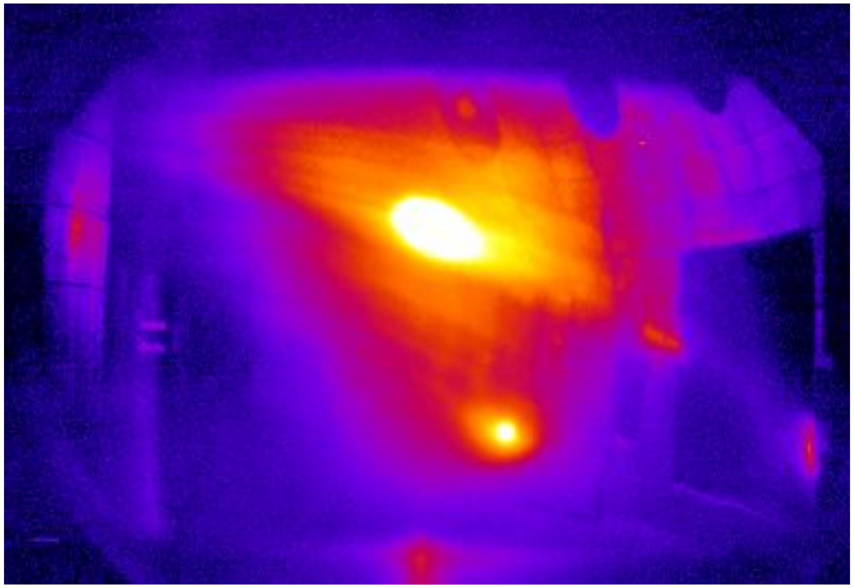
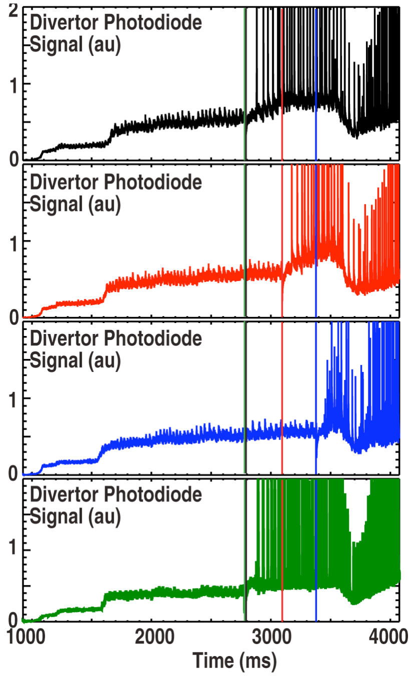
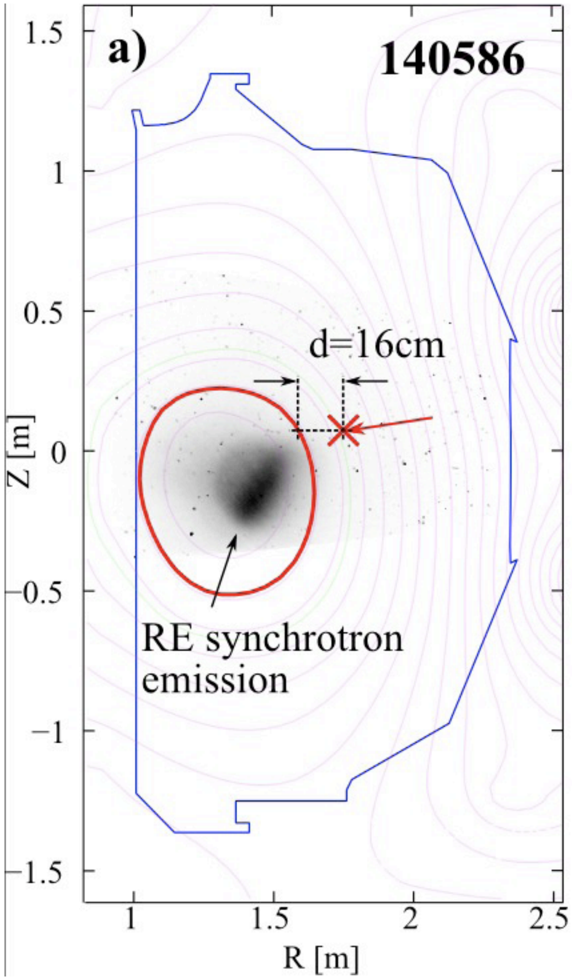
ITER Physics: 2010 experiments

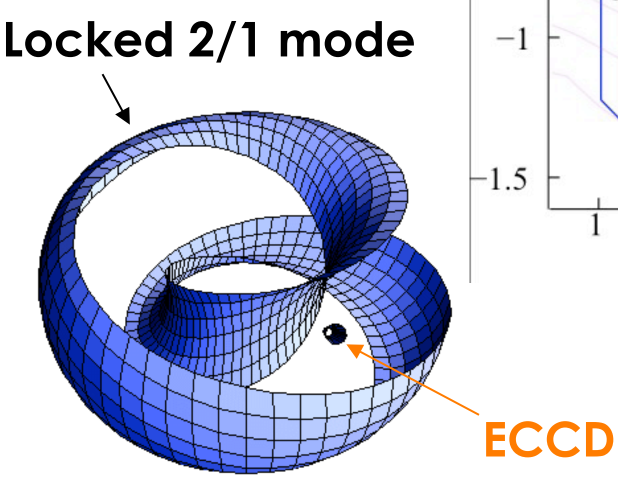
Ted Strait
for the ITER Physics group

DIII-D Year-End Review
June 8-9, 2010









Thanks to all who contributed material and suggestions for this talk!

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M. Jakubowski
A. James
R. La Haye
W. Solomon
F. Volpe
J. Wesley
J. Yu

Mission: “Provide physics solutions to key design and operational issues for ITER”

Working groups address key issues for ITER

- **ELM control for ITER** (T. Evans, R. Moyer)
  - High Priority working group
- **Hydrogen/Helium plasmas** (P. Gohil)
- **ITER demonstration discharges** (E. Doyle)

  } Combined for 2010 campaign
- **Disruption characterization and avoidance** (J. Wesley)
- **NTM stabilization** (R. La Haye)

Urgent topics for ITER were also addressed in other groups

… including …

- Error fields, ELM control *(Nonaxisymm. Fields Task Force)*
- Error fields *(Test Blanket Module Task Force)*
- Disruption mitigation *(Rapid Shutdown Task Force)*
- ITER startup & Rampdown *(Plasma Control)*
- Hydrogenic retention *(Plasma Boundary Interface)*
- Advanced inductive scenarios *(Steady State Integ.)*
- Feedback stabilization of RWM *(Steady State Integ.)*

10 experimental days were allocated in 2010 +1.5 days of Director's Reserve

	Days	(+ DR)
ELM control for ITER	4	+ 1
Hydrogen/Helium plasma operation and ITER demonstration discharges	3	+ 0.5
Disruption characterization and avoidance	2	
NTM stabilization	1	
TOTAL	10	+ 1.5

ELM control for ITER

High Priority Working Group for 2010

Goals:

- **Develop the physics basis for ELM mitigation and suppression using RMPs**
- **Develop the physics basis for pellet pacing of ELMs**
- **Explore and develop alternate approaches to ELM control**
  - QH-mode
  - AC magnetic perturbations

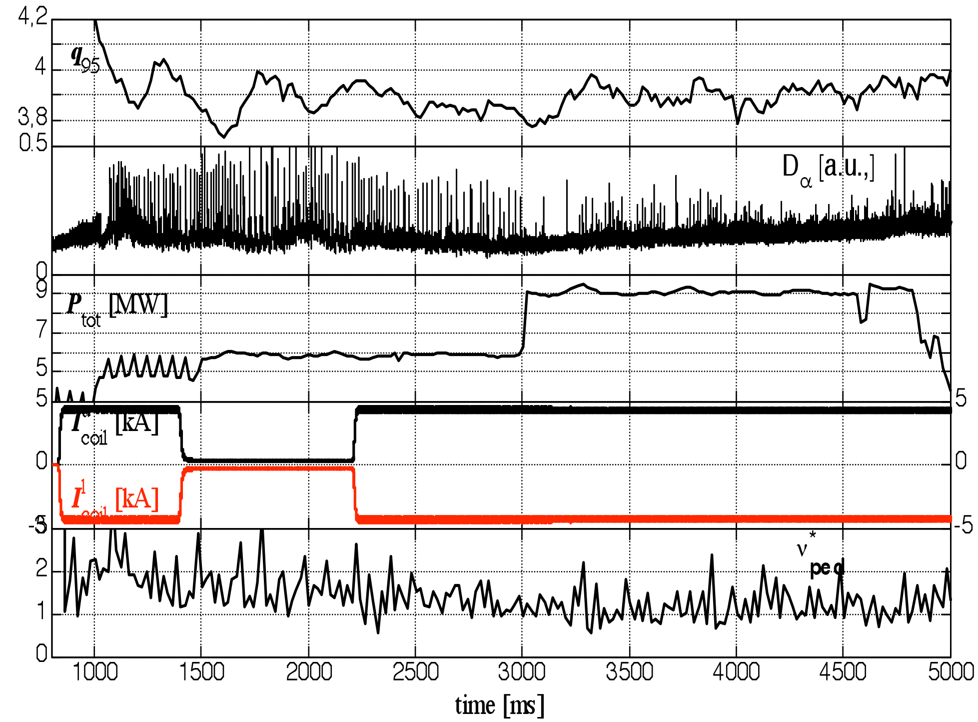
Related work also carried out in 3D Fields Task Force

ELM control for ITER - 4 days (+1)

- **31-1. 3D heat flux with RMP**
  - Quantify peak heat flux with ELM mitigation by RMP
  - Quantify steady-state heat flux with ELM suppression by RMP
- **31-2. RMP effect on L-H power threshold**
  - Does n=3 RMP have a resonant effect on the L-H transition?
- **31-4. Compatibility of pellets and RMP ELM suppression (0.5 day)**
  - Does pellet fueling trigger ELMs? Compare HFS and LFS pellets.
- **31-5. ELM triggering by pellet injection (0.5 day)**
  - Dependence on injection location and penetration
- **31-3. ELM pacing with AC magnetic perturbation**
  - Requirements for RMP amplitude & frequency, effect on heat flux
- **99-30. ELM suppression in double null plasmas with stellarator symmetry (Director's Reserve)**
  - ELM suppression in balanced double null (similar to MAST, NSTX)
  - Data for input to stellarator equilibrium and stability codes

Highlights from 2009-10 ELM Control for ITER Working Group Experiments

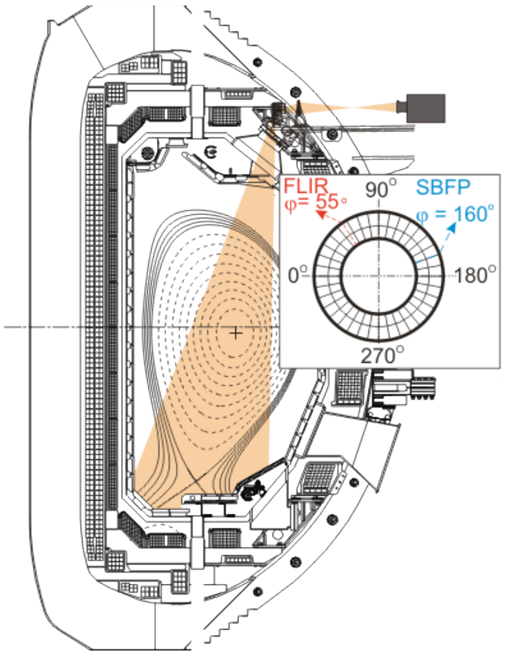
- **ELM mitigation reduces divertor energy impulses as P_{inj} increases (6 MW->9 MW)**
  - ELM frequency increase and amplitude decreases
  - Energy impulses limited to less than 2 kJ (measured at 2 toroidal locations)

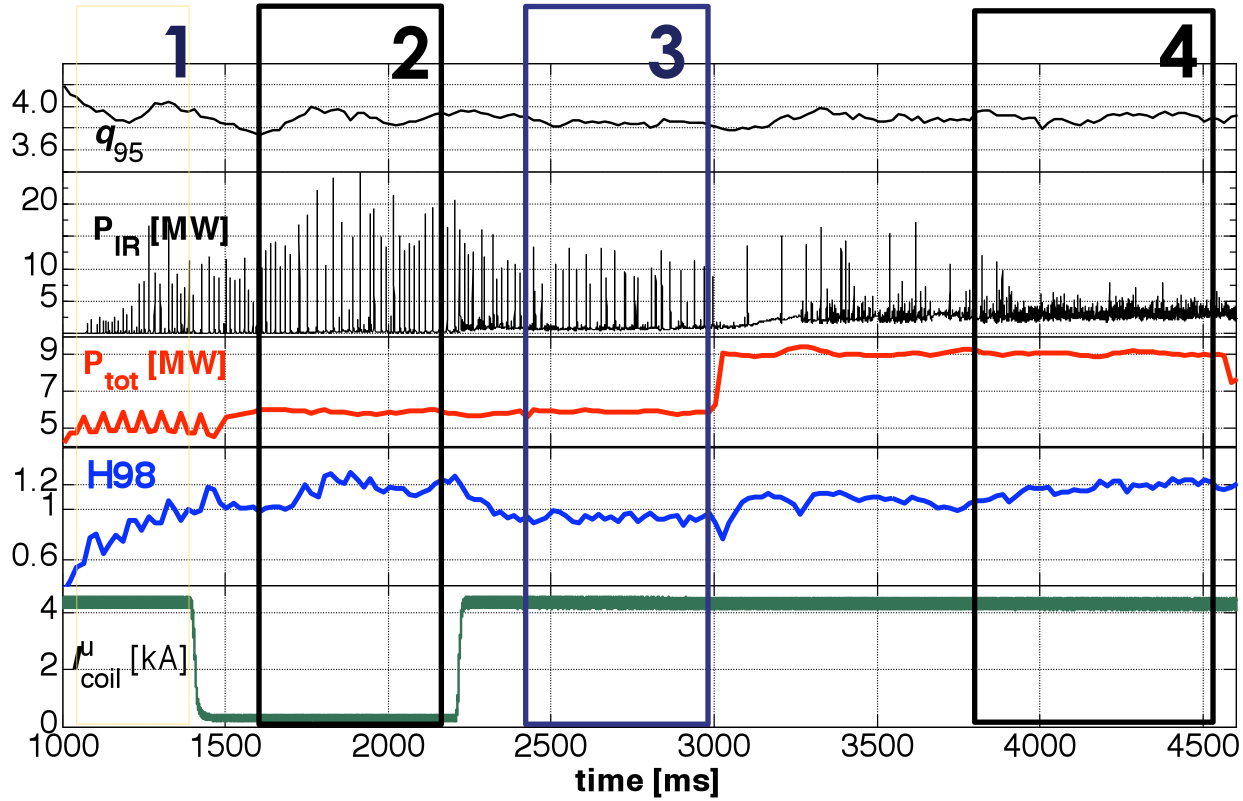


- **L-H power threshold sensitive to q_{95} with even parity n=3 RMP fields**
  - No change when using off-resonance RMP fields
  - Maximum 40% increase with resonant RMP fields

- **Low-field side versus high-field side pellet fueling asymmetry identified during ELM suppression with RMP fields**

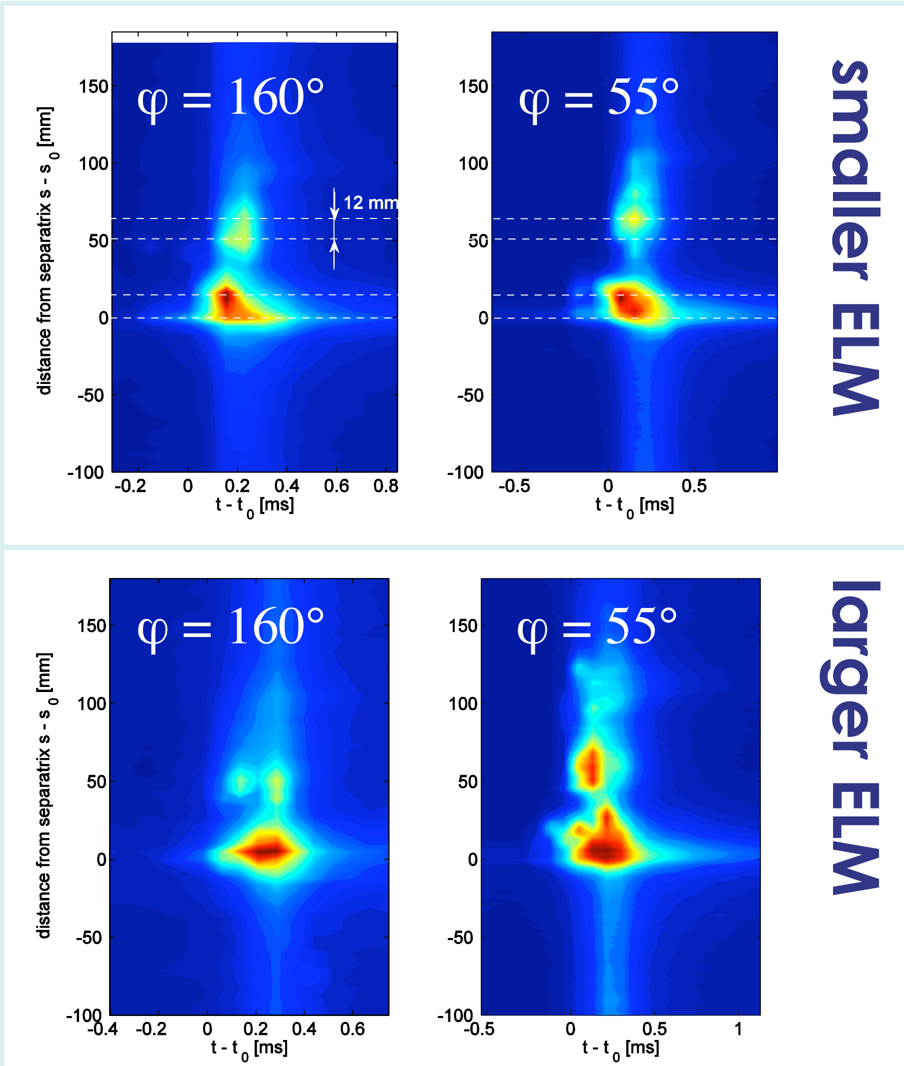
Heat loads due to mitigated ELMs with q95 outside suppression window



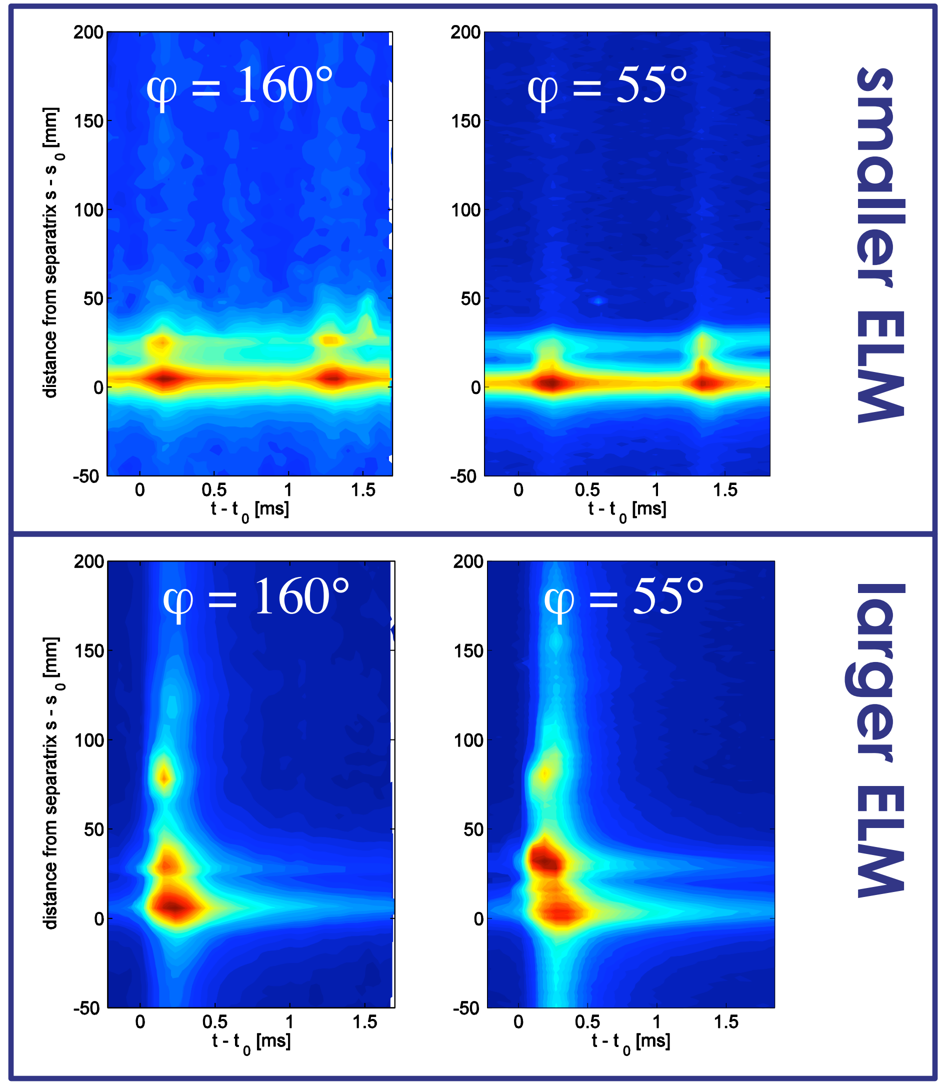


- **ELMs in phase 4 deposit on average 3 kJ to lower divertor**
  - compatible with ITER guidelines
  - H98 at pre-RMP value of 1.2

Without RMP: ELM evolution shows 3D dynamics



With RMP: evolution of ELM structure formed by stochastic boundary



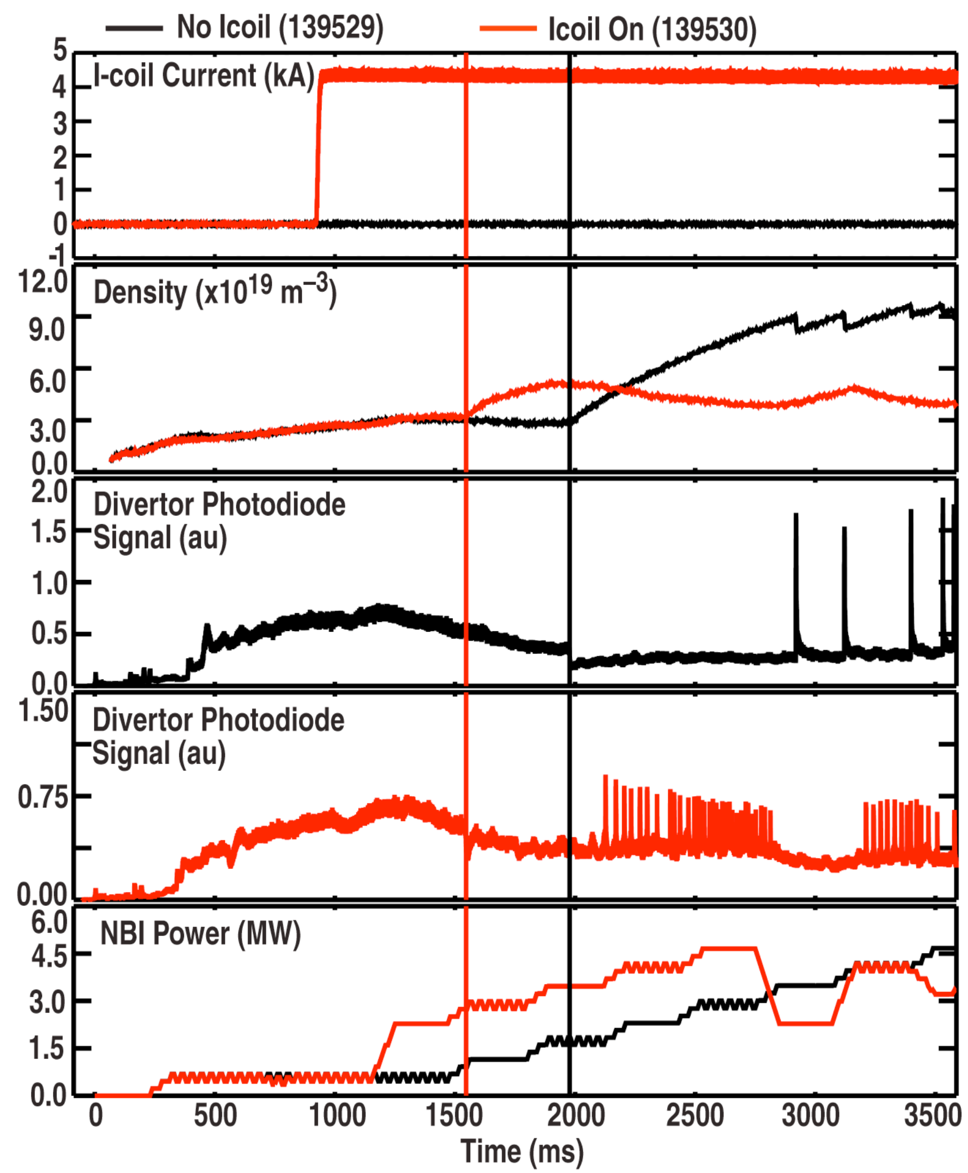
RMP has a significant effect on L-H Power Threshold

Goal

- **Determine the dependence of the H-mode power threshold on the n=3 RMP with the Icoils (D-NBI→D plasmas)**

Results

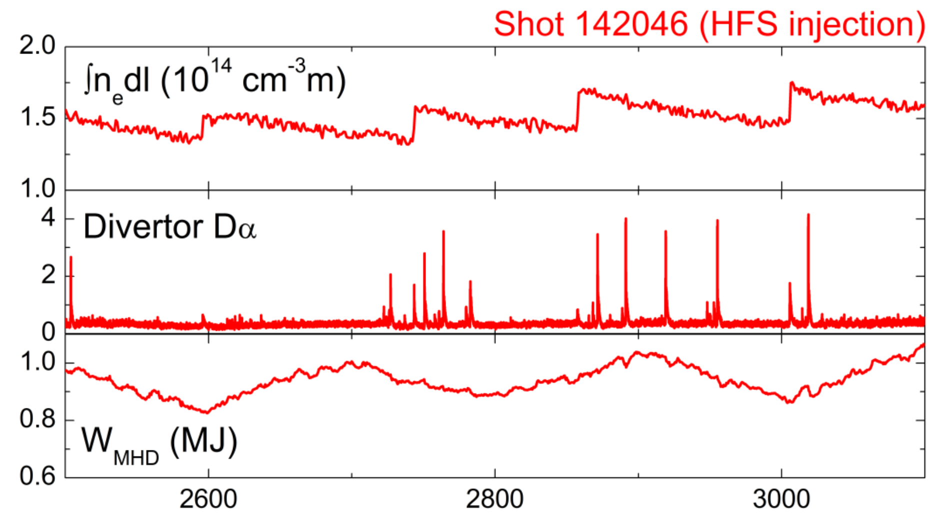
- **Clear effect of increased H-mode power threshold with RMP Icoil current**
- **Determined for NBI (co- and balanced) and with ECH heating**
- **Effect has a threshold in I-coil current**
  - Discernible above 3 kA
  - H-mode power threshold increases with I-coil current
- **Effect has a q dependence**
  - Strong effect at same q_{95} (~3.5) as required for ELM suppression
  - Weak effect off resonance (q_{95} ~4.1)

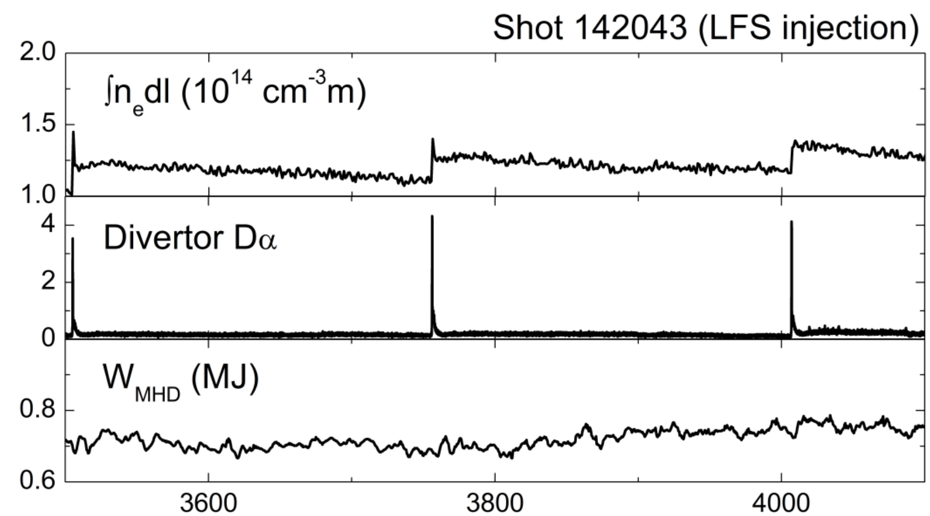


LFS injection could allow pellet fueling without triggering ELMs

- **LFS pellet injection could be a solution to compatibility with RMP:**
  - No real ELM synchronized with the injections (both LFS and HFS)
  - After HFS injection: several ELMs are triggered (observable energy loss)
  - No ELM after LFS injections
  - But fuelling efficiency of LFS pellets appears low
  - Pump-out compensated around 50% without losing the ELM suppression

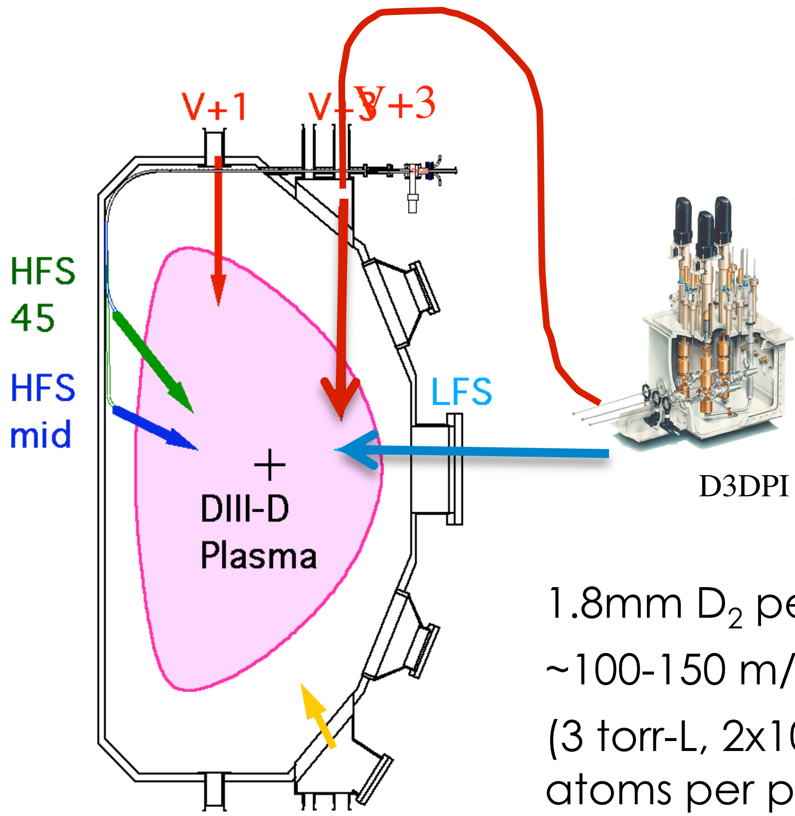
- **<u>BUT</u> difficult to isolate the effect of the pellet injection configuration because of significant differences in average density for the two cases**



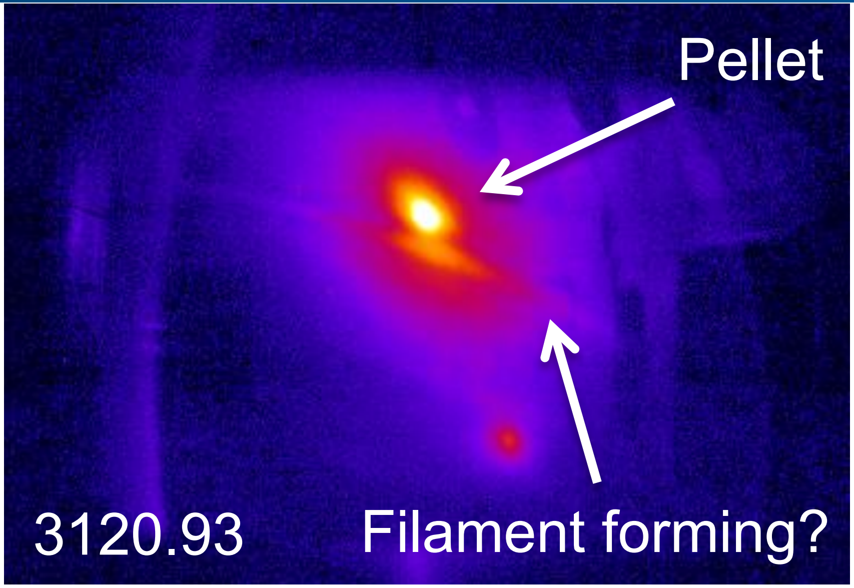


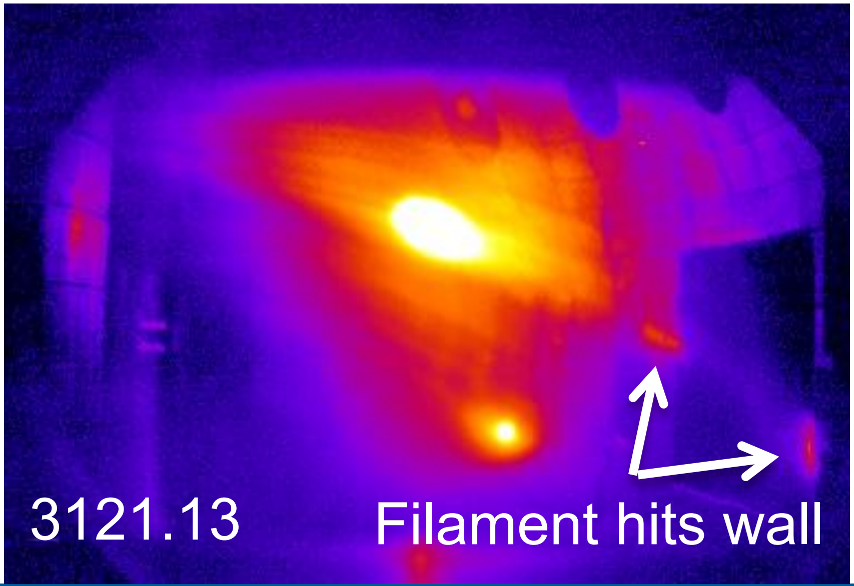
Low-Field Side pellet injection triggers ELMs

- **Requires only a few cm penetration**
- **Fast camera images suggest a single filament is released near the pellet**



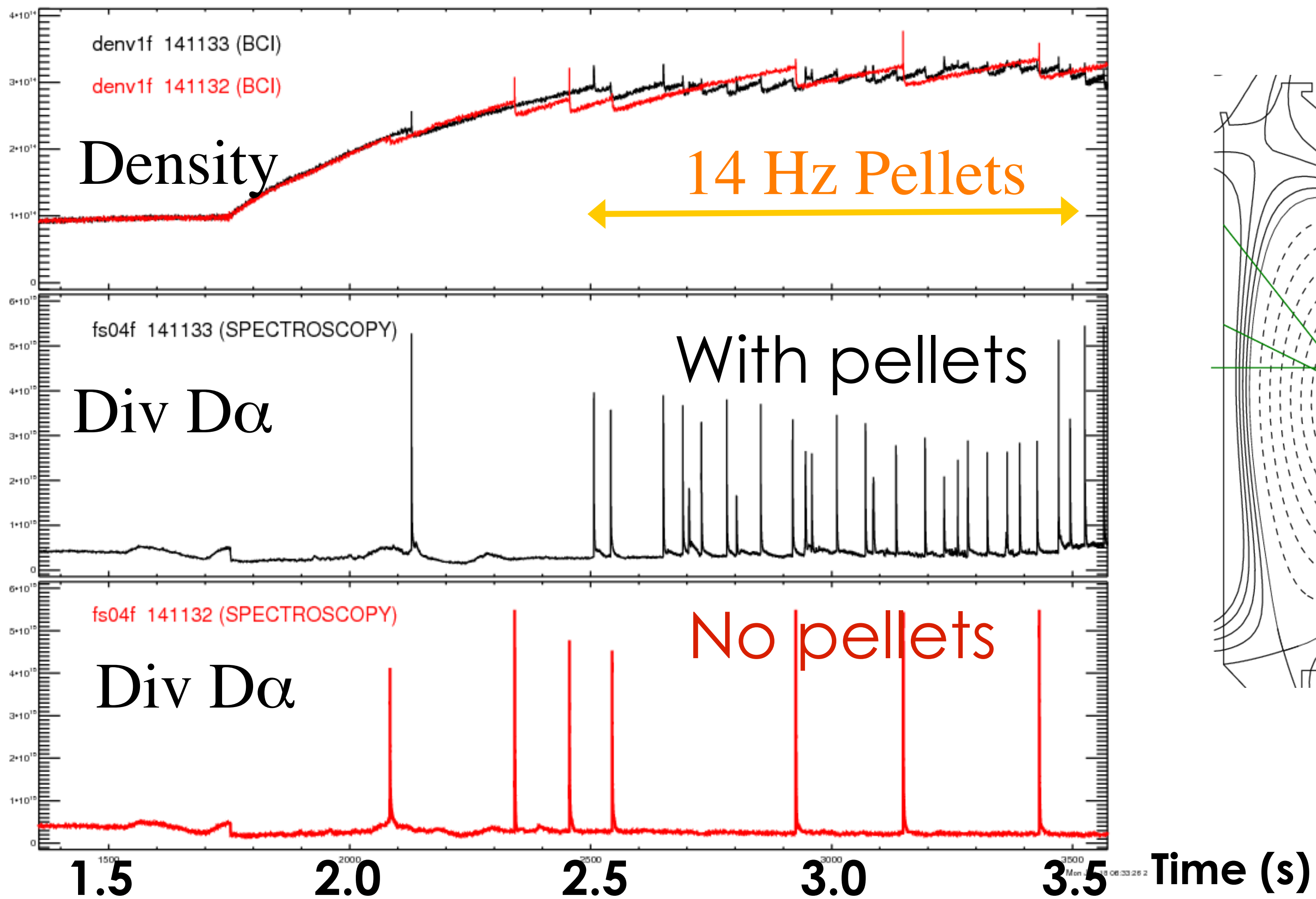
1.8mm D_2 pellets
~100-150 m/s
(3 torr-L, 2×10^{20} atoms per pellet)

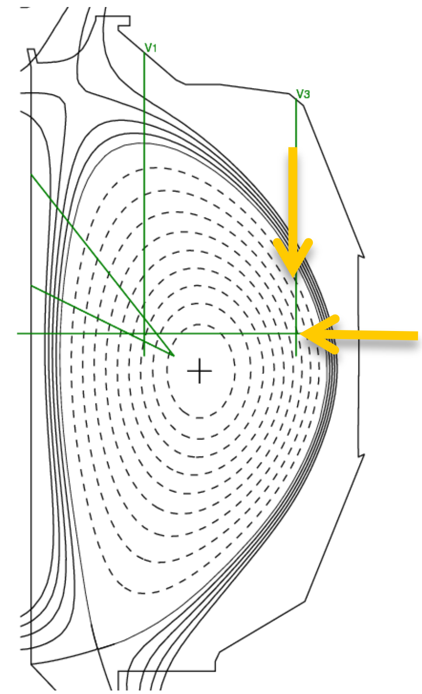




ELM pacing by pellet injection

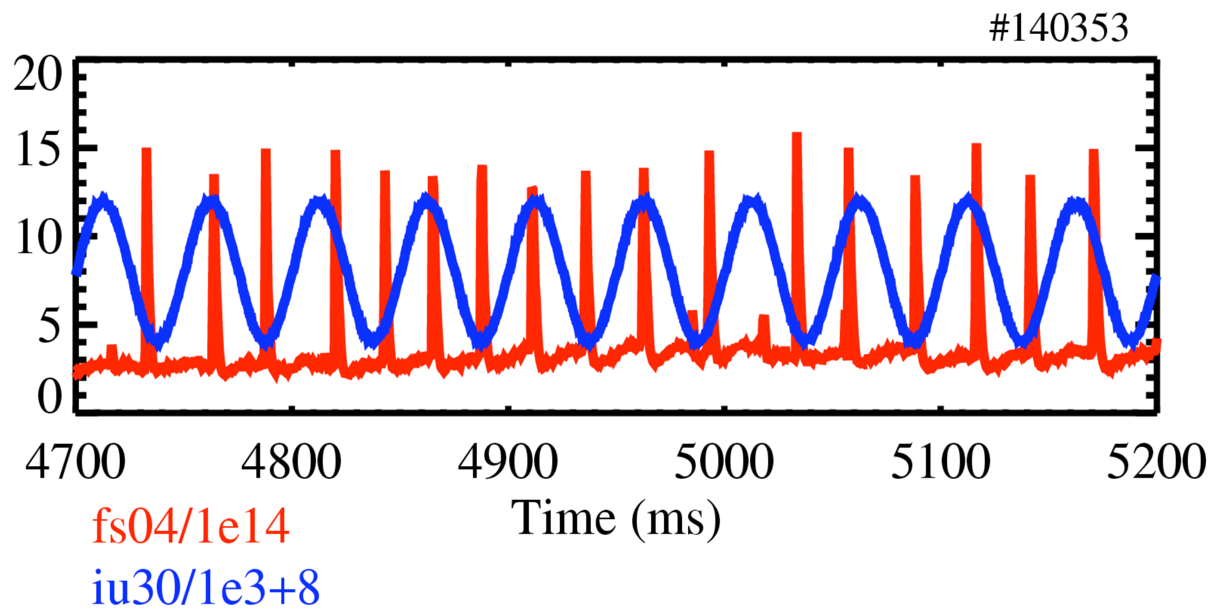
- **14 Hz pellets increase ELM frequency from ~5 Hz to ~25 Hz**
  - Smaller ELM amplitude
  - Little effect on core density

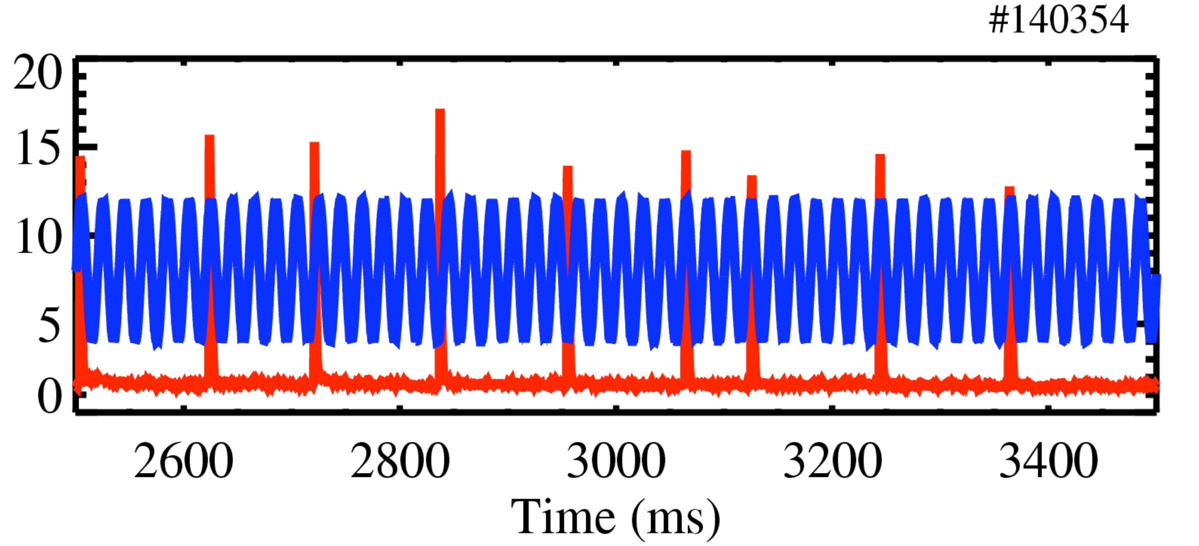




ELM pacing by magnetic perturbation

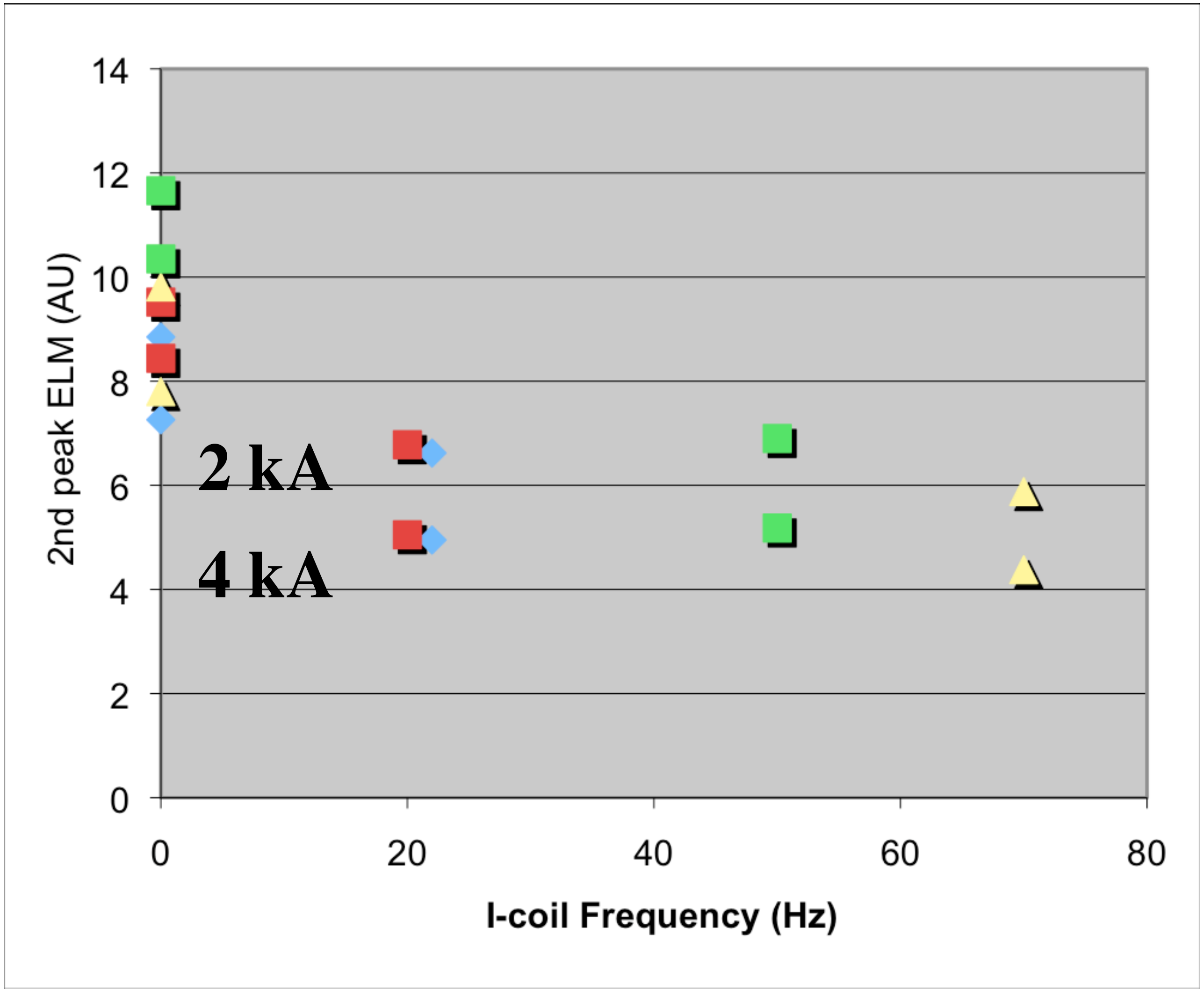
- **Oscillating n=3 field is applied by the I-coil**
- **At 20 Hz, ELMs are perfectly entrained**
- **At higher frequency, entrainment is weak**
  - ELMs still appear to be synchronized to the I-coil field





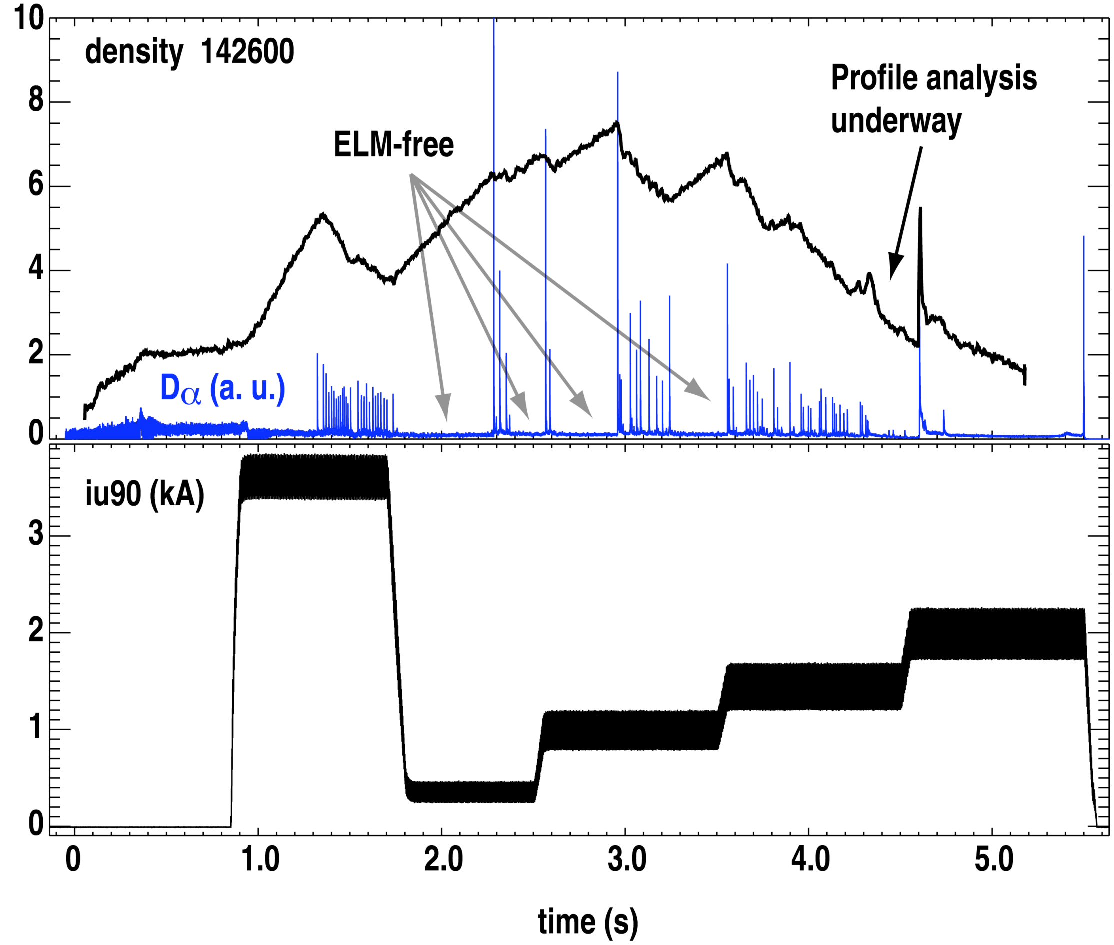
ELM Amplitude Appears To Be Immediately Affected By Modulated I-coil

- **Only minor reduction in amplitude with increasing frequency**
- **Natural ELM frequency is 30 Hz**
  - Pacing with 20 Hz I-coil (=40 Hz ELMs) already reduces amplitude near factor of 2



ELM suppression in DN plasmas with stellarator symmetry

- **Goals:**
  - Use n=3 magnetic perturbations to suppress type-I ELMs in DN plasmas
  - Obtain stellarator symmetric data for 3D equilibrium, stability and transport modeling
- Results:
  - Obtained DN discharges with good shape control
  - I-coil RMP fields successfully used to control early n_e
  - I-coil current scan
    - 0.5-1.0 kA -> mixed ELM-free and ELMing periods
    - Above 1 kA -> large n_e pump out
  - Discharge may be in L-mode when ELMs disappear at 4.3 s
    - Profile analysis underway



Hydrogen and Helium plasmas … combined with ITER demonstration discharges

Goals:

- **Determine H-mode accessibility in ITER's non-activation phase**
  - Ion species dependence of L-H power threshold
- **Predict ITER's performance in non-activation phase: Ion species dependence of**
  - ELM, pedestal characteristics
  - ELM control techniques
  - Transport, turbulence, ρ^* scaling
  - SOL, divertor characteristics

Hydrogen and Helium plasmas – 3 days (+0.5)

- **35-1. RMP ELM suppression in helium plasmas (hydrogen NBI)**
  - Use RMP fields to control the density rise in ELM-free H-mode
  - Test RMP ELM control in helium plasmas
- **35-2. H-mode power threshold and H-mode characteristics in helium plasma with hydrogen NBI**
  - Quantify the power threshold and torque dependence with H→He
  - Evaluate ITER baseline scenario performance in helium plasma
- **35-3. H-mode power threshold and H-mode characteristics in deuterium plasma with deuterium NBI**
  - Quantify the effects of density, torque, magnetic geometry, and RMP on the H-mode power threshold with D→D, for comparison to previous H→H, He→He, and H→He cases.
- **99-20. H-mode Power Threshold as function of helium purity (Director's reserve: 0.5 day)**
  - Threshold in D plasmas with varying He dilution, after boronization

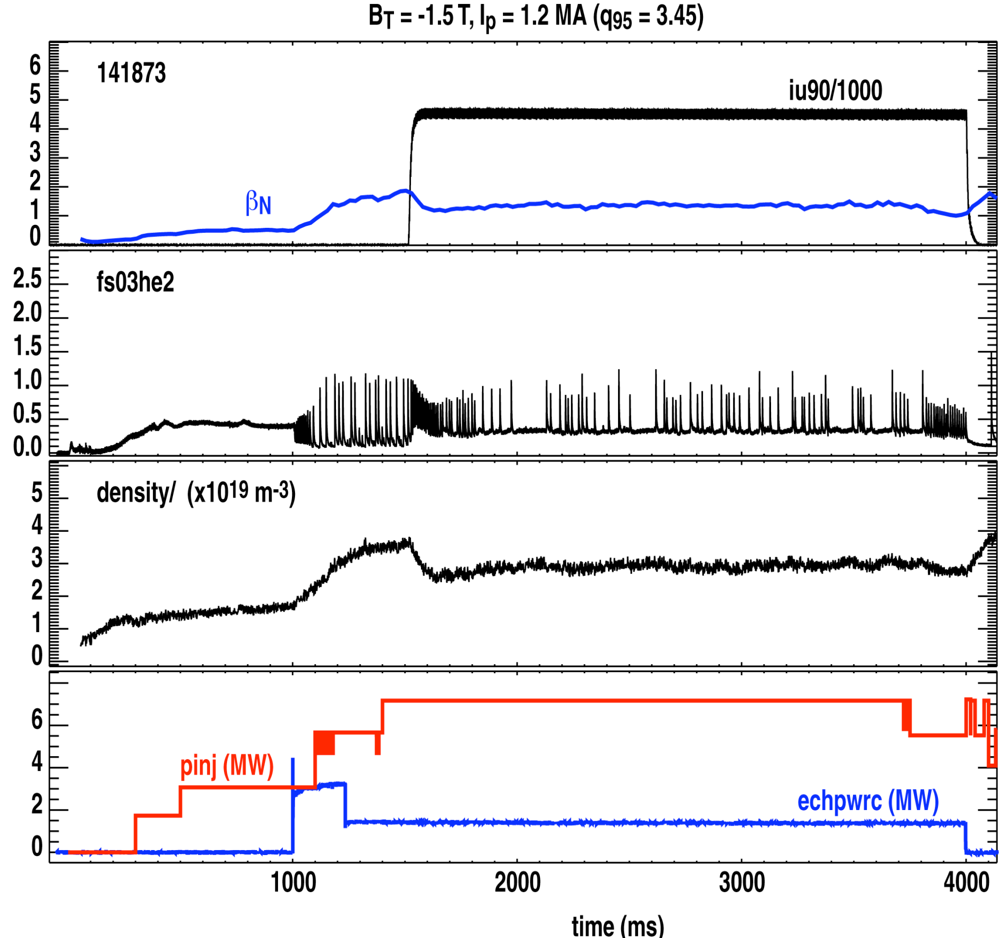
RMP density control and ELM suppression in helium plasmas

Goal:

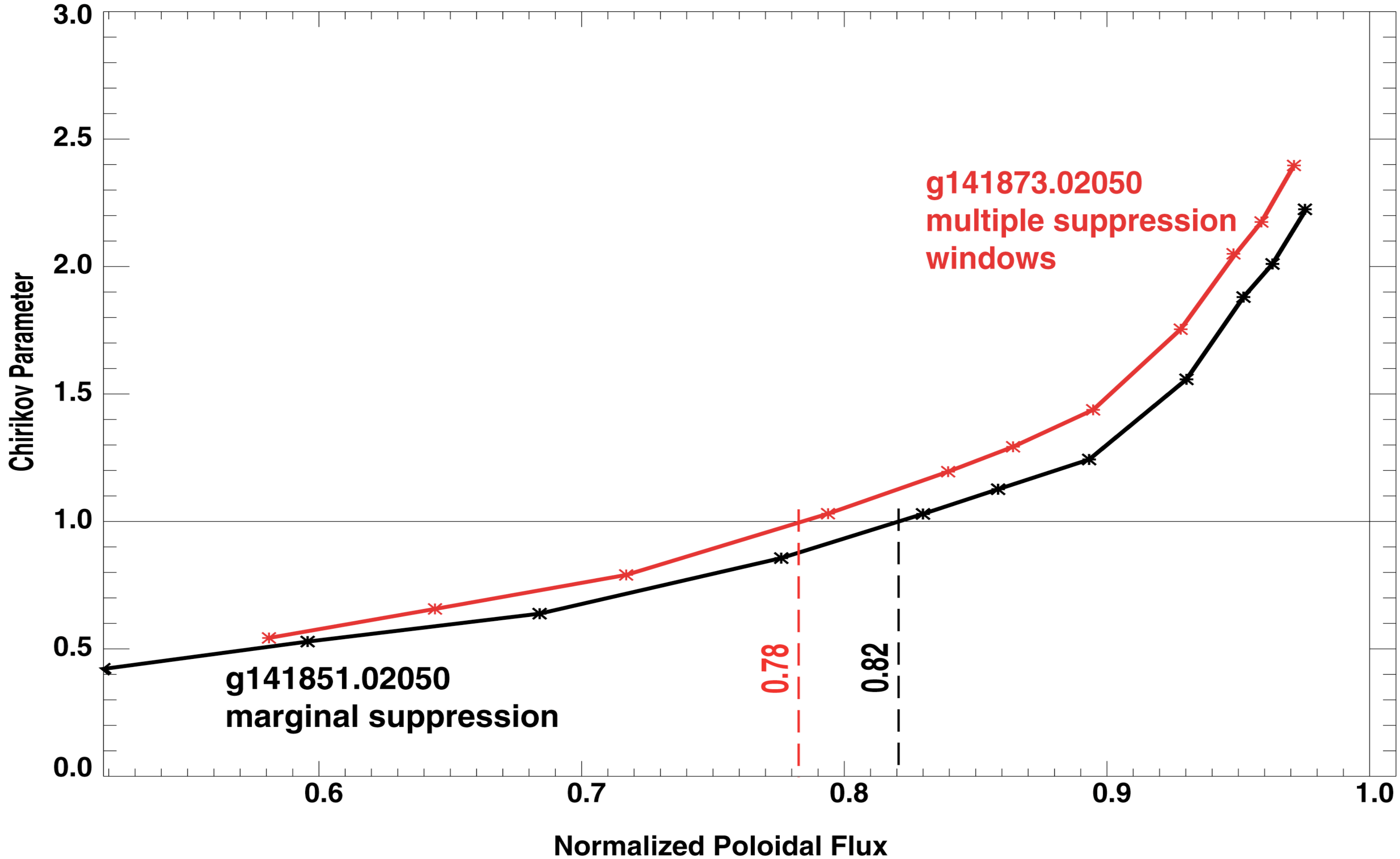
- Use n=3 RMP fields to control the H-mode density and suppress type-I ELMs in ITER similar shaped helium plasmas with hydrogen NBI and ECH.

Results:

- Obtained density control in He plasmas with H beams
  - > Collisionality was still larger than the typical range for ELM suppression in deuterium
- Obtained brief ELM suppression windows with n=3 RMPs
  - > Required higher RMP fields than usual by combining I-coil fields with C-coil fields



ELM suppression in He plasmas requires a wider stochastic layer ($\Delta\psi_{N-chir}$) than in D_2 plasmas



- $\Delta\psi_{N-chir}$ = 0.22 required to obtain small He ELM suppression windows compared to $\Delta\psi_{N-chir}$ = 0.16 for full ELM suppression in D2 plasmas

H-mode Power Threshold and H-mode Characteristics in Helium Plasmas with Hydrogen NBI

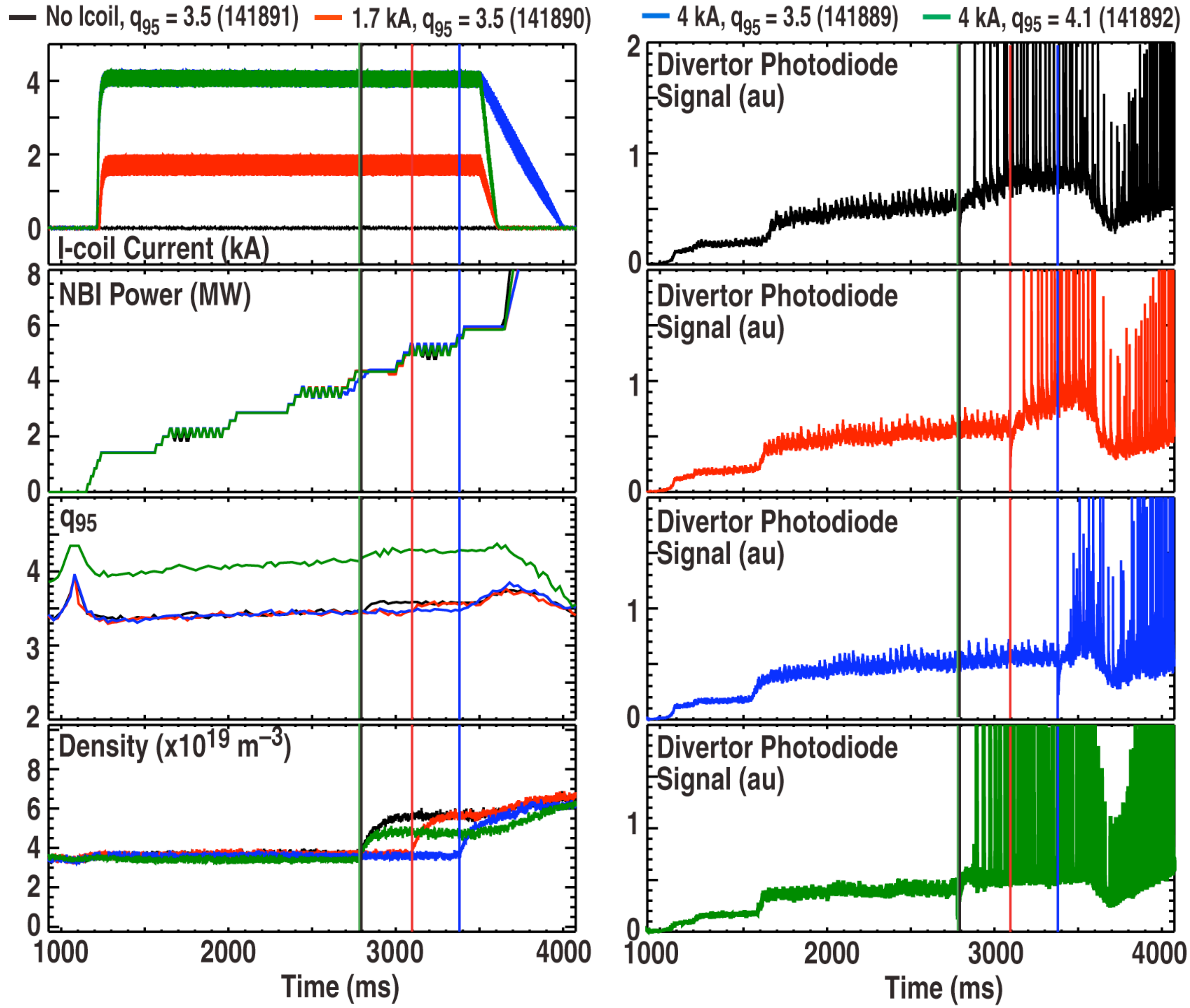
Goal

- **Determine the H-mode power threshold and H-mode characteristics in helium plasmas using hydrogen NBI and ECH**
  - As function of target density, I-coil current and X-point height

Results:

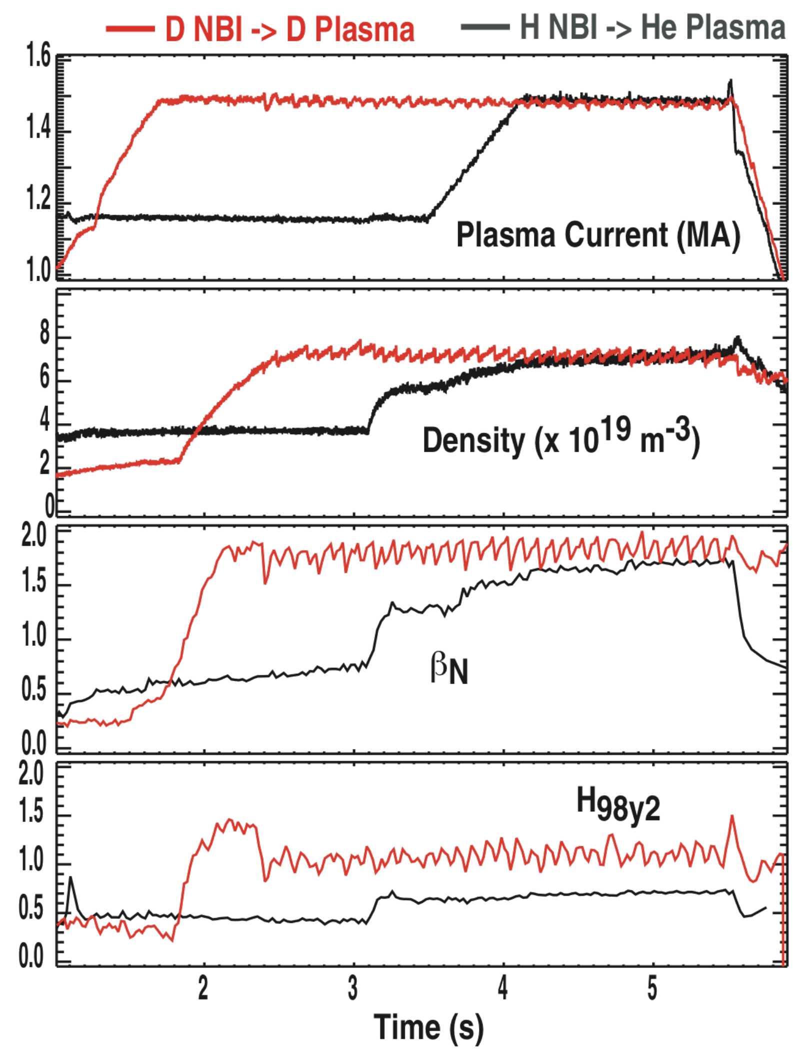
- **The H-mode power threshold for H→He is between those for He→He and H→H**
  - Expected due to dilution of He plasmas with H beam fueling
  - Still larger than D→D (in contrast to ASDEX Upgrade results: He and D ~same)
- **H-mode threshold decreases continuously as He dilution of D plasma decreases**
  - Separate experiment: Director's reserve day
- **H-mode threshold with ECH alone is lower (no dilution effects) than with H-NBI**
- **Clear increase in H-mode threshold with I-coil current (effect discernable at lower I-coil current than that for D plasmas)**
- **Significant decrease (> factor of 2) in NBI power threshold with reduced X-point height**
  - Confirms trend observed in He plasmas with ECH alone
- **Performance with H-NBI into He plasmas is substantially lower than with D-NBI into D plasmas**

Application of Icoil at resonant q_{95} increases H-mode Power Threshold (H → He, Balanced NBI)



Baseline scenario performance with H→He plasma is substantially lower than with deuterium (D→D)

- **Piggyback experiments used "ITER-similar" shape**
  - I/aB similar to ITER baseline, q95 ~ 3.2
- **NBI power to maintain β_N~1.8 is 8.6 MW (H→He plasma) vs. 2.8 MW (D→ D plasma)**
  - H_{98} is reduced by about 40% (effect of Z is not included in the ITER H-mode scaling)



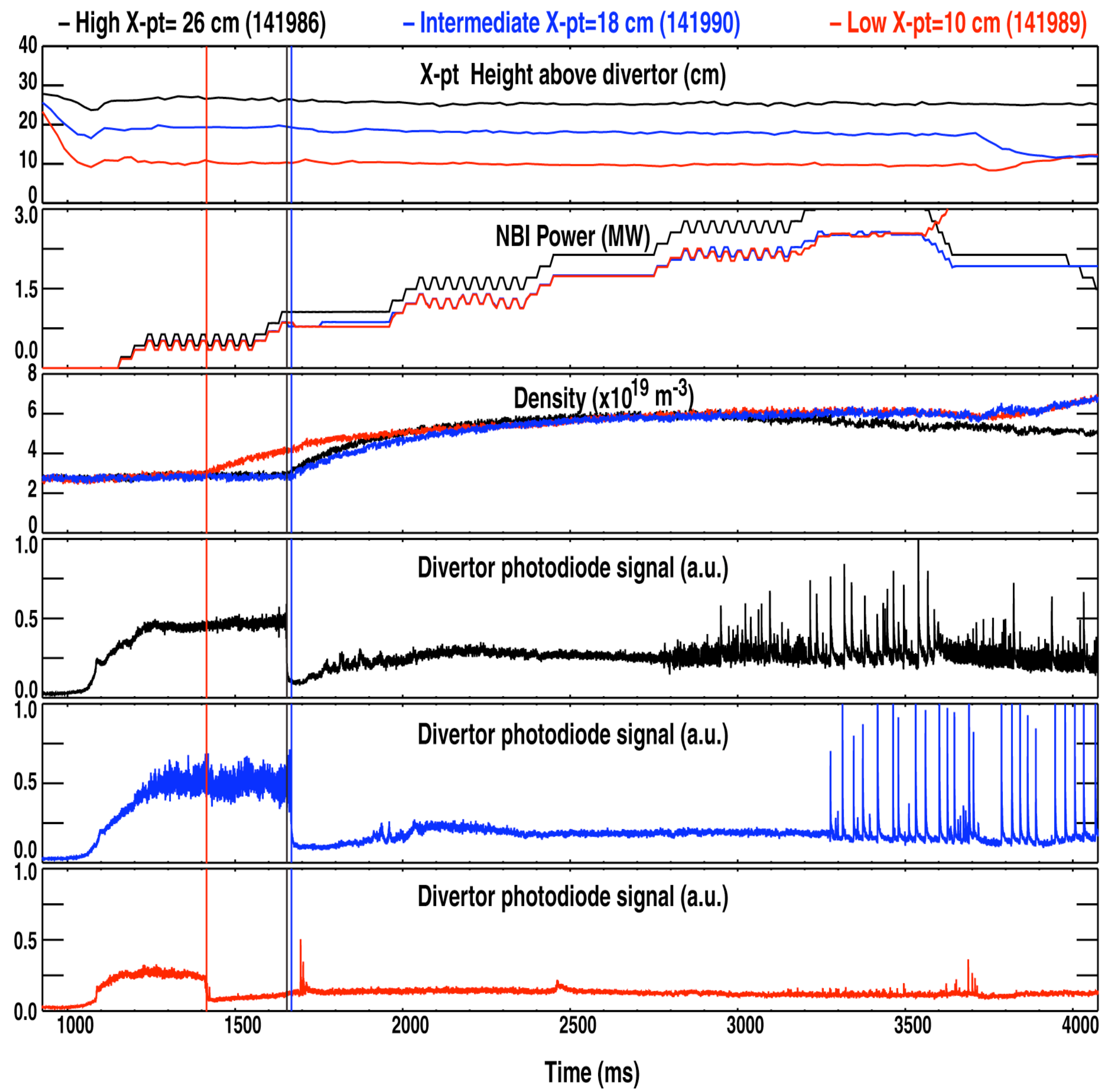
H-mode Power Threshold and H-mode Characteristics in D Plasmas with D-NBI

Goal

- **Determine H-mode power threshold and H-mode characteristics in D→D plasmas for comparison with results with H and He plasmas**

Results

- **Obtained good data for D plasmas with D-NBI (co- and balanced) and with ECH on**
  - Density dependence
  - I-coil current dependence
  - Dependence on X-point height above divertor
- **Piggyback experiment after 3500 ms: ITER demo discharges in D plasmas for comparison with He plasmas**



Disruption characterization & avoidance

Goals:

- **Characterize causes and consequences of disruptions**
  - VDE forces and thermal loads
  - Runaway electron generation and loss
- **Develop strategies toward disruption-free operation**
  - Prediction and precursor detection
  - Active means to avoid or postpone disruption

Complementary to Rapid Shutdown Task Force

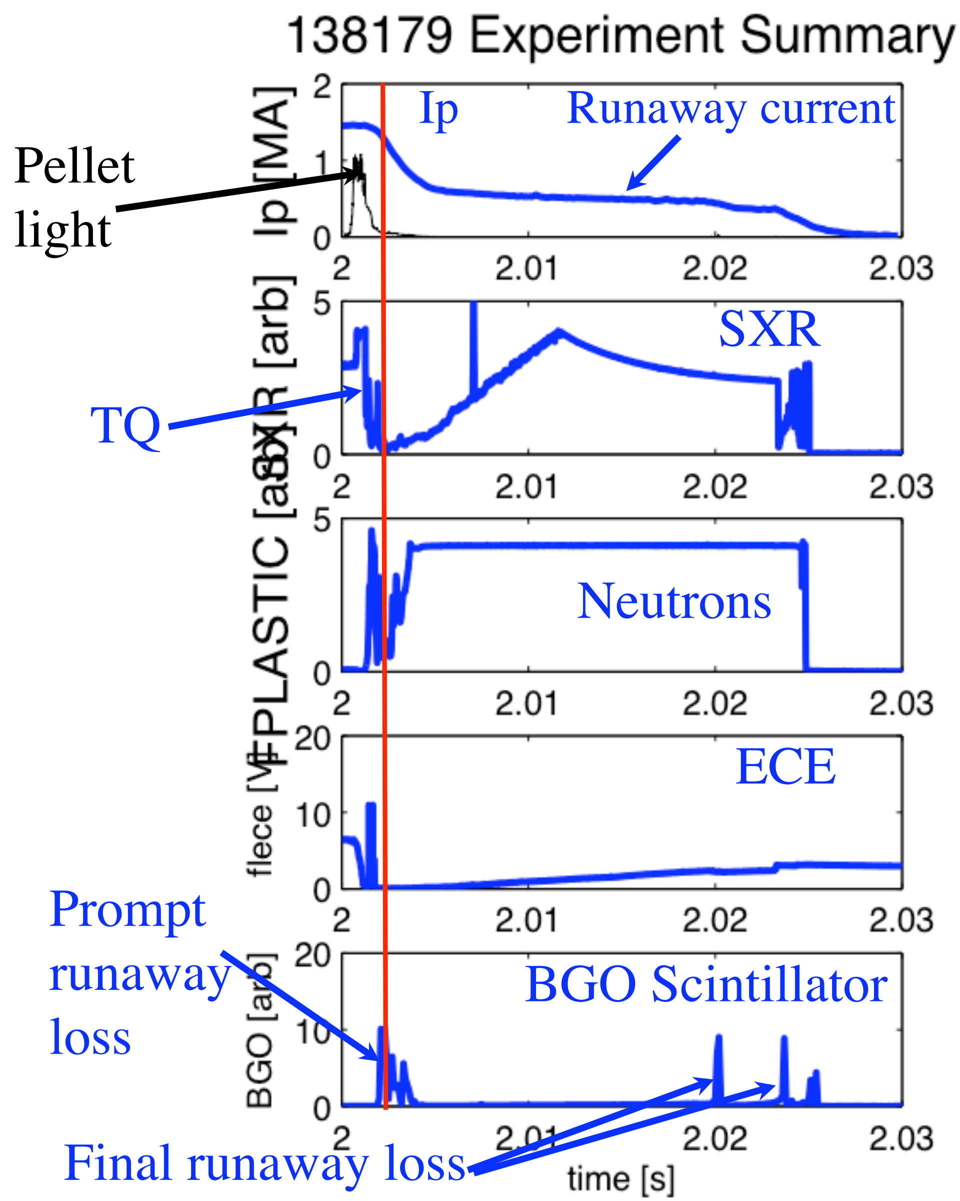
Disruption characterization & avoidance – 2 days

Focus in 2010: Runaway electron physics

- **32-1. Formation of runaway electrons**
  - Develop reproducible generation of runaway electrons
  - Characterize mechanisms for runaway electron generation
- **32-2. Control of runaway electron current channel**
  - Develop feedback control of runaway electron beam position
  - Develop a target for slow suppression of runaway beam
- **99-25. Control of runaway electron current channel (Director's reserve: 0.5 day in Rapid Shutdown TF)**
  - Improve control of runaway electron beam position
  - Control runaway duration with E-coil voltage (first demonstration)

Runaways Produced by Ar Pellet Injection

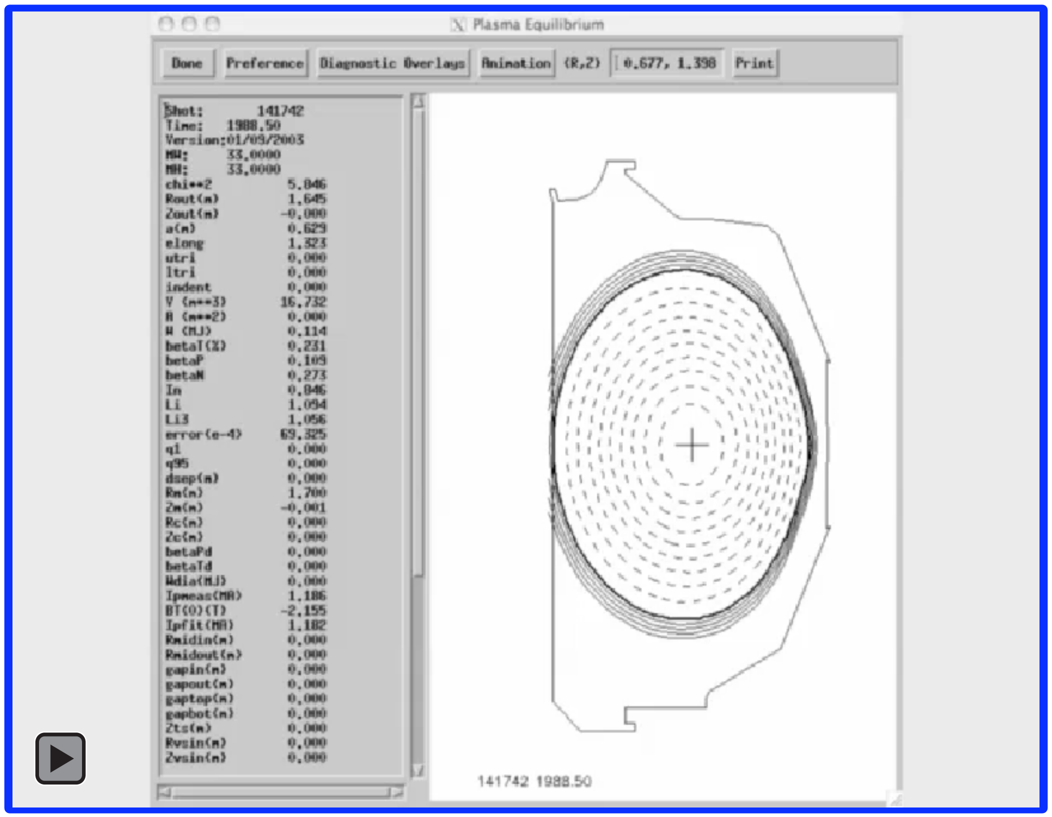
- **Ar pellets injected:**
  - Cools plasma edge, contracts profile
  - Triggers thermal quench MHD
  - Current profile flattening from reconnection
- **Runaways produced in TQ/flattening process:**
  - Large E-fields produced
  - Low kappa, limited plasmas reliably produce runaway current channel
- **Runaways avalanche to become visible current channel:**
  - Reduced island overlap in low kappa allows increased seed confinement



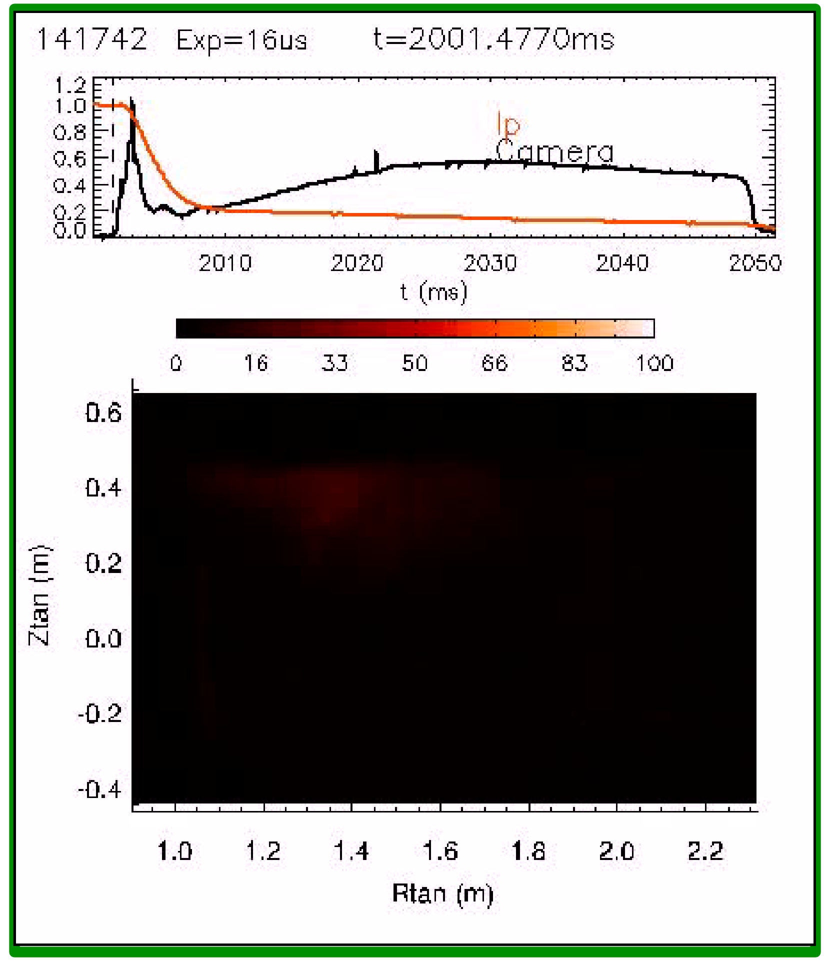
New position control scheme successfully holds runaway electron channel on the midplane

- **Switch to simple R,Z position control algorithm during & after CQ**
  - Advanced boundary control algorithms fail during rapid CQ
- **Vertical position control is effective**
  - Limited ability for radial control

Real-time EFIT



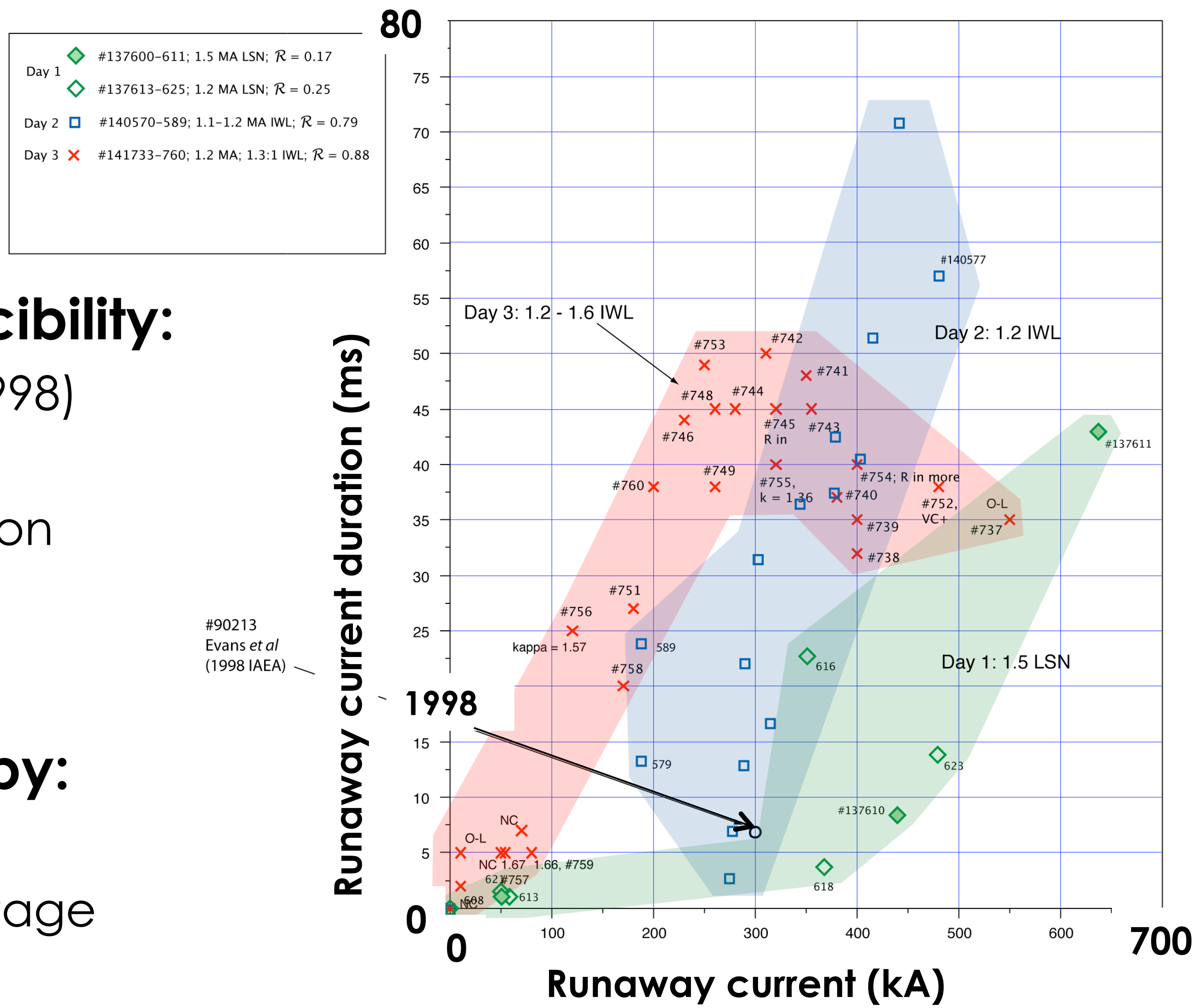
Fast Camera



2010 experiments increased the magnitude and duration of runaway electron current

- **Several factors for improved reproducibility:**
  - Ar pellet (Evans, 1998)
  - ECH
  - Reduced elongation
  - R, Z control

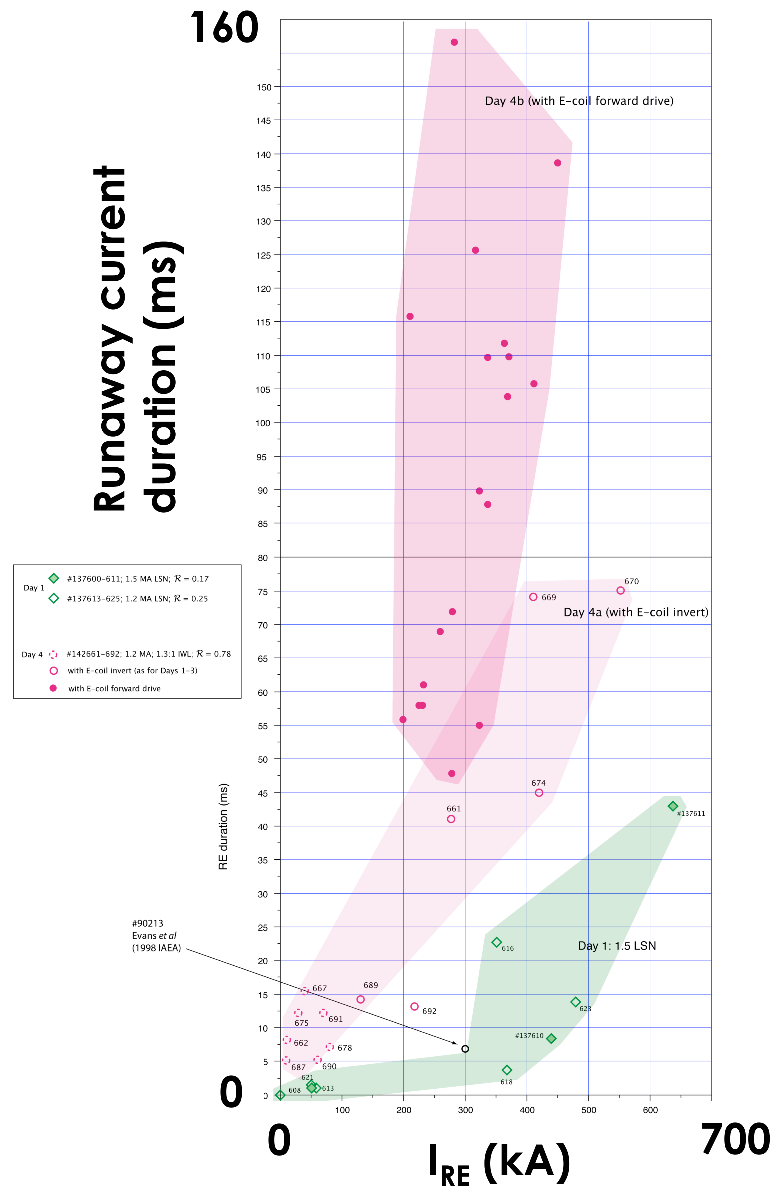
- **Duration is limited by:**
  - Vertical instability
  - Negative loop voltage



E-coil drive offsets the resistive decay, extends runaway current duration

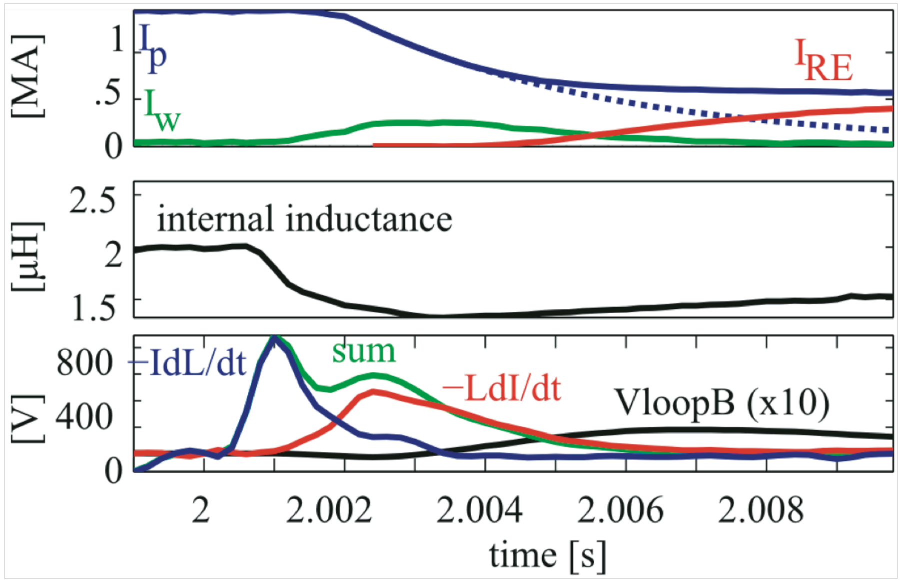
- **Full E-coil drive sustains or increases I_{RE}**
  - "natural" decay γ_{RE} ~5 MA/s
  - 15 V/turn maintains $I_{RE} \geq 300$ kA

- **Duration is limited by:**
  - Vertical instability (ℓ_i increase)
  - E-coil voltage, volt-sec limits

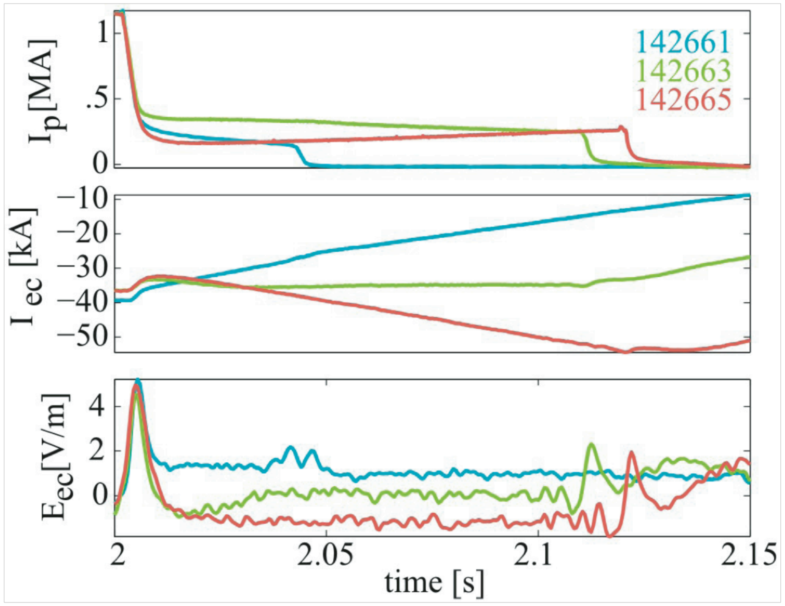


Reproducible, sustained runaway beam enables studies of generation and loss mechanisms

- **Large loop voltage at end of thermal quench**
  - From drop in internal inductance
  - JFIT analysis

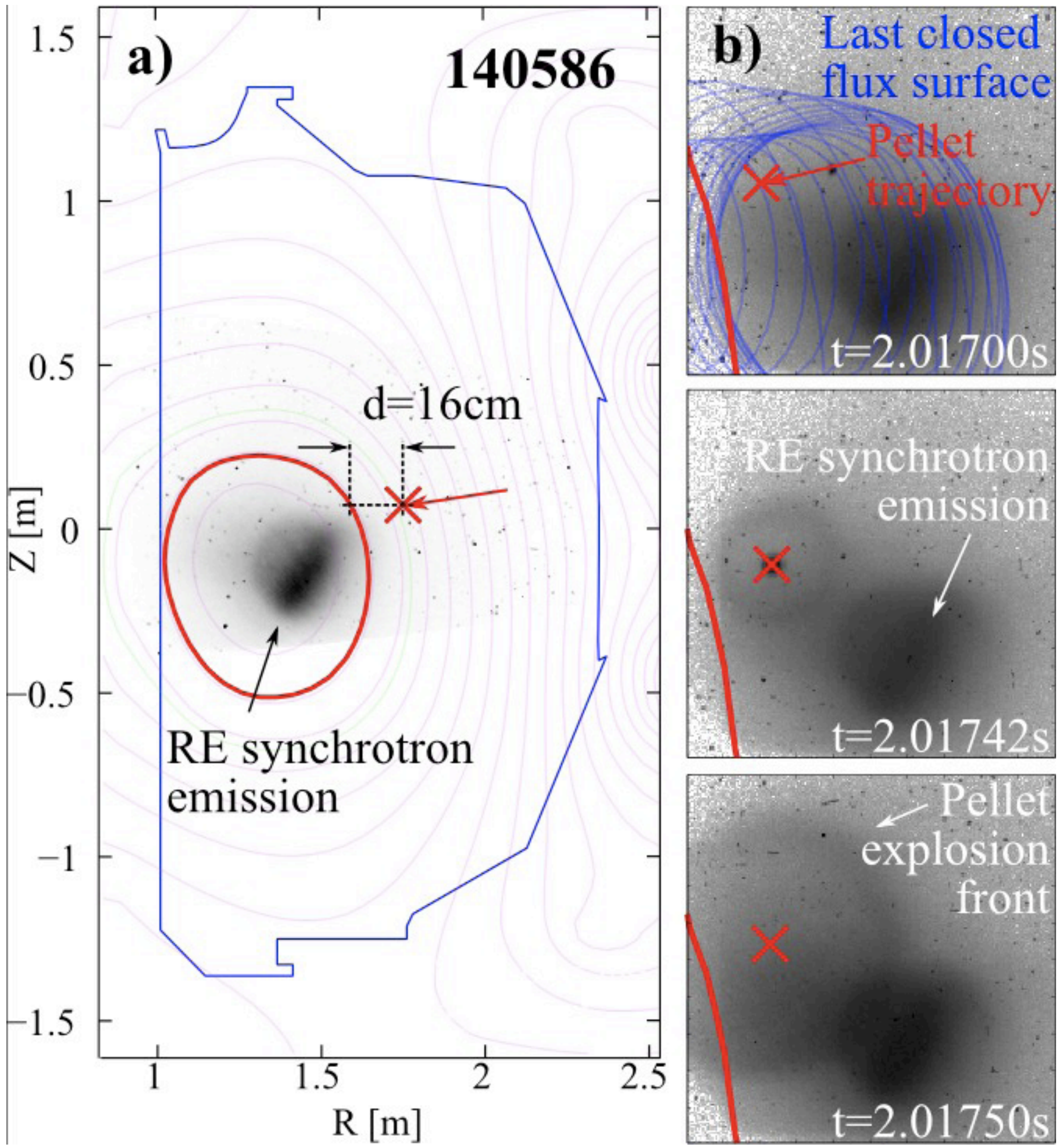


- **Rate of change of current depends on electric field**
  - Allows a test of avalanche theory: $\gamma_{RE} \propto E - E_{crit}$ (Rosenbluth; Parks)
  - Analysis is in progress
  - A promising result for ITER



Impurity pellet injection probes the runaway beam

- Sudden explosion of polystyrene pellet suggests volumetric heating
- Explosion ~16 cm outside LCFS consistent with relativistic drift orbit displacement (E_e ~17 Mev)
- Absence of visible synchrotron radiation suggests lower energy than in the core RE channel



NTM stabilization

Goals:

- **Validate models for ECCD stabilization of NTMs in ITER**
  - Effect of ECCD modulation
  - Requirements for current drive width and alignment
- **Develop alternative approaches to NTM control in ITER**
  - RMP "steering" of locked mode to ECCD location
  - Entrainment and acceleration of locked mode
- **Develop control algorithms for NTM stabilization and disruption avoidance**

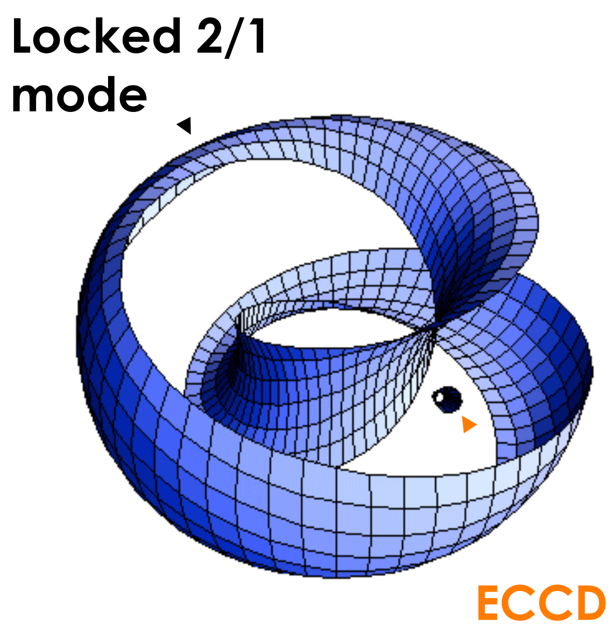
Complementary to NTM stability studies in Fusion Science

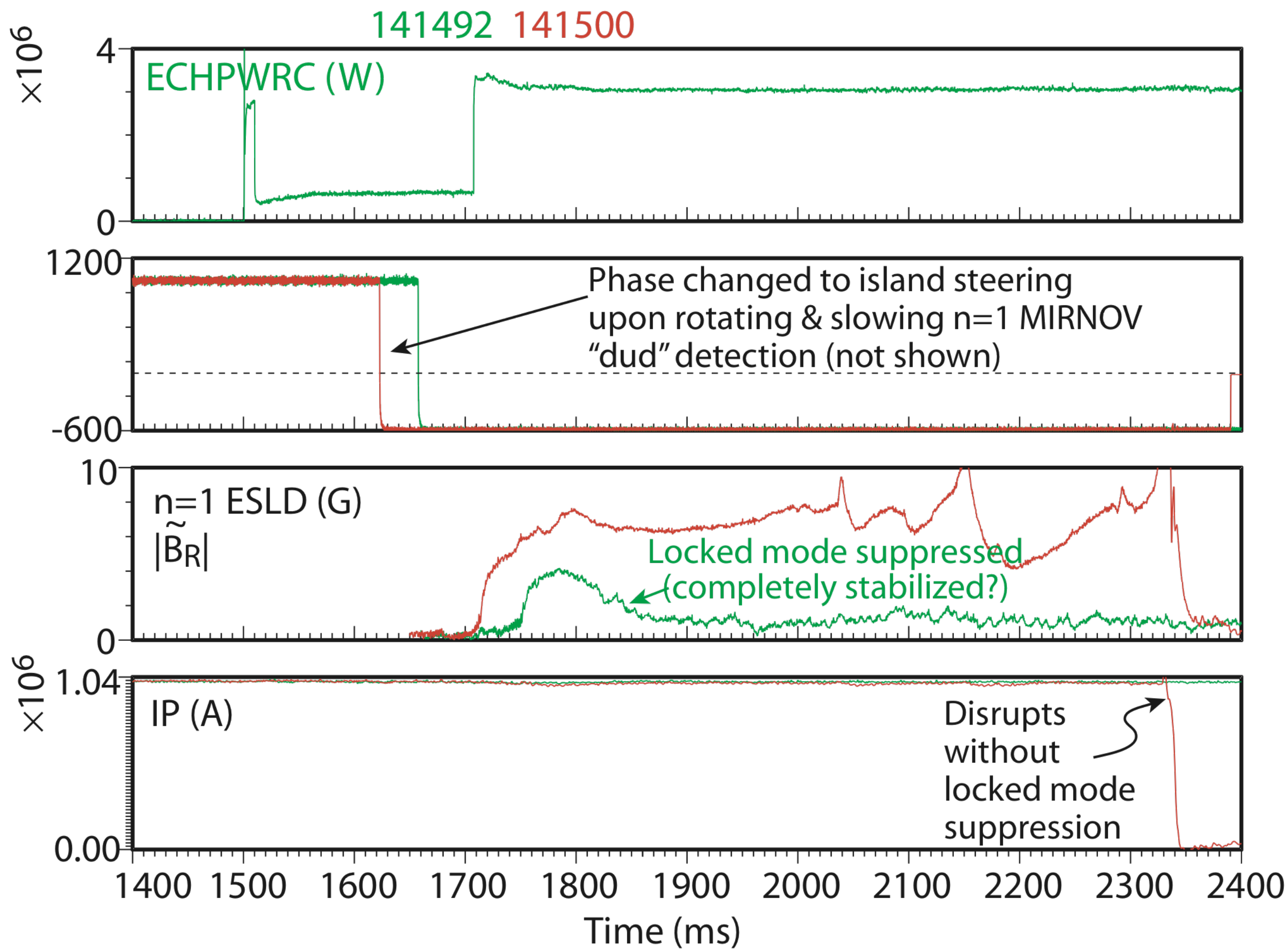
NTM stabilization - 1 day

- **33-1. Active control of locked modes**
  - First demonstration of stabilization of a locked mode
- **(piggyback) First demonstration in DIII-D of real-time mirror steering for ECCD**
  - Pre-requisite for routine NTM stabilization

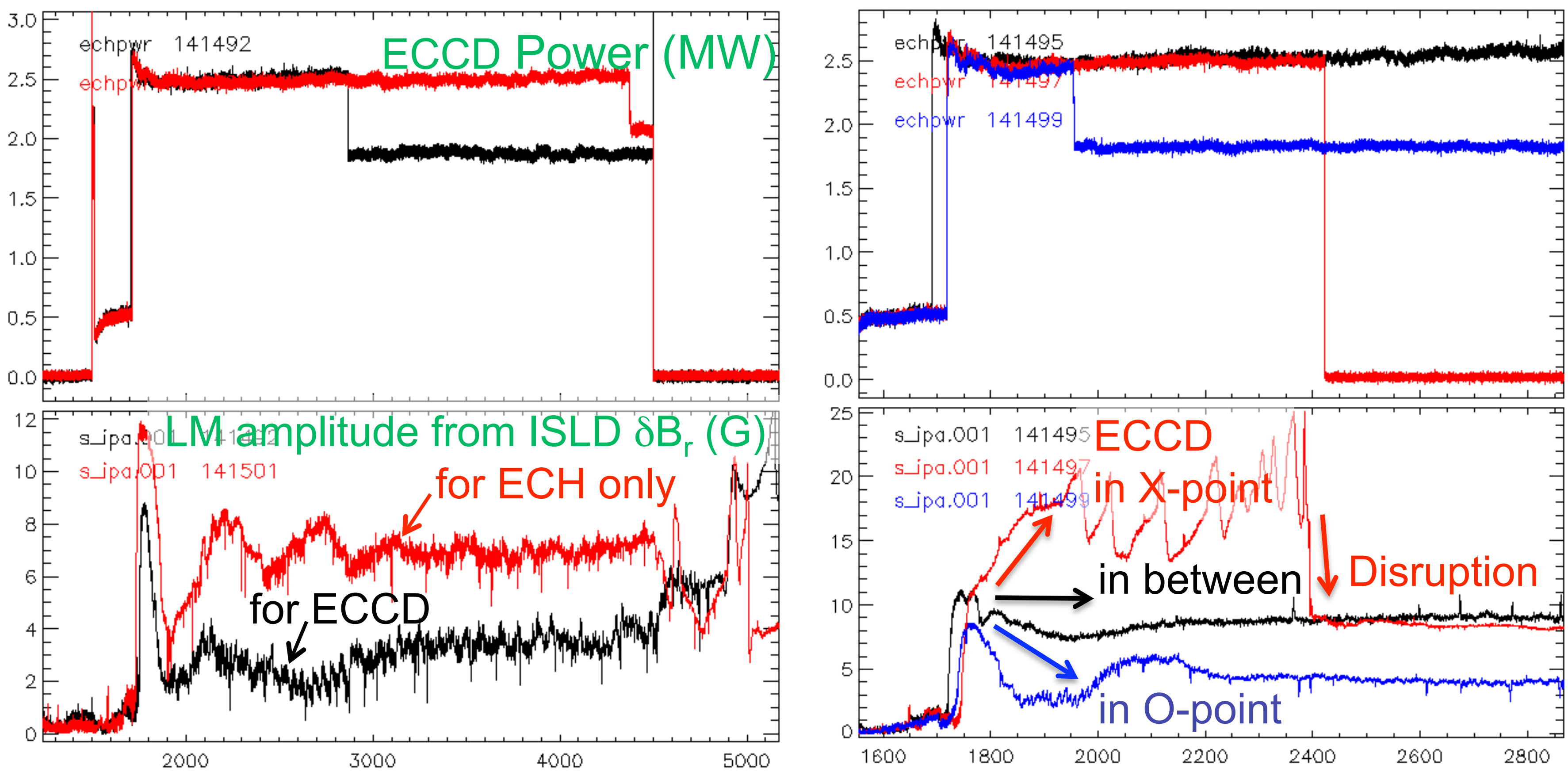
Locked mode can be caught and steered by I-coil

- **Locked mode is suppressed by ECCD**
  - Causes disruption without ECCD



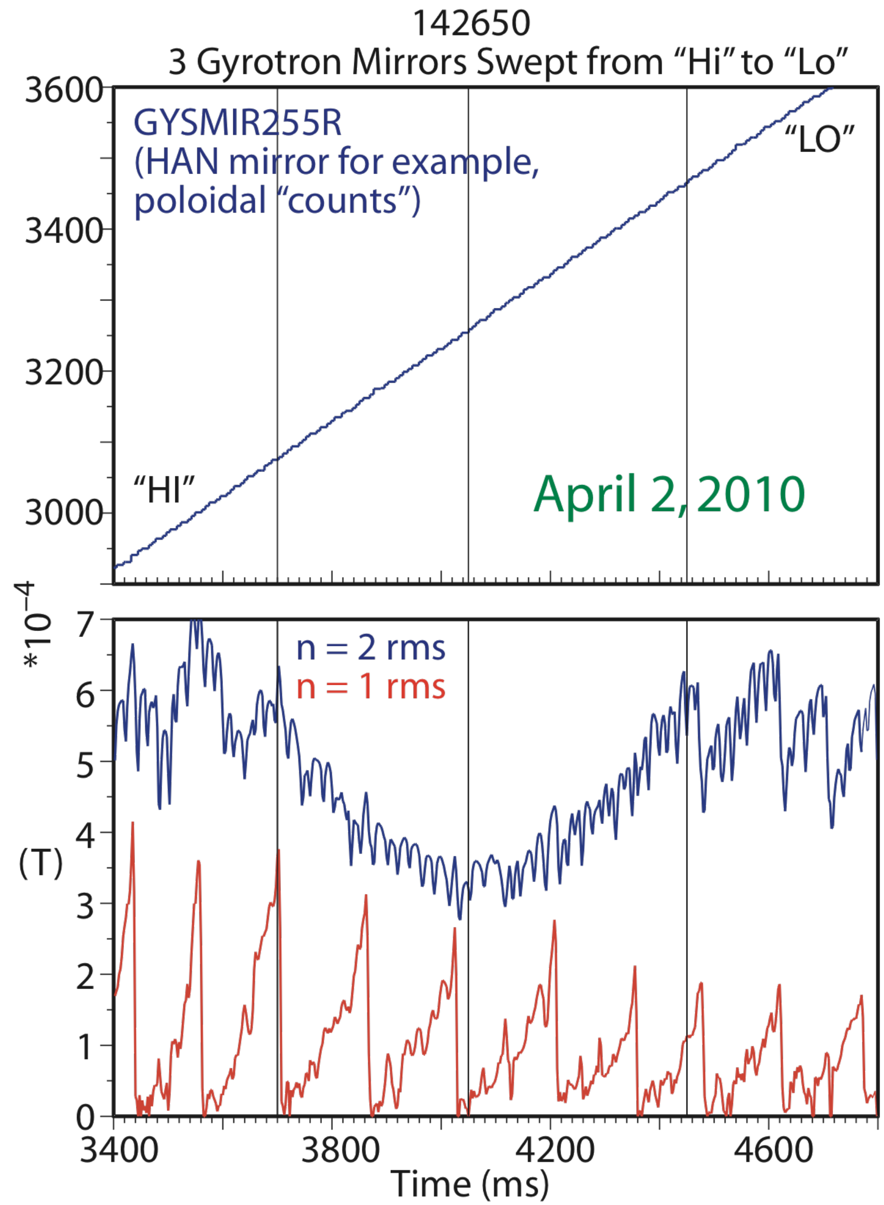


ECCD is more effective than ECH at stabilizing locked mode and depends on toroidal phasing, controlled by I-coils.



First test of real-time ECCD mirror steering

- **Mirror with motor drive for poloidal scanning of ECCD beam**
  - First test under PCS control
- **Sweeping mirror position during 3/2 NTM**
  - Dip in the 3/2 amplitude indicates optimum position



Highlights of 2010 experiments

ELM control

- ELM mitigation by RMP increases ELM frequency and reduces divertor energy impulses
- Shallow pellet injection increases ELM frequency, little effect on core n_e
- AC magnetic perturbations increase ELM frequency, reduce amplitude

Helium plasmas and ITER demonstration discharges

- Brief periods of ELM suppression were obtained in helium plasmas
- n=3 RMP at resonant q_{95} increases H-mode power threshold
- Baseline scenario performance with H→He plasma is substantially lower than with deuterium (D→D)

Disruption characterization and avoidance

- Position control extends runaway electron current duration
- Runaway current can be altered by applied electric field

Neoclassical tearing mode stabilization

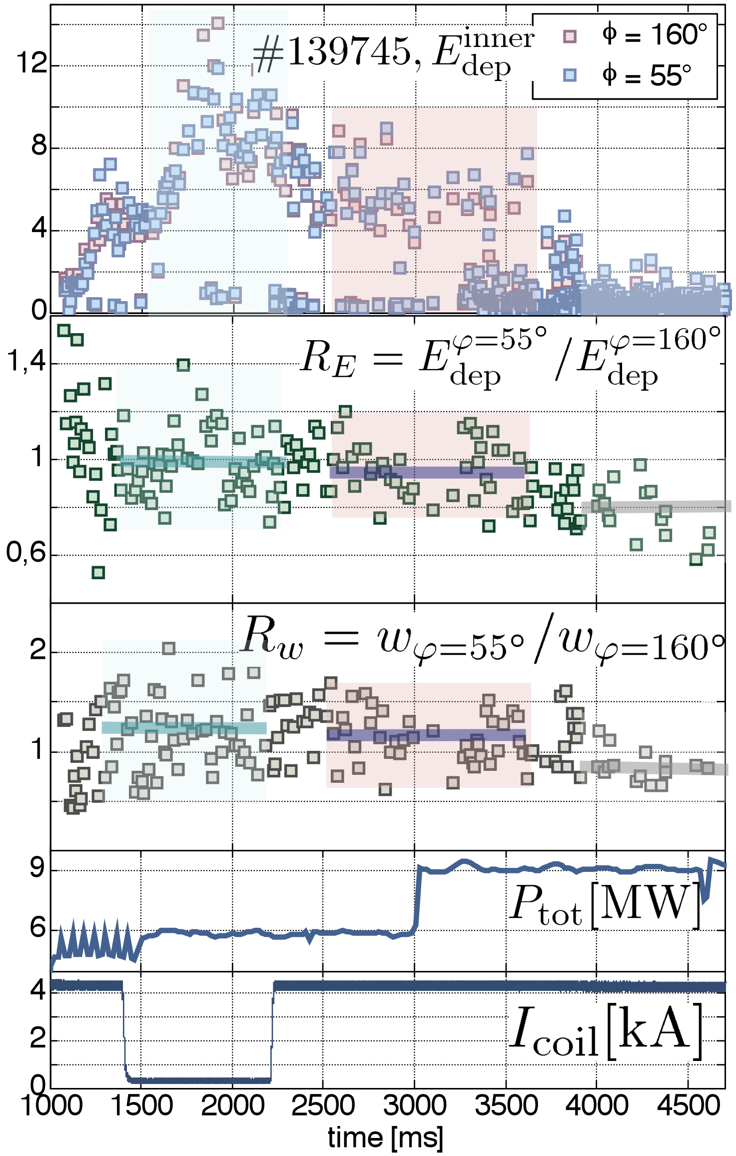
- First demonstration of active stabilization of a locked mode

Directions for future research

- **ELM control**
  - Extend RMP suppression to other tokamaks – e.g. MAST scenario
  - Demonstrate ELM suppression in low-torque ITER-relevant plasmas
  - Develop alternatives to RMP
- **ITER demonstration discharges, Hydrogen/helium plasmas**
  - Demonstrate ITER baseline scenario with low rotation
  - Transport physics vs. ion mass
- **Disruption characterization and avoidance**
  - Controlled reduction of confined runaway electron current
  - Routine control strategies for disruption detection and avoidance
- **NTM stabilization**
  - Develop routine ECCD stabilization with real-time mirror steering

BACKUP SLIDES

RMP reduces the variability of deposited energy and wetted area between toroidal locations



- Application of RMP significantly reduces ELM energies. Higher heating power (9 MW) results in stronger ELM mitigation.
- Without RMP some ELMs show toroidal asymmetries up to 50%. On average there is no toroidal asymmetry (R_E) between energy deposited on two toroidal locations
- Without RMP there is also rather strong variability of wetted area (R_w) between two locations.
- Introducing RMP reduces variability of deposited energy and wetted area, but creates small asymmetries in deposited energy.

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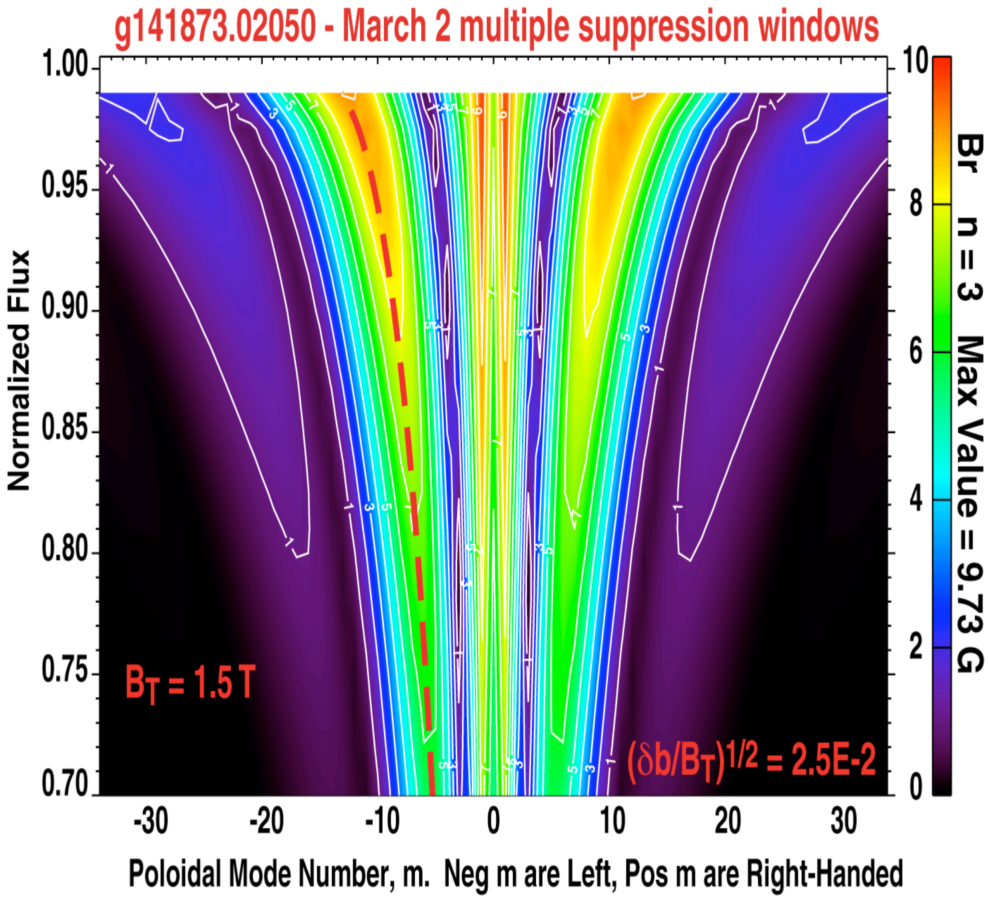
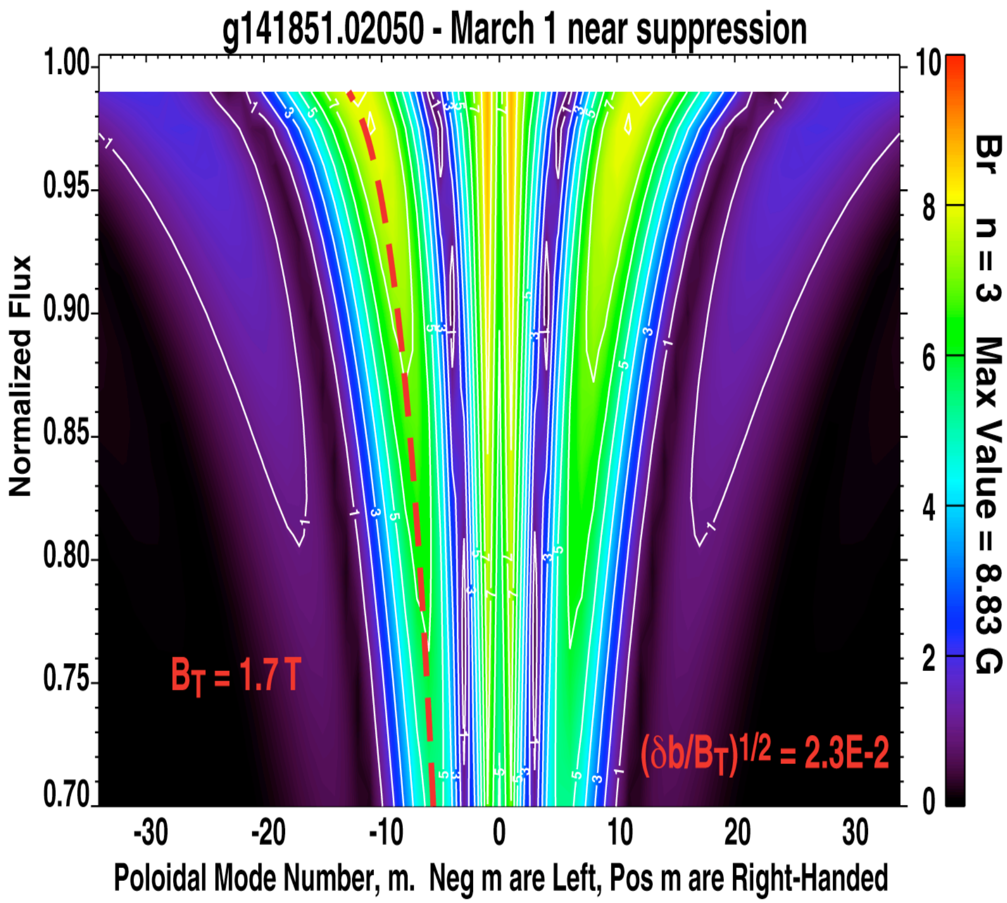
A significant increase in $\delta b/B_T$ is needed in He plasmas to obtain marginal ELM suppression





- Marginal ELM suppression obtained in He plasmas by:
  - Reducing B_T to 1.5 T resulting in 8% increase in the peak $(\delta b/B_T)^{1/2}$ n=3 field
  - Plus increasing the n=1 C-coil current by 50% compared to ELM suppression in D_2 plasmas