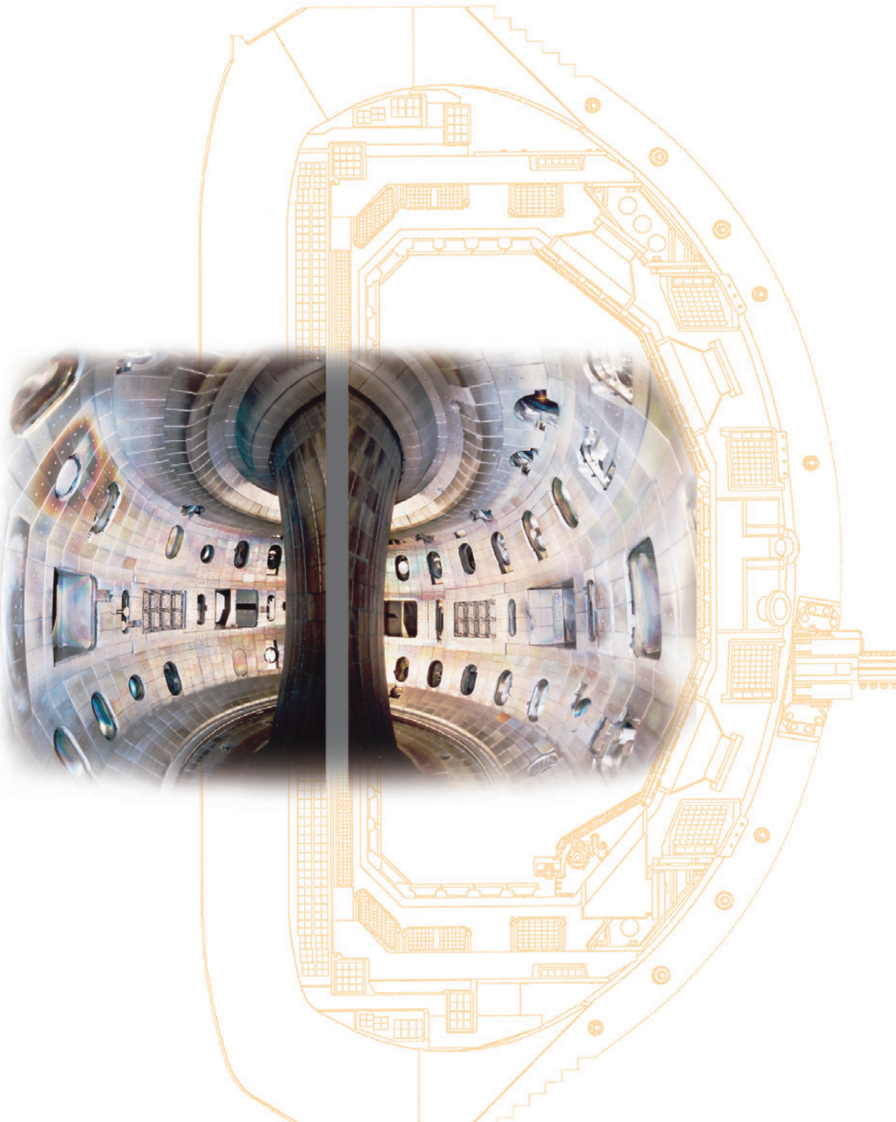
The ROLE of Neutrals in H–mode Pedestal Formation



by
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DIII–D NATIONAL FUSION FACILITY
GENERAL ATOMICS
UNIVERSITY OF WISCONSIN MADISON
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- A. Mahdavi, R. Colchin, A. Leonard, L. Owen, T. Osborne, G. Porter, have made major contributions to this work
- Thanks to R. Boivin for many useful discussions
- Thanks to the entire DIII–D group for its support

OUTLINE

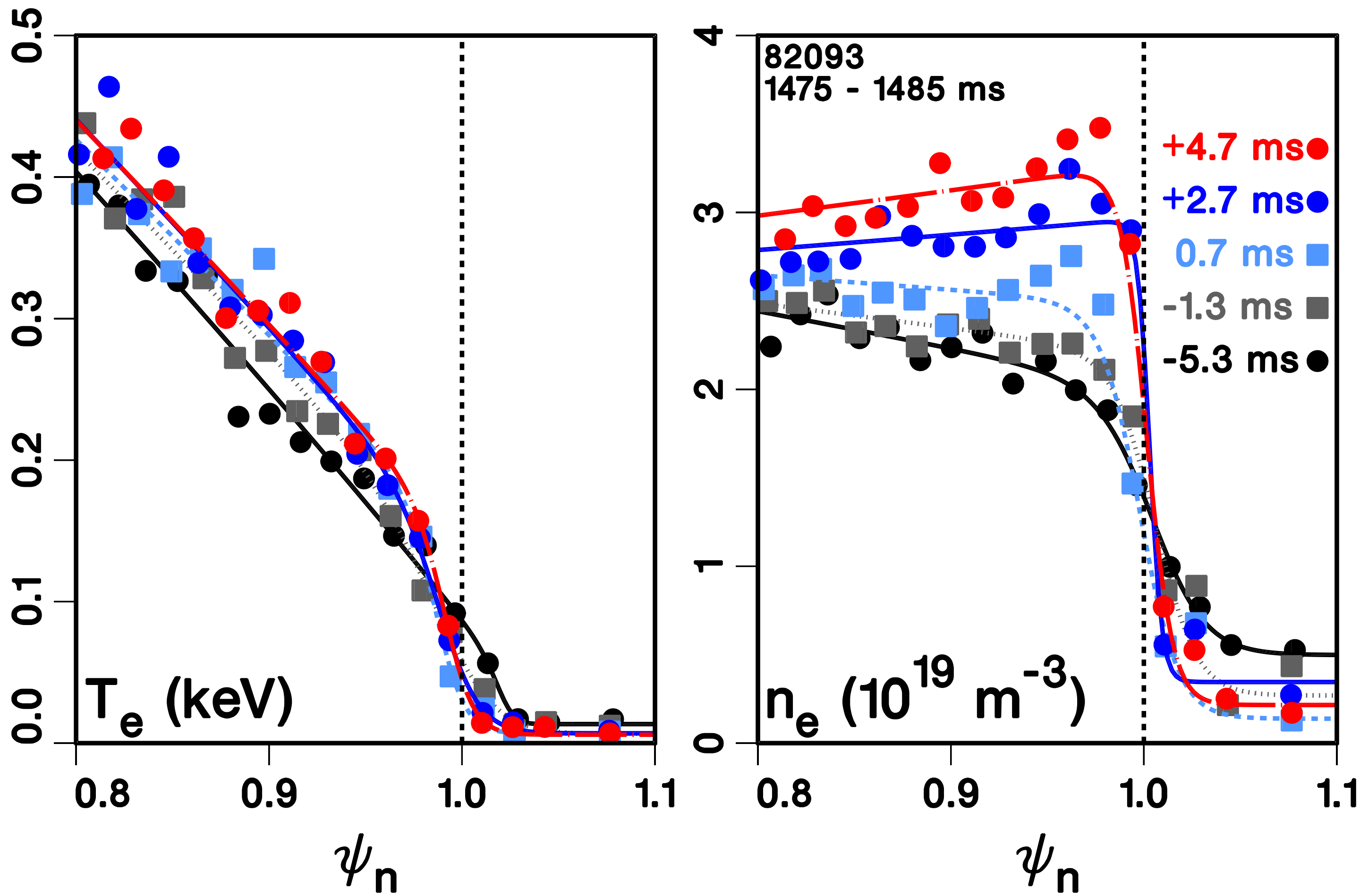
- Introduction
  - Importance of H-mode pedestal
  - We focus on electron density profile
- Analytic model for edge n_e and n_n profiles
  - For spatially uniform D, profiles have same scale lengths
  - Consistent with many experimental observations
  - At low temperature: $\Delta_{ne} \sim n_{e,ped}^{-1}$; $\nabla n_e \sim n_{e,ped}^{2}$
  - Important limitation for higher temperatures
- Relationship between T_e and n_e H-mode barriers
  - Barriers tend to be close
  - Sometimes T_e barrier extends further into plasma
- Summary and conclusions

KEY POINTS

- A simple analytic model for edge density profiles is consistent with DIII–D data
- *The edge electron density and neutral profiles are predicted to have same characteristic scale length*
  - *For spatially uniform particle diffusion*
- *In the fuelling zone, this length is the neutral penetration length*
- Thus, the model provides insight into the physics of the width of H–mode pedestal for density

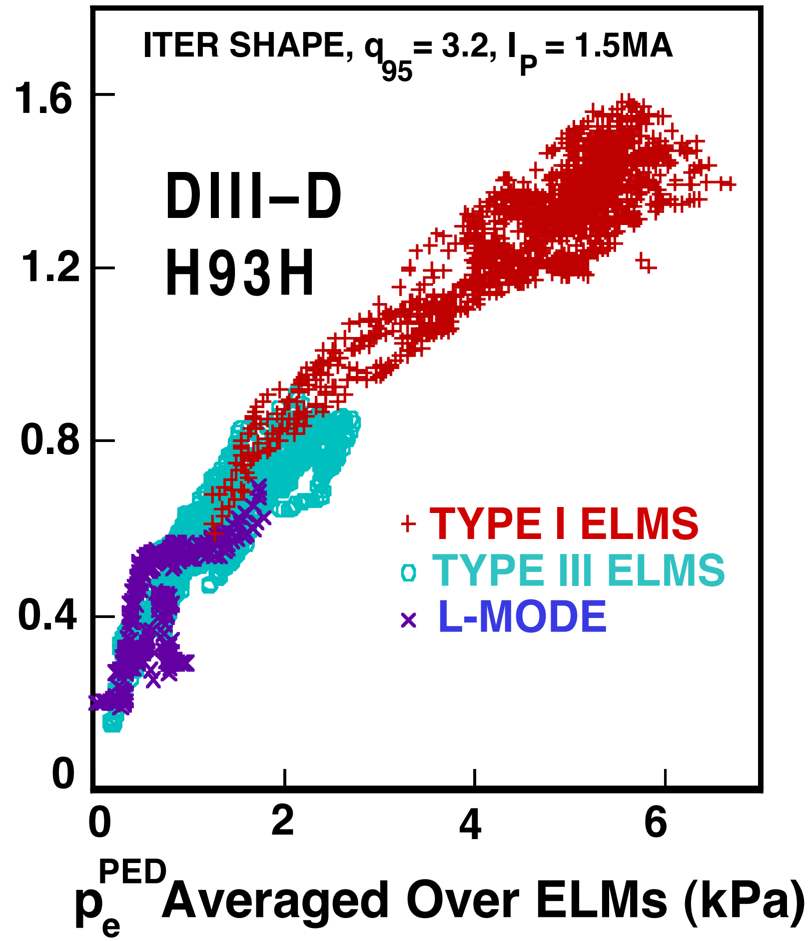
H–MODE PLASMAS HAVE LARGE EDGE GRADIENTS AND EDGE PEDESTALS

Gradients and Pedestals Develop Across L-H Transition



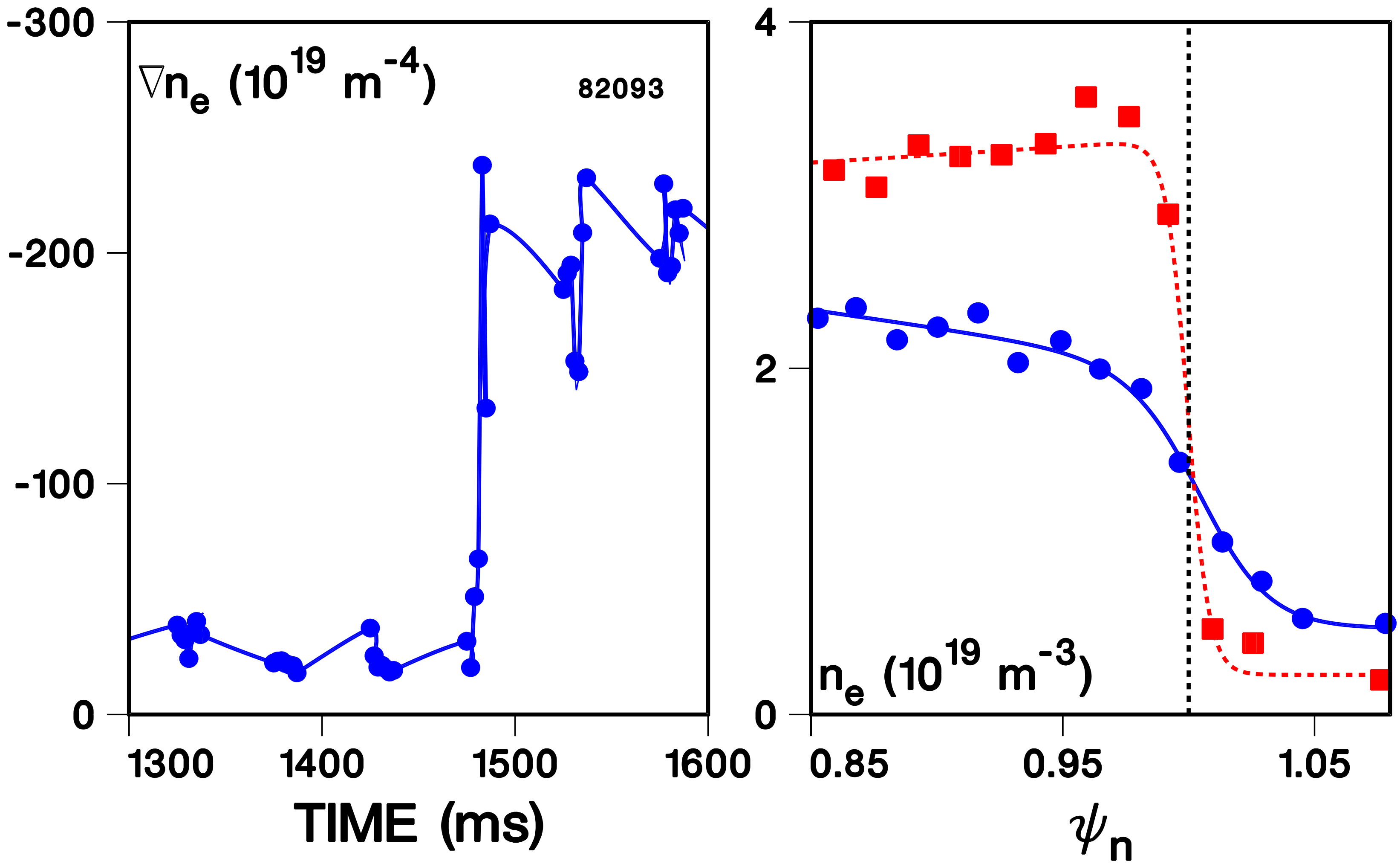
TO PREDICT CORE CONFINEMENT, WE NEED TO PREDICT PEDESTAL SIZE

- Core confinement increases with pedestal pressure or temperature
- Predicting core confinement requires predicting pedestal height
- Physics controlling pedestal width not understood



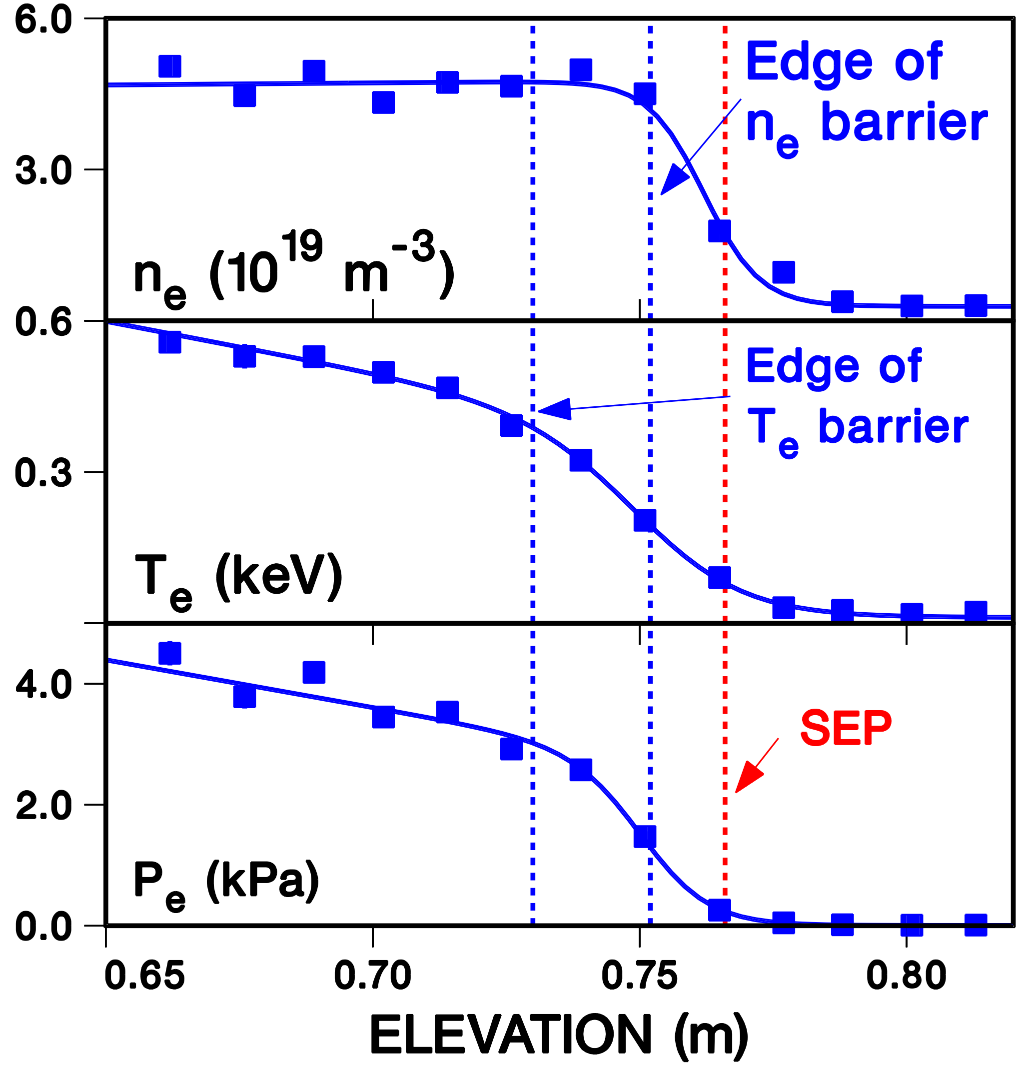
T. Osborne, et. al., 24th EPS Conf. *21A*, 1101 (1997)

A STANDARD PICTURE: WIDTH OF PEDESTAL IS SAME AS ZONE OF REDUCED TRANSPORT



HOW DO WE UNDERSTAND AN n_e BARRIER WHICH IS NARROWER THAN THE T_e BARRIER?

- Expect that D and χ are reduced in same zone
- T_e barrier indicates that D and χ are reduced over wider region than the n_e barrier
- Why is n_e barrier so narrow?



THEORY AND EXPERIMENT POINT TO ROLE OF NEUTRALS IN FORMING EDGE n_e PROFILE

- Transport models emphasize role of particle flux in barrier formation of H-mode transport barrier
  - Hinton & Staebler - *Phys. Fluids B* **5** *1281 (1993)*
  - Lebedev, Diamond, Carreras - *Phys. Plasmas* **4** *1087 (1997)*
  - Width of density barrier is set approximately by neutral penetration length
- C-MOD shows that edge n_e profile is produced by particle transport (D) and fuelling (ν_i, n_n, V_n)
  - Boivin, Carreras et al. - *Phys Plasmas* ***7,*** *1919 (2000)*

$$\Delta_{ne} = 2\sqrt{D/2\nu_i} \qquad n_{e,ped} = n_n\sqrt{2V_n^2/D\nu_i}$$

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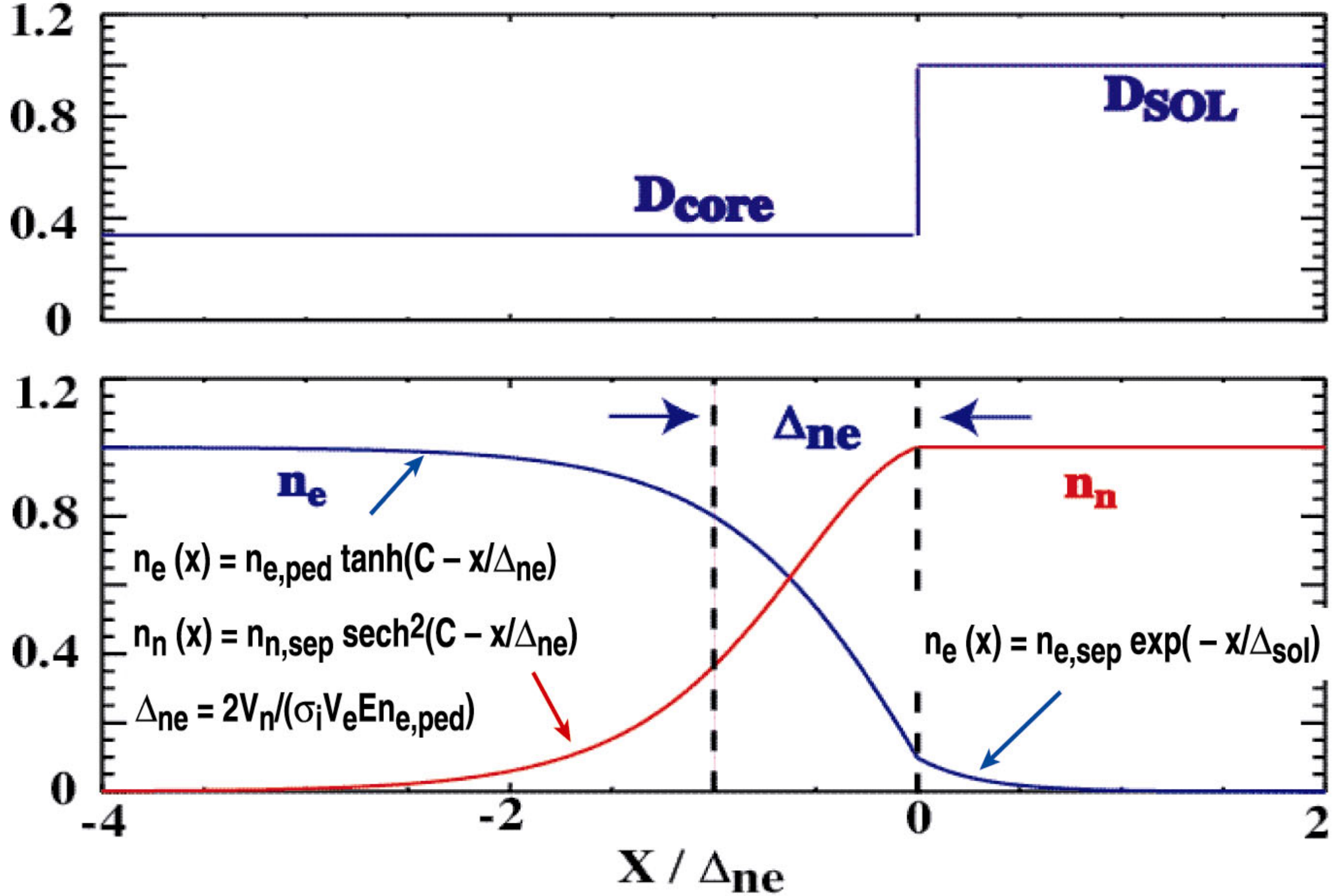
AN ANALYTIC MODEL IS FORMULATED TO RELATE PEDESTAL WIDTH TO PEDESTAL HEIGHT

- Use coupled, steady-state, particle continuity equations for electron density and neutral hydrogen atoms (Engelhardt[1])
  - Solve on open and closed field lines with matching at LCFS
- Model extended by Mahdavi[2] to include poloidal variation in neutral source, separate *D* in SOL and core.
- Assume neutral temperature at LCFS is same as ion temperature, due to charge exchange in SOL
- Goal is to model n_e from LCFS inwards
- For low temps, there is about one CX event per ionization
  - Thus, multiple charge exchange is ignored

[1] W. Engelhardt, W. Fenenberg, J. Nucl. Mater. 76-77 (1978) 518.
[2] M.A. Mahdavi et al., 2000 IAEA meeting, to be published in Nucl. Fusion

SCALE LENGTHS ARE SAME IN ANALYTIC MODEL



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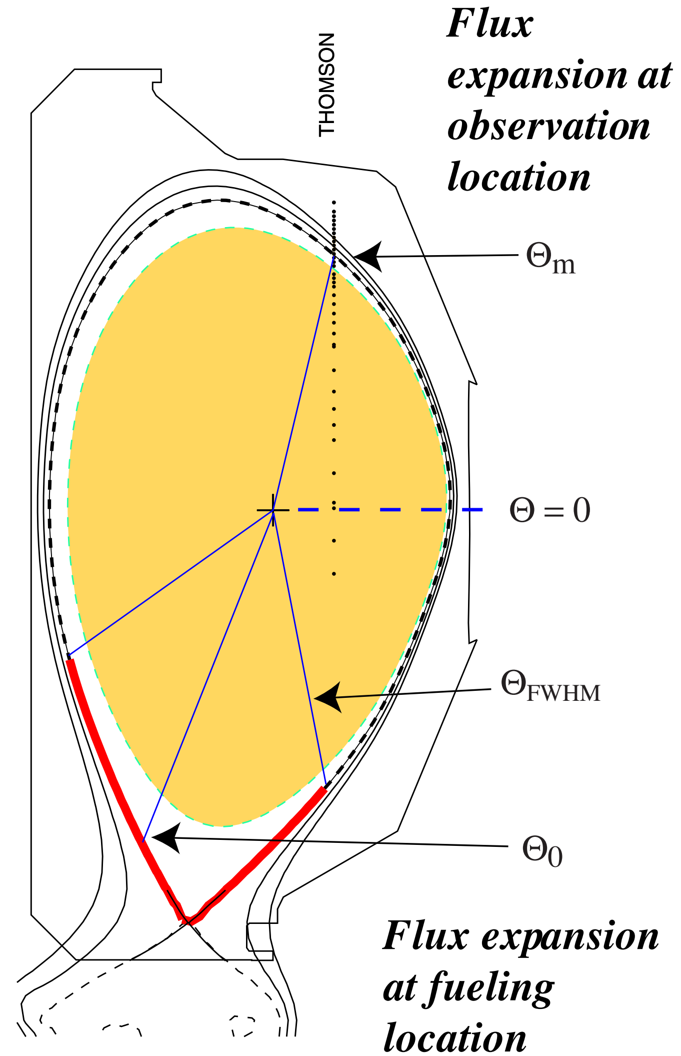
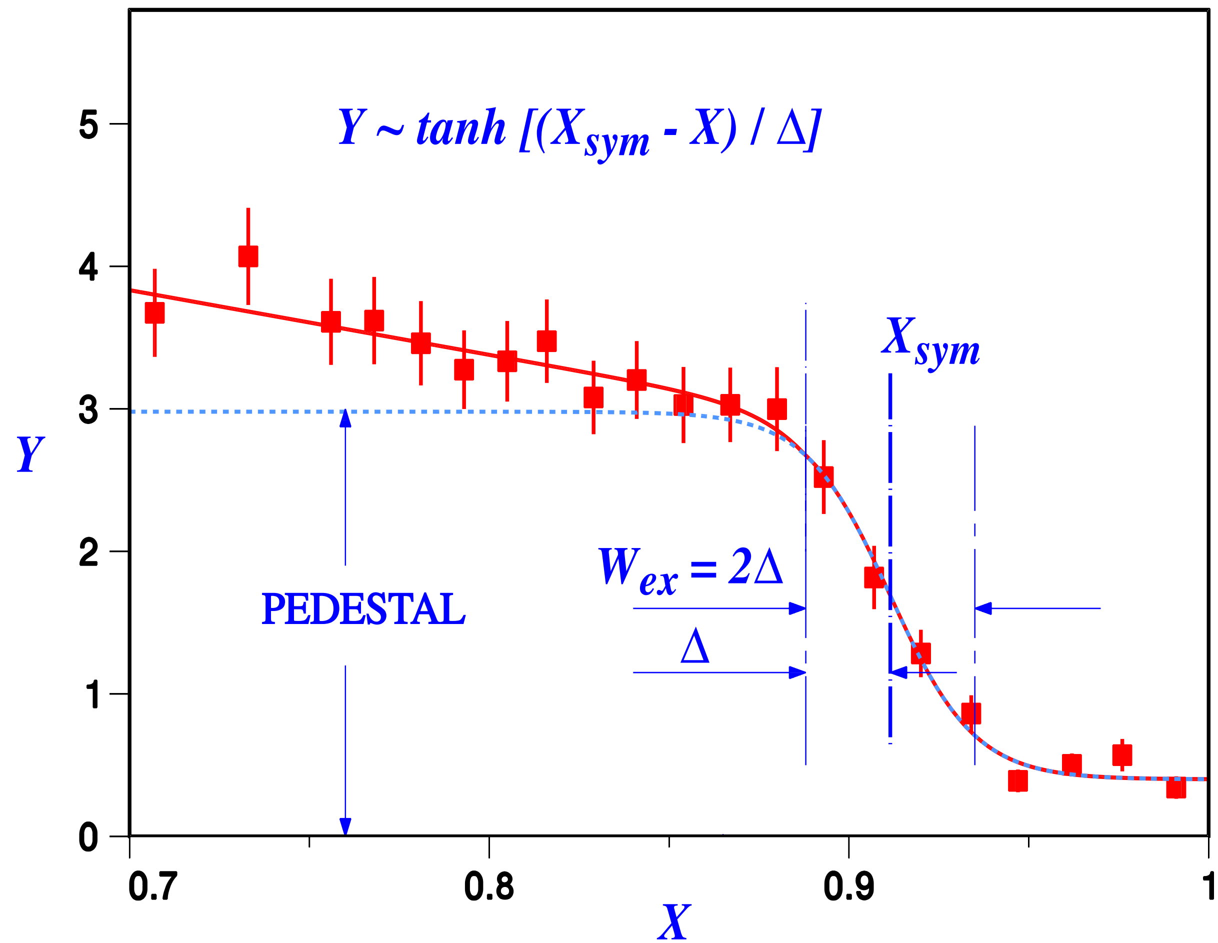
LOCATION OF FUELLING AFFECTS DENSITY WIDTH

- *E* is ratio of flux expansion at fuelling location θ_0 to expansion at measurement location θ_m
- In reality, *E* is some average over extended neutral source
  - FWHM is ~ 55° in this example from a DEGAS calculation
- From neutral model in UEDGE, average *E* is estimated at 3 to 4 for divertor fuelling
- If fuelling were from outer midplane, *E* would be ~ 0.5
  - Would disagree with results



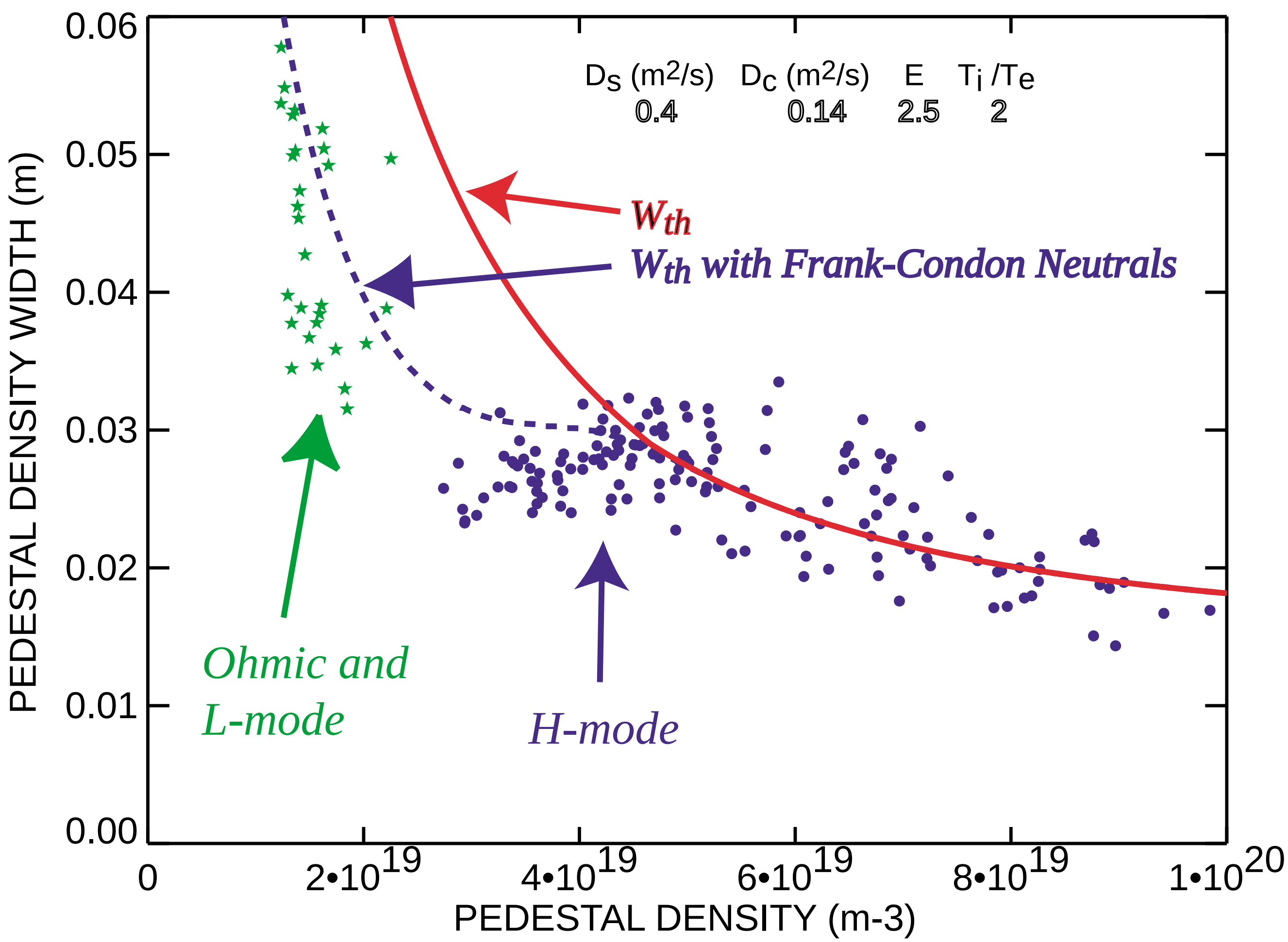
MODEL PREDICTS THAT n_e PROFILES HAVE "TANH" SHAPE - AS OBSERVED

- Experimental edge n_e profiles routinely are fit well with the "TANH" shape
- A "modified" TANH is used to give continuous first derivative everywhere



MODEL PREDICTS QUALITATIVE AND QUANTITATIVE DEPENDENCE OF EXPERIMENTAL WIDTH W_{ex} ON $n_{e,ped}$

- Theoretical width W_{th} is defined to emulate W_{ex}
- W_{th} is distance from 12% to 88% of $n_{e,ped}$ in model function
- Parameters in model are typical values



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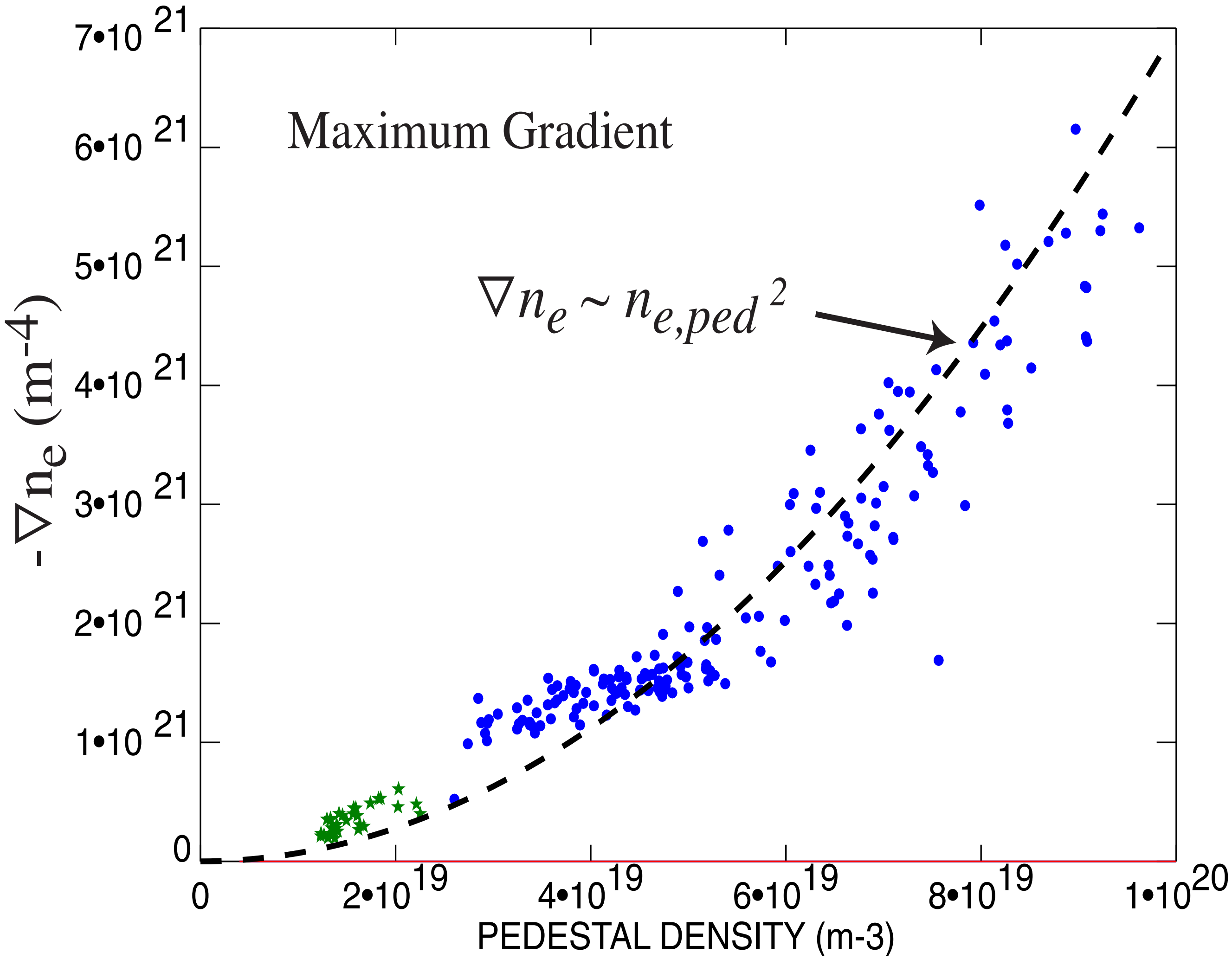
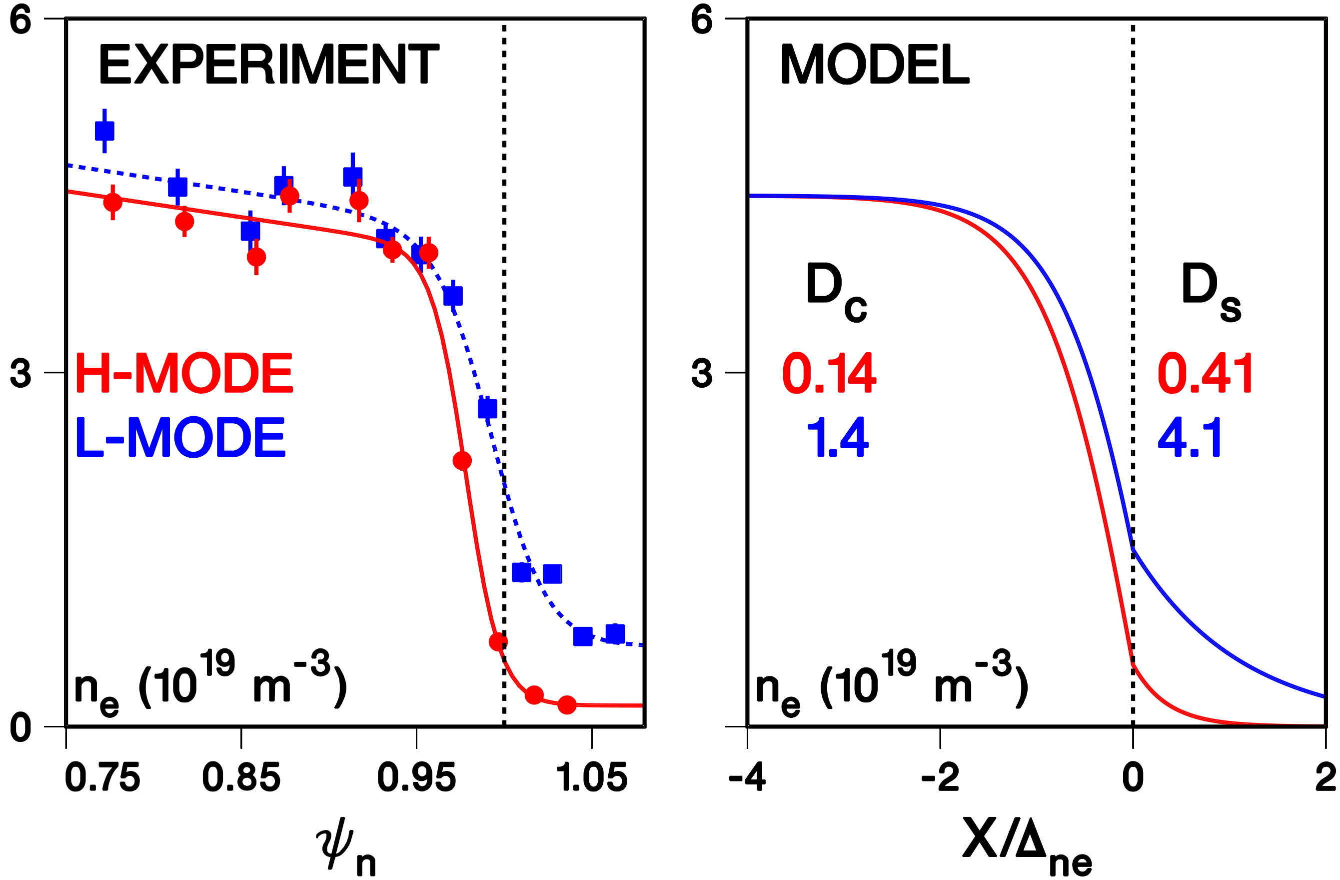
MODEL PREDICTS THE QUALITATIVE DEPENDENCE: MAXIMUM $\nabla n_e \sim n_{e,ped}^2$



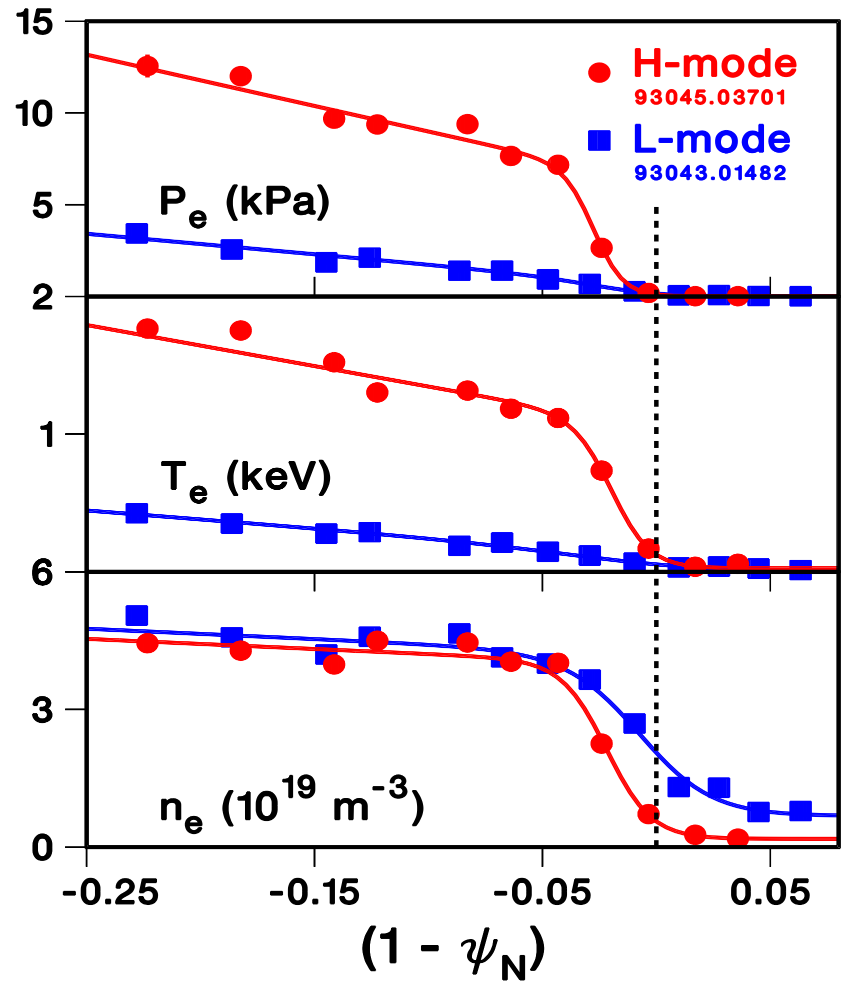
MODEL PREDICTS: L–MODE AND H–MODE n_e PROFILES, WITH SAME $n_{e,ped}$, HAVE SIMILAR SHAPE

- Widths from LCFS to pedestal are similar.
  Different $n_{e,sep}$ can be explained by different transport coefficients.



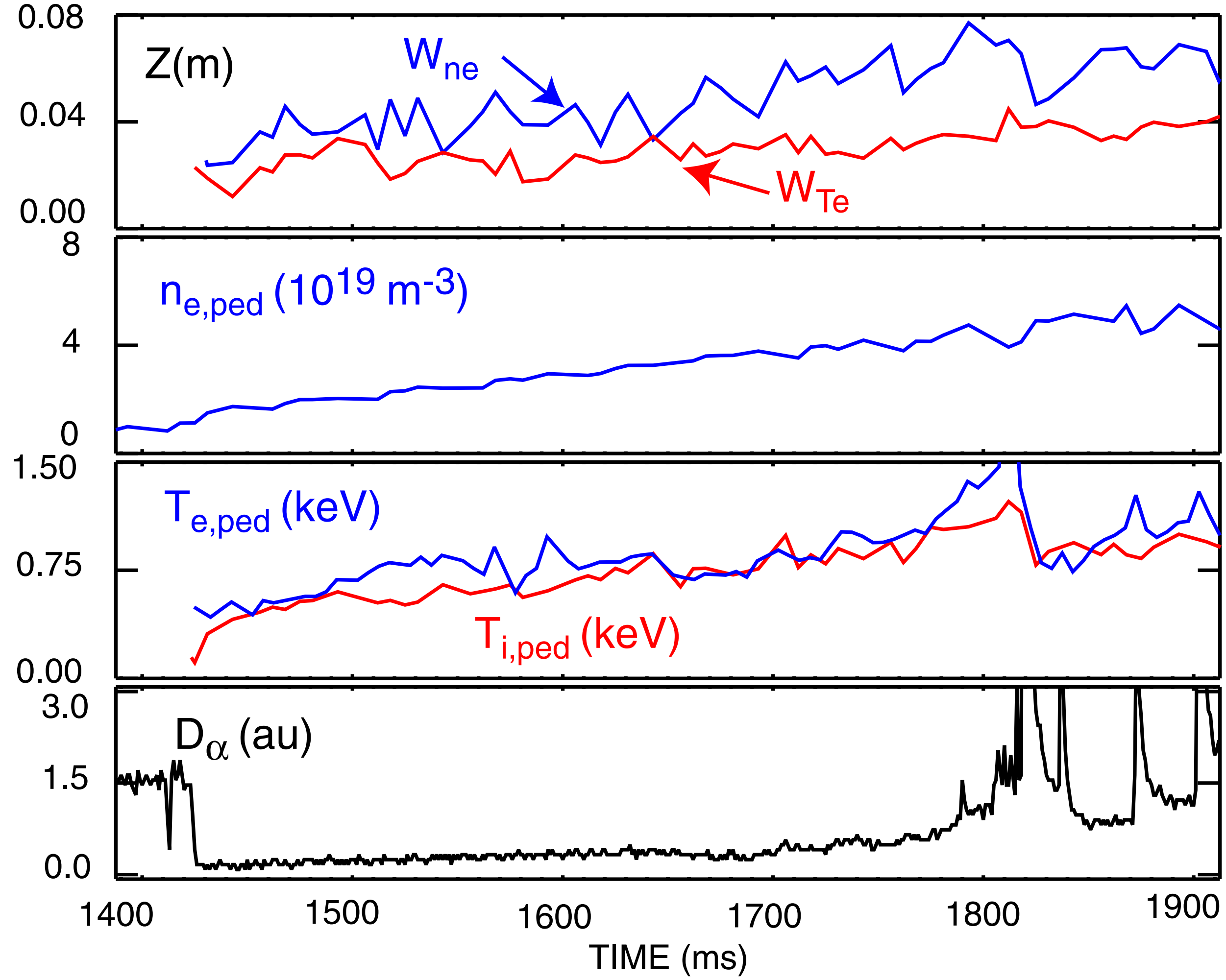
TRANSPORT WAS MUCH HIGHER IN L–MODE THAN IN H–MODE

- H-mode gradients for P_e and T_e were ~ order of magnitude higher in H–mode
- Implies significantly higher transport in L–mode
- *Higher transport in L–mode required higher neutral source (gas puff) to match H-mode pedestal density!!!!!!!!*



THE MODEL HAS AN IMPORTANT LIMITATION, RELATED TO HIGH TEMPERATURE

- Sometimes, barrier width increases as $n_{e,ped}$ increases
- Correlated with pedestal temps of ≥ 0.5 keV
- Possibly due to multiple CX events, ignored by model



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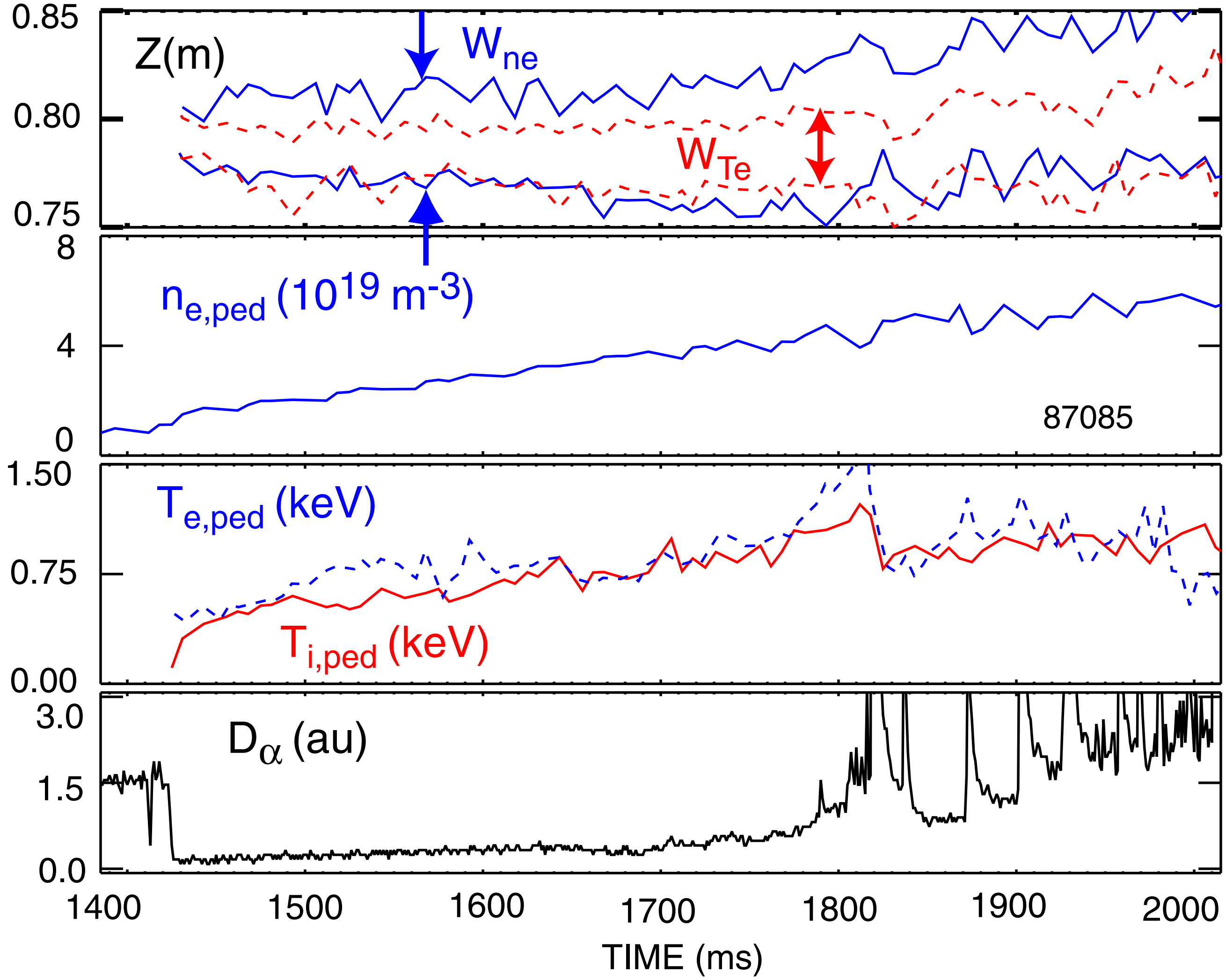
THEORIES IMPLY THAT T_e AND n_e BARRIERS APPROXIMATELY OVERLAP IN SPACE

- Transport barrier theories say that heat and particle fluxes make transport barriers
  - Edge particle flux is dominant flux for H-mode barrier
  - However, heat source might also play a role
- Implication is that temperature barrier should be close to or slightly inboard of density barrier
- Experiment shows this behavior
- Theories are not quantitative about relationship between T_e and n_e barriers
  - Thus, further testing not possible

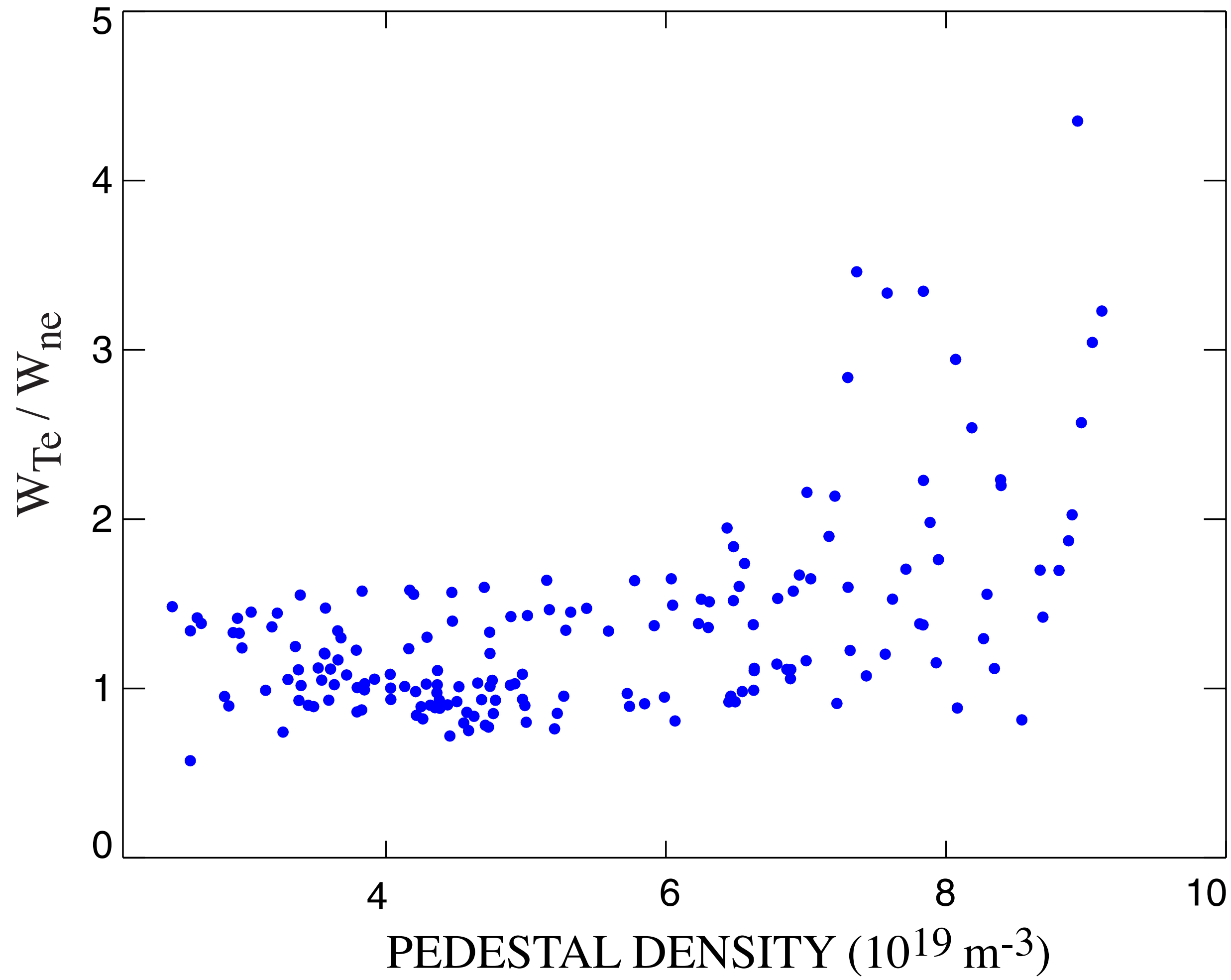
INNER EDGES OF T_e AND n_e TRACK AS BARRIER WIDTH INCREASES

- Barrier widths (T_e, n_n) grow in time
- Inner edges of both barriers are close in position
- Inner edges of both barriers tend to move together

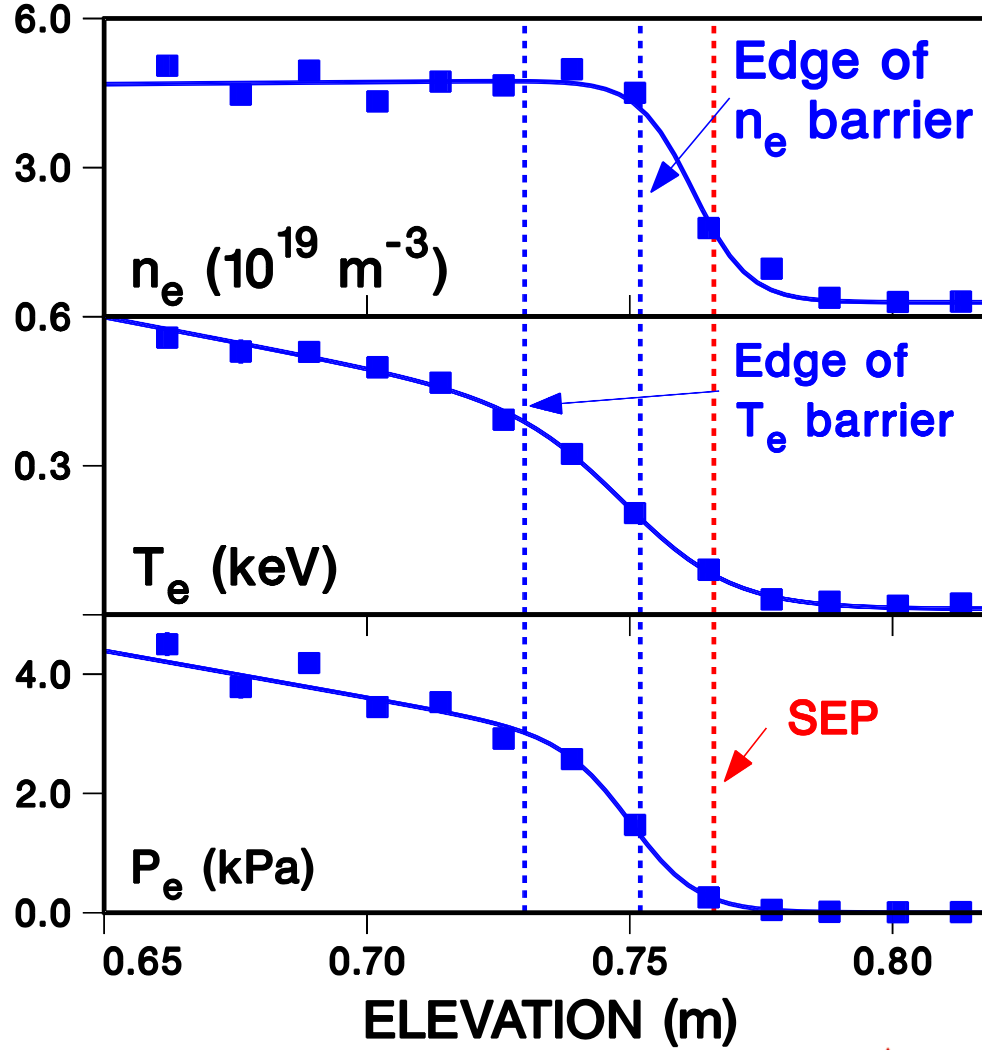


WIDTH OF T_e BARRIER IS COMPARABLE TO OR GREATER THAN WIDTH OF n_e BARRIER

- Data from previous database
- Effect is even stronger than shown here, because some of W_{ne} is from SOL



PROFILES SHOW THAT T_e BARRIER IS WIDER THAN n_e BARRIER



SUMMARY AND CONCLUSIONS

- **Analytic model developed for edge n_e and n_n profiles**
- **Model is consistent with several observations in DIII-D, for low edge temperature**
  - n_e profile has *tanh* shape in L-mode and H-mode
  - W_{ne} scales qualitatively and quantitatively with $n_{e,ped}^{-1}$
  - ∇n_e scales with $n_{e,ped}^2$
  - L– and H–mode profiles with same $n_{e,ped}$ have similar shape
- ***Edge electron density and neutral profiles have same characteristic scale length (for L-mode or H-mode)***
  - *This length is neutral penetration length*
  - *Determined self-consistently by particle transport and fuelling*
  - *Caveat - particle transport assumed constant*

SUMMARY AND CONCLUSIONS

- For high edge temperature (above ~500 eV), W_{ne} increases with $n_{e,ped}$
- *Multiple charge exchange and other temperature effects are important*
  - — *Ignored by present version of model*
  - — *Multiple CX allows deeper neutral penetration*
  - — *Could CX provide an apparent dependence of width on T_i?*
- T_e and n_e barriers tend to track one another
  - — T_e barrier often extends inwards of n_e barrier
  - — This behavior is qualitatively consistent with barrier models
- *Better understanding of transport is required to quantify the relation between T_e and n_e barriers*