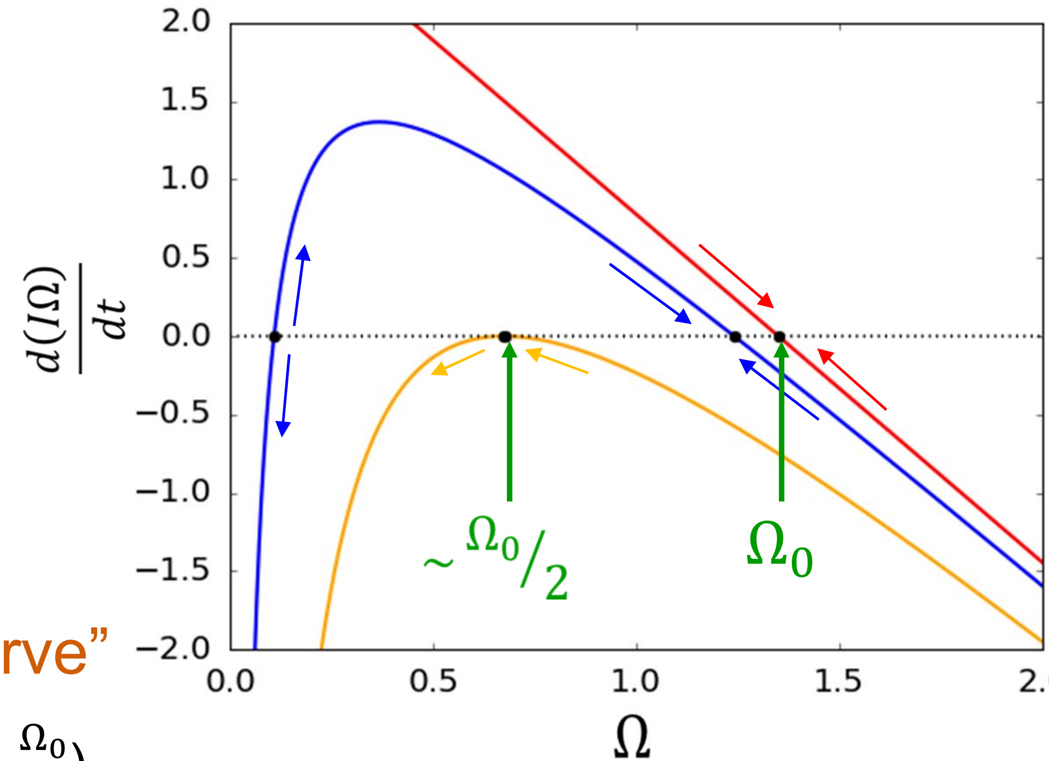
The model using a "no slip" condition has no steady state solutions at a large enough island width (k_1)

- For steady state

solutions: $\left(\frac{d(I\Omega)}{dt} = 0\right)$

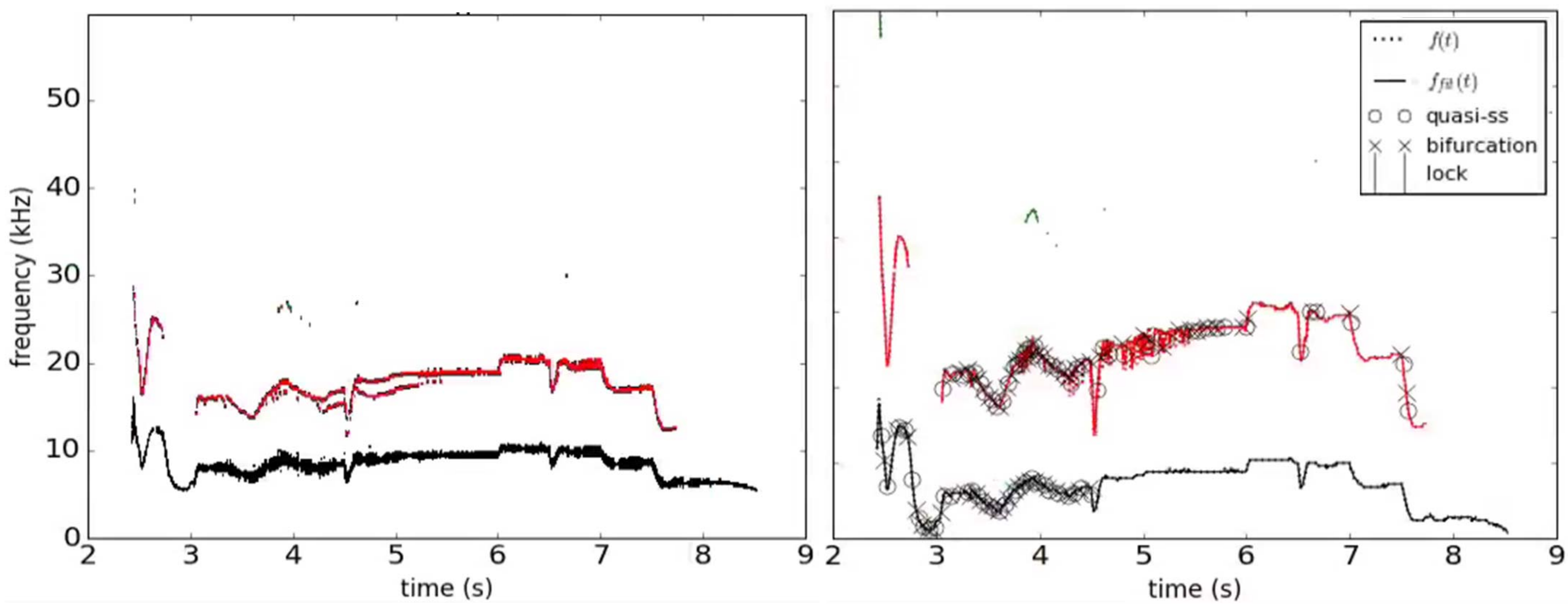
- k_1 = 0 : "red curve"
  - No mode present
- $k_1 < \frac{{T_{aux}}^2 \tau_{2D}}{4I}$: "blue curve"
  - Two steady state solution
- $k_1 = \frac{{T_{aux}}^2 \tau_{2D}}{4I}$: "orange curve"
  - One steady state solution ($\sim \frac{\Omega_0}{2}$)

$$\frac{d(I\Omega)}{dt} = T_{aux} - \frac{k_1}{\Omega} - \frac{(I\Omega)}{\tau_{2D}}$$



- Bifurcation
  - At close to half the steady state natural rotation frequency (Ω_0)

KSTAR



frequency (kHz)
50
40
30
20
10
0
2
3
4
5
6
7
8
9
time (s)
f(t)
$f_{fit}(t)$
quasi-ss
bifurcation
lock

Outline (~25 slides)

- Introduction (2)
- Algorithm description (5)
- Criteria description (4)
- Results (10)
  - NSTX (5)
    - Case 1
    - Case 2
    - Case 3
  - KSTAR (5)
    - Case 1
    - Case 2
    - Case 3
- Concl. & next steps (larger database, more machines, bifurcation) (2)