X-POINT NEUTRAL DENSITY MEASUREMENT AND MODELING IN DIII-D

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*X–Point Neutral Density Measurement and Modeling in DIII–D: Consequences for L-H Transition Theories**

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L-H transition theories have long predicted that high neutral density in the edge plasma could delay and possibly even suppress the L-H confinement transition. Experiments designed to investigate the effect of neutrals on the transition have been hampered by the lack of a convenient method to measure the neutral density. This work describes results of a method of measuring the neutral density in the X–point region, where 2-D plasma and neutrals simulations indicate it is a maximum. The measurement utilizes D_α light from a TV camera viewing the divertor region and electron densities and temperatures from a divertor Thomson scattering diagnostic. The TV camera data are reconstructed onto a poloidal plane and normalized by calibrated D_α monitors.

The effect of neutrals on the L-H transition is usually associated with the charge-exchange damping of the poloidal ion rotation accompanying the transition. This damping competes with neoclassical viscous damping and can only dominate if the neutral density $\bar{n}_0$ is above a threshold value, $\bar{n}_0 \geq \mu_{neo} V_{\theta i} / \left[\langle \sigma v \rangle_{cx} \left(V_{\theta i} - V_{\theta n} \right) \right]$ where μ_{neo} is the neoclassical poloidal damping, $\langle \sigma v \rangle_{cx}$ is the charge exchange rate, and $V_{\theta i}$, $V_{\theta n}$ are the ion and neutral poloidal velocities. The X–point neutral densities observed in DIII–D are near the predicted threshold value of $\bar{n}_0 \approx 10^{11}$ atoms/cm^3.

Neutral density profiles in the X–point region have been obtained from an L–mode discharge just below the L-H power threshold level and also in the H–mode phase following an increase in the heating power. Several X–point heights were executed in each condition to create a reasonable dataset for comparison with simulations. These discharges have been simulated with the 2-D plasma code, B2.5, and the 2-D neutral transport code, DEGAS. Good agreement is found between the neutral density measurements and data-constrained simulations. Previous simulations[1] in the absence of neutrals measurements indicated that edge neutral density was indeed high enough to affect the poloidal momentum balance and the L-H transition. These discharges are very similar to the ones analyzed in,[1] permitting validation of the data-constrained analysis procedure employed there and corroborating the previous conclusions.

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[1]B.A. Carreras, L.W. Owen, R. Maingi, P.K. Mioduszewski, T.N. Carlstrom, and R.J. Groebner, Phys. Plasmas **5**, 2623 (1998).

SUMMARY

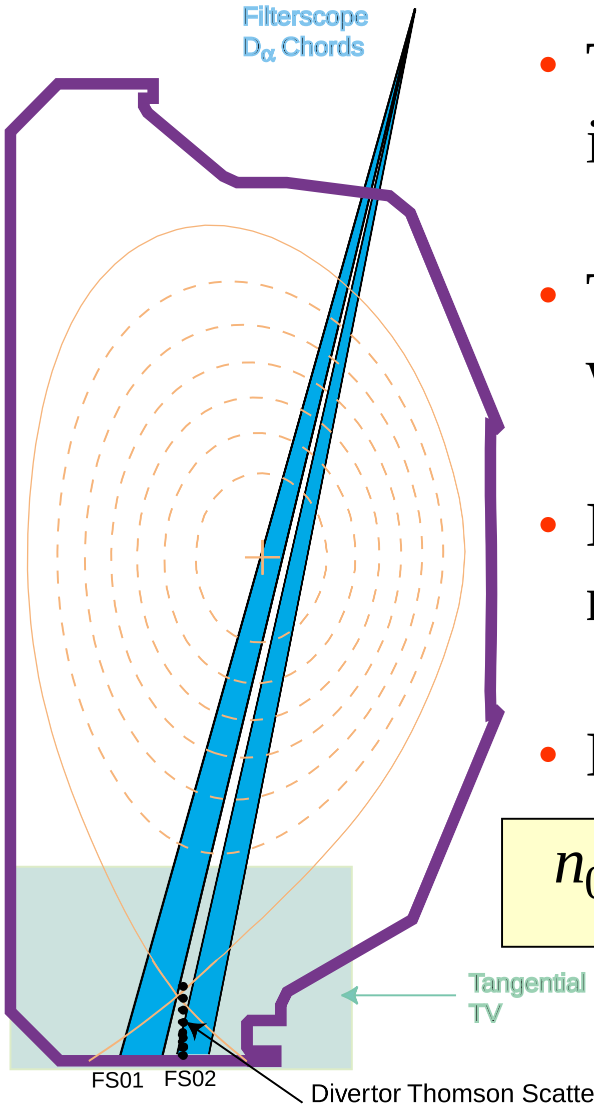
1) Previously we concluded that edge neutral density (n_0^{edge}) in DIII-D pumped discharges was sufficient to affect the poloidal momentum balance and L-H power threshold, based on data-constrained 2-D plasma/neutrals modeling
2) We recently devised a technique to measure neutral density in the X-point region and find that neutral density near X-point is generally higher in H-mode than L-mode
3) We examined 2 discharges: #96747 had an L-H transition triggered by NBI power increase, and #96333 had an L-H transition triggered by outward shift of the X-point
4) We benchmarked previous 2-D modeling with new data from L-mode and found good agreement with measured n_0

NEUTRAL DENSITY MEASUREMENT TECHNIQUE

- The method [Colchin, et. al., "Measurement of Neutral Density in the DIII-D tokamak", submitted to Nucl. Fusion 4/99] for determining n_0 near the X-point uses D_α data from a tangentially-viewing video camera calibrated by a vertically-viewing photomultiplier
- The 3-D tangential D_α video image is reconstructed into a 2-D poloidal profile. [M.E. Fenstermacher, *et al*., Rev. Sci. Instrum. **68** (1997) 97]
- D_α from the video image is averaged over a 2-cm-high by 6-cm-wide area of the poloidal plane. Resulting signal-to-noise levels are 0-20.
- The neutral density is determined by $I_{D_\alpha} = n_e n_0 \langle \sigma(T_e, n_e) v \rangle_{exc.}$.

  T_e and n_e are determined by the divertor Thomson scattering system. [D.G. Nilson, *et al*., Fusion Eng. & Design **34-35** (1997) 60]

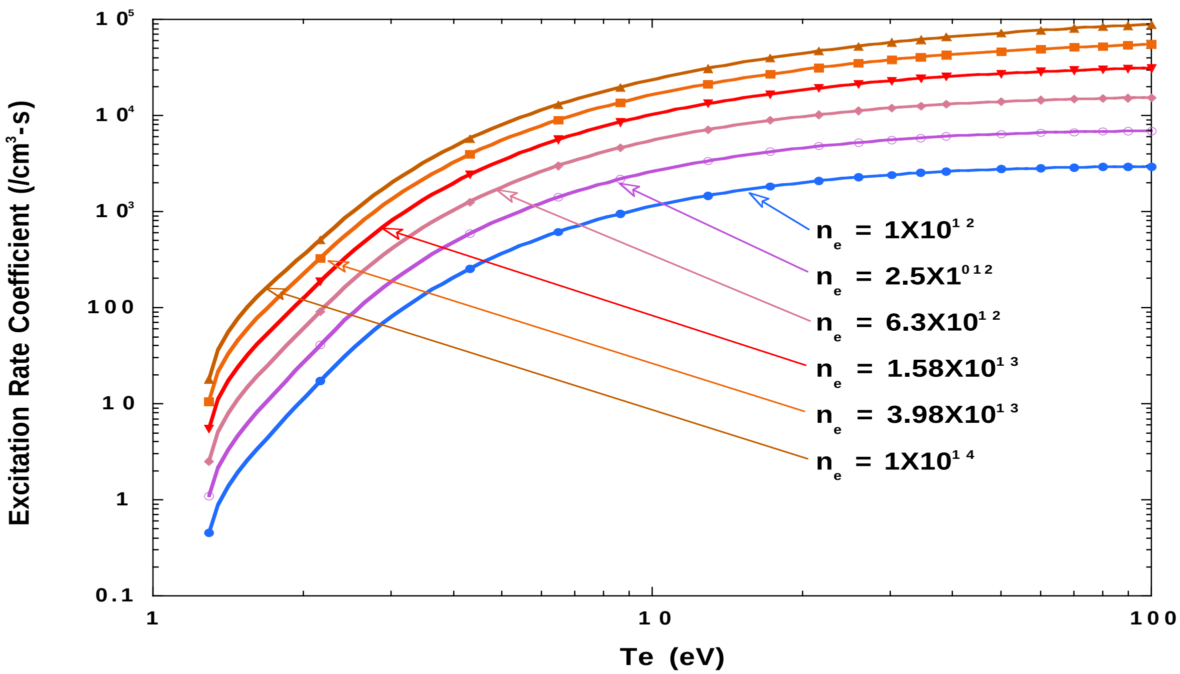
DIAGNOSTICS SETUP



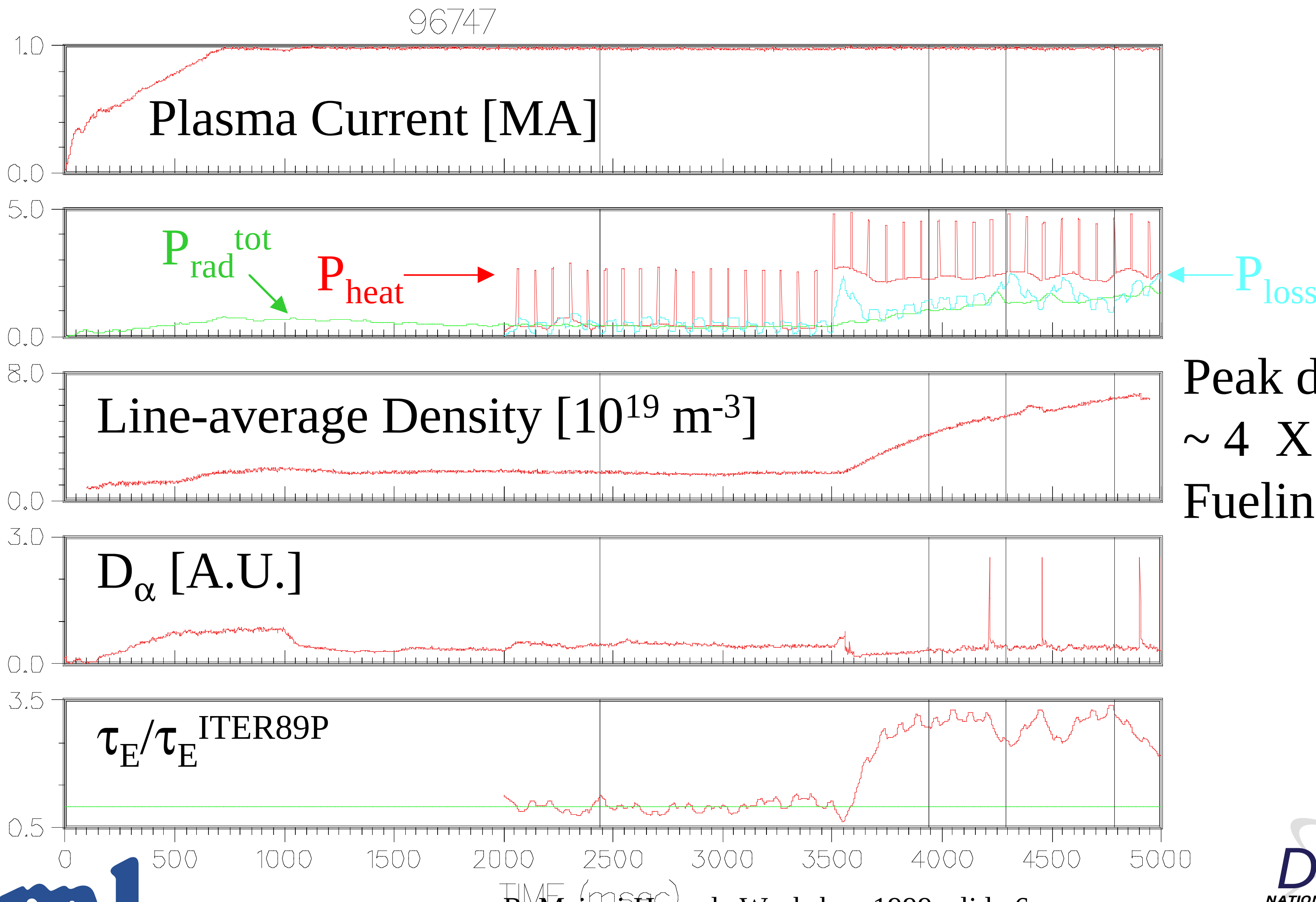
- Tangential TV semi-toroidal view inverted for poloidal D_α profile
- TTV intensity cross-calibrated with vertical D_α chords
- Divertor Thomson Scattering gives n_e and T_e for $<\sigma v>_{exc}$
- Neutral density computed from:

$$n_0(z) = I_{D_\alpha}(z) / n_e(z) <\sigma v>_{exc}(n_e(z), T_e(z))$$

D_α EXCITATION RATE COEFFICIENT VARIES STONGLY WITH n_e AND T_e

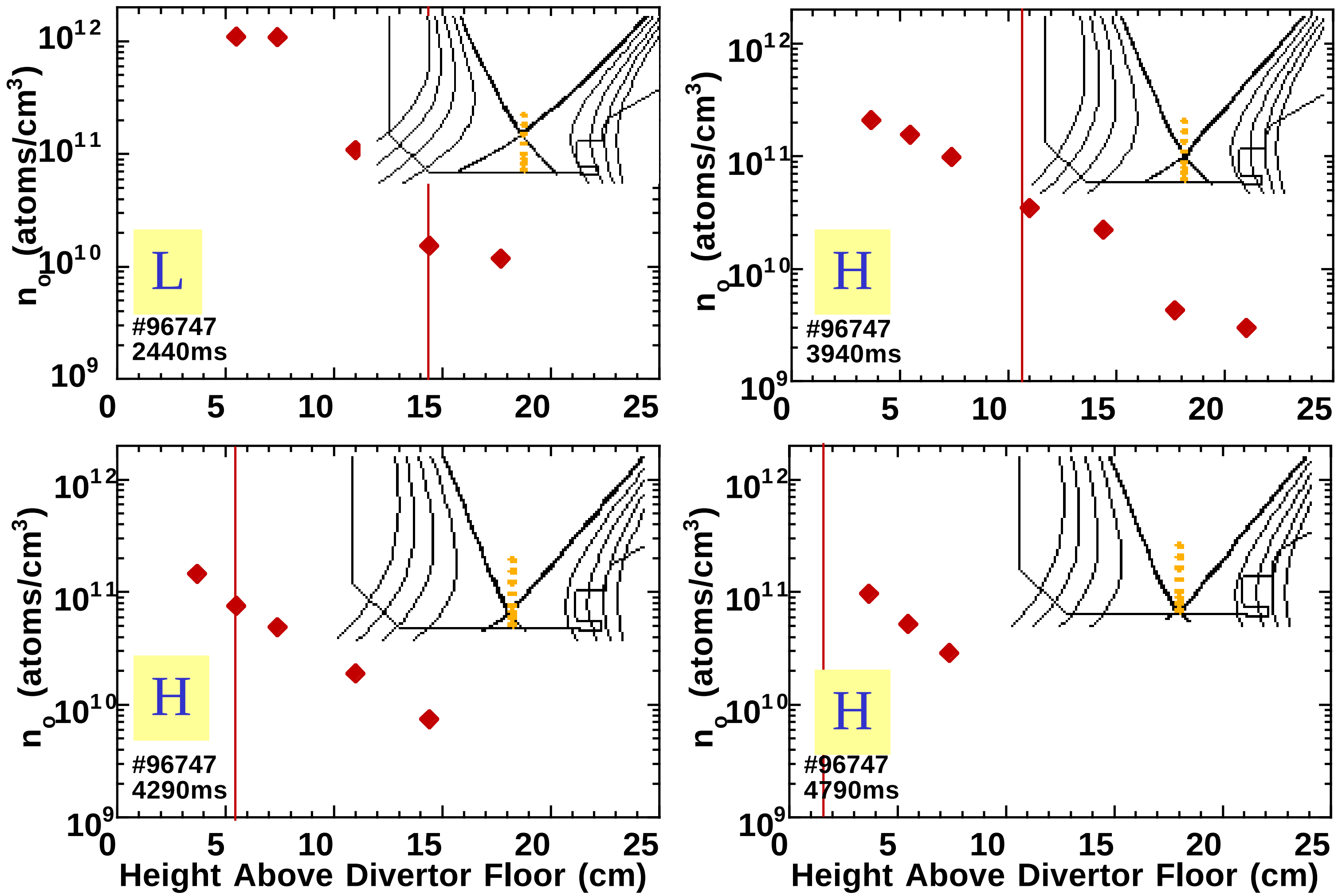


Discharge with L-H Transition Triggered by NBI Increase



Peak dN_e/dt ~ 4 X Beam Fueling Rate

H-MODE NEUTRAL DENSITY HIGHER THAN L-MODE



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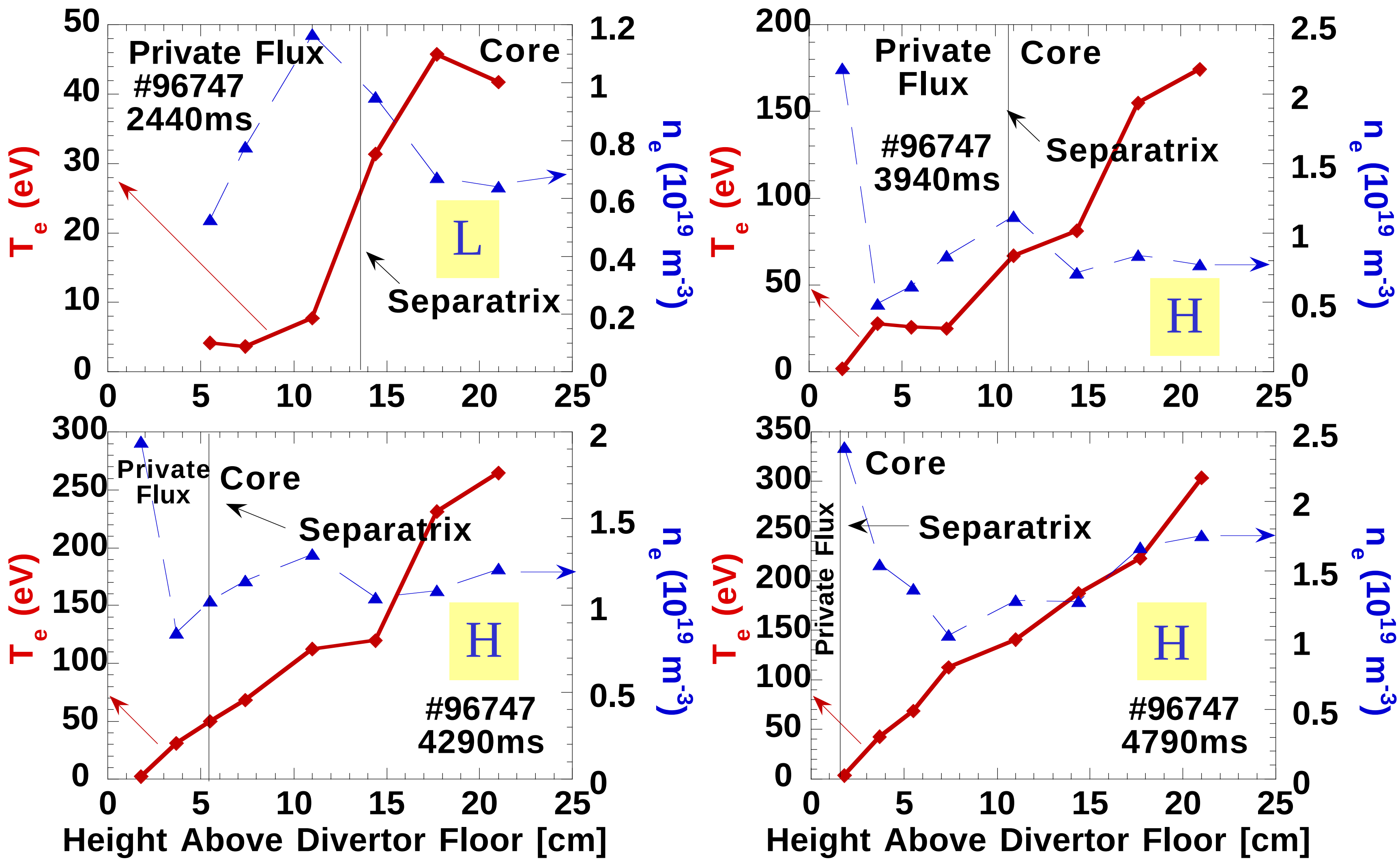
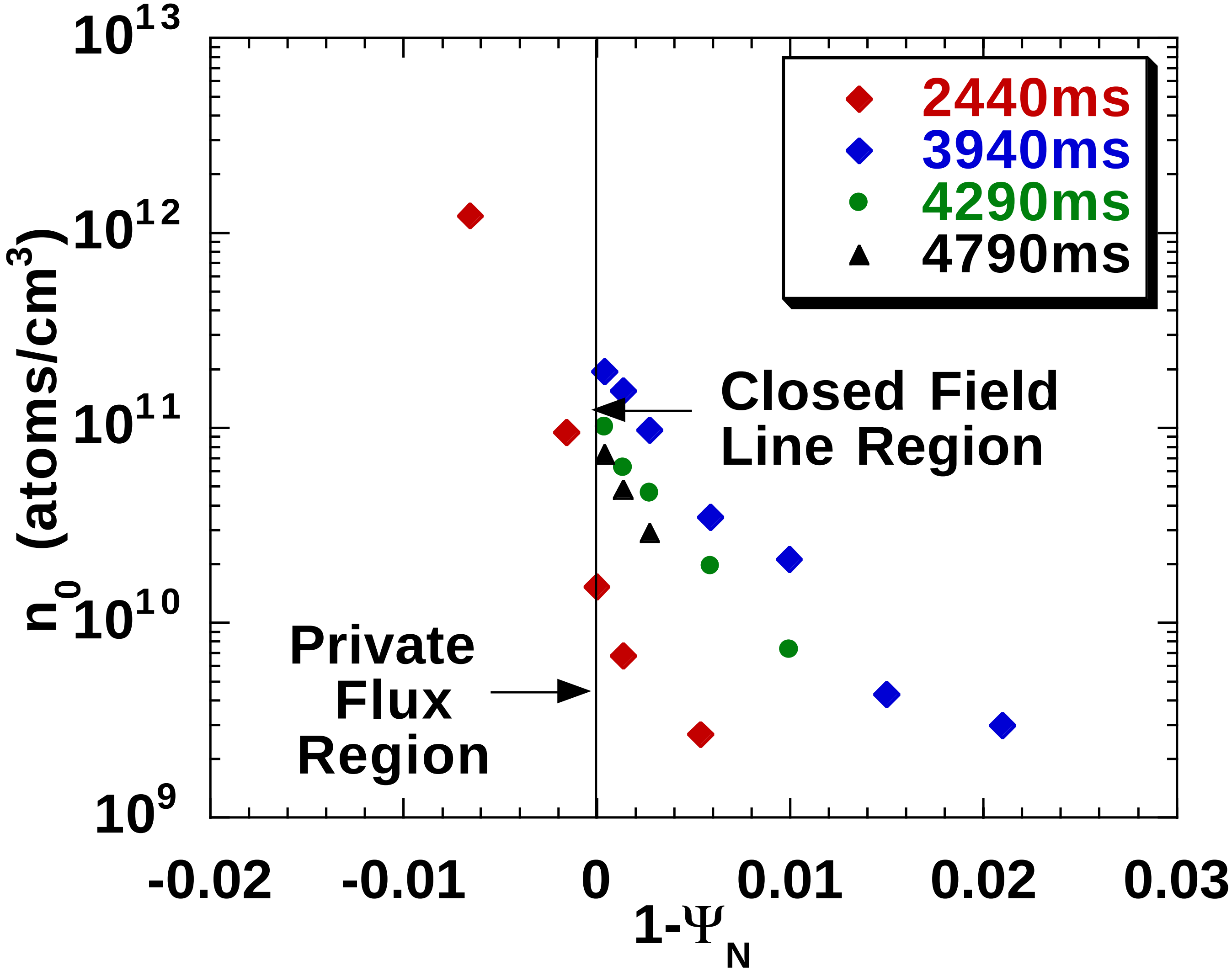
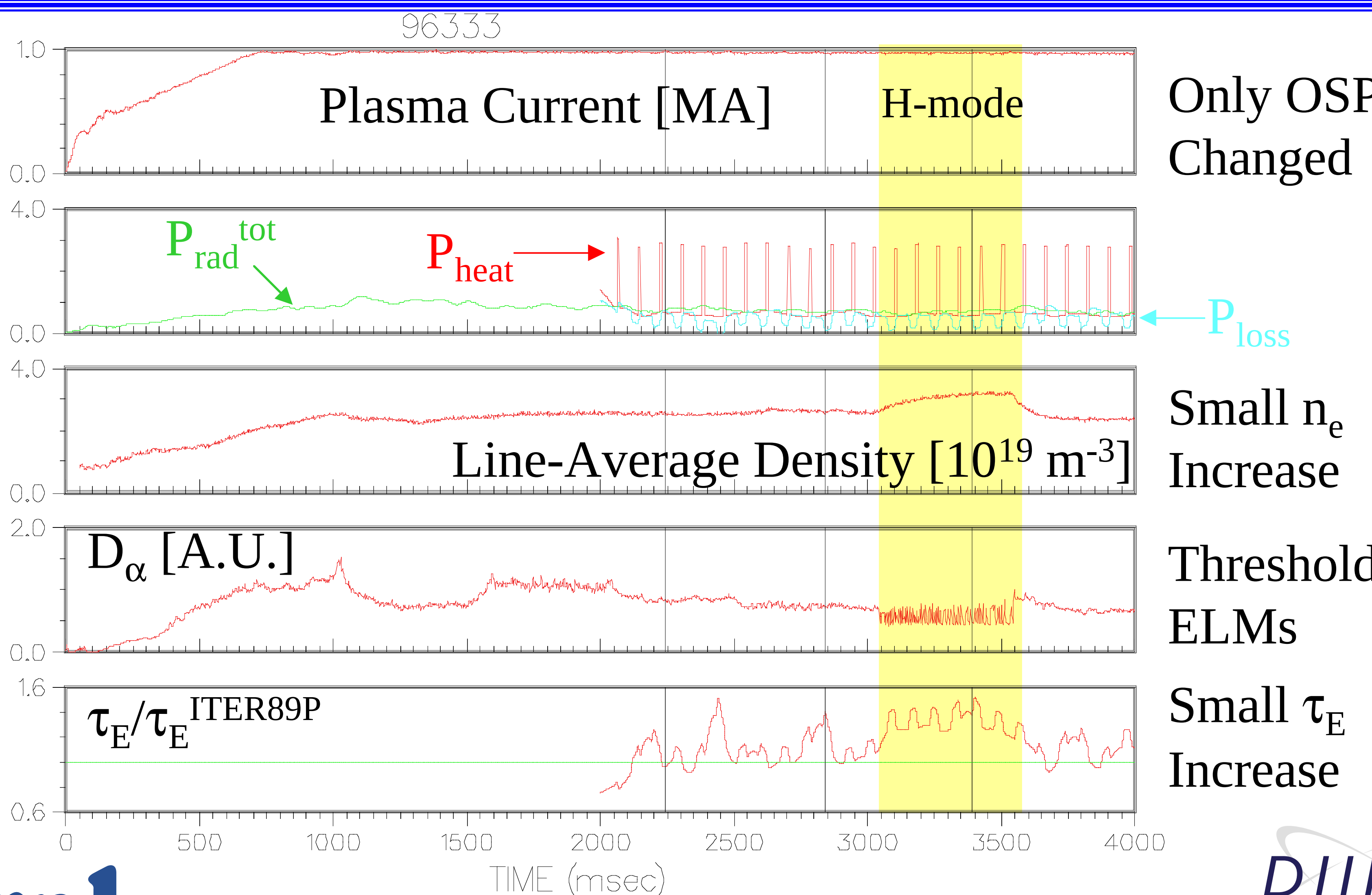
#96747 n_e and T_e Data Near X-point Show MARFE Not Present



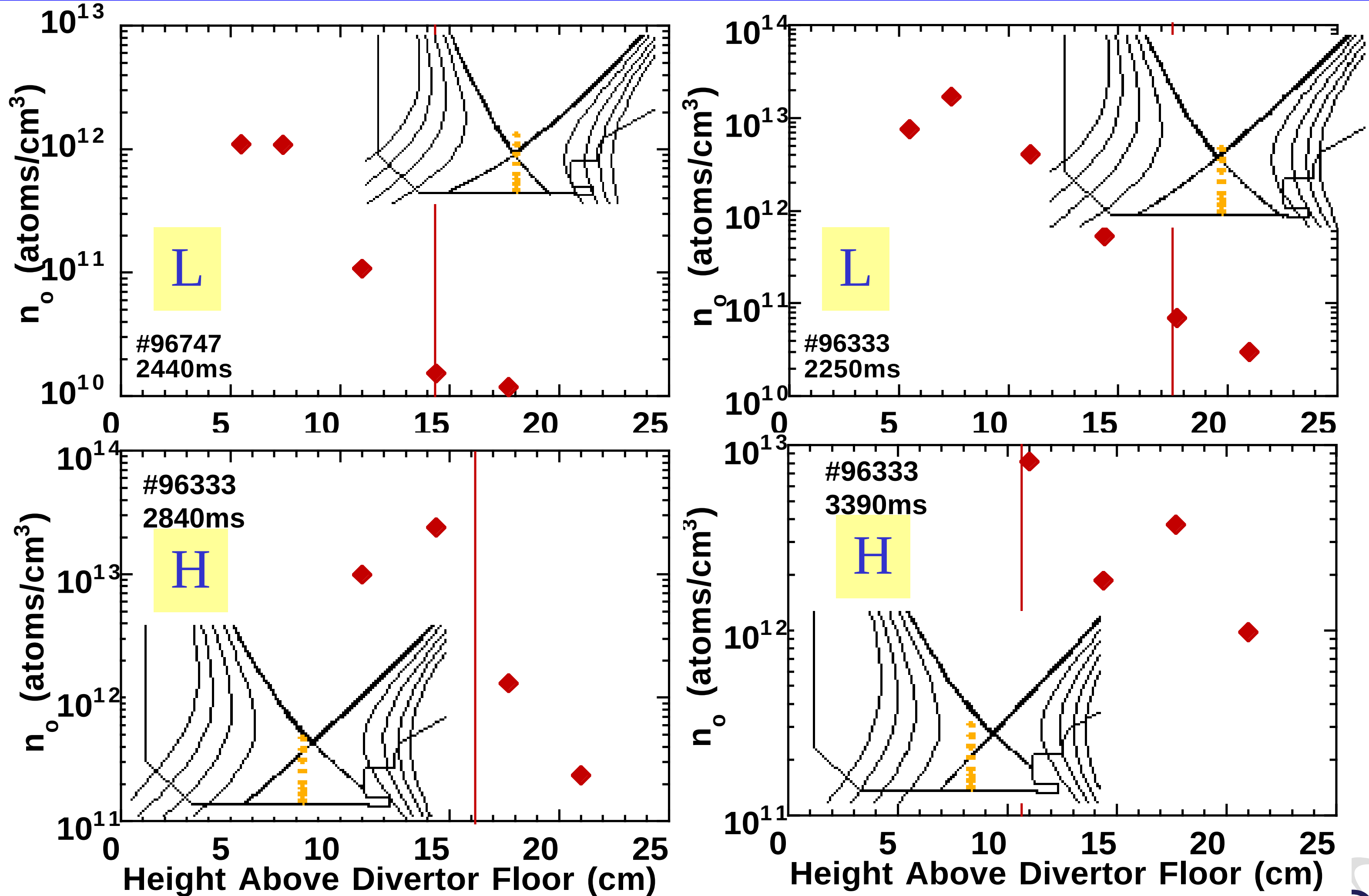
L/H-Mode Neutral Densities in 1-Ψ Coordinates #96747



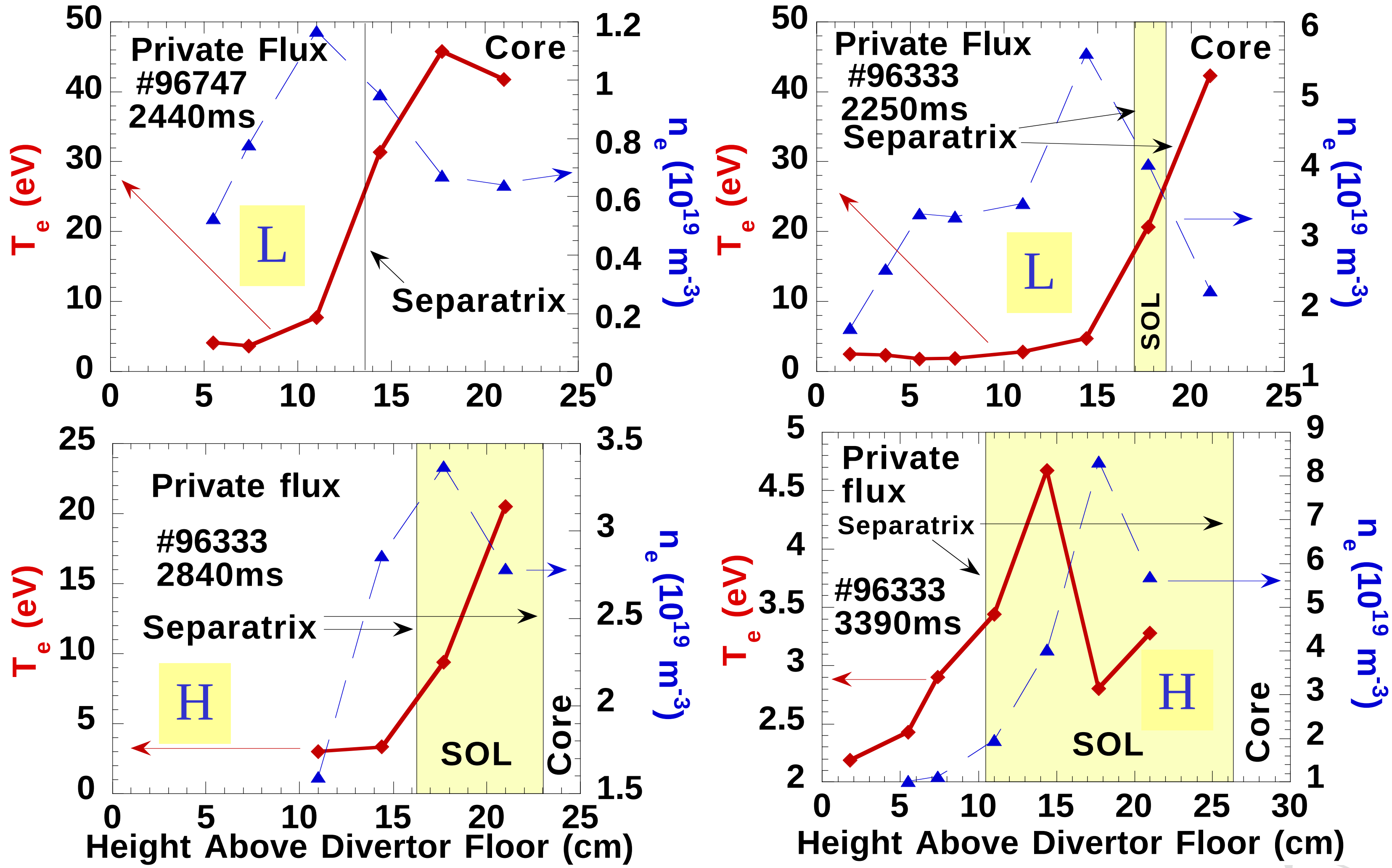
Discharge With L-H Transition Triggered by X-point Radius Increase



H-MODE NEUTRAL DENSITY HIGHER THAN L-MODE



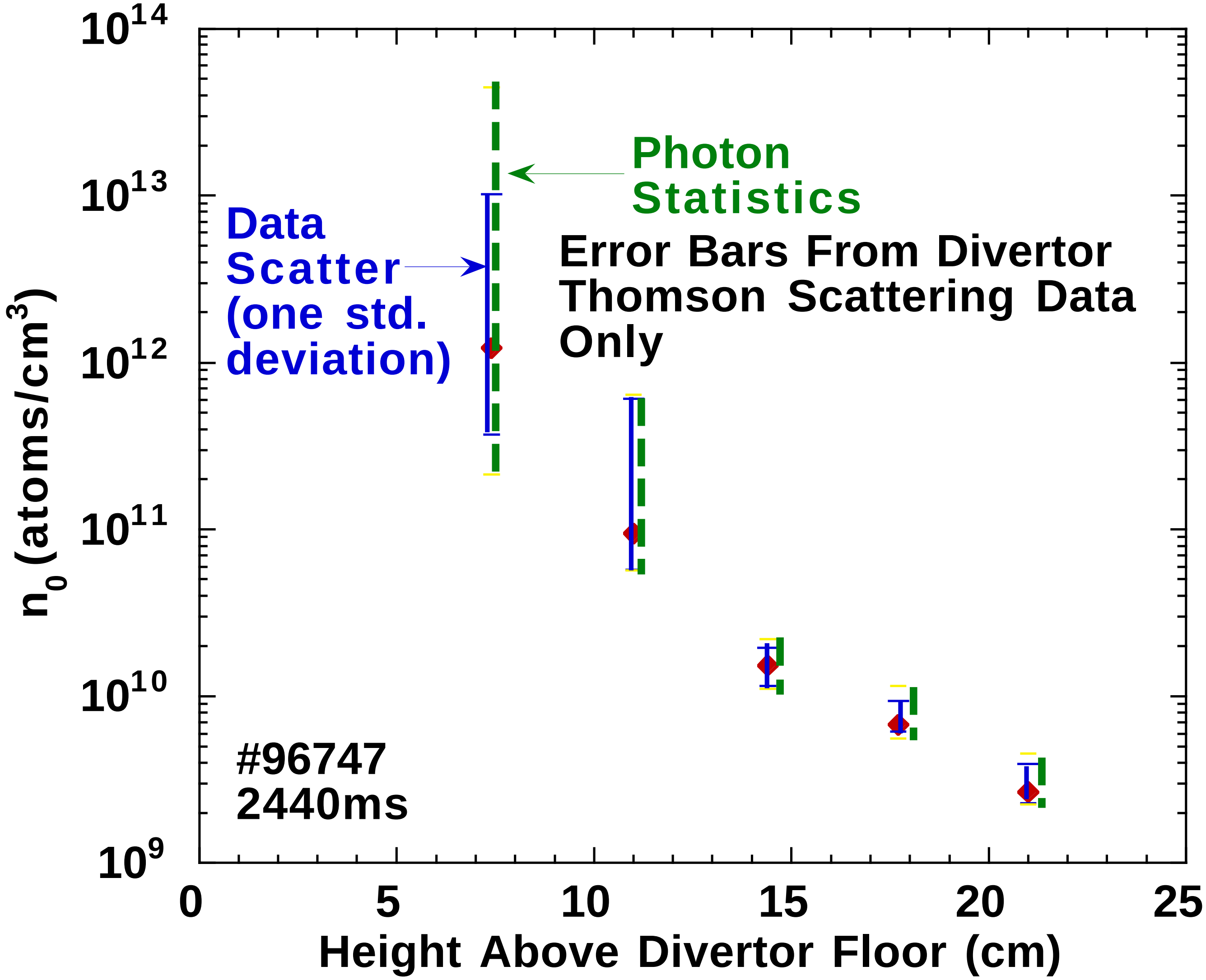
#96333 DATA SUGGEST PRIVATE FLUX MARFE



DISCUSSION

1) Plasma inventory increases at many times beam fuel rate in ELM-free H-mode: $dN_e/dt = S_{NBI} + S_{wall}(t) - N_e/\tau_p$
2) Even if τ_p becomes infinite, a wall (outgassing) source [$S_{wall}(t)$] is required for $dN_e/dt > S_{NBI}$
3) n_0 in X-point region is determined by divertor recycling source, wall outgassing source, and divertor/private flux region plasma ionization and screening
4) DEGAS calcs. show core fueling occurs through X-point
5) If PFR plasma n_e and T_e remain unchanged across L-H transition, then H-mode n_0 in X-point region should increase due to wall source, required for particle balance
6) Statistical error is high: n_0 known within ~ 1 order of magnitude, due to X-point n_e & T_e fluctuations

NEUTRAL DENSITY KNOWN AT BEST TO WITHIN A FACTOR OF 2



2-D Benchmarking: Why is the X-Point Neutral Density Important?

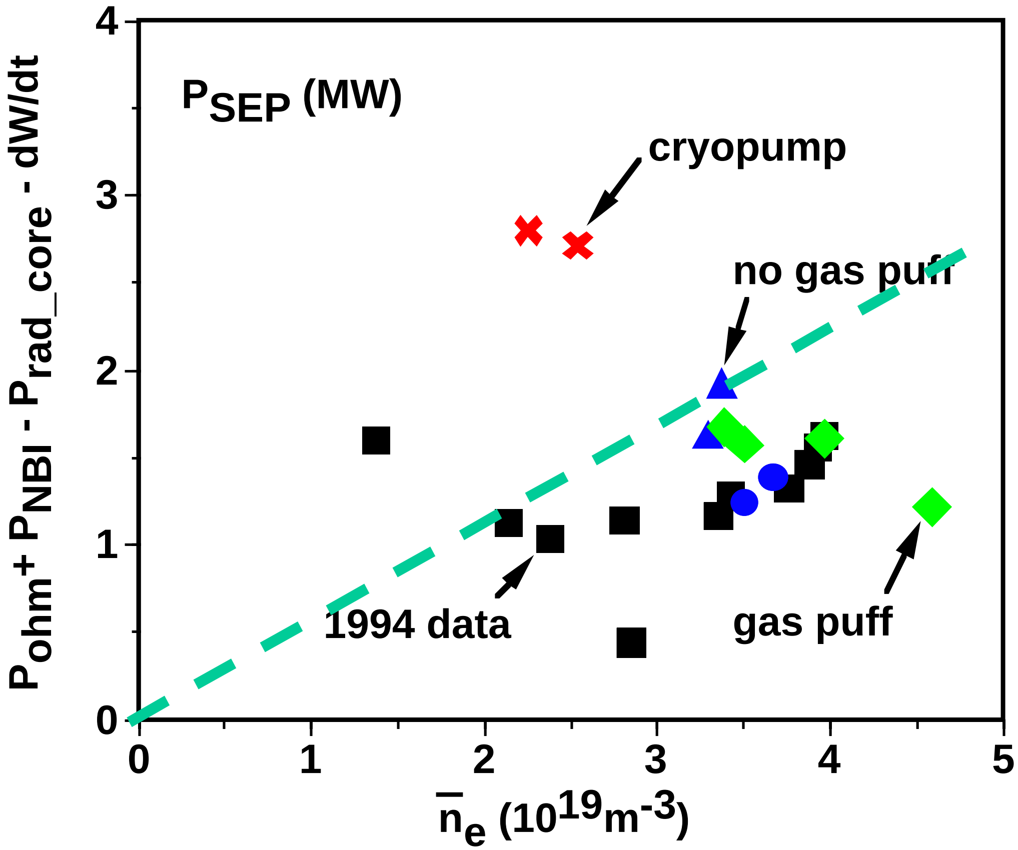
- Neutral densities are highest near the X-point. [Carreras, et al., Phys. Plasma **5** (1998) 2623]
- Neutrals damp the plasma rotation, which tends to stabilize instabilities.
  - This can increase the L-H power threshold. [Itoh, et al., Nucl. Fusion 29 (1989) 1031 + many others]
  - 2-D modeling suggests that n_o near the X-point must be $\geq 10^{11}$ for the neutral density to dominate the damping of the edge ion rotation. [Mahdavi, 1990 - Itoh, 1989 - Shaing 1995 - Carreras, 1998]
- Neutrals also influence the plasma via charge exchange power losses and particle balance.

THE POWER THRESHOLD DOES NOT BEHAVE MONOTONICALLY WITH $\bar{n}_e$

[Carreras, et al., Phys. Plasma **5** (1998) 2623]

- All the experiments were done at a constant magnetic field

- Can the data be described only by a function of the density?



Effect of Neutrals on the L-H Transition

Poloidal ion velocity rate of change (electrostatic turbulence, ignoring the complications introduced by toroidal geometry)

$$\frac{\partial \langle V_{\theta i} \rangle_s}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \langle \tilde{V}_{ri}\tilde{V}_{\theta i} \rangle_s\right) - \mu_{neo}\langle V_{\theta i}\rangle_s - \langle v\sigma\rangle_{cx}\langle n_n\rangle_s\left(\langle V_{\theta i}\rangle_s - \langle V_{\theta n}\rangle_s\right)$$

Reynolds stress

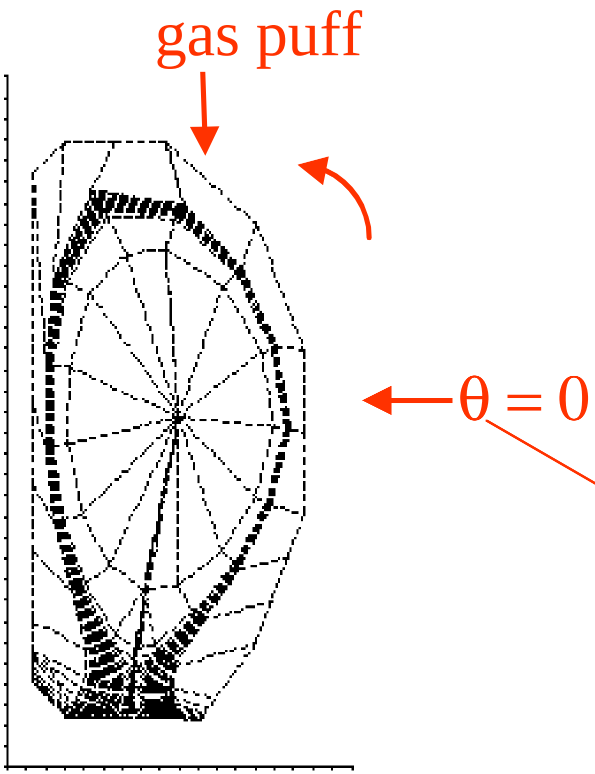
Neoclassical viscous damping

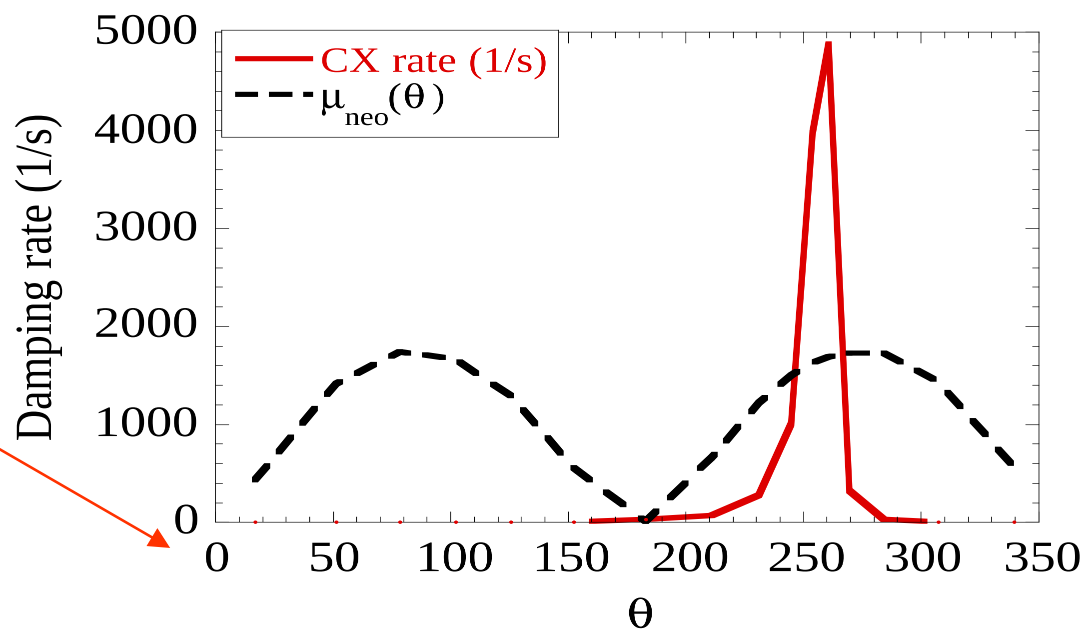
Neutral friction

THE CHARGE EXCHANGE DAMPING TERM CAN DOMINATE IN THE DIVERTOR

[Carreras, et al., Phys. Plasma **5** (1998) 2623]

- The neoclassical damping term has a $\sin^2(\theta)$ poloidal variation



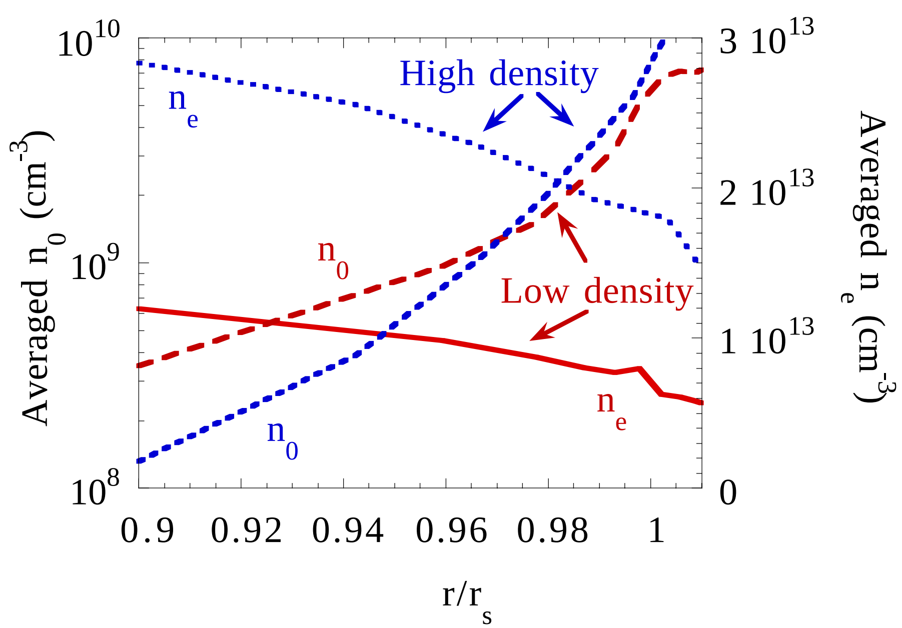


DENSITY SCAN ANALYSIS

- Two factors play a role in determining the neutral density inside the separatrix:
  - the particle source term, increasing with $\bar{n}_e$
  - the neutral penetration depth, decreasing with $\bar{n}_e$

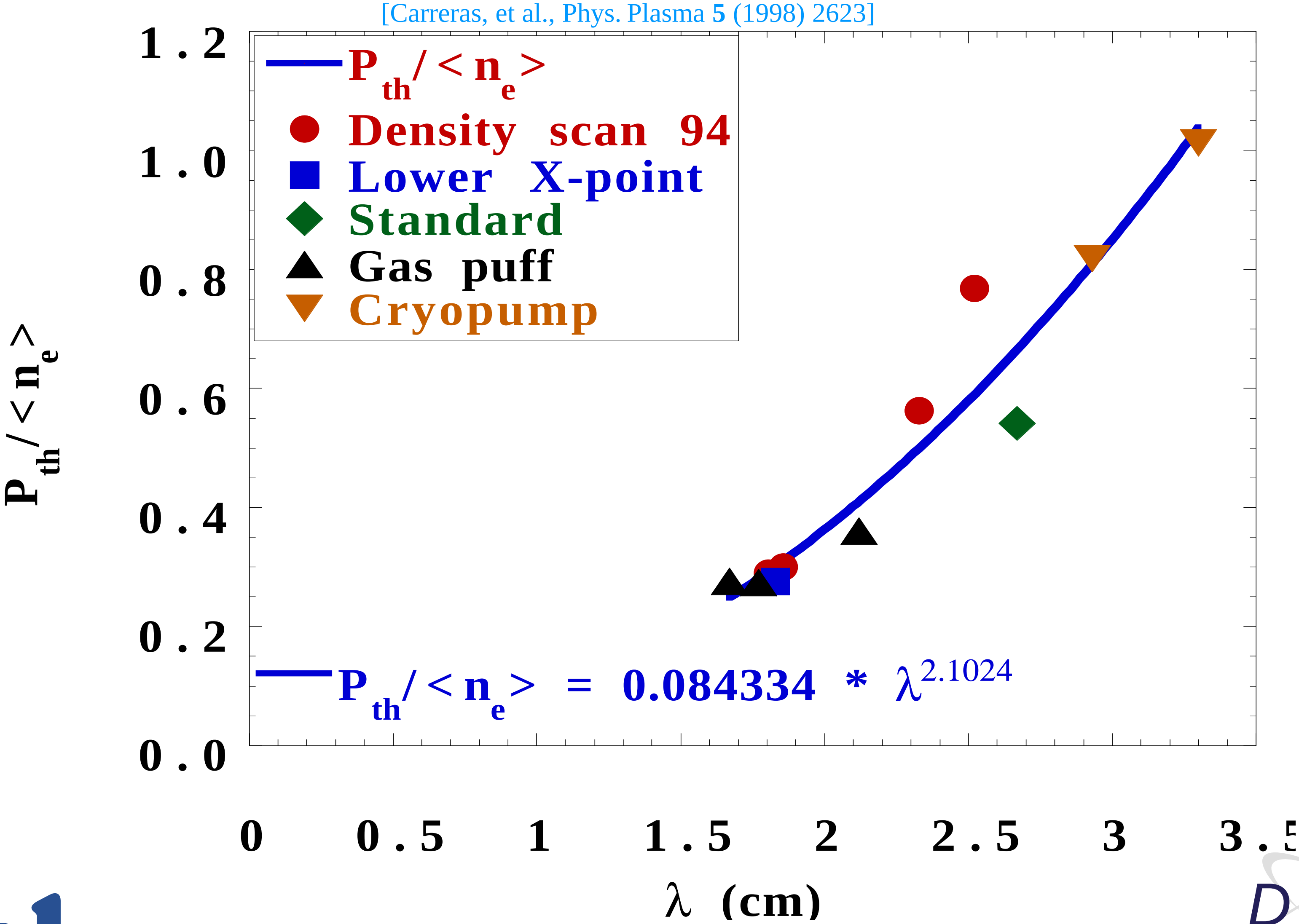
- Inside of the separatrix, the low $\bar{n}_e$ plasma ends up with higher neutral density than high $\bar{n}_e$ plasmas

[Carreras, et al., Phys. Plasma **5** (1998) 2623]



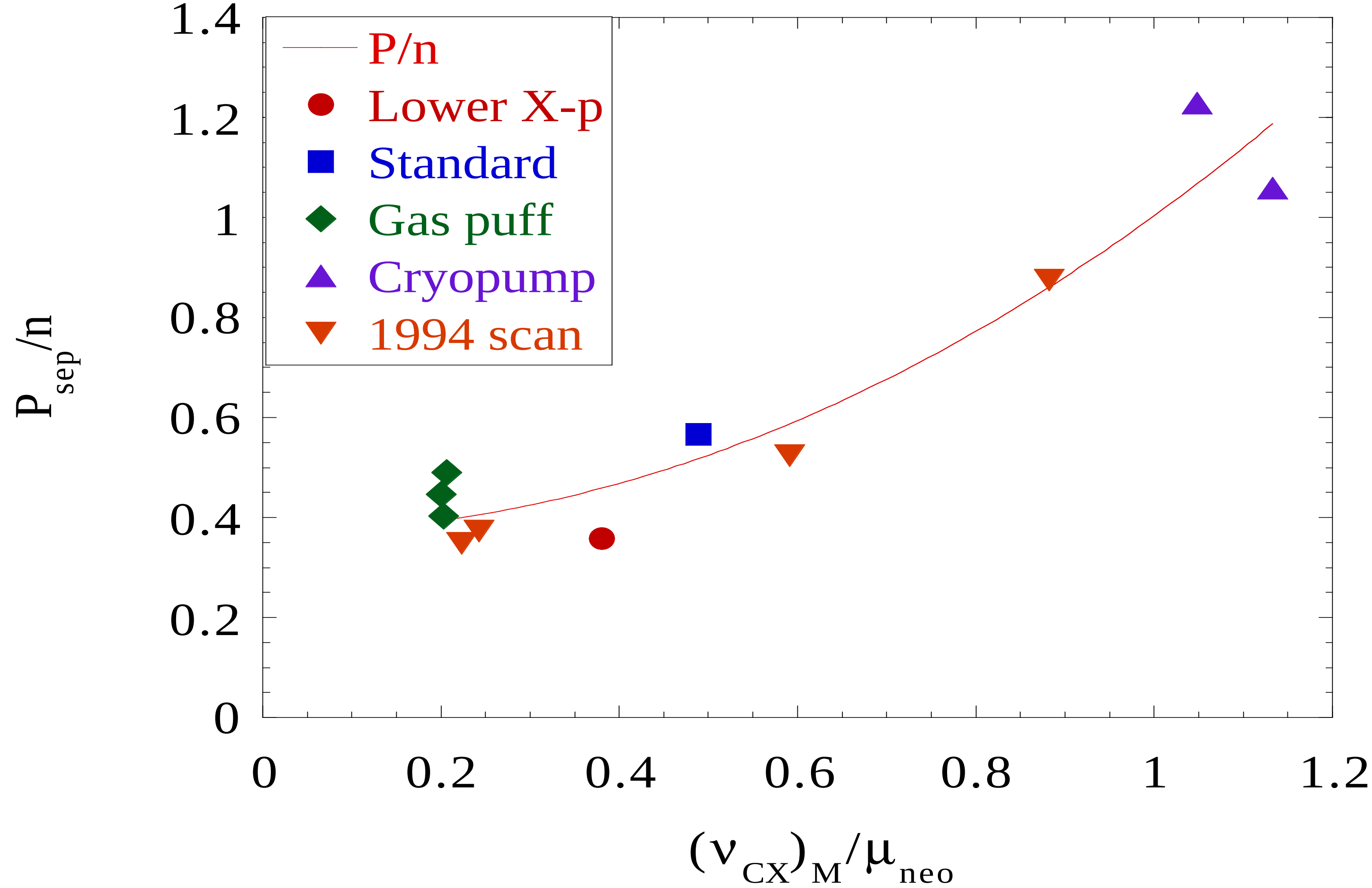
The power threshold correlates with the neutral penetration length (Carreras, PoP 1998)

[Carreras, et al., Phys. Plasma **5** (1998) 2623]



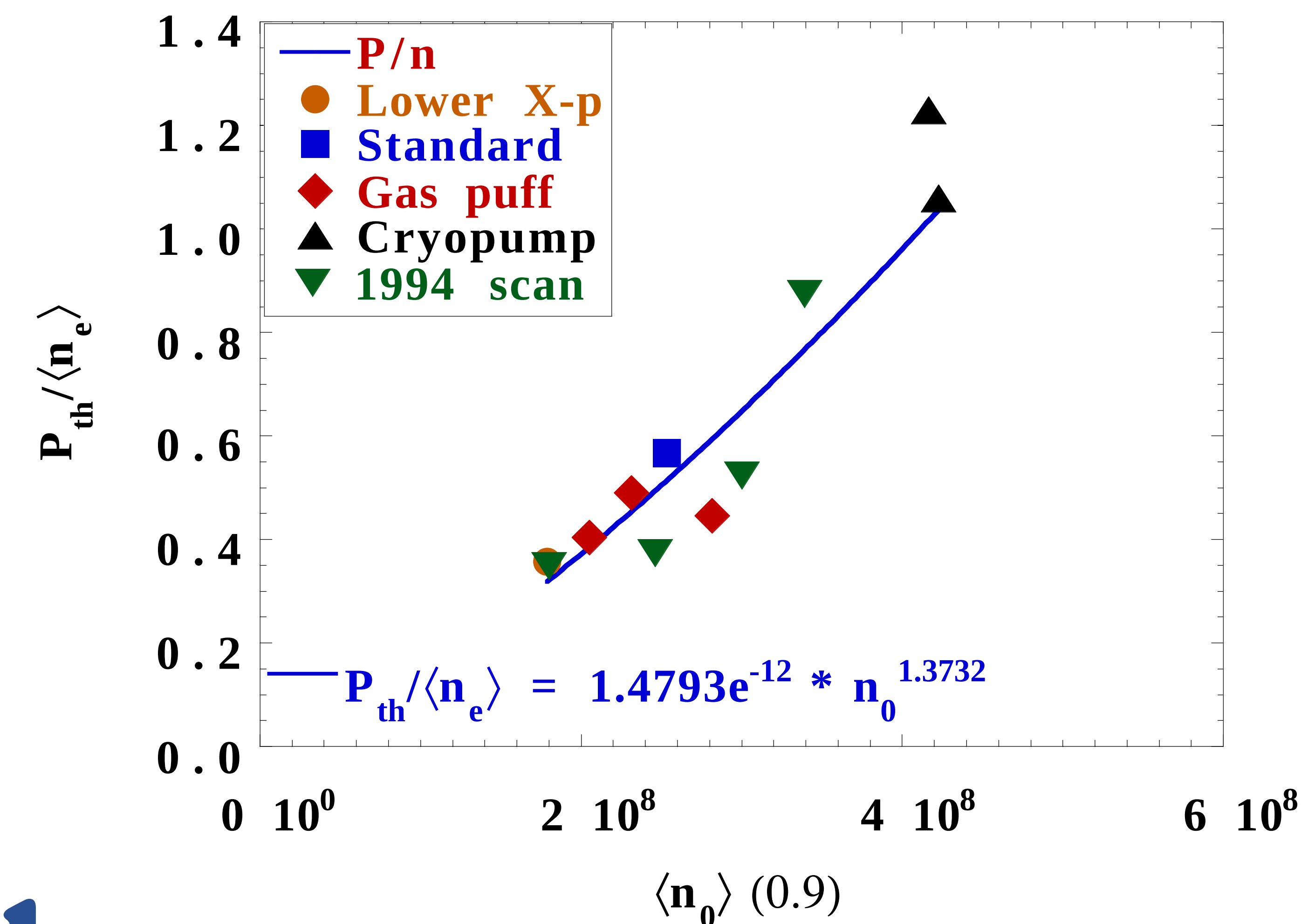
The power threshold correlates with the ratio of the CX damping rate to the neoclassical damping rate (Carreras, PoP 1998)

[Carreras, et al., Phys. Plasma **5** (1998) 2623]



The power threshold correlates with the neutral density in the region 0.9 > r/a > 0.95 (Carreras, PoP 1998)

[Carreras, et al., Phys. Plasma **5** (1998) 2623]



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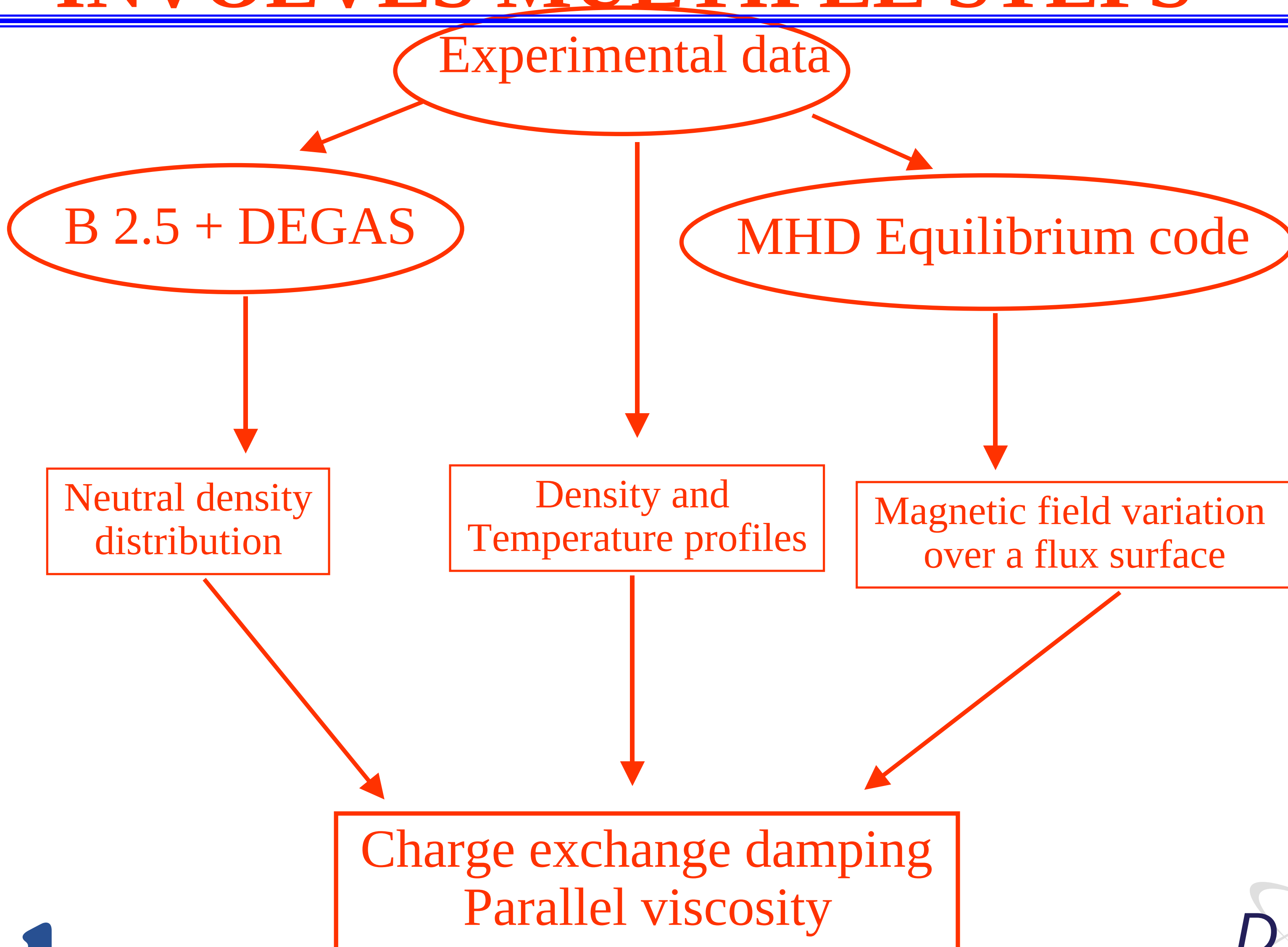
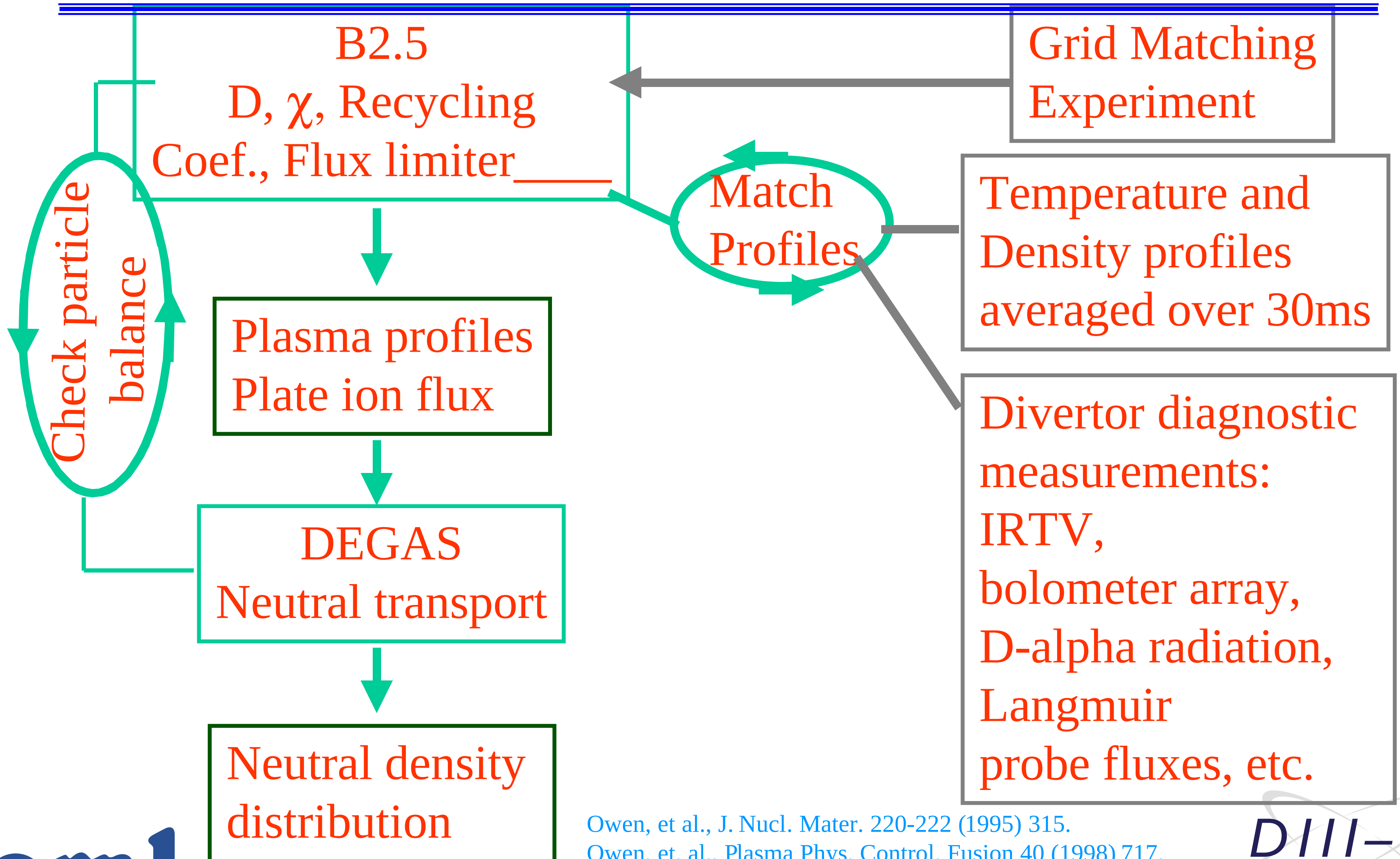
DATA ANALYSIS PROCEDURE INVOLVES MULTIPLE STEPS



EDGE PLASMA ANALYSIS PROCEDURE IS ITERATIVE



Owen, et al., J. Nucl. Mater. 220-222 (1995) 315.
Owen, et. al., Plasma Phys. Control. Fusion 40 (1998) 717.

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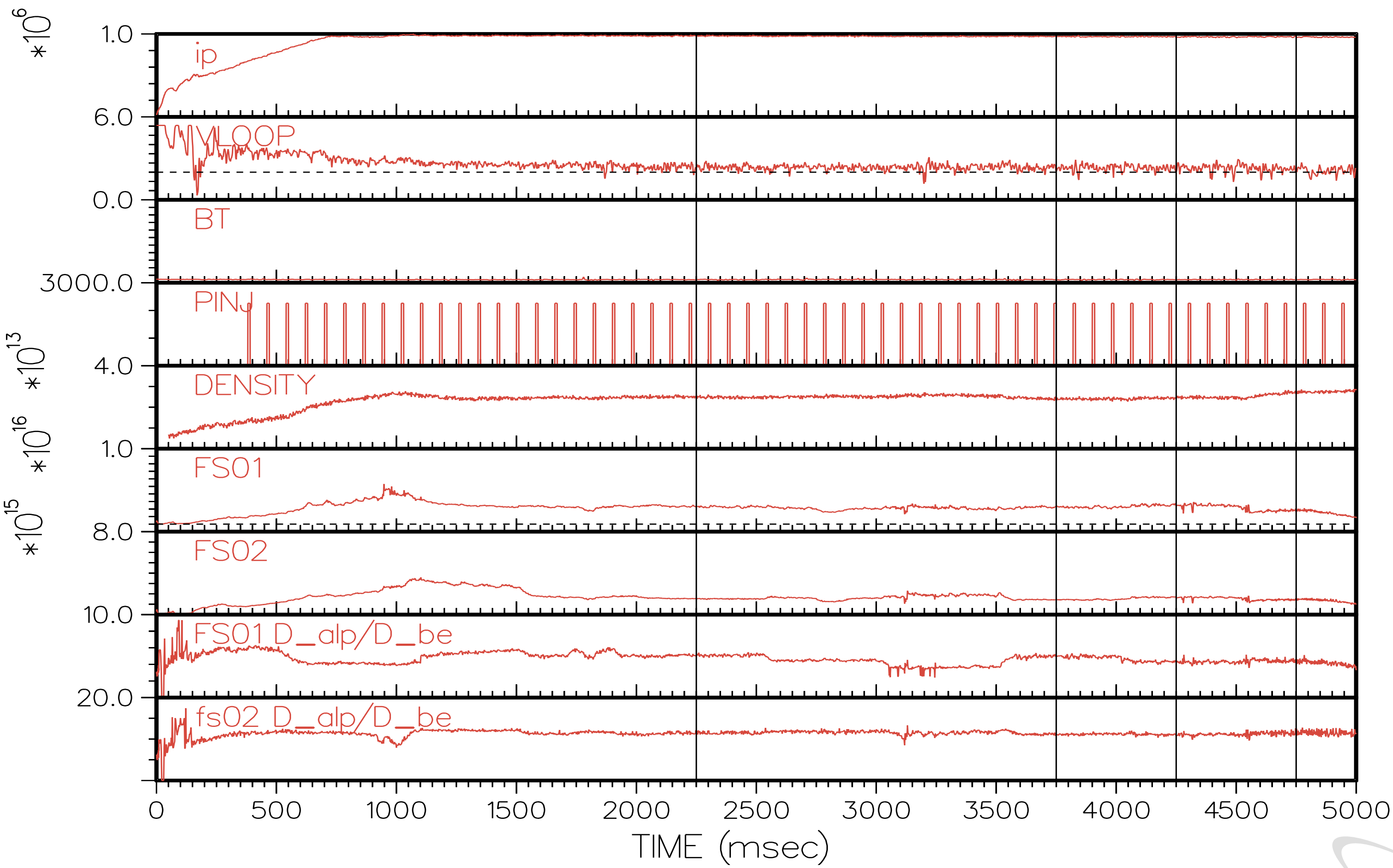
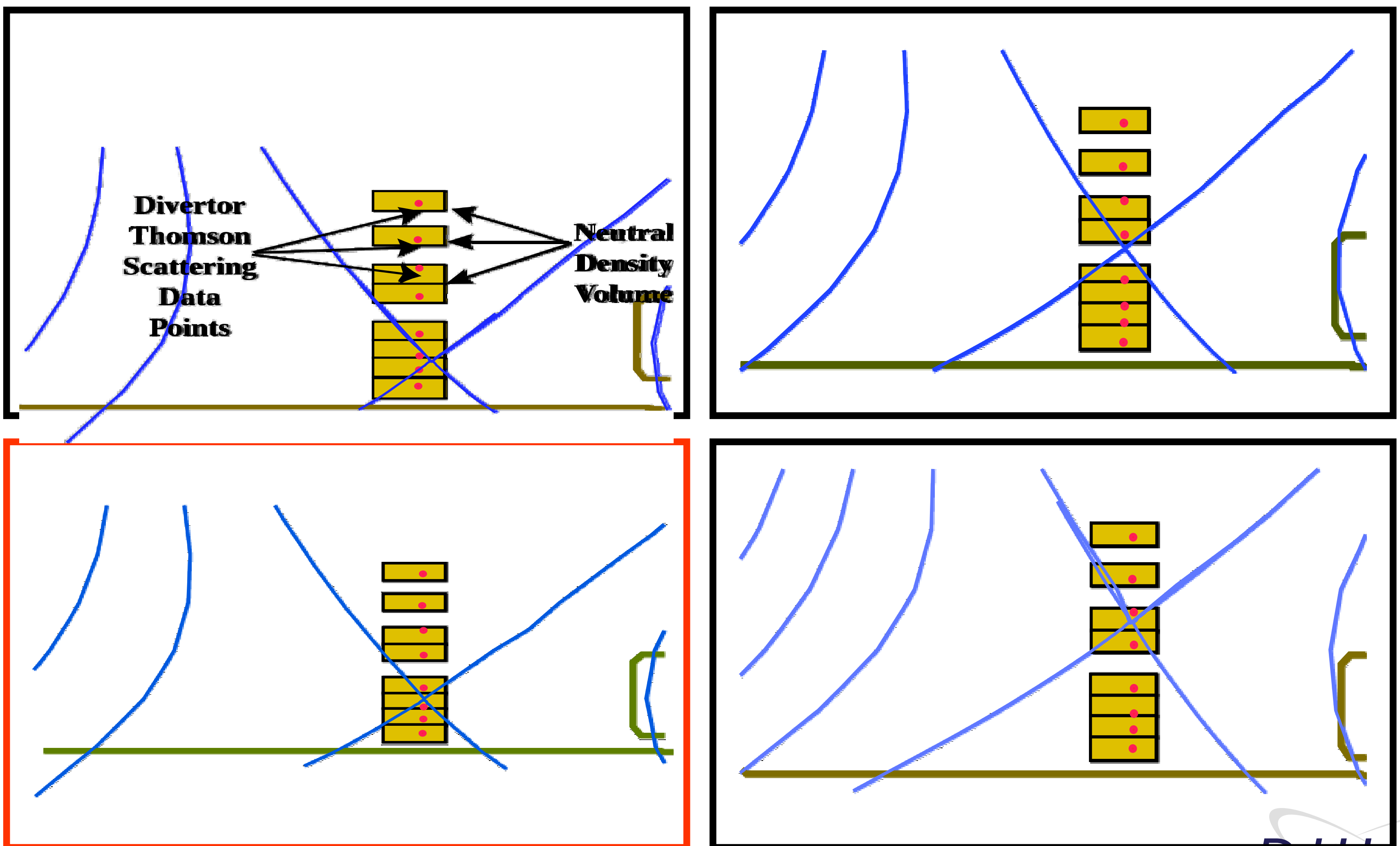
Discharge Data, Shot 96740

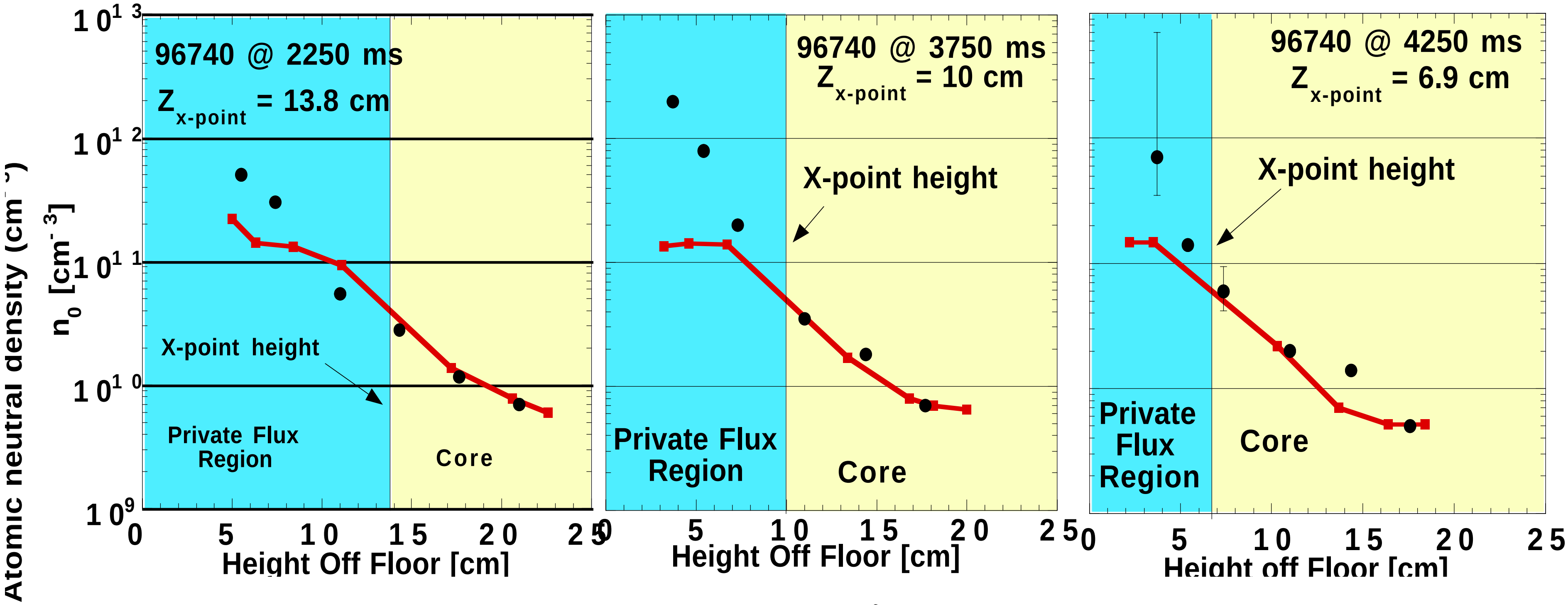


Four X-Point Heights During One Discharge (L-Mode, $\bar{n}_e = 2.5 \times 10^{19}\ m^{-3}$



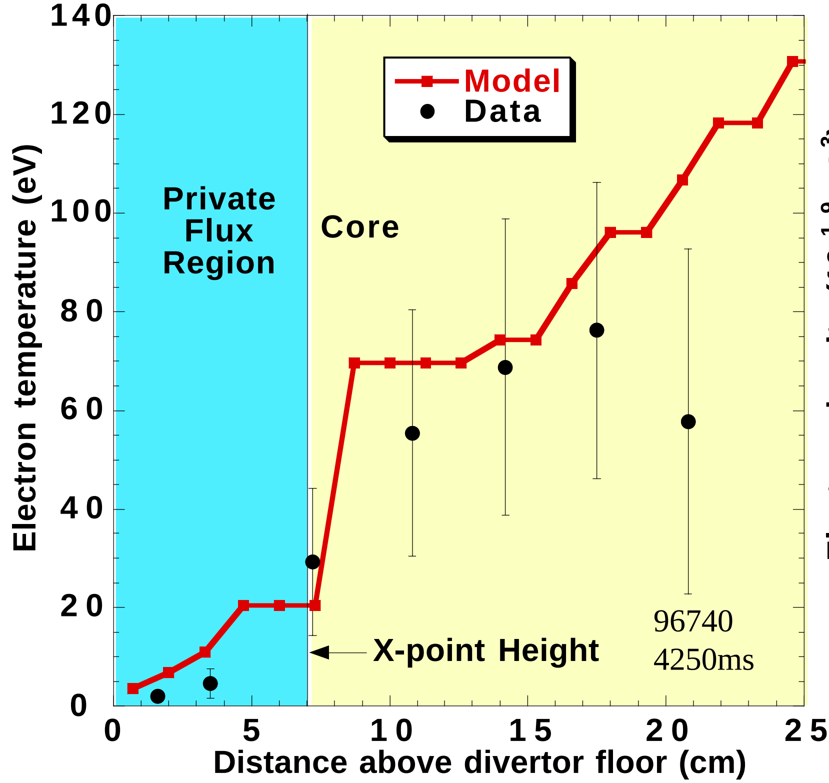
2-D MODEL MATCHES NEUTRAL DENSITY DATA IN CORE

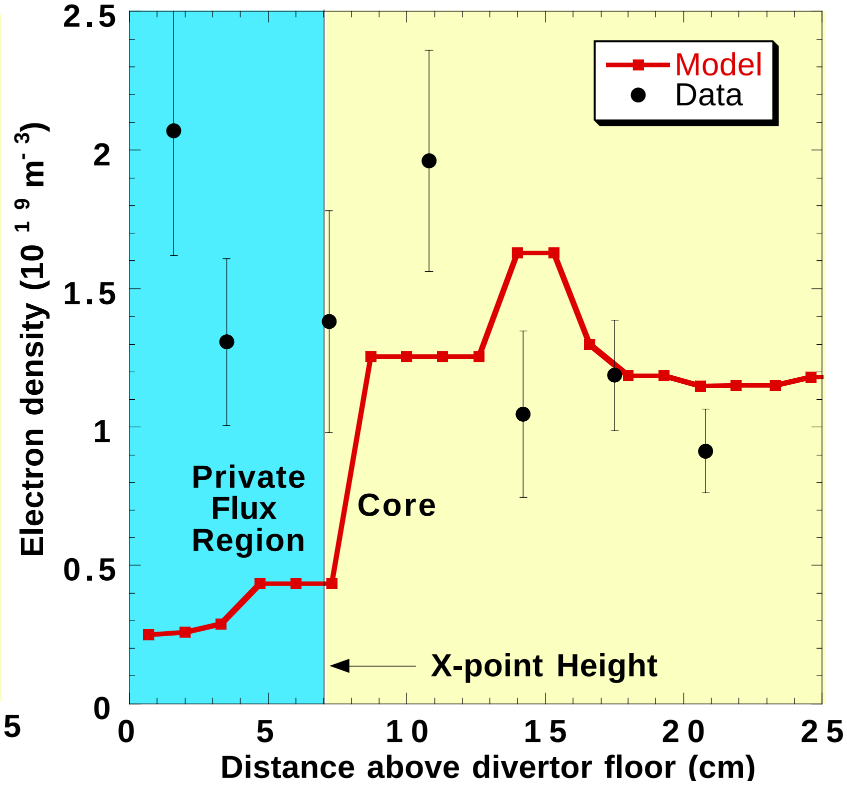
Reference: Maingi, EPS 1999, Maastricht, The Netherlands



- **n_0 e-folding length in core ~ 5cm; λ_{ion} ~ 3-4 cm for 3 eV atom**
- Comparison not as good in private flux region, due to contribution of molecules to D_α light (up to 40% total in DEGAS)

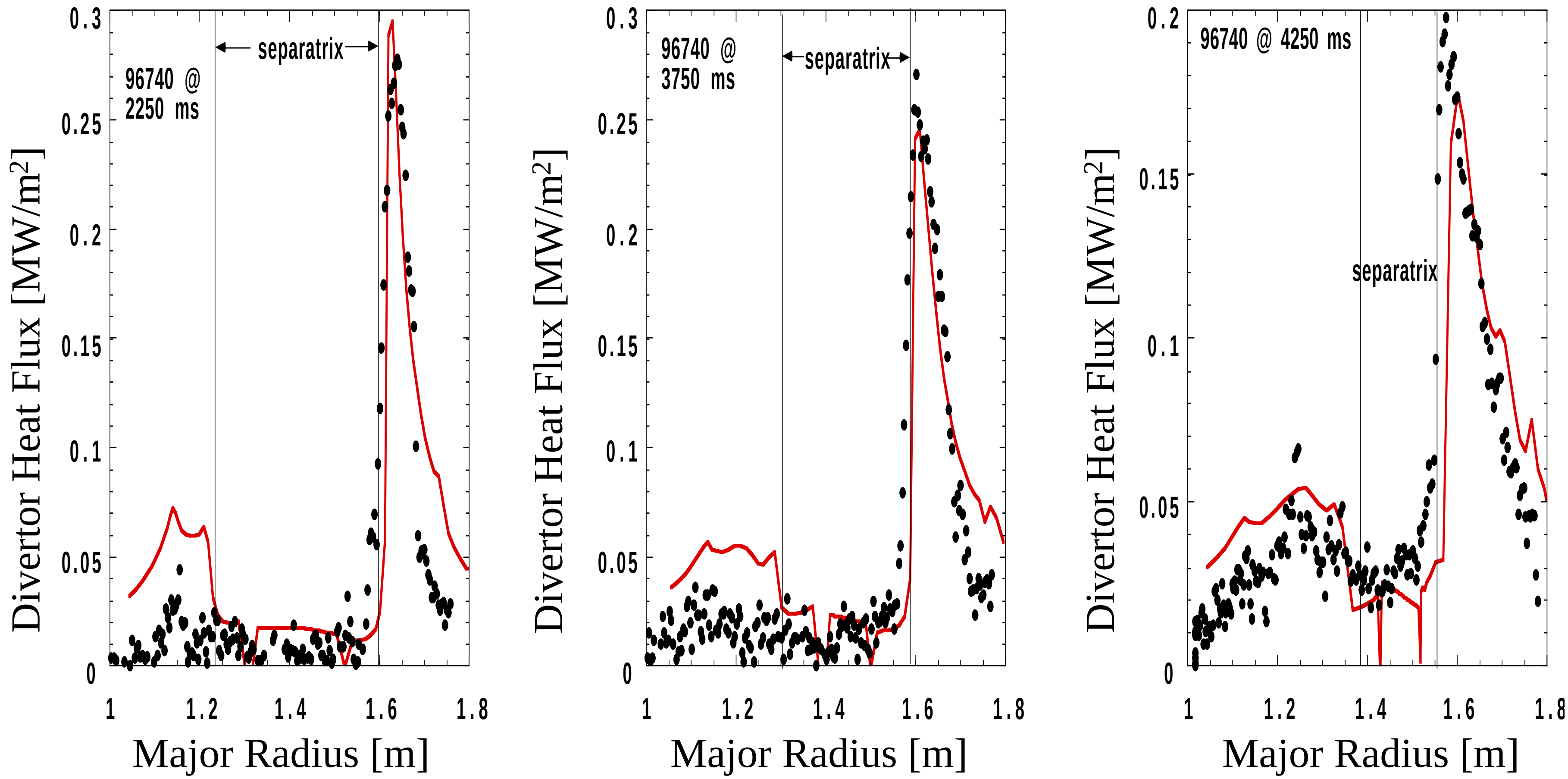
MODEL REASONABLY MATCHES n_e AND T_e ABOVE X-POINT



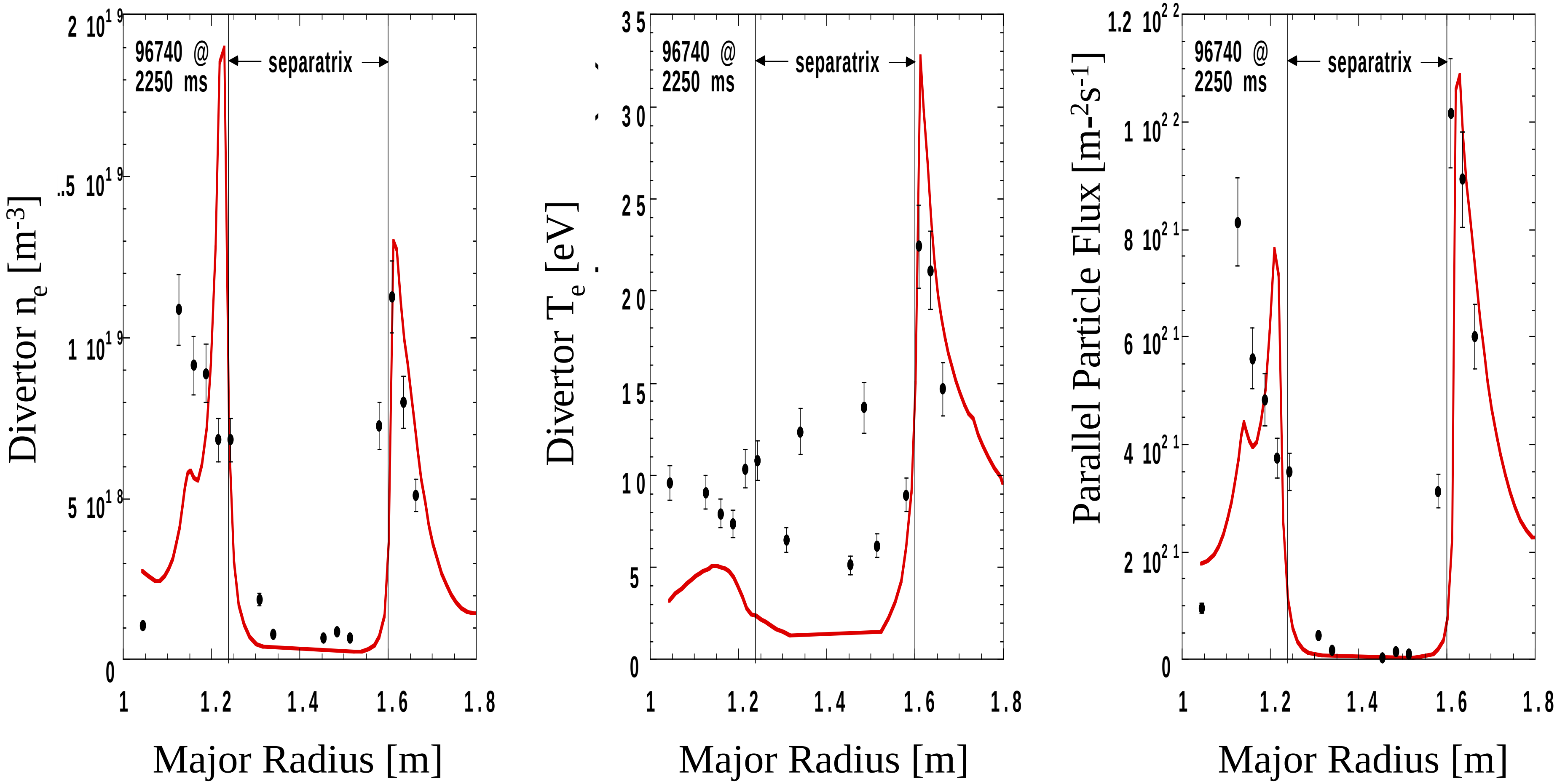


- These data are not used to constrain model free parameters and are an independent check on the calculations

MODEL CALCULATIONS MATCH MEASURED HEAT FLUX PROFILE

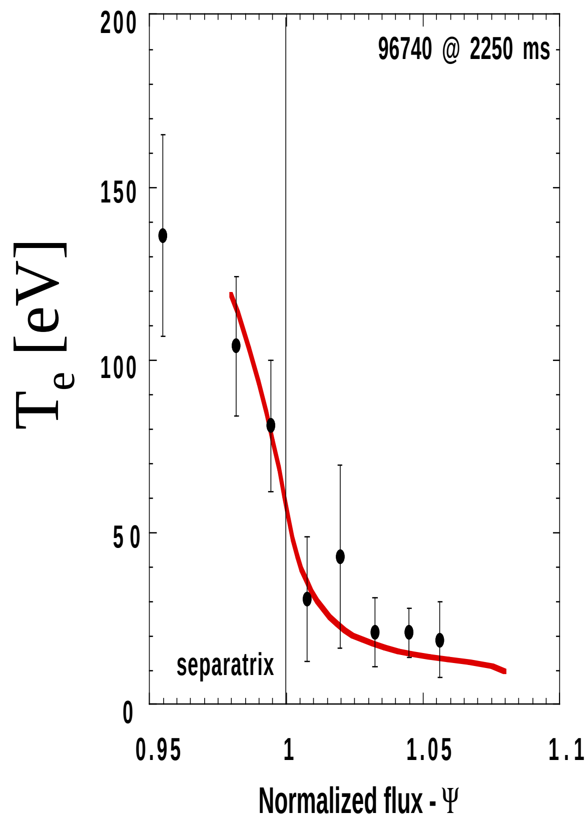


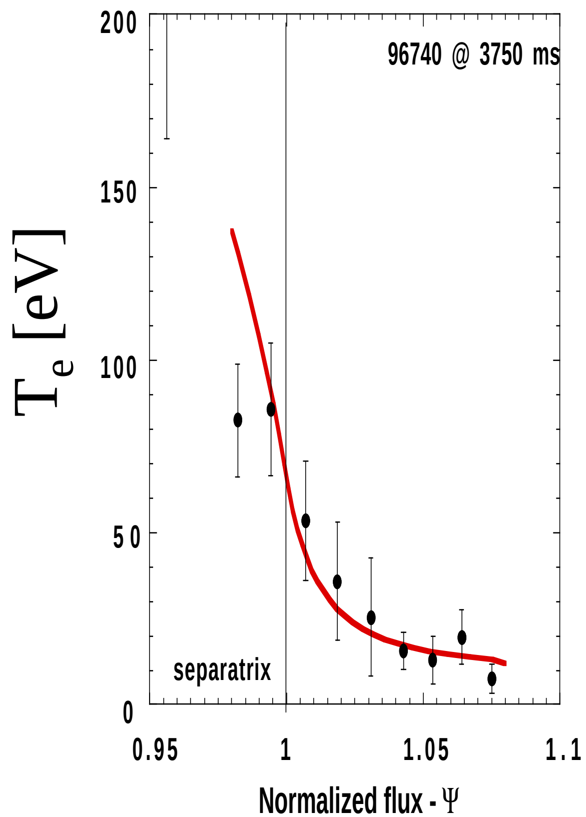
MODEL MATCHES DIVERTOR TARGET PROFILES

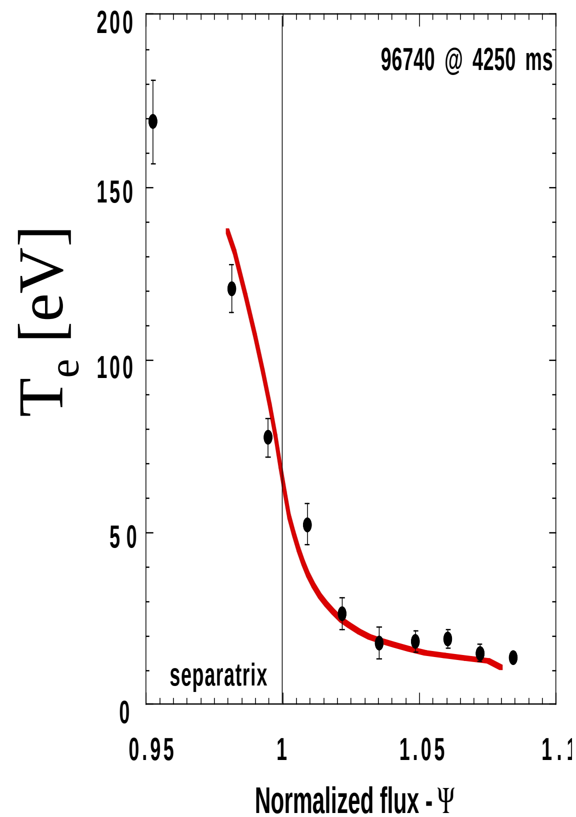


R. Maingi H-mode Workshop 1999: slide 30

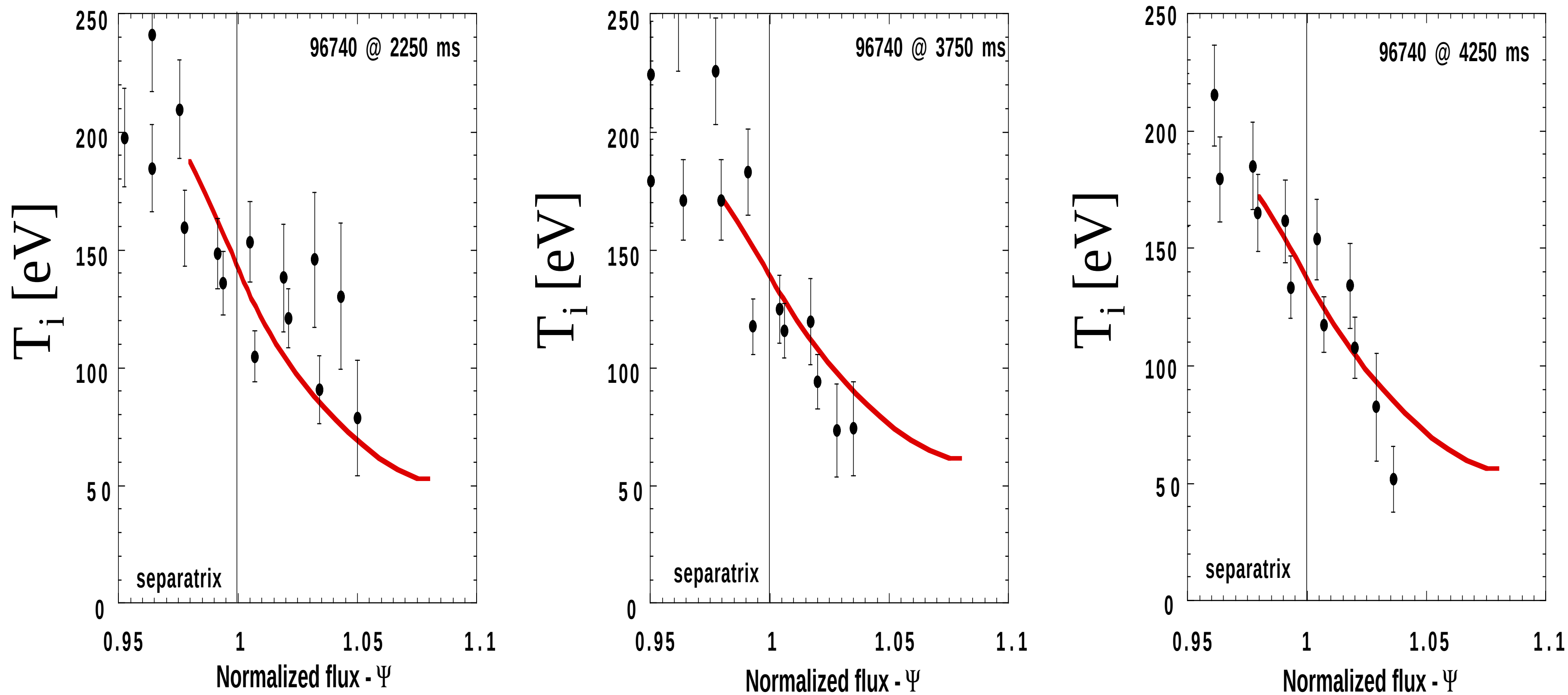
UPSTREAM T_e PROFILE USED TO CONSTRAIN MODEL $\chi_{\perp}^{e}$







UPSTREAM T_i PROFILE USED TO CONSTRAIN MODEL $\chi_{\perp}^{i}$



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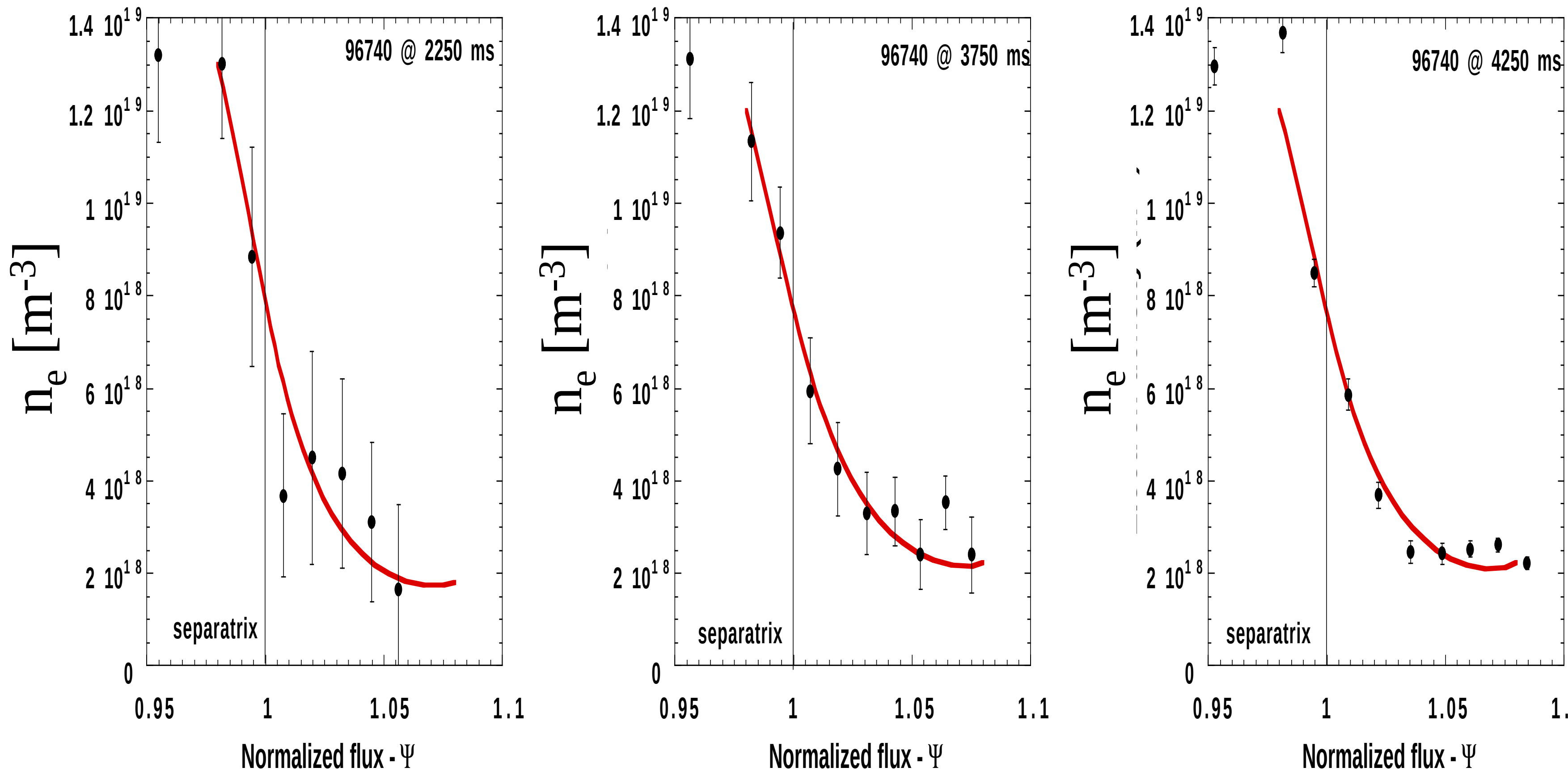
UPSTREAM n_e PROFILE USED TO CONSTRAIN MODEL $D_\perp$



PARTICLE BALANCE SATISFIED WITH B2.5/DEGAS MODEL

Time Slice: 96740	2250	3750	4250
Core Efflux (B2.5) [Amps]	538	555	547
Core Fueling (DEGAS) [Amps]	533	550	563
Power through separatrix [MW]	0.58	0.62	0.59
Total Radiation [MW]	0.42	0.42	0.42
Core Radiation [MW]	0.14	0.14	0.14

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SUMMARY

- X-point n_0 is generally higher in H-mode than L-mode
  -> caused by wall outgassing after L-H transition?
- X-point n_0 comparable in L and H-mode when dN/dt small
- This study corroborates our previous conclusion that edge neutral density is high enough to affect the poloidal momentum balance and L-H threshold in low density DIII-D pumped discharges
- The good agreement between measured and computed neutral density above the X-point (which is ~ 10^9 - 10^{11} cm^{-3}) corroborates our B2./5 DEGAS iterative modeling scheme for other neutral density issues, e.g. core fueling