Enhanced Performance in Alcator C-Mod

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Enhanced Performance in C-Mod

- **High divertor heat and particle flux**
  Wall particle sources dominate
  Detached H-mode reduces heat flux

- **Internal Transport Barriers – AT modes**
  Pellet Enhanced Performance
  Enhanced neutron mode

- **Fast Particle Driven Modes**
  Current rise Toroidal Alfvén Eigenmodes
  Alfvén eigenmodes in EDA H-mode

- **H-mode threshold studies**
  Global and local edge scalings at high nB
  Hysteresis in the threshold power

- **Particles, Momentum and Energy**
  High confinement modes
  Ohmic and ICRF rotation
  Peaked densities in H-mode
  Extrapolated performance

High Divertor Heat and Particle Flux

- **Wall particle flux dominates the divertor**

  Most particles go to the wall with very little communication with the divertor

  Particle diffusion coefficient increases with radius in the SOL outside the LCFS

  At a fixed R, diffusion coefficient increases with collisionality

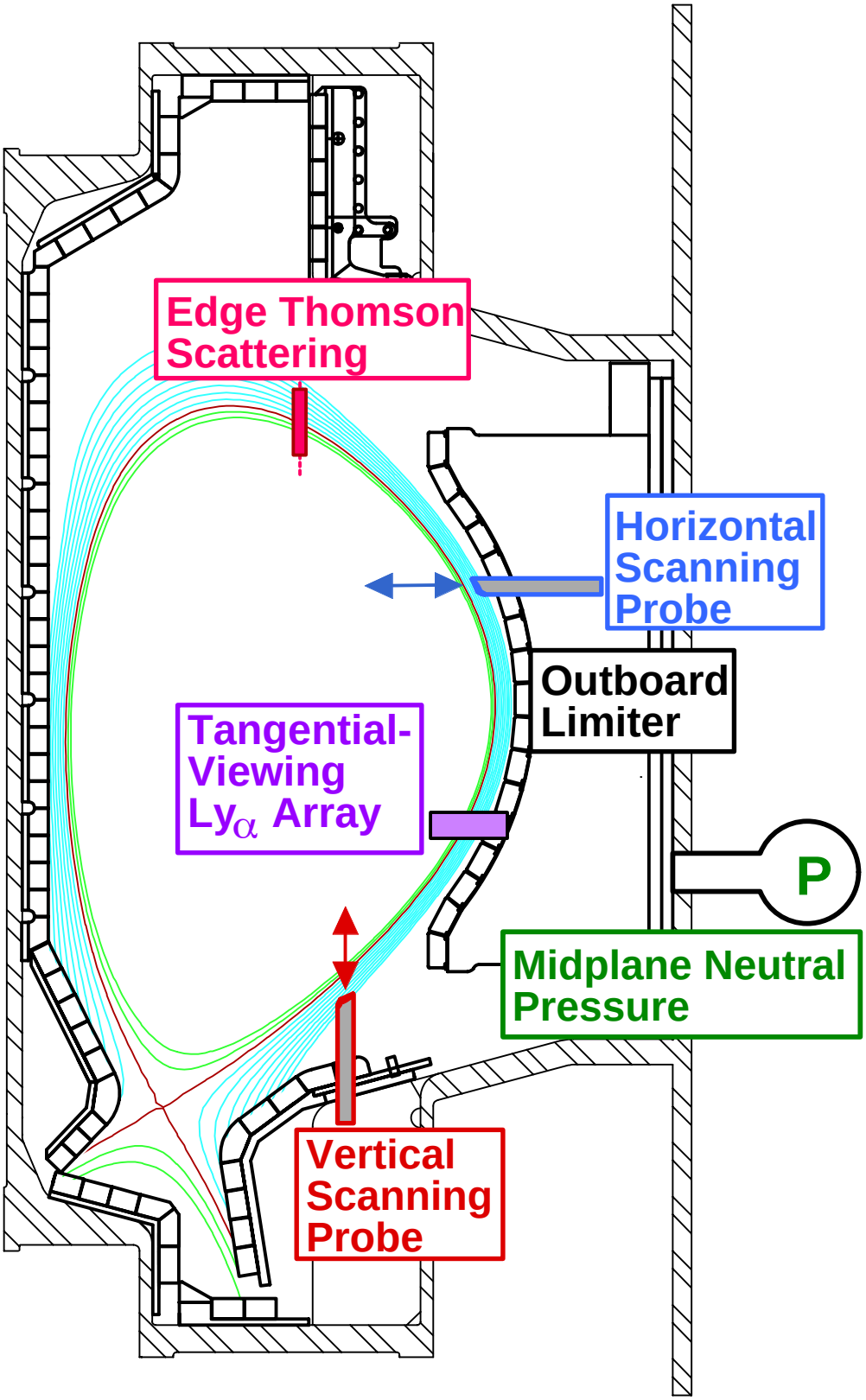
- **Detached H-mode reduces heat flux**

  Steady-state detached Enhanced D_α H-mode achieved with nitrogen puffing

  No impurity accumulation with reasonable confinement $H_{ITER89P} = 1.6$, $Z_{eff} = 1.4$

  Nitrogen puffing produces a radiative divertor and a radiative mantle

Diagnostics for Particle Transport Analysis in Main Chamber Scrape-of Layer



Density & Te Profiles:

Edge Thomson
Scanning probes

Ion Flux to Outboard Limiter:

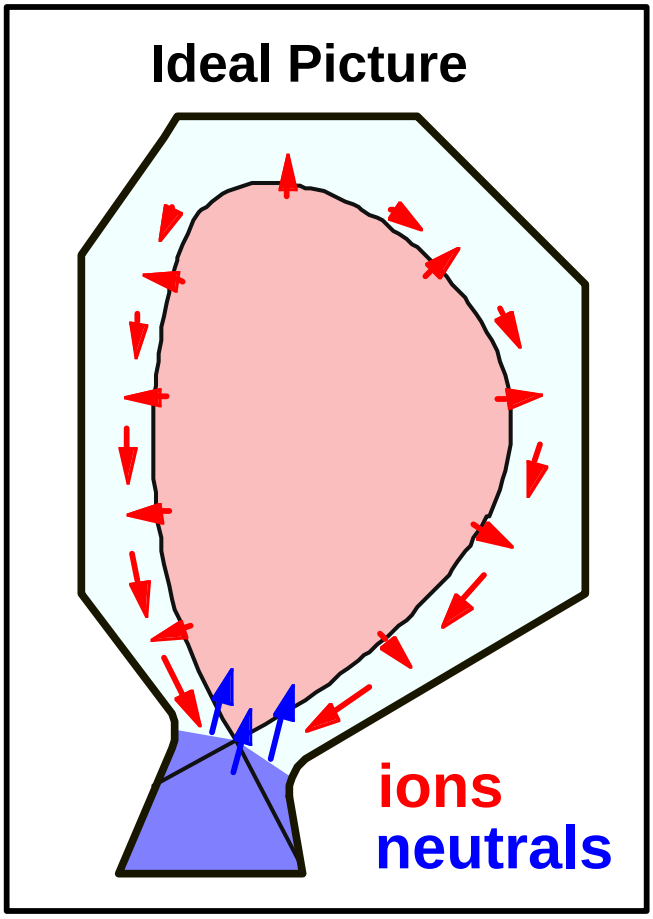
Scanning Probe
Neutral Pressure

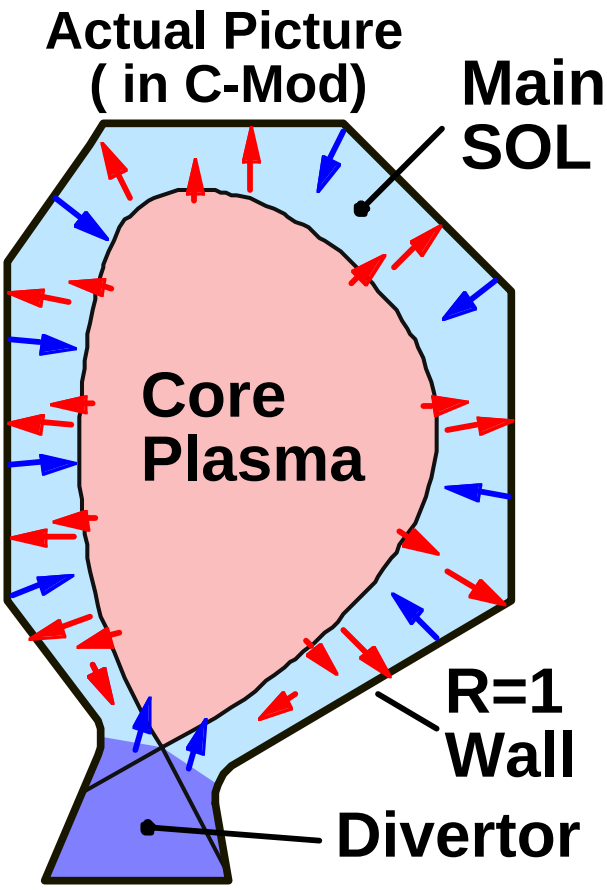
Ionization Source Profile:

Ly$_\alpha$ Array

Ion Flow towards Divertor:

Mach Probe





Summary:

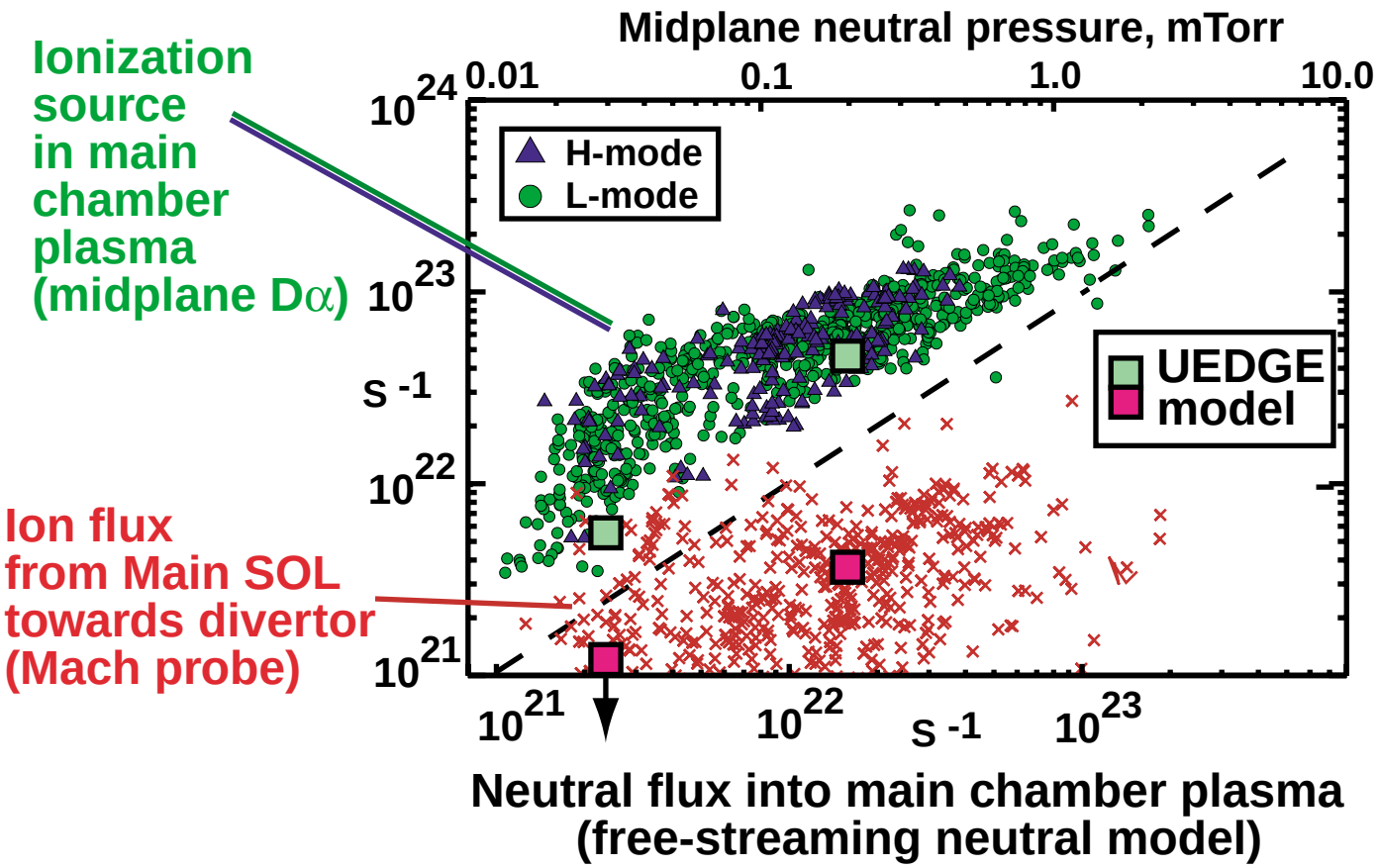
- Particle balance in Main SOL is maintained primarily by a 'radial' ion-neutral flux balance

feedback?

- Anomalous cross-field plasma transport rapidly grows with distance from separatrix
- 'Mid-plane' neutral pressure is set by level of anomalous ⊥ plasma transport, not geometry!
- ⊥ convection and CX important in Main SOL, can impact heat loss through separatrix

=> Will this be the operating regime of a reactor?!

Ionization Source in Main Chamber Plasma Exceeds Plasma Flow Towards Divertor Throat in Alcator C-Mod



> 500 discharges: $0.35 < I_p < 1.1$ MA, $0.7 < \bar{n}_e < 4.8\times10^{20}$ m^{-3}, $2.8 < B_T < 7.9$ tesla, L & H-mode

- **Main chamber ionization source exceeds plasma flow towards divertor throat by an order of magnitude**

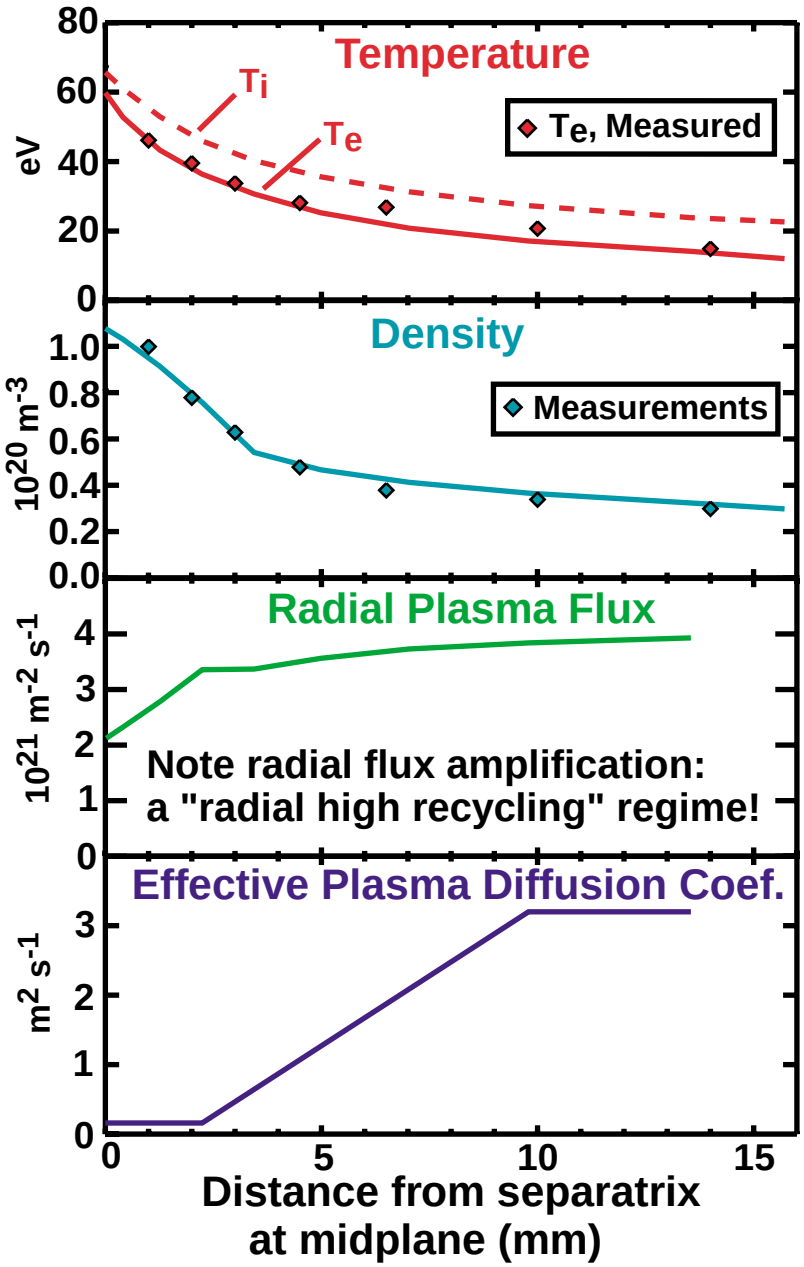
-> Main SOL recycles primarily on the "walls"

-> Divertor and Main SOL recycling are separate!

- **Conclusions supported by UEDGE modeling.....**

Radial Plasma Flux In Main SOL Must Increase with Distance from Separatrix

Illustrative Results: UEDGE Simulation, High P_{mid}

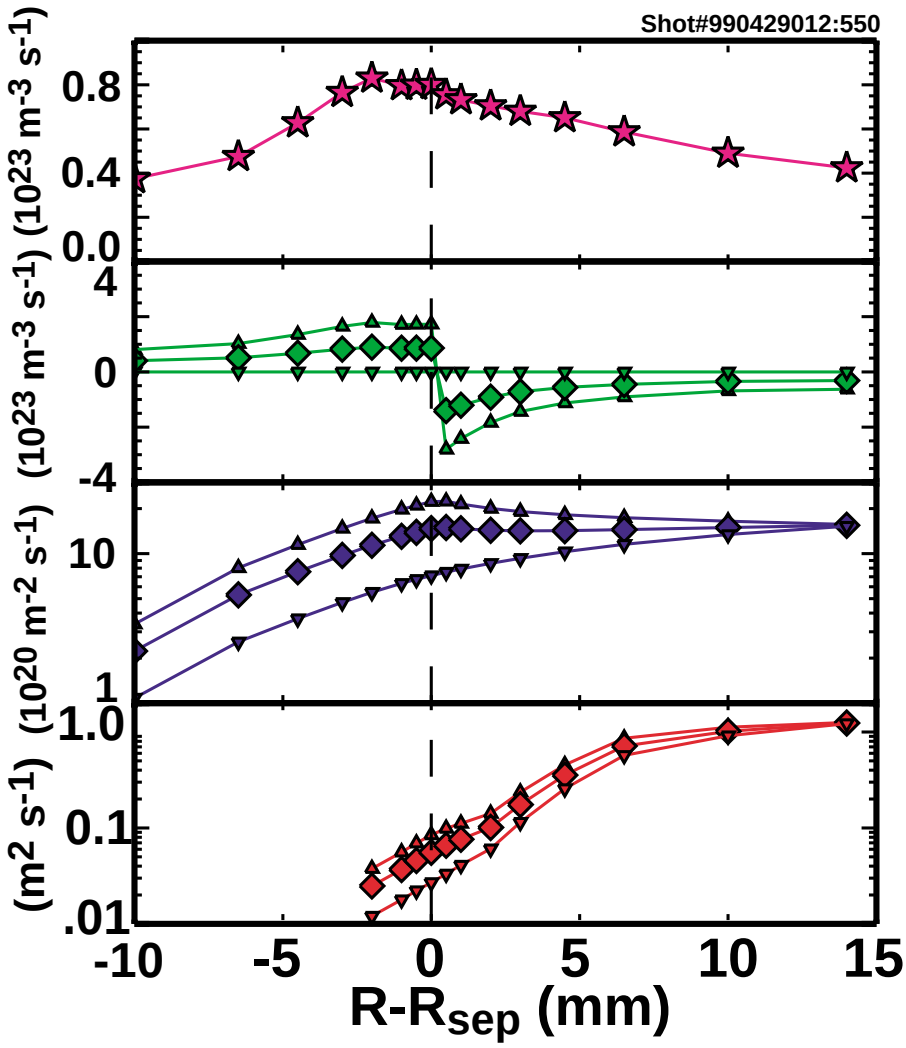


- "Exponentially" decreasing Density profile is measured
- Yet, radial plasma flux (Γ) must increase to balance SOL ionization source!

=> if $\Gamma = -D \nabla n$, then "diffusion coef." must increase strongly across SOL!

=> Wall (midplane) neutral pressure is set more by magnitude of anomalous plasma transport than by divertor/wall geometry!

Inferred Cross-Field Diffusion Coefficients are Not Sensitive to Parallel Divertor Flows



- Ionization Source Profile
- Possible Parallel Flow Source/Sink Profiles
- Radial Flux Profile, $\Gamma_\perp = \int \text{source}\ \delta R$
- Effective Diffusion Coefficient, $D_{eff} = -\Gamma_\perp/\nabla n$

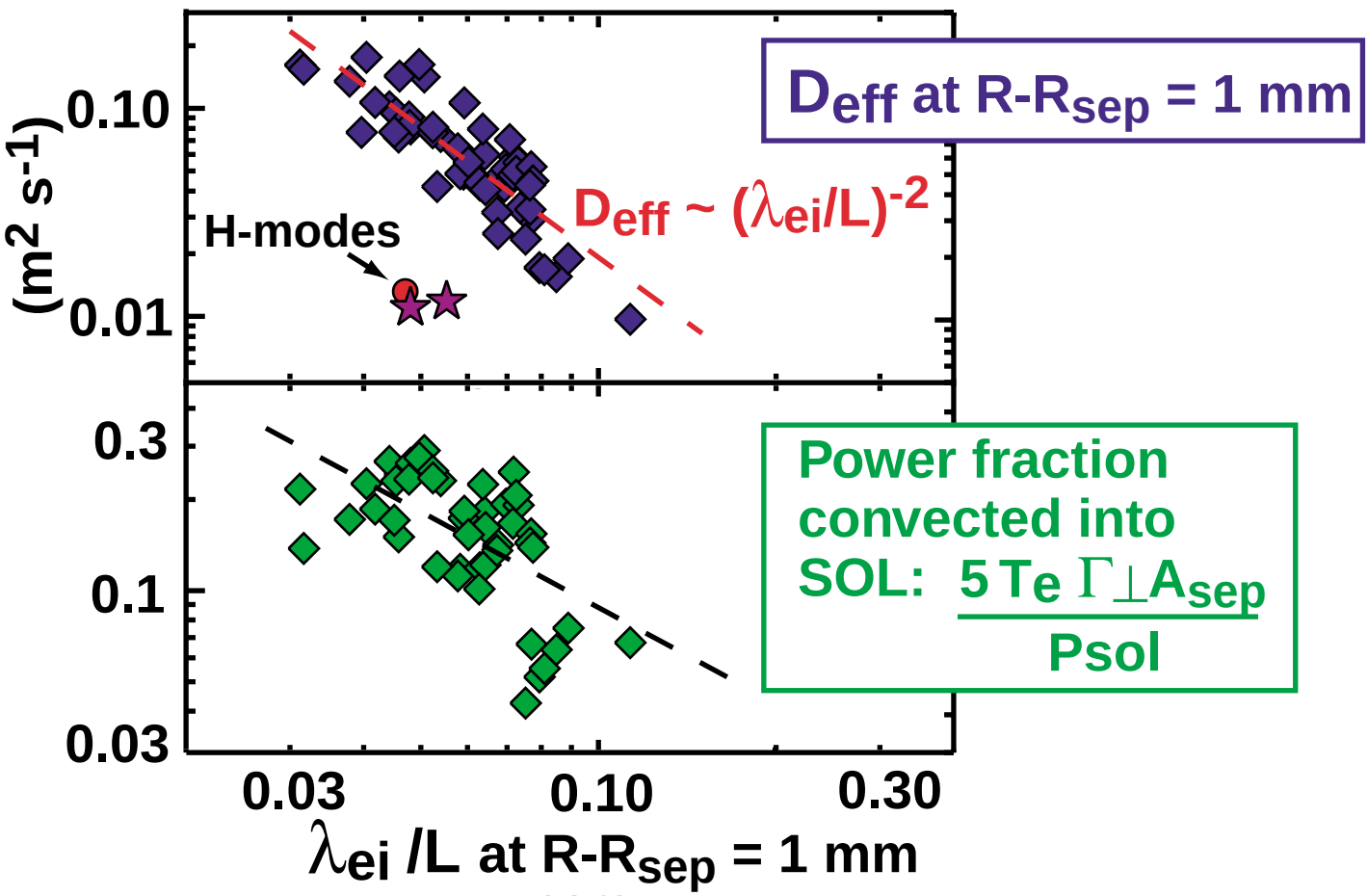
Divertor/Wall Sink Ratio:	△ = 1.0
	◇ = 0.5 ~ measurement
	▽ = 0.0

- D_{eff} at separatrix changes by only 50% in doubling divertor/wall sink ratio from 0.5 to 1

=> Clear trend of D_{eff} increasing by 10 or more with distance from separatrix

D_{eff} at Fixed Location Increases with Collisionality in Scrape-off Layer

Data from ohmic L-mode density scan



High ← core density → Low

$N/N_G \sim 0.35 \longleftrightarrow 0.1$

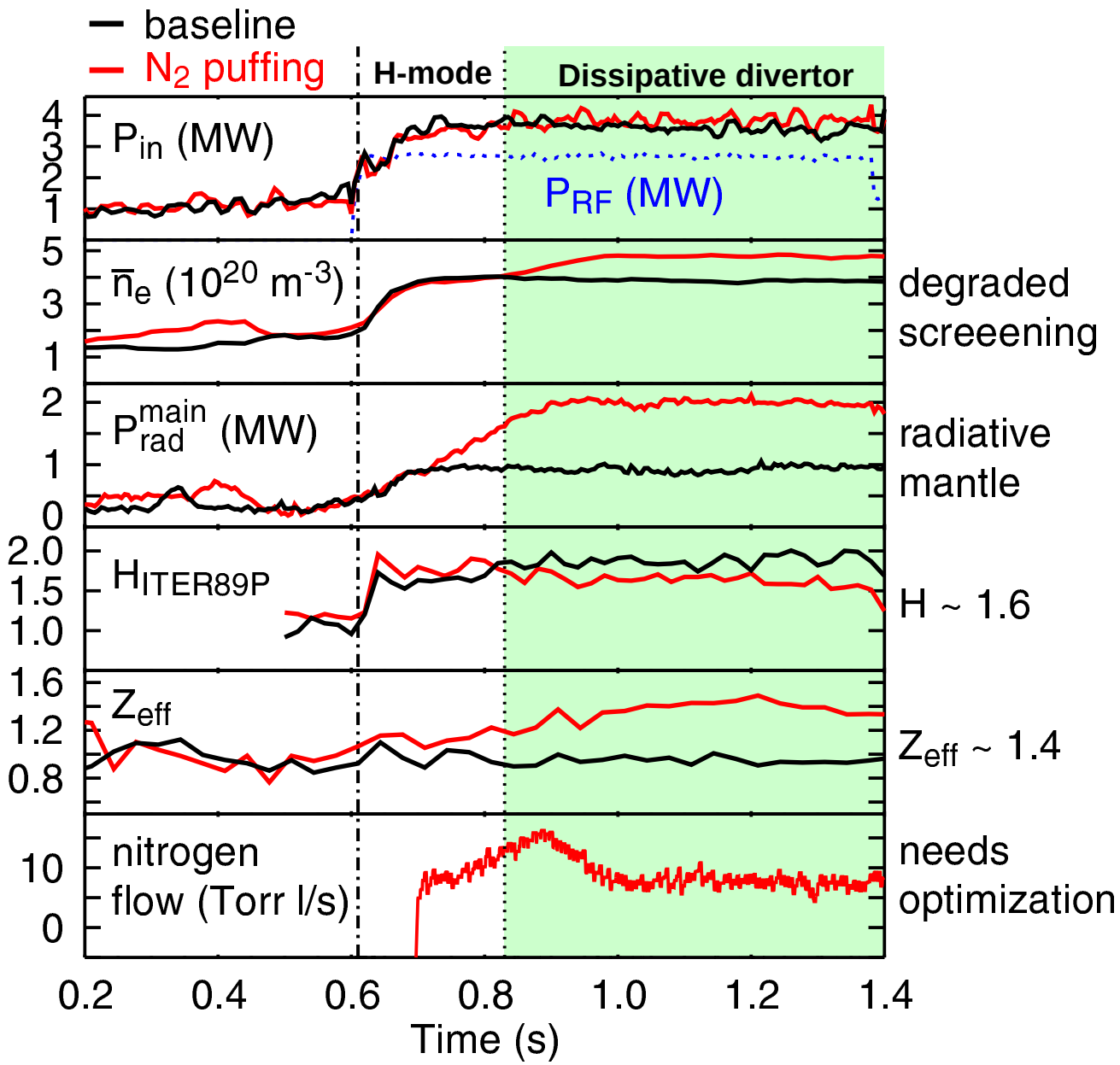
- D_{eff} in H-mode discharges is factor of ~5 smaller than L-mode at same collisionality

- As collisionality increases, ⊥ heat convection across separatrix becomes more important in SOL power balance

positive feedback

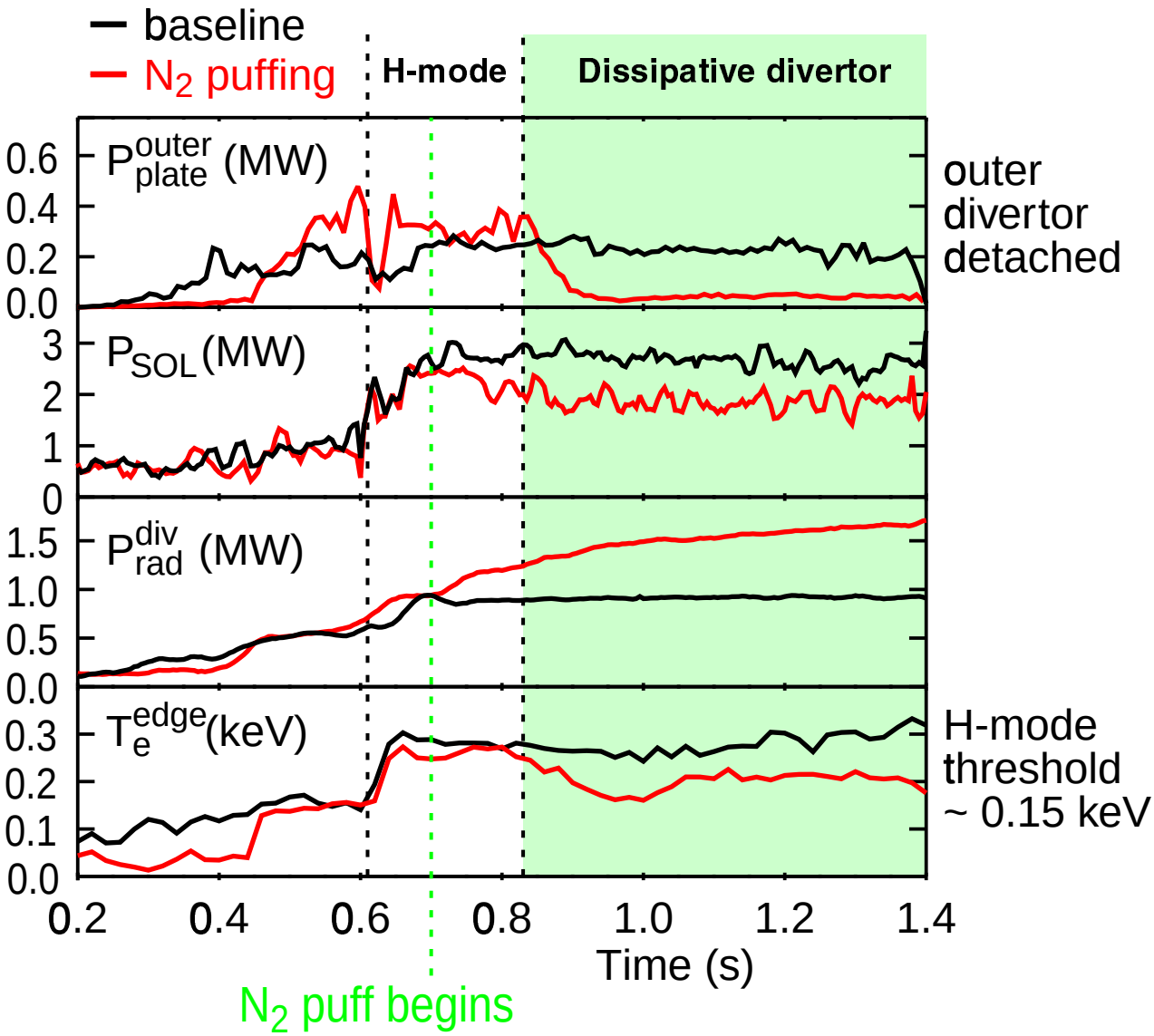
=> Suggests a direct link between scaling of anomalous particle transport and existence of a discharge density limit

Steady-state dissipative divertor H-mode has been achieved with N_2 puffing



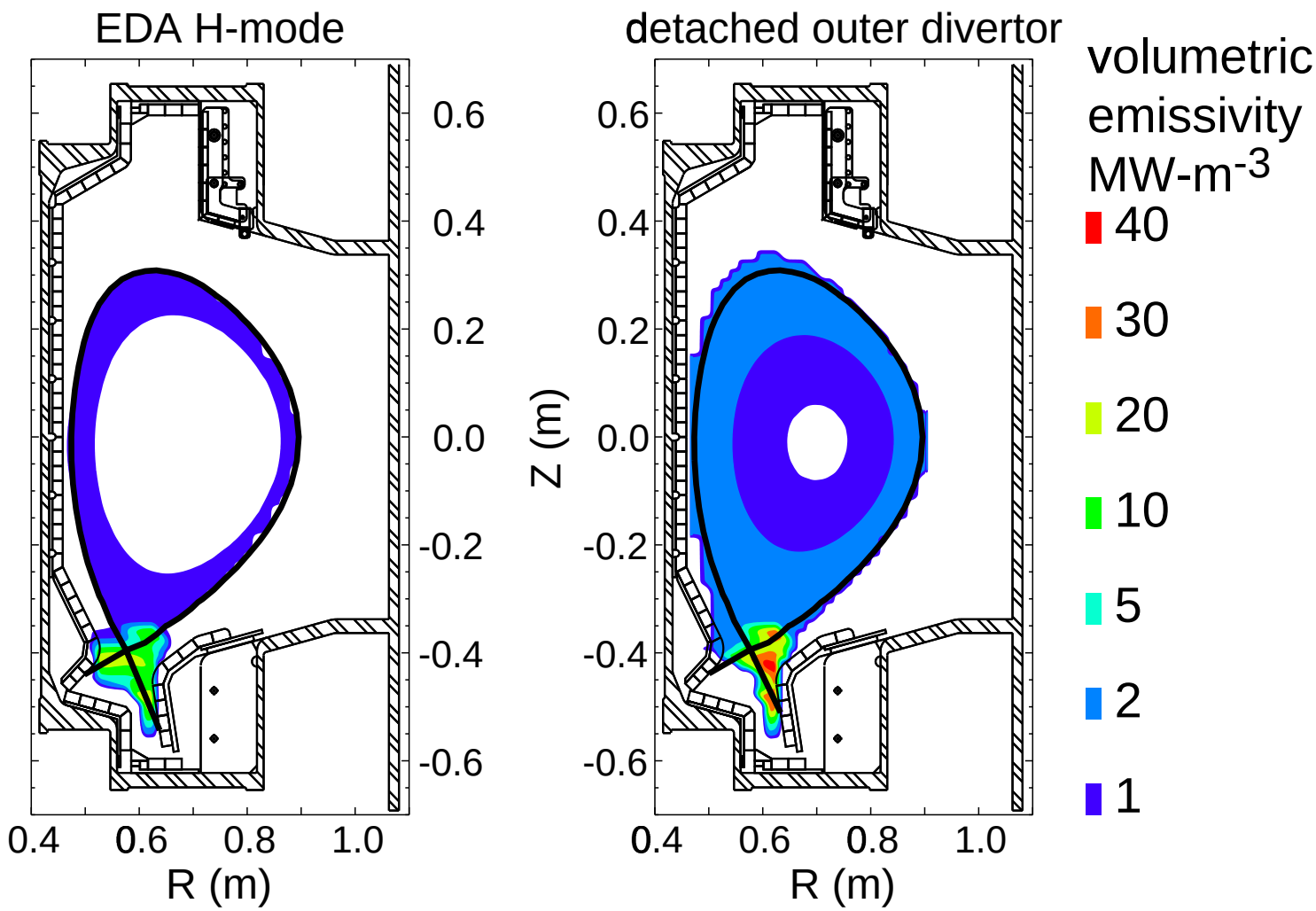
- EDA H-mode is essential for experiment
  - no ELMS
  - no impurity accumulation

Steady-state dissipative divertor H-mode has been achieved with N_2 puffing



- $q_{||}^{SOL} \geq 0.55$ GW-m^{-2} before; ~0.45 GW-m^{-2} after
- $q_{||}^{plate} \sim 0.40$ GW-m^{-2} before; ≤ 0.05 GW-m^{-2} after
- inner divertor appears attached

Nitrogen puffing produces a radiative divertor and a radiative mantle



- Divertor emissivities are 20x those of the main plasma
- Bolometers: core - Abel inversion; divertor - tomography

— SUMMARY —

- Alcator C-Mod has produced steady-state dissipative divertor, high-confinement plasmas using nitrogen puffing.
  - clean core plasma, $Z_{eff} \sim 1.4$
  - good core energy confinement
  - high radiated power fraction, $P_{rad} / P_{in} \geq 0.9$
  - high heat flux, $q_{||}^{SOL} \geq 0.45$ GW / m^2

- Detached divertor characteristics:
  - particles: – volume recombination reduces ion flow under some conditions
    – ion source reduction reduces ion flow under detached H-mode conditions
  - pressure: – measured $v_D / v_{ion} \sim 0.3 \Rightarrow$ good ion-neutral momentum transfer
    – loss explained by friction
  - power: – reduced to low levels by radiation
    – radiation location in divertor is important
  - pedestal: – low Z impurities better for energy confinement
    – radiation location in core is important

Internal Transport Barriers – AT modes

- **Pellet Enhanced Performance**

  Internal transport barriers achieved transiently following Li pellet injection

  Calculated q profile has reversed shear

  Enhanced neutron rates with peaked density profiles in PEP mode

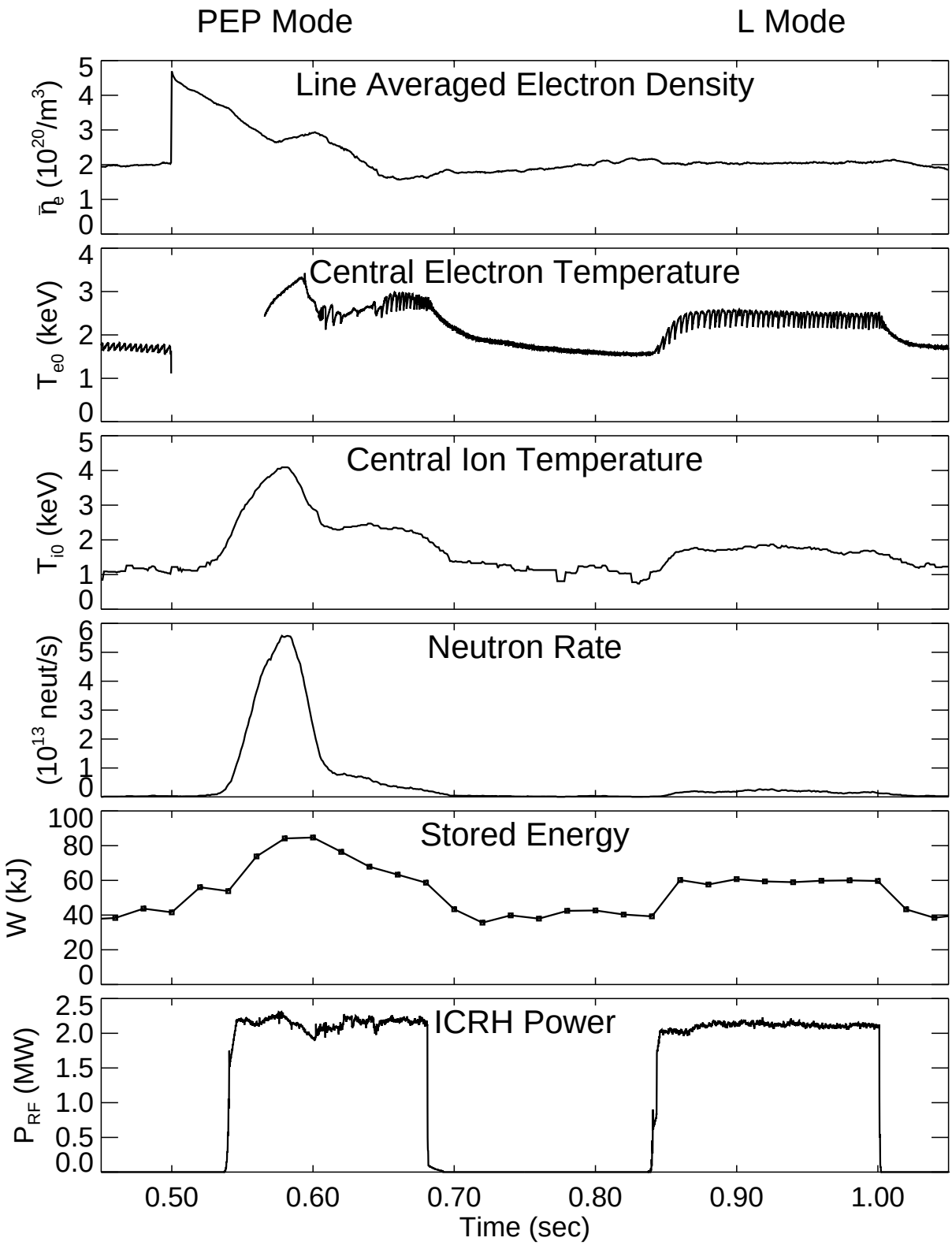
- **Enhanced Neutron Mode**

  Spontaneous increase in neutron rate just after H-L transitions

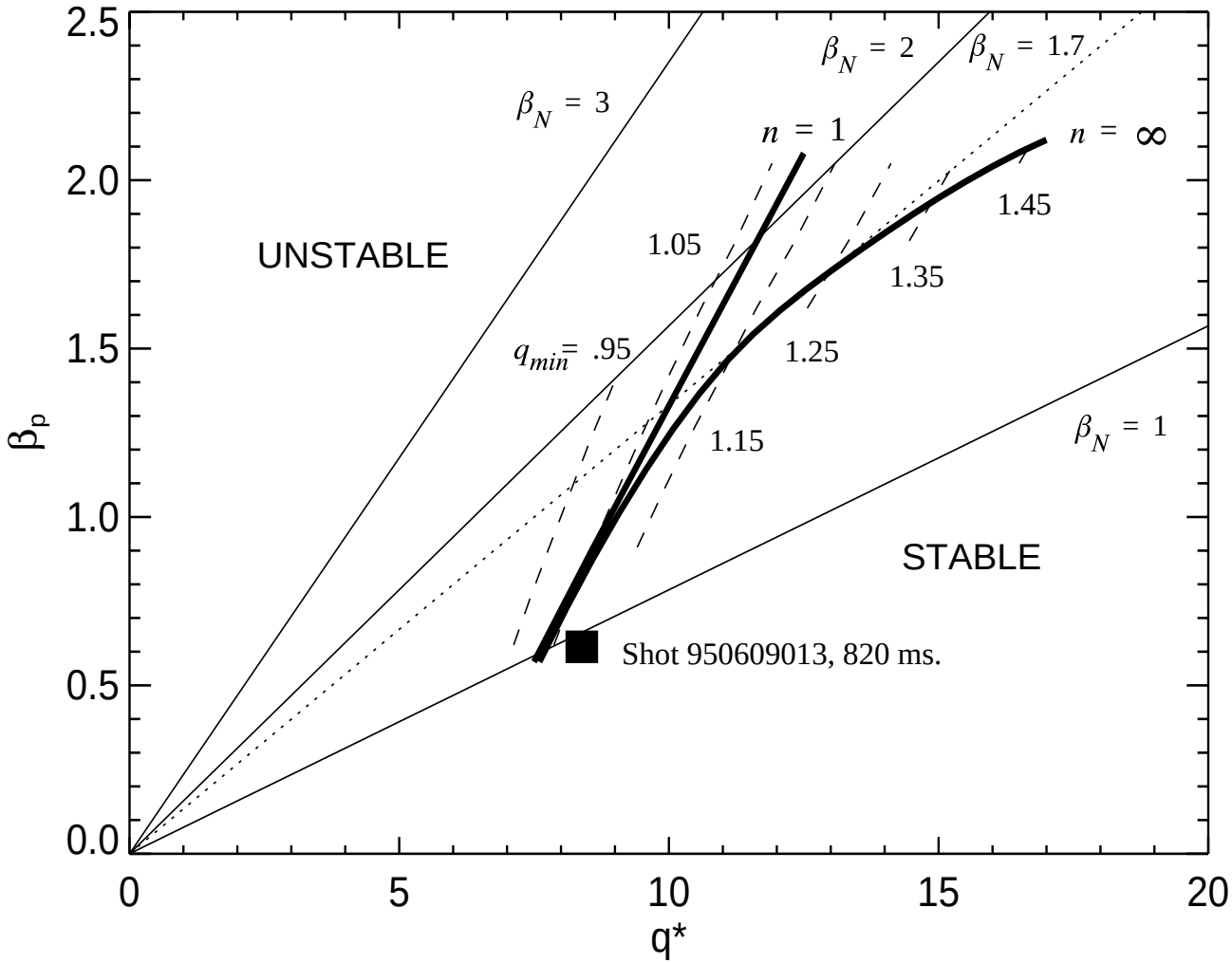
  H-mode edge transport barrier appears to move into the q=1 surface then collapses

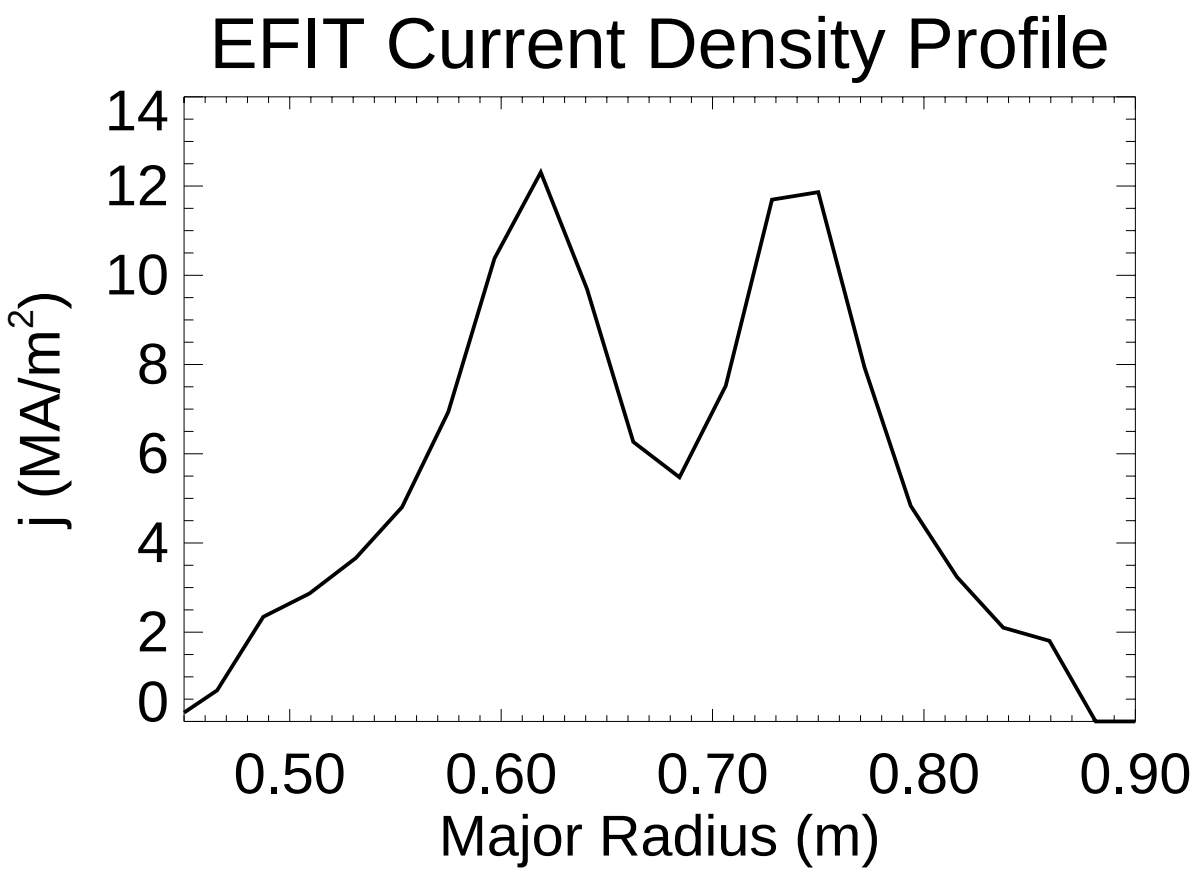
  Collapse often associated with a large oscillating m=1, n=1 mode

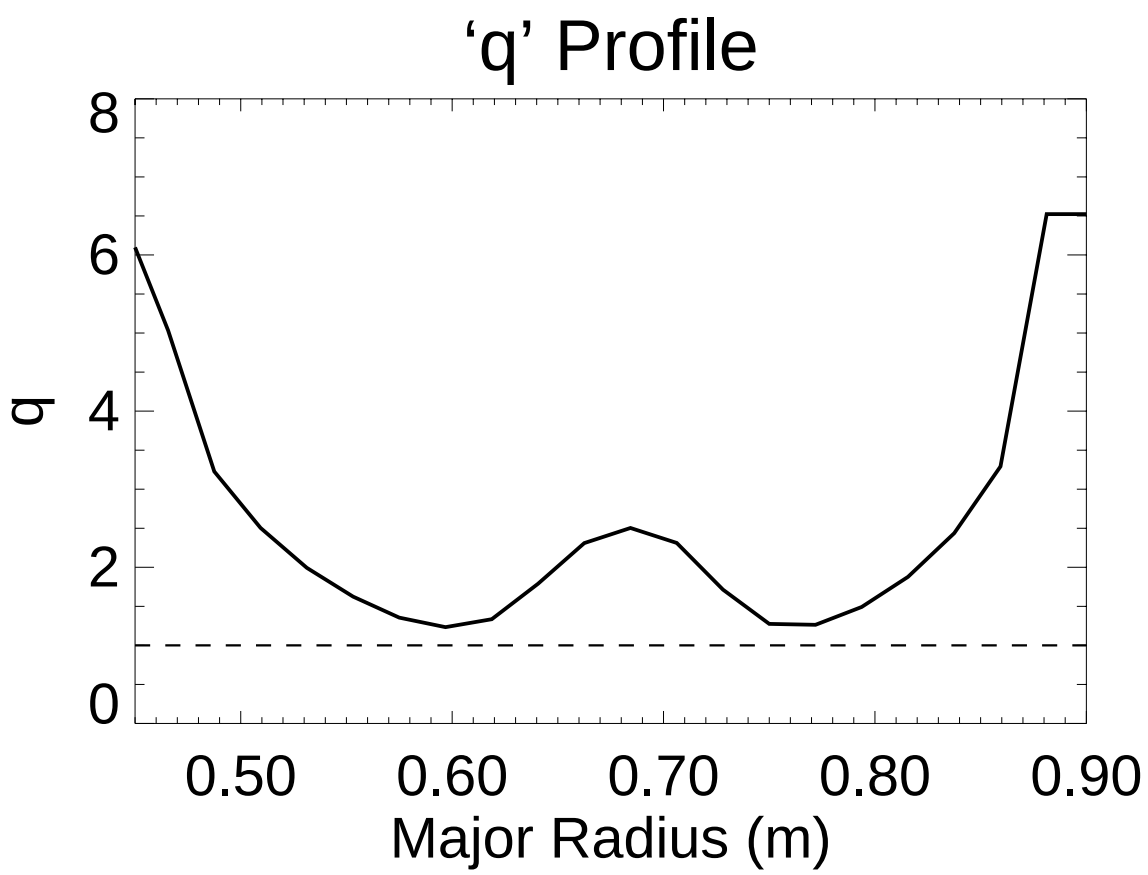
  Increased neutron rate follows from temperature peaking after H-L transition

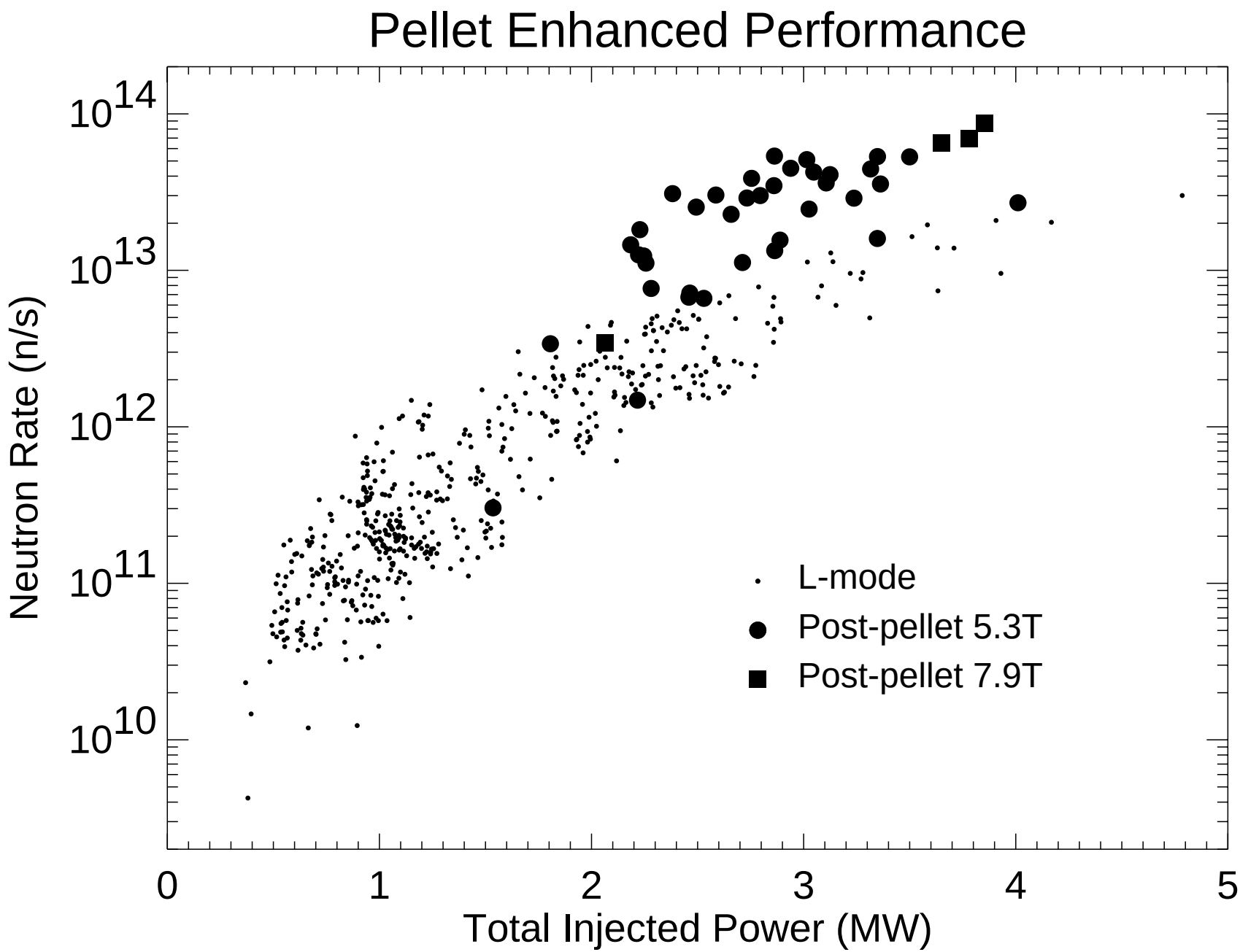

PEP Mode
L Mode
Line Averaged Electron Density
$\bar{n}_e$ (10^{20}/m^3)
Central Electron Temperature
T_{e0} (keV)
Central Ion Temperature
T_{i0} (keV)
Neutron Rate
(10^{13} neut/s)
Stored Energy
W (kJ)
ICRH Power
P_{RF} (MW)
0.50
0.60
0.70
0.80
0.90
1.00
Time (sec)

Ideal MHD Stability Analysis of PEP mode

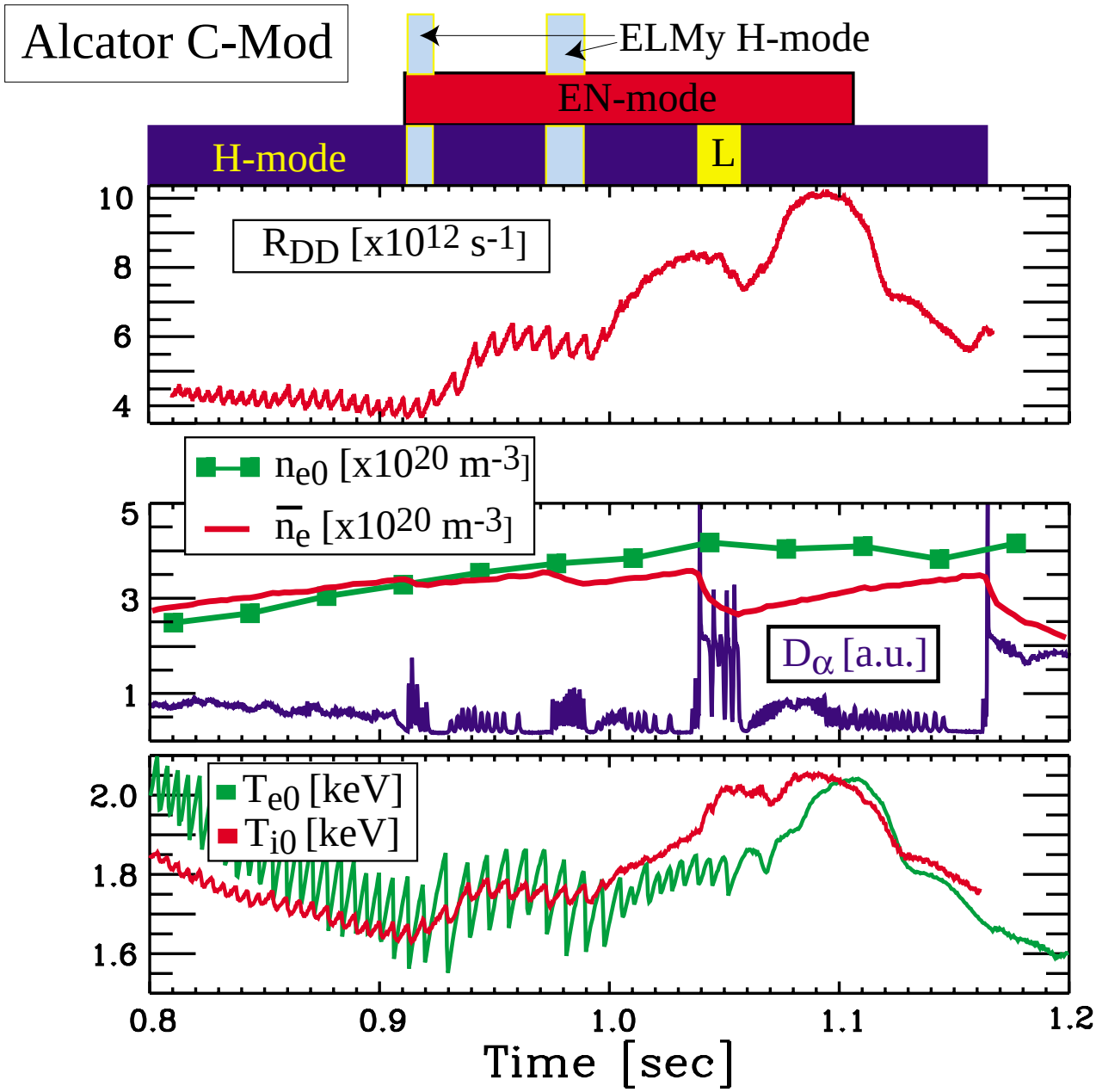



EFIT Current Density Profile
j (MA/m^2)
0
2
4
6
8
10
12
14
0.50
0.60
0.70
0.80
0.90
Major Radius (m)


'q' Profile
q
0
2
4
6
8
0.50
0.60
0.70
0.80
0.90
Major Radius (m)

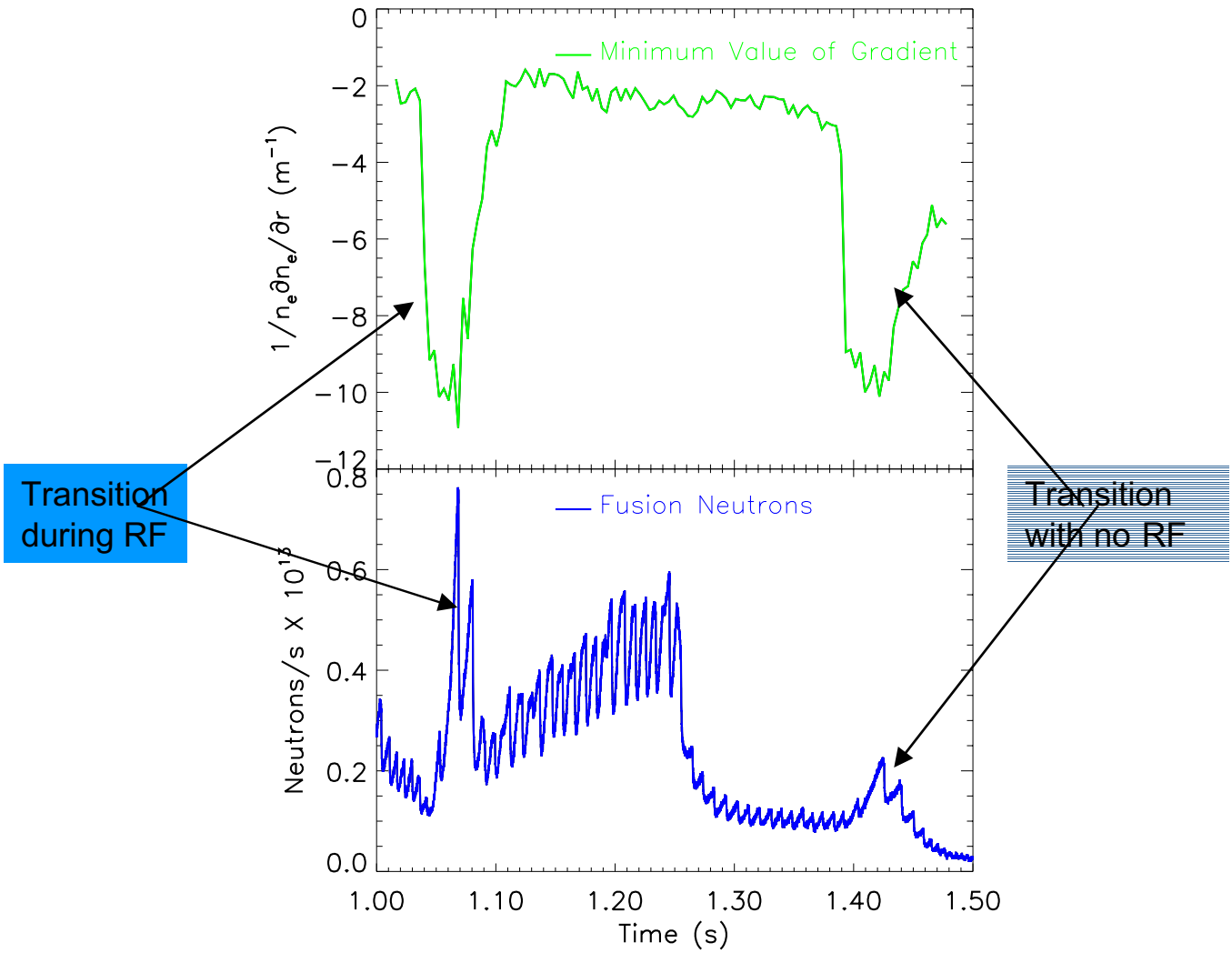

Pellet Enhanced Performance
Neutron Rate (n/s)
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
0
1
2
3
4
5
Total Injected Power (MW)
L-mode
Post-pellet 5.3T
Post-pellet 7.9T

Enhanced Neutron (EN) Mode with Off-axis D(H) Heating



- Central density remains approximately constant (<20% increase) with decrease in average density.
- T_e and T_i increase.

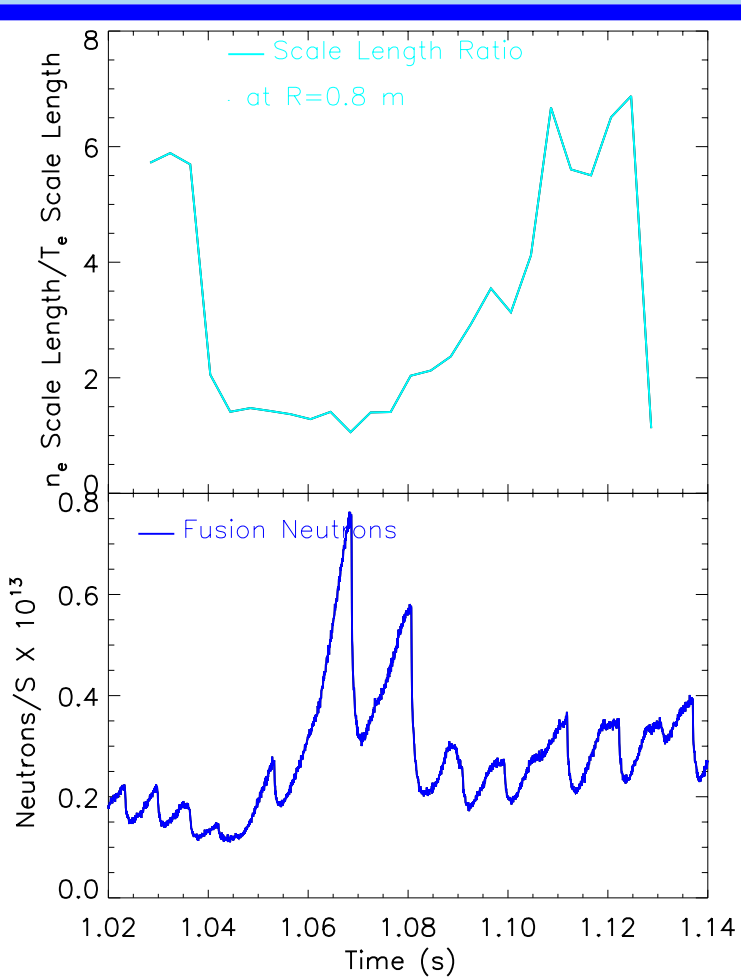
The Enhanced Neutron Mode Occurs at the H to L Back Transition when the Density Gradient Halfway out Becomes Steep



There are two back transitions shown on this shot, and the fusion neutron rate increases accordingly. The first occurs during RF heating, and the second after the RF power is off. The largest negative density gradient corresponds to the peak in the neutron rate.

Courtesy of C. L. Fiore

Neutron Rate Rises when the Ratio of the Density Scale Length Divided by the Electron Temperature Scale Length is Near 1.



The ITG instability should be stable when the ratio of the density scale length to the ion temperature scale length is at or below 1. Ion temperature profiles with fast time resolution are not available, so the electron temperature scale length is compared with the electron density scale length here, in the hope that the ion temperature profile behaves in a similar manner.

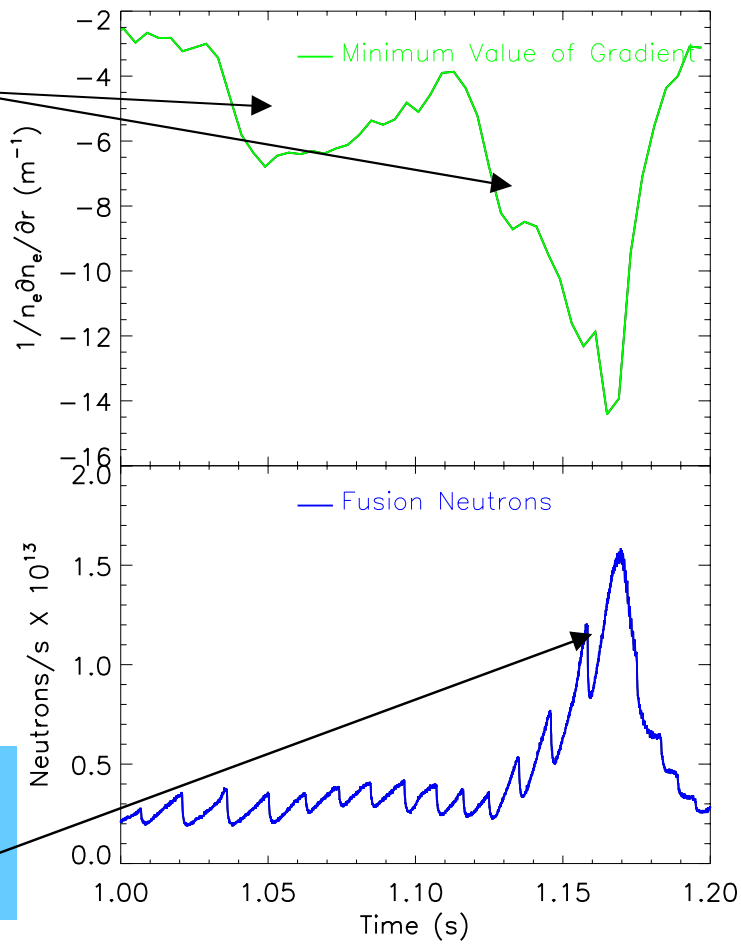
Courtesy of C. L. Fiore

An increase in the neutron rate is not triggered unless the the density gradient is sufficiently steep.

Two back transitions occurred on this shot.

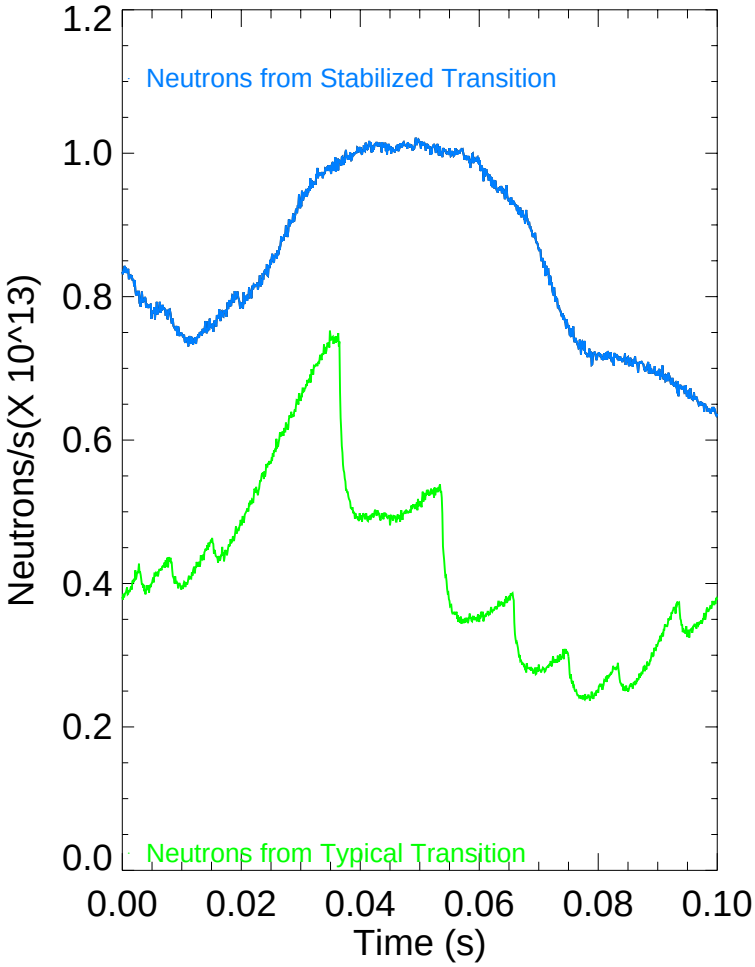
The density gradient becomes steeper for both.

Only the larger gradient results in a neutron rate increase.



Courtesy of C. L. Fiore

Mode lasts longer when off axis RF power injection is used to stabilize sawtooth oscillations



Two examples of neutron rate increases following an H to L back transition are shown. In the upper trace, off-axis RF heating was used to stabilize sawtooth oscillations, and the mode persisted nearly twice as long as in the lower trace, a more typical event.

Courtesy of C. L. Fiore

Fast Particle Driven Modes

- **Current rise Toroidal Alfvén Eigenmodes**

  Strong ICRF heating in the current rise leads to low or reversed shear and excites TAE modes

  Single or multiple low n = 2 - 3 modes observed with rapidly increasing or decreasing frequency from 150 – 450 kHz

  Calculated fast ion distribution peaks ~ 150 keV

- **High frequency modes in EDA H-mode**

  Strong ICRF heating at high density ~ 2 - 3 $\times 10^{20}$ m^{-3} usually only excites a single high n = 5 – 10 mode

  Frequency remains nearly constant ~ 600 kHz, consistent with TAE frequency at q=1

  Calculated fast ion distribution peaks ~ 50 keV with steep gradient near $r_{q=1}$ with sawteeth present

  Modes appear to rotate in the electron diamagnetic drift direction

H-mode Threshold Studies

- **International H-mode threshold database**

  C-Mod is only high field, high density machine in the database, so it plays an important role

  H-mode threshold power increases with density, toroidal field and machine size

  Including absorbed power fraction in C-Mod reduces the H-mode threshold scaling at high field and high density

  JET data indicate a ~25% reduction in threshold for D-T with respect to D-D plasmas

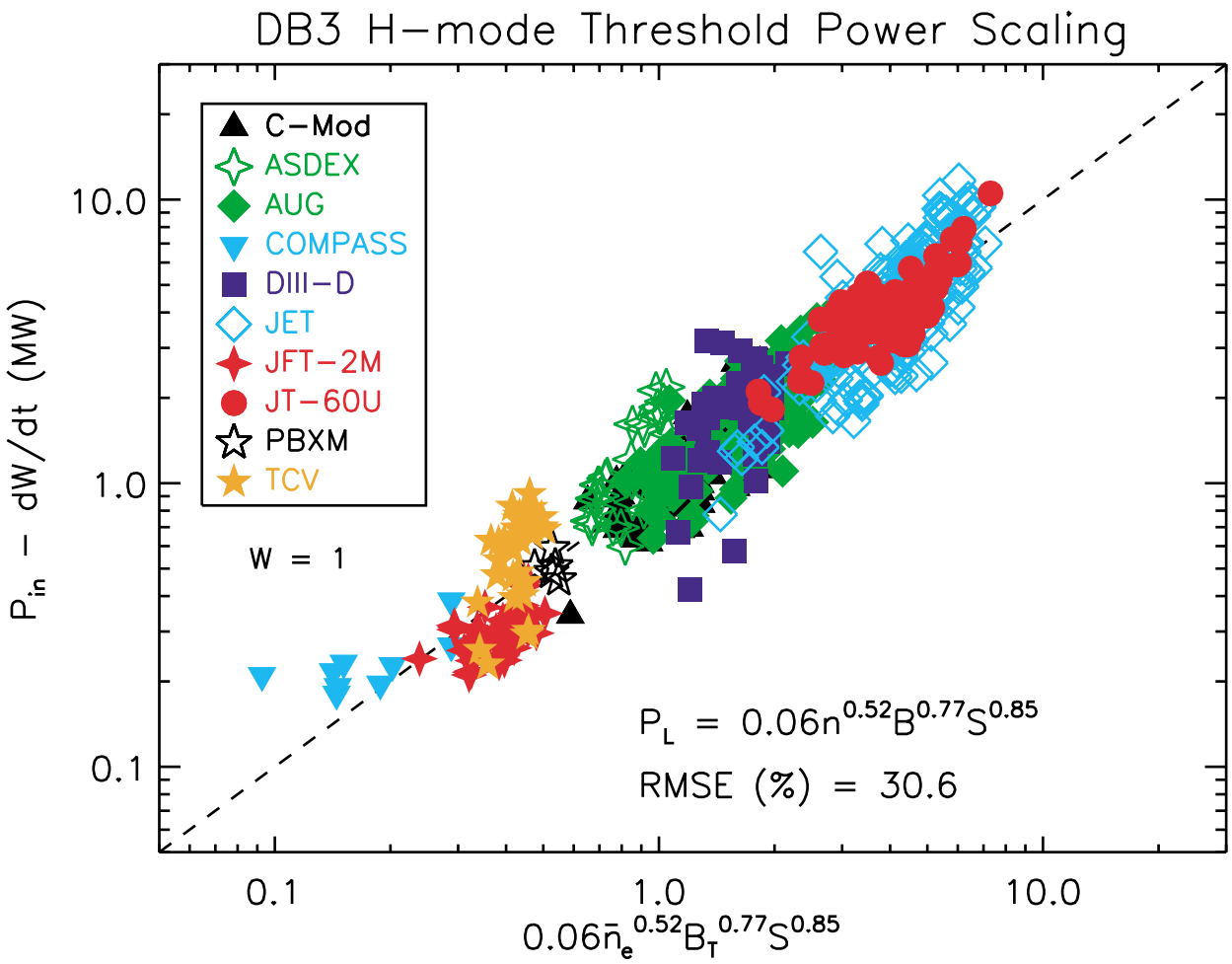
  Limited edge data indicate edge T_e threshold increases linearly with B_T and nearly linearly with machine size

  Factor of ~2 hysteresis in power threshold found in C-Mod with ramping ICRF power or ramping B_T in Ohmic H-mode

H-mode Threshold Cross-Validation Removing One Tokamak at a Time

$$P_{thresh} = C\, \bar{n}_e^{x_n}\, B_T^{x_T}\, R^{x_R}\, a^{x_a}$$

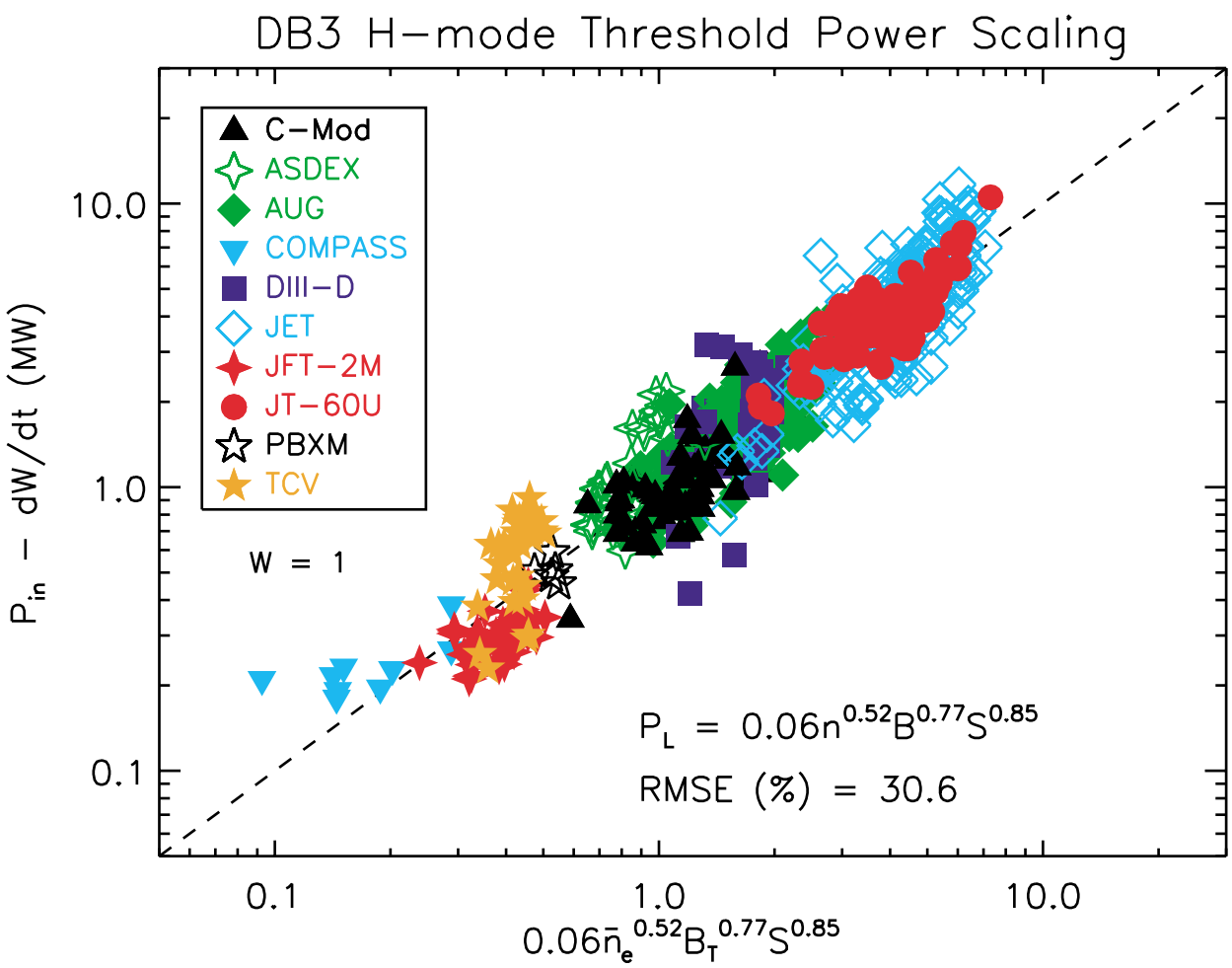
Tokamak (j)	Np (All-j)	RMSE All(j)	RMSE (j)	AVGE All(j)	AVGE (j)	RMSE (ALL)	RMSE (ALL-j)	C	x_n	x_B	x_R	x_a
ALL	787	30.4		4.1				1.87	0.57	0.74	0.83	0.93
C-Mod	668	23.6	41.8	3.4	38.9	31.8	29.7	1.95	0.57	0.98	0.56	0.99
ASDEX	750	33.7	35.5	11.3	13.9	30.6	30.4	2.01	0.59	0.72	0.80	0.98
AUG	634	23.9	23.9	2.6	2.8	30.4	31.8	1.86	0.56	0.75	0.82	0.94
COMPASS	778	59.8	71.1	44.6	55.2	31.0	30.3	1.73	0.61	0.75	0.94	0.88
DIII-D	715	29.6	30.3	4.9	5.5	30.5	30.6	1.87	0.60	0.72	0.88	0.91
JET	578	31.7	31.5	4.1	1.6	29.9	29.4	2.27	0.50	0.74	0.59	1.11
JFT-2M	725	25.1	38.7	-21.7	-37.5	29.4	28.5	1.45	0.53	0.66	1.05	0.64
JT-60U	706	21.5	25.5	6.0	11.3	30.9	31.5	2.14	0.62	0.69	0.80	0.99
PBXM	782	16.8	17.7	11.9	13.1	30.5	30.5	1.91	0.57	0.74	0.81	0.95
TCV	747	61.2	79.0	49.5	67.8	32.8	28.3	1.68	0.54	0.83	0.82	0.97
average	708	32.7	39.5	11.0	9.5	30.8	30.1	1.89	0.57	0.76	0.81	0.94



- Log-linear regression fit to L-H threshold data from all 10 tokamaks satisfying low threshold criteria (SELDB2) with line averaged density, toroidal field, and surface area in units of 10^{20} m^{-3}, T, m^2

- Equal weighting between points was used since equal weighting between tokamaks had somewhat higher RMSE

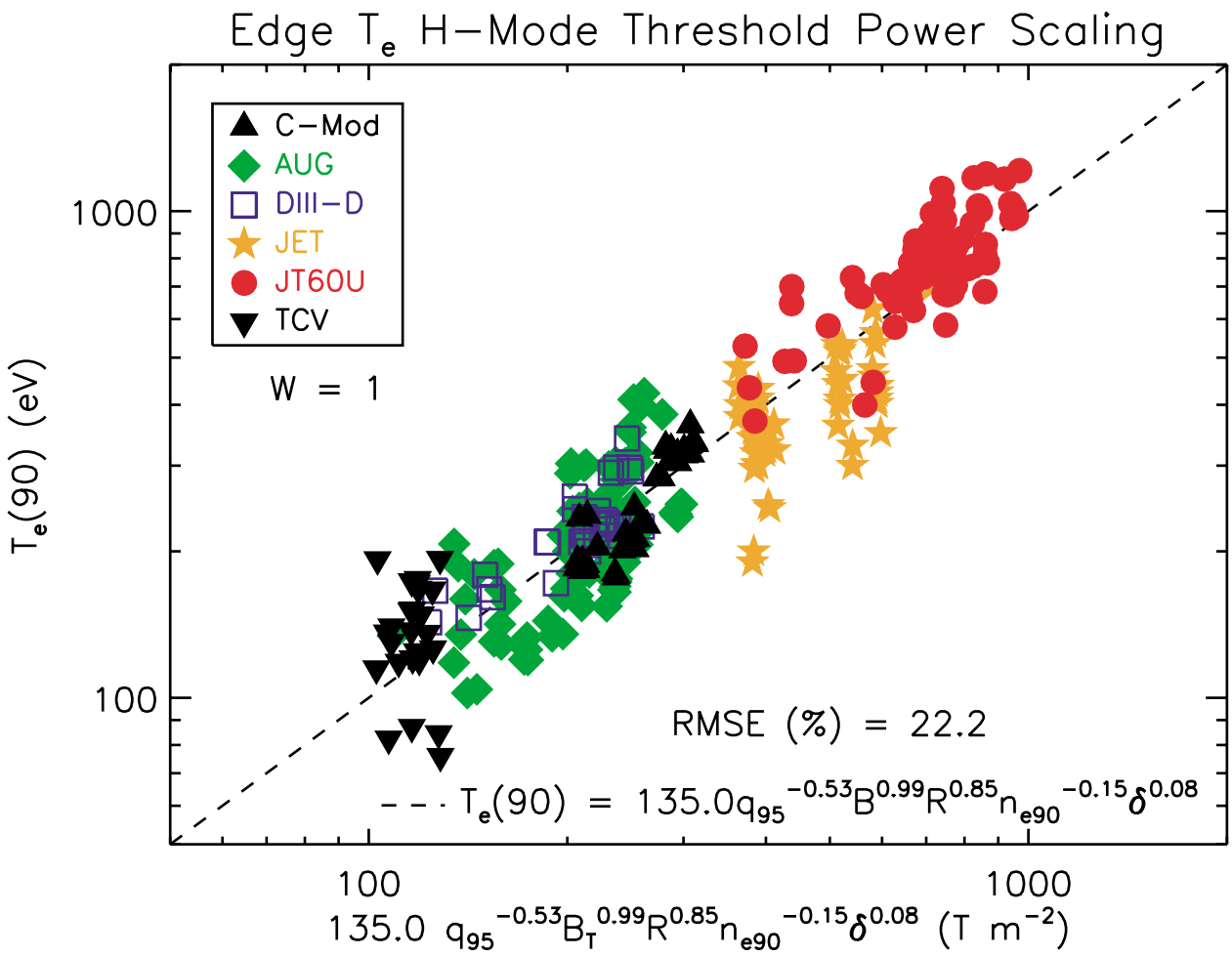
- Only D plasmas used though JET data show a 1/M dependence for hydrogen isotopes (H, D, T)



- Latest log-linear regression fit to deuterium L-H threshold data from all 10 tokamaks in the International H-mode Threshold database

- Alcator C-Mod plays an important role in the H-mode threshold scaling because of its unique high field and high density operating range compared to other tokamaks

- Predicted H-mode threshold in FIRE ~ 13 MW in D-T with a target density of 2 x 10^{20} m^{-3} and B_T = 10 T using 1/M dependence found in JET D-T experiments

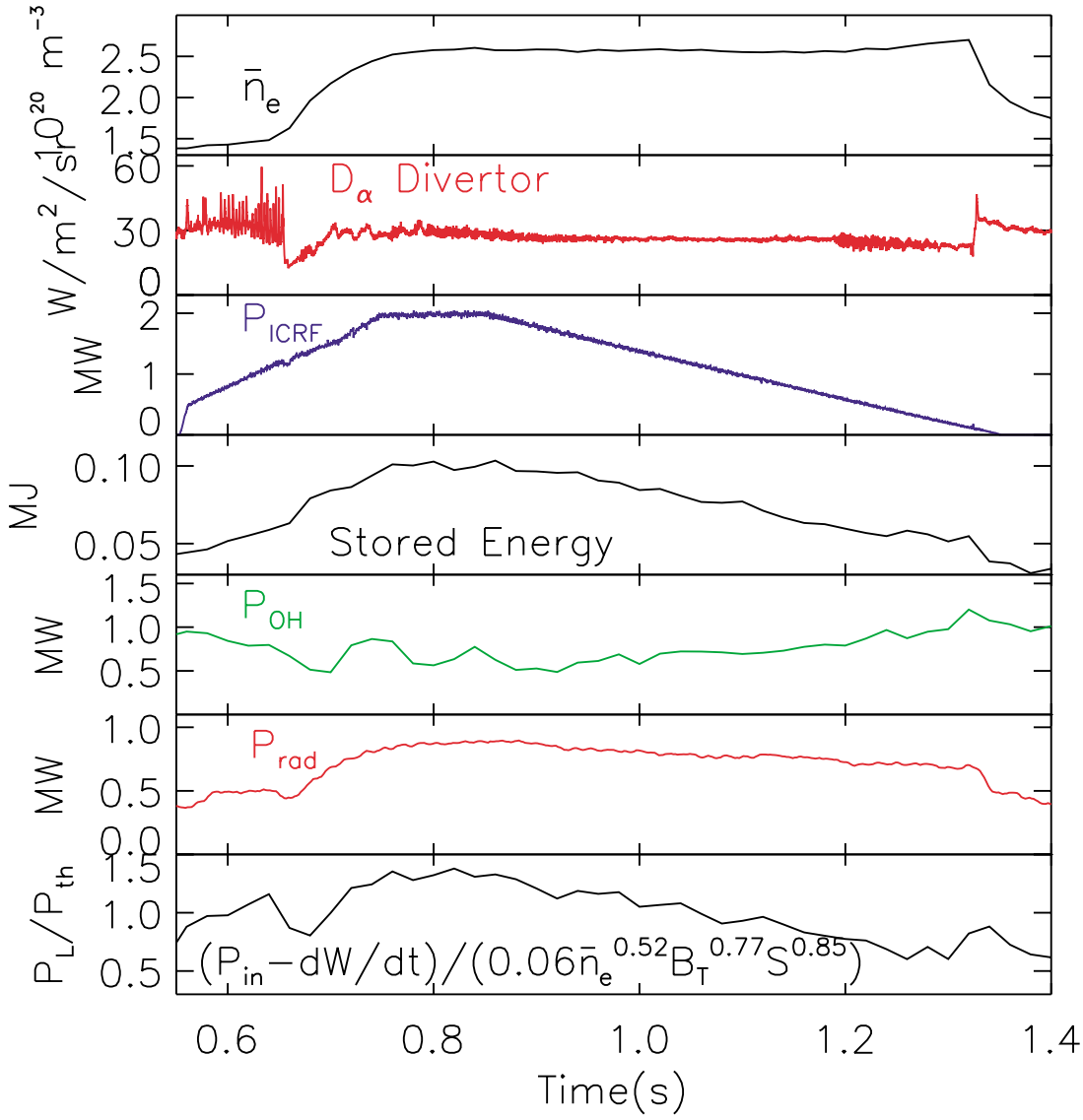


- Only six tokamaks have edge temperature data in the threshold database (C-Mod, AUG, DIII-D, JET, JT-60U, TCV)

- Edge T_{e90} at the H-mode threshold increases with B_T and R with a weaker inverse dependence on q_{95} and n_{e90} and a small positive dependence on triangularity

- Scaling agrees with general trends observed in the data given the large uncertainties in the edge measurements

Hysteresis in the H-mode Threshold with Ramping P_{ICRF} on Alcator C-Mod



- Enters H-mode at $P_L/P_{th} = 1$ but remains in H-mode down to $P_L/P_{th} = 0.5$ as the density increases and P_{ICRF} decreases

- Particle confinement remains high down to $P_L/P_{th} = 0.5$ as the energy confinement returns to L-mode

- Such hysteresis is not observed on JFT-2M or JT-60U

Particles, Momentum, and Energy

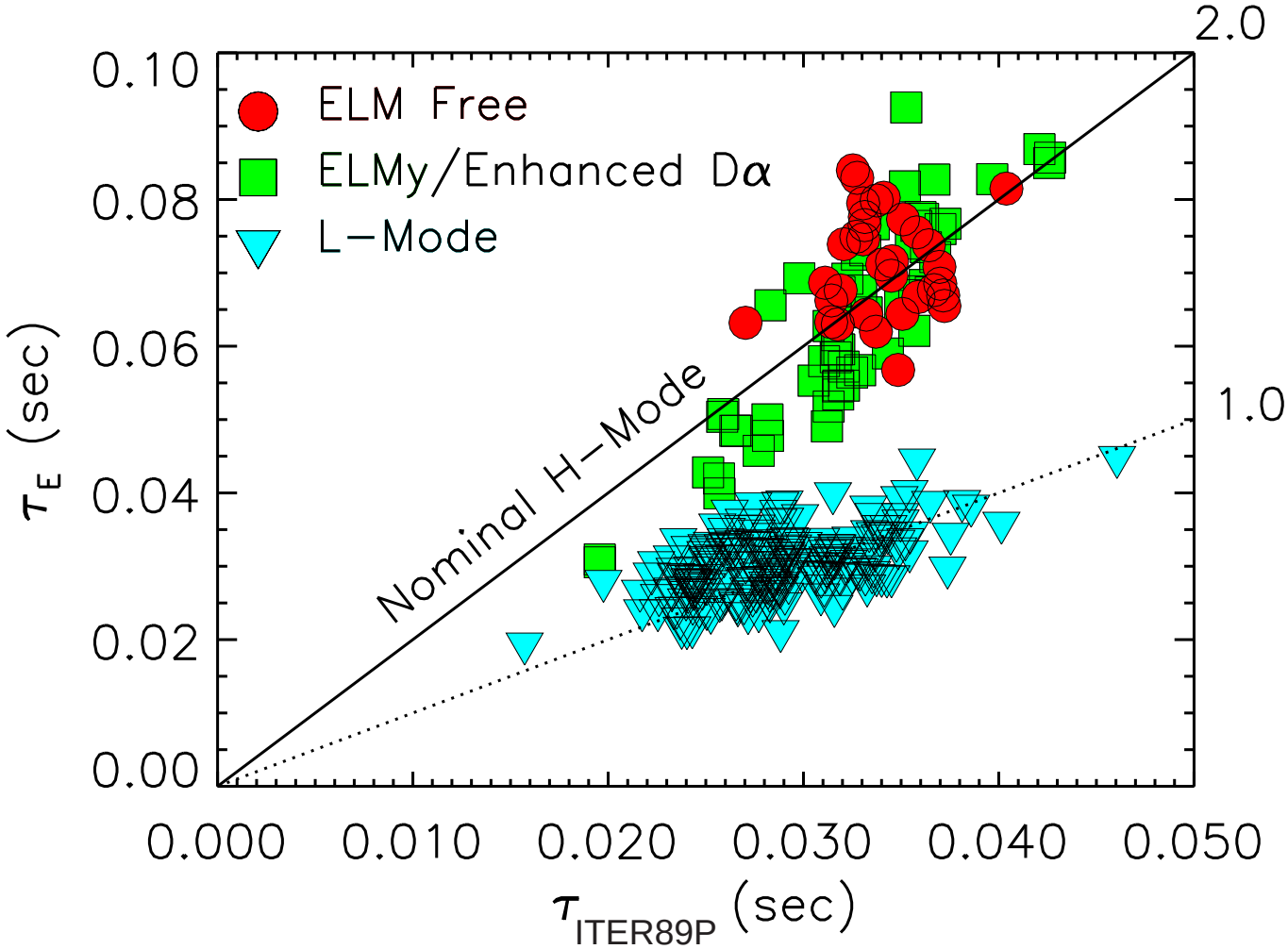
- **High Confinement Modes**
  ELM-free H-mode has high confinement, but accumulates impurities in the core so it cannot be steady-state
  Enhanced D_α H-mode maintains nearly as good energy confinement ($H_{ITER89} \leq 2$) with reduced edge particle confinement so that impurities do not accumulate in the core without large ELM heat loads on the divertor

- **ICRF and Ohmic Plasma Rotation**
  Plasma rotation increases with stored energy in Ohmic and ICRF heated H-mode and L-mode
  Scaling is the same for ICRF and Ohmic data

- **Peaked Density Profiles in H-mode**
  Spontaneous density peaking occurs particularly in Ohmic H-mode with ramping B_T
  Peaking factors of ~3 can be sustained throughout the Ohmic H-mode

- **Extrapolated Fusion Performance**
  Despite its small size, C-Mod can reach exciting fusion energy relevant regimes

Energy Confinement Follows Scaling Law

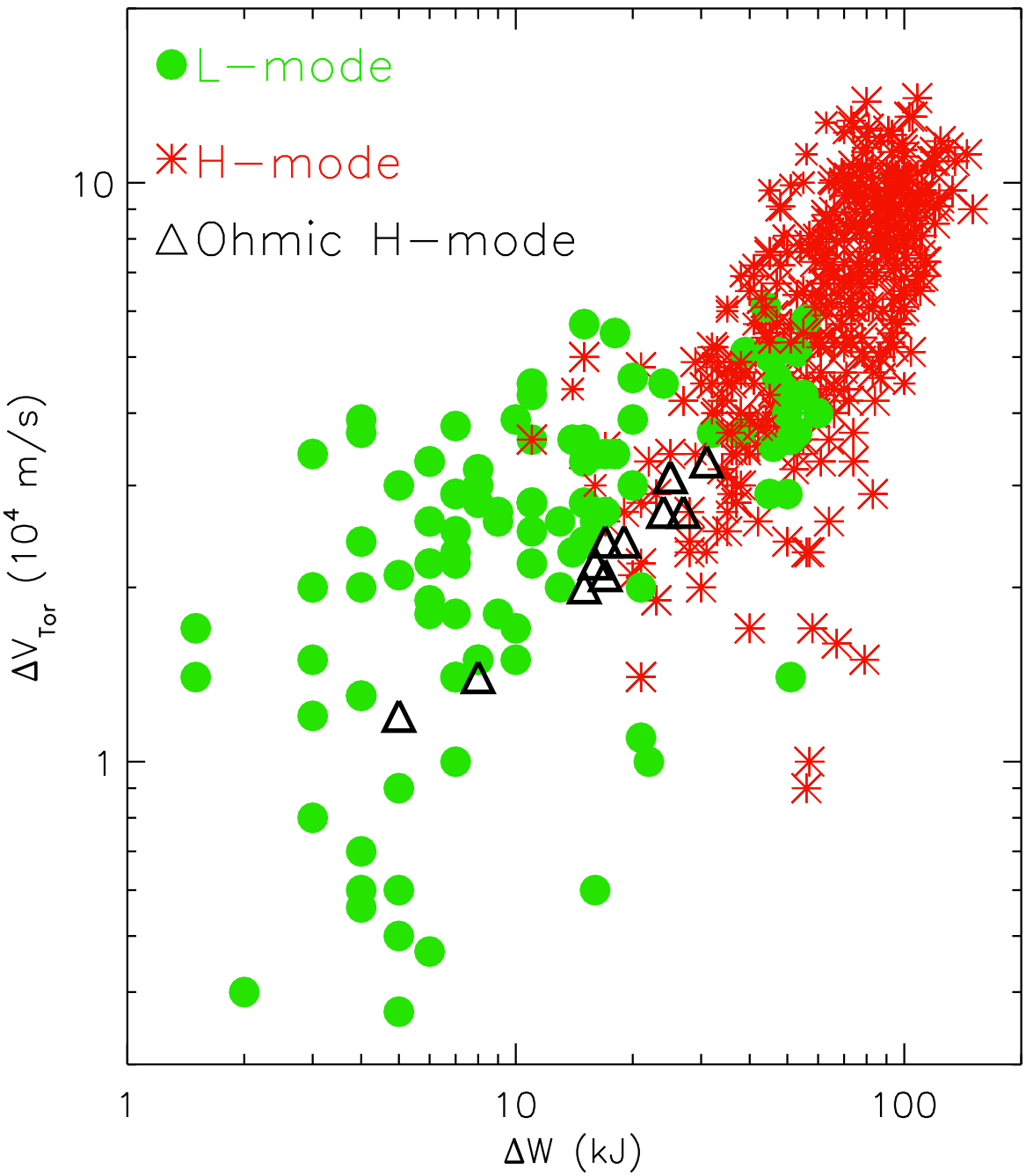


- L-mode data agree with ITER89P scaling:

$$t_{ITER89P} = 0.048\ I_p^{0.85}\ R^{1.2}\ a^{0.3}\ \kappa^{0.5}\ \bar{n}_e^{0.1}\ B_T^{0.2}\ A^{0.5}\ P_{tot}^{-0.5}$$

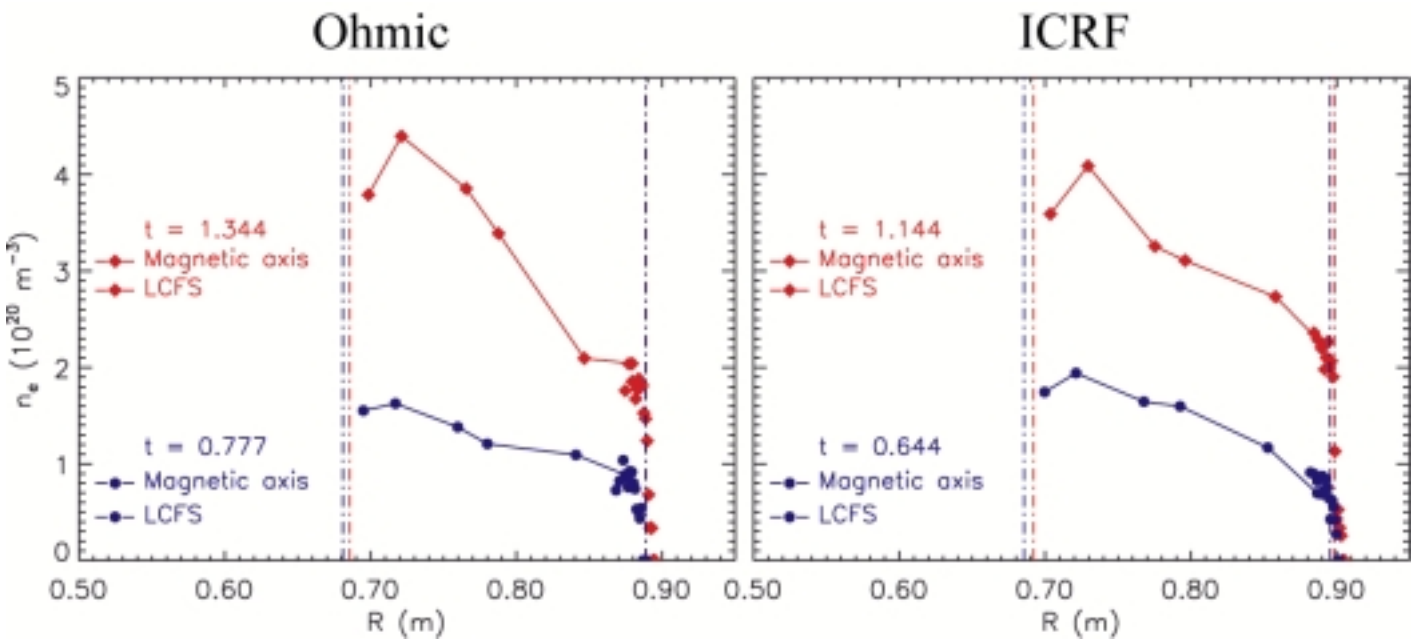
- ELM-free and Enhanced D H-mode double L-mode confinement times

Plasma Rotation Increases with Stored Energy

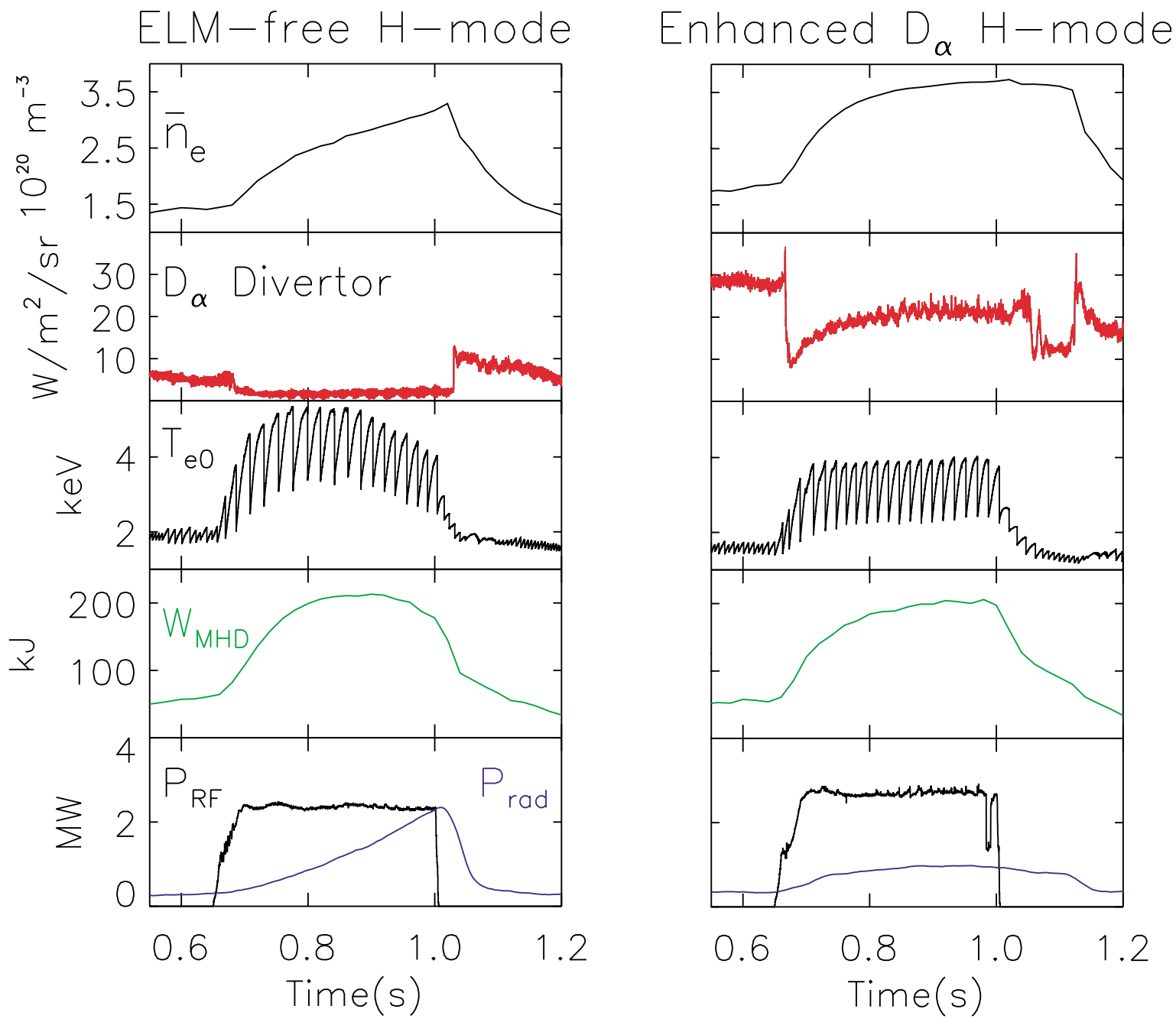


- Ohmic H-mode rotation scales the same as ICRF rotation
- Suggests rotation is driven by transport rather than by ICRF effects

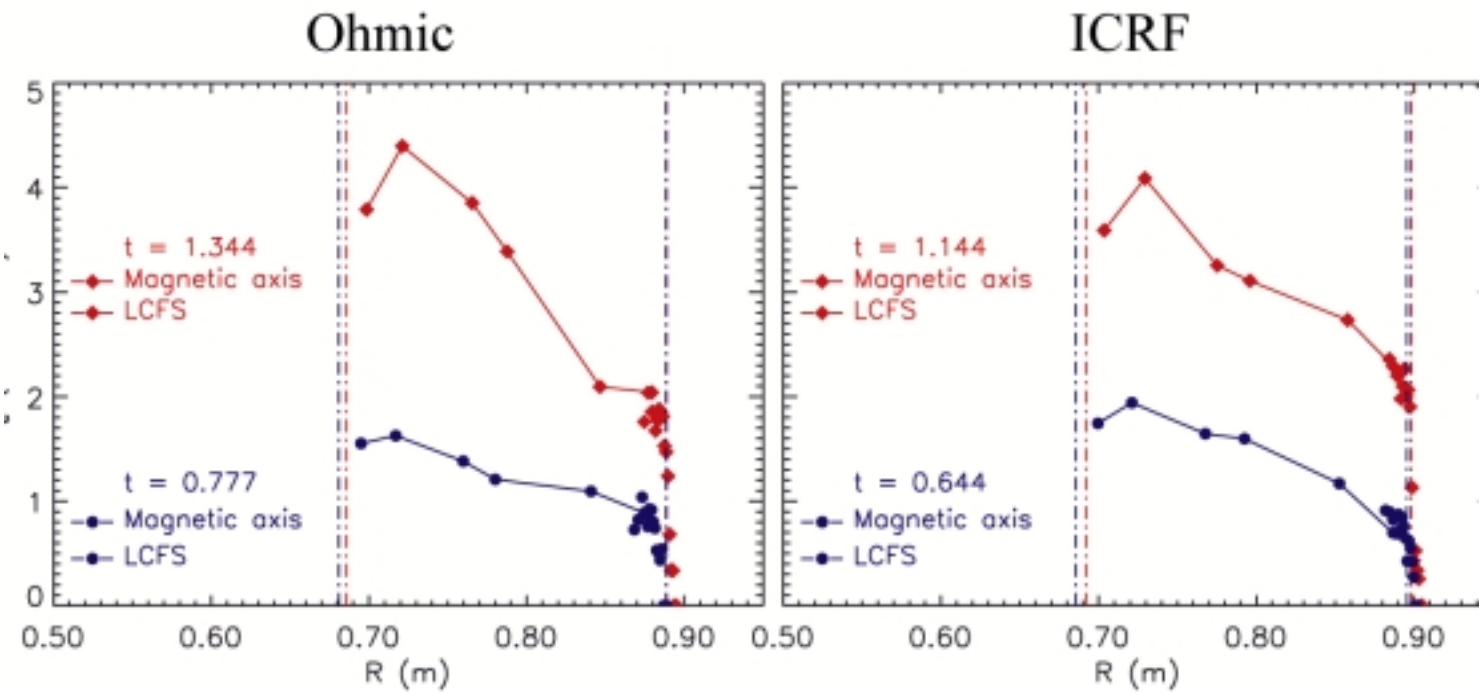
Peaked Density Profiles in Ohmic and ICRF H-mode



- Spontaneous density profile peaking is found particularly in Ohmic H-mode up to $n_0/n_{edge} > 3$ for up to 0.7 s duration
- ICRF H-modes can also peak up transiently to $n_0/n_{edge} \sim 2$
- Will attempt to heat peaked Ohmic H-mode with ICRF to improve fusion performance

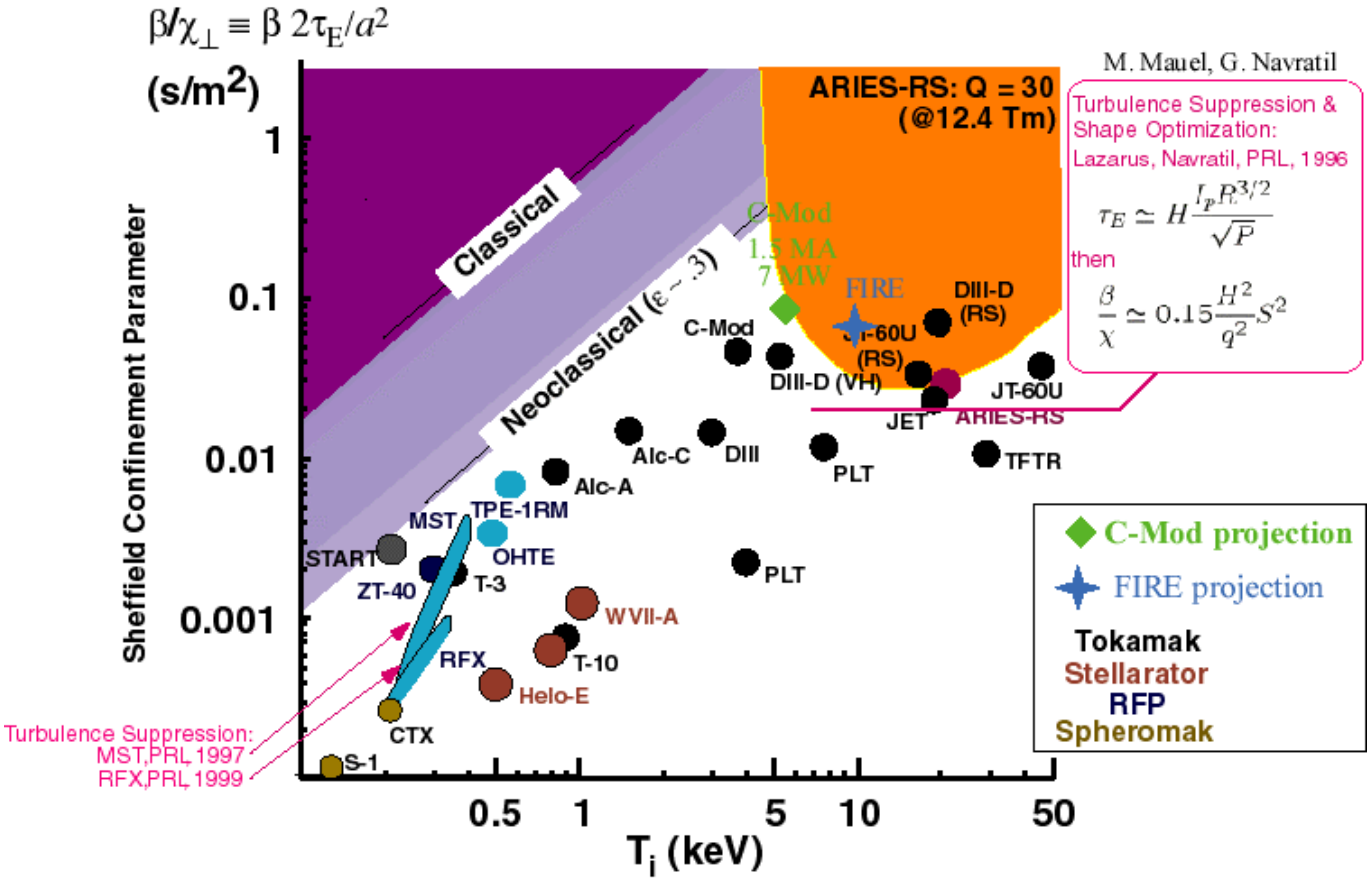

ELM−free H−mode
Enhanced D$_\alpha$ H−mode
$\bar{n}_e$
10^{20} m^{-3}
3.5
2.5
1.5
D$_\alpha$ Divertor
W/m^2/sr
30
20
10
T$_{e0}$
keV
4
2
W$_{MHD}$
kJ
200
100
P$_{RF}$
P$_{rad}$
MW
4
2
0
0.6
0.8
1.0
1.2
Time(s)

Peaked Density Profiles in Ohmic and ICRF H-mode



- Spontaneous density profile peaking is found particularly in Ohmic H-mode up to $n_0/n_{edge} > 3$ for up to 0.7 s duration
- ICRF H-modes can also peak up transiently to $n_0/n_{edge} \sim 2$
- Will attempt to heat peaked Ohmic H-mode with ICRF to improve fusion performance

Fusion Energy Relevant Levels of β/χ have been Achieved for Short Pulses



- C-Mod accesses fusion energy relevant regimes of β/χ and T_i when extrapolated from present EDA H-mode to 1.5 MA and 7 MW

  FIRE accesses higher temperatures but similar β/χ for its Q=10 scenario at $\beta_N = 2.5$ and $P_{aux} = 10$ MW