# Acceptable ELM Regimes for Burning Plasmas

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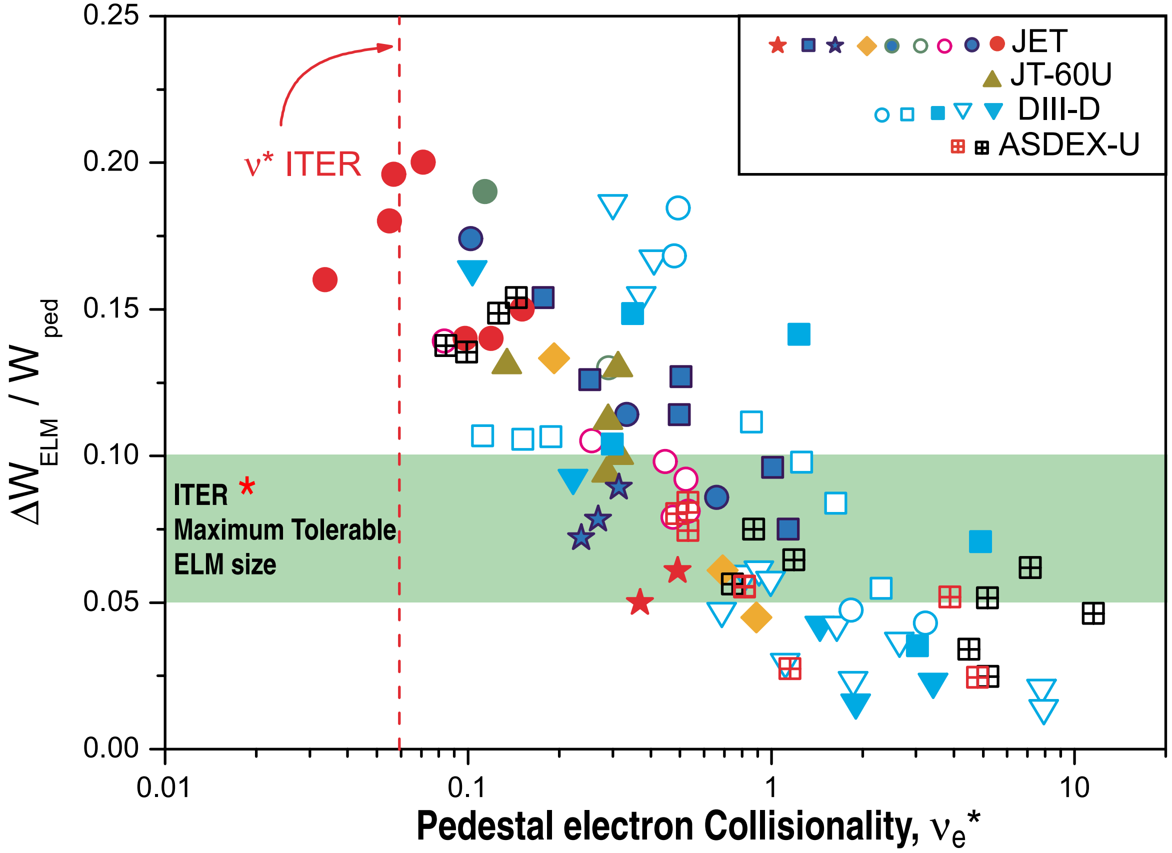
# ELMs are a Significant Concern for a Burning Plasma Divertor

- Both energy confinement and Type I ELM size scale with pedestal pressure
  - Good Confinement ↔ Large ELMs
  - Target ablation if surface temperature rises above sublimation/melting; $\Delta T \propto$ Energy density/(deposition time)$^{1/2}$
- To assess Type I ELM compatibility with a burning plasma device need to scale:
  - ELM energy lost from main plasma
  - Fraction of ELM energy deposited on target plate
  - ELM deposition area
  - ELM deposition duration

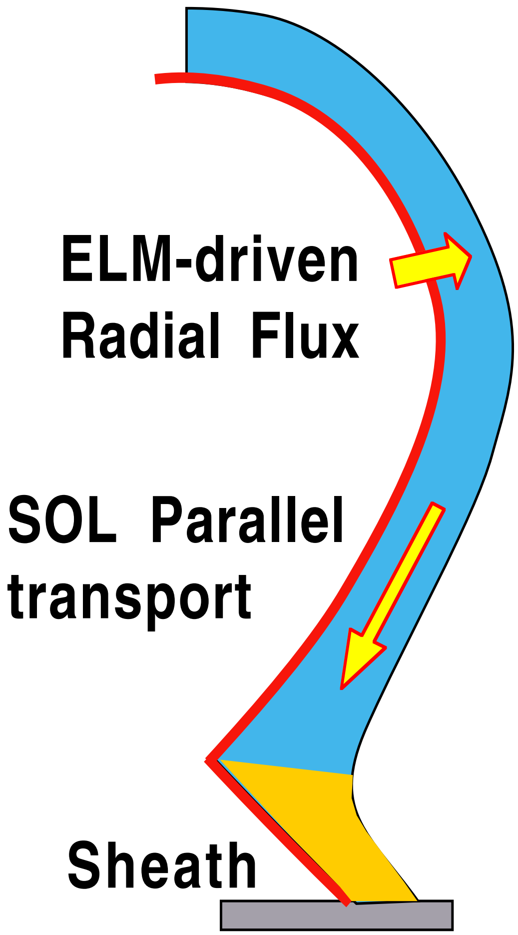
# Type I ELM Size Smaller at High Collisionality, Density



- Multi-machine, ITPA, scaling indicates Type I ELM size tolerable at high pedestal collisionality
- For expected ITER pedestal parameters; ELM energy twice the tolerable limit if collisionality scaling holds
- Understanding of underlying ELM transport needed for reliable scaling

*ELM criteria assumptions: a)50-100% of ELM energy on target, b) deposition area 1-2x steady heat flux width, c) deposition time of ion sound speed from pedestal to target, ~600 μsec, d) carbon target and e) 100 MJ pedestal energy

# ELM Heat Flux Results from Series of Transport Processes

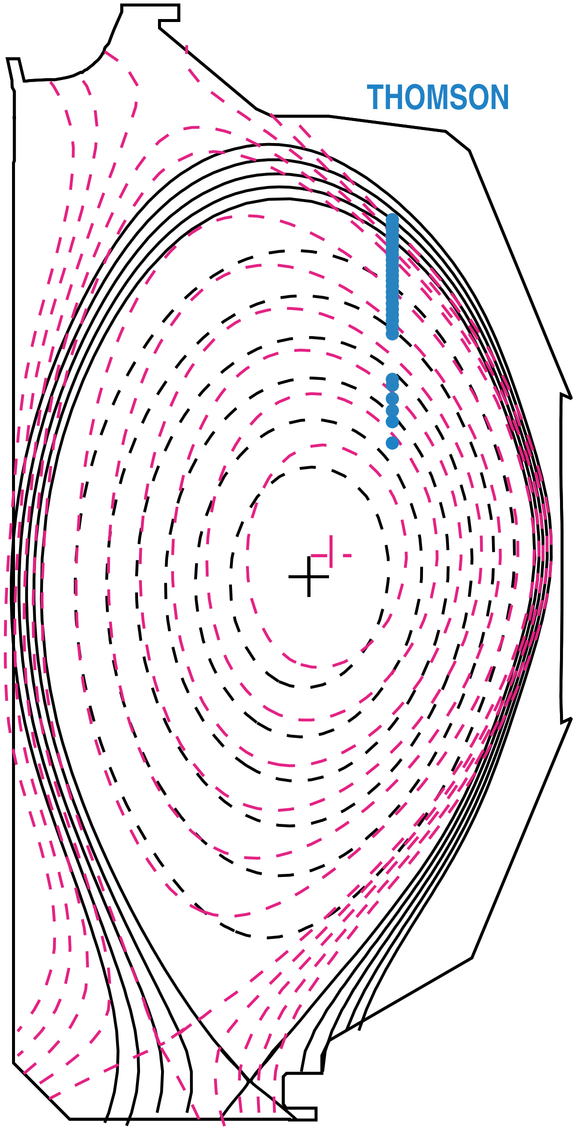


- ♦ Radial Transport at Midplane: ELM instability relieves gradients across separatrix.
- ♦ Transport in SOL: Electron and ion energy carried from midplane into divertor by parallel transport processes.
- ♦ Sheath Limits: Target sheath builds by loss of hot electrons. Heat flux limited by ion flux into sheath.
- ♦ All the above have potential to limit ELM loss from the pedestal
- ♦ ELM heat flux profile at target set by ratio of parallel to perpendicular transport in SOL

# Use DIII-D Scaling Data to Study Transport Processes

- ELM loss from pedestal region
  - Thomson scattering for ELM $\Delta T_e$ and $\Delta n_e$ profiles
  - Integrate perturbed profiles of $\Delta T_e$ and $\Delta n_e$ for convected and conducted ELM energy.
  - Separate scaling of ELM conducted and convected energy with density and/or collisionality
- SOL and divertor transport of ELM flux
  - Fast diagnostics for SOL and divertor
  - Scaling of ELM divertor characteristics with density
- Compare scaling of data with that implied by different ELM transport processes

# ELM Loss from Pedestal Measured by Thomson Scattering



- Collect Thomson profiles over ≥500 msec of steady ELMing conditions, ≥ 40 profiles
- Order data in time to nearest ELM
- Fit each measurement location with pre- and post-ELM linear time dependence. ELM $\Delta T_e$ and $\Delta n_e$ at t=0
- Integrate profile for ELM convected and conducted energy separately
- Experimental scans in density, $I_p$, $B_t$ and triangularity.

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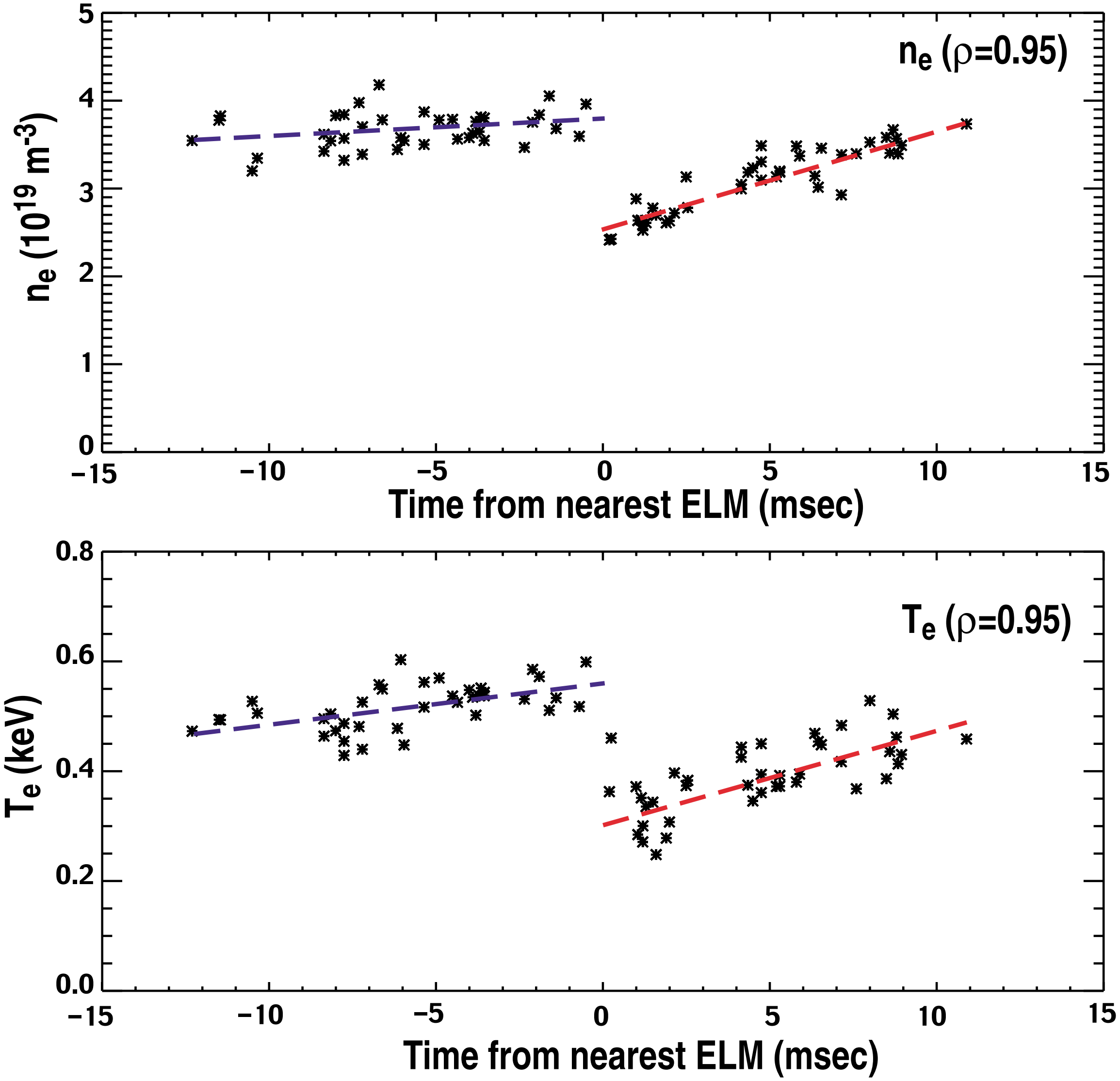
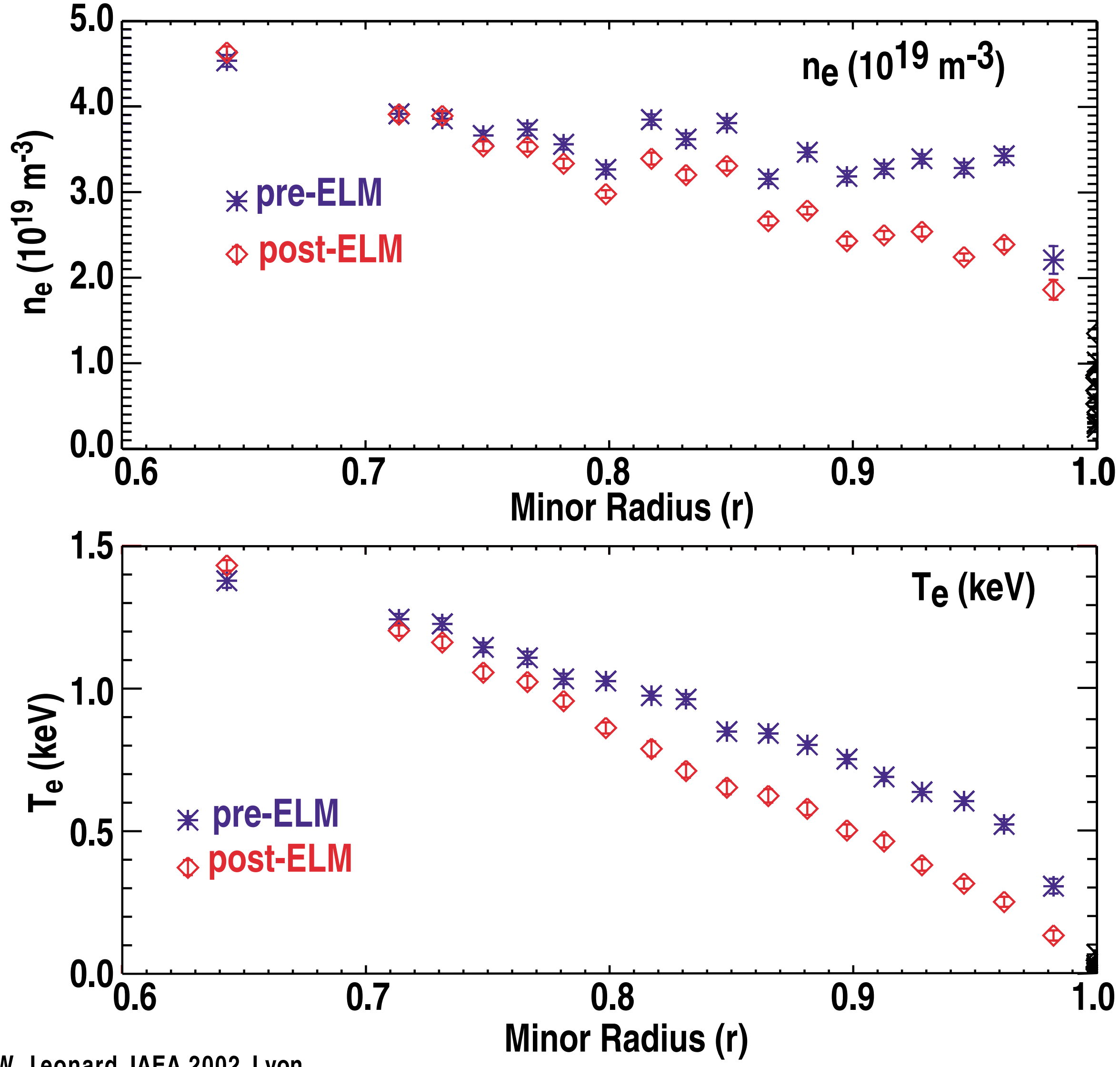
# Fitting for $T_e$ and $n_e$ Before and After an ELM



- $T_e$ and $n_e$ at each Thomson location fit to linear function in time with respect to nearest ELM.
- Pre-ELM and post-ELM values set by intersection with t=0
- Error bars set by uncertainty in linear fit.

# Typical Thomson pre-ELM and post-ELM profiles



- Little change ever observed inside $\rho$=0.7 for Type I ELMs
- Integrate difference in profiles for ELM electron energy

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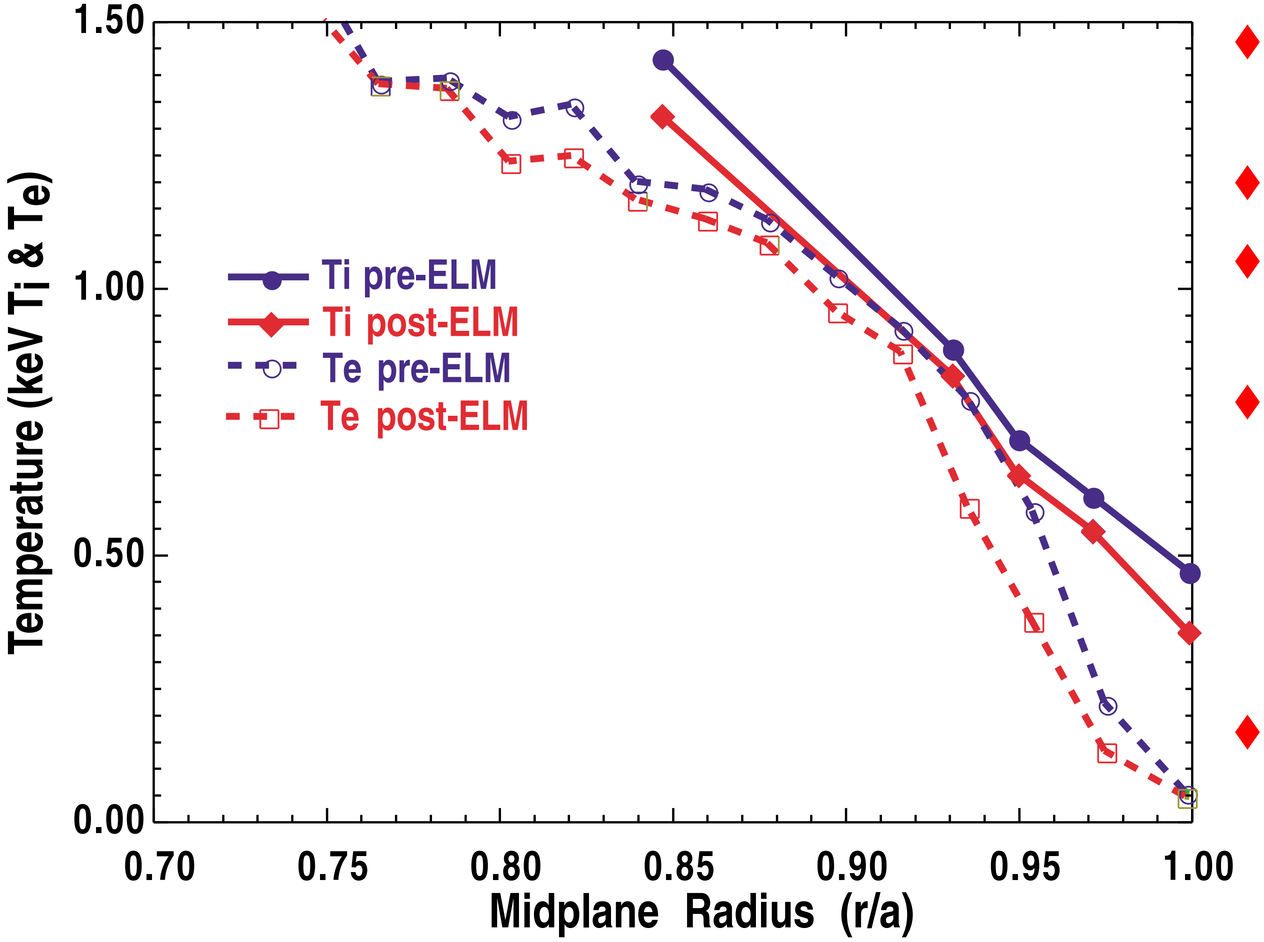
# ELM $\Delta T_i$ Smaller than $\Delta T_e$

ELM Perturbation to Pedestal $T_i$ and $T_e$ Profiles

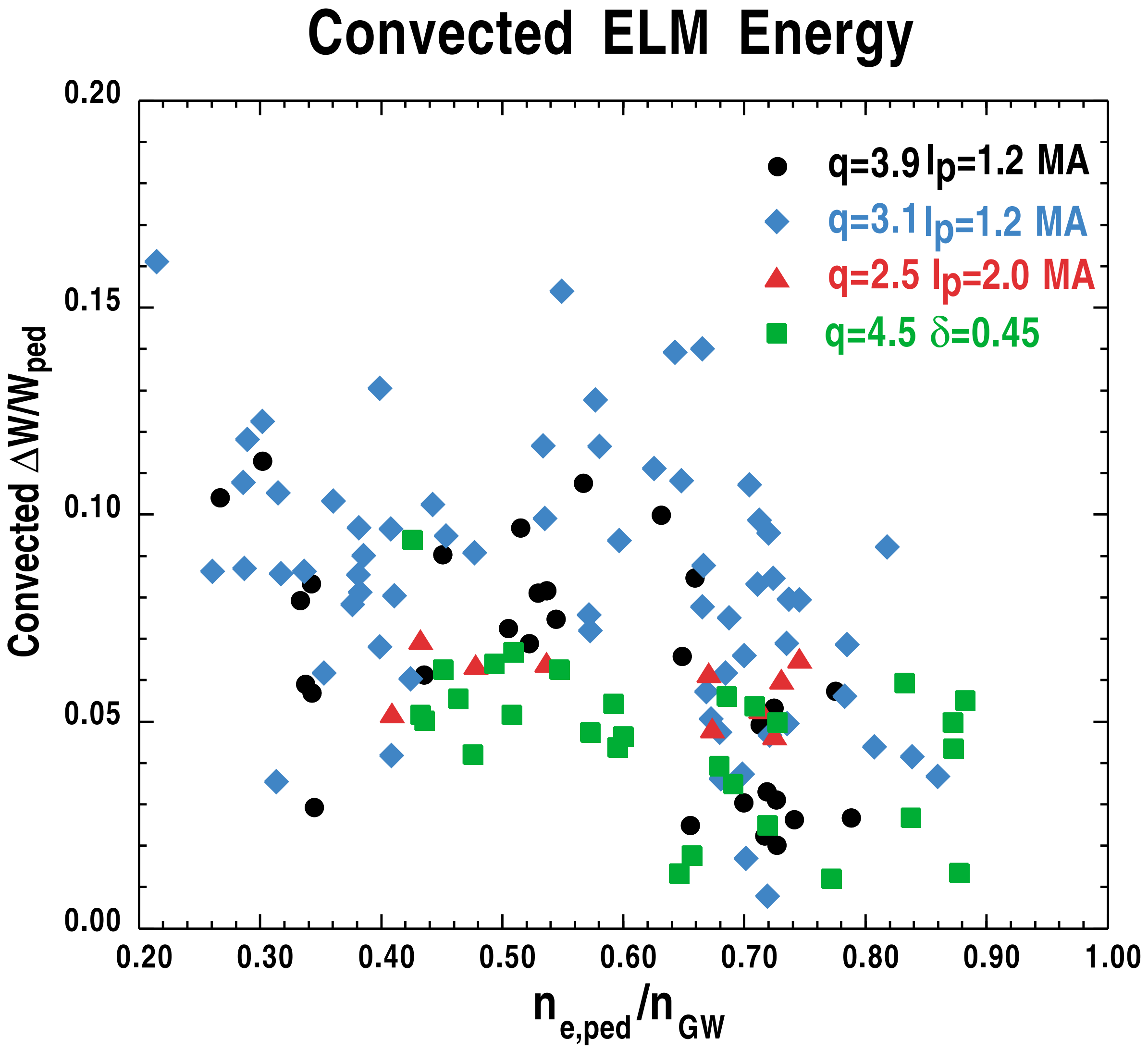


- ♦ ELM $\Delta T_i$ profile from fast CER, CVI, 0.5 msec
- ♦ $\Delta T_i$ less than 1/2 of $\Delta T_e$
- ♦ $T_i > T_e$ in steep gradient region
- ♦ Very limited data set for fast $T_i$ measurements. Need systematic study to determine relationship between $\Delta T_i$ and $\Delta T_e$
- ♦ Assume $\Delta T_i = 0$ for this study

# ELM energy split into convective and conductive channels

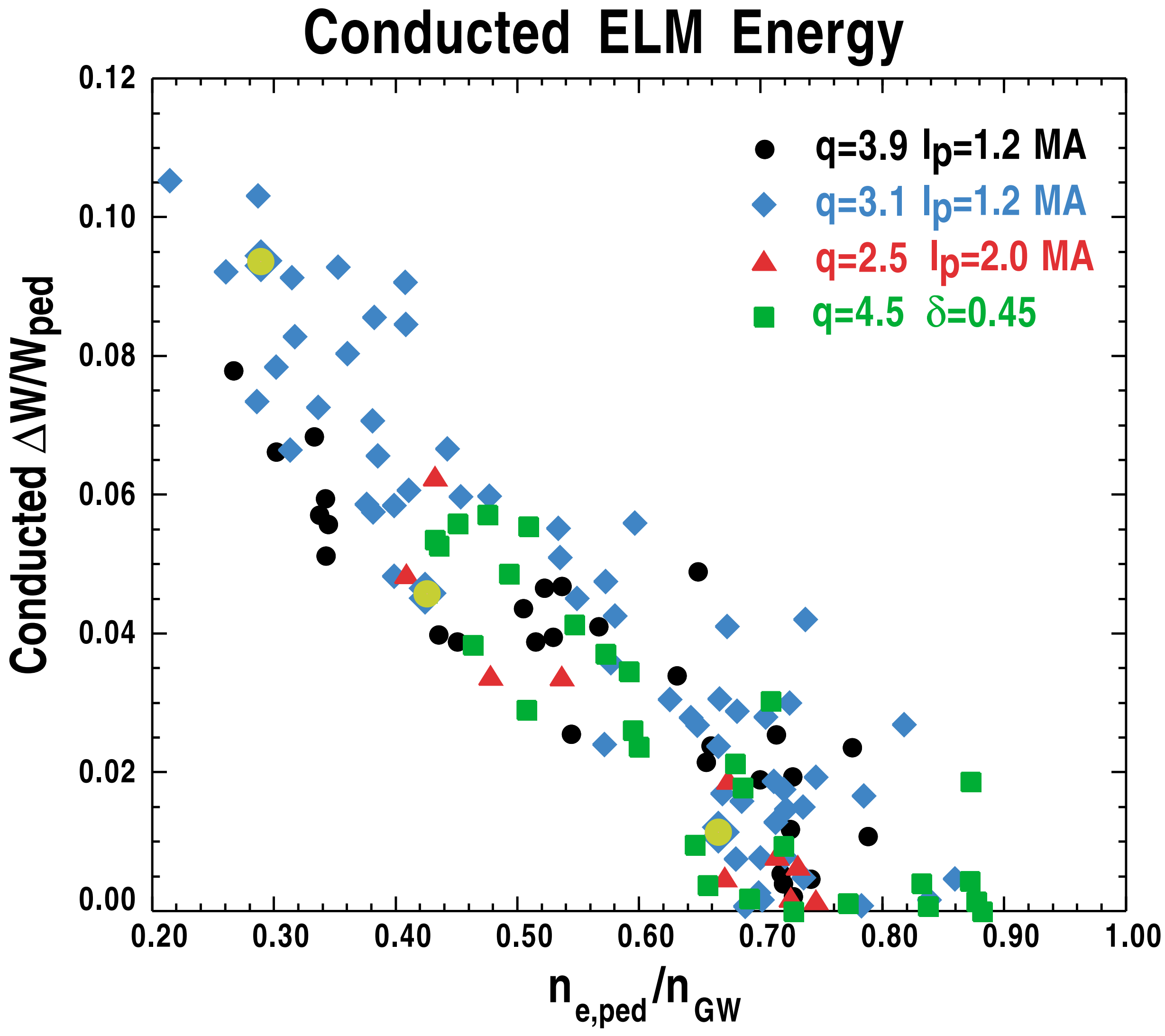
- Integrate Thomson profiles for convective, $<T>\Delta n$, and conductive, $<n>\Delta T$, losses. Separate scaling may indicate underlying transport mechanisms.
- Convective loss; assume ion density perturbation equal to electrons; $\Delta W_{conv}=2.0x\int 3/2<T_e>\Delta n_e dV$
- Conductive loss; assume $\Delta T_i=0$, $\Delta W_{cond}=1.0x\int 3/2<n_e>\Delta T_e dV$
- Need more measurements for variations of $Z_{eff}$ and $\Delta T_i$
- Reasonable agreement with ELM energy from fast magnetic equilibrium analysis

# Little Density Dependence for Convected ELM Energy



- ♦ ELM energy, $\Delta W$, normalized by pedestal energy, $E_{ped}$
- ♦ No systematic change in normalized ELM energy for $n_{e,ped}/n_{GW} \leq 0.7$
- ♦ Large scatter, but no obvious $I_p$ or *q* dependence
- ♦ $E_{ped}$ factor of 2 greater for high $I_p$ and high $\delta$ cases
- ♦ High triangularity case; $<\delta>\sim 0.45$, others at $<\delta>\sim 0.0$

# Conducted ELM Energy Decreases Strongly at Higher Density



- Conducted ELM energy decreases linearly with higher density
- Very small conducted ELM energy at $n_{e,ped}/n_{GW}>0.65$
- Data well ordered by $n_{e,ped}/n_{GW}$ for wide range of $I_p$ and $\delta$
- Edge stability analyzed for highlighted points at q=3.1

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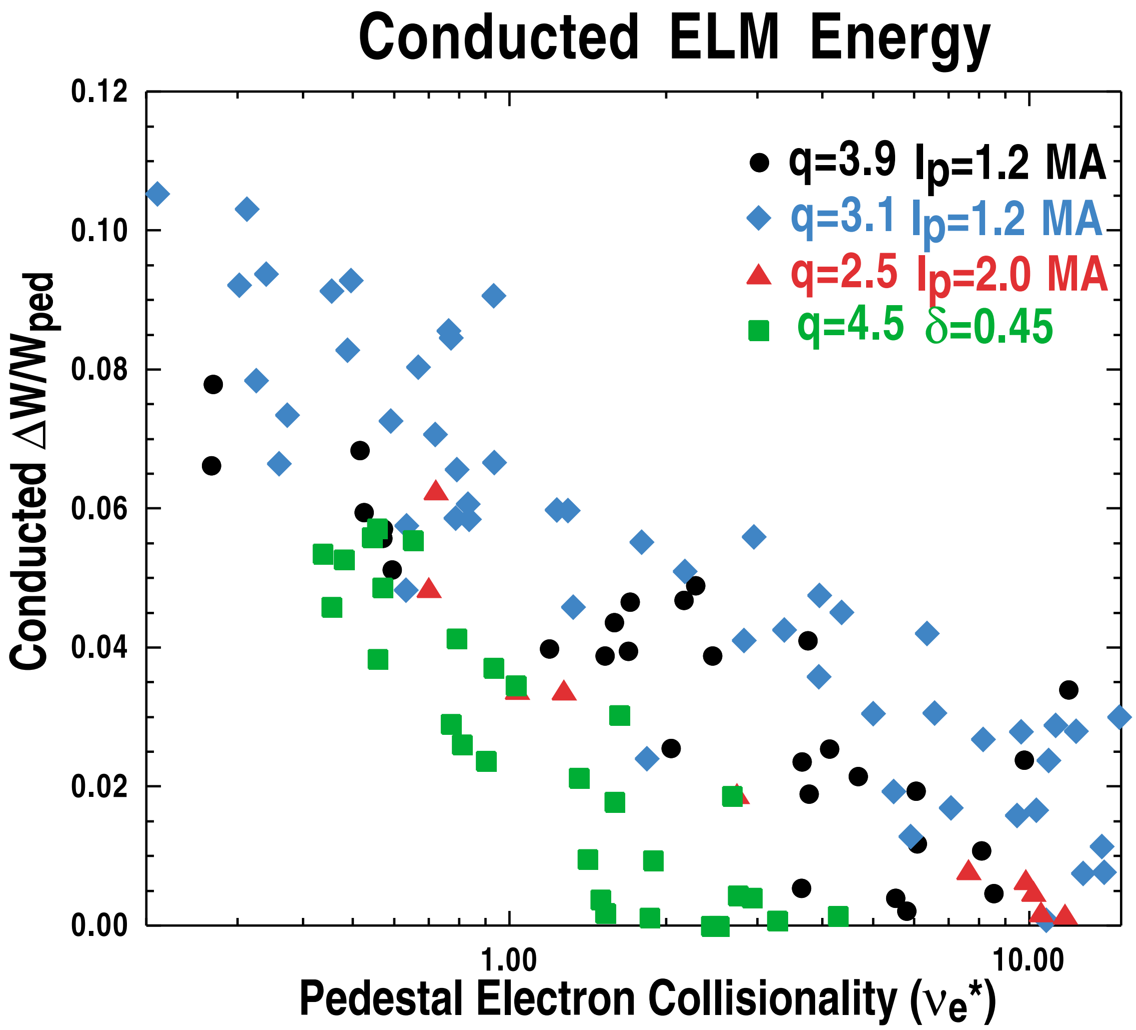
# More than Collisionality Alone needed for Scaling ELM Conducted Energy



- Expect strong collisionality dependence because of bootstrap current role in ELM stability
- Collisionality dependence important because burning tokamak will have a low collisionality pedestal
- Stronger collisionality dependence at high triangularity also suggested by MHD model

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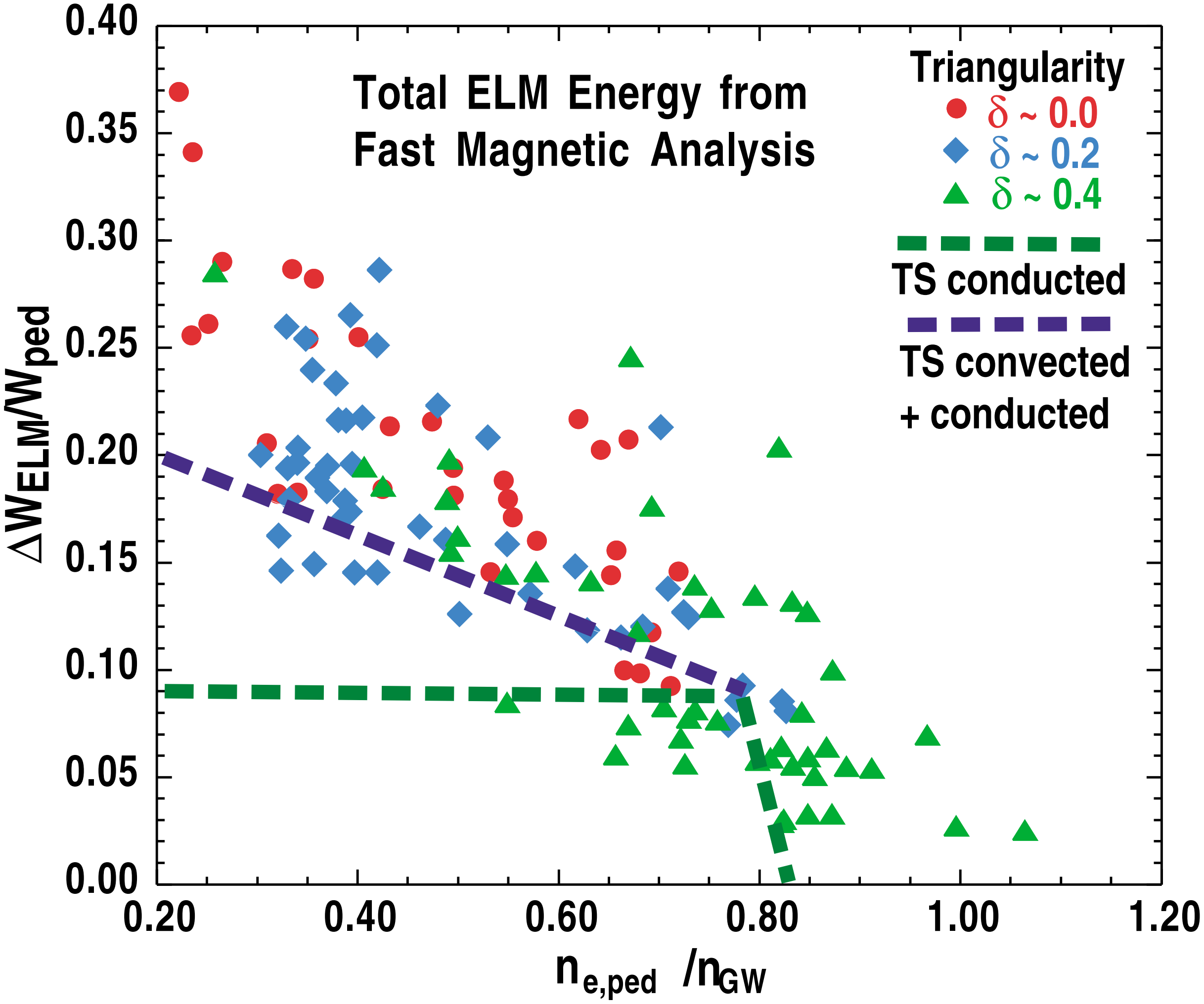
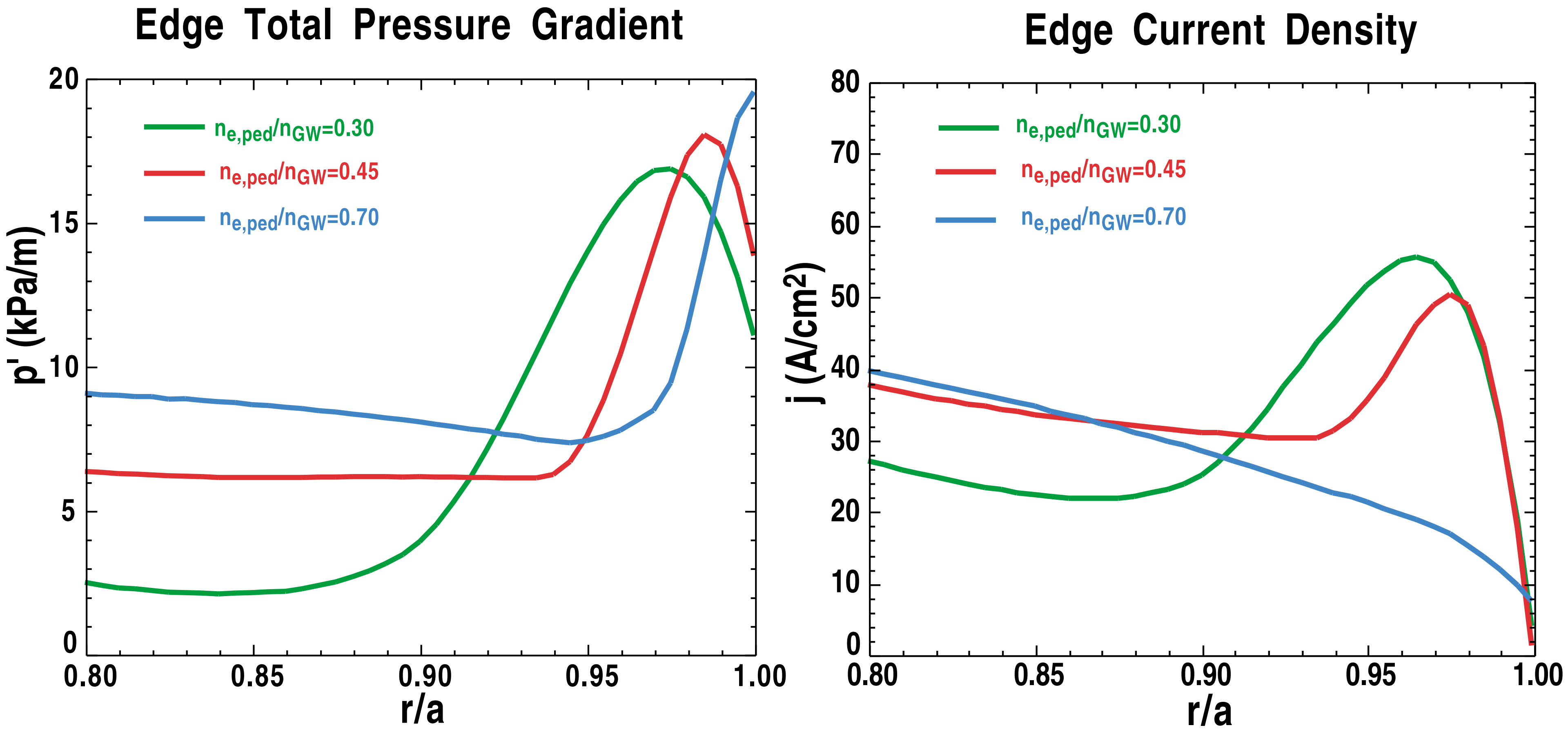
# Total ELM Energy from Magnetics in Basic Agreement with Thomson Analysis



- ♦ Convected and conducted energy from Thomson shown with dashed lines
- ♦ Comparison with Thomson is encouraging given uncertainties
- ♦ Inclusion of $\Delta T_i$ ELM energy should help agreement

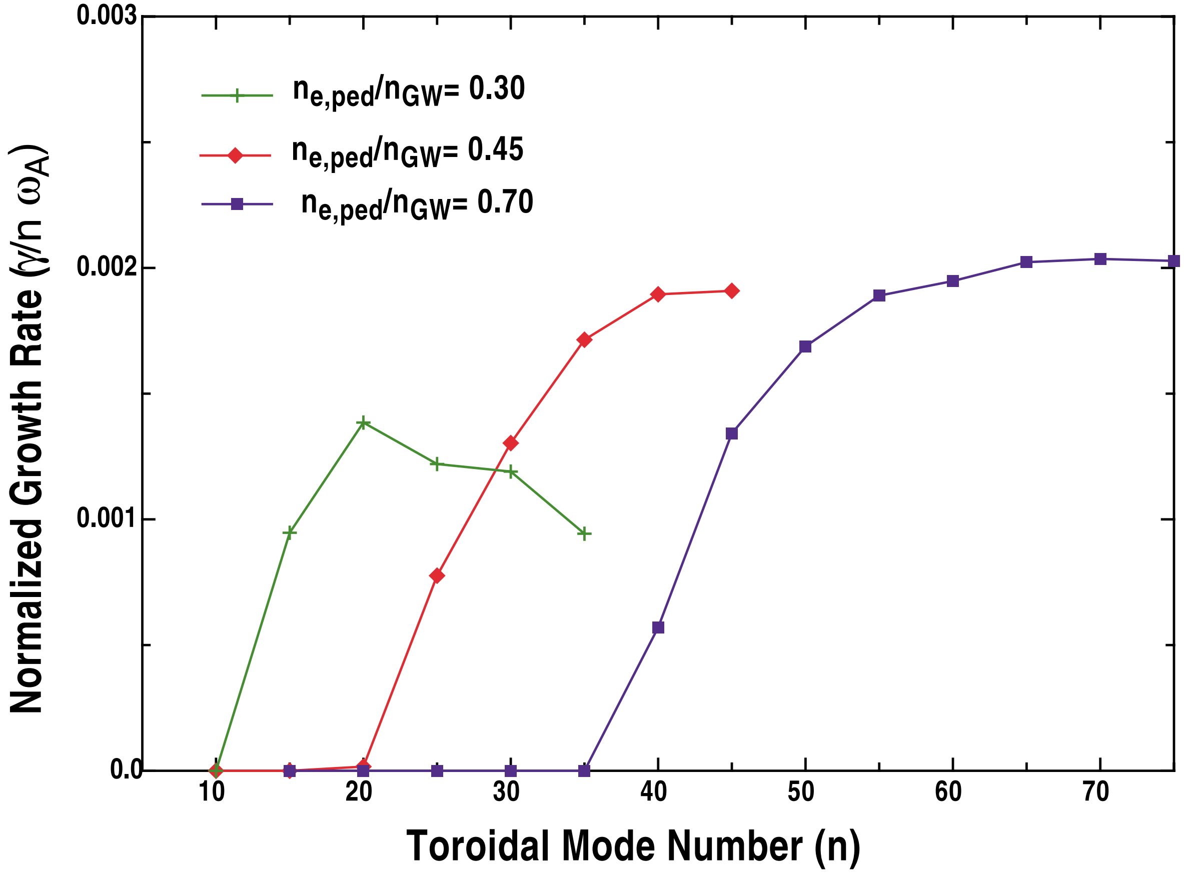
# Edge Profiles Fitted for MHD Analysis of Density Scan



- Pressure gradient from fitted ion and electron density and temperature
- Ohmic current density + modeled collisional bootstrap from fitted profiles

# Stability Analysis Indicates Higher Mode Number at High Density

## Normalized Growth Rate from ELITE



- ♦ Stability analysis using ELITE calculates linear growth rate of peeling-ballooning modes using measured pedestal pressure profile and modeled collisional edge bootstrap current
- ♦ Bootstrap current at low density stabilizes shorter wavelength modes allowing higher pressure gradient to destabilize longer wavelength modes

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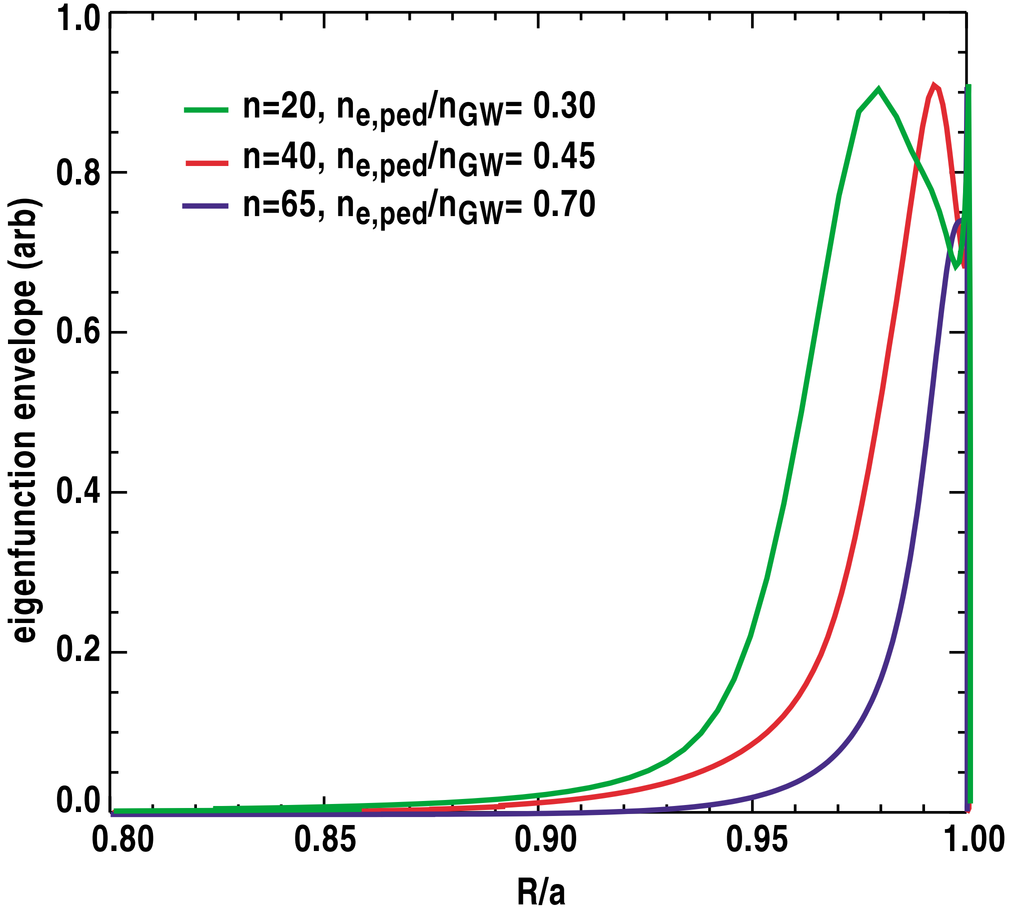
# Narrower Mode Width at High Density

Envelope of most unstable Eigenmode from ELITE



- Eigenmode radial width scales with steep gradient width for higher n modes
- Narrower gradient region at high density for the cases studied
- Narrower pedestal gradient also favors high mode number
- Shorter wavelength modes more localized to the edge speculated to reduce conducted ELM energy at high density

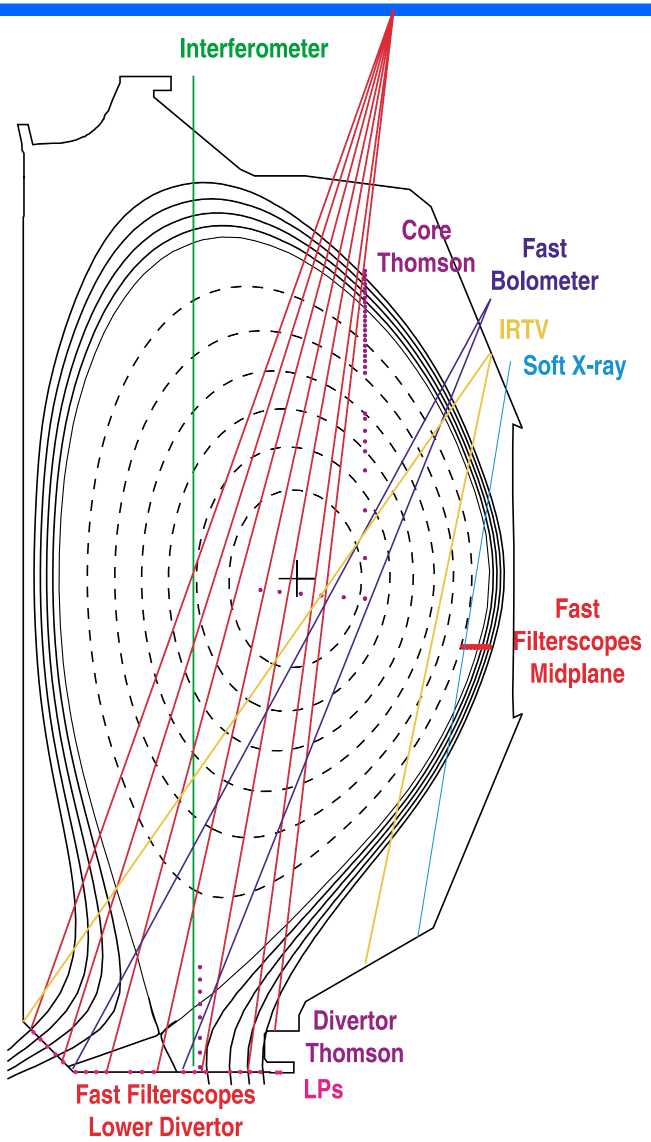
# ELM Stability Analysis Consistent with Experiment, but more Progress Needed

- Two effects favor high toroidal mode number at high density
  - High collisionality reduces bootstrap current stabilization of short wavelength modes. Collisionality effect expected to be stronger at high triangularity because bootstrap current stabilizes modes to lower n
  - Narrow pressure gradient favors higher mode number
- Pedestal width important for mode stability characteristics, but width scaling still very uncertain [Groebner EX/C2-3, OsborneCT-3 ]
- Scaling of conduction and convection suggests two transport processes
  - Conduction: $\Delta T_e$ indicates parallel electron conduction from pedestal to SOL due to overlapping modes, ergodized edge
  - Convection: Parallel convection should be much smaller than electron conduction at pedestal $T_e$. Large $\Delta n_e$ indicates perpendicular, perhaps ExB, transport.
- Linear stability models, *e.g.,* ELITE, cannot follow mode evolution or predict transport. Further theoretical development needed

# ELM Energy Transport for a Simple SOL Model

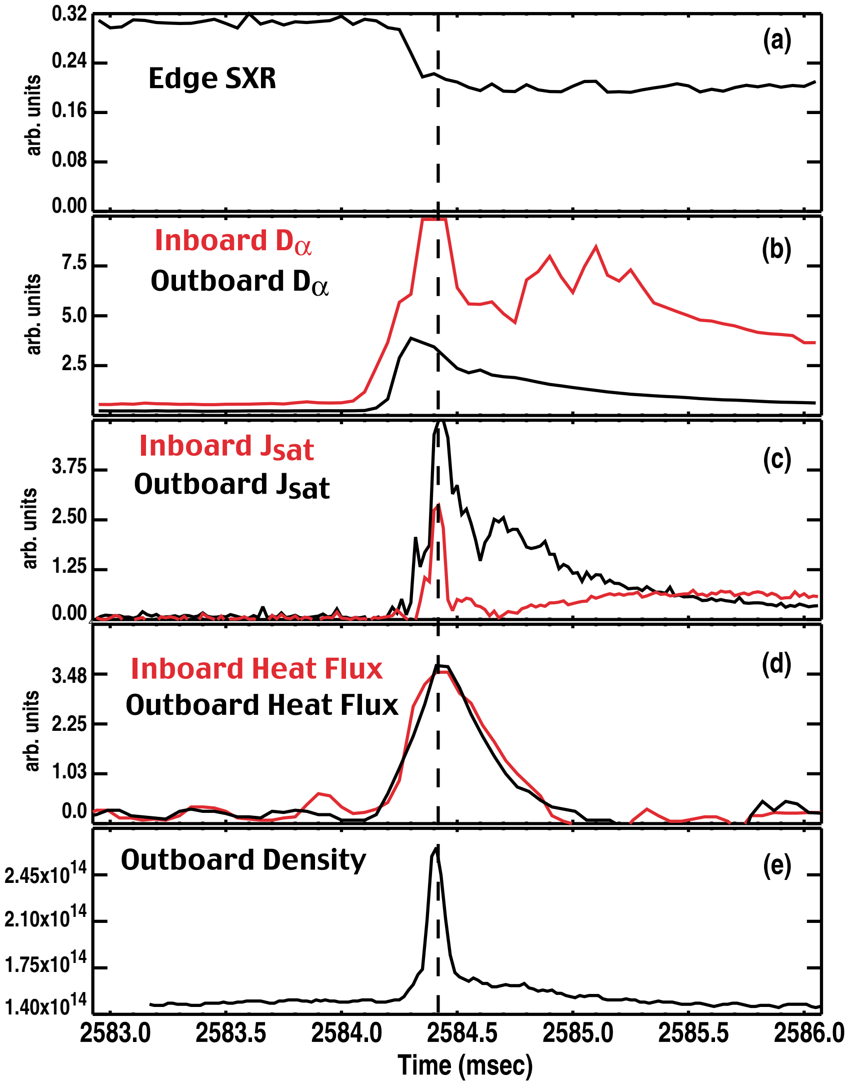
- ELM instability at outer midplane transports plasma from pedestal into SOL.
- Hot electrons quickly reach target raising sheath potential and limiting electron heat conduction to target
- Bulk of target heat flux arrives with ELM ion flux from pedestal
- Parallel transport can limit loss of energy from pedestal
- <u>ELM Characteristics of Simple Model:</u>
  - All energy lost from pedestal falls on target
  - Width of ELM heat flux set by ratio of parallel to perpendicular transport
  - Heat flux duration set by ion sound speed flow from outer midplane to each divertor
  - SOL $T_e$ decays from $T_{e,ped}$ on ELM heat flux timescale

# Fast Edge Diagnostics for Studying ELM Transport



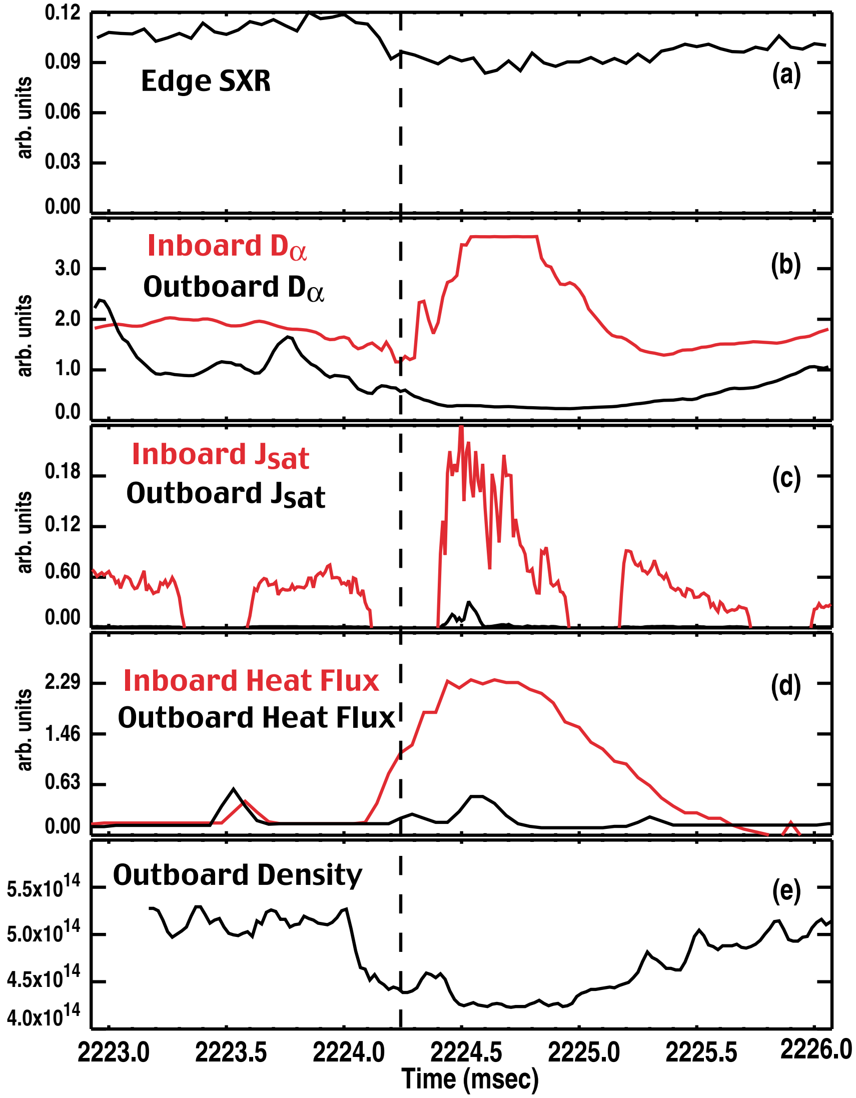
- Edge SXR; pedestal electron temperature
- D$_\alpha$; SOL and divertor particle flux
- Langmuir probes; ion flux to target
- Interferometer; divertor density
- IR camera; target plate heat flux

# Fast Divertor ELM Pulse at Low Density



- ♦ Typical ELM shown. Significant ELM-to-ELM variations can occur
- ♦ Low pedestal density; $n_{e,ped}/n_{GW}$~0.4, $n_{e,ped}$~ $5x10^{19}m^{-3}$, $T_{e,ped}$ ~ 750 eV, Ion sound time to outboard ~50 μsec, inboard ~120 μsec
- ♦ Fast $\Delta T_{e,ped}$ from SXR ≤100μsec.
- ♦ In/out $J_{sat}$, and $D_{\alpha}$ rise together, within 50μsec. Significant $J_{sat}$ variations occur
- ♦ In/out heat flux symmetric within 100μsec, ~ IR camera time resolution
- ♦ Divertor density rise from interferometer, >$2x10^{20}m^{-3}$, rise and fall time ≤100μsec

# High Density ELMs Slower, Asymmetric



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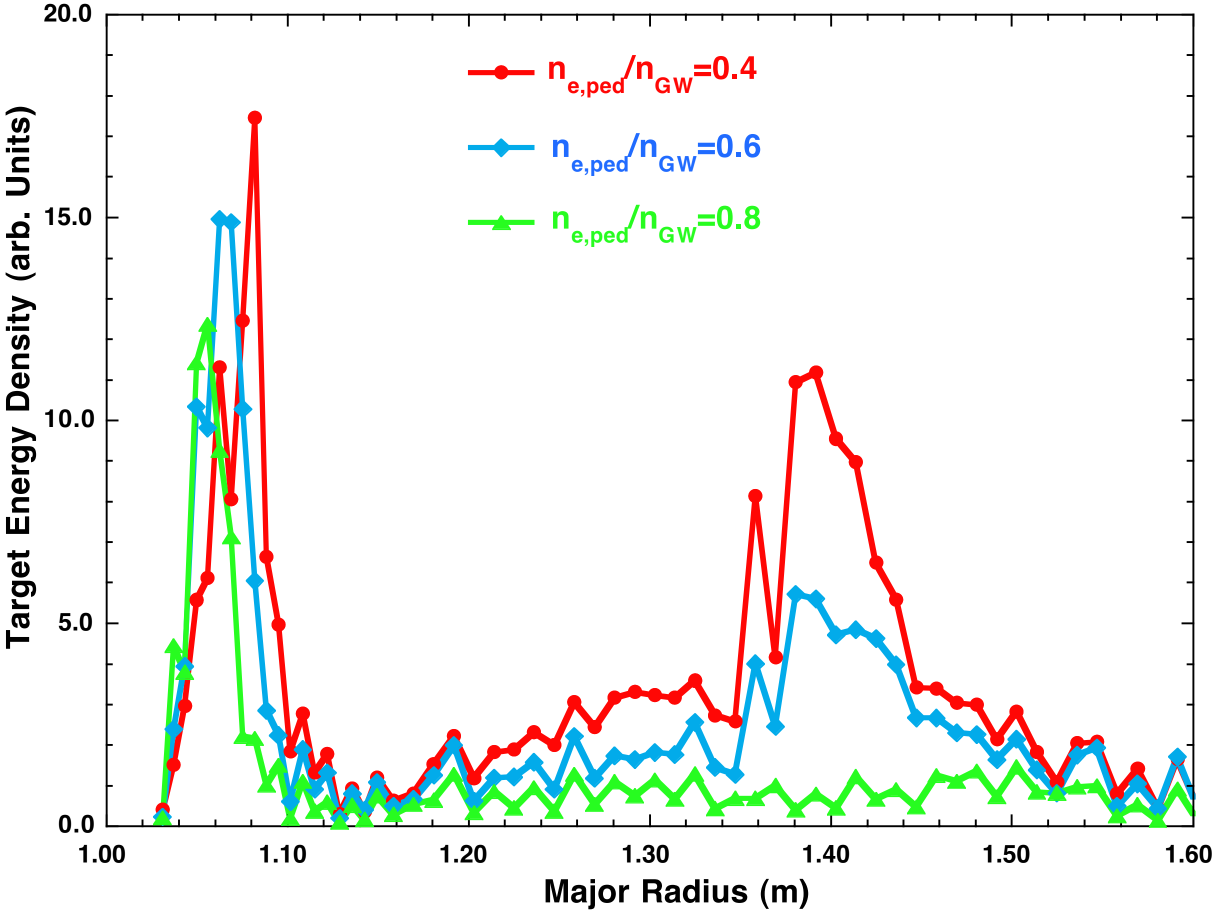
- High pedestal density; $n_{e,ped}/n_{GW}$~0.8, $n_{e,ped}$ ~$1x10^{20}m^{-3}$, $T_{e,ped}$ ~300 eV, Ion sound time to outboard ~75 μsec, inboard ~180 μsec
- Inboard Flux, $J_{sat}$, and $D_{\alpha}$, dominate, but slower rise and longer duration
- ELM heat flux peaked to inboard, slower heat pulse, 0.5-1.0 msec
- Outboard divertor cold and dense before ELM. Divertor density drops as ELM heats outboard divertor plasma

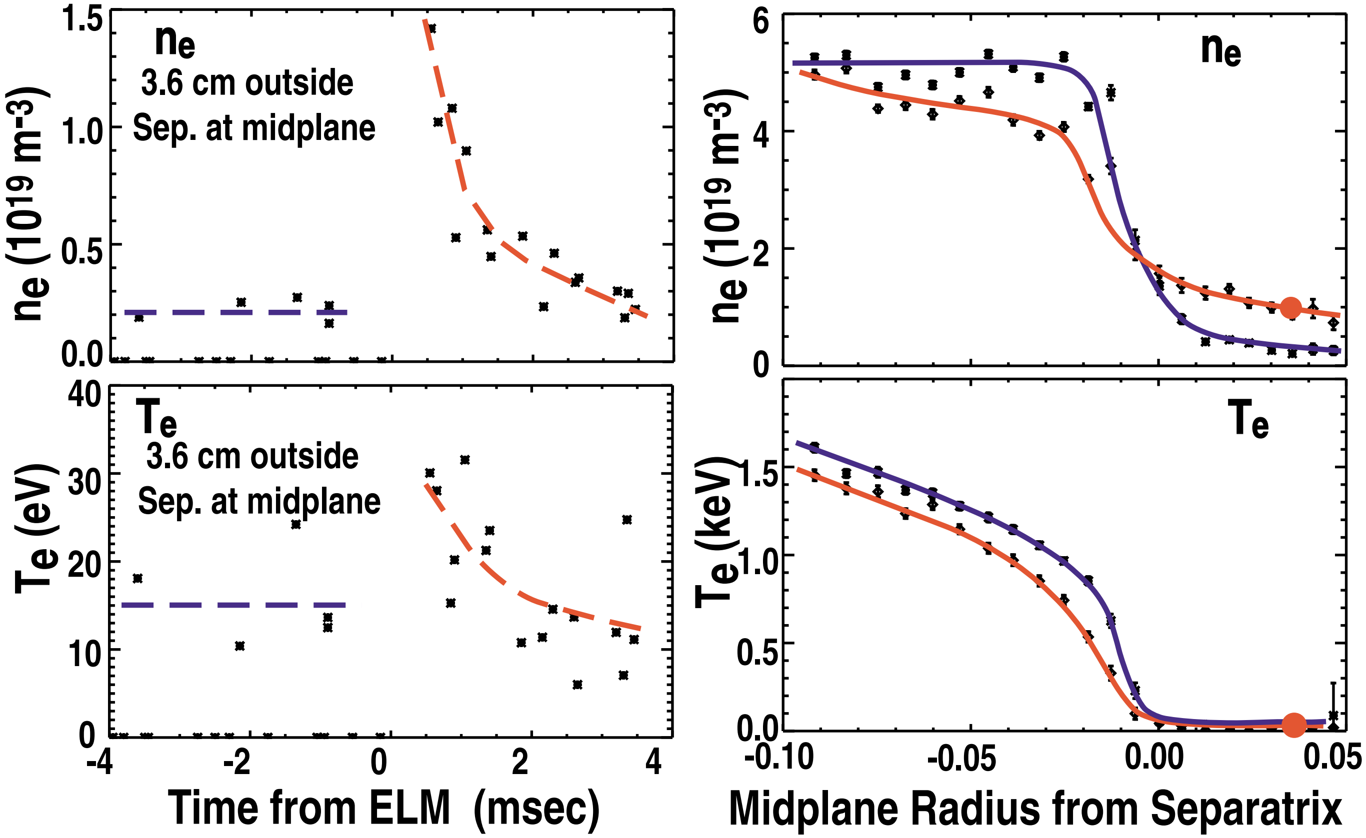
# Heat Flux In/Out Asymmetry Increases at High Density

## ELM Energy on Divertor Target



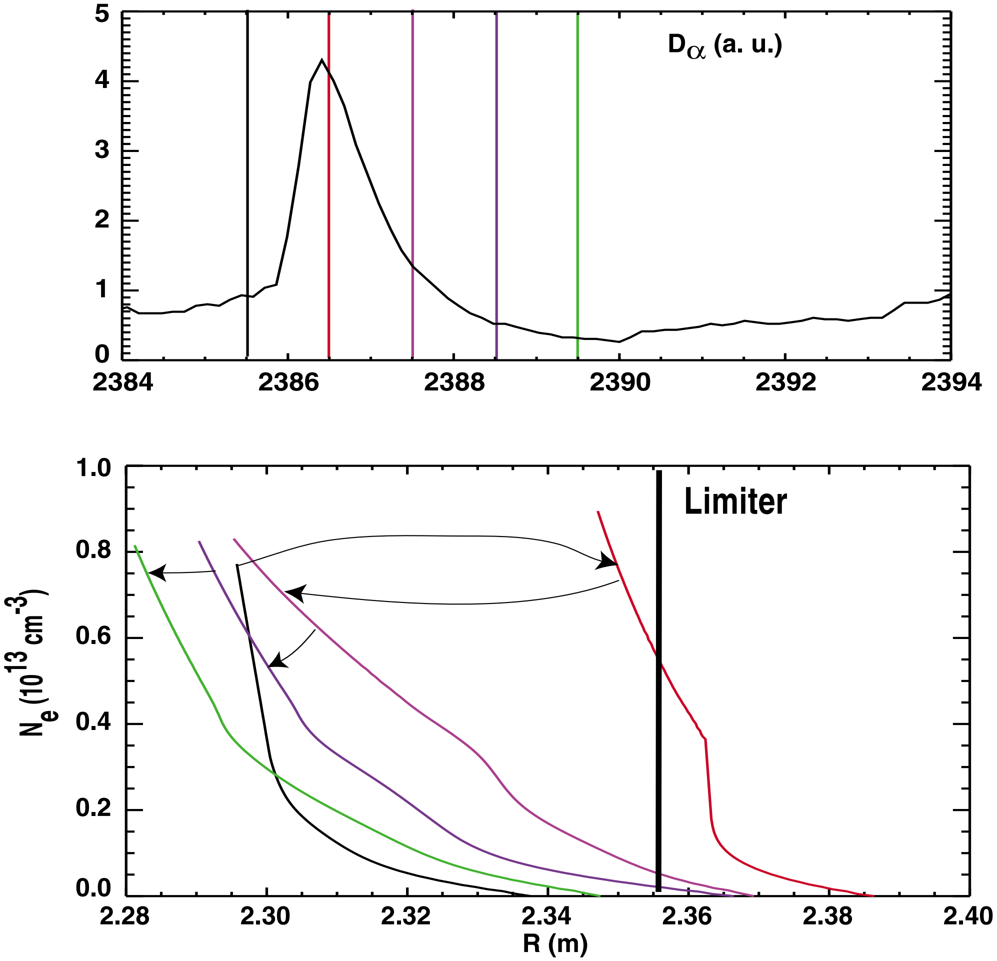
- ♦ Inboard heat flux higher and narrower than outboard due to flux compression
- ♦ ELM heat flux width 1-2cm mapped to midplane. Between ELM heat flux width ~1cm
- ♦ Outboard heat flux decreases at high density
- ♦ ELM heat flux asymmetry not understood

# Fast Density rise in Far SOL at ELM



- Assuming poloidal symmetry SOL density rise roughly accounts for density lost from pedestal
- ELM heat flux width at target is ~1-2cm mapped to midplane, much narrower than SOL density perturbation

# Reflectometry Also Indicates Fast Rise in Far SOL Density



- ♦ Significant density moves to outer midplane limiter in ~500 μsec at ELM
- ♦ Fast rise time suggests SOL density rise due to radial transport rather than recycling of ELM flux in divertor
- ♦ Ion equilibration time of >400 μsec indicates significant fraction of ELM ion energy carried to main chamber wall

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# Variations in SOL Transport from Low to High Density

- Indications of fast SOL conductive transport at low density
  - Large pedestal $\Delta T_e$, electron thermal energy carried to target
  - Rapid rise in divertor density may raise sheath limit
  - No indication of $T_e$ elevated to $T_{e,ped}$ in SOL due to ELM
  - ELM particle flux to main chamber and narrow divertor ELM heat flux indicate target plate ELM heat flux not wholly tied to pedestal ion flux reaching target
- Indications of convective SOL transport at high density
  - No pedestal $\Delta T_e$, large pedestal $\Delta n_e$ indicate convective transport
  - Longer heat pulse duration consistent with ion sound speed flow from midplane to target
- More work needed to asses role of sheath in ELM transport

# Conclusions

- Type I ELMs may be compatible with a burning tokamak IF the energy conducted from the pedestal can be kept small, or zero
  - Low conduction, or purely “convective” Type I ELMs occur in present tokamaks at high pedestal collisionality, suggesting large intolerable ELMs for a burning tokamak with a low collisionality pedestal
  - Other factors such as pedestal width and triangularity may modify the collisionality dependence perhaps allowing access to purely “convective” ELMs in ITER
  - More work needed to asses role of SOL transport in limiting ELM energy
- Purely convective ELMs also help to mitigate the ELM heat flux by lengthening the duration of the ELM energy deposition on the target