OV/4-5 Progress in Disruption Prevention for ITER

E.J. Strait, with

J.L. Barr[1], M. Baruzzo[2], J.W. Berkery[3], R.J. Buttery[1], P.C. de Vries[4], N.W. Eidietis[1], R.S. Granetz[5], J.M. Hanson[3], C.T. Holcomb[6], D.A. Humphreys[1], J.H. Kim[7], E. Kolemen[8], M. Kong[9], N.C. Logan[8], M. Maraschek[10], M. Okabayashi[8], J.K. Park[8], A. Pau[11], G. Pautasso[10], F.M. Poli[8], C. Rea[5], S.A. Sabbagh[3], E. Schuster[12], U.A. Sheikh[9], C. Sozzi[13], F. Turco[3], A.D. Turnbull[1], Z.R. Wang[8], W.P. Wehner[12], L. Zeng[14]

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[6] Lawrence Livermore National Laboratory [7] National Fusion Research Institute (Daejeon) [8] Princeton Plasma Physics Laboratory
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[12] Lehigh University [13] Istituto di Fisica del Plasma (Milano) [14] Institute of Plasma Physics (Hefei)

Burning Plasmas Must Operate with Very Few Disruptions

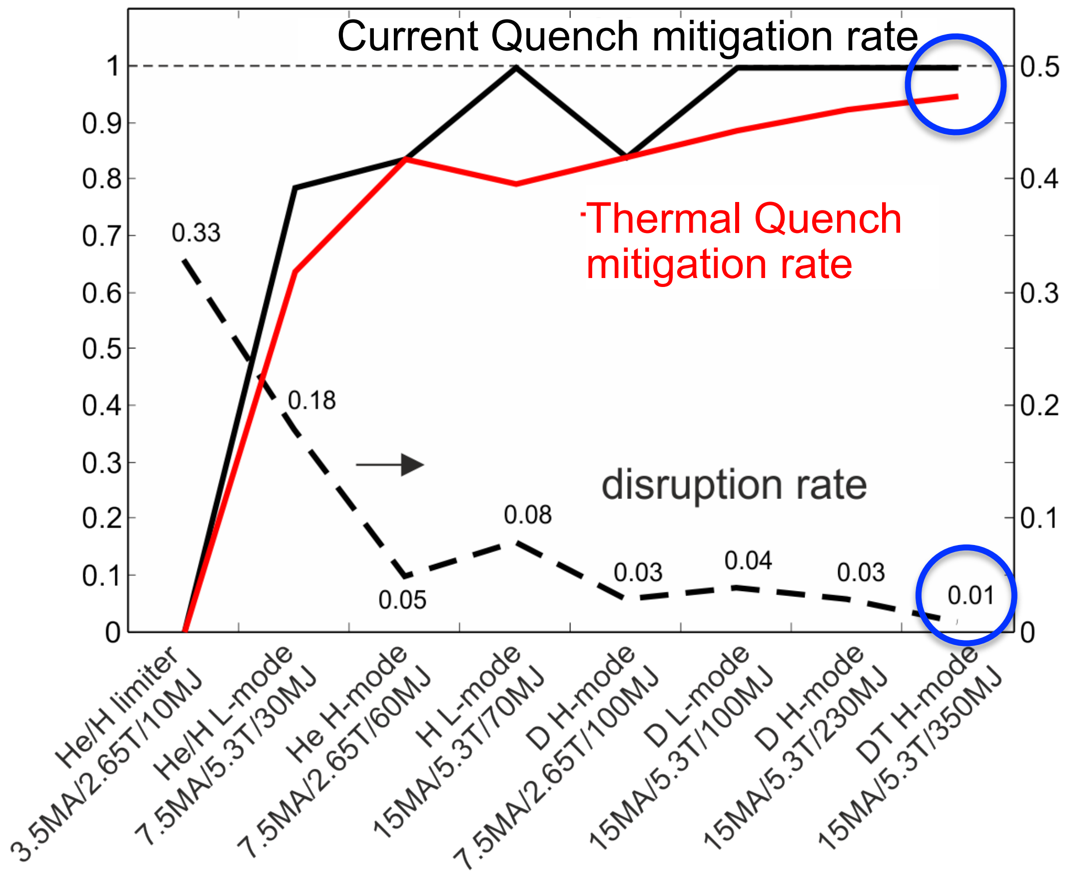
At full Q=10 performance, ITER's disruption budget requires:

- **Nearly disruption-free operation**
  - ≤1 disruption per 100 pulses
- **Accurate prediction of disruptions**
  - Mitigation rate ~95-100%

Mitigation of disruptions is necessary, but not sufficient.

ITER also requires highly reliable methods for preventing disruptions.

A potential scenario for ITER's disruption and mitigation rates



Increasing plasma current & energy →

M. Lehnen, IAEA 2016

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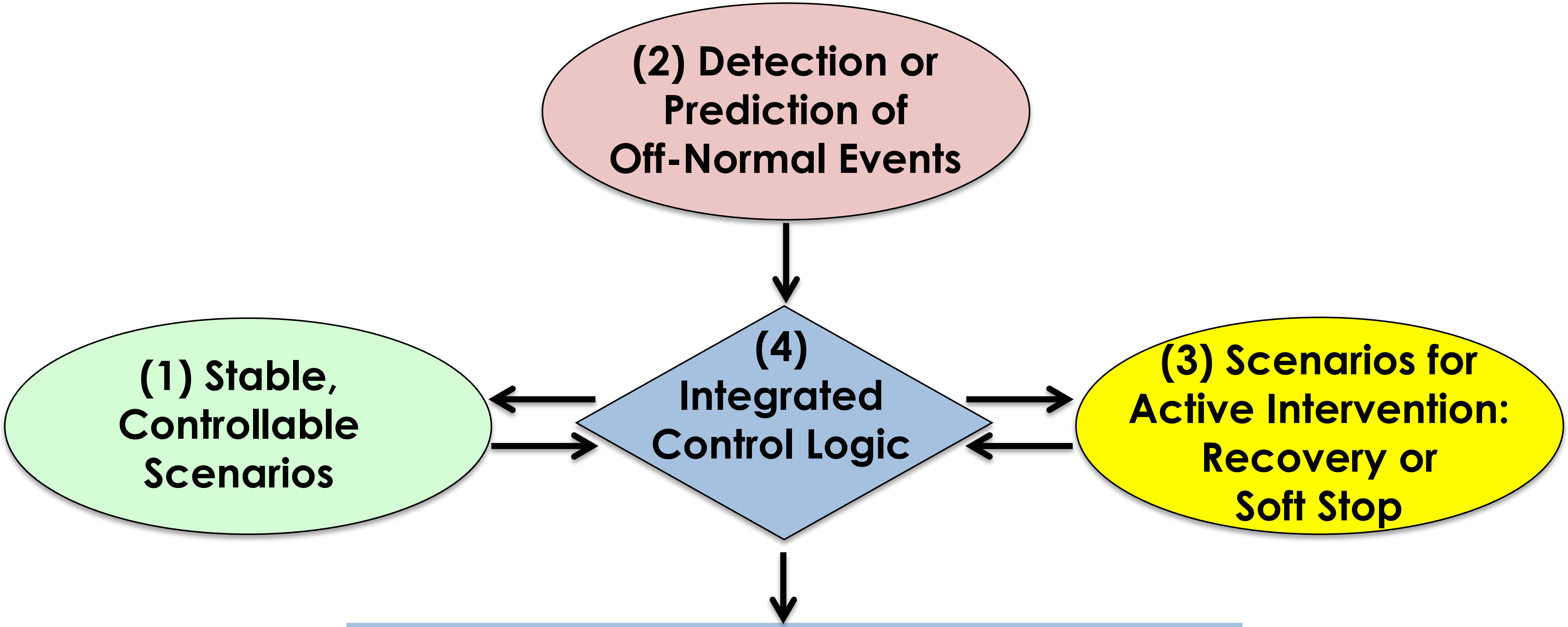
Scope of this talk:

Recent progress (2016-2018) in strategies to prevent disruptions

Please see the preprint for more extensive references to the important and innovative research in this area.

Disruption-Free Tokamak Operation is a Problem of Control

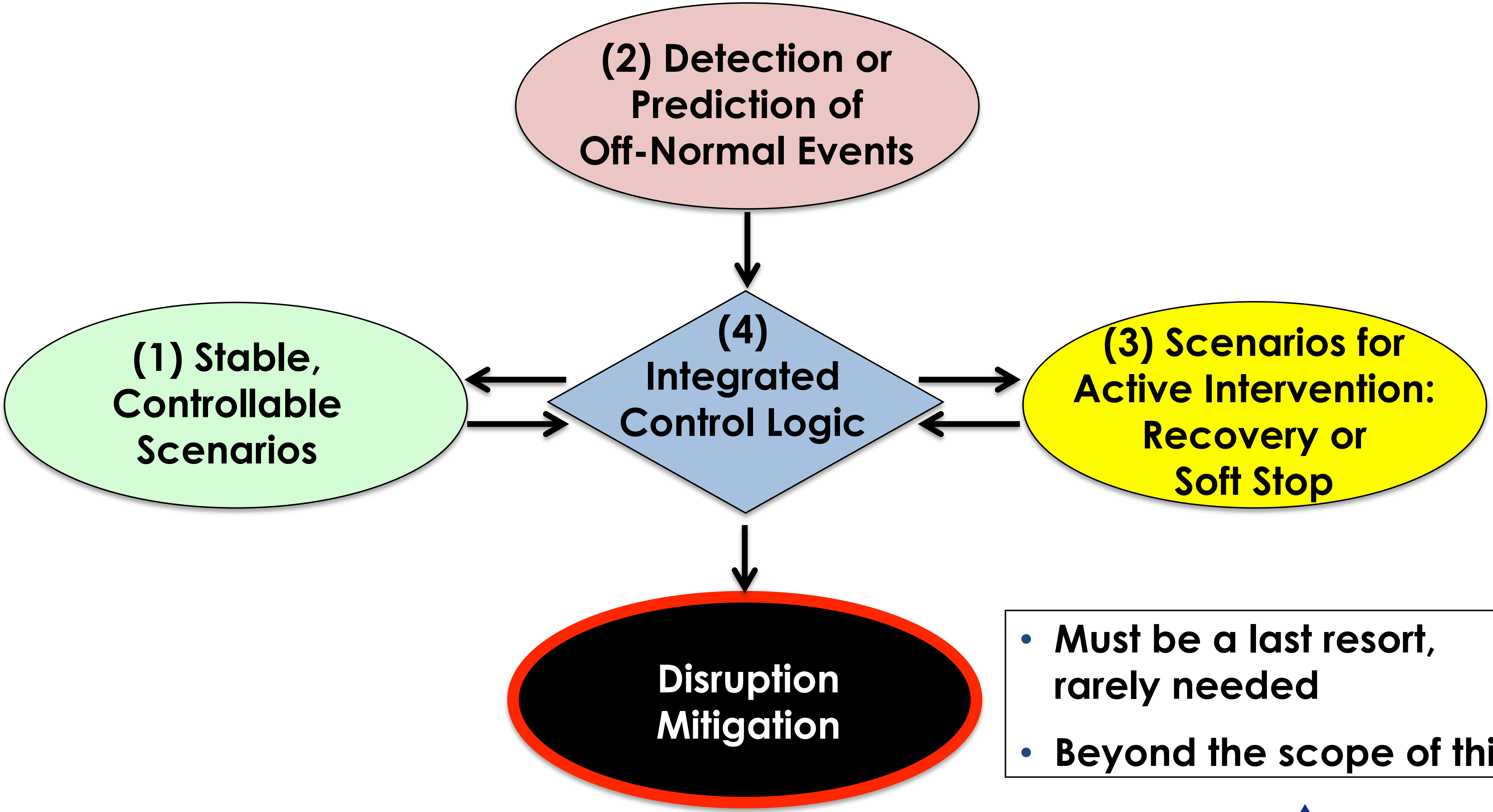


Actuators:

- Heating & current drive (NBI, ECRH, ICRF)
- Gas, pellet injection
- 3D coils

GENERAL ATOMICS

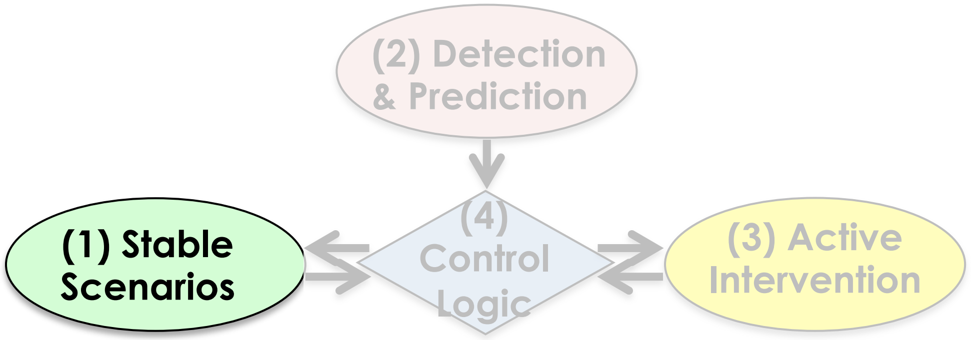
Disruption-Free Tokamak Operation is a Problem of Control



- Must be a last resort, rarely needed
- Beyond the scope of this talk

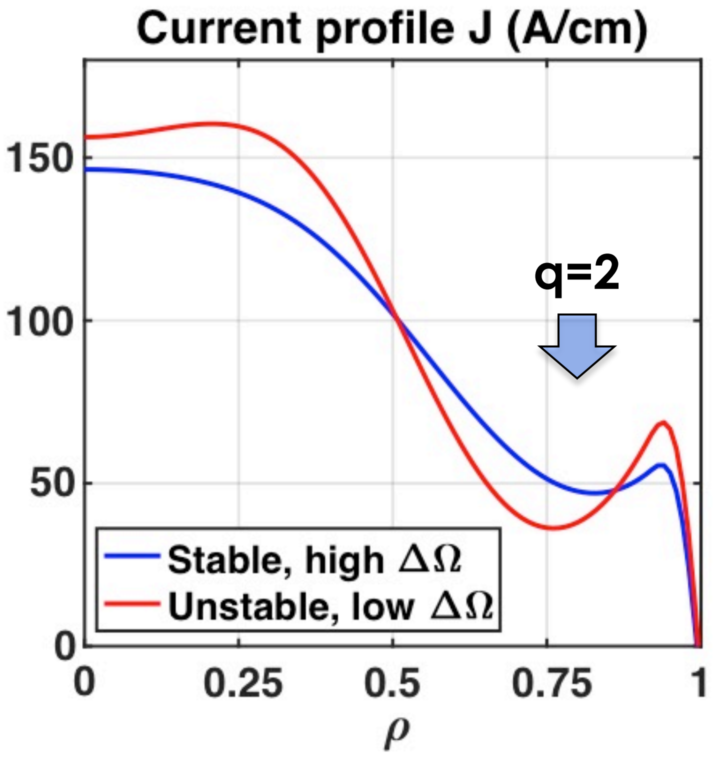
Stable, Controllable Operation Must Be the Normal State

- **Stable plasmas in ITER-relevant scenarios**
- **Robust control to maintain the operational state**
- **Active control to expand stability limits**



Reproducibly Stable Plasmas Have Been Achieved in Zero-Torque ITER Baseline Scenario Discharges

- **Challenge: Maintain stability against tearing modes in ITER Baseline Scenario discharges**
  - $\beta_N \sim 1.8$, $q_{95} \sim 3$
  - Low NBI torque, low rotation
- **Instability correlates with deep J(r) minimum near q=2**



DIII-D: F. Turco, NF 2018; APS 2017

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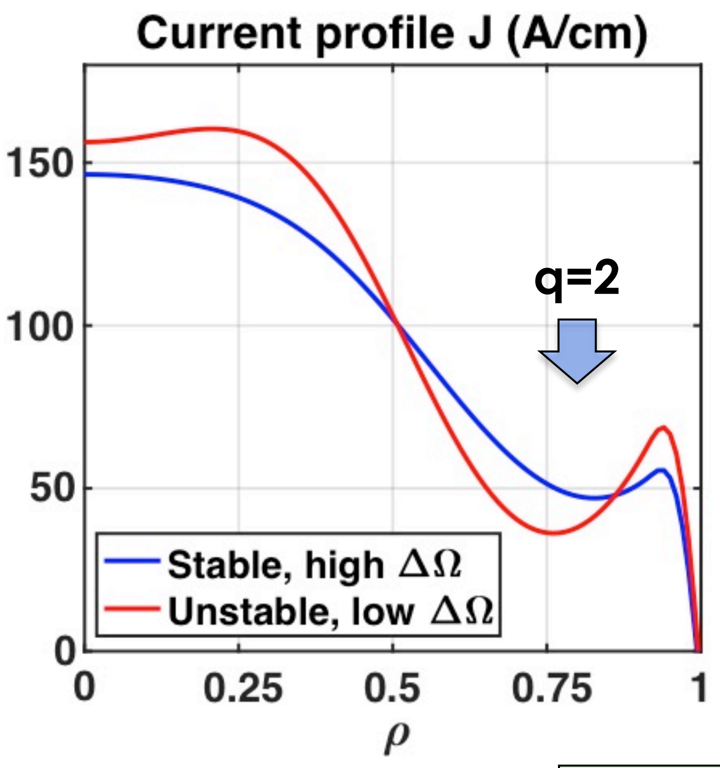
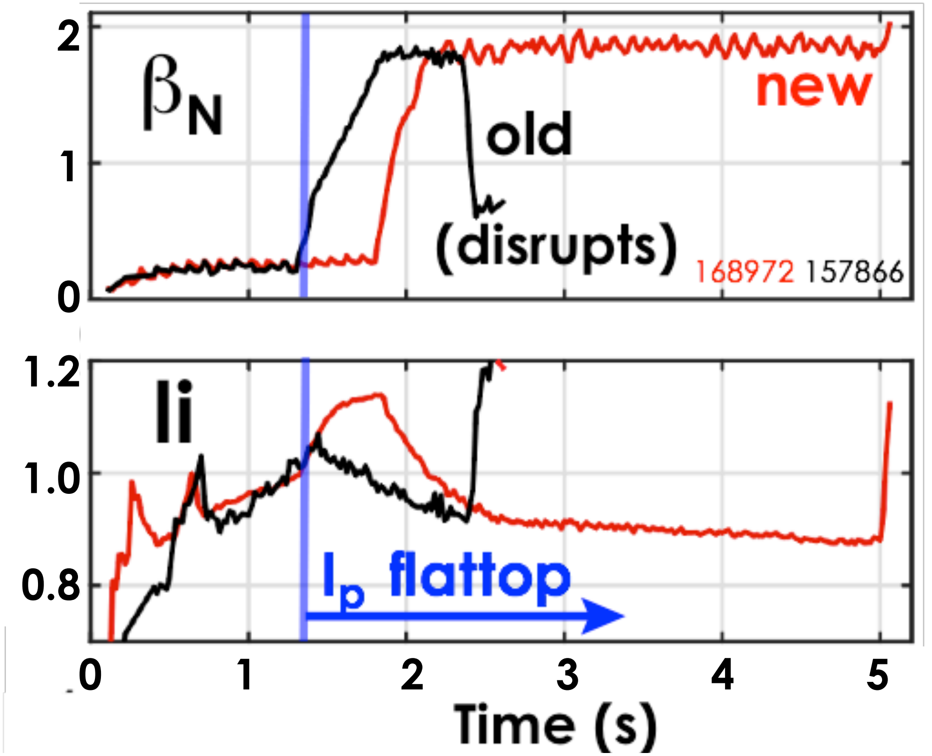


- **Modification of early J(r) evolution improves stability**



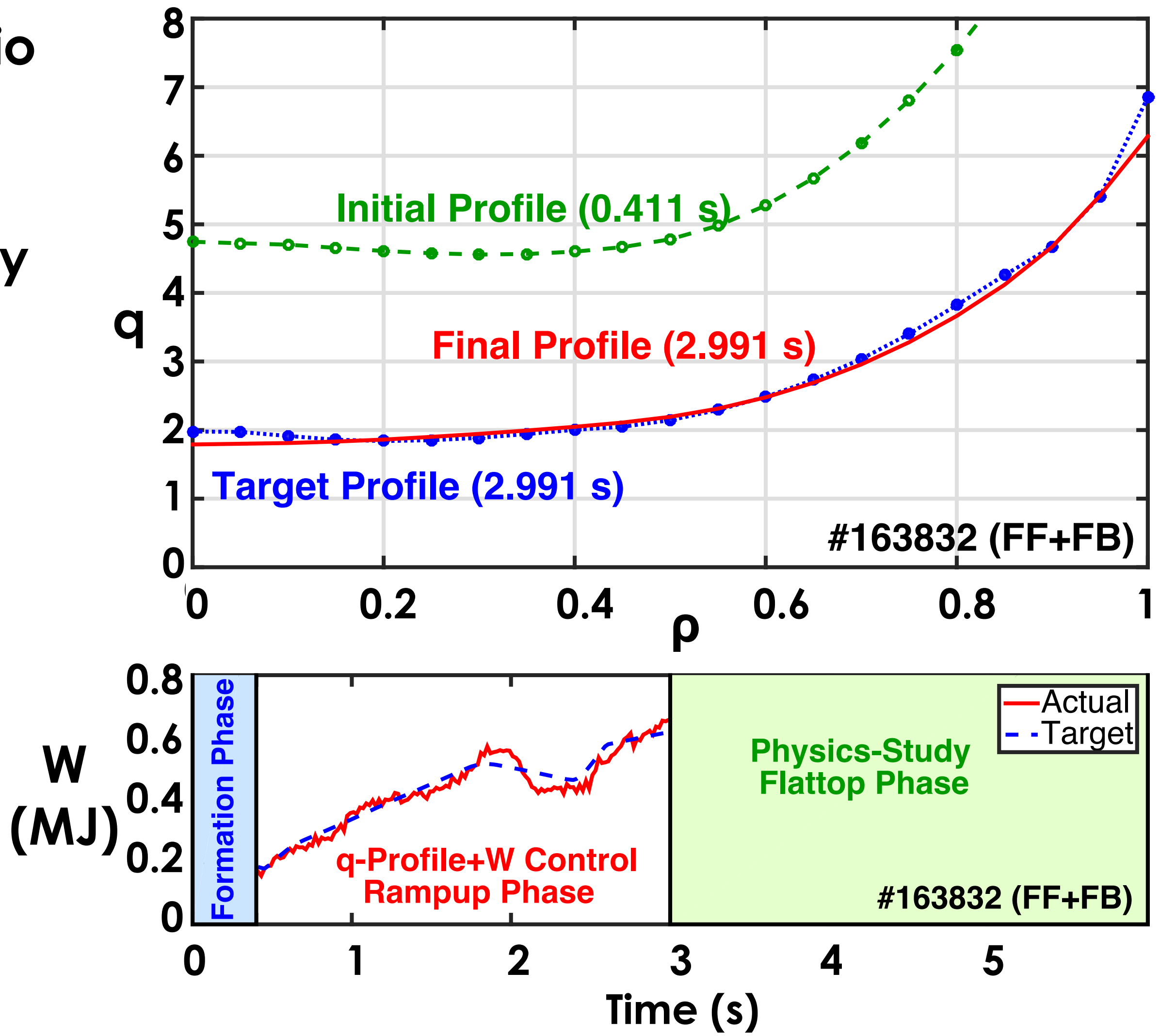
Future work: Extend to ITER-like collisionality, with RMP ELM control.

DIII-D: F. Turco, NF 2018; APS 2017

GENERAL ATOMICS

Profile Control is Essential to Achieve and Sustain Robustly Stable Operation

- **Example: high q_{min} steady-state scenario**
- **Combined feedforward and feedback scheme controls J(r) and plasma energy**
- **Model-based control accounts for bootstrap, EC, and NBI driven current**

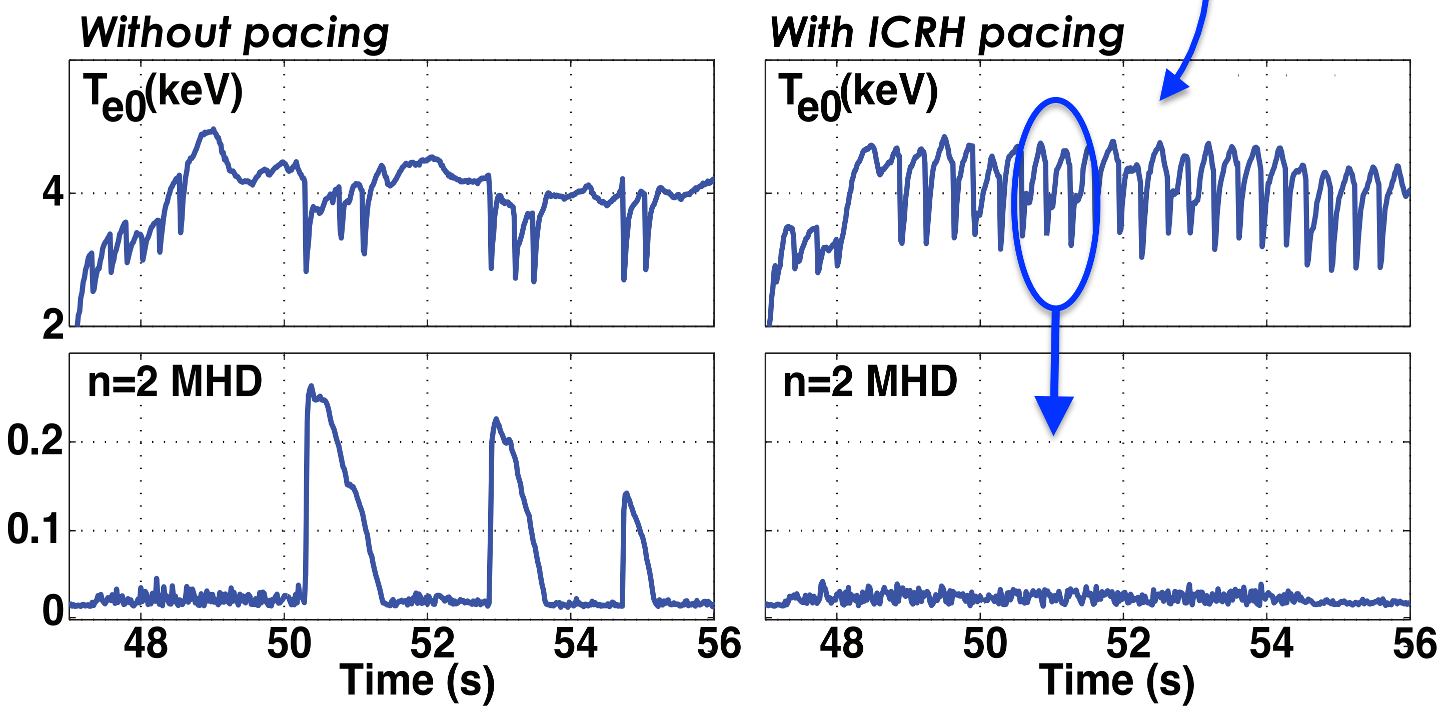


Future work: Profile control in ITER baseline scenario to maintain stable p(r), J(r)

DIII-D: E. Schuster, EX/P6-39

Continuous Control of Instabilities Extends the Range of Stable Operation (e.g. Avoidance of Neoclassical Tearing)

- **Pacing by modulated central ICRH limits the sawtooth amplitude**
- **Smaller sawteeth do not seed NTMs**



JET: E. Lerche, NF 2017

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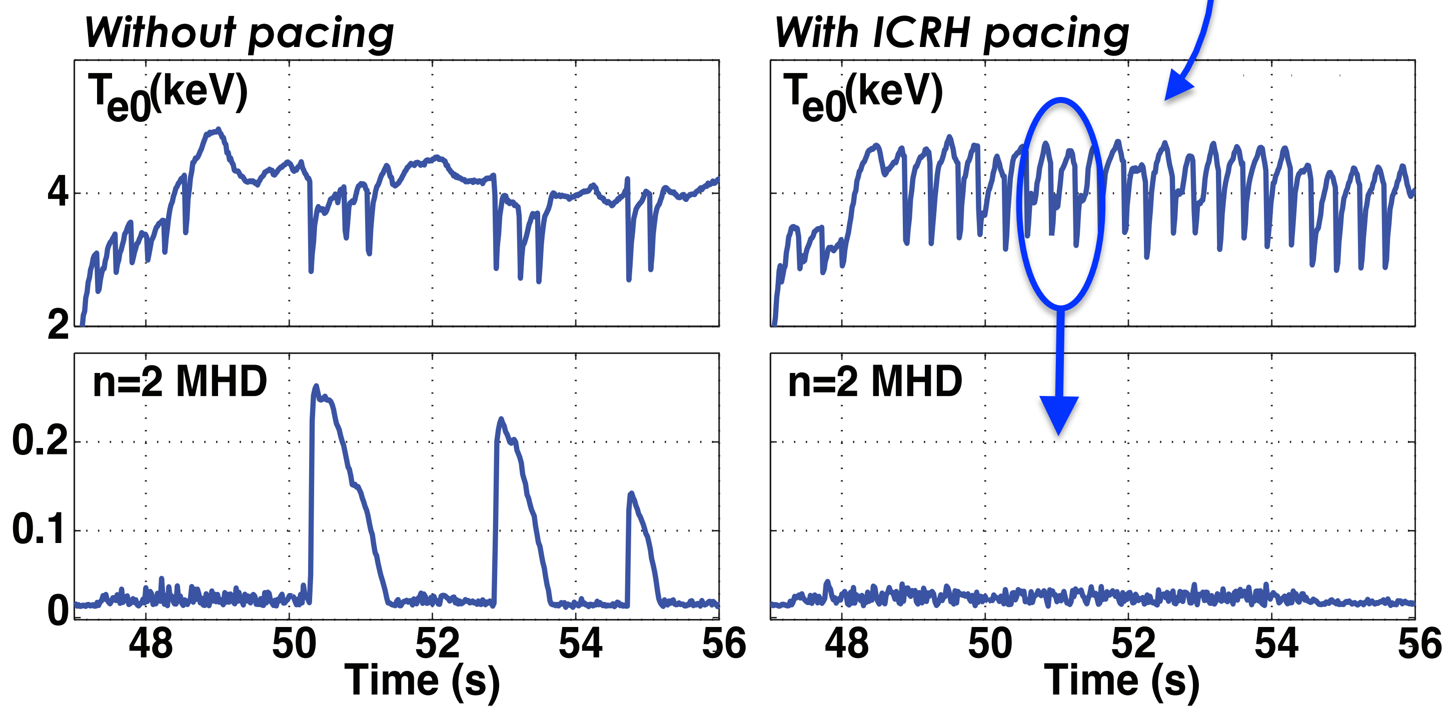
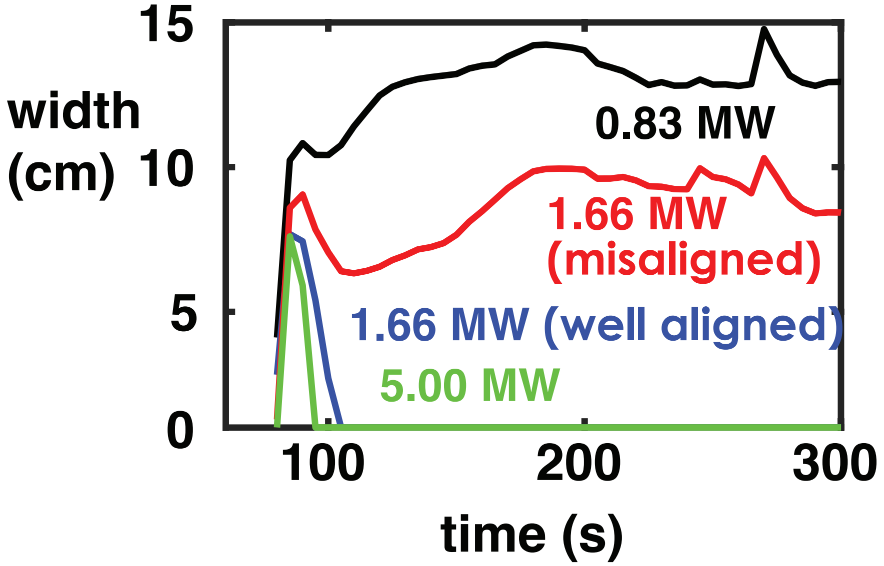


JET: E. Lerche, NF 2017

- **ITER modeling predicts that modest ECCD power can pre-emptively stabilize 2/1 NTM**
  - Less power than "reactive" control
  - Requires good alignment at q=2 surface

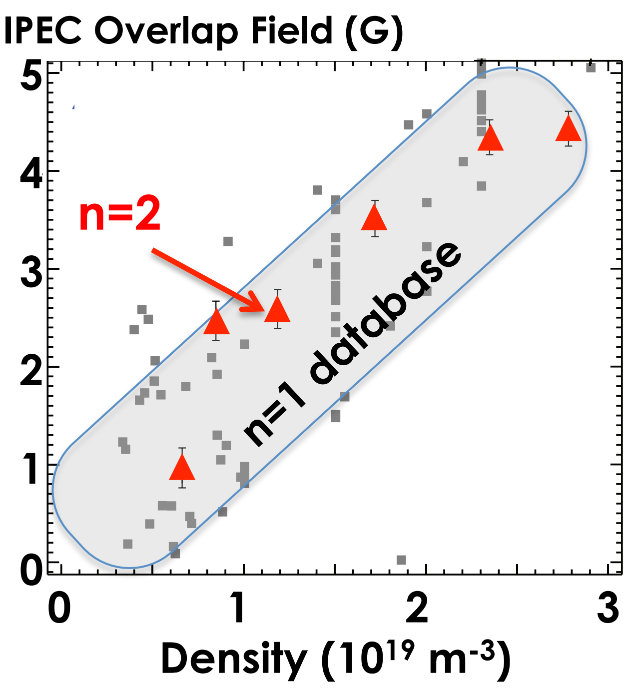


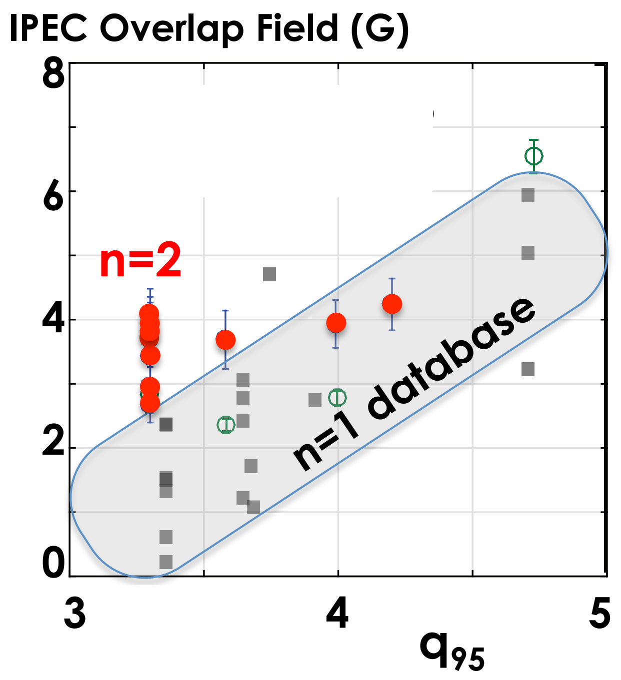
Future work: Test pre-emptive NTM stabilization with ITER-like q-profile, torque, collisionality, …

ITER: F. Poli, NF 2018

Prevention of Driven Tearing Modes Requires Control of 3D Configuration – i.e., Error Field Control

- **n=2 error field in low torque plasmas can penetrate directly → n=2 locked island**
  - … or cause braking of plasma rotation → n=1 locked island
- **Thresholds for n=2 penetration in Ohmic plasmas are comparable to those for n=1**
  - vs. density (DIII-D) and vs. q95 (EAST)

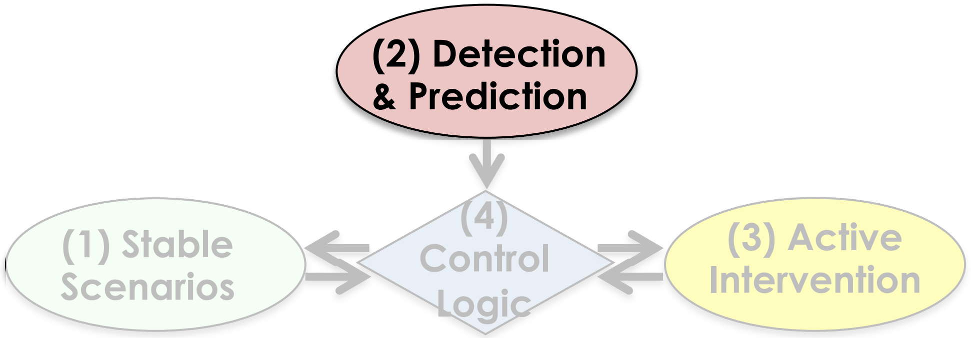




Ongoing work: *Spatial spectrum for EF control with minimal braking;*
n=2 error field criteria for ITER.

DIII-D, EAST: M. Lanctot, NF 2017

Disruption Prevention Requires Prediction and Detection of Instabilities



Requirements differ from those for disruption mitigation

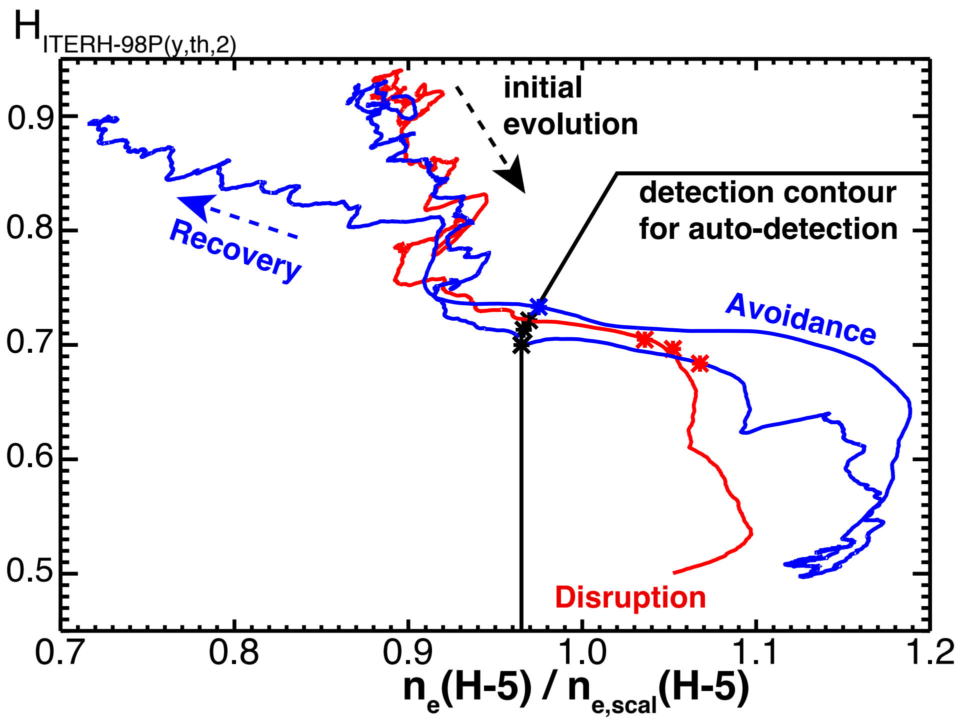
- **Sufficient information to decide on the response**
- **Sufficient time to change the discharge evolution**

A broad range of approaches are being pursued

- **Physics-based predictors**
- **Data-driven predictors ("machine learning")**
- **Direct assessment of plasma stability**

Physics-Based, Path-Oriented Algorithms Detect Early Precursors of Disruptions

- **Detection of H-mode density limit by dimensionless edge density & confinement**
  → recovery by ECCD, reduced fueling



AUG: M. Maraschek, PPCF 2018
Also see: C. Sozzi, EX/P1-22

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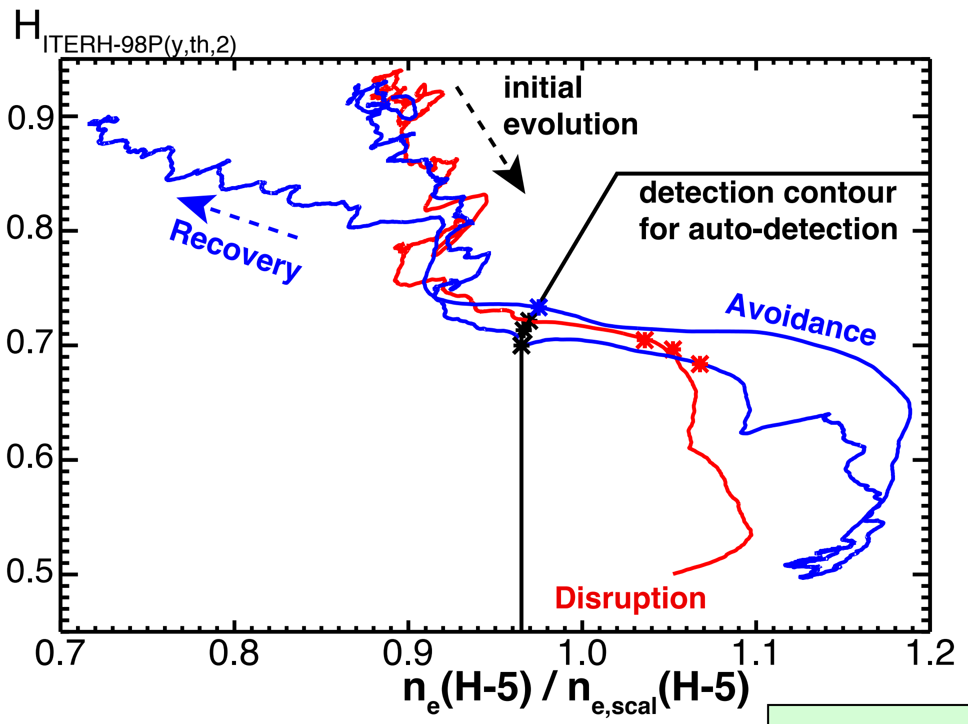
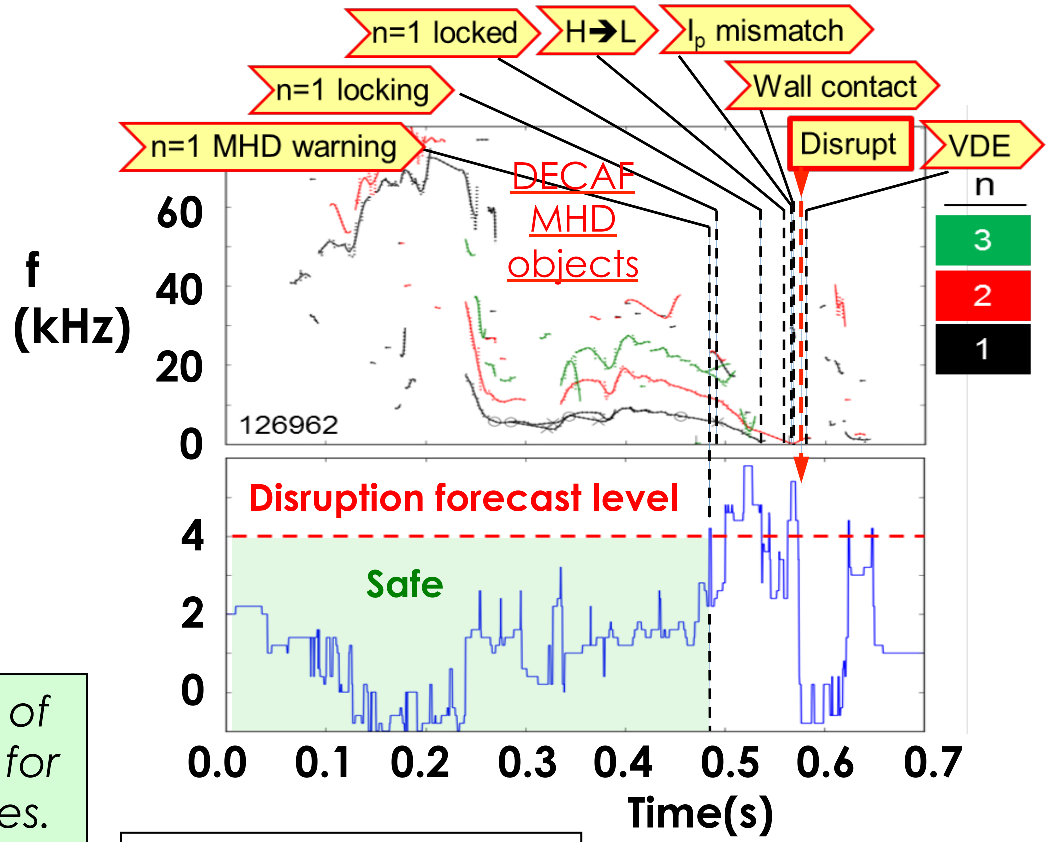


AUG: M. Maraschek, PPCF 2018

Also see: C. Sozzi, EX/P1-22

- **DECAF code identifies the chain of events leading to disruption**
  - Multiple event warnings: MHD stability, density limits, loss of control, …

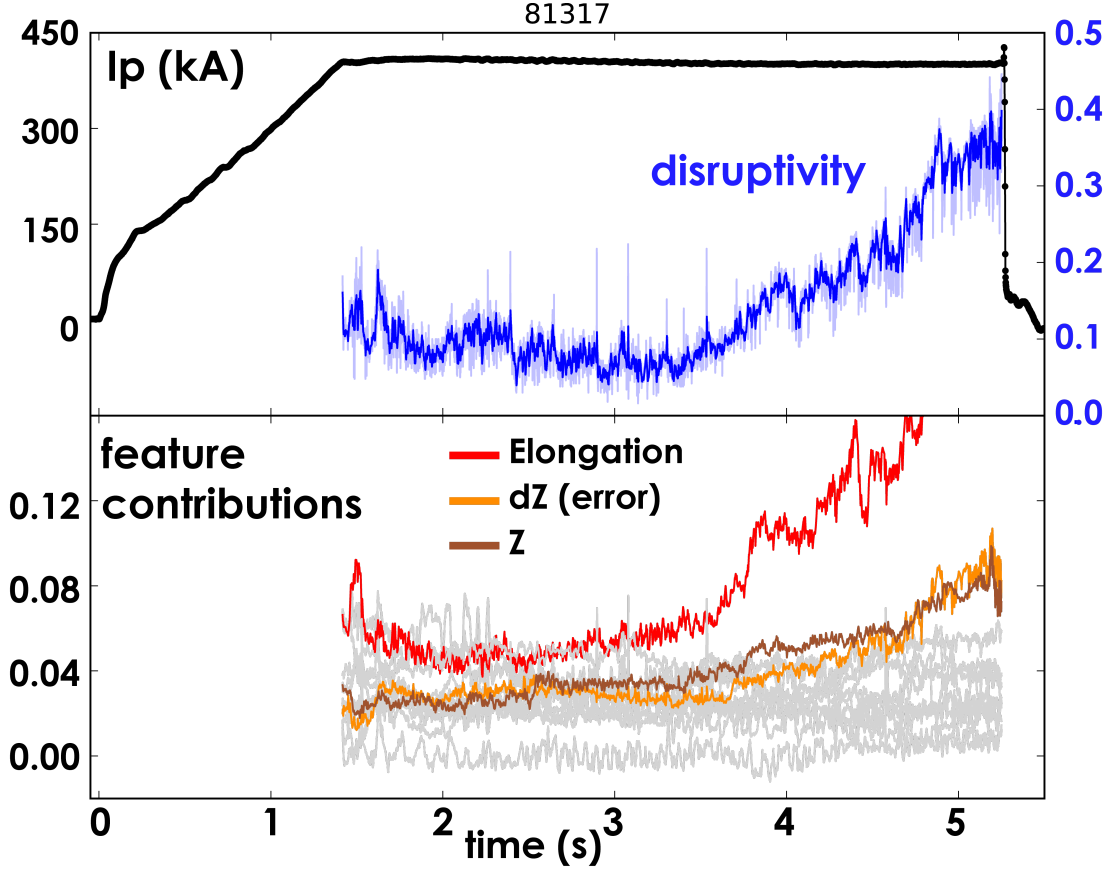


Future work: Integration of path-oriented warnings for multiple disruption causes.

NSTX: S. Sabbagh, EX/P6-26

Data-Driven ("Machine Learning") Disruption Warnings Are Developing Toward More Quantitative Outputs

- **"Random Forest" algorithm allows identification of the cause of disruption**



EAST: R. Granetz, C. Rea, EX/P6-20

GENERAL ATOMICS

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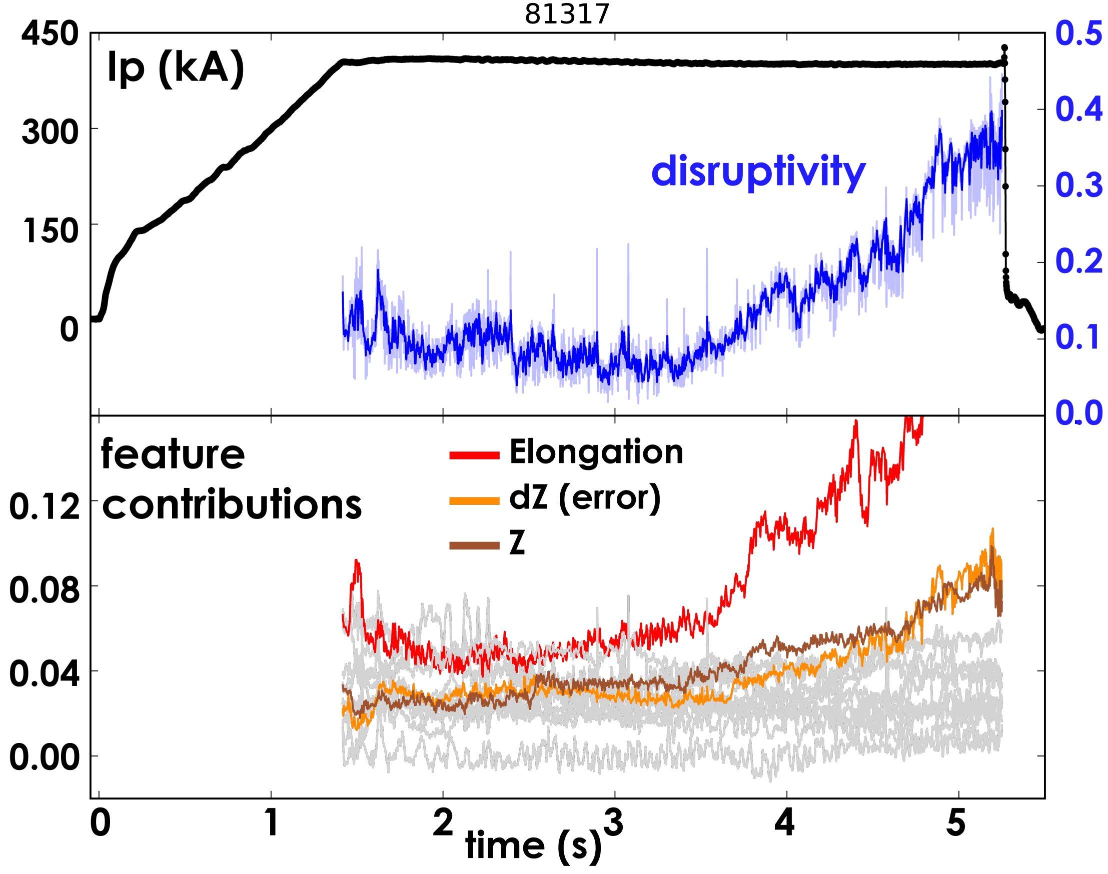
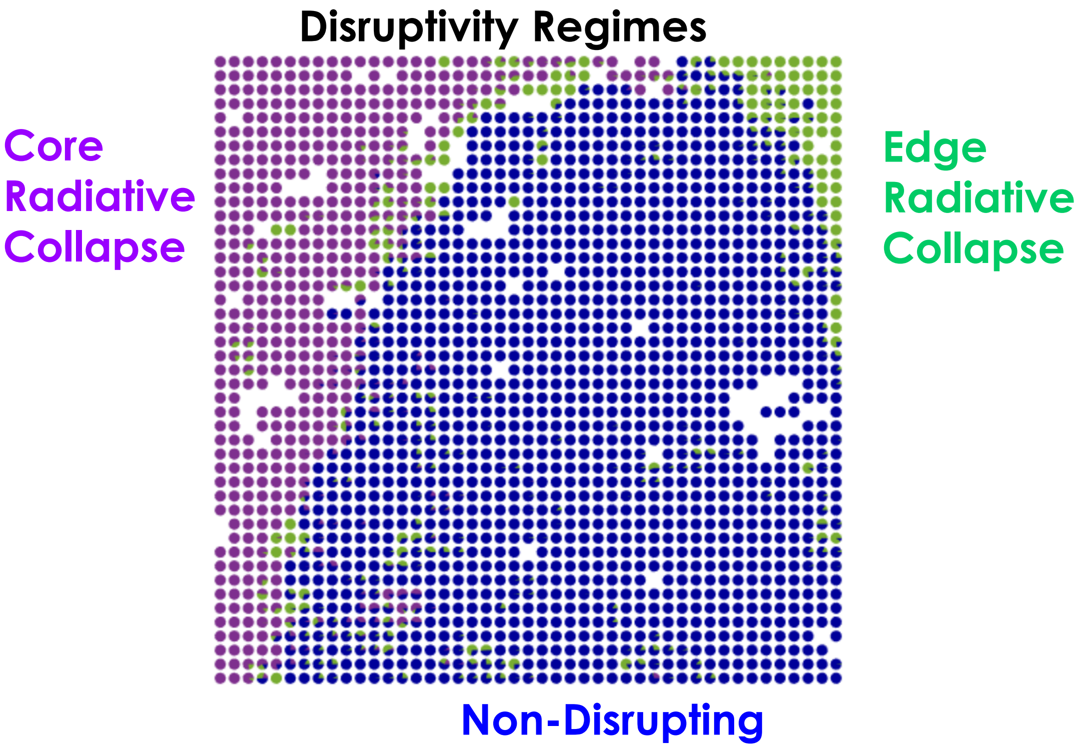


EAST: R. Granetz, C. Rea, EX/P6-20

- **Generative Topographic Mapping reduces multi-dimensional data to a 2D map**
  - Identify and visualize limits of operation

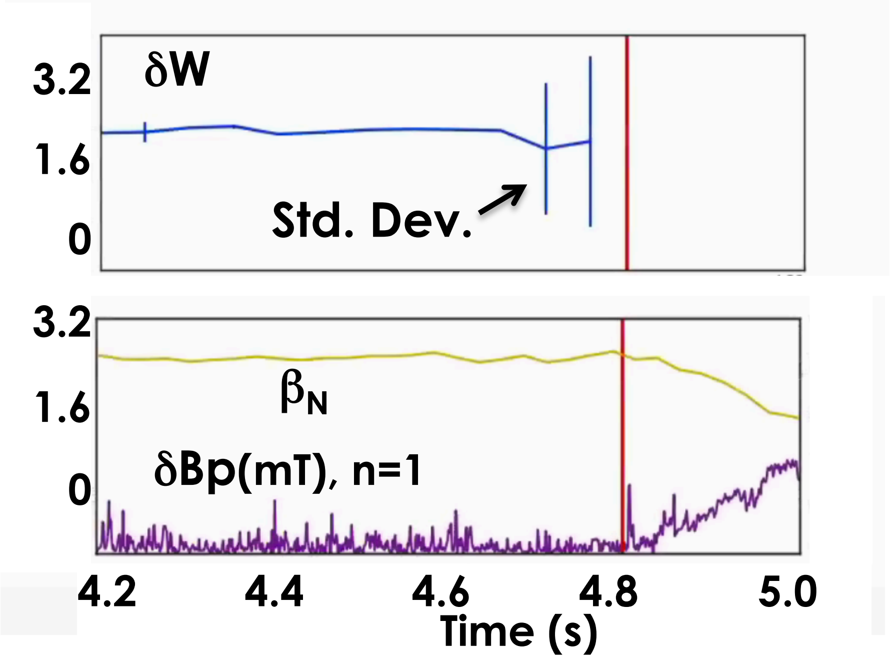


Ongoing work: Warnings that quantify the proximity to a limit, and identify the limit.

JET: A. Pau, IEEE 2018

Proximity to Instability Thresholds is Directly Accessible Through Real-Time Stability Calculation or Active Probing

- **Calculation of ideal MHD stability with parallelized DCON**
  - 200 ms computation time
- **Rising uncertainty of ideal-MHD δW may indicate tearing mode onset**



DIII-D: M. Roelofs, D. Eldon, APS 2017
A.S. Glasser, E. Kolemen, A.H. Glasser, PoP 2018

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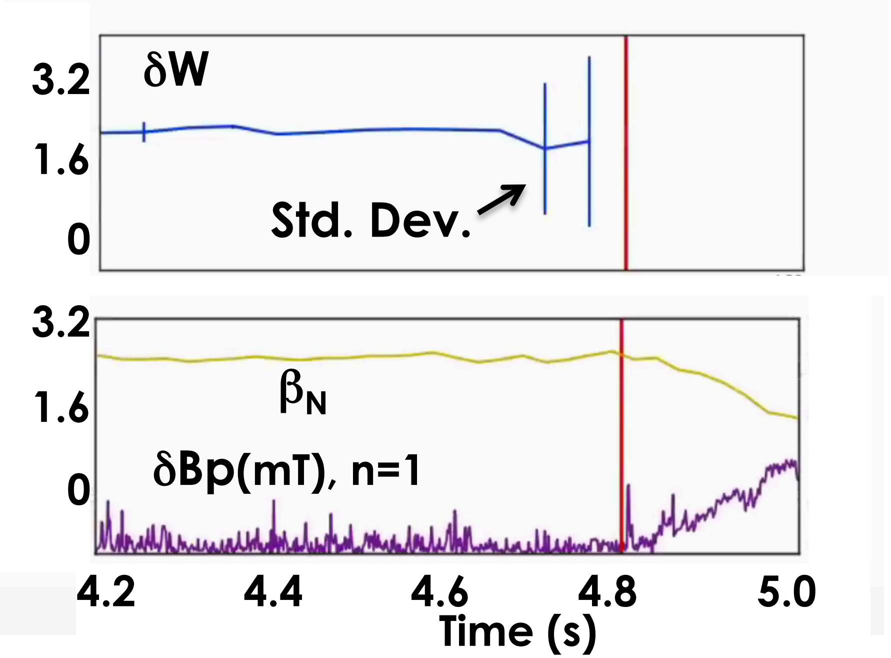
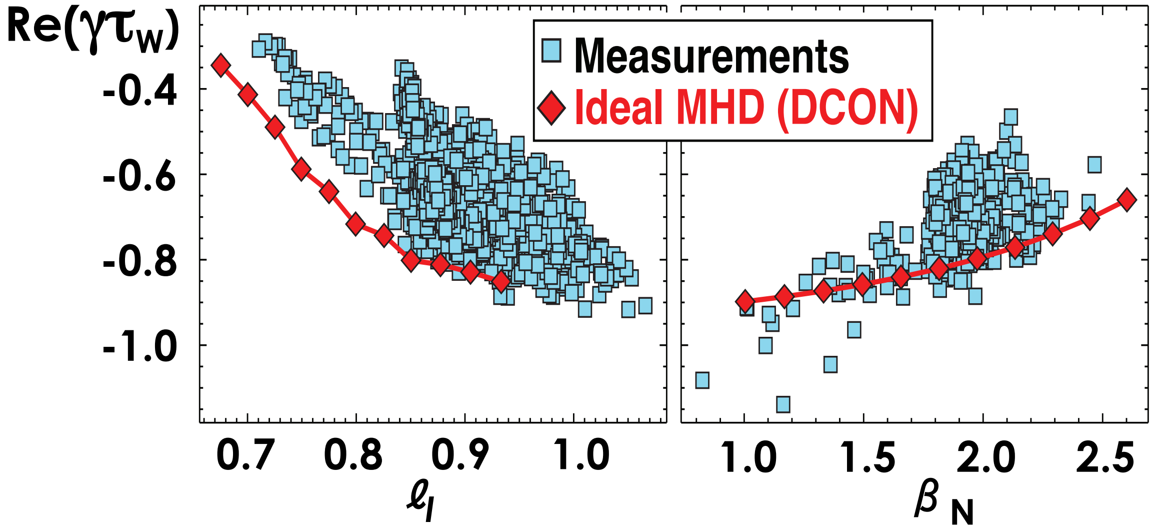


- **Measured damping rate of stable modes**
  - Response to 20 Hz applied n=1 perturbation
- **Inferred damping rate is in qualitative agreement with ideal-MHD DCON**

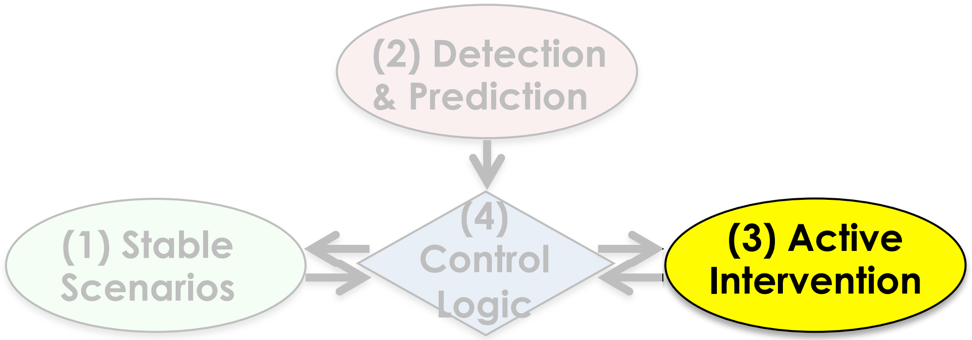


Future work: Routine use of real-time stability calculations. Relationship of calculated/measured ideal-MHD stability to onset of tearing modes?

DIII-D: M. Roelofs, D. Eldon, APS 2017
A.S. Glasser, E. Kolemen, A.H. Glasser, PoP 2018

DIII-D: F. Turco, IAEA 2016
J. Hanson, EPS 2018

Active Management of "Exceptions" Maintains or Recovers Stable Operation



Exceptions may include:

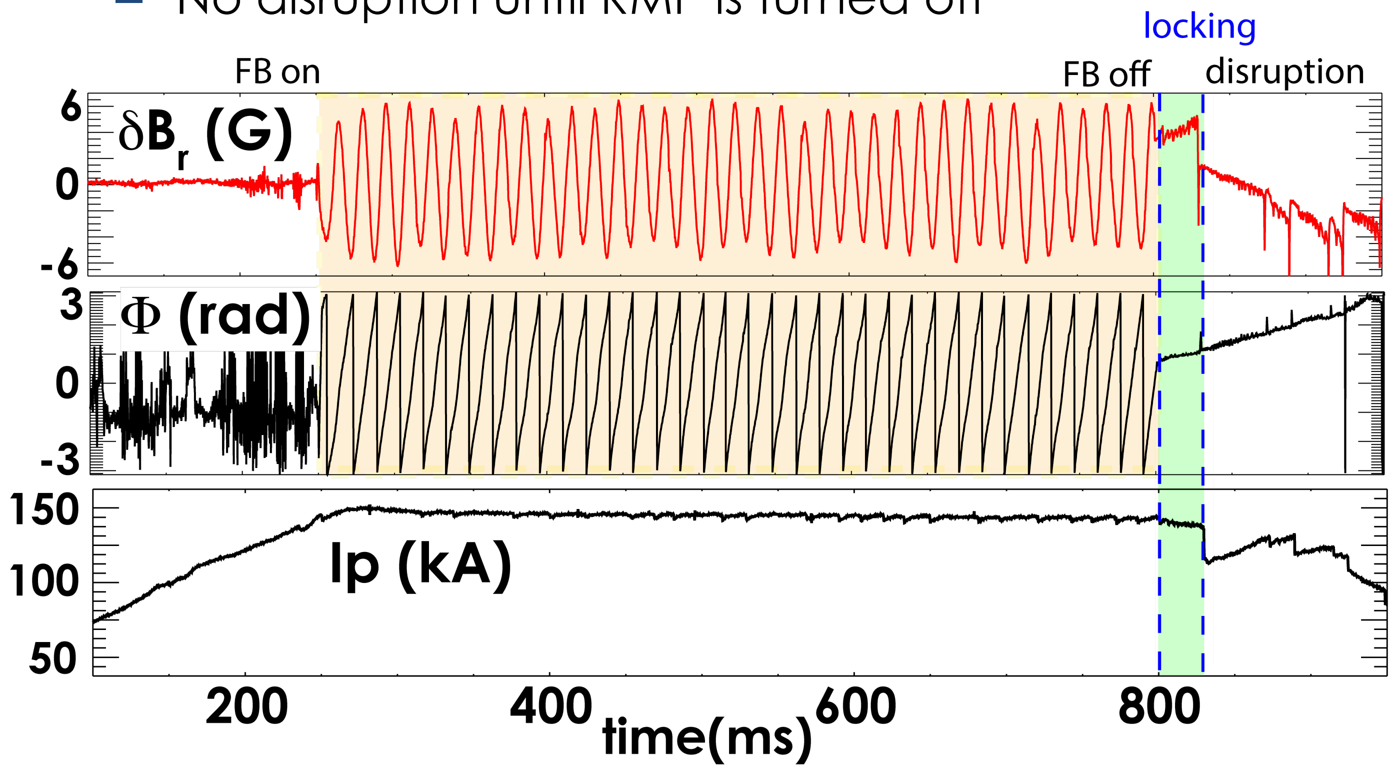
- **Off-normal plasma condition (including instability)**
- **Hardware faults**

Possible actions include:

- **Return to normal operation**
- **Continue the discharge in an alternate scenario**
- **Controlled discharge termination**
- **Rapid shutdown – as a last resort**

Forced Rotation of Magnetic Islands by Applied Magnetic Perturbation Can Prevent Disruption

- **Feedback-driven RMP entrains locked mode at $\omega\tau_{wall}$ ~ 1**
  - No disruption until RMP is turned off



RFX-Mod: M. Okabayashi, NF 2017; EX/P6-25

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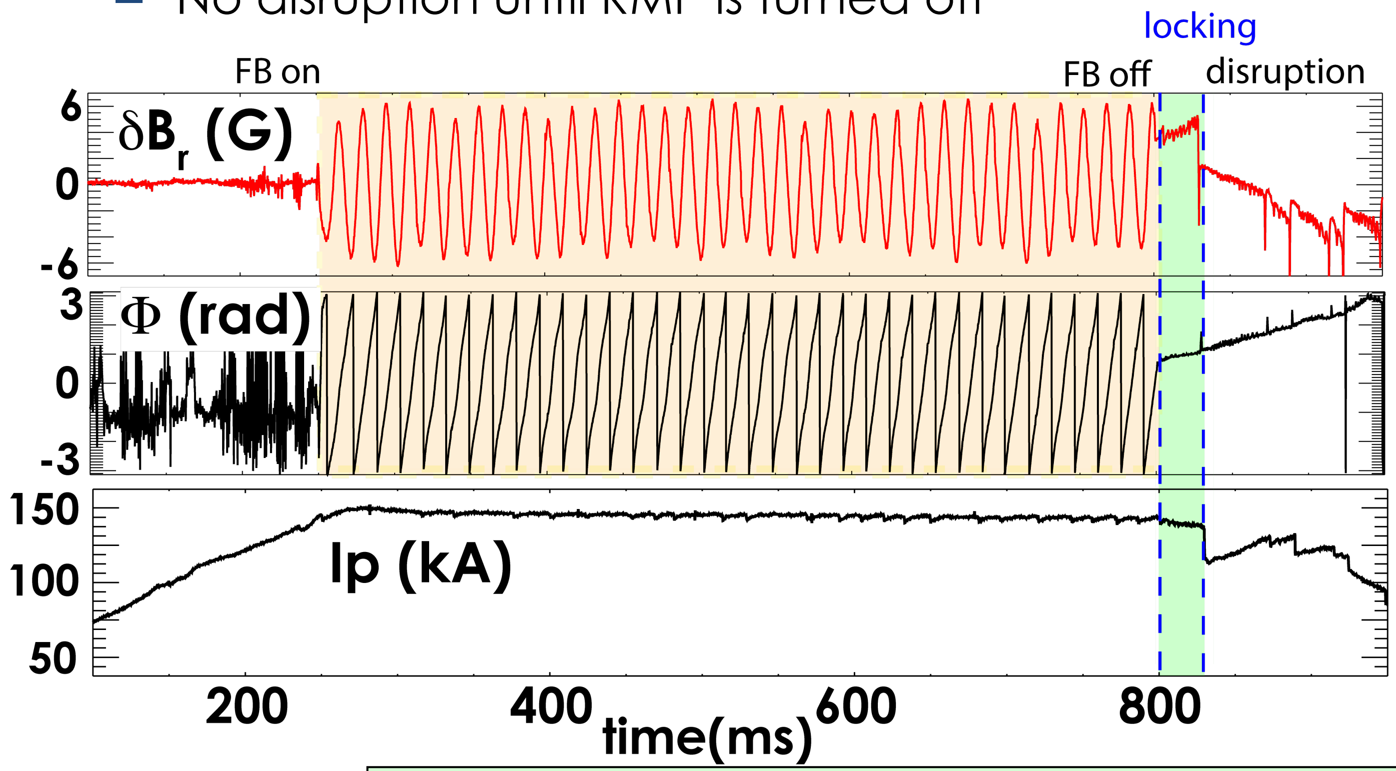
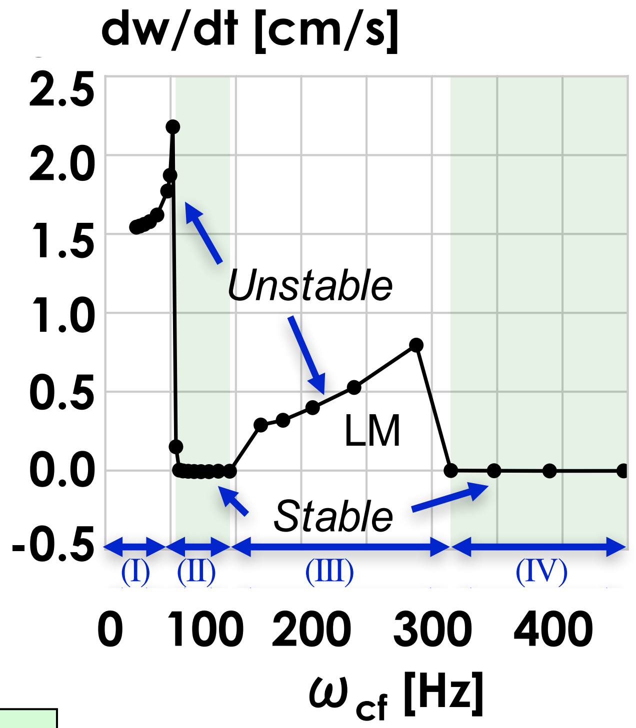


- **AEOLUS reduced MHD simulation shows rotating RMP stabilizes a locked mode**



Future work: Validate models of stabilization by forced rotation. How to recover normal operation?

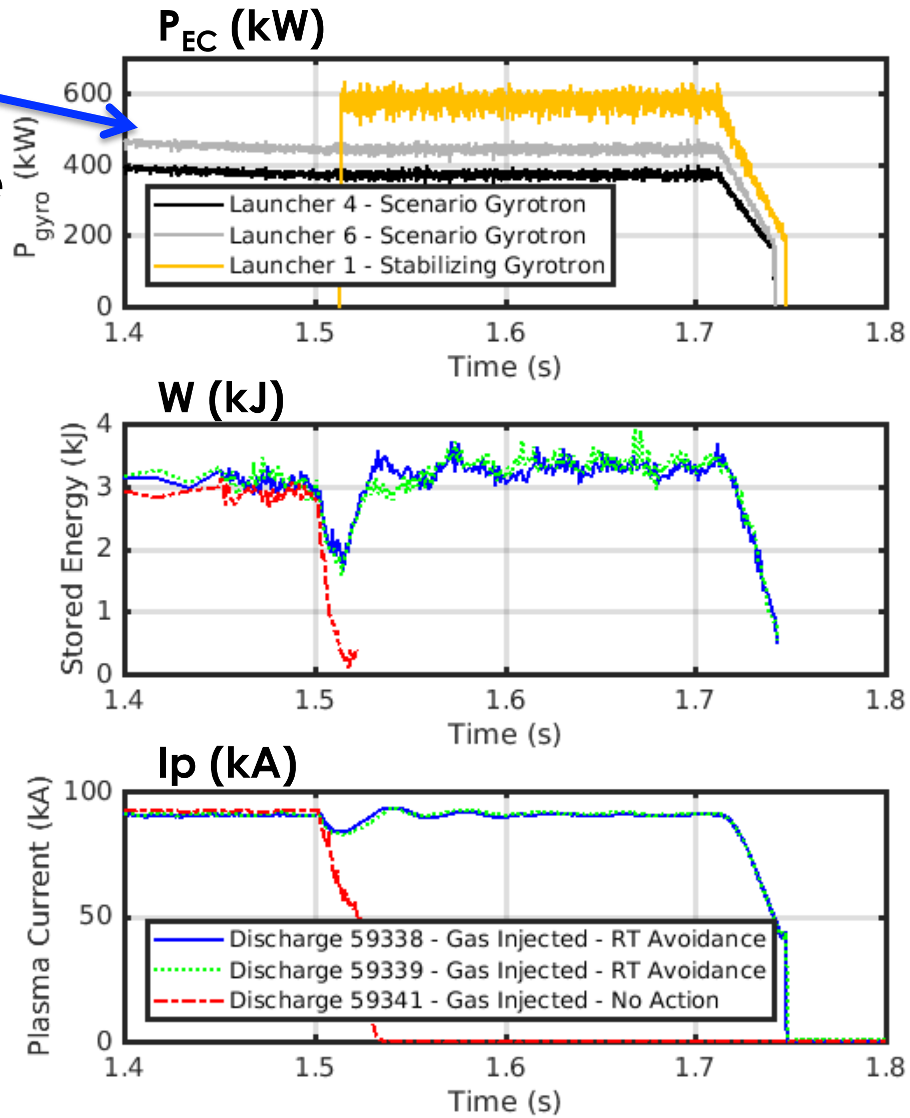
JT-60SA: S. Inoue, TH/P5-24

RFX-Mod: M. Okabayashi, NF 2017; EX/P6-25

Also: Q. Yu, TH/P5-19

ECCD at the Rational Surface Prevents Mode Locking After Impurity Influx

- **Core ECCD induces a pre-existing tearing mode**



TCV: U. Sheikh, NF 2018

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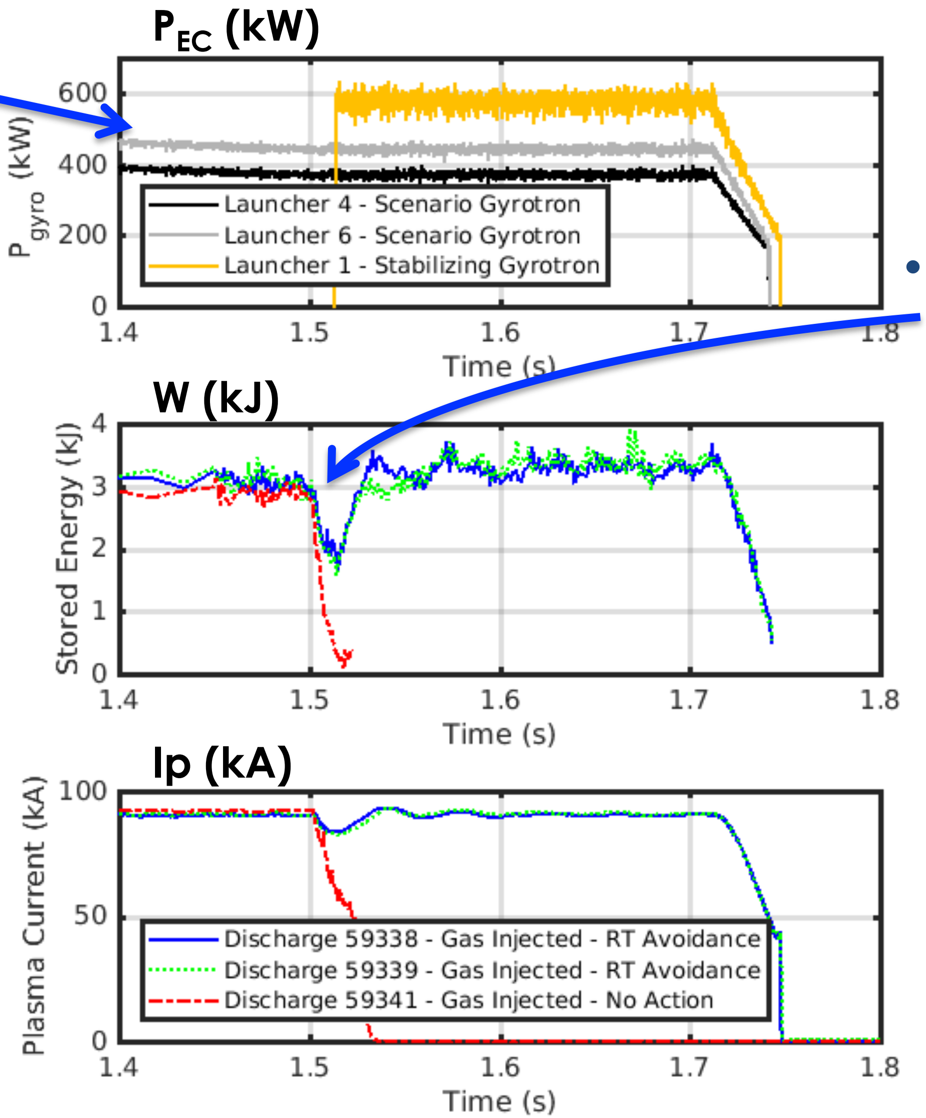
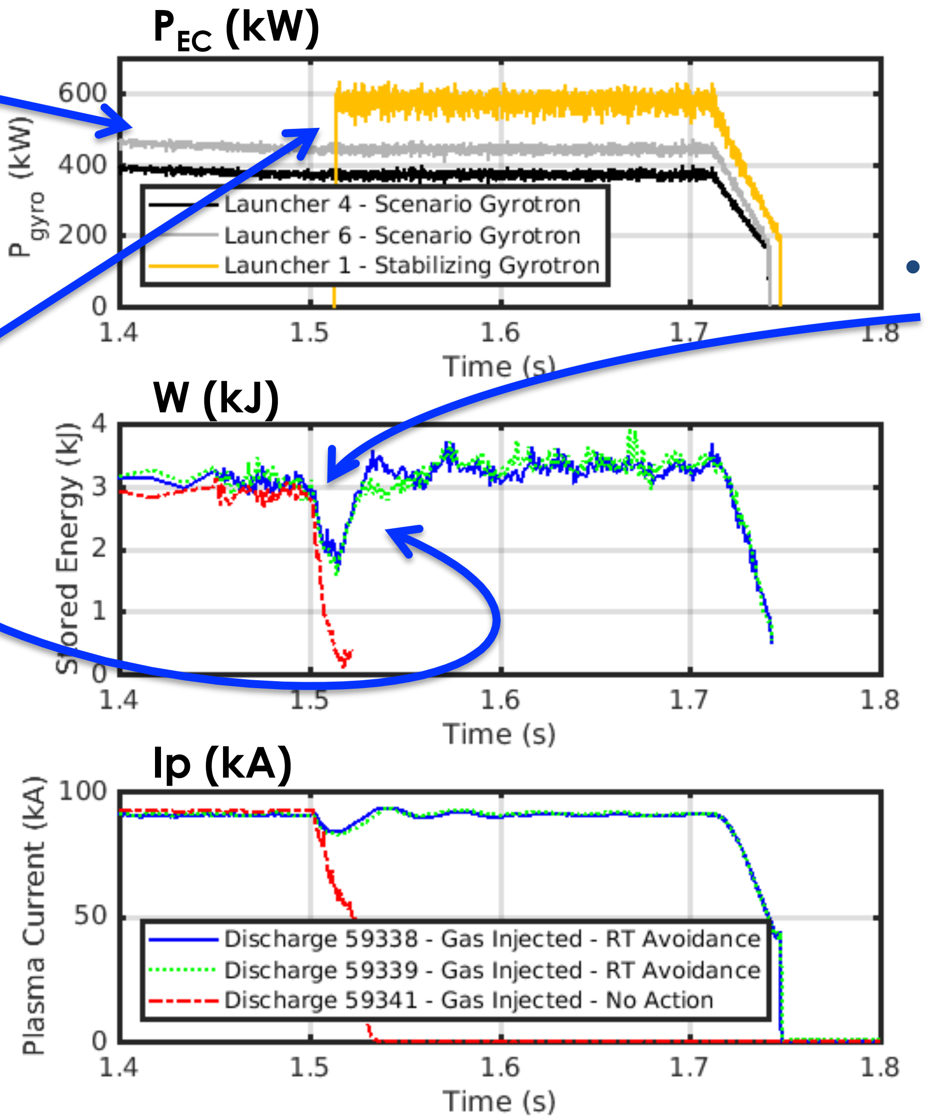


- **Neon injection causes radiative energy loss**
  - And increased plasma resistivity

TCV: U. Sheikh, NF 2018

ECCD at the Rational Surface Prevents Mode Locking After Impurity Influx

- **Core ECCD induces a pre-existing tearing mode**
- **Real-time triggering of ECCD at q=2 enables the discharge to recover**
  - Reduces 2/1 island growth



- **Neon injection causes radiative energy loss**
  - And increased plasma resistivity

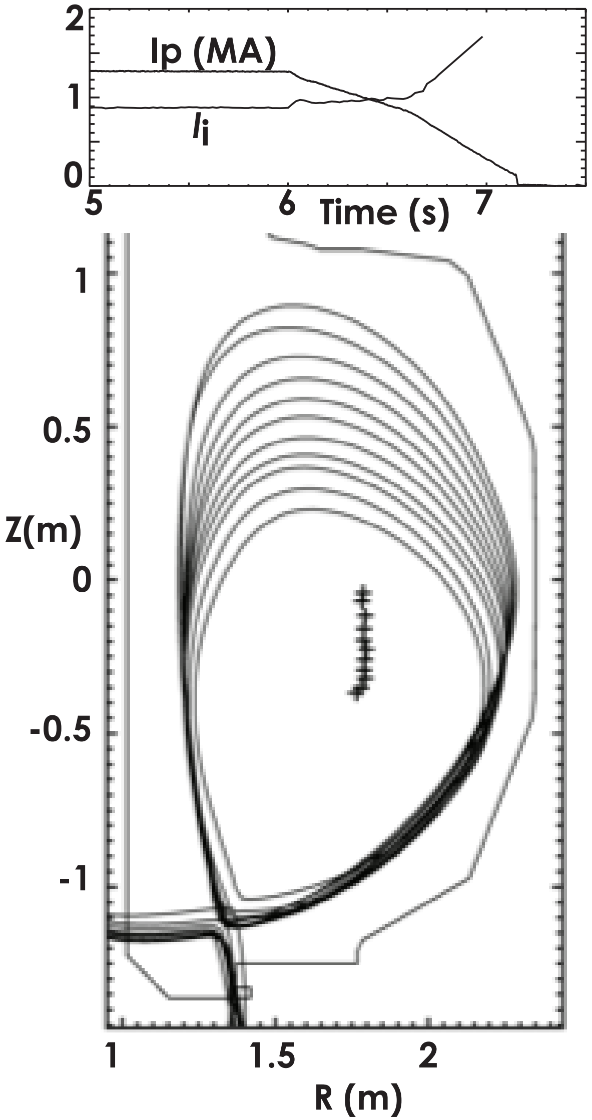
<u>Future work</u>: Role of heating vs. current drive in island stabilization.

Combine EC power with forced rotation by RMP.

TCV: U. Sheikh, NF 2018

Stable Discharge Termination is a Critical Element of Disruption-Free Discharges

- **ITER's rampdown requires reduction of elongation for vertical stability → lower q**
  - Implications for n=1 stability?
- **Stable ITER-like rampdowns in DIII-D & EAST … with $|dI_p/dt|$ up to the maximum expected for an unplanned "soft landing" in ITER**
  - Core heating, ELM control, and H-L transition timing are important for stability



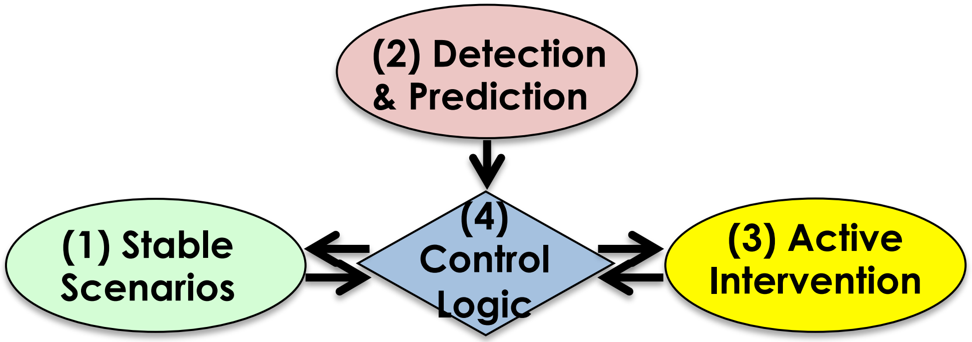
Future work: Develop rampdown with a pre-existing locked mode.

P. de Vries, NF 2018
F. Poli, EX/P7-27

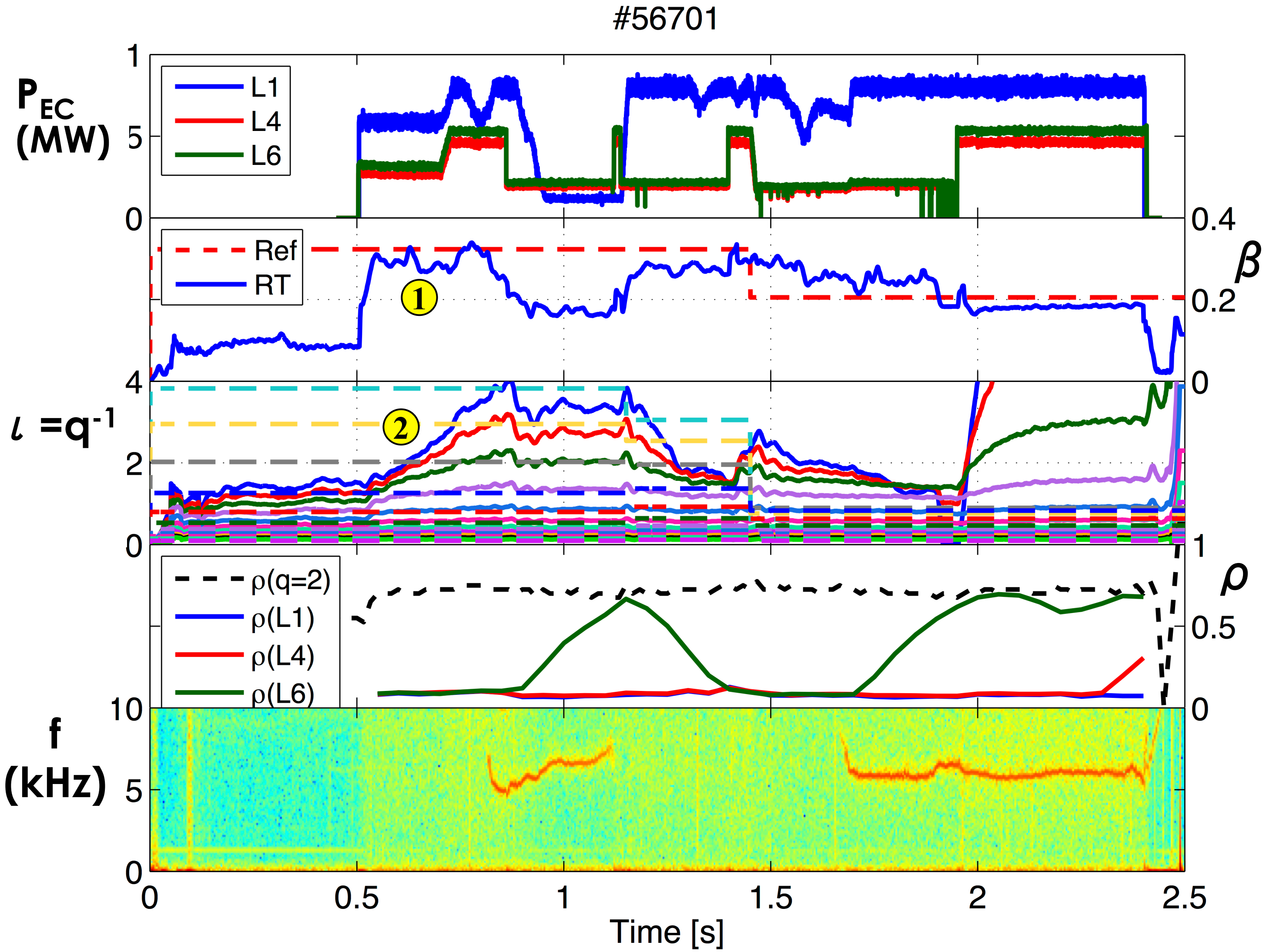
DIII-D: J. Barr, EX/P6-21

Integrated Control Systems Supervise the Recognition of Exceptions and Necessary Responses

- Continuous control of the operational state
- Asynchronous responses to exceptions
- Change of operational state as needed



Integrated Control Includes Actuator Sharing
Example: ECCD for Profile Control and Tearing Mode Control



Normal state:

① EC controls β

② EC controls q-profile

TCV: M. Kong, EPS 2017; EX/P1-25

Also: N. Eidietis, EX/P6-22

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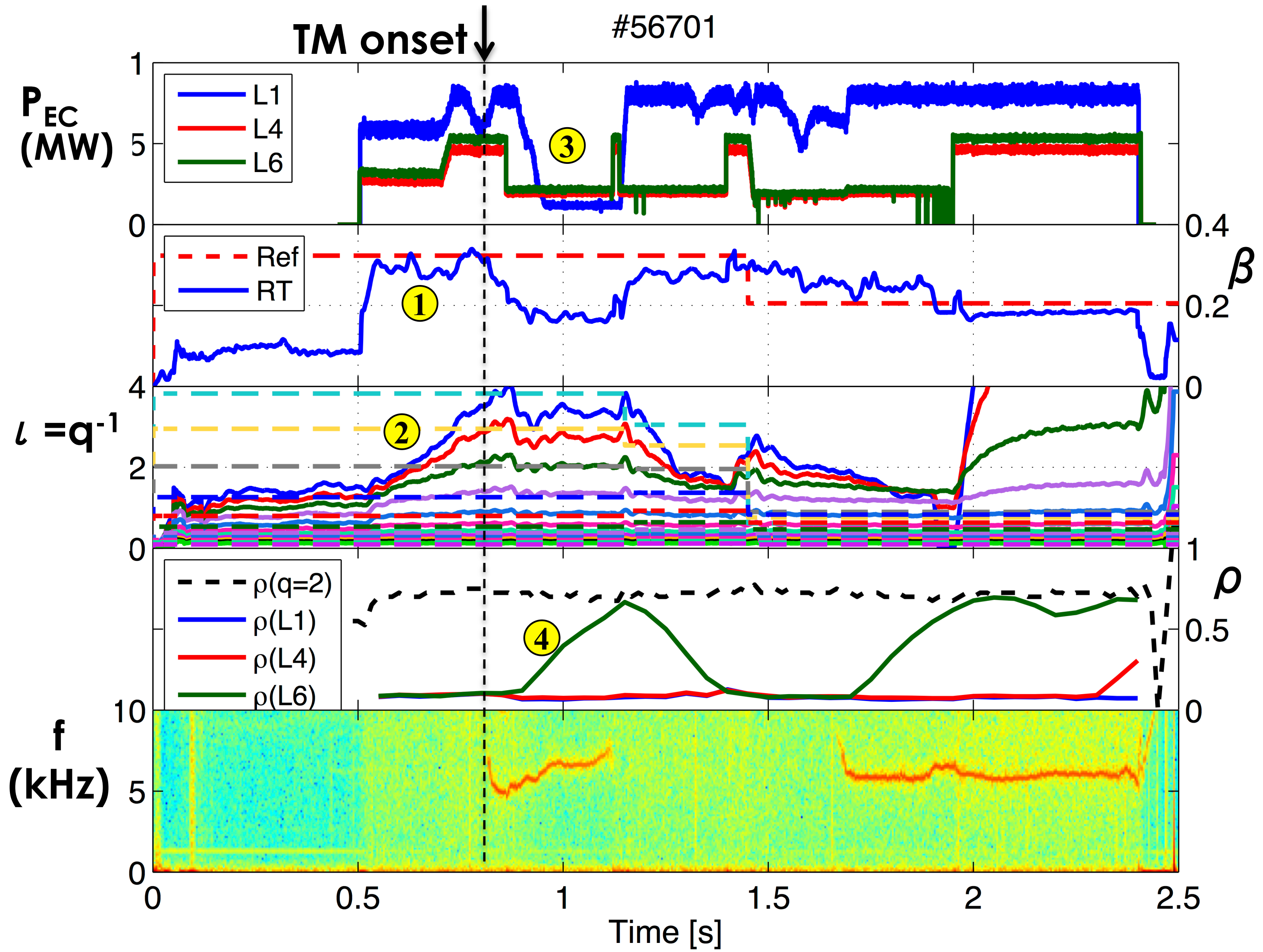

Normal state:

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After Tearing Mode onset:

③ Heating power is reduced

④ One gyrotron re-aims to q=2

TCV: M. Kong, EPS 2017; EX/P1-25

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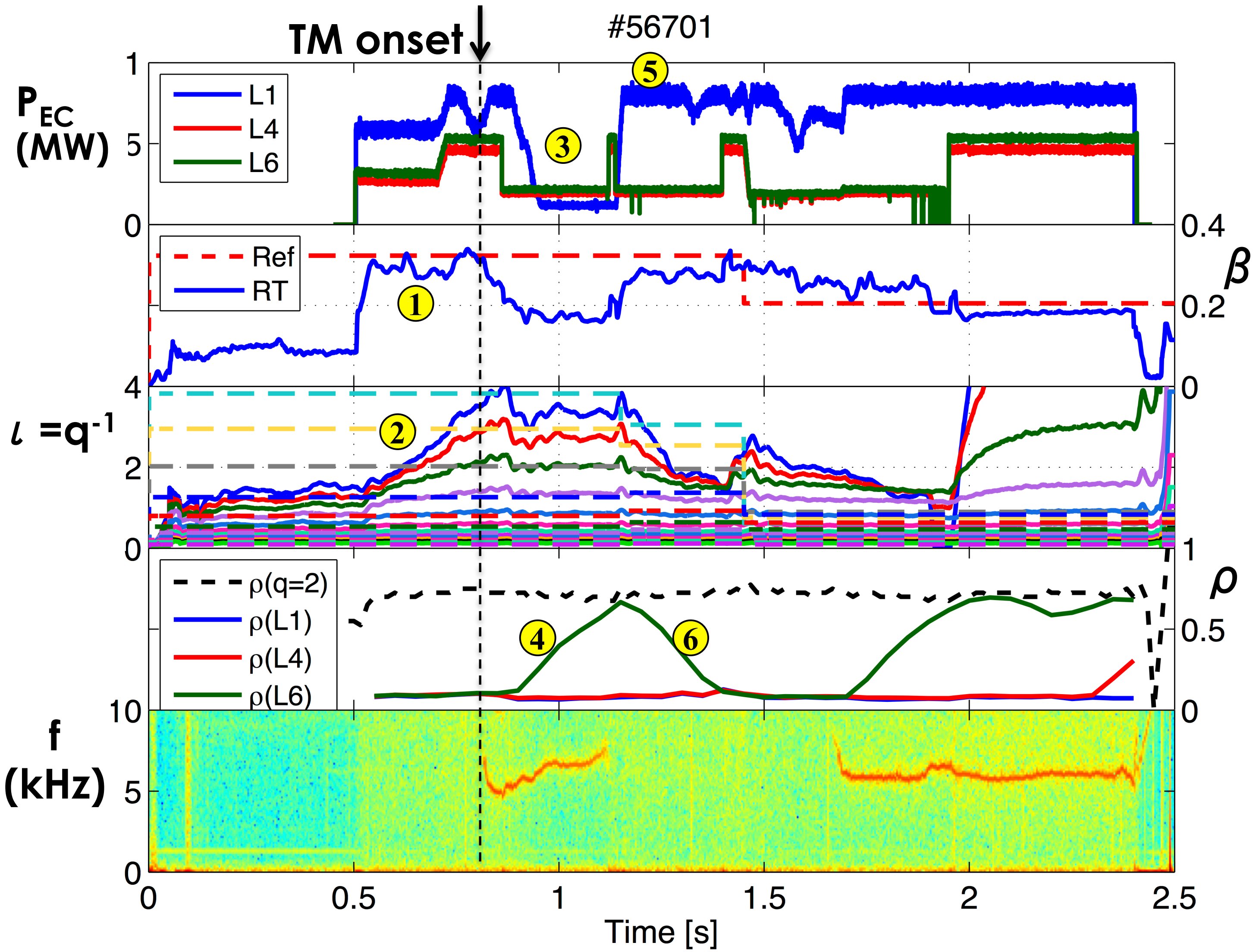

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Tearing Mode is stabilized:

⑤ Heating power is restored

⑥ Gyrotron returns to core ECCD

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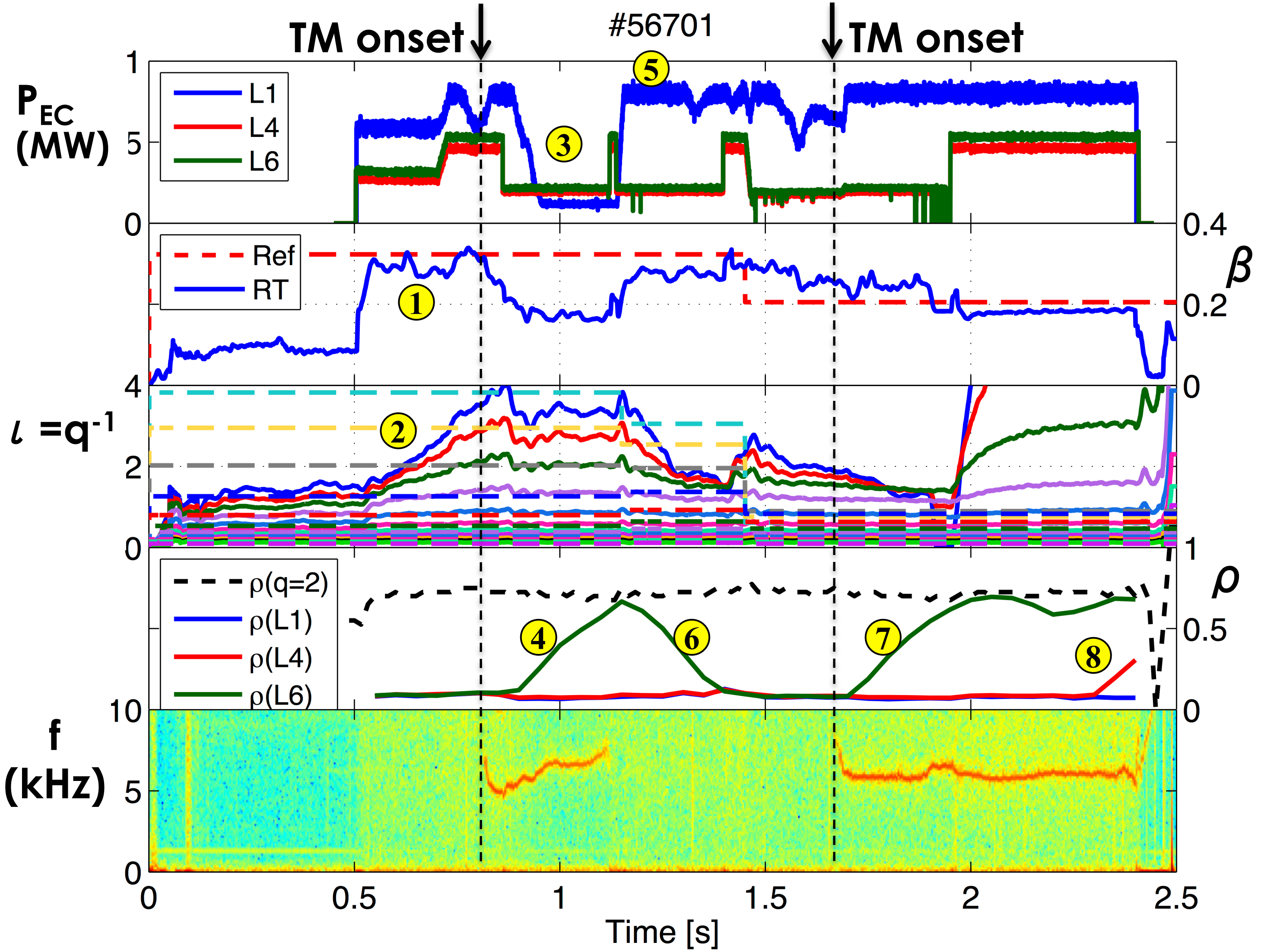

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After Tearing Mode onset:

③ Heating power is reduced

④ One gyrotron re-aims to q=2

Tearing Mode is stabilized:

⑤ Heating power is restored

⑥ Gyrotron returns to core ECCD

Tearing Mode re-appears:

⑦ One gyrotron re-aims to q=2

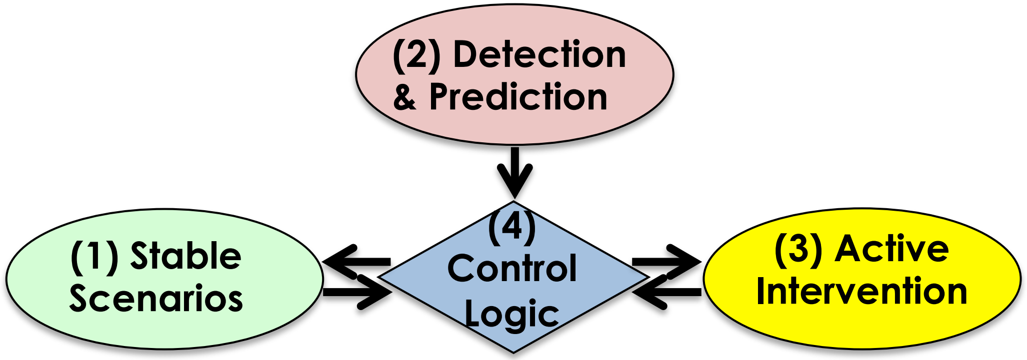
⑧ Second gyrotron re-aims to q=2

TCV: M. Kong, EPS 2017; EX/P1-25

Also: N. Eidietis, EX/P6-22

Integrated Control Will Enable Robustly Stable Discharges with High Fusion Power in ITER

- **Key plasma physics and real-time control elements have been demonstrated**
  - Stable scenarios, real-time warning of instabilities, active management of off-normal states
- **Many challenges remain …**
  - Physics basis of stable, high performance scenarios
  - Accurate prediction, detection, and identification of exceptions
  - Logic for asynchronous responses
  - Physics basis and control testing of intervention and recovery scenarios



- **Recommendation: Make disruption prevention routine in present tokamaks**
  - Beyond "proof of principle" → Demonstrate low rates of disruption over many shots