NSTX-U

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NSTX Upgrade Cryo-pumping Design Progress, Particle Control Plans

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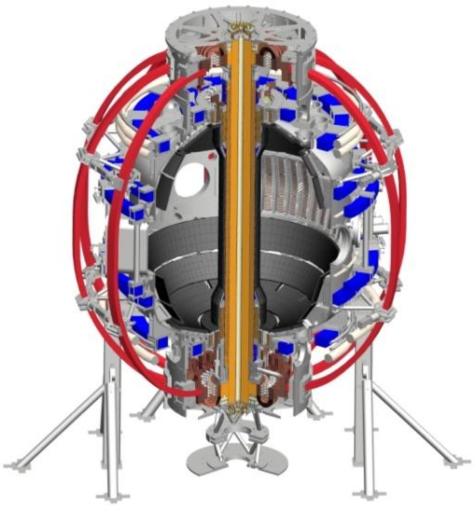
NSTX-U PAC 31
B318, PPPL
April 17th, 2012



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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 Li ELM-free scenario: Type-I 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 Li ELM-free plasmas
  - Long-pulse, ELMy plasmas with partially passivated lithium

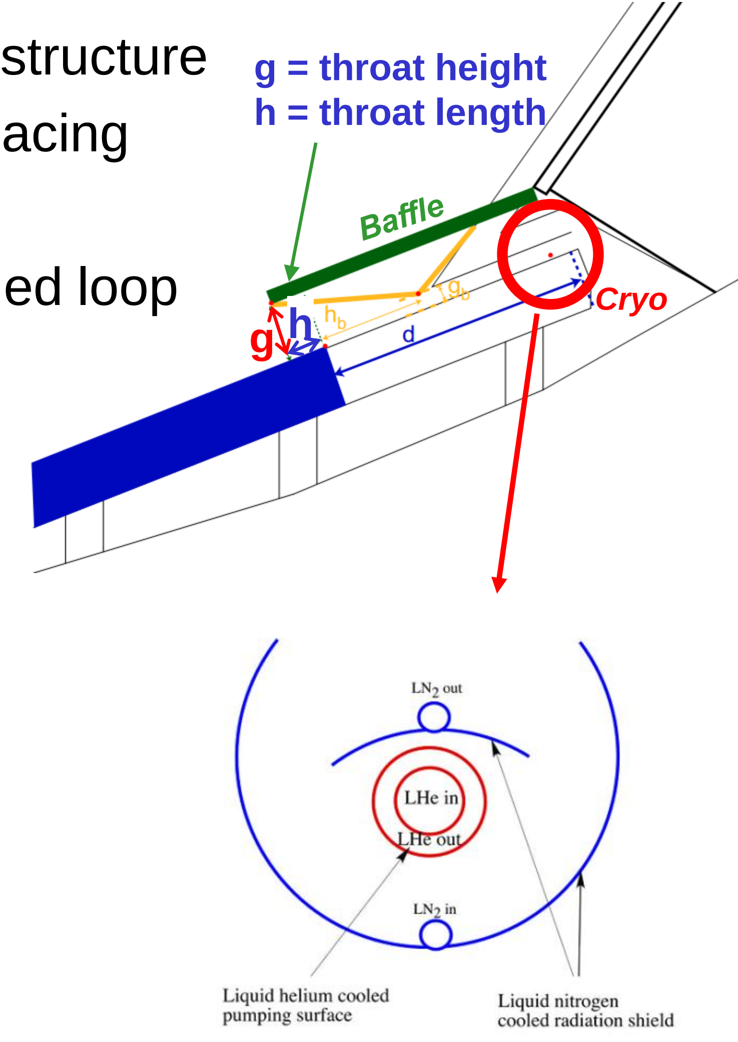
- Future plans
  - Near term analysis
  - Experimental plans for NSTX-U

General design similar to DIII-D lower outer cryo-pump system is taken as starting point for design analysis

- Plenum location studied: under new baffling structure near secondary passive plates, possibly replacing some outer divertor plates and 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.)

Projected divertor parameters combined with semi-analytic pumping model are used to calculate pumping rates

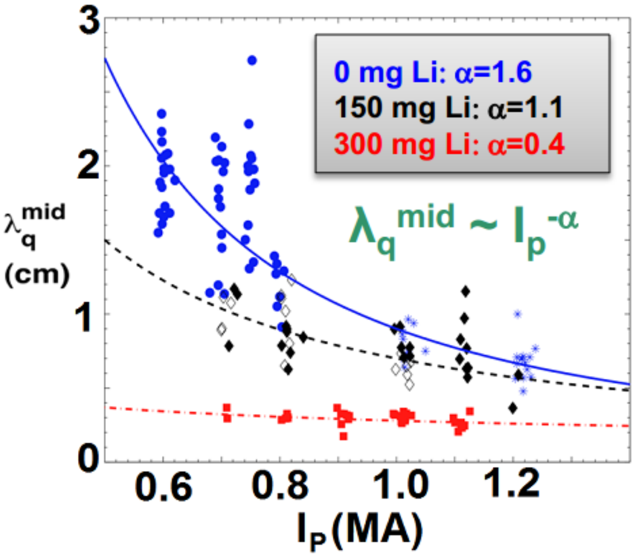
- Analytic model developed for DIII-D pumping studies (Maingi, NF '99)
  - Predicts plenum pressure, validated with DIII-D data
  - Requires divertor n, T, Γ profiles
  - Uses first-flight neutral model (insufficient for detached divertor)

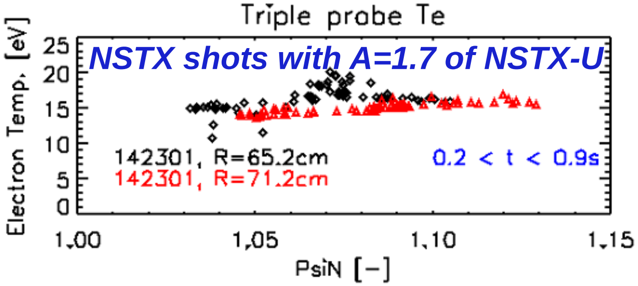
- Heat flux, angle of B wrt PFC surface (α), and plasma temperature are sufficient to calculate n, Γ:

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

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

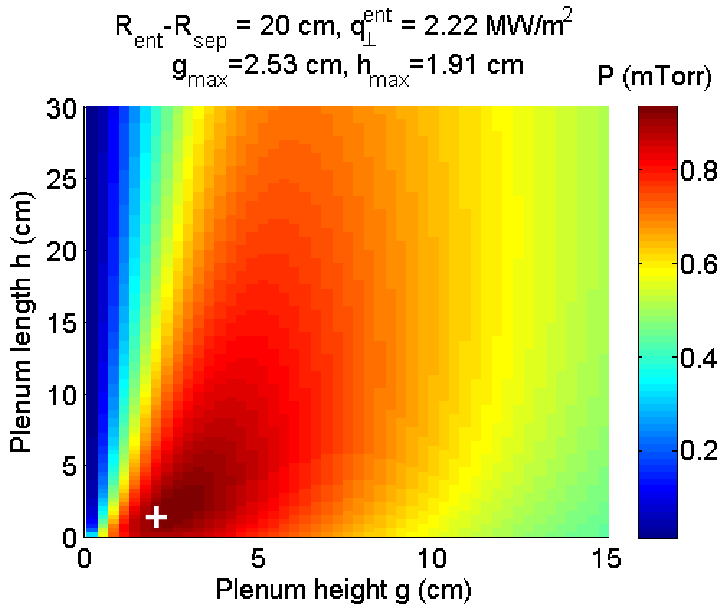
  - Recent experiments yield scaling of SOL heat flux width
    - No-lithium scaling used here, but all trend towards λ_q~3mm at I_p=2MA
    - P_{div} = 5 MW assumed (1/2 of 10 MW input)
  - Langmuir probes show T_e~15-20 eV in far SOL
    - T_e ~independent of I_p
    - T_e~15 eV assumed (NSTX-U-like discharges)

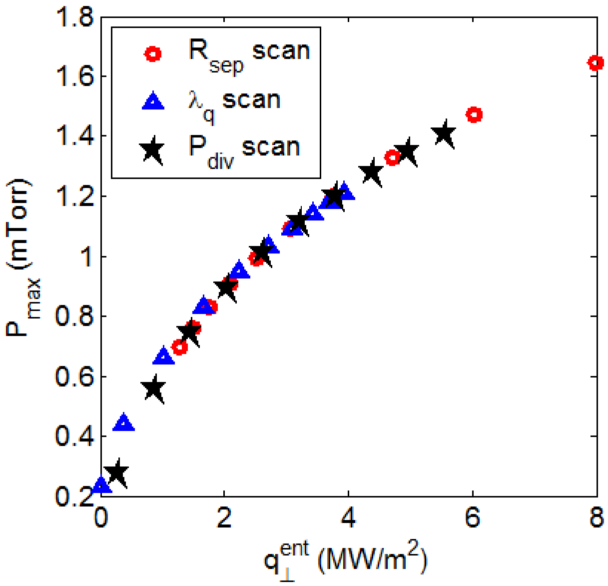




Pressure projections are used to optimize plenum geometry parameters

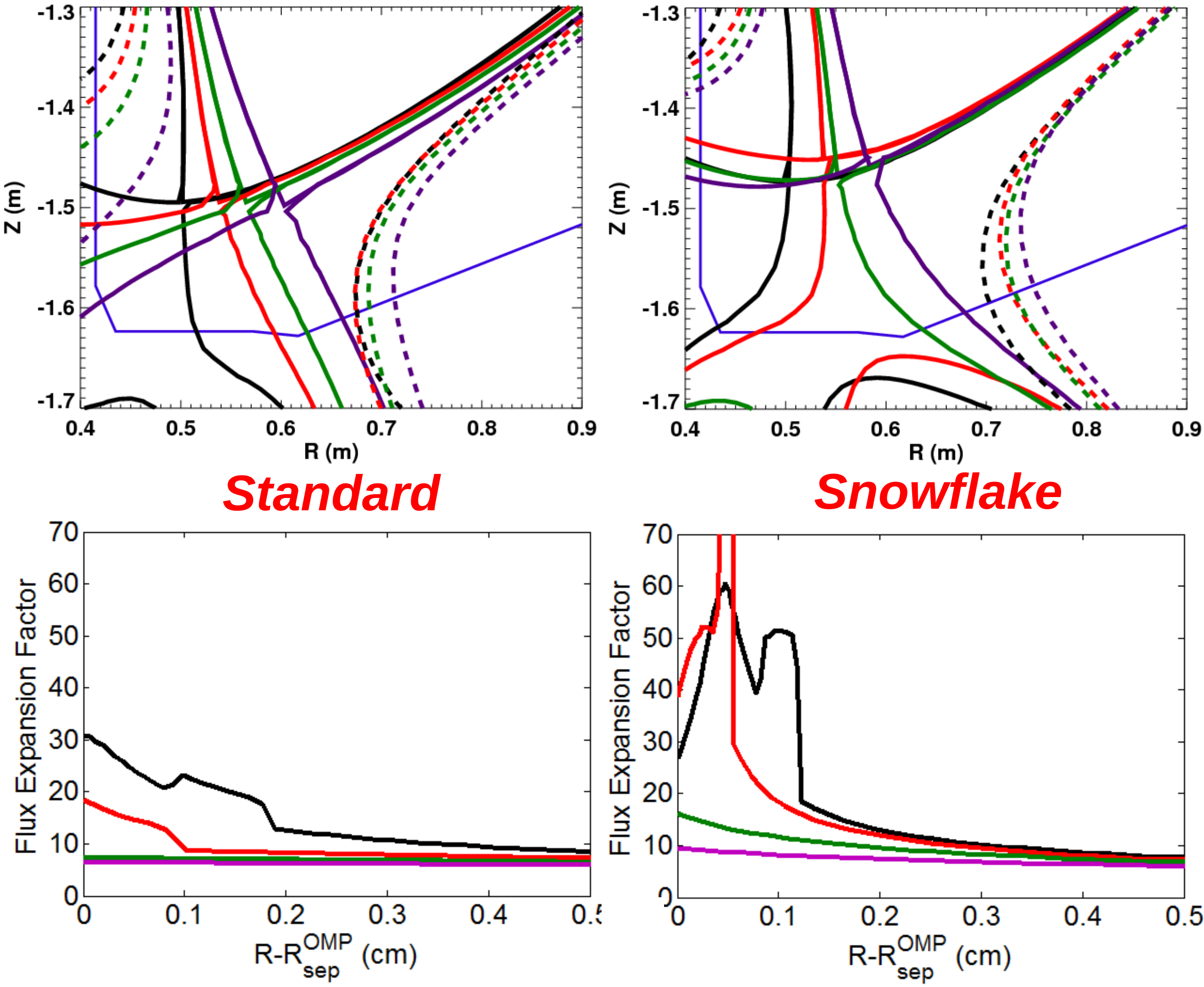
- Exponentially decaying heat flux footprint imposed, with T_e=15 eV
- Plenum entrance height, length are varied to maximize pressure
- Pressure in optimized plenum depends primarily on heat flux at pump entrance
  - Varied through R_{OSP}, flux expansion or P_{tot} ⇒ profile effects not important
  - Reaching P~0.8 mTorr (to pump 10 MW NBI) requires $q_\perp^{ent}$~2 MW/m^2
- Optimal plenum entrance for P=0.8mTorr: height g~2.5 cm, length h~2 cm





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

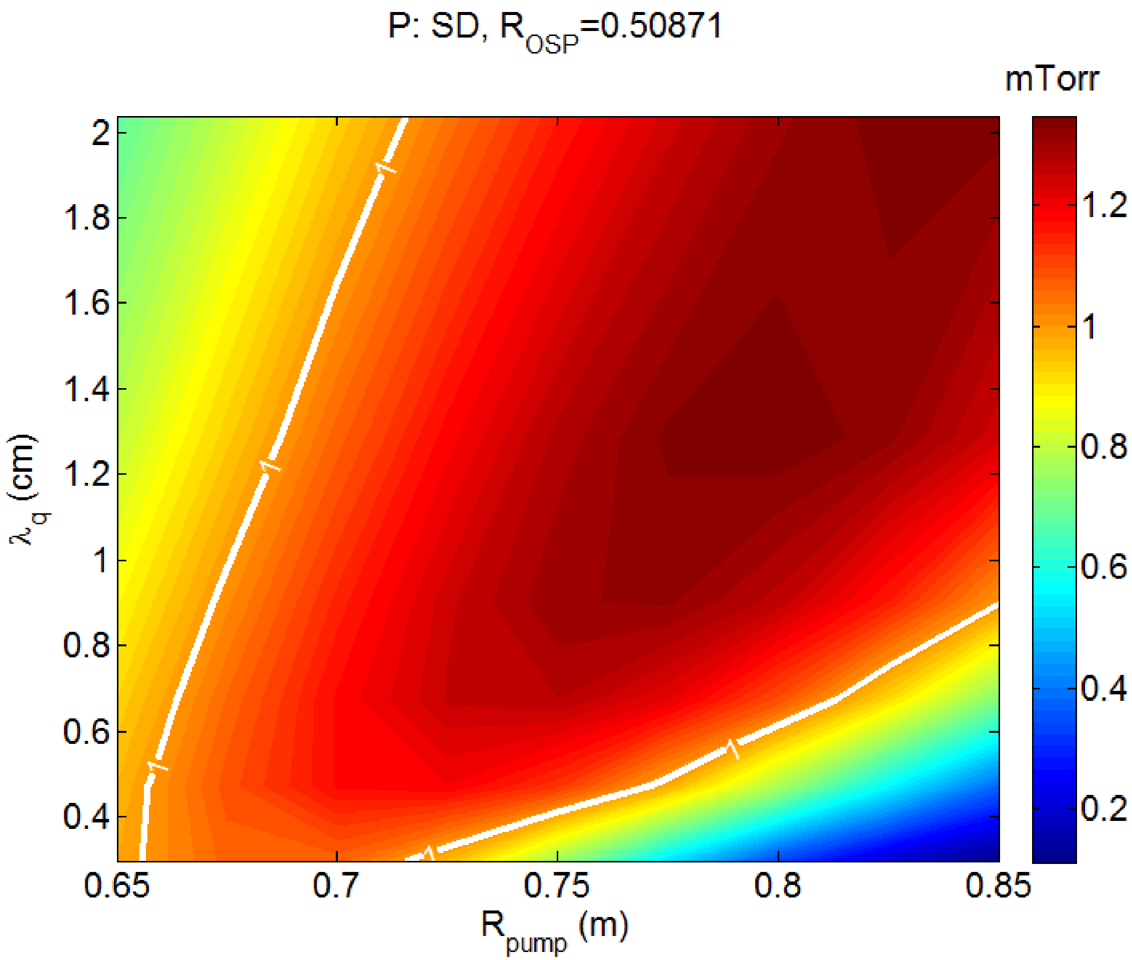
- Standard and snowflake divertors considered
  - Four R_{OSP} each
  - ψ_N=1.0,1.03 shown
  - Movement of ψ_N=1.03 strike line is much less than that of R_{OSP}
- Flux expansion, flux surface geometry used to convert midplane heat flux profile (from scaling) to divertor heat flux
  - As R_{OSP} is increased, flux expansion is decreased


Standard

Snowflake

Realistic equilibria, heat flux scaling, and empirical T_e^{SOL} are used to project plenum pressure for candidate R_{pump}

- Analytic model for plenum pressure with optimized entrance parameters
- Pressure is non-monotonic with R_{pump} due to field geometry
  - At low R_{pump}, α is lower, so $n/\Gamma_\perp$ is increased $\Rightarrow$more neutrals ionized before reaching pump



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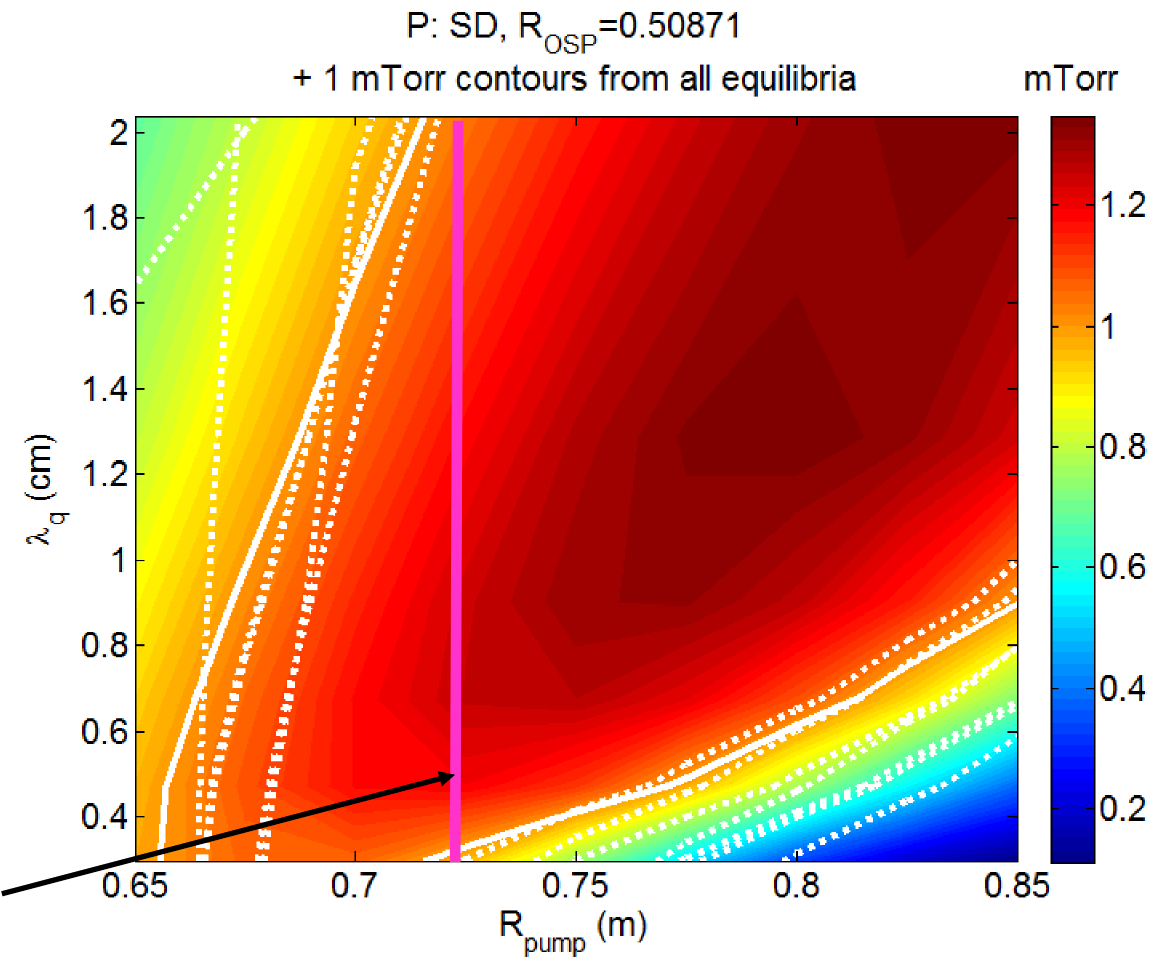
  - At low R_{pump}, α is lower, so $n/\Gamma_\perp$ is increased

    $\Rightarrow$more neutrals ionized before reaching pump
- Optimizing position for narrowest SOL gives R_{pump}~0.7
  - Narrow SOL gives least flexibility in moving R_{OSP} to improve pumping
  - R_{pump}=0.72 gives high P for wide range of SOL width



R_{pump}=0.72 gives n_e control for range of I_p, equilibria

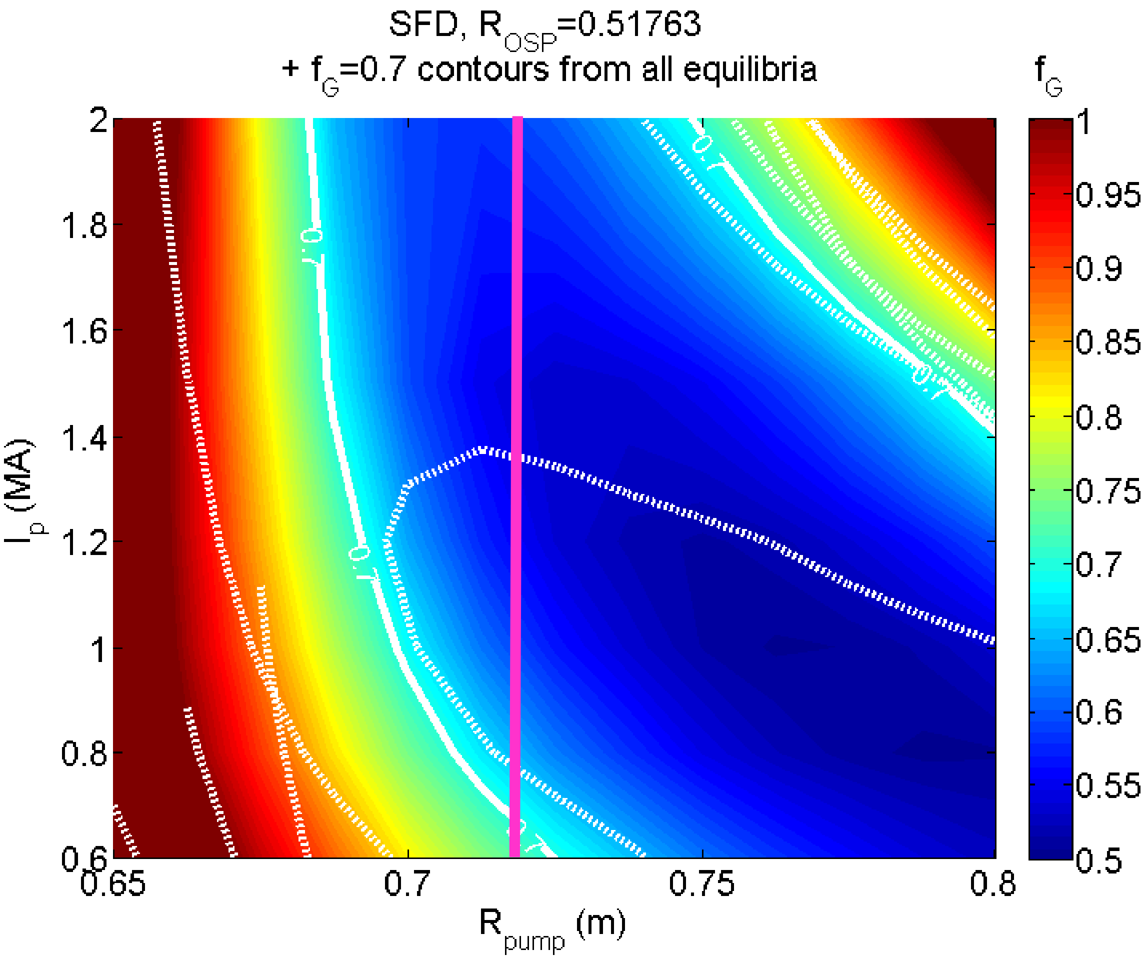
- Modified 2-pt model used to estimate n_e^{sep}

$$T_{OMP} = \left(T_{DIV}^{7/2} + \frac{7}{4\kappa_{0e}} q_{\parallel}^{sep} L \right)^{2/7}$$

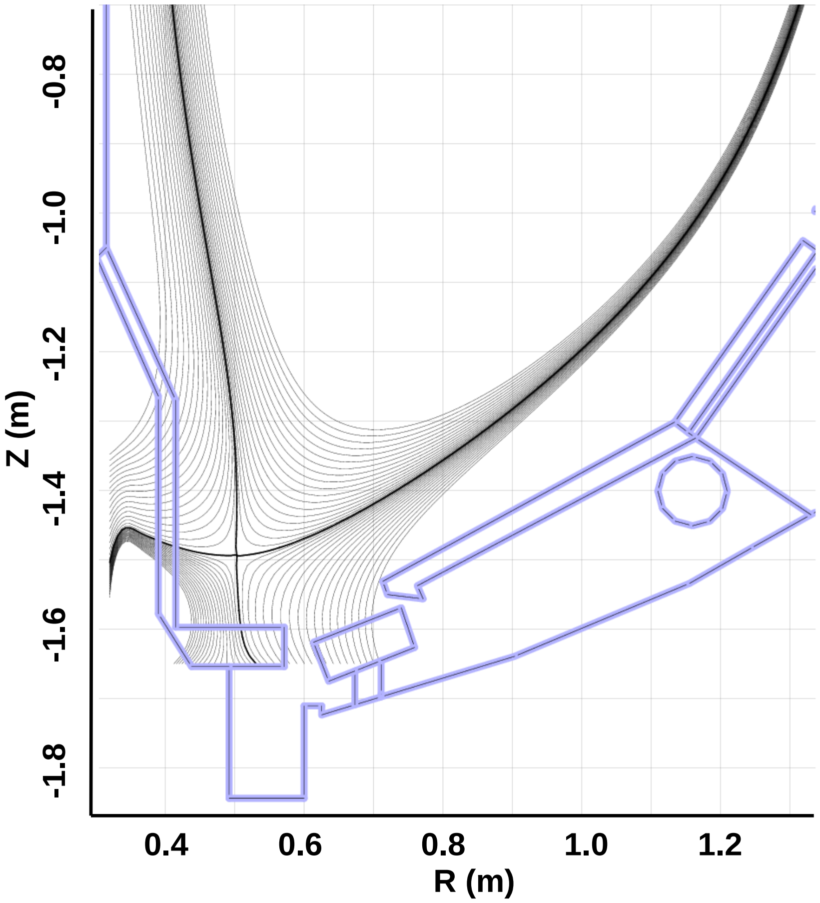
$$n_{OMP} = f_{cal} \frac{2 n_{DIV} T_{DIV}}{T_{OMP}} \frac{B_{OMP}}{B_{DIV}}$$

  - $q_{\|}^{sep}$ from I_p scaling, T_e^{div} varied
  - Final n_e^{sep}: pumping=NBI input

- $\overline{n_e}/n_e^{sep}$ ~ 3 used to estimate $f_G=n/n_G$
  - Consistent with NSTX data

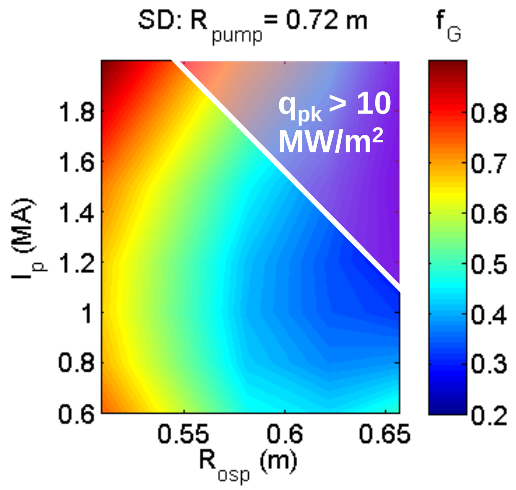


Optimized plenum geometry capable of pumping to low density for a range of R_{OSP}, I_p

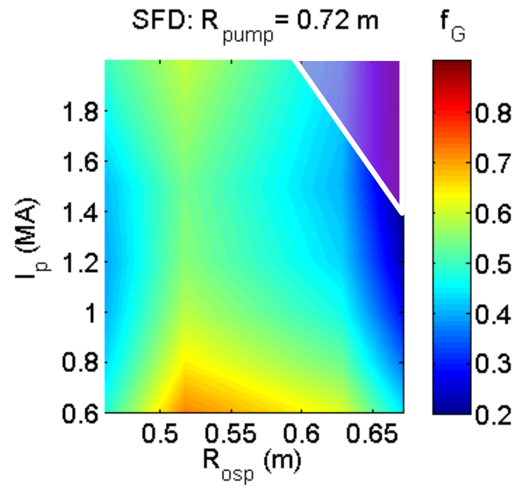


SOLPS geometry to be used in future calculations

- Equilibrium 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
  - More plasma in far SOL near pump
  - More room to increase R_{OSP} at high I_p



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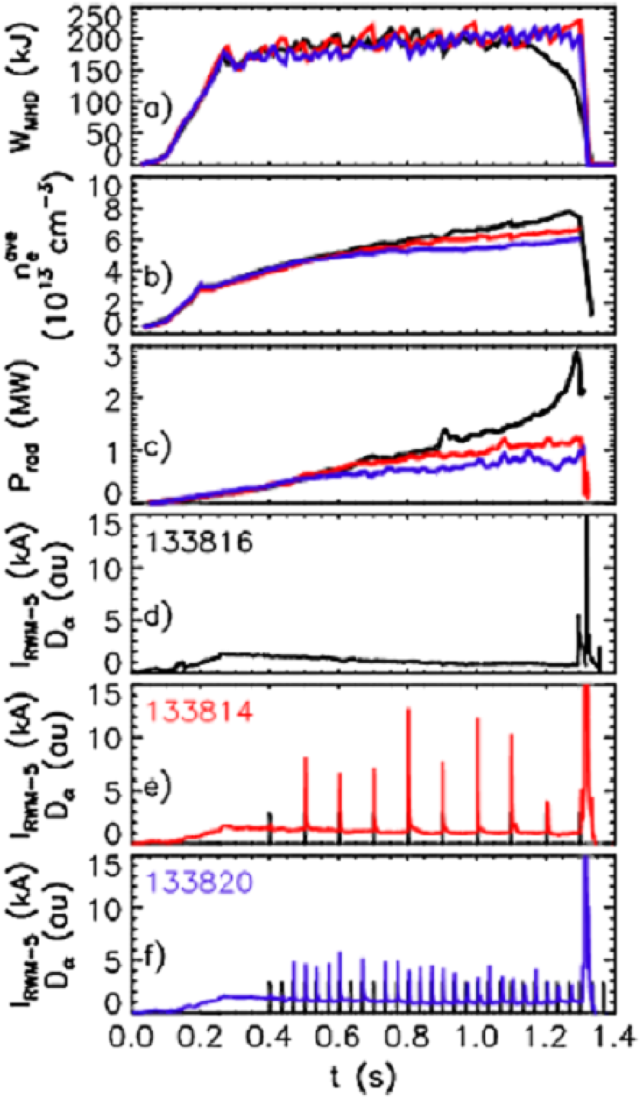
Scenarios with Li coatings and ELMs trend towards stationary D and C inventory—but how do they extrapolate?



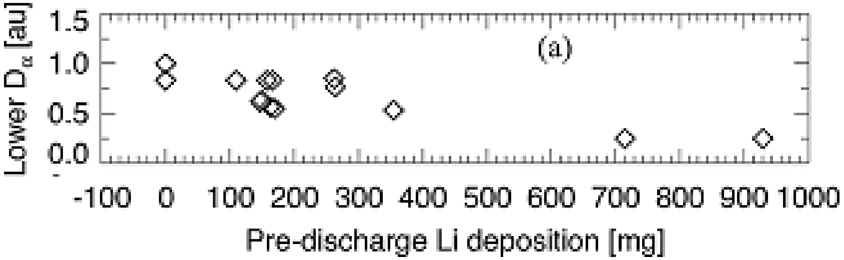
J. Canik - PRL 104, 045001 (2010)

- Li coatings + triggered ELMs come closest to achieving externally controllable stationary D inventory, Z_{eff}
  - Use of triggered ELMs for particle control will be assessed in upgrade
- 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?
  - Part of Milestone R(12-2)
    - Project deuterium pumping capabilities for NSTX-U using lithium coatings and cryo-pumping

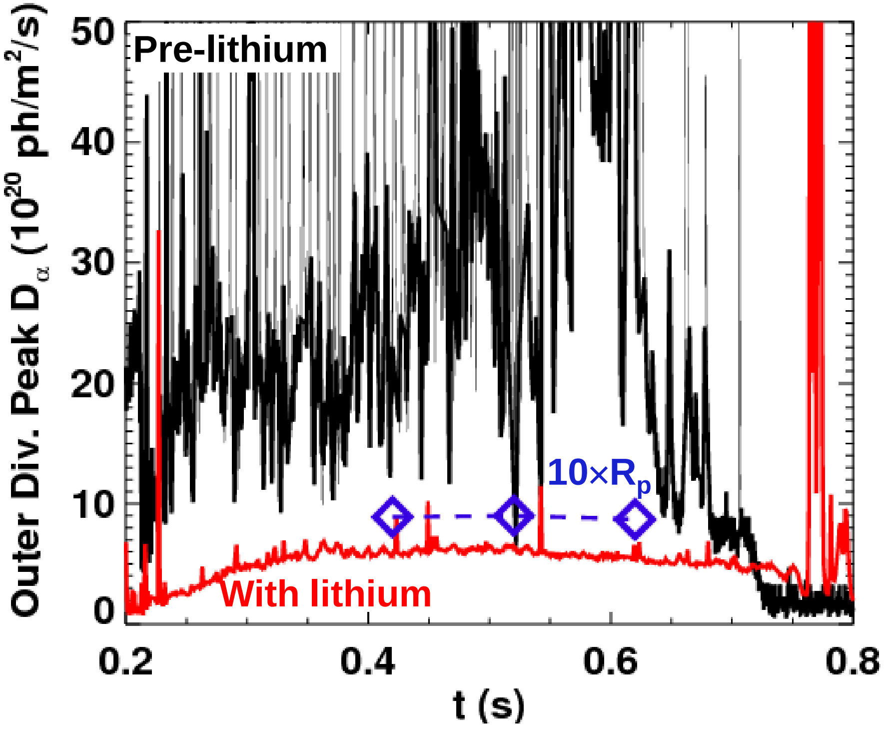
Low-recycling conditions with lithium coatings last throughout NSTX discharges

- Heavily lithium coated, low-recycling, 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 throughout shot
  - Inferred PFC particle recycling coefficient R_p ~ constant



R Maingi, PRL 107, 145004 (2011)



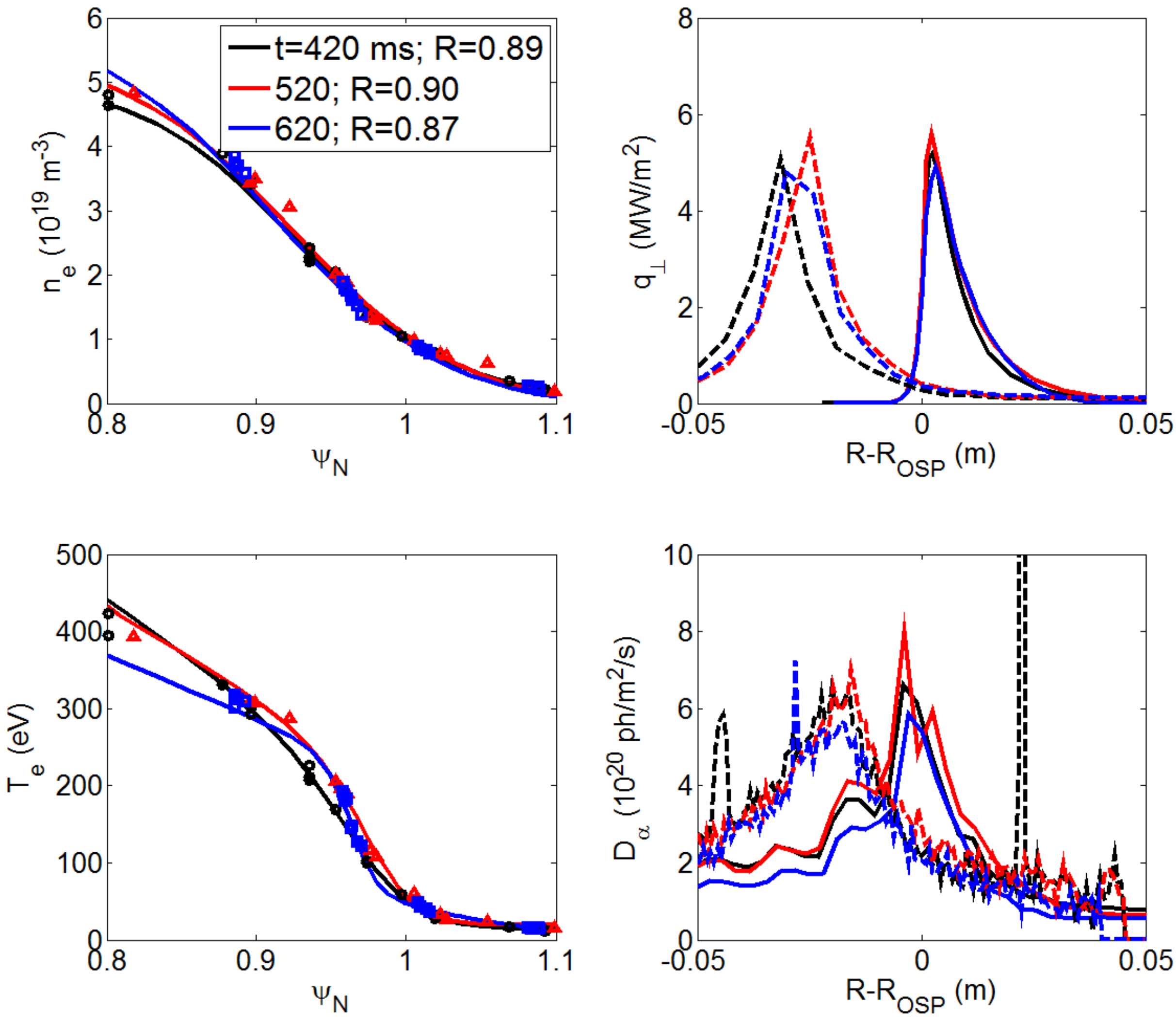
SOLPS modeling indicates recycling coefficient remains low throughout low-δ discharge

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

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

- Inferred R_p remains low
  - 0.89, 0.90, 0.87
  - Without Li: R_p=0.98

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



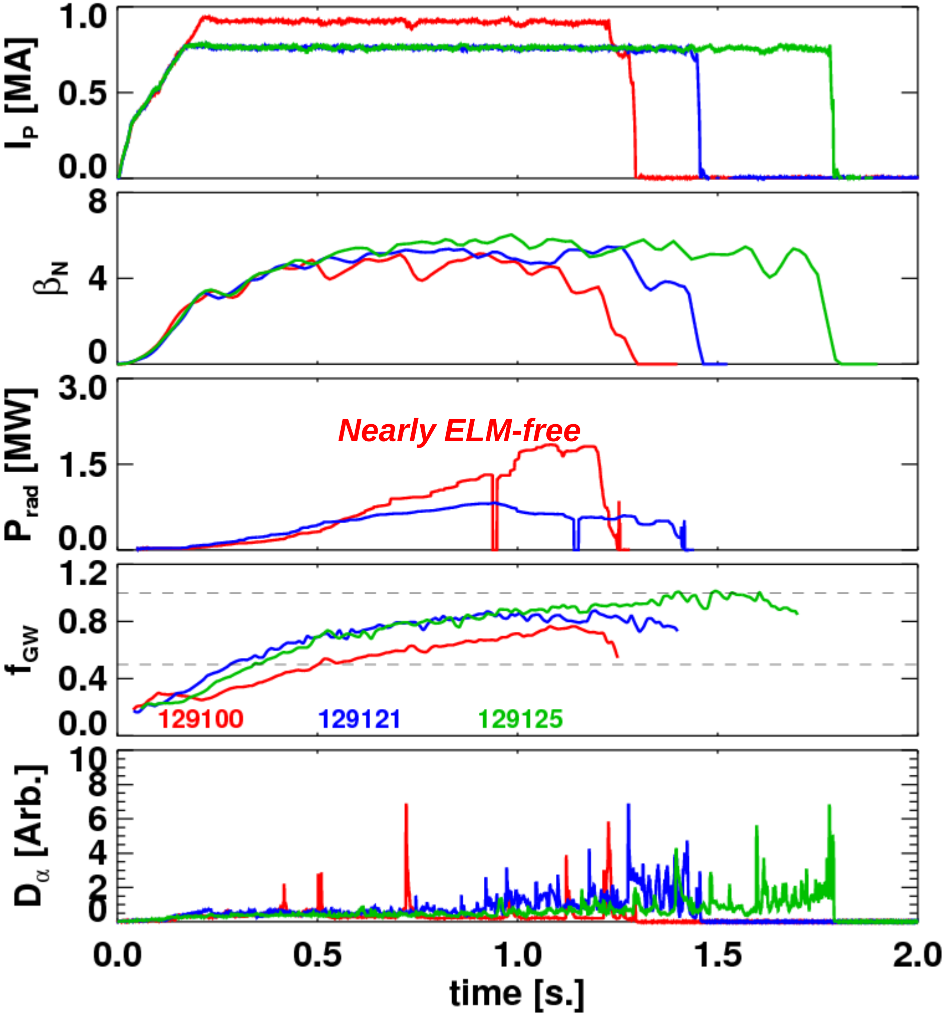
*J Canik, JNM 415, S409 (2011)

Long-pulse discharges following the shut-off of LITER maintained high performance while approaching stationary n_e

- 129100: 900 kA shot just before LITER ran out.
- 129121, 129125: long pulse optimization sequence
  - 129125: longest NSTX shot

- Density time trace (at high f_G) ~stationary after 1 s
  - No large n=1 MHD modes
  - Equivalent to beginning of an NSTX-U shot

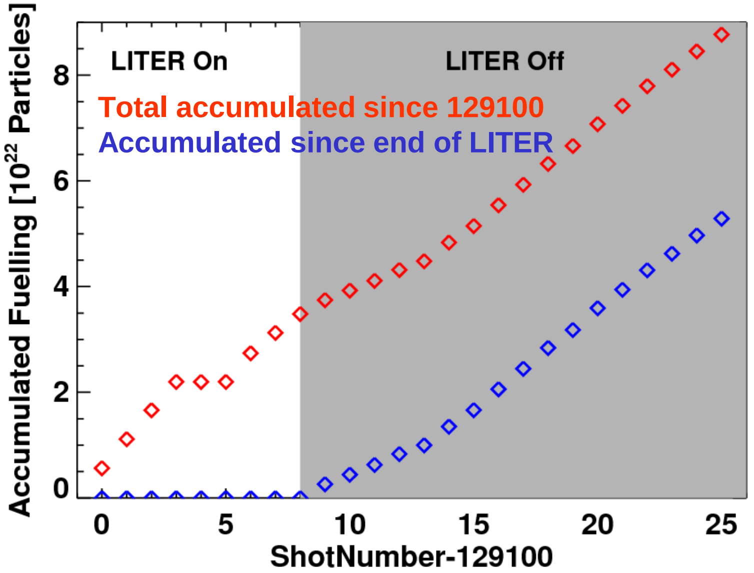
- Without LITER, ELMs returned
  - Mostly small
  - Radiated power reduced

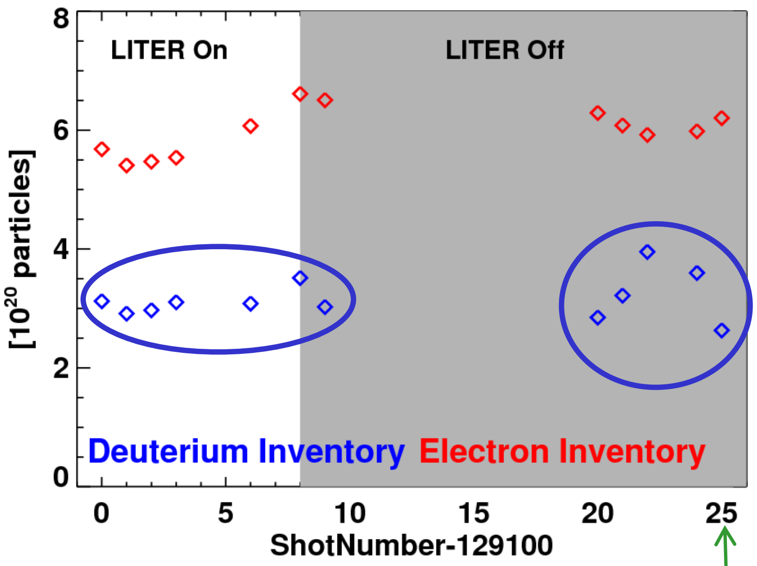


Experiments following LITER shut-off show D inventory control for many shots

- 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
    - ~5 NSTX-U discharges (10 MW, 5s)
  - Plasma not held constant
  - He GDC performed between shots
- Fairly constant D inventory maintained throughout sequence

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





Longest NSTX shot

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Next steps for particle control analysis during Upgrade 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?
    - Prepare for 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
- Begin studying compatibility/interaction of cryo and lithium pumping
  - Could lithium coat the pumping surface?
  - What plenum pressure can be achieved with SOL modified by lithium coatings (e.g., λ_q, P_{div}/P_{tot}, n_e)

Plans for years 1 and 2 of NSTX-U operation

- Validate physics design of cryo-pump
  - Measure plasma parameters at likely pump entrance location
    - Document Γ, T_e as I_p, P, flux expansion, etc are varied
  - Perform engineering design (begin during outage with incremental funding)
- Particle control with lithium coatings
  - Develop ELMy scenarios with lithium coatings
    - Assess ELM triggering with thick lithium coatings
    - Perform experiments with controlled scans lithium deposition amounts (including none), document recycling and ELM characteristics
    - Test passivation of lithium with D_2 glow for control of pumping properties
    - Optimize lithium deposition (ELMs vs. pumping), combine with impurity control techniques (snowflake, gas puff, etc.) towards long-pulse
  - 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 plan: cryo in upper divertor, liquid lithium on lower divertor
  - Contingent on available resources

- 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

Summary

- A promising cryo-pump design point has been identified that is compatible with standard and snowflake divertors
  - Based on semi-analytic pumping model
  - Divertor profile projections based on NSTX data
- D inventory control using lithium coatings appears to extrapolate to 5s NSTX-U discharges
  - Estimated recycling coefficient remains low at R~0.9 for 1 s discharges
  - D inventory in ELMy plasmas controlled ~25 s following LITER shutoff
- Studying compatibility and interplay between cryo-pumping and lithium is an important research goal for NSTX-U

BACKUP

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)

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

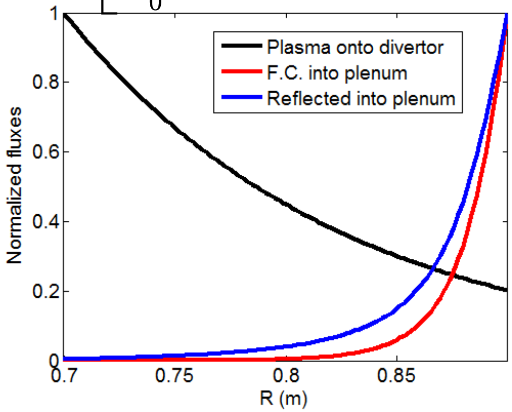
Neutral current into plenum

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

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

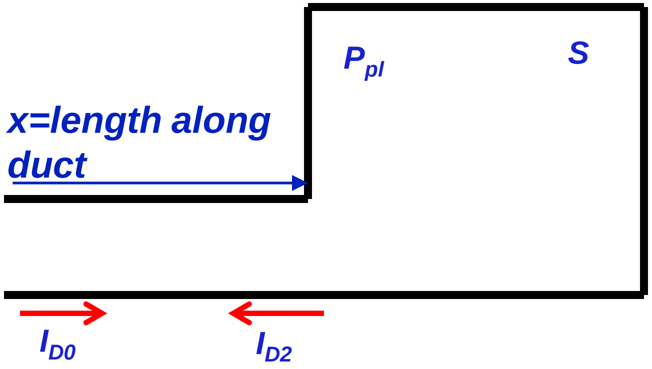


Origin of neutrals making it into plenum tends to be localized to near-entrance region

Dominantly due to solid angle factor

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

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

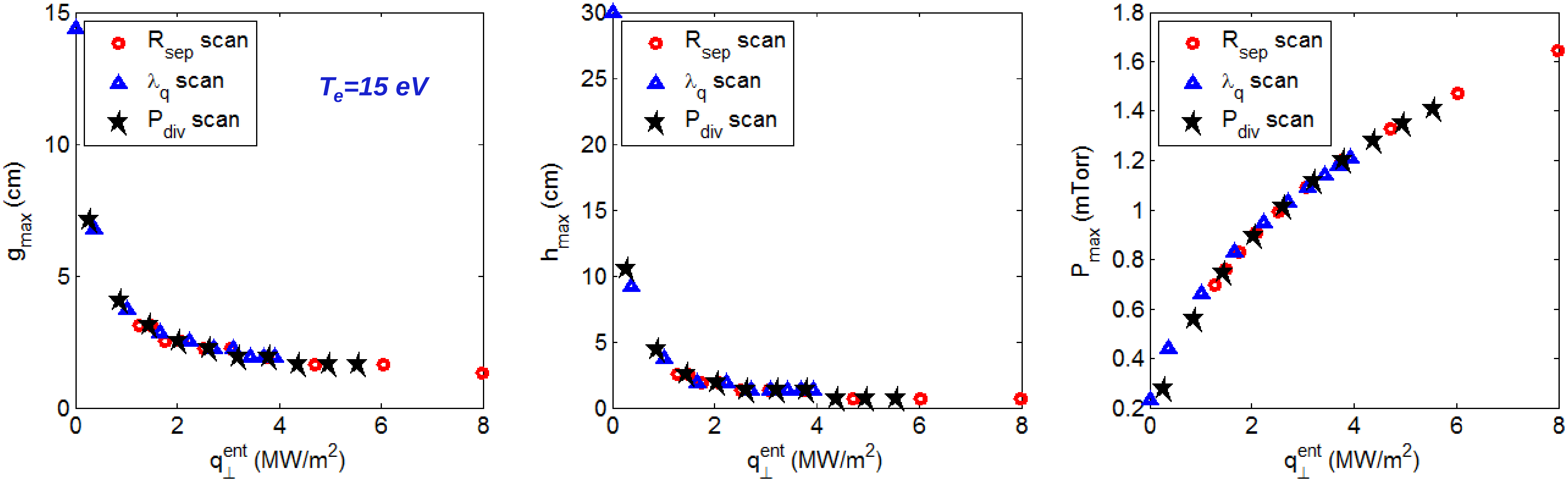
$$P_{pl} = \int_o^h I_{D2}(x)\sigma(x)dx = \int_o^h I_{D0}(x)\sigma(x)dx - \int_o^h P_{pl}S\sigma(x)dx$$

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

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

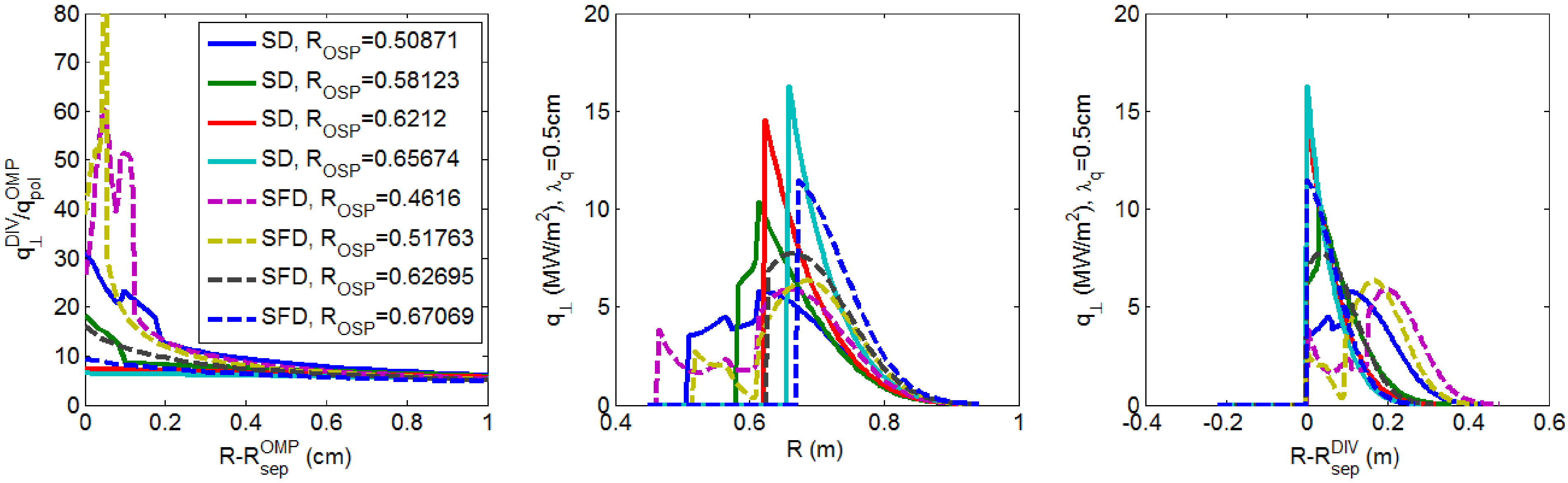
For given pump entrance position, heat flux at pump entrance orders the "optimal" geometry parameters

- 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



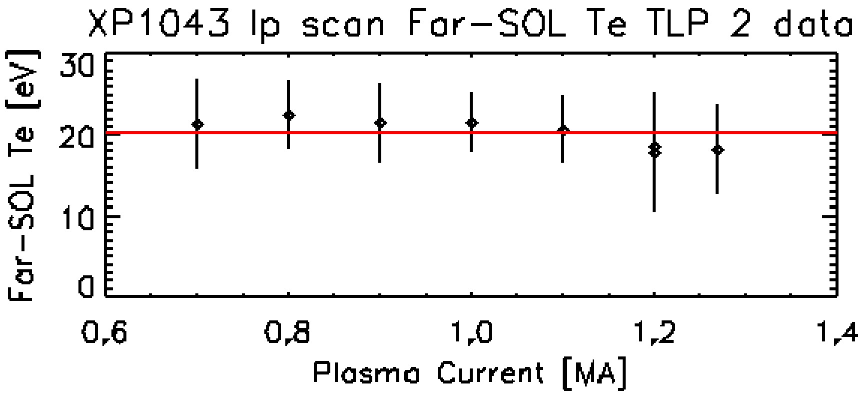
Projecting heat flux profiles

- Exponential poloidal heat flux profile imposed at midplane
  - P=5 MW (e.g., 1/2 of 10 MW goes to outer divertor)
  - λ_q^{OMP} ~ 0.3-2.0 cm
- Mapped along field lines to divertor
  - Total geometric heat flux reduction factor shown on left
  - Example heat flux profiles showing for λ_q^{OMP}=5mm
    - Heat flux high at R=0.7, significantly lower at 0.8



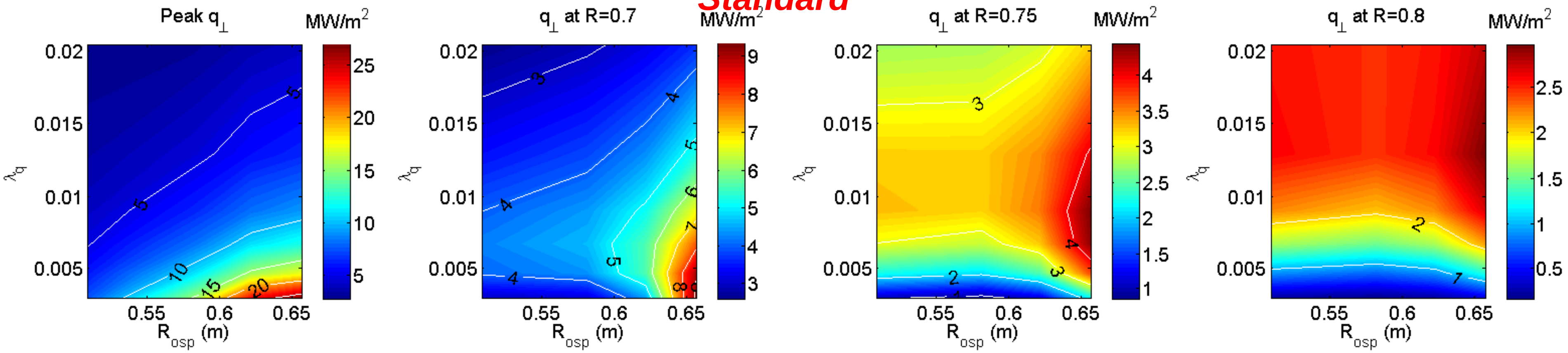
Far-SOL T_e does not vary significantly with I_p

- Triple probe used to determine Te (avoids turbulence issue)
- "Far-SOL" defined as beyond second sep.
- Variation in Te not statistically significant

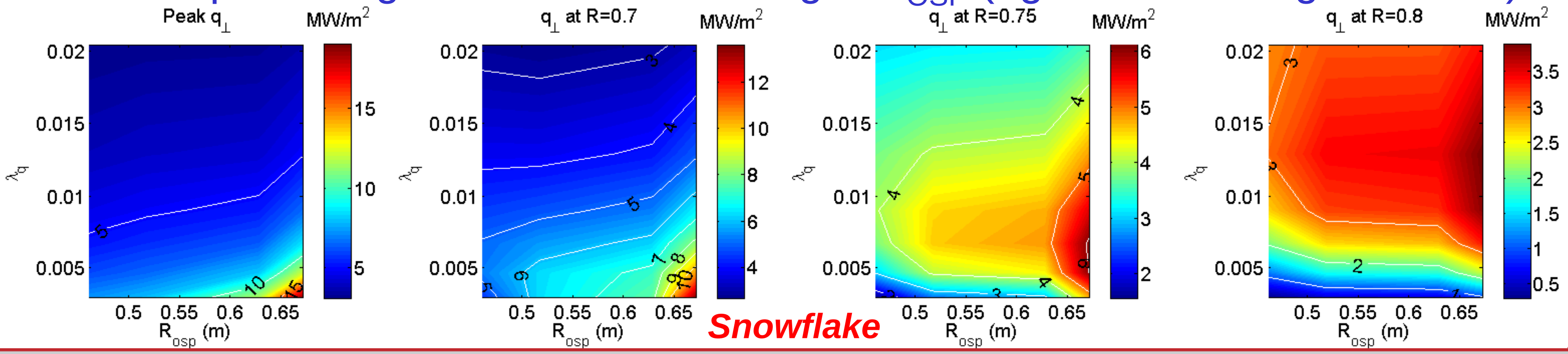


Heat flux projections show plenum entrance at R~0.7-0.75 m likely to provide sufficient pumping

Standard

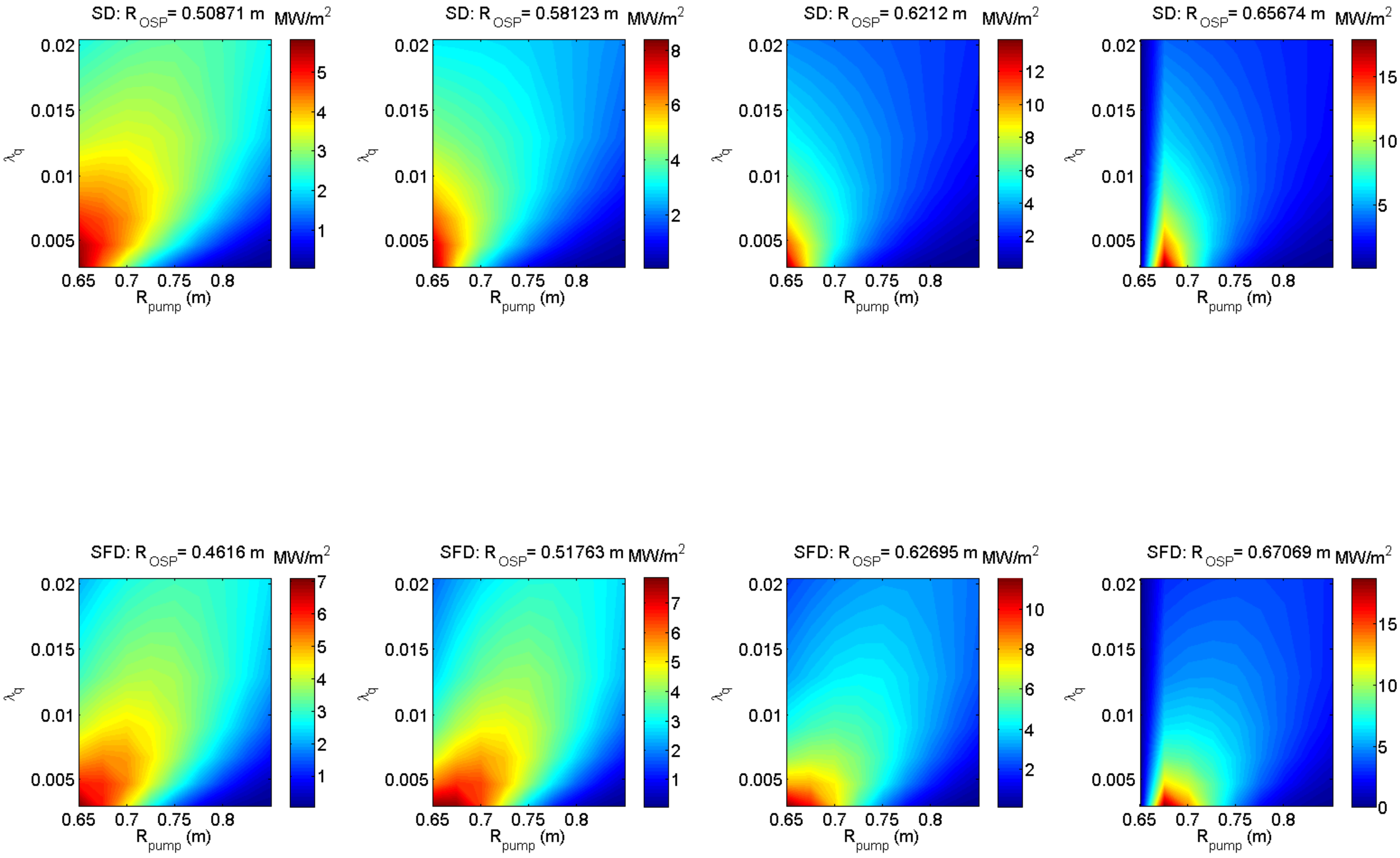


- Power handling: peak heat flux < 10 MW/m^2
  - Restricts R_{OSP} for narrow SOL (wider range for SFD)
- Pumping: $q_\perp^{entrance}$ > ~2 MW/m^2
  - Requires larger SOL widths for larger R_{OSP} (again wider range for SFD)

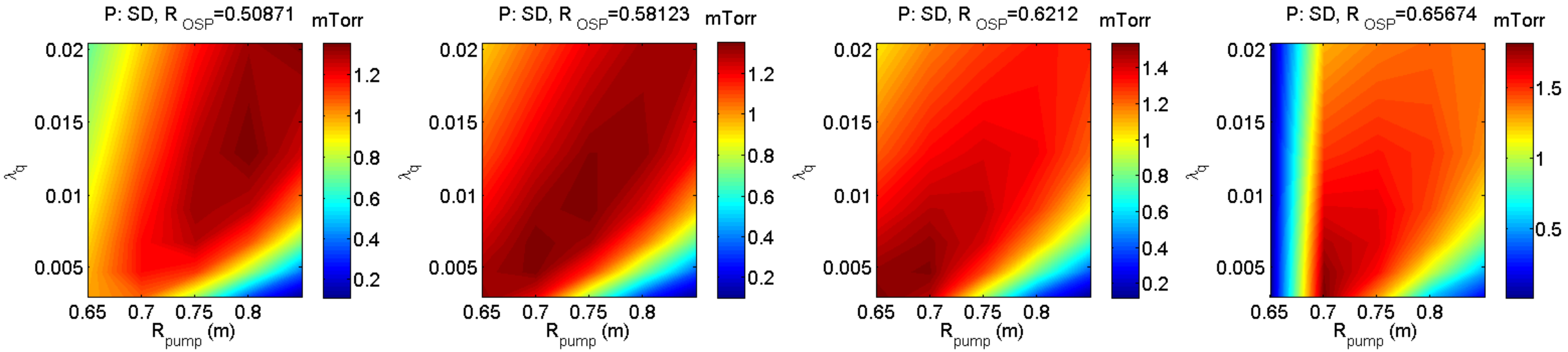


Snowflake

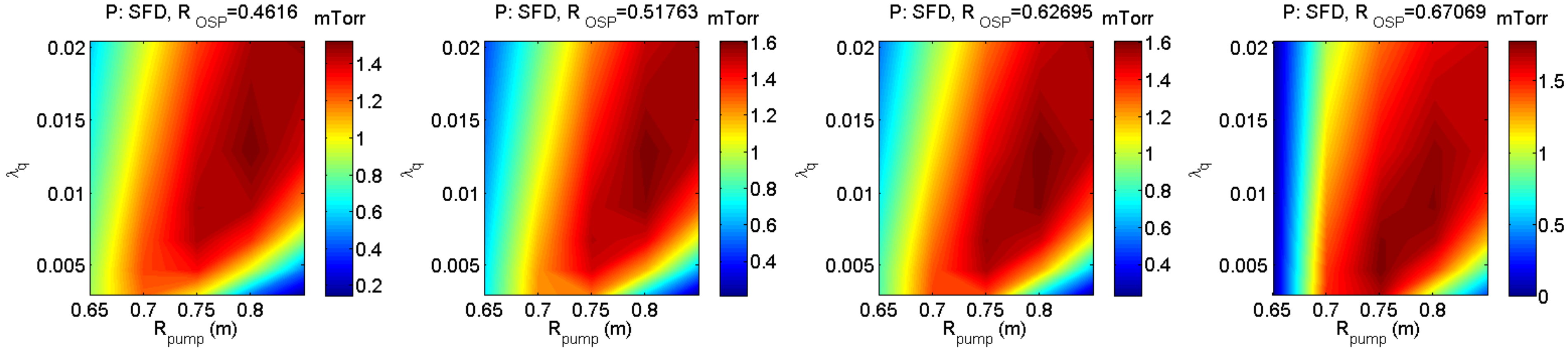
Heat flux at potential plenum entrances for 8 equilibria



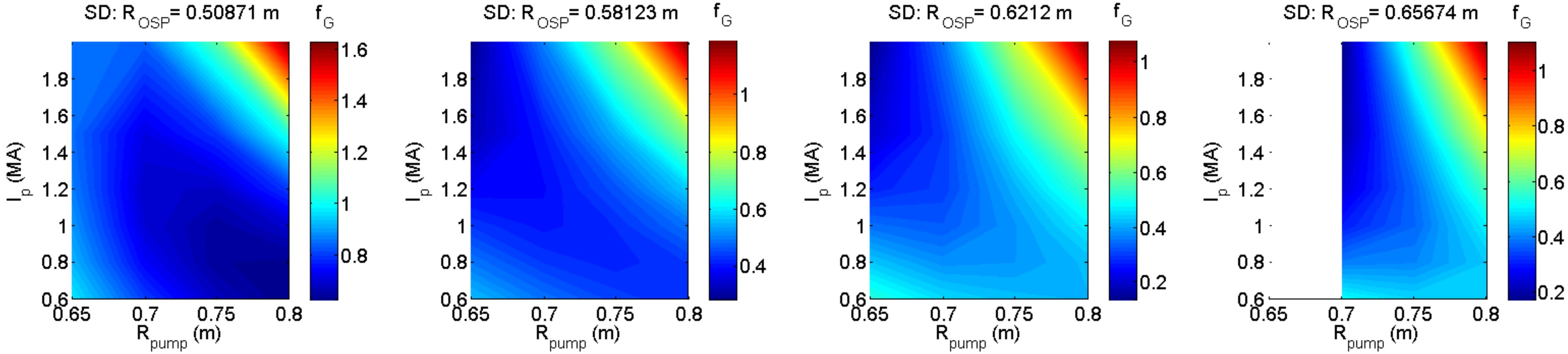
Projections show plenum entrance at R=0.72 can give >1 mTorr for wide range of SOL width, equilibria



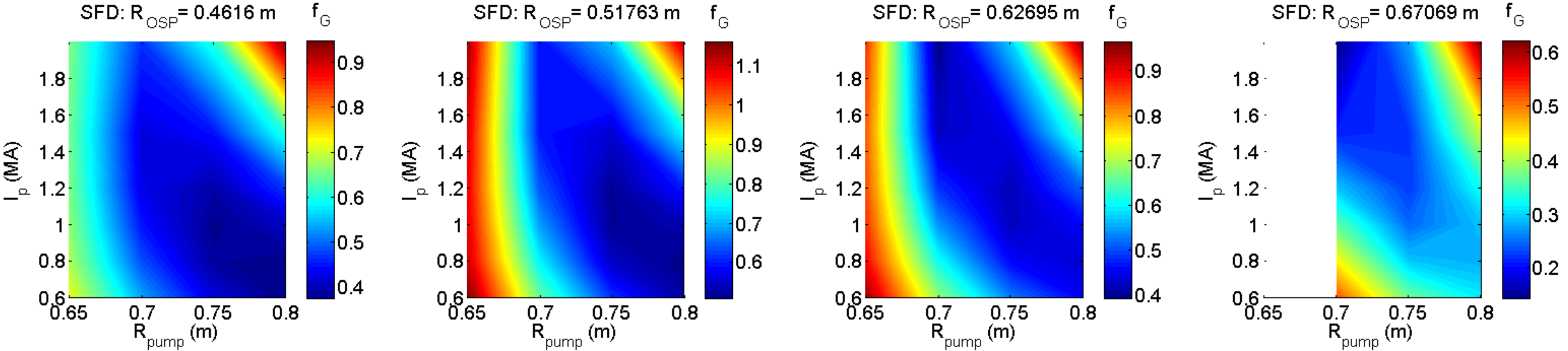
- Heat flux profiles, T_e^{div}, and optimized entrance parameters used in analytic model for plenum pressure
- Optimizing position for narrowest SOL gives R_{pump}~0.72
  - Narrow SOL gives least flexibility in moving R_{OSP} to improve pumping



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

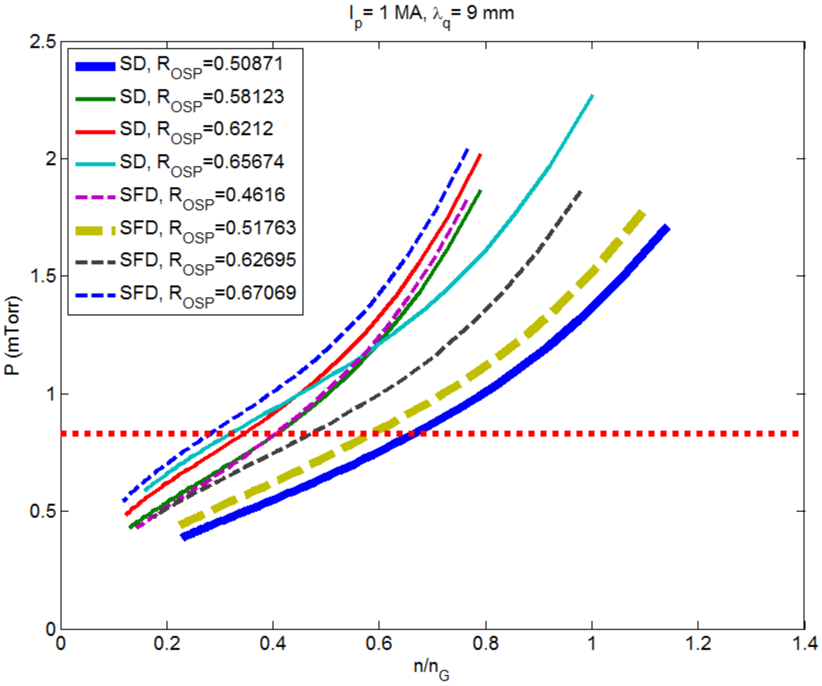


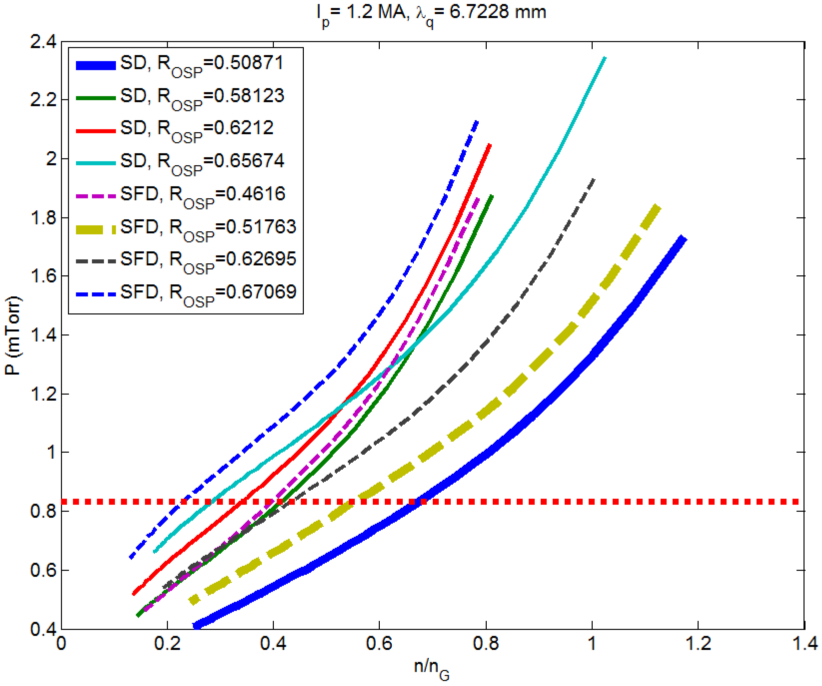
- $q_{||}$sep, T_e^{div} used in modified 2-pt model used to estimate n_e^{sep}
  - $q_{||}^{sep}$ from I_p scaling, T_e^{div} varied
- n_e/n_e^{sep} ~ 3 assumed to estimate f_G
- f_G shown is that at which pumped flux balances NBI input



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





The Basic Two-Point Model

- Begins from the fluid equations and simplifies...
- Provides simple relations for upstream and target (PFC) plasma parameters
- Varying levels of complexity can be implemented
  - Fluid reconstruction via generalized 2-point (e.g. OSM/OEDGE code)
  - Coupling with Monte Carlo neutrals and impurities (e.g. DEGAS 2/EIRENE/DIVIMP)
- **Start with the basics**

Assume:

$T_e = T_i$ & $p = p_e + p_i$

$$\frac{d}{dx}\left[\left(\frac{1}{2}m_i v^2 + 5kT\right)nv - \kappa_{0e} T_e^{5/2}\frac{dT_e}{dx}\right] = Q_R + Q_E$$

Assume:

Conduction Dominates

Neglect Sources

$$\frac{d}{dx}\left[-\kappa_{0e} T_e^{5/2}\frac{dT_e}{dx}\right] = 0$$

$$\boxed{T_u = \left[T_t^{7/2} + \frac{7}{4\kappa_{0e}} q_t L\right]^{2/7}}$$

P.C. Stangeby, ch. 5, 9, or 11, 2000, IoP.

Simple Extensions Attempt to Capture More Physics

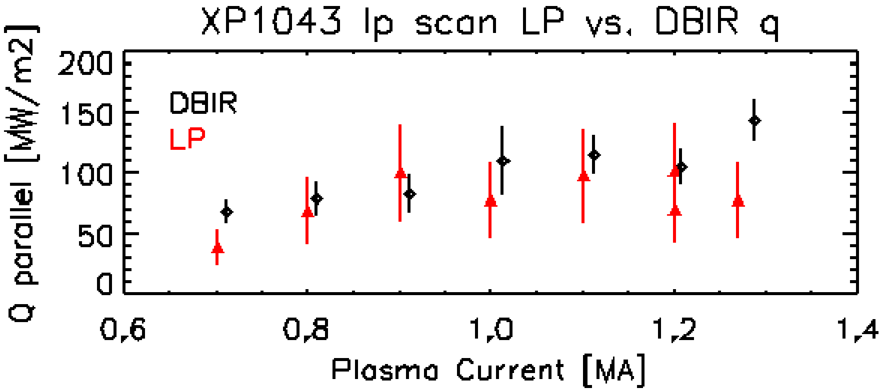
- Volumetric loss terms can be included via f_{power} term
- Term can be estimated with interpretative modeling in lieu of better div. Bolom. Coverage
- Comparison of nominal LP and DBIR results are encouraging
- Two values of fpower used following: 0 and 0.5

Radiation and charge-exchange

$$q_{rad}+q_{cx}=f_{power}q_0$$

$$\boxed{\left(1-f_{power}\right)q_0=q_t=\gamma n_t c_{st} kT_t}$$

$$\frac{T_t}{T_u}\propto\left(1-f_{power}\right)^2$$



Updated Upstream Density

- Force balance in the ST requires modification to 2-PM
  - Typical formulation assumes "straight" flux tubes
  - 1.5m OMP vs. 0.5m target results in significant variation
- Flux-tube definition allows conversion of magnetic field to area
- Not yet consistently applied everywhere in calculations

$$F_u = F_t$$

$$P_u A_u = P_t A_t$$

$$N_u T_u = N_t T_t (1 + M^2) \frac{A_t}{A_u}$$

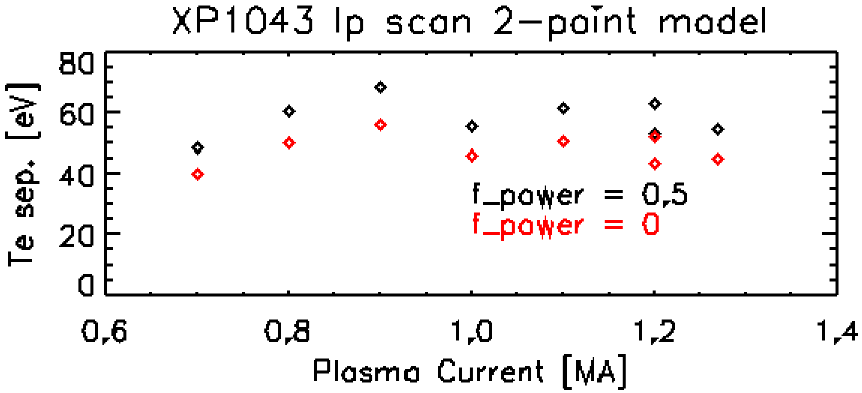
$M = v / c_s \geqslant 1$ Mach No. at sheath

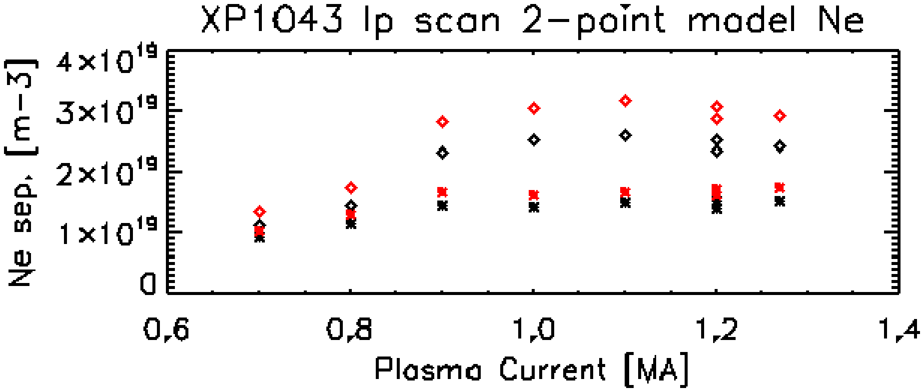
$$B\,A = \Psi_0 = const. \rightarrow \frac{A_t}{A_u} = \frac{B_u}{B_t}$$

$$\boxed{N_u = \frac{N_t T_t (1 + M^2)}{T_u} \frac{B_u}{B_t}}$$

Upstream Quantities Determined via 2-Point Model

- Parallel connection length calculated from EFIT02
  - q_{peak} used to locate nominal Ψ_N value for integration
  - Solution not sensitive to variance in length (robust model from target)
- Interpolated MPTS density at the upstream temperature shown for comparison
- Uncertainty not yet propagated in calculations to determine significance in discrepancy





Wall fuel uptake is ~zero during long-pulse H-modes in pumped machines

- FY09 Joule Milestone Report
- Close balance is observed between particle input (beams+puff) and pumping
  - True for both DIII-D and C-Mod
  - Motivates pumping the beam input as figure of merit

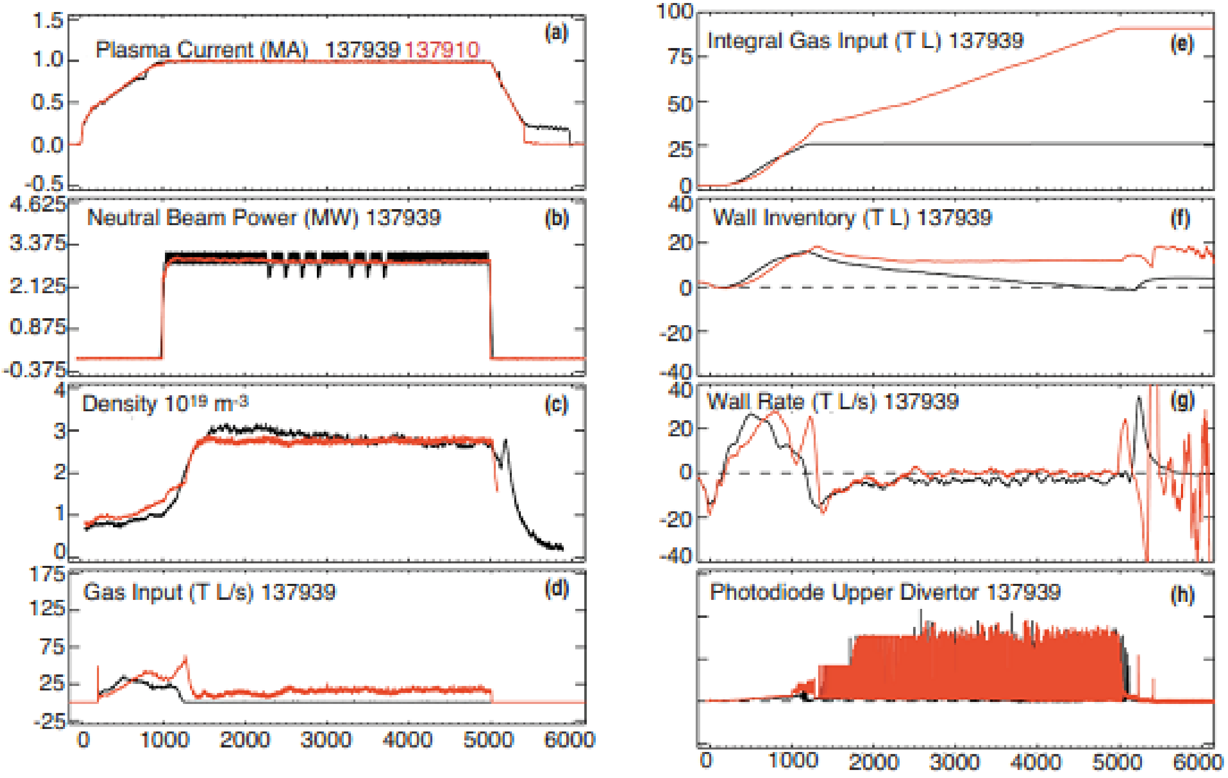


Fig. 2. ECH heated (red) H-mode plasma is compared with a NBI (black) discharge. The plasma current, neutral beam or ECH power, electron density, gas input, integral of the gas input; wall inventory and wall rate from the dynamic particle balance; along with the photodiode signal are compared with a neutral beam heated H-mode DIIID shot. Note that in both cases, the wall flux is quite large in the L-mode period, but during the ELMing H-mode, the wall flux is very close to zero.