NSTX-U

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NSTX Upgrade Cryo-pumping Design Progress, Particle Control Plans

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NSTX-U PAC 31
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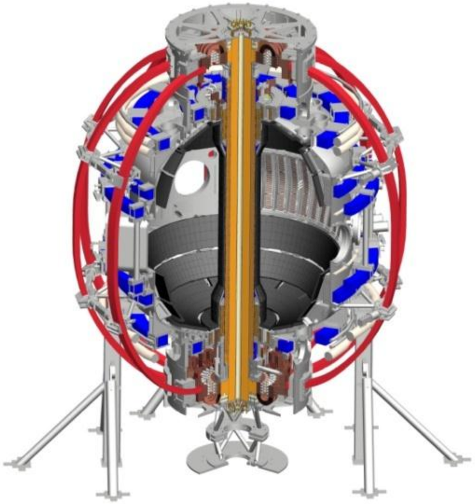

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Motivation

- Particle control is needed to meet NSTX-U programmatic goals
  - Avoid density limit, radiative collapse during long-pulse (5s) discharge
  - Reduce collisionality to access new core physics
  - Control n/n_G for non-inductive scenarios
- Several PAC recommendations concern particle control
  - Perform cryo-pump design study as complement to Li efforts

    PAC 29-4 **PAC 29-5b** **PAC 29-10**

  - Consider alternatives to ELM-free scenario: Type-I ELMy or small-ELM

    PAC 29-40 **PAC 29-42**

- Milestone R(12-2): Project deuterium pumping capabilities for NSTX-U using lithium coatings and cryo-pumping
  - Use existing discharges to assess persistence of pumping by Li coatings, project to NSTX-U pulse lengths
  - Develop cryo-pump design, analyze which scenarios and densities can be pumped with stationary deuterium inventory

Outline

- Progress in cryo-pump design
  - Pumping model developed for use in plenum geometry design
  - Performance and flexibility of optimized system

- Analysis of use of lithium coatings for long-pulse
  - Time-dependent recycling characteristics in ELM-free plasmas
  - Long-pulse, ELMy plasmas with partially passivated lithium

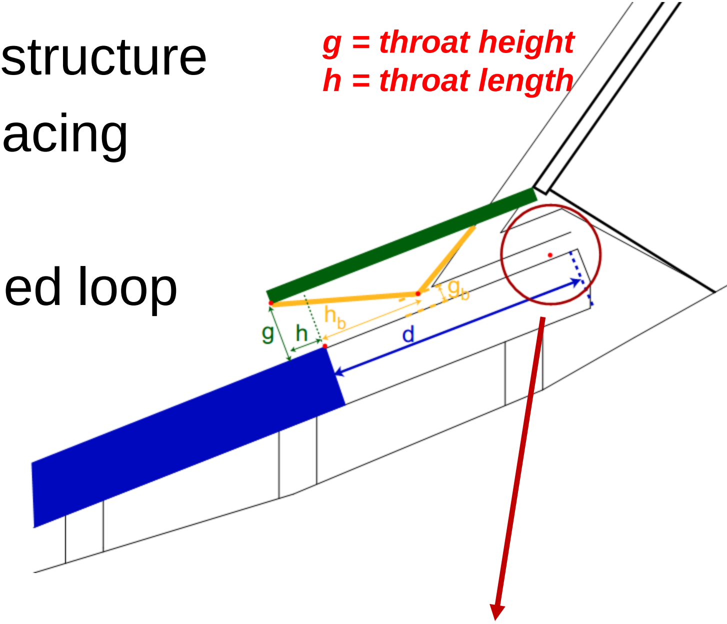
- Future plans
  - Near term analysis
  - Experimental plans for NSTX-U

Cryo pump parameters similar to the DIII-D ADP have been taken as a starting point for design analysis

- Plenum location studied: under new baffling structure near secondary passive plates, possibly replacing some outer divertor tiles
- Pumping capacity of a toroidal liquid He cooled loop (Menon, NSTX Ideas Forum 2002)
  - S=24,000 l/s @ R=1.2m
  - Need plenum pressure of 0.83 mtorr to pump beam input (10MW~20 torr-l/s)
- Pumping rate:

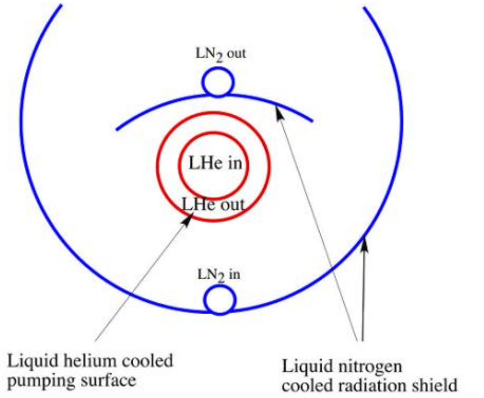
$$I_{pump} = P_{pl} S = \frac{I_0}{S+C} S$$

  - P_{pl} = plenum pressure
  - I_0 = neutral flux into plenum
  - C = throat conductance
- To optimize, need C(g,h), I_0(g,h)



g = throat height

h = throat length



Cross-section of the pump (10 cm outer dia.)

Analytic pumping model* used to optimize pumping chamber

- Uses first-flight model for neutral flux into pump plenum
- Requires knowledge of divertor plasma profiles
- Validated against DIII-D experiments

$$P_{pl} = \frac{I_0}{S+C} \Rightarrow P_{pl} = \frac{I_0}{S+C}\frac{C}{C_{eff}}$$

Plenum pressure corrected for penetration of neutrals through long duct (verified using EIRENE)

$$I_0 = \int_{R_{\min}}^{R_{\max}} \Gamma_0(r) F(r) T(r) 2\pi R_m dr$$

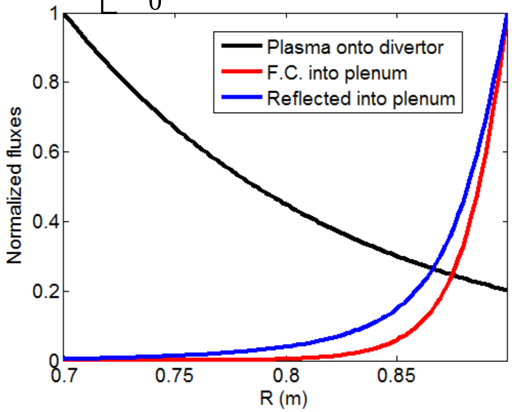
Neutral current into plenum

$$F(r) = \frac{1-\cos\Theta_{\max}(r)}{2}; \Theta_{\max}(r) = \tan^{-1}\left(\frac{g}{R-R_{ent}}\right)$$

Solid angle of plenum entrance

$$T(r) = \exp\left[\frac{-1}{v_0}\int_R^{R_{\max}} n_e(r)\langle\sigma v\rangle_{EII}(r) dr\right]$$

Transmission of neutrals through plasma



Origin of neutrals making it into plenum tends to be localized to near-entrance region

Dominantly due to solid angle factor

**R. Maingi, Nucl. Fus. 39 (1999) 1187*

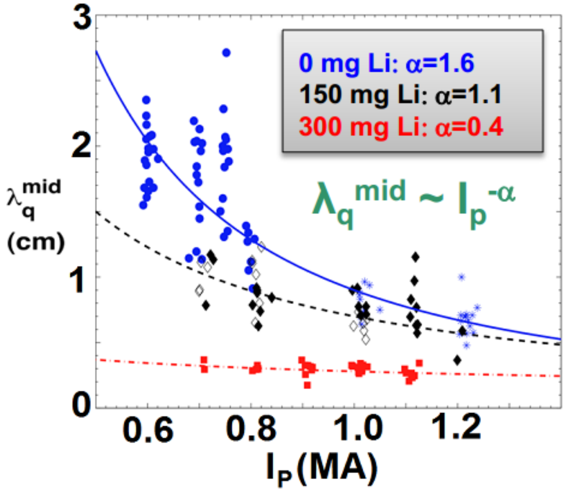
Plasma parameters are estimated to optimize plenum geometry

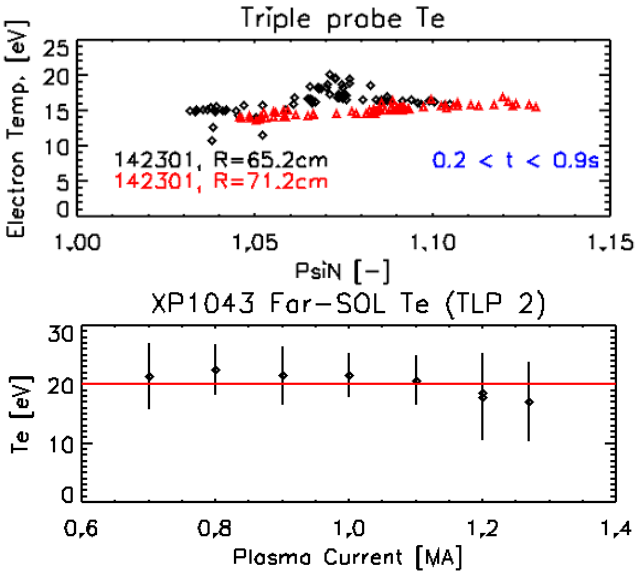
- If heat flux (scaling expts), angle of B wrt surface (α, LRDFIT), and plasma temperature (“typical” T_e from HDLP) are known, -> density and particle flux profiles can be obtained:

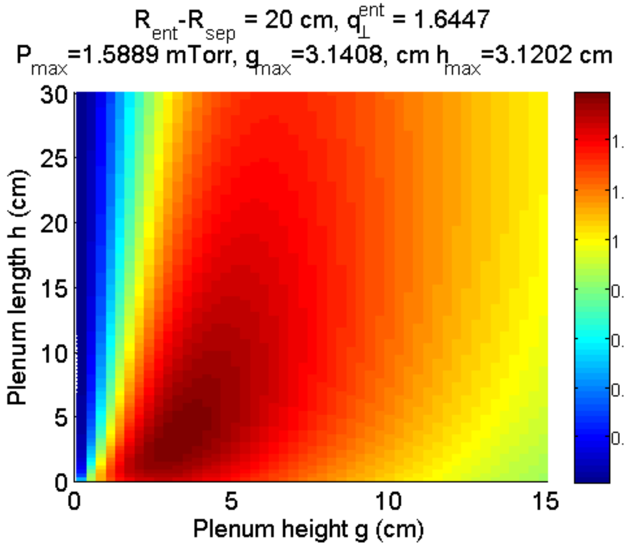
$$\Gamma_\perp = q_\perp / 7T$$

$$n = \Gamma_\perp / \left(\sin\alpha \sqrt{2T/m}\right)$$

- Radial $q_\perp$ profiles used for calculations below, with T_e=15.0 eV
  - P_{div} = 4MW, λ_q=0.5cm, f_{exp}=25
  - A few outer strike point positions tried

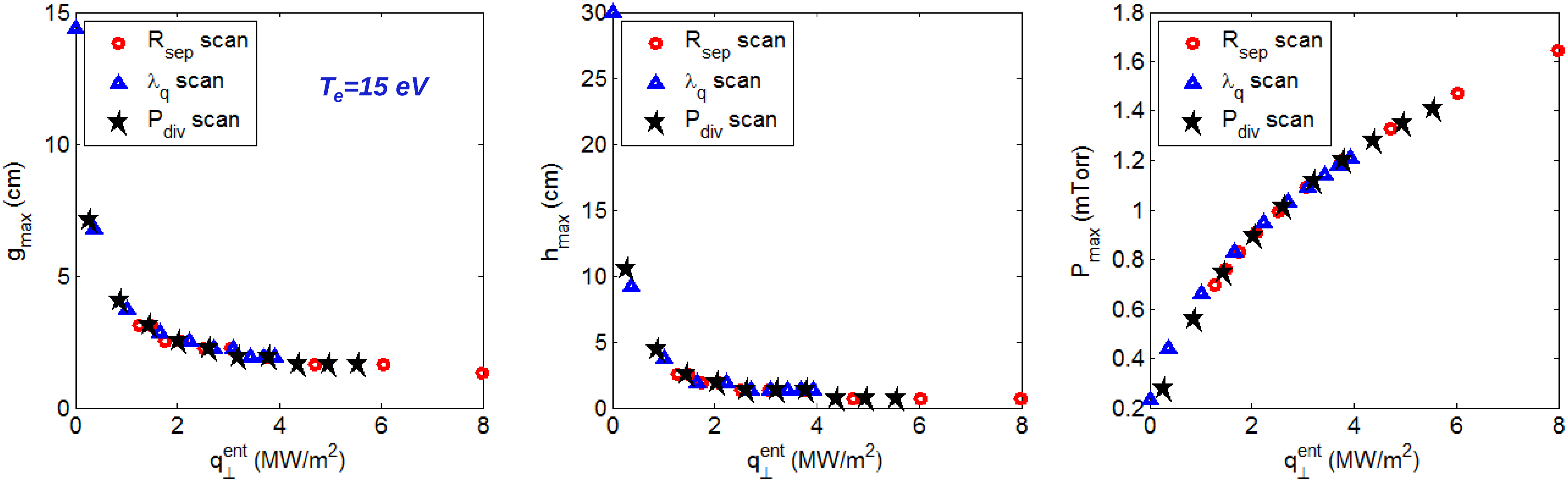






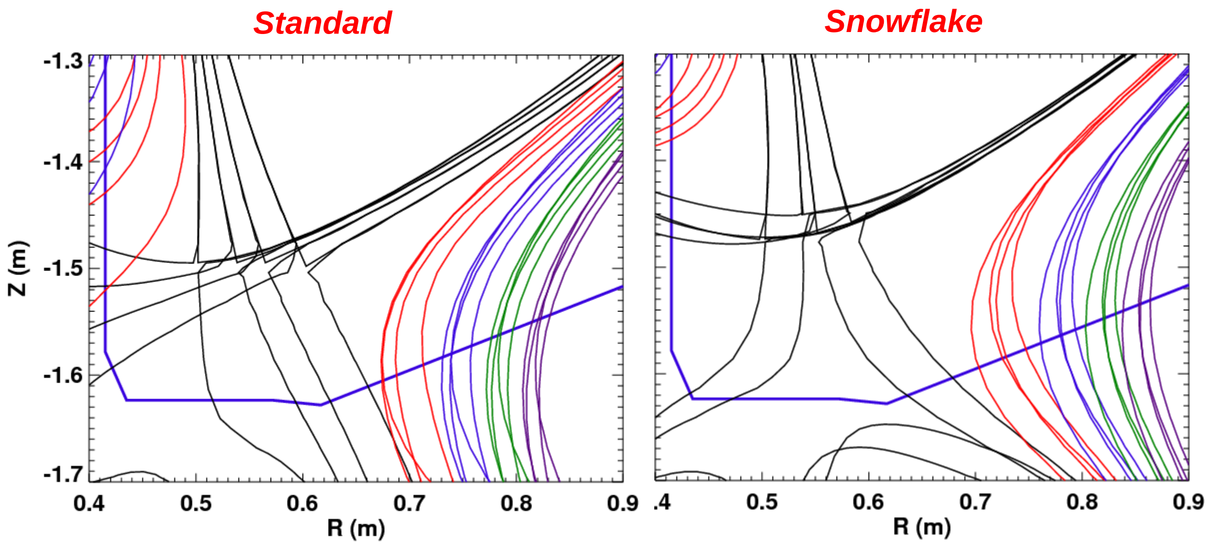
For given pump entrance position, heat flux at pump entrance orders the “optimal” geometry parameters

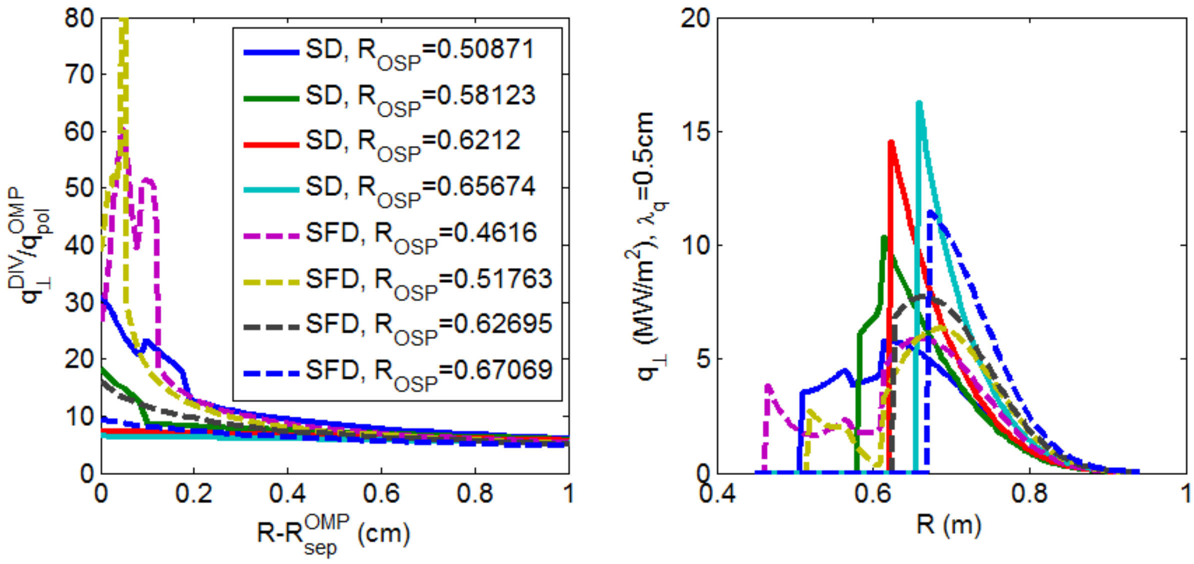
- Optimal throat height/length depend mainly on heat flux near entrance
  - Doesn’t matter if it’s varied by moving the OSP, changing flux expansion, or changing total power
  - T_e affects maximum pressure achievable, but only weakly affects g/h
- Optimizing for P=0.8mTorr at T_e=15.0 eV gives g~2.5 cm, h~2 cm at q~2MW/m^2



Equilibria with variety of R_{OSP}, flux expansion are used to map heat flux profiles, assess candidate pump entrance locations

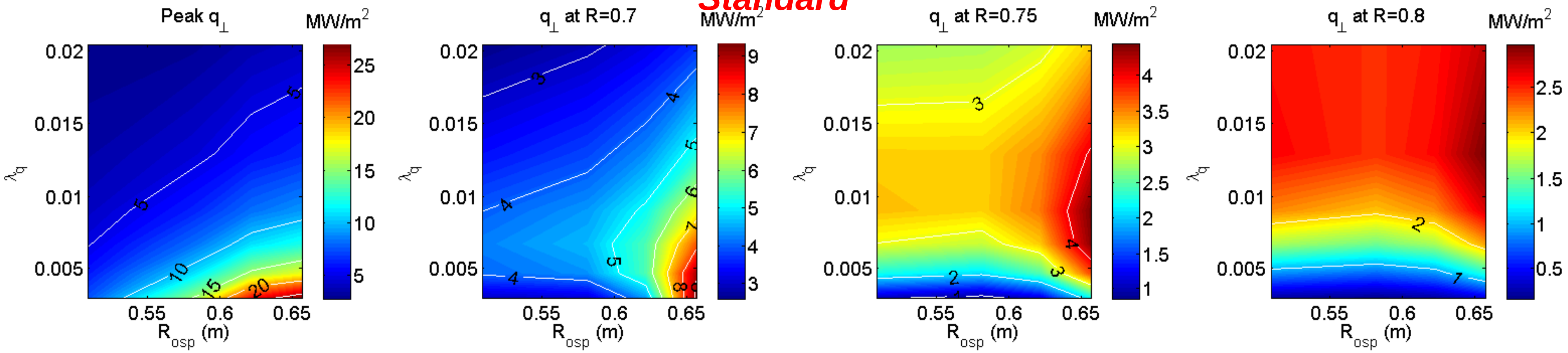
- Standard and snowflake divertors considered
  - Four R_{OSP} each
  - Contours: ψ_N=1.0, 1.03,1.06,1.09,1.12
- Flux expansion, flux surface geometry used to convert midplane heat flux profile (from scaling) to divertor heat flux
  - Assuming P_{DIV}=5MW
  - Indicates $q_\perp$<2 MW/m^2 for R_{pump}>0.8m



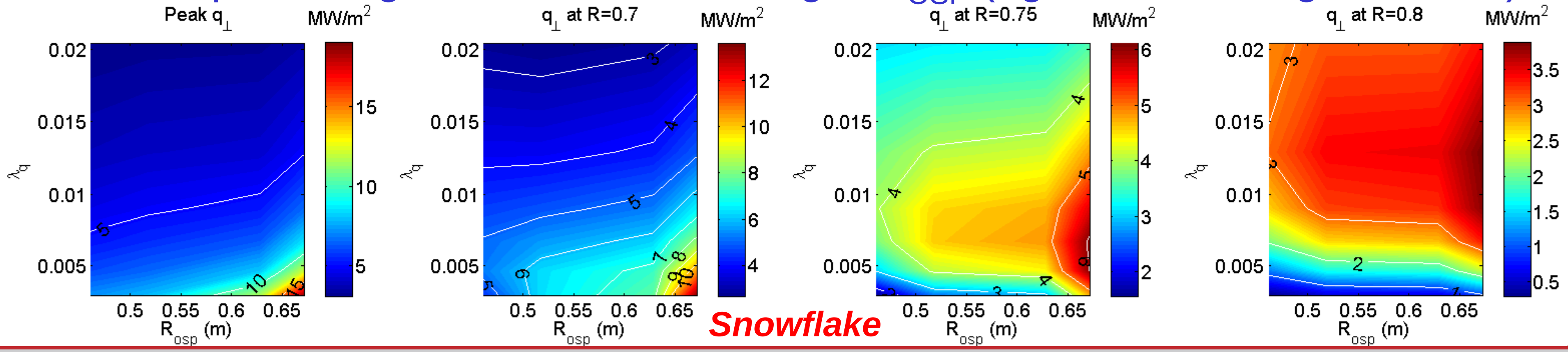


Heat flux projections show plenum entrance at R~0.7-0.75 m likely to provide sufficient pumping

Standard

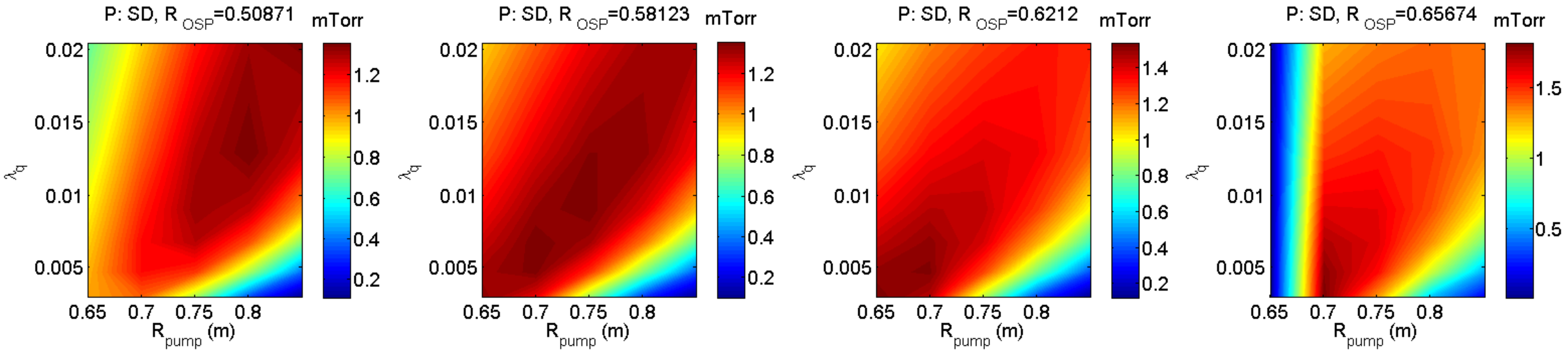


- Power handling: peak heat flux < 10 MW/m^2
  - Restricts R_{OSP} for narrow SOL (wider range for SFD)
- Pumping: $q_\perp^{entrance}$ > ~2 MW/m^2
  - Requires larger SOL widths for larger R_{OSP} (again wider range for SFD)

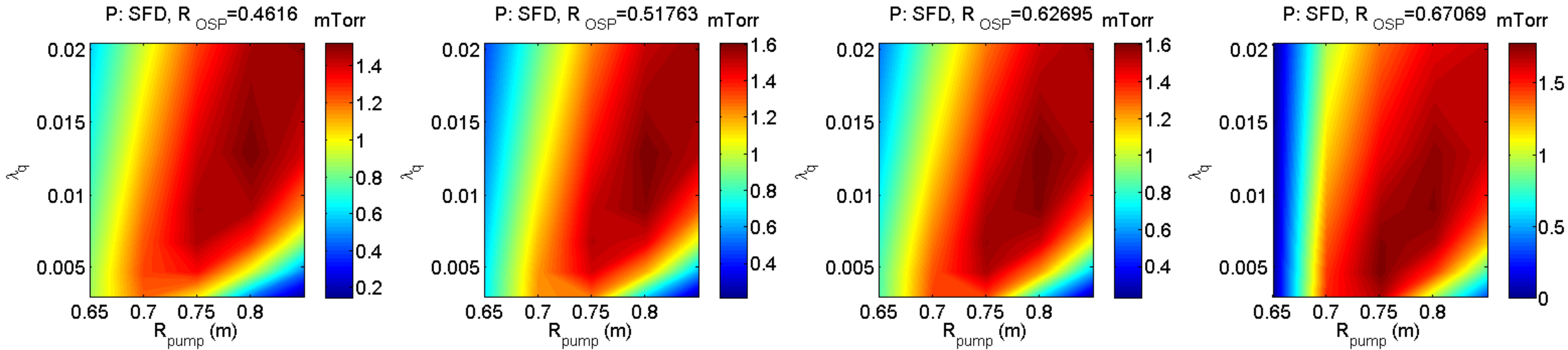


Snowflake

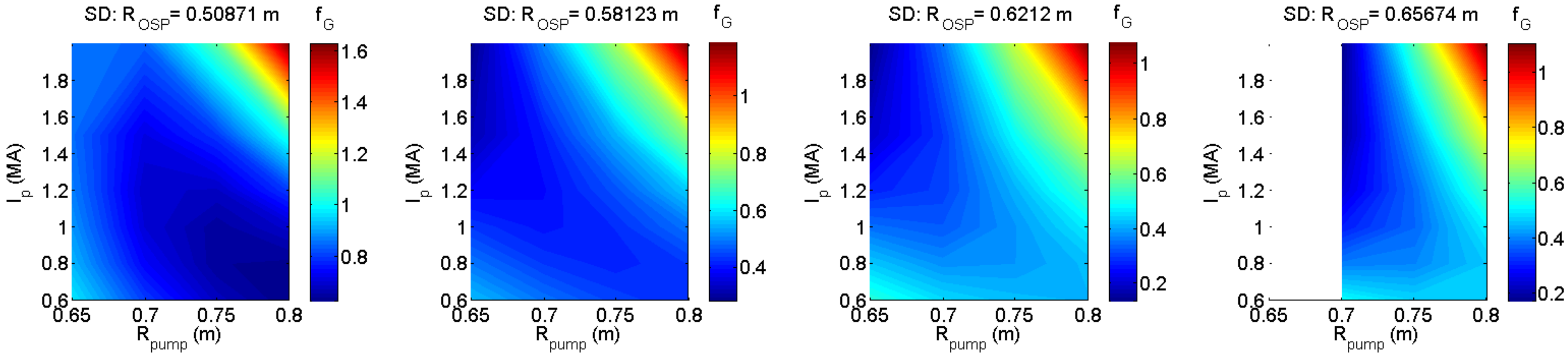
Projections show plenum entrance at R=0.72 can give >1 mTorr for wide range of SOL width, equilibria



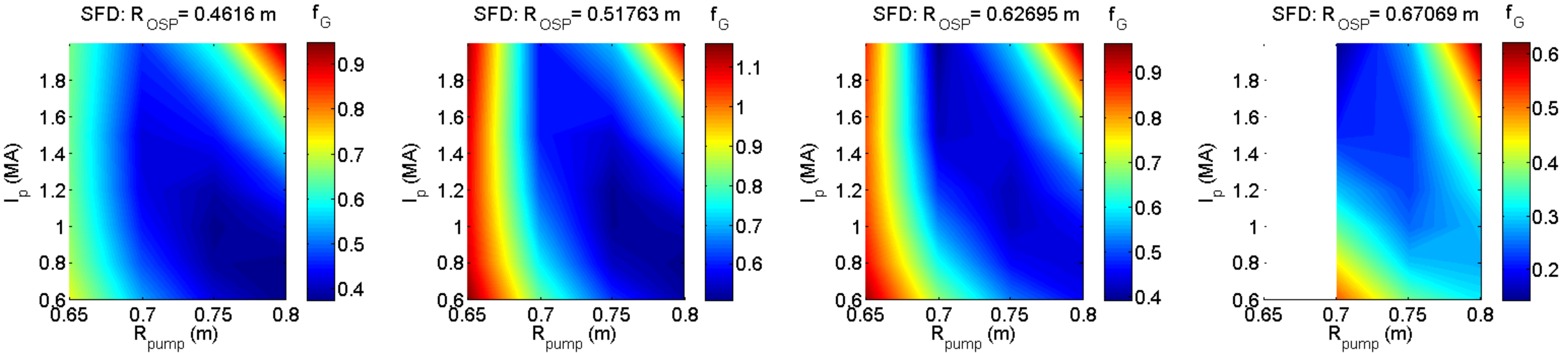
- Heat flux profiles, T_e^{div}, and optimized entrance parameters used in analytic model for plenum pressure
- Optimizing position for narrowest SOL gives R_{pump}~0.72
  - Narrow SOL gives least flexibility in moving R_{OSP} to improve pumping



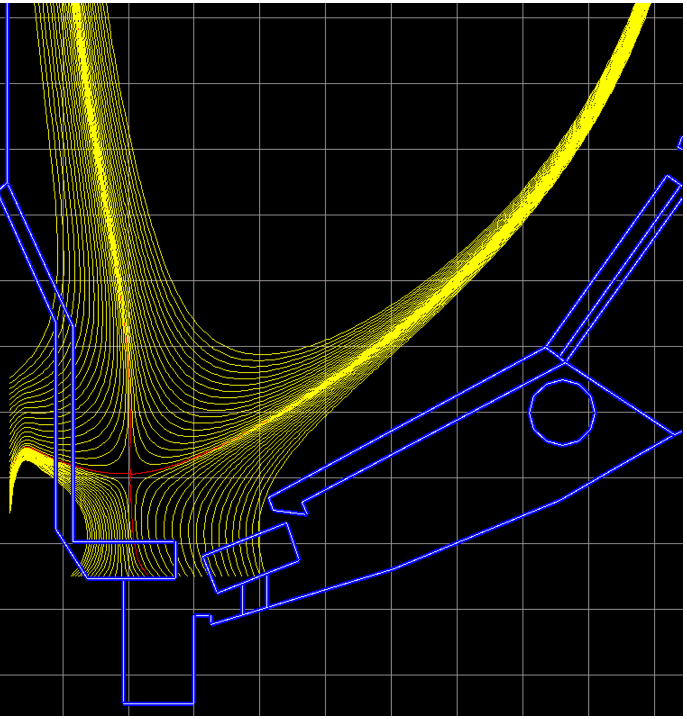
R_{pump}=0.72 supports low Greenwald fraction for range of I_p, equilibria



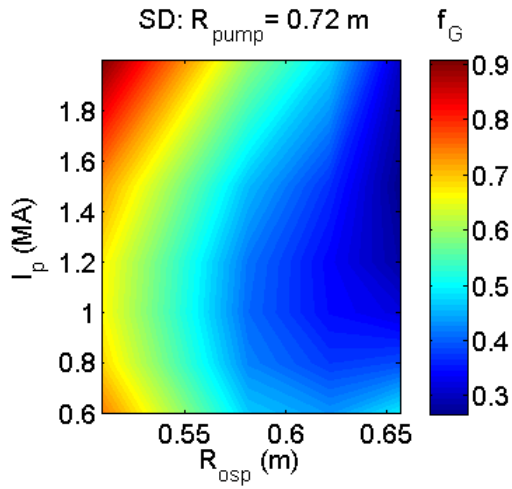
- $q_{||}sep$, T_e^{div} used in modified 2-pt model used to estimate n_e^{sep}
  - $q_{||}^{sep}$ from I_p scaling, T_e^{div} varied
- n_e/n_e^{sep} ~ 3 assumed to estimate f_G
- f_G shown is that at which pumped flux balances NBI input

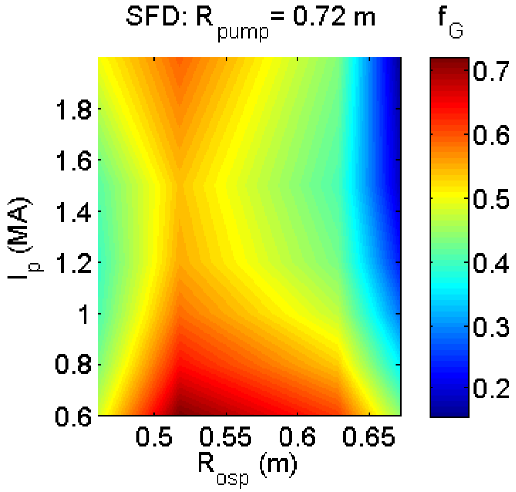


Optimized plenum geometry capable of pumping to low density under a variety of conditions

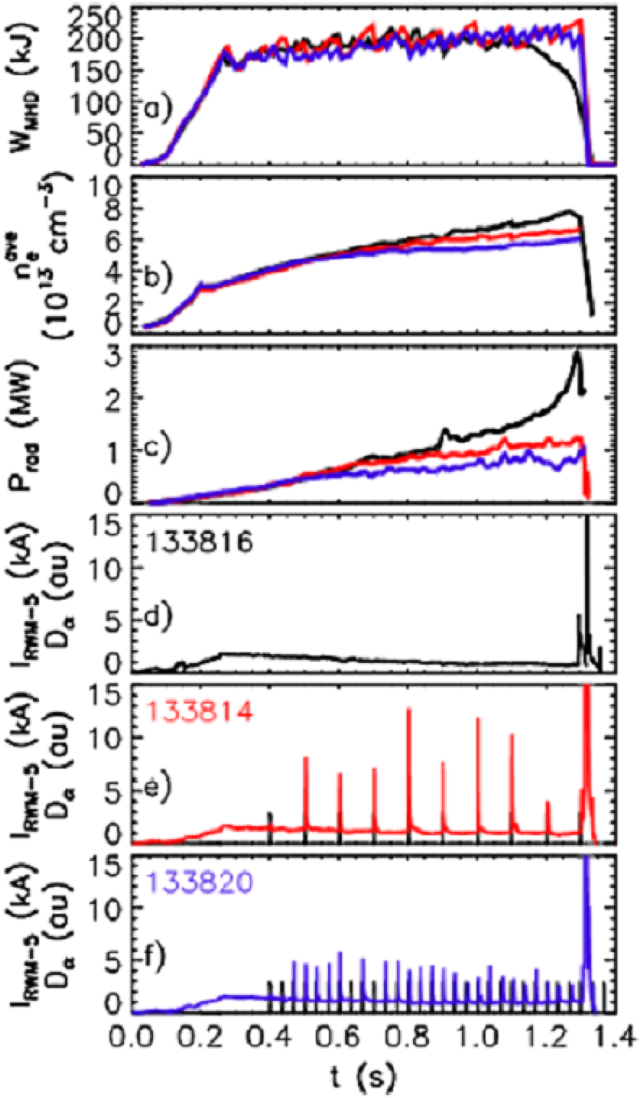


- Achievable f_G down to < 0.5
  - Moving R_{OSP} closer to pump allows lower n_e, but limited by power handling
- High flux expansion in SFD gives better pumping with SOL-side configuration
  - And more room to increase R_{OSP} at high I_p





Scenarios with Li coatings and ELMs trend towards stationary D and C inventory—but how do they extrapolate?



J. Canik - PRL 104, 045001 (2010)

- Li coatings + triggered ELMs come closest to achieving stationary D inventory and Zeff

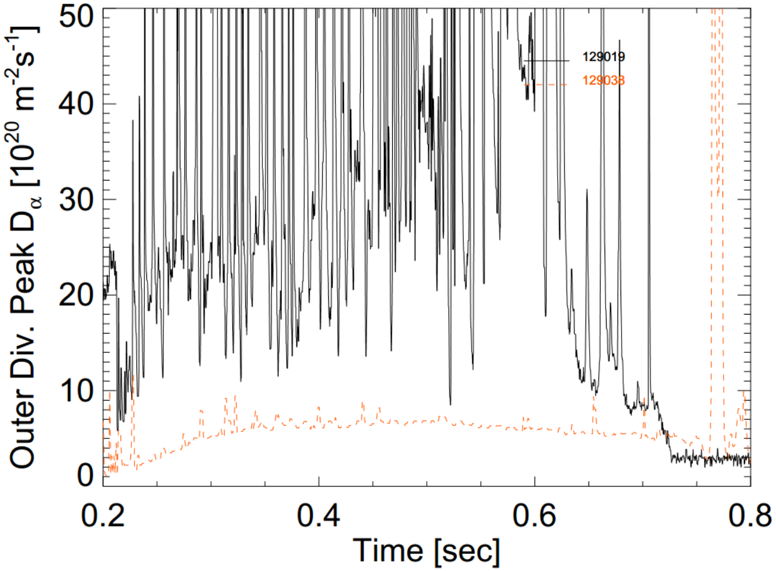
- How do these parameters project to NSTX-U parameters?
  - Up to 5x longer pulse
  - Up to 2x higher NBI fueling

- How persistent is D pumping by Li?

Low-recycling conditions with lithium coatings last throughout NSTX discharges

- Heavily lithium coated, ELM-free discharges studied
  - Most thoroughly analyzed 2008 pre- to post-lithium discharges

- Peak D_α emission at outer divertor does not increase toward the end of the discharge
  - And in fact often decreases
  - Without lithium, recycling increases througout shot



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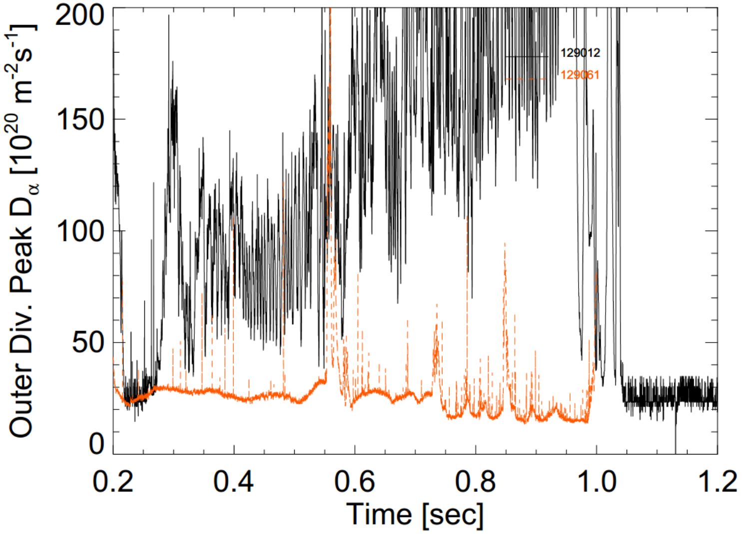


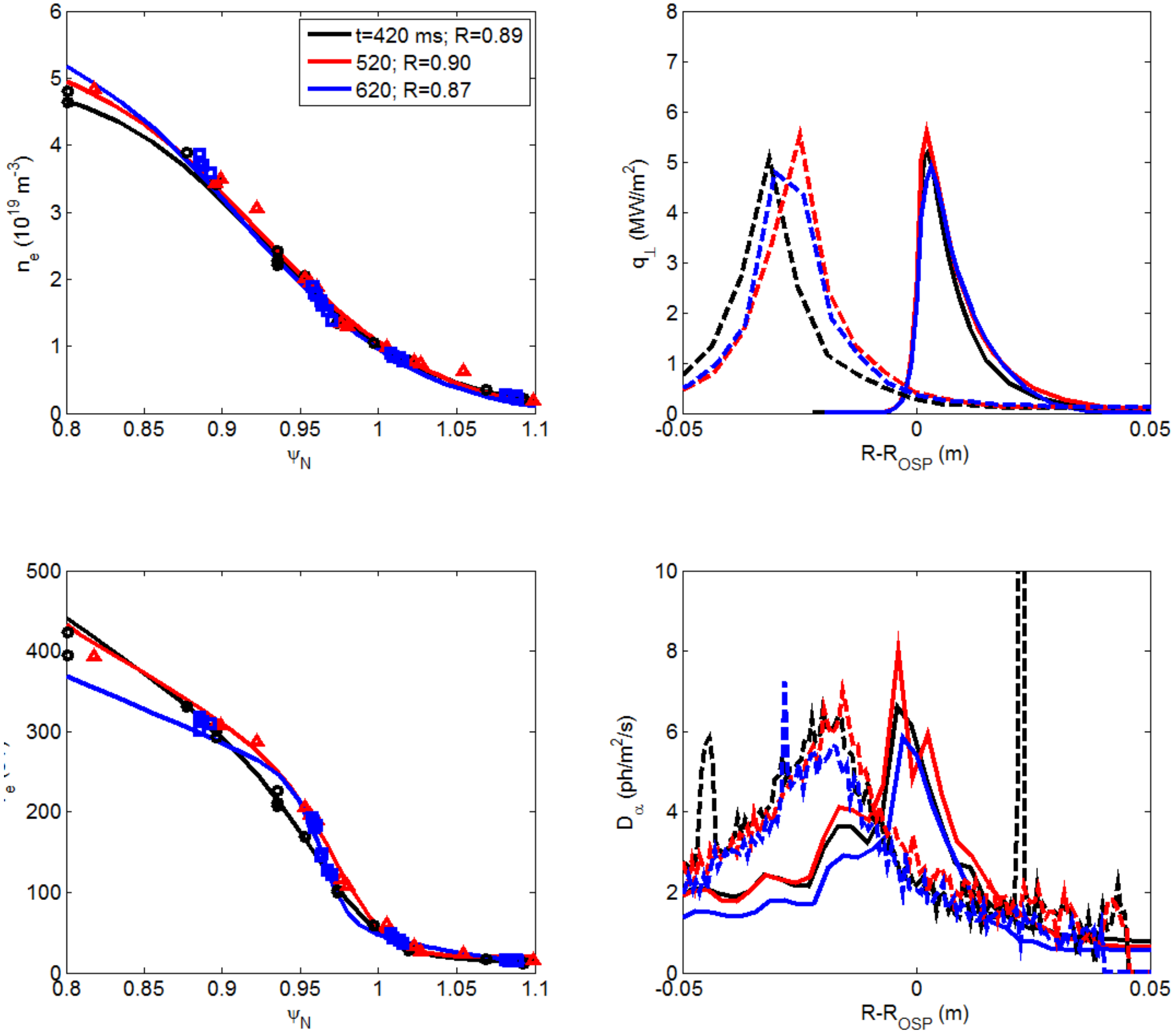
SOLPS modeling indicates recycling coefficient remains low throughout low-δ discharge

- Measurements show little change during shot
  - Points/dashed lines are measurements
  - SOL n_e, T_e, Peak heat flux, D_α all pretty constant

- Constraints in modeling:
  - Fitted n, T profiles
  - Peak q_{div} (T_e^{sep})
  - Peak D_α (R)

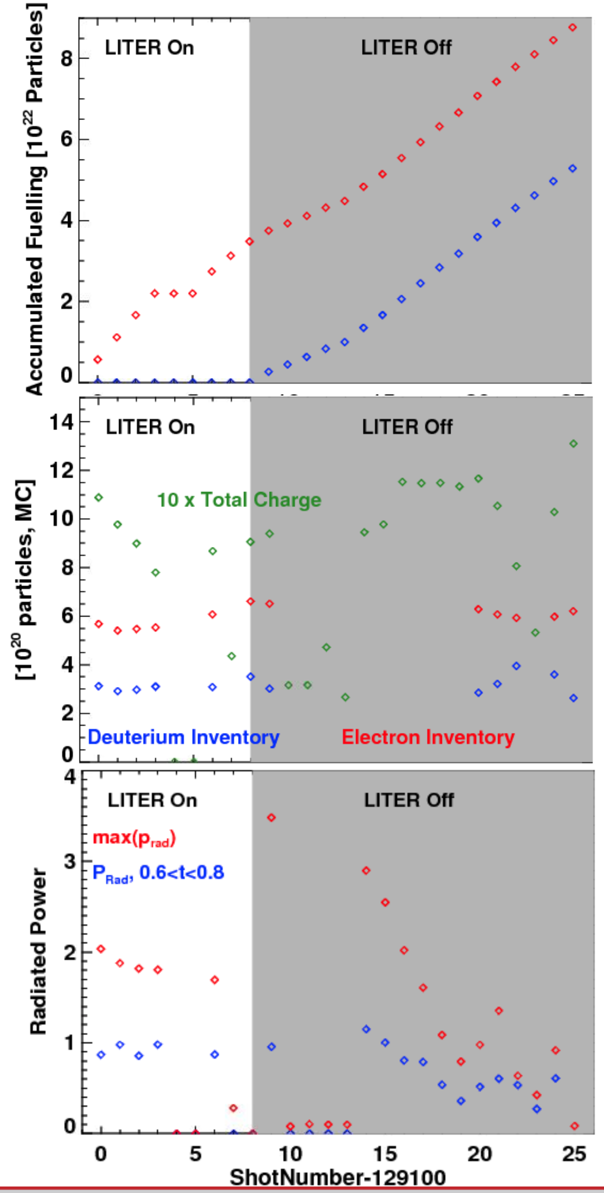
- Inferred R remains low
  - 0.89, 0.90, 0.87

⇒ Li pumping appears to persist over these pulse lengths (~ 1s)



Experiments following the shut-off of LITER show D inventory control for many shots

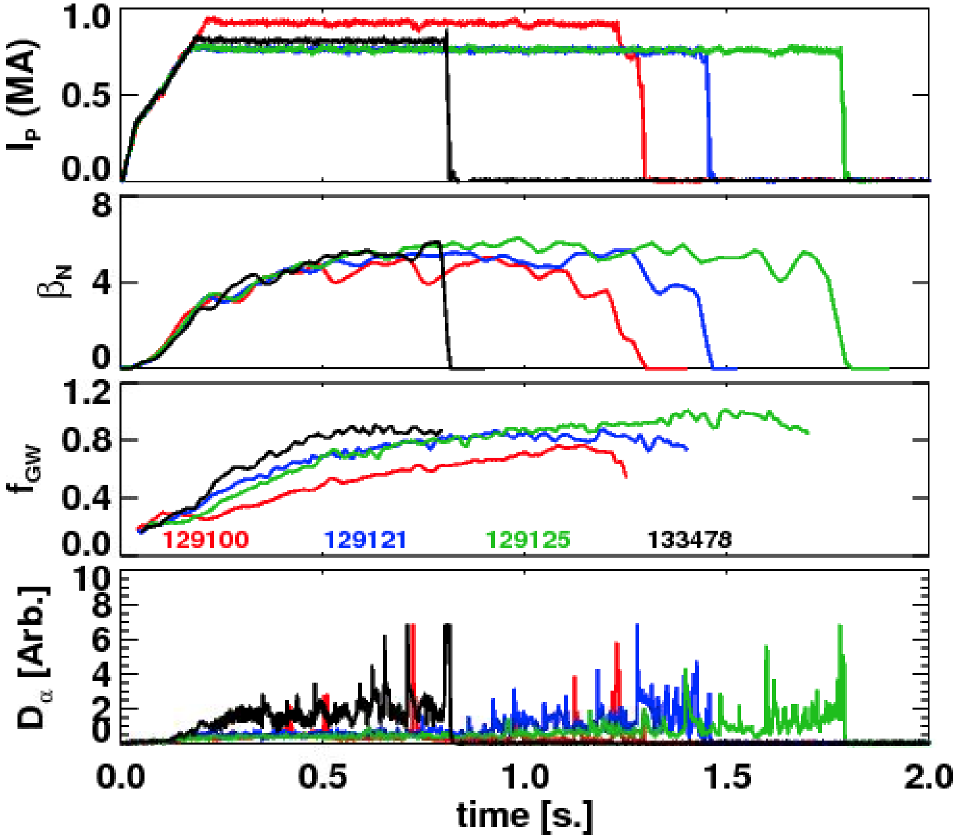
- LITER operated for ~90 discharges prior to lithium running out
- ~20 shots taken without LITER
  - Integrated discharge time ~25 s
  - Accumulated fueling ~5x10^{22} particles
  - Including performance optimization experiments->plasma not held constant
  - He GDC performed between shots
- Without LITER, ELMs returned
  - Mostly small
  - Radiated power progressively reduced
- Fairly constant D inventory maintained throughout sequence



The longest pulse discharges late in the sequence had a flattened out n_e trace while maintaining high performance

- 129100: 900 kA shot just before LITER ran out.
- 129121, 129125: long pulse optimization sequence
- ~5x the number of particles passed through as in an NSTX-U discharge
  - Still able to roll over density time trace (at high f_G)

⇒ May be possible to tailor lithium deposition to provide long-pulse pumping while maintaining ELMs for impurity control



Further analysis plans during outage

- Cryo-pumping design
  - Confirm plenum optimization using SOLPS (B2-EIRENE)
    - More comprehensive treatment of neutral transport (beyond first-flight)
    - Can treat radiative/detached divertor
  - Investigate design details of chosen plenum geometry
    - Is clearing area currently occupied by divertor tiles feasible?
    - Getting closer to engineering design
- Lithium persistence for long-pulse (with ELMs)
  - Further modeling with 2D fluid codes (UEDGE/SOLPS/OEDGE)
    - Recycling analysis for high-δ, longer pulse ELM-free discharges
    - Analysis of long, ELMy discharge
  - Extrapolation to NSTX-U
    - Longer pulse, higher NBI particle input

Plans for years 1 and 2 of NSTX-U

- Cryo-pump design
  - Measure plasma parameters at likely pump entrance location
    - Document Γ, T_e as I_p, P, flux expansion, etc are varied
  - Finalize physics design
- Impurity control with lithium coatings
  - Develop ELMy scenarios with lithium coatings
    - Operate with boronized carbon (no Li) early for comparison to NSTX and to establish reference conditions for NSTX-U
    - Perform experiments with controlled scans lithium deposition amounts, document recycling and ELM characteristics of high-performance plasma
    - Test passivation of lithium with D_2 glow for control of pumping properties
    - Optimize lithium application (pumping vs. ELMs), combine with impurity control techniques (ELM triggering, snowflake, etc) as needed towards steady state plasmas without impurity problems
  - Test persistence of lithium coatings
    - Measure recycling characteristics as power, ion flux, pulse length are varied
    - Use rapid SGI gas pulses to measure SOL pump-out vs time within shot
  - Later stages: measure impurity behavior with Li on Mo tiles

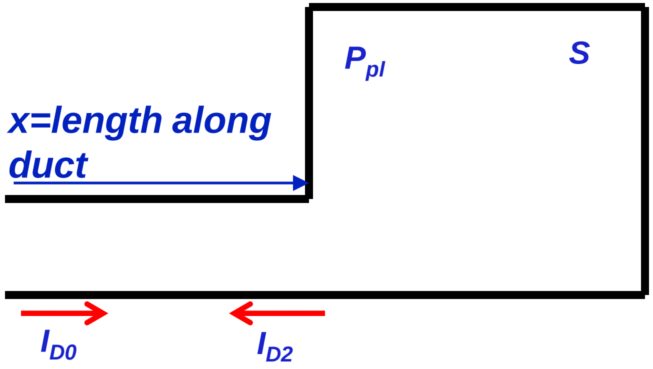
Long term plans (NSTX-U years 3-5)

- Install cryo-pump as part of long-pulse divertor
  - Present thinking is to put cryo in upper divertor, with liquid Li system on lower

- Explore performance of pumping system
  - Document pumping rates as P, I_p, R_{OSP} are varied
  - Test pumping of high flux expansion divertor
  - Assess n/n_G achievable with pumping in various conditions, and develop low-density, high-performance scenario
  - Develop long-pulse, density controlled plasmas for range of n/n_G
  - Compare to lithium-based pumping

BACKUP

Penetration of neutrals through a long throat is accounted for to correct the conductance



- $I_{D0} = I_{D0}(x)$ = current of "fast" atomic deuterium entering from plasma

  If fast atoms are turned into thermal molecules on collision will the wall, then:

  $I_{D0}(x) = I_{D0}(0)*F(x)/F(0)$, where F is the solid angle factor evaluated along x
- I_{D2} = current of thermal molecules leaving
- I_{D2} = volume integral of sources (I_{D0}), sinks ($P_{pl}S$)

  $\Rightarrow I_{D2}(x) = I_{D0}(x) - P_{pl}S$
- Pressure is $\Delta P = \int_o^h I(x)\sigma(x)dx, \sigma = \frac{3}{4\bar{v}}\frac{H}{A^2}, \frac{1}{C} = \int_o^h \sigma(x)dx$
- So plenum pressure is

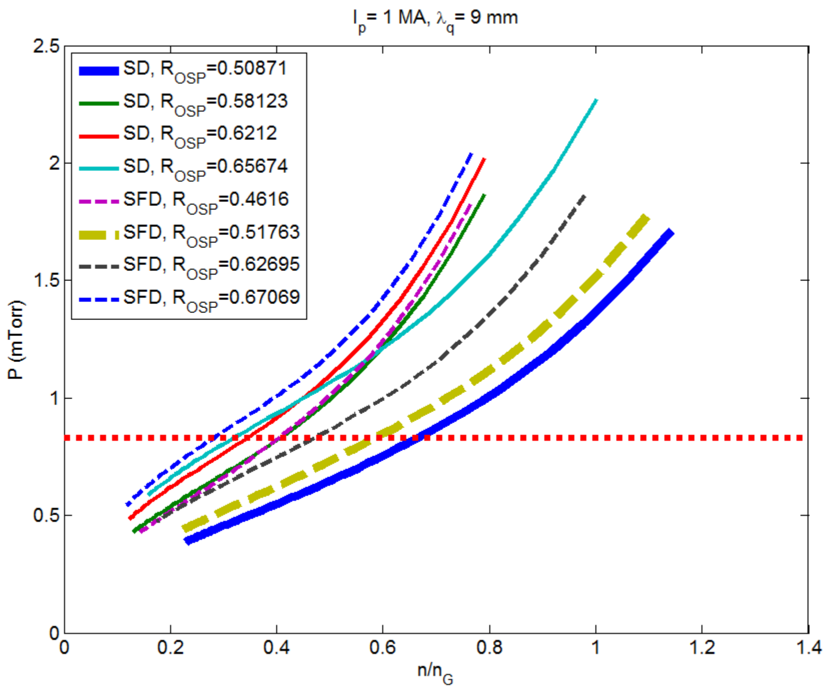
$$P_{pl} = \int_o^h I_{D2}(x)\sigma(x)dx = \int_o^h I_{D0}(x)\sigma(x)dx - \int_o^h P_{pl}S\sigma(x)dx$$

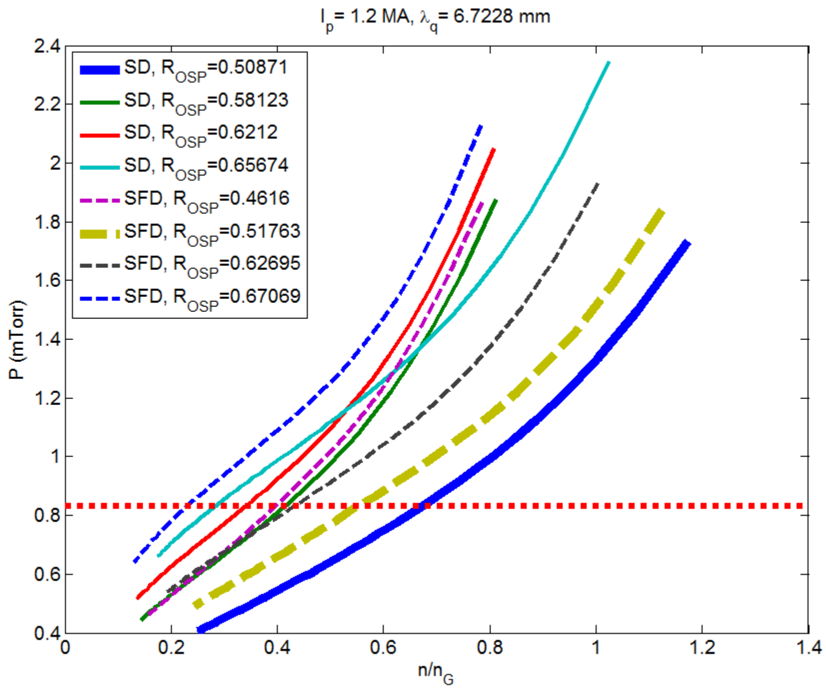
$$= I_{D0}(0)\int_o^h \frac{F(x)}{F(0)}\sigma(x)dx - \frac{P_{pl}S}{C} = \frac{I_{D0}(0)}{C_{eff}} - \frac{P_{pl}S}{C} = \boxed{\frac{I_{D0}(0)}{S+C}\frac{C}{C_{eff}}}$$

$$C_{eff} = \int_o^h \frac{F(x)}{F(0)}\sigma(x)dx$$

Estimating achievable n/n_G

- n/n_G varied by scanning T_e^{div}
- To pump beams, need P~0.8 mTorr
- f_G shown is where the pumping balances beam input
  - – Minimum achievable n_e -> could puff to increase





Projected performance of the optimized plenum geometry