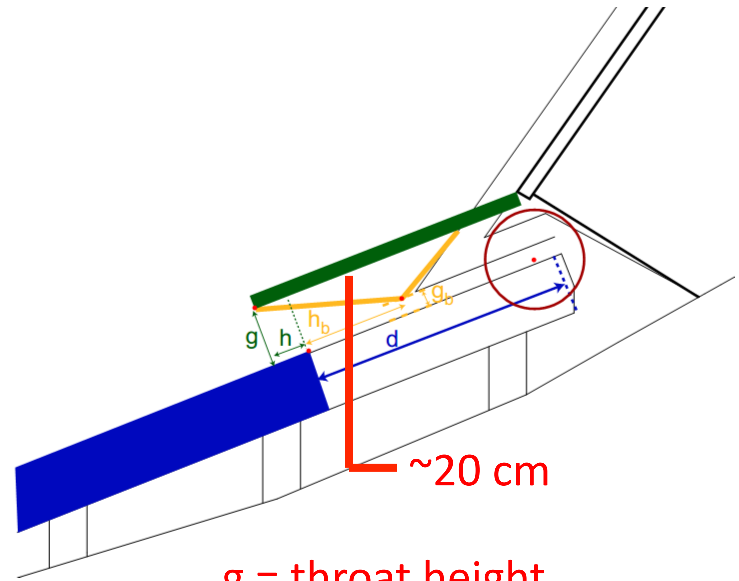
Status of cryopump analysis for NSTX

Some assumed pump parameters

- Pump parameters based on Menon design (similar to D3D)
  - S=24,000 l/s @ R=1.2m
  - Need plenum pressure of 0.83 (~1) 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
  - Assumes that throat conductance is much smaller than conductance to pump within plenum
    - Probably ok as long as "g" is much smaller than the height of the rest of the plenum
    - "g_b" looks like the only threat to this
- To optimize, need C(g,h), I_0(g,h)



g = throat height
h = throat length

Analytic pumping model* used to optimize pumping chamber

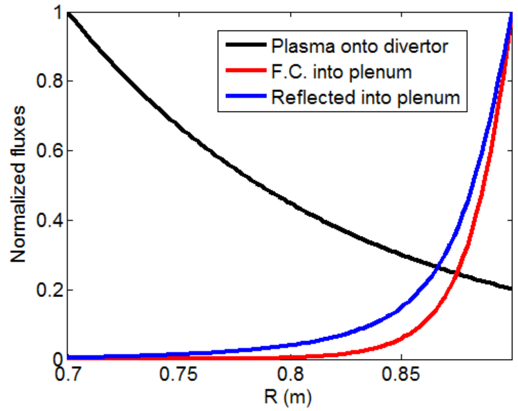
- Uses first-flight model for neutral flux into pump plenum
- Requires knowledge of divertor plasma profiles
- Validated against DIII-D experiments

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

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

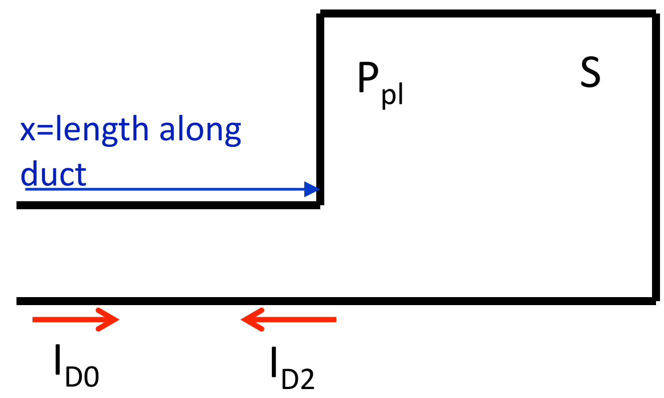


Origin of neutrals making it into plenum tends to be localized to near-entrance region

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

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

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

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

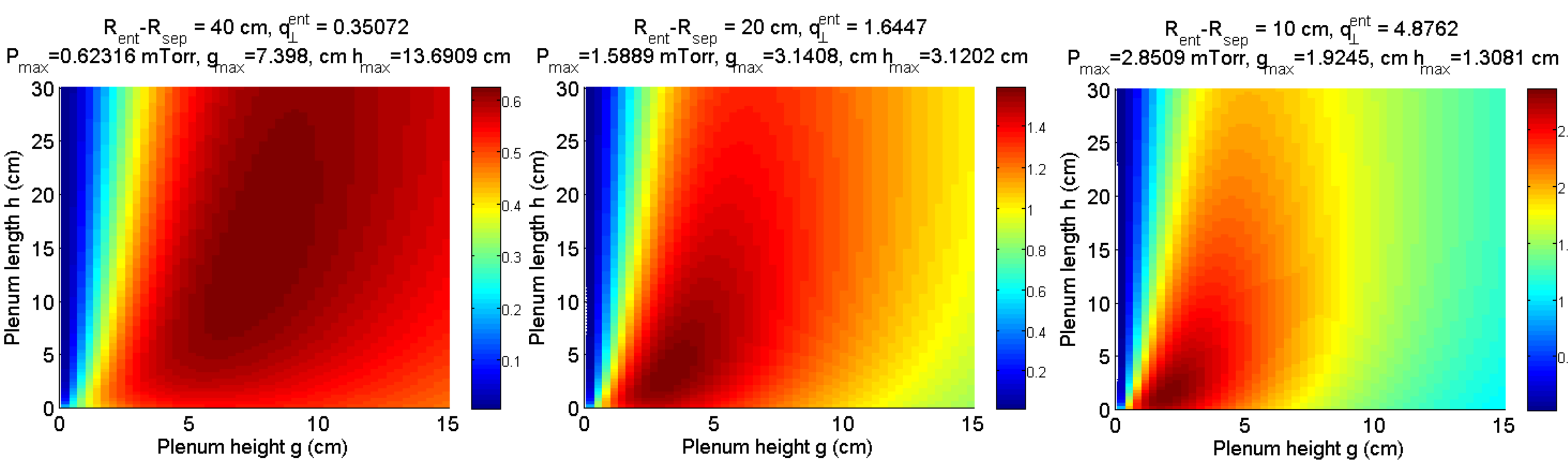
Plasma parameters are estimated to optimize plenum geometry

- Assume heat flux (scaling expts), angle of B wrt surface (α, LRDFIT), and plasma temperature ("typical" T_e from HDLP), -> density and particle flux profiles:

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

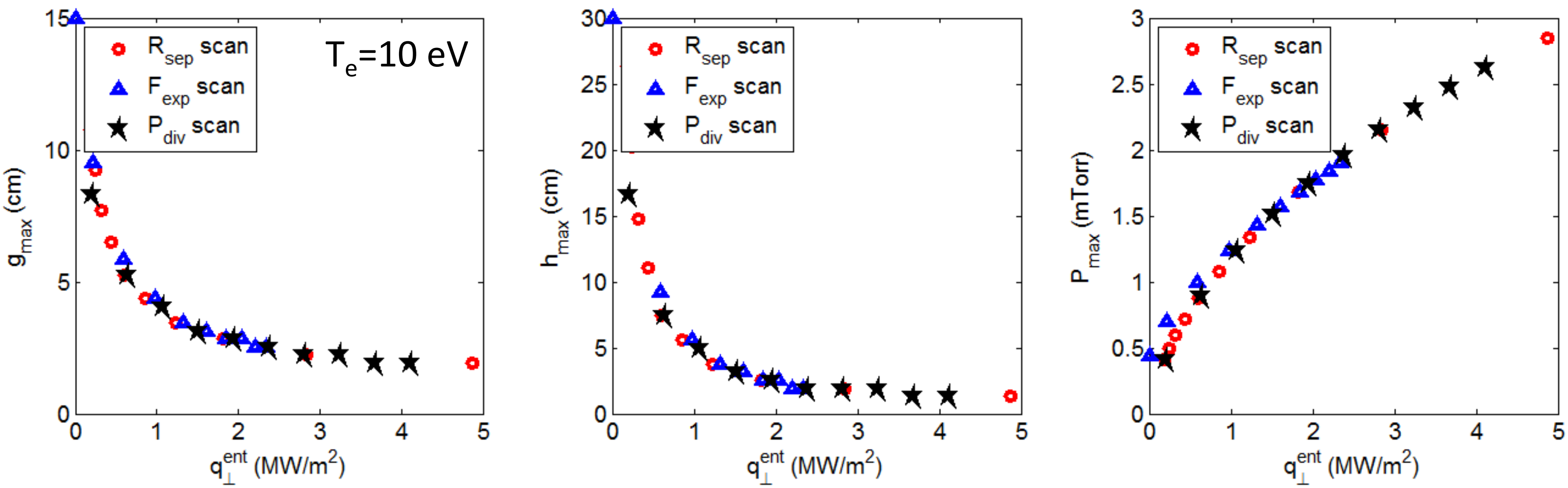
$$n = \Gamma_\perp / \left(\sin\alpha \sqrt{2T/m} \right)$$

- Radial $q_\perp$ profiles used for calculations below, with T_e=10.0 eV
  - P_{div} = 4MW, λ_q=0.5cm, f_{exp}=25
  - A few outer strike point positions tried



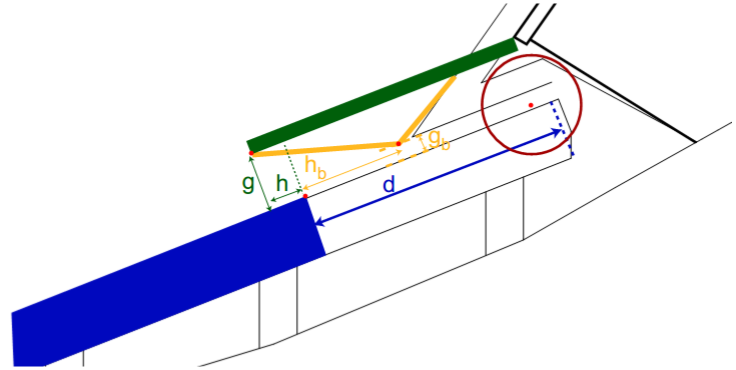
Heat flux at pump entrance orders the "optimal" pump geometry parameters

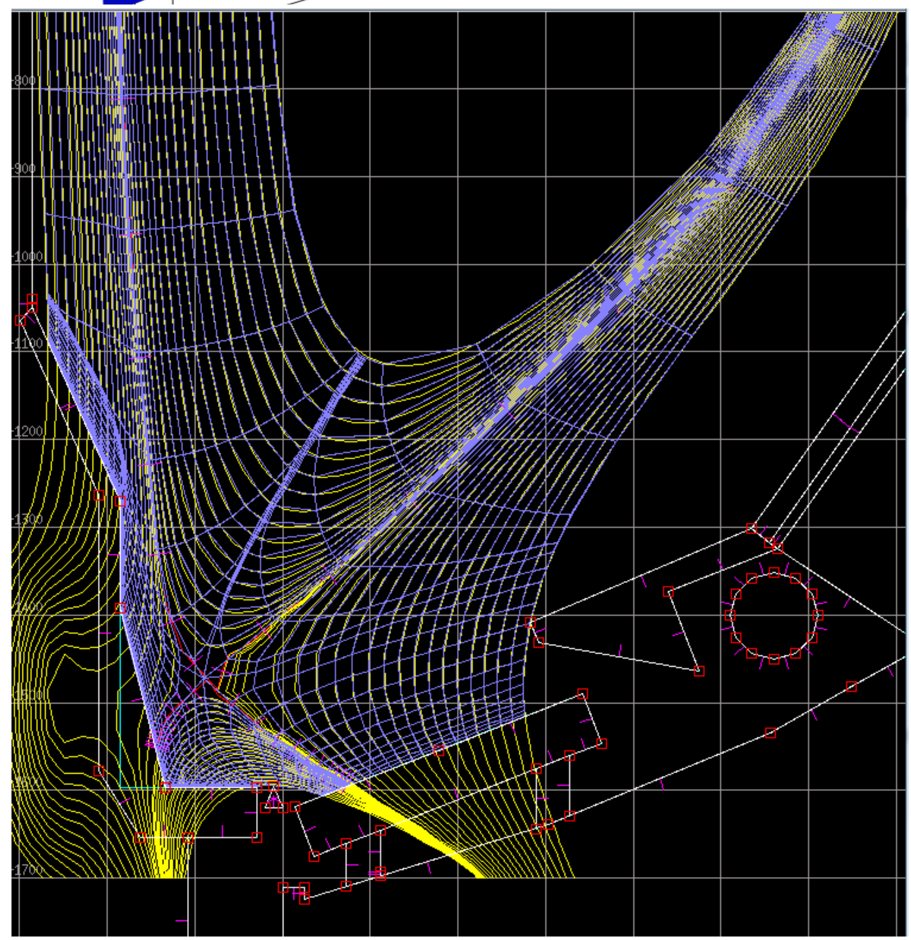
- Optimal throat height/length depend mainly on heat flux near entrance
  - Doesn't matter if it's varied by moving the OSP, changing flux expansion, or changing total power
  - T_e affects maximum pressure achievable, but only weakly affects g/h
- Optimizing for P=1mTorr at T_e=10.0 eV gives g~4 cm, h~5 cm at q~1MW/m^2
  - Need more concrete projections for heat flux, T_e to determine how close to OSP plenum entrance needs to be



Next up: SOLPS modeling (first attempt shown here)

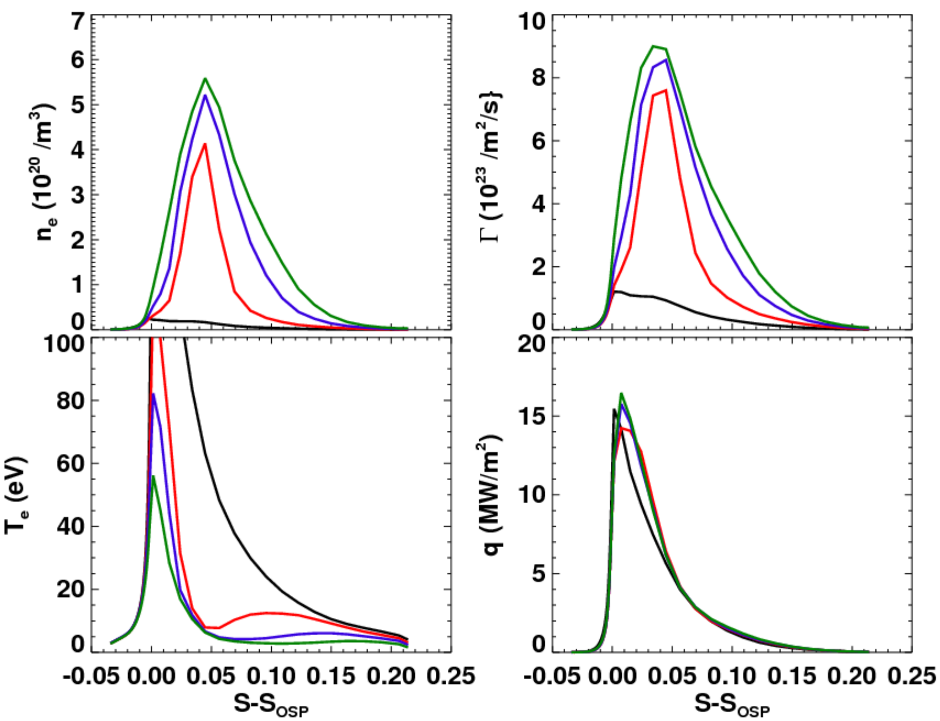
- New equilibrium developed
  - Outer leg flared onto outer divertor
  - Should be good for pumping
- Initial cryo geometry roughly matching optimized parameters
- Constant D=0.5, $\chi_{e,i}$=2.0 m^2/s
  - Gives λ_q^{mid} ~ 5mm
  - But no attempt to match expt
- P=10MW
- n_e at core boundary fixed
  - Particle throughput not controlled, but easy to do density scan
- So far only pumping at target
  - No pumping at cryo
  - Measure P at cryo (will be reduced with pump on)

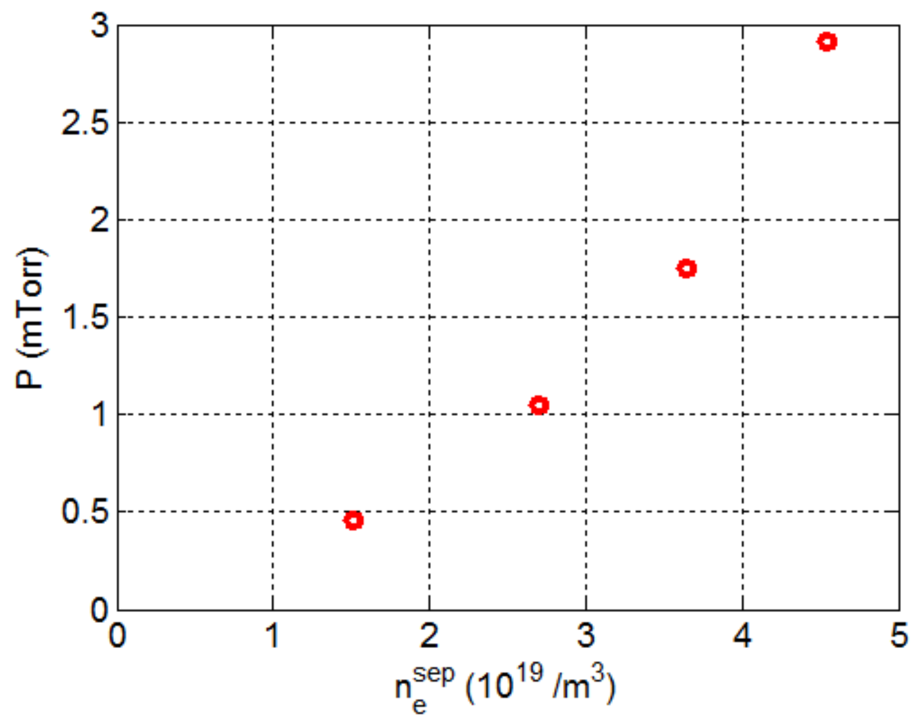




Plenum pressure vs. n_e^{sep}

- Outer divertor profiles shown for density scan (n_e^{core}=3/5/7/9 10^{19} /m^3)
- P>1 mTorr at higher densities/lower temperatures
  - Enough for pumping?
  - This is the pressure without the cryo; will be reduced when pumping is turned on
- So far no attempt to match present experimental profiles
  - Will need radially varying transport coefficients
  - Need to improve basis for projecting near-plenum plasma parameters

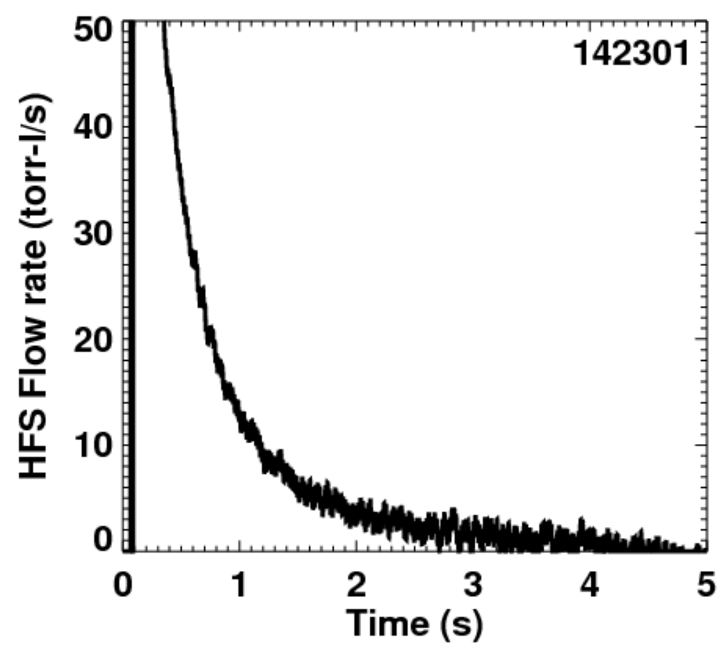




Backup

How much pumping do we need?

- Neutral beam input
  - D3D beams ~2.1 torr-l/s per MW
  - Think we went through this last year, NSTX similar
  - So 10 MW = 21 torr-l/s
- Gas puff can probably be made small for long pulse shots
  - So far CS valve is generally used
  - Can't be turned off during short shots, but can after ~2 s
- So to pump high PNBI shots during later phases of long shots, aim for pumping rate of ~20 torr-l/s
  - To pump before 2s, either increase pumping or replace HFS puff



Conductance vs. throat height

- Conductance through an aperture* (m^3/s, m; molecular flow)

$$C = \frac{\bar{v}}{4} A \approx 36.5 A \sqrt{T / M} \approx 313 A \approx 1970 R_{ent} g$$

- Through a duct of length h (again, units are m and m^3/s)*

$$C = \frac{4}{3} \bar{v} \Big/ \int_0^h \frac{H}{A^2} dl \approx 195 \sqrt{T/M} \frac{A^2}{Hh} \approx 5.3 \times 10^3 \, Rg^2 / h$$

- Here A is the area of the aperture ($=2\pi R_{ent} g$), H is the perimeter length of the aperture ($=4\pi R_{ent}$), and h is the length of the duct
  - I'm ignoring toroidal effects (i.e., treating H and A as constant in the integral)
  - And I've assumed room temperature D2 (sqrt(T/M)~8.59)

- These add in series as 1/Ctot = 1/Cap + 1/Cduct

- For Menon's parameters (g=0.028, h=0.136, R_{ent}=1.0) I get:
  - C_aperture = 55,000, C_duct = 30,500, C_tot = 19,600 l/s
  - He get's 21,000, but he's probably doing things like accounting for toroidicity (boring!)

*Need to check this, correct me if it's wrong

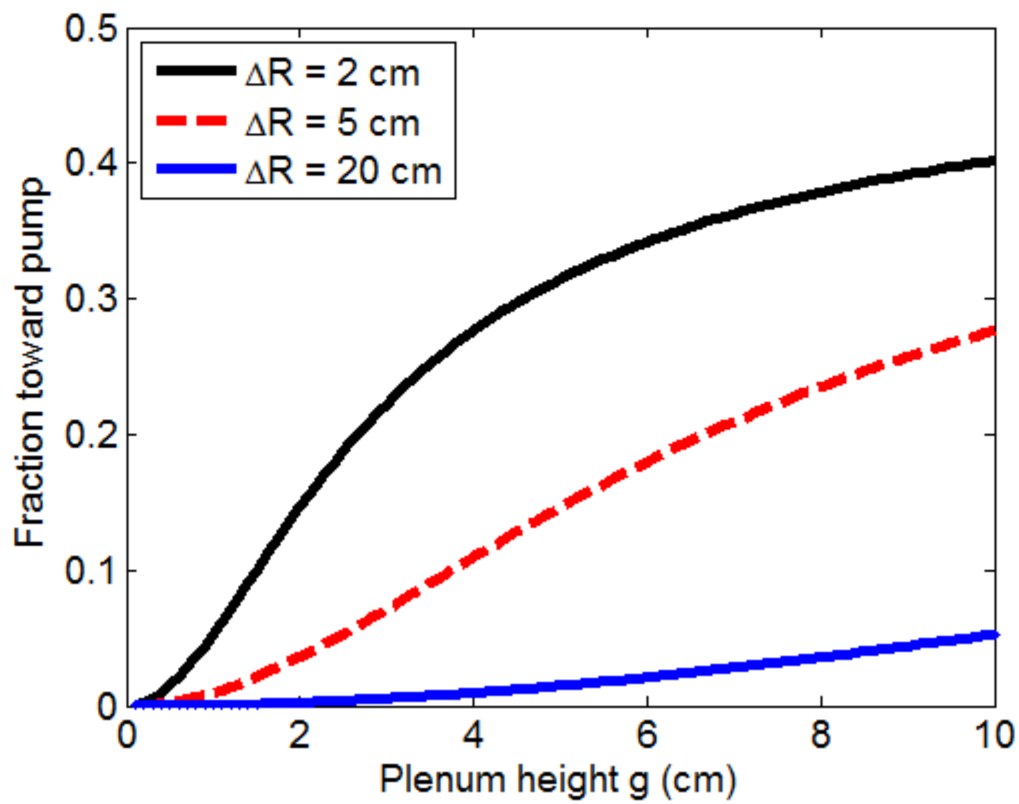
Neutral flux into plenum vs. throat height

- Fraction of neutrals heading towards plenum entrance is

$$F(r) = \frac{1 - \cos\Theta_{\max}(r)}{2}$$

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

- This will depend on the distance from the entrance of the origin of the neutrals
  - Which depends on the neutral mfp for ionization by the plasma
  - For now we can consider a few characteristic radii



Transmission probability of neutrals through divertor plasma

- Transmission factor for Franck-Condon D (i.e., fraction not ionized on its way to the plenum entrance):

$$T(r) = \frac{I_0^{plen}(R_{\max})}{I_0^{plen}(R)} = \exp\left[\frac{-1}{v_0}\int_R^{R_{\max}} n_e(r)\langle\sigma v\rangle_{EII}(r)\,dr\right]$$

- To estimate this, assume heat flux (perpendicular to divertor surface), angle of B wrt surface (α), and plasma temperature, use this to infer density and particle flux profiles

$$\Gamma_\perp = q_\perp / 7T$$
$$n = \Gamma_\perp \Big/ \left(\sin\alpha\sqrt{2T/m}\right)$$

- In the example shown, two plasma Temperatures are used: 20 eV and 3eV Radially constant profiles used, with α=5°
- T doesn't matter much (n<σv>~constant)
- Neutral fall-off lengths in this case ~0.8-8 cm
  - Let's start with throat height of 5 cm