H-MODE REGIMES AND OBSERVATIONS OF CENTRAL TOROIDAL ROTATION IN ALCATOR C-MOD

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OUTLINE

H-Mode Regimes - Enhanced Dα H-Modes (EDA)

- Relation to ELMy H-Modes
- Particle and Energy Confinement
- Edge Fluctuations
- Boundary Between EDA and ELM-free H-Mode

Toroidal Rotation With ICRF Heating

- Measurement and Phenomenology
- Scaling with Plasma Parameters
- Possible Origin

Characteristics of Alcator C-Mod Tokamak

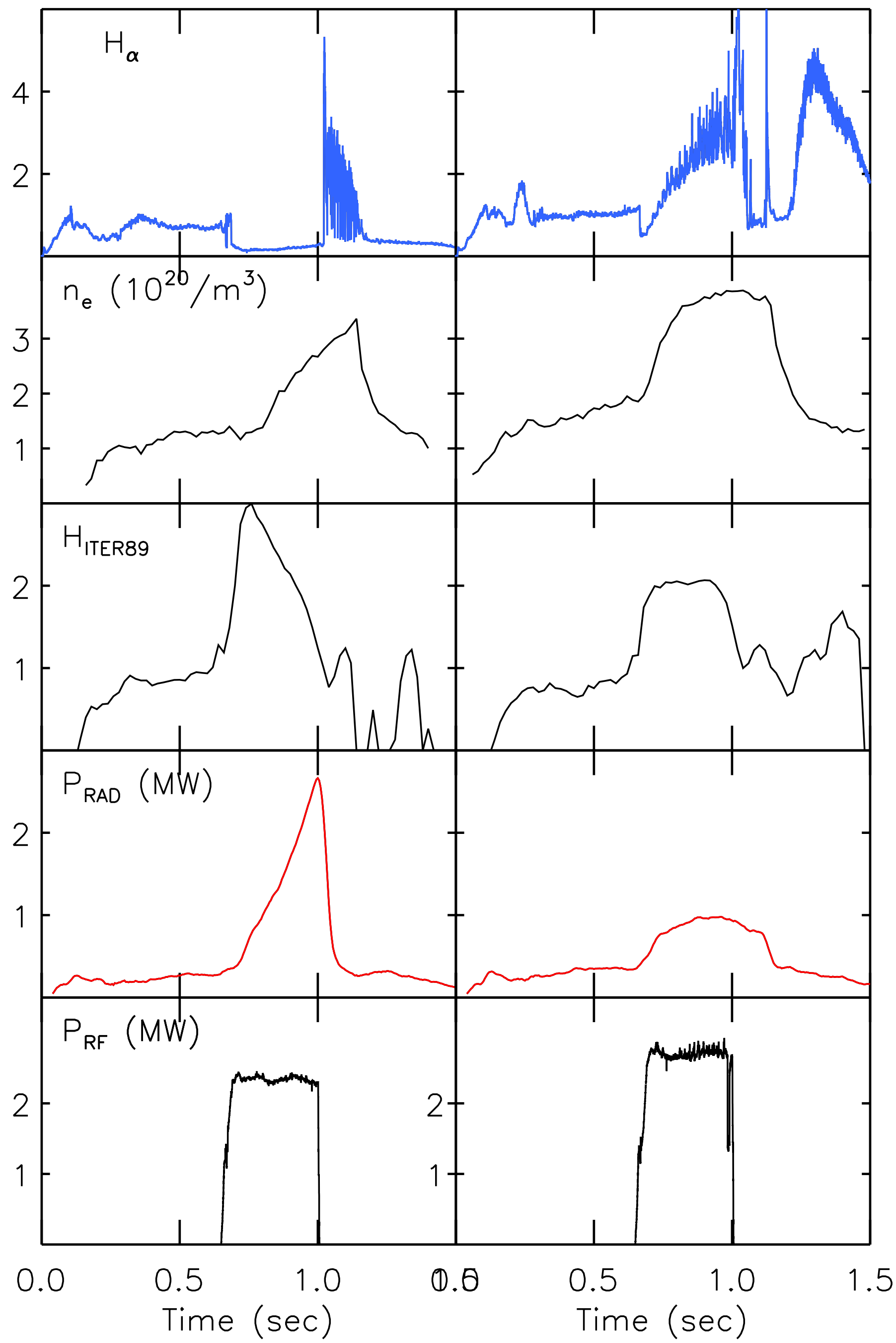
- High B/R, ne, neutral pressure
- Strong ICRF heating
- Closed Divertor
- Molybdenum walls - boronized

TYPE I ELMY DISCHARGES ARE NOT SEEN IN C-MOD INSTEAD, A REGIME THAT WE HAVE CALLED EDA (ENHANCED $D\alpha$) IS OBSERVED

- First signature - enhanced level of light from neutral deuterium
- Particle confinement much lower than ELM-free
- **No strong accumulation of impurities**
- Energy confinement slightly lower than ELM-free (10-20%)
- **No large discrete ELMs**
- So far, we don't see type I ELMs, though pressure gradient challenges MHD ballooning stability limit
- T_e above type III boundary
- EDA regime shows **continuous** degradation of pedestal rather than relaxation oscillation

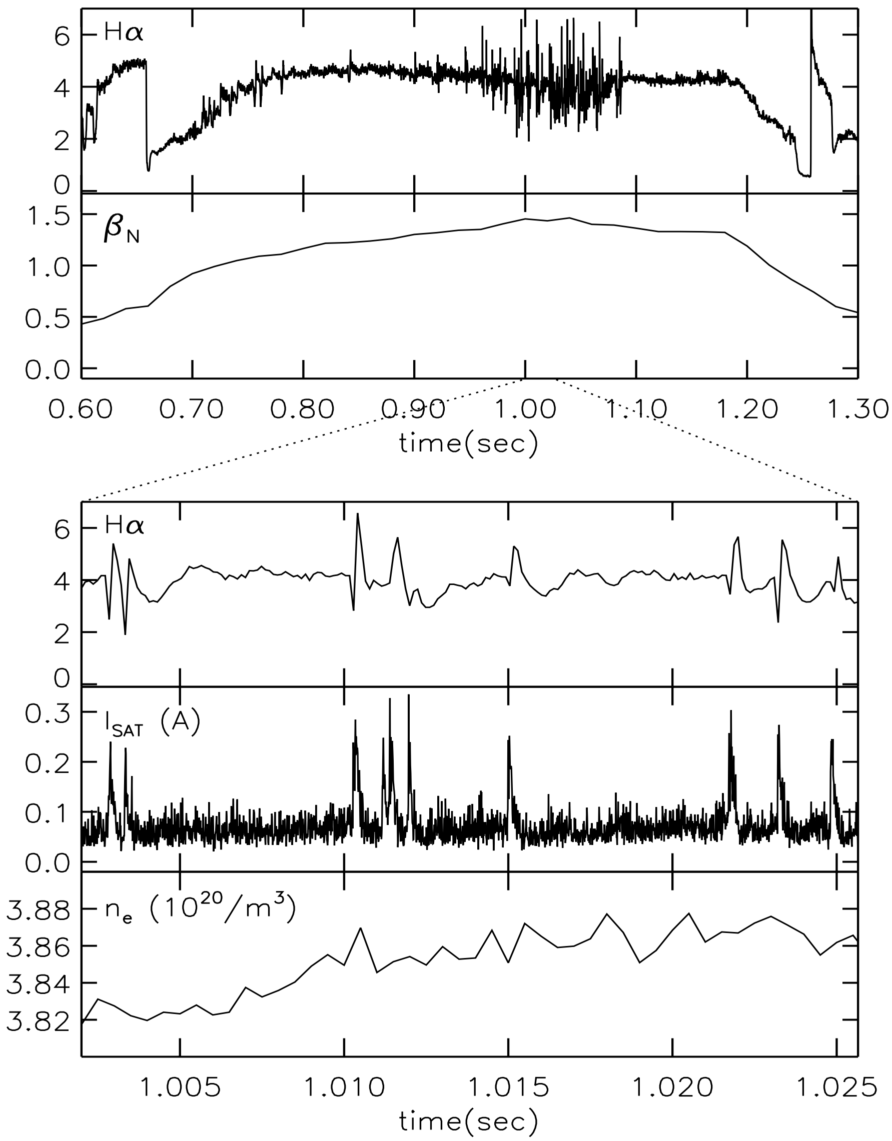
EDA may be closely related to JET LPC H-mode
Shares many characteristics with type II or other "small" ELM regimes (DIII-D, JT60-U).

EDA H-MODES DO NOT SHOW IMPURITY ACCUMULATION



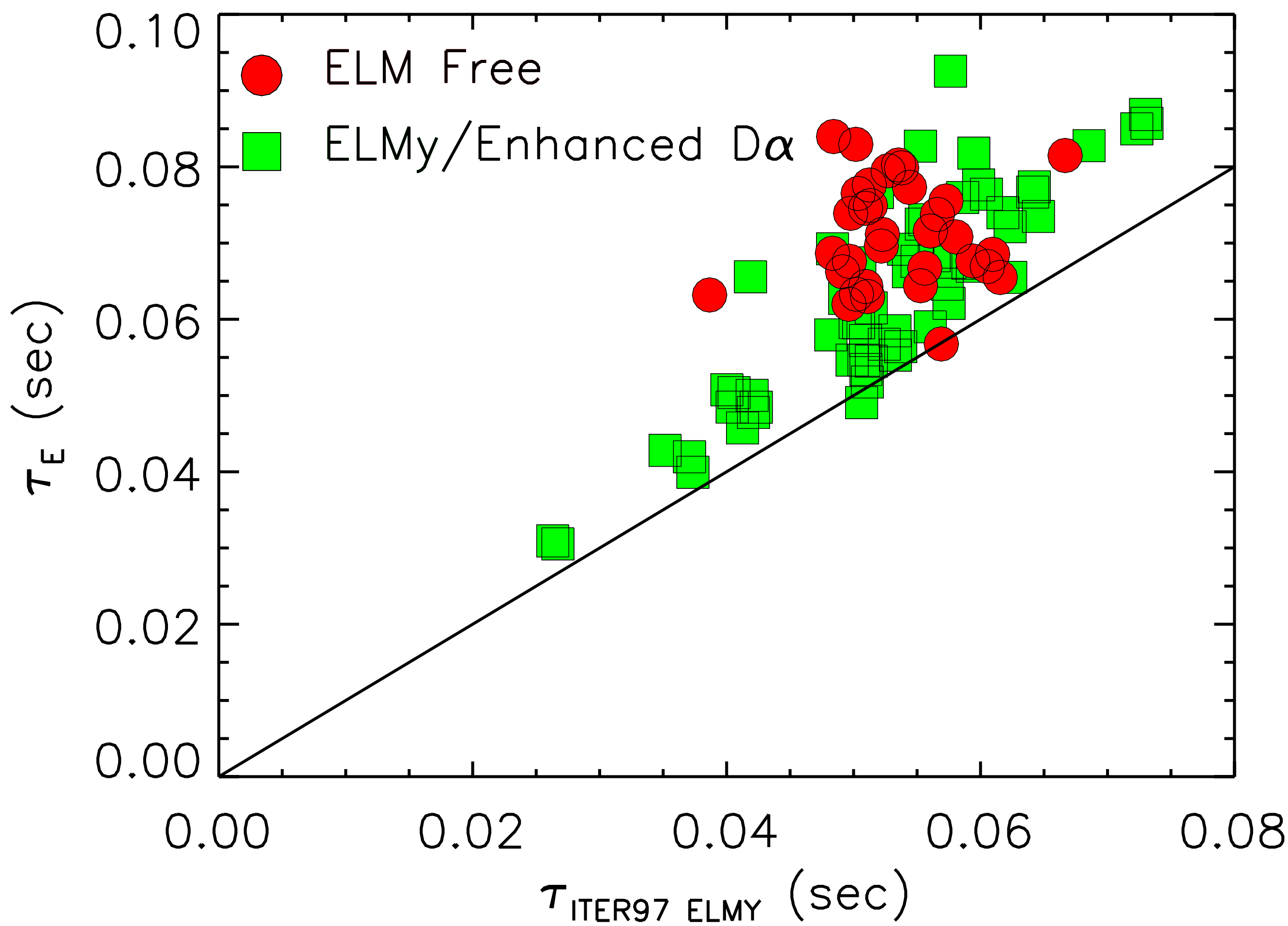
ELM-free **EDA**

SMALL ELMS ARE OFTEN SEEN ON TOP OF EDA



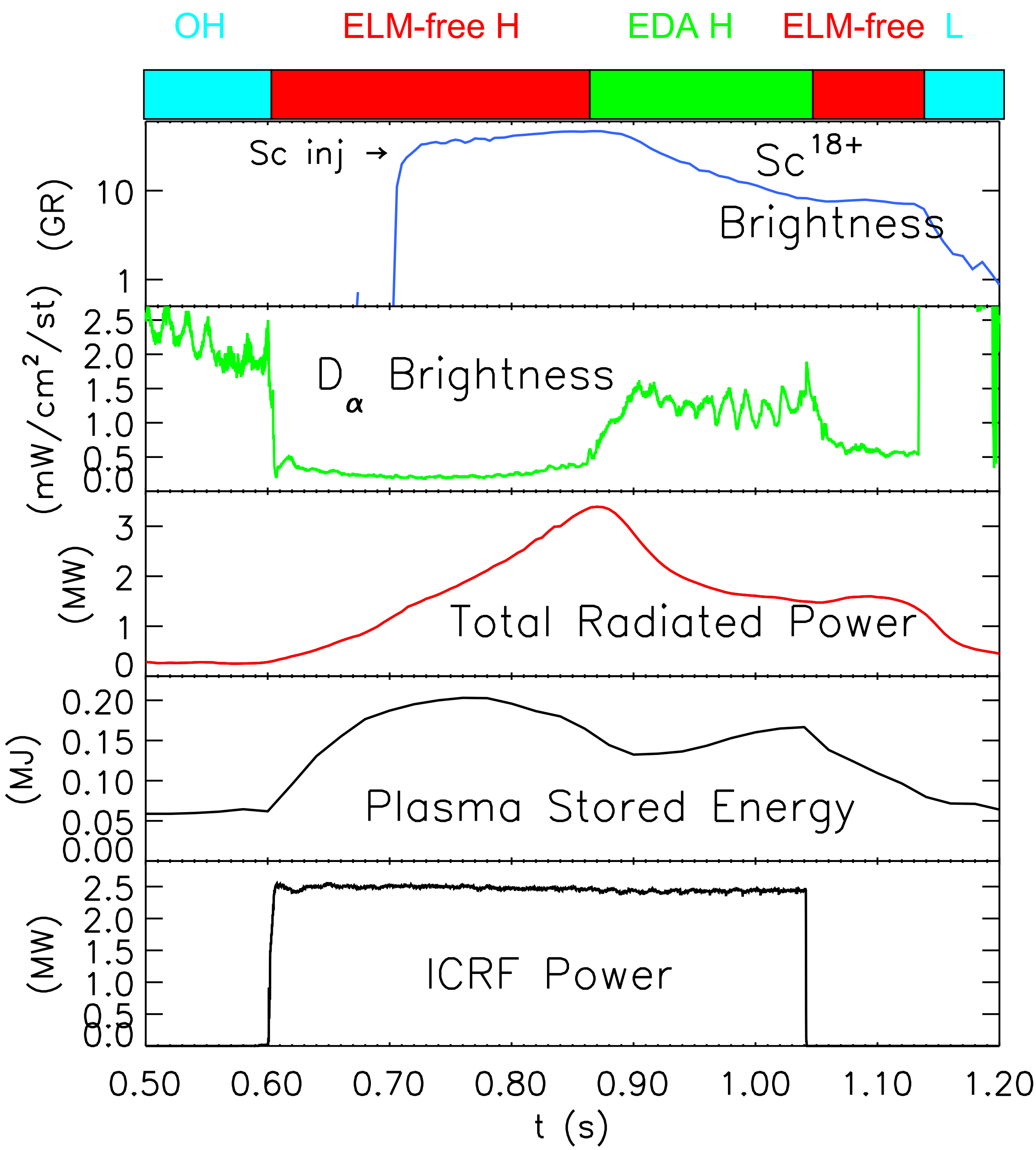
- Seen when $\beta_N > 1.2 – 1.3$
- Negligible net loss of energy or particles detected by core diagnostics

EDA DISCHARGES HAVE ENERGY CONFINEMENT ONLY SLIGHTLY LESS THAN ELM-FREE

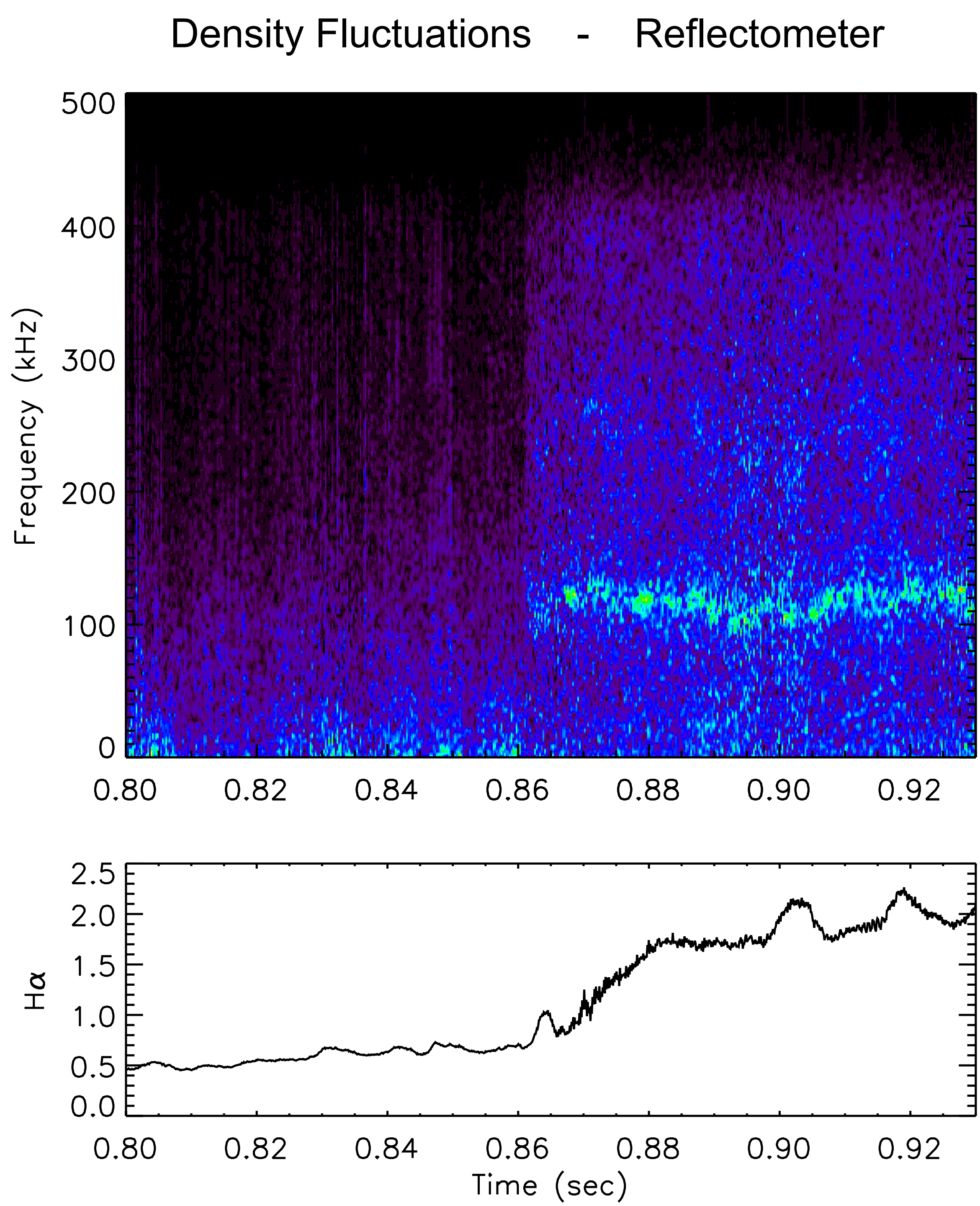


- C-Mod data are in rough agreement with latest ITER H-mode scaling laws (though about 15% higher)
- for ELM-free: $H_{ITER89} = 2.1$
- for EDA: $H_{ITER89} = 1.9$

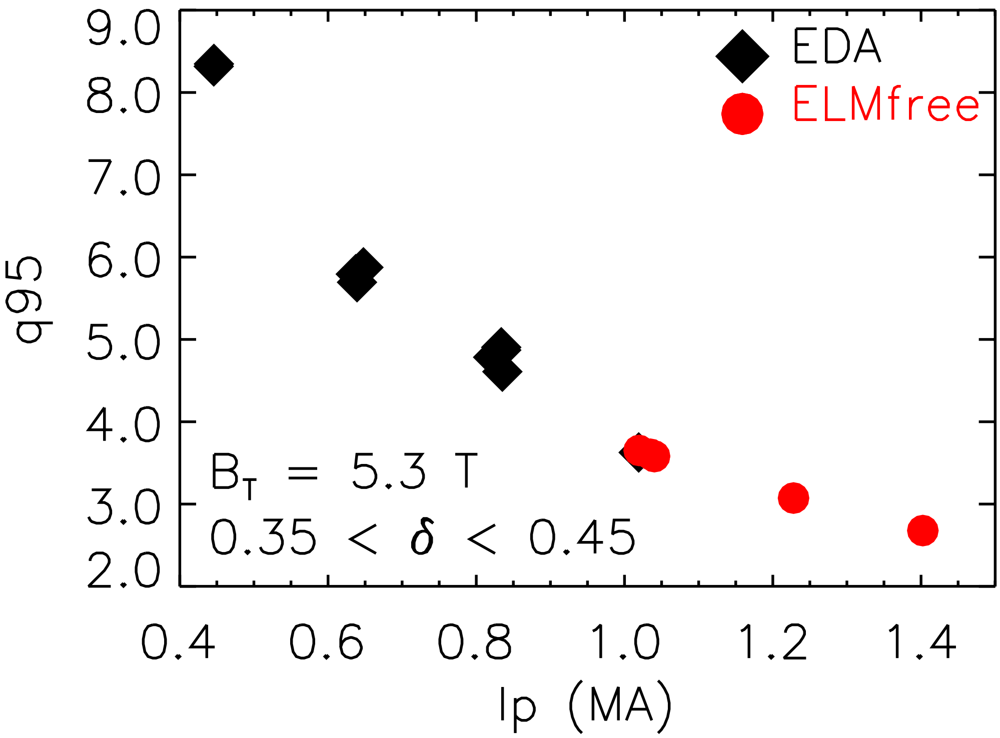
THE BEHAVIOR OF INJECTED IMPURITIES IS CONSISTENT WITH THAT OF INTRINSIC IMPURITIES

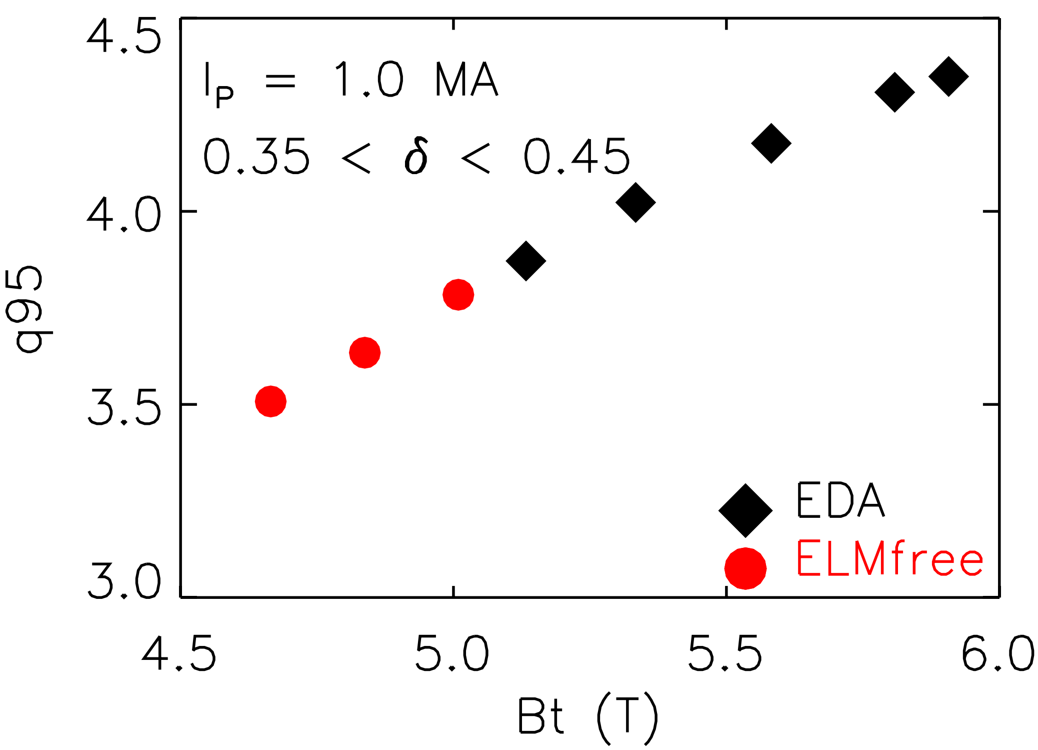


STRONG FLUCTUATIONS ARE SEEN IN THE EDGE OF EDA PLASMAS

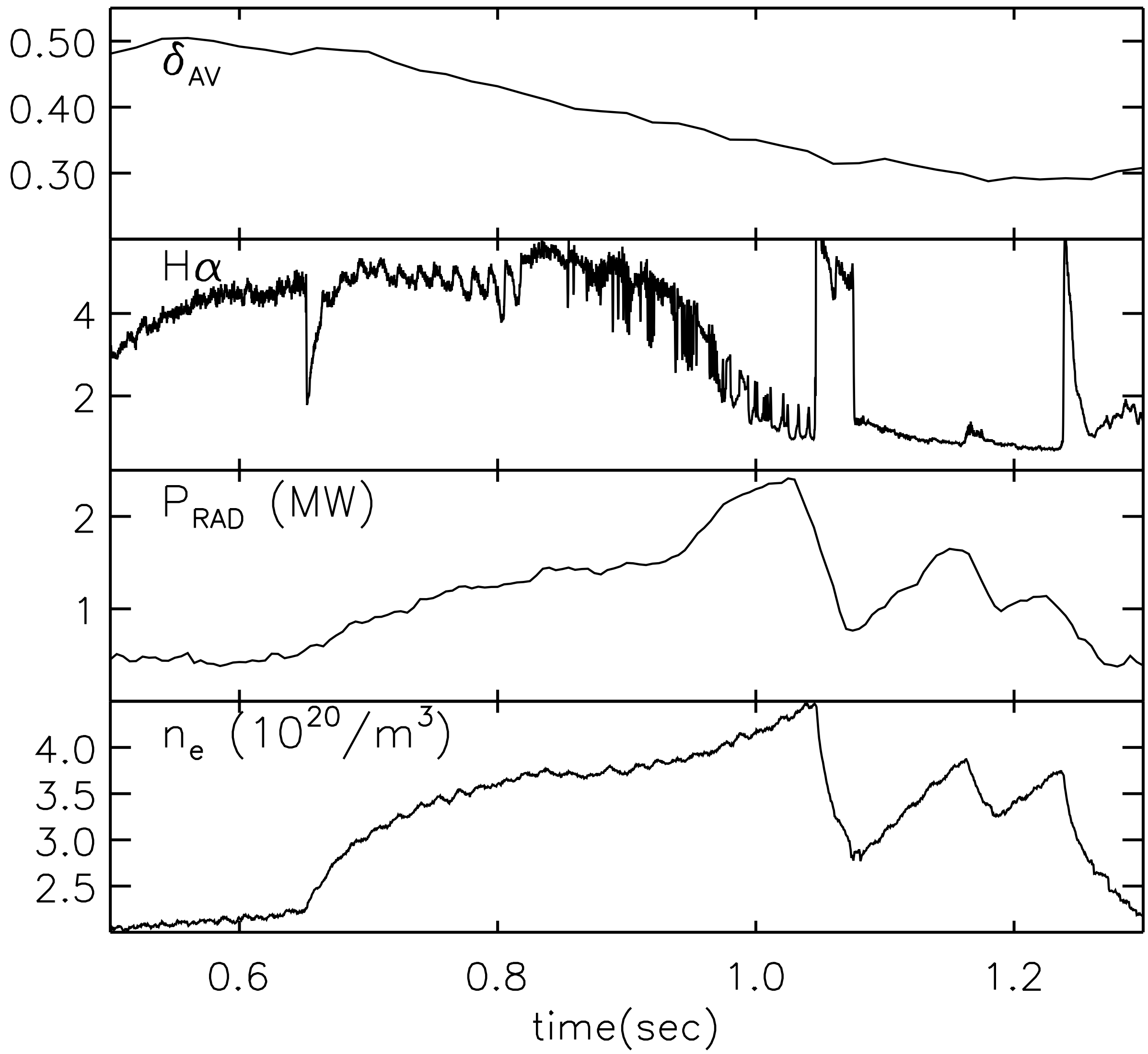


EDA IS MORE LIKELY AT Q95 > 4



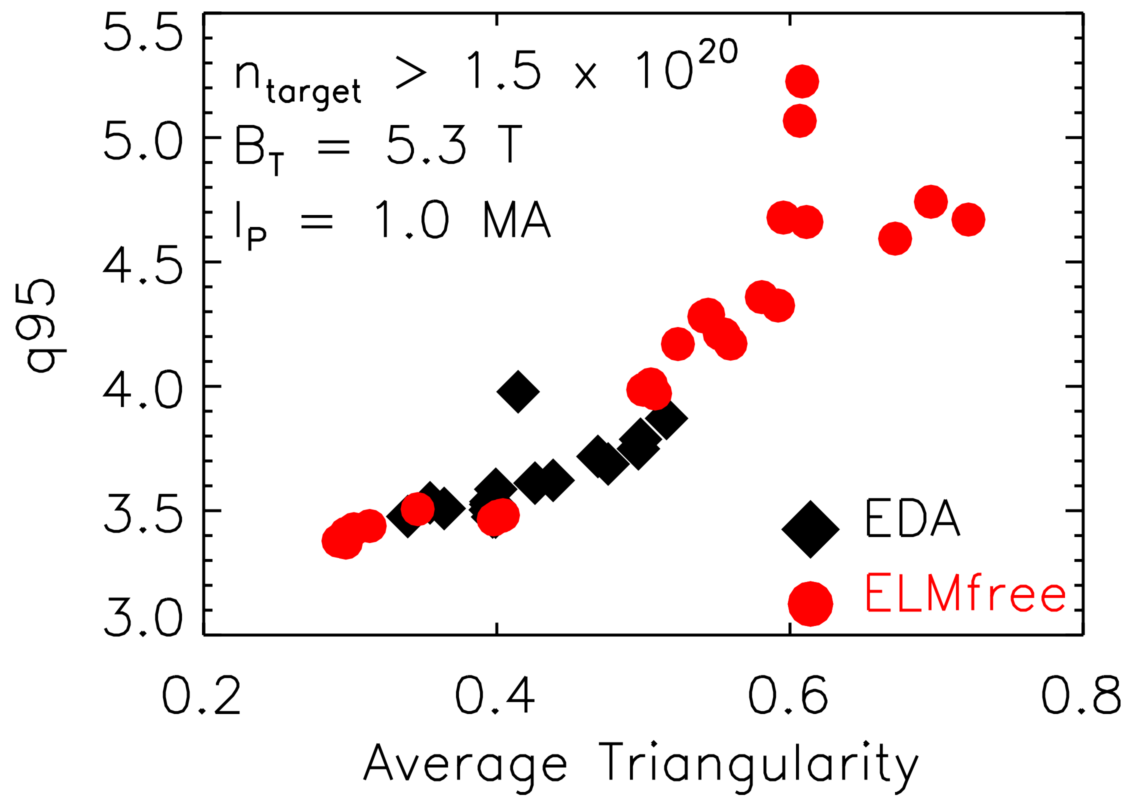


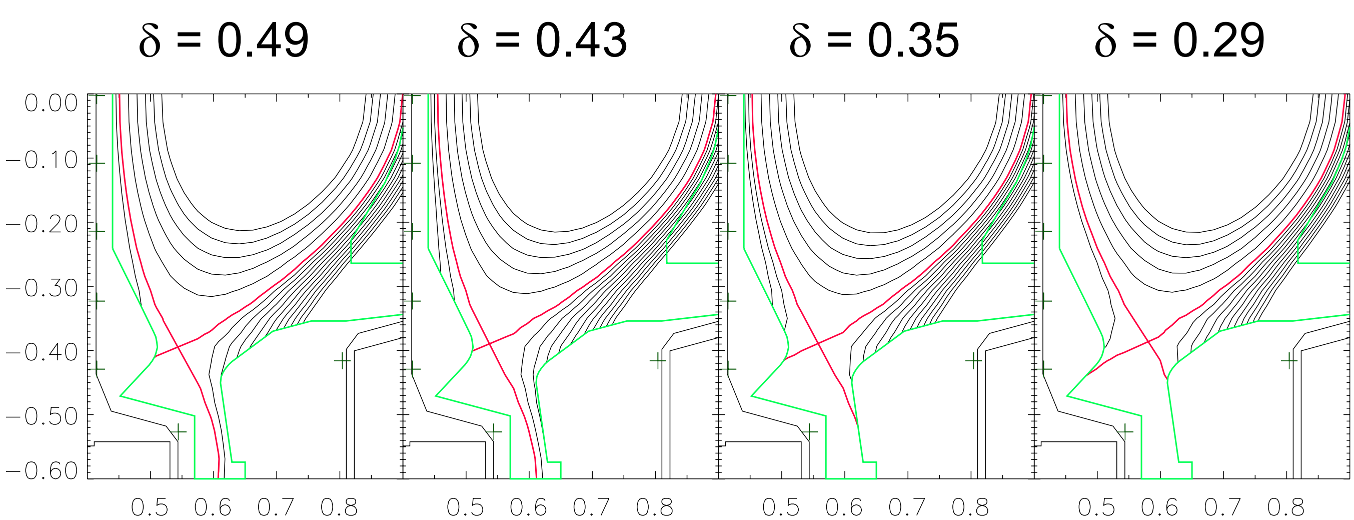
EDA-ELM-free BOUNDARY IS A FUNCTION OF δ



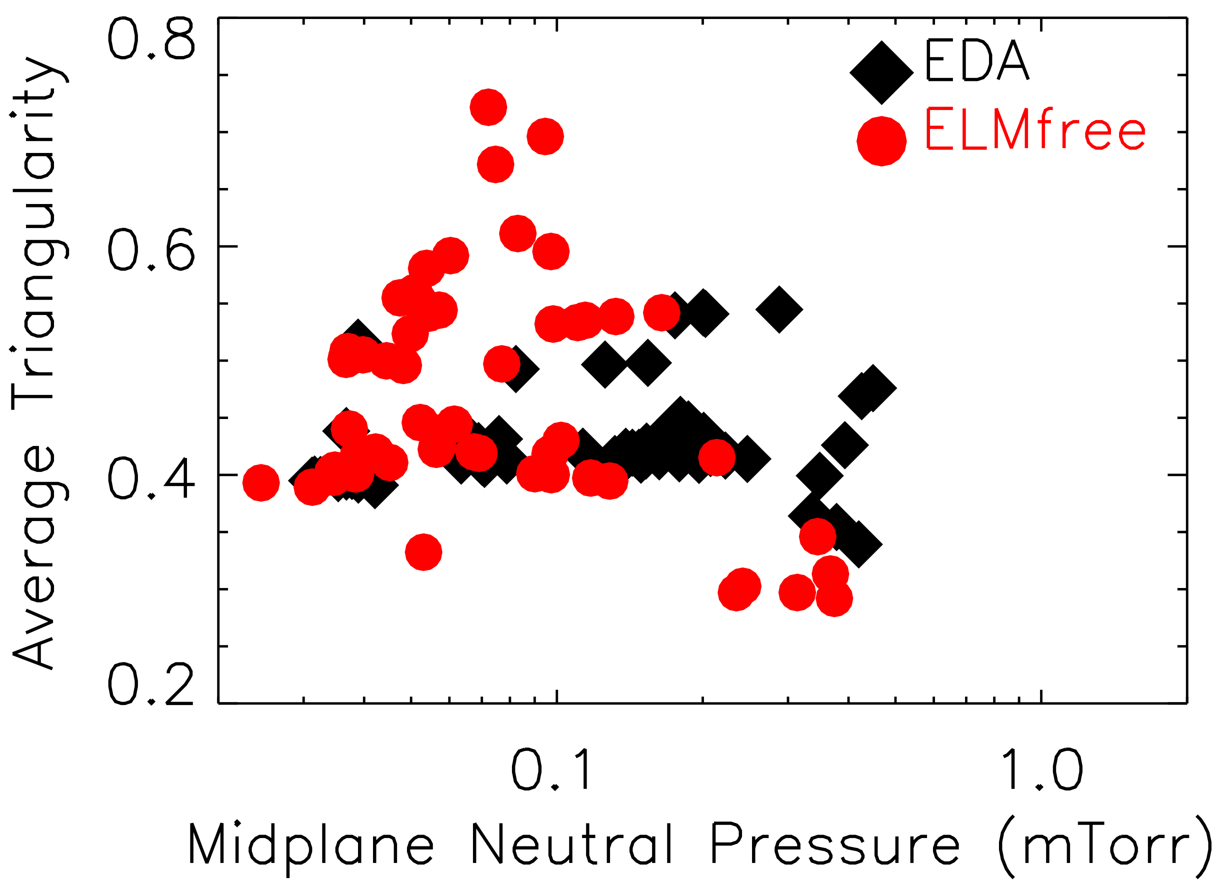
In this δ scan, the plasma makes a transition to ELM-free as δ drops below 0.4

EFFECT OF δ CANNOT BE EXPLAINED AS q_{95} DEPENDENCE, BUT DIVERTOR INTERACTIONS MAY BE IMPORTANT





EDA IS MOST EASILY ACHIEVED AT MODERATE TRIANGULARITIES AND AT HIGH NEUTRAL PRESSURE



- The dependence on δ and q are reminiscent of the MHD calculations done by Miller et al. (Bootstrap current and access to 2^{nd} stability).
- However, to interpret our results in that light, it would be necessary to identify EDA as the **more** stable state

HIGH NEUTRAL PRESSURE CAN HAVE A PROFOUND EFFECT ON PLASMA BEHAVIOR

- Neutrals “attacking” plasma come from recycling in main chamber not from divertor or x-point in C-Mod
- Energy confinement deteriorates at highest pressures
- Edge MHD mode rotation is damped
- Neutrals can effect edge plasma directly:
  - Cooling by ionization and convection
- Or indirectly:
  - Viscous damping of poloidal rotation in transport barrier
- In either case, the edge cools
- Pressure gradients are likely reduced
- Collisionality increases $\Rightarrow$ less bootstrap current,

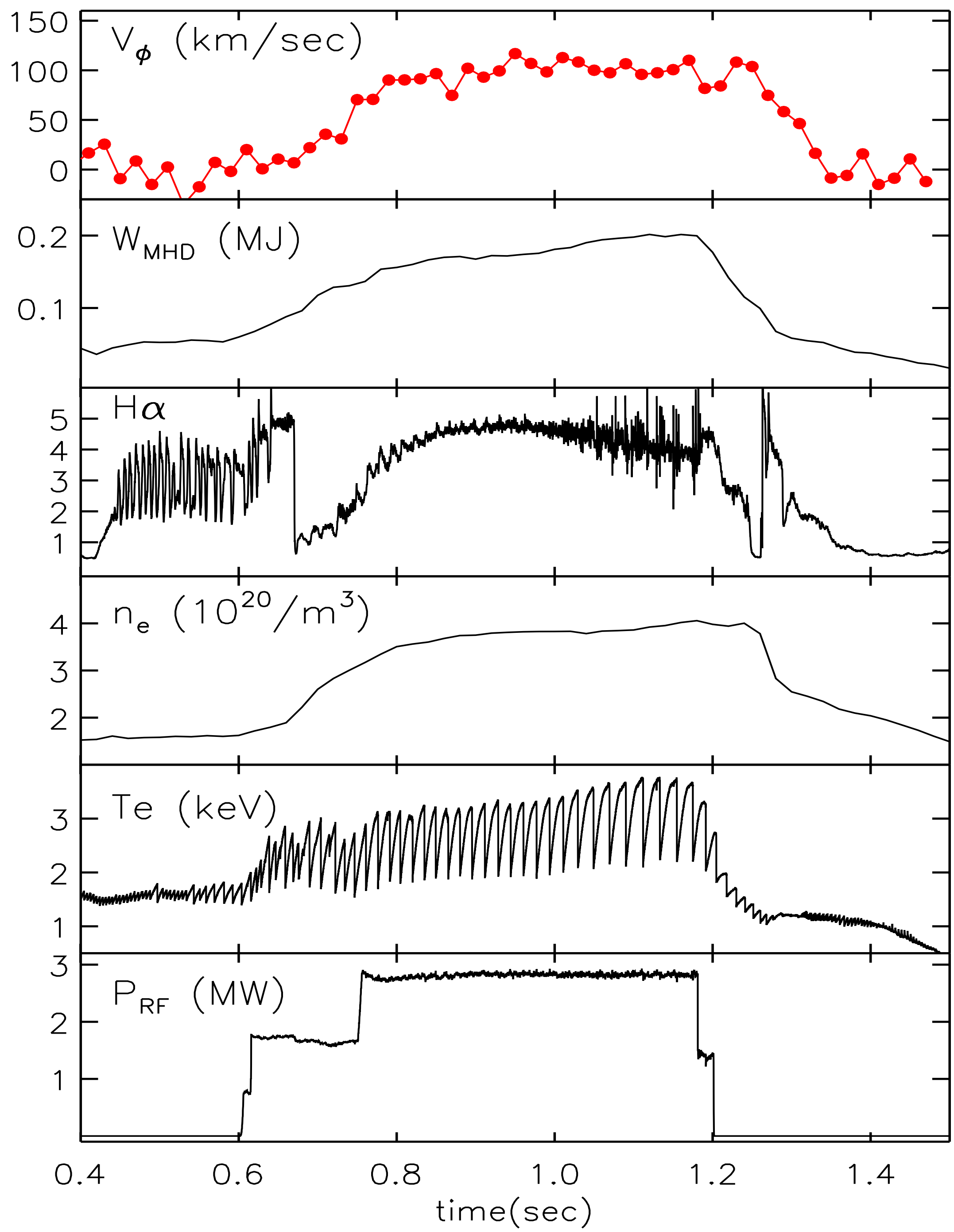
  less stability to ballooning, more stability to peeling?

STRONG TOROIDAL ROTATION IS OBSERVED WITH ICRF HEATING ALONE

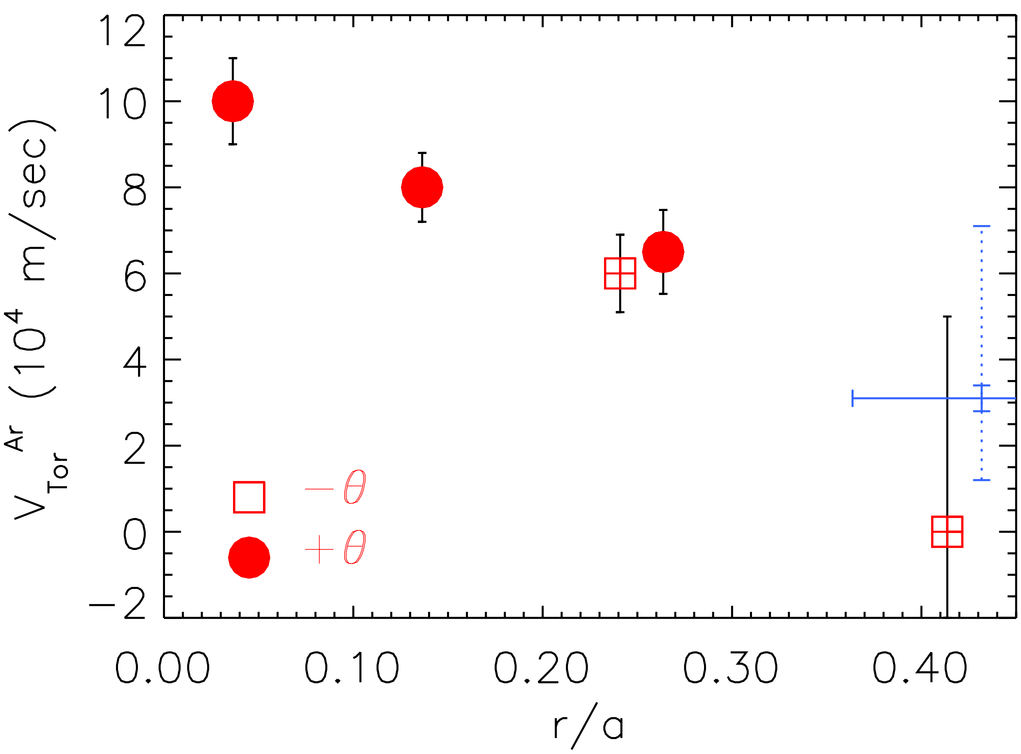
- An array of high resolution soft x-ray spectrometers is used to measure spectra of highly ionized states of argon in the plasma core
- Spectra analyzed to give $n_i(r)$, $T_i(r)$, $V(r)$
- The array can view positive and negative toroidal and poloidal angles – can distinguish velocity components
- Strong rotation is observed with ICRF heating in both L and H-modes ($V_\phi \geq 100$ km/sec, $M < 0.2$-0.3)
- Rotation with RF is always in the co-current direction
- For a high Z impurity like argon, the rotation measurement is direct evidence for E_r

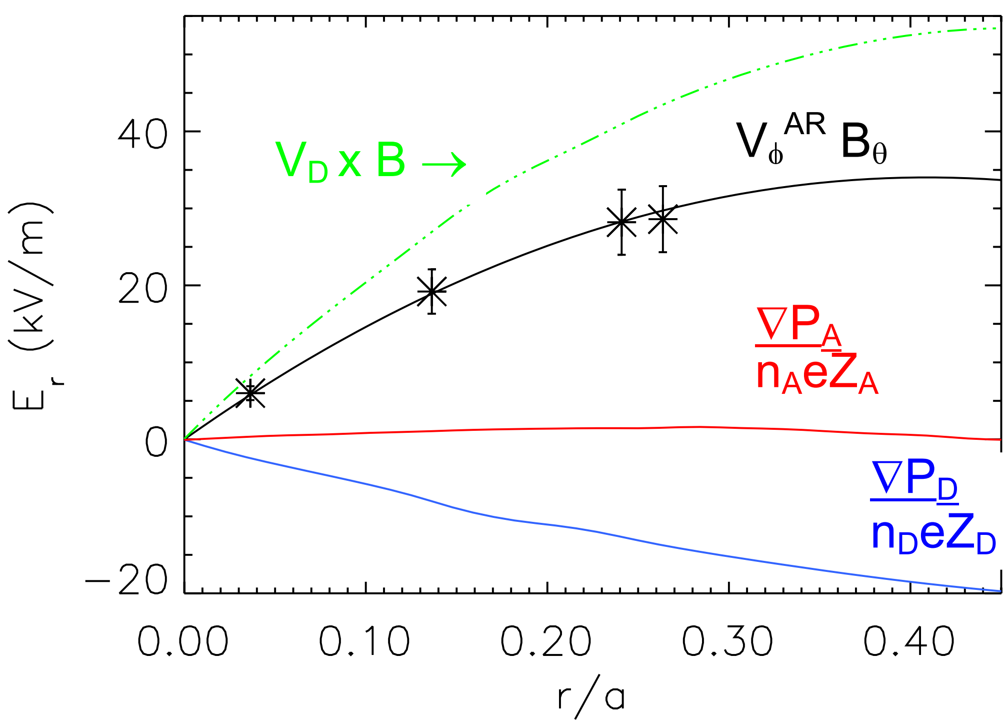
$$E_r = \frac{\nabla p}{neZ} + V_\phi B_\theta - V_\theta B_\phi$$

THE STRONGEST CORE ROTATION IS SEEN IN DISCHARGES WITH THE MOST STORED ENERGY

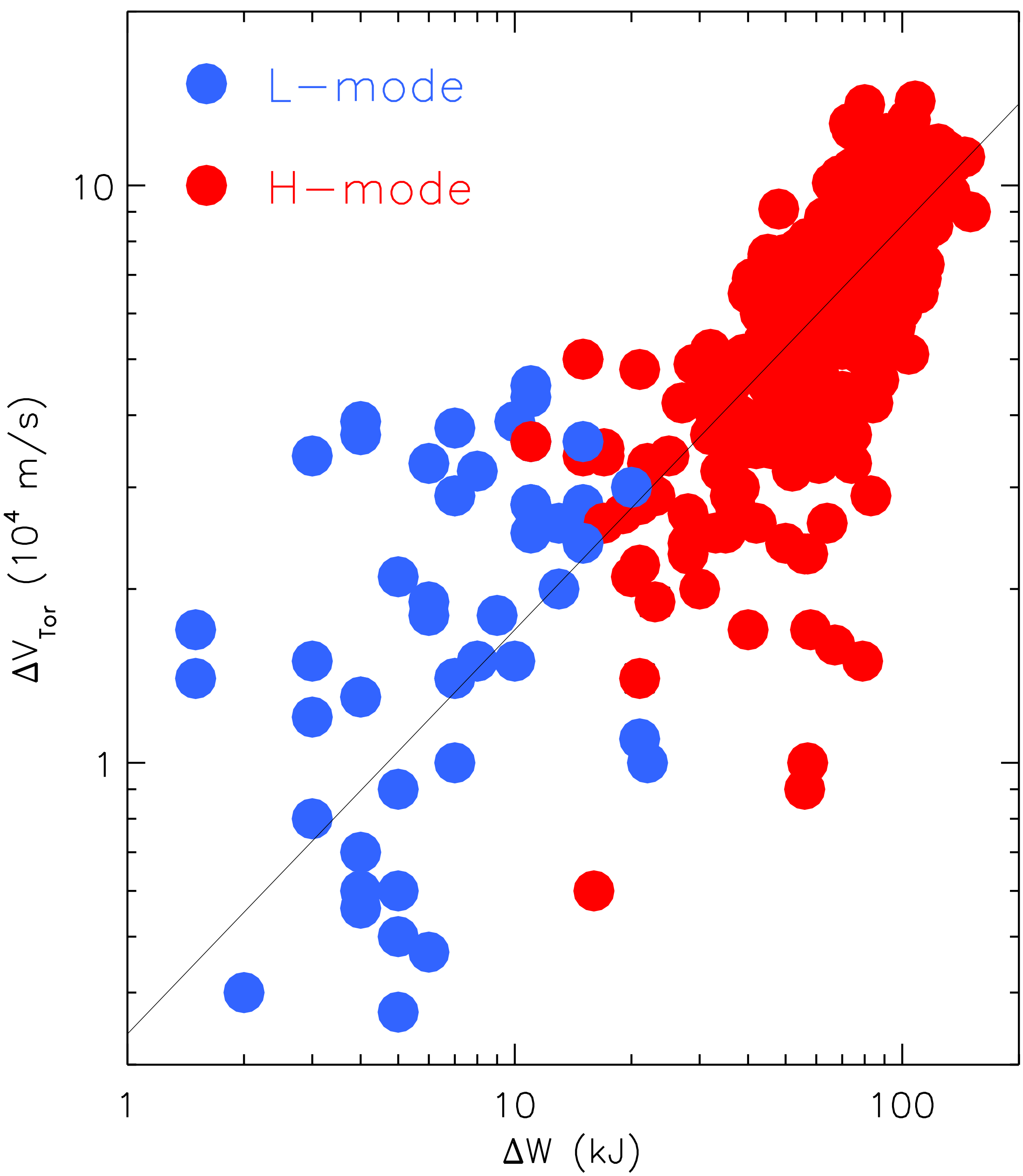


PROFILES SHOW THE ROTATION LOCALIZED IN THE PLASMA CORE

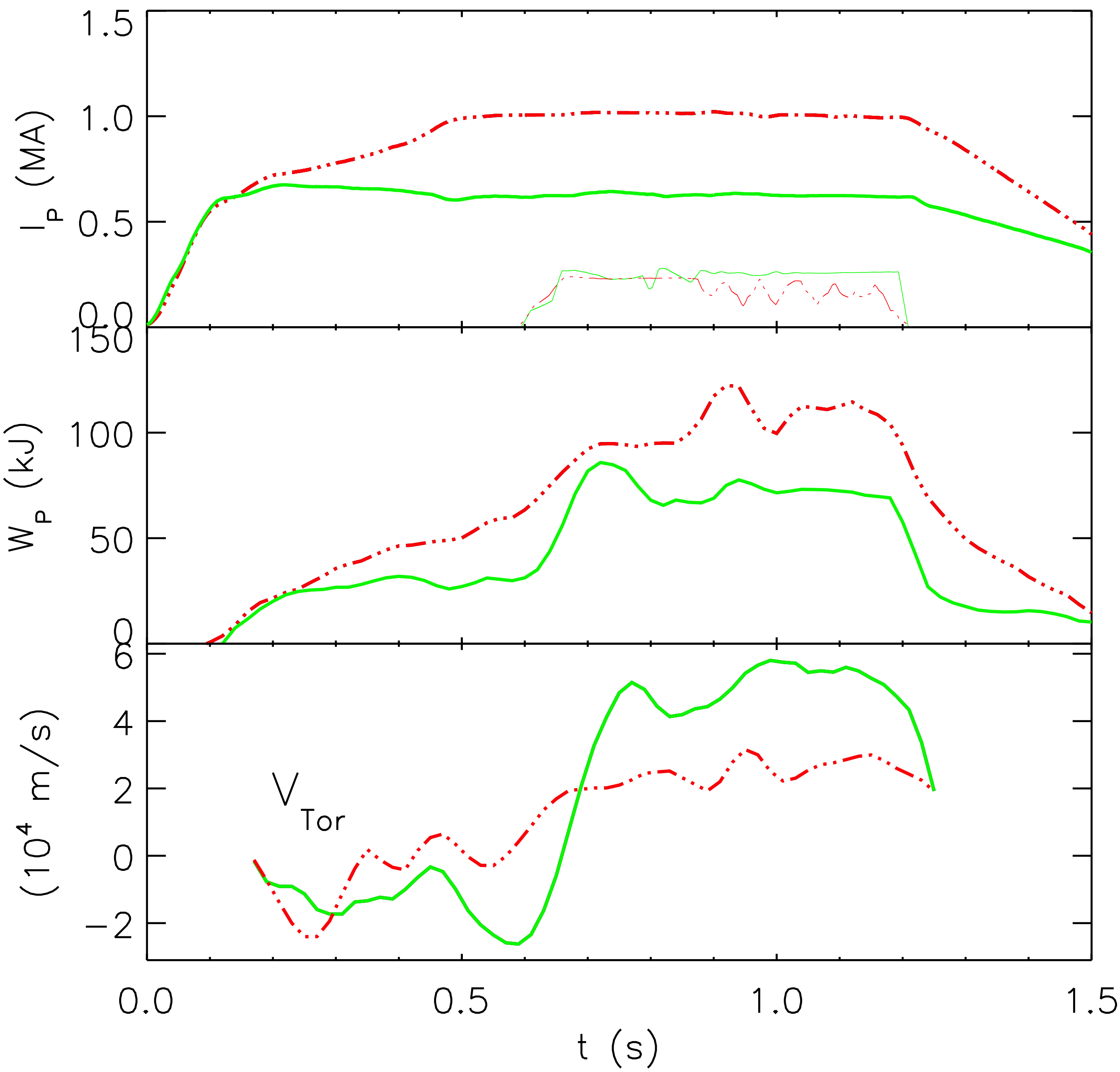




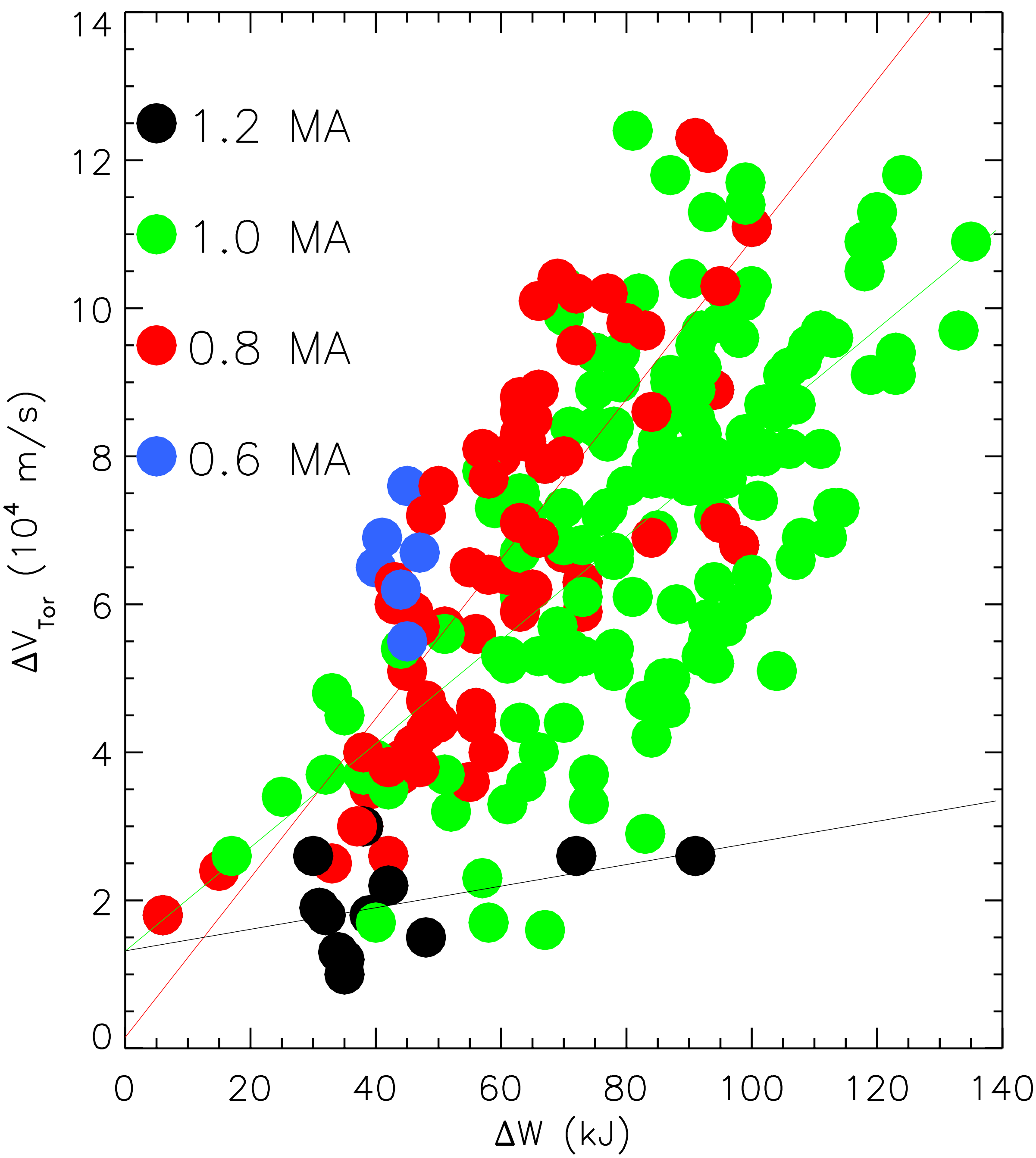
ROTATION SCALING WITH ΔW FOR BOTH L AND H MODES



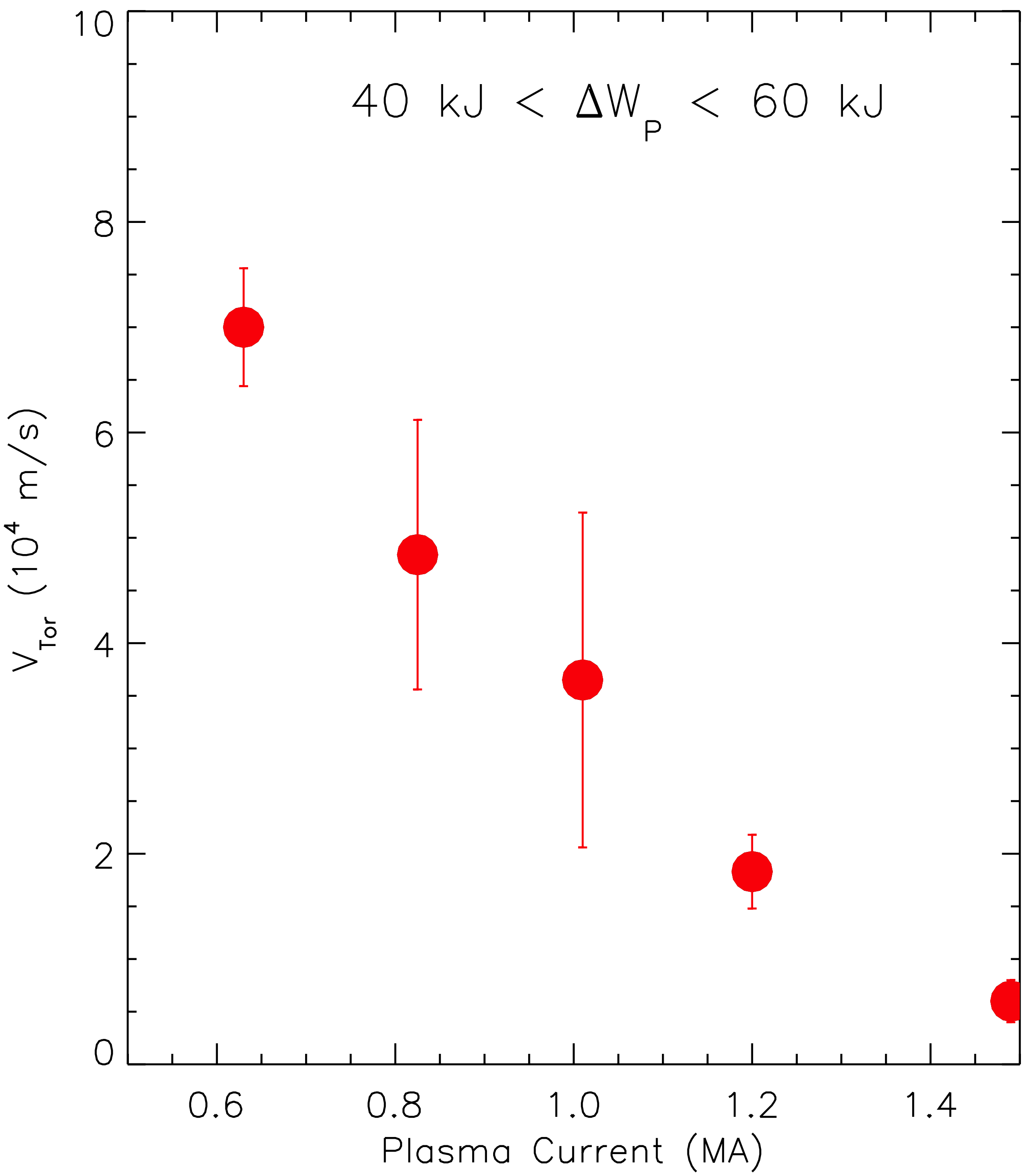
PLASMA CURRENT HAS A LARGE EFFECT ON THE ROTATION MAGNITUDE



FOR A GIVEN STORED ENERGY INCREASE, THE LARGEST ROTATION IS OBSERVED AT LOW PLASMA CURRENT



ROTATION VELOCITY VARIES ROUGHLY AS $1/I_P$



THEORY FOR ROTATION

- Chang has suggested a mechanism for generating the observed rotation. *(see THP2/34)*
- ICRF resonance is shifted by ion velocity, $\omega = \omega_{ci} - k_{||} v_{||}$
- For a symmetric k spectrum, one might expect RF interaction equally with co and counter ions.
- However, when the neo-classical orbit shift is of the same order as the resonance shift, the symmetry can be broken
- ICRF heating of passing particles, then results in a net inward shift of ions, leading to a positive E_r and toroidal rotation.
- In addition to the correct directionality and magnitude of the rotation, this model can also explain the observed I_P dependence.

SUMMARY

Enhanced Dα H-modes (EDA)

- The EDA regime combines good energy confinement, moderate particle confinement and no energy impulses to the first wall.
- The pedestal is limited by a continuous rather than intermittent process, probably related to density and magnetic fluctuations which are observed.
- EDA is most easily accessed at q95 > 3.8, 0.55 > δ > 0.35, and at high neutral pressure (or target density).

Rotation

- Strong central toroidal rotation is observed with ICRF heating
- The rotation is always in the co current direction
- The rotation increases with stored energy and decreases with plasma current
- A theory based on neo-classical orbit shifts explains many of the observations

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Presentation

Possible vugraphs

- Title/authors
- Intro – topics + C-Mod character
- <u>EDA/EF</u>
- Questions to answer
    - Characteristics
    - Relation to other elm types
    - Quantized (dithering/fluct)
    - Underlying physics
- Eda/ef comparison
    - Typical traces
    - High beta elms
    - TauE
    - Tauimp
    - Fluctuations, density, magnetic
- Boundary
    - Ip scan – time trace
    - Ip scatter plot
    - Bt scan – time trace
    - Bt scatter plot
    - Delta scan – time trace
    - Equilibrium series for delta scan
    - Delta scatter plot
- Delta vs po
- Neutral effects
    - Confinement deterioration
    - Mode rotation damping
- Dithering

Rotation

Intro

Diagnostics

Typical time traces

Er and neoclassical calculations

Profiles of Vphi, Er

Scalings

- Vs W for both L and H
- Time traces for current dependence
- Scatter plot and vs current

Theory

Effects on confinement

♦ TOPICS KEEP FOR APS!

Intro to cmod and eda hmodes

Steady last duration of RF pulse, no sign of change, approx 10 tauE

Halpha ambiguity

Comparison with JET LPC, jt60 high triangularity, d3d type II elms

Small high beta elms

Eda confinement and fluctuation properties

Eda boundaries and possible physics

Triangularity, ip and pressure/density effects

Relation to mhd stability

Connor model/ peeling mode stability

Higher collisionality in C-Mod edge

Edge current density – effects of pressure gradients and collisionality (see miller)

Neutral effects

Experiment – confinement degradation, mode rotation slow down

Source – main chamber, see umansky results, owens and carerras

Neutrals inside separatrix follow Po

Cause or effect, higher taup (in elmfree) means lower source rate => fewer neutrals

Why does halpha drop at L/H transition

EDA development in time/transient, development of barrier and pedestal

Impurity effects, halpha response to imp injection, prad effect

Relation to observations on other machines

Lpc hmode

Type II ELMs

Jt60 small elms

Dithers between eda and elmfree

Discussion of type I elms in cmod

Since seen in all other machines, no reason to think that it would be excluded a priori from cmod

Perhaps not seen because of edge parameter trajectory

Hypothesis that elmfree hmodes sit at ballooning limit while J(a) evolves toward peeling boundary

For cmod, impurity accumulation might take place faster? Since particle and current diffusion

Should have similar spatial dependence – hard to see why there would be a difference from one

Machine to another. Perhaps its due to high Z impurities – more radiation and cooling?

Pedestals

stability

rotation

origin and scaling

effects on confinement