SUMMARY of

STABILITY and ENERGETIC PARTICLES

WAVES and CURRENT DRIVE

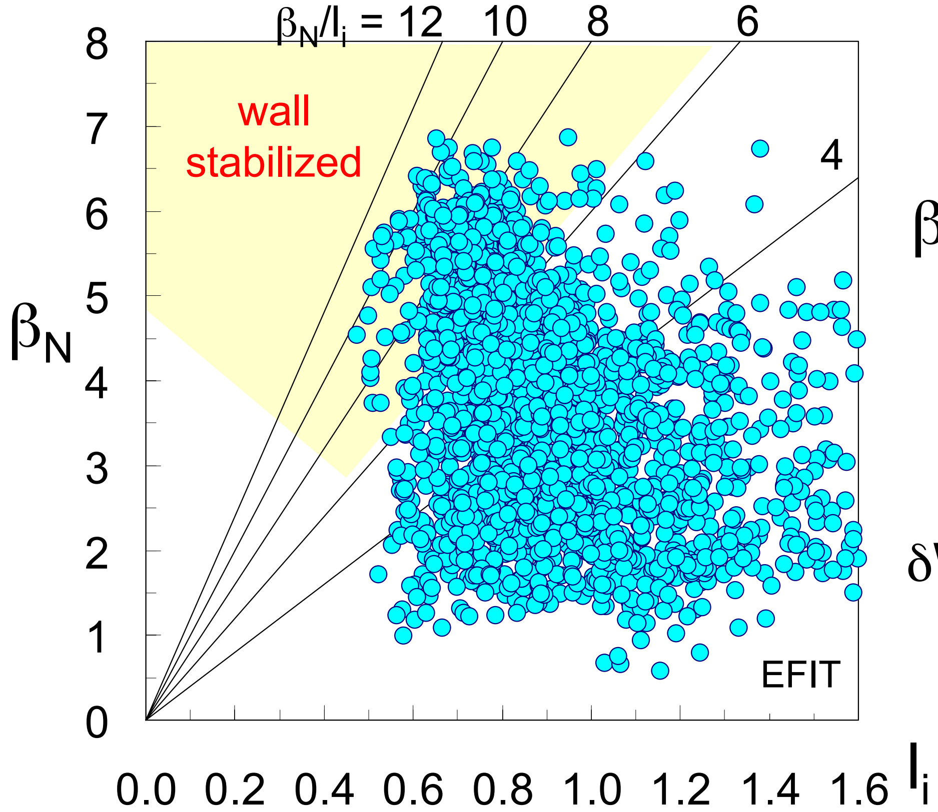
IAEA 2004

R. D. Stambaugh

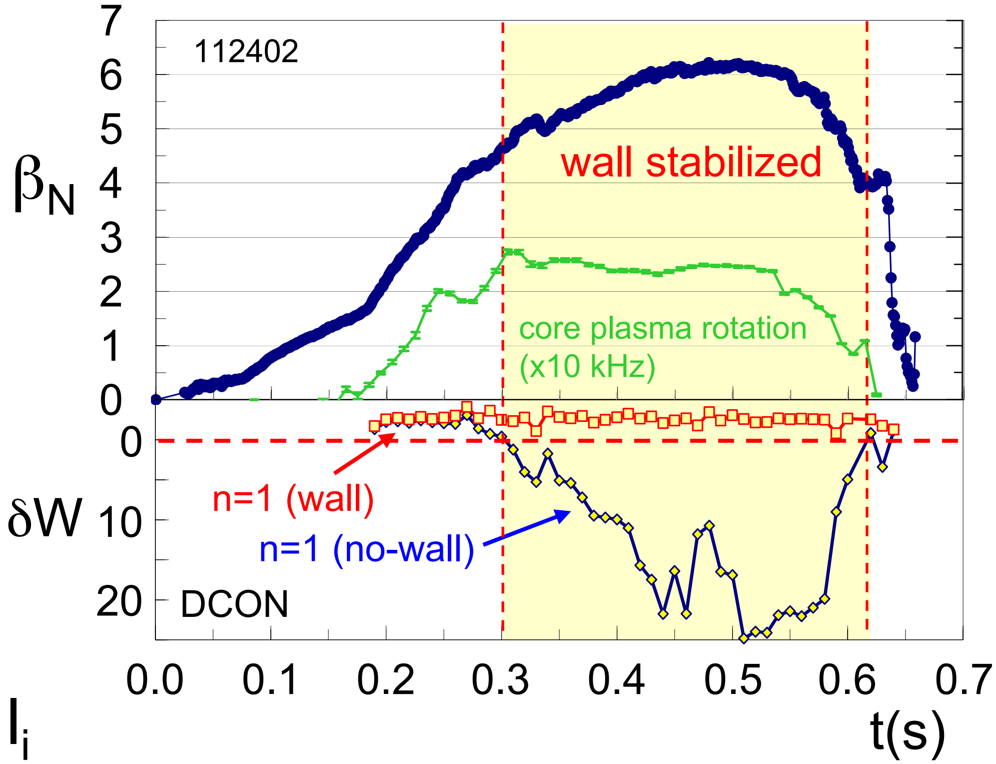
SUBJECT	PAPERS
RWM	7
Disruptions	6
NTM	6
ELMS, Pedestal	13
Other Stability	9
Alfven Modes	9
Wave Physics	10
Current Drive	5
Total	65

Wall stabilization physics understanding is key to sustained plasma operation at maximum β

- High β_t = 39%, β_N = 6.8 reached



- Operation with $\beta_N/\beta_N^{no\text{-}wall}$ > 1.3 at highest β_N for pulse >> τ_{wall}



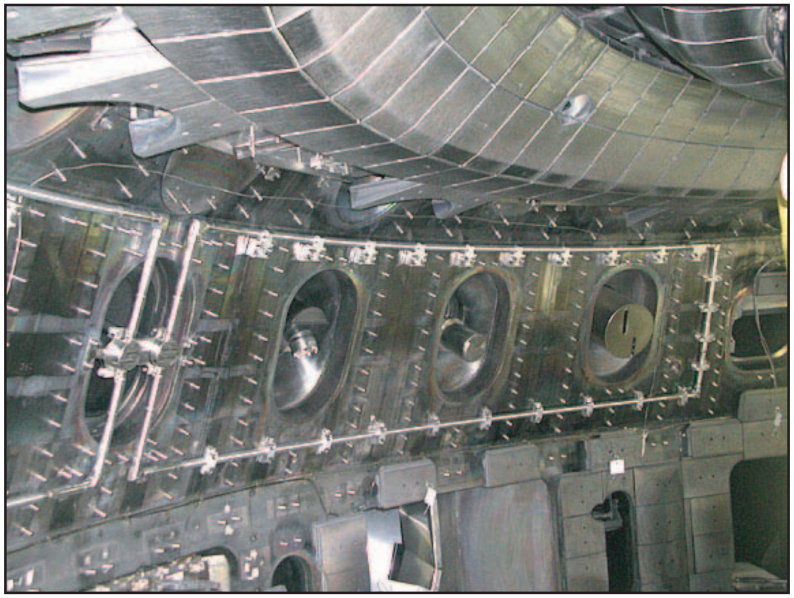
- Global MHD modes can lead to rotation damping, β collapse
- Physics of sustained stabilization is applicable to ITER

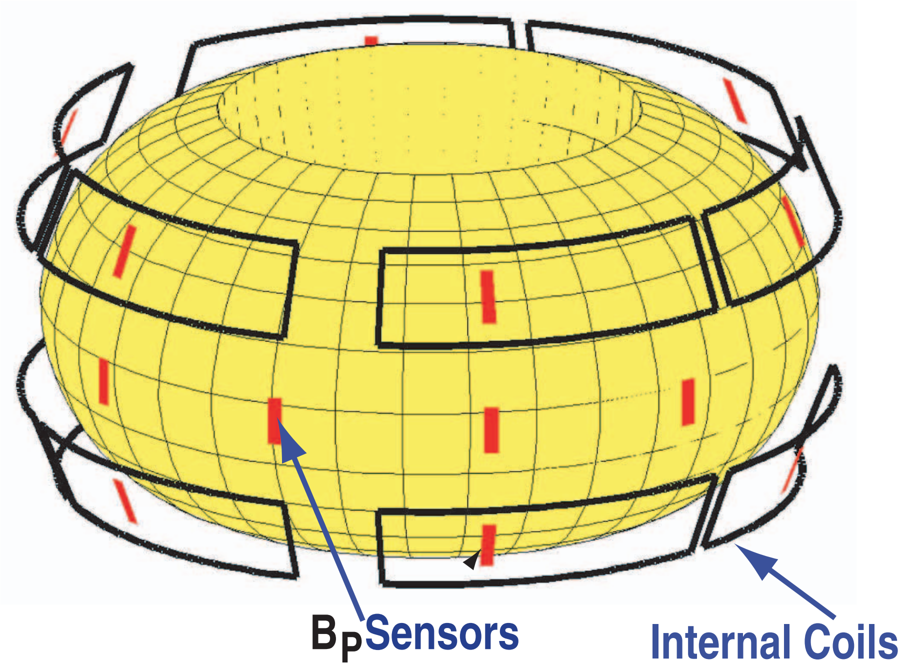
NSTX

Sabbagh, EX/3-2

NEW INTERNAL CONTROL COILS ARE AN EFFECTIVE TOOL FOR PURSUING STABILIZATION OF THE RWM

- Inside vacuum vessel: Faster time response for feedback control
  Closer to plasma, flexible magnetic field pattern: more efficient coupling

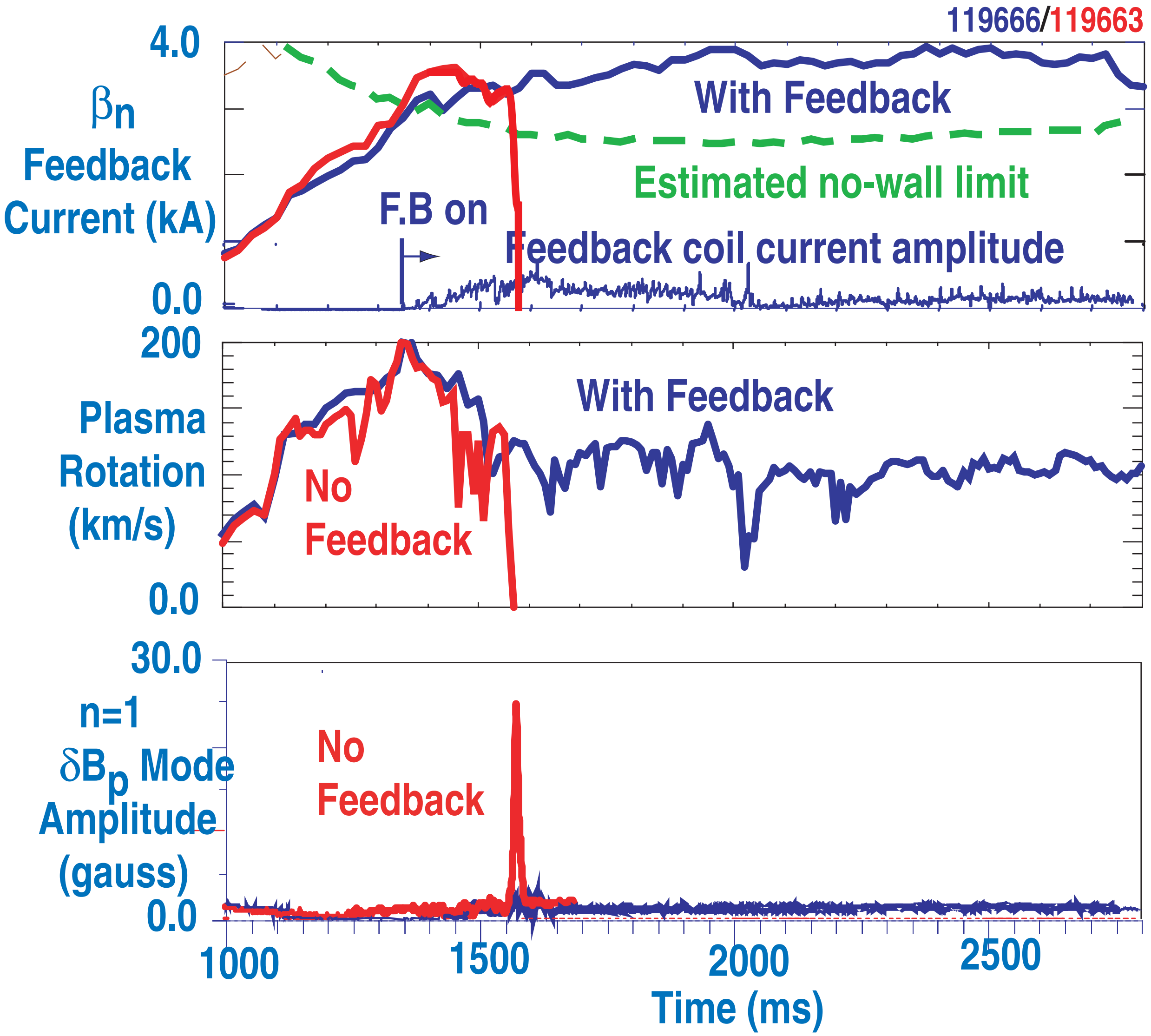


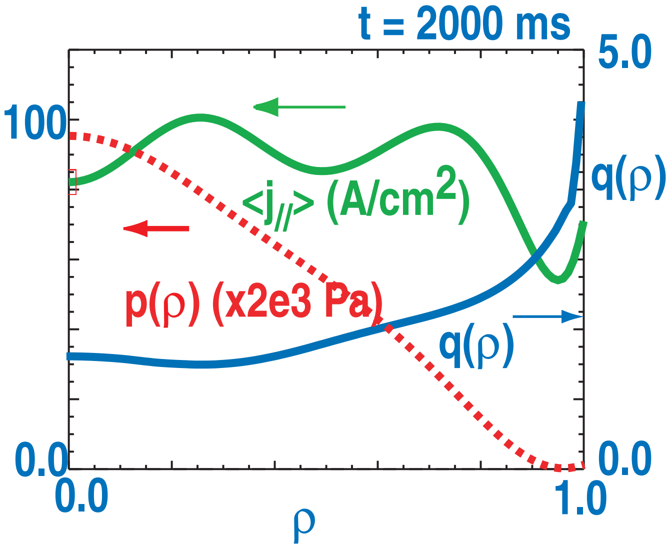


- 12 "picture-frame" coils
- Single-turn, water-cooled
- 7 kA max. rated current
- Protected by graphite tiles
- 10 gauss/kA on plasma surface

Okabayashi	EX/3-1Ra
Reimerdes	EX/3-1Rb

RWM FEEDBACK ASSISTS IN EXTENDING $\beta_N \approx 4$ ADVANCED TOKAMAK DISCHARGE MORE THAN 1 SECOND





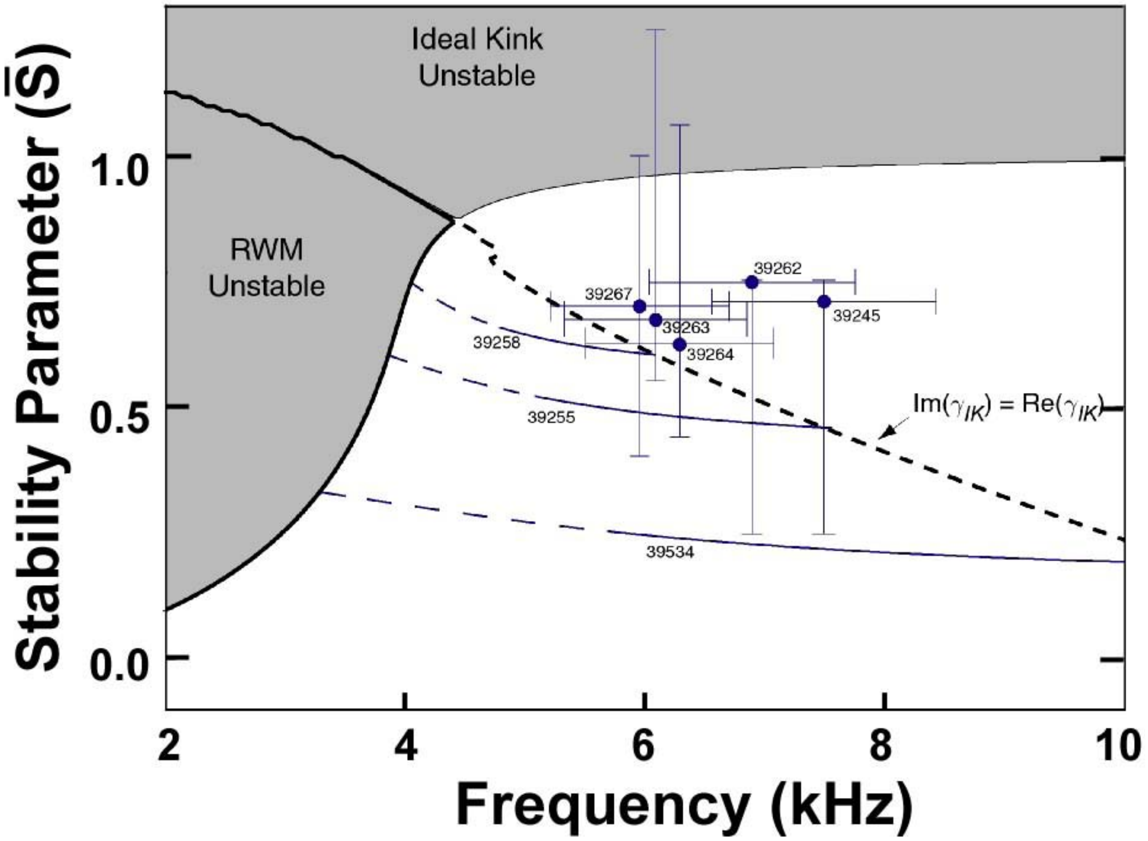
Okabayashi EX / 3-1Ra
Reimerdes EX / 3-1Rb
see also Ferron EX/P 2-21
"Optimizing the Beta Limit in DIII-D"

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

- The rotation is similar for both cases

269-04/MO/jy

Both the ideal kink and RWM mode branches must be considered in feedback dynamics



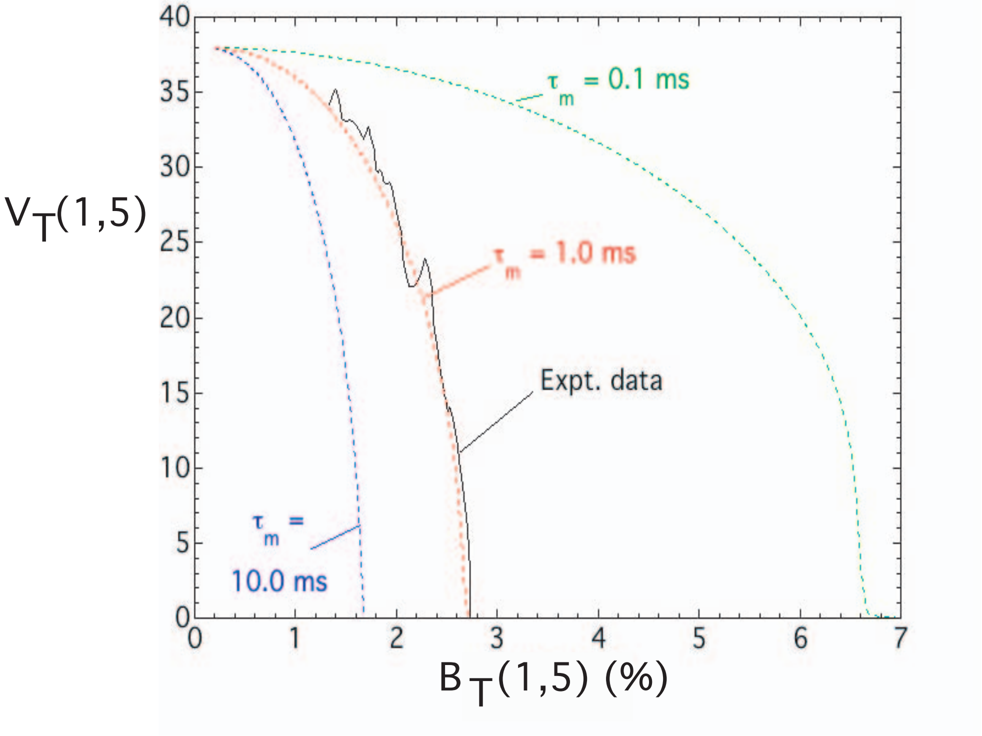
Discharge #	▮ Estimate	τ_r (ms)	f_r (kHz) ± 1 kHz
39262	0.50 ± 0.25	0.70 ± 0.2	5.5
39263	0.92 ± 0.33	0.50 ± 0.15	5.1
39267	0.72 ± 0.30	0.50 ± 0.15	4.8
39245	0.51 ± 0.25	0.60 ± 0.2	6.1
39264	0.75 ± 0.31	0.43 ± 0.15	5.3
39258	0.24 ± 0.20	0.23 ± 0.1	< 4.0
39534	0.11 ± 0.15	0.15 ± 0.1	< 6.5
39255	0.22 ± 0.18	0.30 ± 0.1	< 3.5

- Coupled kink-wall mode system has two weakly damped roots in rotationally-stabilized regime.
- At low *s*, response decays quickly.
- Near ideal-wall limit, rotating plasma root decays slowly and phase-oscillations indicate plasma root's real frequency.

WALL STABILIZATION IN THE RFP

MST: test theory of mode locking by wall eddy currents

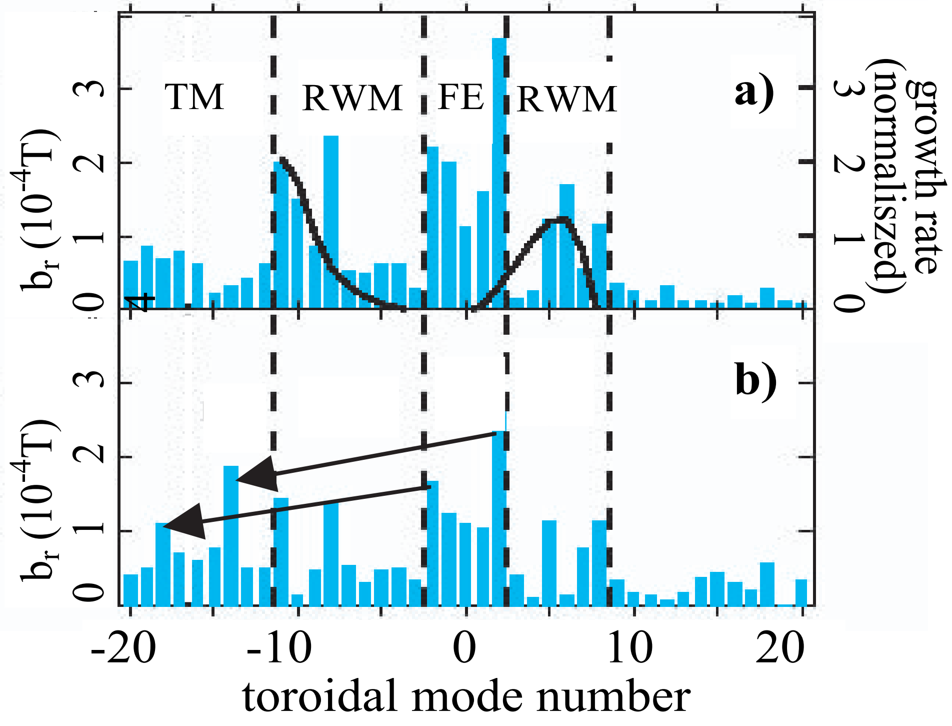
One free parameter:
momentum confinement time



Experiment consistent with theory

Prager **OV / 4-2**

EXTRAP T2R: Feedback coils (16 toroidal and 4 poloidal) suppress a spectrum of unstable modes

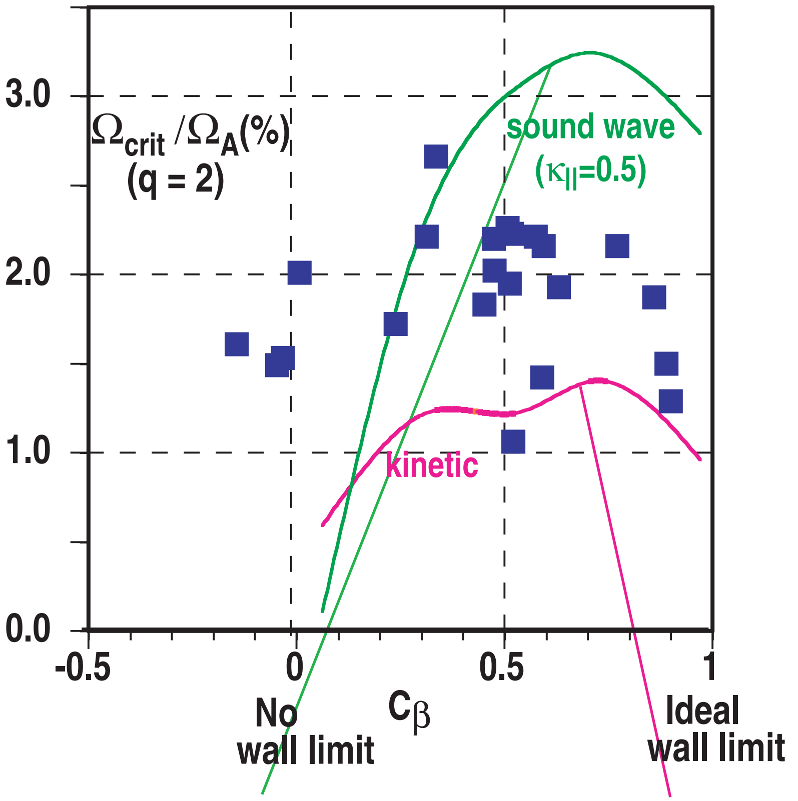


Drake **EX/P 2-20**

WHAT DISSIPATION MECHANISMS PROMOTE STABILITY?

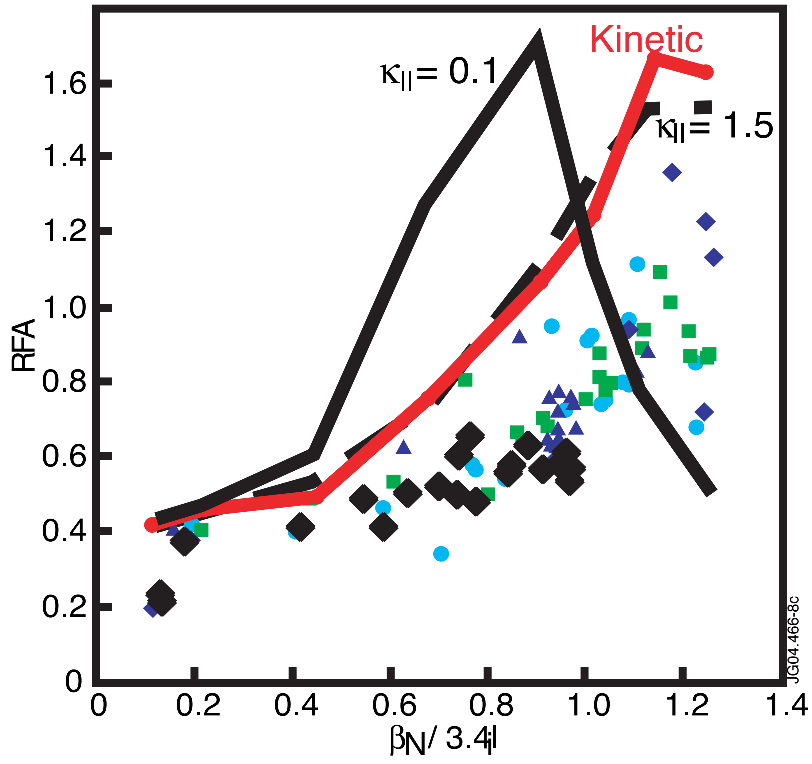
Comparisons with MARS calculations:

- Critical rotation velocity
- Resonant Field Amplification



Soundwave damping overestimates the critical rotation

Kinetic damping underestimates the critical rotation



DIII-D

Okabayashi EX/3-1Ra

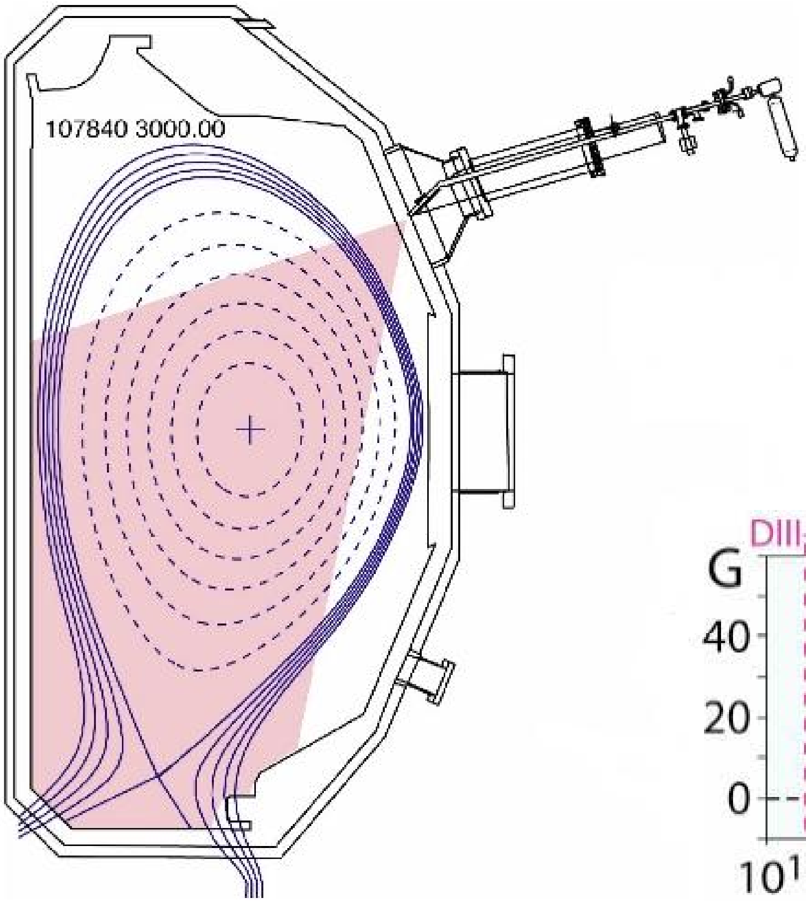
Reimerdes EX/3-1Rb

JET

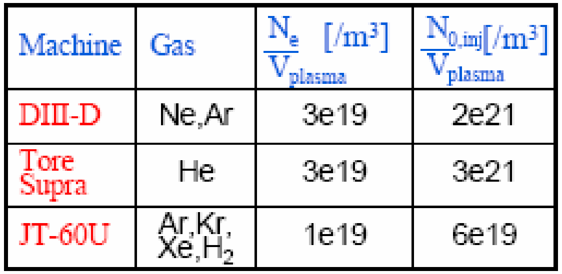
Hender EX/P 2-22

Other papers: Liu TH/2-1 and Strauss TH/2-2

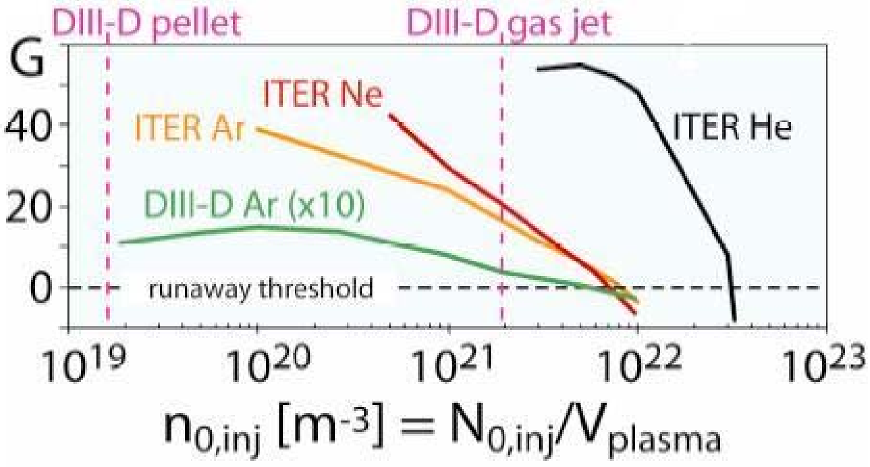
Successful Disruption Mitigation by Massive Gas Injection.



Runaway avalanche suppressed with sufficient electron injection.

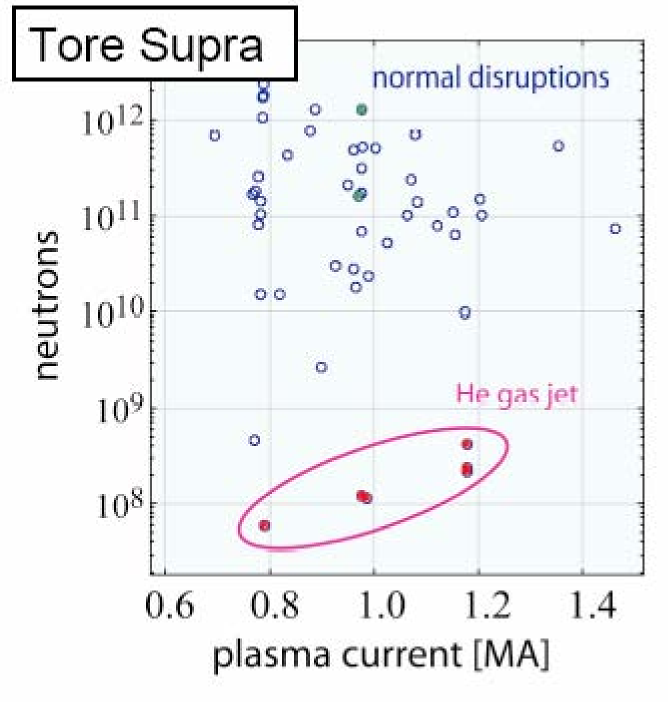


Machine	Gas	$\frac{N_e}{V_{plasma}}$ [/m³]	$\frac{N_{0,inj}}{V_{plasma}}$[/m³]
DIII-D	Ne,Ar	3e19	2e21
Tore Supra	He	3e19	3e21
JT-60U	Ar,Kr, Xe,H_2	1e19	6e19

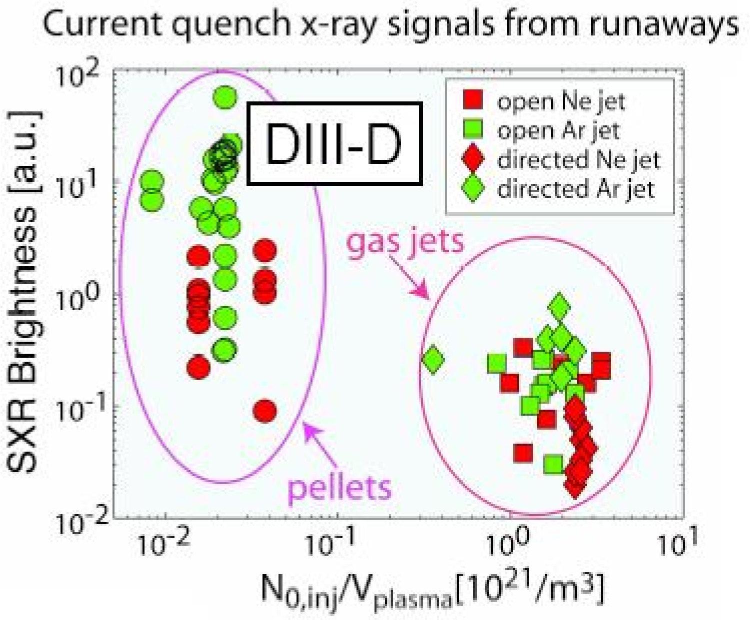


Runaways Tremendously Suppressed.

He Jet, EX/10-6Rc Tore-Supra

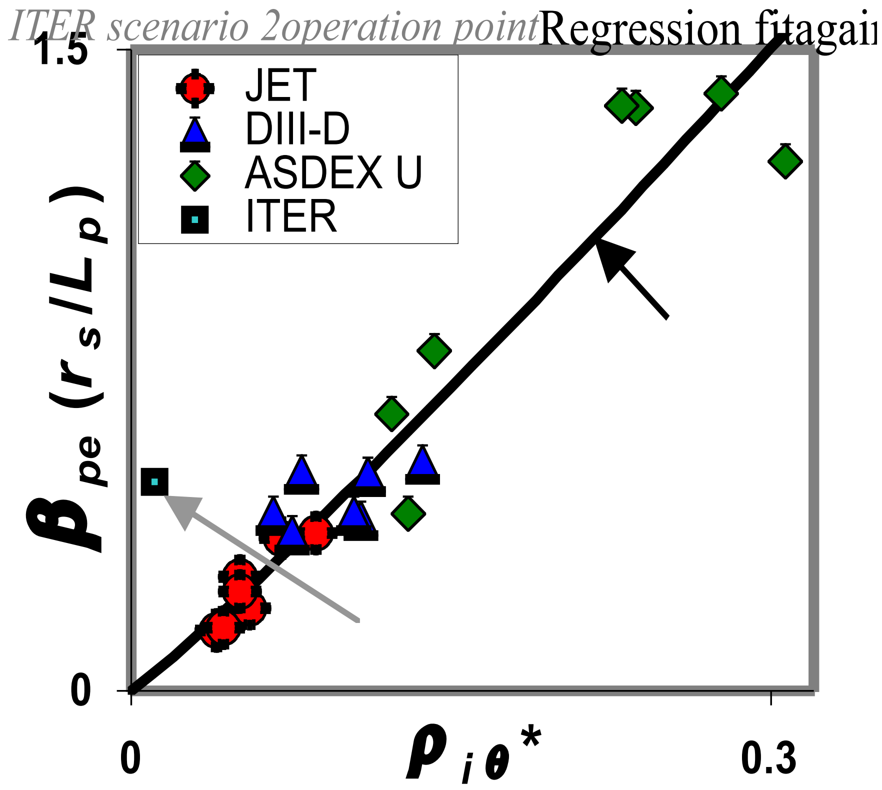


Gas Jets Better Than Pellets.
EX/10-6a DIII-D Hollmann



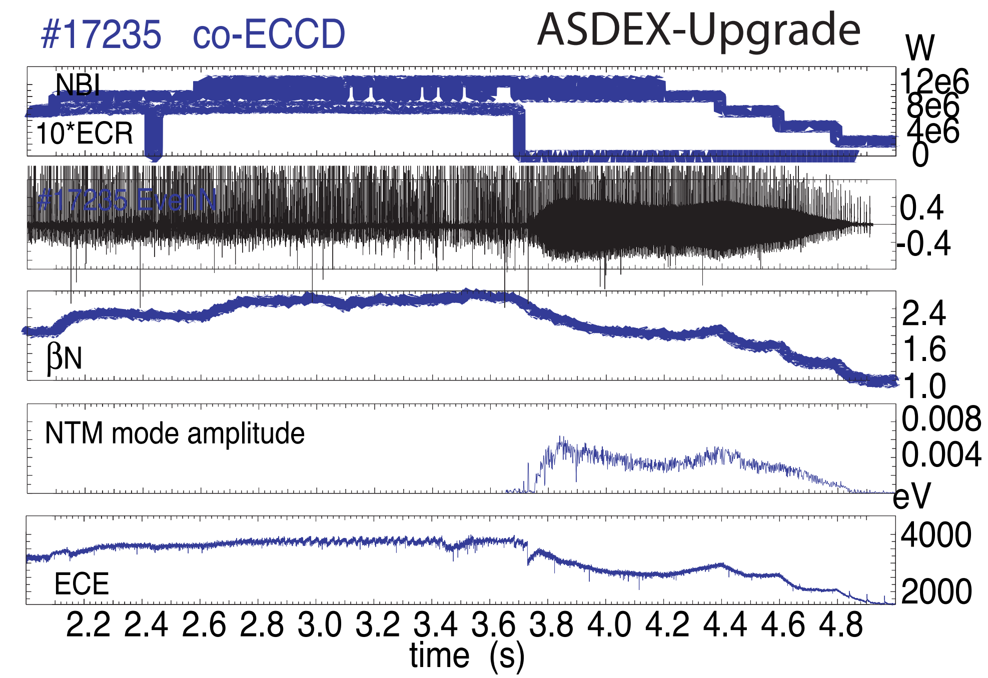
How do the ρ^* scalings do?

Pretty good in terms of underlying NTM physics and metastable threshold...

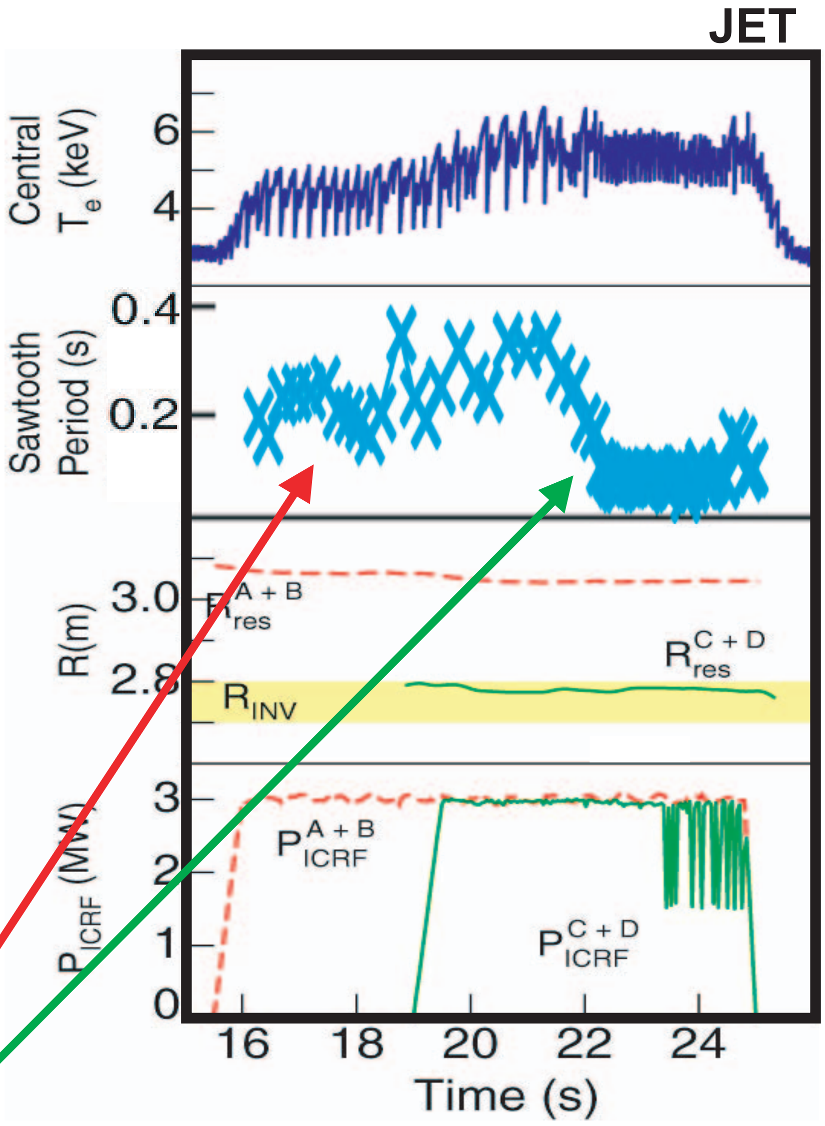


- power ramp-down experiments measure **β** at which 3/2 NTM self-stabilises
- **ITER baseline operation point deeply into metastable region**
  - small triggers can excite mode
  - mode removal requires driving island down to small sizes

SAWTOOTH CONTROL PREVENTS SEEDING OF NTMS



Maraschek EX / 7-2



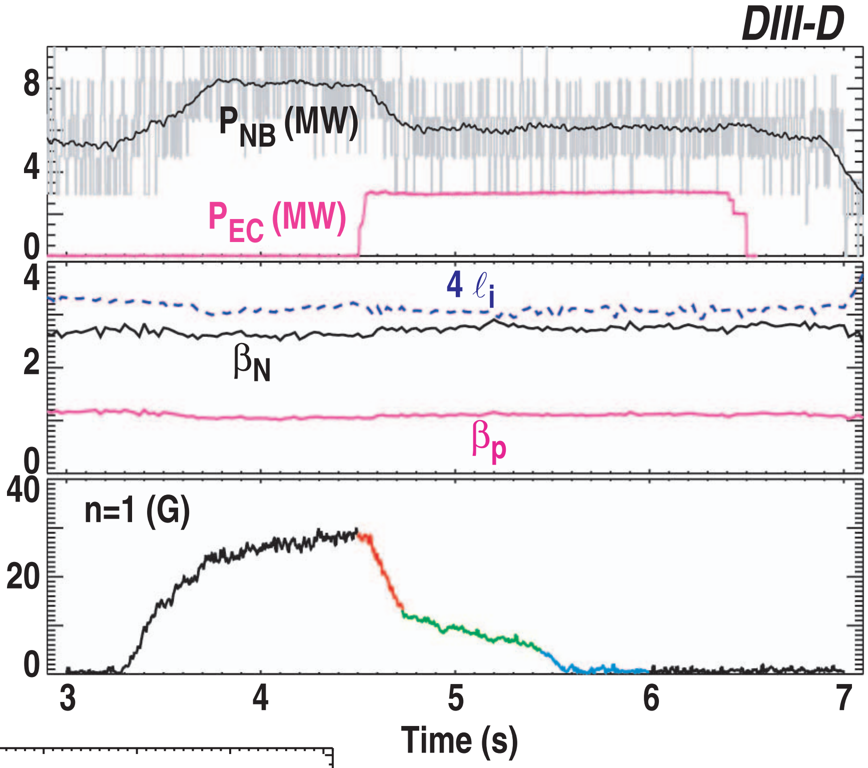
Destabilisation of fast particle stabilised sawteeth now achieved:

- core ICRH stabilises sawteeth
- ICCD destabilises as inversion radius is approached

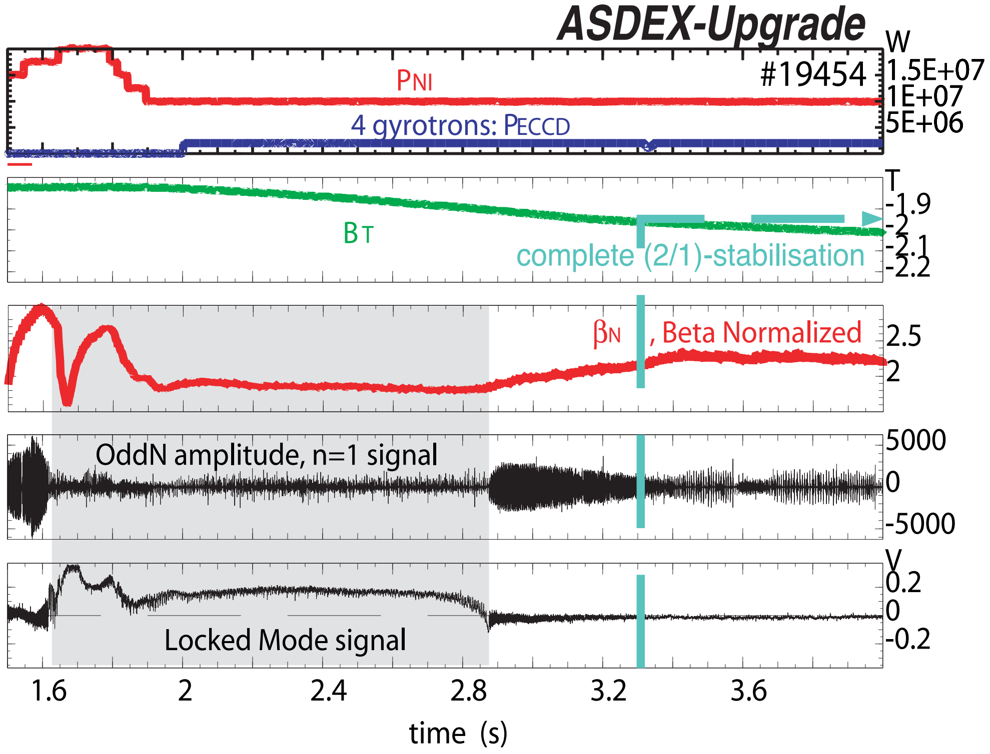
Buttery EX / 7-1

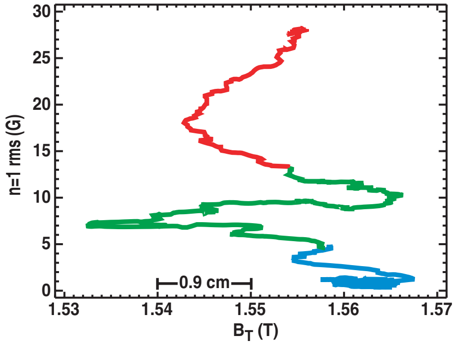
2/1 TEARING MODE IS COMPLETELY SUPPRESSED BY ECCD

2/1 mode suppressed in hybrid discharge with β_N well above ITER baseline scenario



The (2/1)-NTM is preceded by a phase (grey shaded) where the mode is locked to the vacuum vessel





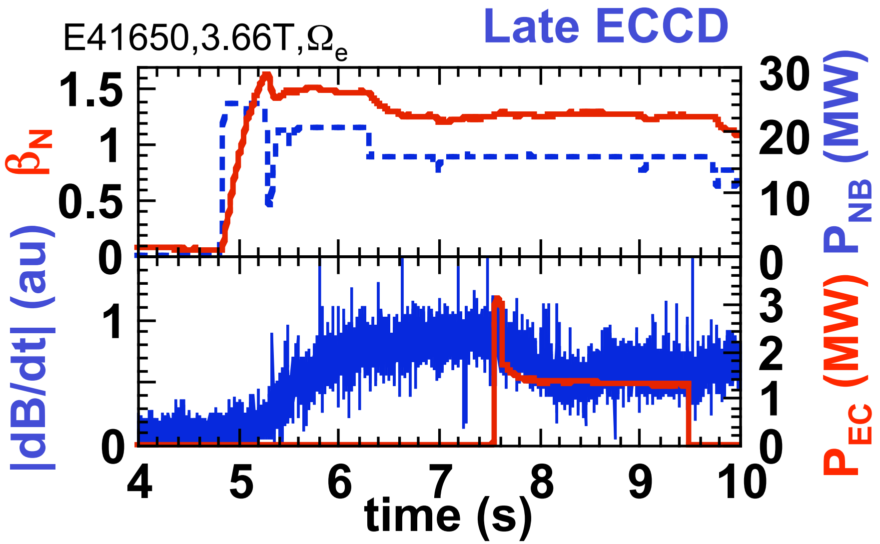
"Target lock" algorithm uses small, rapid variations in B_T to optimize suppression

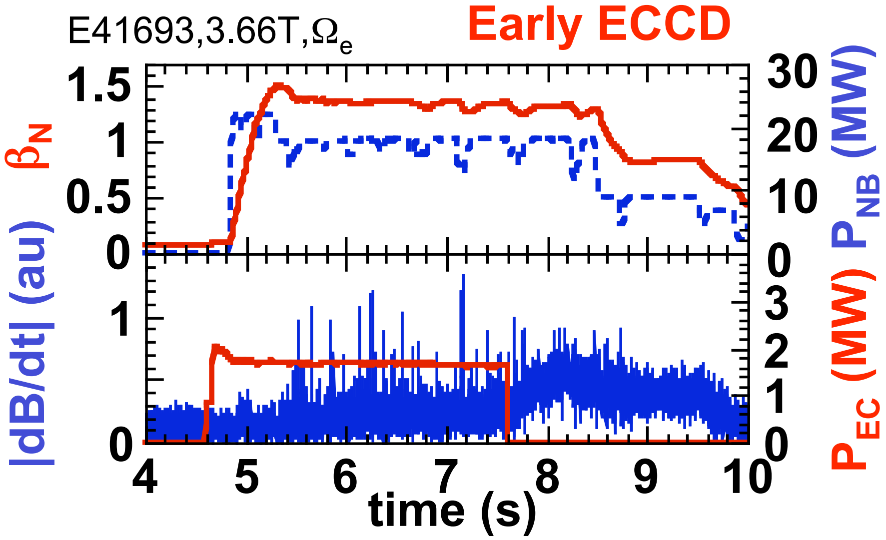
Petty EX / 7-3

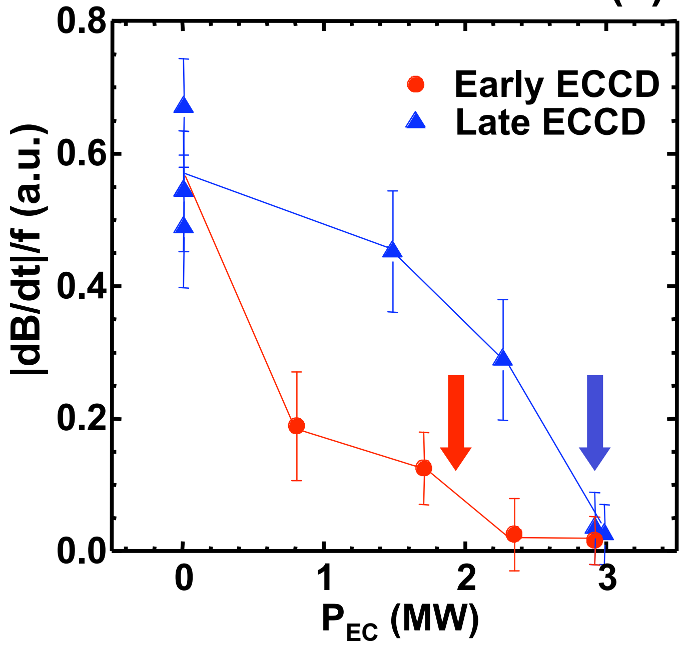
Maraschek EX / 7-2

Early ECCD is more effective for an NTM suppression, even at high β_N

JT-60U



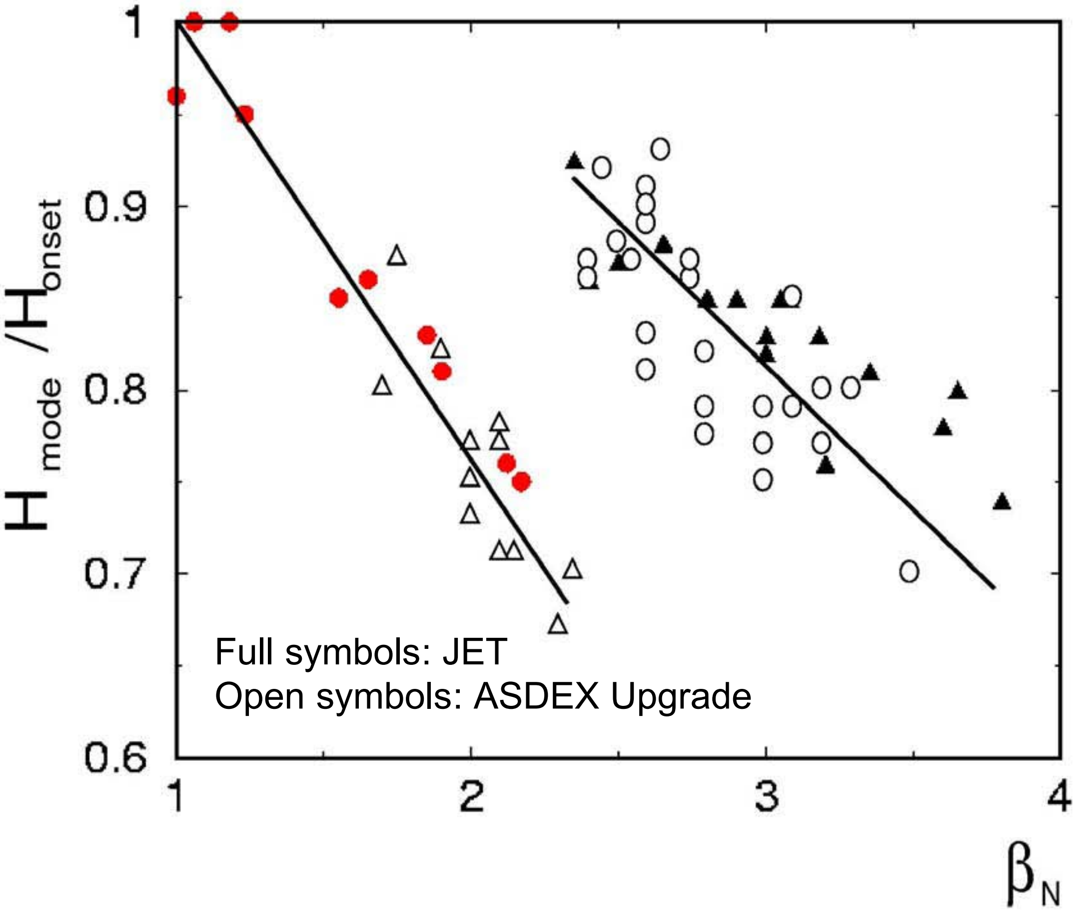


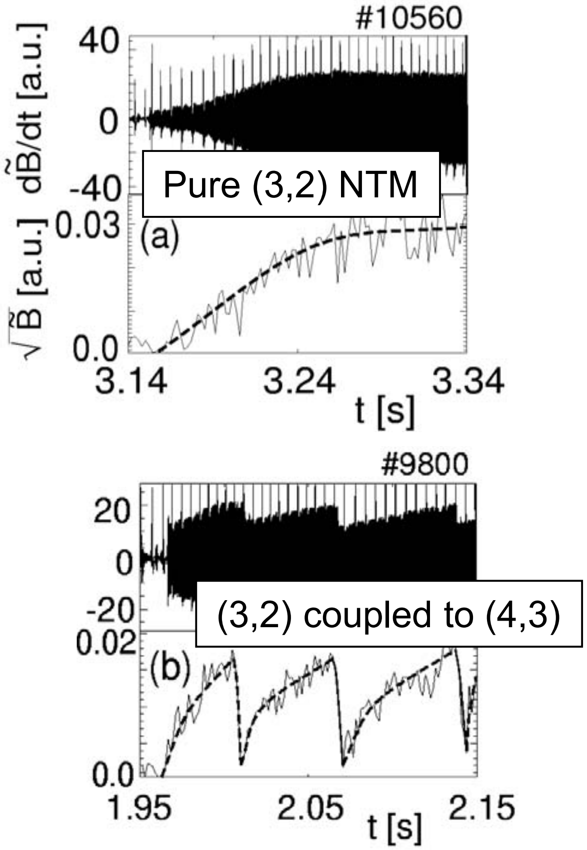


- **Early ECCD is more effective to suppress NTM:**
  - –island size (~|dB/dt|/f) quickly suppressed
  - –less power for full stabilization
  - –calculated necessary power for full suppression based on mod. Rutherford eq. agrees well with the experiments (arrows).

K. Nagasaki (EX/10-3, Thu.)

(3,2) NTMs in FIR regime for $\beta_N > 2.3$





Pure (3,2) NTM

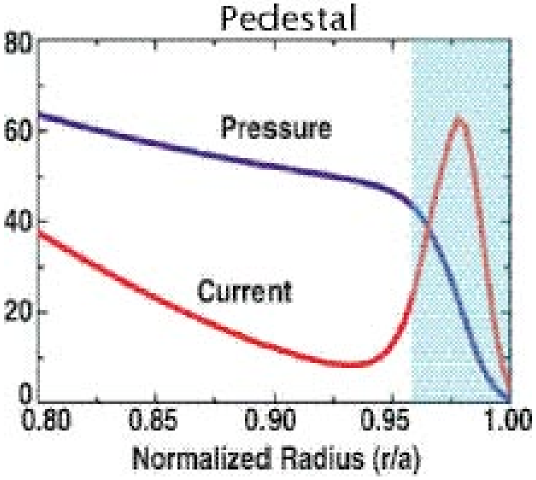
(3,2) coupled to (4,3)

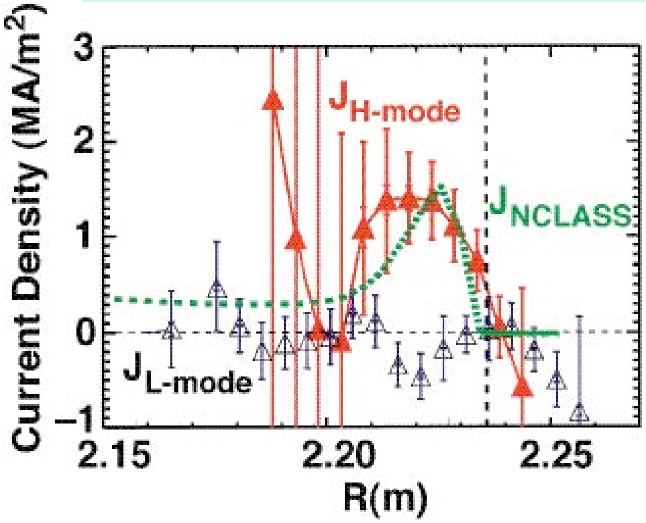
FIR regime similar in dimensionless parameters (ASDEX Upgrade and JET)
Active stabilization on ITER only for (2,1) NTM needed?

Guenter OV / 1-5
Maraschek EX / 7-2

PEELING-BALLOONING MODEL OF ELMS CONVERGING

EX/2-5Rb DIII-D Fenstermacher

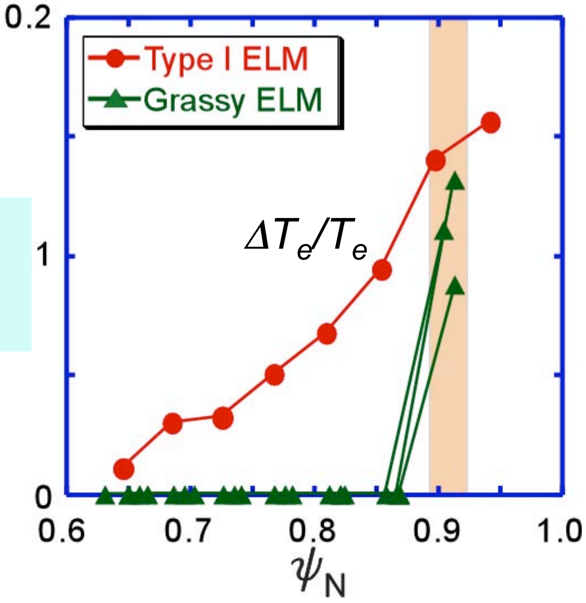




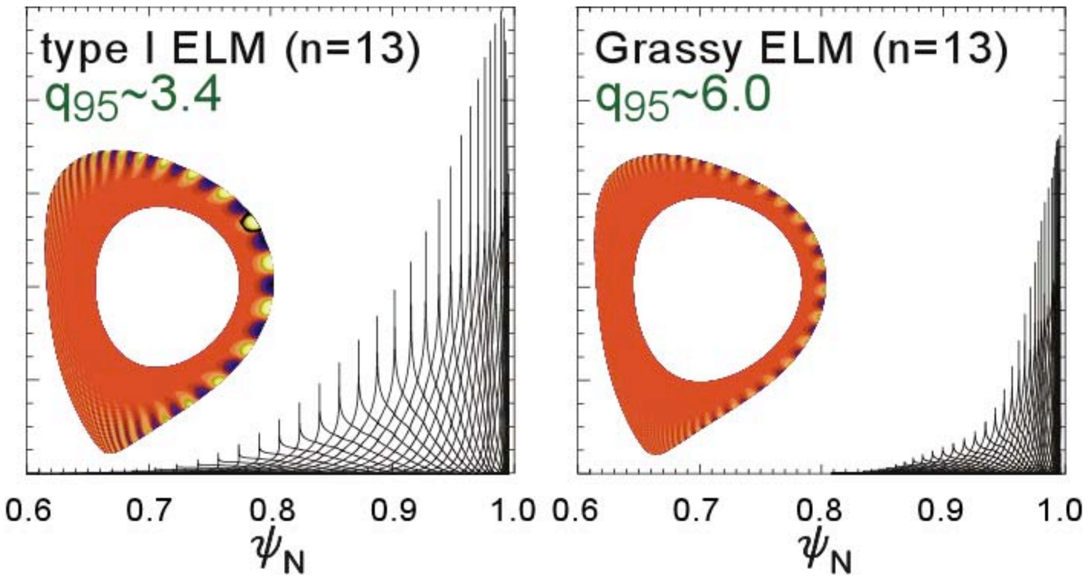
EX-P/1-4
JET
Stober

EX-P/3-4
AUG
Horton

EX/2-1
JT-60U
Oyama

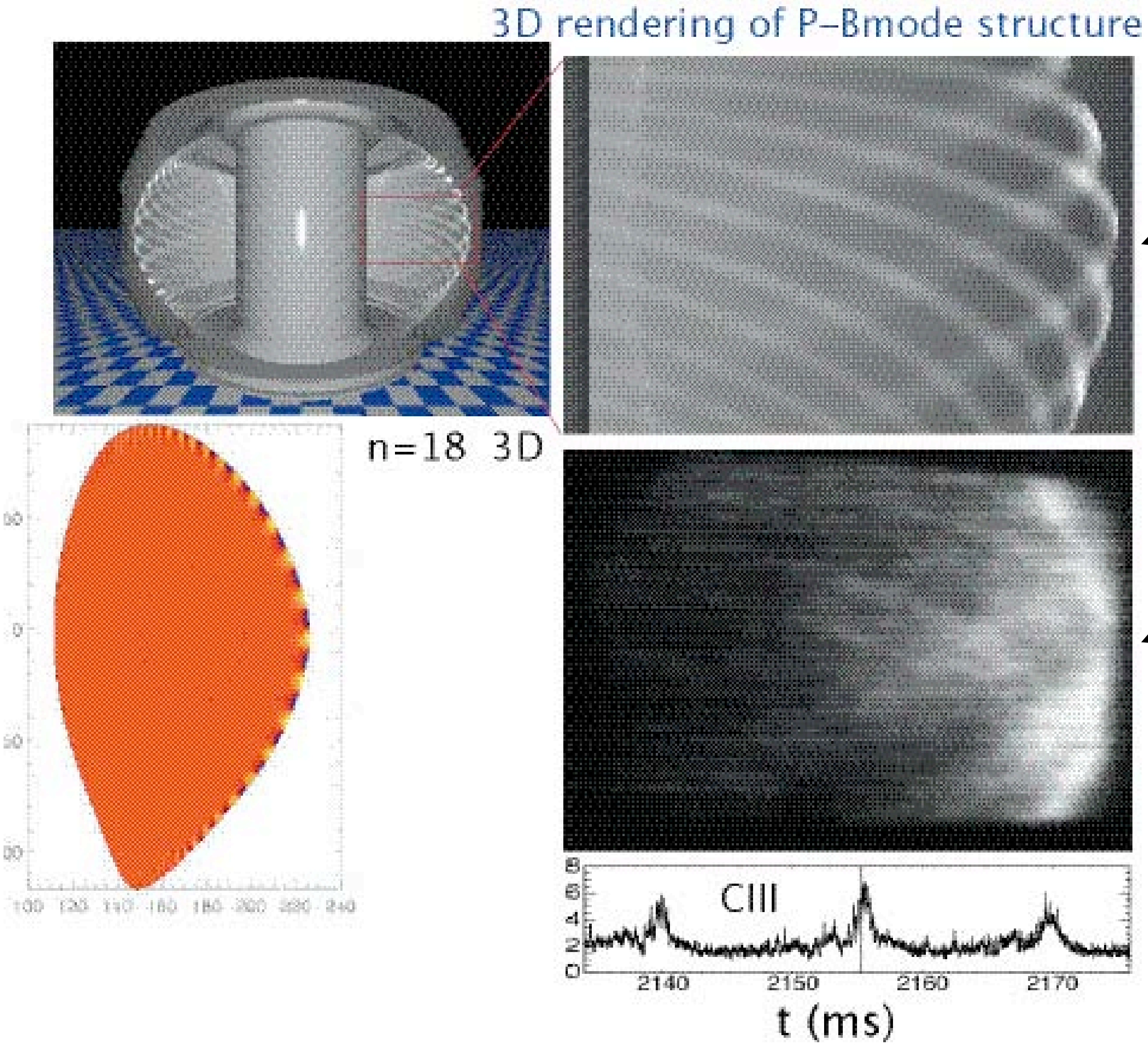


ELITE



FILAMENTARY STRUCTURE OF ELMS – MAJOR SUBJECT

EX/2-5Rb DIII-D Fenstermacher

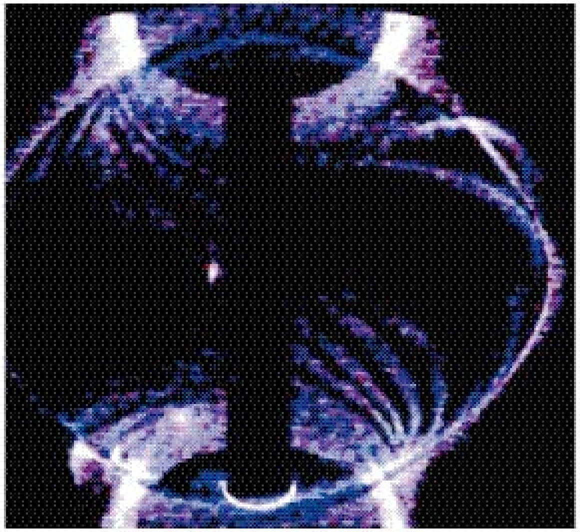


Most unstable modes from ELITE linear P-B stability analysis are 16 ≤ n ≤ 24

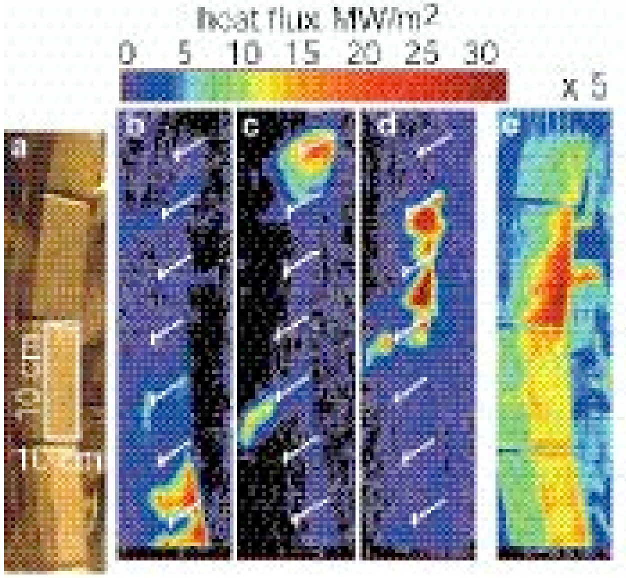
CIII emission structure during ELM suggests n ~17

FILAMENTARY STRUCTURE SEEN IN MANY MACHINES

EX/2-3 MAST Kirk

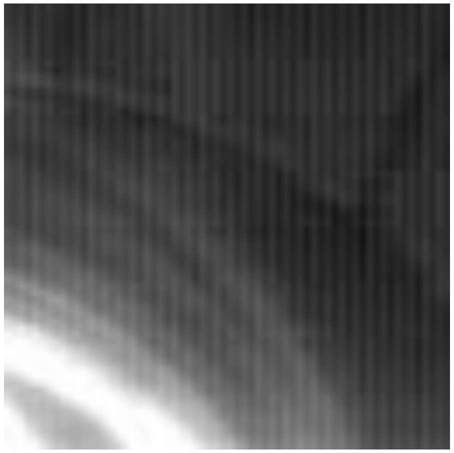


EX/2-4Rb AUG Hermann



EX/2-6
AUG
Lang

EX/2-2
NSTX
Maingi



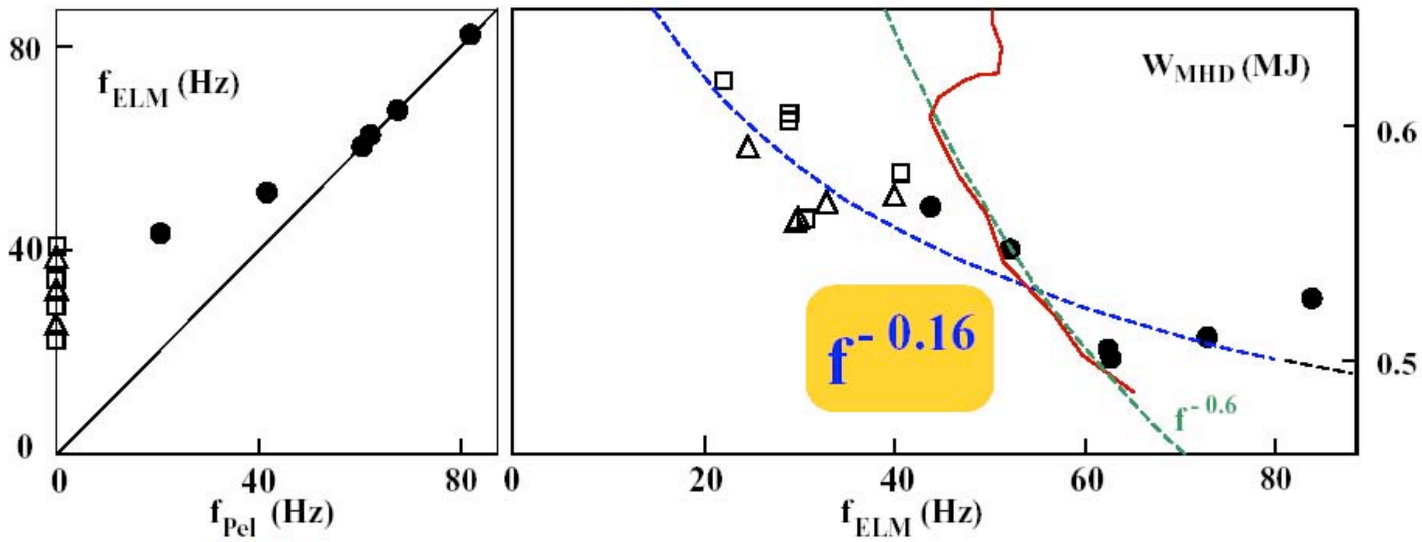
Detailed Filamentary Nature of ELMs
In EX/2-4Ra JET Fundamenski

Strike Point Jump
EX/P1-3 JET Solano

ELM CONTROL BY PELLET PACE MAKING

Replace linearly unstable peeling/ballooning mode by local trigger perturbation

OV/1-5
AUG
Guenter



Pace making

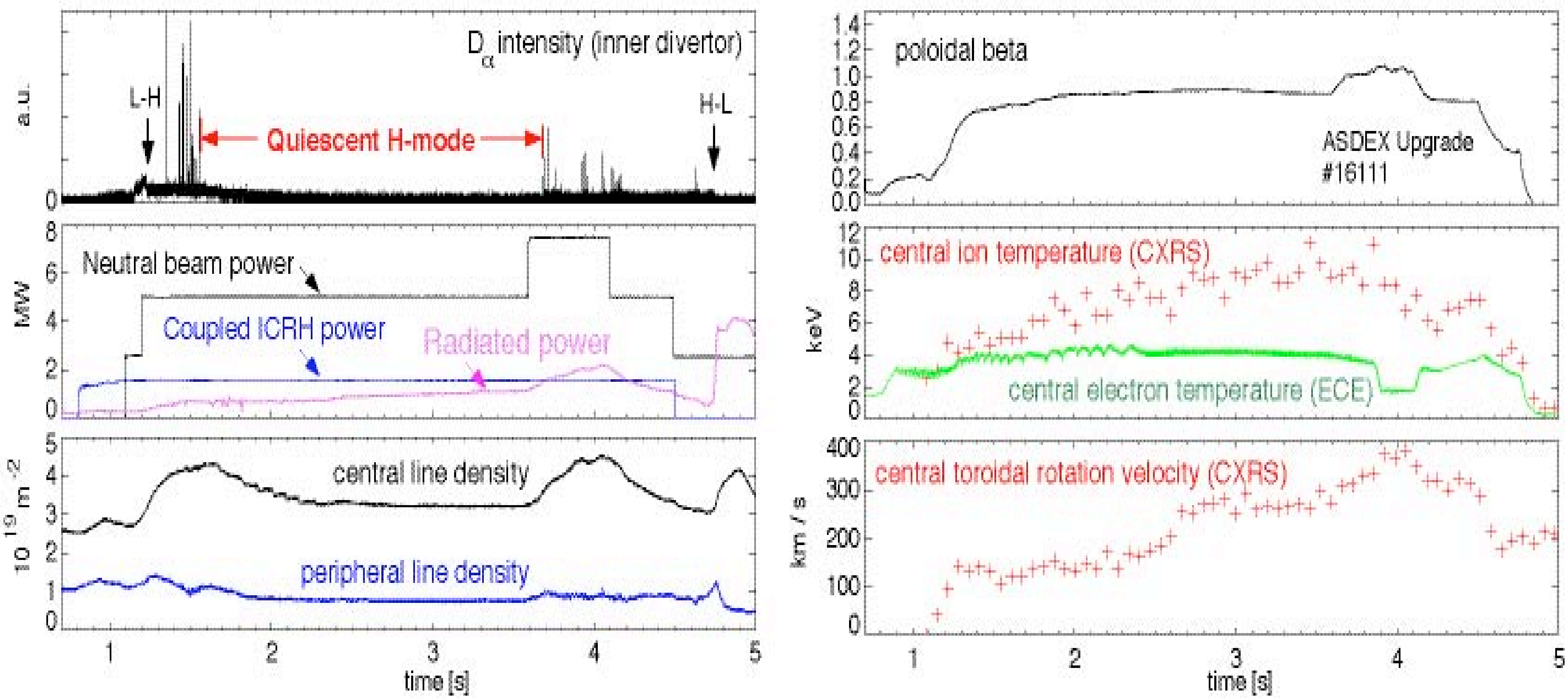
Performance

EX/2-6
AUG
Lang

- only minor confinement degradation with increased ELM frequency compared to, e.g., gas puffing (pedestal temperature reduced!)
- energy loss per ELM for pellet triggered ELMs as for “natural” ELMs
- successful ELM control also by small wobbling

QH-MODE IN ASDEX UPGRADE

EX/1-4 AUG Suttrop

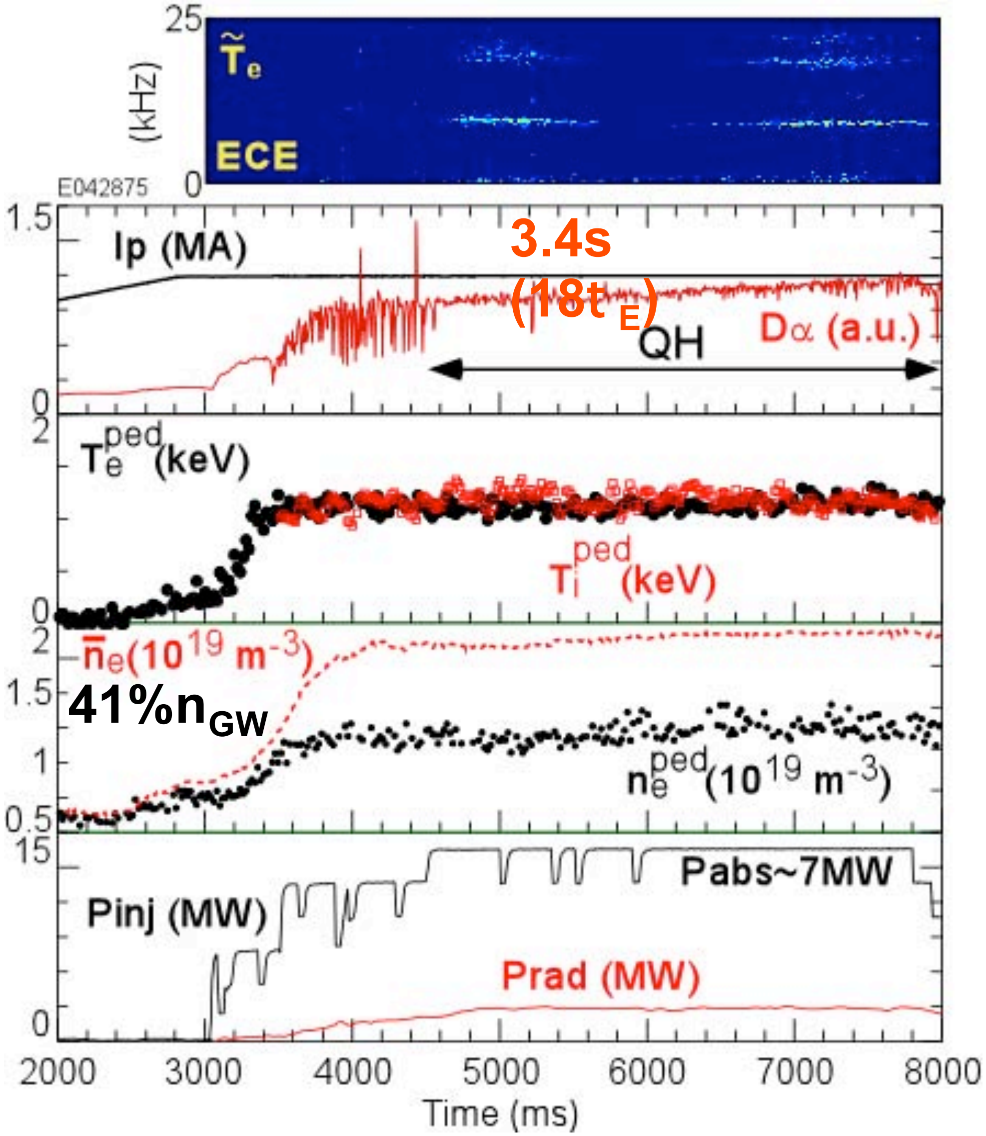


- Large E_R in the barrier, 2 × normal H-mode
- Energetic particle effects near the barrier
- EHO/HFO necessary features

QH-MODE IN JT-60U

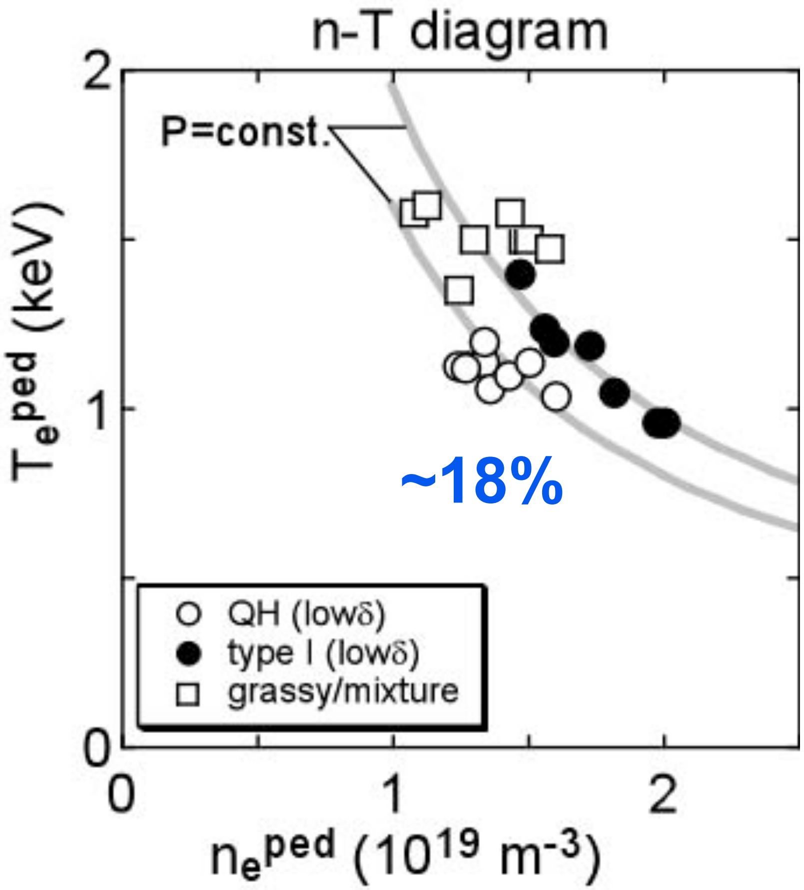
EX/2-1 JT-60U Oyama

- **Pedestal parameters almost constant during QH phase**



3.4s $(18t_E)$

41%n_{GW}



~18%

T_i^{ped} also smaller in QH phase

ELM AMPLITUDE AND FREQUENCY CAN BE CHANGED BY TOROIDAL ROTATION

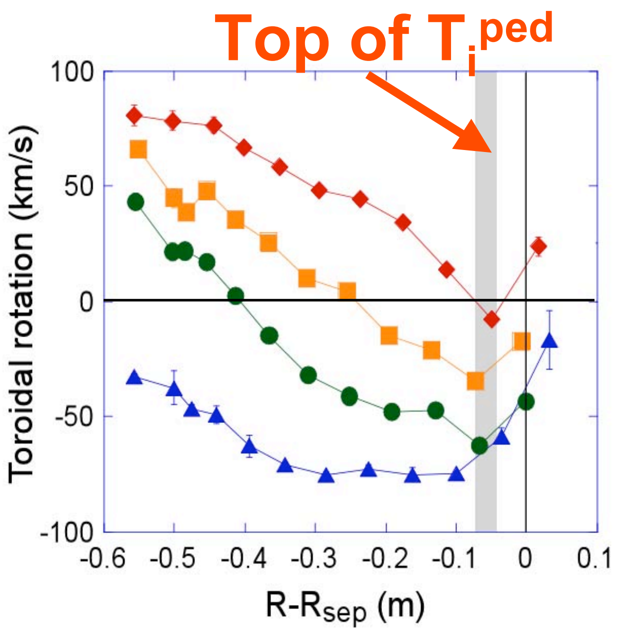
JT-60U

EX/2-1 JT-60U Oyama

- Larger counter rotation leads to smaller ELM and higher f
- New parameter for access to grassy ELM regime.

  Absolute value? or Sign?
- No edge fluctuations were observed even in larger counter rotation phase.

Top of T_i^{ped}

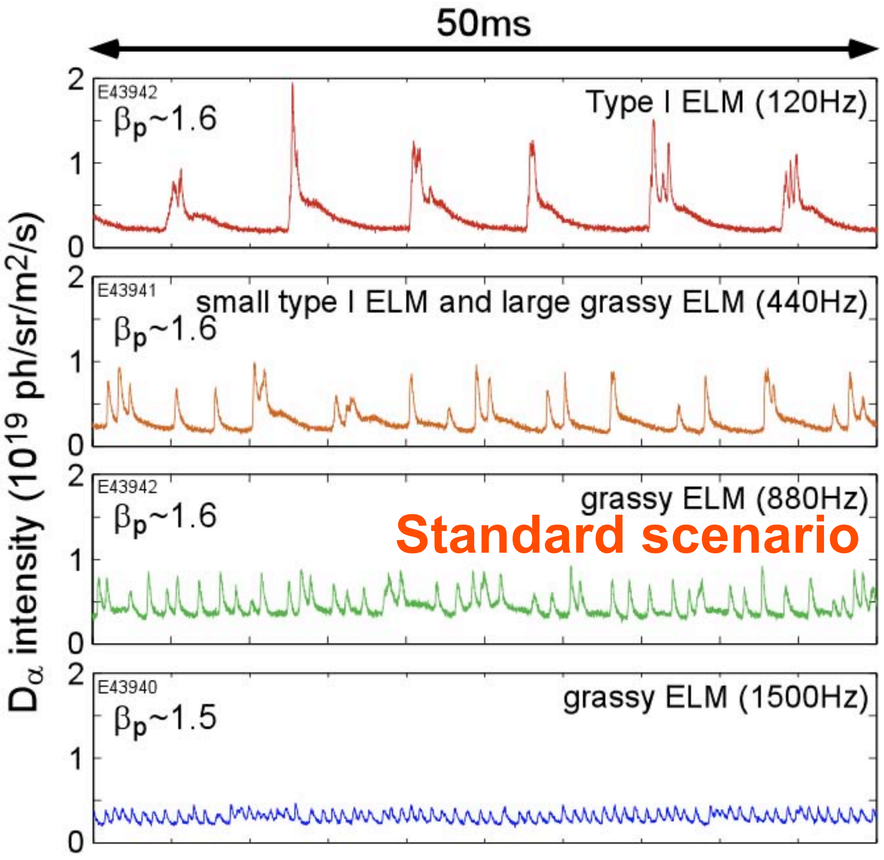


Toroidal rotation profile

(q_{95}~4.9, d~0.6)

small $CTR-V_T$

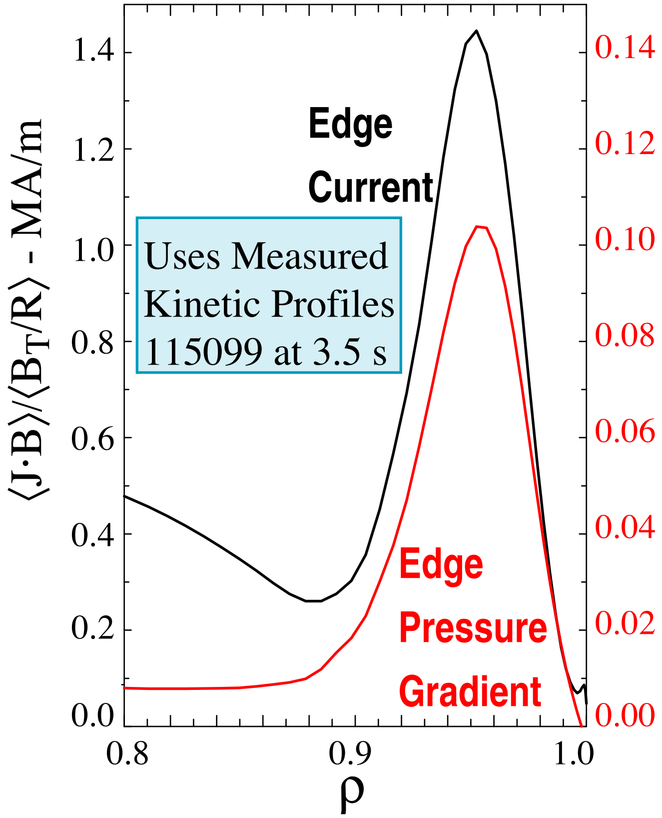
large $CTR-V_T$



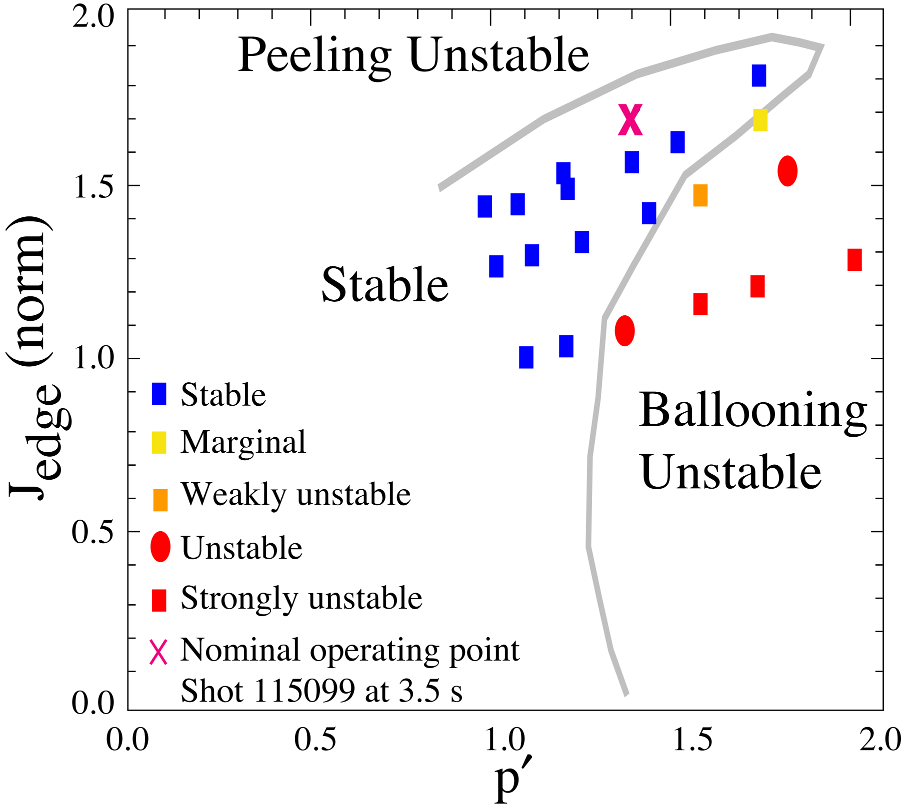
Standard scenario

ELITE STABILITY MODELING: QH MODE IS <u>MARGINALLY</u> STABLE TO CURRENT DRIVEN PEELING/BALLOONING MODES

Edge Current (from NCLASS) and Pressure Profiles in CORSICA equilibrium



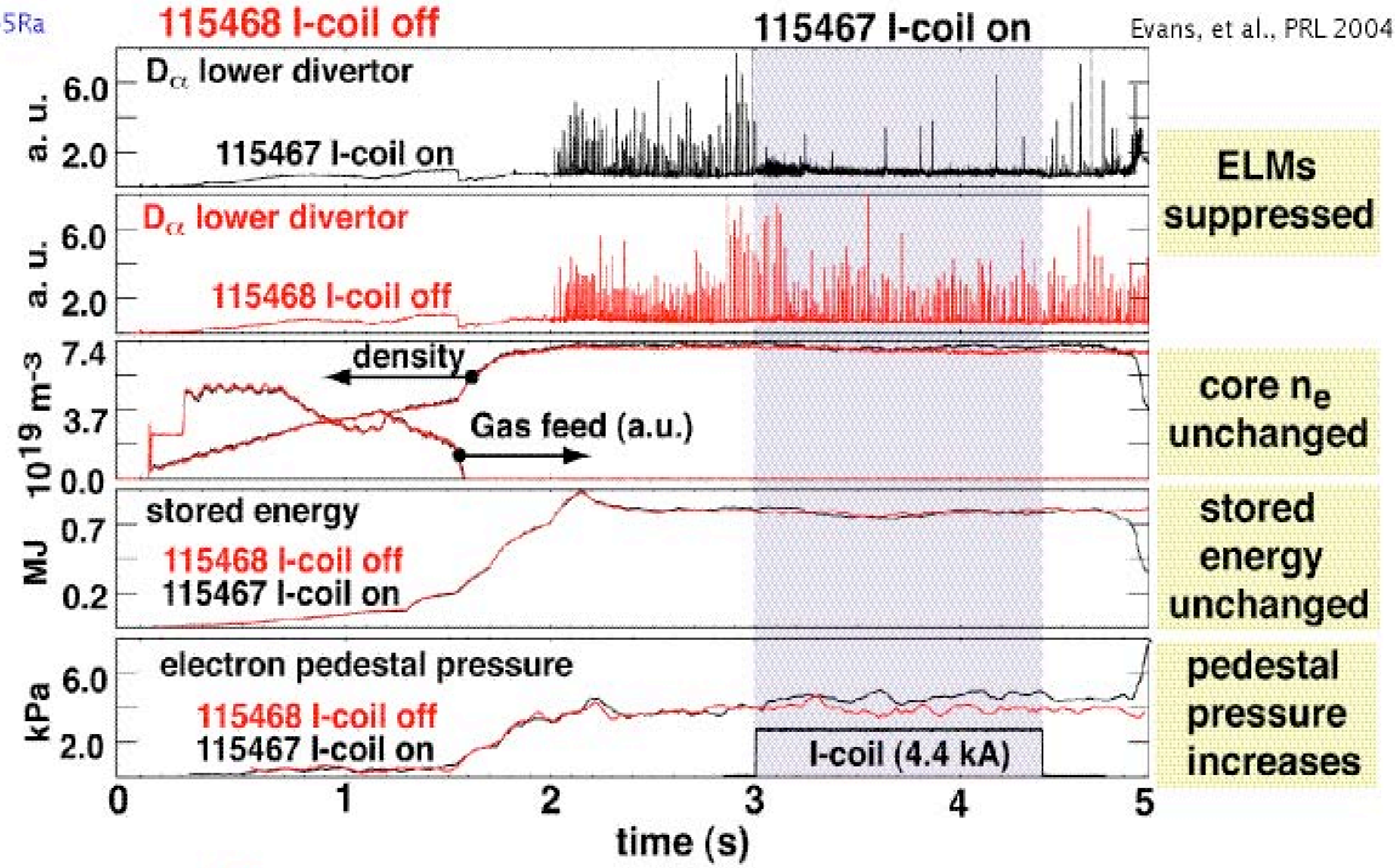
ELITE Stability Diagram from the experimental case, x, and perturbed equilibria, ■



Upward I_P ramps during QH operation induce ELMS, supporting the ELITE result of marginal stability to current driven modes.

EDGE FIELD PERTURBATION CAN SUPPRESS ELMS WITHOUT DEGRADING CONFINEMENT

Evans EX2-5Ra



Evans, et al., PRL 2004

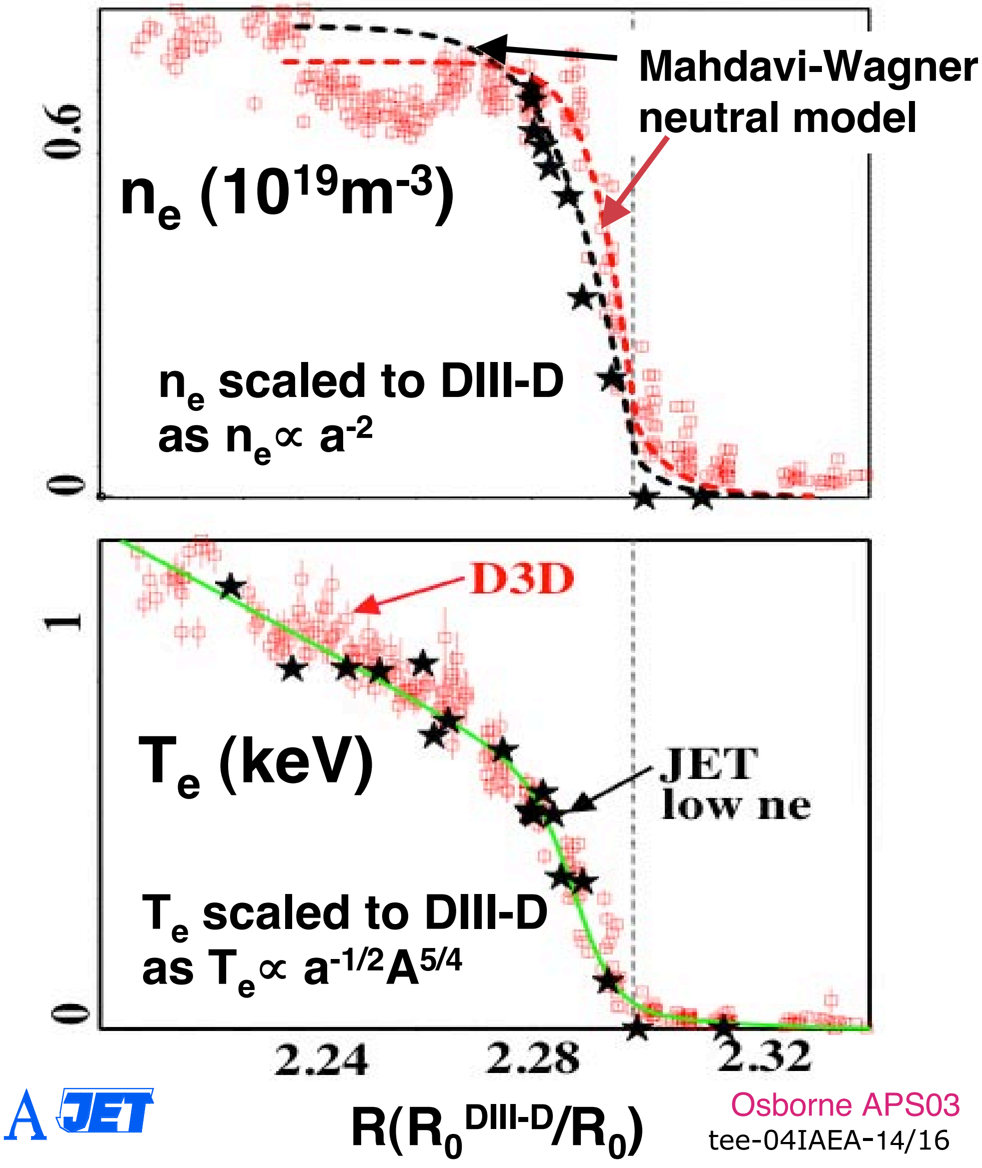
- Several isolated ELM-like events remain
- ELMs return after I-coil pulse turns off

DIII-D/JET pedestal similarity experiments show importance of neutral penetration

Fenstermacher
EX2-5Rb

- **Matched shapes and (β, ν_*, ρ_*, q) at top of pedestal**
- **Neutral penetration physics dominates in setting the density width**
  - **Mahdavi-Wagner model reproduces differences in DIII-D vs JET profiles**
- **Plasma physics dominates in setting the transport barrier**
  - **T_e width $\propto$ a**

EX/2-5Rb DIII-D Fenstermacher.
See also EX/P3-4 AUG Horton



Mahdavi-Wagner neutral model

n_e scaled to DIII-D as $n_e \propto a^{-2}$

T_e scaled to DIII-D as $T_e \propto a^{-1/2}A^{5/4}$

Osborne APS03

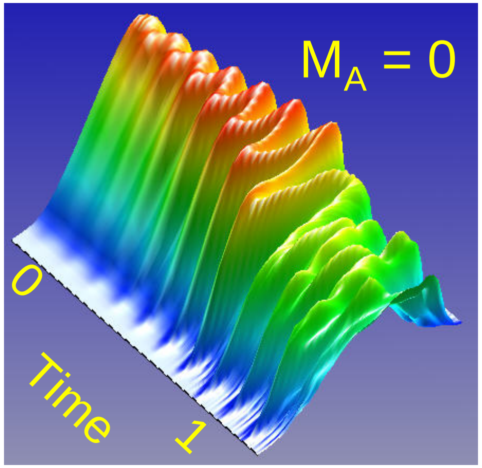
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

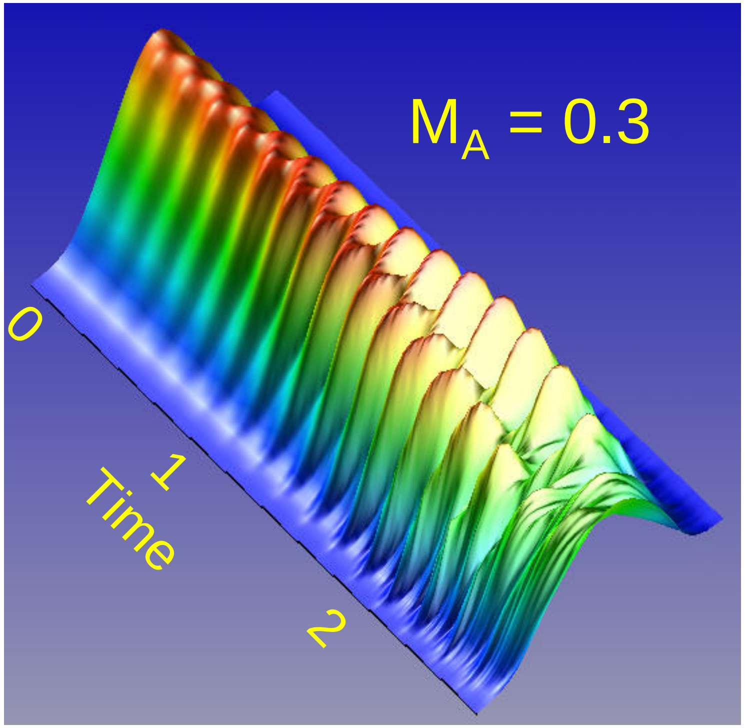
EFDA JET

M3D: Sheared-flow reduces growth rate by factor of 2-3

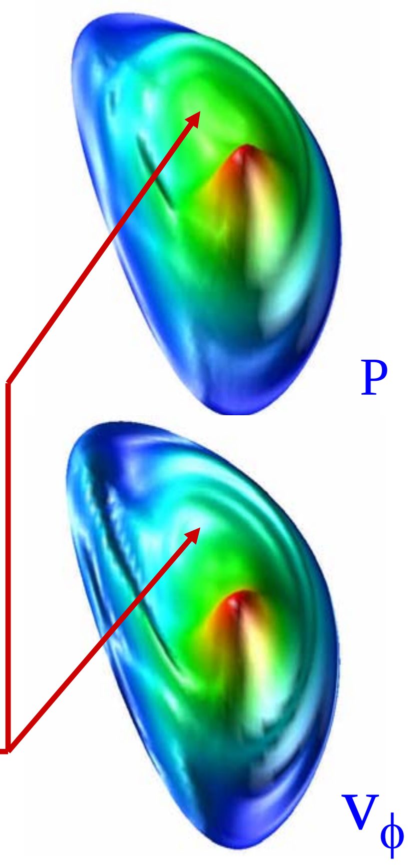
- **Possible because $\gamma_{\text{shear}} \sim \Omega_{\text{rotation}}$ can be of > γ_{linear}**

Simulated SXR signals



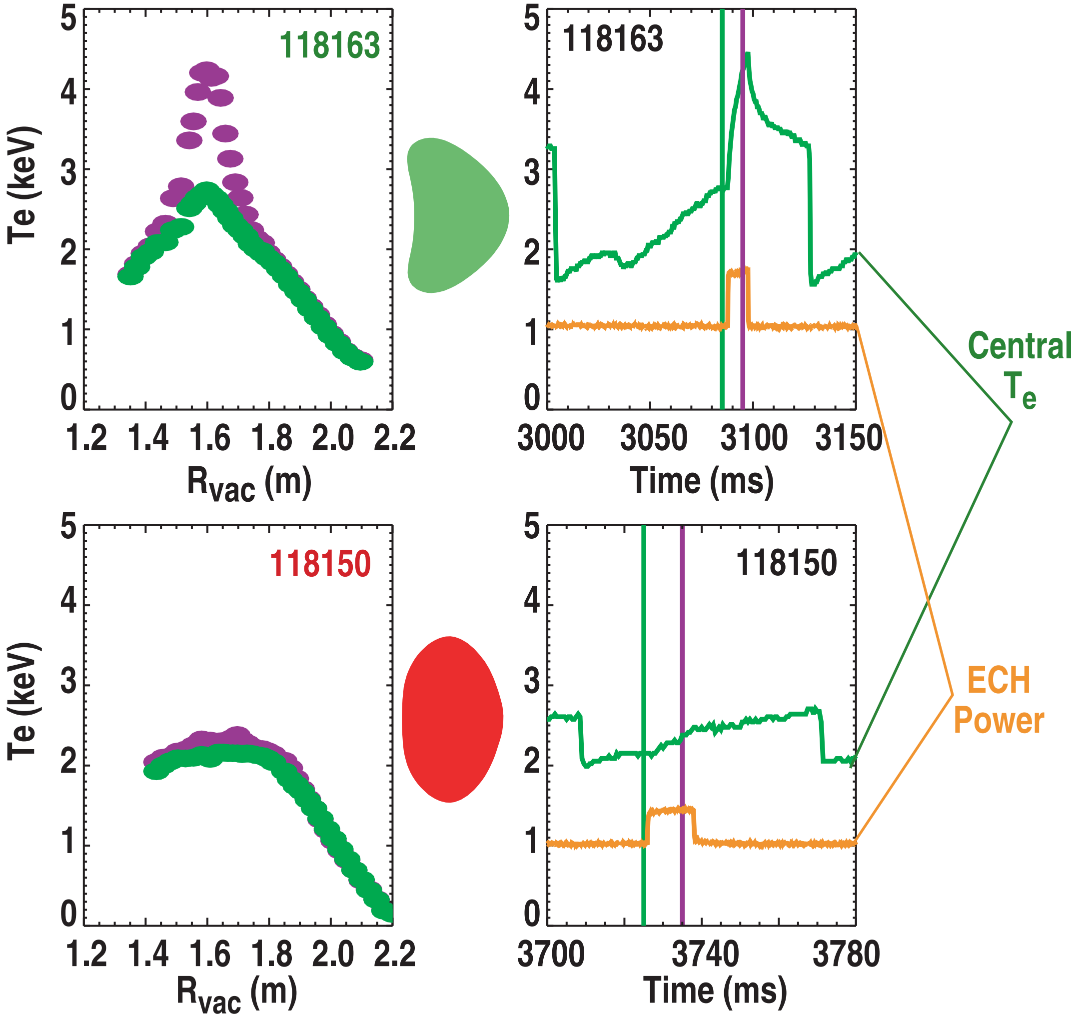


M3D simulations



- In experiment, the NBI power is held roughly fixed
- In **M3D**, with a *fixed momentum source rate*, the v_ϕ and ***p*** profiles *flatten* inside the island, **reconnection *still* occurs (saturated state rare)**

PLASMAS THAT VIOLATE THE MERCIER CRITERION DO NOT SUPPORT AN ELECTRON PRESSURE GRADIENT



Indented Plasmas:

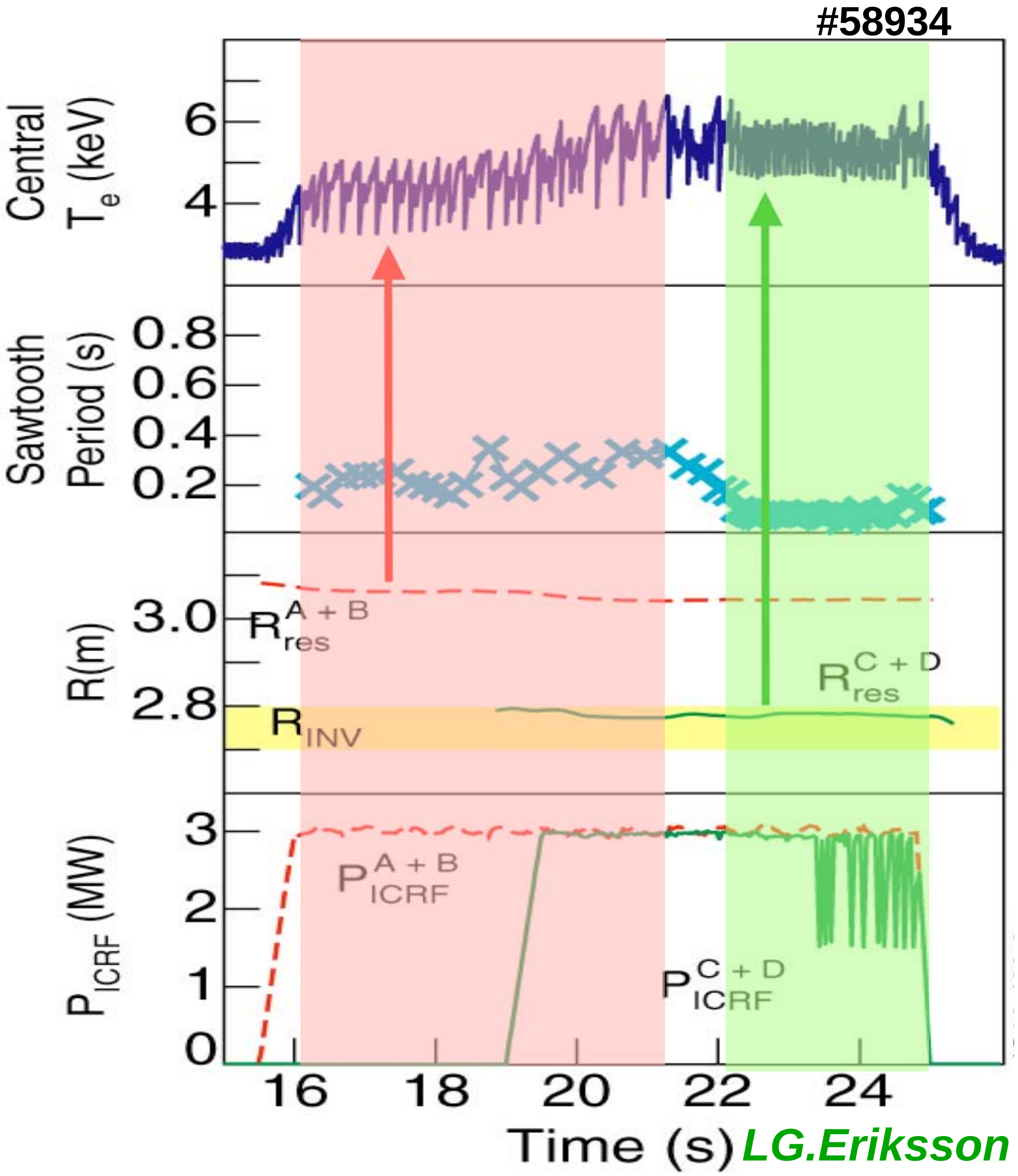
- Mercier limit occurs at q<1
- Local electron heating results in strongly increased gradient

Oval Plasmas:

- Mercier limit occurs at q>1
- Local electron heating results in almost no change in gradient

Lazarus – Fri. AM Poster

‘Monster’ sawtooth control



core +90º phasing ICRH to make fast particles and large sawteeth (period up to 0.4s)

q=1 -90º phasing ICRH for current drive sawtooth destabilisation

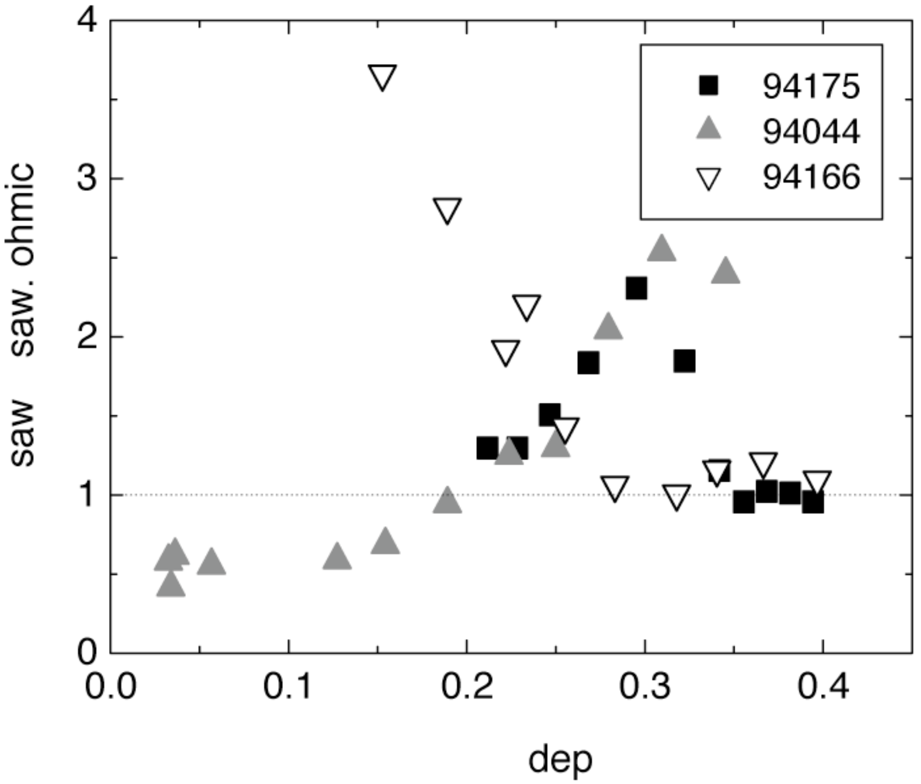
Essential technique for ITER to control fast alphas stabilised sawteeth

R.Buttery, EX/7-1

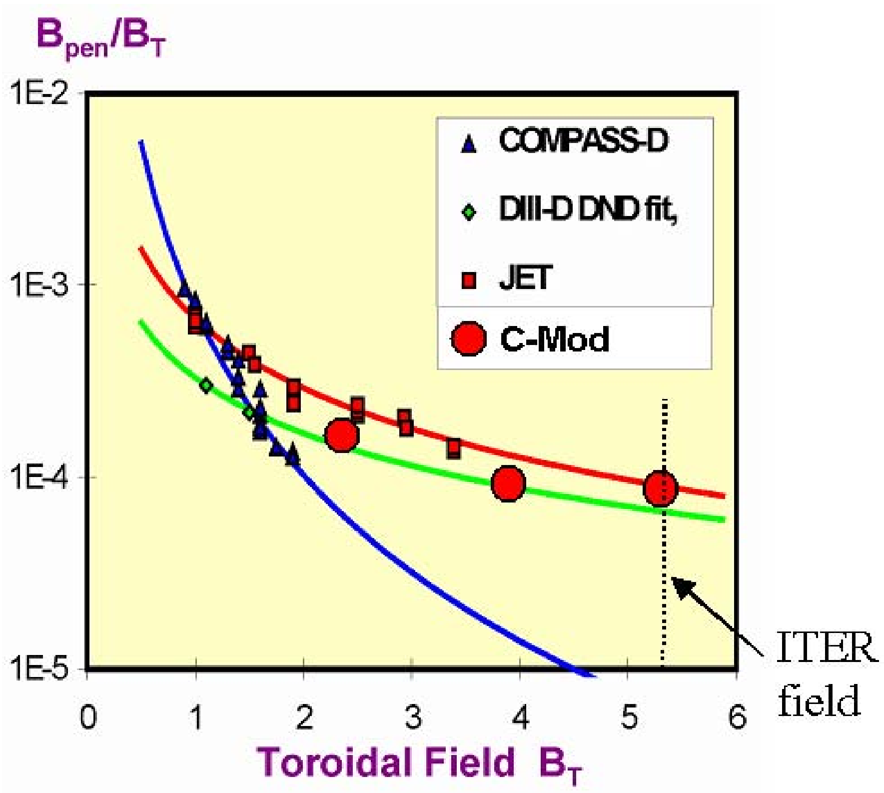
LG.Eriksson et al PRL92 (2004)235004

EC Effects on Sawtooth Period

EX-P/5-16 TEXTOR Westerhof



LOCKED MODE THRESHOLD HAS WEAK SIZE SCALING

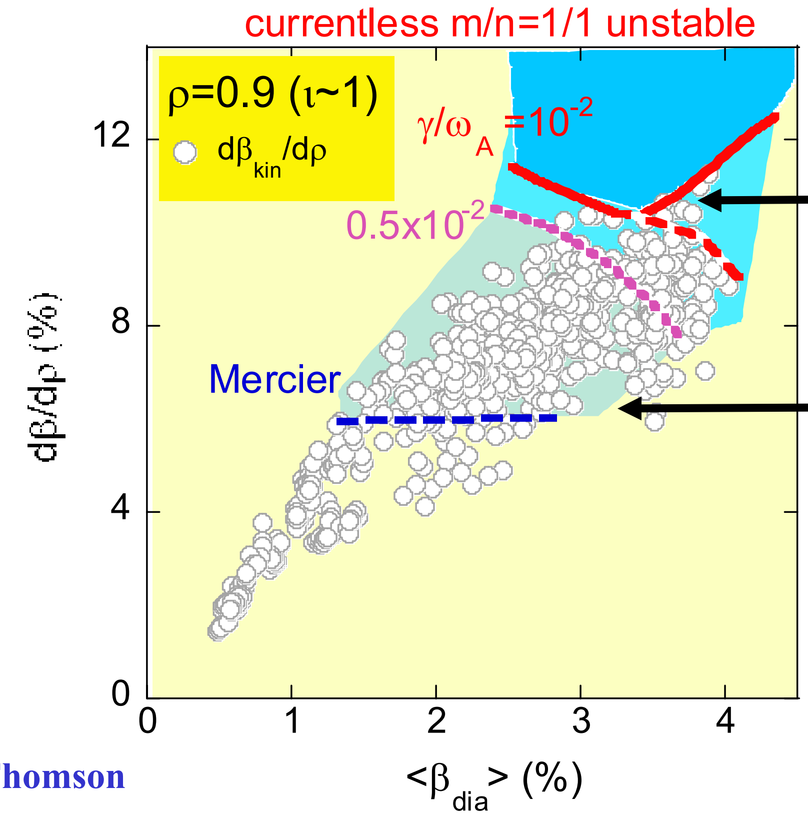


Hutchinson EX/P5-6

- Set of external non-axisymmetric control coils installed.
- Allow determination of intrinsic error field and mode locking threshold.
- Dimensionless identity experiments performed w/JET, DIII-D.
- Weak size scaling found.
- Locked modes should not be worse for ITER than for current machines
- Coils allowed suppression of locked modes, 2 MA operation.

Study on MHD stability limit of high beta plasma

Role and Function of Boundary



Achieved beta is close to the m/n=1/1 ideal mode limit

Achieved beta significantly exceeds the Mercier limit

γ=1.22

(γ=n/m·a_c/R=$\kappa\varepsilon$)

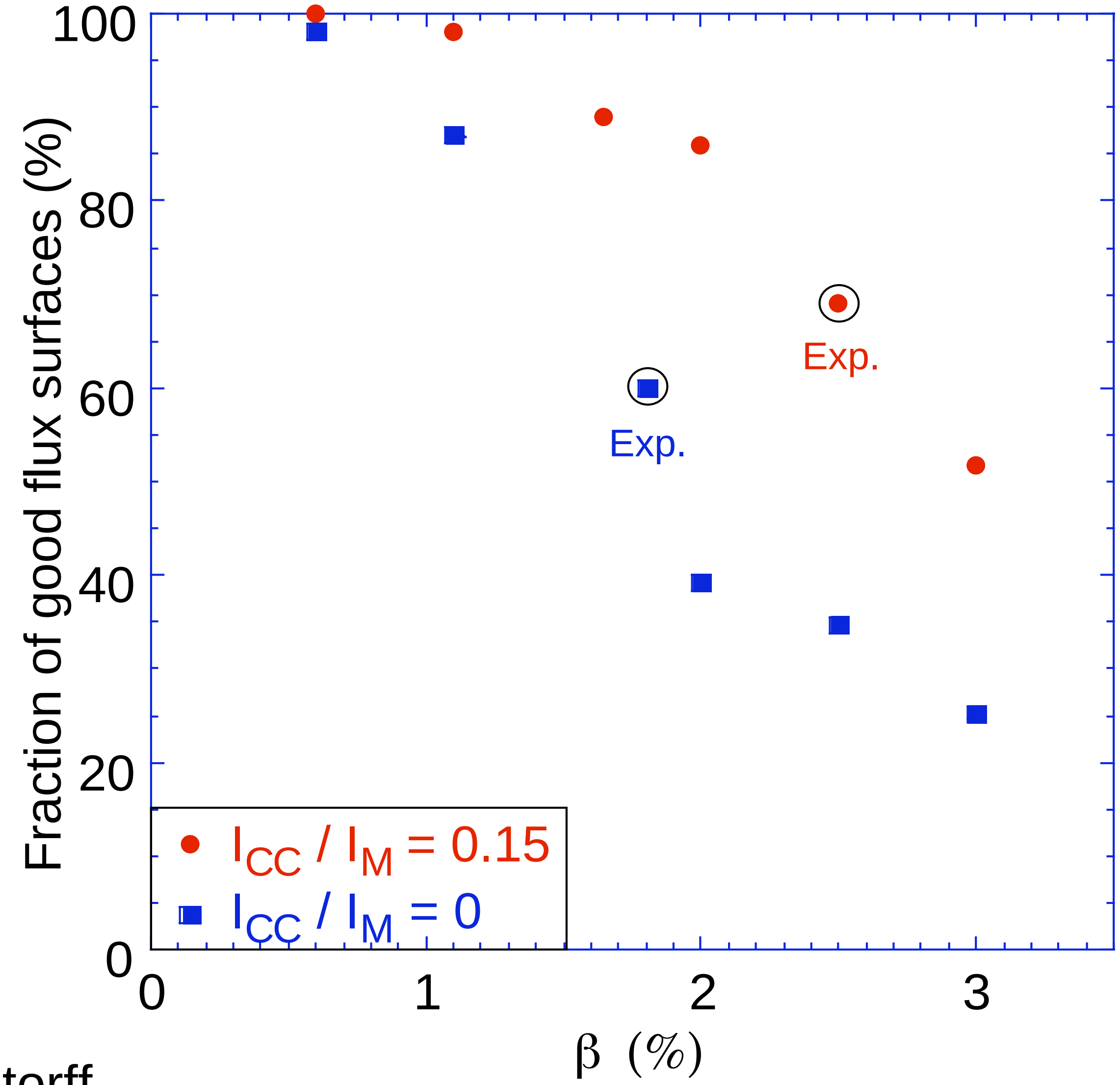
$T_e(T_i)$: Thomson
n_e:FIR

- β values achieved significantly exceeds the Mercier limit and increases up to m/n=1/1 ideal MHD limit

kinetic beta gradients at ρ=0.9 ($\iota/2\pi$ = 1) in $<\beta>$-$d\beta/d\rho$ diagram.

Degradation of Equilibrium May set β Limit

- PIES equilibrium calculations indicate that fraction of good surfaces drops with β
- Drop occurs at higher β for higher I_{CC} / I_M
- Experimental b value correlates with loss of ~35% of minor radius to stochastic fields or islands
- Loss of flux surfaces to islands and stochastic regions should degrade confinement. May be mechanism causing variation of β.



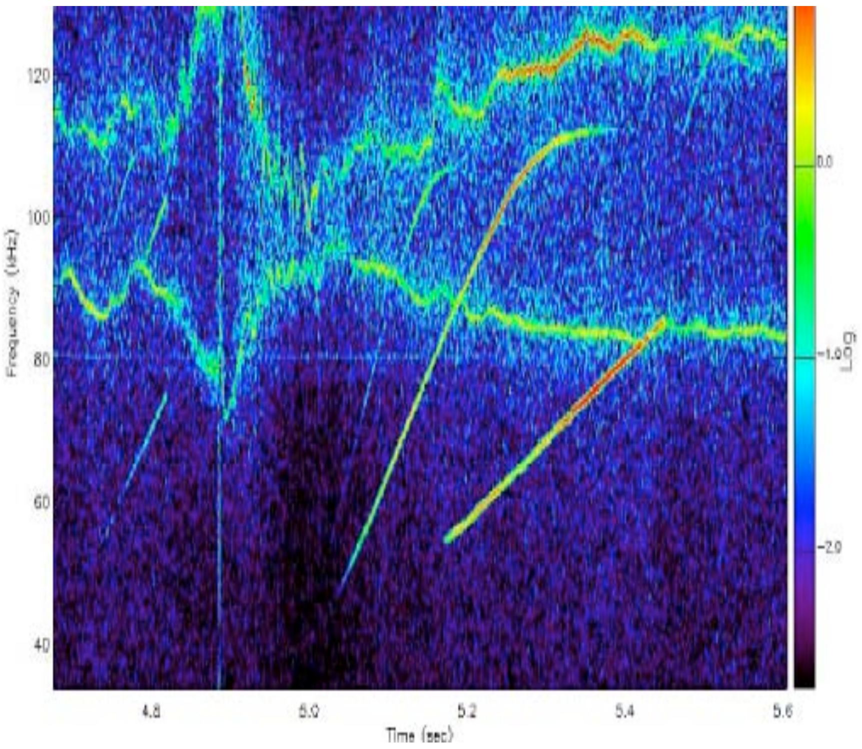
EX/3/4 W7-AS Zarnstorff

Other Stability Results

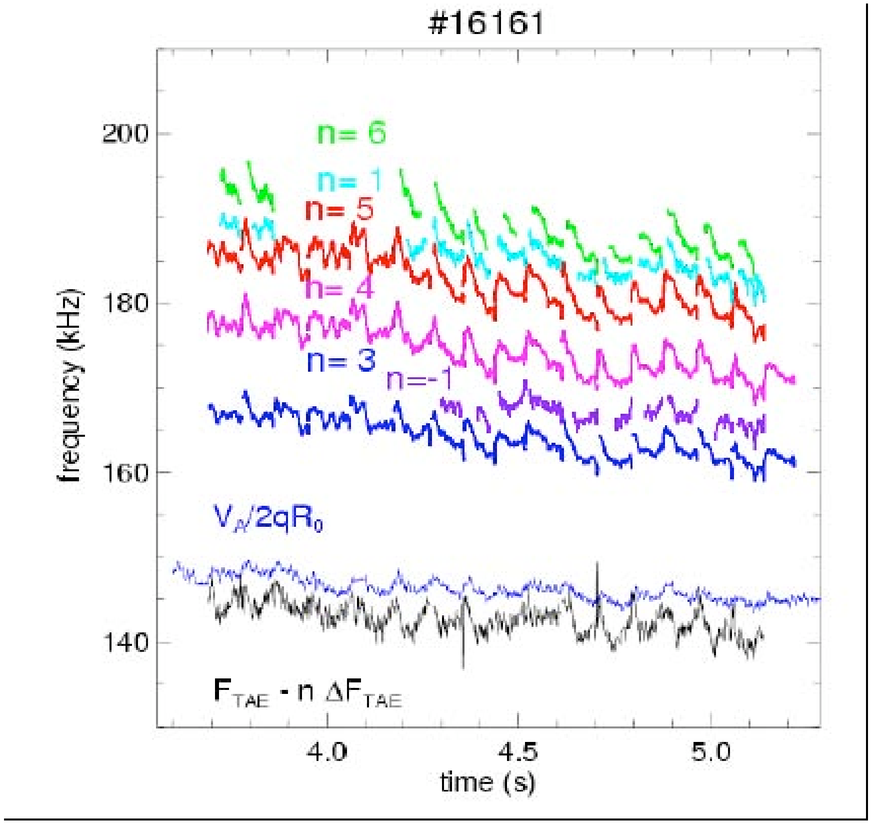
- EX-P/5-8 CT-6B Khorshid - Limiter Biasing Affects Rotation Which Affects MHD Stability
- EX-P/5-12 HL-1M Liu - Snake Perturbations Excited by Pellet Injection and During LHCD
- EX-P/9-6Rb HANBIT Jhang - Interchange Stability Window with Strong RF

ALFVEN EIGENMODES

Alfven cascades excited by ^{4}He ions in JET reversed-shear discharge
EX/5-2 Sharapov

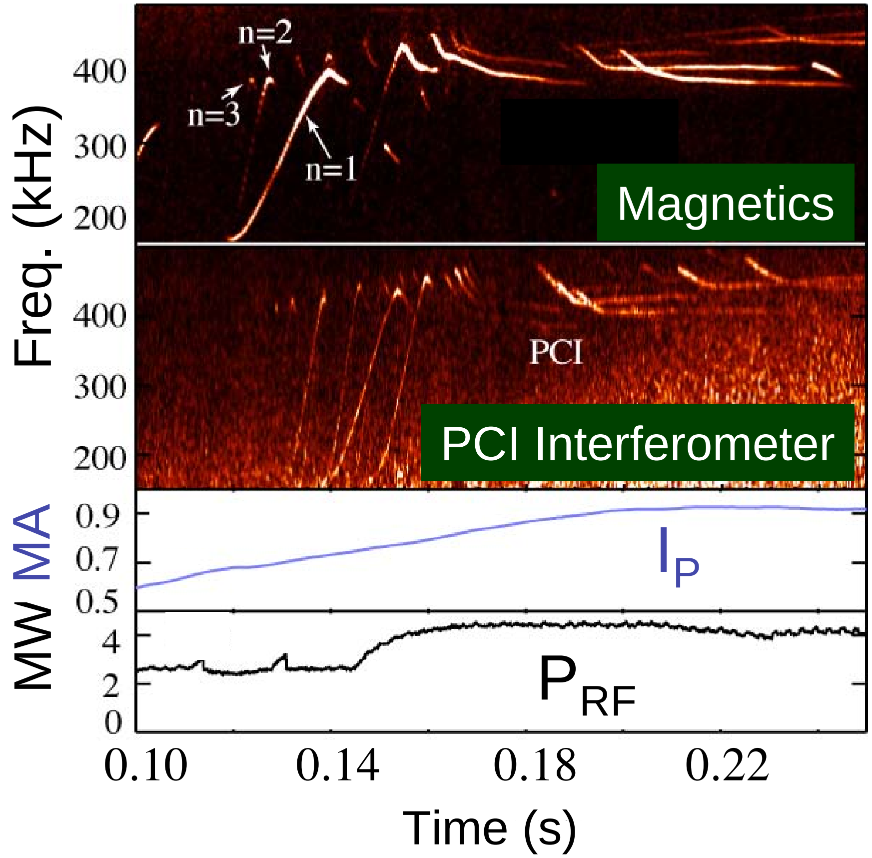


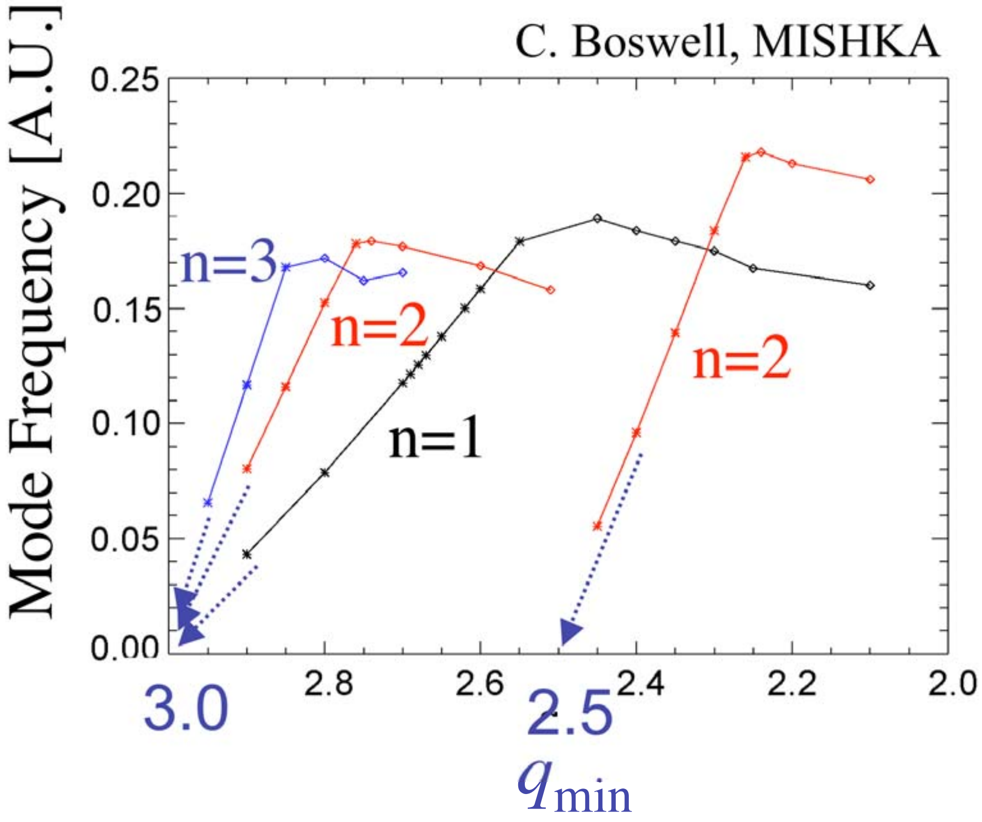
TAE modes in low density ICRH heated discharges in ASDEX-Upgrade
EX-P/4-37 Borba



MHD Spectroscopy and the Evolution of q_{min} in the Current Rise of Alcator C-MOD

EX/5-1 Nazikian

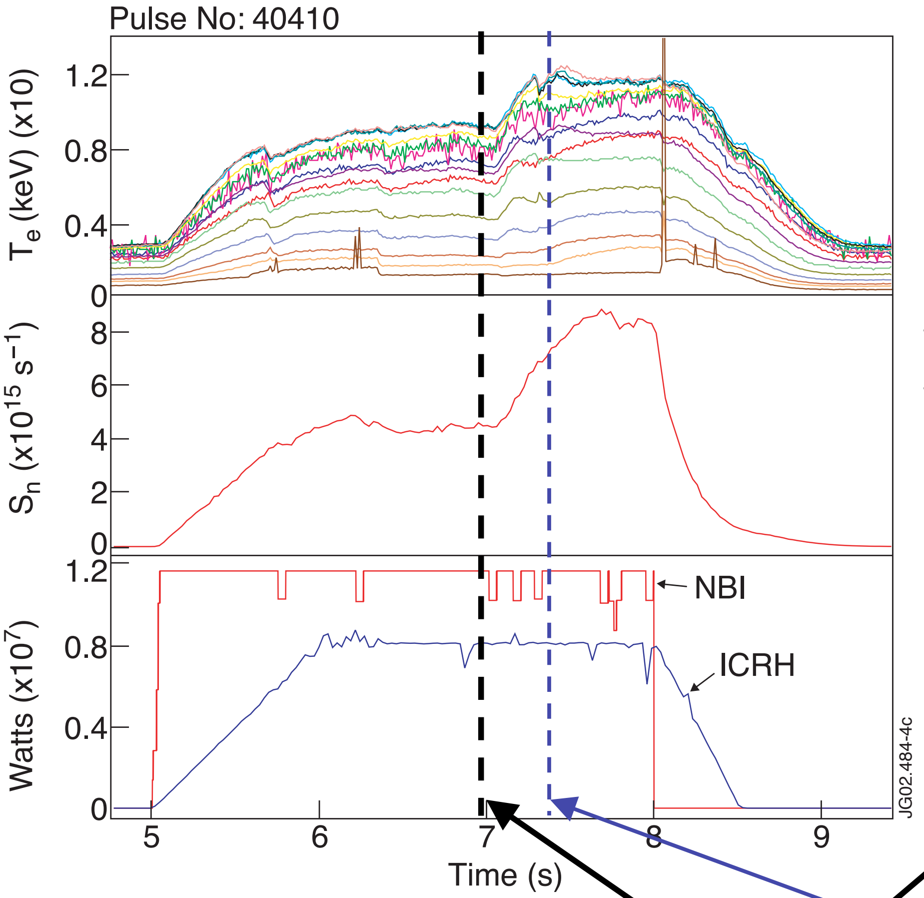


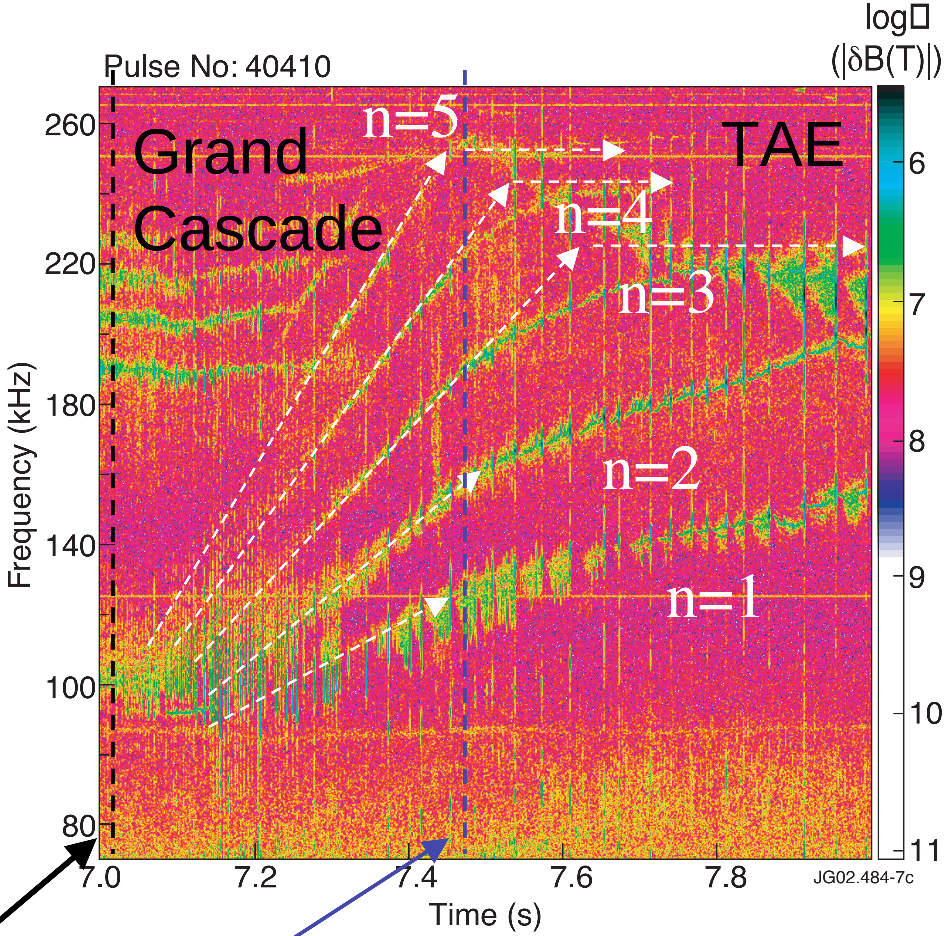


J. A. Snipes et al., Proc. 31st EPS (2004)

- MHD spectroscopy useful when MSE is challenging
- Higher-n gives higher q_{min} resolution
- Core fluctuations measurements access higher-n

Application of MHD Spectroscopy: Onset of ITB Triggered by Integer q_{min} Crossing on JET





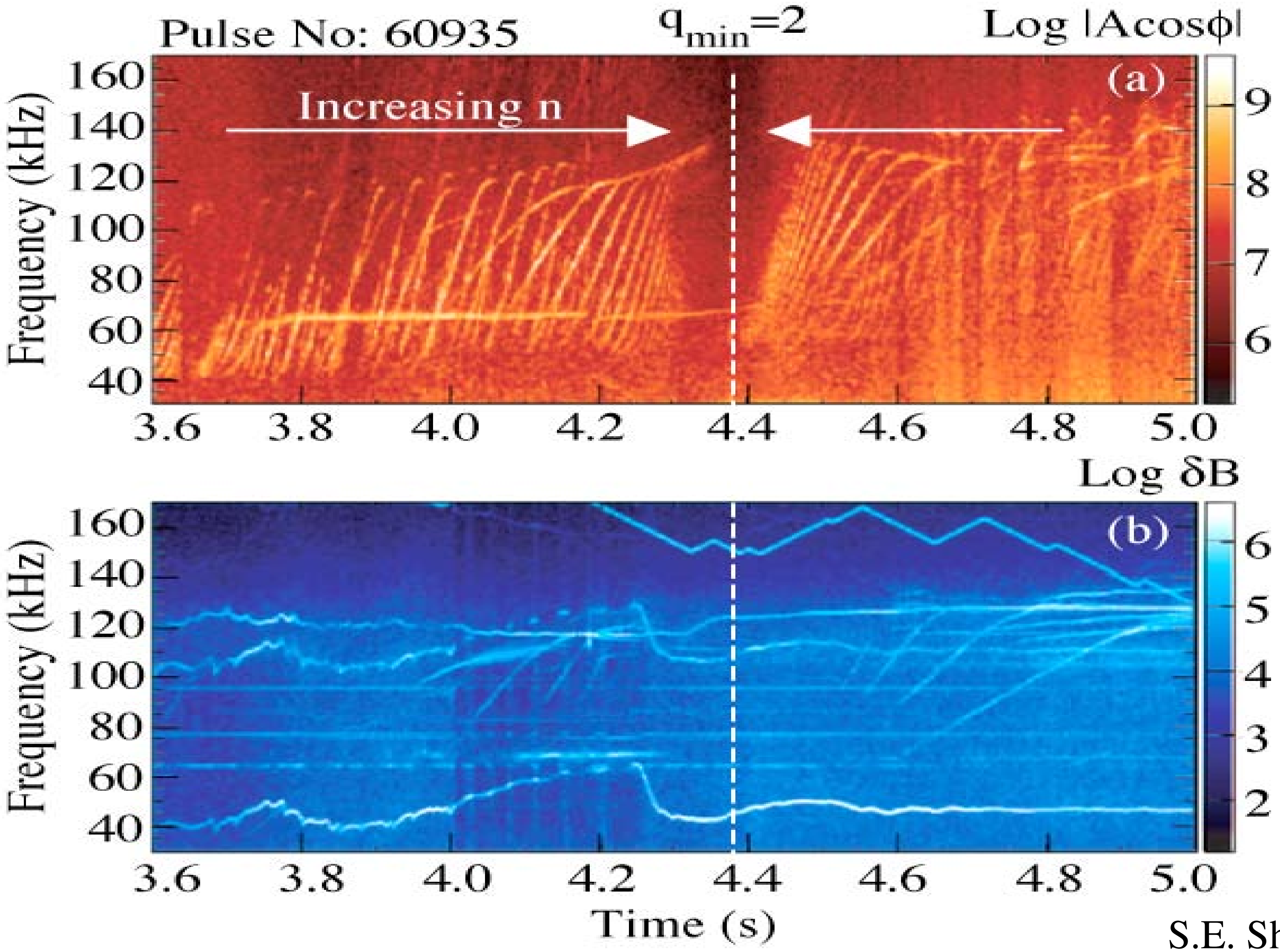
E.Joffrin et al., PPCF **44** (2002) 1739

q_{min}=2.0 q_{min}=1.9

EX/5-1 Nazikian

- What role do Cascades play in ITB triggering ?

Breakthrough: Interferometer Measurements Reveal Many Hidden Modes in Reverse Shear Plasmas on JET



- Interferometer
  n >16
- Reflectometer
  $\tilde{B}/B \approx 1.5$ x 10^{-4}
  for n=3

- Magnetics
  n < 5

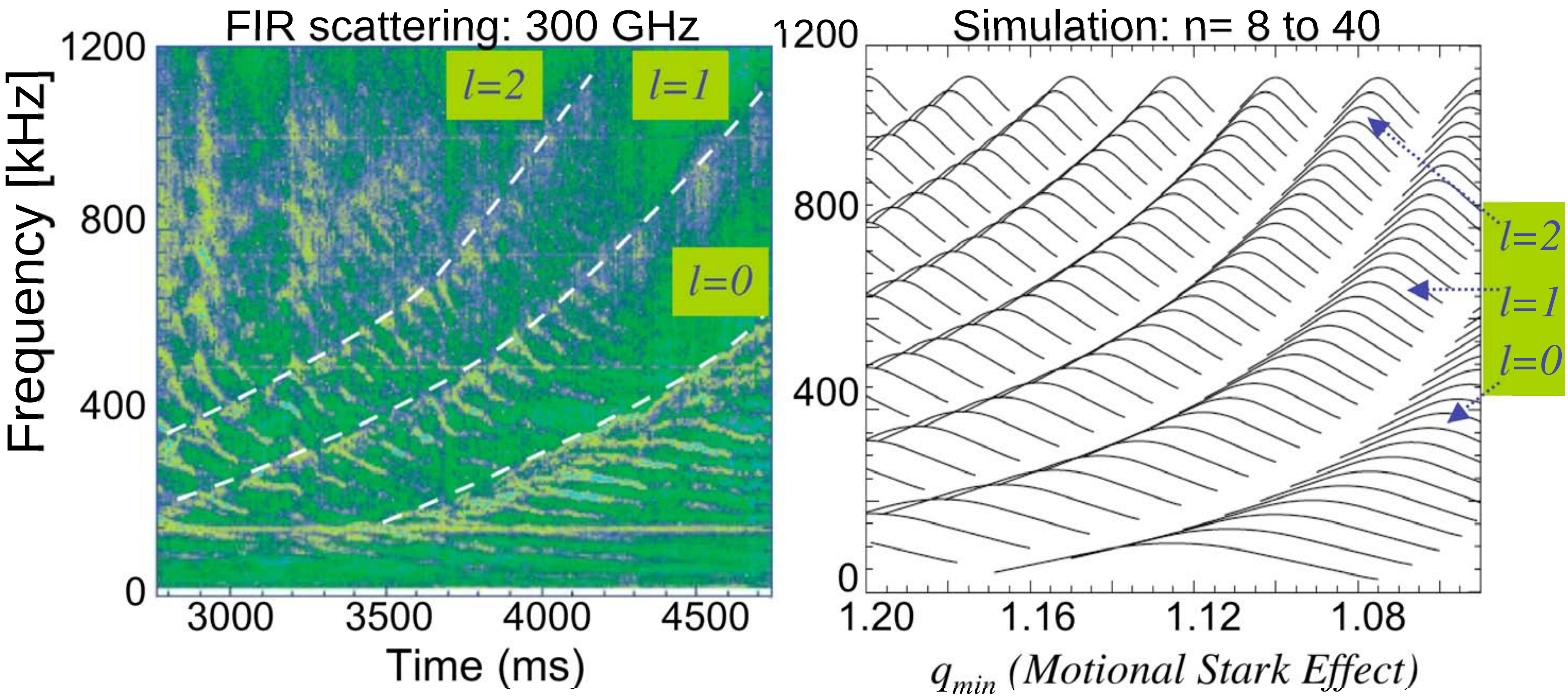
EX/5-1 Nazikian
EX/5-2Ra
Sharapov

- Fast ion loss not observed

S.E. Sharapov et al., PRL **93** (2004) 165001

A “Sea of Alfvén Eigenmodes” Observed in DIII-D Plasmas Driven by 80 keV Neutral Beams

EX/5-1 Nazikian



- Bands of modes $m=n+l$, $l=0, 1, 2, \dots$: $w_{n+1}-w_n \approx w_{rot}$ (CER)
- Neutral beam injection opposite to plasma current: $V_{||} \approx 0.3 V_A$
- $8 < n < 40$, k_q up to 2.0 cm^{-1} (Turbulent scale length !!)

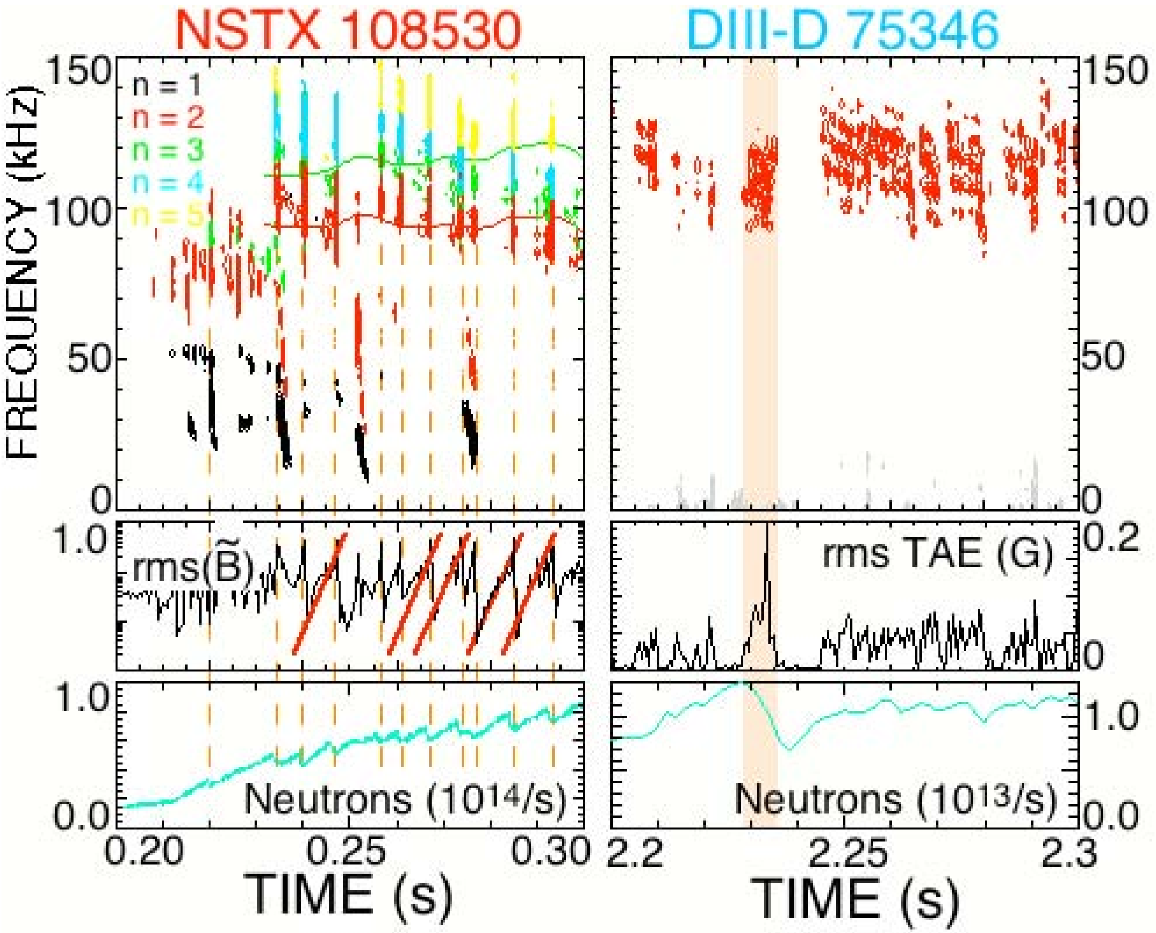
TAE can cause significant losses at both low and high aspect ratio,

- Largest losses occur with multiple unstable modes.

On NSTX:

- TAEs most virulent in low-shear, q(0) ≈ 2 regime*.
  - TAE seen at toroidal b's greater than 20%.
  - Observed growth rates in good agreement with NOVA estimates.
  - Up to 15% drops in DD neutron rate from TAE.
- With higher shear, TAE not bursting
  - no enhanced fast ion loss

EX/5-3 Frederickson



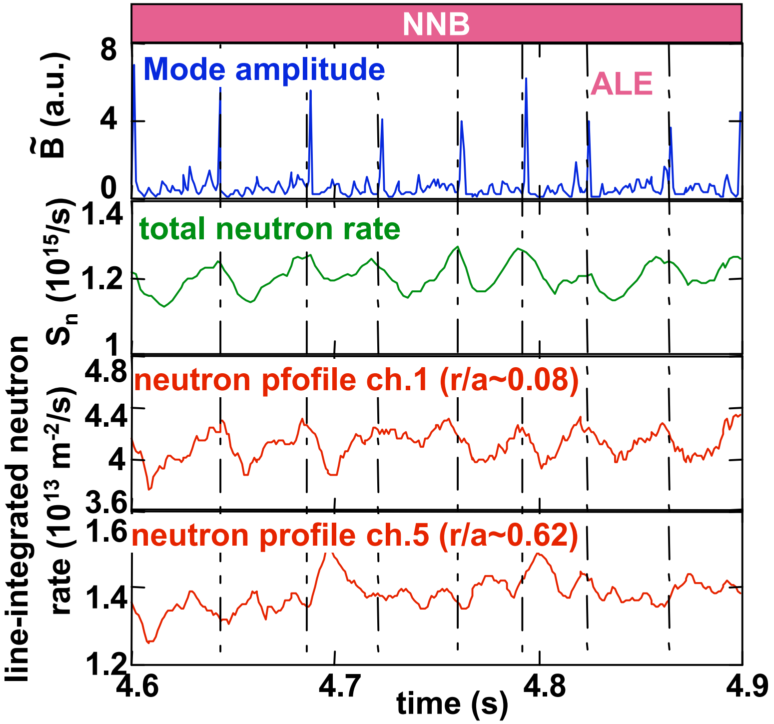
*N.N. Gorelenkov, et al., Phys.Plasmas **7** (2000) 1433.

Confinement of energetic ions at ALE

K. Ishikawa (EX/5-2Rb, Thu., poster Fri.)

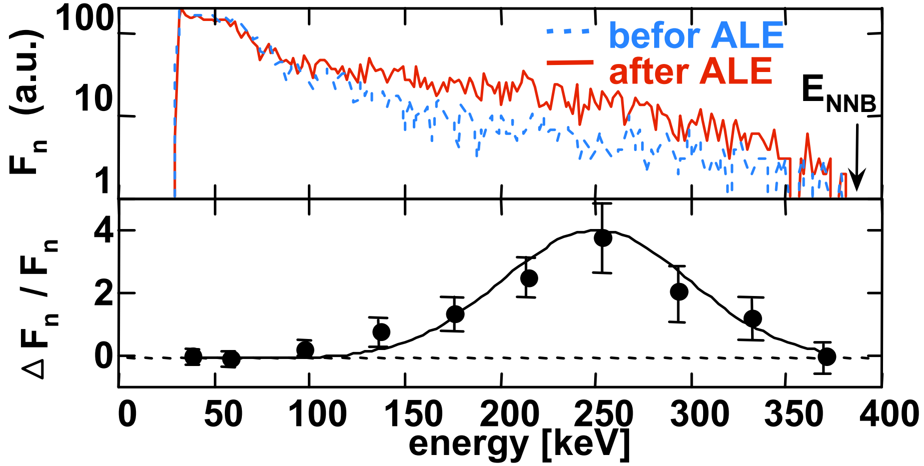
JT-60U

E43014, Ip=0.6MA Bt=1.2T
P_{NNB}~ 4.8MW, ENNB~387keV
<neutron emission>



- In a JT-60U weak shear plasma, N-NB drives bursting mode in the TAE freq. range.
  => Abrupt Large Event (ALE)
- **How are energetic ions affected?**

<energy distribution of neutral particle>



- Only ions in limited energy are affected.
  =>Agrees with AE resonant condition

=>Contribution to theory/modeling towards burning experiments.

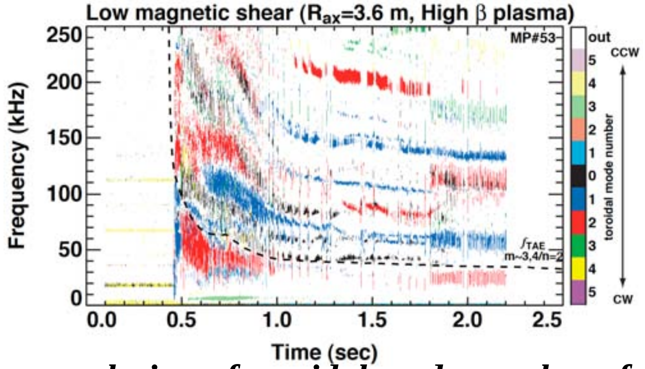
EX/5-4Rb Configuration Dependence of Energetic Ion Driven Alfvén Eigenmodes in the Large Helical Device

S. Yamamoto[1], **K. Toi**[2], **N. Nakajima**[2], **et. al.,**
1) *Institute of Advanced Energy, Kyoto University, Uji, Japan*
2) *National Institute for Fusion Science, Toki, Japan*

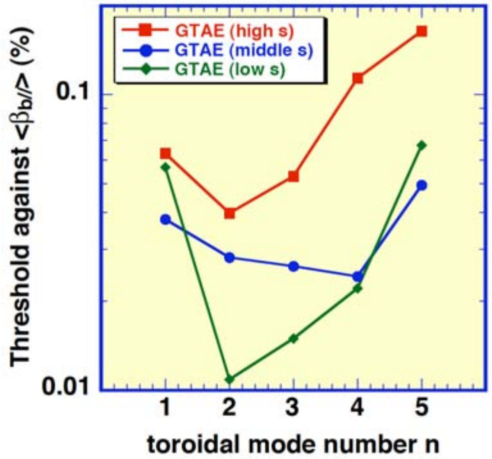
◆ Motivation

It is important to clarify the configuration dependence of Alfvén eigenmodes (AEs) because the existence and stability of them sensitively depend on the profiles of the rotational transform $\iota/2\pi$ and magnetic shear s.

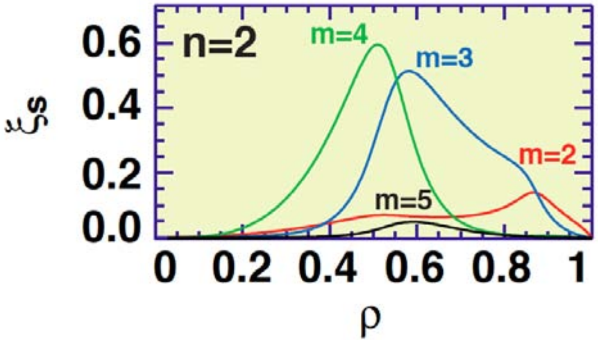
➔ We have experimentally studied the AEs in various magnetic configurations (high, middle and low s).



Time evolution of toroidal mode number of AE in the plasma with low magnetic shear



Mode number dependence of threshold of observed TAE

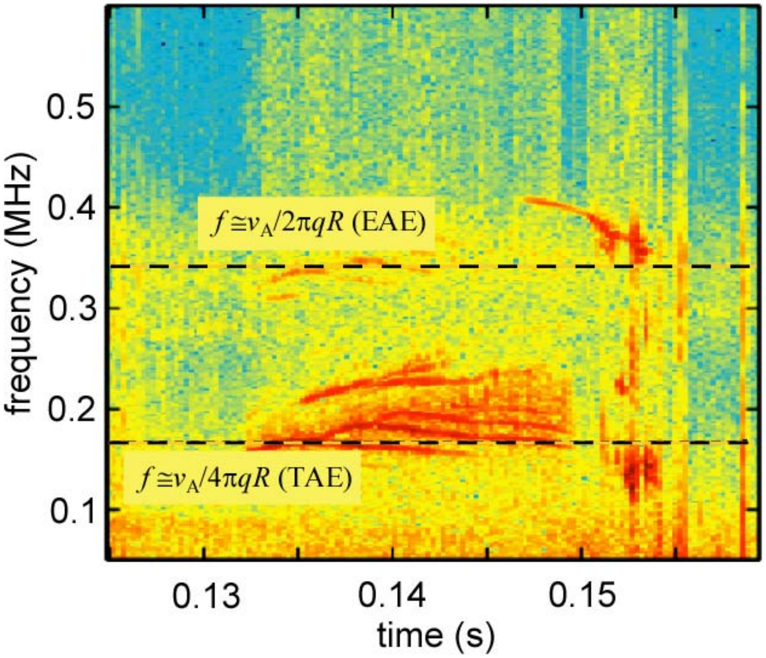


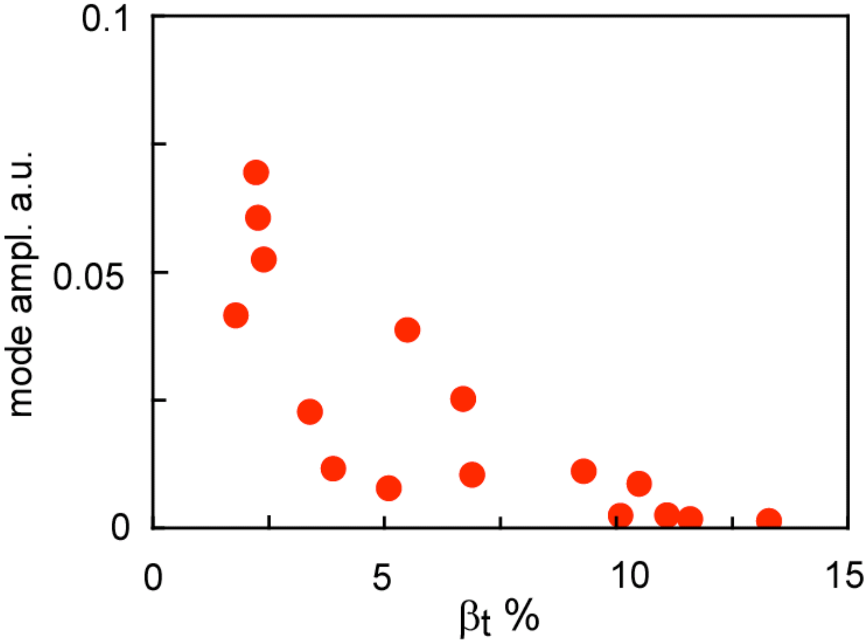
Calculated mode profile of bursting TAE with n = 2

◆ Conclusion

Continuum damping, of which damping rate is related to the magnetic shear and toroidal mode number *n* ($\gamma_c \sim n^{3/2}$ and ~ s), would be the most important damping mechanism in the LHD plasma.

EPM activity reduces with β on MAST





For β > 5% TAE and EAE activity become dominated by non perturbative down-frequency chirping modes

The **amplitude of these modes falls sharply with increasing β**, vanishing for β > 15%

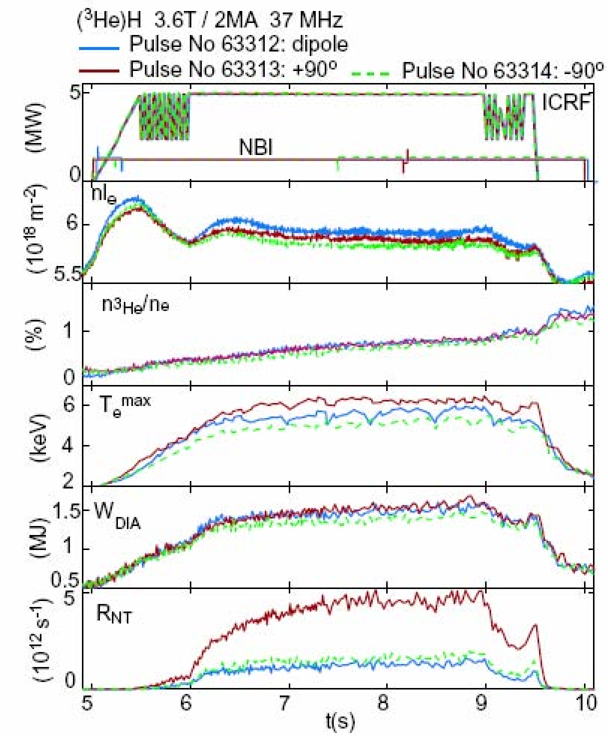
⇒ AE activity likely to be absent in a future ST device where β on axis would approach 100%

See S. Sharapov EX/5-2Ra

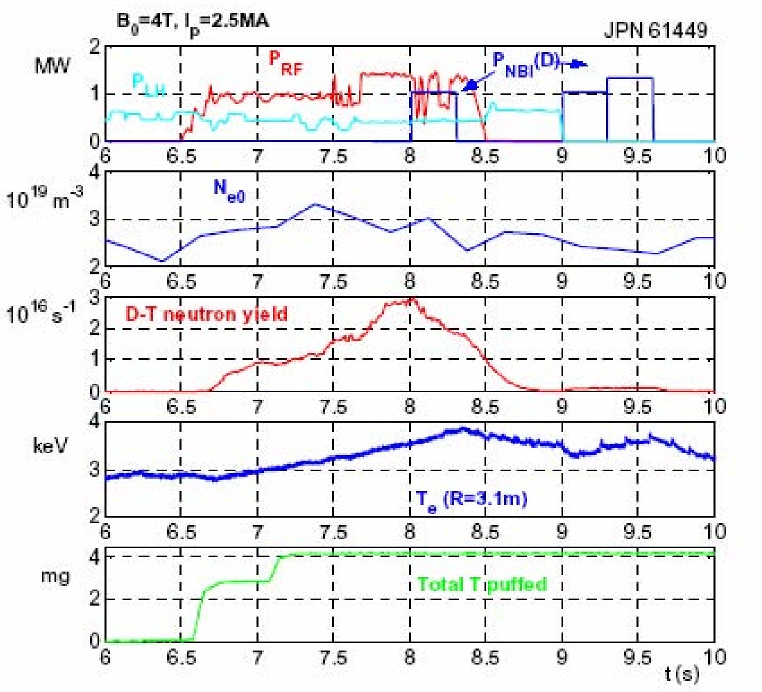
Validation of key ICRF scenarios for ITER are being carried out

(^{3}He)H used on JET for pre-activation experiments in ITER

(T)D used when T experiments begin



+90 deg phasing more efficient due to improved ion orbits

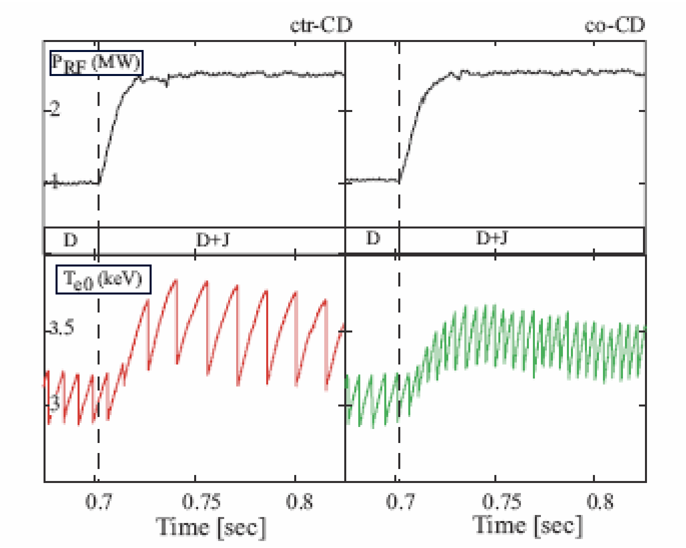


strong increase in reactivity observed with 1.4 MW ICRF

EX/P4-26 Lamalle

ICRF is useful in experimental applications

Mode conversion current drive



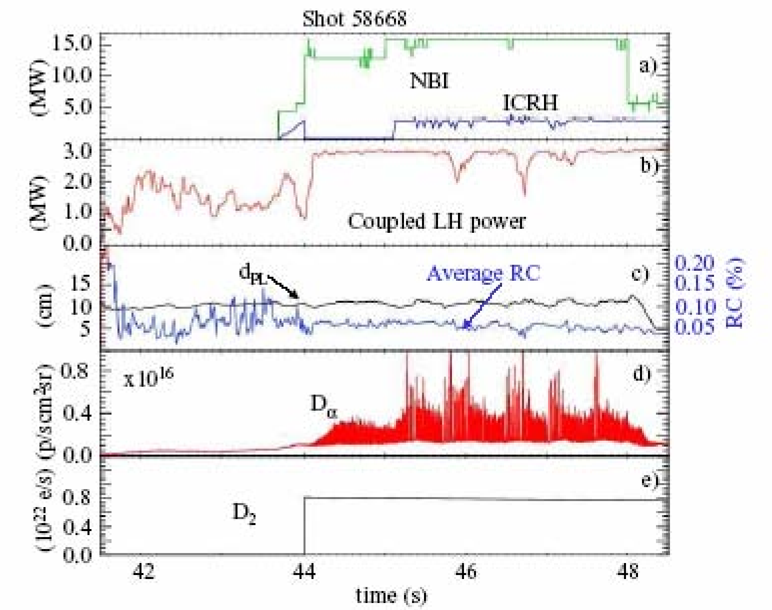
sawtooth control found in Alcator C-Mod

EX/P4-32 Porkolab; TH/P4-35 Wright

- Direct launch IBW in FTU (OV/4-6 Gormezano)
- Heating from ICRF (H)D found in Globus-M (EX/P4-24 Gusev)
- Fundamental heating of H found in T-11M (EX/P4-29 Maltsev)
- FWCD for heating on NSTX, but edge absorption a problem (OV2-3 Kaye)

ITER relevant coupling of Lower Hybrid Waves

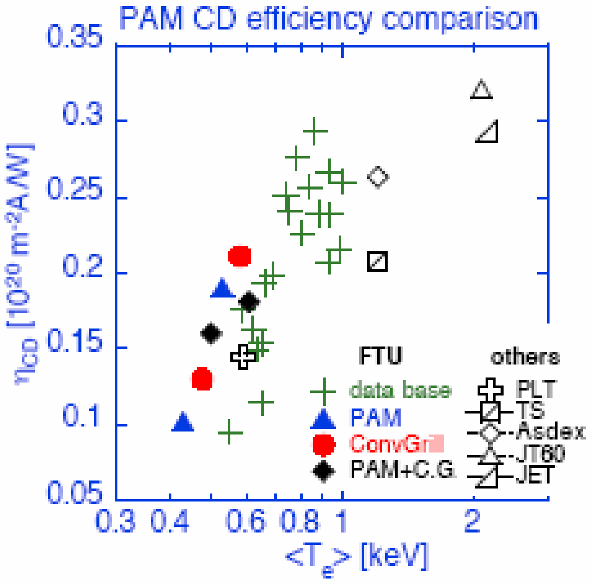
D injection improves LH coupling over large gap



3 MW coupled, but D affects ELMs
Doesn't affect ITB

EX/P4-28 Mailloux

Successful use of PAM obtained in FTU

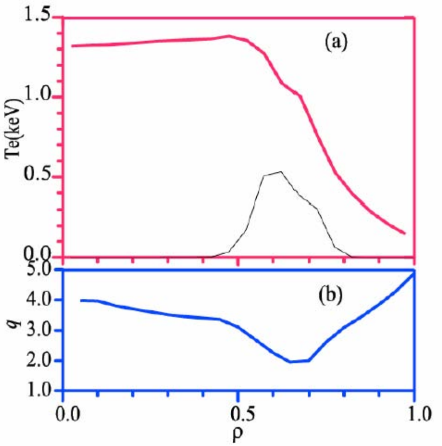


Efficiency of PAM equal that of other antennas(EX5/5 Pericoli)

Multijunction antenna with improved directionality successfully used in HT-7 (EX/P4-19 Ding)

LHCD is useful in present experiments

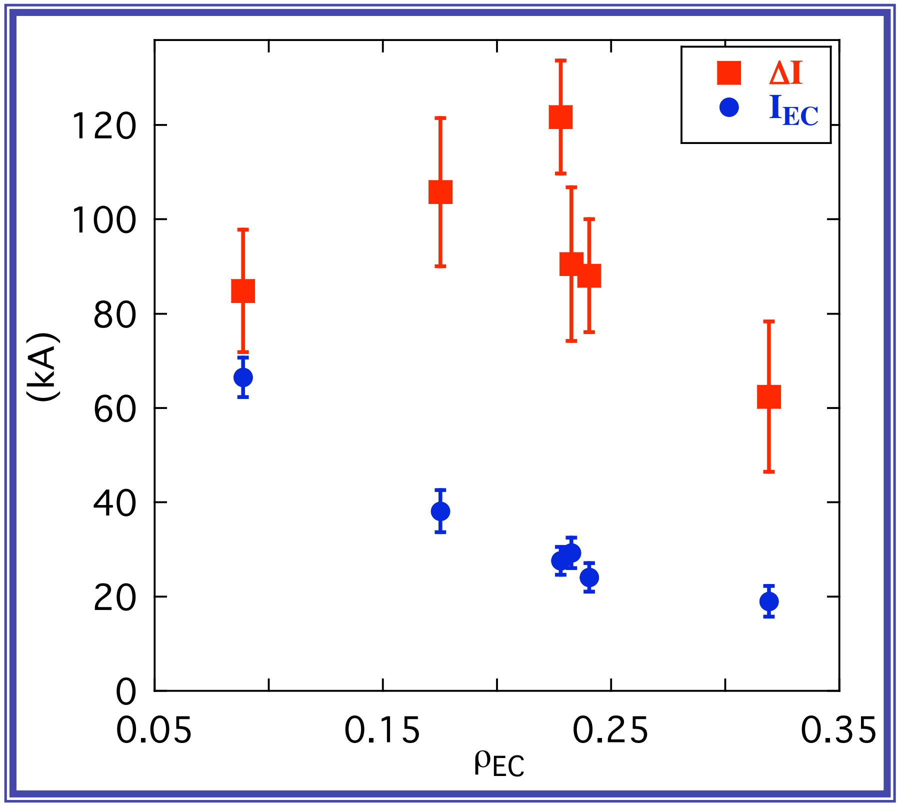
- **Control of CD location by phase control found on JT-60U**
- **6.5 minute discharge sustained by LHCD on Tore Supra**
- **5.6 hour discharge sustained by LHCD on TRIAM-1M**
- **H-mode by off-axis LHCD in HT-7 (OV-1Rb, Wan)**
- **Current profile by LHCD used on HL-2A to generate RS**



EX/P4-21 Gao

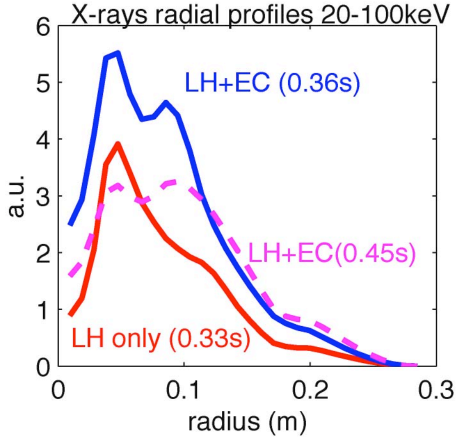
Synergy between RF waves can increase current drive efficiency

EX/P4- 22 Tore Supra Giruzzi LHCD + ECCD

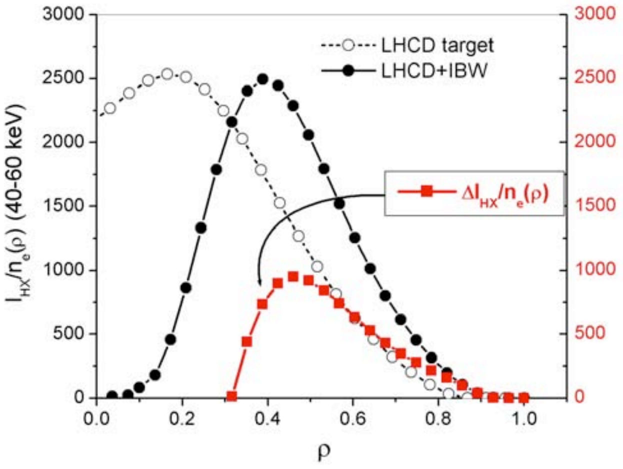


Synergy when LH and EC waves absorbed at same location

OV/4-6 FTU Gormezano

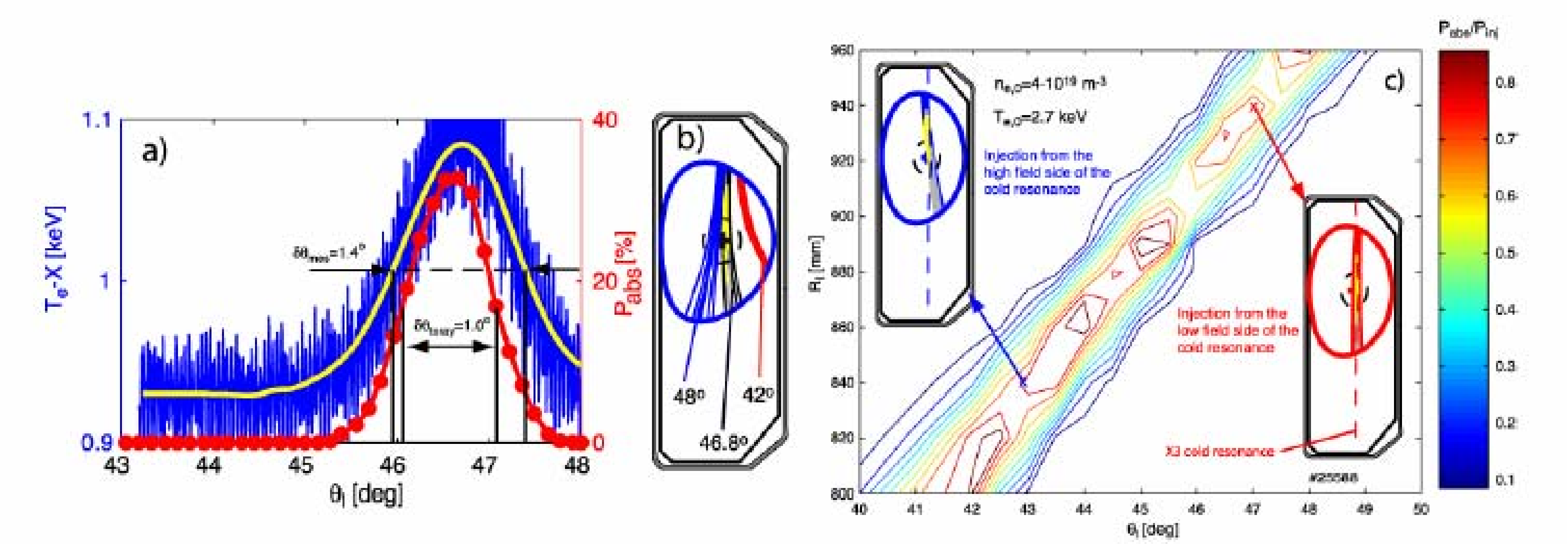


OV/5-1Rb HT7 Wan LH + IBW



ECH predictability is addressing the extremes

Third-harmonic, top-launch, ECRH experiments on TCV Tokamak



Theory and experiment are well coordinated
Feedback system successfully used

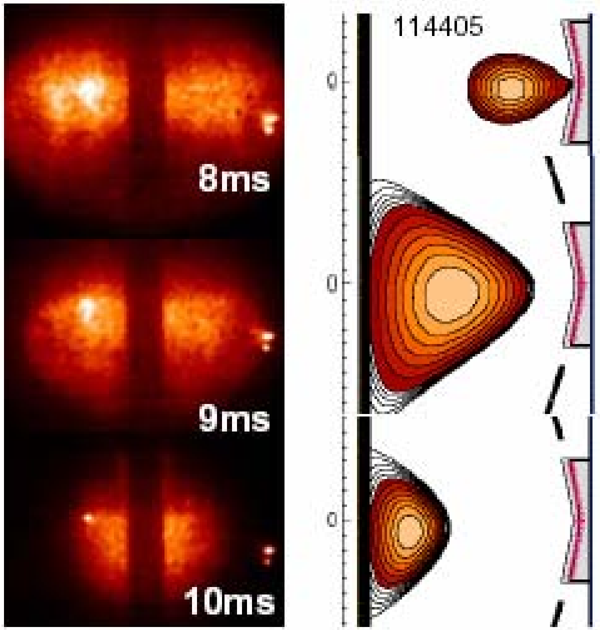
EX/P4-17 Alberti

Toroidal Current Generated Without a Solenoid

Non-solenoidal current generation/sustainment essential in future ST

1) PF-only startup

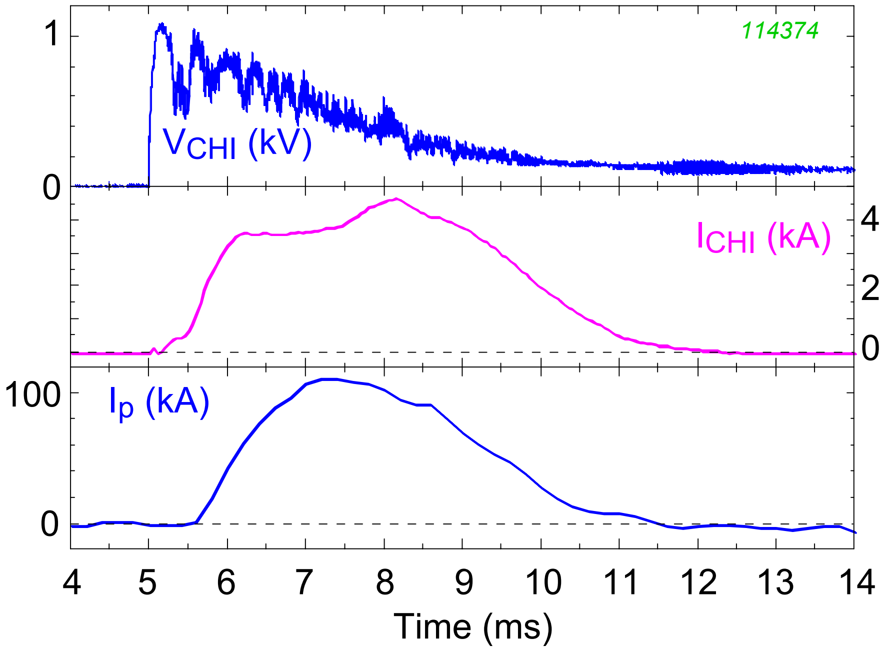
- 20 kA generated



Goal is to maintain plasma on outside where V_{loop} is high

2) Transient Co-Axial Helicity Injection

- I_p up to 140 kA, $I_p/I_{injector}$ up to 40



Goal is to extend I_p beyond duration of $I_{injector}$

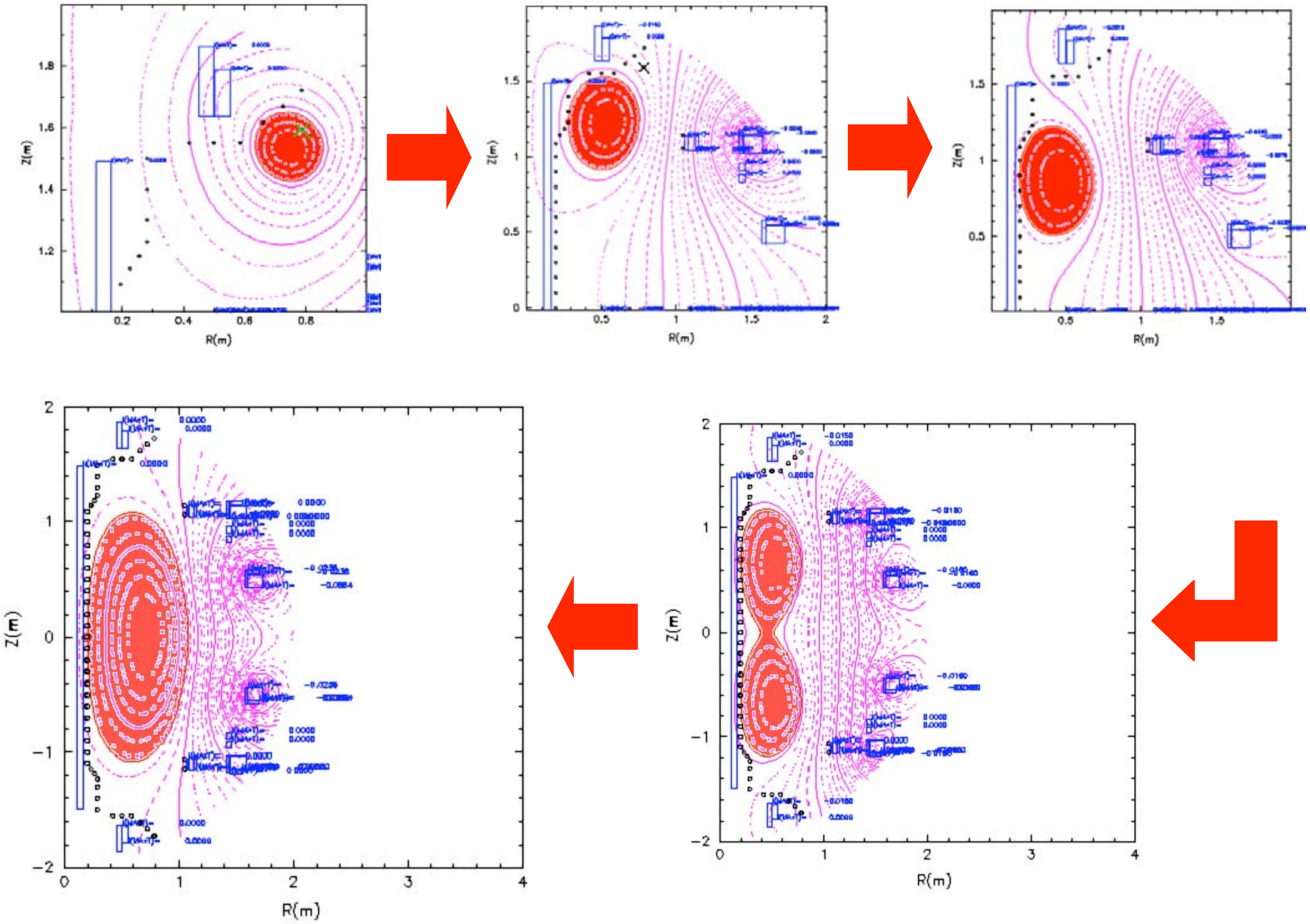
Alternative start-up schemes investigated

One such scheme is being developed in association with ENEA

Double-null merging (DNM) involves **breakdown at a quadrupole null** between pairs of poloidal coils in upper and lower divertor

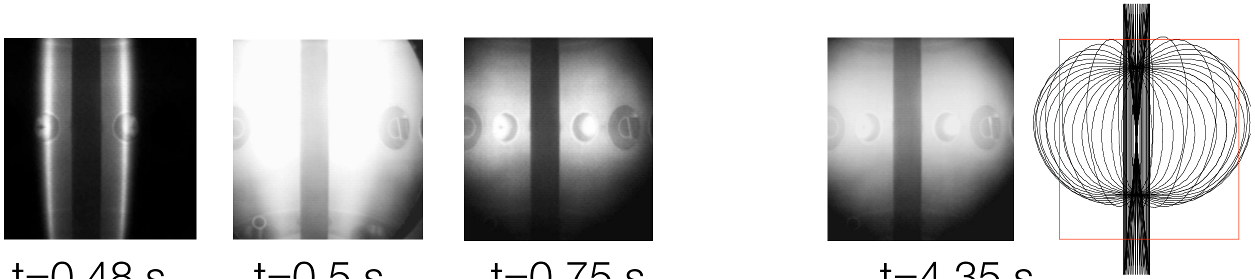
Modelling predicts **merging of plasma rings** as current in coils ramped to zero

DNM is compatible with future ST design

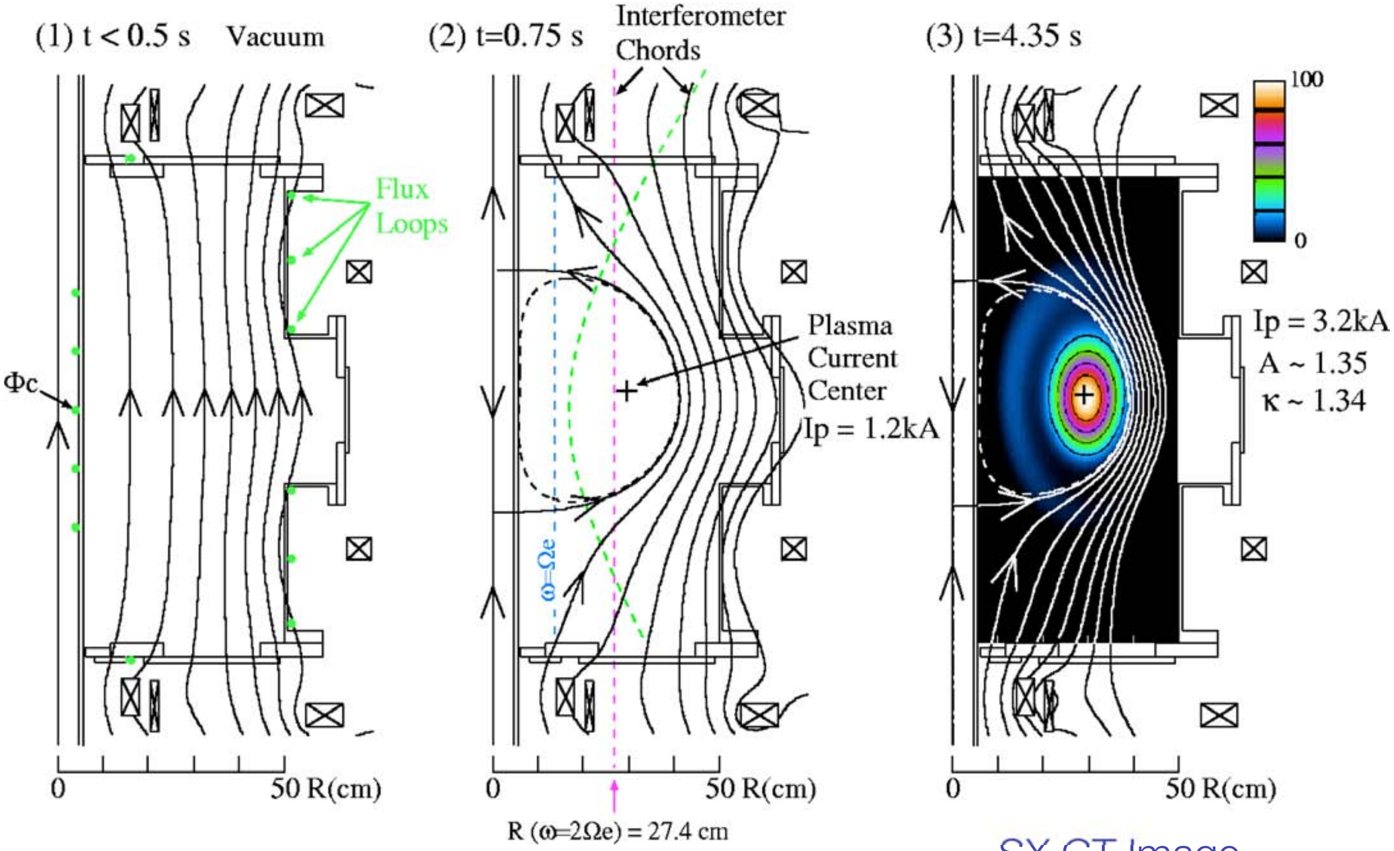


OV/2-4 MAST Counsell

Transformerless Startup by ECH and Bv in LATE EX-P/4-27 Maekawa



t=0.48 s t=0.5 s t=0.75 s t=4.35 s

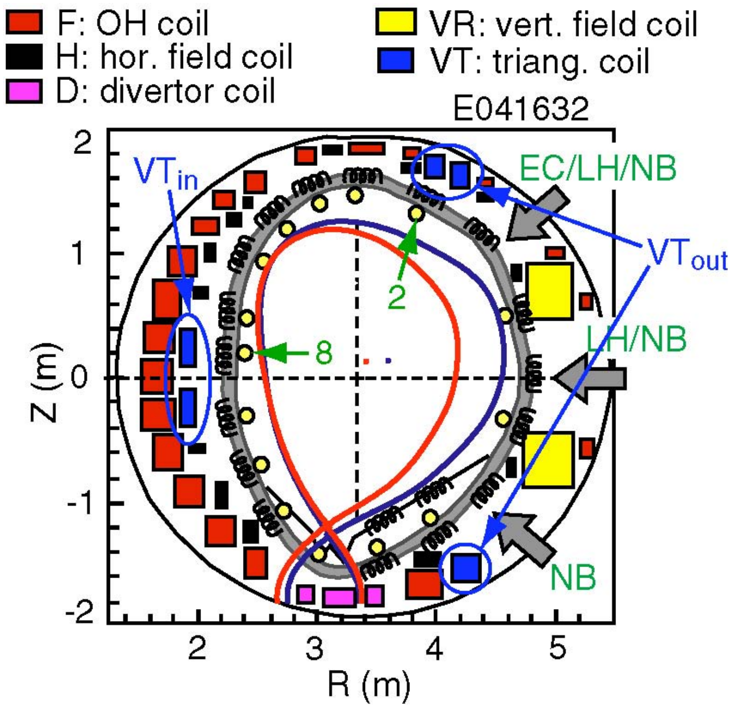


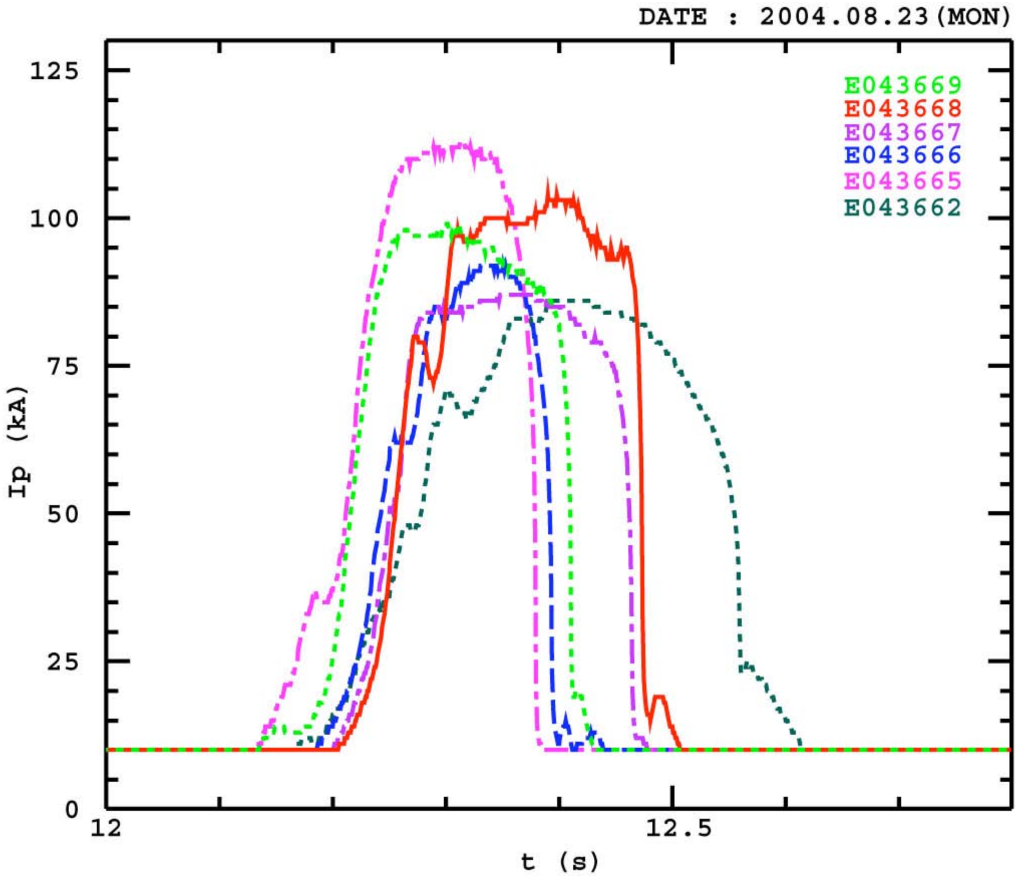
2nd Harmonic EC
Heating by EBW

SX CT Image

Completely CS-less Start-up in JT-60U

100 kA maintained for 0.2 sec





- Start-up with VR and VT_{out} only (VT_{in} coil not used)
- With strong enough EC ionization, Ip starts up with Bv in the negative direction (no field null)

EX/P4-34 Y. Takase, et al.

How is the dynamo current generated in the RFP?

$$\langle E\rangle + \langle \tilde{v}\times\tilde{B}\rangle - \frac{\langle \tilde{j}\times\tilde{B}\rangle}{ne} = \eta\langle j\rangle$$

MHD dynamo

The standard model

Hall dynamo,

two-fluid effect

significant in quasilinear theory

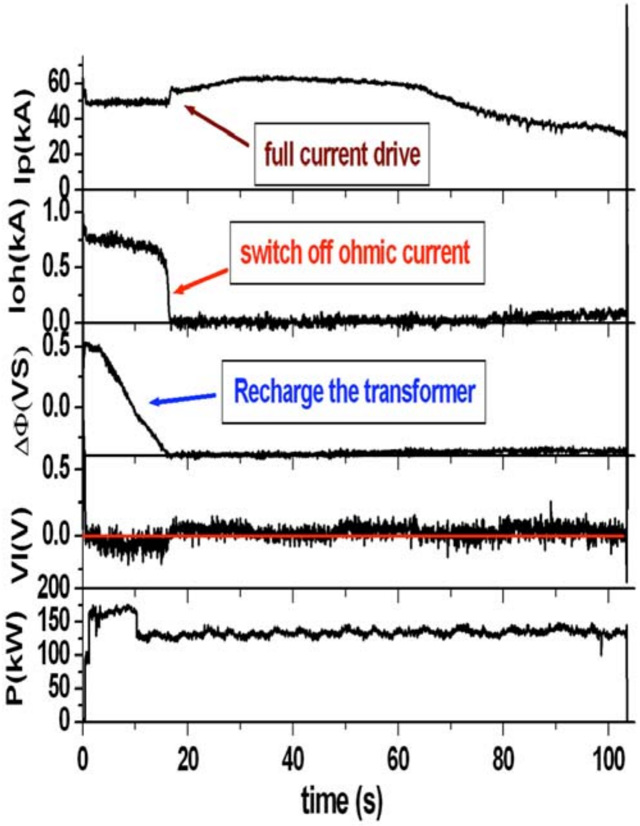
OV/4-2 MST Prager

j and B measured by Laser Faraday Rotation

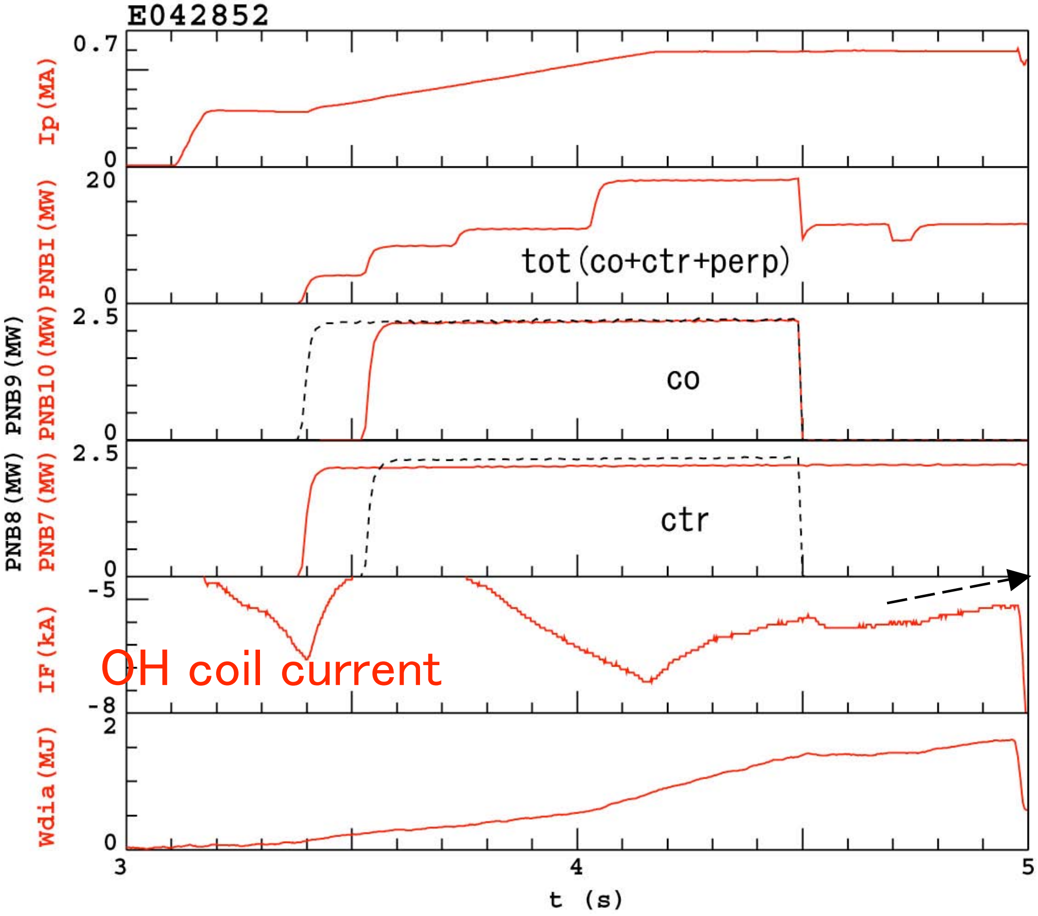
(UCLA)

Transformer Recharging by Excess Non-Inductive Current Drive

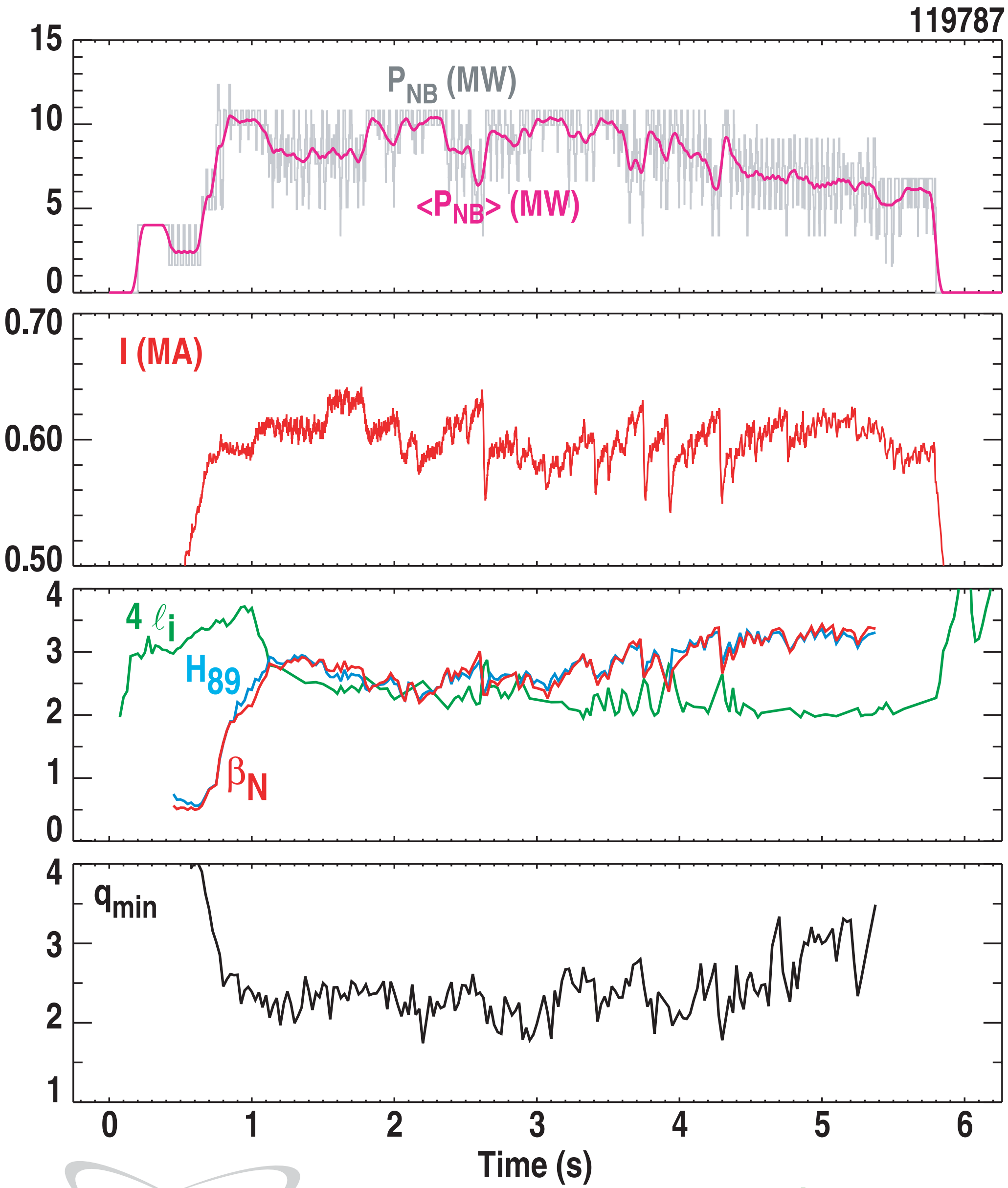
LHCD OV/5-1Rb HT-7
Wan



Bootstrap Overdrive EX-P/4-34 JT-60U Takase



TRANSFORMERLESS OPERATION SHOWS CONTROL OF HIGH BOOTSTRAP FRACTION PLASMAS WILL BE CHALLENGING



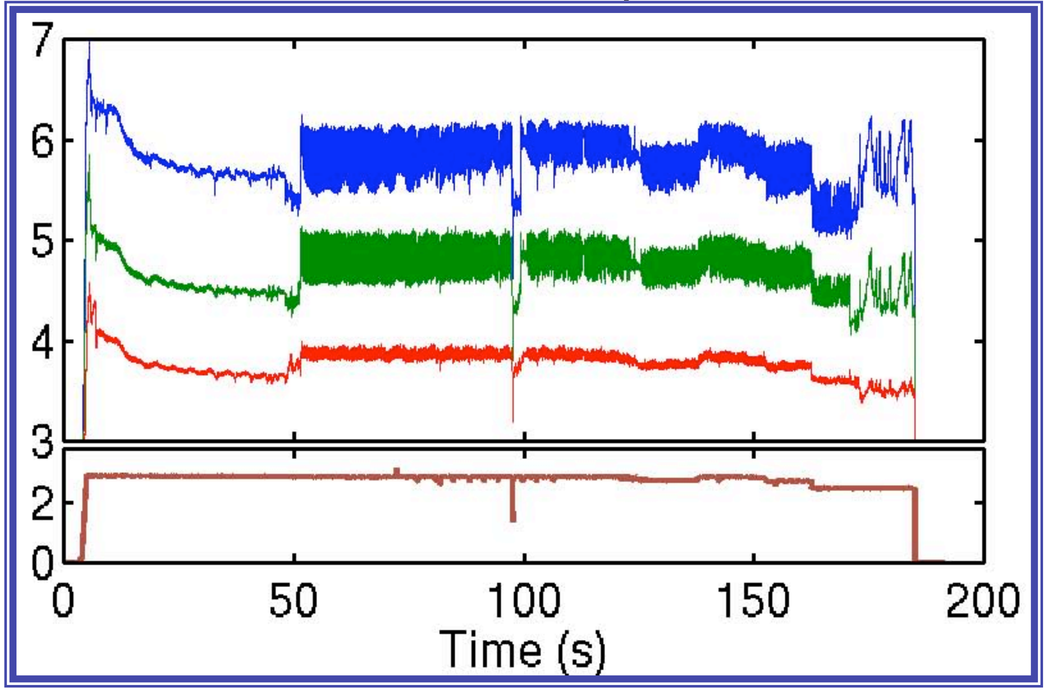
- The desired steady-state operating point may not be a stationary solution to the coupled fluid equations. If not, active control is required.
- Inductive control of the plasma current may be desirable ⇒ non-inductive overdrive will be required.
- At high safety factor (q_{95}~10) and high qmin (~3), the bootstrap current fraction is >80%.

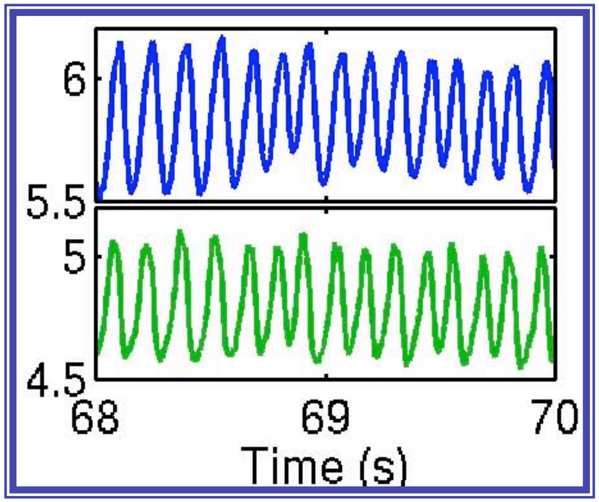
Politzer – Wed. PM Poster

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Long Time Scale Oscillations

Temperature Oscillations in Tore-Supra
Poster EX/P6-16 Tore-Supra Imbeaux et al.





Radial structure, low frequency (a few Hz)

Non linear interplay between transport and current profile at the onset of the core ITB

➔RT control of current profile required (for ex, ECCD)

See also150 second PWI related oscillations in TRIAM-1M OV/5-2 Zushi

SUMMARY CONCLUSIONS

RWM – Progress in fundamental understanding and direct feedback with low rotation.

NTM - ECCD suppression becoming an application.

Disruptions – Massive Gas Injection mitigates all consequences.

ELMS – Peeling-Ballooning Model Converging.
Many avenues of approach to tolerable ELMS.

Stability - Stellarator Beta limit studies beginning.

Alfven – Internal plasma diagnostics show modes more pervasive than was thought.

Waves - Synergy between waves can increase current drive efficiency.

Current Drive – Long pulse, transformerless operation challenging for the future.