Research Supported by

Progress on Predictive 0-D Modeling of Pumping Schemes for NSTX

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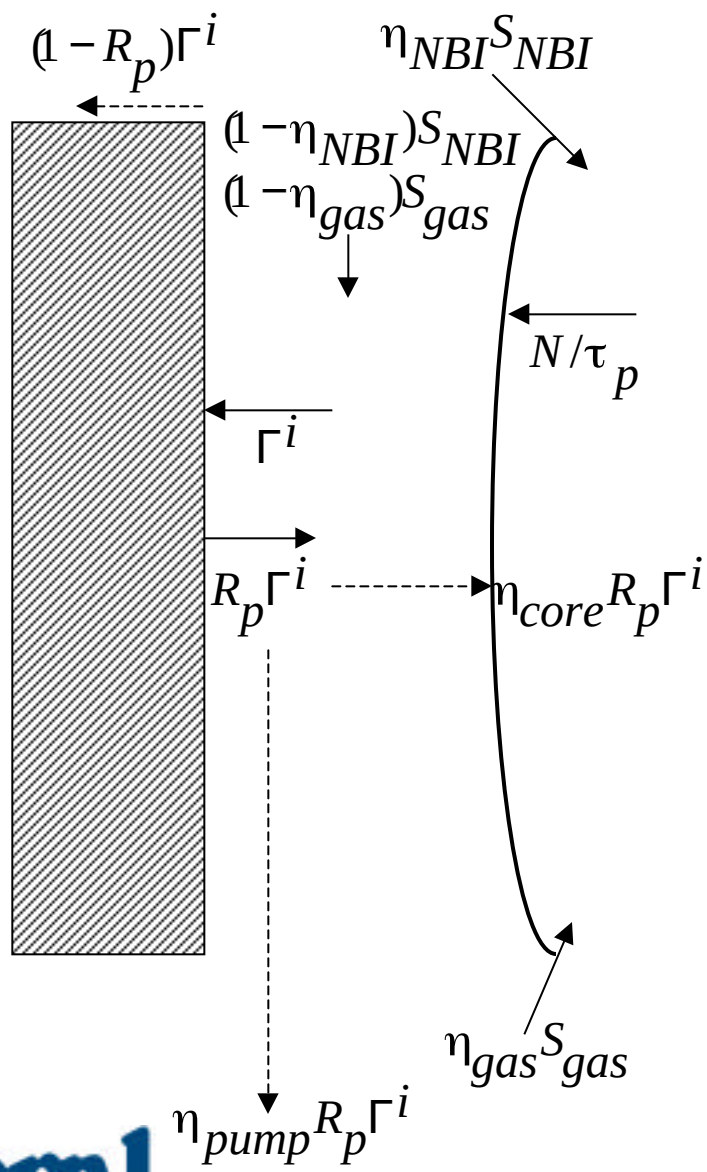
Motivation and Technique

- 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

Particle Balance and Recycling Model



- Consider core and SOL particle content equations

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

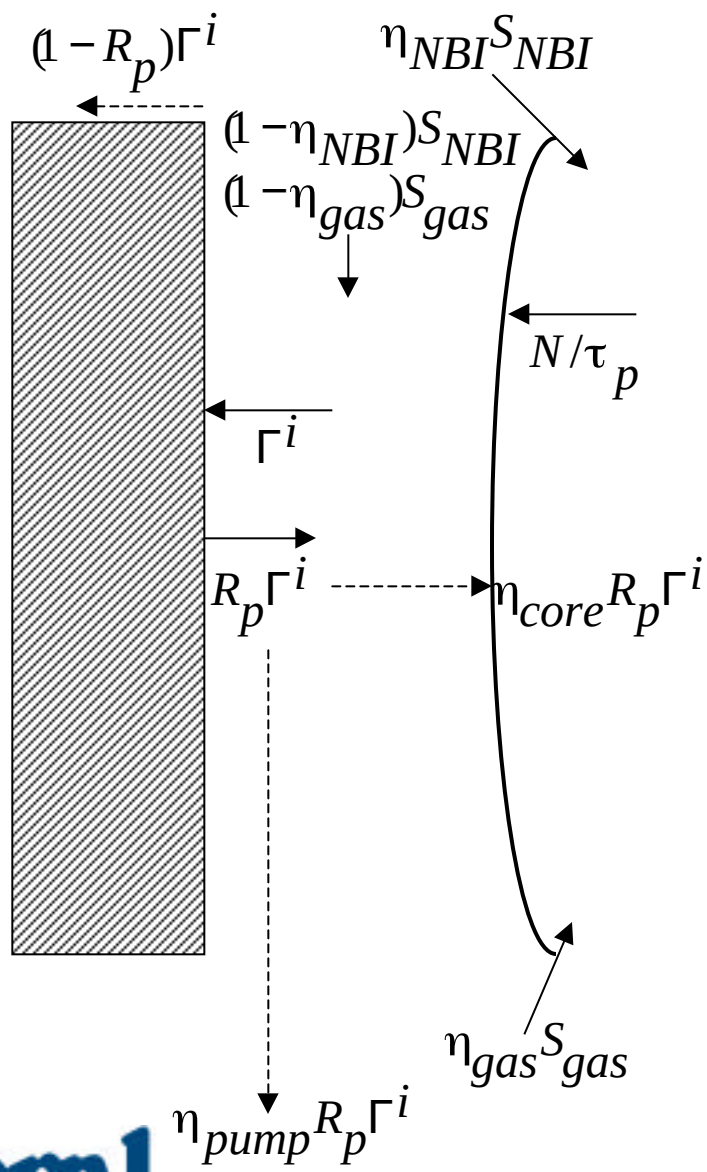
$$\frac{dN_i^{SOL}}{dt} + \frac{dN_0^{SOL}}{dt} = (1-\eta_{NBI})S_{NBI} + (1-\eta_{gas})S_{gas} + \frac{N}{\tau_p} - (1-R_p)\Gamma^i - R_p\Gamma^i(\eta_{pump} + \eta_{core})$$

- 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:

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

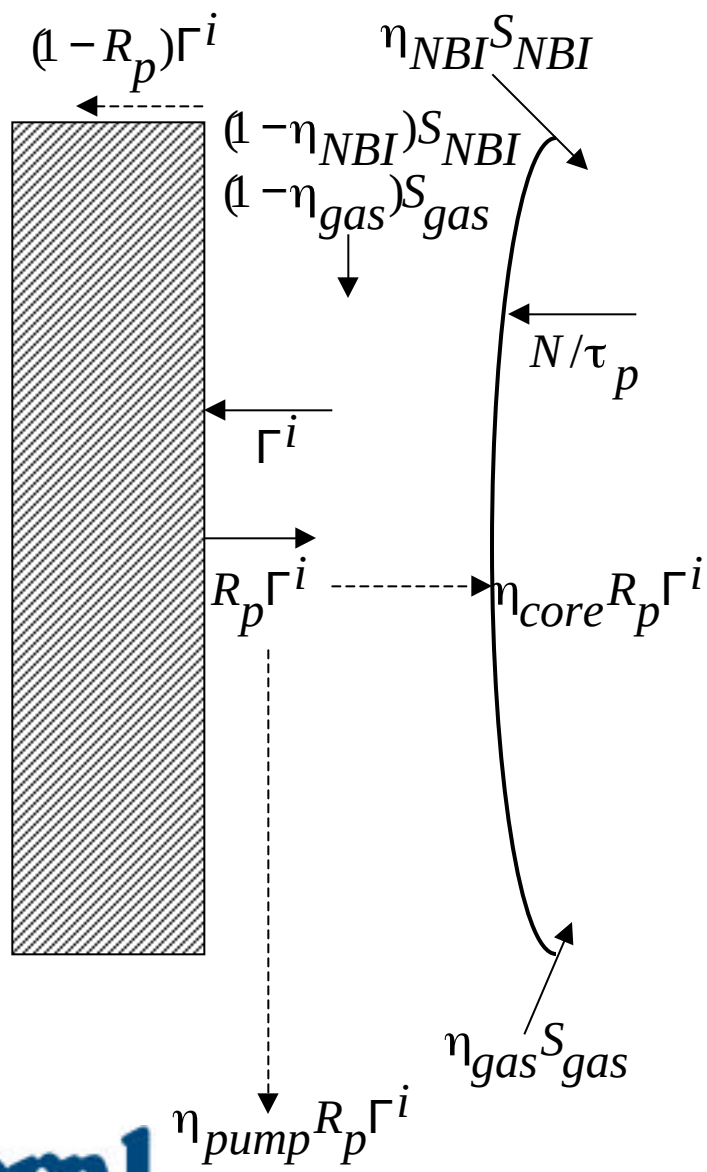
Let $S = S_{NBI} + (1+\beta(1-\eta_{gas}))\eta_{gas}S_{gas}$

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 ($\eta_{pump}>0$)

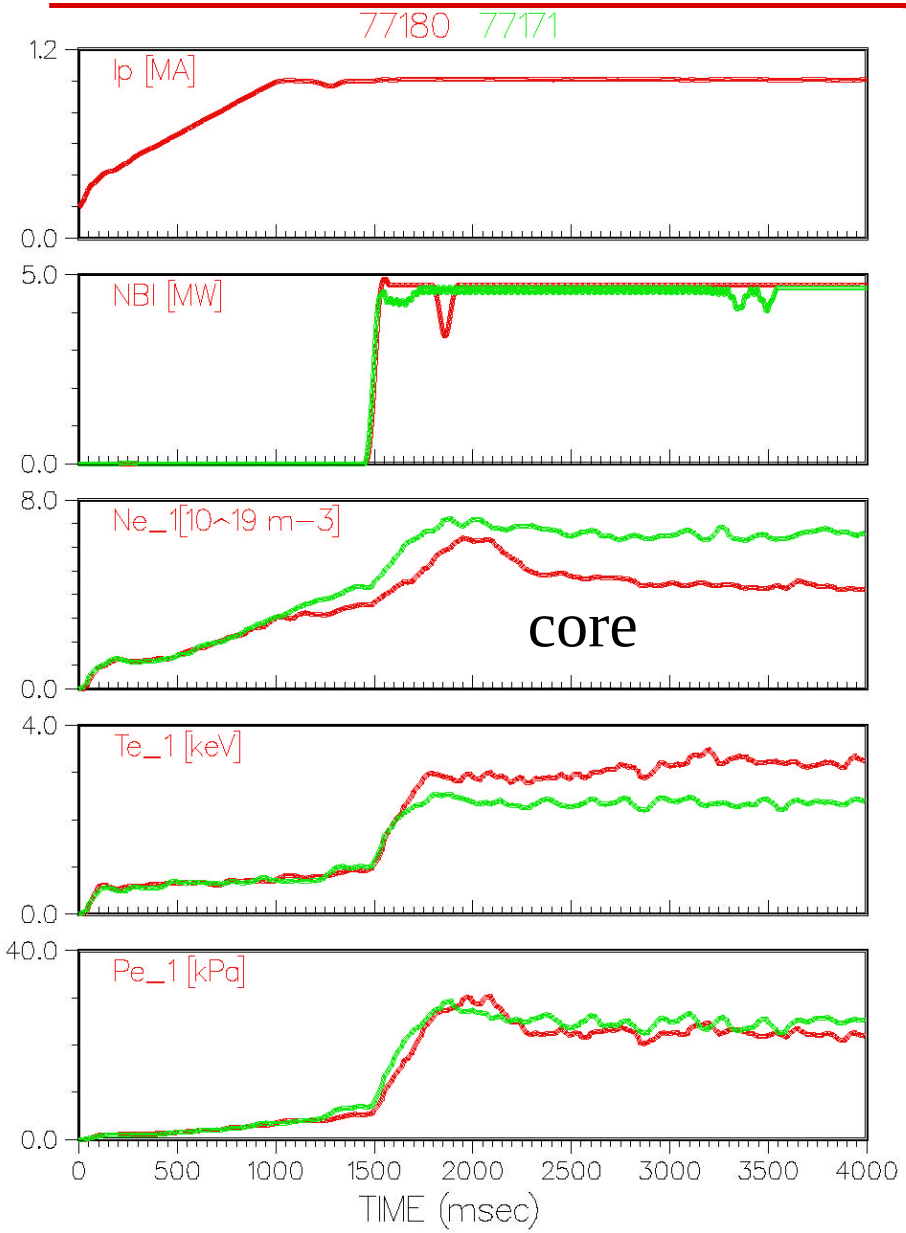
Limits of Particle Balance and Recycling Model



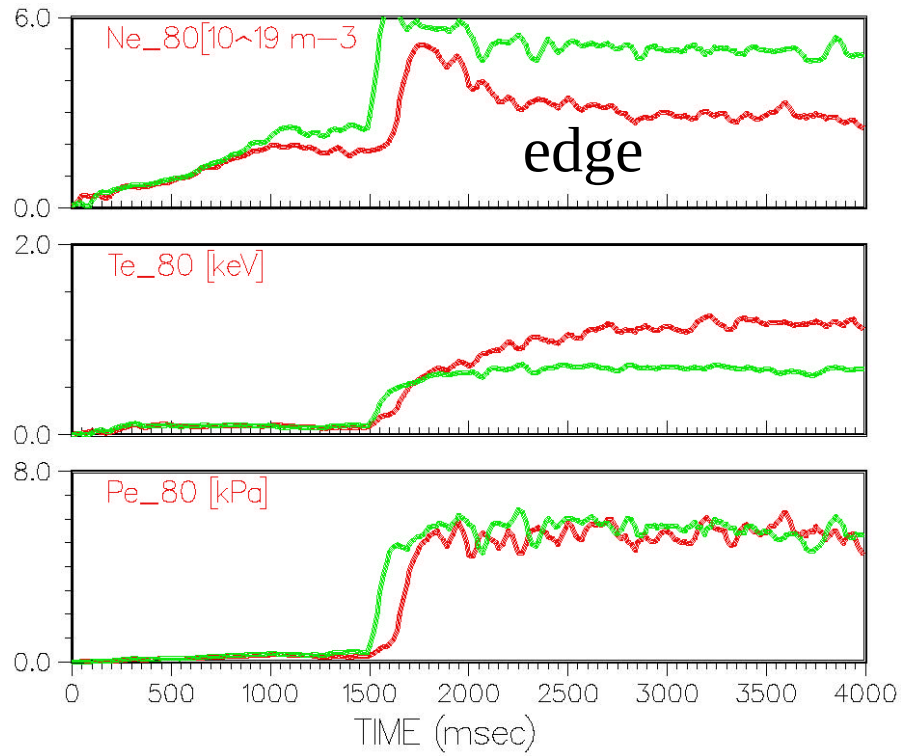
- Note $\tau_p^*/\tau_p = 1/(1-\beta)$
- Pump off: $\tau_p^*/\tau_p \sim 1+ \eta_{core}R_p/(1-R_p)$
  - $\tau_p^*/\tau_p \sim 6$
- Pump on: $\tau_p^*/\tau_p \sim (\eta_{core}+\eta_{pump})/\eta_{pump}$
  - $\tau_p^*/\tau_p \sim 2$

  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)

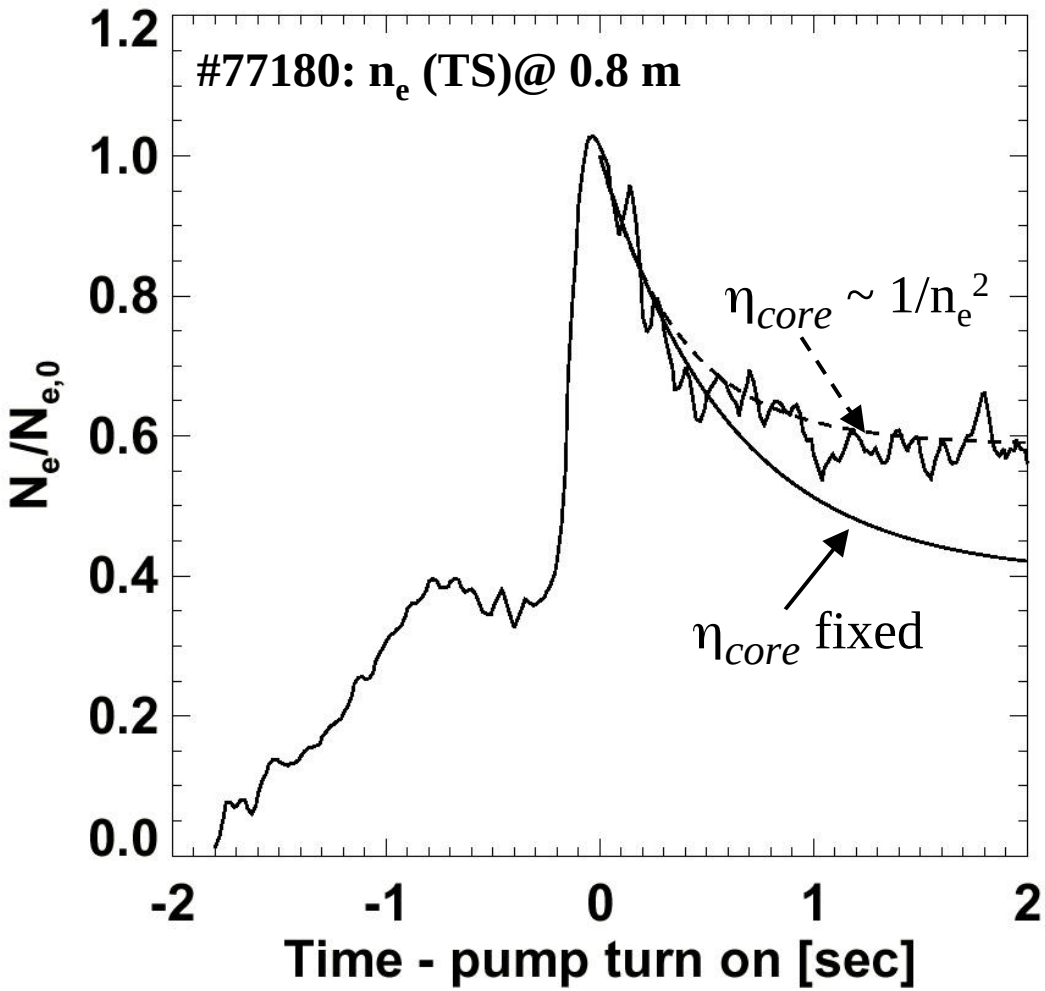
Comparison of Unpumped and Pumped DIII-D Discharges



- 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

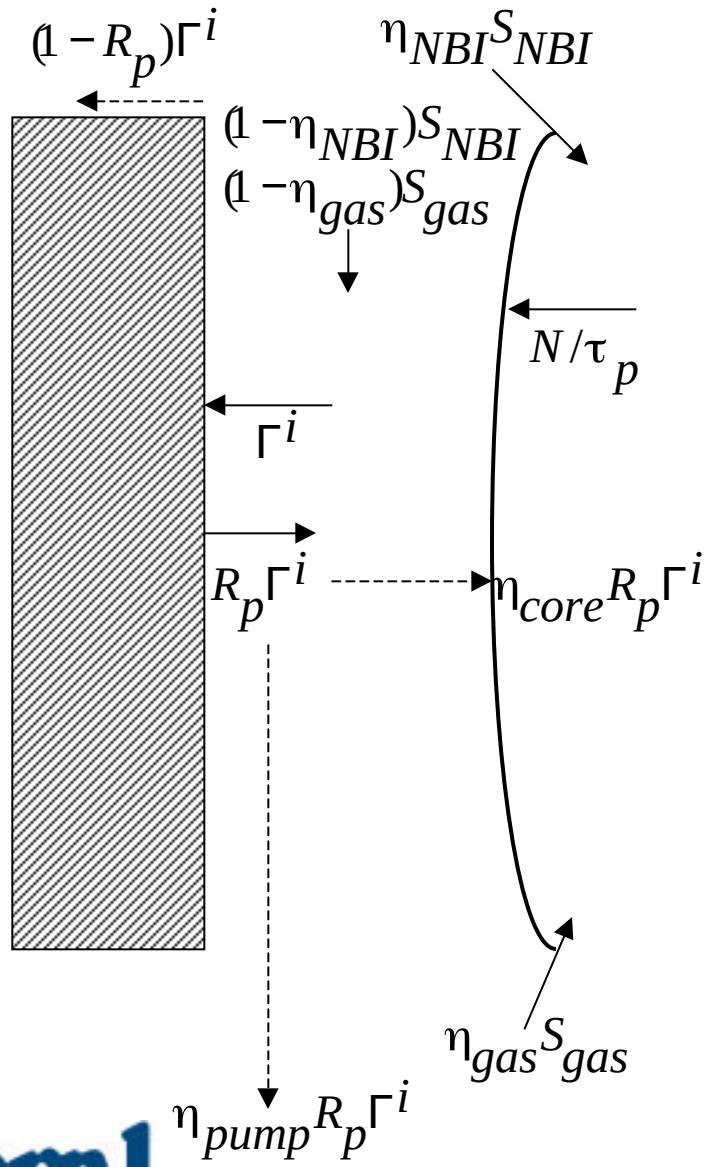


- DIII-D specific data:
  - $R_p \sim 0.98$ for carbon (reference?)
  - R_p changes slowly (Maingi, NF 1996)
  - $\eta_{core} \sim 0.05$-0.15 (Rensink, PoF B 1993)
  - $\eta_{pump} \sim 0.1$ (Maingi, NF 1999)
  - $\eta_{gas} \sim 0.1$ (Maingi, JNM 1997)
  - $\tau_p / \tau_E = 2.5$ (~ Owen, JNM 1997)
- 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^*

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

Limits of Particle Balance and Recycling Model

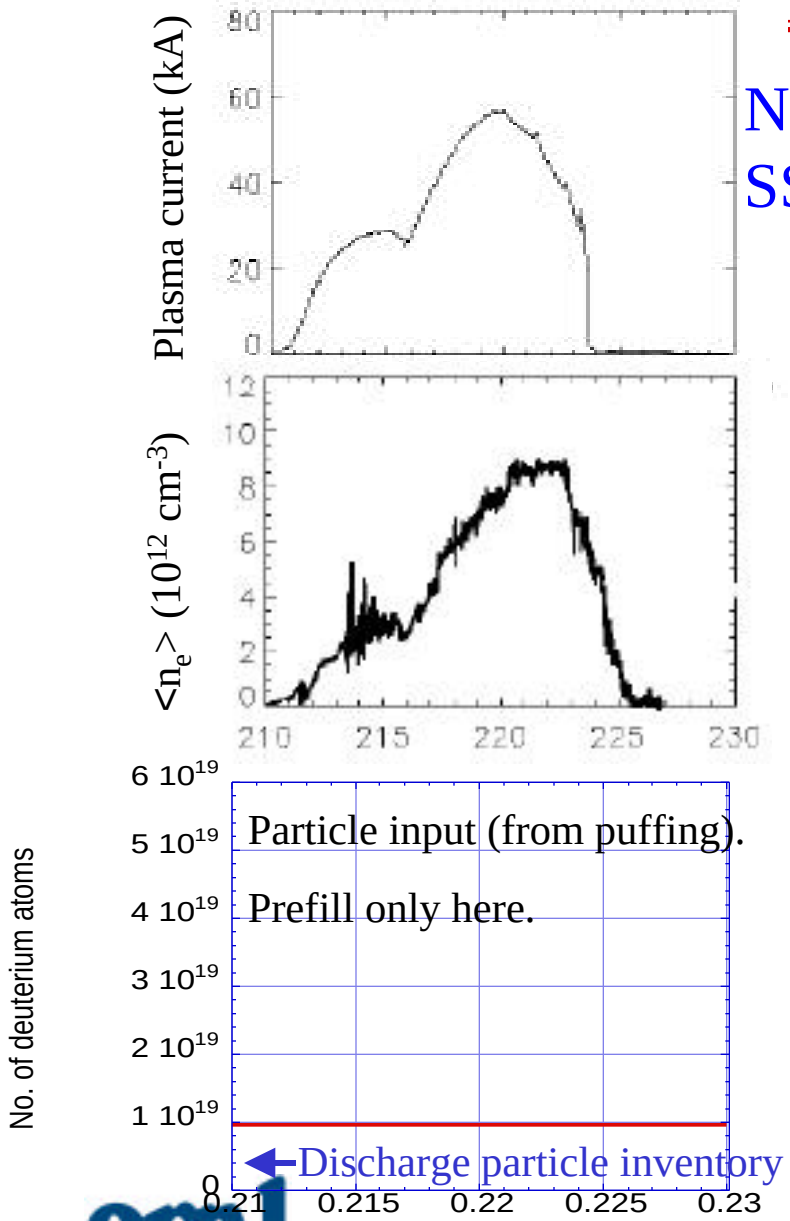


- Note $\tau_p^*/\tau_p = 1/(1-\beta)$
- Pump off: $\tau_p^*/\tau_p \sim 1+ \eta_{core}R_p/(1-R_p)$
- CDX-U specific data:
  - $R_p \sim 0.98$ for carbon (reference?)
  - $R_p \sim 0.2$-0.5 (≤ 0.1 for liquid lithium)
  - $\eta_{core} \sim 0.5$ (guess)

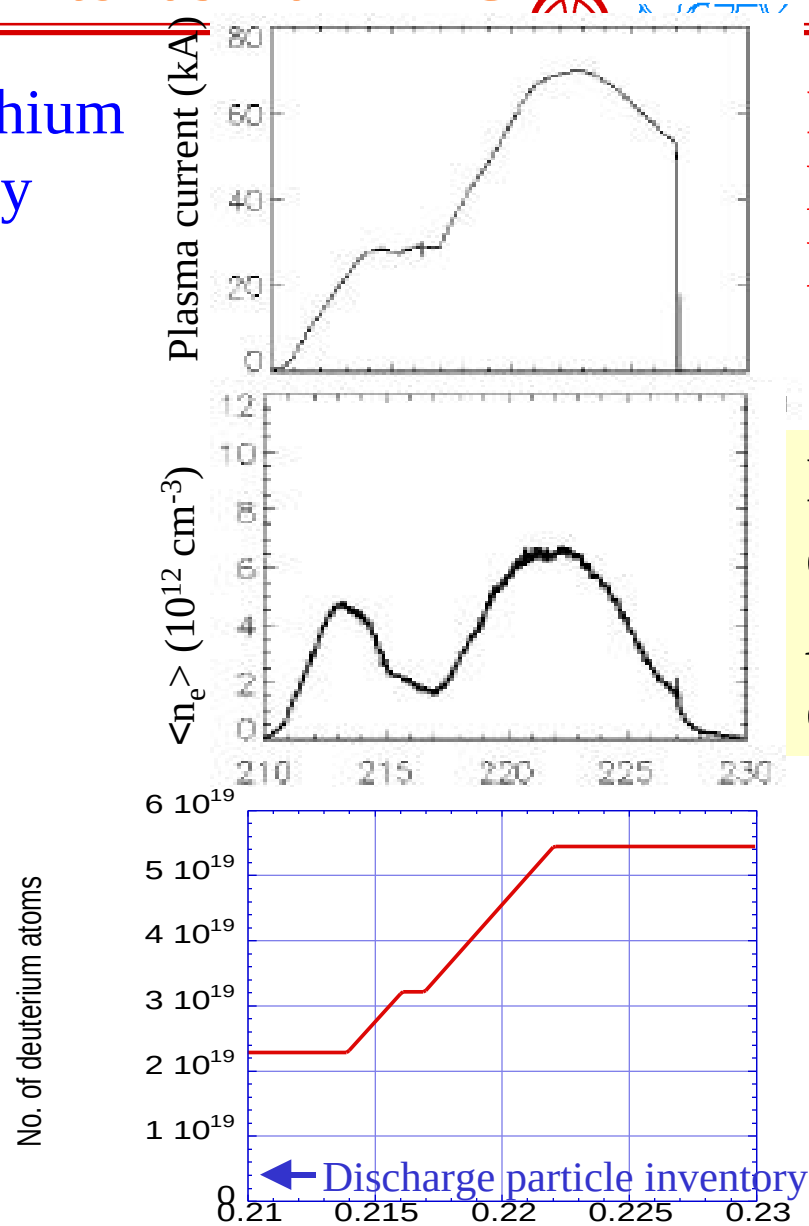
    $\tau_p^*/\tau_p \sim 25$ (SS), 1.5 (lithium)

  n_e should go down by 94% w/pumping or fueling should increase by 16-17x at constant density
- Actual fueling increased by ~ 8x

Fueling/Density Increased by 8x in CDX-U with Liquid Lithium limiter as main PFC



No lithium
SS tray

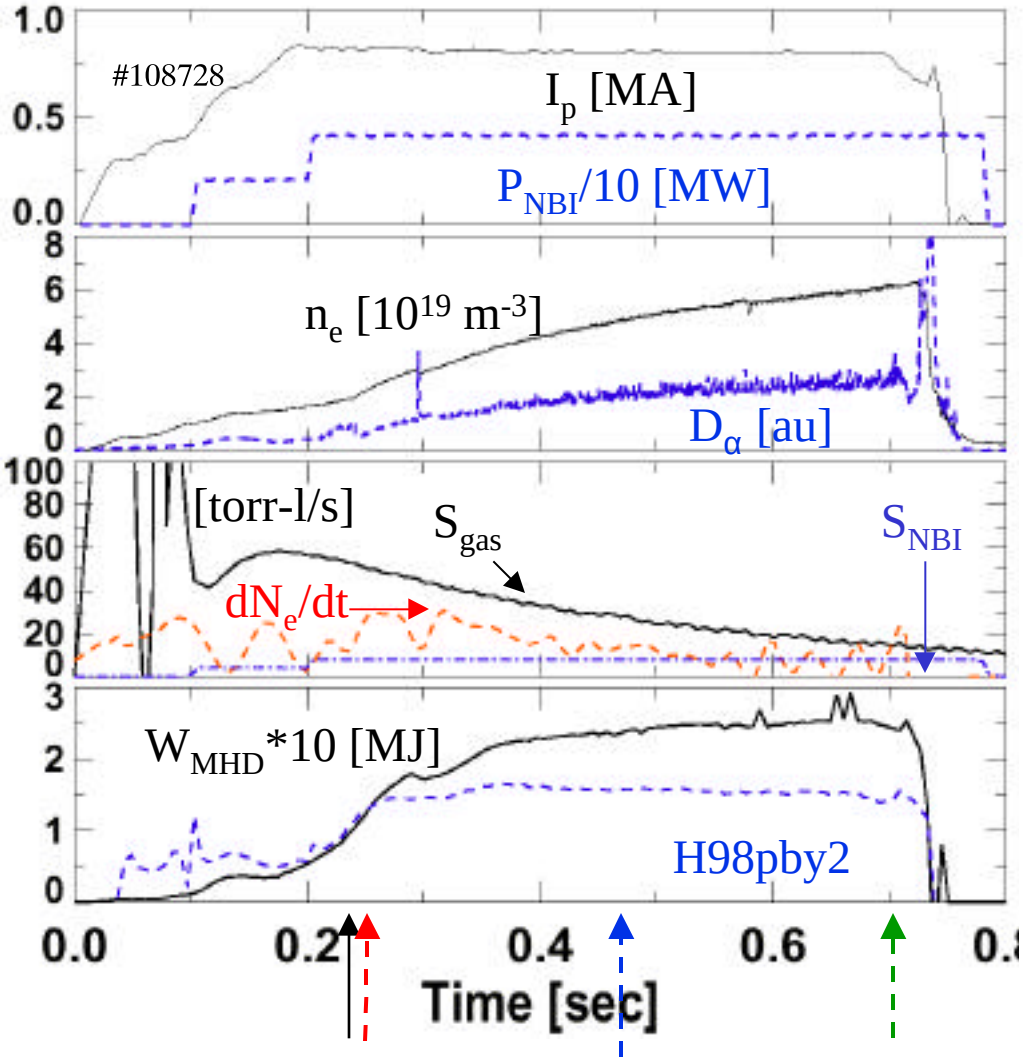


Liquid
lithium
limiter

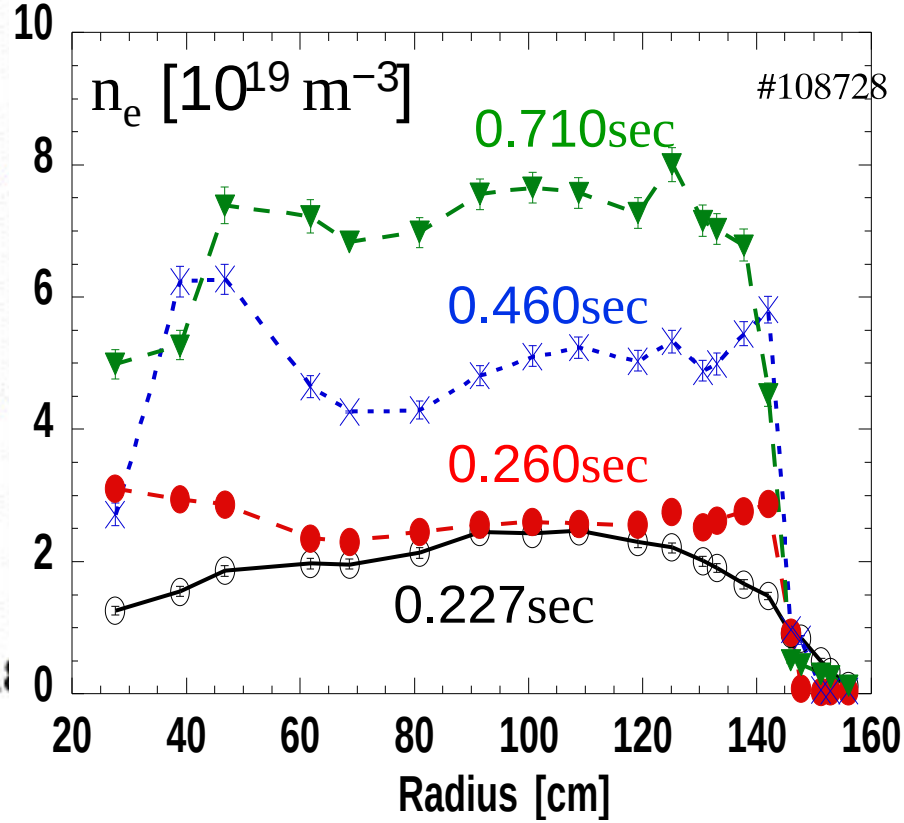
Need to estimate R_p for either case

Majeski, Kaita

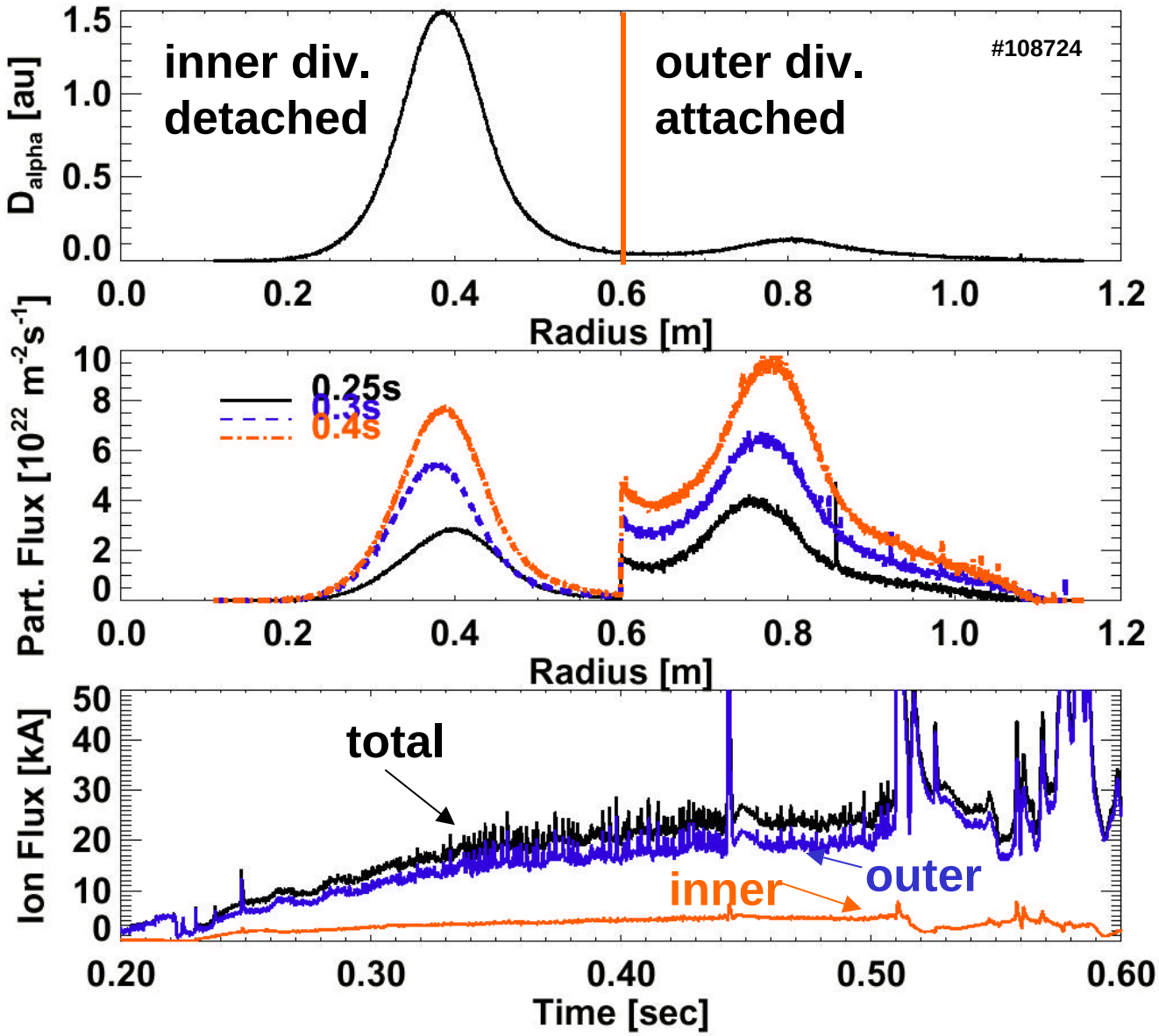
Uncontrolled (non-disruptive) density rise in long pulse H-modes in NSTX



- High τ_p and continued gas puffing both contribute to dN/dt
- Core fills in with time



NSTX D_α Peaked on Inboard Side, but Particle Flux Peaked on Outboard side if Inner Divertor is 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.

Classic Density Rise Model Can Be Modified with Realistic Time Dependencies

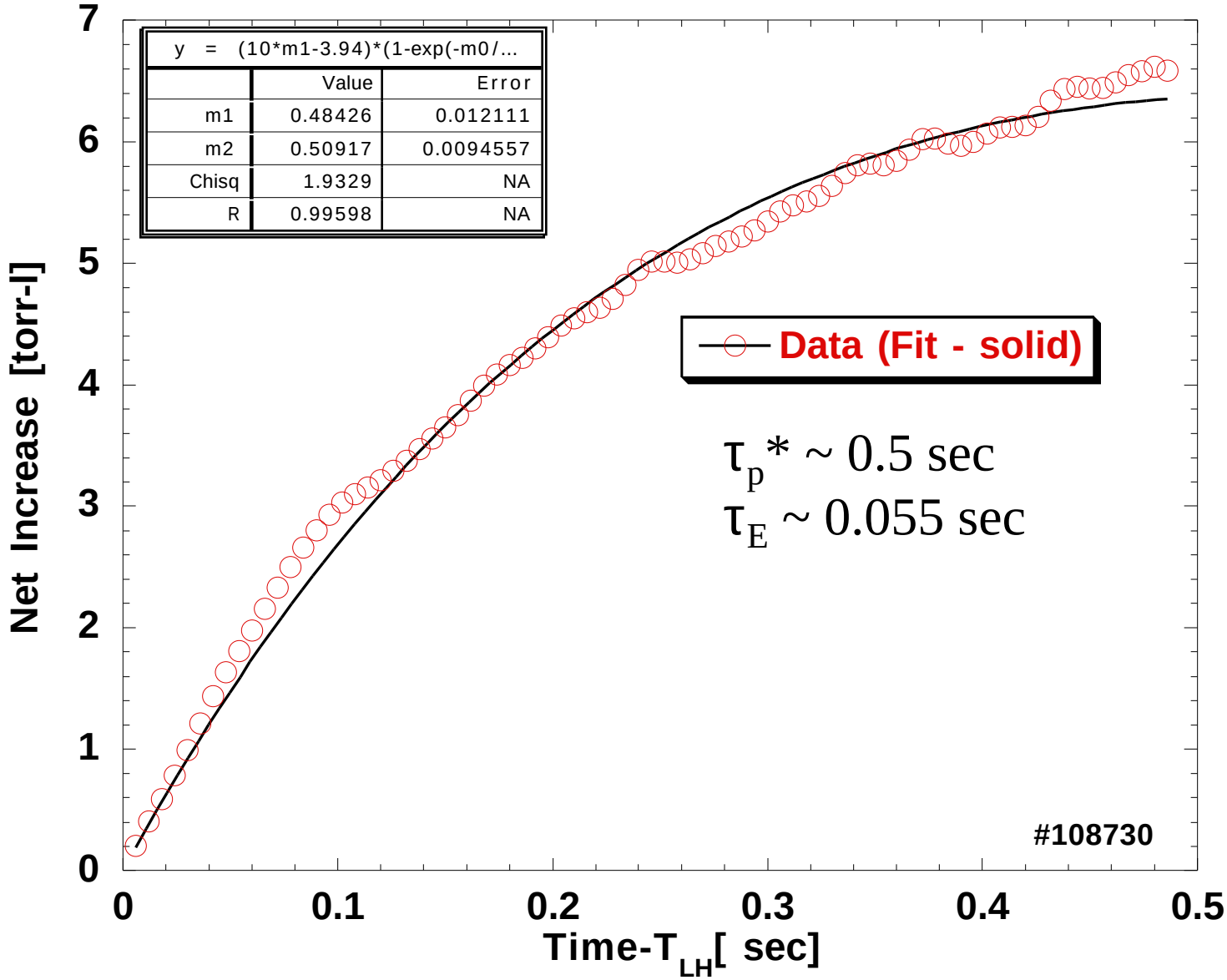
- Assuming time dependent gas source term; time dependence of plasma content has analytic solution

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

where $S_{gas}(t) = S_{gas,0} \exp\left(-\frac{t}{\tau_{gas}}\right); \tau_{gas} \sim 0.55\text{sec}$

$$N(t) - N_o = \left(\eta_{NBI} S_{NBI} \tau_p^* - N_o\right)\left(1 - \exp\left(-\frac{t}{\tau_p^*}\right)\right) + \frac{\eta_{gas} S_{gas,0} \tau_{gas} \tau_p^*}{\tau_{gas} - \tau_p^*}\left[\exp\left(-\frac{t}{\tau_{gas}}\right) - \exp\left(-\frac{t}{\tau_p^*}\right)\right]$$

Particle Containment Times ~ 0.5 sec. in NSTX with more realistic gas fueling rate model



Remarks about Cryopump and Lithium Comparison

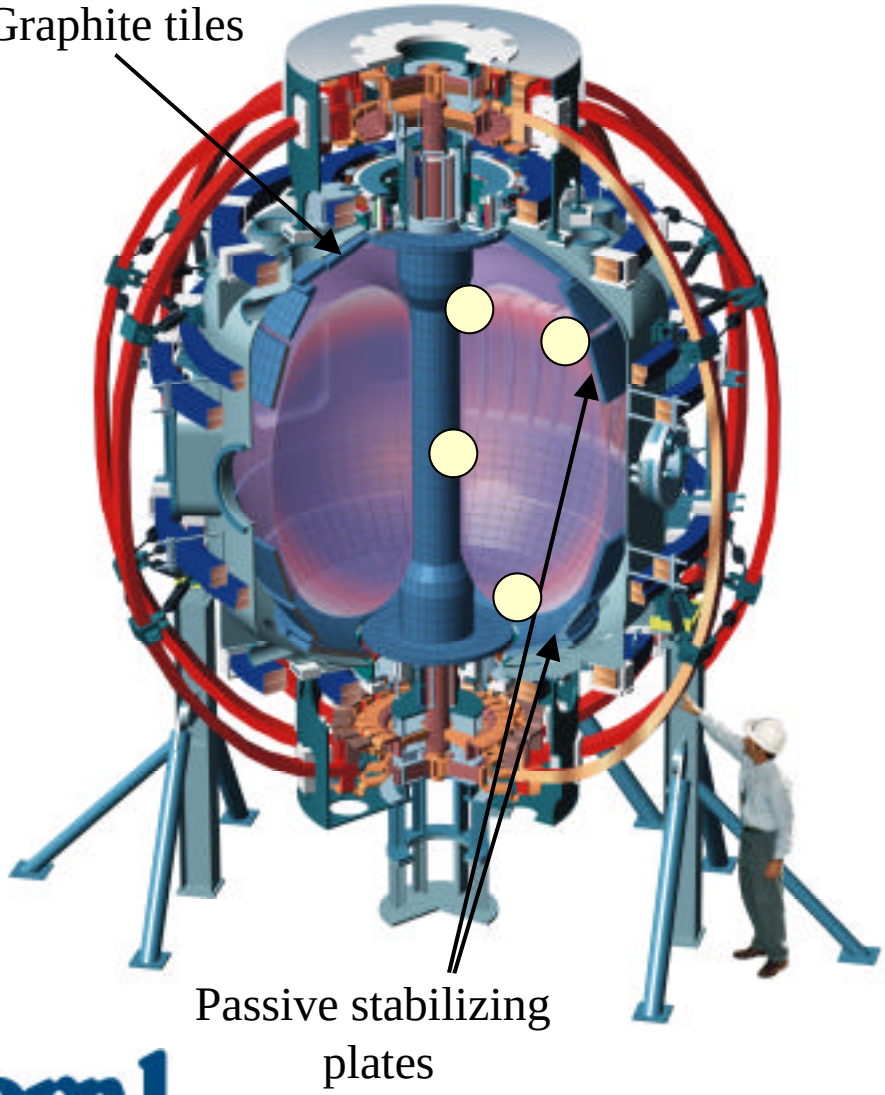
- If outer cryopump optimized, NSTX edge density control should be similar to DIII-D
  - plenum capture fraction should be comparable =
  - similar ratio of $\tau_p^*/\tau_p \leq 10$ in un-pumped discharges =
  - higher outboard fraction of outer particle flux +
  - possibly higher core fueling efficiency (conductance, density) –
- Impact of lithium on NSTX won't be as strong as CDX-U
  - core fueling efficiency lower in NSTX, so reduction in τ_p^* won't be as large
- Either system will likely provide adequate density control

Action Items

- NSTX: Measure particle flux profile with Langmuir probes
- NSTX: Estimate core fueling efficiency with UEDGE/ DEGAS-2 (and assess role of main chamber recycling)
- CDX-U: develop technique to estimate R_p with SS tray
- NSTX: predict R_p with lithium coating system (module A) and flowing liquid lithium (module B)
- NSTX: compute effect of change in edge ionization source on core transport with WHIST or QUIST

Backup

NSTX Explores Low Aspect Ratio (A=R/a) physics regime



Parameters	Design	Achieved
Major Radius	0.85m	A ≥ 1.27
Minor Radius	0.67m	
Plasma Current	1MA	1.5MA
Toroidal Field	0.6T	0.6T
Heating and Current Drive		
NBI (100keV)	5MW	7 MW
RF (30MHz)	6MW	6 MW

Wall Conditioning:

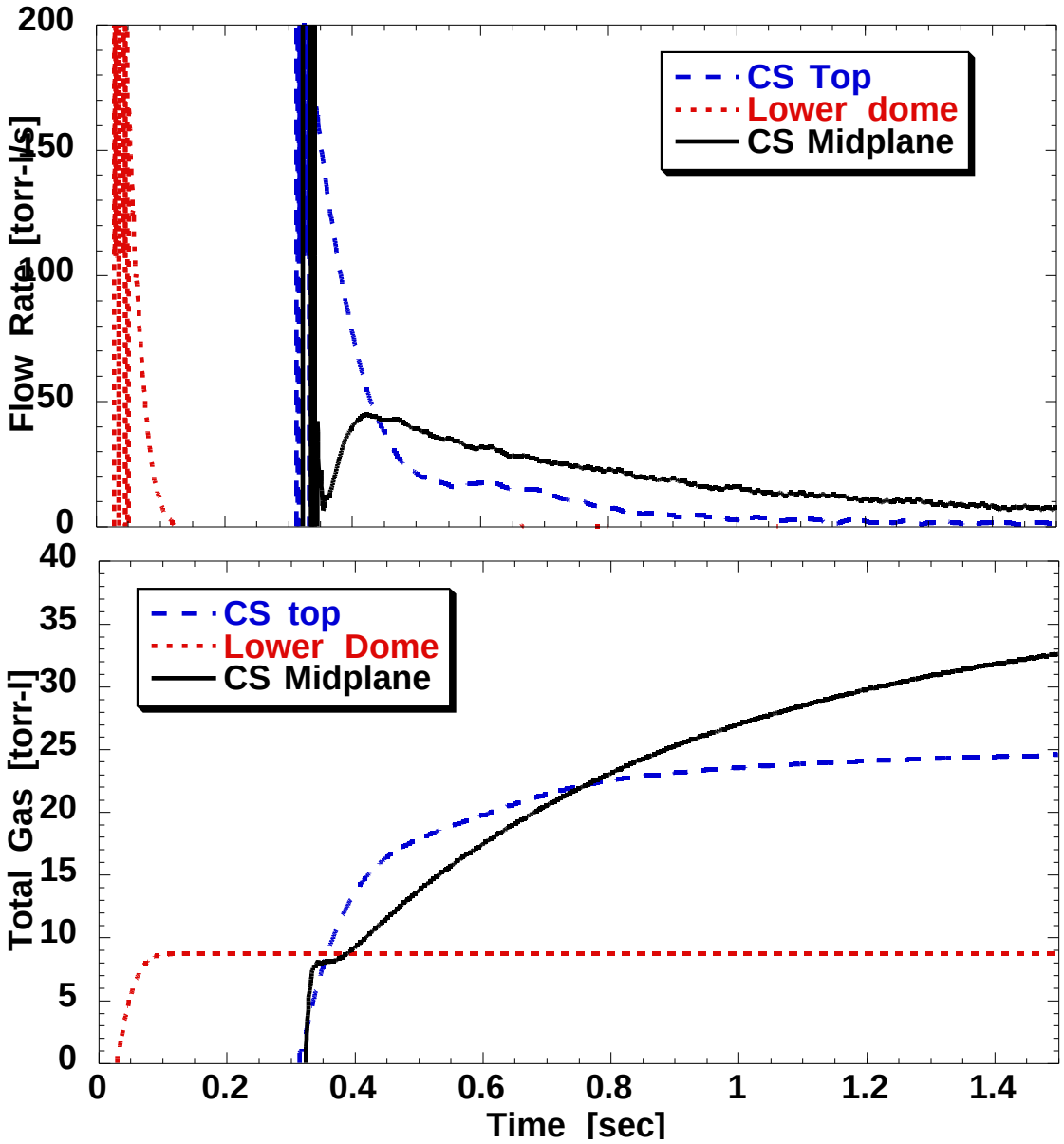
350 deg. bakeout of graphite tiles

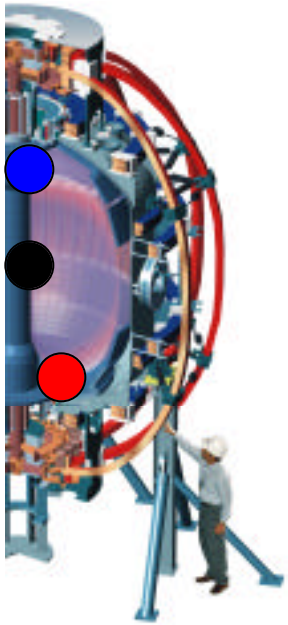
Regular boronization (~3 weeks)

Helium Glow between discharges

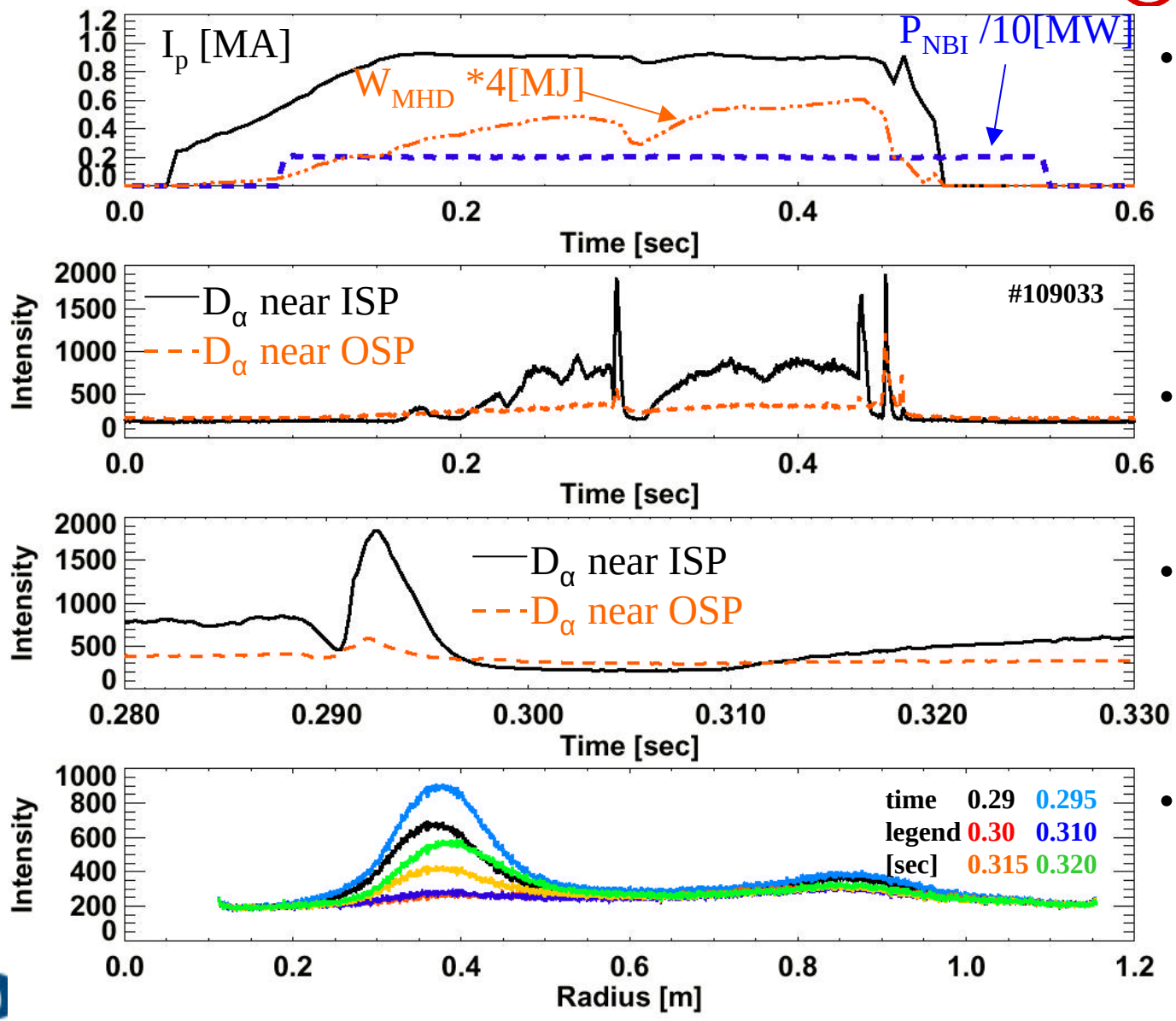
Center stack gas injection

Load-and-Dump Gas Injectors Have Different Flow Characteristics and Delay Time

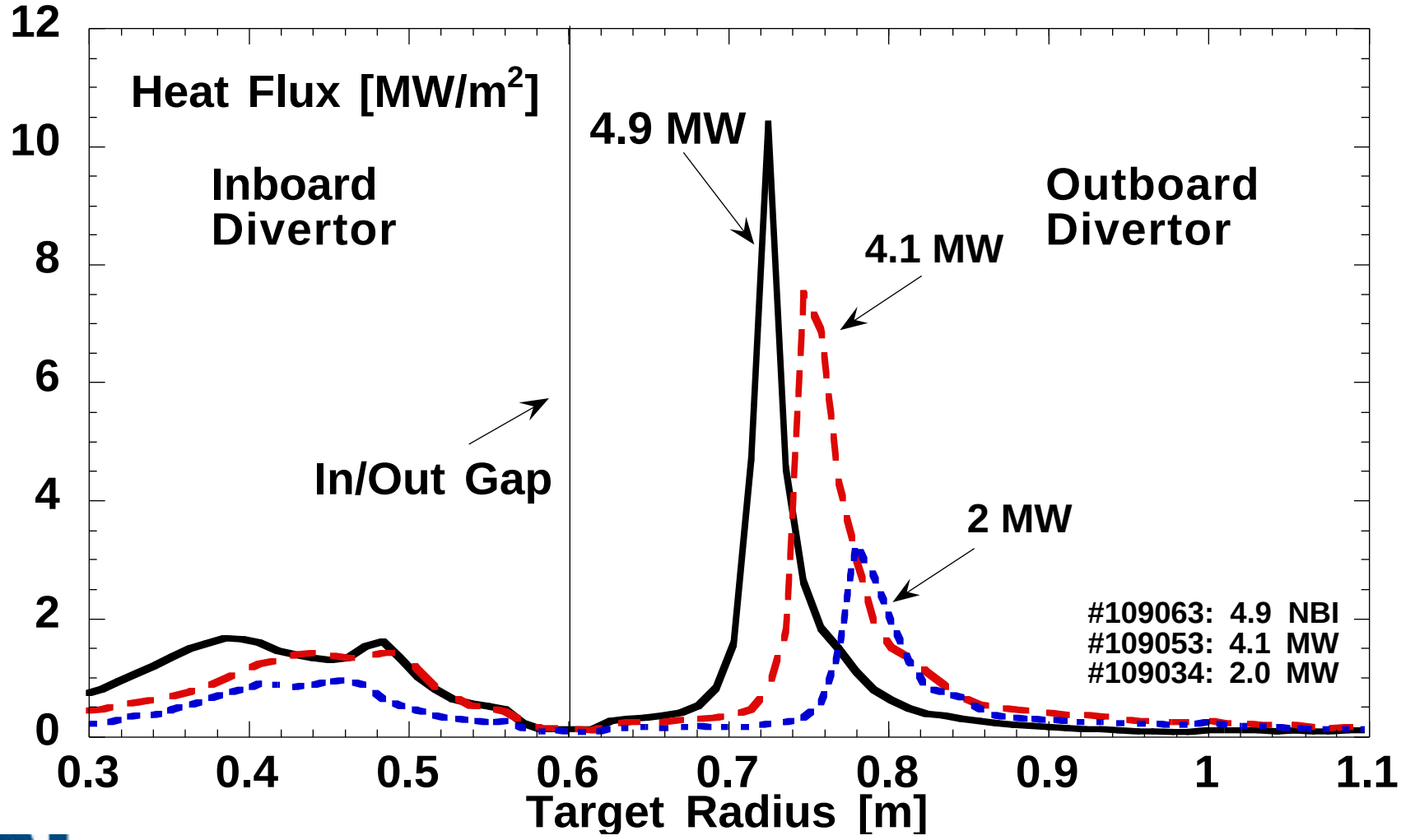




D_α profile normally peaks near Inner Strike Point, but reverses during heat pulse



- Reversal of in/out D_α profile during heat pulse is consistent with inner side being detached
- Similar situation in pre-cryopump days at DIII-D
- Reduced recycling will probably re-attach ISP, so D_α will go down
- Likely more particles near OSP; need LP data to confirm

Peak heat flux always peaks near outer strike point in lower-single null configuration

- Good power accountability: $P_{div}^{in+out} \sim 70\%$ of P_{SOL}