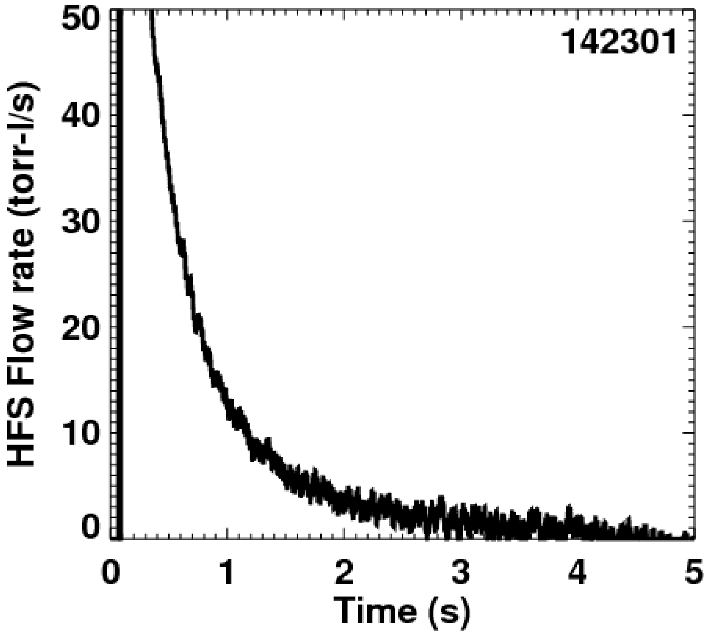
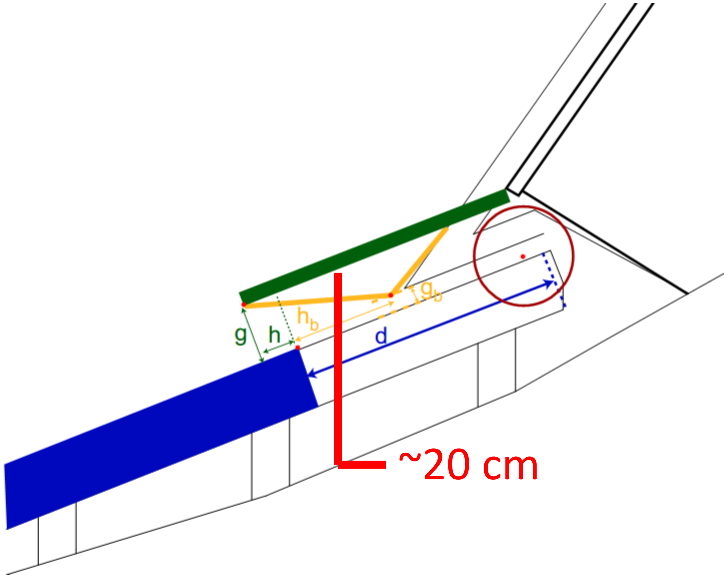
Some notes on cryo pumping for NSTX

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



Some pump parameters



- Menon design (similar to D3D)
  - S=24,000 l/s @ R=1.2m
  - Need plenum pressure of 0.83 (~1) mtorr
- 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)

Conductance vs. throat height

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

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

- 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

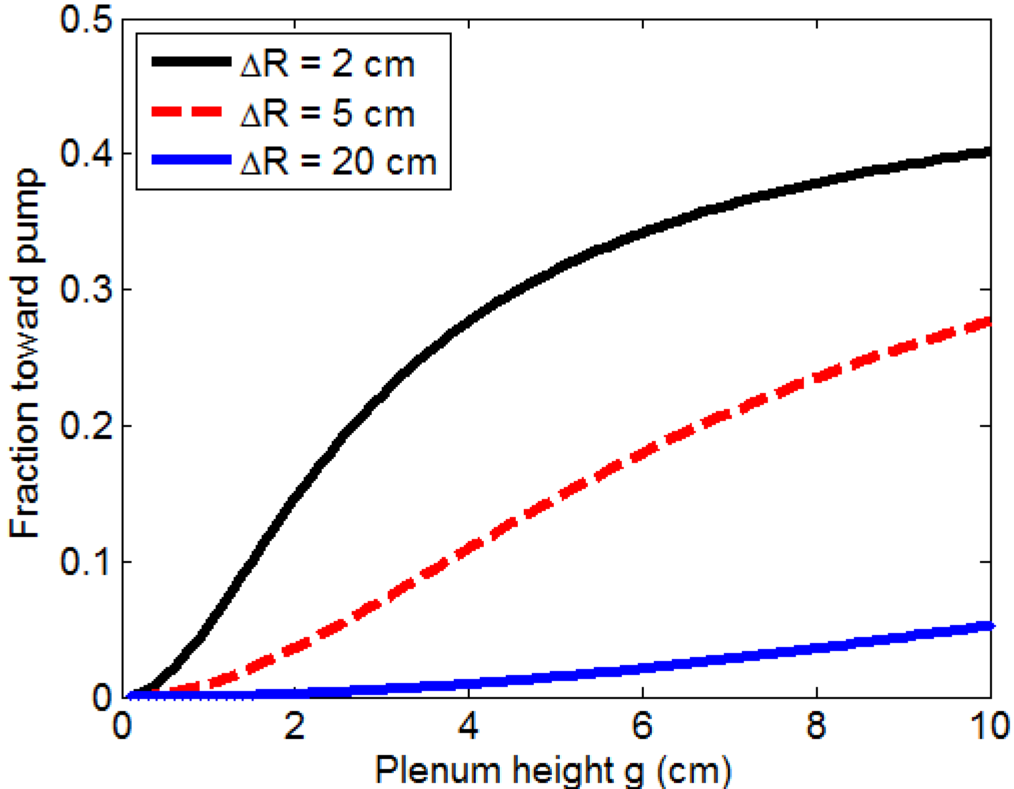
Neutral flux into plenum vs. throat height

- Fraction of neutrals heading towards plenum entrance is

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

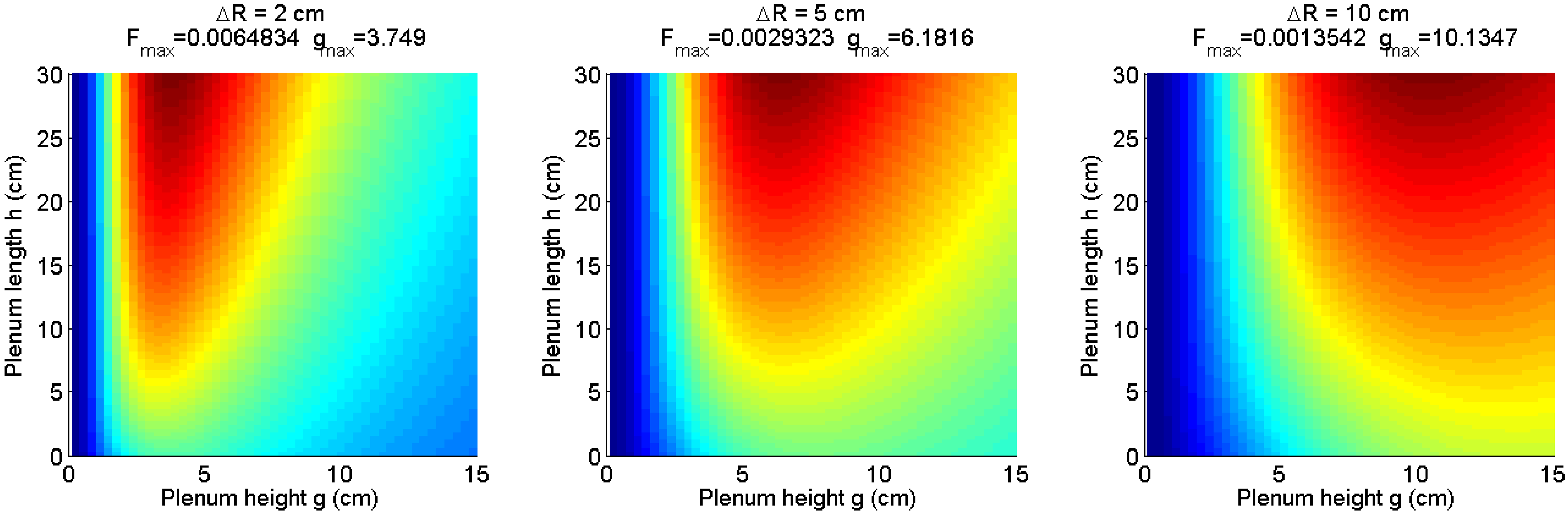
$$\Theta_{\max}(r) = \tan^{-1}\left(\frac{g}{R - R_{ent}}\right)$$

- 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



Maximizing pumping: geometry only

- Want to maximize $I_0/(S+C)\sim F/(S+C)$ (contours below, $R_{ent}=0.9$)
  - S=24,0000 l/s
  - C increases with g, decreases with h
  - I_0 increases with g, independent of h
- Make h as large as possible (minimizes C without hurting I_0)
- Optimum g depends on where the neutrals are coming (ΔR)
  - Roughly speaking, make $g\sim\Delta R$



ΔR = 2 cm
F_{max}=0.0064834 g_{max}=3.749

ΔR = 5 cm
F_{max}=0.0029323 g_{max}=6.1816

ΔR = 10 cm
F_{max}=0.0013542 g_{max}=10.1347

But this isn’t quite the right way to calculate conductance

- So far this method assumes that any neutral crossing the plenum entrance plane is “in the plenum.”
  - We’re assuming here that there’s a current of “fast” D originating from the plasma flux, balance by a current of thermal D2 coming out of the plenum
  - But if a fast D hits the duct wall and is thermalized before it makes it through into the larger volume, can we count it in the fast current?
  - For example, if there’s a bend in the throat, no fast neutrals will make it past the bend, and so you shouldn’t count the conductance of the throat past the bend
    - So there’s zero fast neutrals making it all the way into the plenum, but there’s still a pressure drop along the throat up to the bend

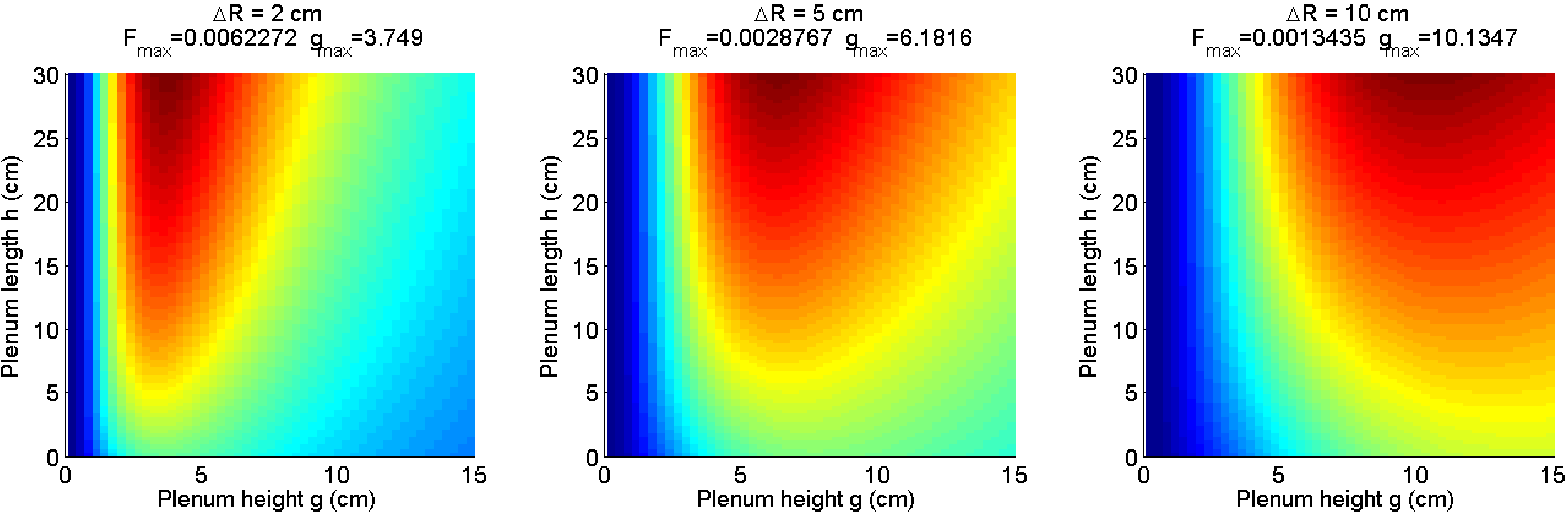
Better calculation of effective conductance: doesn't make a difference

- Instead of P=I/C (with no pumping), use

$$\Delta P = \int_{o}^{h} I(l)\sigma(l)dl \qquad C = \frac{4}{3}\bar{v} \Big/ \int_{o}^{h} \frac{F(l)}{F(0)}\frac{H}{A^2}dl \approx 1.7\times 10^3 \Big/ \int_{o}^{h} \frac{F(l)}{F(0)}\frac{H}{A^2}dl$$

$$\sigma = \frac{3}{4\bar{v}}\frac{H}{A^2}$$

- Where I(l) is the fast D current
- Assume that fast D is stopped and thermalized on hitting the duct wall. Then I is proportional to the solid angle factor F(l) along the duct (not at the entrance only) ->define an effective conductance (above)



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):

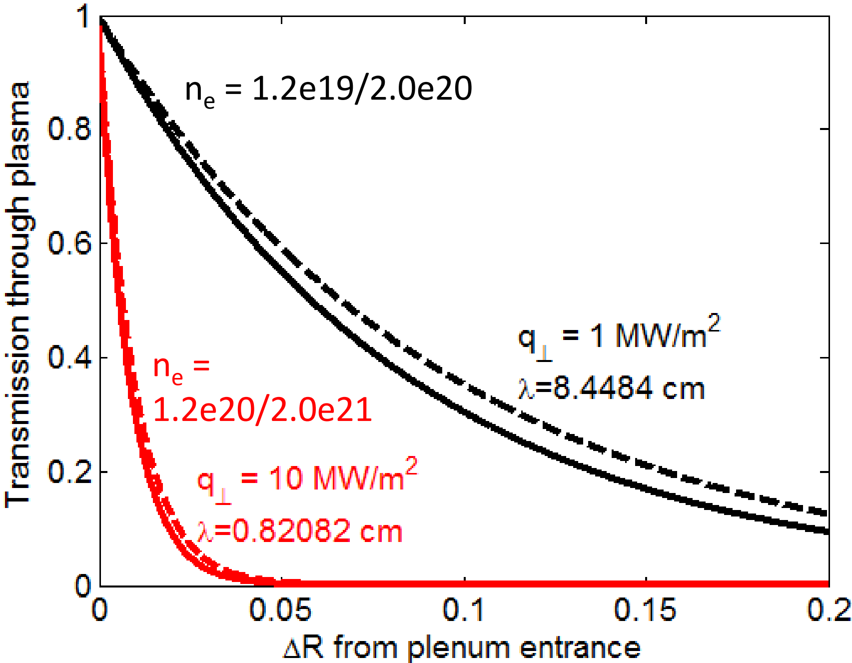
$$T(r)=\frac{I_0^{plen}(R_{\max})}{I_0^{plen}(R)}=\exp\left[\frac{-1}{v_0}\int_R^{R_{\max}} n_e(r)\langle\sigma v\rangle_{EII}(r)\,dr\right]$$

- 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

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

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

- 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

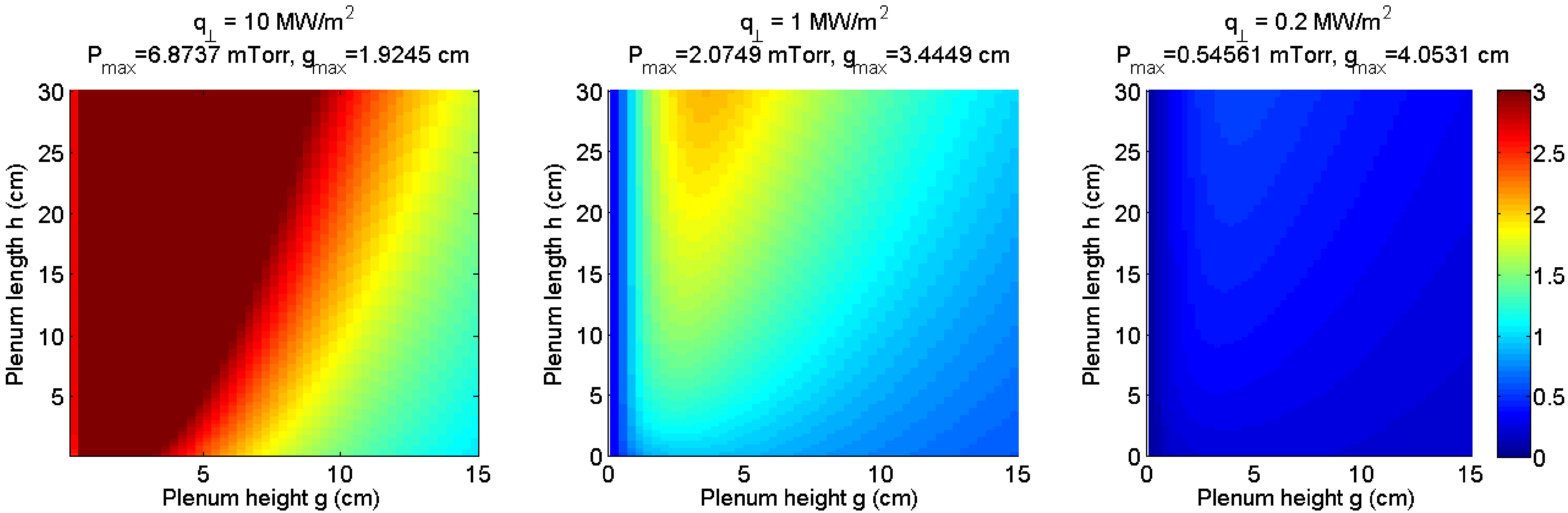


Optimizing for plenum pressure directly

- Now we have everything to calculate the plenum pressure:

$$P_{pl} = \frac{I_0}{S+C}, I_0 = \int_{R_{\min}}^{R_{\max}} \Gamma_0(r) F(r) \mathit{\Gamma}(r) 2\pi R_m dr$$

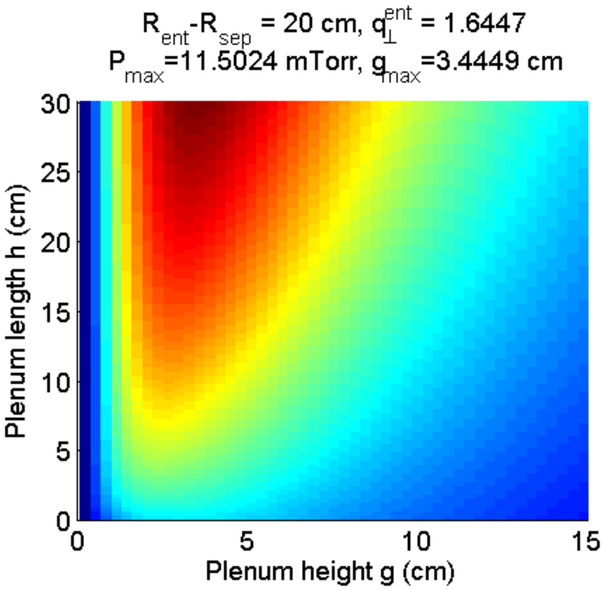
- To start with, use radially constant $q_\perp$ and T_e profiles to define plasma parameters, as on previous slide
  - Neglects profile effects, but the neutral flux into the plenum is dominated by near-entrance region
  - First case: T_e = 10.0 eV
  - Still the case that the longer the duct, the better
  - Best height depends on plasma parameters, but in the range of a few cm



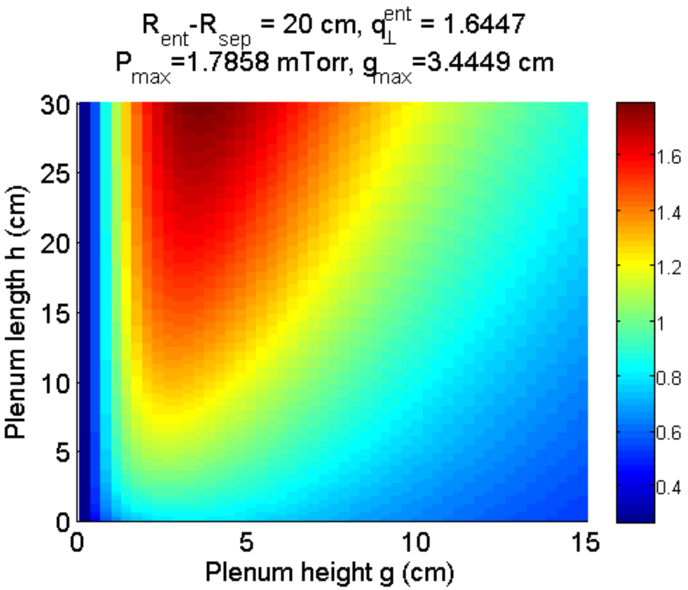
Including radial profiles

- Assume R_{sep}, λ_q, flux expansion, total power to divertor to get heat flux profile, then use T_e=const again to get n_e, Γ
- Here P_{div} = 4MW, λ_q=0.5cm, f_{exp}=25 used (q^{pk}=10MW/m^2)
  - Choice of T_e only affects magnitude of pressure, not g/h dependence
  - Profile of T_e might change this, but again pumping is dominated by near-entrance region

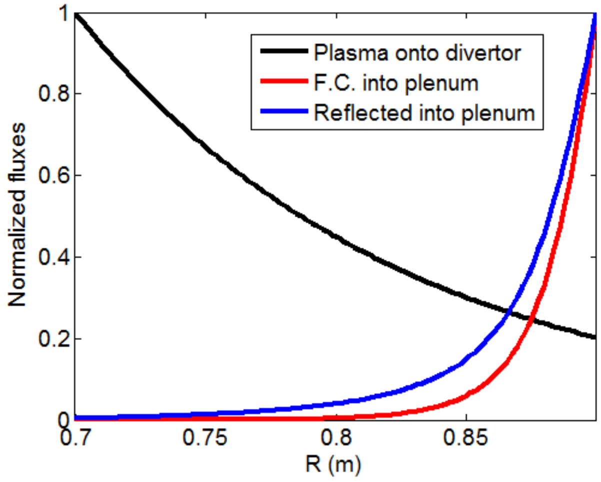
T_e=3eV



T_e=20eV

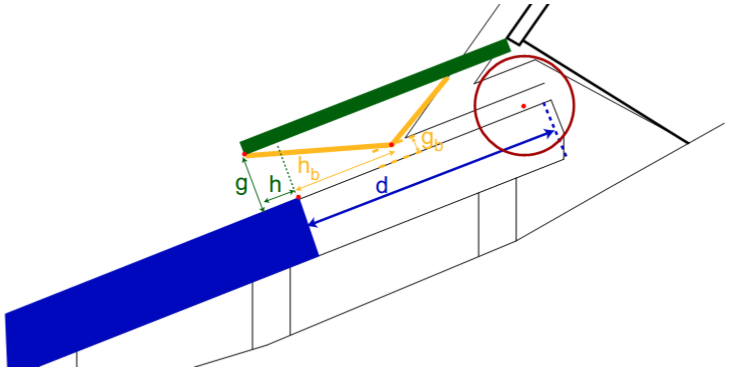


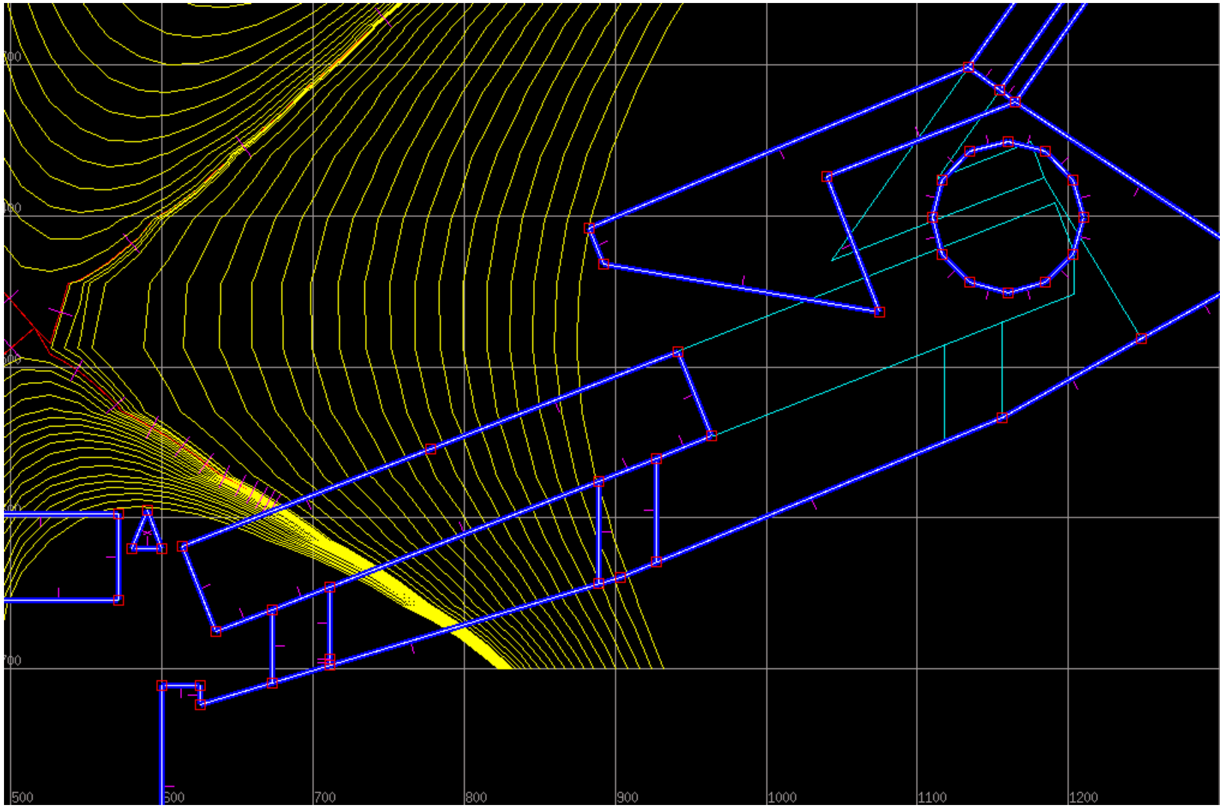
T_e=20eV



Maximizing h in NSTX geometry

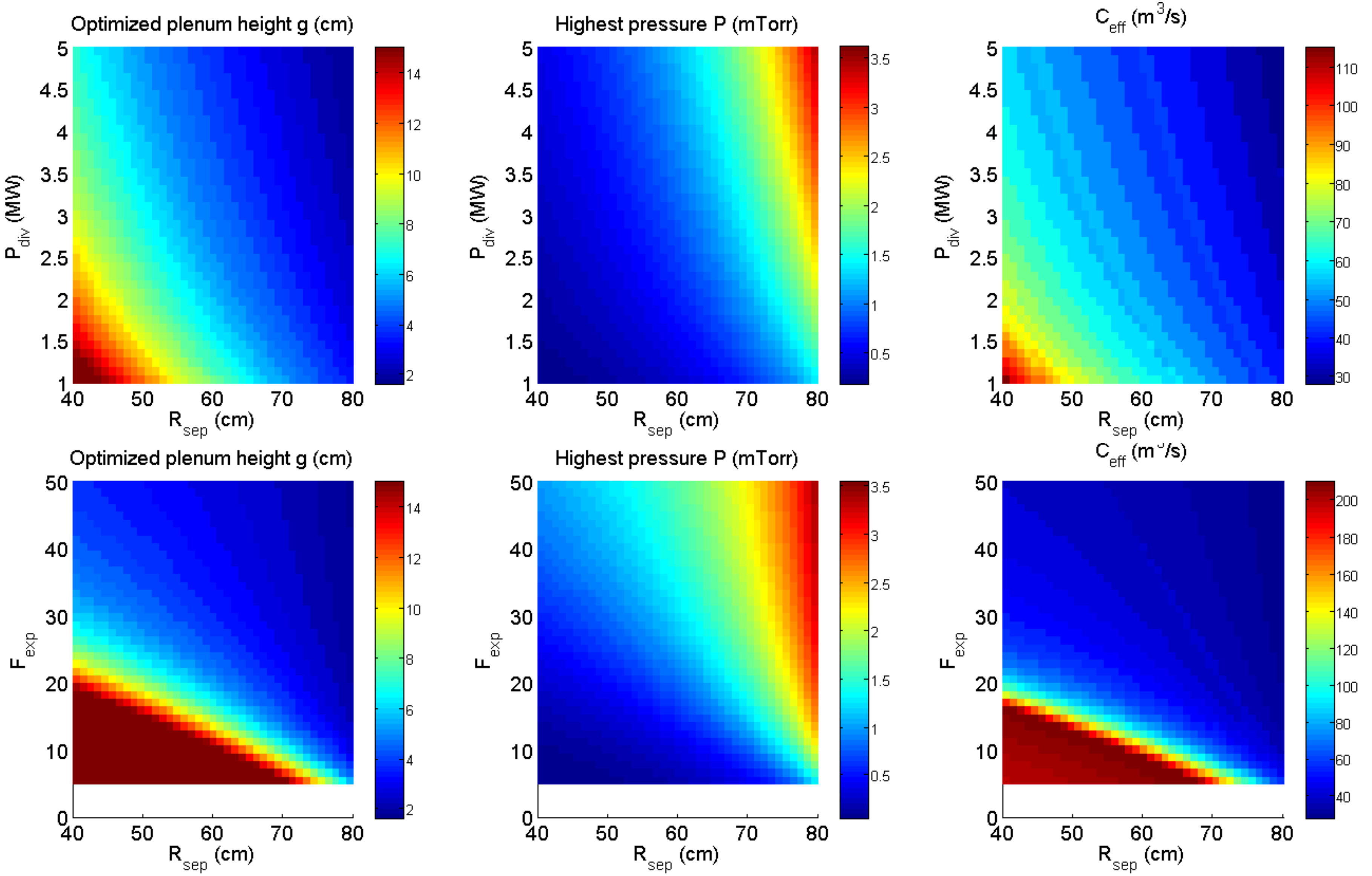
- Blue lines are Daren’s fist pumping chamber outline
- Thinner green lines represent the present NSTX hardware
- Can only make about 20 cm before running into pump
- So from now on, assume h=20 cm





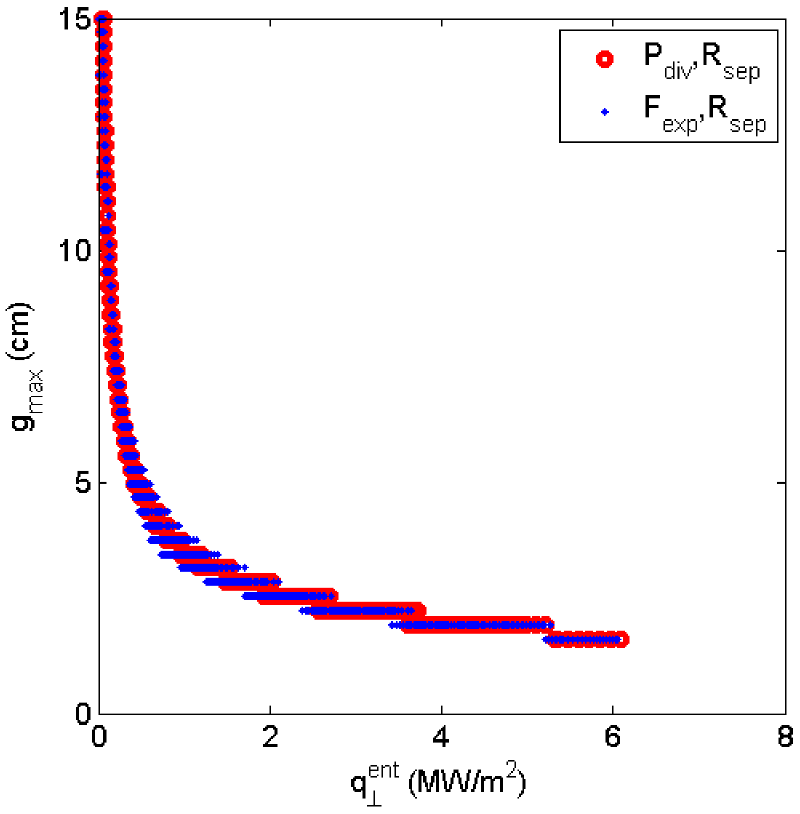
“Best” g for h=20cm, range of R_{sep}, f_{exp}, and P_{div}

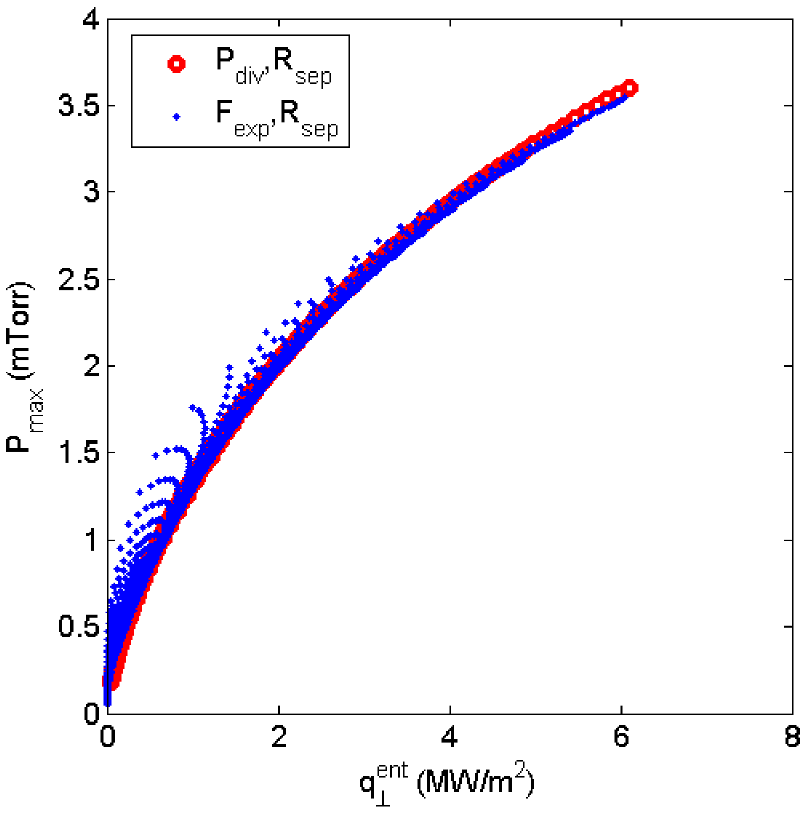
- Fixed λ_q=5mm, T_e=10 eV



Heat flux near duct entrance orders results

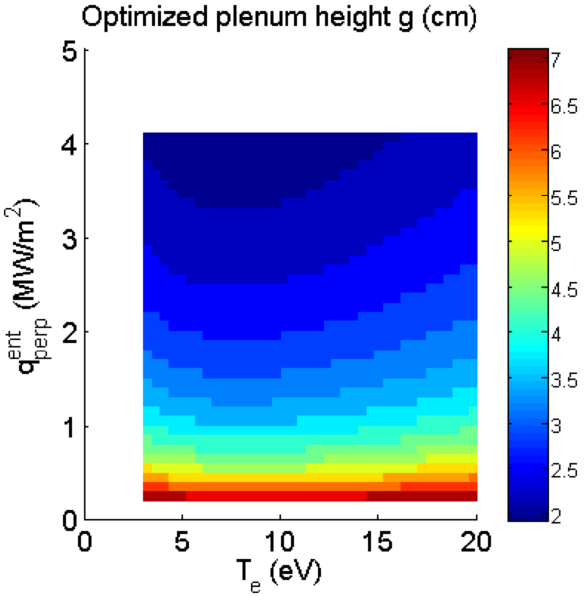
- Previous slide: heat flux varied by scanning separatrix, flux expansion and total power
- Despite profile changes, g_{max} and P follow heat flux near plenum
  - So what we really need to know are the parameters near entrance
  - E.g., heat flux from recent scaling experiments, and characteristic T_e

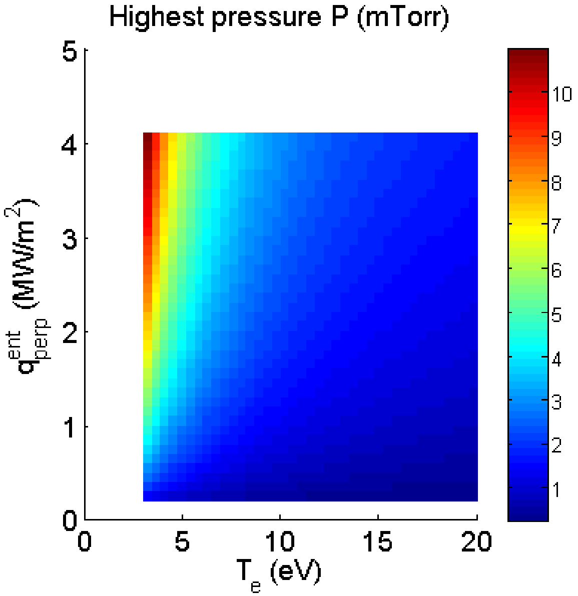


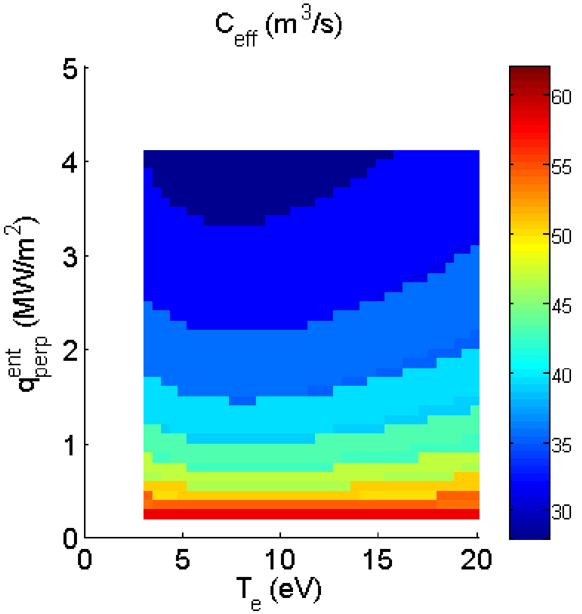


“Best” g, P_{max}, variations with $q_{\perp}^{ent}$, T_e

- The lower the T_e and higher $q_{\perp}^{ent}$, the higher P
  - Both make Γ higher
  - Pretty broad range with P > 1 mTorr
  - Optimal duct height pretty much tracks 1/q
    - Tall entrance (7cm) best for low power
    - But even so, P might be too low (< 1 mTorr)


Optimized plenum height g (cm)


Highest pressure P (mTorr)


C_{eff} (m^3/s)