NSTX

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Recap of 0-D projections and 2-D SOLPS interpretive modeling of density control from lithium

R. Maingi, J.M. Canik

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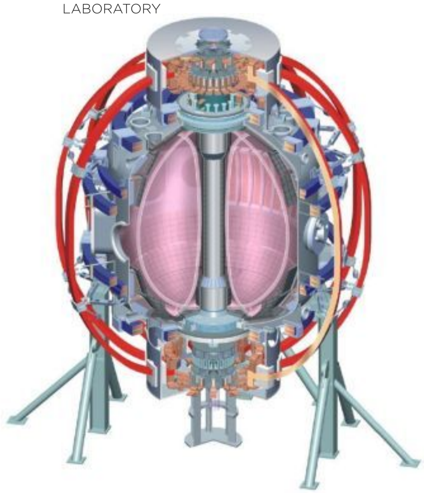

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Summary of 0-D predictive modeling and 2-D interpretive modeling of lithium coatings in NSTX

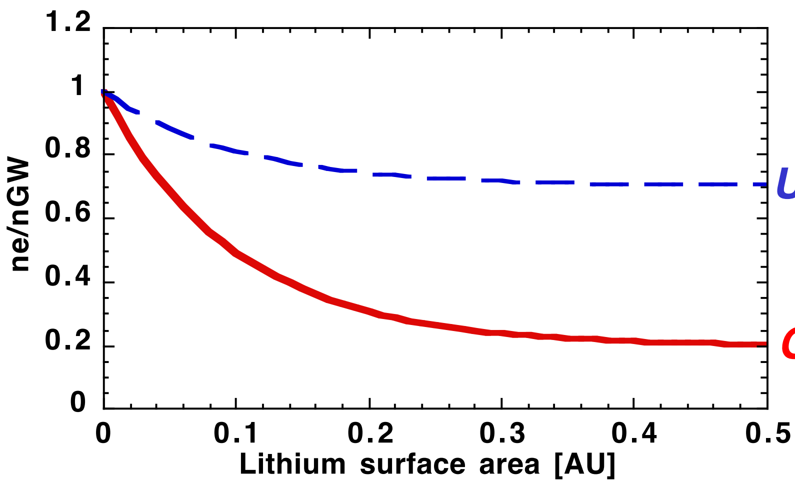
- 0-D predictive modeling was done for guidance of LLD location and width
  - Assumed ideal sticking of D to liquid lithium (R_p=0.15), and an application of lithium to LLD only
  - Predicted 20-50% density reduction with LLD
  - Actual experiment had lithium deposited mostly away from LLD on inboard side: lithium pumping on graphite would dominate the LLD effects for short pulse lengths
  - NSTX-U: need local lithium deposition on LLD to isolate effect

- 2-D SOLPS interpretive modeling of lithium on graphite was performed
  - For $\delta \sim 0.5$, R_p went from 0.98 to ~ 0.9 (Canik, PoP 11)
  - For $\delta \sim 0.8$, R_p dropped to ~ 0.85 (Pigarov, Smirnov)

Calculations needed for LLD Tray Design Specification

- The following LLD design parameters need to be specified (target: April 15, 2007):
  1) Tray Width
  2) Tray Major Radius R_{tray}
  3) Number of tray segments, gap size(s) between segments, and clocking of segments $(\phi_{min}-\phi_{max})$
- Minimum density will depend on tray-OSP distance

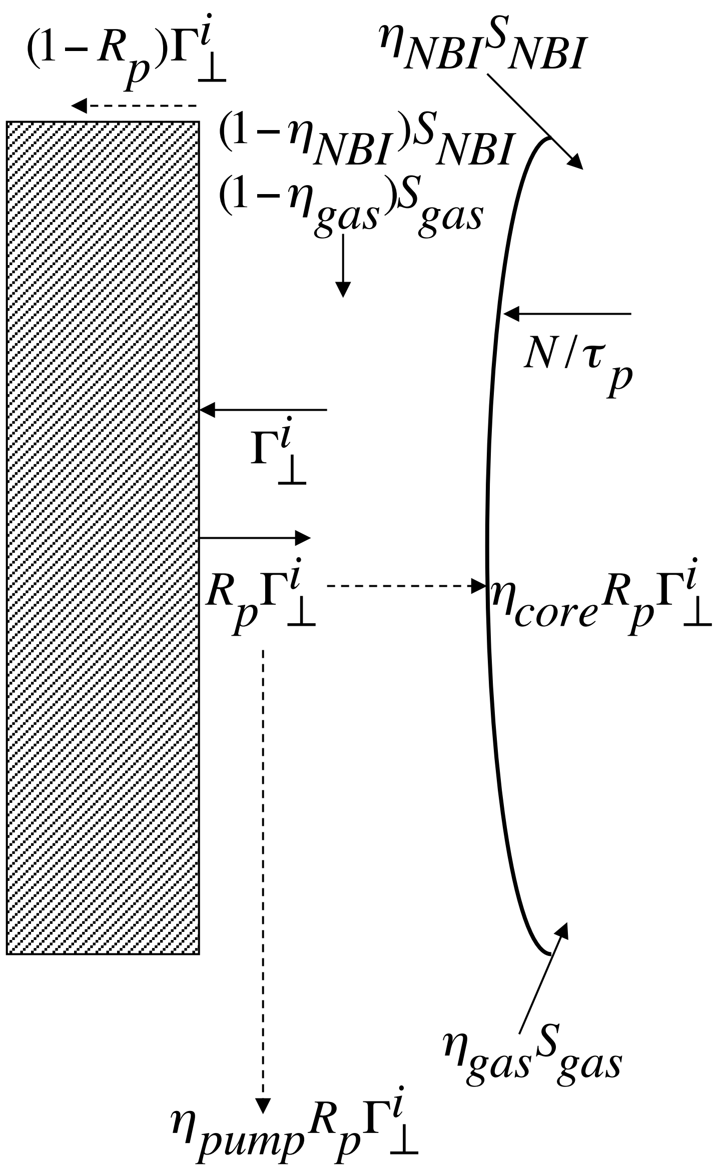
Large distance between OSP and LLD radius



Un-optimized pumping

Optimized pumping

Particle Balance and Recycling Model



- Consider core and SOL particle content equations

$$\frac{dN}{dt} = \eta_{NBI}S_{NBI} + \eta_{gas}S_{gas} - \frac{N}{\tau_p} + \eta_{core}R_p\Gamma_\perp^i$$

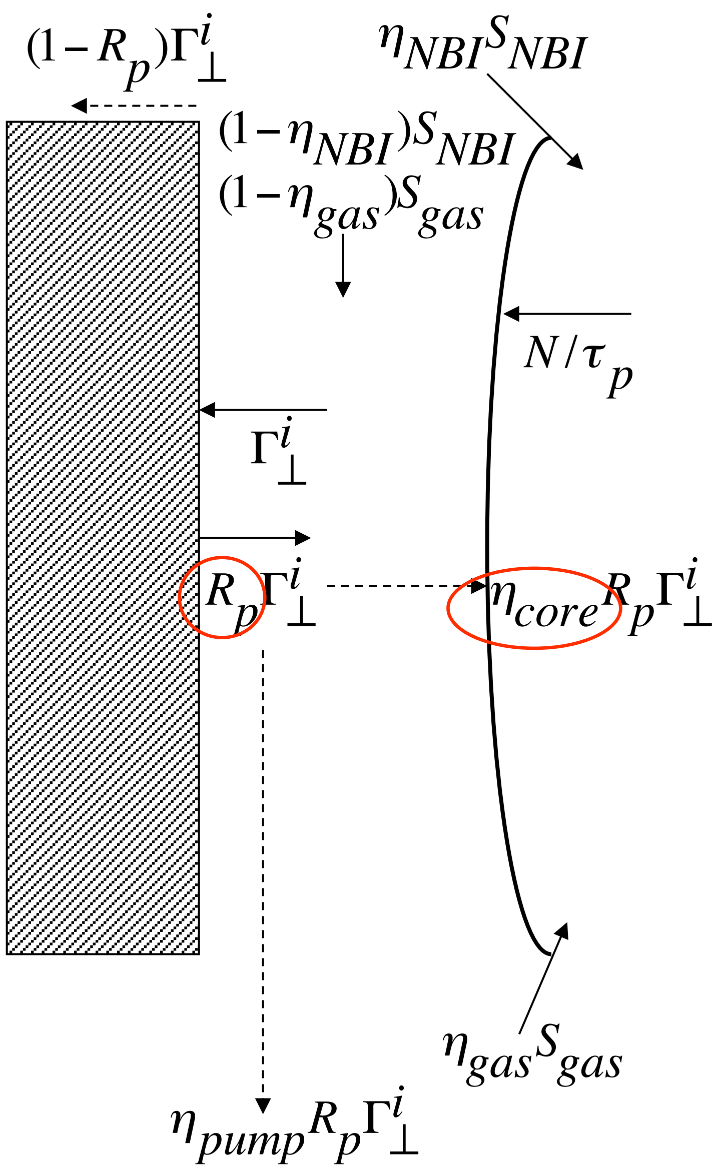
$$\frac{dN_i^{SOL}}{dt} + \frac{dN_0^{SOL}}{dt} = (1-\eta_{NBI})S_{NBI} + (1-\eta_{gas})S_{gas} + \frac{N}{\tau_p} - (1-R_p)\Gamma_\perp^i - R_p\Gamma_\perp^i(\eta_{pump} + \eta_{core})$$

- Assume SOL neutral and ion density in steady state

$$\frac{dN}{dt} = (1+\beta-\beta\eta_{NBI})S_{NBI} + (1+\beta-\beta\eta_{gas})S_{gas} - \frac{N(1-\beta)}{\tau_p}, \text{ where}$$

$$\beta \equiv R_p\eta_{core} \Big/ \left[(1-R_p) + R_p(\eta_{pump} + \eta_{core})\right]$$

Particle Balance and Recycling Model



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$$\frac{dN}{dt} = \eta_{NBI}S_{NBI} + \eta_{gas}S_{gas} - \frac{N}{\tau_p} + \eta_{core}R_p\Gamma^i_\perp$$

$$\frac{dN_i^{SOL}}{dt} + \frac{dN_0^{SOL}}{dt} = (1-\eta_{NBI})S_{NBI} + (1-\eta_{gas})S_{gas} + \frac{N}{\tau_p} - (1-R_p)\Gamma^i_\perp - R_p\Gamma^i_\perp(\eta_{pump} + \eta_{core})$$

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$$\beta \equiv R_p\eta_{core} \Big/ \left[(1-R_p) + R_p(\eta_{pump} + \eta_{core})\right]$$

Method to Relate 0-D Pump Probability to Divertor Plasma and Lithium tray parameters

NSTX

Li surface particle sticking probability - 0.85

In/out particle flux ratio - 0.8

Tray toroidal coverage - 0.9

$$\eta_{pump} \cong \gamma_{Li}^{sticking} \frac{\int_{R_{\min,tray}}^{R_{\max,tray}} \Gamma_{\perp}(R) R dR}{\int_{R_{\min}}^{R_{\max}} \Gamma_{\perp}(R) R dR} \left(\frac{\Gamma_{out}}{\Gamma_{in} + \Gamma_{out}} \right) \left(\frac{\Gamma_{down}}{\Gamma_{up} + \Gamma_{down}} \right) f_{\phi}$$

Impact of R_{tray}, Δ_{tray}, $(R_{OSP} - R_{tray})$
(Γ *estimated from* D_{α} *profile*)

Up/down particle flux ratio
0.5 (δ_r^{sep} important)

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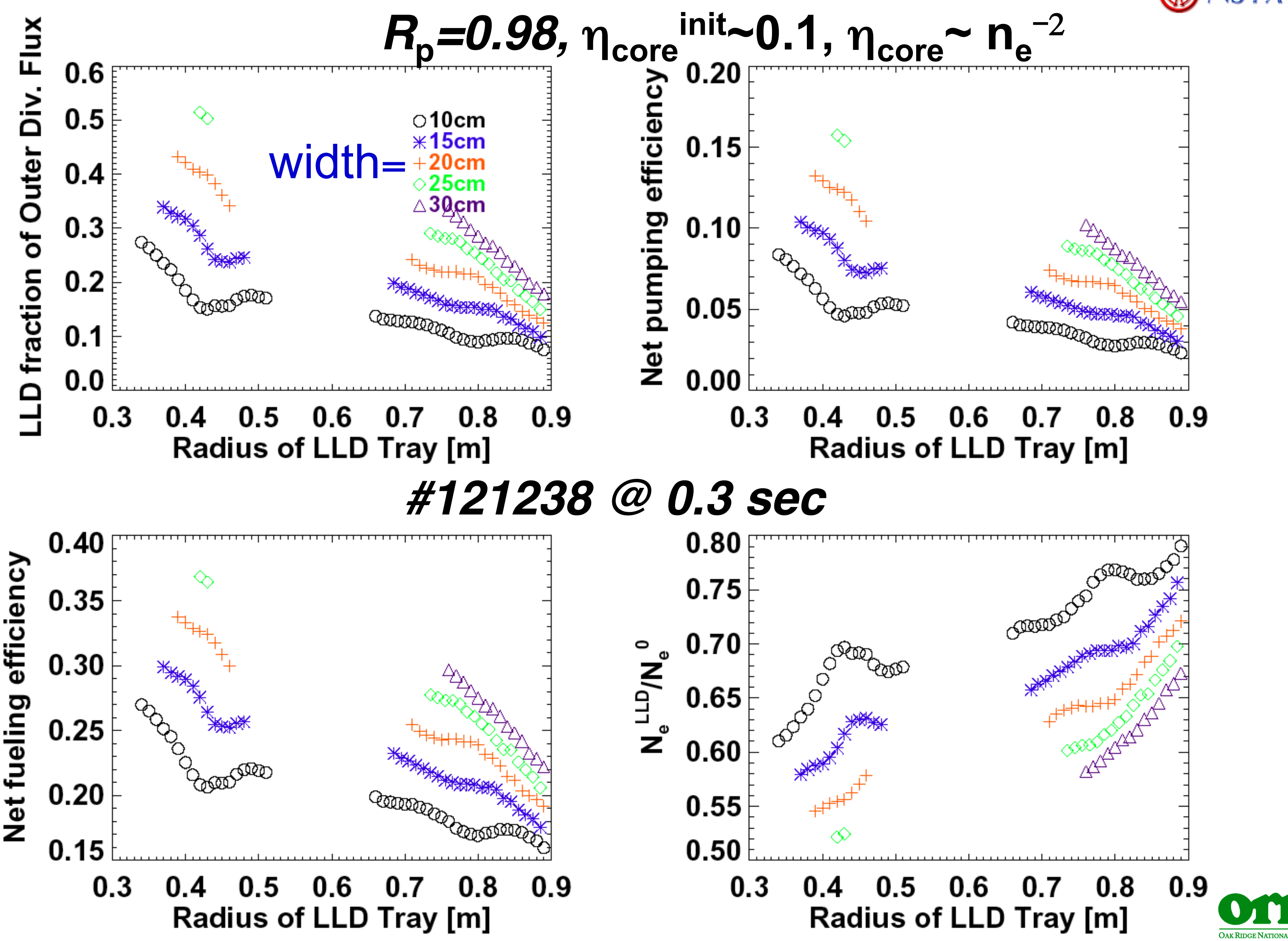
Achievable edge density reduction depends on tray radius and width in high δ discharge



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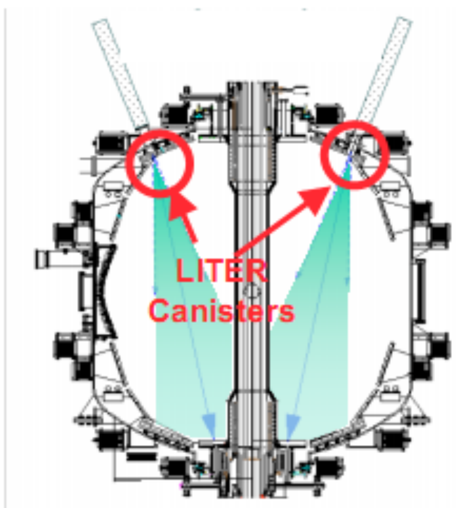
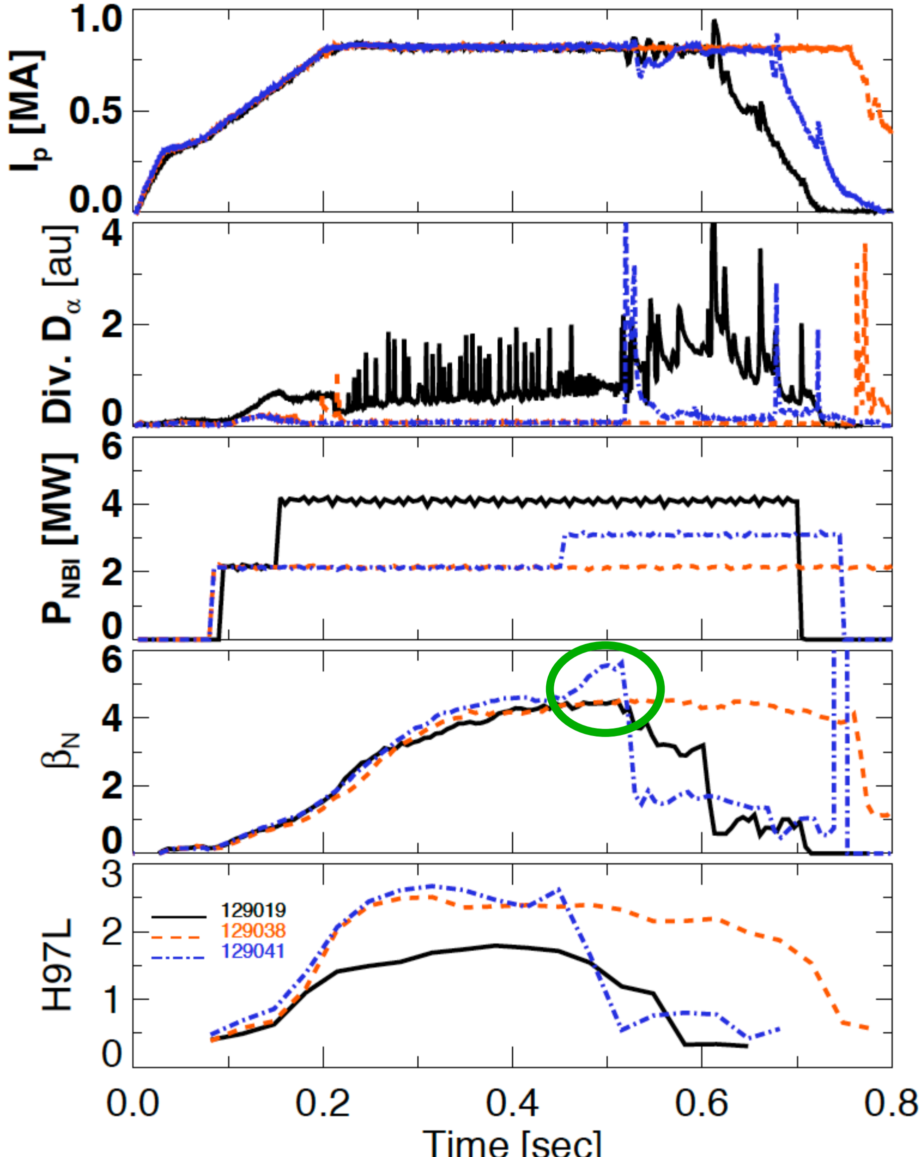
Edge stability limits pushed beyond global stability limits with lithium coatings in NSTX

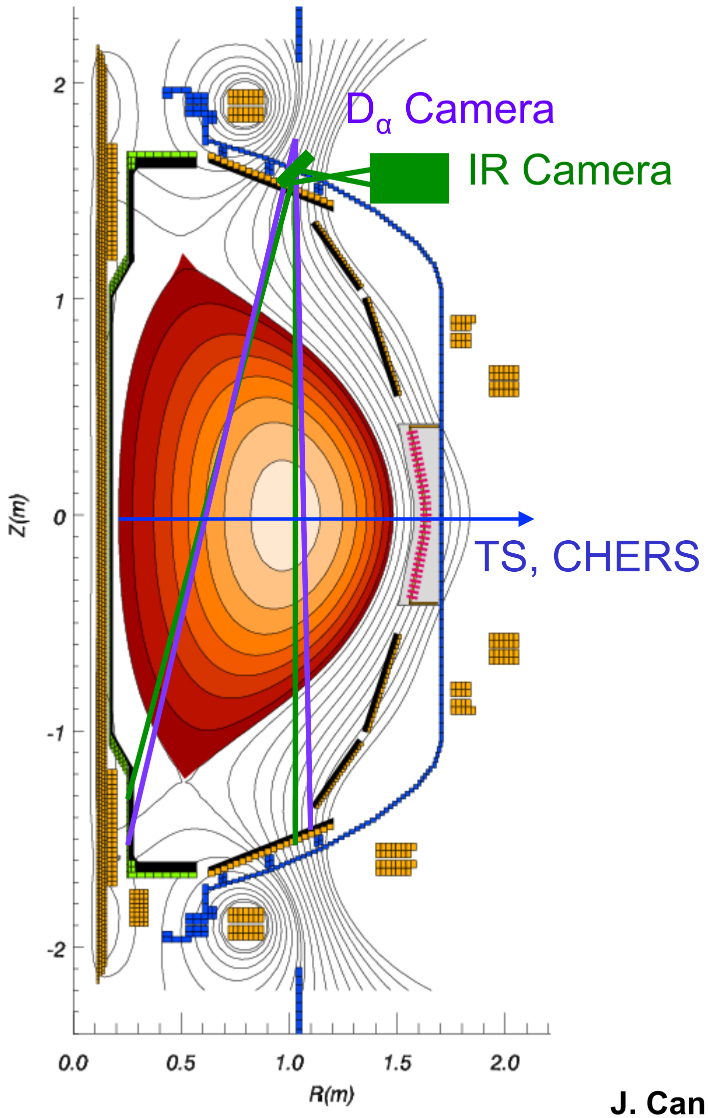




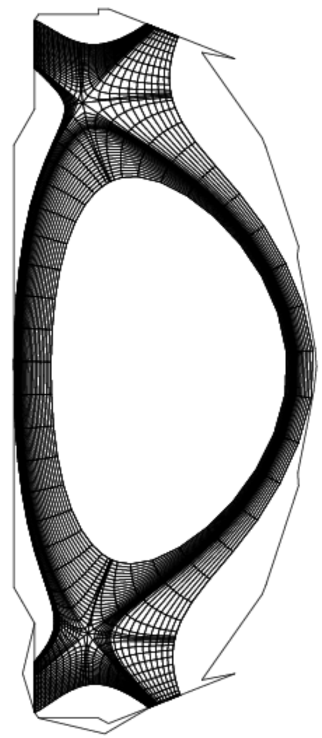
- Without Li, With Li, With Li
- ELM-free, reduced divertor recycling
- Power scan to identify β limit
- Core β limit observed, but no ELMs

D. Mansfield, JNM 09
R. Maingi, PRL 09

Divertor recycling and cross-field transport coefficients quantified with data-constrained interpretive modeling



SOLPS Grid



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- SOLPS (B2-EIRENE: 2D fluid plasma + MC neutrals) used to model NSTX experimental data
  - Iterative Method
  - ✓ Neutrals, impurities contributions
  - ✓ Recycling changes due to lithium

Parameters adjusted to fit data	Measurements used to constrain code
Radial transport coefficients $D_\perp$, χ_e, χ_i	Midplane n_e, T_e, T_i profiles
Divertor recycling coefficient	Calibrated D_α camera
Separatrix position/ T_e^{sep}	Peak divertor heat flux

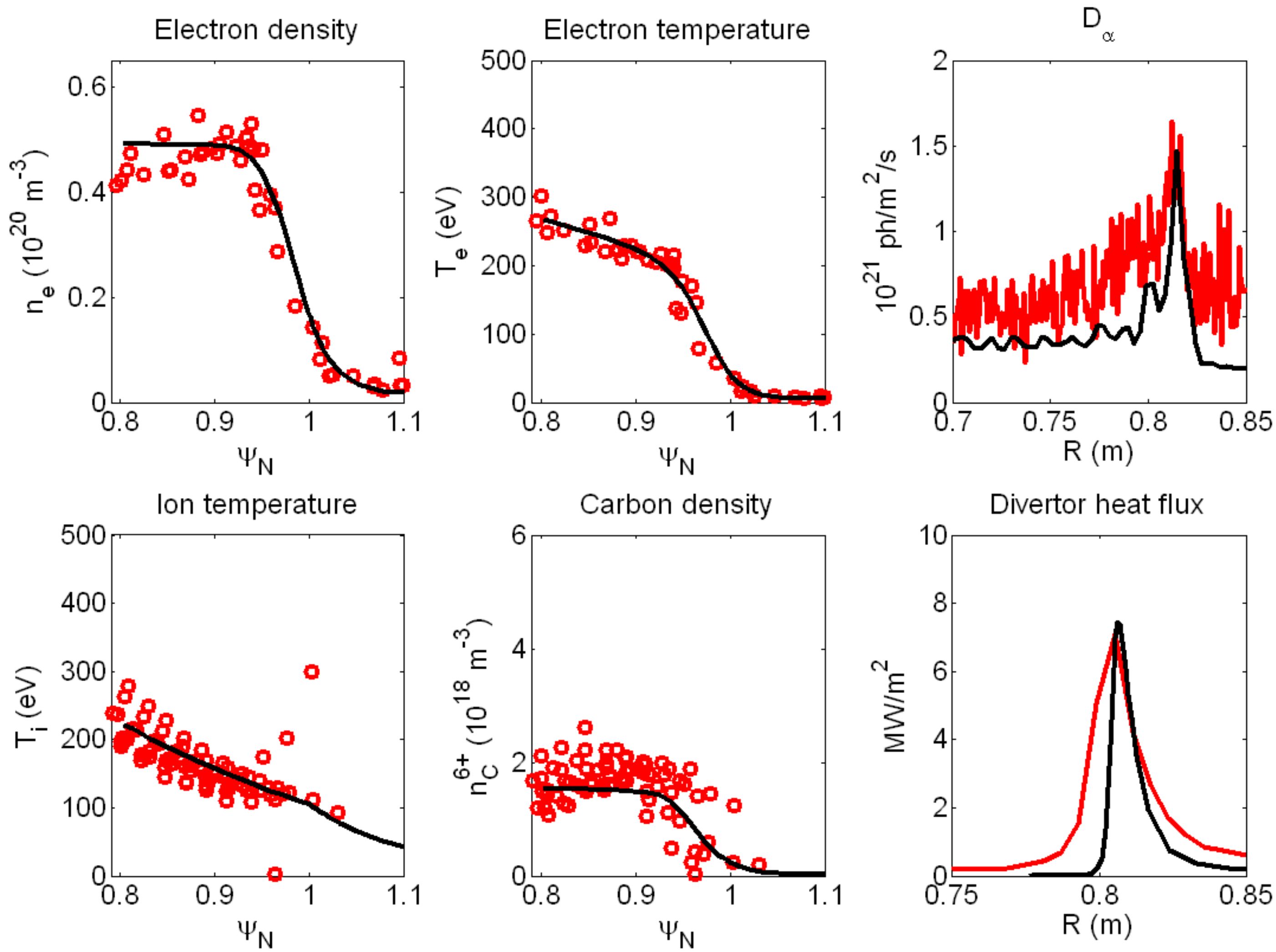
Midplane and divertor profiles from modeling compare well to experiment for the pre-lithium case

- P=3.7 MW
- R=0.98

- Good match to midplane profiles

- Carbon included: sputtering from PFCs, inward convection to match measured n_C^{6+}

- Heat flux and D_α, radial decay sharper than experiment



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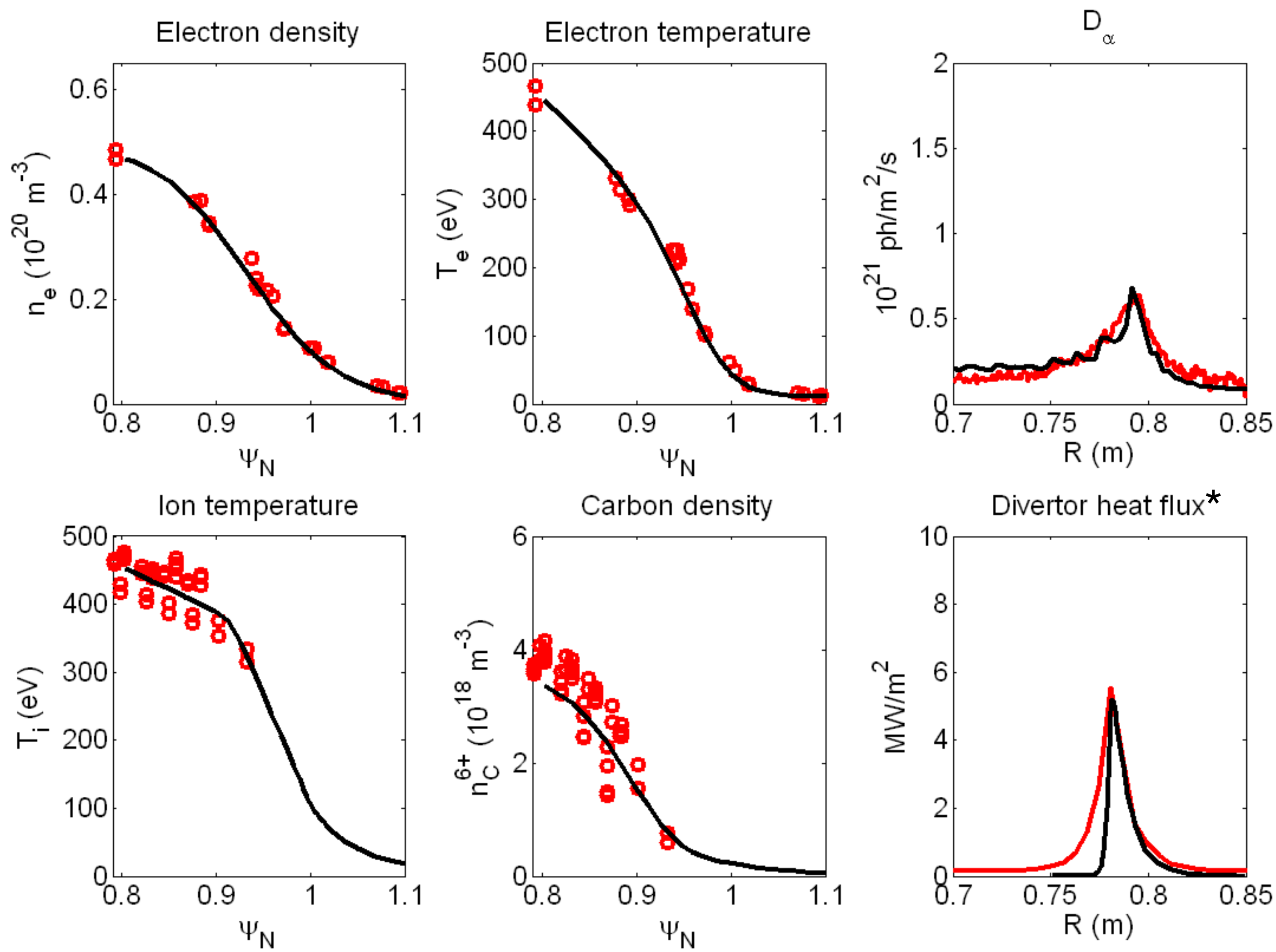
Combining reduced recycling and transport changes gives match to measurements with lithium

- P=1.9 MW
- R=0.90

- Transport coefficients adjusted to recover fit to upstream data

- Good match to both peak and profile for heat flux and D_α (except PFR)

*Uncertainty exists in IR measurements, due to emissivity change with lithium films



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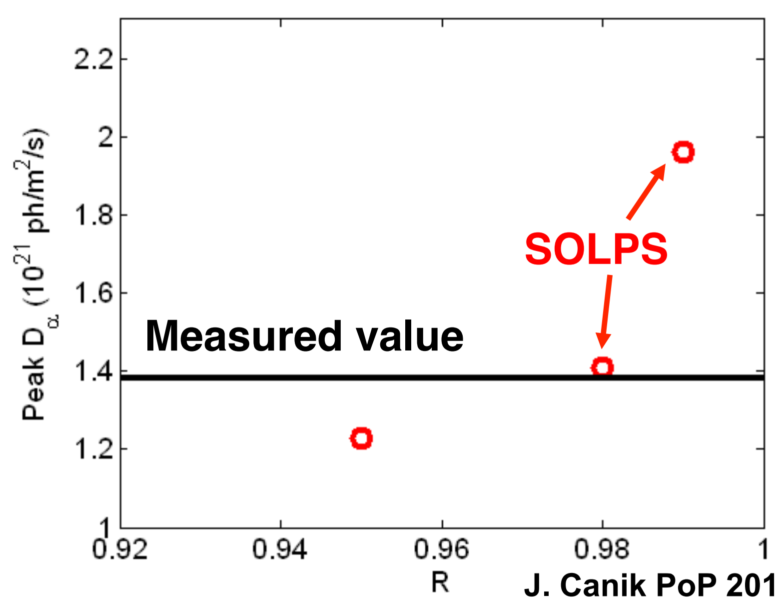
Peak D_α brightness is matched to experiment to constrain PFC recycling coefficient: lithium reduces R from ~.98 to ~.9

- For each discharge modeled, PFC recycling coefficient R is scanned
  - Fits to midplane data are redone at each R to maintain match to experiment
- D_α emissivity from code is integrated along lines of sight of camera, compared to measured values
  - Best fit indicates reduction of recycling from R~0.98 to R~0.9 when lithium coatings are applied

Pre-lithium



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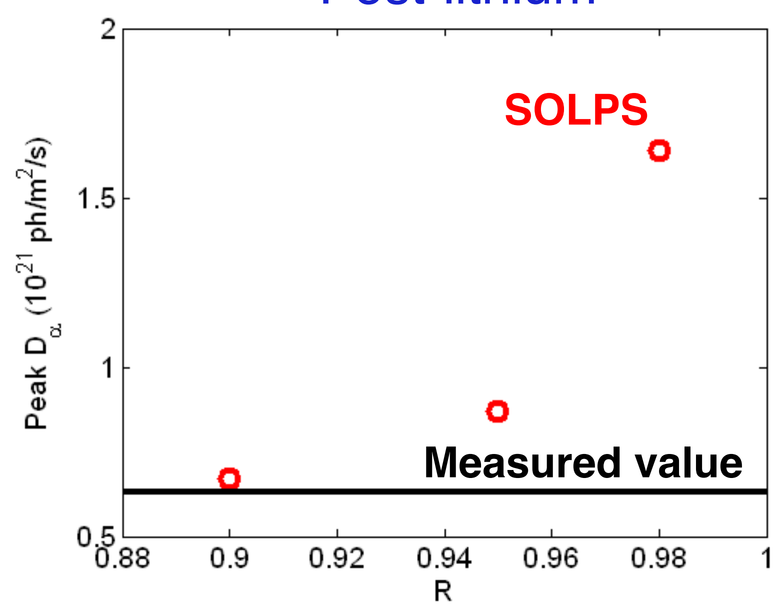
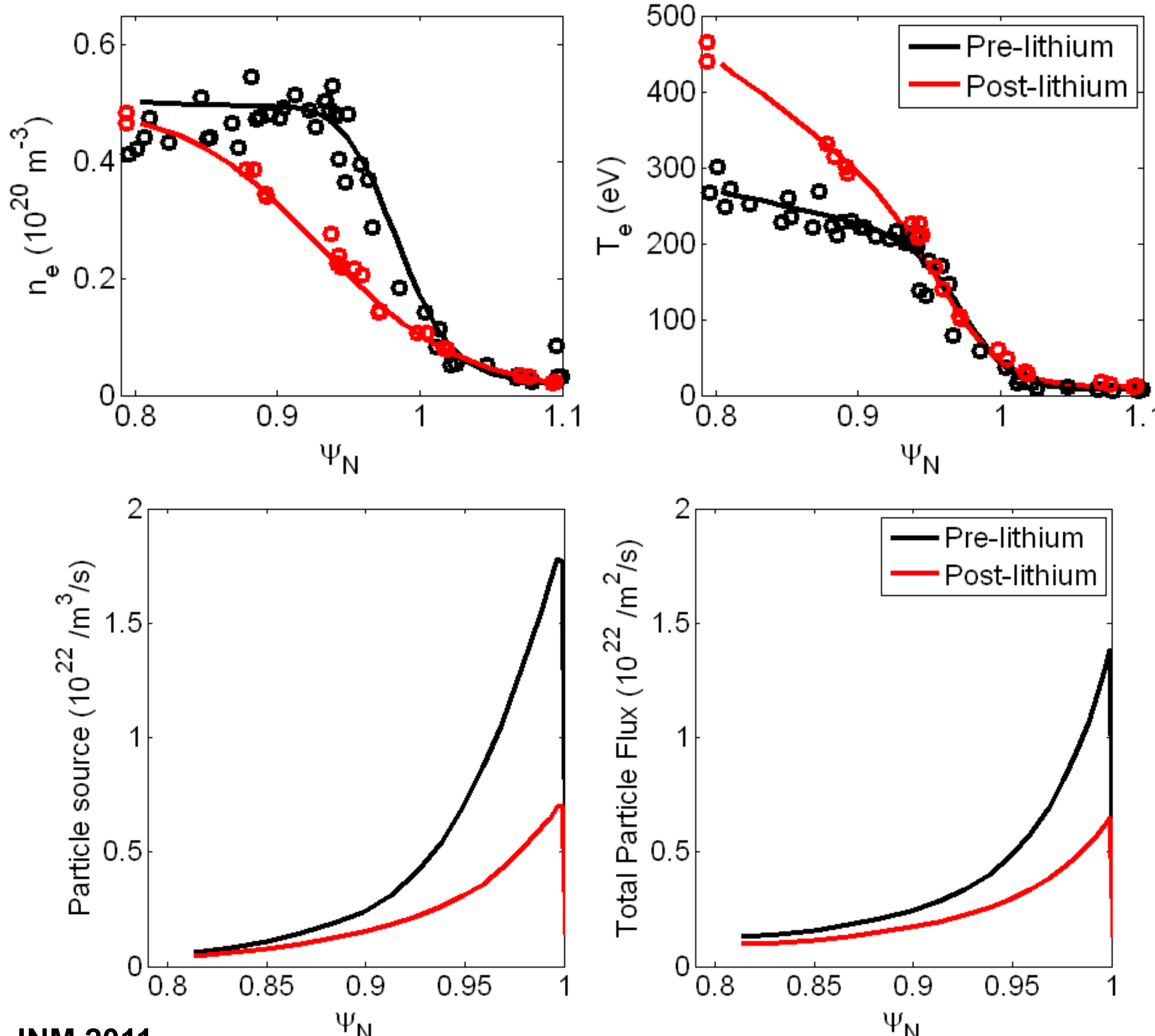
Post-lithium



Particle and heat sources are reduced with lithium

- Pre-lithium case shows typical H-mode structure
  - Barrier region in D, χ_e just inside separatrix
- Pedestal is much wider with lithium
  - $D_\perp$, χ_e similar outside of ψ_N~0.95
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)
- Changes to profiles with lithium are due to reduced fluxes combined with wide transport barrier



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Possible next steps

- Extend 0-D predictive model to include variable lithium deposition as in NSTX, and compute effect of LLD
- Extend 0-D model to NSTX-U with improved lithium deposition control?
- Continue 2-D SOLPS interpretive modeling of I_p=1.2 MA discharges to obtain transport coefficients
  - Extrapolate to NSTX-U using known heat flux width scaling in absence of lithium and with lithium
- Extend SOLPS modeling to snowflake scenarios? (being done with UEDGE)

Backup

Motivation and Technique

- Desire predictive models for effect of pumping on NSTX edge plasma
  - Provide means for comparing density control schemes, e.g. different Lithium tray design parameters (or even in-vessel cryopumping)
  - Should be compared with other experiments and more detailed calculations

- Consider simple recycling model to evaluate examples of each scheme
  - DIII-D data from first cryopump in 1993
  - CDX-U data from liquid Lithium

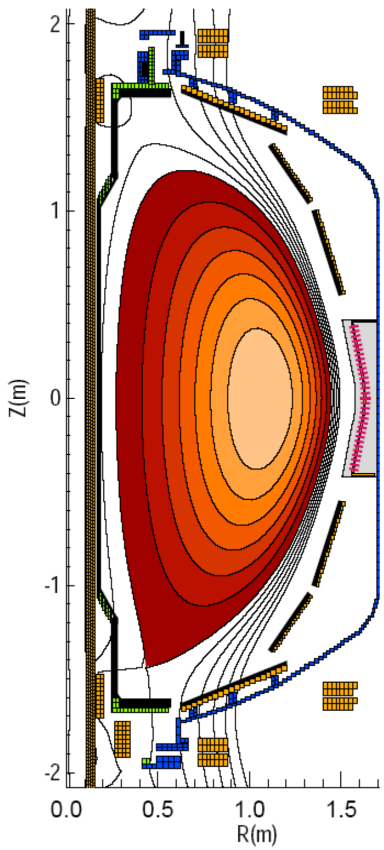
- Goal: Predict range of reduction in edge density in H-mode

Pumping calculations will help specify the LLD design parameters

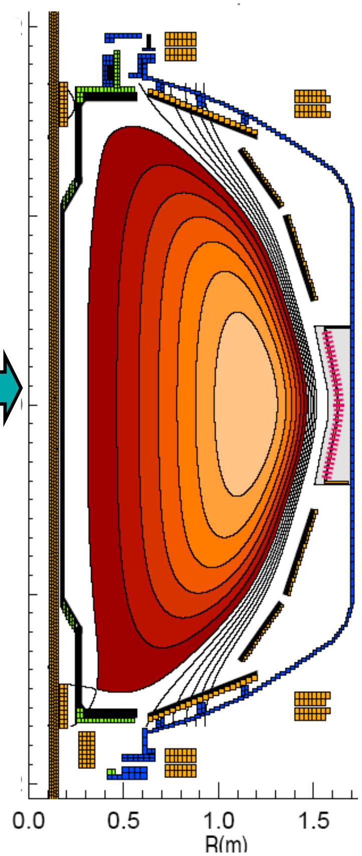
- ***0-D calculations presented in this talk:***
  - ***Parameterized as ratio of pump to core fueling probabilities***
  - ***Requires an assumed relation between pump probability and lithium surface area***
- 1-D calculations
  - Onion-skin OEDGE type, *requires assessment for NSTX*
- 2-D fluid calculations (model)
  - T. Rognlien did NSTX calculations in the past for ALPS/APEX
- 2-D fluid + lithium transport calculations (model)
  - T. Rognlien/J. Brooks did NSTX calcs in the past for ALPS/APEX
- 2-D fluid plasma (data-constrained base case)
  - G. Porter, L. Owen, and R. Maingi have done these for DIII-D
- 2-D fluid plasma + kinetic neutrals (data-constrained base case)
  - L. Owen, M. Rensink, and R. Maingi have done these for DIII-D

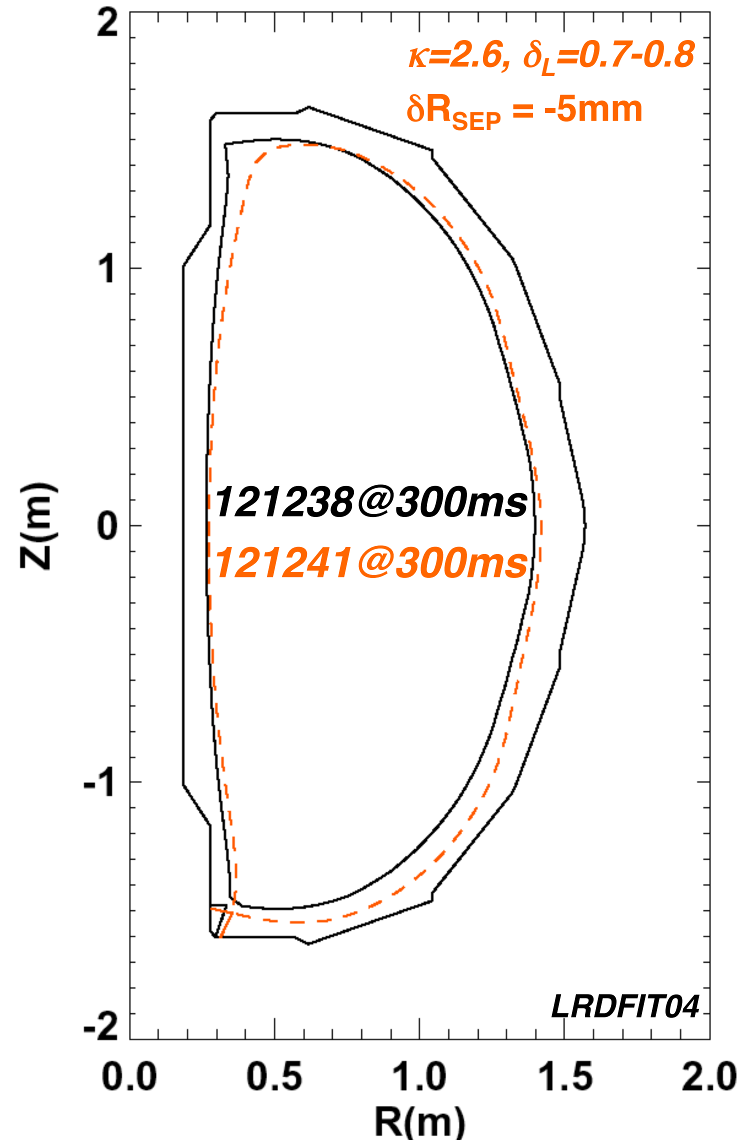
Discharges #116318 @ 0.6 sec and #121238 @ 0.3 sec used for design calculations

Existing #116313
κ= 2.3, δ_{X-L} = 0.75
δR_{SEP} = -1cm

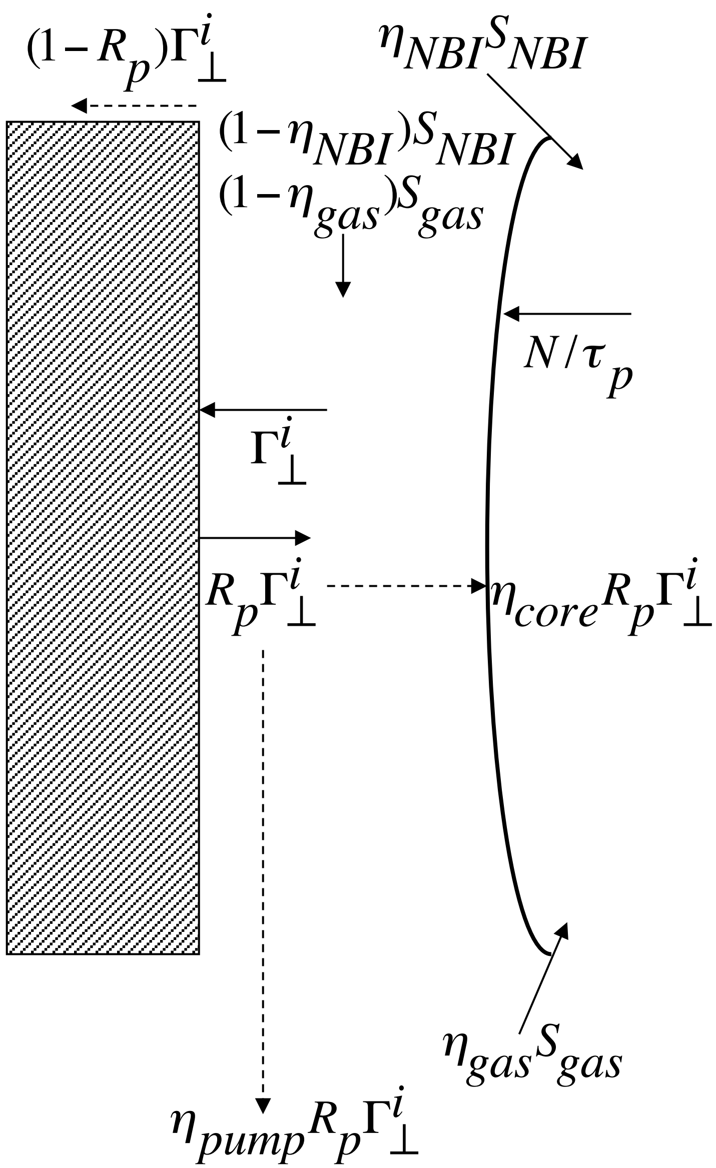


New target shape
κ= 2.6, δ_{X-L} = 0.85
δR_{SEP} = -2mm





Simplified Particle Balance and Recycling Model



- Define $\tau_p^* = \tau_p/(1-\beta)$
  - Steady state: $\tau_p^* = N/(S_{NBI}+S_{gas})$
- Normal assumptions:
  - $\eta_{NBI} \sim 1$
  - ~~$R_p(\eta_{pump} + \eta_{core}) >> (1-R_p)$~~
  - η_{pump}, η_{core} independent of time
- Particle balance equation becomes:

$$\frac{dN}{dt} = S_{NBI} + (1+\beta(1-\eta_{gas}))S_{gas} - \frac{N}{\tau_p^*}$$

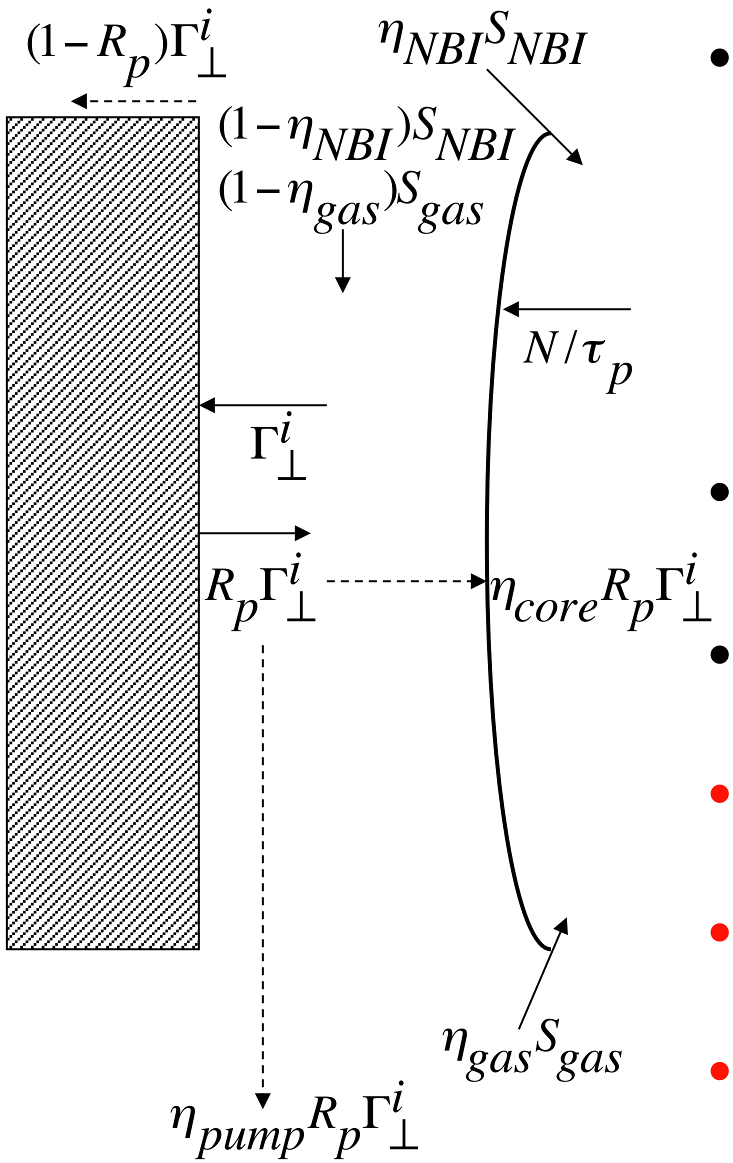
Let $S = S_{NBI} + (1+\beta(1-\eta_{gas}))S_{gas}$

Solution:

$$N(t) = S\tau_p^{*,1} + S(\tau_p^{*,2} - \tau_p^{*,1})\exp-(t/\tau_p^{*,2})$$

- Has been used to model step change in τ_p (L-H) and pumping ($\eta_{pump}>0$)

Simplified Particle Balance and Recycling Model



- Density reduction factor

  $n_e^{red} = \tau_{p,pump}^* / \tau_{p,nopump}^*$

  $= (1-\beta)_{noLi} / (1-\beta)_{Li}$ {constant τ_p}

- $\beta_{noLi} = \eta_{core} R_p / ((1-R_p) + R_p * \eta_{core})$

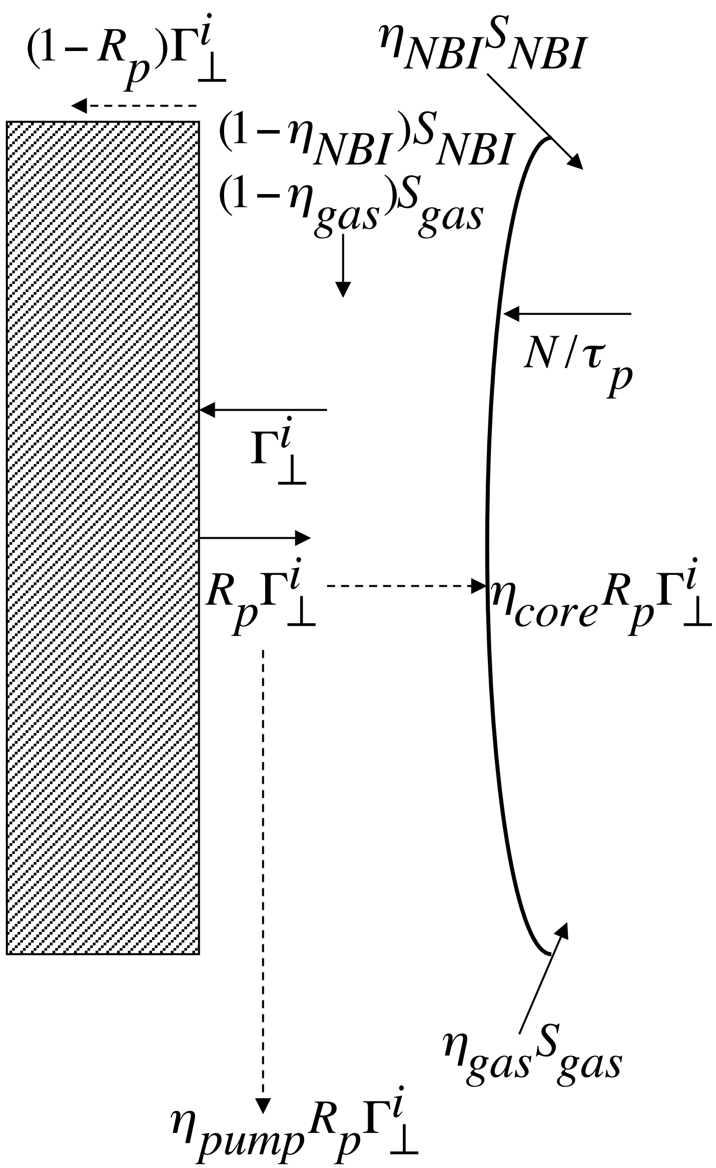
- $\beta_{Li} = \eta_{core} R_p / ((1-R_p) + R_p * (\eta_{core} + \eta_{pump}))$

- **Need prescription to estimate η_{Li}**

- **Is η_{core} really independent of n_e?**

- **Is τ_p really independent of n_e?**

Limits of Particle Balance and Recycling Model



- Note $\tau_p^*/\tau_p = 1/(1-\beta)$
- Pump off: $\tau_p^*/\tau_p \sim 1+ \eta_{core}R_p/(1-R_p)$
  - $\tau_p^*/\tau_p \sim 6$
- Pump on: $\tau_p^*/\tau_p \sim (\eta_{core}+\eta_{pump})/\eta_{pump}$
  - $\tau_p^*/\tau_p \sim 2$
- n_e should go down by 2/3 w/pumping

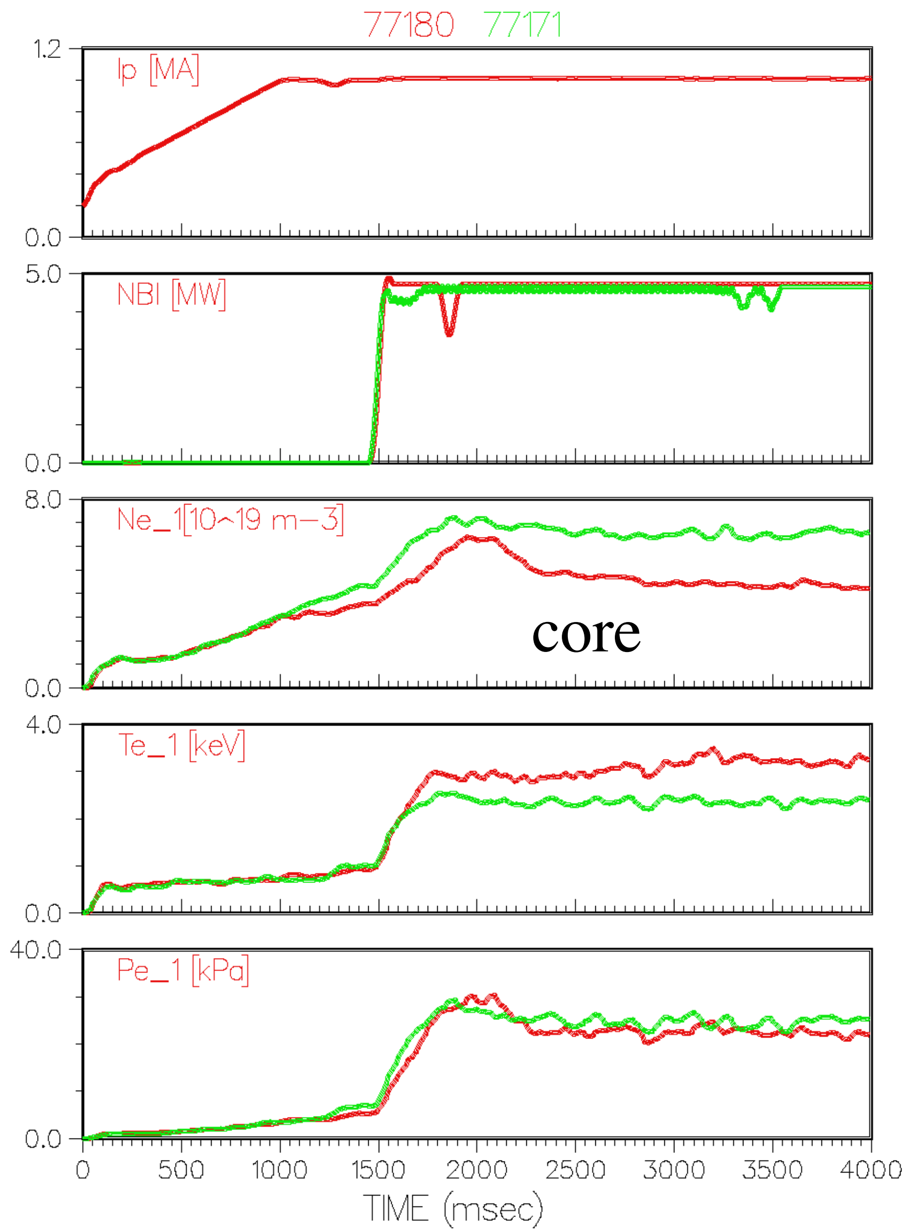
  $\Rightarrow$ *Smaller n_e reduction observed, maybe due to increased core fueling probability at low n_e*
- Input data (from DIII-D studies):
  - $R_p \sim 0.98$ for carbon (reference?)
  - $\eta_{core} \sim 0.1$ (Rensink, PoF B 1993)
  - $\eta_{pump} \sim 0.1$ (Maingi, NF 1999)

Procedure

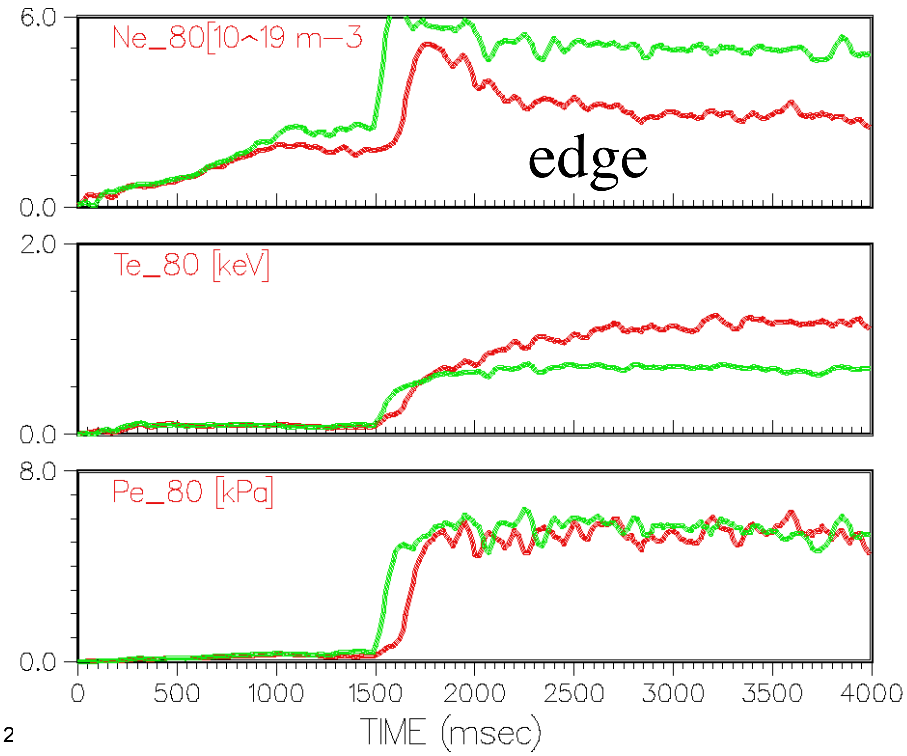
- Convert D_α to particle flux with magic number of 20 ionizations per photon
- Estimate LLD flux intercept fraction from data for a given R_{tray}, W_{tray}, etc. for a given time slice
  - Vary R_{tray} 1 cm at a time
    - R_{tray} starting point a few cm inside of the outer strike point; avoids interpretation of partially detached inner region
    - Avoid covering CHI gap with tray
  - Iterate on $\eta_{core} \sim 1/n_e^\alpha$ (default: α=2)
- Repeat for different W_{tray}, R_p, and other input parameters
- Repeat calculations for different shots with different poloidal flux expansion

Comparison of Unpumped and Pumped DIII-D Discharges

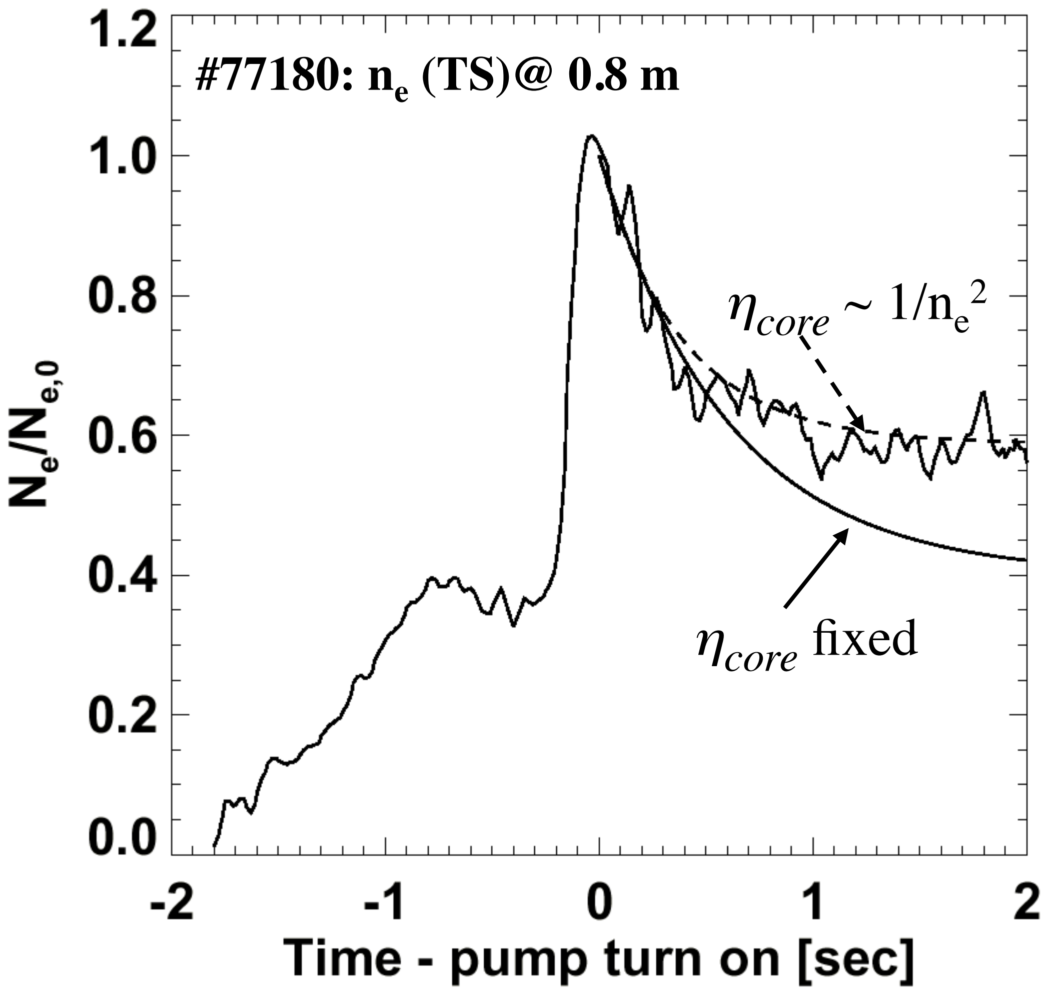
NSTX



- Edge electron pressure holds constant as n_e reduced
- Relative change in edge n_e larger than core



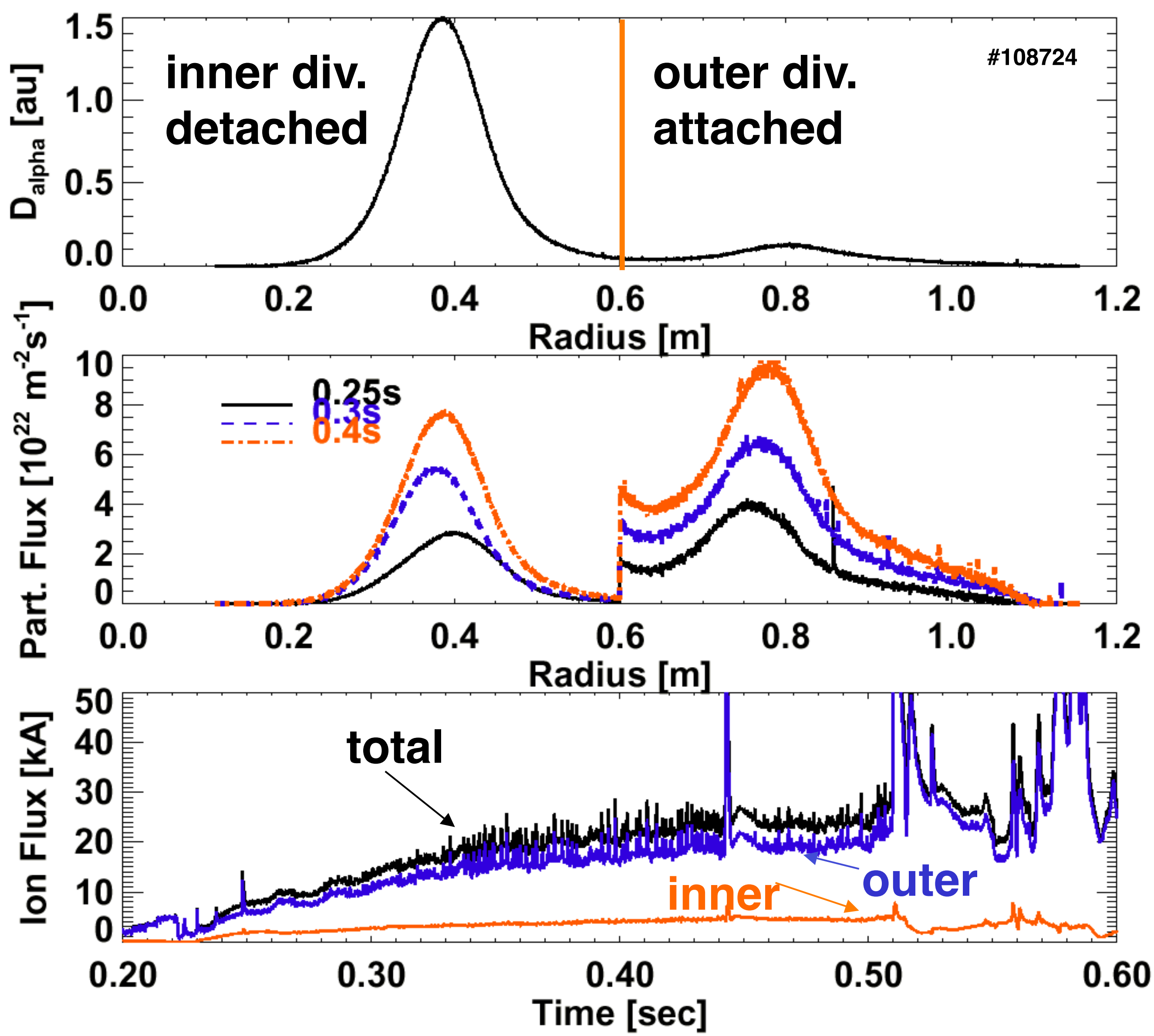
Particle Balance and Recycling Model - DIII-D cryopump



- DIII-D specific data:
  - $R_p \sim 0.98$ for carbon (reference?)
  - R_p changes slowly (Maingi, NF 1996)
  - $\eta_{core} \sim 0.05\text{-}0.15$ (Rensink, PoF B 1993)
  - $\eta_{pump} \sim 0.1$ (Maingi, NF 1999)
  - $\eta_{gas} \sim 0.1$ (Maingi, JNM 1997)
  - $\tau_p / \tau_E = 2.5$ (~ Owen, JNM 1997)
- Solid η_{core} - fixed in time
  - N_e goes down on τ_p^* timescale
- Dashed $\eta_{core} \sim 1/n_e^2$
  - τ_p^* increases with time
  - N_e equilibrates faster than initial τ_p^*

NSTX D_α Peaked on Inboard Side, but Particle Flux Peaked on Outboard side because Inner Divertor is Usually Partially Detached

NSTX



- Inner side detached
- Outer side attached
- Ions/ photon=1 (detach)
- Ions/ photon=20 (attach)
- Division at R ~ 0.6m
- Out div. has ~ 4x times current of inner div.

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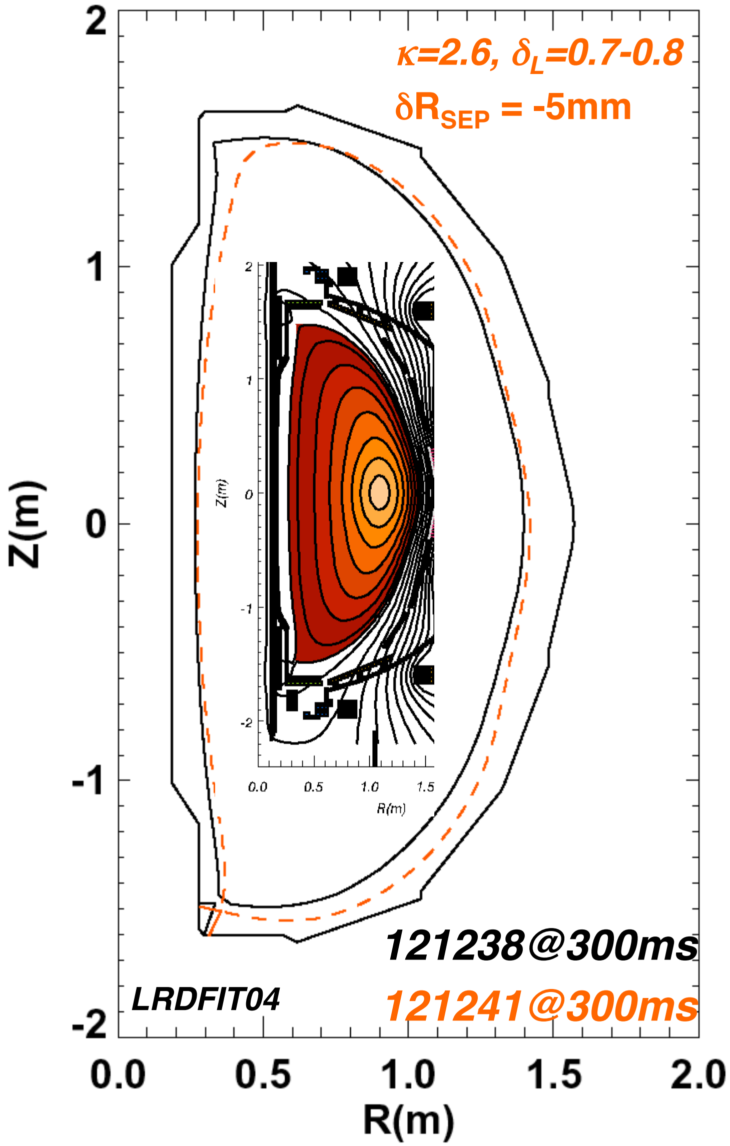
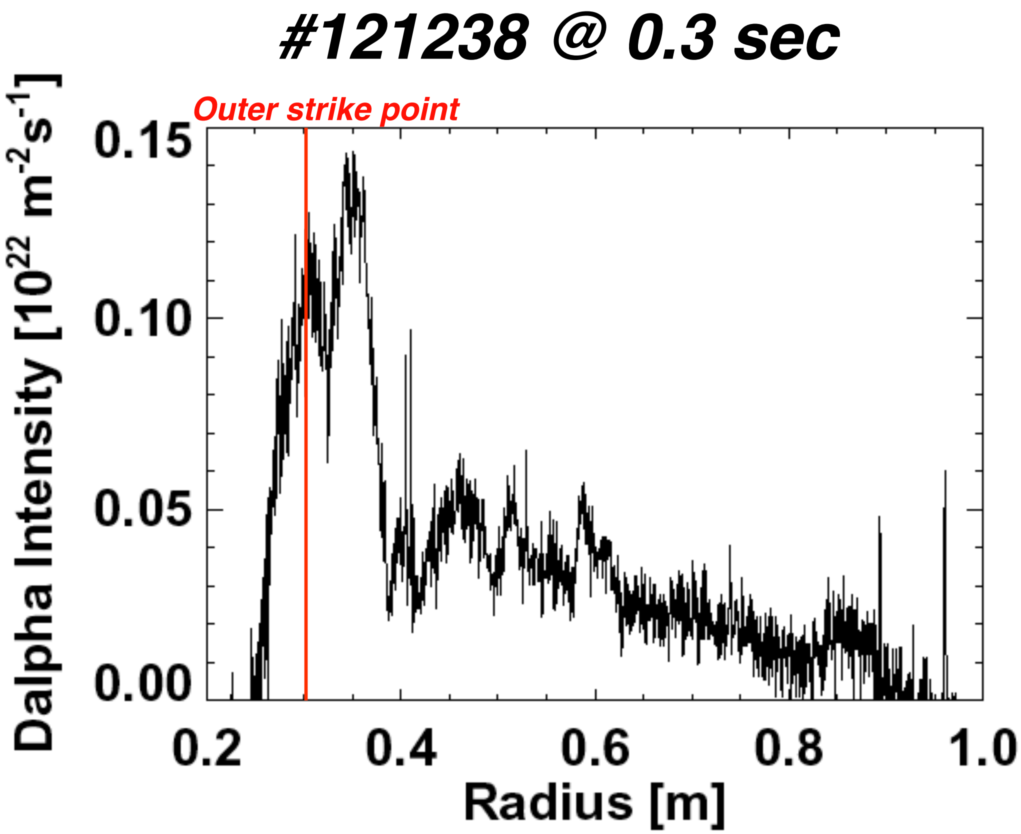
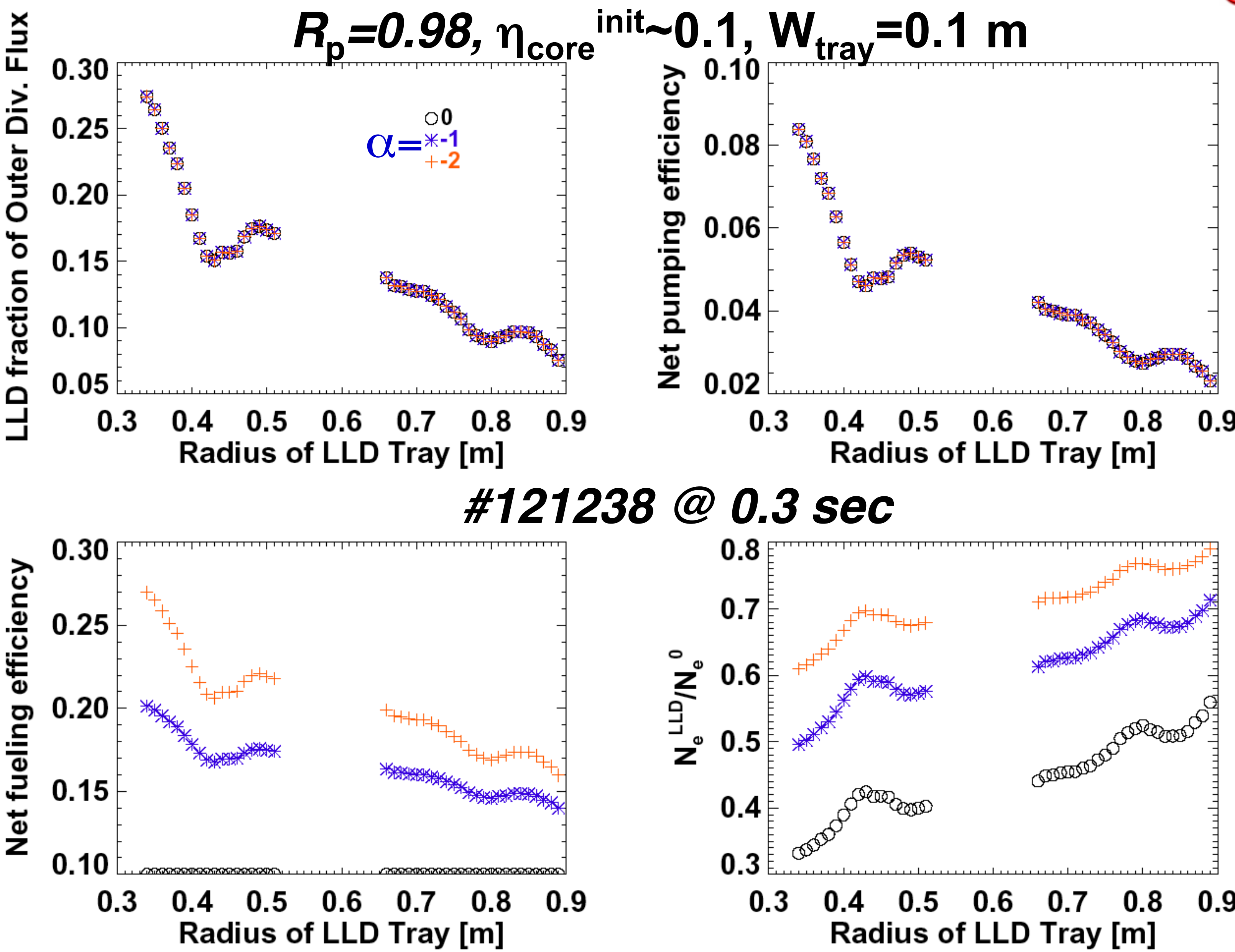
Broad SOL D_α profile in high δ (pf1a) #121238





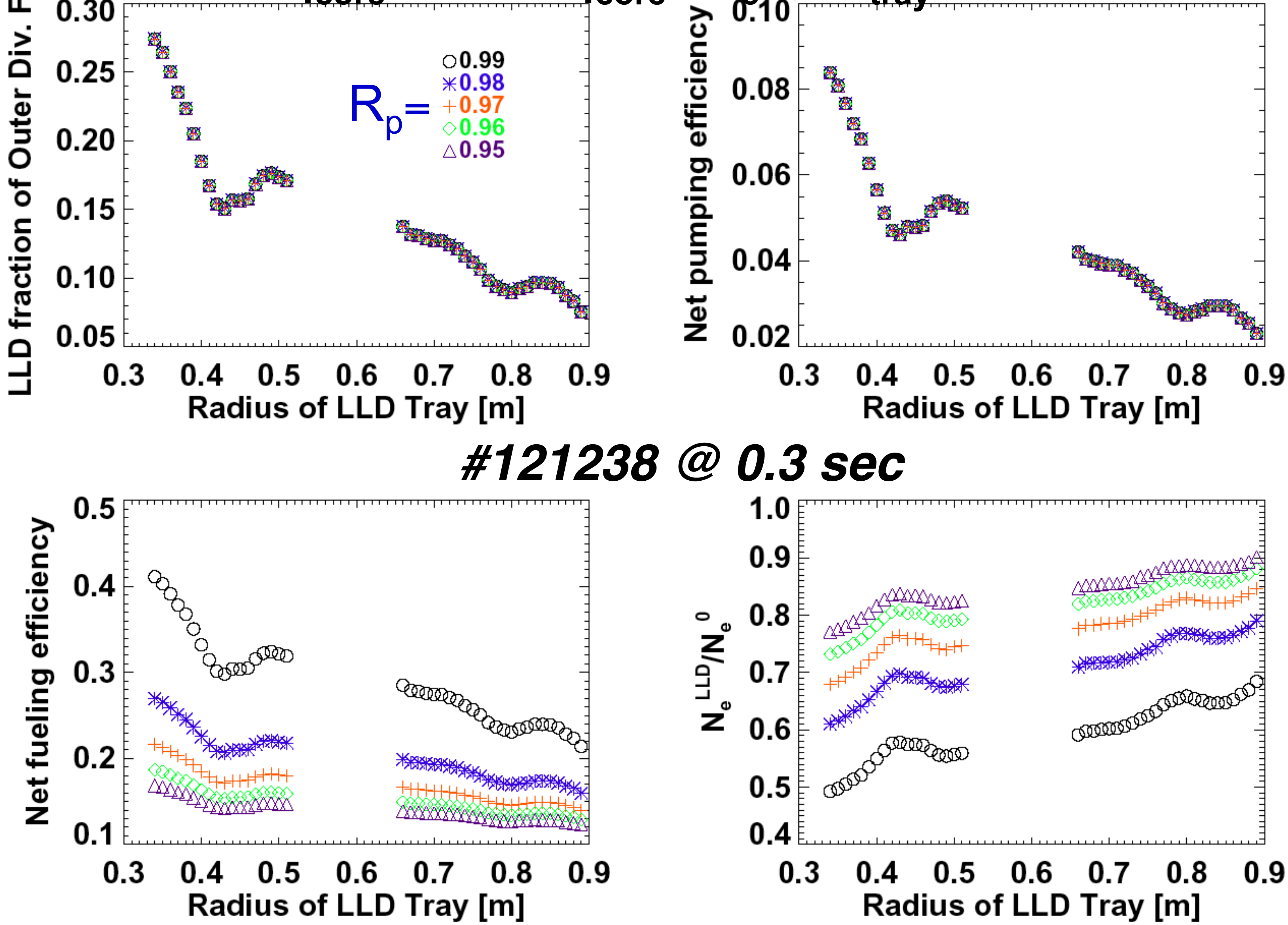
Soukhanovskii

Achievable edge density reduction is reduced if core fueling efficiency $\eta_{core} \sim n_e^{\alpha}$

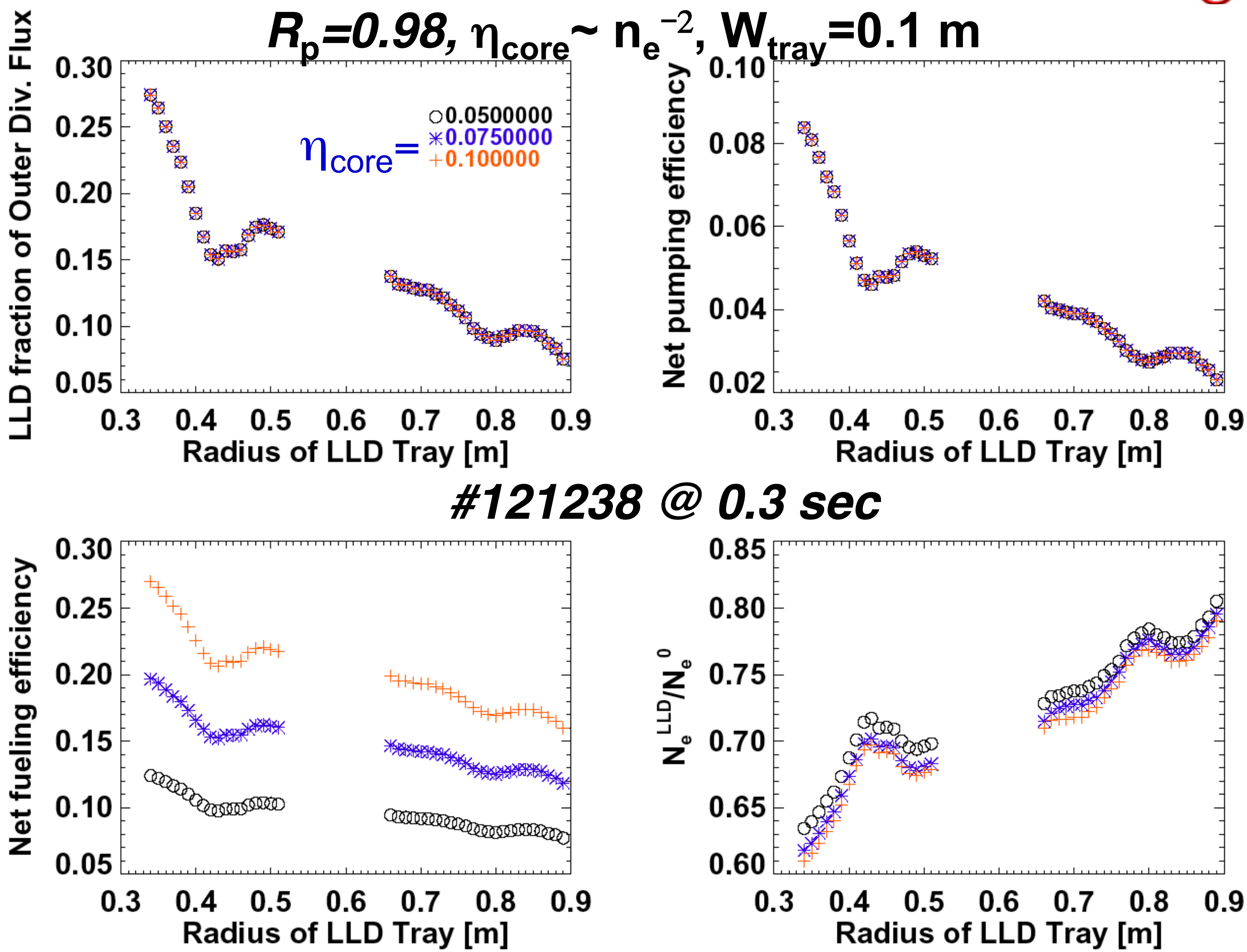


Achievable edge density reduction decreases with assumed initial wall recycling coefficient, R_p

η_{core}^{init}~0.1, η_{core}~ n_e^{-2}, W_{tray}=0.1 m

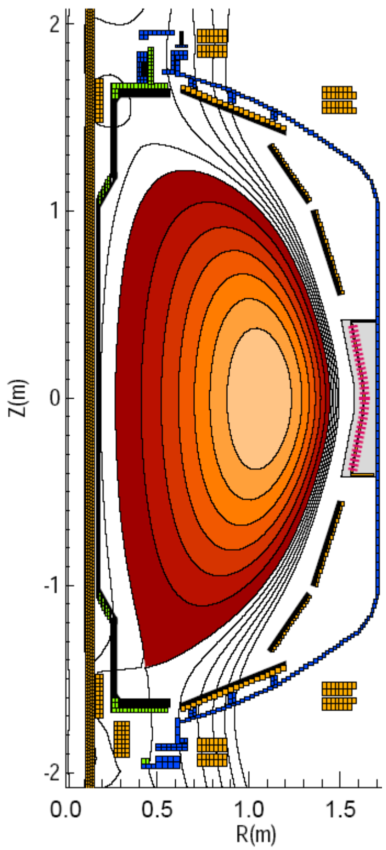


Achievable edge density reduction nearly independent of initial core fueling probability, η_{core}



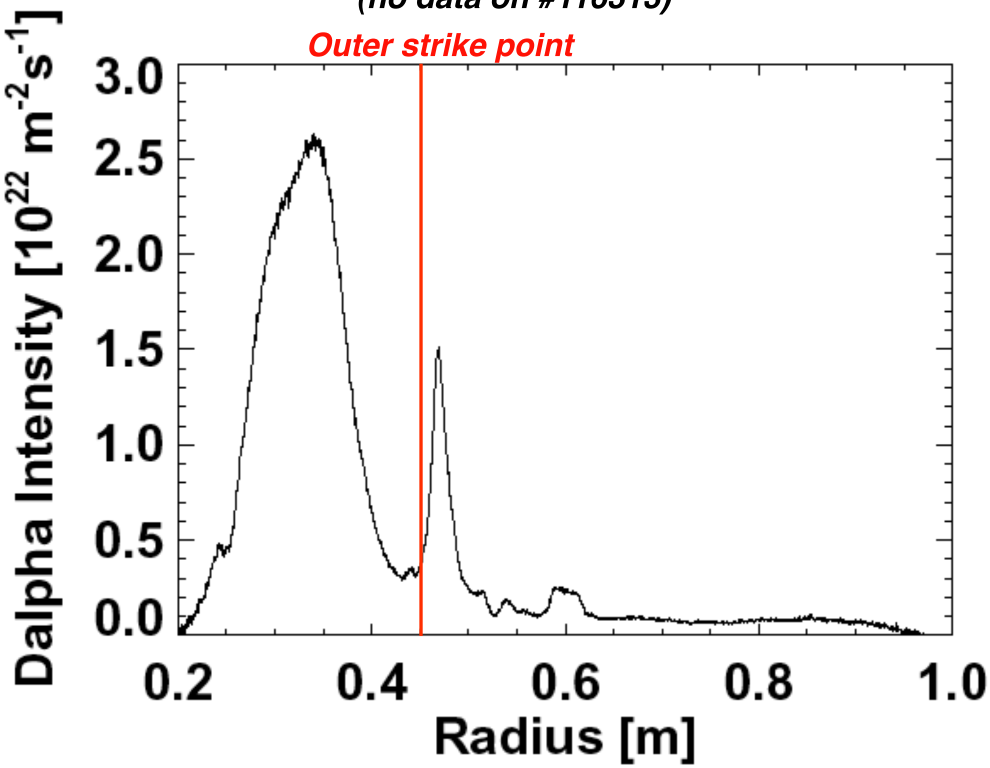
Narrow SOL D_α profile in medium δ (pf1b) #116318

Existing #116313
κ= 2.3, δ_{X-L} = 0.75
δR_{SEP} = -1cm



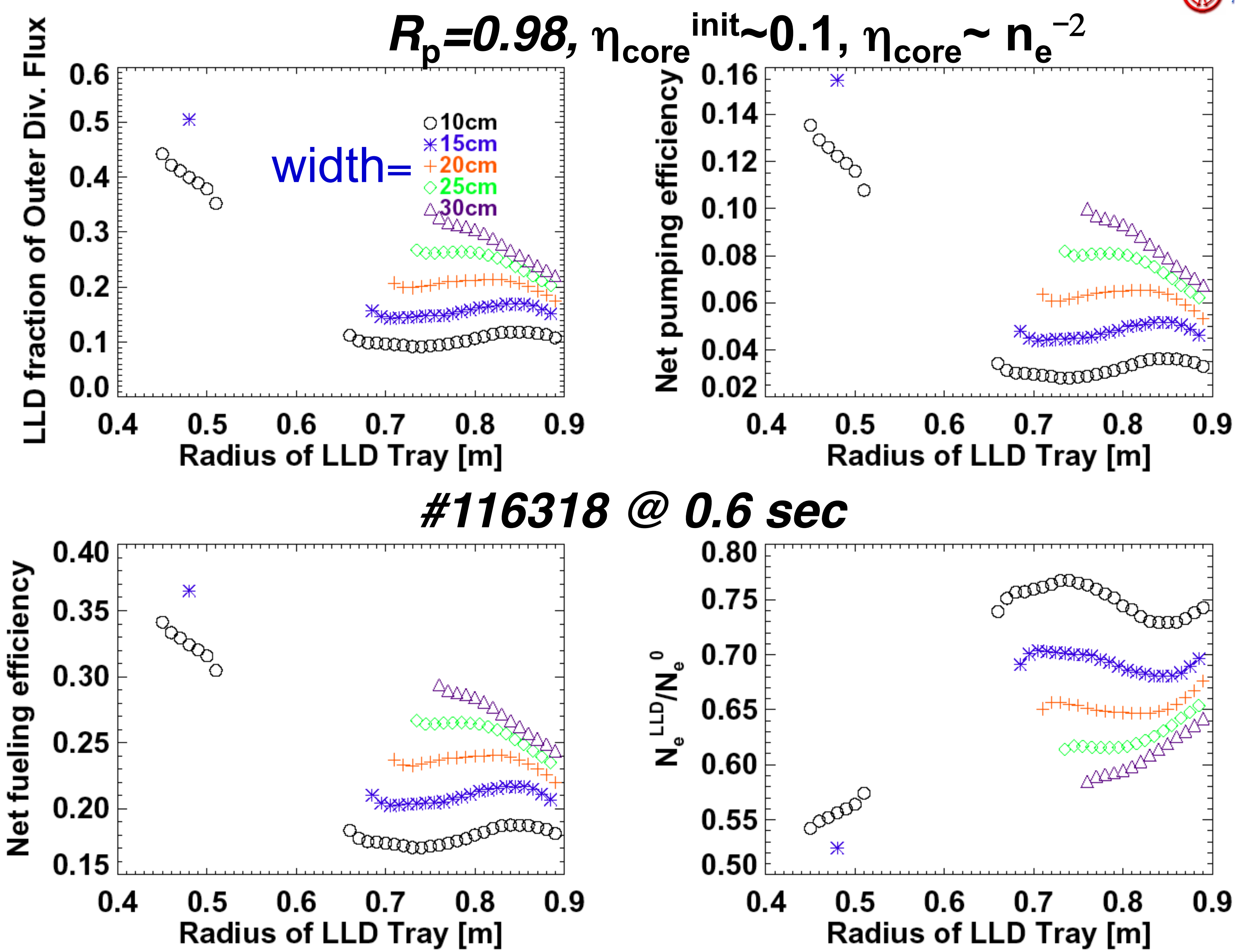
#116318 @ 0.6 sec

(no data on #116313)

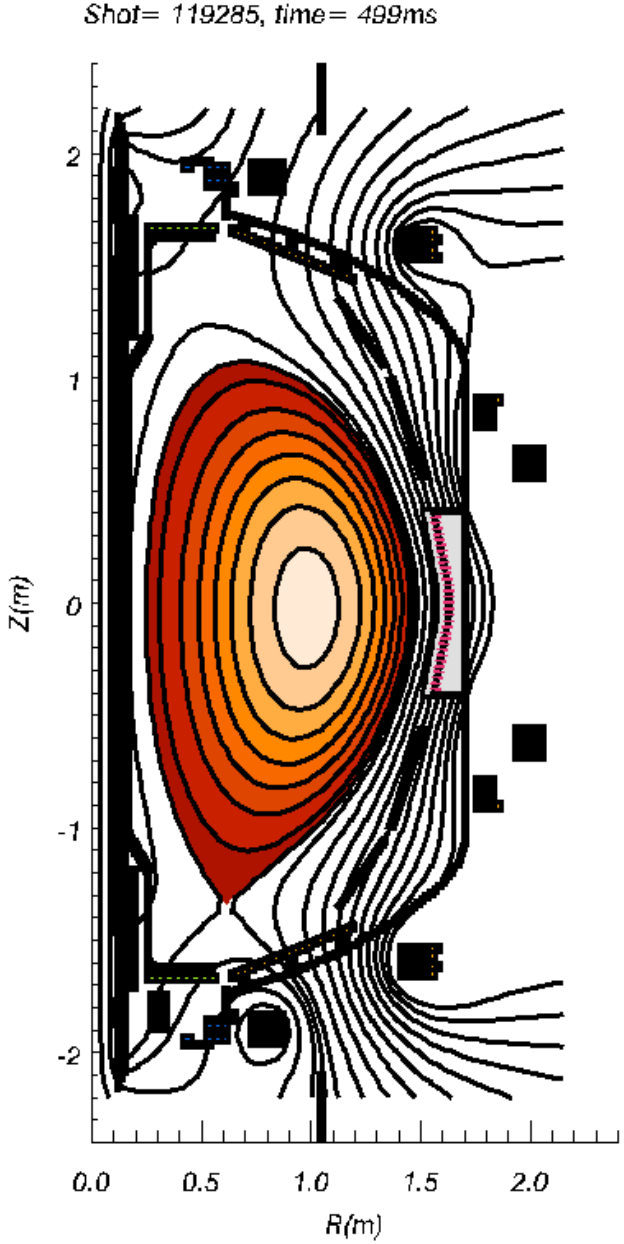


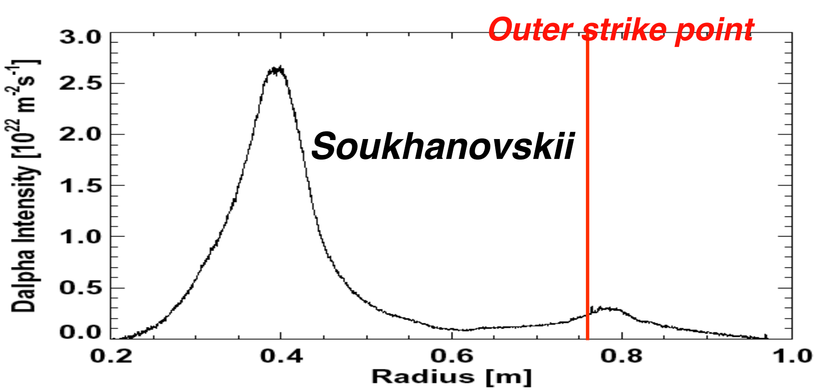
Soukhanovskii

Achievable edge density reduction depends on tray radius and width

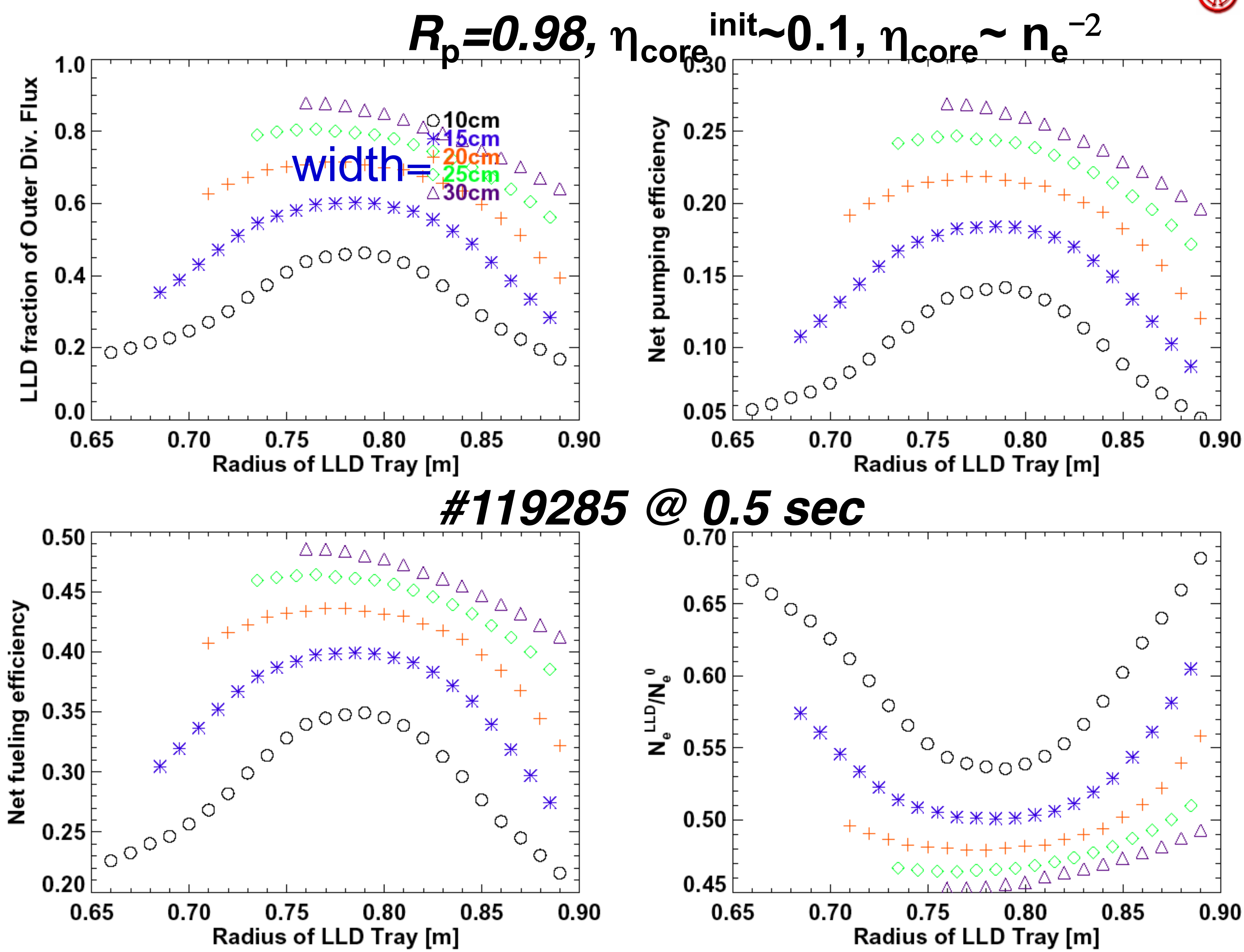


Narrow SOL D_α profile in low δ (pf2) #119285





Achievable edge density reduction depends on tray radius and width

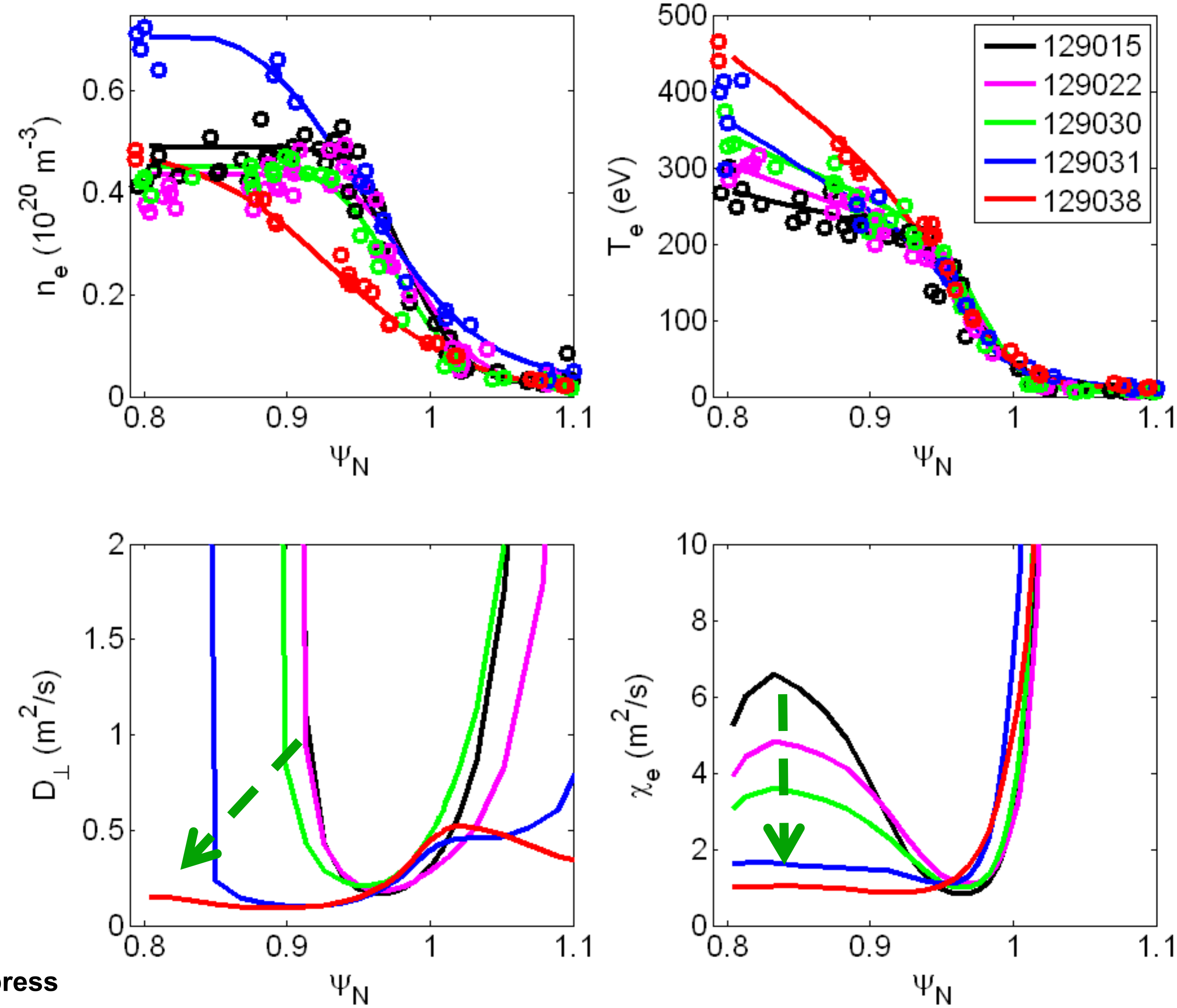


Discussion and Conclusions

- 20cm wide tray just outboard of the CHI gap likely to provide sufficient density reduction as required for long pulse high non-inductive fraction reported at the Dec. 2006 research forum
- To get a full 50% density reduction will probably require a tray near the outer strike point
  - Inboard of CHI gap for high δ discharges
  - Outboard of CHI gap for low δ discharges
- Actual density reduction factor depend strongly on how quickly core fueling efficiency increases with decreasing density, and the pre-Li global wall recycling coefficient
- Intend to compare with 2-D calculations, when available

Inner region: as lithium coatings thicken, transport barrier widens, pedestal-top χ_e reduced

- Several shots analyzed with increasing lithium thickness (direction of arrow) – →
- ELMy to reduced frequency to ELM-free



J. Canik PoP 2011 at press