Summary:
Innovative Confinement Concepts, Operational Scenarios and Confinement

23rd IAEA Fusion Energy Conference

R. J. Hawryluk

October 16, 2010

Acknowledgments to:

E. Belova, D. Gates, T. S. Hahm, S. Kaye, C. Kessel, R. Maingi, G. H. Neilson, S. Prager, W. Solomon and M. Zarnstorff

Outline

Topical Area:	*Number of Papers*
Innovative Confinement Concepts	**10**
Operational Scenarios	**28**
– Stellarators	
– Elmy H-modes	
– Advanced Operating Modes	
Confinement Experiments	**51**
– Energy Transport and Turbulence	
– Particle Transport	
– Rotation and Momentum Transport	
– L-H transition and Pedestal	

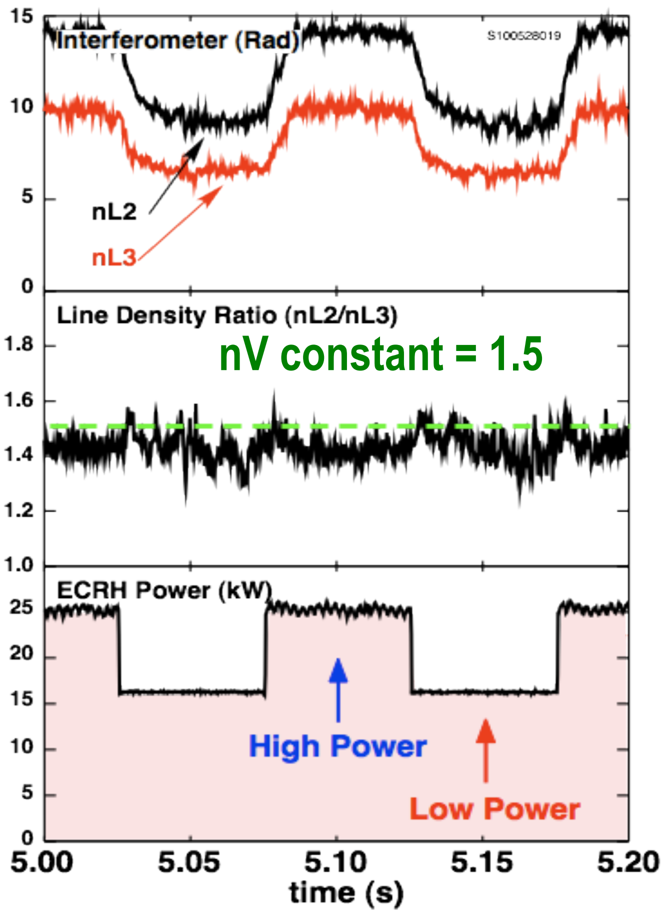
Innovative Confinement Concepts Stimulate New Ideas

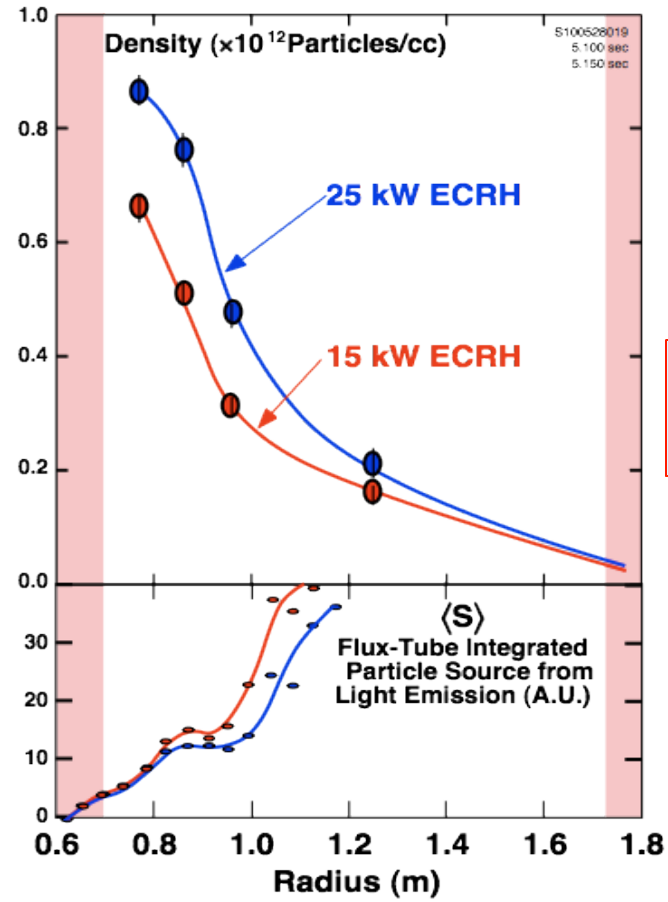
Address a broad range of configurations and topics:

- ✓ *Levitated Dipole*
- ✓ *Field Revered Configuration*
- ✓ *Mirror machines*
- – Spheromaks
- – Helical-tokamak hybrid
- – Magneto-inertial fusion
- – Direct energy conversion

Levitated Dipoles (LDX and RT-1) Demonstrate Inward Turbulent Pinch and Validates Flux Expansion Concept

Profile shape remains unchanged near nV=constant while source term is modulated.





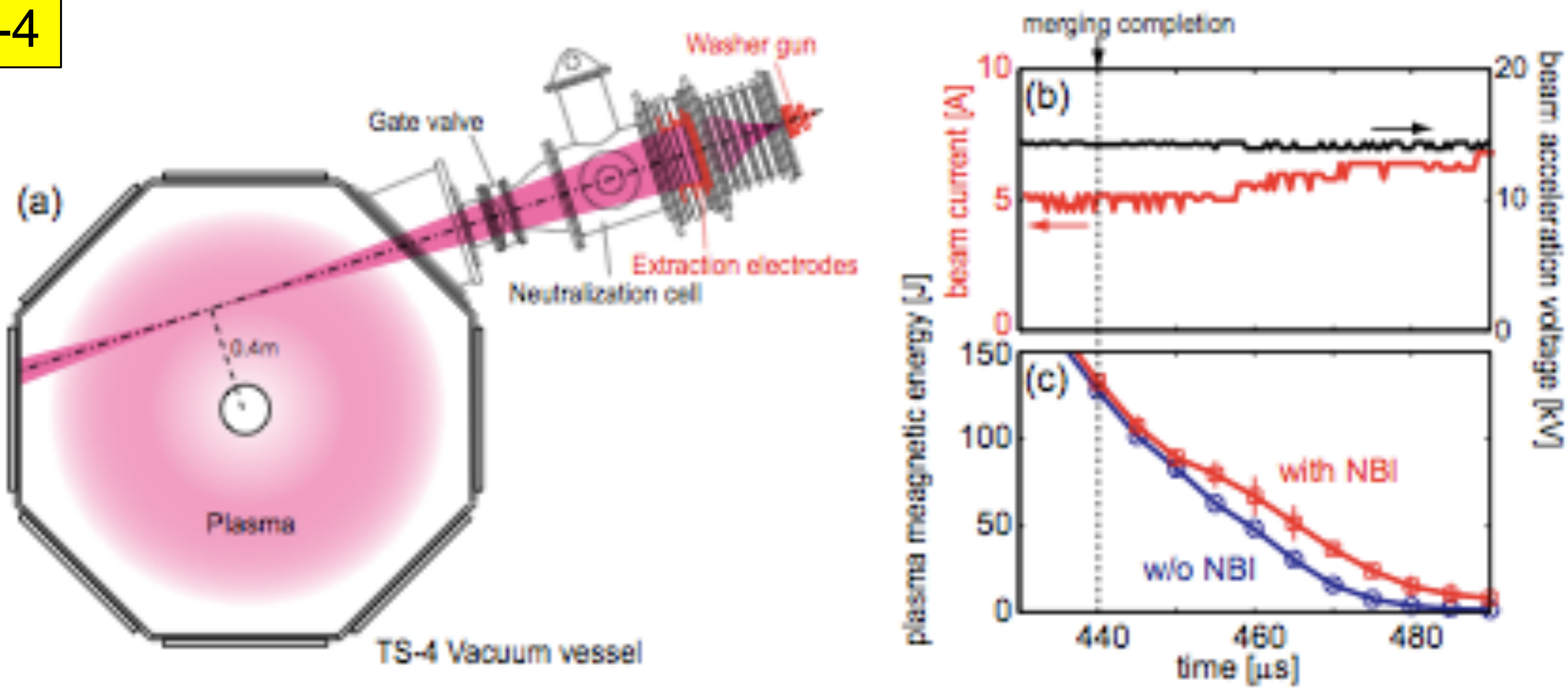
LDX

D. T. Garnier, ICC/1-1ra

Error field optimized RT-1 plasma achieved peak 70% beta (H. Saitoh, EXC/9-4b).

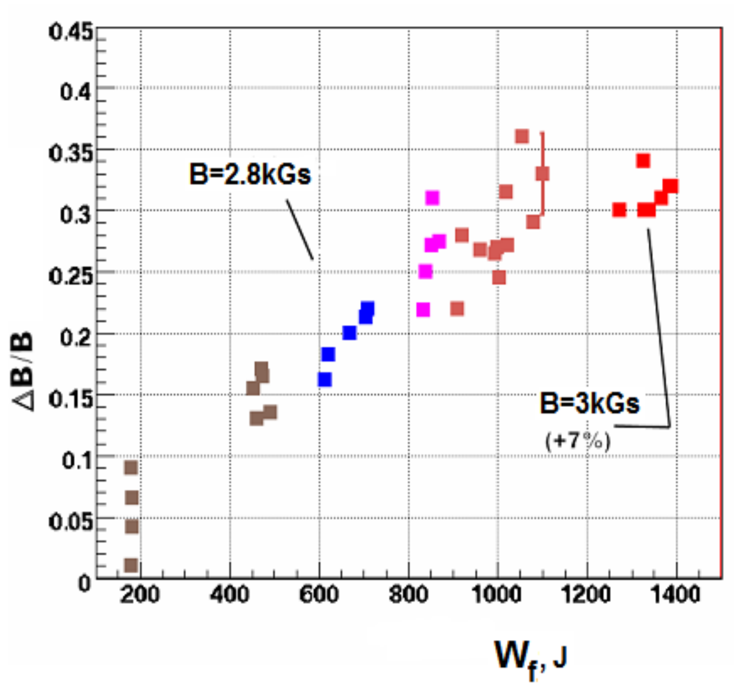
FRC Decay Time Increased by Neutral Beam Injection Suggesting MHD Stabilization

TS-4



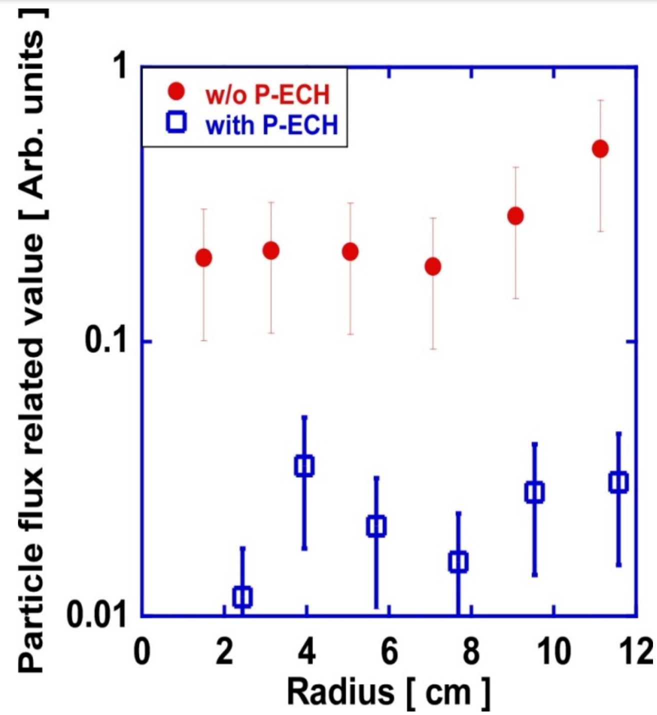
M. Inomoto ICC/P7-01

Increased Heating Power Extended Mirror Machine Performance



E. P. Kruglyakov, OV/P-6

GDT achieved 60% beta and reached ballooning limit



M.Yoshikawa, EXC/P8-21

In Gamma10, ECH reduced fluctuations and inferred radial particle flux.

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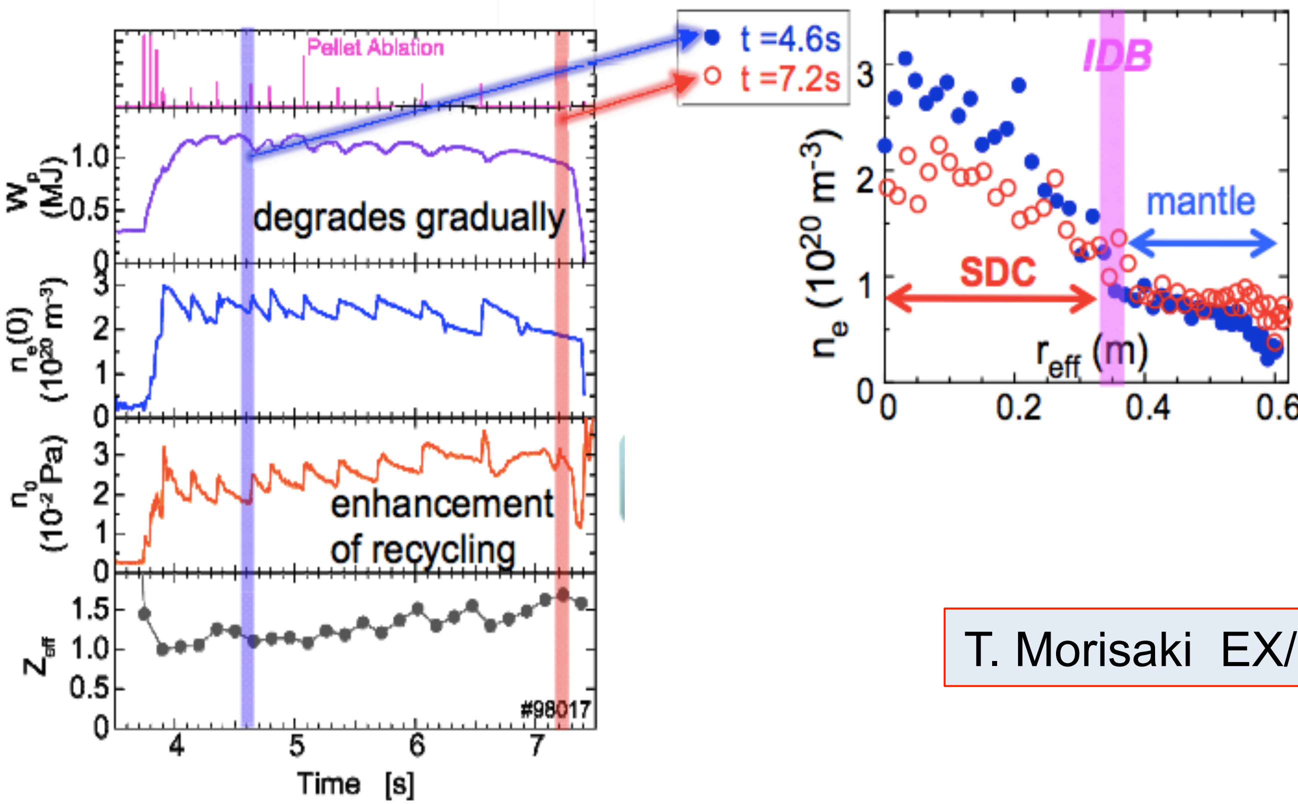
Sustainment of Super-Dense Core by Pellet Injection and Internal Diffusion Barrier in LHD



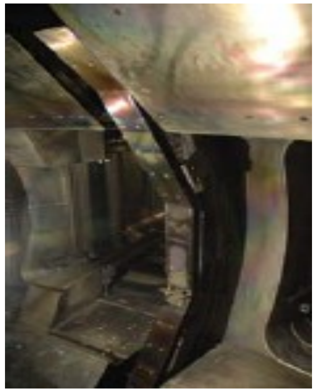
T. Morisaki EX/1-5

- **Diffusion in edge mantle much greater than in the core.**
  - Enhanced by the application of resonant magnetic field perturbations
- **Impurity accumulation in the core avoided.**
- **LHD has also attained 15keV peak electron temperatures in plasmas with electron ITB (H. Takahashi, EXC/P8-15)**

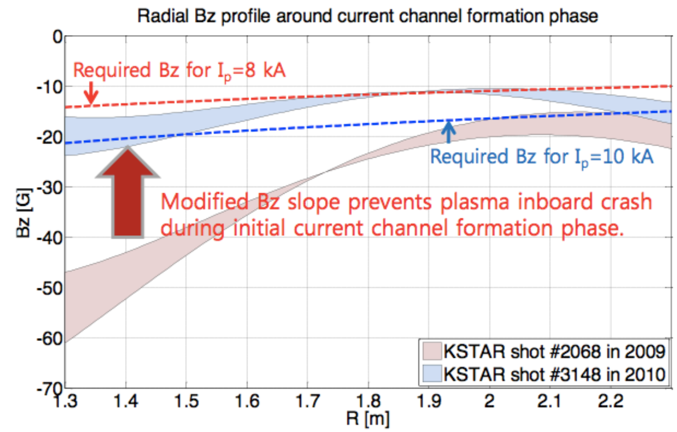
Operational Challenges of Superconducting Tokamaks Successfully Being Met by KSTAR and EAST

EAST

J. Li, OV/1-2



RF Conditioning Antenna



Compensation for ferromagnetic material

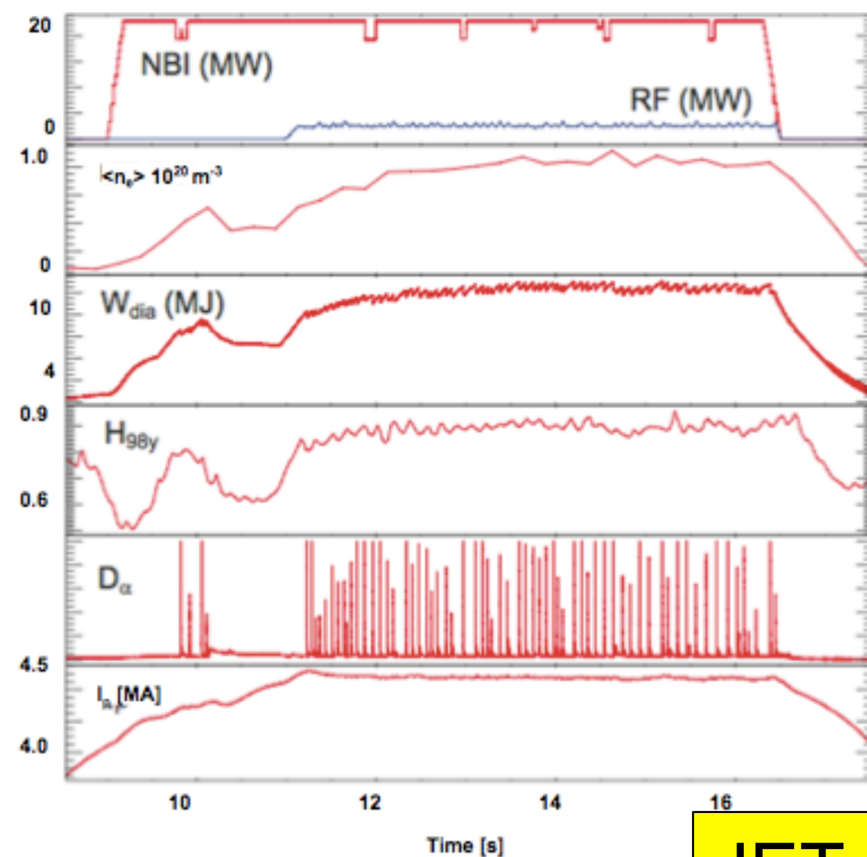
KSTAR

M. Kwon, OV/1-1

- **Wall conditioning: ICRF conditioning, HF GDC, Li Wall Coatings (EAST OV1-2)**
  - Also on Tore Supra (D. Douai, FTP/P1-26)
- **Low voltage startup (0.9MA EAST OV/1-2, 0.5MA KSTAR OV/1-1)**
  - ECH assisted startup (also FTU, A. Tuccillo, OV/4-2)
  - Lower hybrid assisted current ramp (also, E. Marmar, OV/3-2)
- **Magnetic material and eddy current compensation for discharge evolution on KSTAR. (S. W. Yoon, EX/5-1)**

Progress Developing ITER 15MA Startup and Shutdown Scenarios

- **JET 4.5MA operation reestablished**
- **Active ELM moderation required about 3.5MA to prevent carbon ablation.**
  – Modest impact on τ_E
- **Successful startup and shutdown techniques for ITER demonstrated on JET, DIII-D, and C-Mod**
  – See A. C. C. Sips, EXC/P2-08,
    J. R. Wilson, EXC/P2-02,
    G. L. Jackson, EXS/P2-11

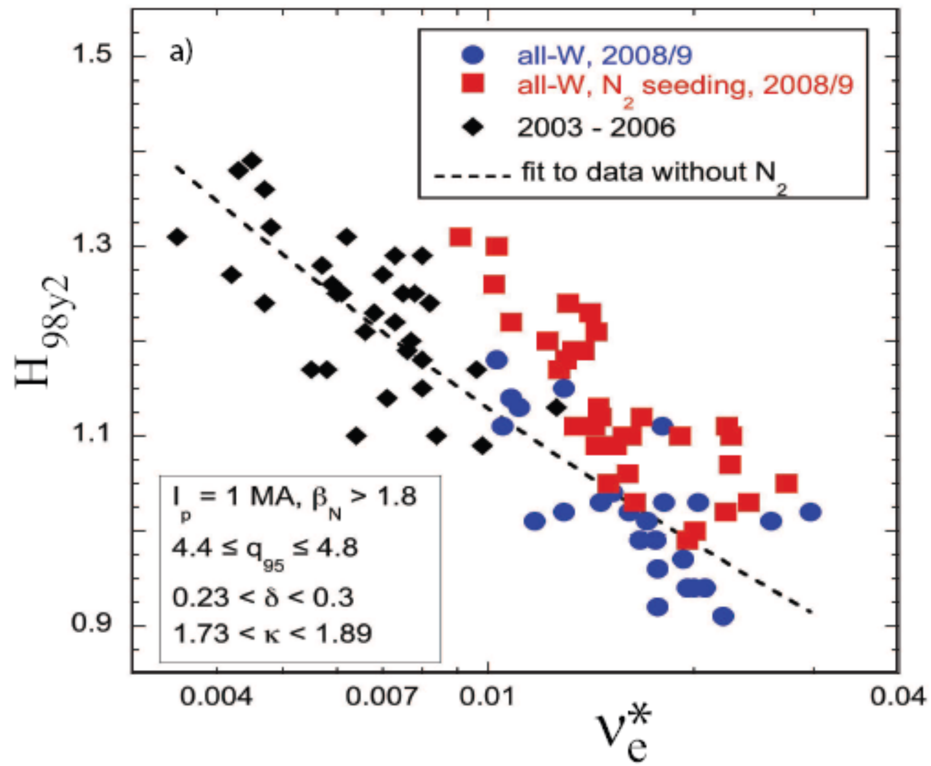


I. Nunes, ECX/P8-03

JET

Impurity Seeding Successfully Reduced Divertor Heat Flux

- **Improvement in τ_E obtained in AUG**
  - Critical for operation with tungsten divertor.
- **JET and C-Mod obtained similar reductions in heat load and operational benefits but did not obtain an improvement in τ_E.**
  - See C. Giroud, EXC/P3-2 and J. Hughes, EXC/P3-6



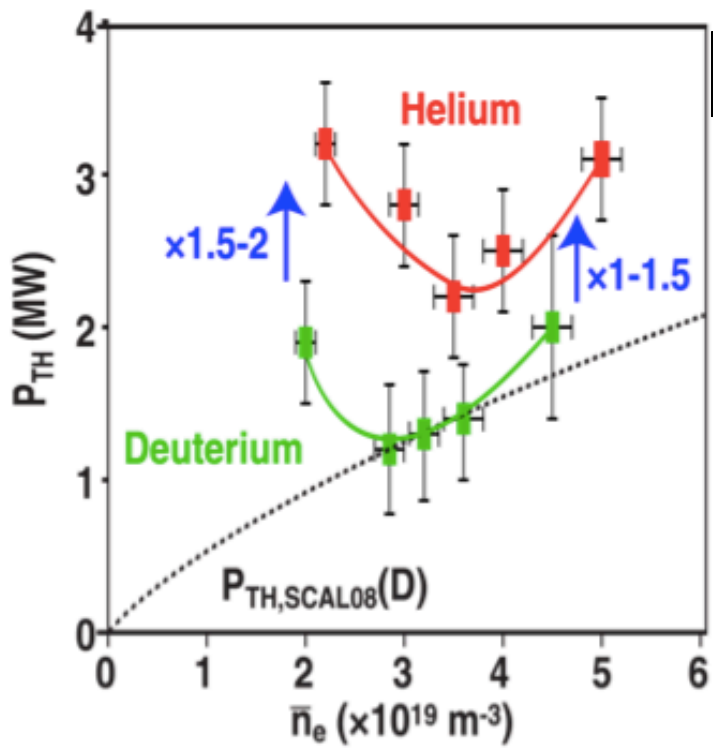
AUG

J. Schweinzer, EXC/P2-07

Threshold Power Required for Transition from L to H-mode Has Been Better Characterized for ITER

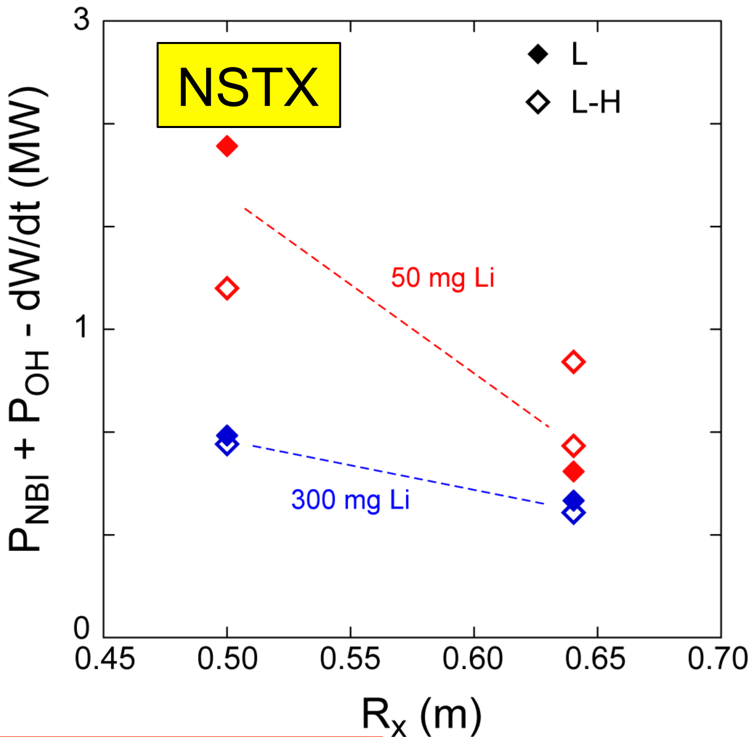
- **P_{LH} compared for He with D for ITER non-nuclear phase:**
  - Threshold is density dependent (DIII-D, EXC/2-4Ra and JET, EXC/2-4Rb)
  - In NSTX, P_{LH} is 20 to 40% greater (NSTX, EXC/2-3Rb)
- **Low n perturbation increase P_{LH} by 50% (NSTX, EXC/2-3Rb) and 80% (MAST, EXC/2-3Ra)**
- **P_{LH} significantly increased in DIII-D due to RMP perturbations above a threshold level,**
  - Smaller change for non-resonant fields
  - No significant change in DIII-D test blanket simulation. (M. J. Schaffer, ITR/1-3)

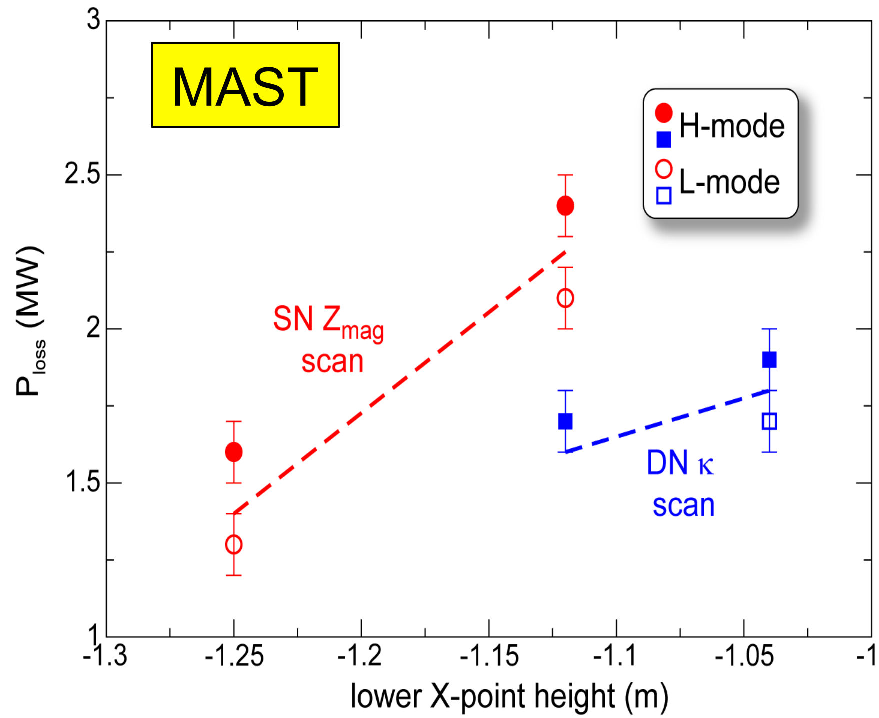
DIII-D



P. Gohil, EXC/2-4Ra

Recycling Conditions Have a Large Impact on L to H Power Threshold





S. Kaye, EXC/2-3Rb

H. Meyer, EXC/2-3Ra

Lithium decreases P_{LH} (NSTX)

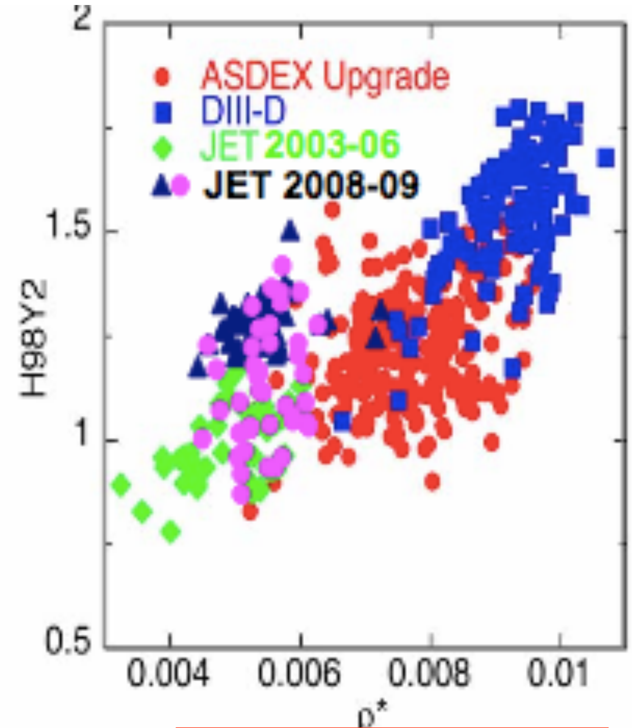
Low triangularity decreases P_{LH} (NSTX)

Depends on height of the x-point (MAST, DIII-D, P. Gohil, EXC/2-4Ra)

Too many hidden variables remain unaccounted for in P_{LH} scaling.

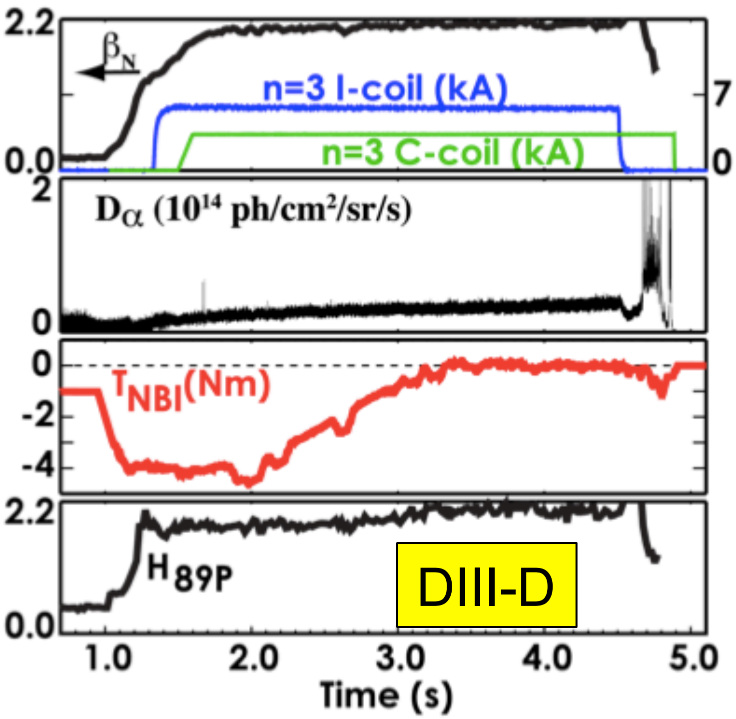
Advanced Inductive Scenarios Are Potentially Attractive Long Duration Discharges in ITER

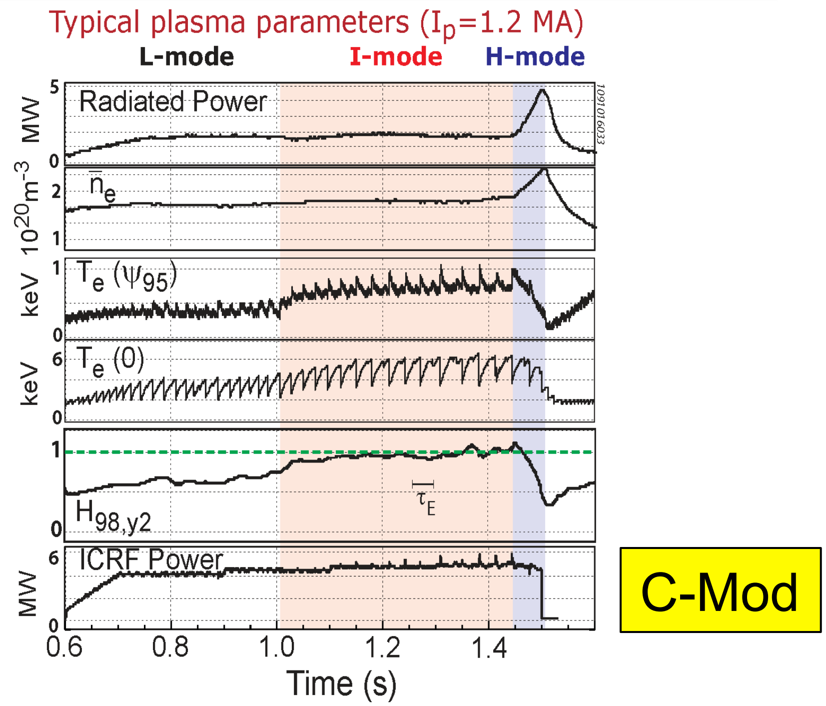
- **Advanced inductive discharges operate at lower current enabling longer duration discharges.**
- **Recent JET experiments, by ramping the current down prior to main heating phase achieved H_{98}~1.3.**
  - Significantly improved relative to earlier data.
- **Further work is planned on ρ* and ν* scaling to improve the extrapolation to ITER:**
  - Bohm ρ* scaling between JET and DIII-D
  - Current penetration mechanism



E. Joffrin, EX/1-1
T.C. Luce, ITR/1-5

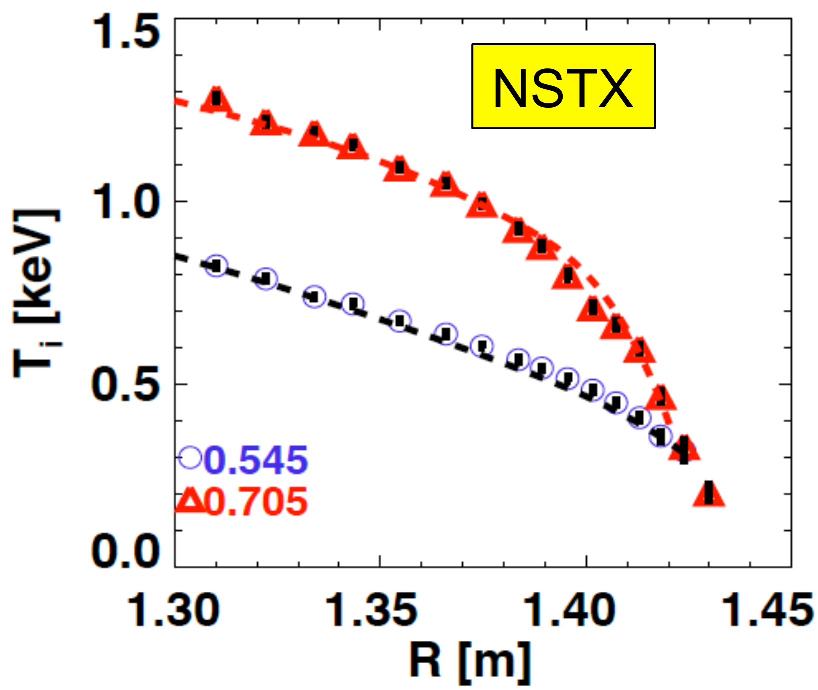
QH-mode and I-mode Offer the Possibility of ELM Suppressed Operation

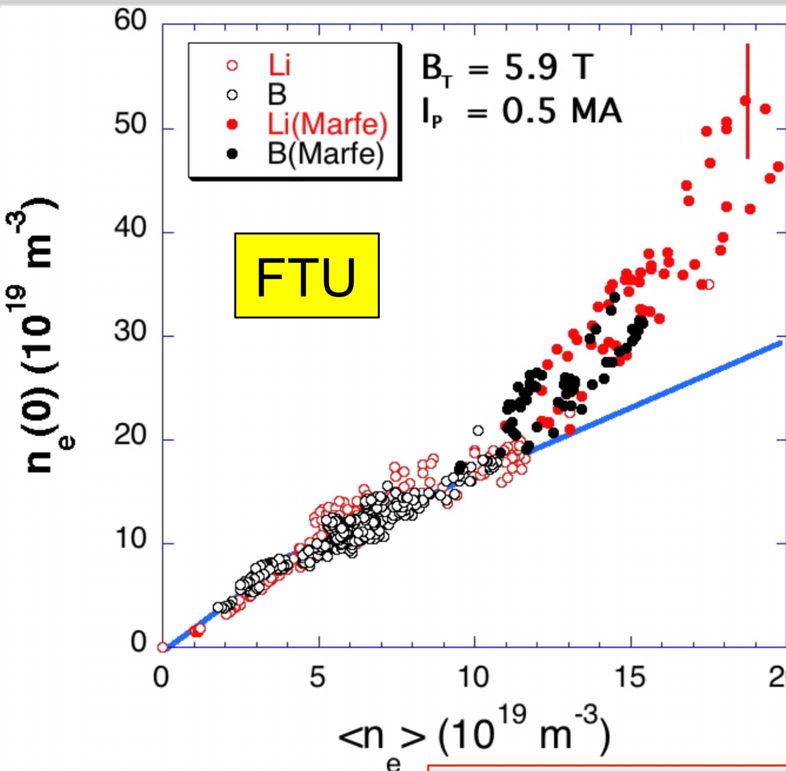




- **NTV provides ExB shear to maintain QH-mode even after NBI torque ramped to zero using non-resonant fields. (A. Garofalo, EXS/1-2).**
- **I-mode usually accessed by operating in unfavorable B×∇B direction (away from active X-point) D. Whyte, EX/1-3**
- ***Can these scenarios be used on ITER?***

Lithium Improves Energy Confinement and Widens the Operating Window in a Number of Devices



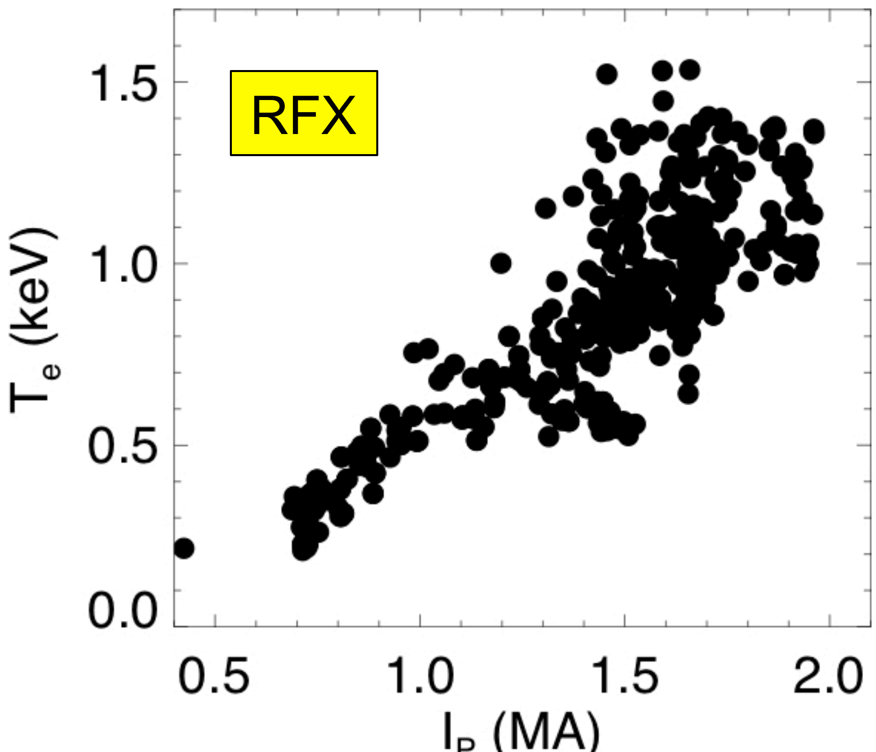


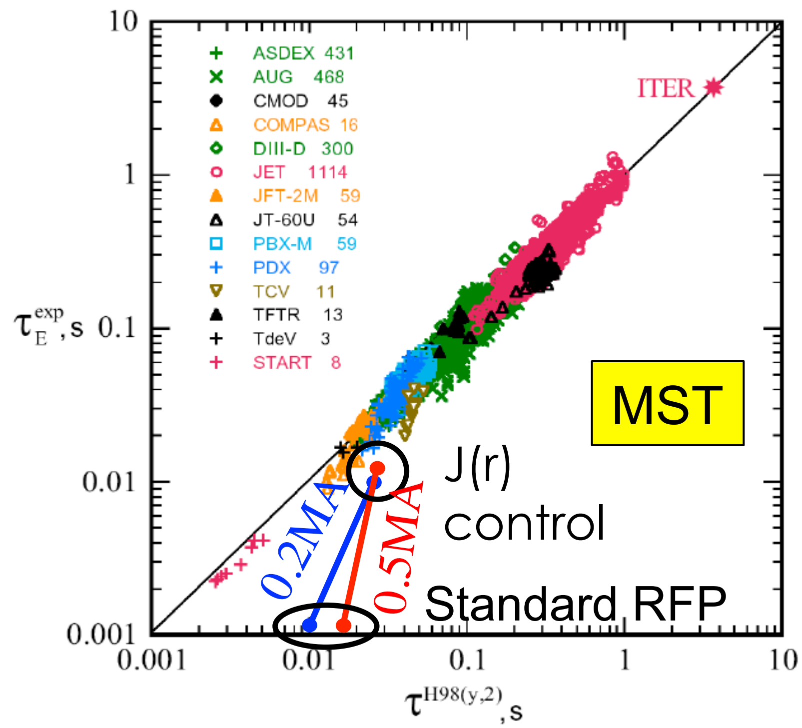
R. Maingi, EXC/2-2

G. Mazzitelli, EXC/6-3

- **FTU, NSTX and TJ-II have obtained up to ~50% τ_E enhancements**
  - FTU obtained peaked profiles with n_e up to ~1.6 n_e^{GW} at high q.
  - TJ-II obtained more peaked density profiles
  - NSTX combined lithium with EP H-mode to achieve H_{98}~1.8

RFX and MST Have Extended Their Operating Regimes





P. Martin, OV/5-3Ra

B. Chapman, EXC/P5-01

RFX observed linear increase in Te with Ip.

MST attained τ_E = 12 ms by current profile control

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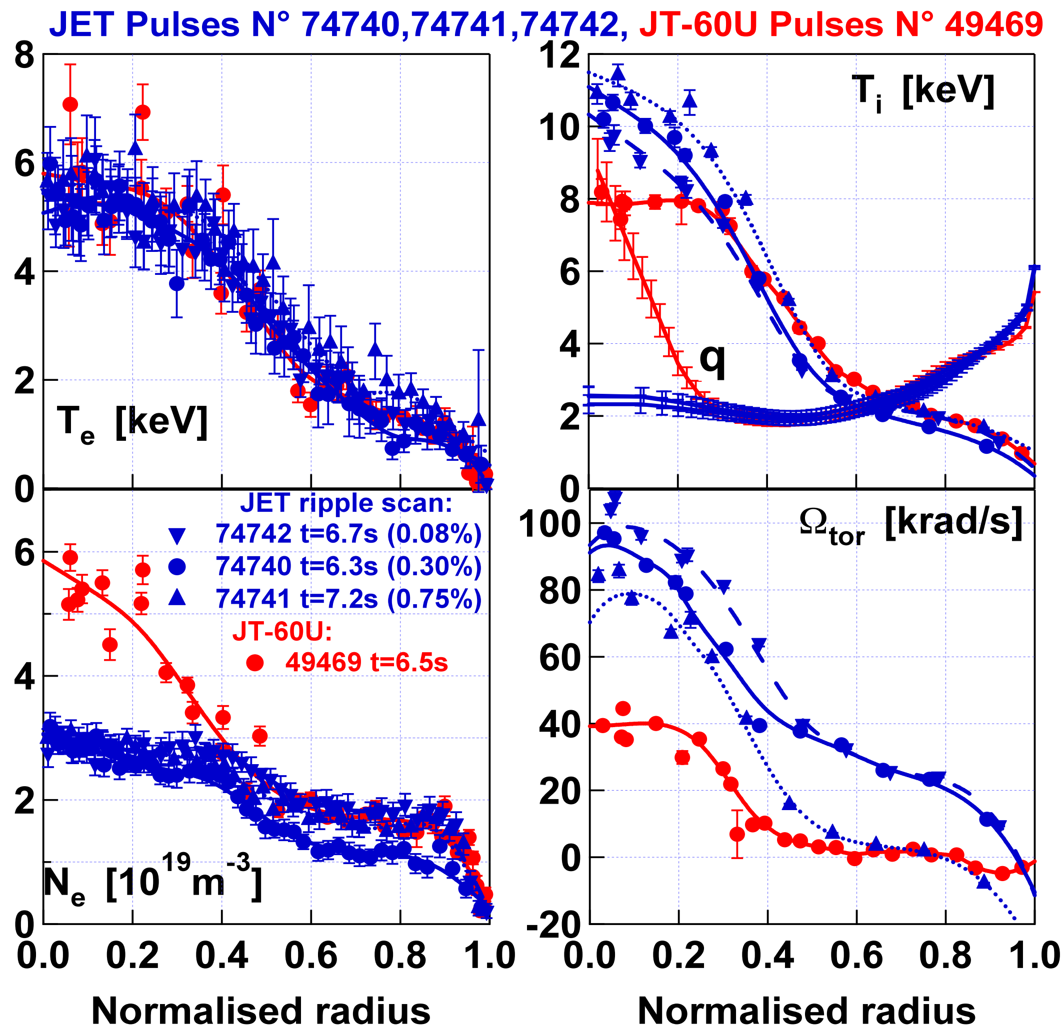
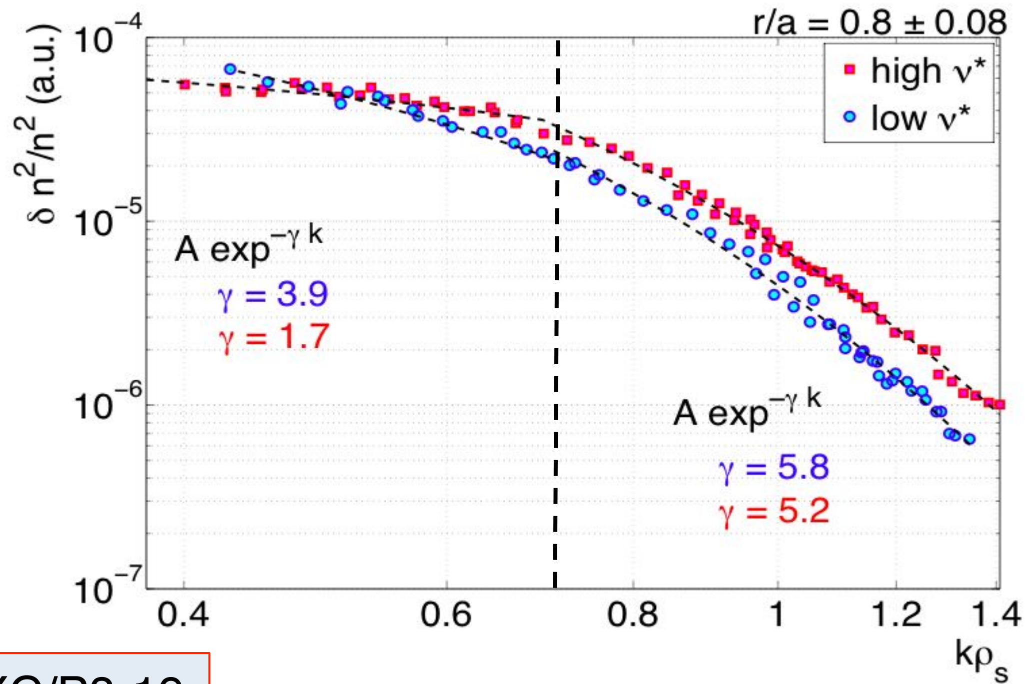
Subtle Differences in Electron Transport and NBI Sources Lead to Different Reversed Shear States in JET and JT-60U

- **Good match in dimensionless parameters except:**
  - Mach number
  - Differences in ν^* and β due to density profile.
- **Density profile peakedness in JT-60U enables a higher bootstrap current fraction.**
- ***Need good predictive model to extrapolate to ITER.***



X. Litaudon, EXC/P4-12

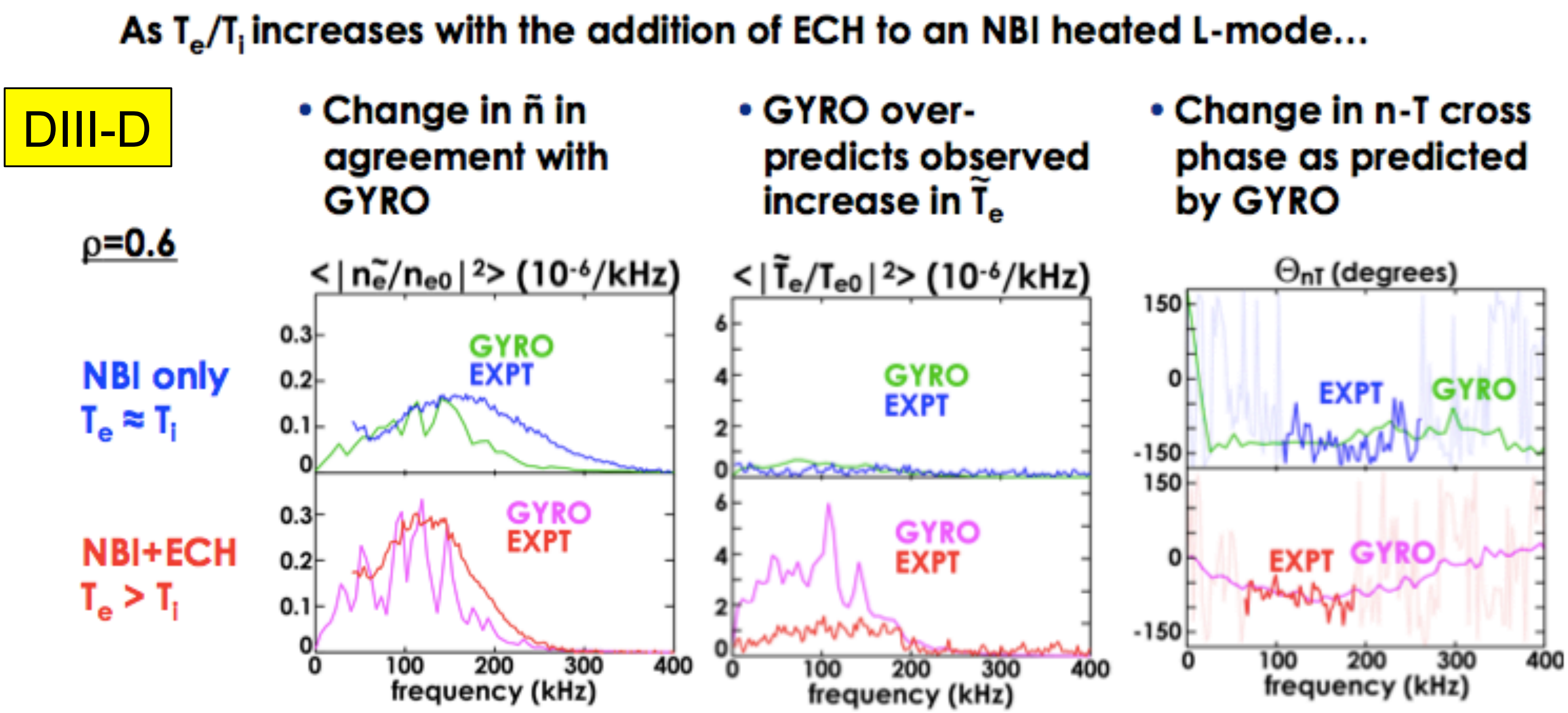
Influence of Collisionality on Turbulence Spectra Studied in Tore Supra



L. Vermare, EXC/P8-19

- **Dimensionless scans were conducted to determine the effect of ν***
- **Does not support standard explanation on effect of ν* on zonal flows.**

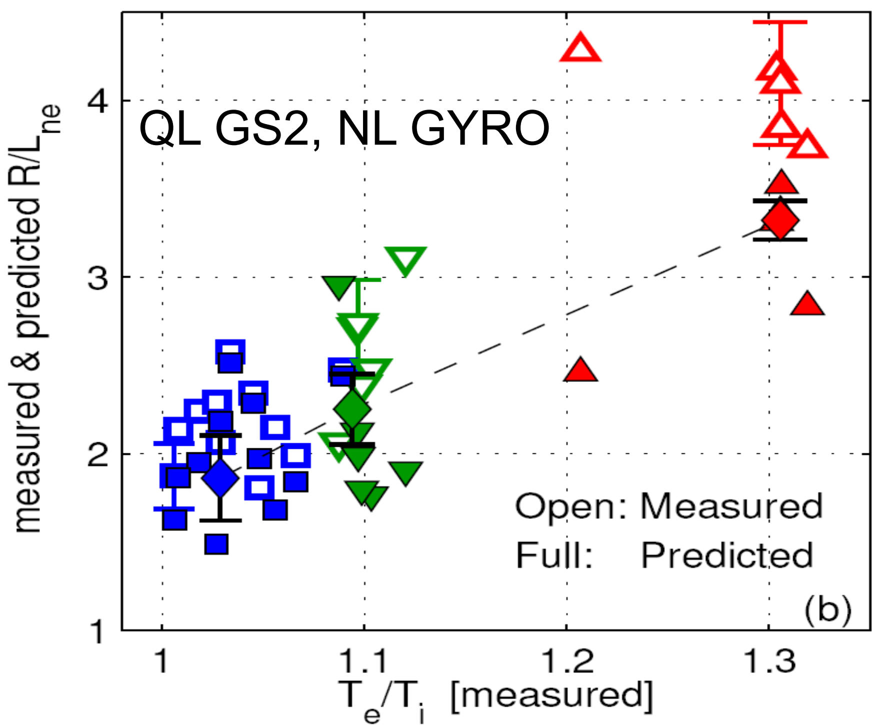
Experimental Test of Predicted Turbulence Amplitudes and Cross-Phases Conducted in the Core



T. L. Rhodes, EXC/7-2

- **GYRO reproduces many features in the core but not in the edge (ρ > 0.75) or the core of L-mode discharges.**
  - Experiments used to establish the range of validity of the codes.

Density Profile Peaking is Reproduced by Gyrokinetic Modelling (at r/a= 0.5)



AUG

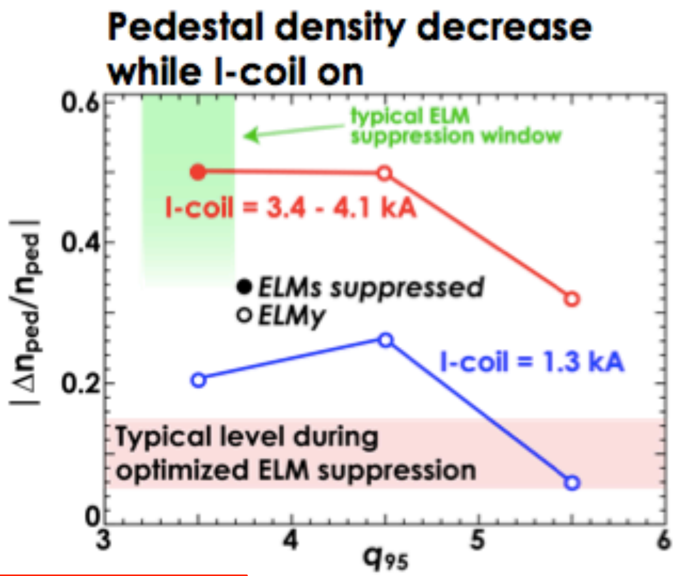
A. Kallenbach, EXC/OV3-1

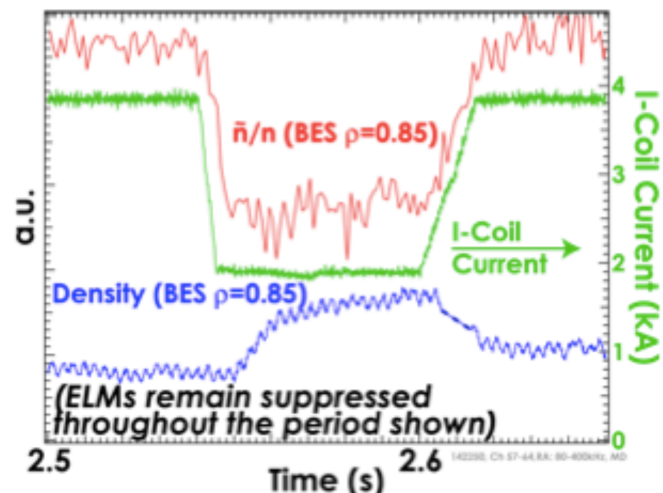
- **Central density increases with the application of ECH to NBI heated plasmas.**
  - Flattens the ion temperature and rotation profile
- **In simulations the measured profiles are used as input.**
- **Results are sensitive to input parameters (e.g. T_e/T_i, R/L_{Te}, ν_{ei})**

Initial DIII-D Measurements Near Top of the Pedestal Indicate Non-axisymmetric Fields Modify Density Turbulence

- Density decrease observed over a range of q_{95}

- Particle transport correlated with increased fluctuations at higher I-coil current



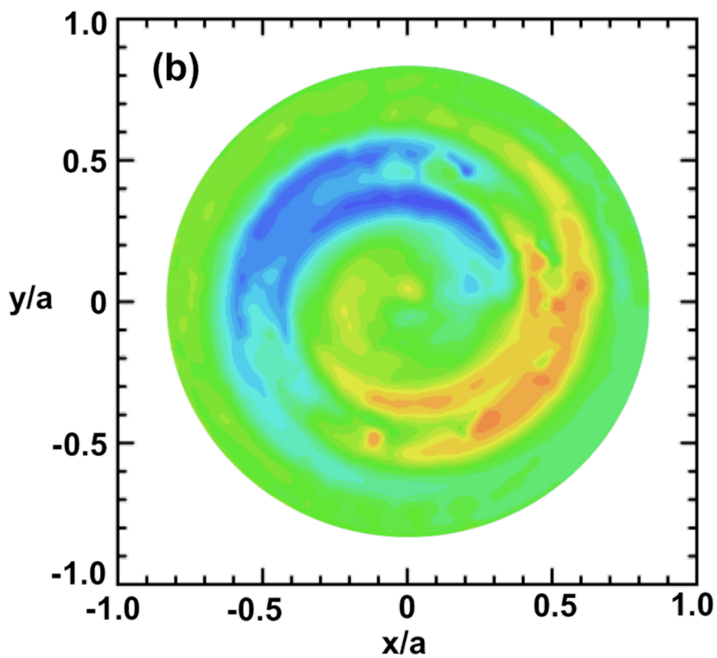


Z. Yan, EXC/P3-05

DIII-D

- **Increased particle transport also occurs outside of ELM suppression window.**

Long Coherence Length Temperature Fluctuations Found in LHD



S. Inagaki, EXC/7-4

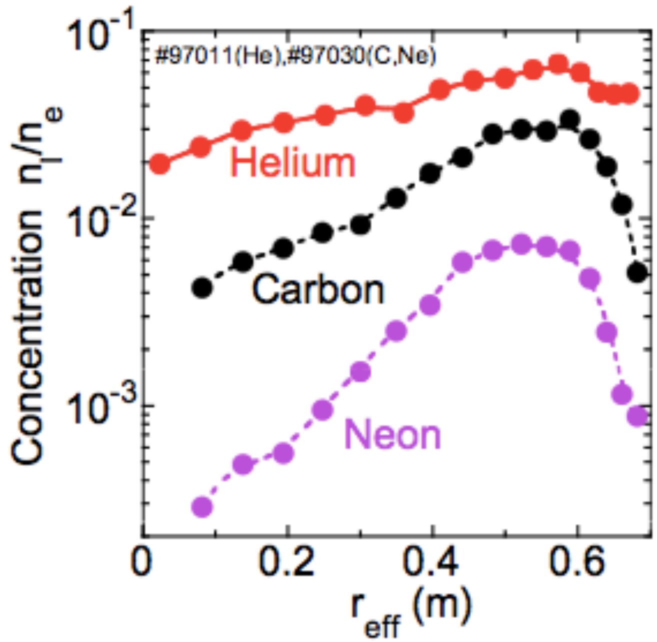
Radial correlation length ~ a

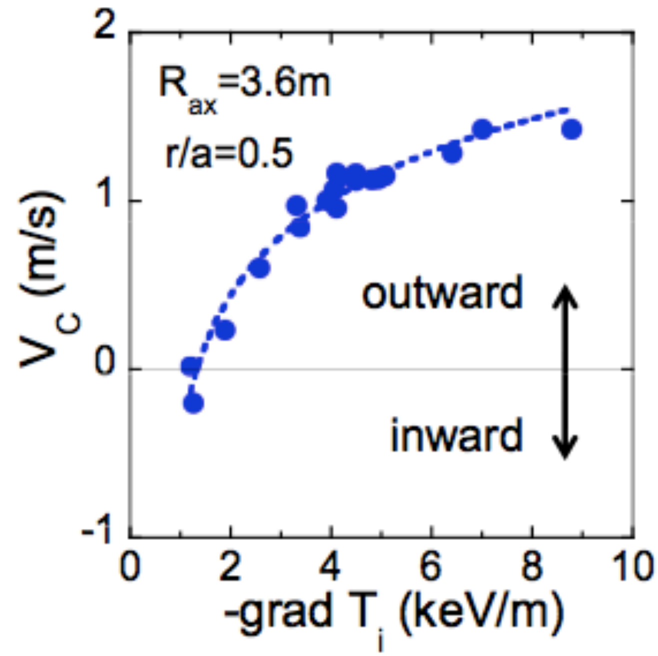
Ballistic transport from core to the edge inferred

Impact of long-range fluctuations on transient particle transport was studied.

Is this the long sought explanation for cold pulse propagation or non-local transport?

"Impurity Holes" Observed in LHD in Discharges with Large T_i Gradients



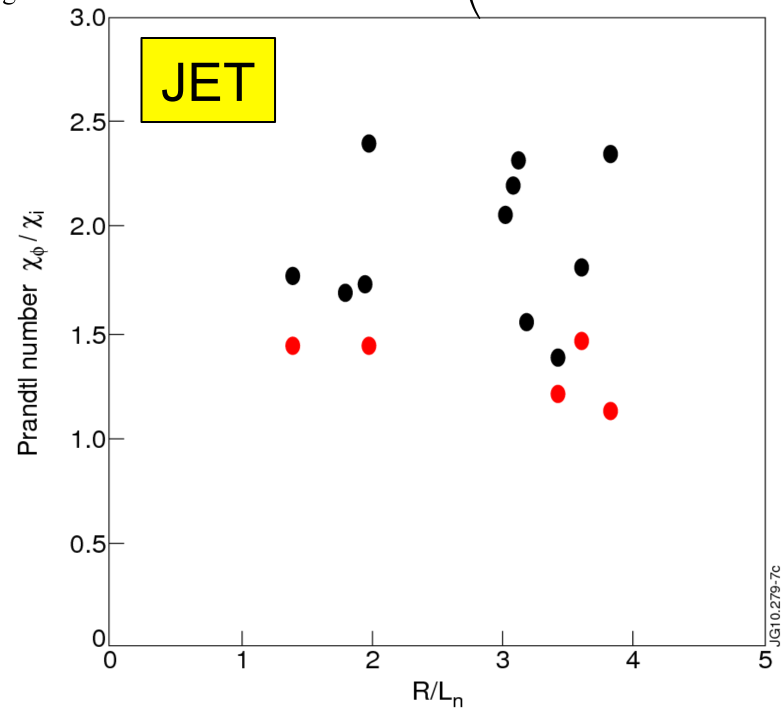


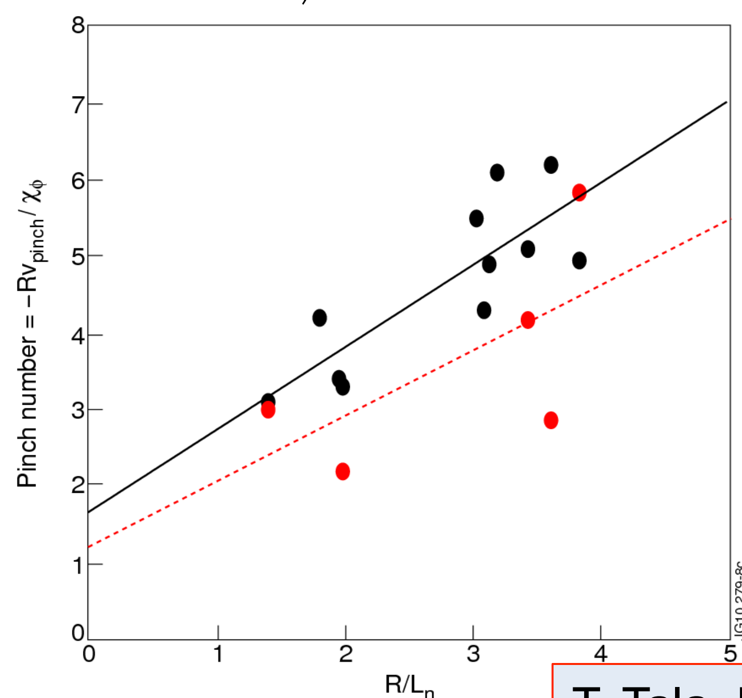
M. Yoshinuma, EXC/9-1

- **Large anomalous outward convective impurity transport inferred.**
  - In spite of negative E_r

Momentum Transport Studies Show No Dependence on Collisionality of Either Prandtl or Pinch Numbers

$$\underbrace{mR\frac{\partial nV_\phi}{\partial t}}_{\substack{\text{Rate of change of}\\ \text{angular momentum}}} = \underbrace{\sum\eta}_{\text{Input torque}} - \nabla\cdot\left(-mnR\left(\underbrace{\chi_\phi\frac{\partial V_\phi}{\partial r}}_{\text{diffusion}} - \underbrace{V_\phi V_{pinch}}_{\text{pinch}}\right) + \underbrace{\Pi_{RS}}_{\substack{\text{Residual stress}\\ \text{"Intrinsic source"}}}\right) - \underbrace{\frac{mnR\left(V_\phi - V_\phi^{\,*}\right)}{\tau_{damp}}}_{\text{Neoclassical viscous drag}} + \underbrace{\left\langle \tilde{J}\times\tilde{B}\right\rangle}_{\text{Maxwell stress}} + \ldots$$

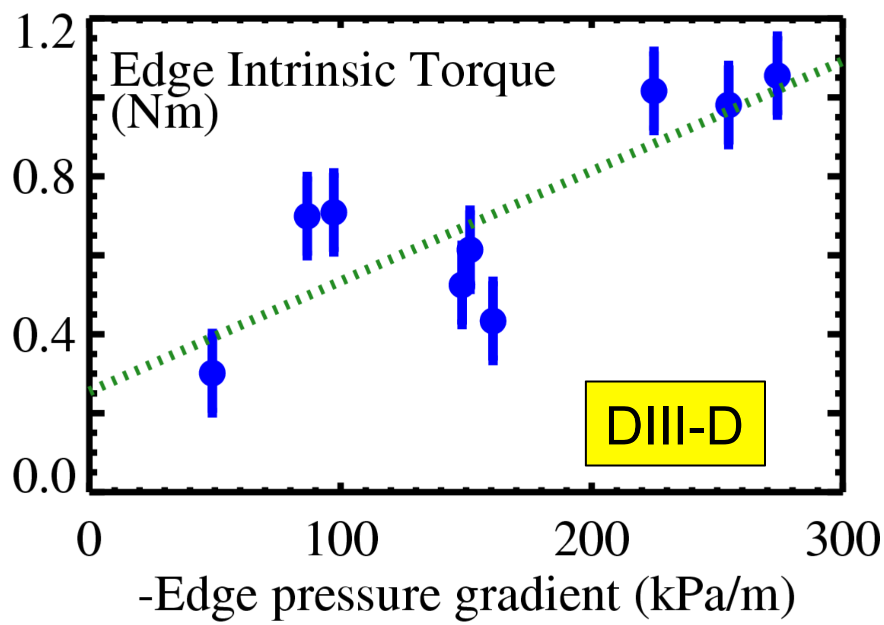




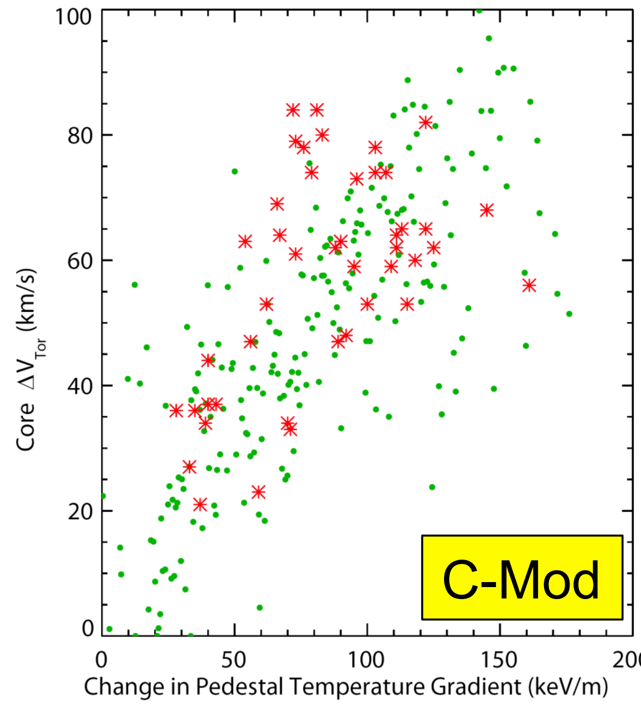
T. Tala, EXC/3-1

JET experimental data is compared with GS2 calculations in red.

Edge Intrinsic Rotation Appears to Be Driven by Pedestal Gradients



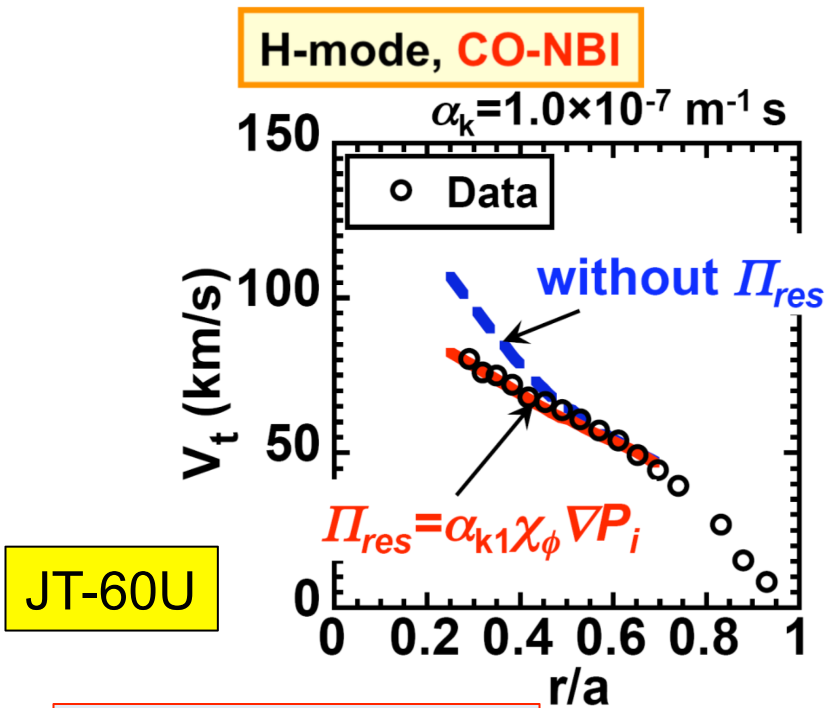
W. Solomon, EXC/3-5

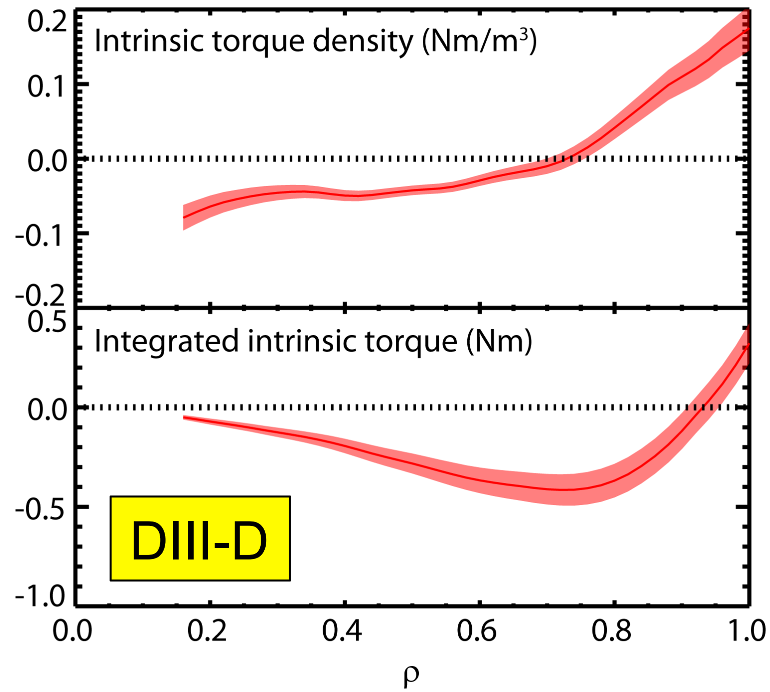


J. Rice, EXC/3-3

- **Suggestive that turbulent residual stress may be key in generating intrinsic rotation (DIII-D, C-Mod, LHD, JT-60U, …)**
- **Reynolds stress sufficient to account for intrinsic rotation in CSDX at UCSD, but not on DIII-D.**

Intrinsic Drive in the Core Can Also Influence Rotation Shear



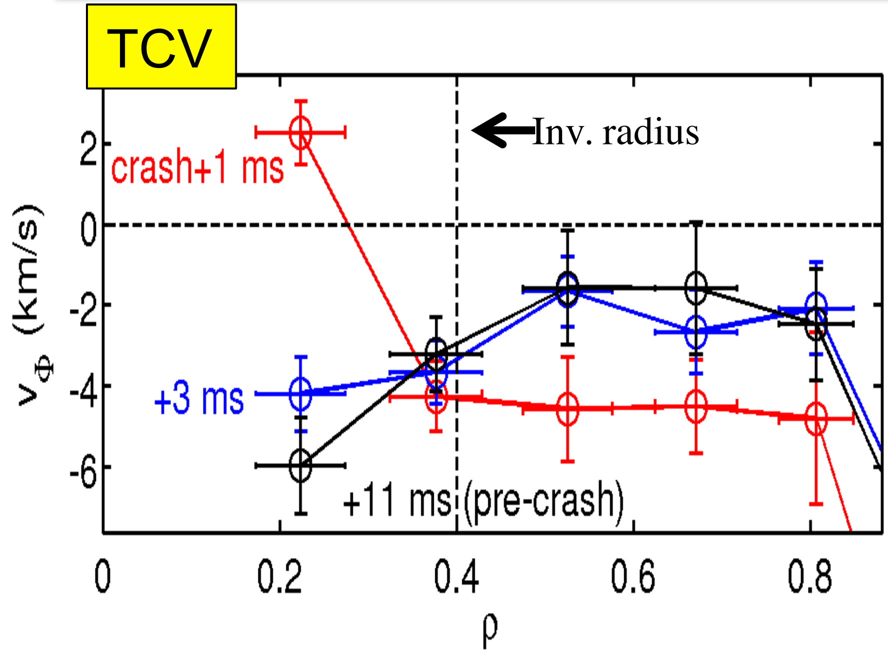


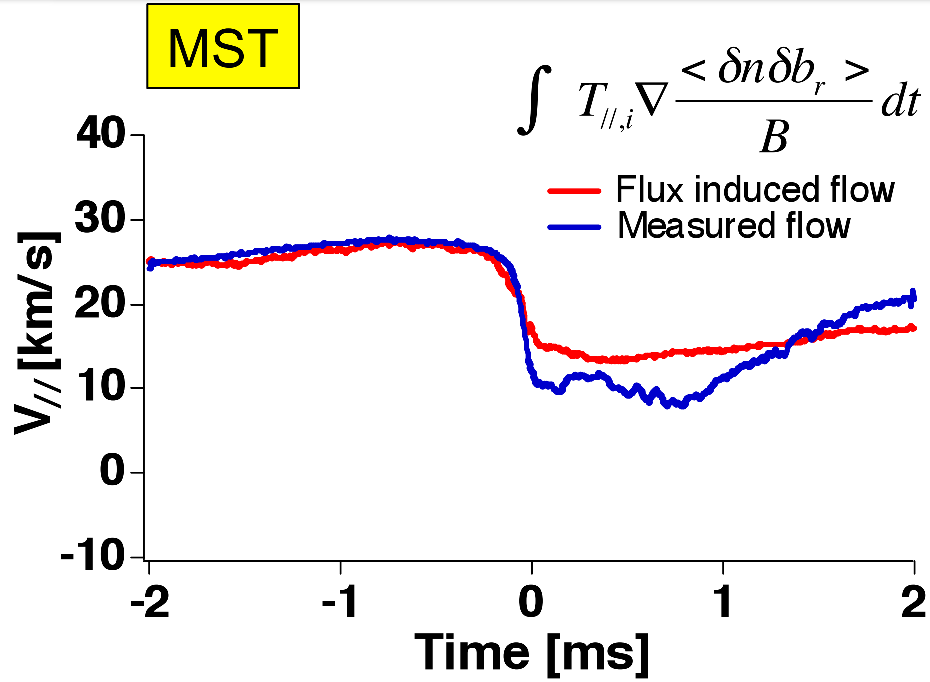
M. Yoshida, EXC/3-2

W. Solomon, EXC/3-5

- **ITBs with strong pressure gradients (JT-60U)**
- **Other residual stress drive, including effect of ECH observed on DIII-D.**

Core MHD Can Also Modify Rotation Profile





B. P. Duval, EXS/P4-01

D. Brower, EXC/P4-02

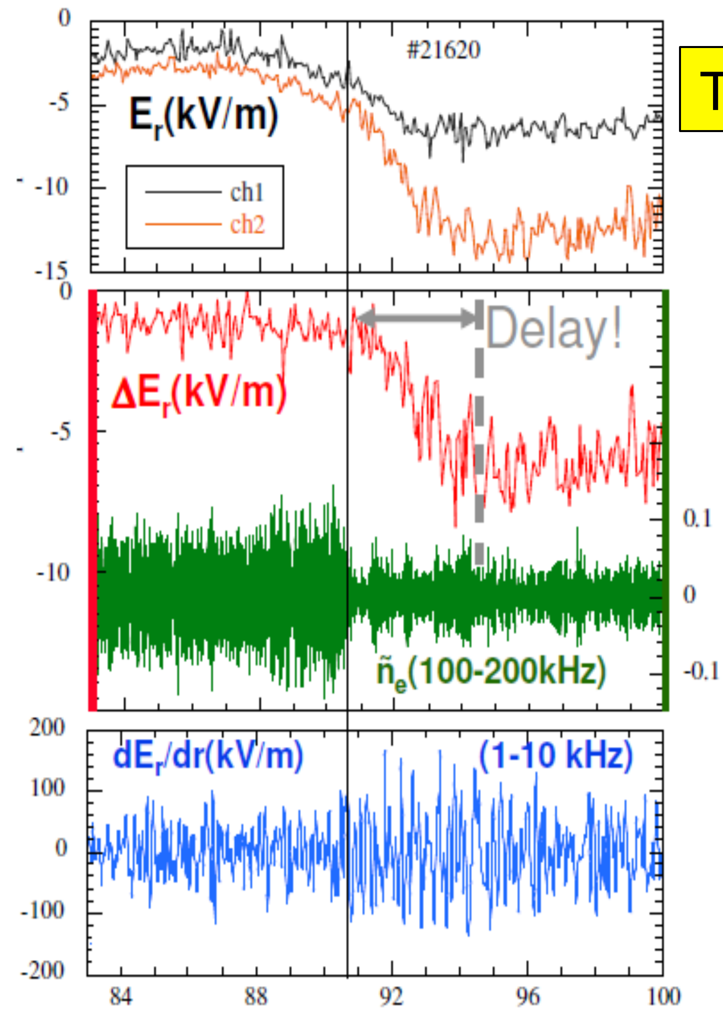
- **Rotation profile in TCV modified by sawteeth crash.**
- **Detailed measurements of Maxwell stress in MST following a sawtooth event in agreement with flux induced flow.**
- ***Extrapolation to ITER remains to be established.***

Role of Fluctuating Sheared Flows in L-H Transition Is Identified to Be Important

The L-H transition appears more correlated with the development of fluctuating flows than mean shear E_r effects

- TJ-II as well as MAST (H. Meyer, EXC/2-3Ra) and NSTX (S. Kaye, EXC/2-3Rb) reported no significant change in mean shear prior to transition.

Doppler reflectometry enables local measurements of oscillating radial flows.

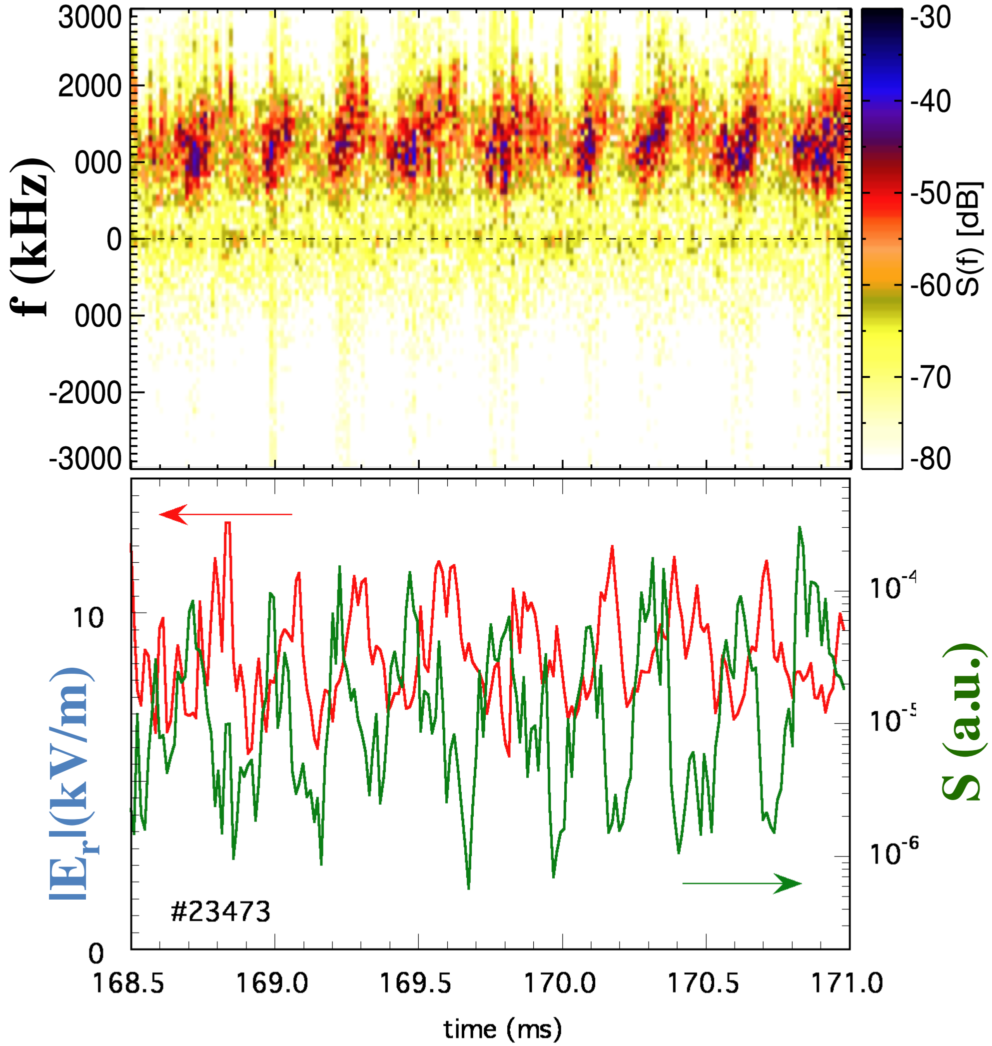


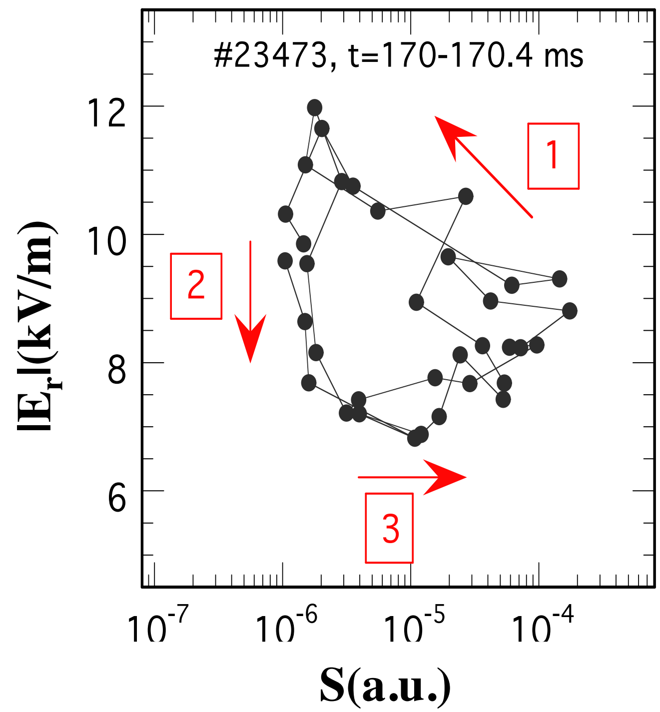
TJ-II

T. Estrada, EXC/P3-01

Time Evolution of Flows and Turbulence in a Slow Transition to H-Mode Indicates a Predator-Prey Behavior

TJ-II



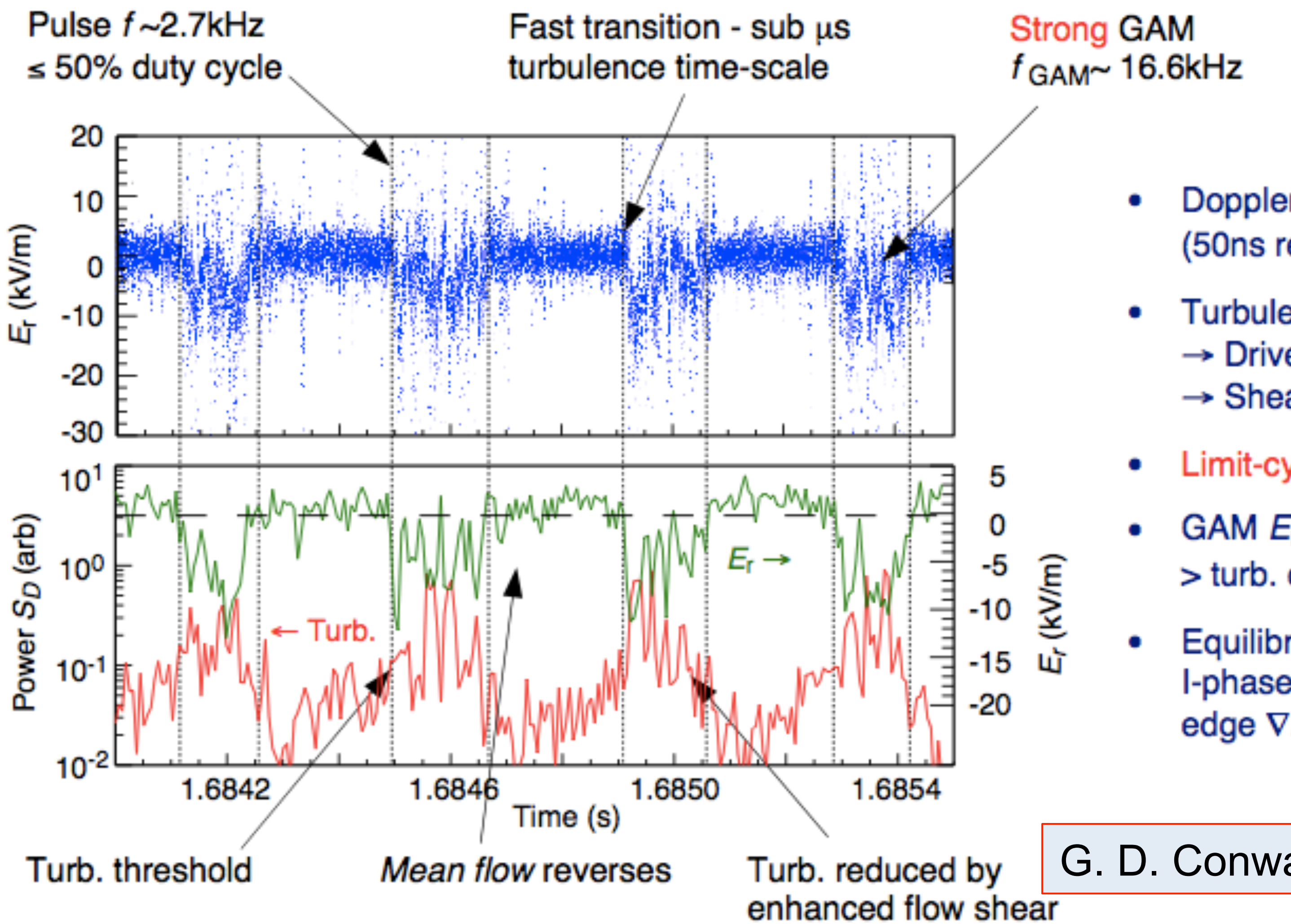


Is this a high frequency dithering H-mode?

T. Estrada, EXC/P3-01

Are GAM's the Missing Link During the Intermediate Phase Prior to Transition to H-mode?

AUG



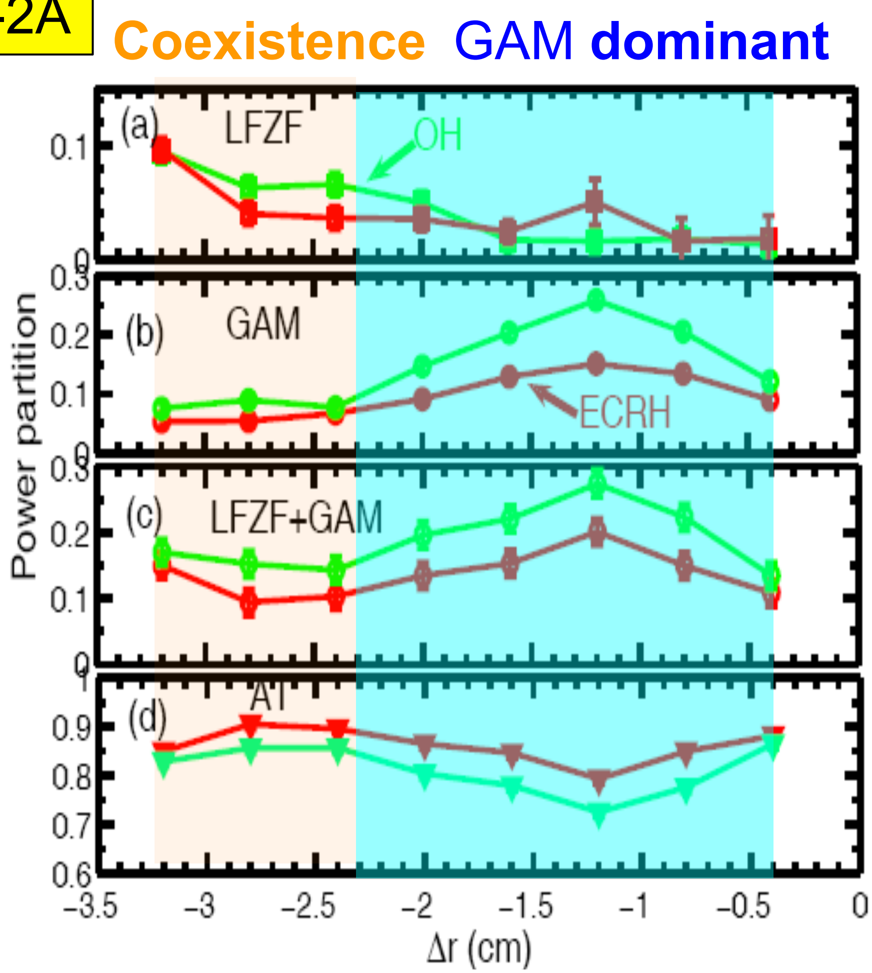
- Doppler $f_D = d\phi/dt$ (50ns resolution)
- Turbulence threshold
  → Drives flow & GAM
  → Shear erodes turb.
- Limit-cycle behaviour
- GAM E_r shearing rate > turb. de-correlation τ_c
- Equilibrium time scale: I-phase supports larger edge ∇P → mean flow

G. D. Conway, EXC/7-1

- *Is the AUG I(ntermediate)-phase related to the C-Mod I-mode?*

What Are the Role of Zonal Flows?

HL-2A



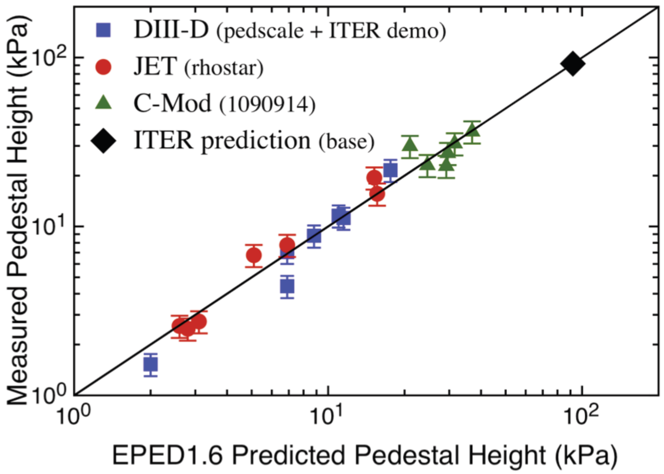
K. J. Zhao, EXC/7-3

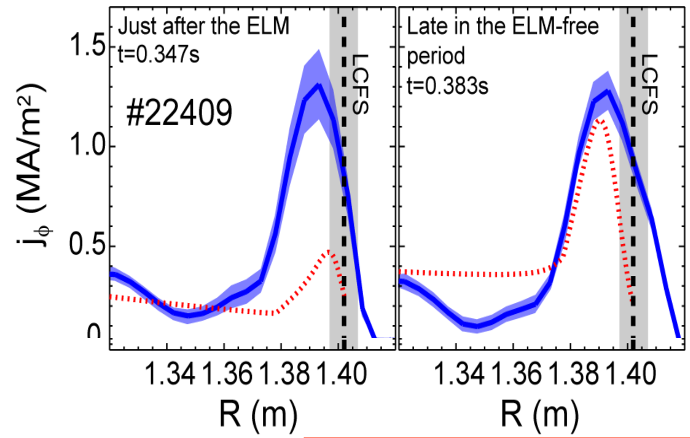
Probe measurements in the edge (near LCFS) of HL-2A indicate that GAMs are dominant

- Further inside GAMs and Zonal Flows coexist.
- Also see Y. Xu, EXC/9-3

To fully understand the dynamics of the turbulence in the edge leading to an L to H transition would want to measure the spatial evolution of turbulent structures.

Detailed tests of EPED Model and Peeling/Ballooning Paradigm in Progress





MAST

P. Snyder, THS/1-1

H. Meyer EXC/2-3a

- **EPED 1.6 works well for range of devices**
  - High frequency coherent modes during QH-mode looks like KBM in DIII-D (Z. Yan, EXC/P3-5)
- **Pressure gradients saturate at least ½ way thru ELM cycle in AUG**
  - edge current diffusion calculations suggest j_{BS} equilibrates rapidly
    - What kicks off the next ELM? (B. Kurzan, EXC/P3-3)
- **MAST plasma can stay above ballooning boundary for ~10ms before ELM**
  - New MSE measurements of bootstrap current compared with neoclassical model

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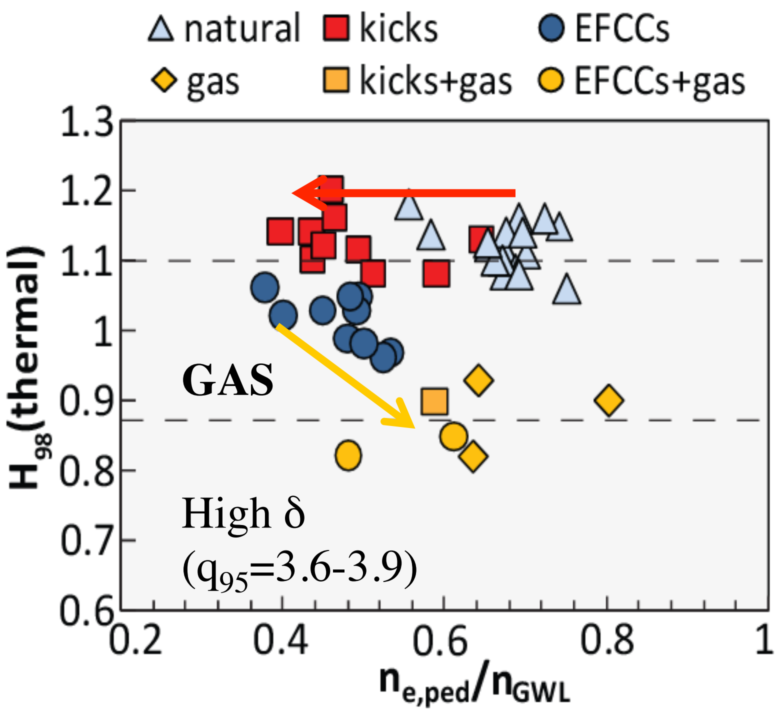
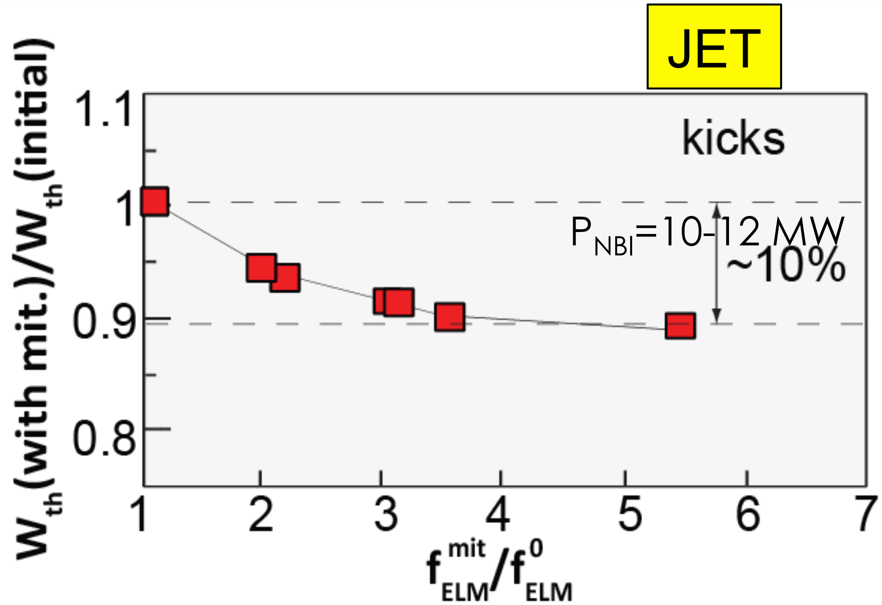
ELM Mitigation Results in Loss of Density and/or Confinement



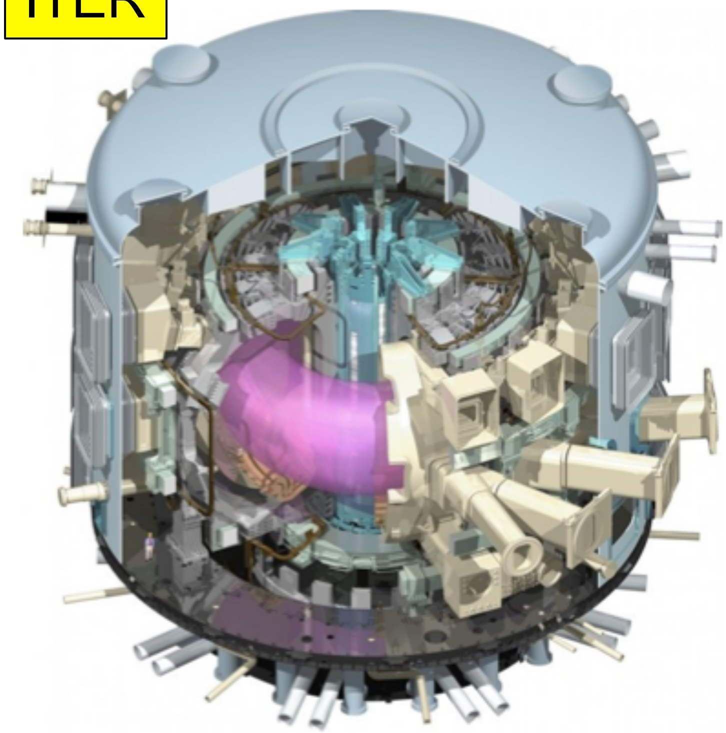


E. de la Luna, EXC/8-4

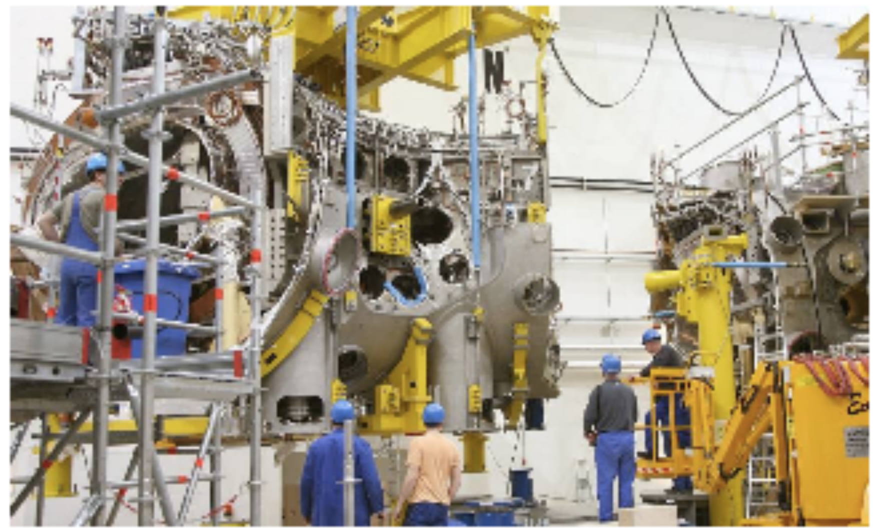
- **Good confinement during ELM mitigation (unfuelled) →H_{98}~1.1 but density reduced by 20%**
- **Density can be restored by gas fuelling but confinement decreases.**
- ***Ultimately may have to reduce ITER performance to avoid ELM damage to divertor tiles.***

Congratulations on Excellent Progress!

ITER



W7-X



Results presented at the 23rd FEC meeting are significant contributions to the success of ITER and W7-X.