Modifications to H-mode pedestal structure via particle control and topology variation on Alcator C-Mod

(Contains some preliminary data)

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Alcator C-Mod

Abstract

Edge profile structure is characterized in H-modes on the Alcator C-Mod tokamak, with the objective being a physics-based understanding of factors setting the pedestal height and width. Because large Type I edge-localized modes (ELMs) are rare on C-Mod, H-mode pedestal studies typically concentrate on steady H-modes either in the enhanced D-alpha (EDA) regime or, at higher power levels, operating with small grassy ELMs. Transient ELM-free H-modes with low particle transport are also considered in the study of profile structure. Across this range of operation, pedestal width shows little systematic variation, while the pedestal height is strongly linked to total plasma current I_P. In particular, the height of the H-mode density pedestal n_{ped} appears to be regulated by plasma transport such that $n_{\mathrm{ped}} \sim 0.3\, n_G$, where n_G is the Greenwald density limit. In addition, plasma transport governs the edge pressure profile such that, across a wide spectrum of operational parameters, the poloidal beta gradient is a decreasing function of collisionality. These correlations among density, pressure and current have been further explored, using both active particle pumping and variations of magnetic topology. Active pumping significantly reduces edge collisionality and increases both pedestal pressure gradient and global H-mode confinement. This effect comes about via only a modest reduction to n_{ped}, accompanied by a boost in pedestal temperature. Magnetic topology is found to have a substantial effect on pedestal density, in both pumped and unpumped discharges. For single null discharges with the same engineering parameters, n_{ped} is lowered by ~20% when ion grad-B drift is directed away from the active x-point, independent of field direction. The density pedestal in nearly double null discharges is a sensitive function of the proximity of the equilibrium to magnetic balance, such that slight variations in topology about double null gave the potential to regulate H-mode density and collisionality. Details of pedestal structure (*e.g.* widths, gradients) in these configurations will be presented.

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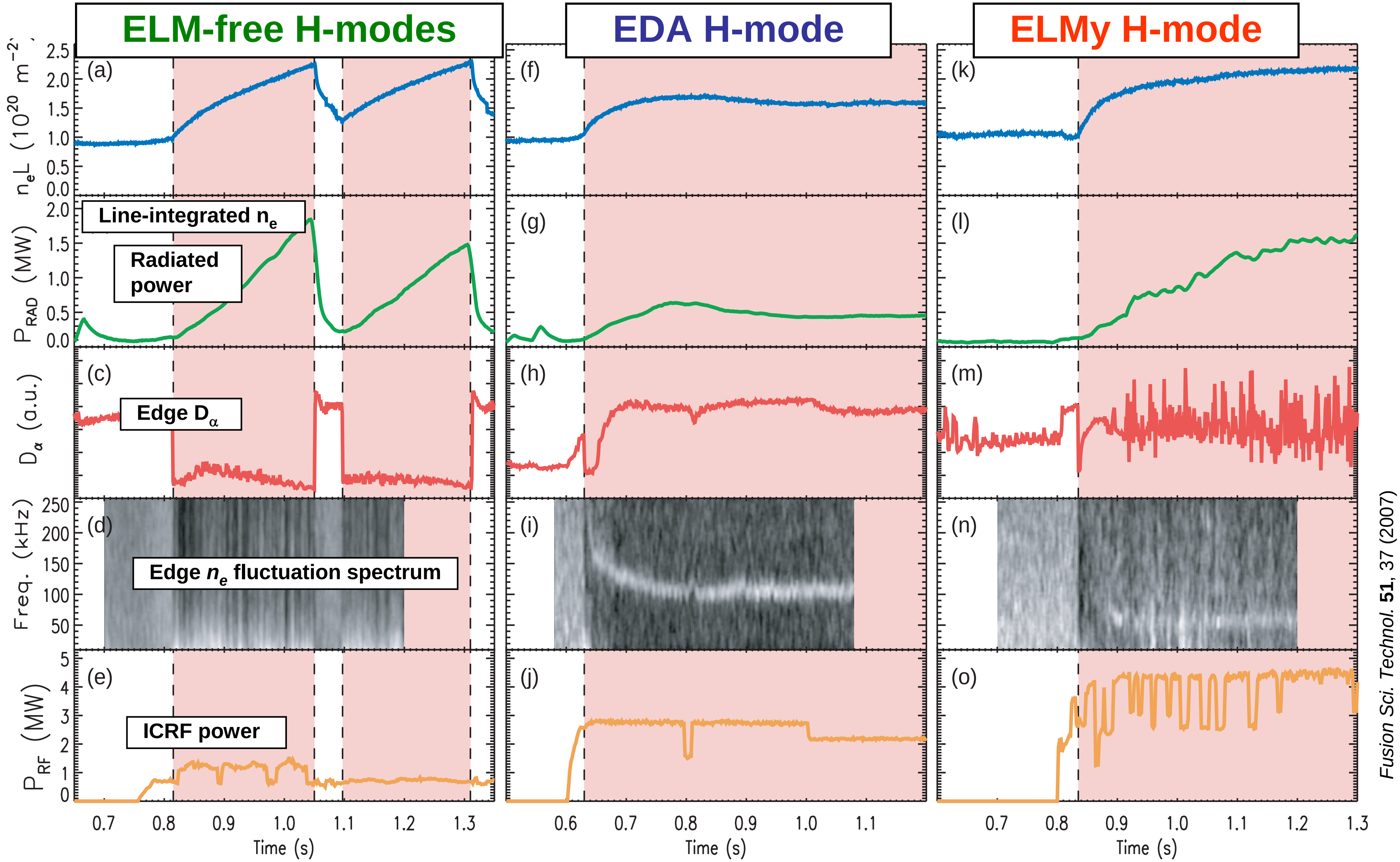
Goal: Understand influences of particle control on H-mode behavior

- Density control desirable in H-mode
  - Mitigate unwanted density rises that deteriorate confinement
  - Extend operation to lower collisionality for studies of ELMs and core density peaking
  - Low-density targets for lower hybrid current drive, advanced scenario development
- Fueling control in C-Mod discharges has typically been limited to gas puffing . . . did this limit attainable pedestal parameters?
- Active pumping now routine on C-Mod
  - H-mode density determined by interplay of neutral fueling and edge plasma transport
  - Upper chamber cryopump → particle control sensitive to magnetic topology
  - But, pedestal transport can also be effected by magnetic topology
- Current studies use neutral pumping and control of magnetic balance for pedestal optimization

First, some background . . .

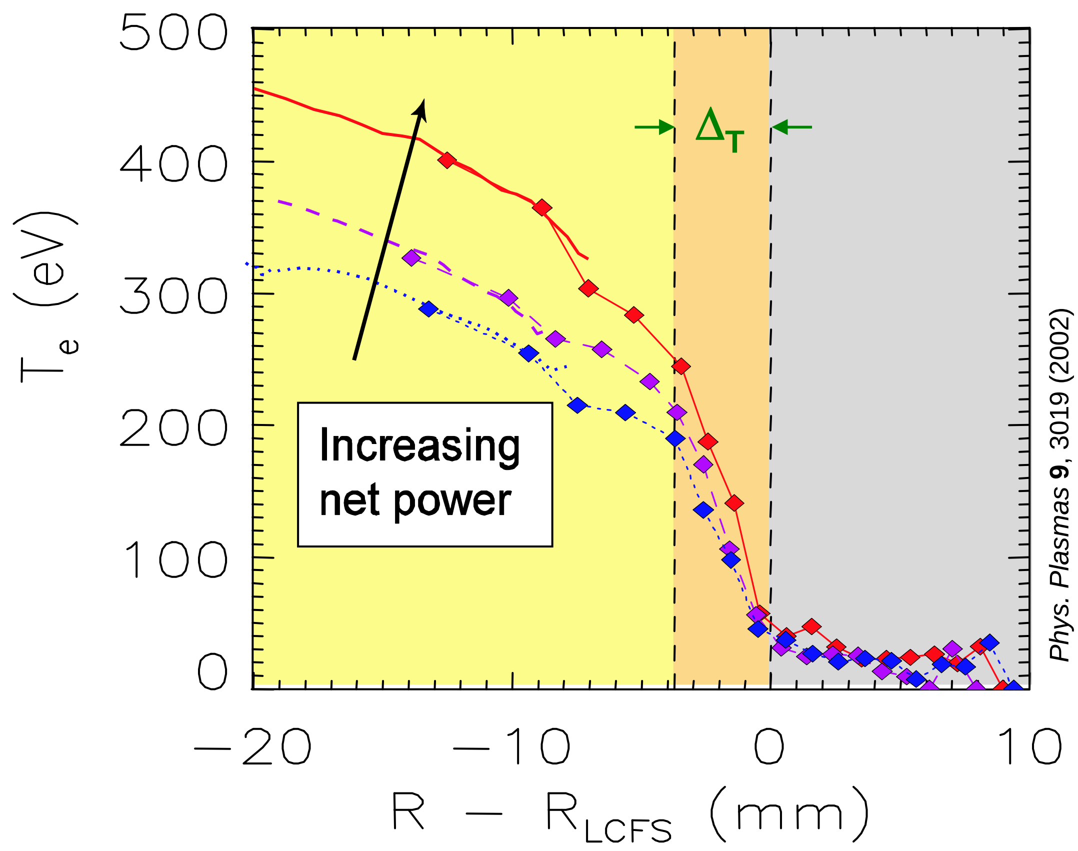
Several H-mode regimes are available on C-Mod [1]

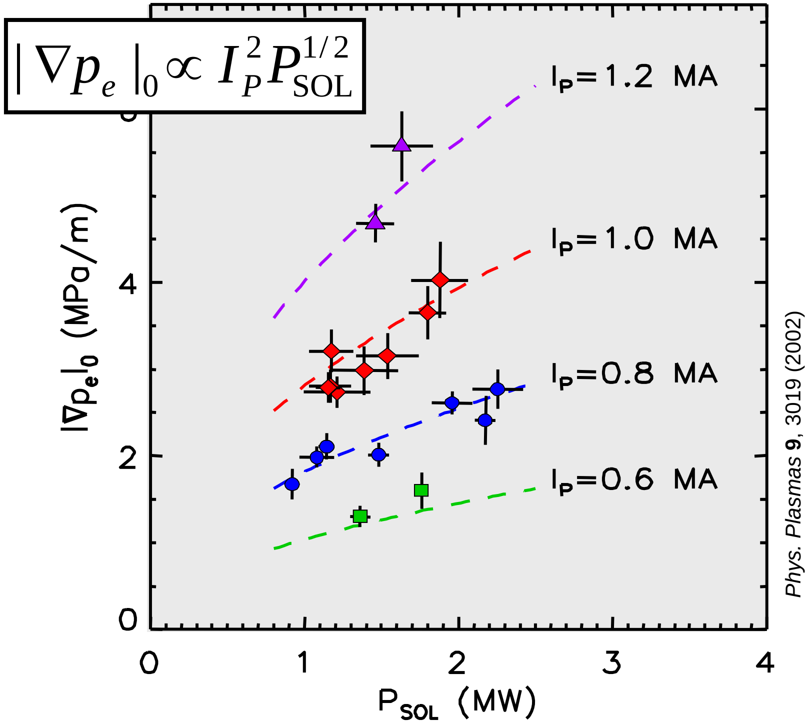


Typ. q_{95}<4 or low density → Higher q_{95}, higher ν* → Higher input power

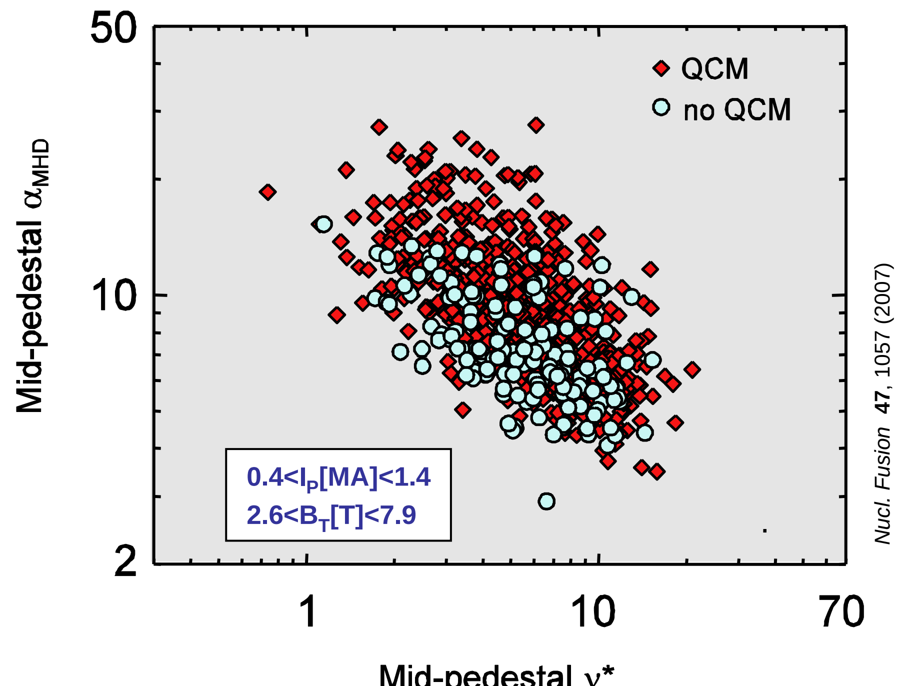
Pedestal scalings demonstrate width invariance, profile stiffness [2,3]

- Pedestal width insensitive to most plasma parameters
- Increasing power has not been seen to increase width
- Rather, T_e gradient increases (L_T~constant)
- Increasing power flux has no significant effect on *density* pedestal
- Pressure profiles exhibit a *ballooning-like* scaling in H-mode, even in absence of ELMs





- Dominating the pressure pedestal is an I_P^2 scaling, suggesting a critical α limit
- But, edge is found stable to ideal MHD modes
- I_P^2-limit is "soft"; $|\nabla p_e|$ scales weakly with power
- α_{MHD} and ν^* coalesce pedestal data set over a wide range of parameters



- QCM apparently not required to achieve this pressure "stiffness"
- No ELMs in these discharges; similarities to inter-ELM profiles on other machines?
- What are the transport mechanisms governing the profiles?

H-mode edge density profiles resilient to modification from fueling [4]

- Varying plasma current I_P systematically varies pedestal plasma transport, in particular regulating $n_{e,PED}$. Typically, $n_{e,PED}$ ~ 0.3—0.4 x n_G
- D_2 puffing experiments in steady enhanced D_α (EDA) H-modes show clamped ∇n, ∇p
- Suggestive of transport regulation via critical gradient physics
- Measured particle diffusivity varies with plasma current

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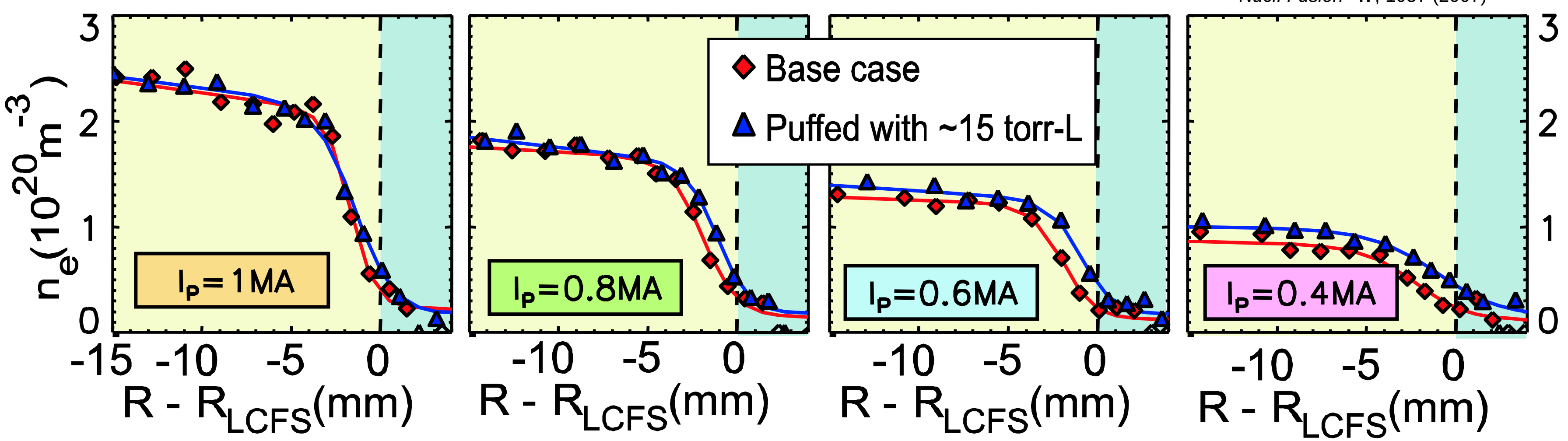
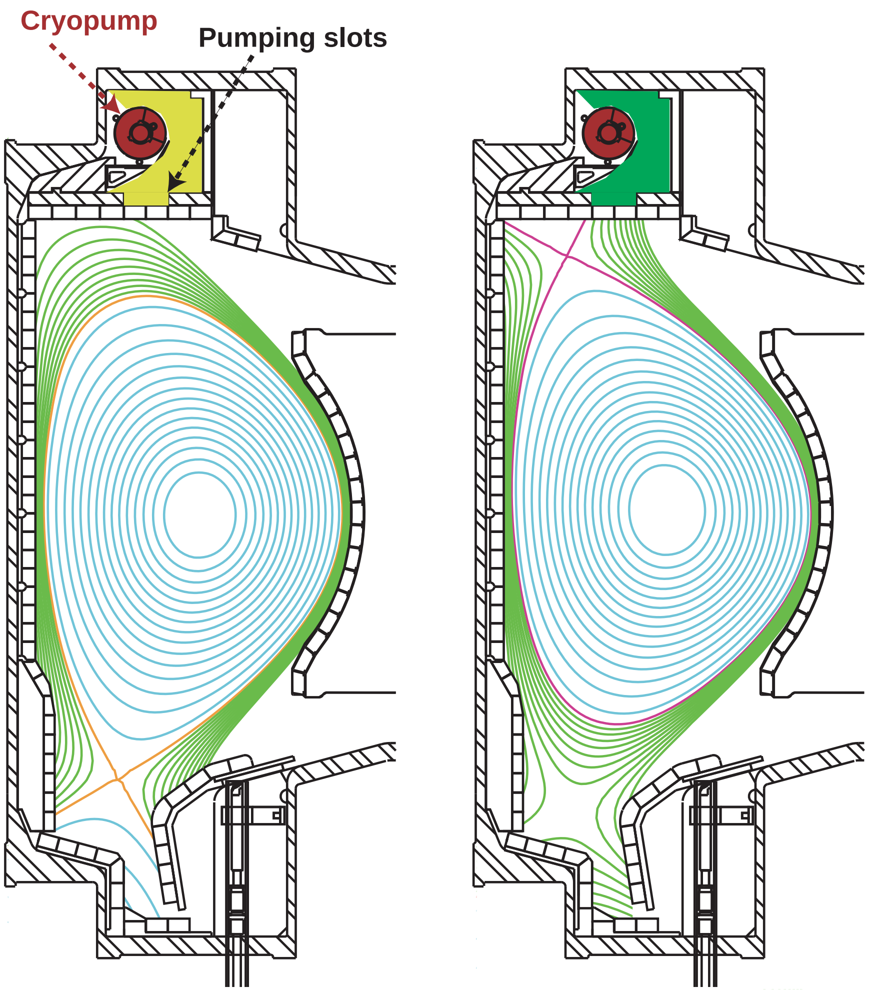
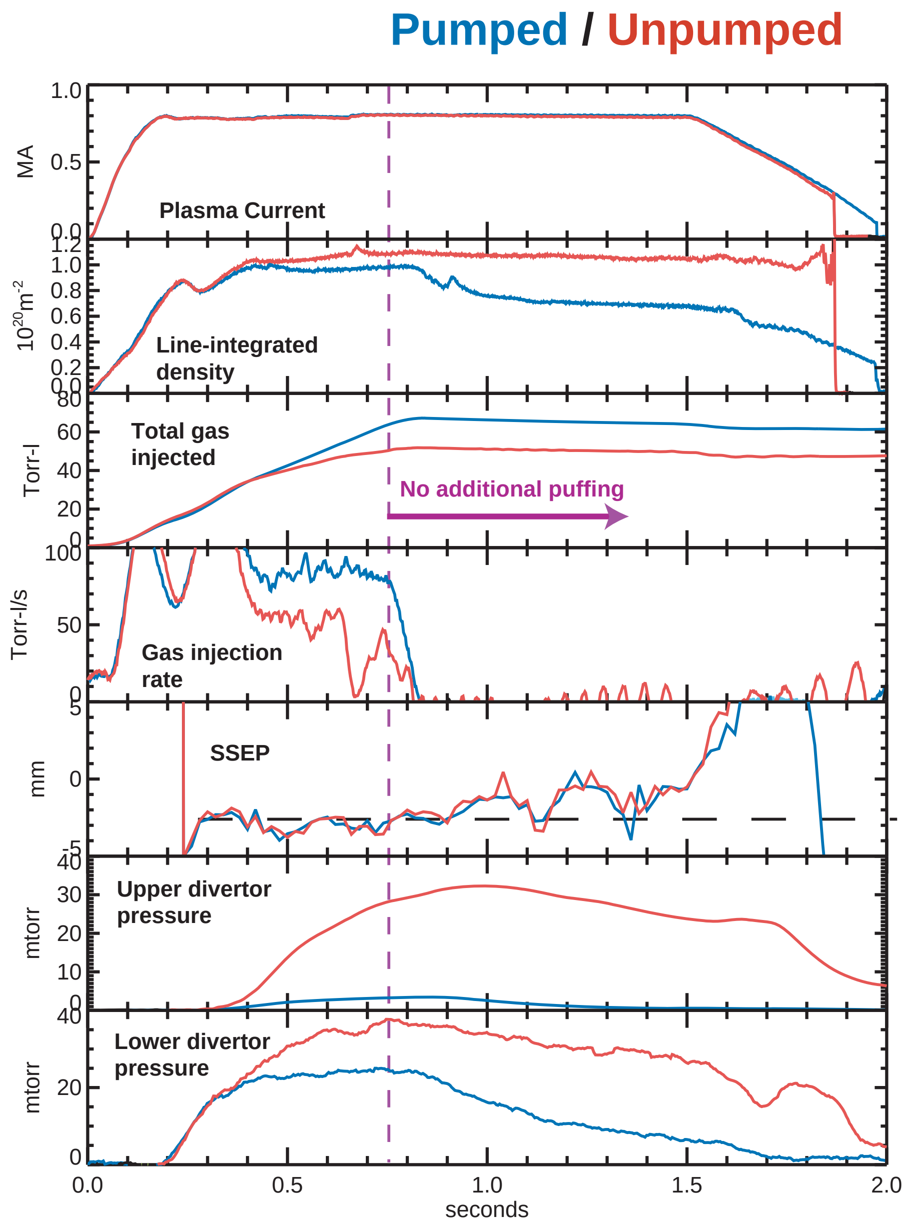


Addition of cryopump to C-Mod provides new tool for particle control [5]

- Toroidally arrayed pumping slots sample recycling neutrals from the upper divertor target
- Significant particle flux to plate at the slot location is prerequisite for high neutral compression in cryopump chamber (i.e. strong pumping)
- Most significant effect on upper null, near double null discharges
  - Places constraints on operating magnetic topology
  - Relative direction of magnetic balance and B x ∇B influences H-mode access, pedestal physics



- Direct comparisons of Ohmic discharges were performed with and without pumping
- With active pumping, higher gas fueling required to reach same target density
- In unpumped case, discharge density maintained by wall recycling, following cessation of gas puff feedback
- With pumping, substantial density reduction observed in first 100-200ms following end of puff
- Additional pump-out on longer time scales
- Penalty paid on the gas in lower divertor for (even slightly) LSN discharges



H-mode operation with cryopump: Questions

- Can we use the cryopump as a tool to push to lower-collisionality H-mode regimes?
- What are the limitations to particle control? Is the H-mode edge as resilient to pumping as it is to puffing?
- Can edge relaxation mechanisms be significantly modified?
- Is there a suitable quasi-stationary H-mode on C-Mod compatible with cryopumping?

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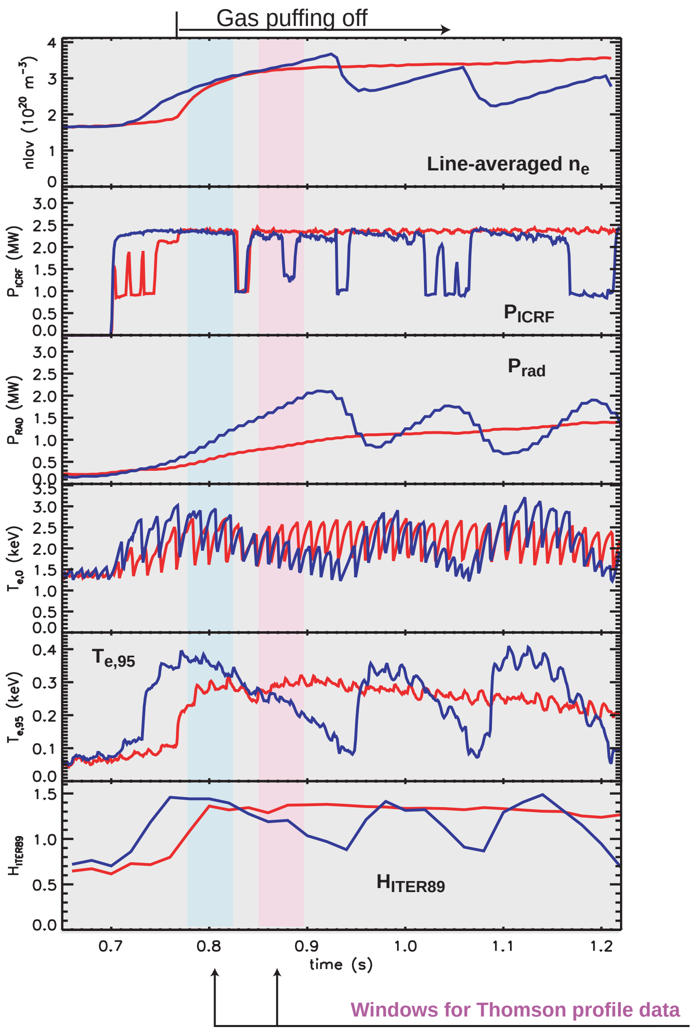
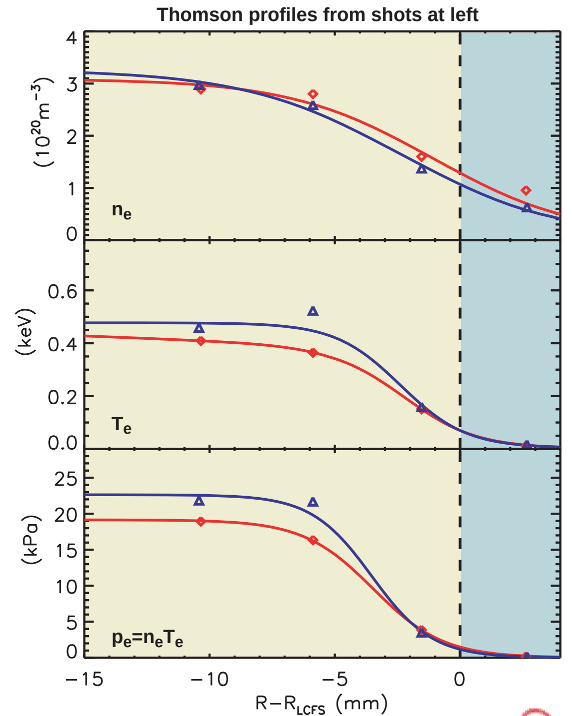
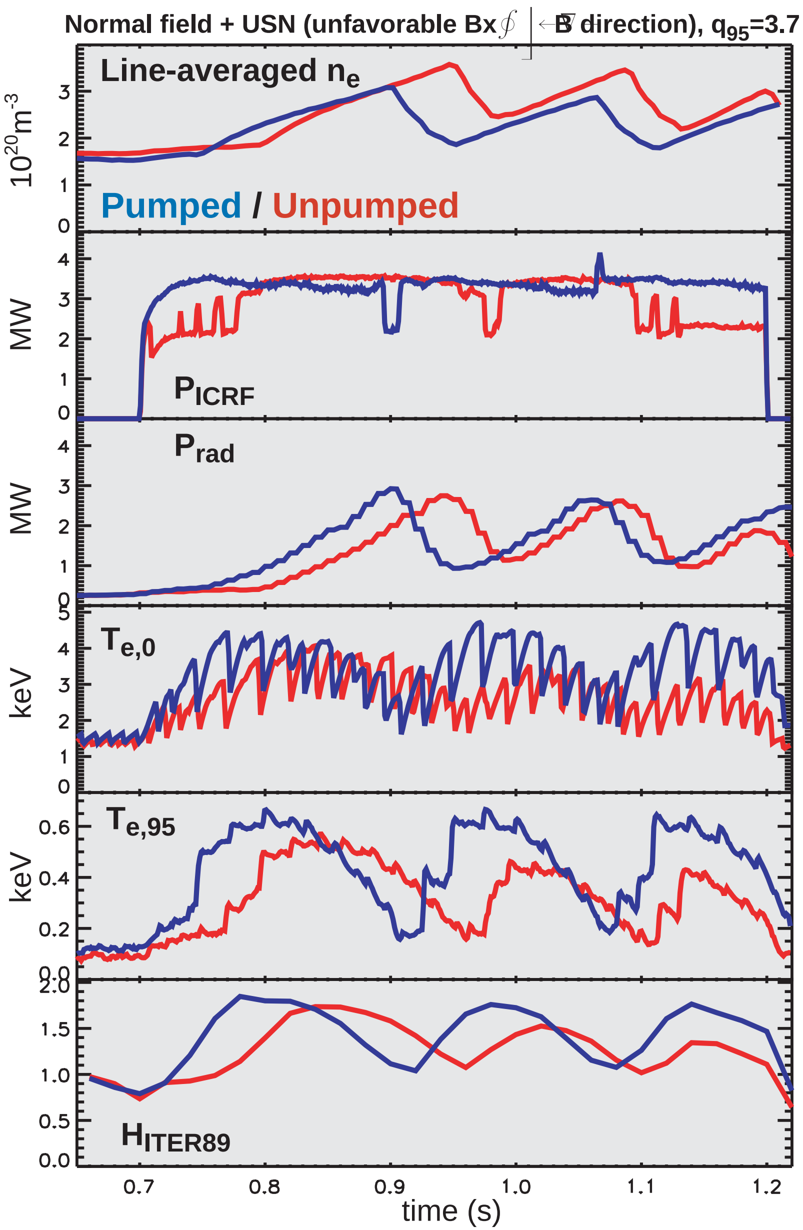
Pumping on H-modes: Three examples

Near DN case, 1MA, 5.4T   Pumped / Unpumped

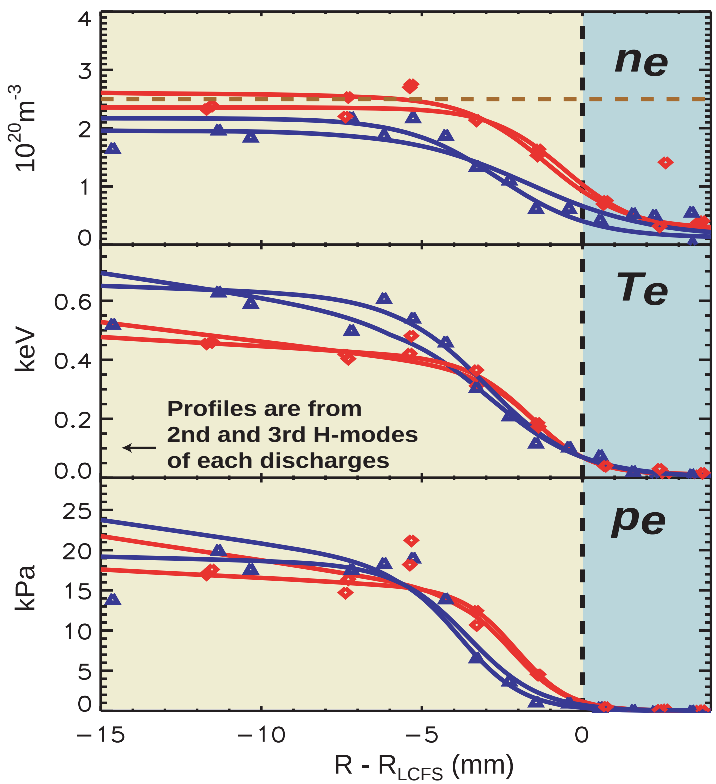


- Effect on H-mode pedestal parameters is measured by comparing H-modes in identical target plasmas with and without pumping
- Gas feedback used to maintain constant L-mode line-averaged density; turns off after H-mode formation
- In ***slightly LSN*** discharge at right (S_{SEP}~-3mm), edge T_e boost is obtained, though density pedestal formation is unaffected
- Transiently higher pressure pedestal, confinement, but H-modes eventually radiatively collapse; more typical of ELM-free operation than EDA



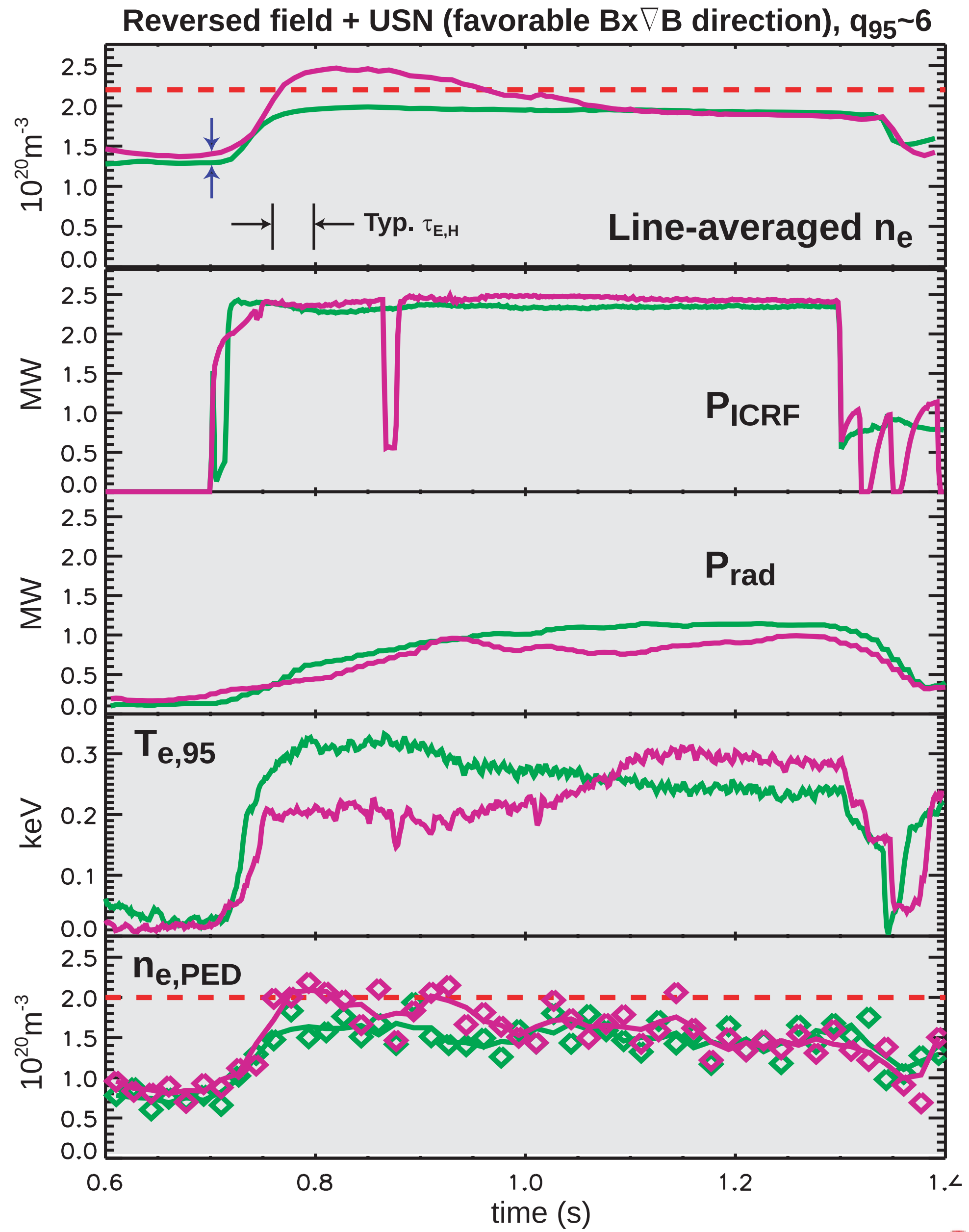


- **For USN ELM-free H-mode target**, $n_{e,PED}$ reduced by 15-20% when pumped
- Pumping lowers edge collisionality promptly by lowering edge n_e at roughly fixed p_e
- Transient improvement of confinement in pumped case

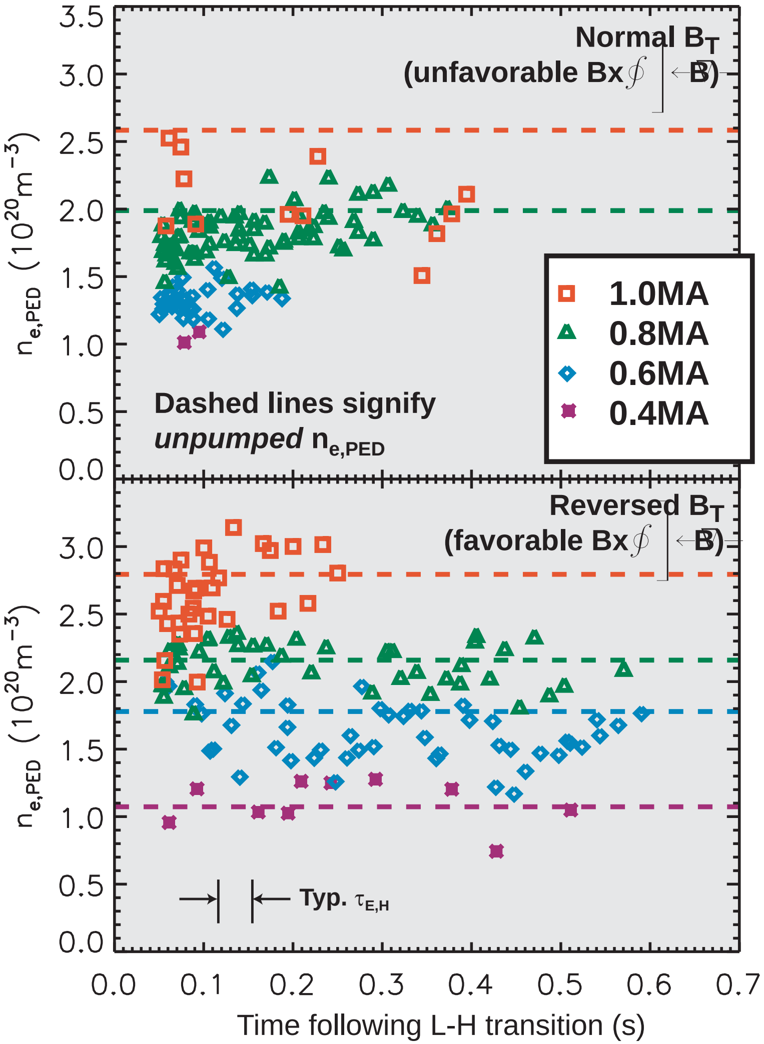


Thomson scattering profiles

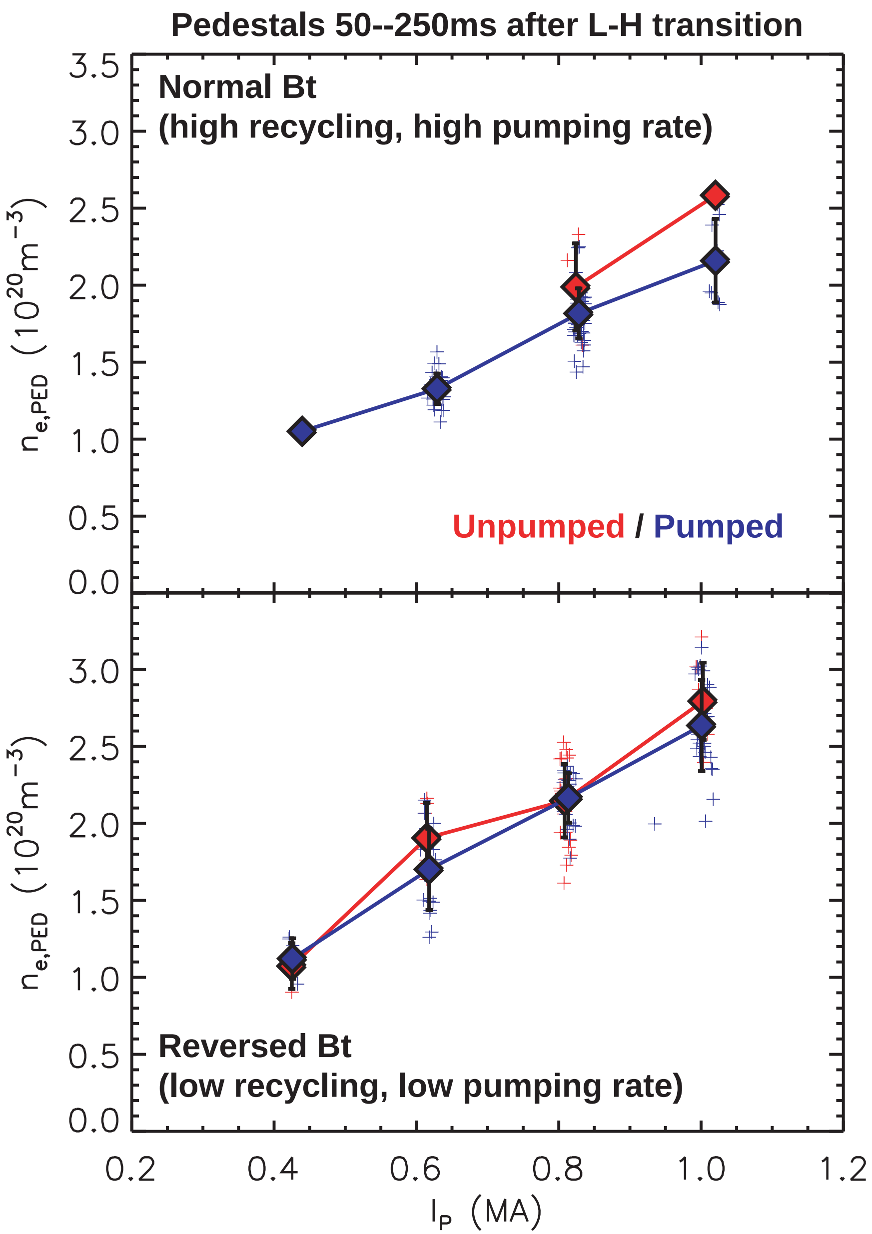
- **“Pump-out” of higher q EDA H-modes**
- Examples at left have varied L-mode fueling
- Pumped H-modes reach identical equilibrium values of both global and pedestal n_e
- Steady state $\langle n_e \rangle$, $n_{e,PED}$ independent of the initial H-mode starting condition, and lower than in nominal unpumped case
- Core plasma sheds particle inventory on 100-200ms time scale
- Edge T_e rises in response to density drop, so that initial edge pressure is approximately maintained
- Resembles a time-reversal of H-mode D_2 puffing experiments! [3,4]



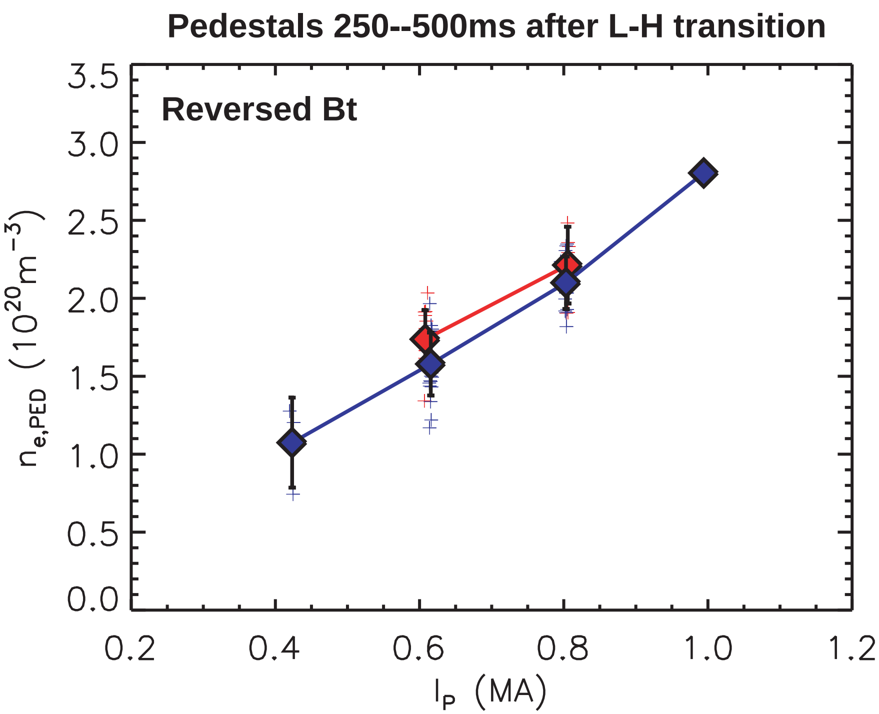
H-mode density reduction in USN



- USN discharges evaluated with both B_T directions
- In both cases, $n_{e,PED}$ scales with I_P
- ***Normal field:*** Bx∇B directed away from X-point
  - Lower starting $n_{e,PED}$ than for favorable ∇B drift
  - Unvaforable drift direction -> radiative ELM-free H-modes, typically of short duration [6]
  - Ohmic core pump-out times ~ 100-200ms
- Reversing field gives favorable ∇B drift
  - Promotes longer, EDA target plasmas for comparison
  - Somewhat reduced pumping capacity due to lower recycling at the pumping slot (reversal of in-out divertor asymmetry)
  - Note that *unpumped* $n_{e,PED}$ slightly larger than in the unfavorable drift direction case
- Pedestal density slightly lower on average when pumping, most prominently at higher I_P (q_{95}<4)



- Prompt pump-out observed only in strongly-pumped, low-q cases
  - Is the EDA density pedestal more stiff?
- A hint of long-term pump out, in the weakly pumping case



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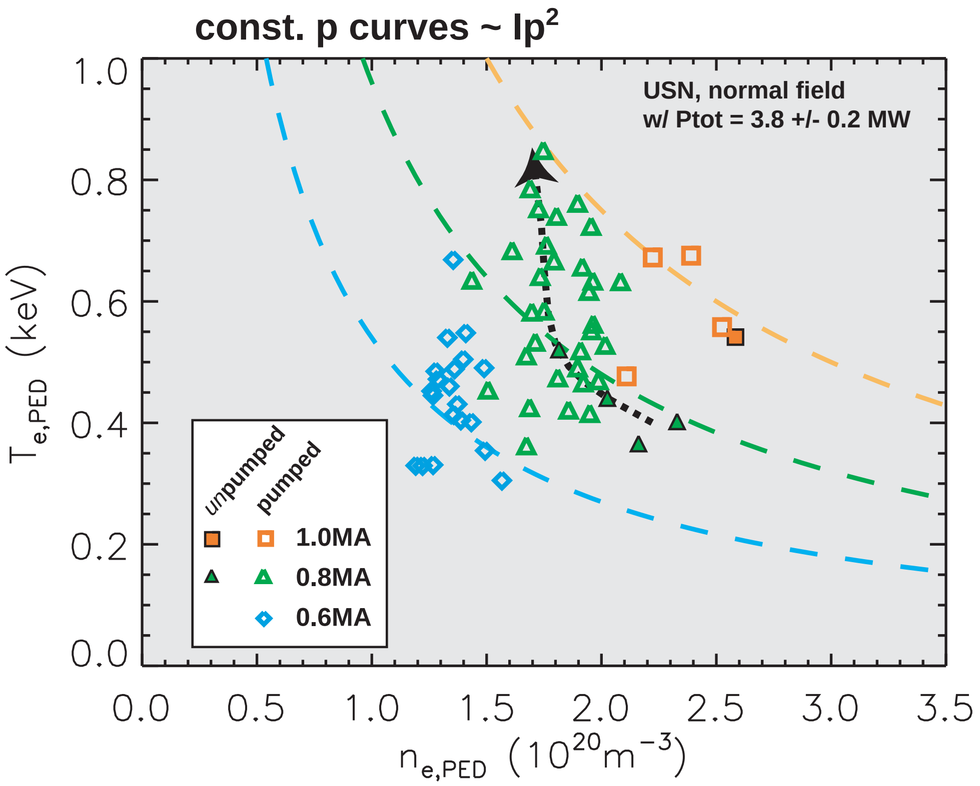
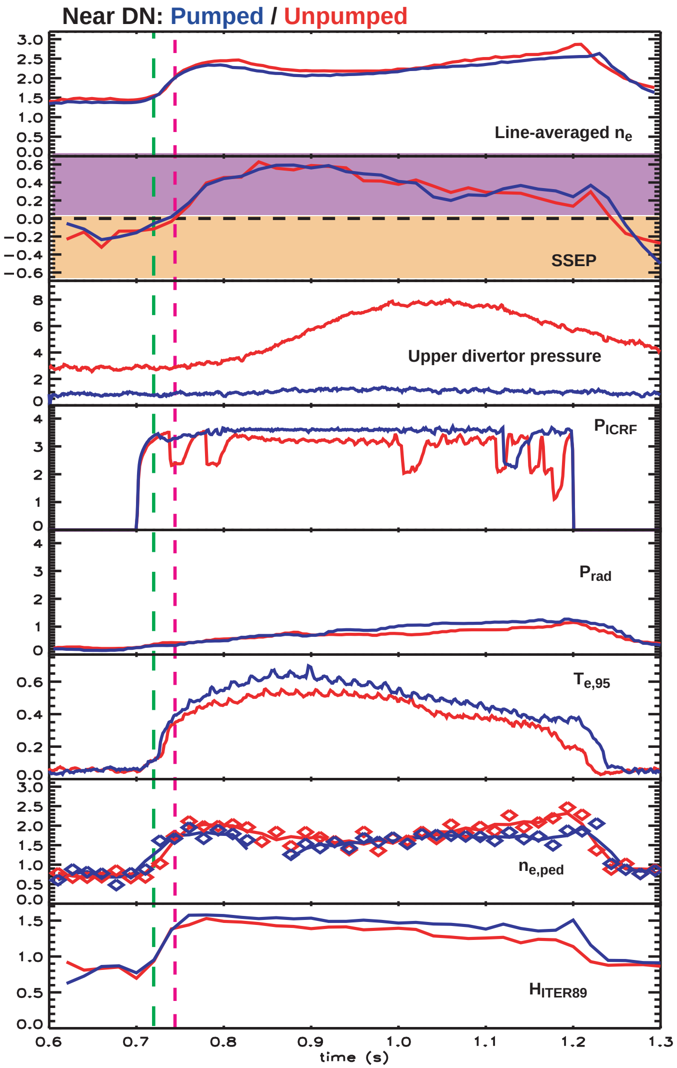
Observed increases in confinement linked to edge pedestal modification

- Many H-mode regimes (moderate density, q_{95}) exhibit very little density drop when pumped
- Stiff density gradients at fixed pedestal width a possible explanation
- Even in cases with clamped density pedestals, pumping provides a significant reduction in edge collisionality, via $T_{e,PED}$ increase
- Likely a modification of SOL n_e, T_e is lowering the separatrix collisionality
- **Boost in edge ∇p** is obtained by reducing ν^*, consistent with prior observations
- Provided radiation is kept low, pumping enhances H-mode performance through core profile stiffness



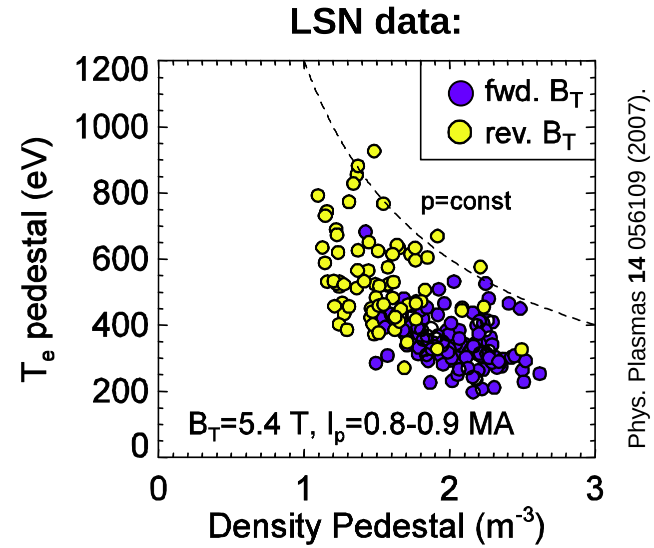
Scans of magnetic balance explored in pumping experiments

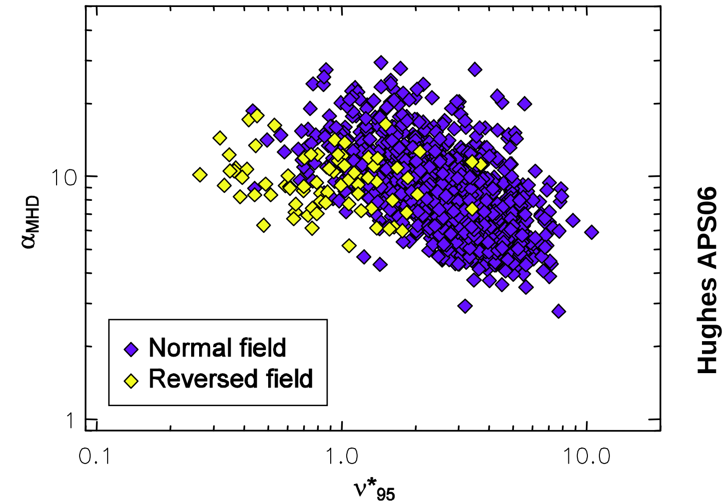


- An additional approach designed to combine strong pumping with ease of H-mode access is the S_{SEP} scan through double null, with field in the normal direction
- H-mode is triggered by ICRF while plasma is biased LSN (favorable ion ∇B drift)
- Scan to USN while maintaining H-mode, placing increasing particle flux on the upper target; favorable H-mode hysteresis prevents H-L back-transition
- Density depression (and T_e increase) observed when plasma becomes biased toward USN, *in both pumped and unpumped cases!*
- Longer term density depression later in H-mode (t>1s), resulting in improved sustainment of edge T_e, H-factor.
- Results motivated additional study of detailed topology effects on pedestal near DN

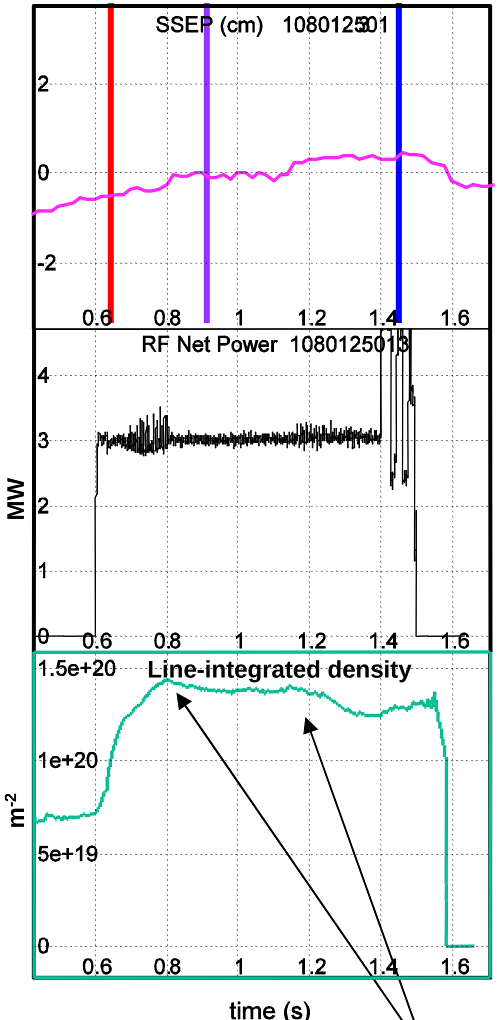
What is the role of magnetic balance in regulating the H-mode pedestal?

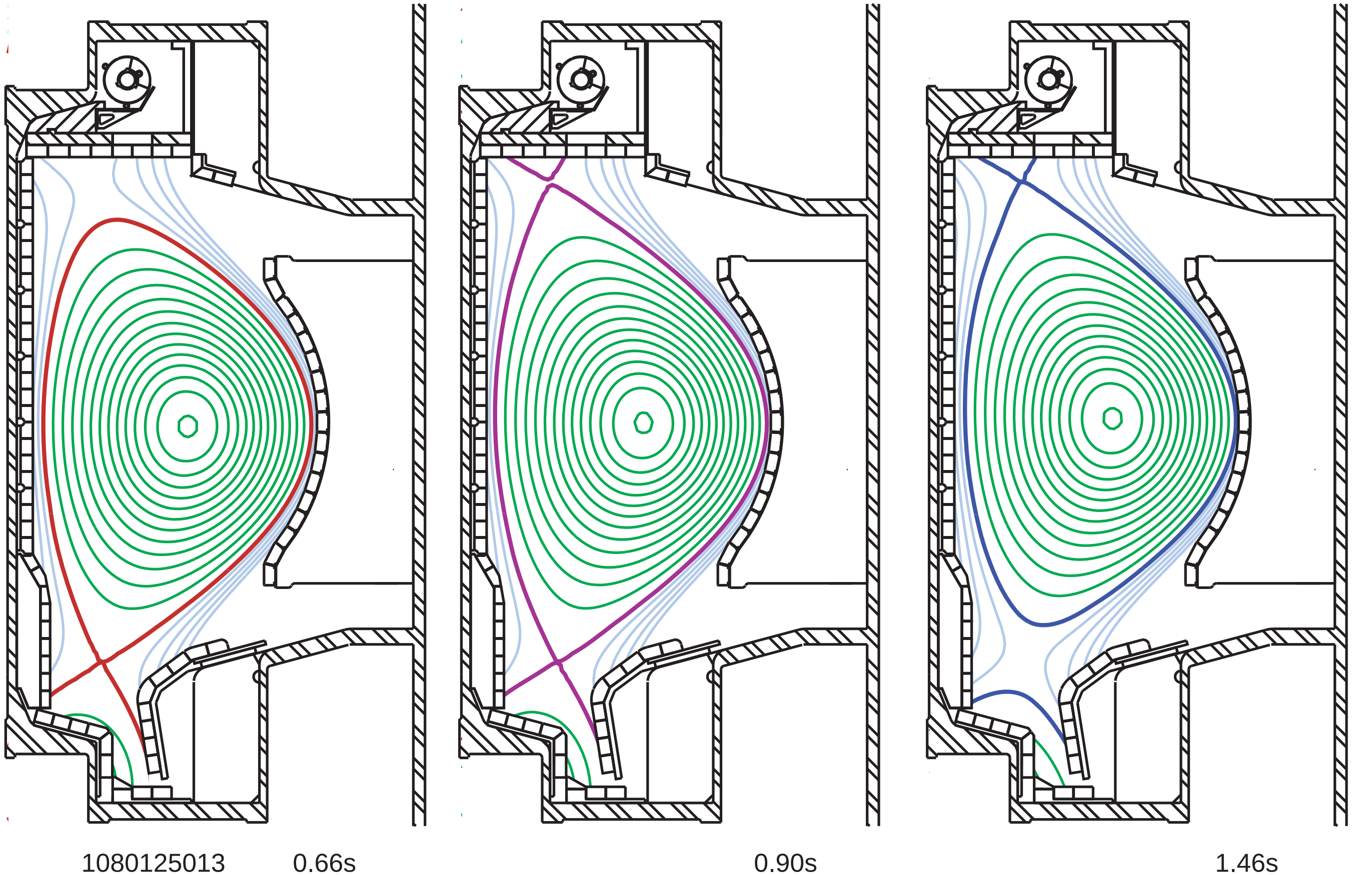
- Have observed distinct differences in pedestals obtained in favorable *vs.* unfavorable ∇B drift direction [6]
  - Collisionality drops considerably when ion ∇B drift away from active X-point
  - Starting T_e higher due to higher L-H power threshold
  - Also a density effect: lower $n_{e,ped}$ obtained in unfavorable case
- L-H transition power, core rotation have been shown to vary continuously across the transition through balanced DN → does H-mode pedestal vary smoothly as well?
- Can we learn something about pedestal physics?
  - Do pedestal widths differ? How are confinement properties affected?
  - Should we worry about proximity to DN in ITER?





H-mode experiments performed with varied S_{SEP} programming in *normal field direction*





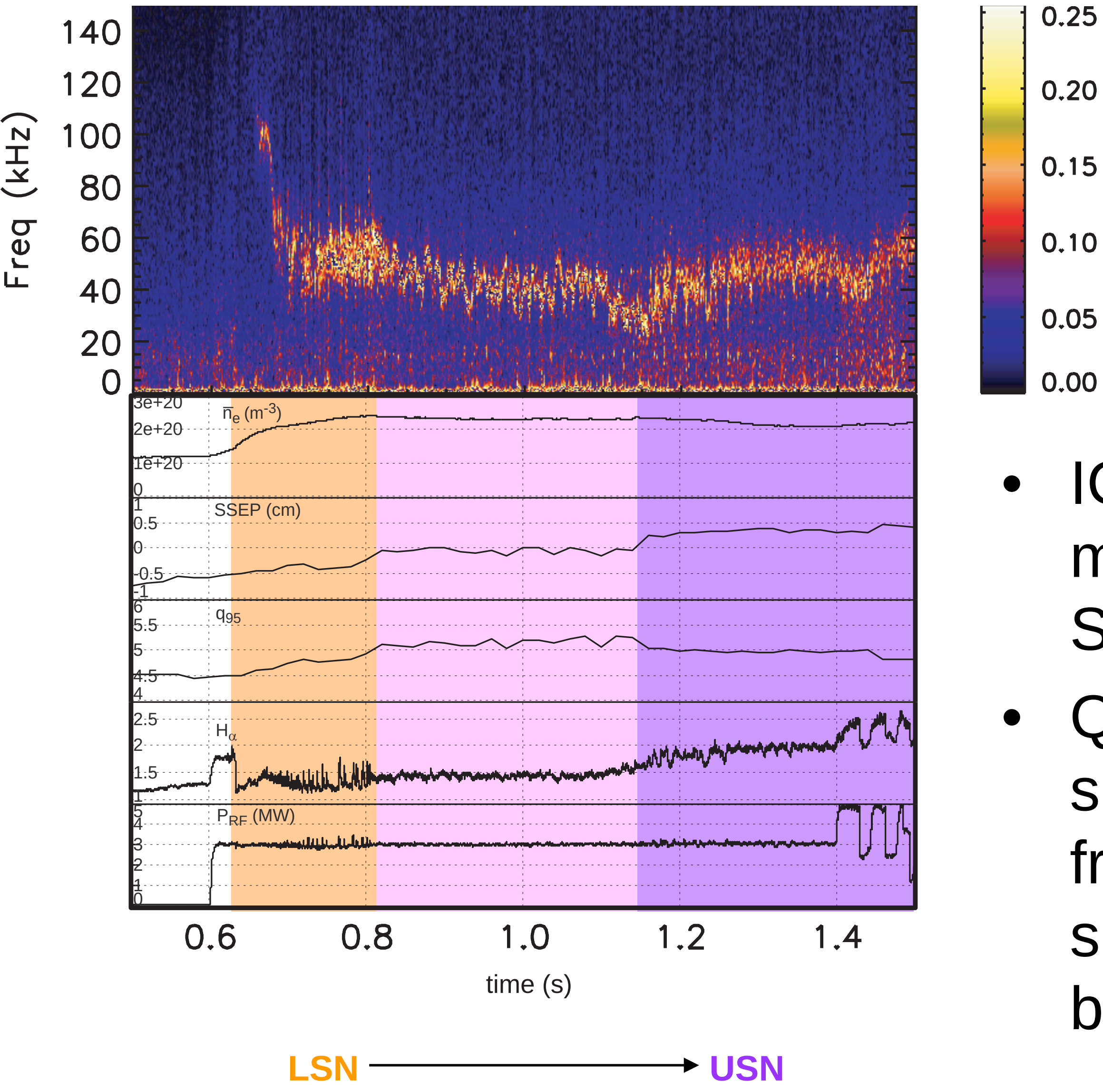
S_{SEP} ~ -5mm

S_{SEP} ~ 0mm

S_{SEP} ~ +5mm

Density drops associated with S_{SEP} upward jogs

Line-integrated n_e fluctuations from phase contrast imaging

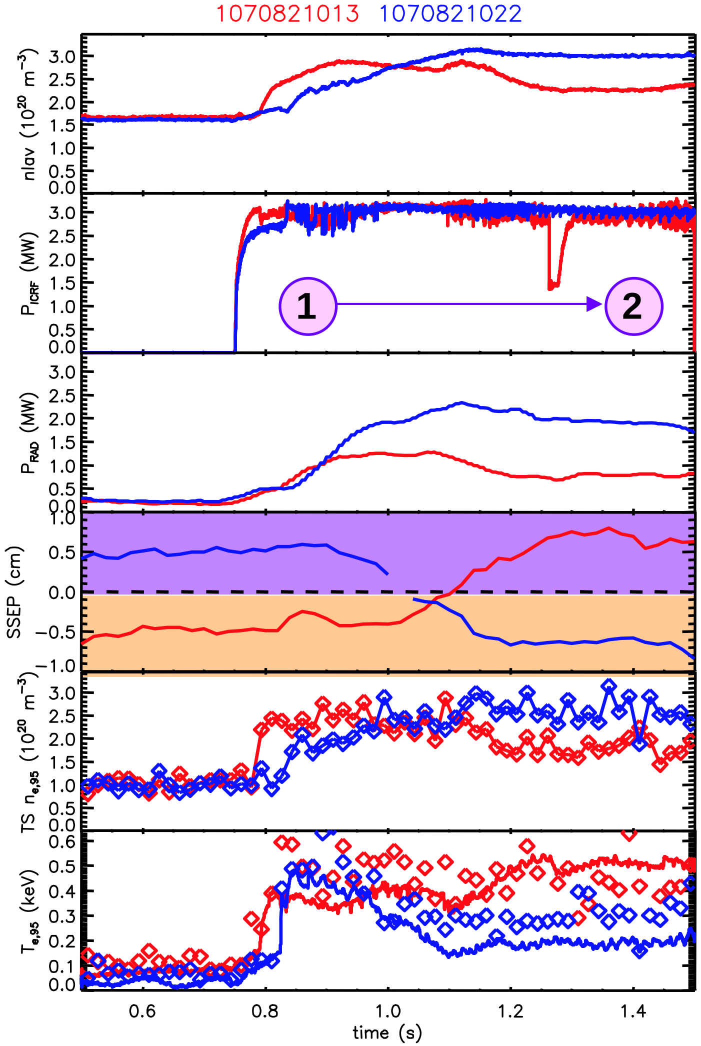


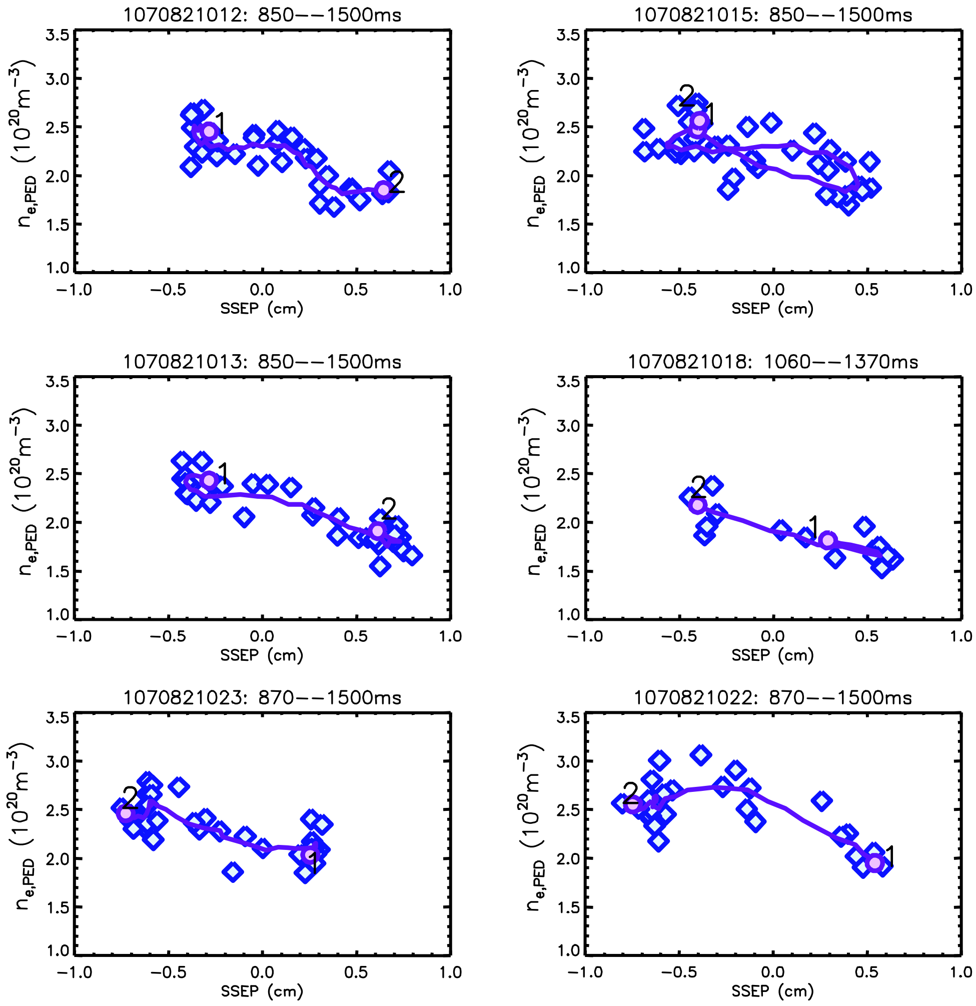
- q_{95}~5 gives nominal EDA target (sometimes with small ELMs)

- ICRF power, H-mode maintained throughout S_{SEP} sweeps
- QCM persists, with small changes in frequency, throughout shifts in magnetic balance

(Phase contrast imaging data courtesy L. Lin)

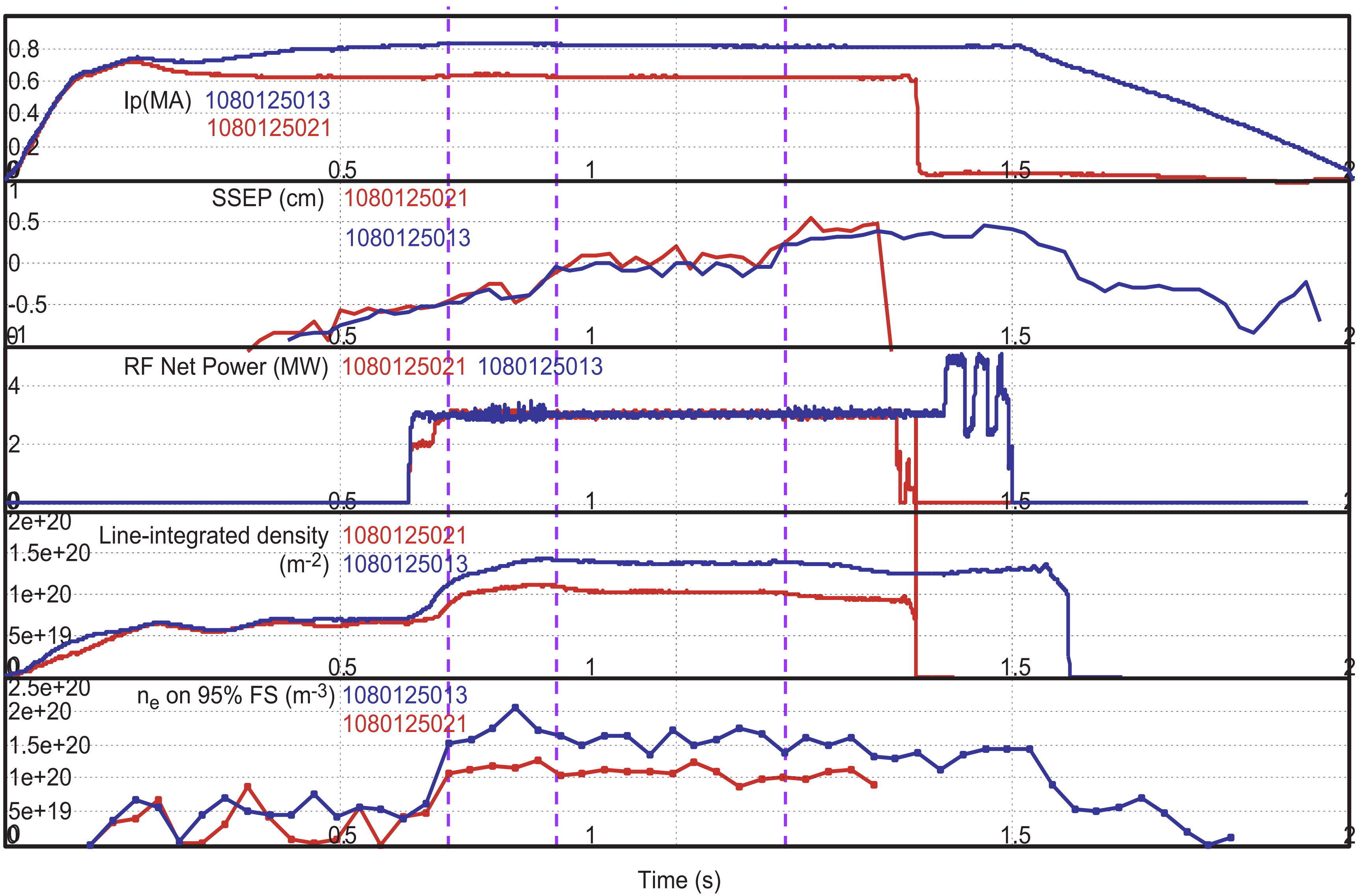
- 800kA H-modes, nominally EDA.
- No cryopumping; ICRF power fixed at 3MW for all shots (*radiation is not*)
- LSN→USN regularly *lowers* density. USN→LSN regularly *raises* density



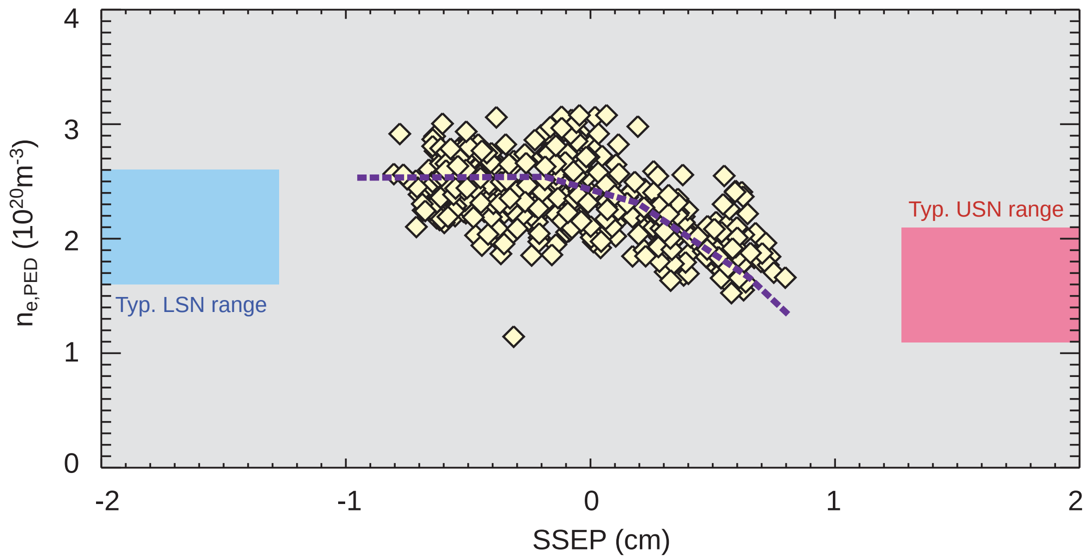


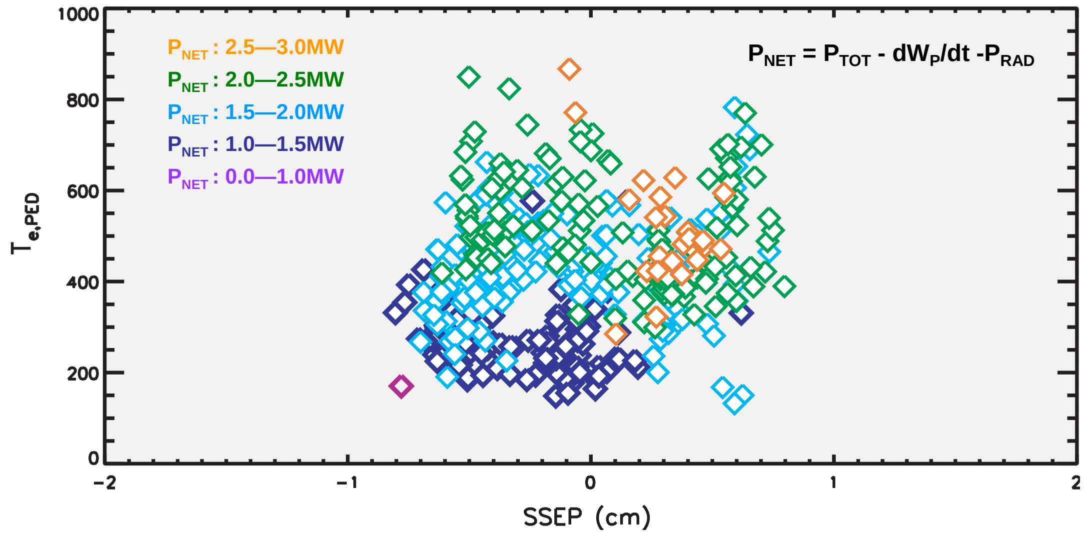
Alcator C-Mod

- Pedestal density reduction with S_{SEP} increment demonstrated at in EDA discharges at q_{95} ~5, 6



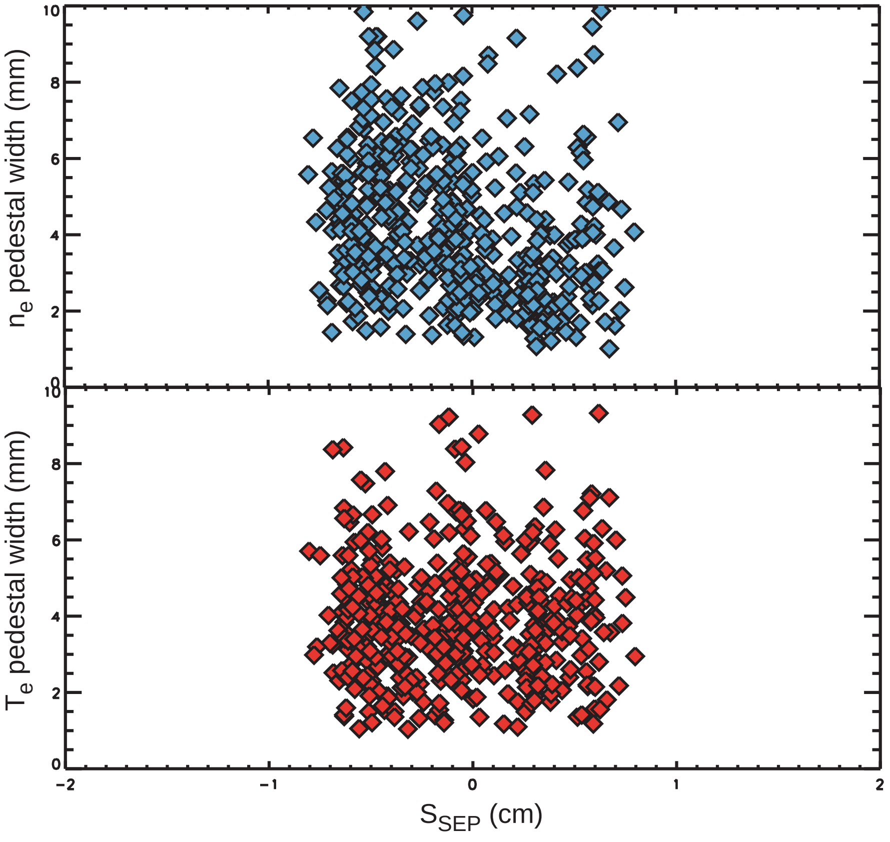
- For S_{SEP} between 0 and 5mm, steady state H-modes at q_{95}>4 are possible
- Density pedestal reduction for S_{SEP}>0 gives a fairly smooth transition to usual USN result
- $T_{e,PED}$ depends on power into the SOL P_{NET} as always
- Temperature does not rise to maintain a constant $p_{e,PED}$ in the slightly USN cases



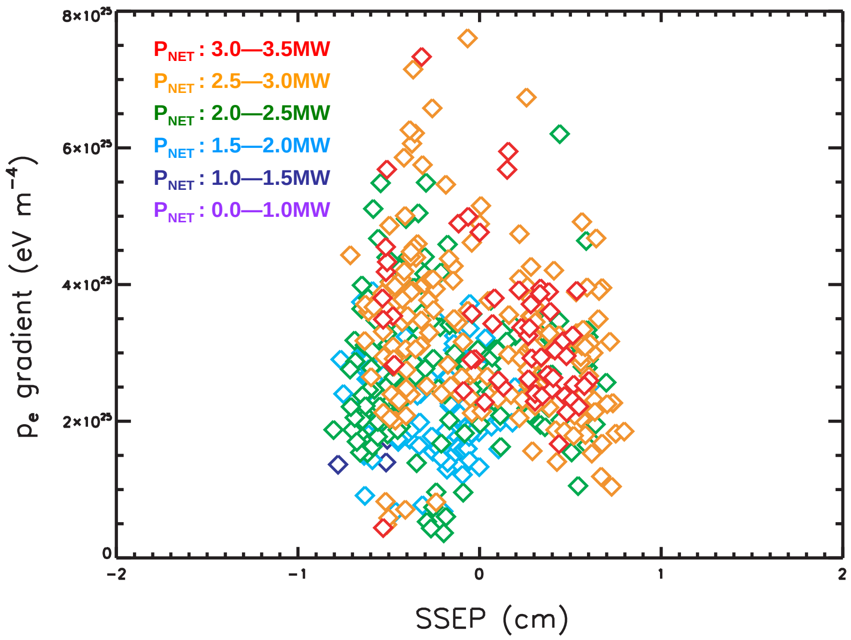


All pedestal parameters taken from fits to modified *tanh*, as defined in [2]

- Density pedestal width reduced on average for $S_{SEP}>0$
- For similar values of P_{NET}, a peak pressure gradient reduction is also seen in the slightly USN cases
- Best steady state confinement thus observed for S_{SEP} slightly *negative*

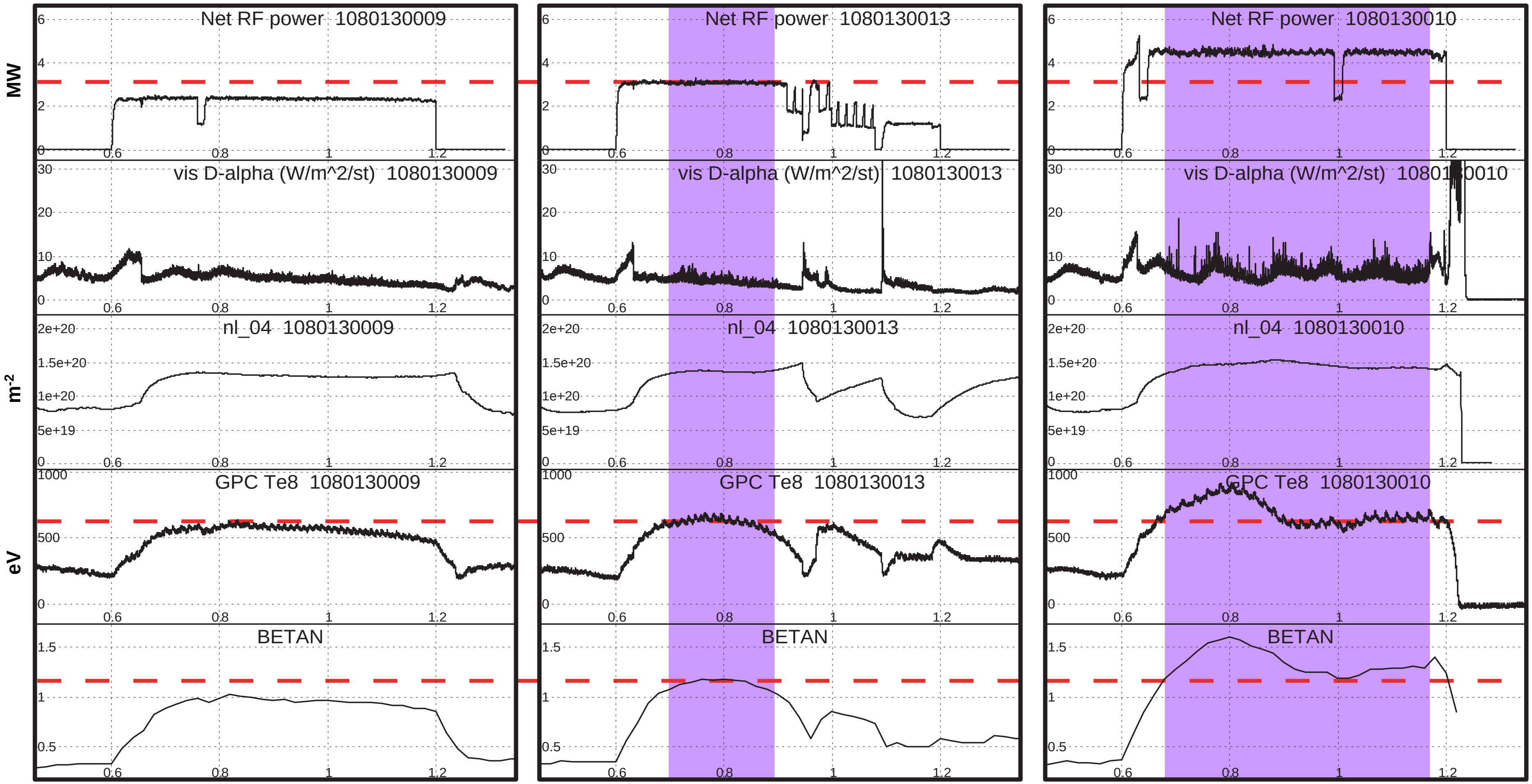


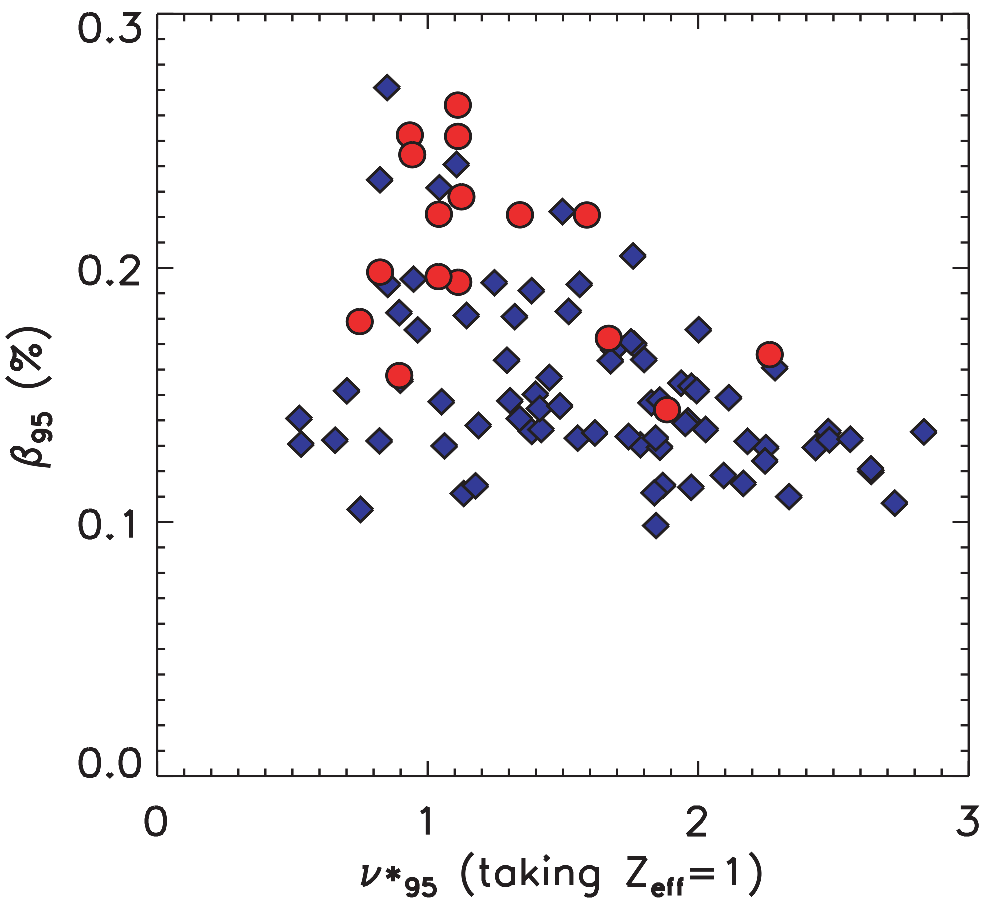
(Preliminary results)



All pedestal parameters taken from fits to modified *tanh*, as defined in [2]

- S_{SEP} of -5mm allowed steady H-modes with good confinement, small ELMs
- Reasonably modest ICRF power required to access ELMs (>~3MW)
- Threshold for ELM access corresponds to $T_{e,PED}$>~600eV or β_N>~1.2

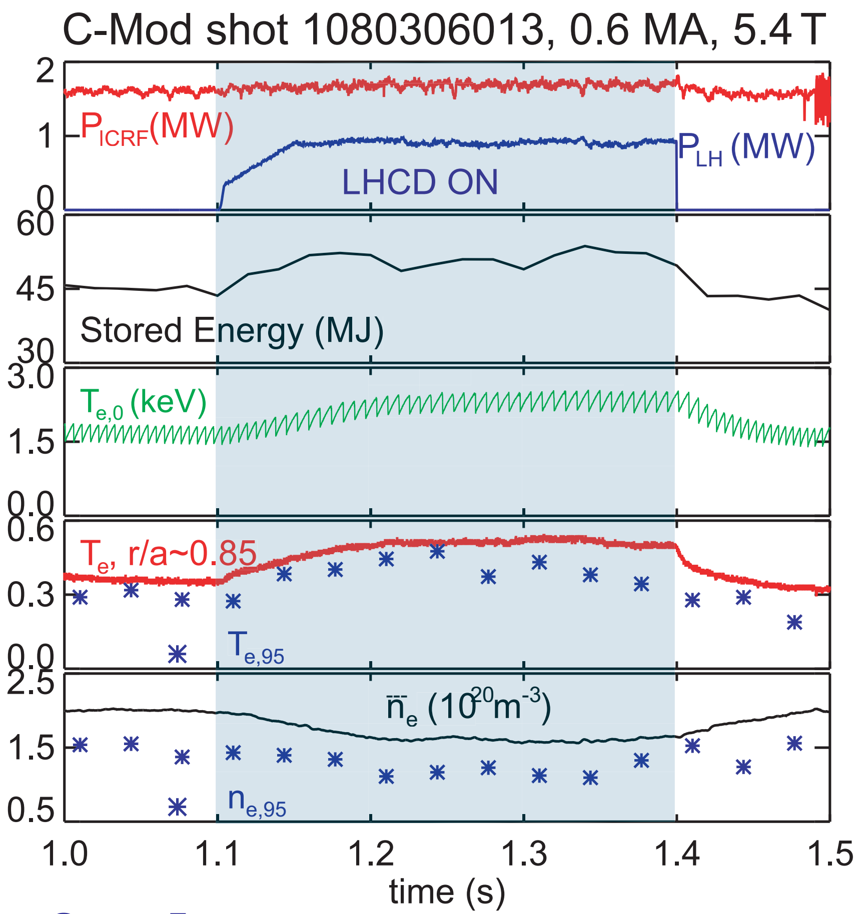




(Preliminary results)

- Substantial amounts of small ELMy data obtained at I_P=800kA, δ_L=0.55
- Power, density scans yield variation in edge β–ν space
- Similar in character to prior grassy ELMs [7] observed to develop in EDA plasmas
  - Sufficient T, grad-p required for ELM access
  - Do not altogether replace the QCM
- Accessed at relatively low net power in the near DN case with S_{SEP}~-5mm

Pedestal optimization experiments led to development of H-mode targets for LHCD

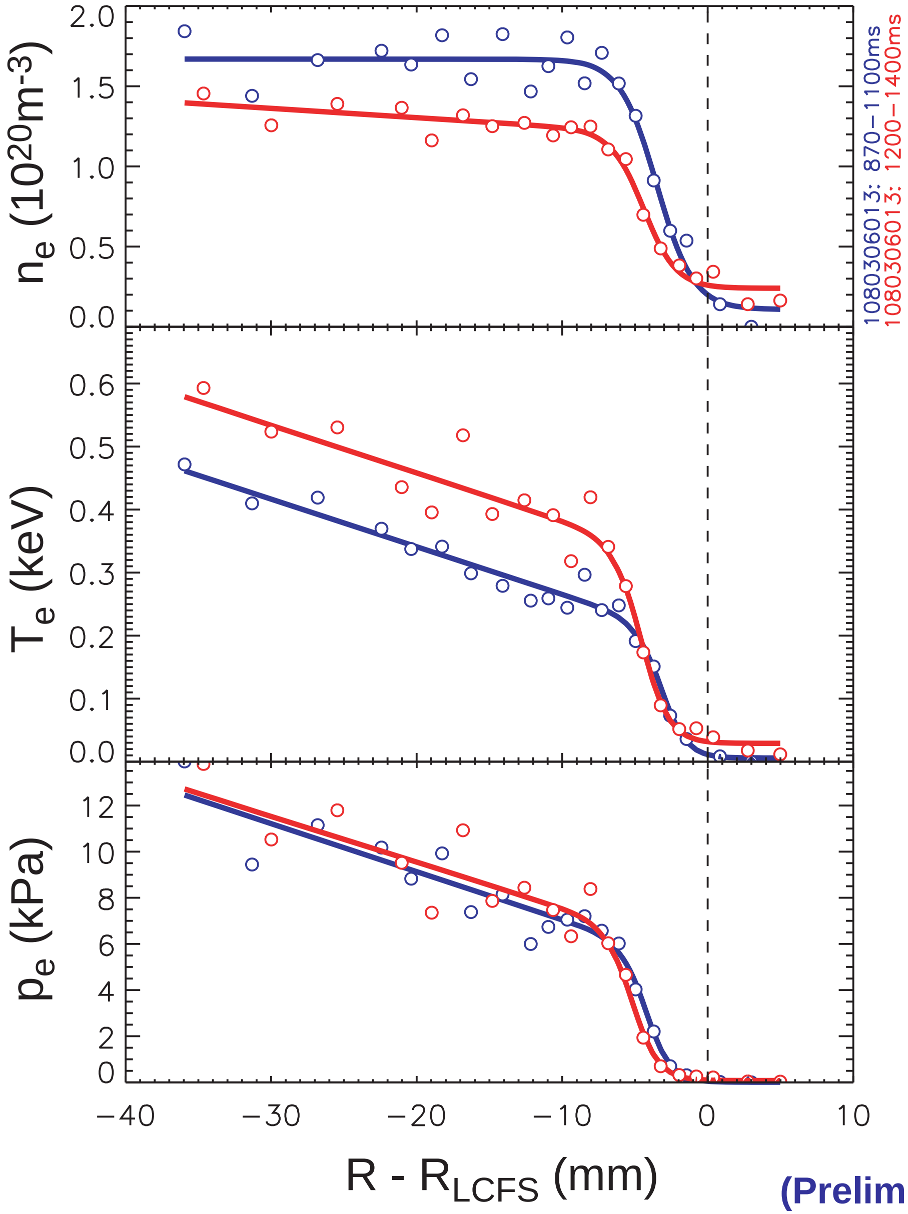


S_{SEP}~+5mm

- Pumped 600kA discharges biased slightly upper null chosen for low $n_{e,PED}$ → good lower hybrid accessibility
- 1MW of LH power coupled into H-mode
- At similar levels of core energy confinement, substantial *drop in density* obtained

(Preliminary results)

Edge pedestal: LH off / LH on



- Application of LH waves results in a prompt modification of the density pedestal
  - Relaxed density gradient
  - Increased SOL n_e, recycling
  - T_e rises, maintaining invariant pressure profile
- What is the mechanism behind this modification?
  - Similar to DIII-D RMP results?
  - Effect of current drive at r/a>0.5, or a local pedestal/SOL effect?
  - Can it be applied to higher I_P, $n_{e,PED}$, or is core accessibility to LH waves necessary?

(Preliminary results)

Summary

- H-mode pedestal optimization explored with a combination of active neutral pumping and variation of magnetic balance
- Pumping depletes SOL effectively and keeps pedestal temperature high in most cases
  - Lower pedestal collisionality, accompanied by higher pressure gradient, improved confinement
  - Typically modest decrease in $n_{e,PED}$, with some exceptions at low q_{95} in USN
  - Plasma transport appears to maintain fairly stiff gradients in the face of reduced neutral source
- Near DN operation has shown sensitivity of pedestal parameters, confinement to magnetic balance
  - Strong pedestal density reduction in slightly USN configurations
  - However, obtainable pressure gradient is lower
  - Best confinement metrics obtained in slightly LSN, with S_{SEP}~-5mm
- Pedestal optimization studies have opened up new pathways for other experiments
  - Small ELM regime readily accessed in the near DN discharges with good confinement
  - Low-density H-mode targets developed for LHCD
- Future work
  - Will explore in more detail pedestal/SOL structure, flows, fluctuations in these configurations
  - Understand additional density pedestal suppression due to LH waves

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