Physics design of a cryo-pumping system for NSTX-U

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54th APS-DPP Meeting
Providence, RI
Oct 31st, 2012

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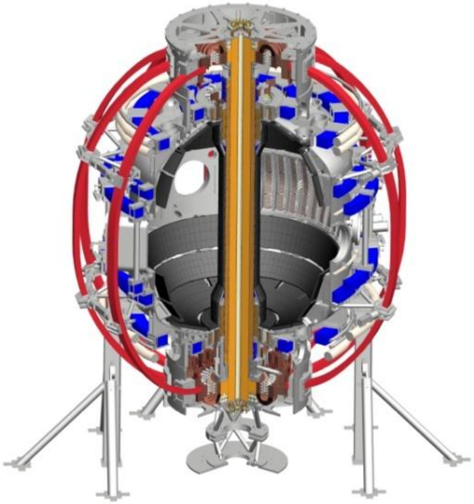

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Motivation

- 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

- Lithium coatings on PFCs sufficient for deuterium control, but ELMS are eliminated, leading to impurity accumulation
  - High Z_{eff}, prone to radiative collapse
  - Can be mitigated by ELM pace-making with 3D field pulses

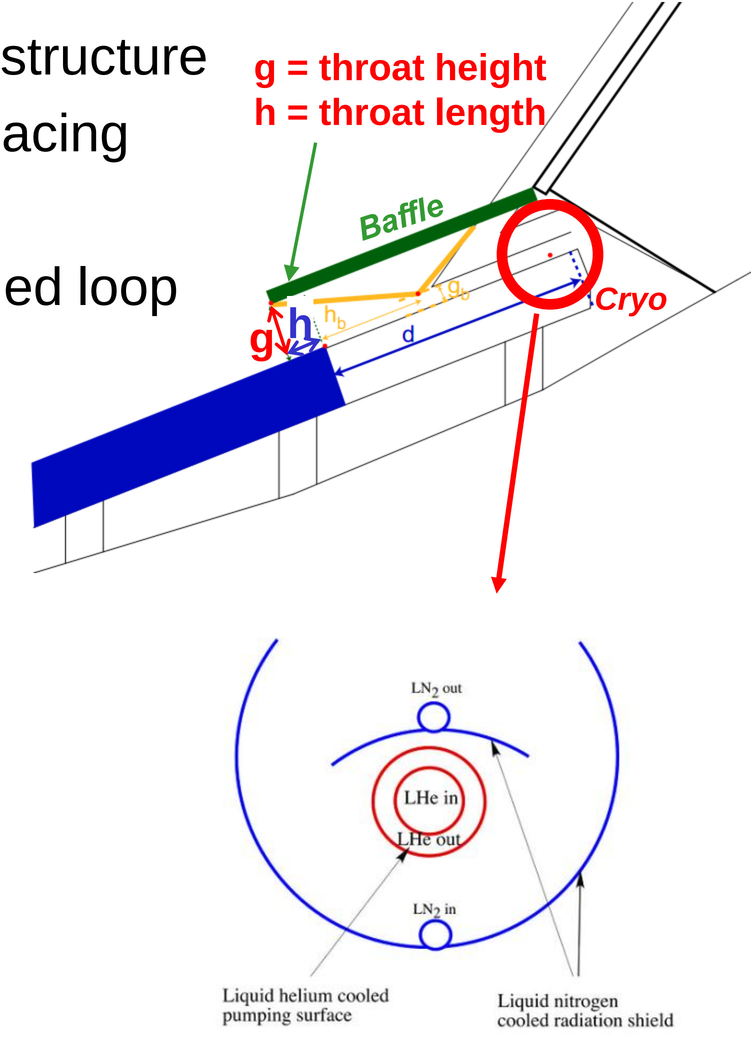
- Cryo-pumping is being explored as a complement to lithium
  - Proven technique to control density in higher R/a tokamaks
  - May allow deuterium pumping without eliminating ELMs, so avoiding impurity accumulation problems

General layout 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)



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

Semi-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)

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

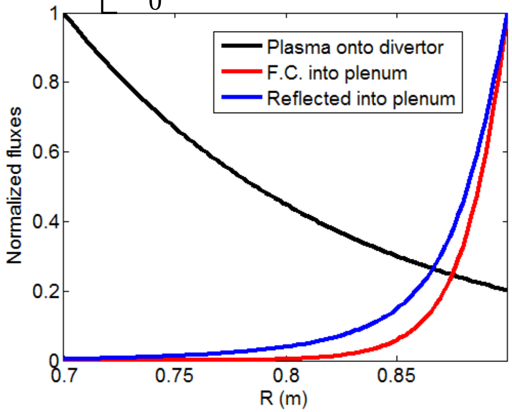
Neutral current into plenum

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

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

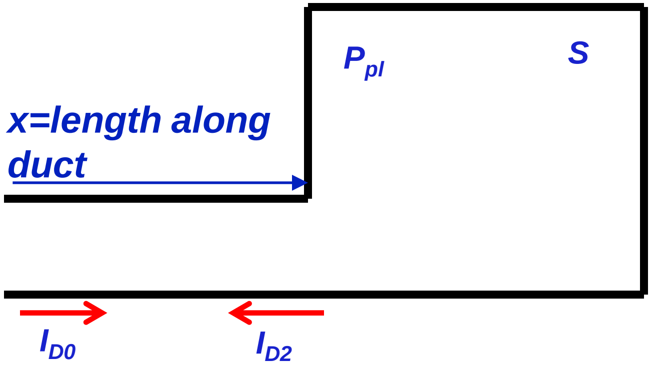


Origin of neutrals making it into plenum tends to be localized to near-entrance region

Dominantly due to solid angle factor

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

Model upgraded to include conductance correction in a long channel



- $I_{D0} = I_{D0}(x)$ = 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

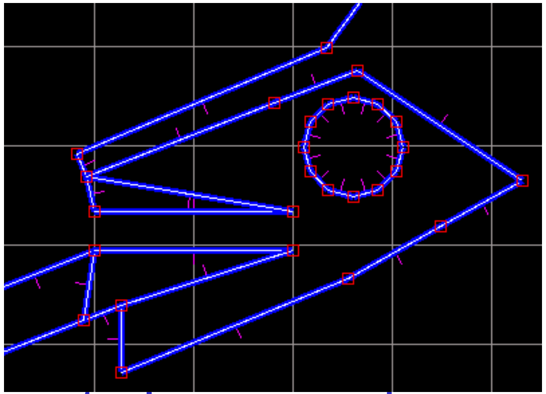
$$P_{pl} = \int_o^h I_{D2}(x)\sigma(x)dx = \int_o^h I_{D0}(x)\sigma(x)dx - \int_o^h P_{pl}S\sigma(x)dx$$

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

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

Expressions for conductance, pressure have been checked with Monte Carlo neutral code EIRENE

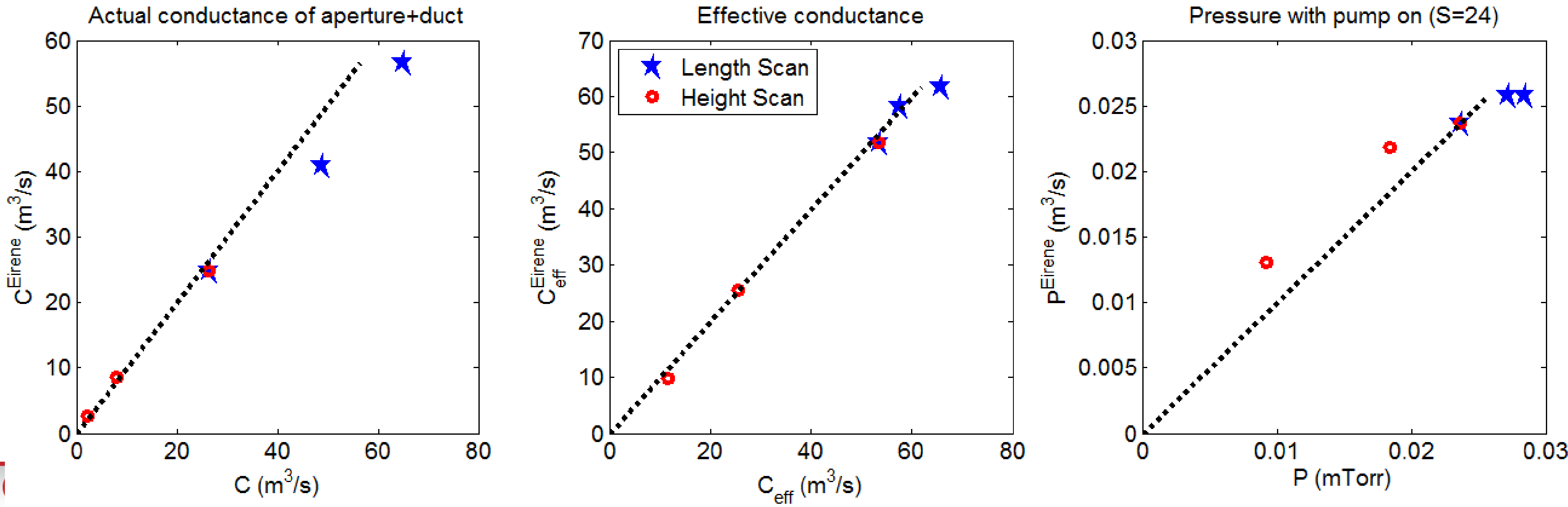
- Set of ducts constructed in EIRENE, varying length and height
- Three calculations made for each:
  - No pumping, gas source inside plenum
    - Gives the actual conductance of duct/aperture
    - $C = I_{pl}/P_{pl}$
    - (I_{pl}=source in plenum, P_{pl}=plenum pressure)



  - No pumping, gas source outside plenum (mimic neutrals coming from plasma)
    - Gives effective conductance, accounts for how far neutrals make it down duct before hitting the walls
    - $C_{eff} = I_{ent}/P_{pl}$
    - (I_{ent}=current of neutrals crossing duct entrance)
  - Pumping on ($S=24$,m^3/s), gas source outside plenum
    - Check pressure against analytic expression:
    - $P = (C/C_{eff})*I_{ent}/(S+C)$

EIRENE confirms pressure variations with plenum entrance geometry

- X-axis: analytic expressions, Y-axis: values calculated with EIRENE
- Conductances are ok, but duct expression is somewhat off (based on length scan on left)
- Pressure variations from EIRENE largely agree with analytic expressions
  - Difference is largely due to the conductances: if the EIRENE-calculated conductances are used, pressures lie on the line
  - Just using P=I/(S+C) gives numbers higher by ~x2-3, trends off



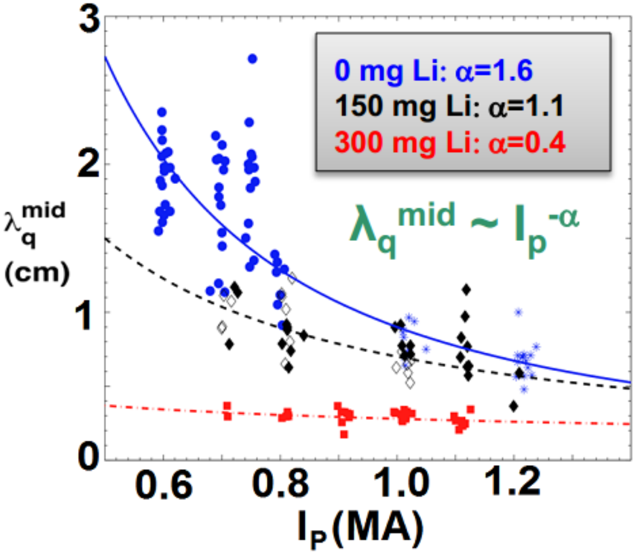
Projected divertor parameters combined with semi-analytic pumping model are used to calculate pumping rates

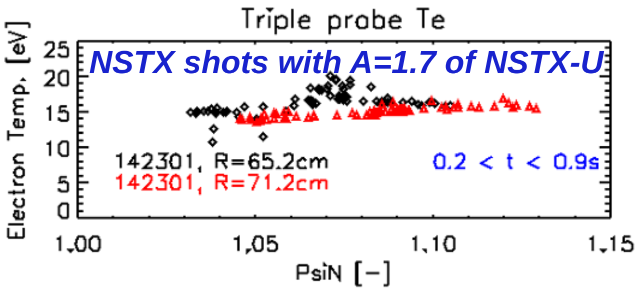
- Analytic model requires divertor n, T, Γ profiles
- Heat flux, angle of B wrt PFC surface (α), and plasma temperature are sufficient to calculate n, Γ:

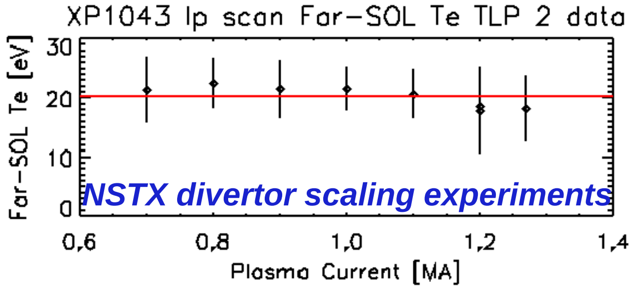
$$\Gamma_\perp = q_\perp / 7T$$

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

  - 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, with lithium radial, I_p dependence
    - T_e~15 eV assumed (NSTX-U-like discharges)

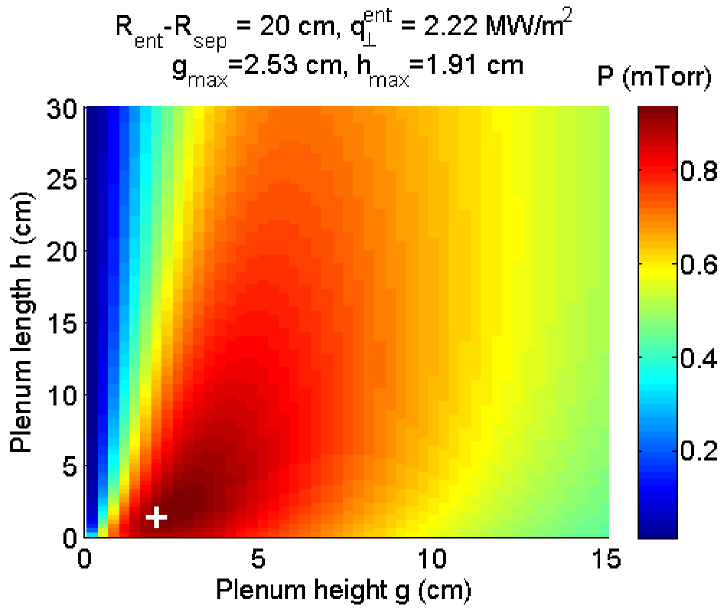


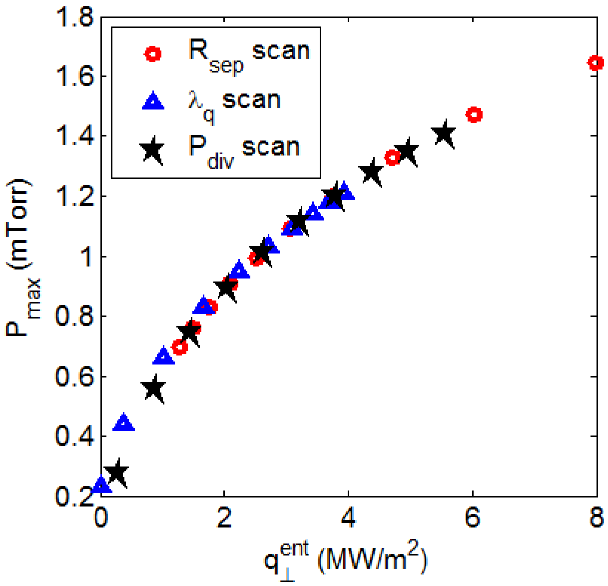




Pressure projections are used to optimize plenum geometry parameters

- 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} $\Rightarrow$ 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

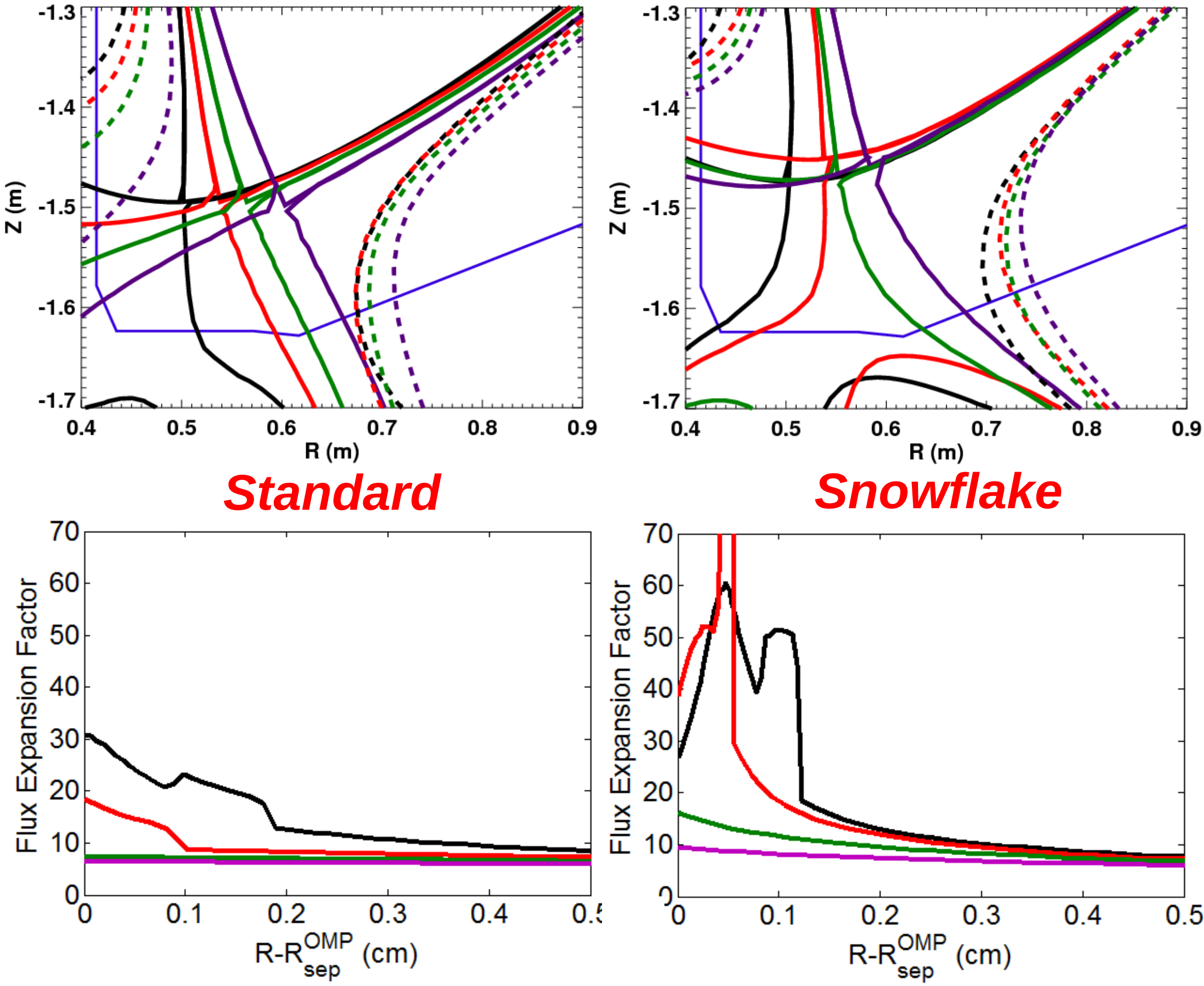




Equilibria with variety of R_{OSP}, flux expansion are used to map heat flux profiles, assess candidate pump entrance locations

- 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}

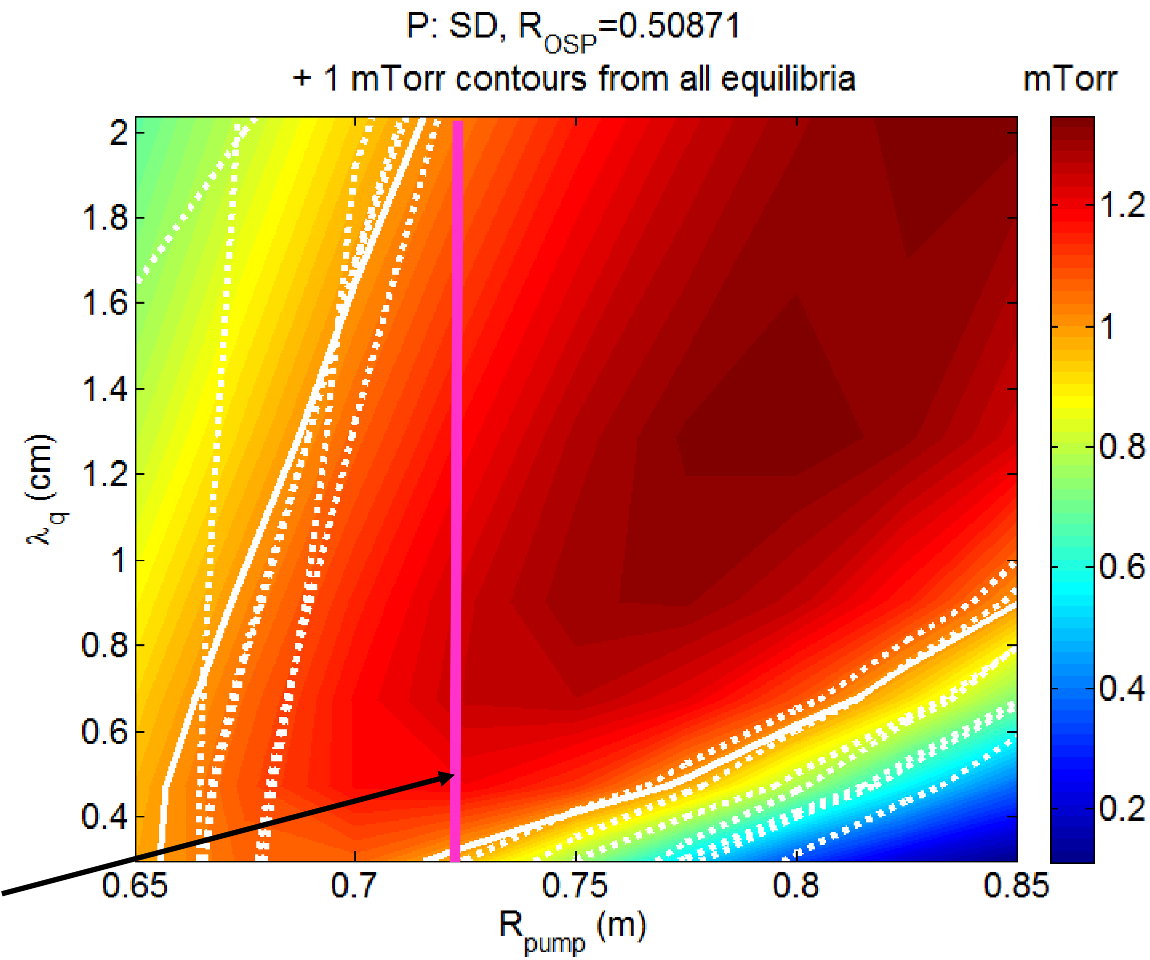
- Flux expansion, flux surface geometry used to convert midplane heat flux profile (from scaling) to divertor heat flux
  - As R_{OSP} is increased, flux expansion is decreased



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

STANDARD DIVERTOR P_0



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

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

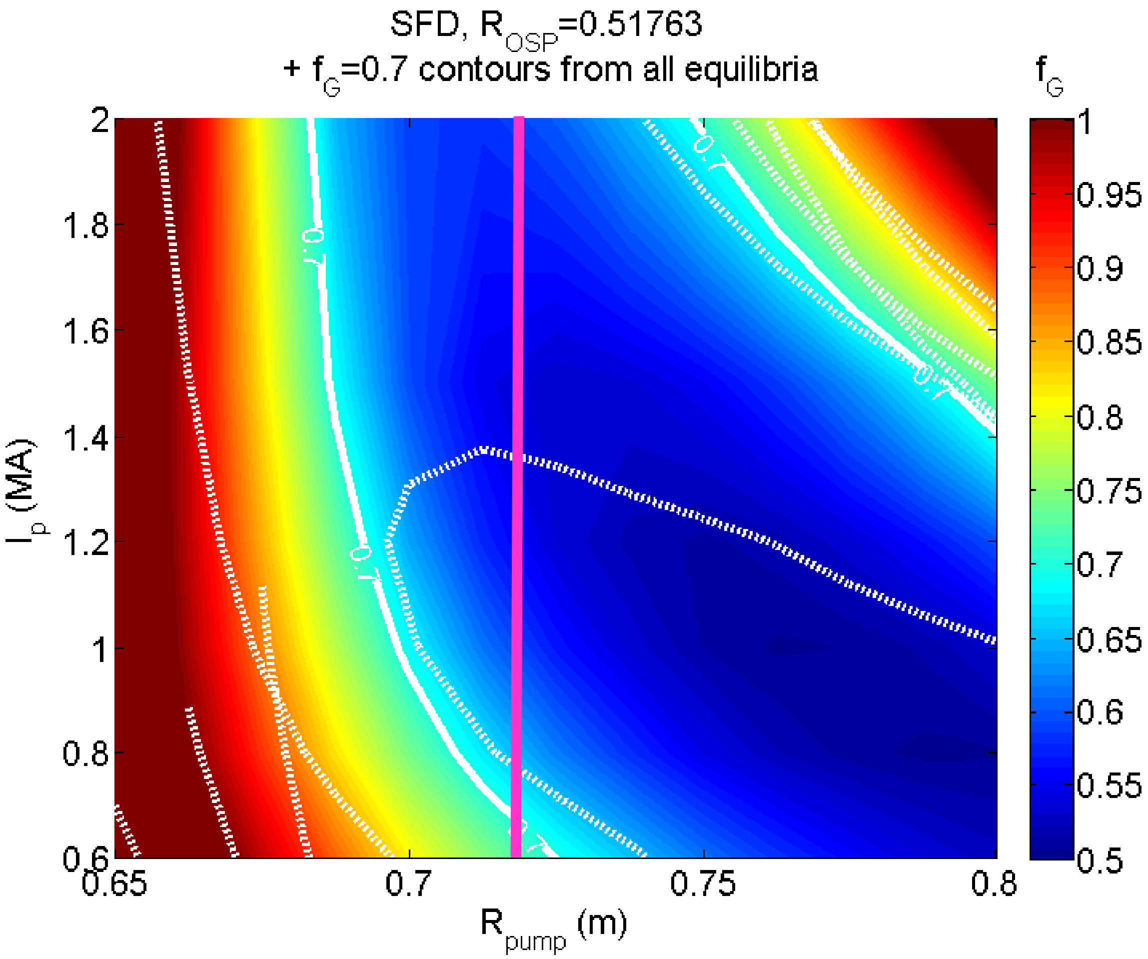
$$T_{OMP} = \left(T_{DIV}^{7/2} + \frac{7}{4\kappa_{0e}} q_{\parallel}^{sep} L \right)^{2/7}$$

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

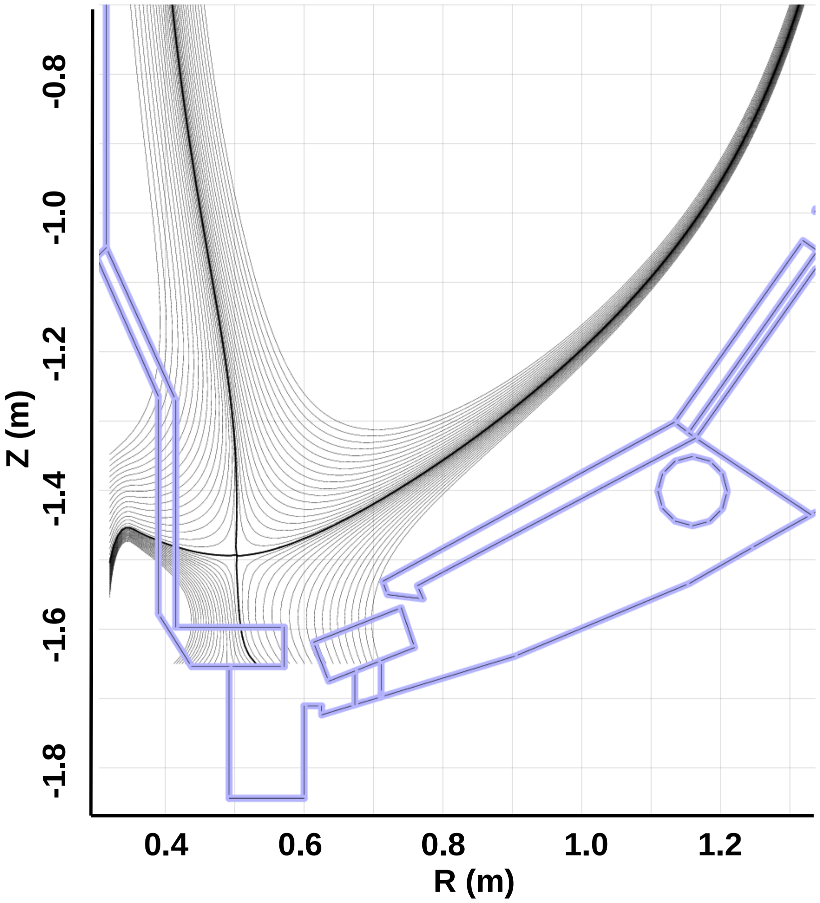
  - $q_{||}^{sep}$ from I_p scaling, T_e^{div} varied
  - Final n_e^{sep}: pumping=NBI input

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

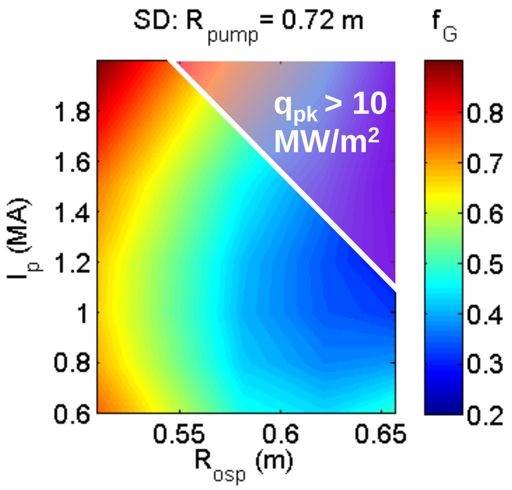
SNOWFLAKE DIVERTOR n/n_G

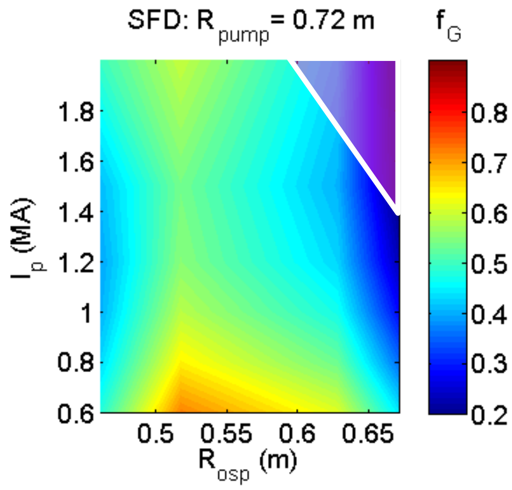


Optimized plenum geometry capable of pumping to low density for a range of R_{OSP}, I_p



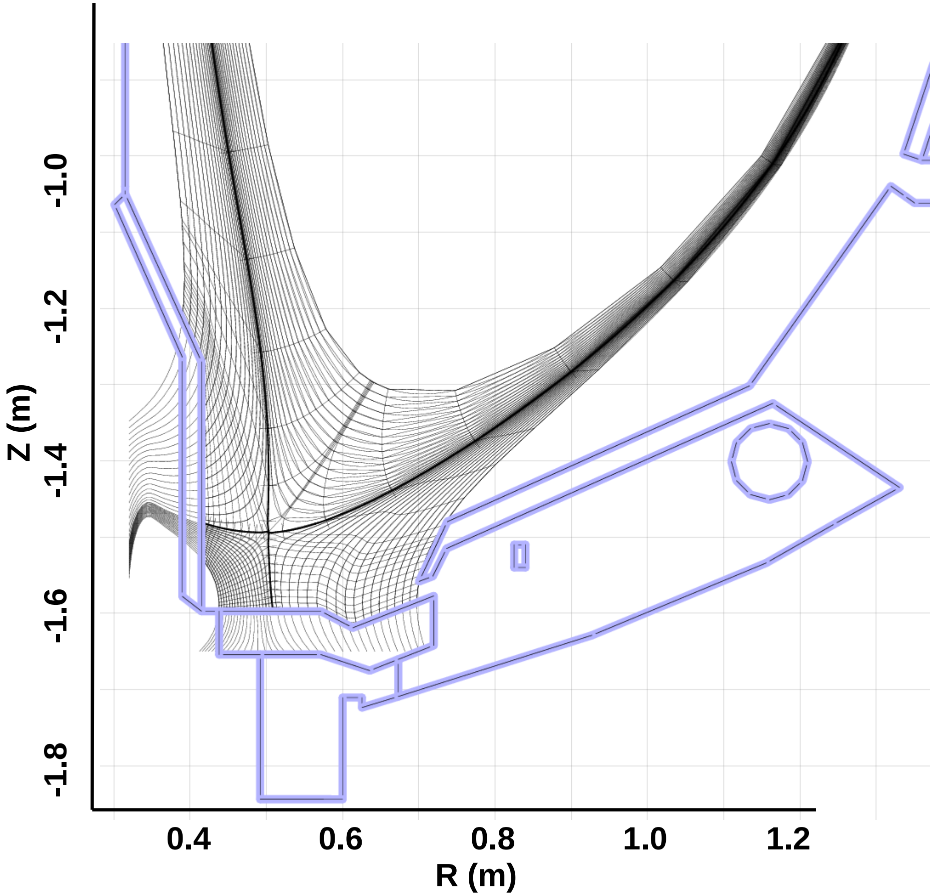
- Equilibrium f_G down to < 0.5
  - Moving R_{OSP} closer to pump allows lower n_e, but limited by power handling
- High flux expansion in SFD gives *better* pumping with SOL-side configuration
  - More plasma in far SOL near pump
  - More room to increase R_{OSP} at high I_p





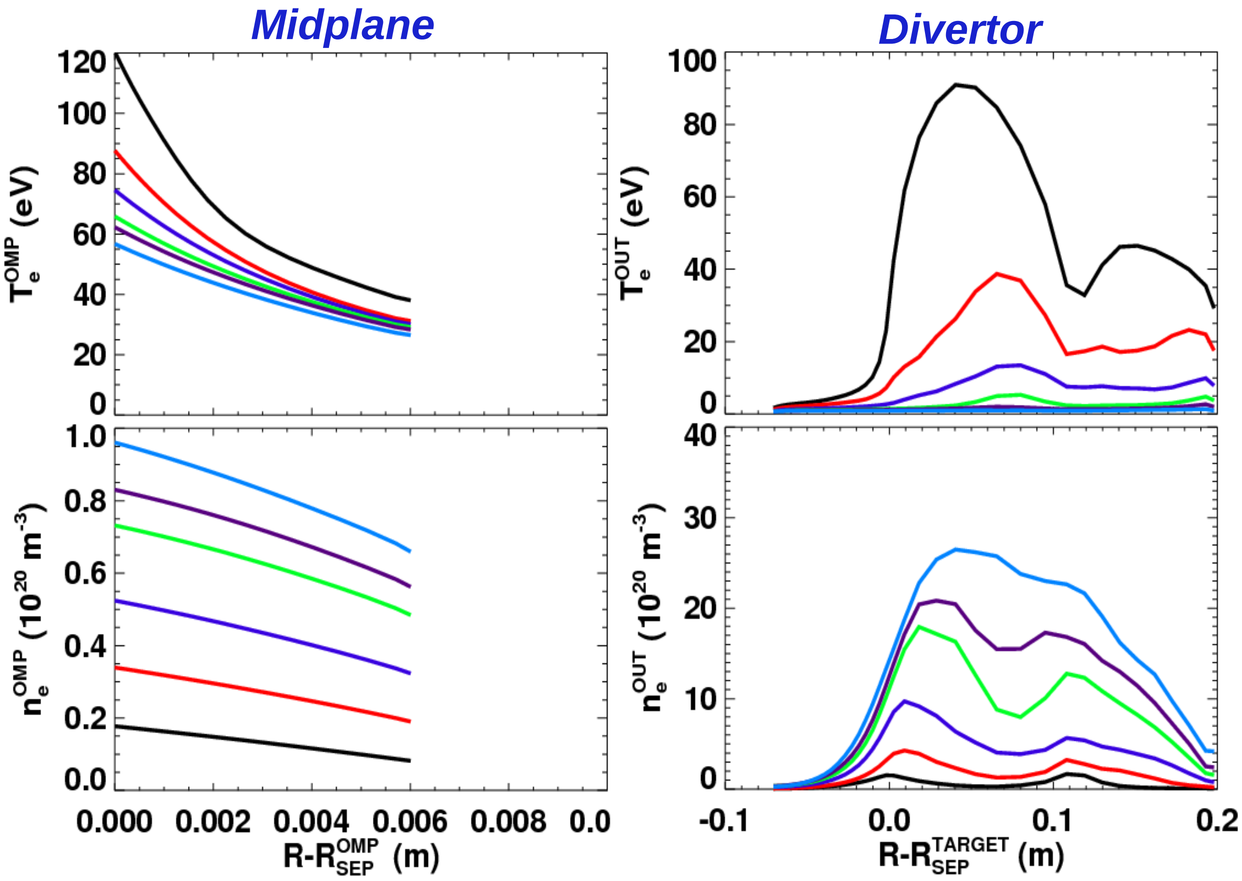
SOLPS is used to analyze pumping including near-detached conditions

- SOLPS: 2D fluid plasma/neutral transport
  - Plasma transport classical parallel to B (+kinetic corrections), ad-hoc cross-field transport coefficients
  - Kinetic neutral transport using MC code EIRENE
    - More comprehensive treatment of neutral transport (beyond first-flight)
    - Can treat radiative/detached divertor
- Both standard and snowflake divertor with R_{OSP}~0.5m studied
  - Note that grid can't extend past pump, so only small SOL region modeled
- Constant D=0.5, $\chi_{e,i}$=2.0 m^2/s
  - Gives $\lambda_q^{mid} \sim 3mm$
  - No attempt to match expt
- Simulations both without and with carbon included have been performed



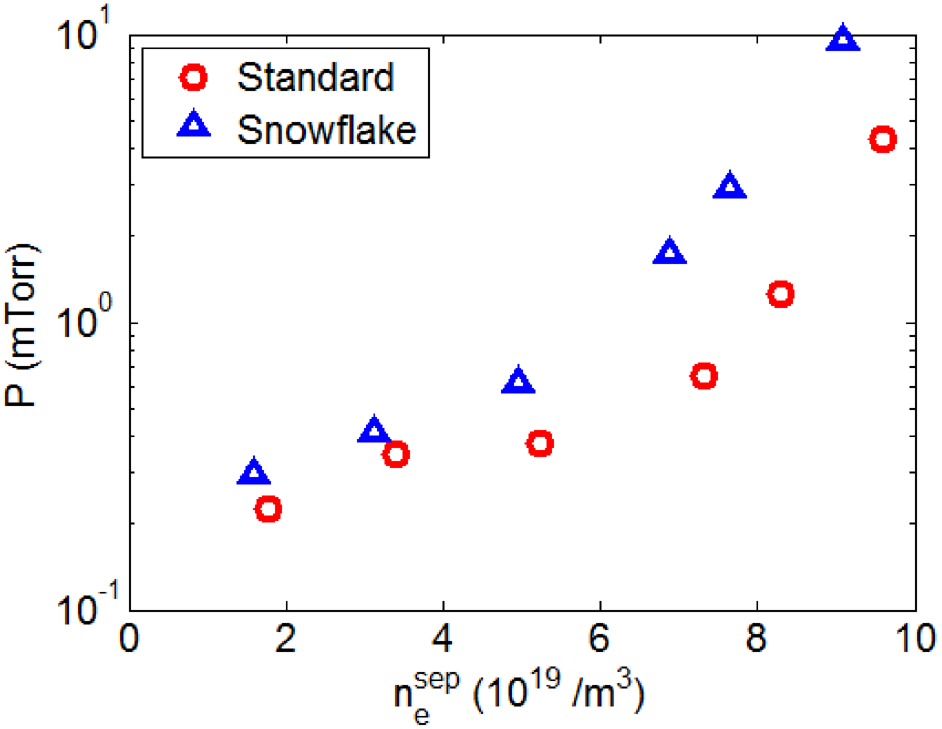
A wide range of divertor plasma parameters have been modeled

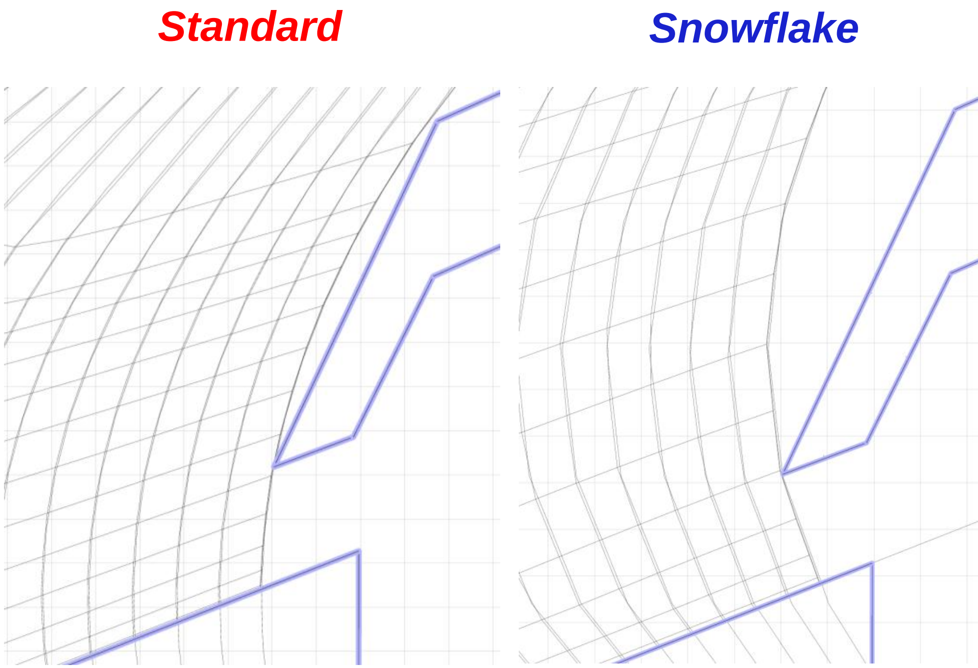
- Input power P=10MW in all cases
- n_e at core grid edge set as boundary condition
  - Scanned to vary divertor conditions
- Resulting divertor parameters vary from strongly attached to nearly detached (T_e~1eV)



Snowflake shows higher plenum pressures that standard divertor for similar conditions

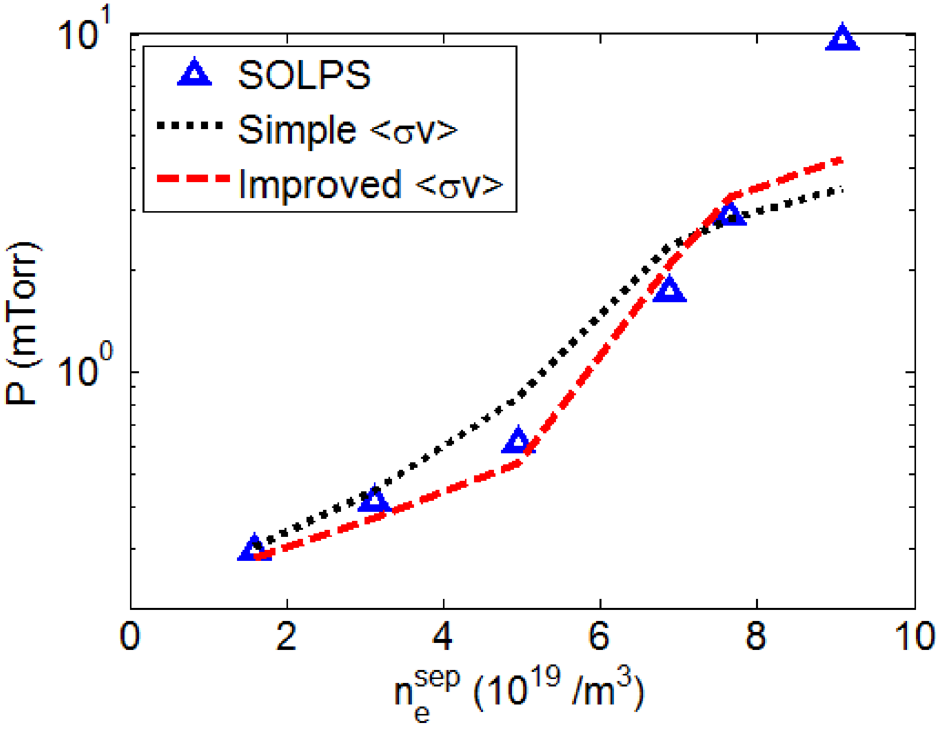
- At same separatrix density, pressure is ~2x higher with Snowflake divertor configuration
- Partially due to geometry of field lines at pump entrance (plasma flux reaches nearer entrance; not accounted for in earlier projections)
- Pressures above 1 mTorr can be reached at high n_e in both cases

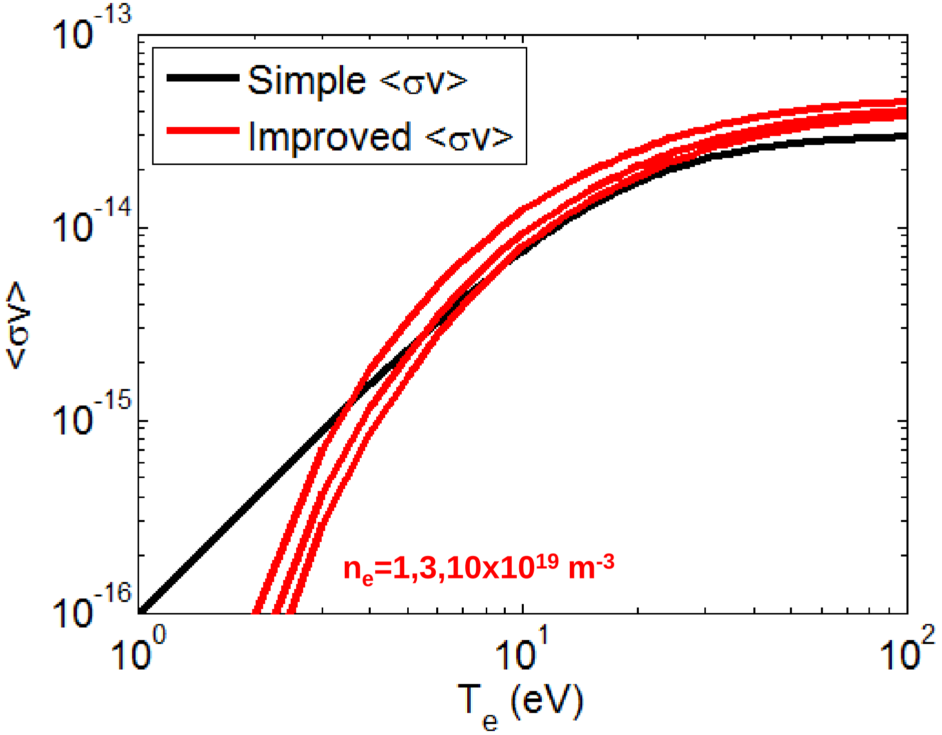




Plenum pressure from SOLPS shows good agreement with semi-analytic expressions when divertor is attached

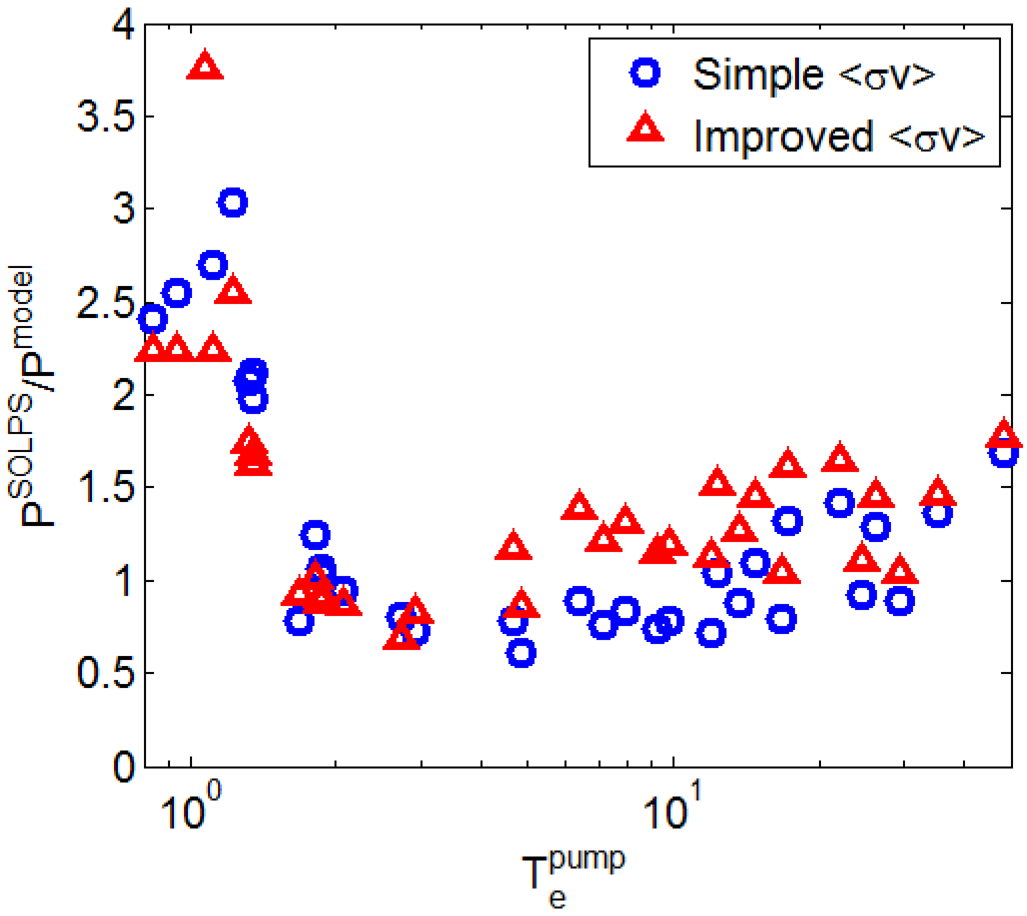
- Divertor n_e, T_e, $\Gamma_\perp$ from SOLPS used in semi-analytic model
- Model reproduces pressure within factor of ~2 (except high n_e)
- Agreement is improved using more accurate ionization rate
  - Simple rate coefficients used in original model: $\langle\sigma v\rangle_{EII}(r) \approx \dfrac{3\times10^{-16}T_e^2(r)}{3+0.01T_e^2(r)}$
  - Interpolating tables of $\langle\sigma v\rangle(n_e,T_e)$ as in EIRENE improves comparison





Semi-analytic model underestimates pressure under detached conditions

- Model pressure close to SOLPS calculation for T_e>2 eV
  - Often underestimates by ~50%
  - Model does not give large overestimate in any cases
- For T_e<2 eV SOLPS-calculated pressure is up to ~3x higher than model
  - First-flight neutral model expected to break down
  - Consistent with DIII-D pumping observations



⇒ Optimization of design presented here is conservative

- ***Pumping likely to be stronger for realistic conditions***

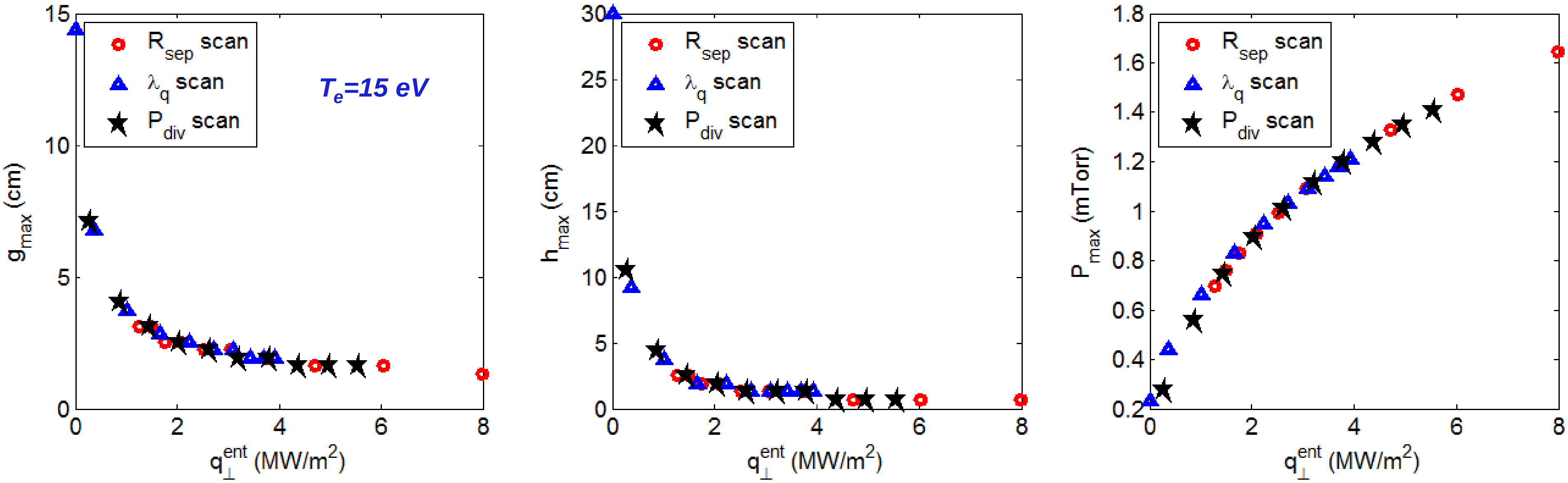
Summary

- 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
  - Snowflake shows better pumping that standard divertor
- SOLPS calculations confirm approach taken in design optimization
  - Pumping model adequate under attached conditions
  - Pressure significantly larger than model for T_e<2eV
- Next steps in pump design
  - Investigate details of plenum design, compatibility with engineering
    - Begin engineering design
  - Explore interaction between cryo and lithium coatings
    - Coating of pumping surface?
    - Pumping of lithium-modified SOL?

BACKUP

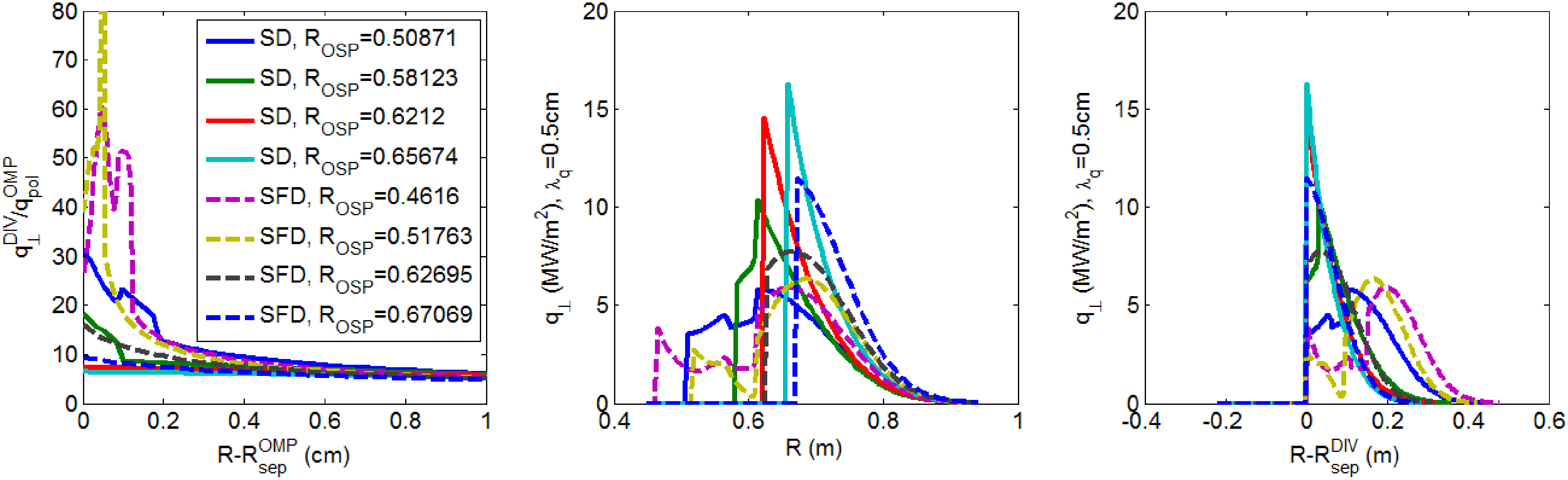
For given pump entrance position, heat flux at pump entrance orders the “optimal” geometry parameters

- 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



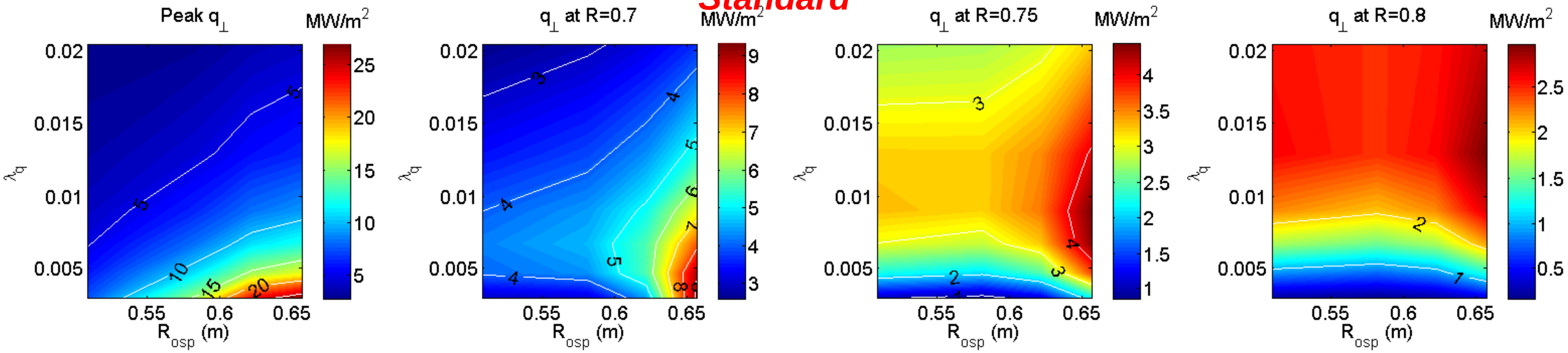
Projecting heat flux profiles

- 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

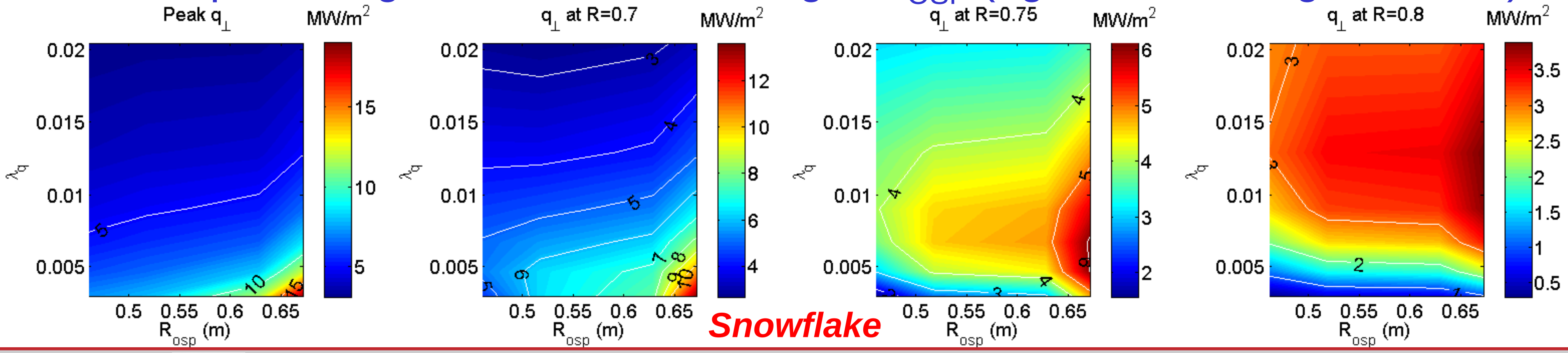


Heat flux projections show plenum entrance at R~0.7-0.75 m likely to provide sufficient pumping

Standard

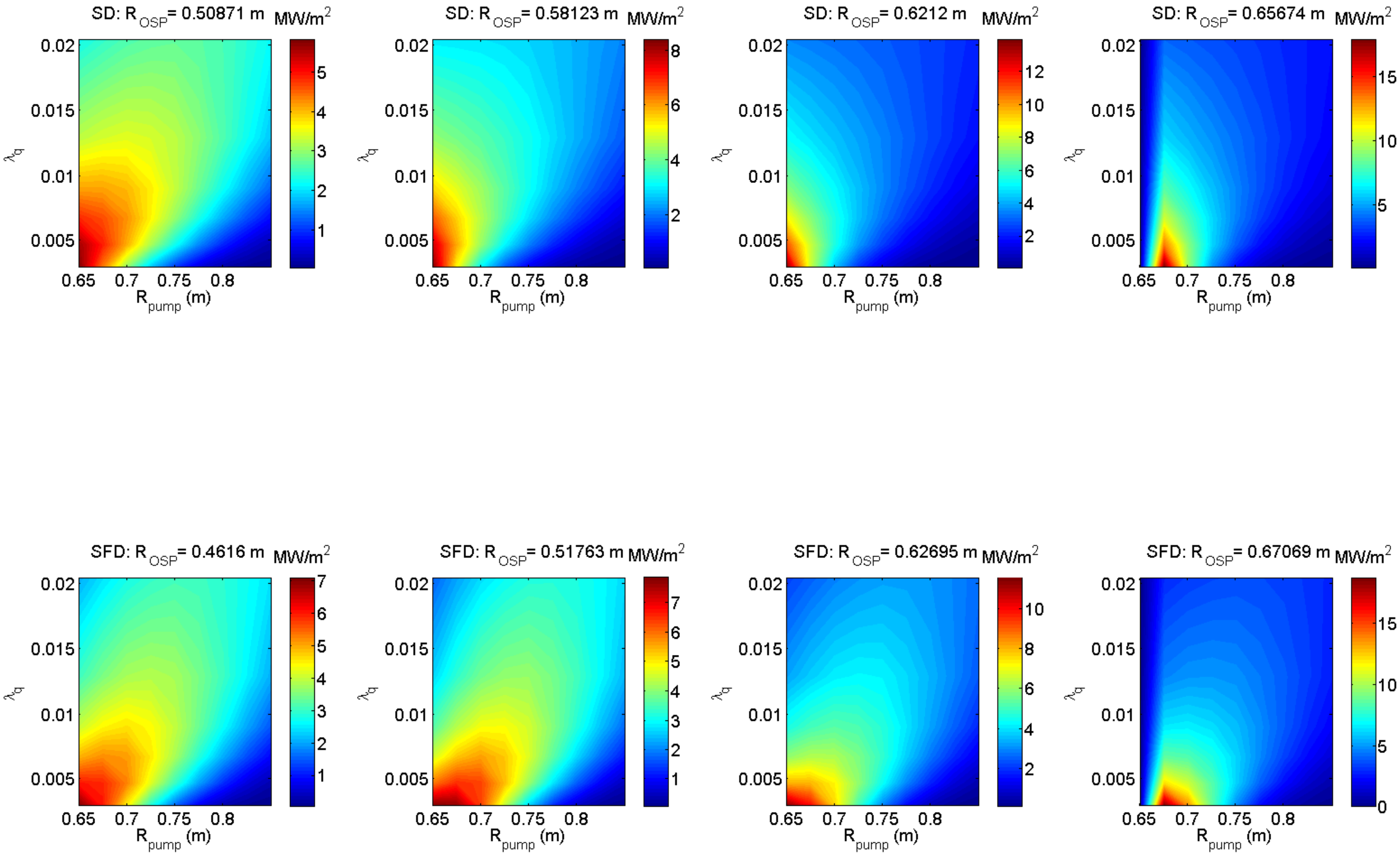


- Power handling: peak heat flux < 10 MW/m^2
  - Restricts R_{OSP} for narrow SOL (wider range for SFD)
- Pumping: $q_\perp^{entrance}$ > ~2 MW/m^2
  - Requires larger SOL widths for larger R_{OSP} (again wider range for SFD)

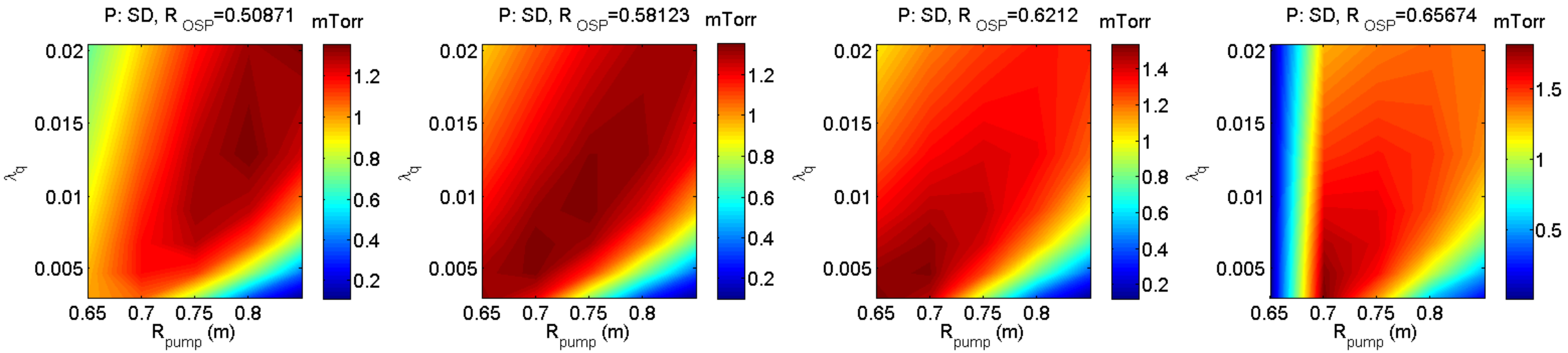


Snowflake

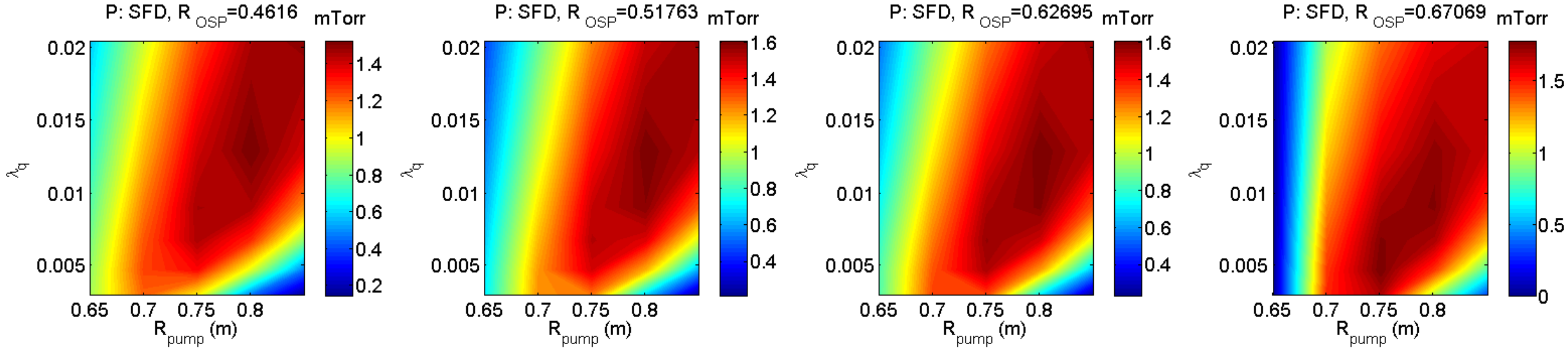
Heat flux at potential plenum entrances for 8 equilibria



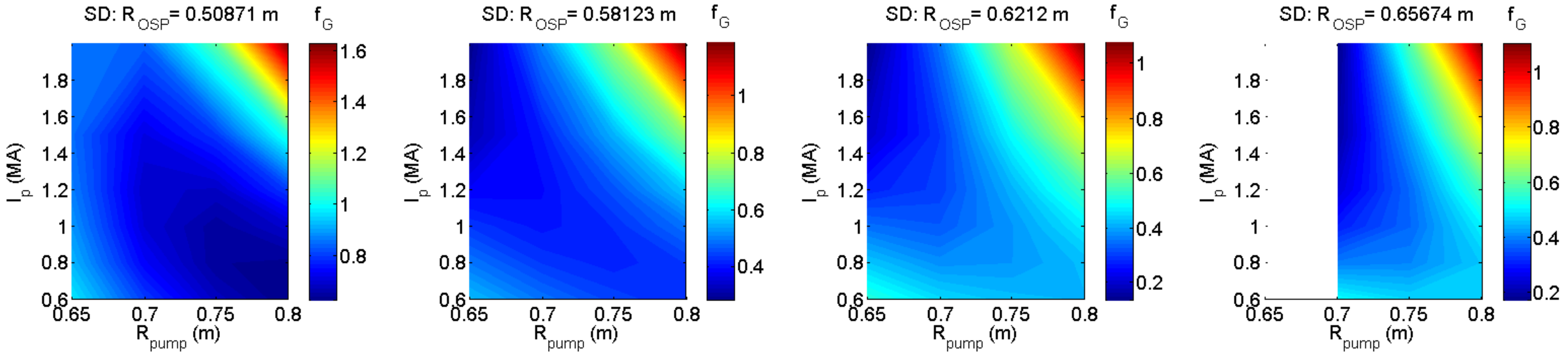
Projections show plenum entrance at R=0.72 can give >1 mTorr for wide range of SOL width, equilibria



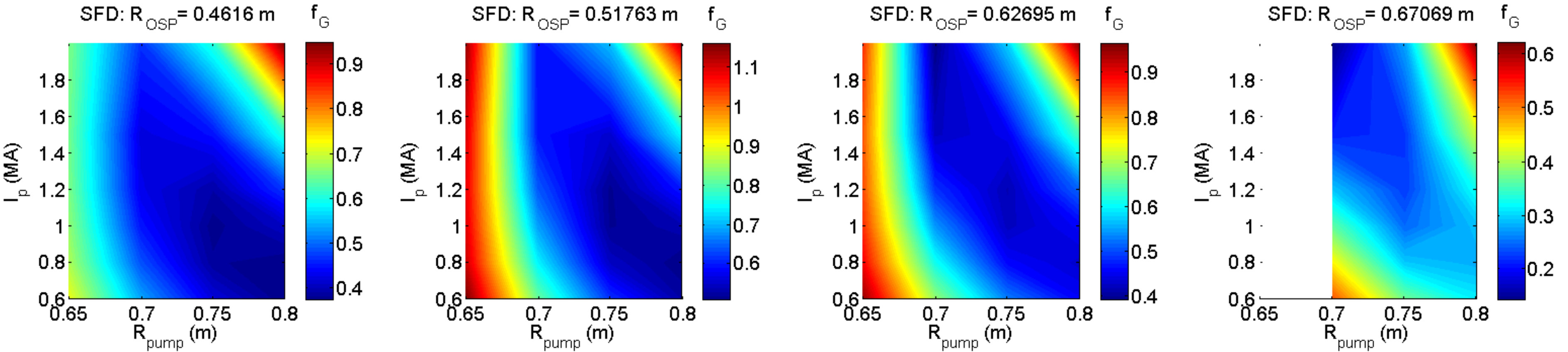
- Heat flux profiles, T_e^{div}, and optimized entrance parameters used in analytic model for plenum pressure
- Optimizing position for narrowest SOL gives R_{pump}~0.72
  - Narrow SOL gives least flexibility in moving R_{OSP} to improve pumping



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

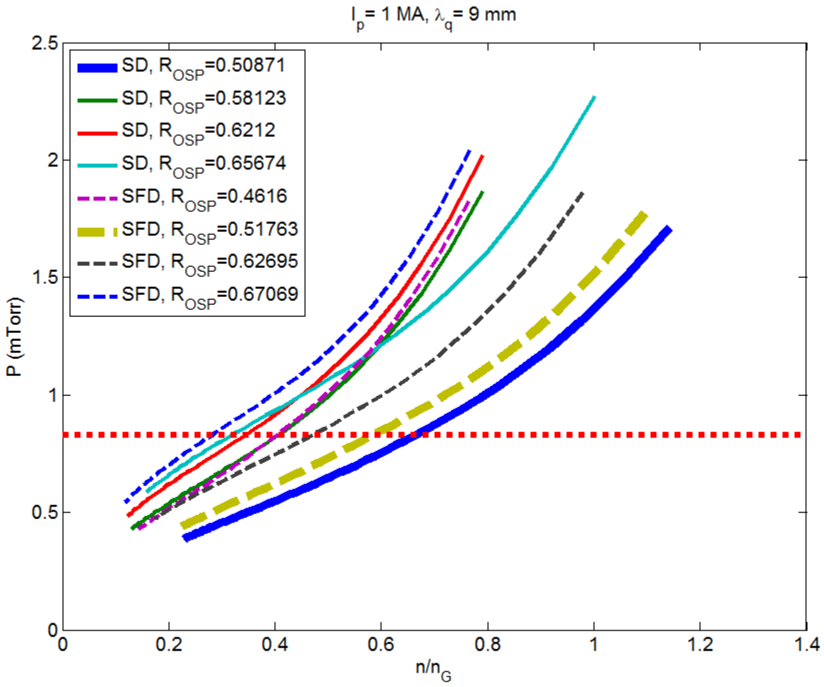


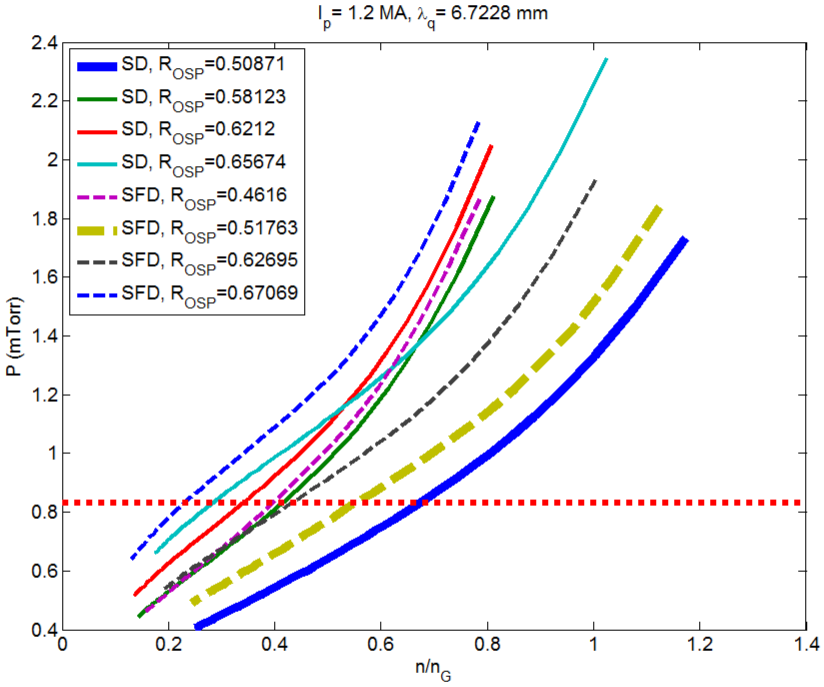
- $q_{||}$sep, T_e^{div} used in modified 2-pt model used to estimate n_e^{sep}
  - $q_{||}^{sep}$ from I_p scaling, T_e^{div} varied
- n_e/n_e^{sep} ~ 3 assumed to estimate f_G
- f_G shown is that at which pumped flux balances NBI input



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

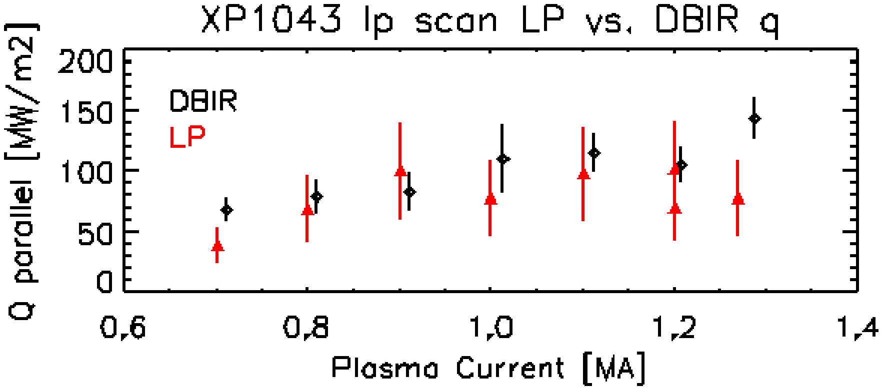
- Volumetric loss terms can be included via f_{power} term
- Term can be estimated with interpretative modeling in lieu of better div. Bolom. Coverage
- Comparison of nominal LP and DBIR results are encouraging
- Two values of fpower used following: 0 and 0.5

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

$$F_u = F_t$$

$$P_u A_u = P_t A_t$$

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

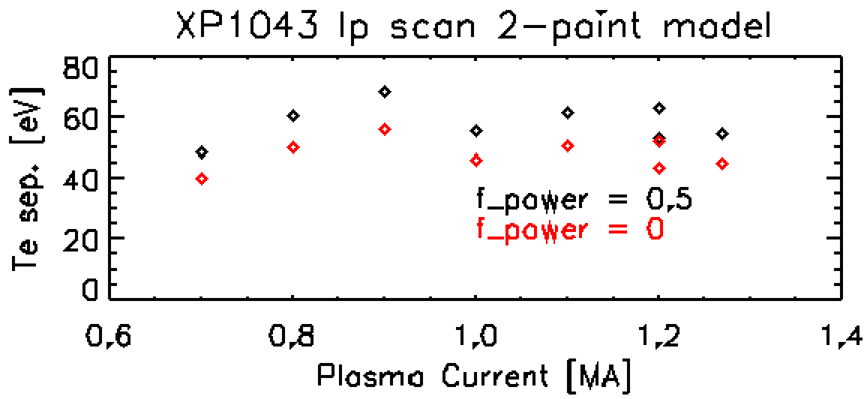
$M = v / c_s \geqslant 1$ Mach No. at sheath

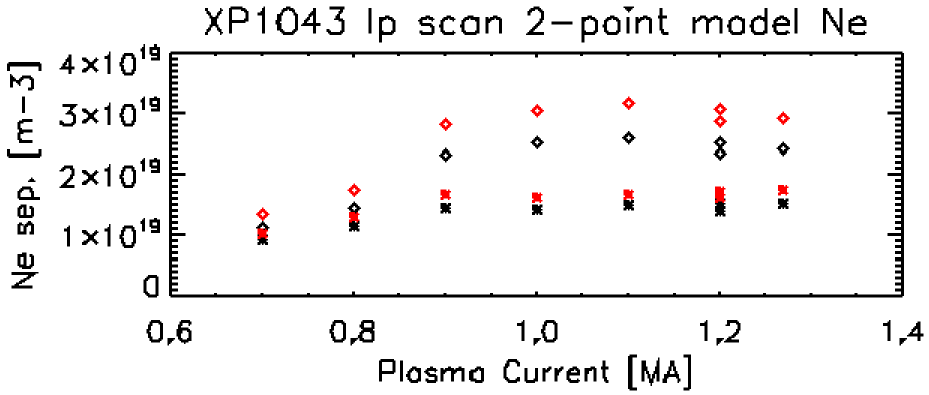
$$B\,A = \Psi_0 = const. \rightarrow \frac{A_t}{A_u} = \frac{B_u}{B_t}$$

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

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

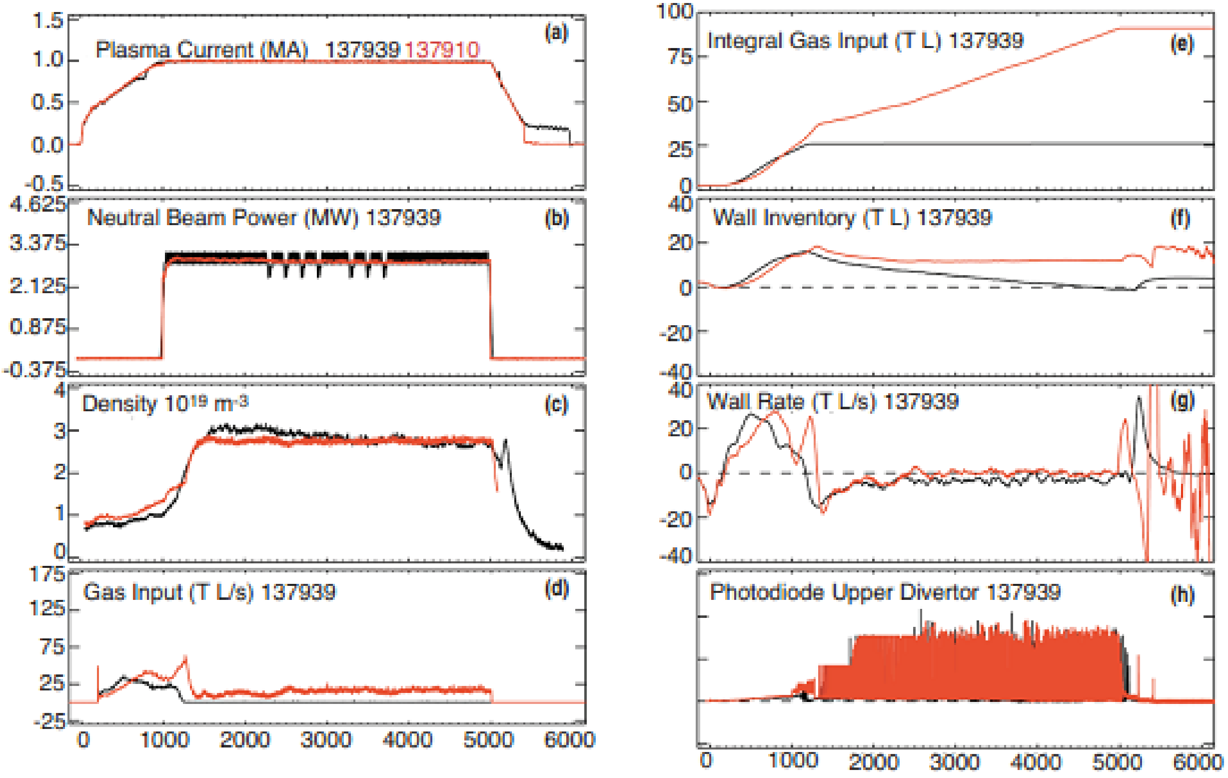


Fig. 2. ECH heated (red) H-mode plasma is compared with a NBI (black) discharge. The plasma current, neutral beam or ECH power, electron density, gas input, integral of the gas input; wall inventory and wall rate from the dynamic particle balance; along with the photodiode signal are compared with a 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.