Liquid Lithium Divertor 0-D Pumping Projections and Sensitivities

R. Maingi, ORNL

*With Acknowledgement to
V.A. Soukhanovskii for Lower Divertor D_{α} data

Liquid lithium divertor physics design discussion

Princeton, NJ
April 3, 2007

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

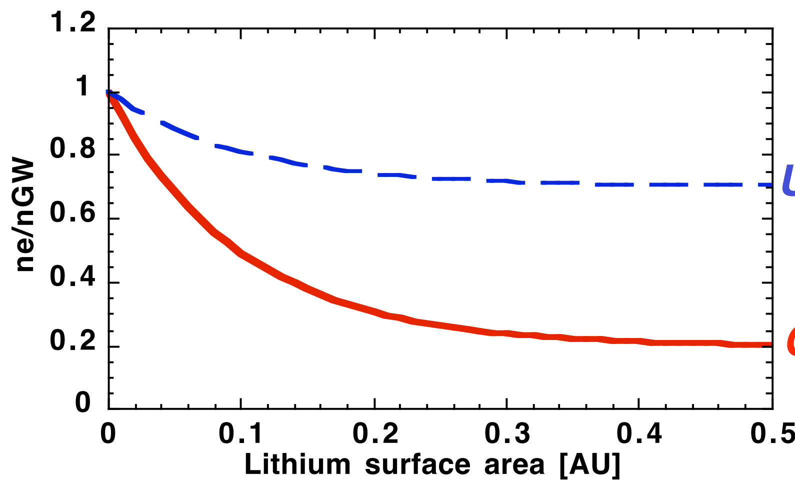
Pumping calculations will help specify the LLD design parameters

- ***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

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

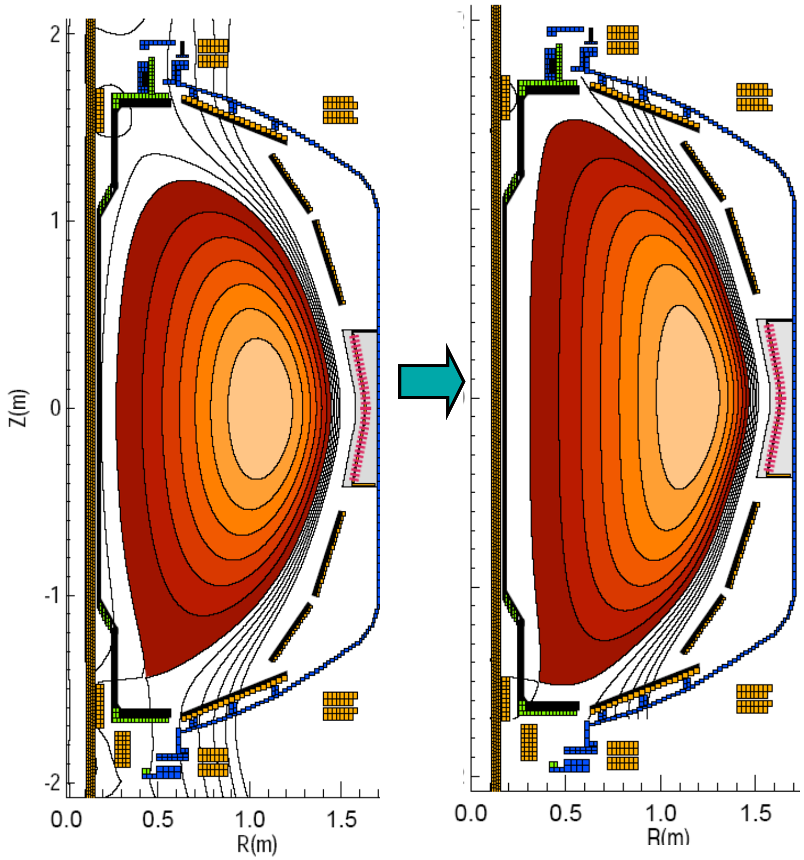
Optimized pumping

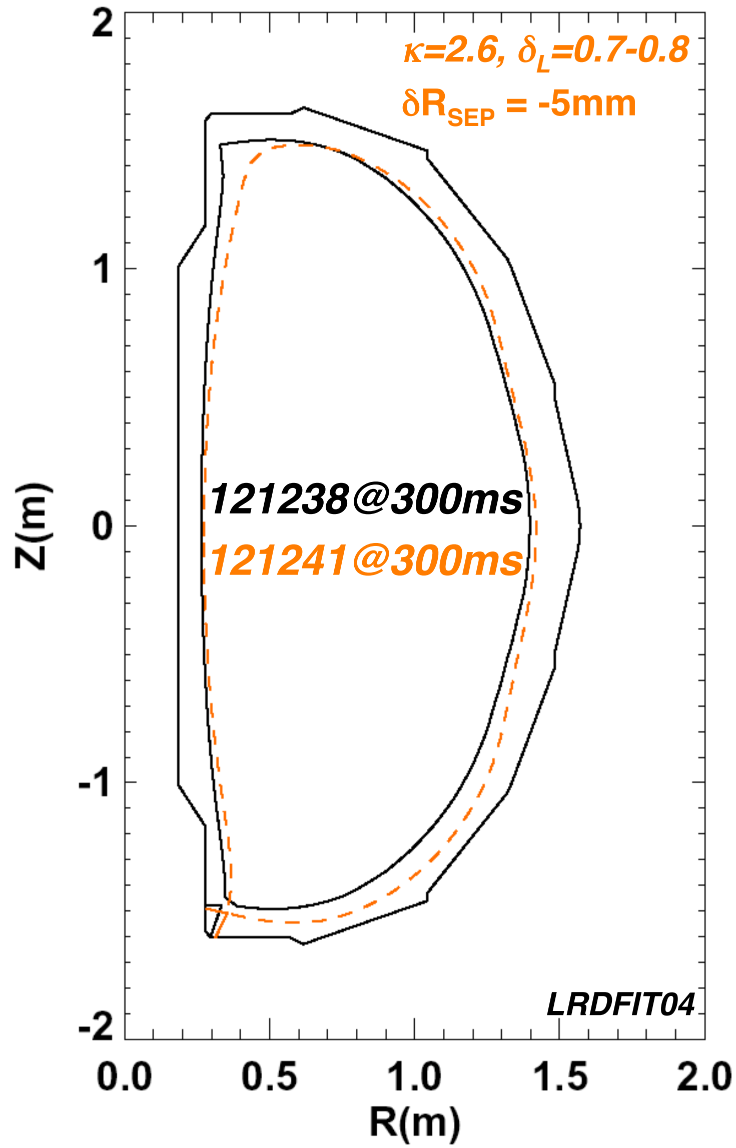
Discharges #116318 @ 0.6 sec and #121238 @ 0.3 sec used for design calculations

NSTX

Existing #116313
κ= 2.3, $\delta_{X\text{-}L}$ = 0.75
δR_{SEP} = -1cm

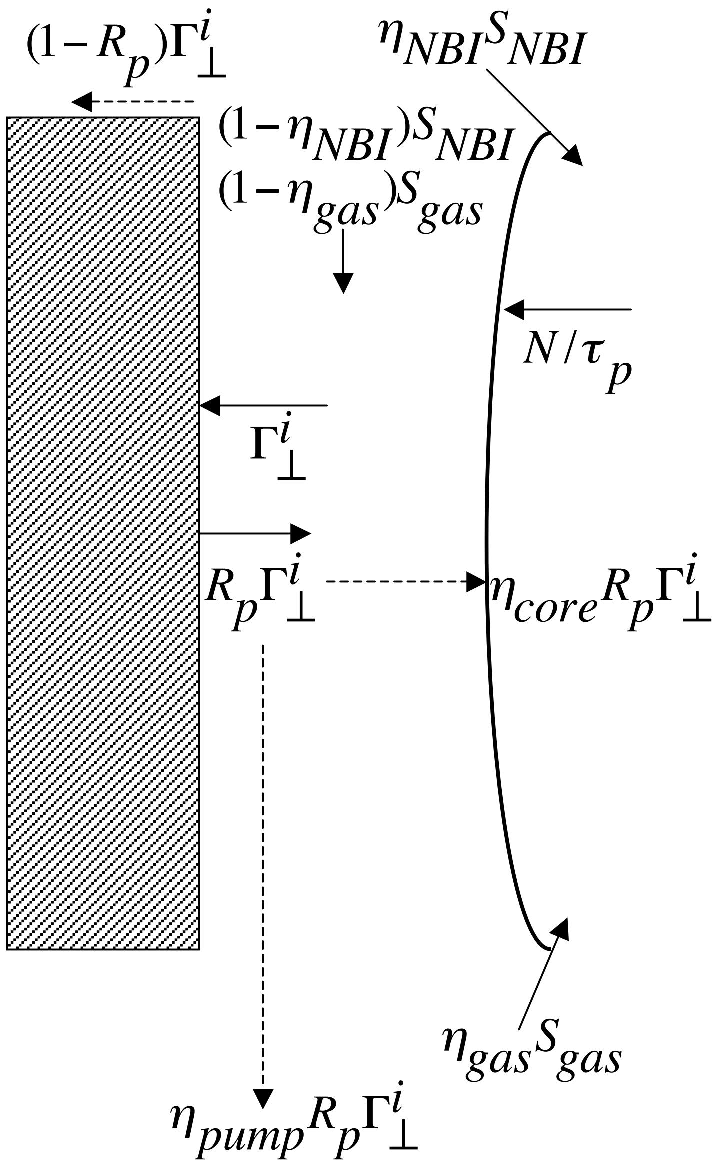
New target shape
κ= 2.6, $\delta_{X\text{-}L}$ = 0.85
δR_{SEP} = -2mm





ornl
Oak Ridge National Laboratory

Particle Balance and Recycling Model



- Consider core and SOL particle content equations

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

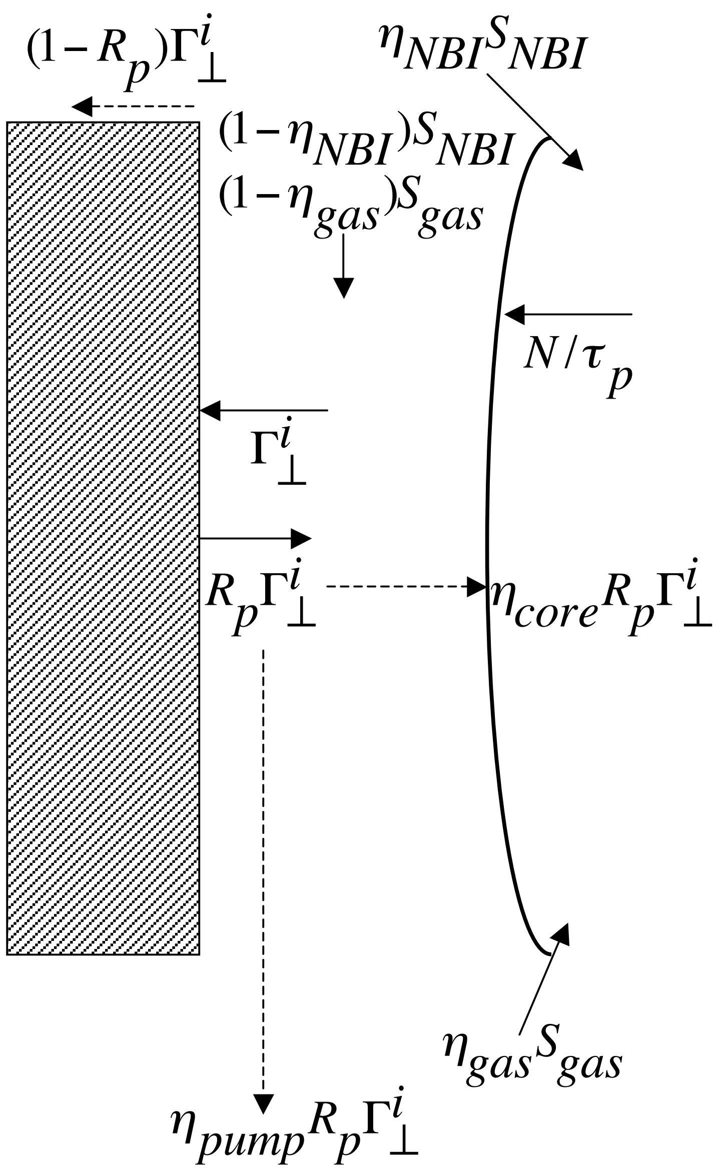
$$\frac{dN_i^{SOL}}{dt} + \frac{dN_0^{SOL}}{dt} = (1-\eta_{NBI})S_{NBI} + (1-\eta_{gas})S_{gas} + \frac{N}{\tau_p} - (1-R_p)\Gamma_\perp^i - R_p\Gamma_\perp^i(\eta_{pump} + \eta_{core})$$

- Assume SOL neutral and ion density in steady state

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

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

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:

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

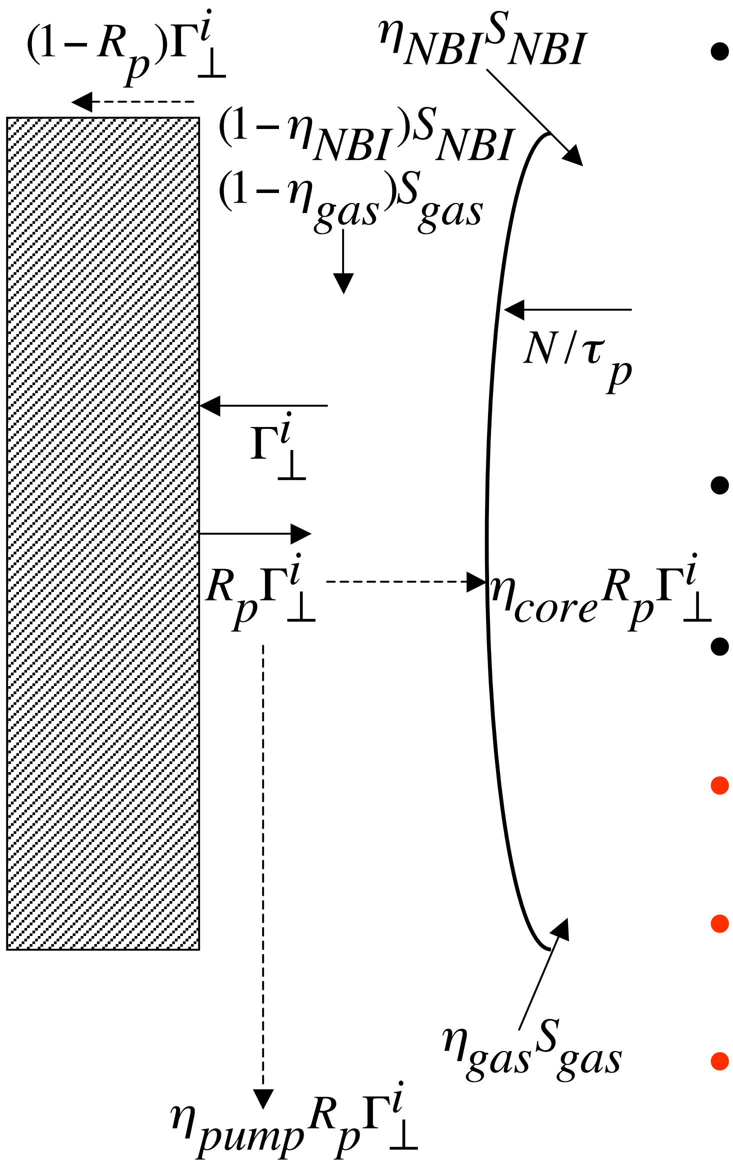
Let $S = S_{NBI} + (1+\beta(1-\eta_{gas}))\eta_{gas}S_{gas}$

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}

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

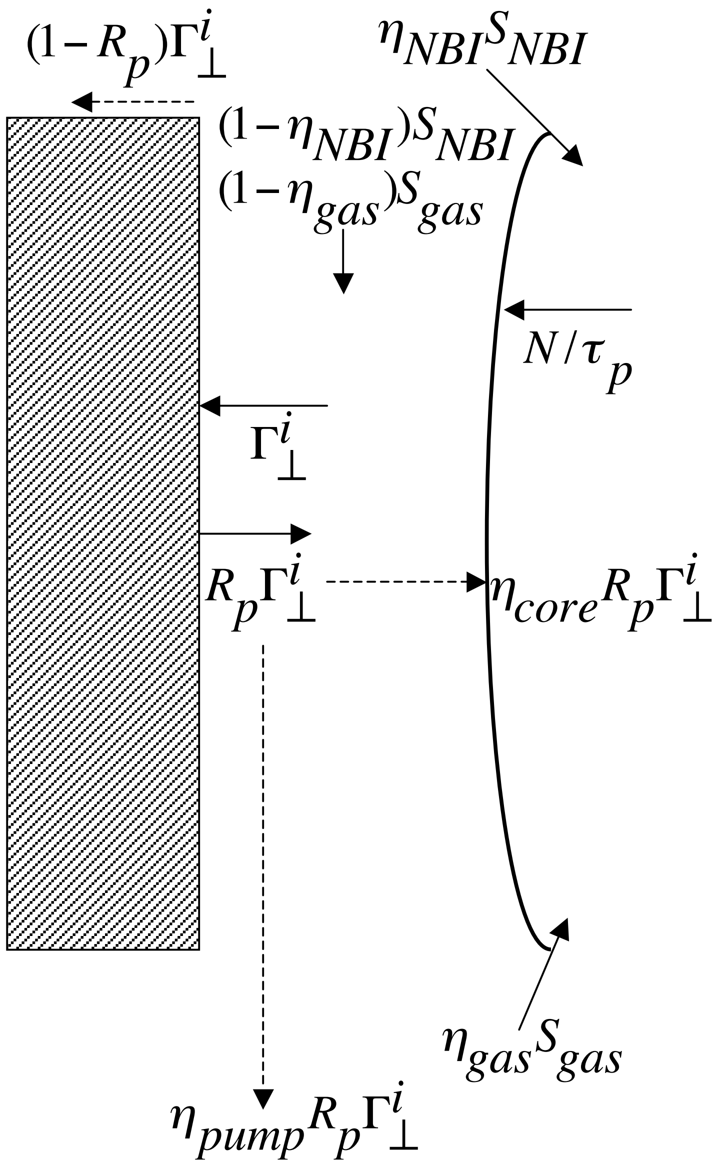
- $\beta_{Li} = \eta_{core}R_p/((1-R_p) + R_p{*}(\eta_{core} + \eta_{pump})$

- **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

  ⇒*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)

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 available from Vlad*)

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

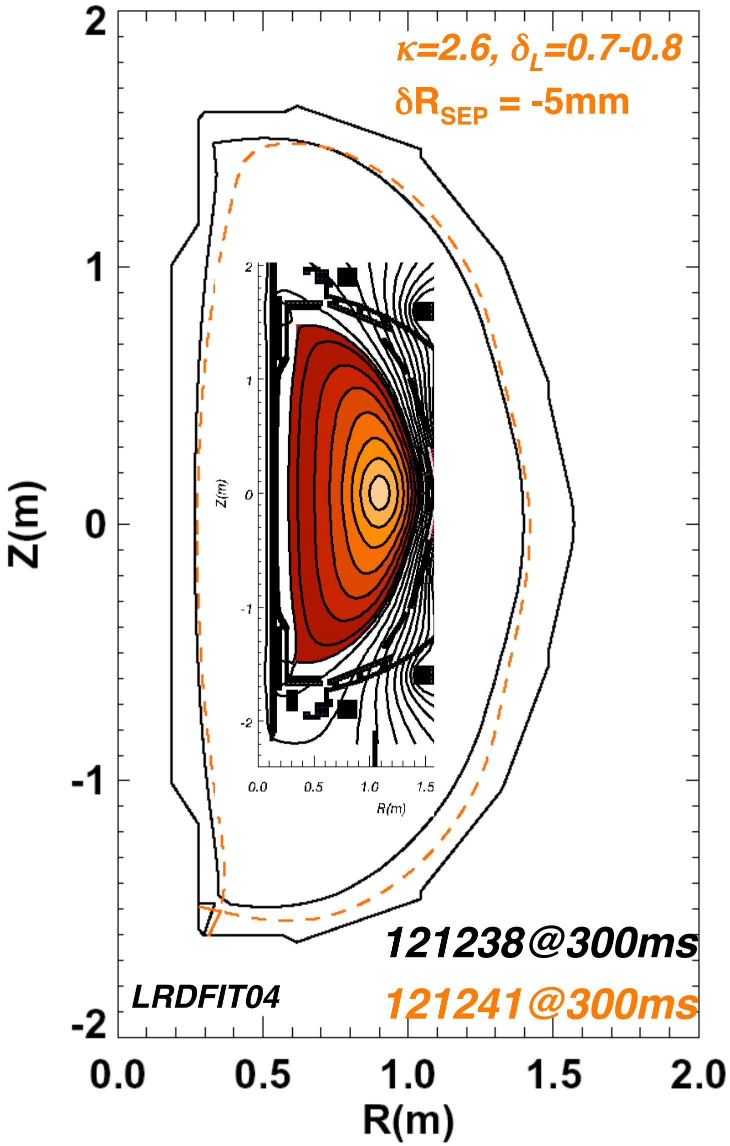
*Red items to be estimated from Vlad's CCD camera data

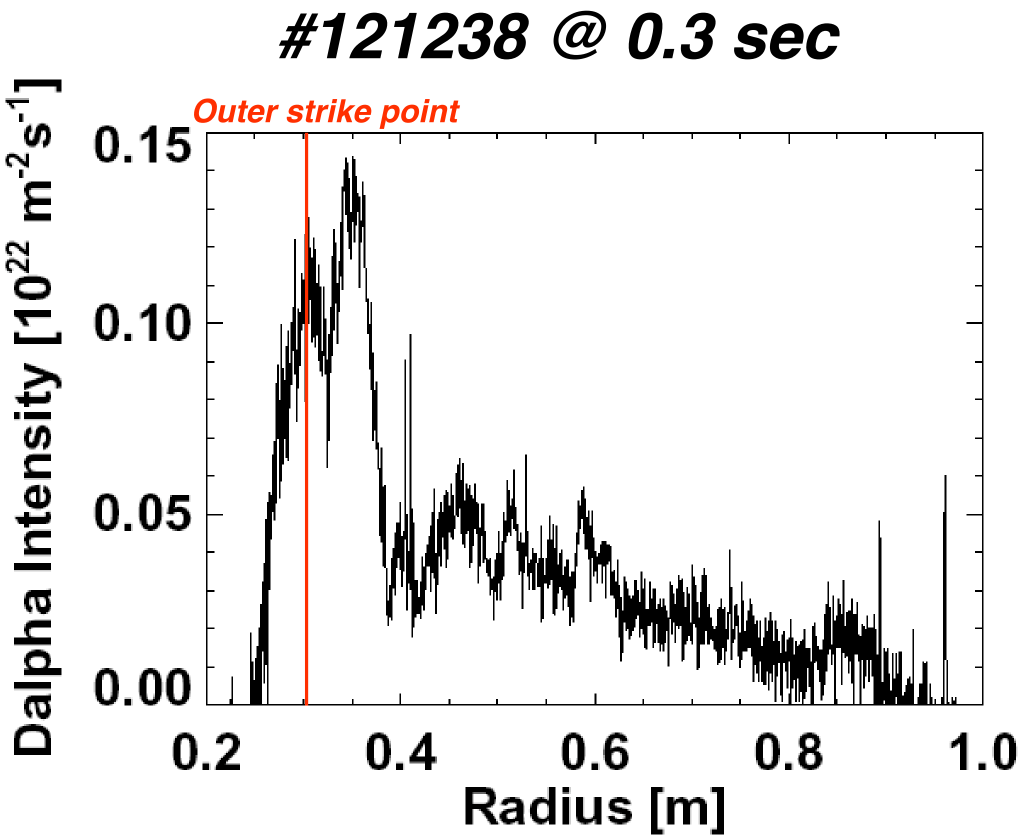
ornl
OAK RIDGE NATIONAL LABORATORY

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

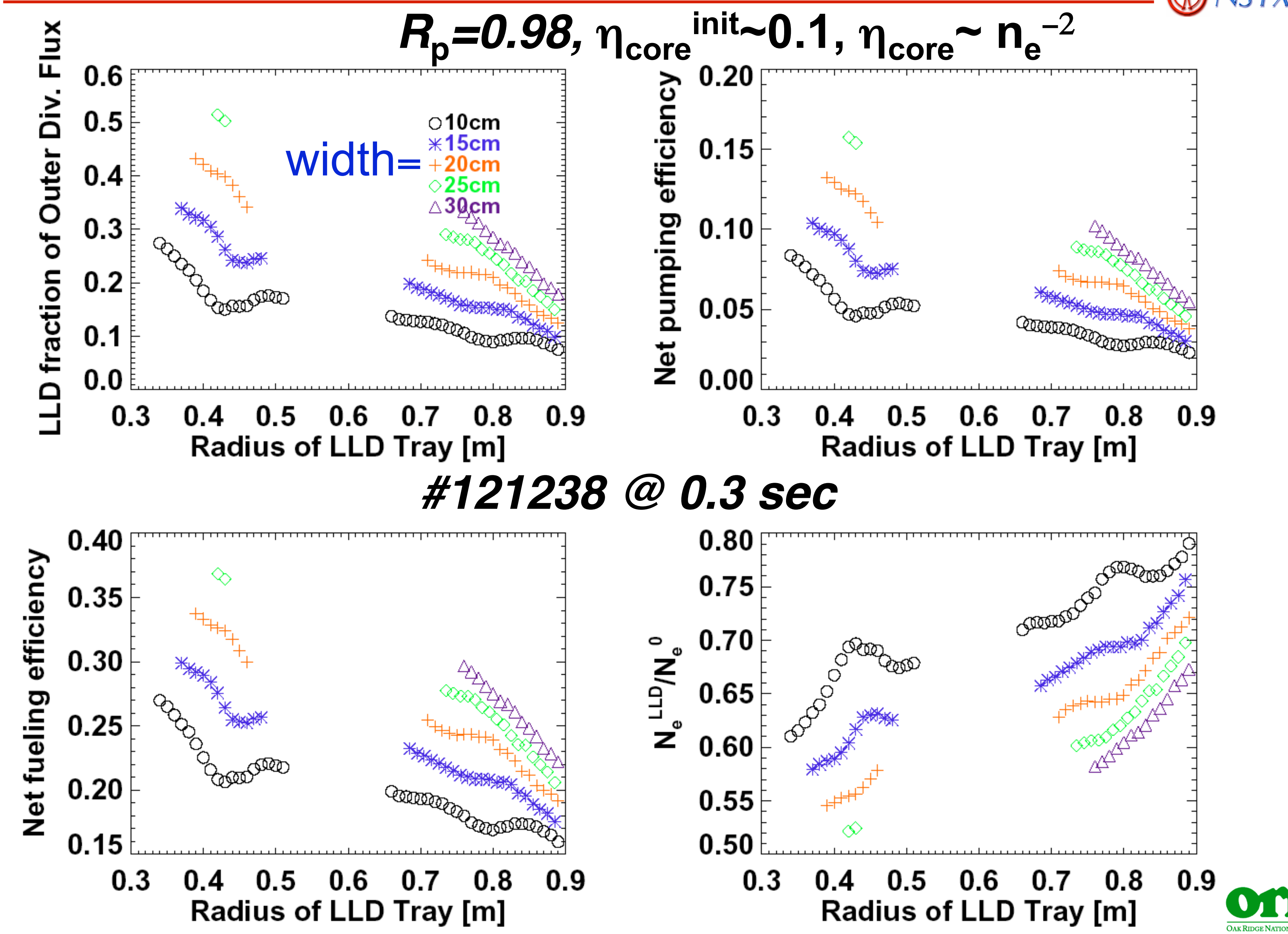
Broad SOL D_α profile in high δ (pf1a) #121238



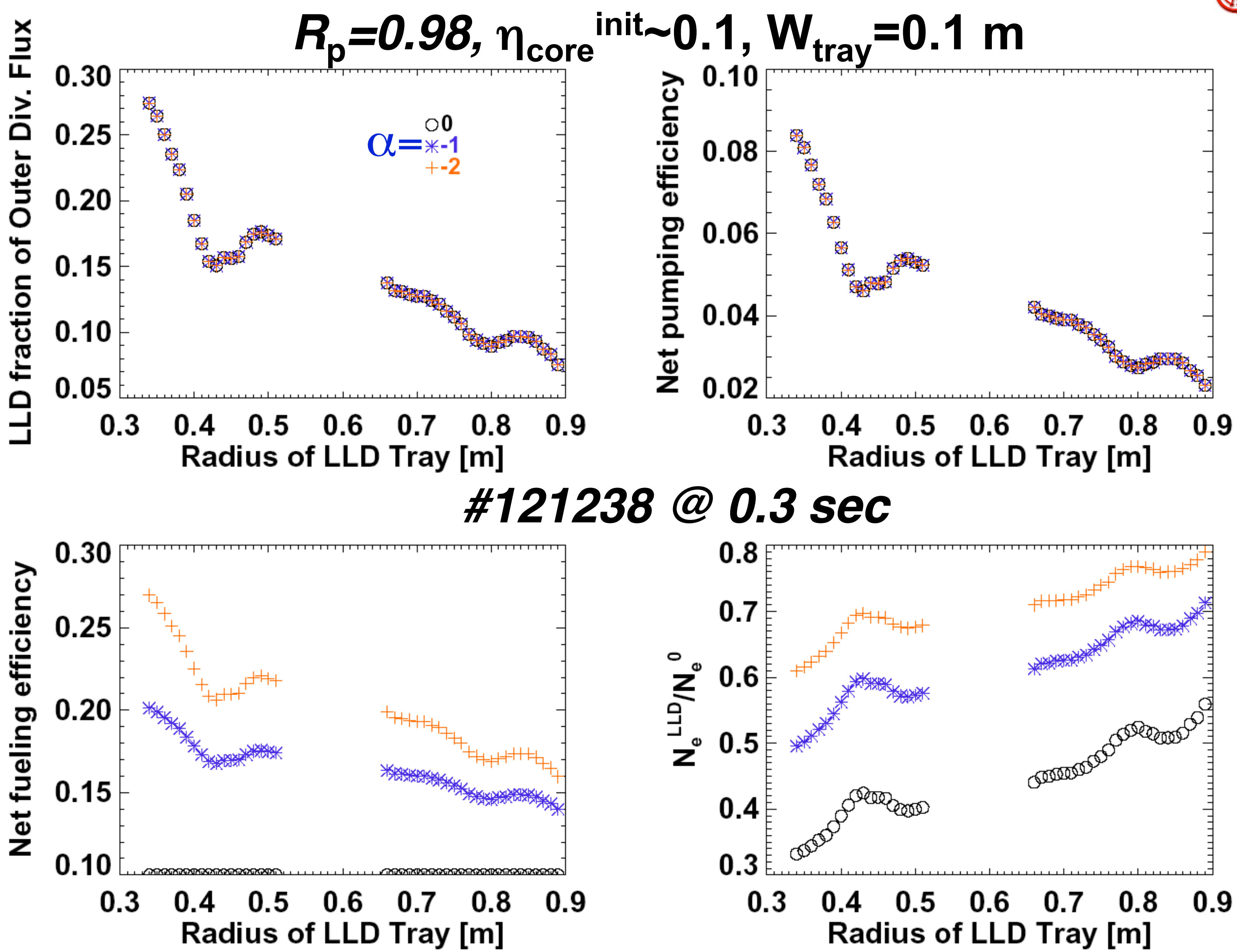


Soukhanovskii

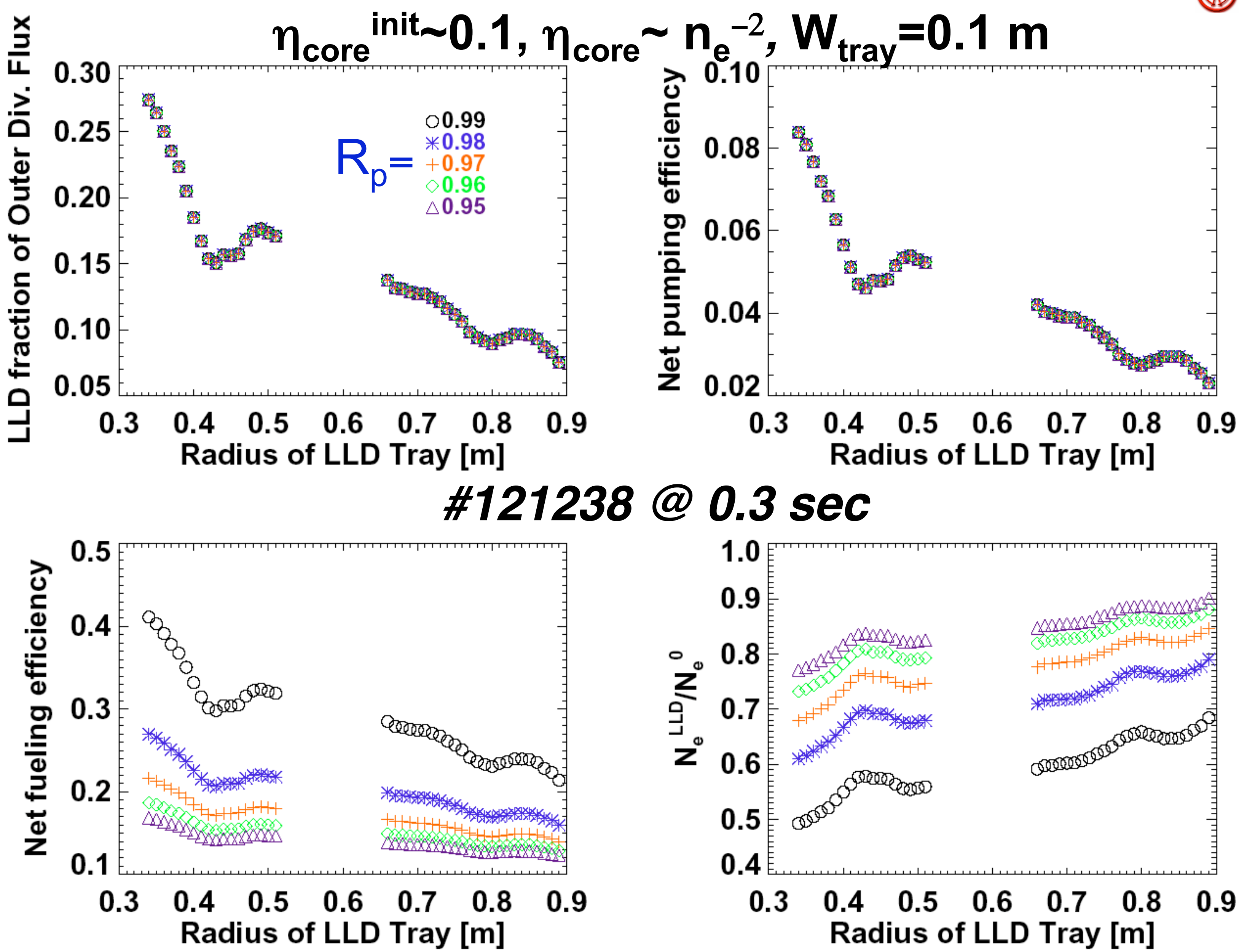
Achievable edge density reduction depends on tray radius and width



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

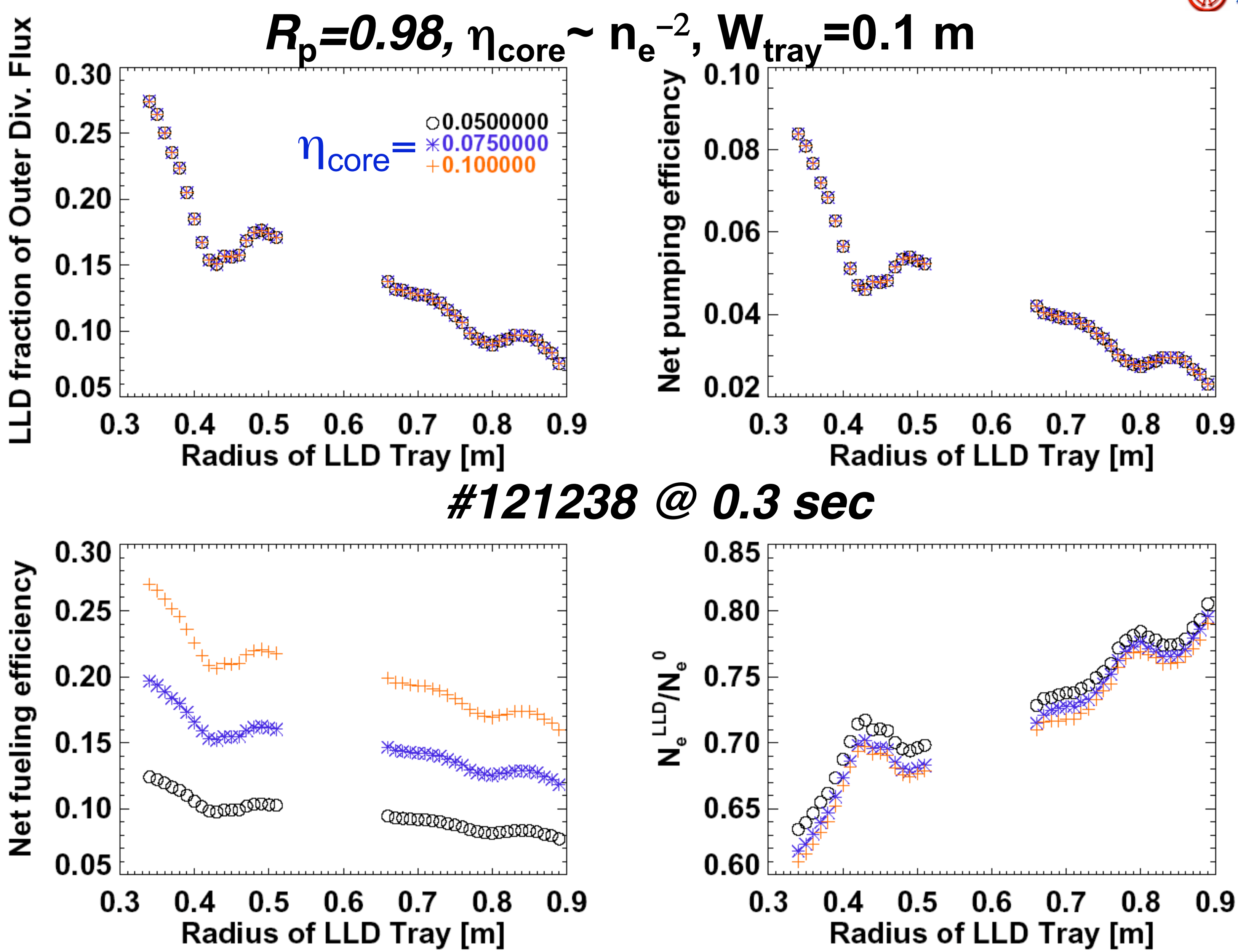


Achievable edge density reduction decreases with assumed initial wall recycling coefficient, R_p



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

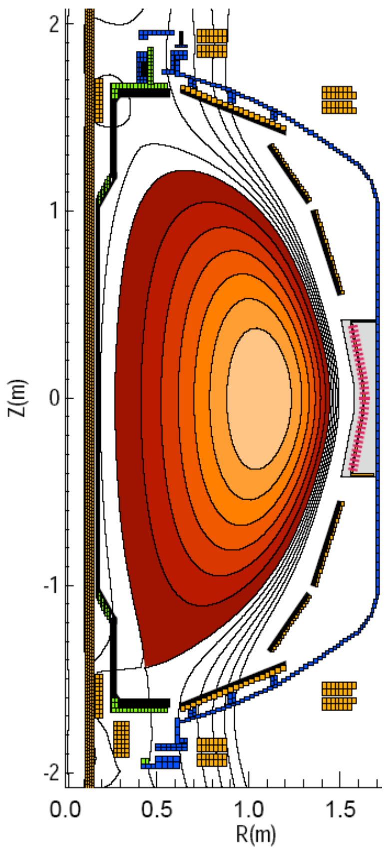
NSTX



ornl
OAK RIDGE NATIONAL LABORATORY

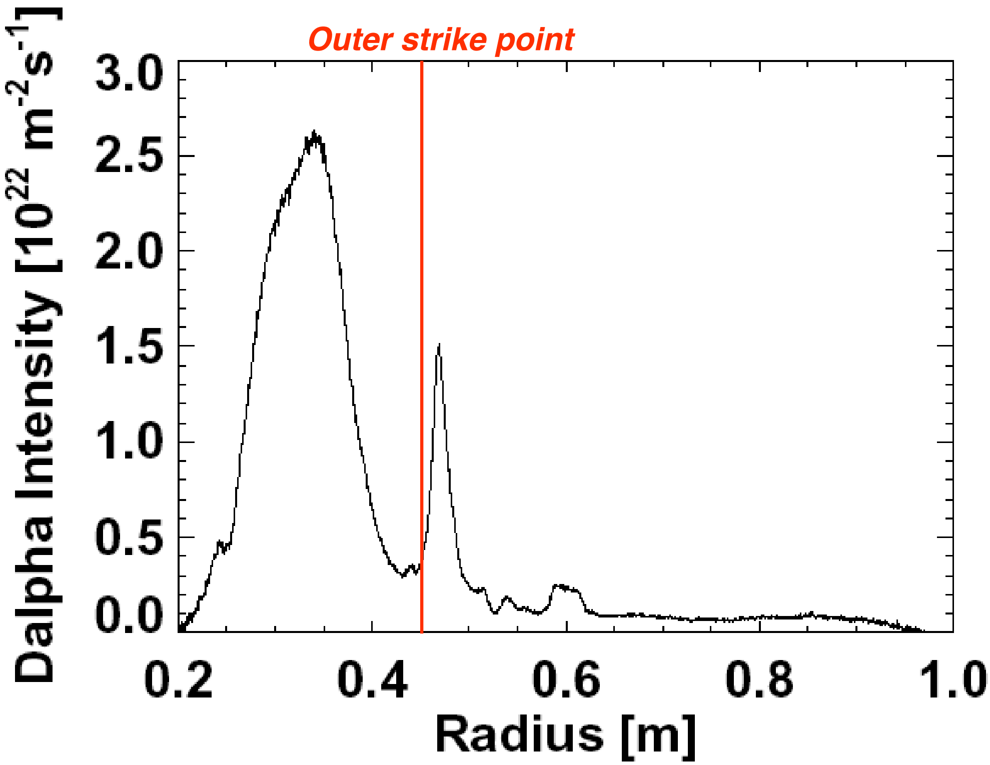
Narrow SOL D_α profile in medium δ (pf1b) #116318

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



#116318 @ 0.6 sec

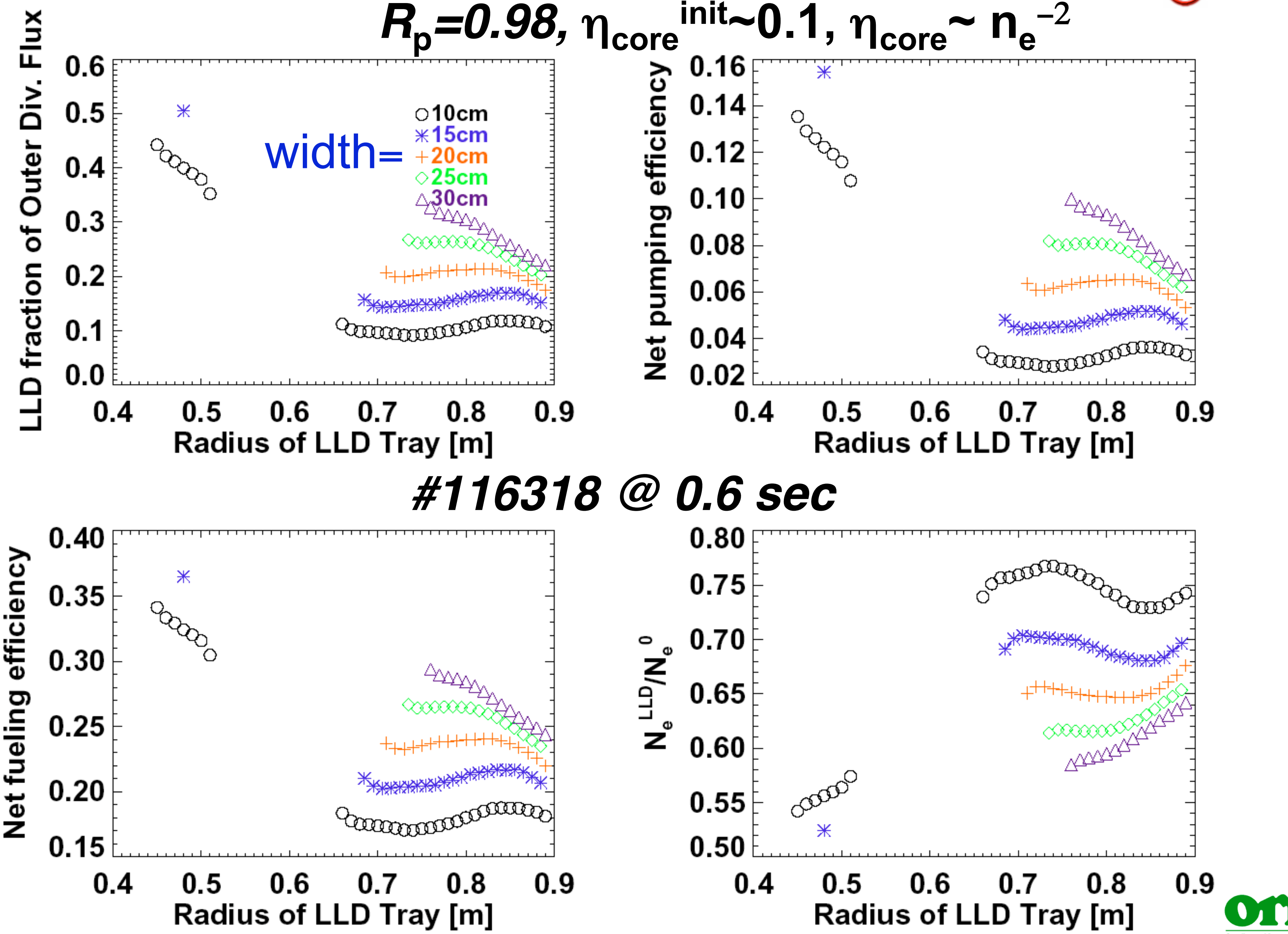
(no data on #116313)



Soukhanovskii

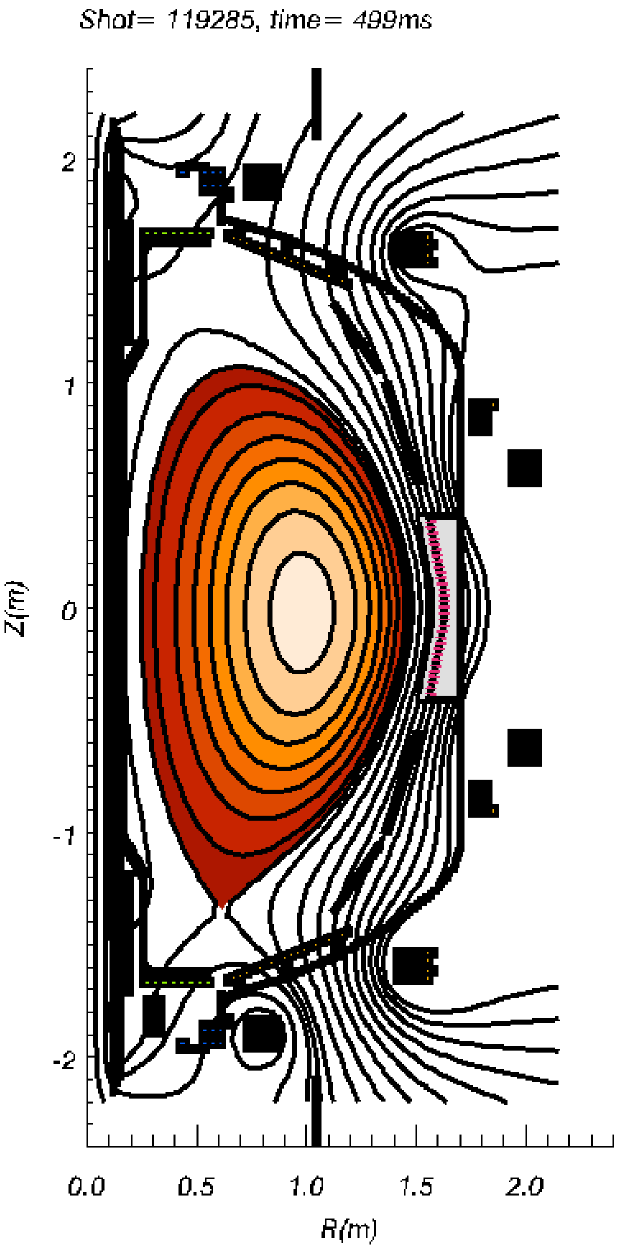
Achievable edge density reduction depends on tray radius and width

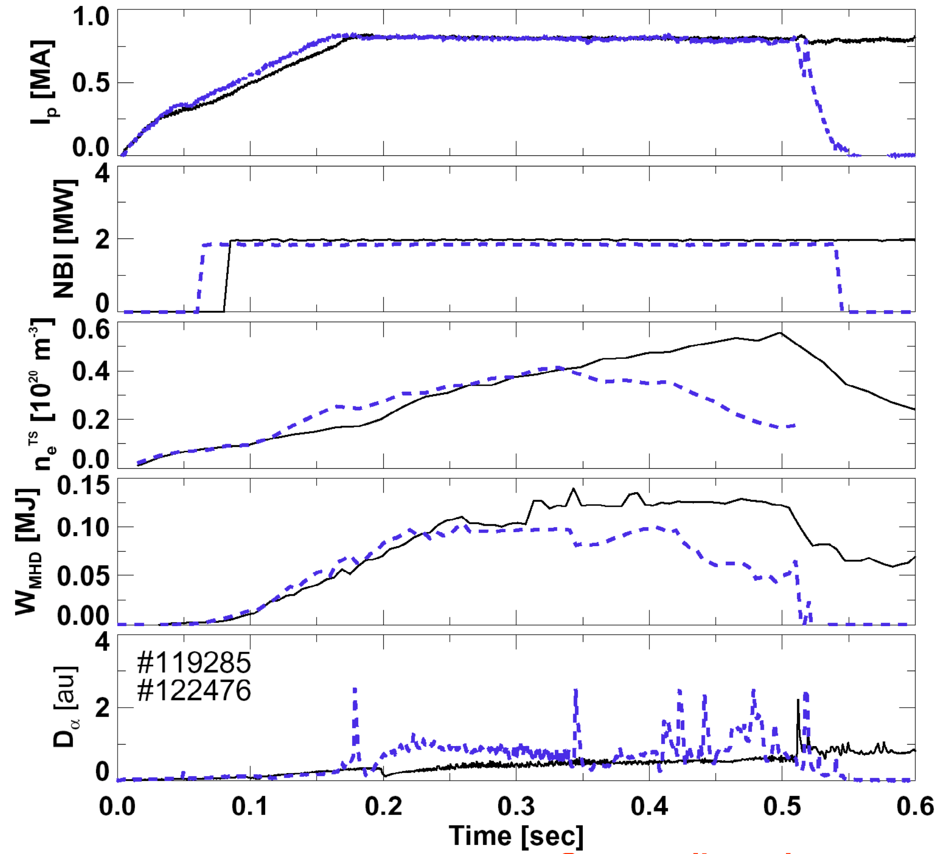
R_p=0.98, η_{core}^{init}~0.1, η_{core}~ n_e^{-2}

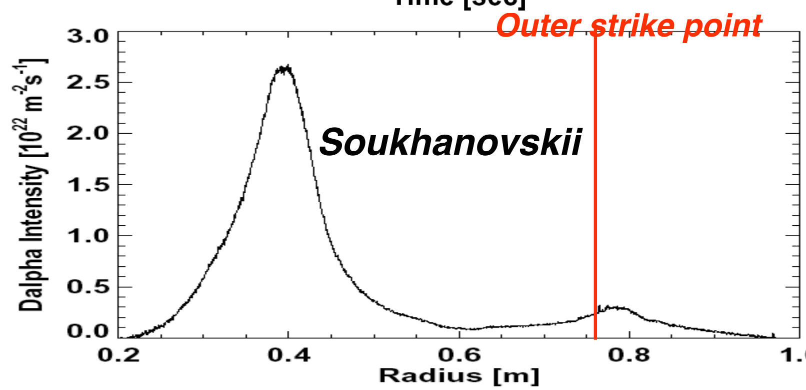


#116318 @ 0.6 sec

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

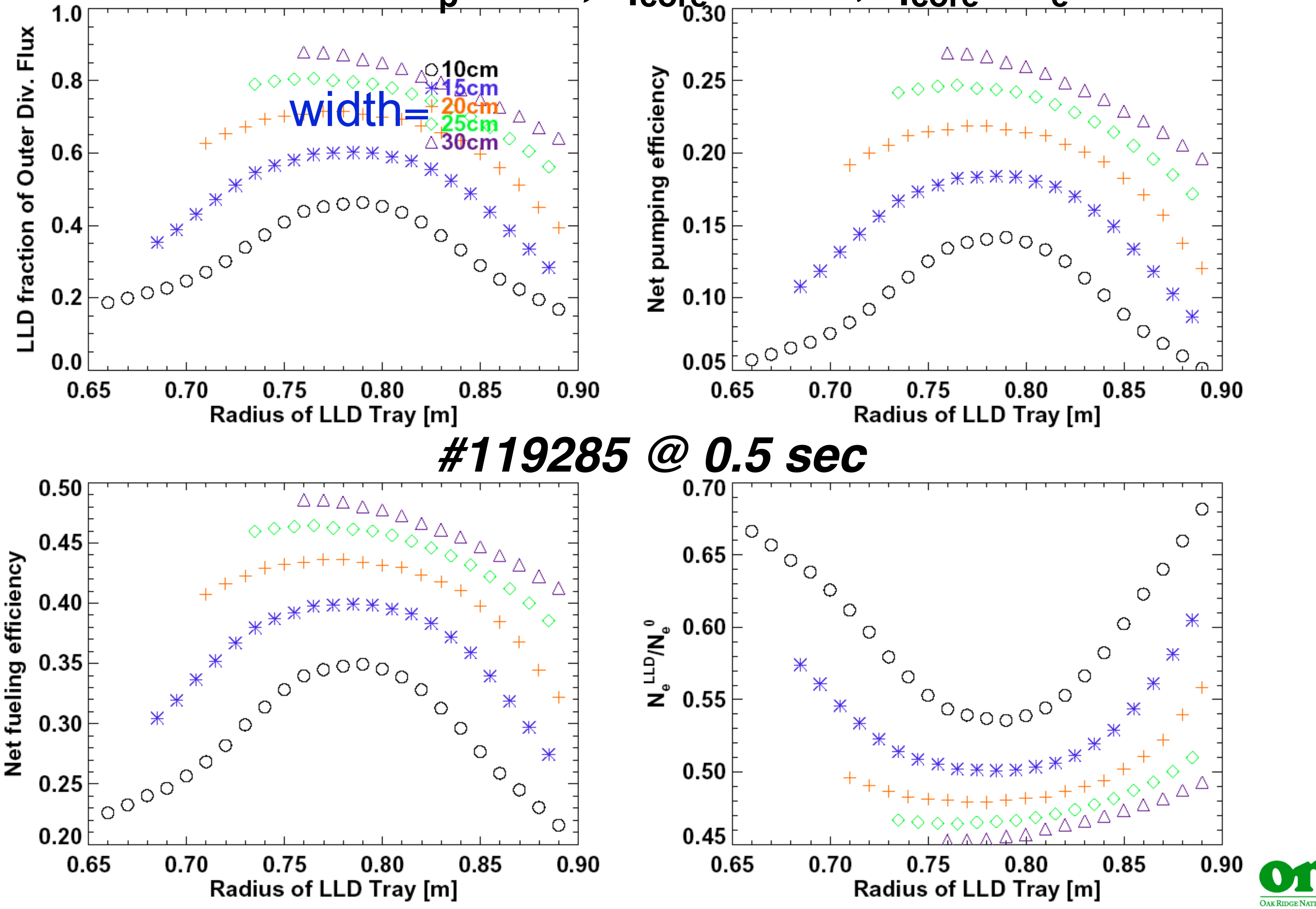






Achievable edge density reduction depends on tray radius and width

R_p=0.98, η_{core}^{init}~0.1, η_{core}~ n_e^{-2}



Discussion and Conclusions

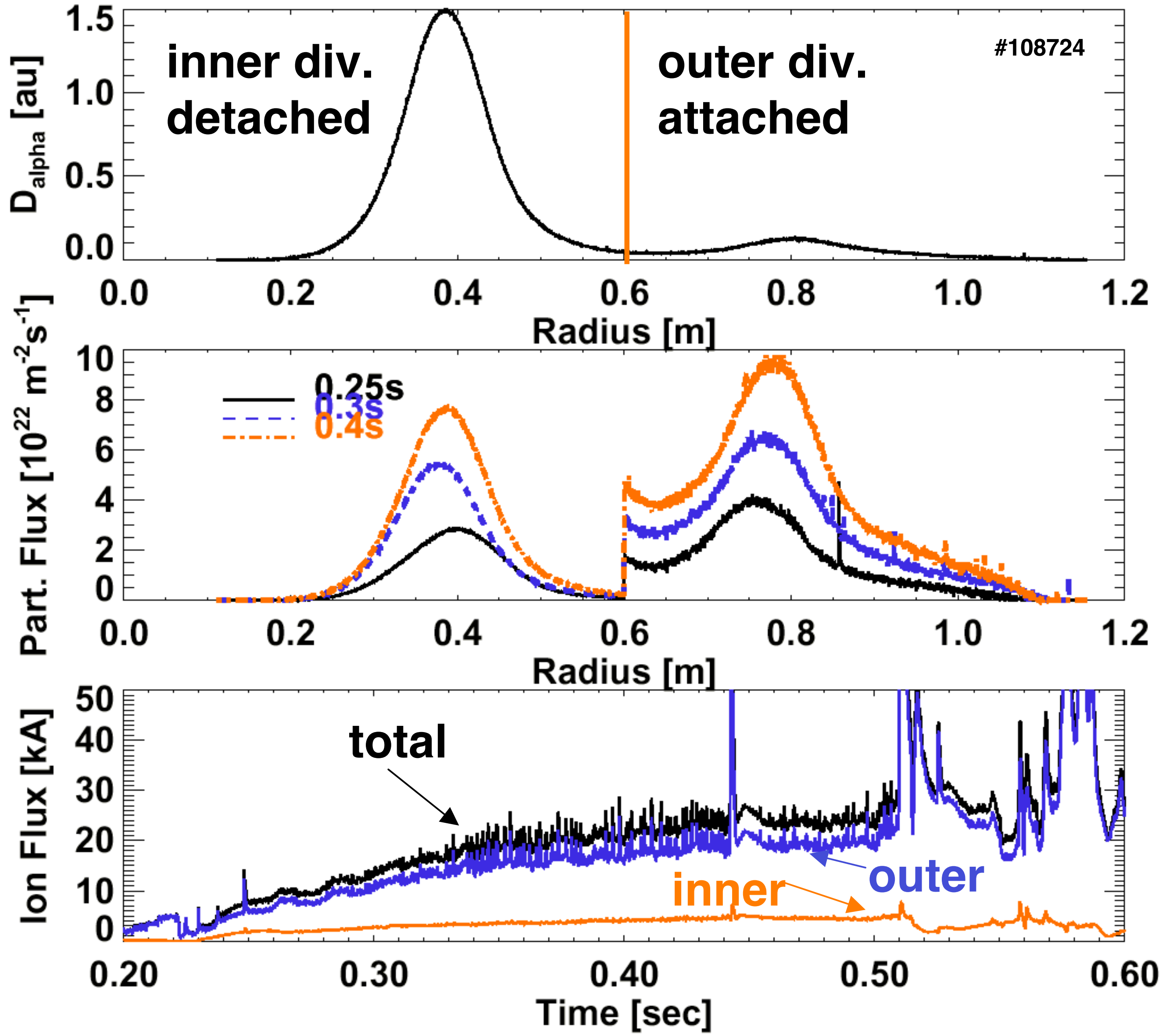
- 20cm wide tray just outboard of the CHI gap likely to provide sufficient density reduction as required for long pulse high non-inductive fraction reported at the Dec. 2006 research forum
- To get a full 50% density reduction will probably require a tray near the outer strike point
  - Inboard of CHI 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 UEDGE calculations, when available

Backup

NSTX

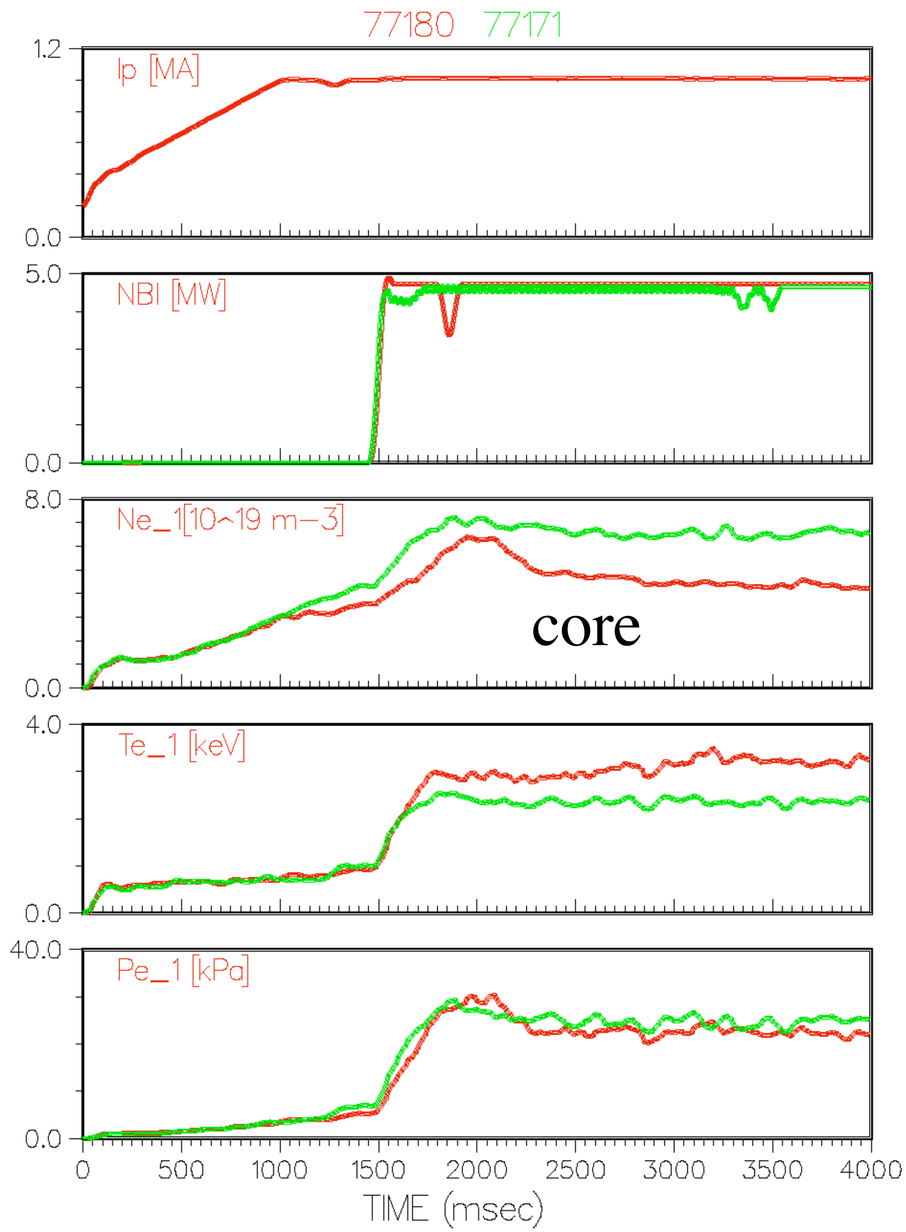
ornl
OAK RIDGE NATIONAL LABORATORY

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

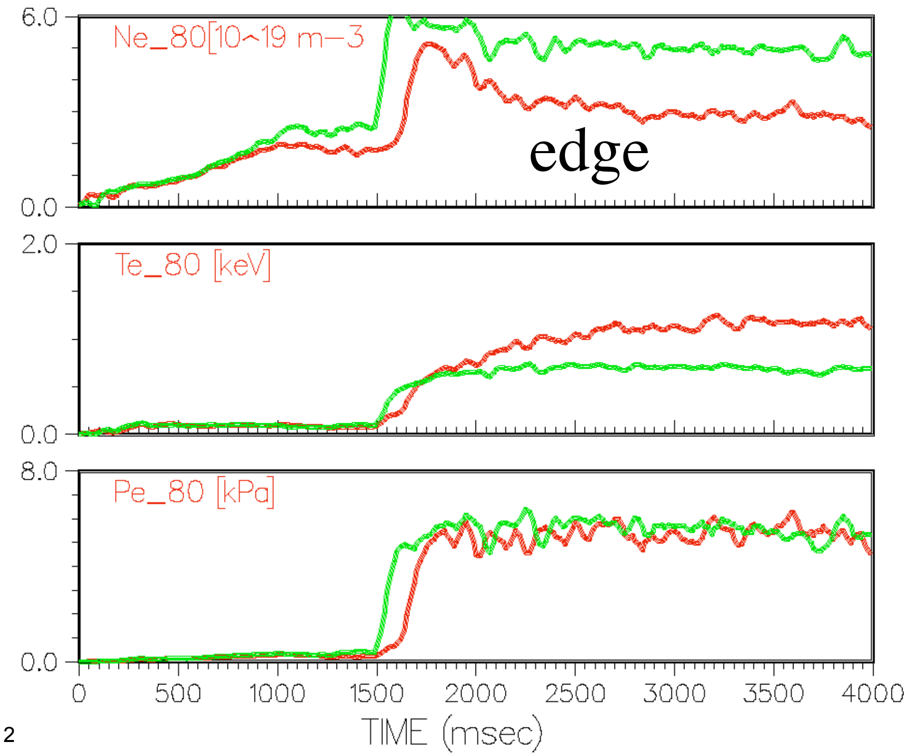


- Inner side detached
- Outer side attached
- Ions/photon =1 (detach)
- Ions/photon =20 (attach)
- Division at R ~ 0.6m
- Out div. has ~ 4x times current of inner div.

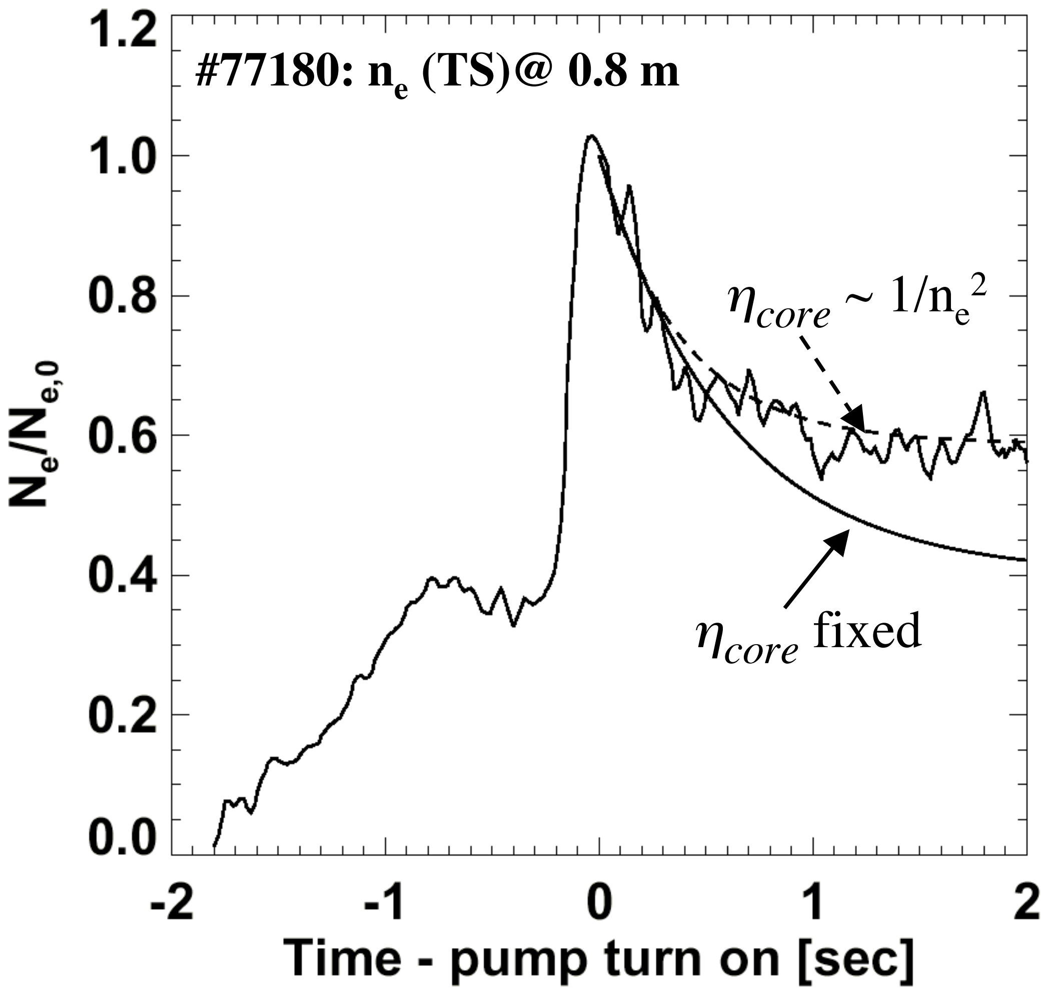
Comparison of Unpumped and Pumped DIII-D Discharges



- 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 ~ 0.98 for carbon (reference?)
  - R_p changes slowly (Maingi, NF 1996)
  - η_{core} ~ 0.05-0.15 (Rensink, PoF B 1993)
  - η_{pump} ~ 0.1 (Maingi, NF 1999)
  - η_{gas} ~ 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^*