Physics Considerations for the Design of the Liquid Lithium Divertor for NSTX

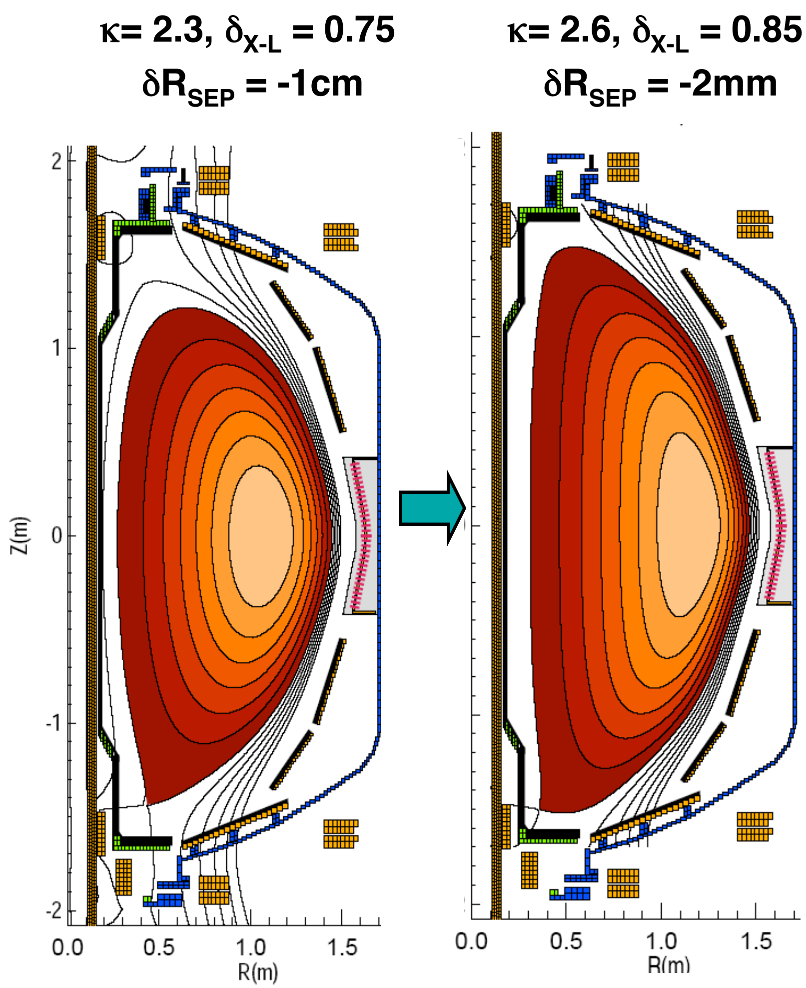
R. Maingi, ORNL

Liquid lithium divertor physics design discussion

Princeton, NJ
March 9, 2007

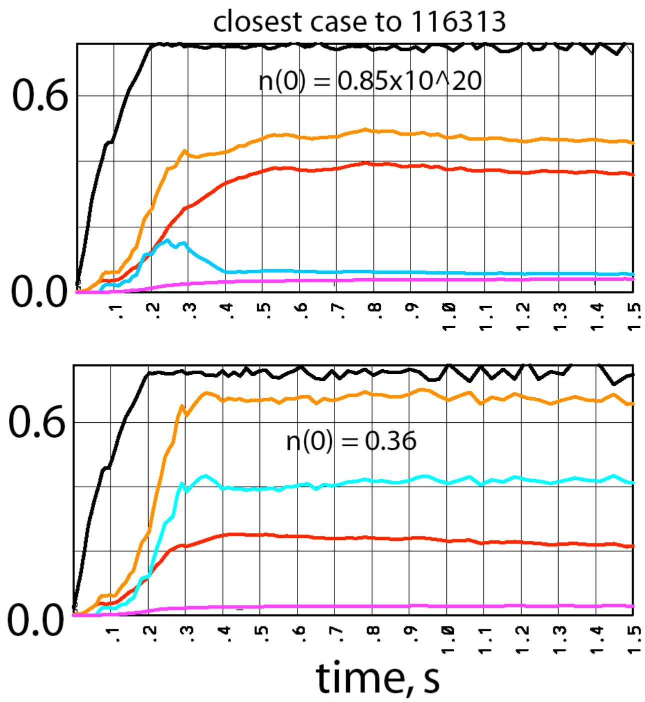
Possible Physics Design Goals of the LLD project

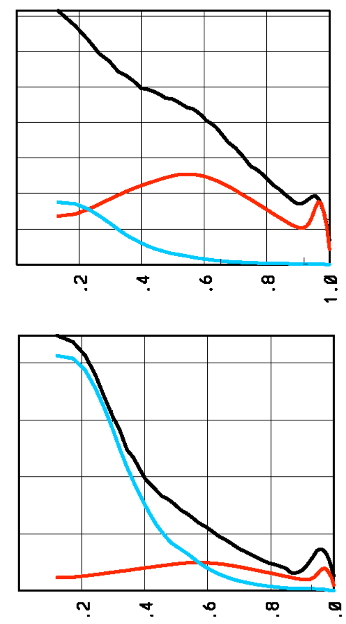
- **Reduce the steady H-mode density down to the target value in the ISD simulations, i.e. by 15-25% in I_P~0.75 MA long pulse scenario (0.67 - 0.8 * n_{GW})**
  - **Specific shape implied**
- **Allow a full factor of two density range in an optimized plasma shape for collisionality scans**
- **Test power handling capability of a liquid lithium divertor?**



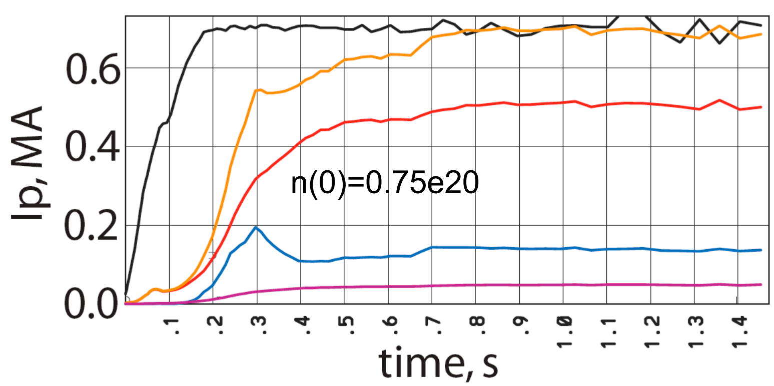
Integrated modeling points to importance of shaping, reduced n_e, and increased T_e/τ_E for higher f_{NI} and high β_N

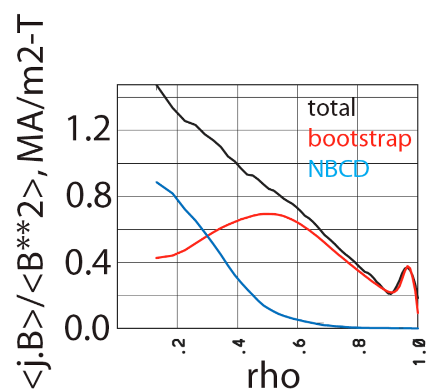
total
total NI
bootstrap
NBCD
grad p





- $n_{20}(0)$=0.85,
  κ=2.2
  H_{98}=1.1
  β_N = 5.6
  q(0) ≥ 1.15
- $n_{20}(0)$=0.36,
  κ=2.2
  H_{98}=1.1
  β_N = 5.6
  q(0) = 1 @ 0.8 s



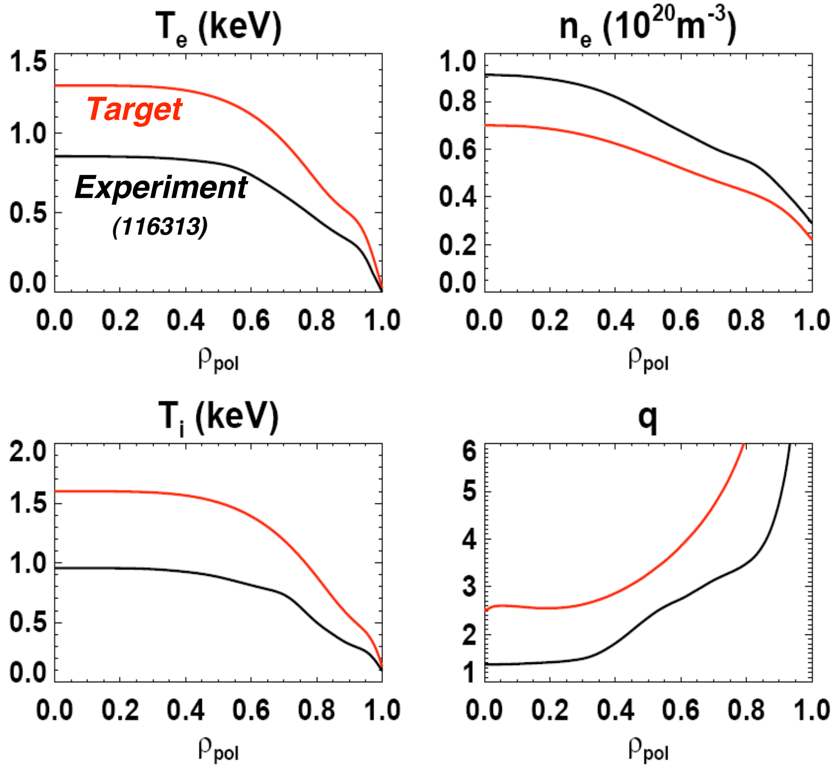


- $n_{20}(0)$=0.75,
  κ=2.55
  H_{98}=1.35
  β_N = 6.6
  q(0) ≥ 1.4

Kessel

Fully non-inductive scenario at high β_N requires higher confinement, higher *q*, strong plasma shaping

NSTX

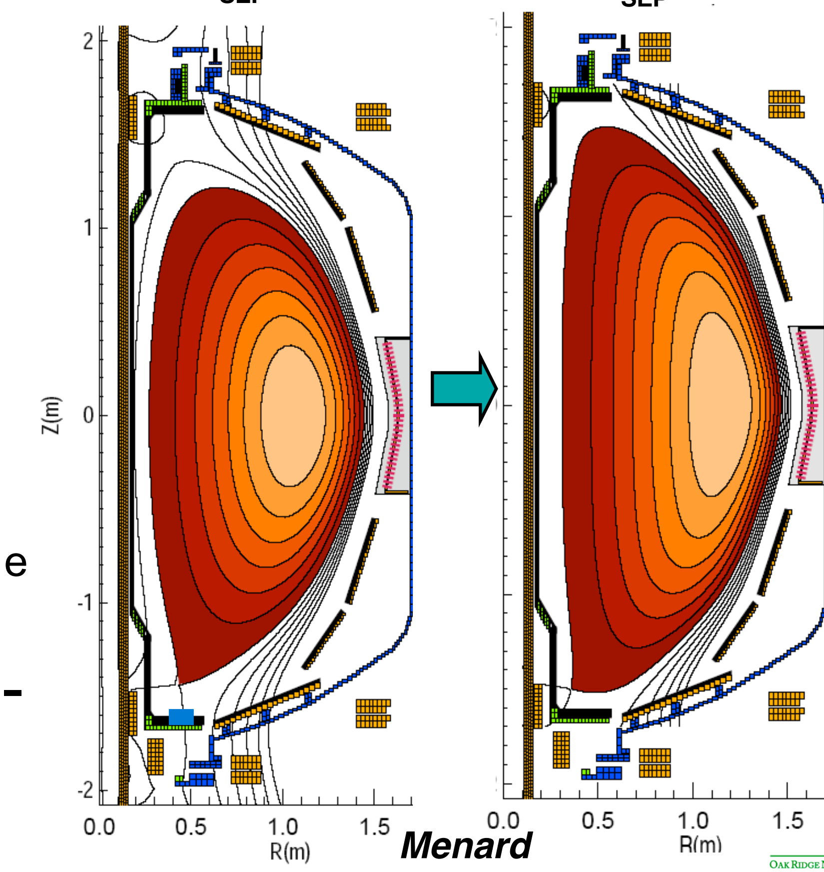


- Need 60% higher T, 25% lower n_e
- higher $q_0 \approx q_{min} \approx 2.4$ (higher with-wall limit $\beta_N \leq 7.2$)

- Higher κ for higher q, β_P, f_{BS}
- High δ for improved kink stability

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



Menard

Process needed for LLD Tray Design Specification

NSTX

- 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 (ϕ_{min}–ϕ_{max})

Tray parameters can be related to total lithium surface area

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Process needed for LLD Tray Design Specification

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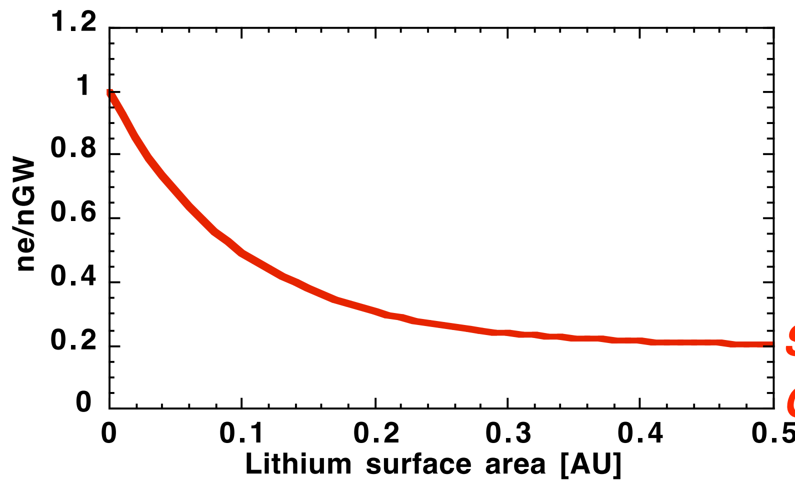
Tray parameters can be related to total lithium surface area

- Possible figure of merit (for a given shape, R_{tray}):



Small distance between OSP and LLD radius

Steady H-mode density
Optimized pumping

Process needed for LLD Tray Design Specification

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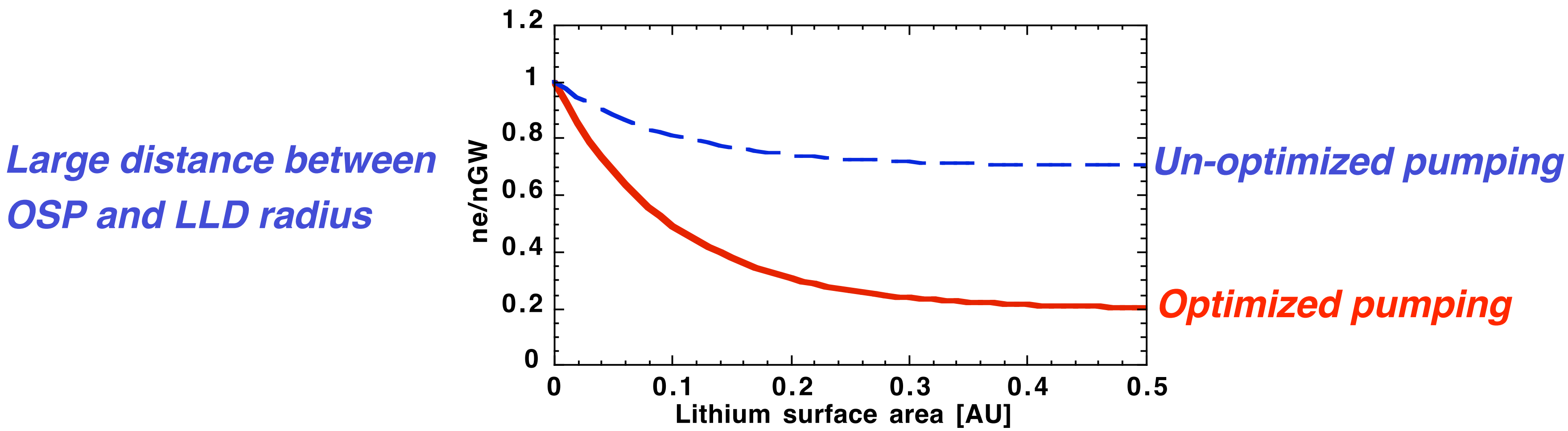
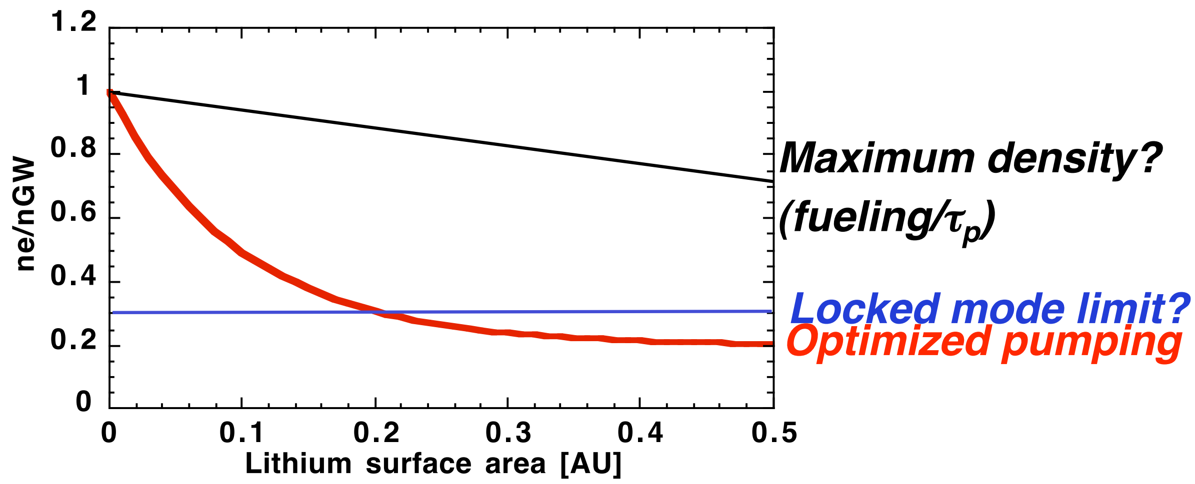
  1) Tray Width
  2) Tray Major Radius R_{tray}
  3) Number of tray segments, gap size(s) between segments, and clocking of segments ($\phi_{min}-\phi_{max}$)
- Minimum density will depend on tray-OSP distance



Process needed for LLD Tray Design Specification

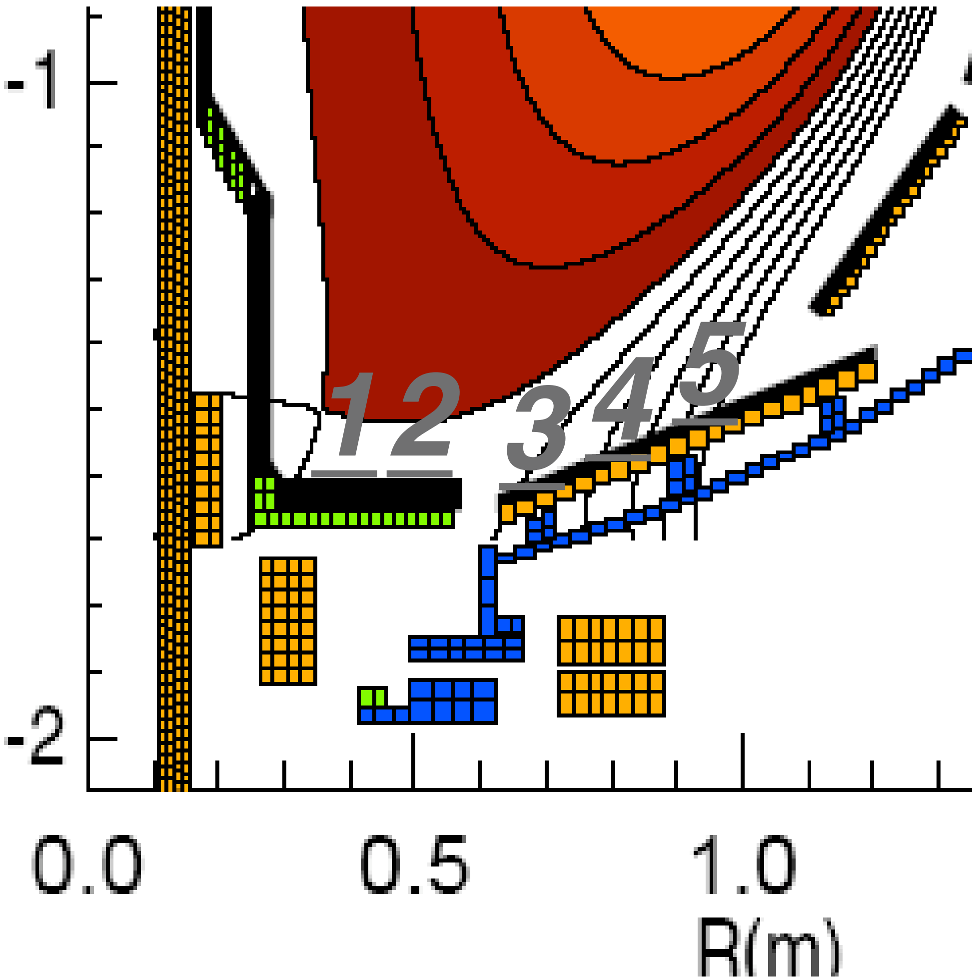
- The following LLD design parameters need to be specified (target: April 15, 2007):
  1) Tray Width
  2) Tray Major Radius R_{tray}
  3) Number of tray segments, gap size(s) between segments, and clocking of segments ($\phi_{min}-\phi_{max}$)
- Other physics limits may impact density window



Pumping calculations will help specify the LLD design parameters

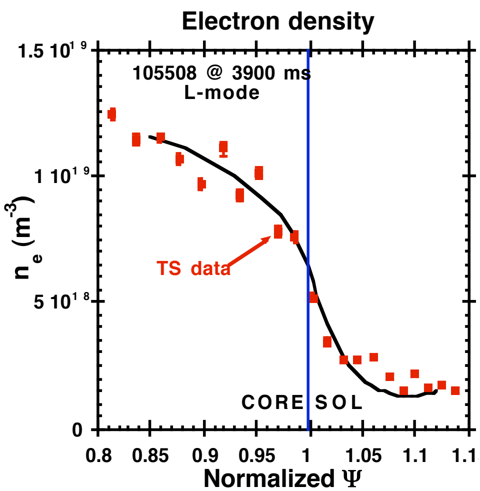
- 0-D calculations
  - Parameterized as ratio of pump to core fueling probabilities
  - Requires an assumed relation between pump probability and lithium surface area
- 1-D calculations
  - Onion-skin OEDGE type, *requires assessment for NSTX*
- 2-D fluid calculations (model)
  - T. Rognlien did NSTX 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

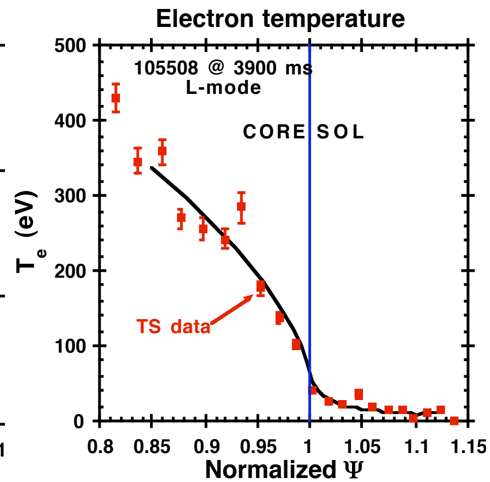
Propose to do UEDGE and maybe DEGAS-2 calculations with several candidate locations

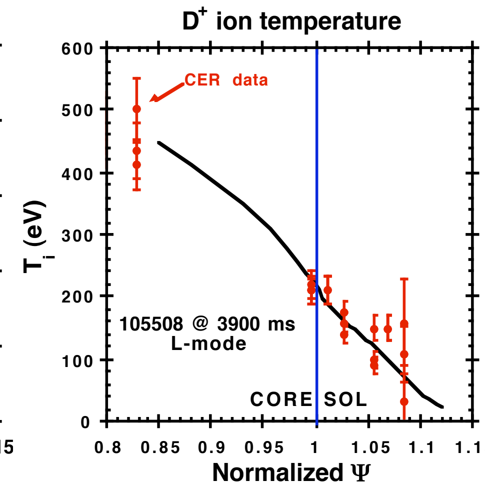


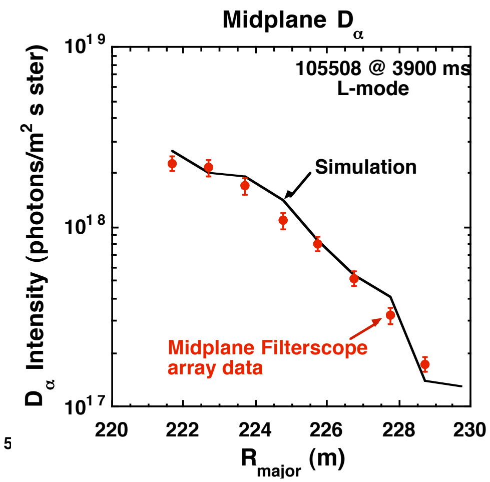
- **<u>Perform data-constrained base case</u>**
- **Vary the recycling coefficient from base case (~0.98) to 0.1 or 0.2 over a ~ 10cm wide region (<u>*1*</u>)**
- **Move the LLD farther from outer strike point (<u>*2*</u>-<u>*5*</u>)**
- **Determine if wider tray calculations desired**
- **<u>Need to determine which equilibrium to start from</u>**

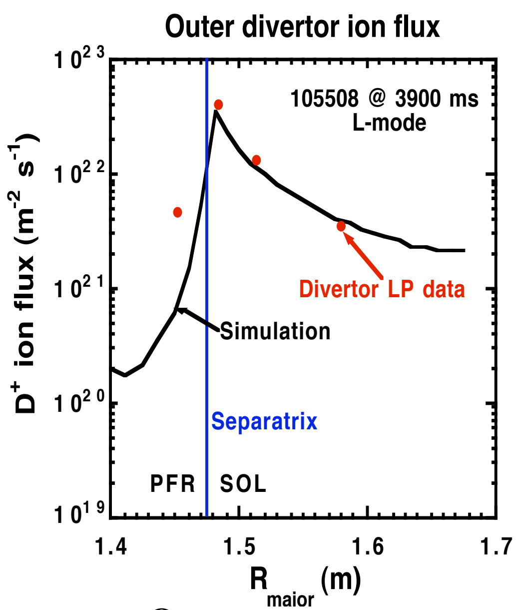
Free Parameters in Plasma Simulation will be varied to match measured profiles in midplane and divertor



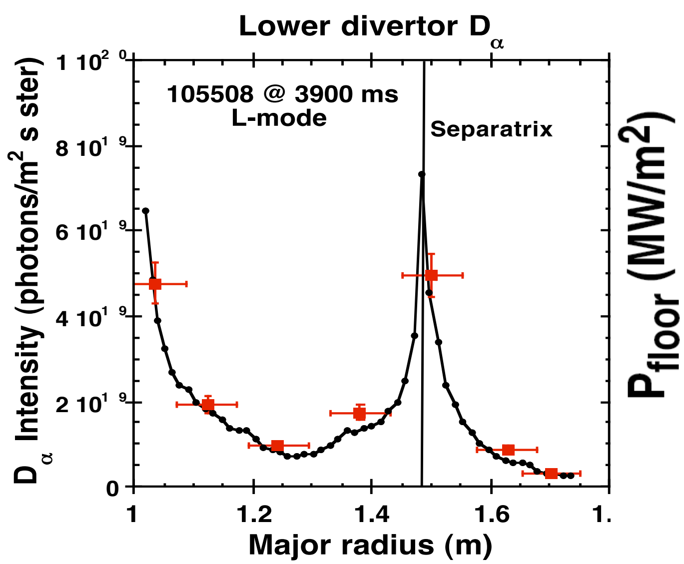


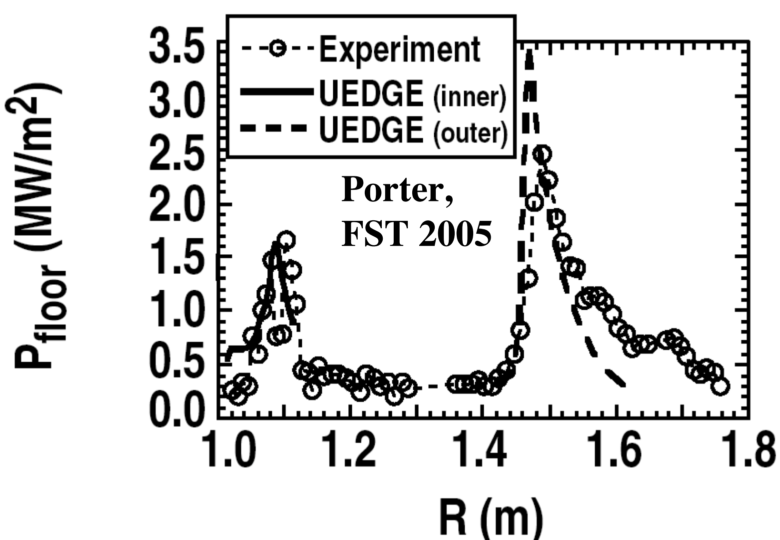






Owen

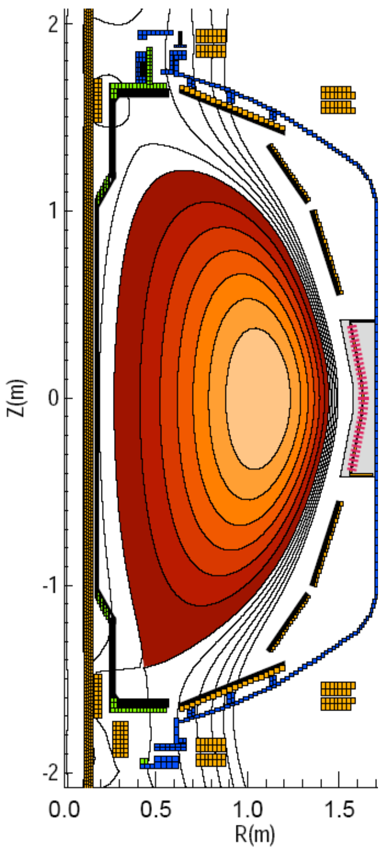




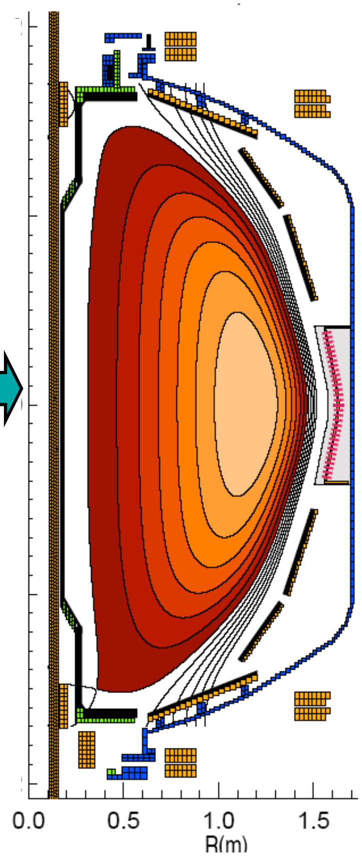
Also center stack + upper divertor D_α in NSTX

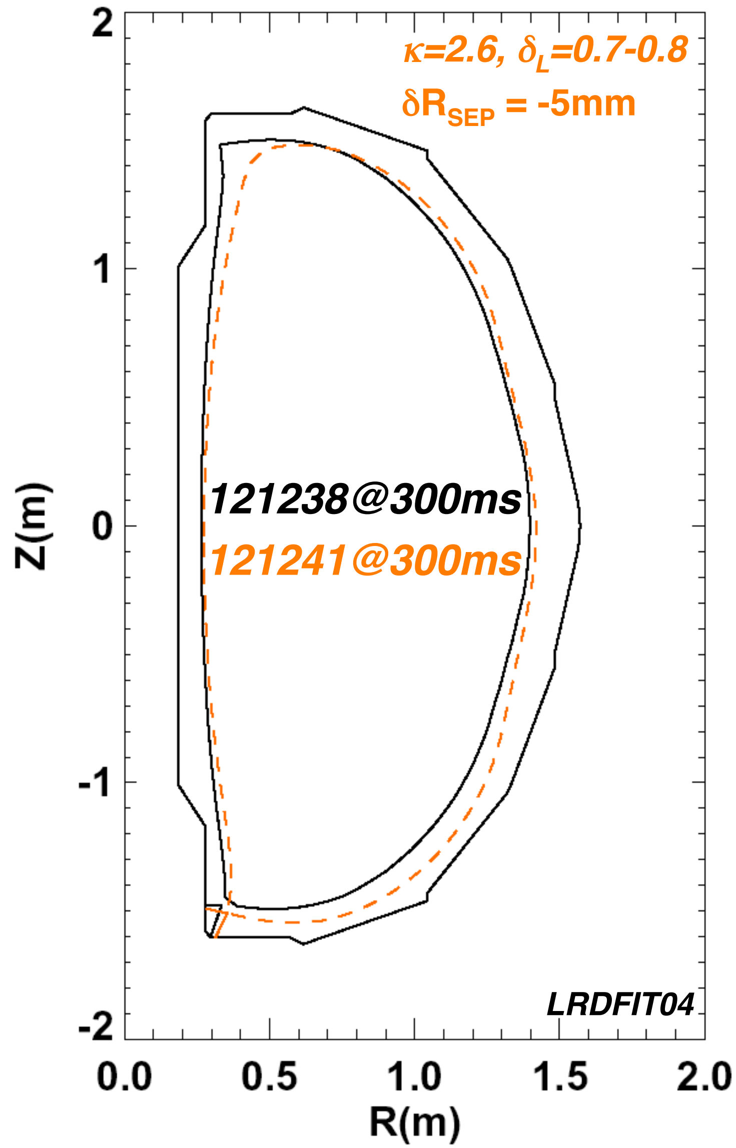
Propose to use #121238 or 121241 @ 0.3 sec as target shape for calculations

Existing shape
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





Semi-Analytic Predictive 0-D Modeling of Pumping Schemes for NSTX

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Motivation and Technique

NSTX

- Desire predictive simple model for effect of pumping on NSTX edge plasma
  - Provide means for comparing density control schemes, e.g. Lithium systems vs. in-vessel cryopumping
  - Should be benchmarked against other experiments
- 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/pedestal density in H-mode, and resulting transport and CD efficiency changes

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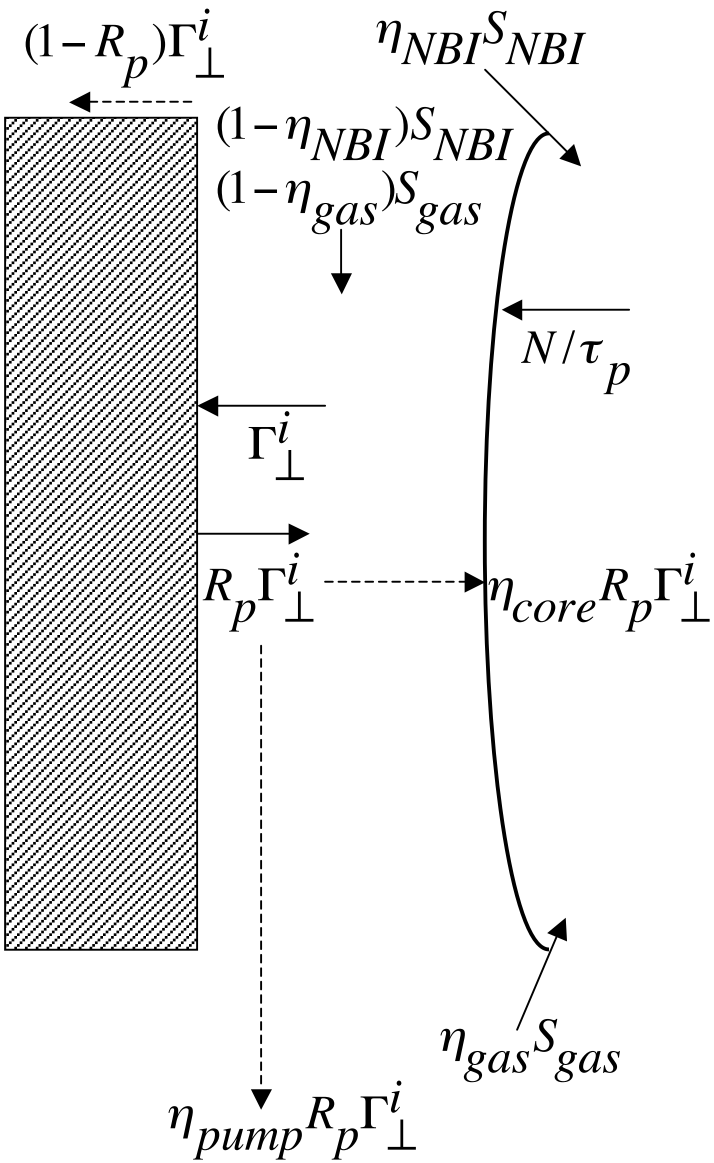
Particle Balance and Recycling Model



- Consider core and SOL particle content equations

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

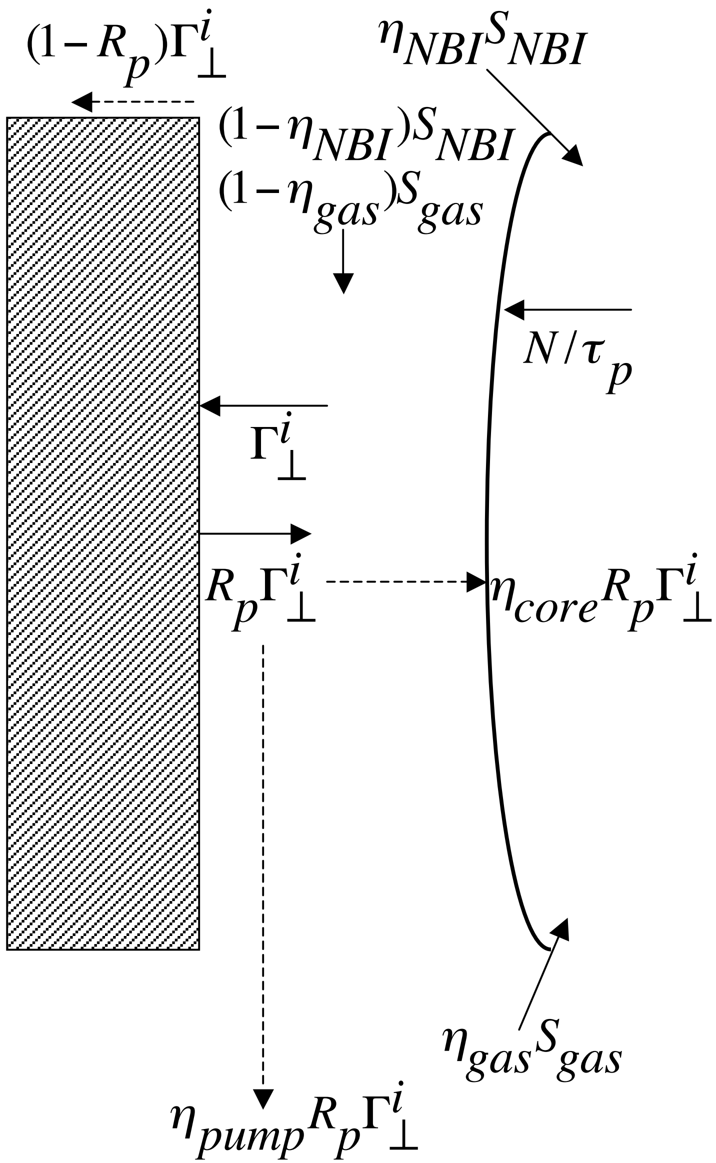
$$\frac{dN_i^{SOL}}{dt} + \frac{dN_0^{SOL}}{dt} = (1-\eta_{NBI})S_{NBI} + (1-\eta_{gas})S_{gas} + \frac{N}{\tau_p} - (1-R_p)\Gamma_\perp^i - R_p\Gamma_\perp^i(\eta_{pump} + \eta_{core})$$

- 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:

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

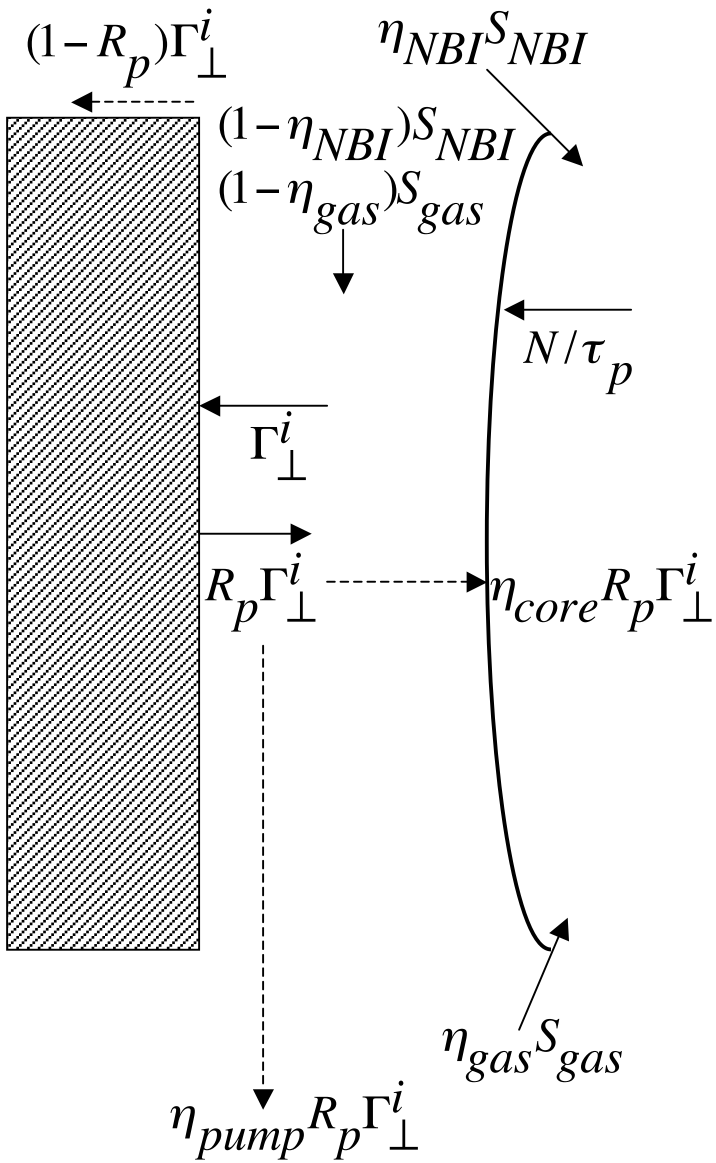
Let $S = S_{NBI} + (1+\beta(1-\eta_{gas}))\eta_{gas}S_{gas}$

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 ($\eta_{pump}>0$)

Limits of Particle Balance and Recycling Model

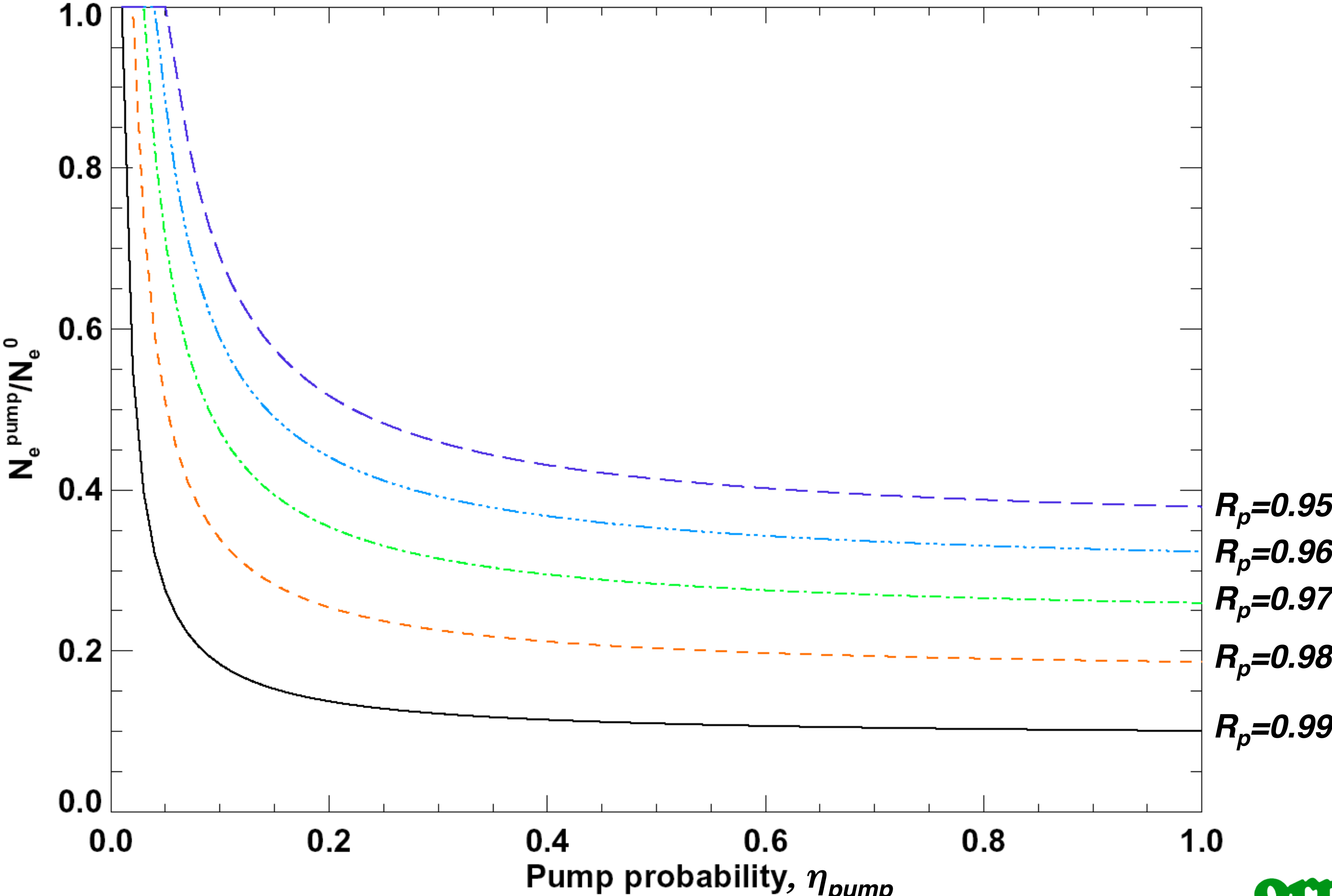


- Note $\tau_p^*/\tau_p = 1/(1-\beta)$
- Pump off: $\tau_p^*/\tau_p \sim 1+ \eta_{core}R_p/(1-R_p)$
  - $\tau_p^*/\tau_p \sim 6$
- Pump on: $\tau_p^*/\tau_p \sim (\eta_{core}+\eta_{pump})/\eta_{pump}$
  - $\tau_p^*/\tau_p \sim 2$

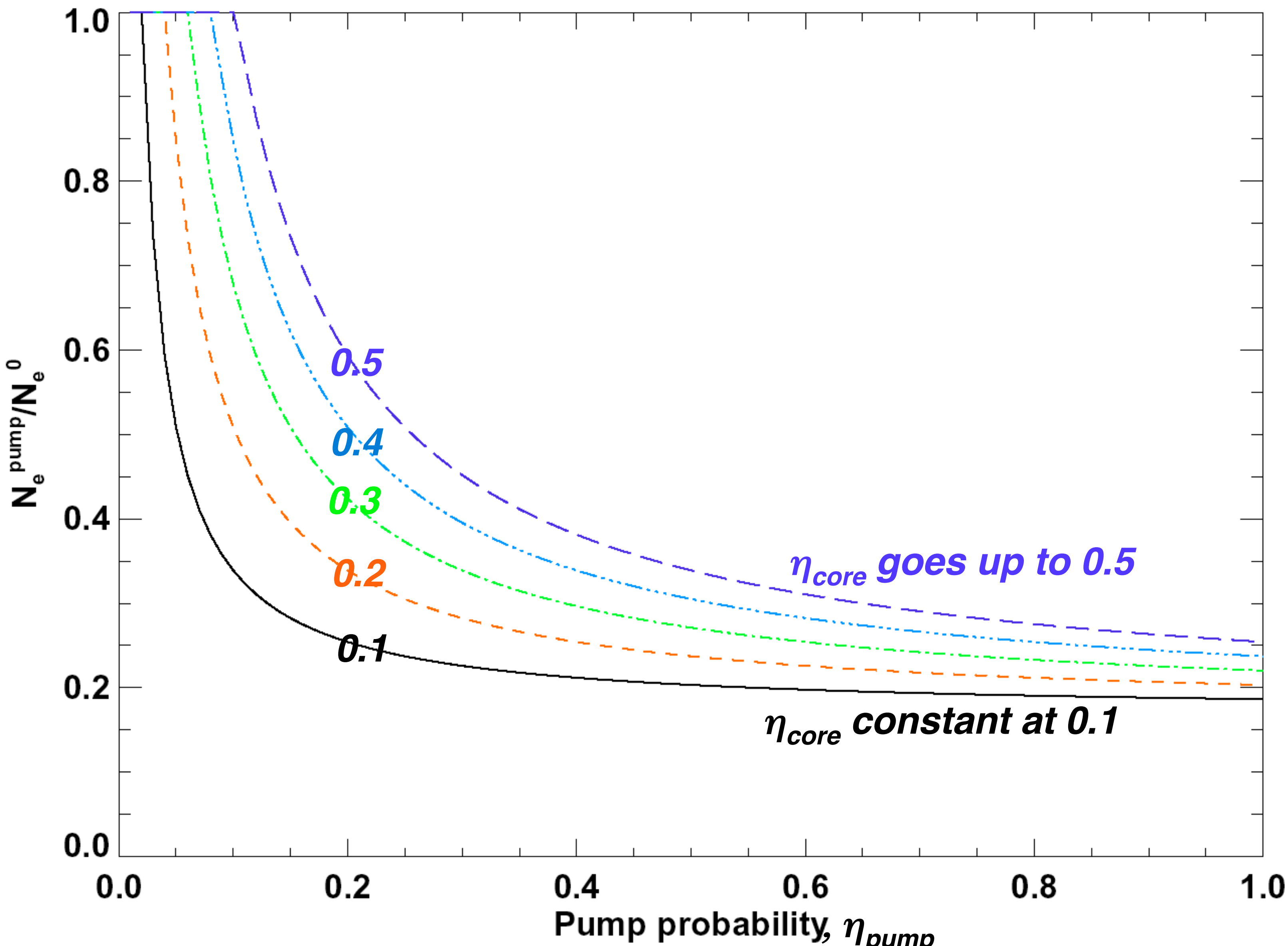
$\Rightarrow n_e$ should go down by 2/3 w/pumping

- DIII-D specific data:
  - $R_p \sim 0.98$ for carbon (reference?)
  - $\eta_{core} \sim 0.1$ (Rensink, PoF B 1993)
  - $\eta_{pump} \sim 0.1$ (Maingi, NF 1999)

Achievable edge density reduction depends on initial recycling state



Achievable edge density reduction also depends on increase in core fueling probability as density reduced



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

NSTX

In/out particle flux ratio (data)

Li surface particle sticking probability

Tray toroidal coverage

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

Impact of R_{tray}, Δ_{tray}, (R_{OSP}- R_{tray})
(Γ from data)

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

Backup

NSTX

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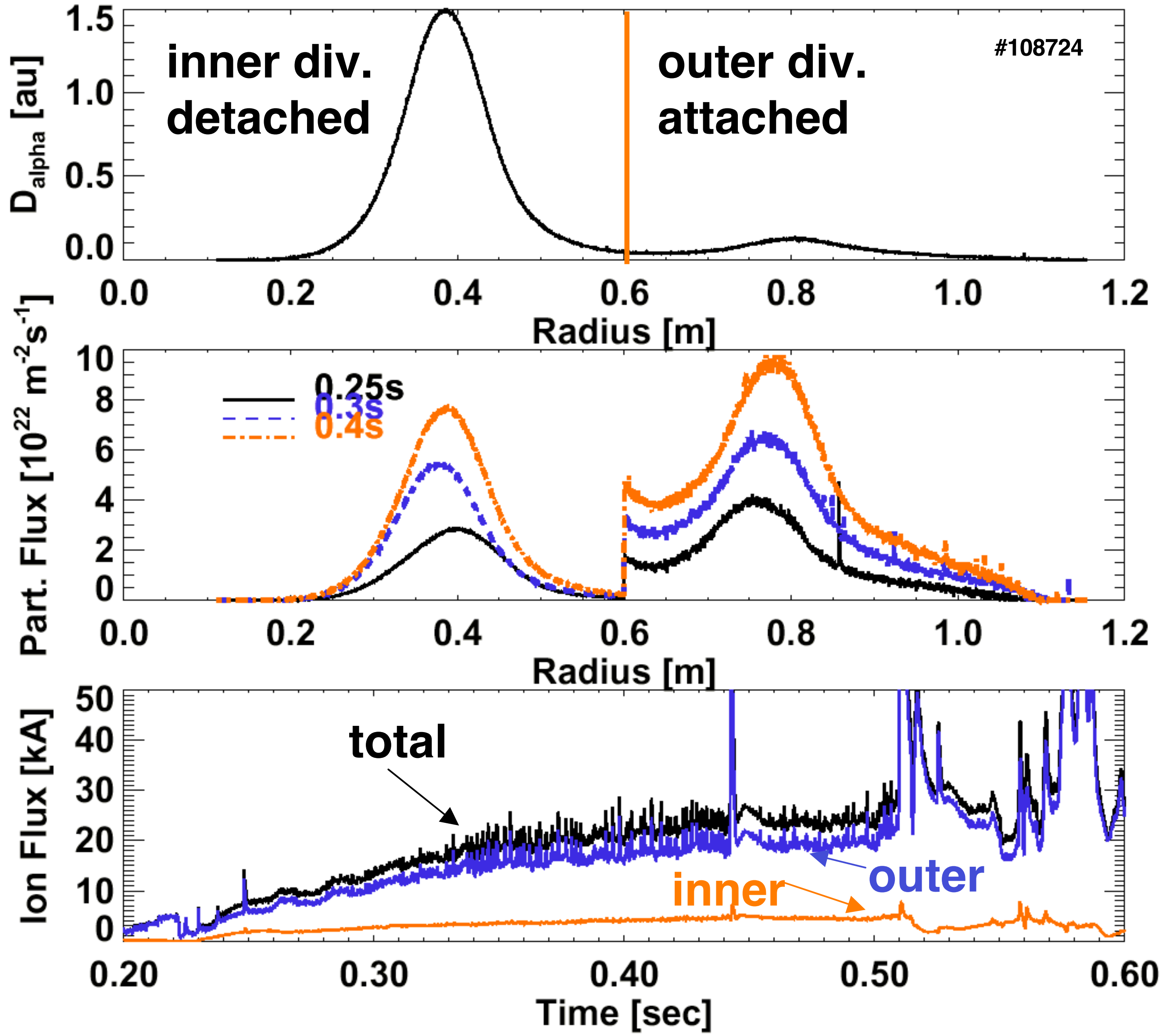
NSTX D_α Peaked on Inboard Side, but Particle Flux Peaked on Outboard side because Inner Divertor is Usually Partially Detached

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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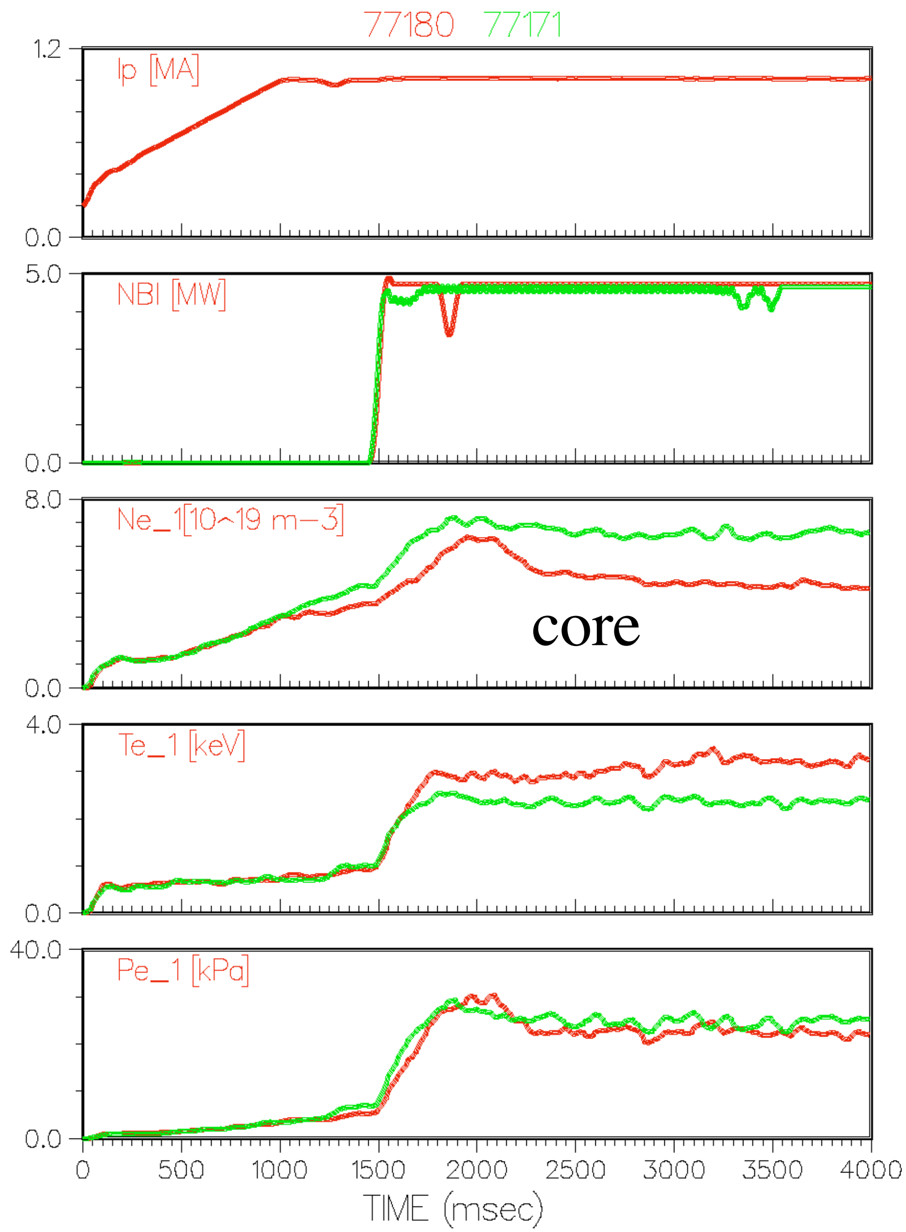
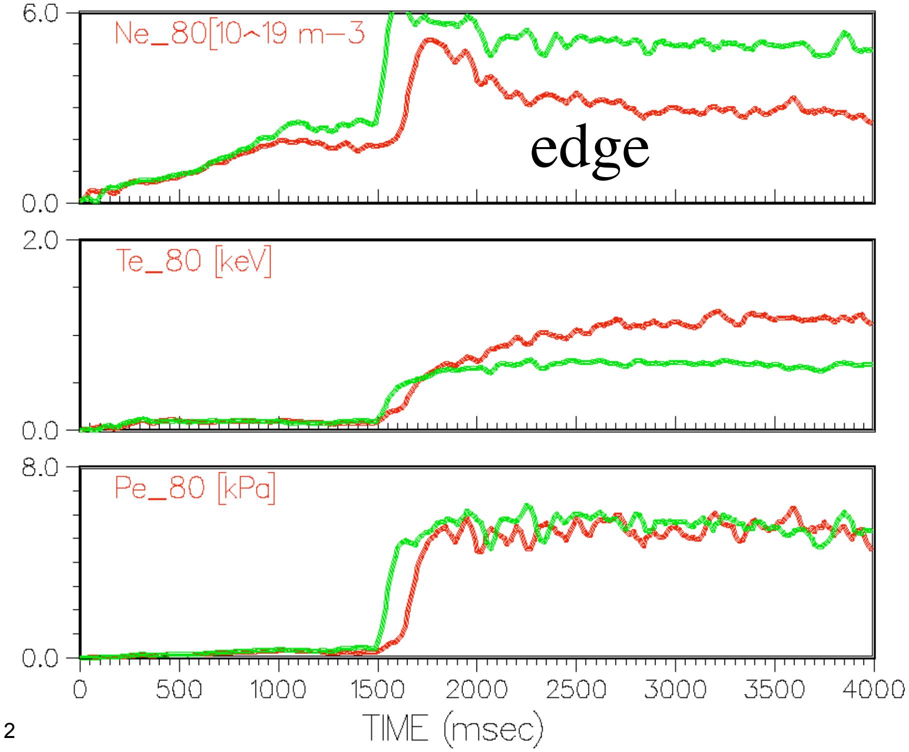
Comparison of Unpumped and Pumped DIII-D Discharges

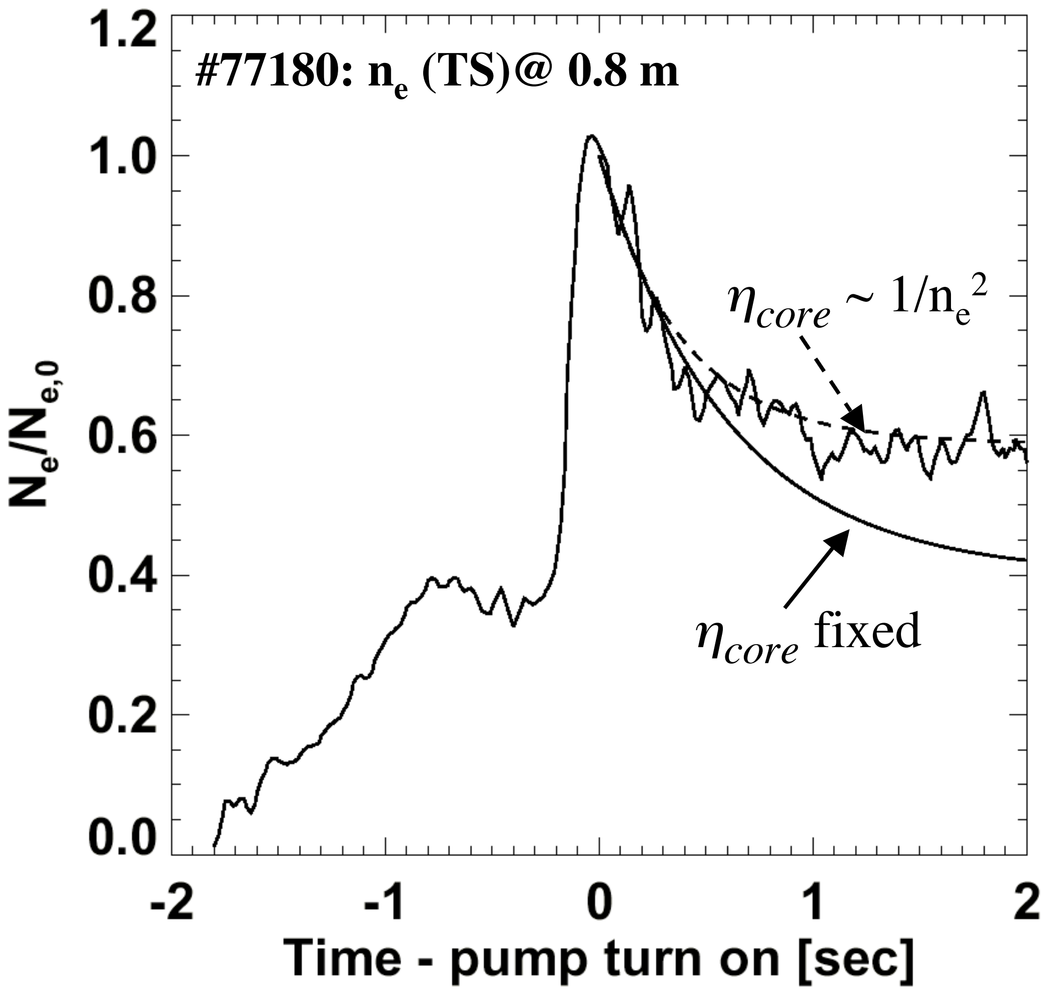
NSTX



- 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 ~ 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^*

Simple Model Can Reproduce DIII-D Data

- τ_p / τ_E is effectively an input, but within range of previous studies (2-4). Note that τ_p is estimate of core confinement.
- τ_p^* increases with time, so that apparent density roll-off faster than simple e-folding with initial τ_p^*
- Diminishing returns as n_e goes down since SOL shielding efficiency goes down, and core fueling fraction increases relative to pump fraction
- Edge n_e goes down more than core n_e - profile more peaked
- Model can be extrapolated for multiple pumps